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Watershed modeling to assess the sensitivity of streamflow, nutrient and sediment loads to potential climate change and urban development in 20 U.S. watersheds

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Watershed Modeling to Assess the Sensitivity of Streamflow, Nutrient, and Sediment Loads to Potential Climate Change and Urban Development in 20 U.S. Watersheds

National Center for Environmental Assessment
Office of Research and Development
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DISCLAIMER

ABSTRACT

Watershed modeling was conducted in 20 large, U.S. watersheds to characterize the sensitivity of streamflow, nutrient (nitrogen and phosphorus), and sediment loading to a range of plausible mid-21st century climate change and urban development scenarios. The study also provides an improved understanding of methodological challenges associated with integrating existing tools (e.g., climate models, downscaling approaches, and watershed models) and data sets to address these scientific questions. The study uses a scenario-analysis approach with a consistent set of watershed models and scenarios applied to multiple locations throughout the nation. Study areas were selected to represent a range of geographic, hydrologic, and climatic characteristics. Watershed simulations were conducted using the Soil Water Assessment Tool (SWAT) and Hydrologic Simulation Program―FORTRAN (HSPF) models. Scenarios of future climate change were developed based on statistically and dynamically downscaled climate model simulations representative of the period 2041−2070. Scenarios of urban and residential development for this same period were developed from the EPA's Integrated Climate and Land Use Scenarios (ICLUS) project. Future changes in agriculture and human use and management of water were not evaluated.

Results provide an improved understanding of the complex and context-dependent relationships between climate change, land-use change, and water resources in different regions of the nation. As a first-order conclusion, results indicate that in many locations future conditions are likely to be different from past experience. Results also provide a plausible envelope on the range of streamflow and water quality responses to mid-21st century climate change and urban development in different regions of the nation. In addition, in many study areas the simulations suggest a likely direction of change of streamflow and water quality endpoints. Sensitivity studies evaluating the implications of different methodological choices help to improve the scientific foundation for conducting climate change impacts assessments, thus building the capacity of the water management community to understand and respond to climate change. This information is useful to inform and guide the development of response strategies for managing risk.

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LIST OF ABBREVIATIONS

ACE	air, climate, and energy
AET	actual evapotranspiration
ANOVA	analysis of variance
BASINS	Better Assessment Science Integrating Point and Nonpoint Sources
BCSD	bias-corrected and statistically downscaled
CAT	Climate Assessment Tool
CCSM	Community Climate System Model
cfs	cubic feet per second
CGCM3	Third Generation Coupled Global Climate Model
CMIP3	Coupled Model Intercomparison Project Phase 3
CN	curve number
CRCM	Canadian Regional Climate Model
CV	coefficient of variation
DEM	digital elevation model
E	Nash-Sutcliffe coefficient of model fit efficiency
E_1'	Garrick's baseline adjusted coefficient of model fit efficiency
ET	evapotranspiration
FTable	hydraulic functional table (in HSPF)
GCM	global climate model
GFDL	Geophysical Fluid Dynamics Laboratory global climate model
GFDL hi res	Geophysical Fluid Dynamics Lab. 50-km global atmospheric time slice model
GIS	geographic information system
HadCM3	Hadley Centre Coupled Model, version 3
HRM3	Hadley Region Model 3
HRU	hydrologic response unit
HRU	Hydrologic response unit
HSG	hydrologic soil group
HSPF	Hydrologic Simulation Program—FORTRAN
HUC	hydrologic unit code
HUC-2	HUC 2-digit watershed
HUC-4	HUC 4-digit watershed
HUC-8	HUC 8-digit watershed
HUC-10	HUC 10-digit watershed
ICLUS	Integrated Climate and Land Use Scenarios
IMPLND	impervious land segment (in HSPF)
INFILT	nominal infiltration rate parameter (in HSPF)
IPCC	Intergovernmental Panel on Climate Change
LZETP	lower zone evapotranspiration parameter
LZSN	lower soil zone nominal soil moisture storage
MSL	mean sea level
MUSLE	Modified Universal Soil Loss Equation
NARCCAP	North American Regional Climate Change Assessment Program
NARR	North American Regional Reanalysis
NCAR	National Center for Atmospheric Research

LIST OF ABBREVIATIONS (continued)

ND	no data
NHD	National Hydrography Dataset
NLCD	National Land Cover Dataset
NRCS	Natural Resource Conservation Service
PCS	Permit Compliance System
PERLND	pervious land segment (in HSPF)
PET	potential evapotranspiration
PRMS	Precipitation Runoff Modeling System
QAPP	Quality Assurance Project Plan
RCHRES	stream reach segment (in HSPF)
RCM	regional climate model
RCM3	Regional Climate Model, version 3
SERGoM	Spatially Explicit Regional Growth Model
SPARROW	Spatially-Referenced Regression On Watershed attributes
STATSGO	State Soil Geographic Database
SWAT	Soil Water Assessment Tool
TMDL	total maximum daily load
TN	total nitrogen
TP	total phosphorus
TSS	total suspended solids
UCI	user control input file (in HSPF)
U.S. EPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey
USLE	Universal Soil Loss Equation
WDM	watershed data management binary file (for HSPF)
WinHSPF	Windows interface to Hydrologic Simulation Program—FORTRAN
WRFP	Weather Research and Forecasting Model
WXGEN	weather generator (in SWAT)

PREFACE

This report was prepared by U.S. Environmental Protection Agency (EPA)'s Air, Climate, and Energy (ACE) research program, located within the Office of Research and Development. The ACE research program is designed to address the increasingly complex environmental issues we face in the 21^{st} century. The overarching vision of ACE is to provide the cutting-edge scientific information and tools to support EPA's strategic goals of protecting and improving air quality and taking action on climate change in a sustainable manner.

Climate change presents a risk to the availability and quality of water resources necessary to support people and the environment. EPA, with Contractor support from Tetra Tech, Inc., recently completed a large-scale modeling effort to assess the sensitivity of streamflow and water quality in different regions of the nation to a range of mid-21^{st} century climate change and urban development scenarios. This report describes the methods, models, scenarios, and results of this project.

Responding to climate change is a complex issue. The information in this report is intended to inform and help build the capacity of EPA and EPA clients to understand and respond to the challenge of climate change. This final report reflects consideration of peer review and public comments received on an External Review Draft report released in March, 2013 (EPA/600/R-12/058A).

AUTHORS, CONTRIBUTORS AND REVIEWERS

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1. EXECUTIVE SUMMARY

There is growing concern about the potential effects of climate change on water resources. The 2007 Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) states that warming of the climate system is now unequivocal (IPCC, 2007). Regionally variable changes in the amount and intensity of precipitation have also been observed in much of the United States (Groisman et al., 2012). Climate modeling experiments suggest these trends will continue throughout the 21st century, with continued warming accompanied by a general intensification of the global hydrologic cycle (IPCC, 2007; Karl et al., 2009; Kharin et al., 2013). Over the same time horizon, human population is expected to continue to increase, with accompanying changes in land use and increased demand on water resources. In many areas, climate change is expected to exacerbate current stresses on water resources from population growth and economic and land-use change, including urbanization (IPCC, 2007). Responding to this challenge requires an improved understanding of how we are vulnerable and development of strategies for managing future risk.

This report describes watershed modeling in 20 large, U.S. drainage basins (6,000−27,000 mi^2) to characterize the sensitivity of streamflow, nutrient (nitrogen and phosphorus), and sediment loading to a range of potential mid-21st century climate futures; to assess the potential interaction of climate change and urbanization in these basins; and to improve our understanding of methodological challenges associated with integrating existing tools (e.g., climate models, downscaling approaches, and watershed models) and data sets to address these scientific questions.

Study areas were selected to represent a range of geographic, hydroclimatic, physiographic, and land-use conditions, while also meeting practical criteria such as the availability of data to calibrate and validate watershed models. Climate change scenarios are based on mid-21st century climate model projections downscaled with regional climate models (RCMs) from the North American Regional Climate Change Assessment Program (NARCCAP; Mearns, 2009) and the bias-corrected and statistically downscaled (BCSD) data set described by Maurer et al. (2007). Urban and residential development scenarios are based on the U.S. Environmental Protection Agency (EPA)’s national-scale Integrated Climate and Land Use Scenarios (ICLUS) project (U.S. EPA, 2009c). Watershed modeling was conducted using the Hydrologic Simulation Program―FORTRAN (HSPF) and Soil and Water Assessment Tool (SWAT) watershed models.

Climate change scenarios based on global climate model (GCM) simulations in the NARCCAP and BCSD data sets project a continued general warming trend throughout the nation over the next century, although the magnitude of the warming varies from place to place. Wetter winters and earlier snowmelt are likely in many of the northern and higher elevation watersheds. Changes in other aspects of local climate, such as the timing and intensity of precipitation, show greater variability and uncertainty. ICLUS urban and residential development scenarios project continued growth in urban and developed land over the next century throughout the nation with most growth occurring in and around existing urban areas. Model simulations of watershed response to these changes provide a national-scale perspective on the range of potential changes in streamflow and water quality in different regions of the nation. Simulations evaluating the variability in watershed response using different approaches for downscaling climate data and different watershed models provide guidance on the use of existing models and data sets for assessing climate change impacts. Key findings are summarized below.

There is a high degree of regional variability in the model simulated responses of different streamflow and water quality endpoints to a range of potential mid-21st century climatic conditions throughout the nation. Comparison of watershed simulations in all 20 study areas for the 2041−2070 time horizon suggests the following hydrologic changes may occur:

- Potential streamflow volume decreases in the Rockies and interior southwest, and increases in the east and southeast coasts.
- Higher peak streamflow will increase erosion and sediment transport; loads of nitrogen and phosphorus are also likely to increase in many watersheds.
- Many watersheds are likely to experience significant changes in the timing of streamflow and pollutant delivery. In particular, there will be a tendency to shift from snowmelt-dominated spring runoff systems to rain-dominated systems with greater winter runoff.
- Changes in nutrient and sediment loads are generally correlated with changes in hydrology.

Changes in watershed water balance and hydrologic processes are likely in many regions of the nation. Changes in streamflow are determined by the interaction of changes in precipitation and evapotranspiration (ET). Model simulations in this study suggest that in many regions of the nation, the fraction of streamflow derived from surface stormflow will increase, while groundwater-supported baseflow and recharge to deep groundwater aquifers may decrease.

The simulated responses of streamflow and water quality endpoints to climate change scenarios based on different climate models and downscaling methodologies span a wide range in many cases and sometimes do not agree in the direction of change. The ultimate significance of any given simulation of future change will depend on local context, including the historical range of variability, thresholds and management targets, management options, and interaction with other stressors. The simulation results in this study do, however, clearly illustrate that the potential streamflow and water quality response in many areas could be large. Given these uncertainties, successful climate change adaptation strategies will need to encompass practices and decisions to reduce vulnerabilities and risk across a range of potential future climatic conditions.

Simulated responses to increased urban development scenarios are small relative to those resulting from climate change at the scale of modeling in this study. This is likely due to the relatively small changes in developed lands as a percent of total watershed area at the large spatial scale of watersheds in this study. The finest spatial scale reported in this study is that of an 8-digit hydrologic unit code (HUC), and most urbanized areas are located on larger rivers downstream of multiple 8-digit HUCs. Over the whole of individual study areas, urban and residential growth scenarios represented changes in the amount of developed land on the order of <1 to about 12% of total watershed area, and increases in impervious surfaces on the order of 0 to 5% of total watershed area. As would be expected, such small changes in development did not have a large effect on streamflow or water quality at larger spatial scales. It is well documented, however, that urban and residential development at higher levels can have significant impacts on streamflow and water quality. At smaller spatial scales where changes in developed lands represent a larger percentage of watershed area, the effects of urbanization are likely to be greater. The scale at which urbanization effects may become comparable to the effects of a changing climate is uncertain.

Simulation results are sensitive to methodological choices such as different approaches for downscaling global climate change simulations and use of different watershed models. Watershed simulations in this study suggest that the variability in watershed response resulting from a single GCM downscaled using different RCMs can be of the same order of magnitude as the ensemble variability between the different GCMs evaluated. Watershed simulations using different models with different structures and methods for representing watershed processes (HSPF and SWAT in this study) also resulted in increased variability of outcomes. SWAT simulations accounting for the influence of increased atmospheric carbon dioxide (CO_2) on evapotranspiration significantly affected results. One notable insight from these results is that, in many watersheds, increases in precipitation amount and/or intensity, urban development, and atmospheric CO_2 can have similar or additive effects on streamflow and pollutant loading (e.g., a flashier runoff response with higher high and lower low flows).

Significance and next steps. The model simulations in this study contribute to a growing understanding of the complex and context-dependent relationships between climate change, land-use change, and water resources in different regions of the nation. As a first order conclusion, results indicate that in many locations future conditions are likely to be different from past experience. In the context of decision making, being aware and planning for this uncertainty is preferable to accepting a position that later turns out to be incorrect. Results also provide a plausible envelope on the range of streamflow and water quality responses to mid-21st century climate change and urban development in different regions of the nation. In addition, in many study areas the simulations suggest a likely direction of change of streamflow and water quality endpoints. This information can be useful in planning for anticipated but uncertain future conditions. Sensitivity studies evaluating the implications of different methodological choices help to improve the scientific foundation for conducting climate change impacts assessments, thus building the capacity of the water management community to understand and respond to climate change.

Understanding and responding to climate change is complex, and this study is only an incremental step towards fully addressing these questions. It must be stressed that results are conditional upon the methods, models, and scenarios used in this study. Scenarios represent a plausible range but are not comprehensive of all possible futures. Several of the study areas are also complex, highly managed systems; all infrastructure and operational aspects of water management are not represented in full detail. Successful climate change adaptation strategies will need to encompass practices and decisions to reduce vulnerabilities across a wide range of plausible future climatic conditions. It is the ultimate goal of this study to build awareness of the potential range of future watershed response so that where simulations suggest large and potentially disruptive changes, the management community will respond to build climate resiliency.

2. INTRODUCTION

It is now generally accepted that human activities including the combustion of fossil fuels and land-use change have resulted, and will continue to result, in long-term changes in climate (IPCC, 2007; Karl et al., 2009). The 2007 Fourth Assessment Report of the IPCC states that "warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice and rising global average sea level" (IPCC, 2007). Regionally variable changes in the amount and intensity of precipitation have also been observed in much of the United States (Allan and Soden, 2008; Groisman et al., 2012). Climate modeling experiments suggest these trends will continue throughout the 21st century, with continued warming accompanied by a general intensification of the global hydrologic cycle (IPCC, 2007; Karl et al., 2009; Kharin et al., 2013; Emori and Brown, 2005). While uncertainty remains, particularly for precipitation changes at regional spatial scales, the presence of long-term trends in the record suggests many parts of the United States could experience future climatic conditions unprecedented in recent history.

Water managers are faced with important questions concerning the implications of climate change for water resources. Changes in climate will vary over space and time. The hydrologic response to climate change will be further influenced by the attributes of specific watersheds, including physiographic setting, land use, pollutant sources, and human use and management of water. Runoff is generally expected to increase at higher latitudes and in some wet tropical areas, and decrease over dry and semiarid regions at mid-latitudes due to decreases in rainfall and higher rates of evapotranspiration (IPCC, 2007; Karl et al., 2009). Northern and mountainous areas that receive snow in the winter are likely to see increased precipitation occurring as rain versus snow. In addition, most regions of the United States are anticipated to experience increasing intensity of precipitation events; that is, warming-induced intensification of the global hydrologic cycle will increase the fraction of total precipitation occurring in large magnitude events. Precipitation changes can result in hydrologic effects that include changes in the amount and seasonal timing of streamflow, changes in soil moisture and groundwater recharge, changes in land cover and watershed biogeochemical cycling, changes in nonpoint pollutant loading to water bodies, and increased demands on water infrastructure, including urban stormwater and other engineered systems. Regions exposed to increased storm intensity could experience increased coastal and inland flooding. Such changes challenge the assumption of stationarity that has been the foundation for water management for decades (e.g., Milly et al., 2008).

Changes in climate and hydrology will also affect water quality. Although less studied, potential effects include changes in stream temperature and hydrologic controls on nutrient, sediment, and dissolved constituent loads to water bodies. Hydrologic changes associated with climate change could also influence pollutant loading from urban and agricultural lands. Previous studies illustrate the sensitivity of stream nutrient loads, sediment loads, and ecologically relevant streamflow characteristics to changes in climate (e.g., see Poff et al., 1996; Williams et al., 1996; Murdoch et al., 2000; Monteith et al., 2000; Chang et al., 2001; Bouraoui et al., 2002; SWCS, 2003; Marshall and Randhir, 2008; Wilson and Weng, 2011; Tong et al., 2011). A review (Whitehead et al., 2009) details progress on these questions but emphasizes that still relatively little is known about the link between climate change and water quality.

Many watersheds are currently impacted by existing stressors, including land-use change, water withdrawals, pollutant discharges, and other factors. It is important to recognize that climate change will not act independently, but will interact in complex and poorly understood ways with existing and future changes in nonclimatic stressors. One area of concern is the interaction of climate change and urban development in different watershed settings. Throughout this century, urban and residential development is expected to increase throughout much of the nation (U.S. EPA, 2009c). Stormwater runoff from roads, rooftops, and other impervious surfaces in urban and residential environments is a well-known cause of stream impairment (Walsh et al., 2005; Paul and Meyer, 2001). Changes in rainfall associated with climate change will have a direct effect on stormwater runoff (Pyke et al., 2011). More generally, changes in climate could exacerbate or ameliorate the impacts of other nonclimatic stressors. This understanding is particularly important because in many situations, the only viable management strategies for adapting to future climatic conditions involve improved methods for managing and addressing nonclimatic stressors.

Understanding and adapting to climate change is complicated by the scale, complexity, and inherent uncertainty of the problem. We currently have a limited ability to predict long-term (multidecadal) future climate at the local and regional scales needed by decision makers (Sarewitz et al., 2000). It is therefore not possible to know with certainty the future climatic conditions to which a particular watershed will be exposed. Scenario analysis using simulation models is a useful and common approach for assessing vulnerability to plausible but uncertain future conditions (Lempert et al., 2006; Sarewitz et al., 2000; Volkery and Ribeiro, 2009). Evaluation of multiple scenarios can provide understanding of the complex interactions associated with watershed response to climate change and other watershed stressors, and identify uncertainties associated with changes in different drivers (such as climate and land-use change) and uncertainties associated with different analytical approaches and methods. This information is useful for developing an improved understanding of system behavior and sensitivity to a wide range of plausible future climatic conditions and events, identifying how we are vulnerable to these changes, and ultimately to guide the development of robust strategies for reducing risk in the face of changing climatic conditions (Sarewitz et al., 2000; Lempert et al., 2006; Johnson and Weaver, 2009).

2.1. ABOUT THIS REPORT

This report describes the structure—including methods, models, scenarios, and results—of a large-scale watershed modeling study designed to address gaps in our knowledge of the sensitivity of U.S. streamflow, nutrient (nitrogen and phosphorus), and sediment loading to potential mid-21st century climate change. Modeling also considers the potential interaction of climate change with future urban and residential development in these watersheds and provides insights concerning the effects of different methodological choices (e.g., method of downscaling climate change data, choice of watershed model, etc.) on simulation results.

Watershed modeling was conducted in 20 large U.S. watersheds using a scenario analysis approach. Study sites were selected to represent a range of geographic, hydrologic, and climatic characteristics throughout the nation.

Model projections consider the effects of climate change alone, urban and residential development alone, and the combined effects of climate change and urban development on streamflow, total nitrogen (TN), total phosphorus (TP), and total suspended solids (TSS) loads. Climate change scenarios were based on downscaled climate model projections from two sources; the NARCCAP and the BCSD archive from the Bureau of Reclamation/Santa Clara University/Lawrence Livermore. Scenarios of urban and residential development were based on projections from EPA's ICLUS project.

All 20 watersheds were modeled with the SWAT model using a consistent set of climate and land-use change scenarios. In a subset of five study watersheds, referred to as pilot sites, additional simulations were conducted to address methodological questions related to the conduct of climate change impacts assessments. In these watersheds, a second watershed model, the HSPF, was run using the same climate and land-use scenarios used with SWAT to assess the influence of different watershed models on watershed simulations. Pilot watersheds were also evaluated for additional climate change scenarios to assess hydroclimatic sensitivity to different methods of downscaling climate data. All watershed models are constructed at a scale approximating HUC-10s, but the finest spatial resolution of model calibration and output was on the order of HUC-8 watersheds.

As with any study of this type, simulation results are conditional on the specific methods, models, and scenarios used. Given the difficulty and level of effort involved with modeling at this scale, it was necessary to standardize model development for efficiency. Several of the study areas are complex, highly managed systems. We do not attempt to represent all these operational aspects in full detail. Future changes in agriculture and human use and management of water were also not evaluated.

This report consists of a main volume and 26 appendices. The main volume describes the study methods, models, scenarios, and results. The appendices contain additional information on model setup, calibration, and additional modeling results (at HUC 8-digit spatial scale) not included in the main report. Supplementary data sets summarizing SWAT simulation results at all 20 study areas are also available at EPA's ICLUS web page http://map3.epa.gov/ICLUSonline/.

3. STUDY AREAS

This project evaluates watershed response to climate change and urban development scenarios in 20 large drainage basins, ranging in size from approximately 6,000 to 27,000 mi^2, located throughout the contiguous United States and Alaska (see Figure 3-1 below). Study areas were selected based on both geographic and practical considerations. Sites were selected to represent a broad range of geographic, physiographic, land use, and hydroclimatic settings (see Table 3-1). Site selection also considered the availability of necessary data for calibration and validation of watershed models, including a selection of U.S. Geological Survey (USGS) streamflow monitoring gages (at varying spatial scales) and an adequate set of water quality monitoring data (e.g., USGS National Water Quality Assessment study areas). Finally, study areas were selected to leverage, where possible, preexisting calibrated watershed models.

The 20 study areas selected cover a wide range of geology and climate (see Table 3-1), with elevations ranging from sea level to over 14,000 feet, average annual temperatures from 34 to 68°F, and average annual precipitation ranging from 15 to 66 inches. Figure 3-2 shows the distribution of average annual precipitation and temperature among the study sites, indicating a wide range of climatic conditions, from dry to wet and cold to warm. The ratio of winter (January−March) to summer (July−September) precipitation varies from about 0.1 to 11 while the fraction of runoff derived from snowmelt ranges from 0 to 54%. The study areas also sample all of the Level I ecoregions in the contiguous United States (CECWG, 1997), with the exception of the Tropical Wet Forests ecoregion (present within the contiguous United States only in southern Florida). Many of the study areas are in the Eastern Temperate Forests ecoregion, but this region occupies most of the eastern half of the contiguous United States.

The selected study areas also cover a range of land-use conditions, with agricultural land occupying from 0 to 78% of the land area and urbanized areas (impervious plus developed pervious land) occupying up to 38%. Overall imperviousness of the study areas (at approximately the HUC-4 scale) ranges from near zero to about 14%; however, individual subwatersheds within a study area have substantially greater imperviousness. For instance, within the Apalachicola-Chattahoochee-Flint River watersheds (ACF) study area the individual modeling subbasins (at approximately the HUC-10 scale) range from 0.15 to 27.44% impervious.

A detailed summary of current land use and land cover in the 20 study areas is shown in Table 3-2, based on 2001 data from the National Land Cover Dataset (NLCD).

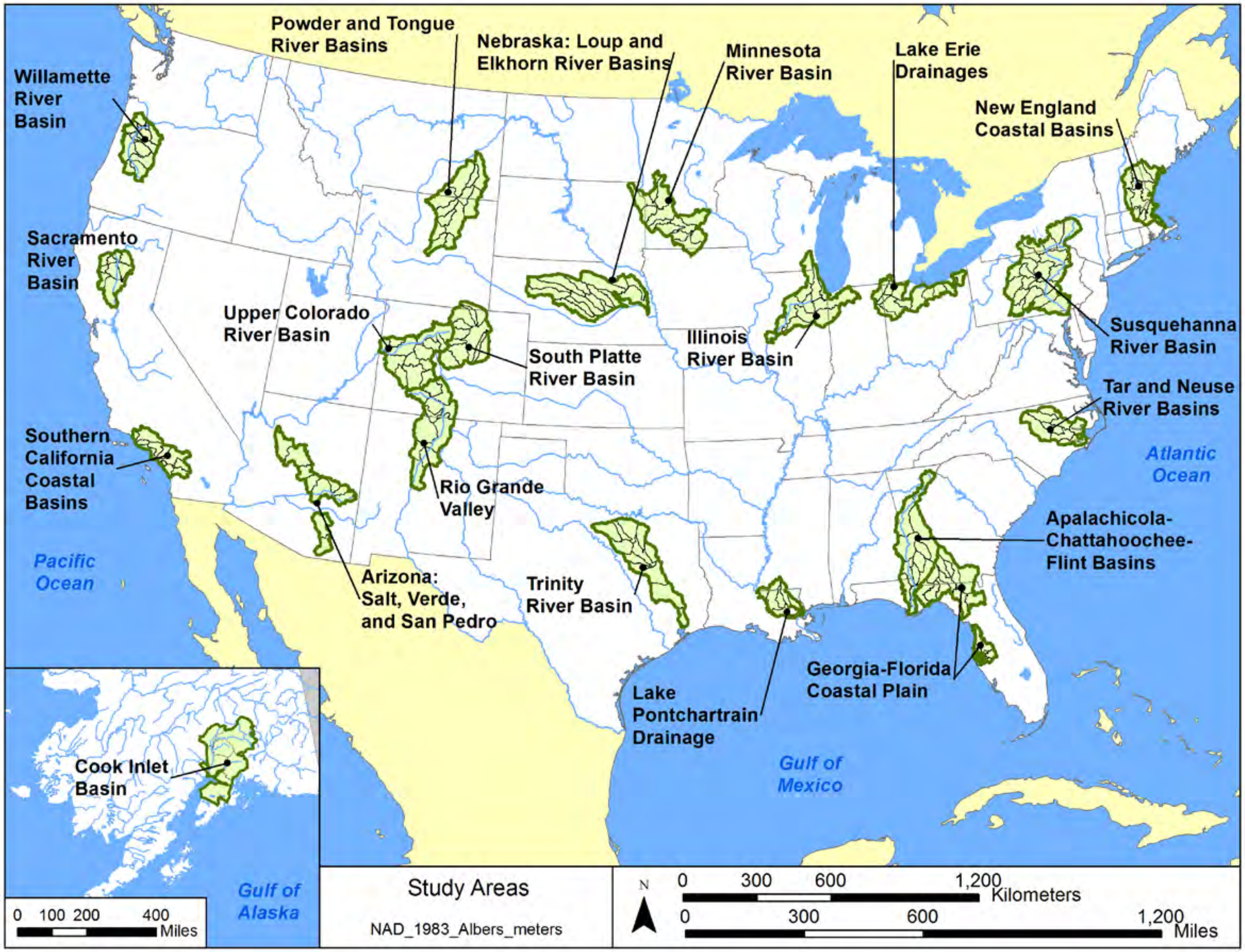

Figure 3-1. Locations of the 20 study areas with HUC 8-digit watershed boundaries.

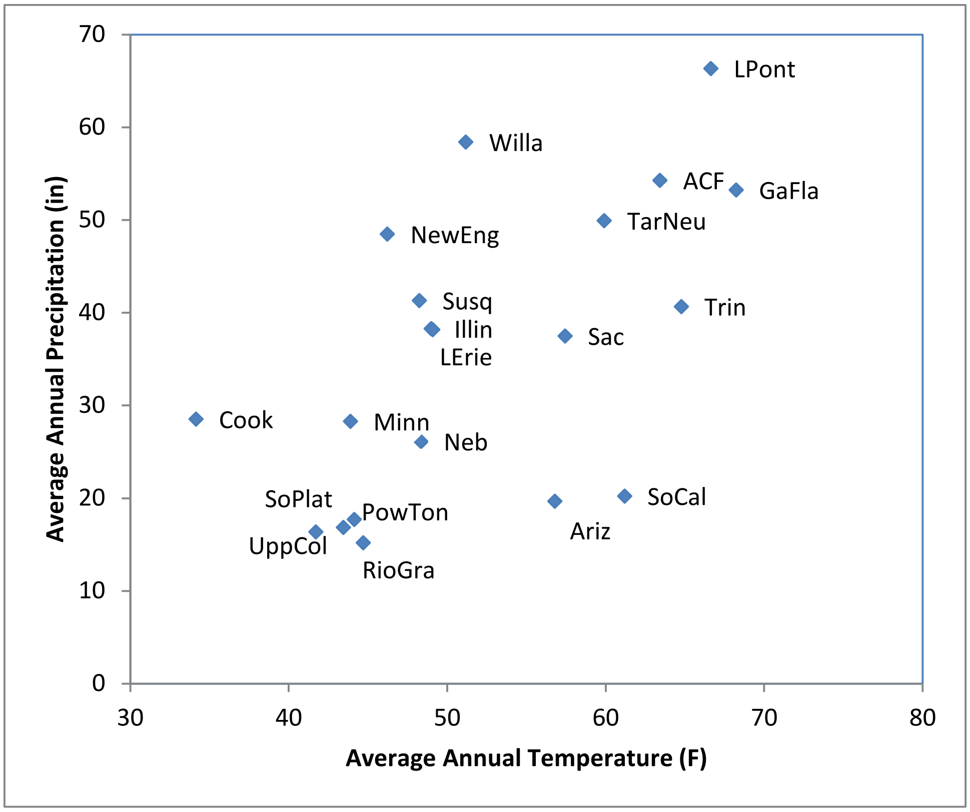

Figure 3-2. Distribution of precipitation and temperature among the study areas.

Note: Precipitation and temperature are averages over the weather stations used in simulation for the modeling period (approximately 1970−2000, depending on model area).

The USGS (Seaber et al., 1987) has classified watershed drainage areas in a hierarchical system in which each hydrologic unit is assigned a Hydrologic Unit Code (HUC). The first four levels of the hierarchy (occupying eight digits) identify the region (HUC-2), subregion (HUC-4), basin (HUC-6), and subbasin (HUC-8). The United States contains 222 HUC-4s with an average size of 16,800 mi^2. The 20 study areas selected for this study are of a similar scale to HUC-4 basins, ranging in size from approximately 6,000 to 27,000 mi^2, but do not correspond exactly with the boundaries of established HUC-4 basins. Each study area comprises from 7 to 19 HUC 8-digit watersheds. The individual HUC 8-digit watersheds in the study areas have a median size of 1,164 mi^2, and an interquartile range from 805 to 1,808 mi^2. In some cases study areas are composed of a single, contiguous watershed. In other cases, study areas include several adjacent but noncontiguous watersheds (e.g., separate rivers draining to the coast). Where possible, watersheds strongly influenced by upstream dams, diversions, or other human interventions were avoided to simplify modeling.

Maps of the individual study areas are provided in Figures 3-3 through 3-23. Detailed descriptions of each study area are presented in Appendices D through W, which describe model development and calibration for the individual study areas.

Table 3-1. Summary of the 20 study areas

Study area	Site ID	Location (states)	Total area (mi2)	Elevation range (ft MSL)	Average precip (in/yr)	Averag e temp (°F)	Ratio winter to summer runoff	Fraction of runoff as snowmelt (%)	Level I ecoregions	Major cities
Apalachicola-Chattahoochee-Flint Basins (Pilot Site)	ACF	GA, AL, FL	19,283	0−4,347	54.26	63.43	2.01	0.7	Eastern Temperate Forests	Atlanta, GA
Arizona: Salt, Verde, and San Pedro (Pilot Site)	Ariz	AZ	14,910	1,918−11,407	19.67	56.81	2.06	9.3	Temperate Sierras, Southern Semi-arid Highlands, North America Deserts	Flagstaff, AZ; Sierra Vista, AZ
Cook Inlet Basin	Cook	AK	22,243	0−18,882	28.50	34.16	0.11	53.8	Marine West Coast Forests, Northwest Forested Mountains	Anchorage, AK
Georgia-Florida Coastal Plain	GaFla	GA, FL	17,541	0−485	53.21	68.24	1.29	0.1	Eastern Temperate Forests	Tallahassee, FL; Tampa, FL
Illinois River Basin	Illin	IL, IN, WI	17,004	365−1,183	38.25	49.00	1.24	13.3	Eastern Temperate Forests	Chicago, IL; Milwaukee, WI; Peoria, IL
Lake Erie Drainages	LErie	OH, IN, MI	11,682	339−1,383	38.15	49.10	2.60	13.4	Eastern Temperate Forests	Fort Wayne, IN; Cleveland, OH; Akron, OH
Lake Pontchartrain Drainage	LPont	LA, MS	5,852	0−502	66.33	66.64	1.70	0.5	Eastern Temperate Forests	New Orleans, LA; Baton Rouge, LA
Minnesota River Basin (Pilot Site)	Minn	MN, IA, SD	16,989	683−2,134	28.26	43.90	0.50	14.8	Great Plains, Eastern Temperate Forests	Mankato, MN, Minneapolis, MN

Table 3-1. Summary of the 20 study areas (continued)

Study area	Site ID	Location (states)	Total area (mi^2)	Elevation range (ft MSL)	Average precip (in/yr)	Average temp (°F)	Ratio winter to summer runoff	Fraction of runoff as snowmelt (%)	Level I ecoregions	Major cities
Nebraska: Loup and Elkhorn River Basins	Neb	NE	22,095	1,069−4,292	26.10	48.35	0.91	12.6	Great Plains	No major cities
New England Coastal Basins	NewEng	MA, NH, ME	10,359	0−5,422	48.45	46.23	1.41	21.1	Northern Forests, Eastern Temperate Forests	Portland, ME, Greater Boston, MA
Powder and Tongue River Basins	PowTon	MT, WY	18,800	2,201−13,138	17.70	44.15	1.18	30.2	Great Plains, North American Deserts, Northwestern Forested Mountains	No major cities
Rio Grande Valley	RioGra	NM, CO	18,959	4,726−14,173	15.18	44.71	0.52	23.8	Northwest Forested Mountains, North American Deserts, Temperate Sierras	Santa Fe, NM; Albuquerque, NM
Sacramento River Basin	Sac	CA	8,316	17−10,424	37.47	57.45	1.61	17.6	Mediterranean California, Northwest Forested Mountains	Chico, CA; Reading, CA
Southern California Coastal Basins	SoCal	CA	8,322	0−11,488	20.21	61.20	5.94	4.9	Mediterranean California	Greater Los Angeles, CA
South Platte River Basin	SoPlat	CO, WY	14,668	4,291−14,261	16.82	43.46	0.49	28.3	Great Plains, Northwest Forested Mountains	Fort Collins, CO; Denver, CO
Susquehanna River Basin (Pilot Site)	Susq	PA, NY, MD	27,504	0−3,141	41.30	48.26	2.06	16.6	Eastern Temperate Forests, Northern Forests	Scranton, PA; Harrisburg, PA

Table 3-1. Summary of the 20 study areas (continued)

Study area	Site ID	Location (states)	Total area (mi^2)	Elevation range (ft MSL)	Average precip (in/yr)	Average temp (°F)	Ratio winter to summer runoff	Fraction of runoff as snowmelt (%)	Level I ecoregions	Major cities
Tar and Neuse River Basins	TarNeu	NC	9,972	0−854	49.91	59.91	1.59	3.3	Eastern Temperate Forests	Raleigh, NC; Durham, NC; Greenville, NC
Trinity River Basin	Trin	TX	17,949	0−2,150	40.65	64.78	1.45	1.6	Great Plains, Eastern Temperate Forests	Dallas, TX
Upper Colorado River Basin	UppCol	CO, UT	17,865	4,323−14,303	16.36	41.73	0.31	42.4	Great Plains, Eastern Temperate Forests	Grand Junction, CO; Edwards, CO
Willamette River Basin (Pilot Site)	Willa	OR	11,209	8−10,451	58.38	51.19	10.99	4.5	Marine West Coast Forests, Northwest Forested Mountains	Portland, OR; Salem, OR; Eugene, OR

MSL = mean sea level

Notes: Precipitation and temperature are averages over the weather stations used in simulation for the modeling period (approximately 1970−2000, depending on model area). The ratio of winter (January−March) to summer (July−September) runoff and the fraction of runoff as snowmelt are derived from the calibrated SWAT model applications described in this report.

Table 3-2. Current (2001) land use and land cover in the 20 study areas

Study area	Total area (mi^2)	Water (%)	Barren (%)	Wetland (%)	Forest (%)	Shrub (%)	Pasture/hay (%)	Cultivated (%)	Developed pervious* (%)	Impervious (%)	Snow/ice (%)
ACF	19,283	1.8	0.4	9.3	47.9	9.6	9.1	12.4	7.3	2.0	0.0
Ariz	14,910	0.2	0.3	0.3	41.9	56.0	0.1	0.1	1.0	0.2	0.0
Cook	22,243	2.55	18.97	7.59	24.10	38.11	0.05	0.11	0.58	0.24	7.70
GaFla	17,541	0.9	0.4	25.7	33.5	10.1	7.2	10.9	8.8	2.5	0.0
Illin	17,004	1.9	0.1	1.4	10.3	2.1	3.6	62.6	11.9	6.2	0.0
LErie	11,682	1.1	0.1	2.7	13.0	1.5	5.8	61.2	11.2	3.5	0.0
LPont	5,852	3.3	0.4	32.3	23.1	14.3	10.3	4.5	8.5	3.2	0.0
Minn	16,989	3.0	0.1	4.9	2.9	4.6	5.9	72.1	5.5	1.1	0.0
Neb	22,095	0.8	0.1	3.2	1.1	64.5	1.1	26.5	2.4	0.4	0.0
NewEng	10,359	4.2	0.5	7.6	63.6	2.2	4.5	1.1	10.8	5.6	0.0
PowTon	18,800	0.1	0.7	1.7	10.0	85.5	0.6	1.0	0.4	0.1	0.0
RioGra	18,959	0.3	1.0	2.1	35.3	54.2	4.1	0.7	1.7	0.5	0.0

Table 3-2. Current (2001) land use and land cover in the 20 study areas (continued)

Study area	Total area (mi^2)	Water (%)	Barren (%)	Wetland (%)	Forest (%)	Shrub (%)	Pasture/hay (%)	Cultivated (%)	Developed pervious* (%)	Impervious (%)	Snow/ice (%)
Sac	8,316	0.5	0.5	2.0	22.4	48.3	2.3	19.7	3.6	0.7	0.0
SoCal	8,322	0.6	0.6	0.4	10.6	50.9	1.0	2.8	19.4	13.8	0.0
SoPlat	14,668	0.9	1.0	2.3	23.7	46.4	1.5	16.5	5.0	2.1	0.7
Susq	27,504	1.1	0.4	1.2	61.1	1.8	17.1	9.8	5.9	1.5	0.0
TarNeu	9,972	4.5	0.2	14.1	33.5	10.0	7.3	21.1	7.7	1.7	0.0
Trin	17,949	3.7	0.3	7.8	16.4	30.6	20.6	7.0	9.4	4.2	0.0
UppCol	17,865	0.5	3.8	1.6	53.9	33.9	3.2	1.1	1.0	0.4	0.7
Willa	11,209	0.9	0.9	1.8	56.2	12.3	12.5	8.2	4.7	2.5	0.0

*Developed pervious land includes the pervious portion of open space and low, medium, and high density land uses.

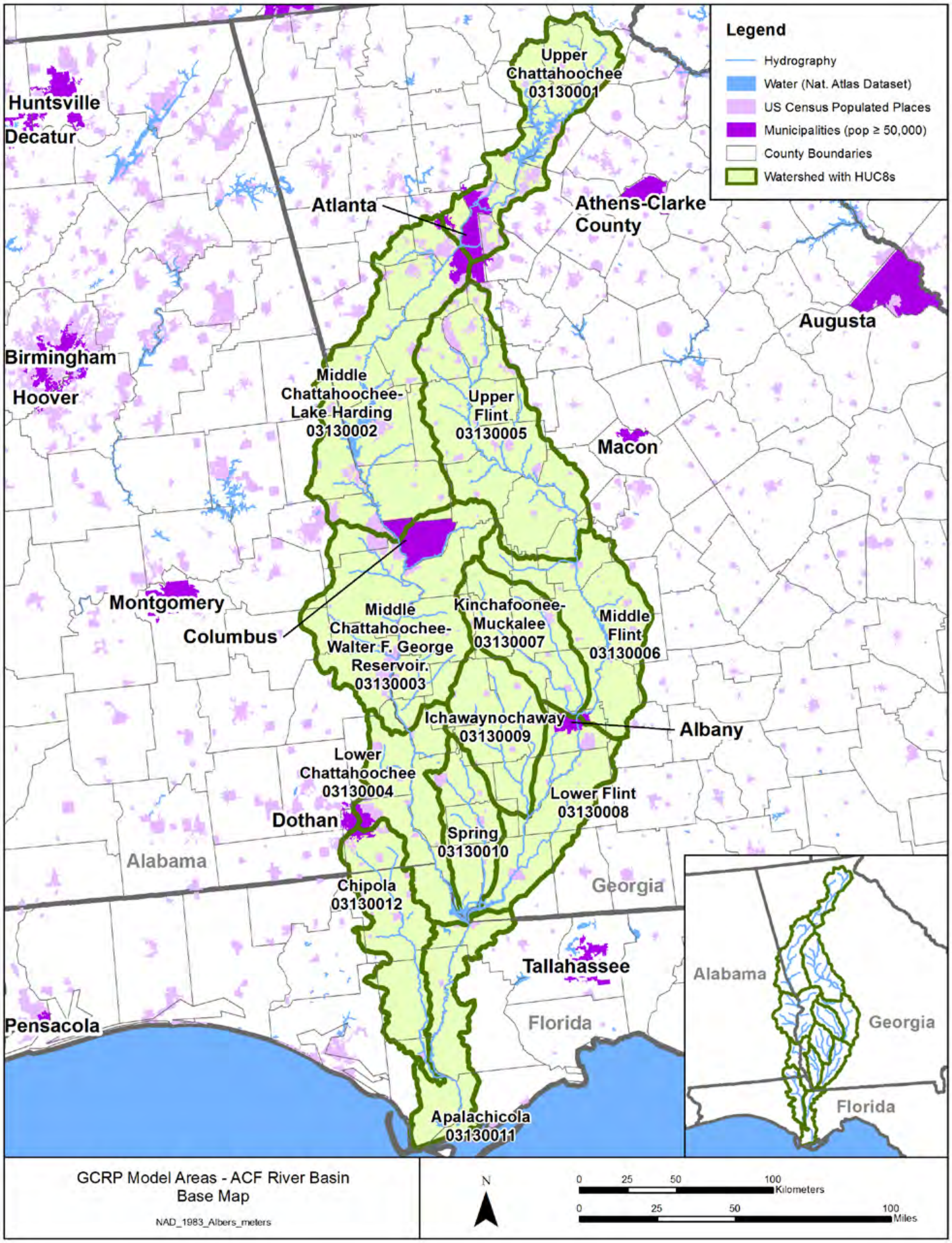

Figure 3-3. Apalachicola-Chattahoochee-Flint basins study area.

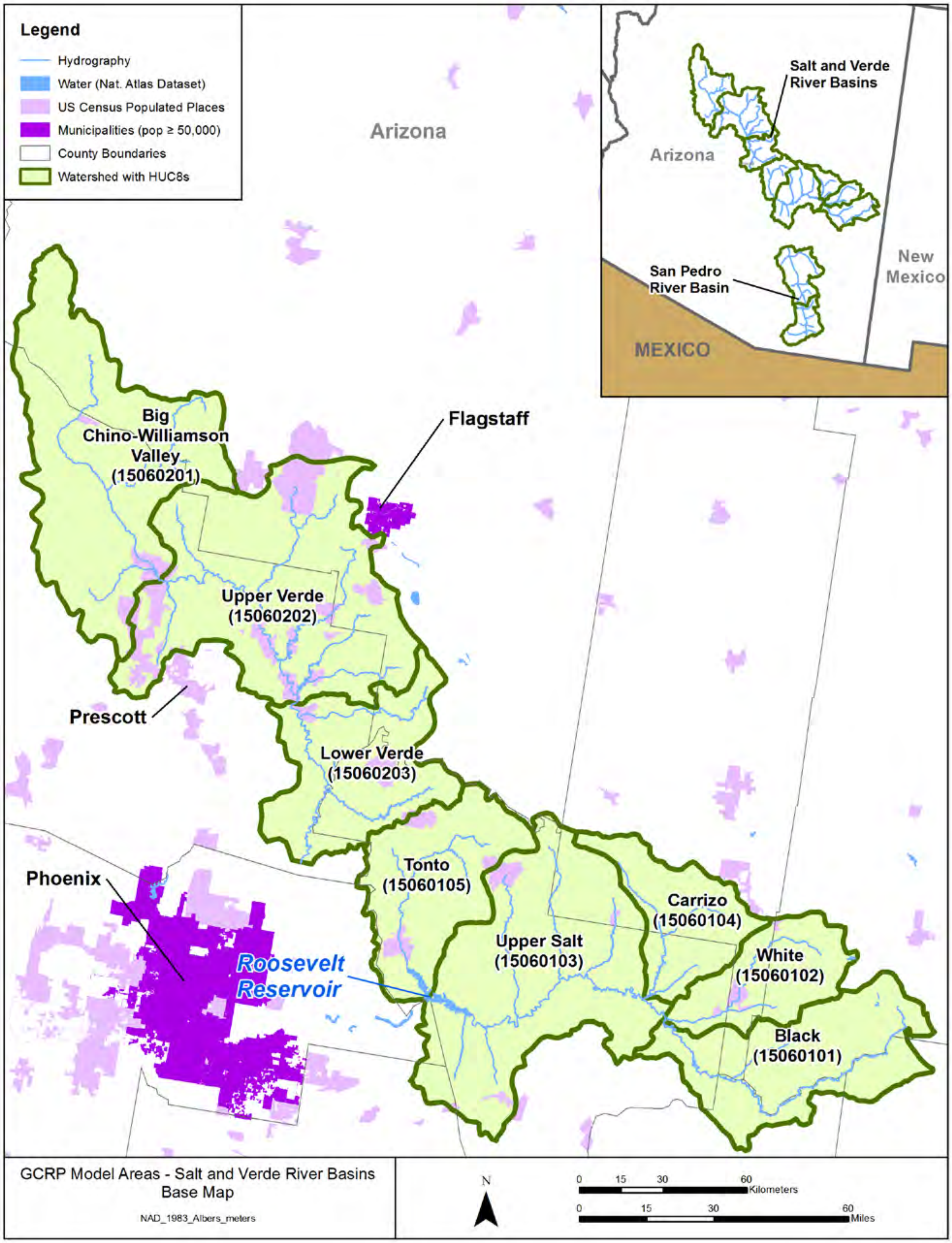

Figure 3-4. Arizona: Salt and Verde River section of study area.

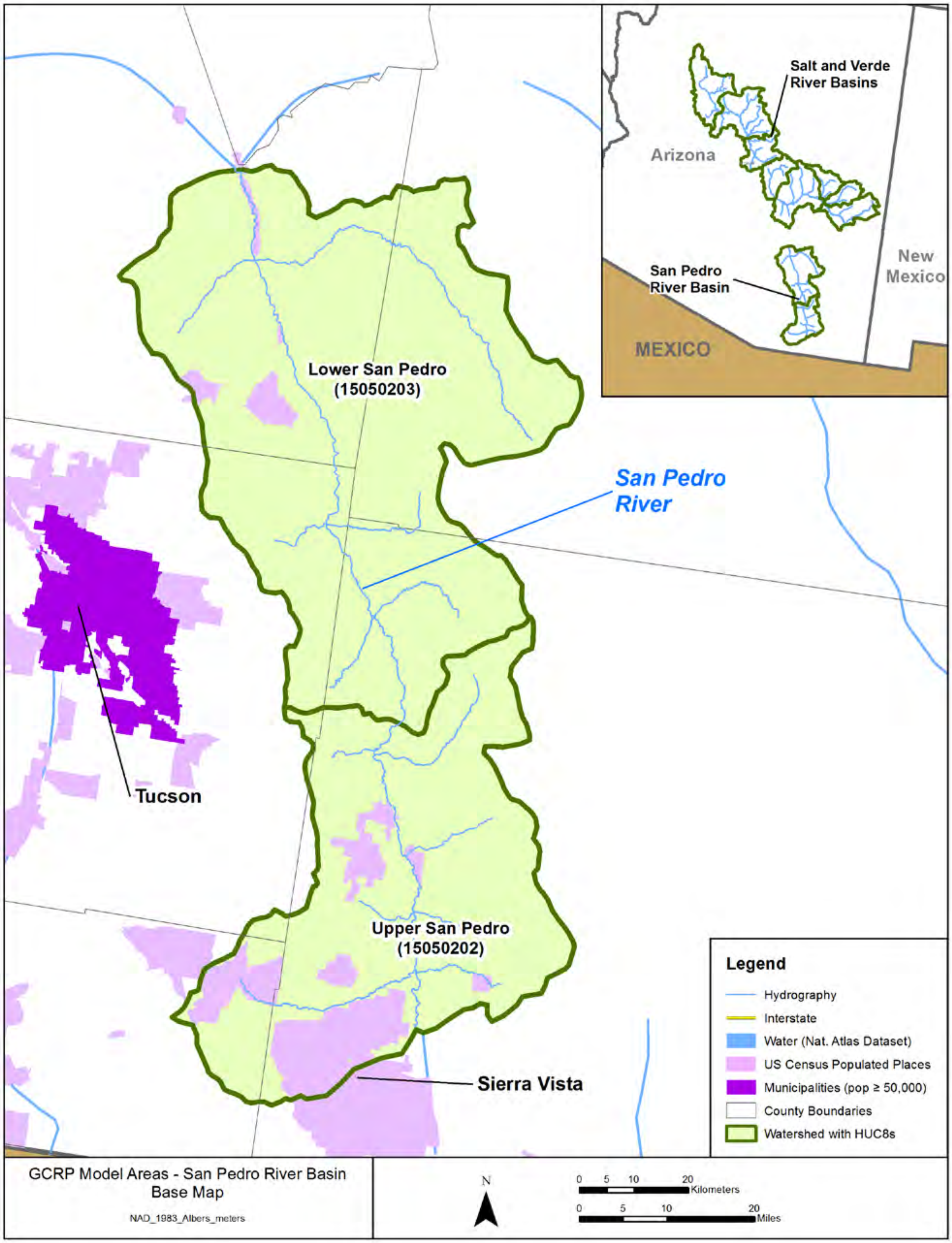

Figure 3-5. Arizona: San Pedro River section of study area.

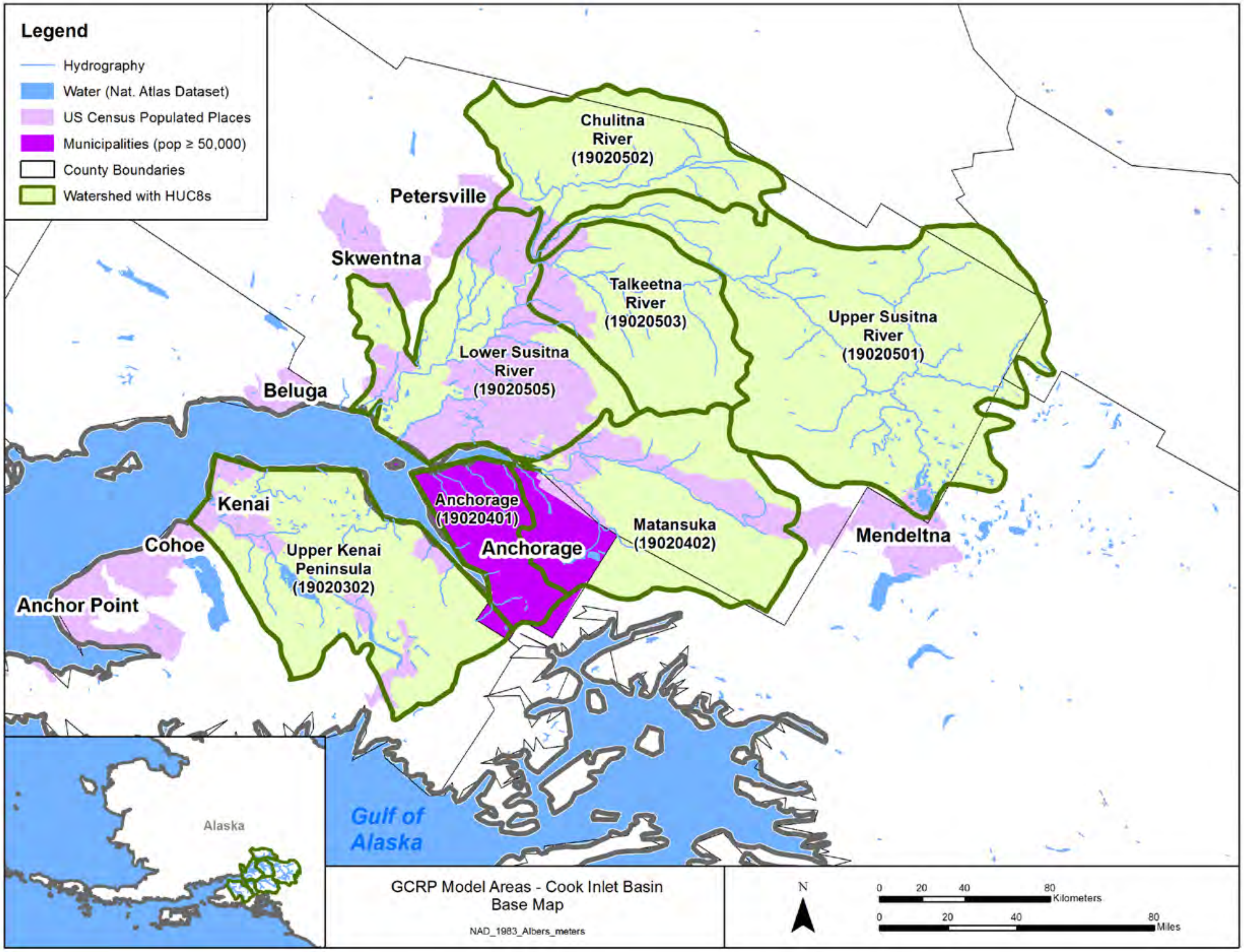

Figure 3-6. Cook Inlet basin study area.

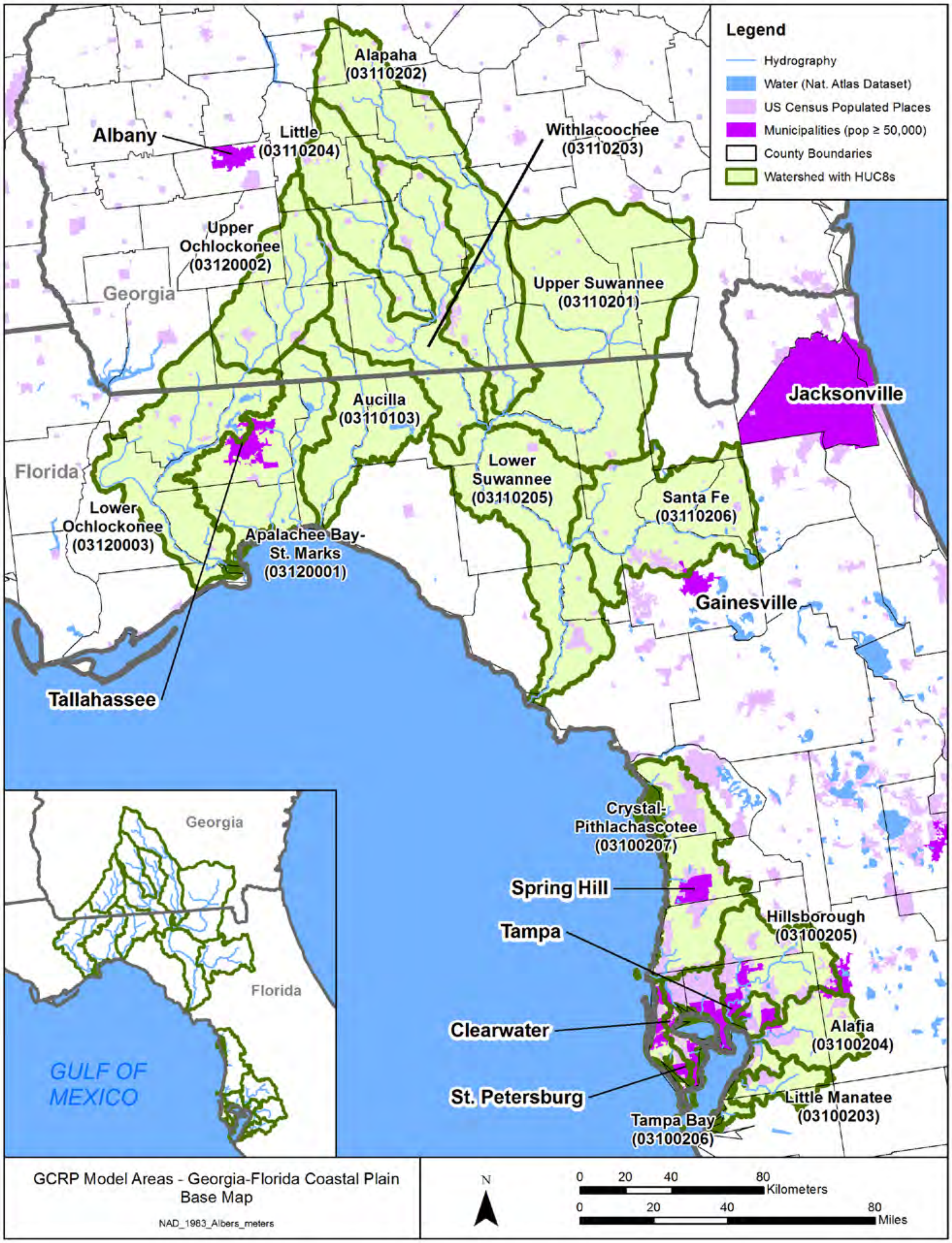

Figure 3-7. Georgia-Florida Coastal Plain study area.

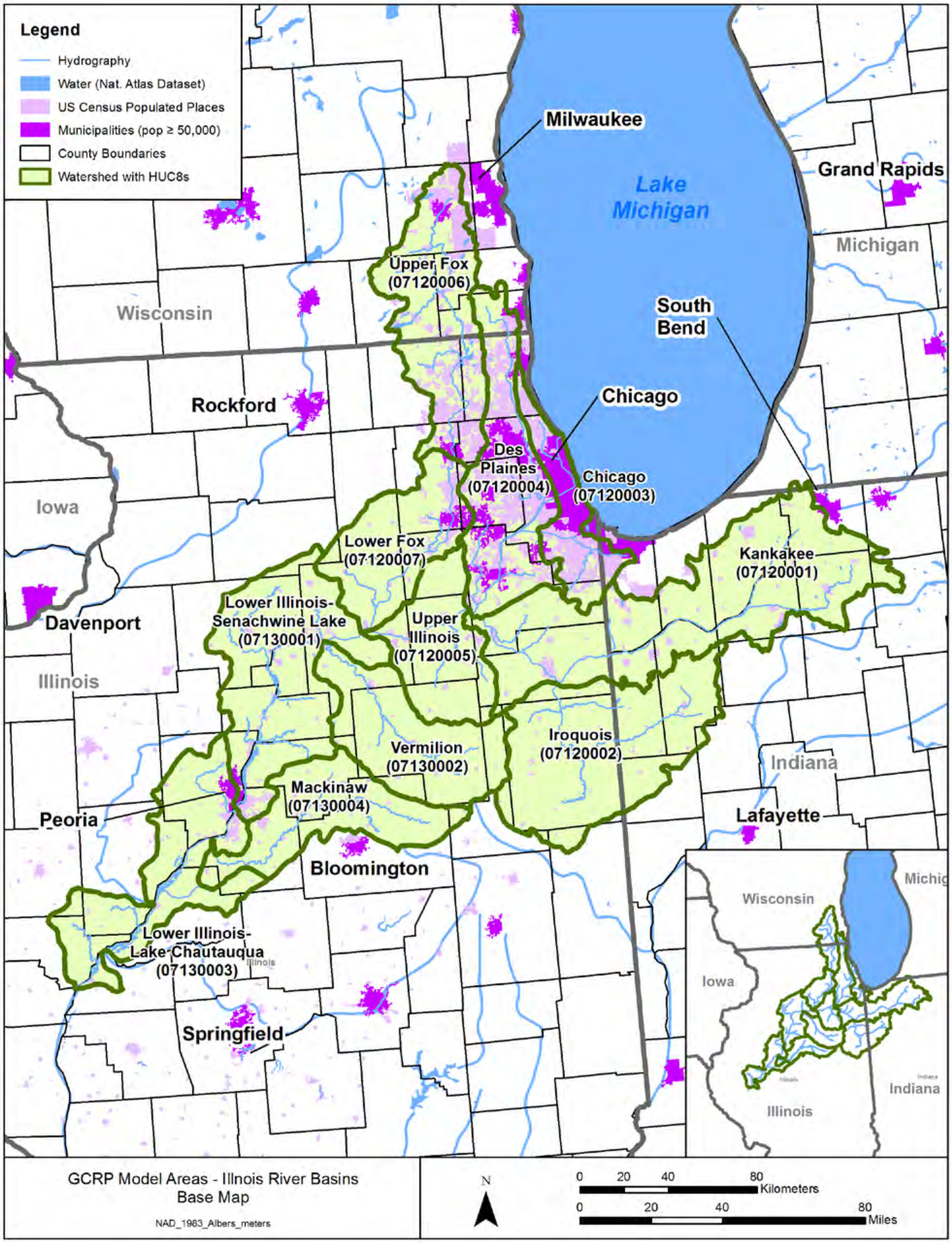

Figure 3-8. Illinois River basin study area.

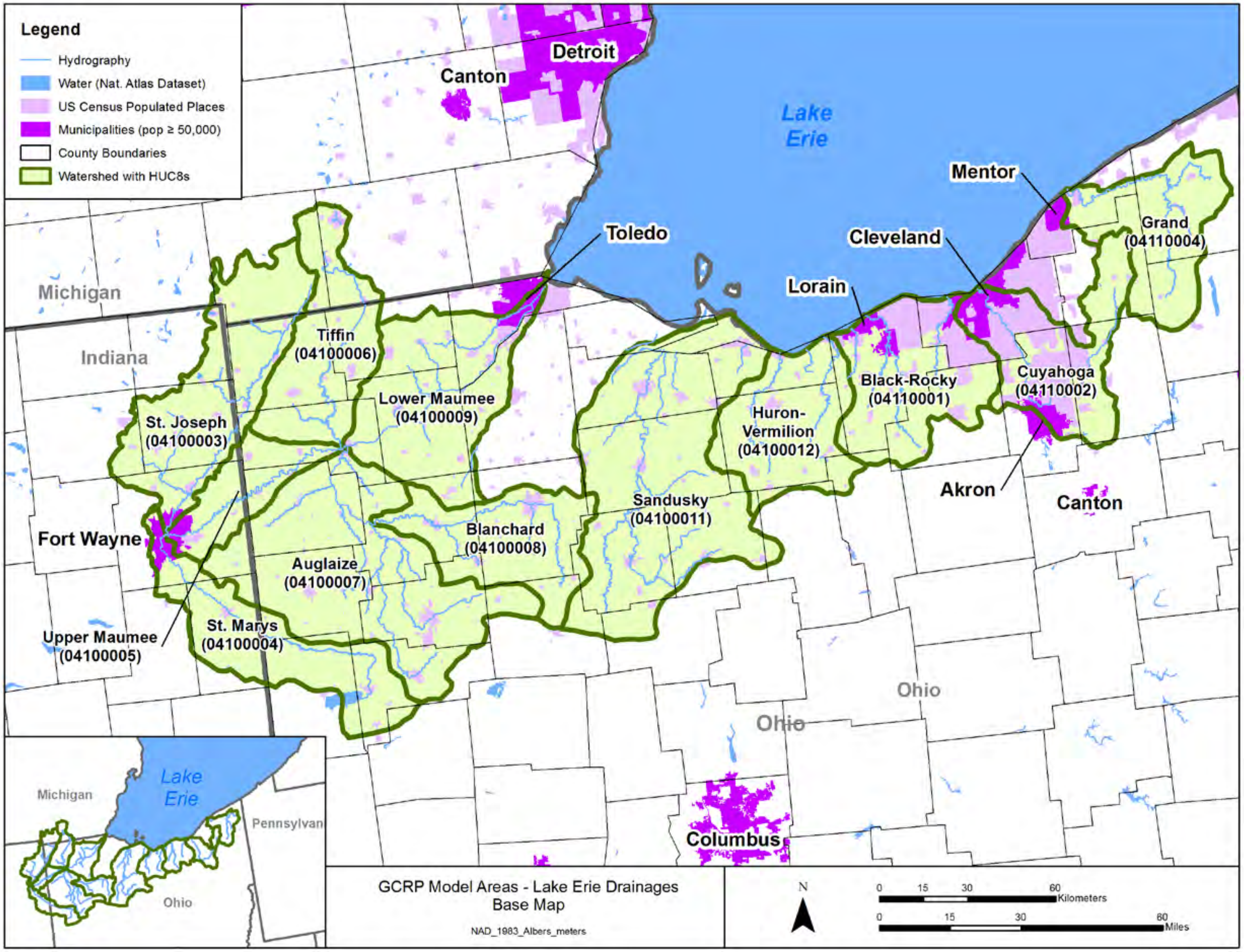

Figure 3-9. Lake Erie drainages study area.

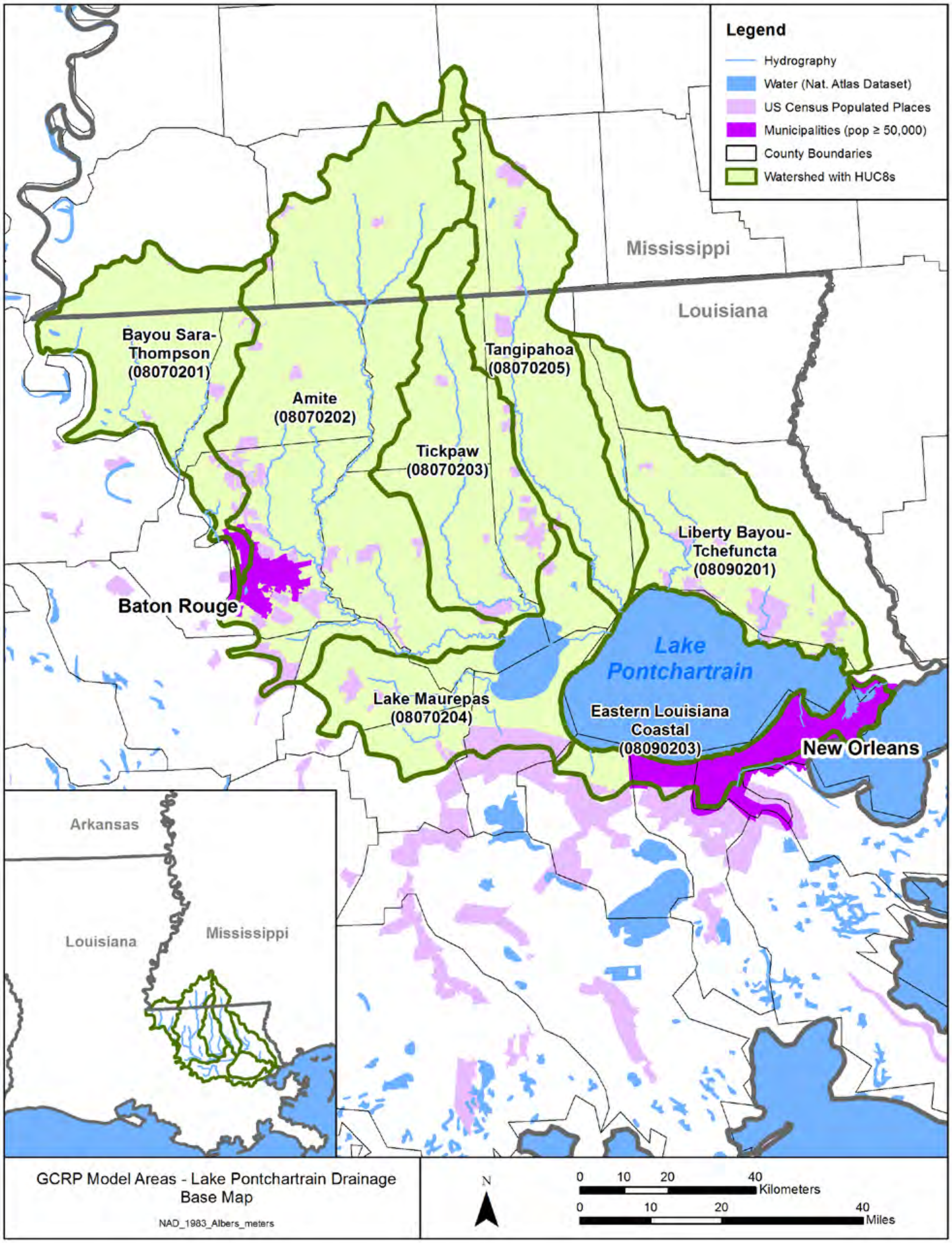

Figure 3-10. Lake Pontchartrain drainage study area.

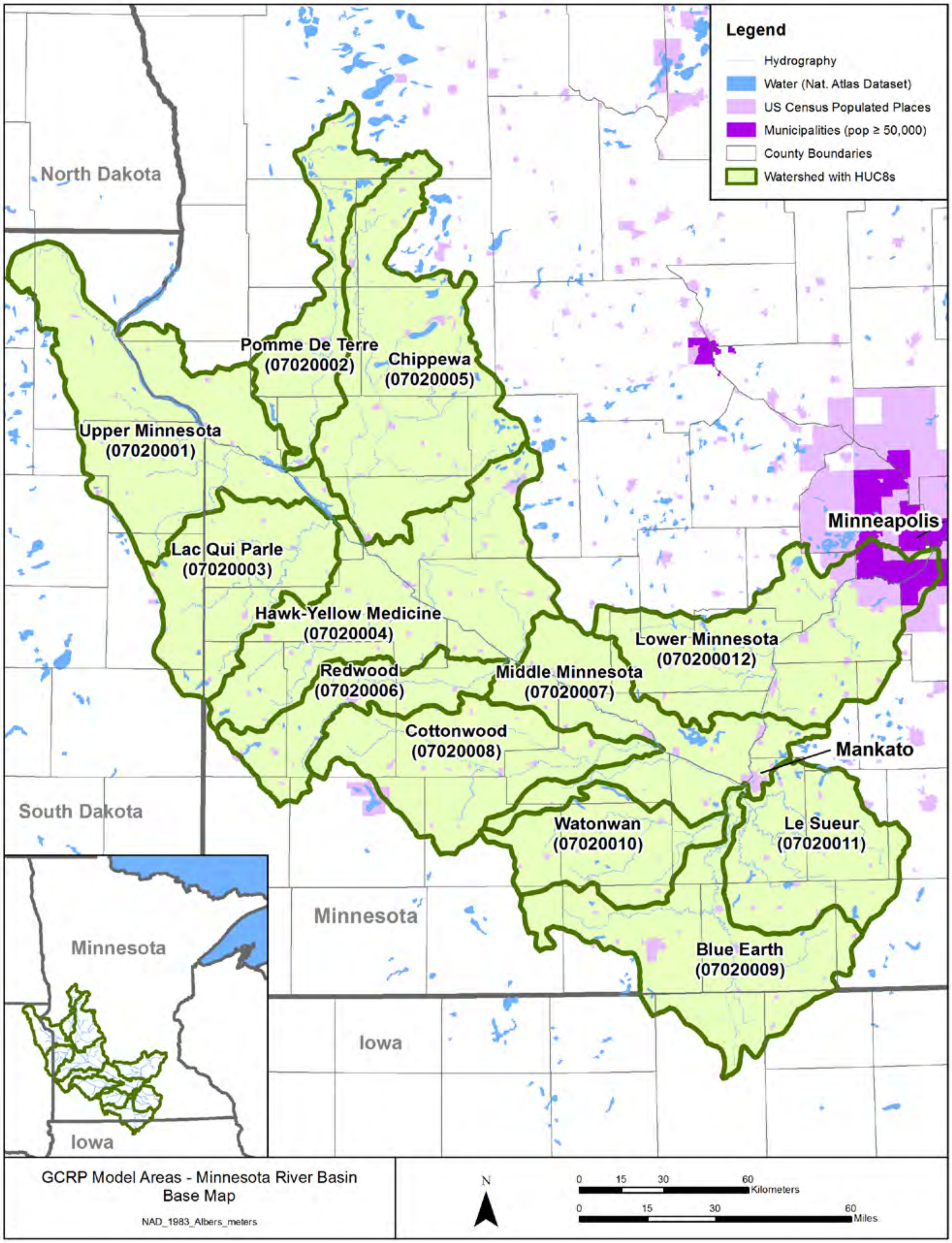

Figure 3-11. Minnesota River basin study area.

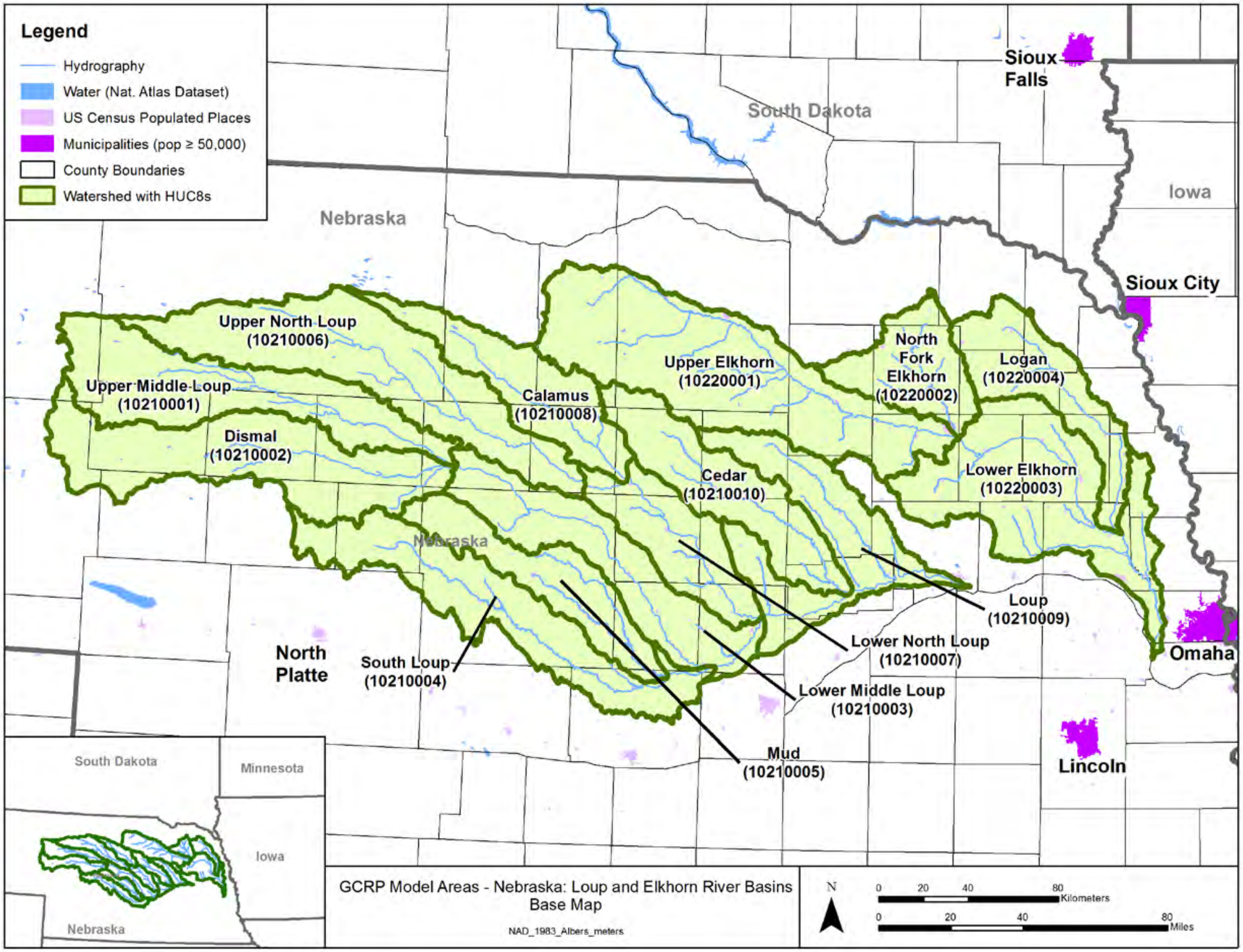

Figure 3-12. Nebraska: Loup and Elkhorn River basins study area.

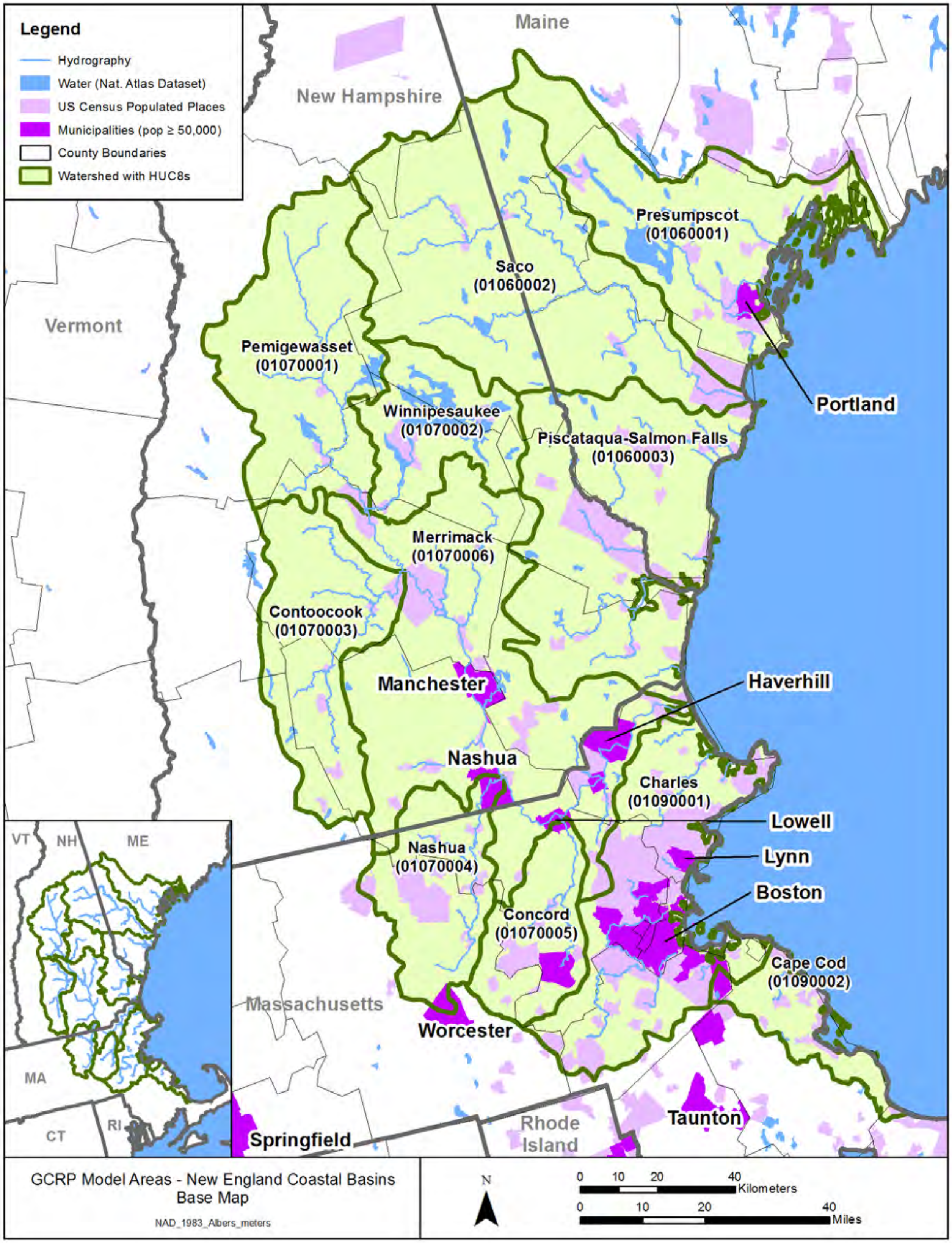

Figure 3-13. New England Coastal basins study area.

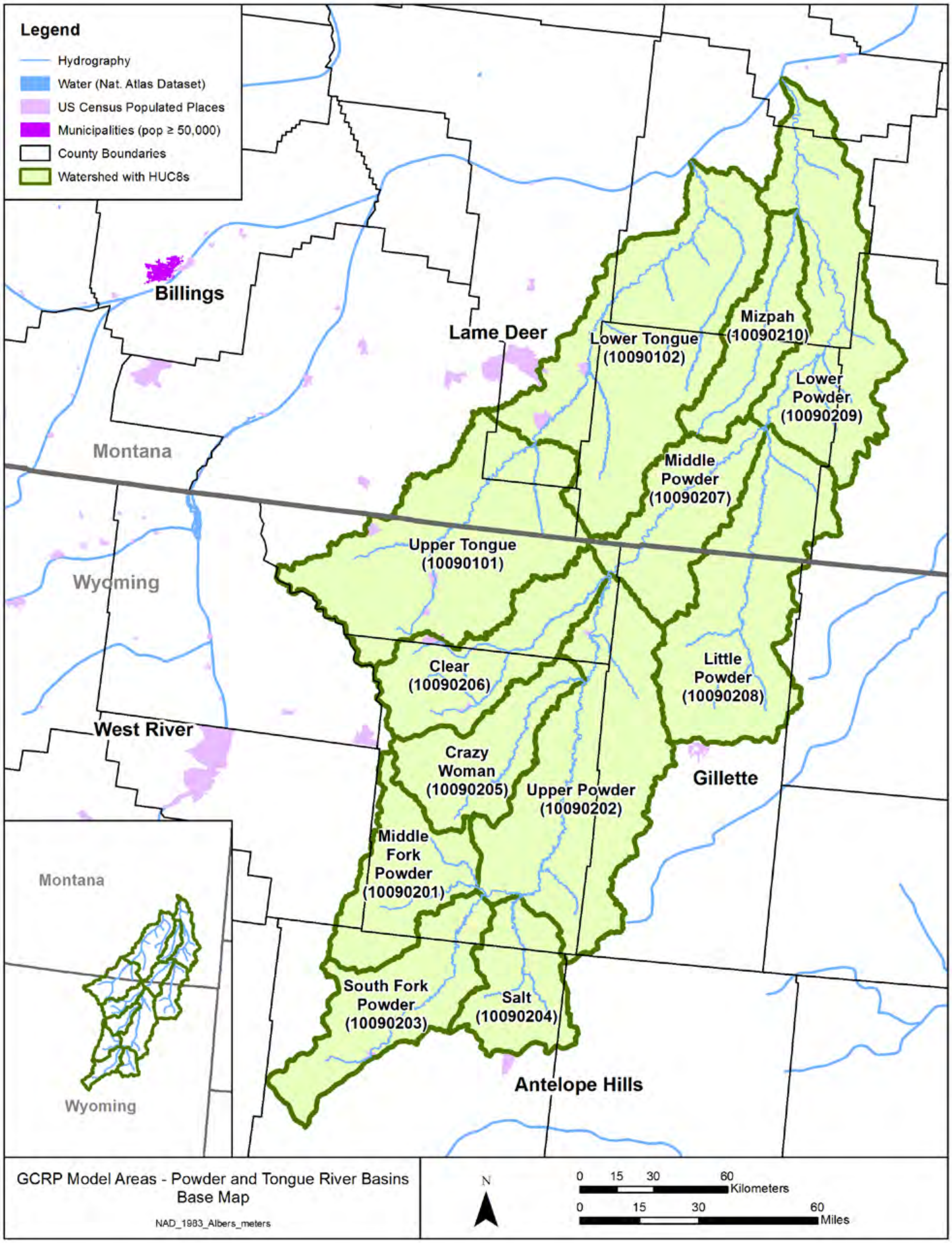

Figure 3-14. Powder and Tongue River basins study area.

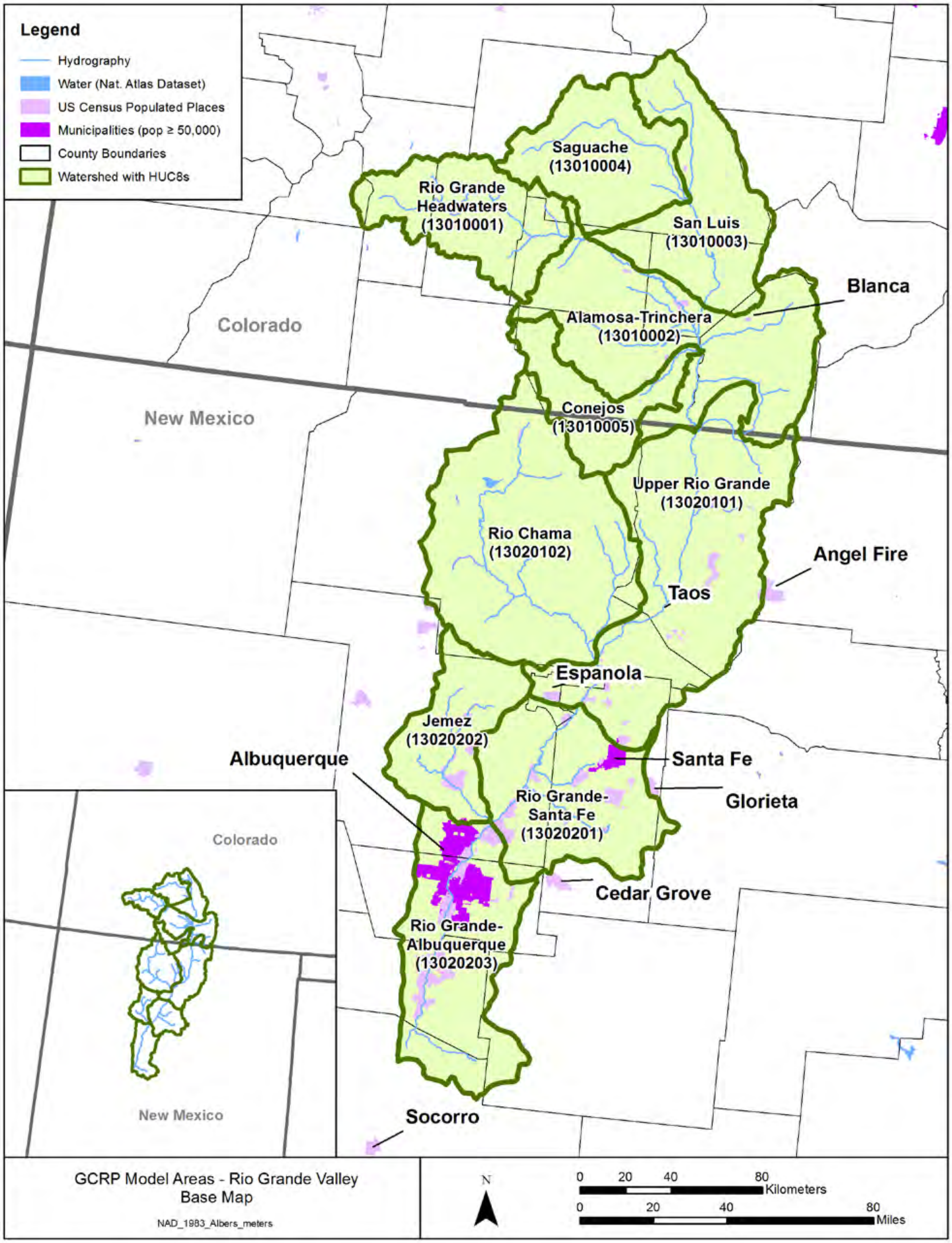

Figure 3-15. Rio Grande Valley study area.

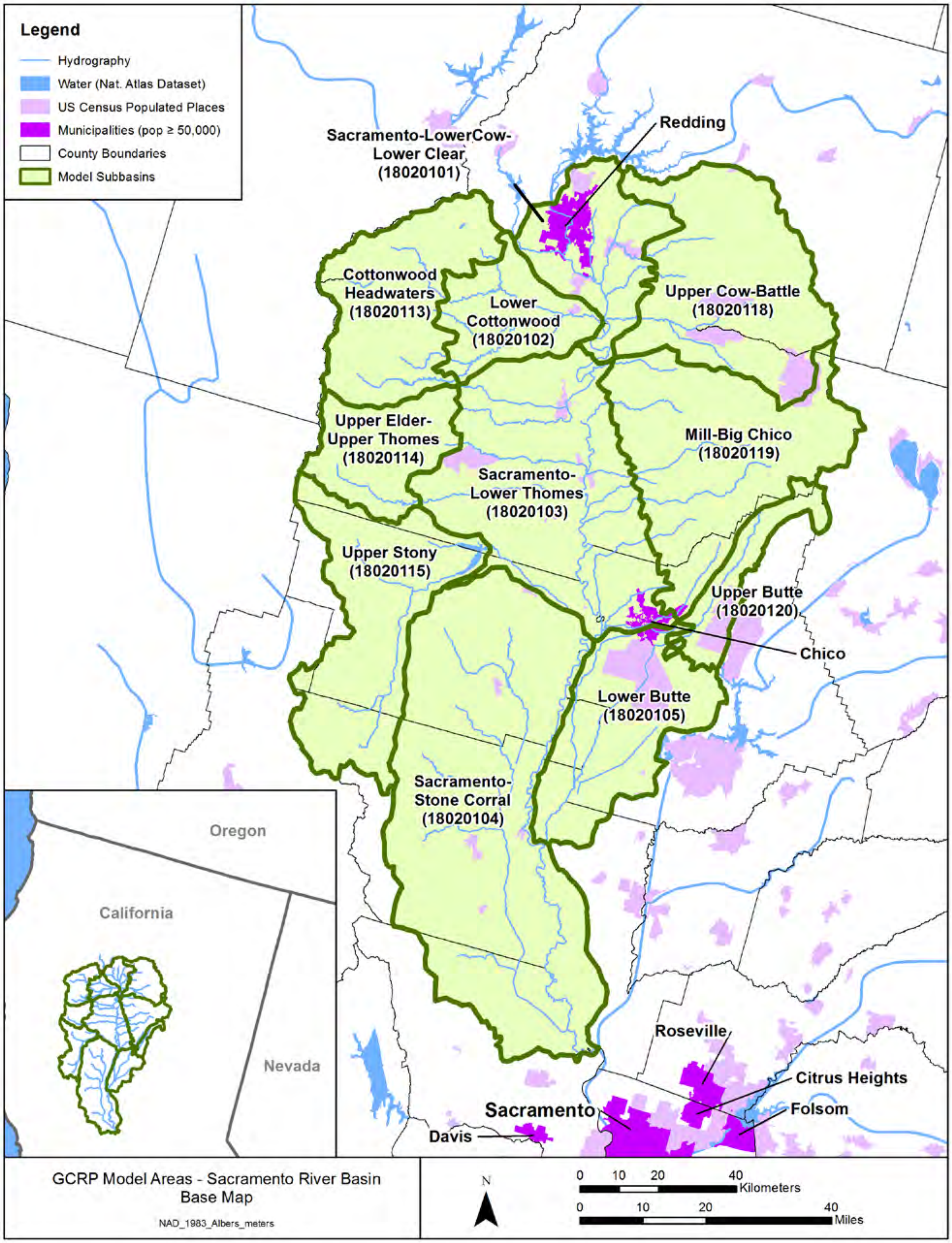

Figure 3-16. Sacramento River basin study area.

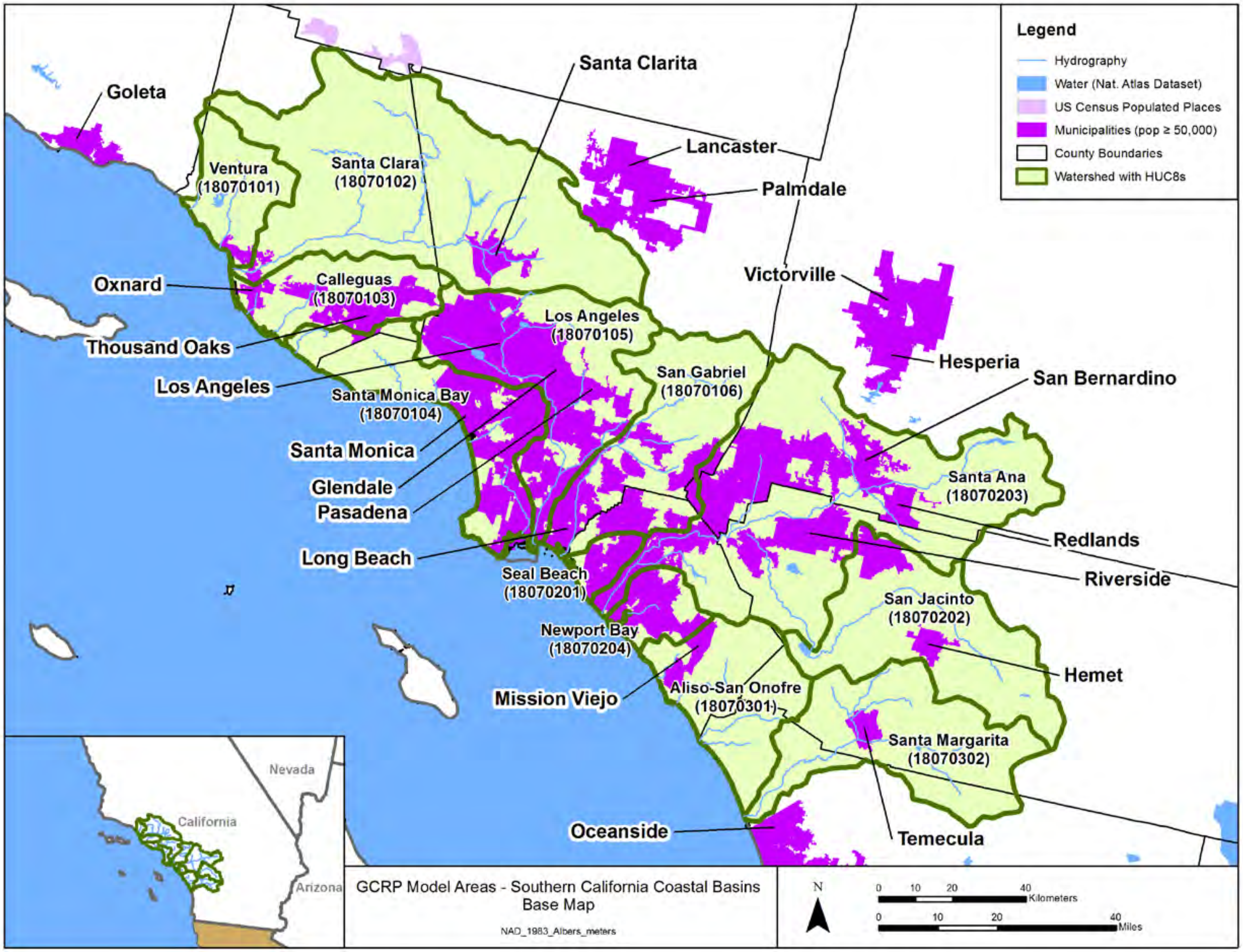

Figure 3-17. Southern California Coastal basins study area.

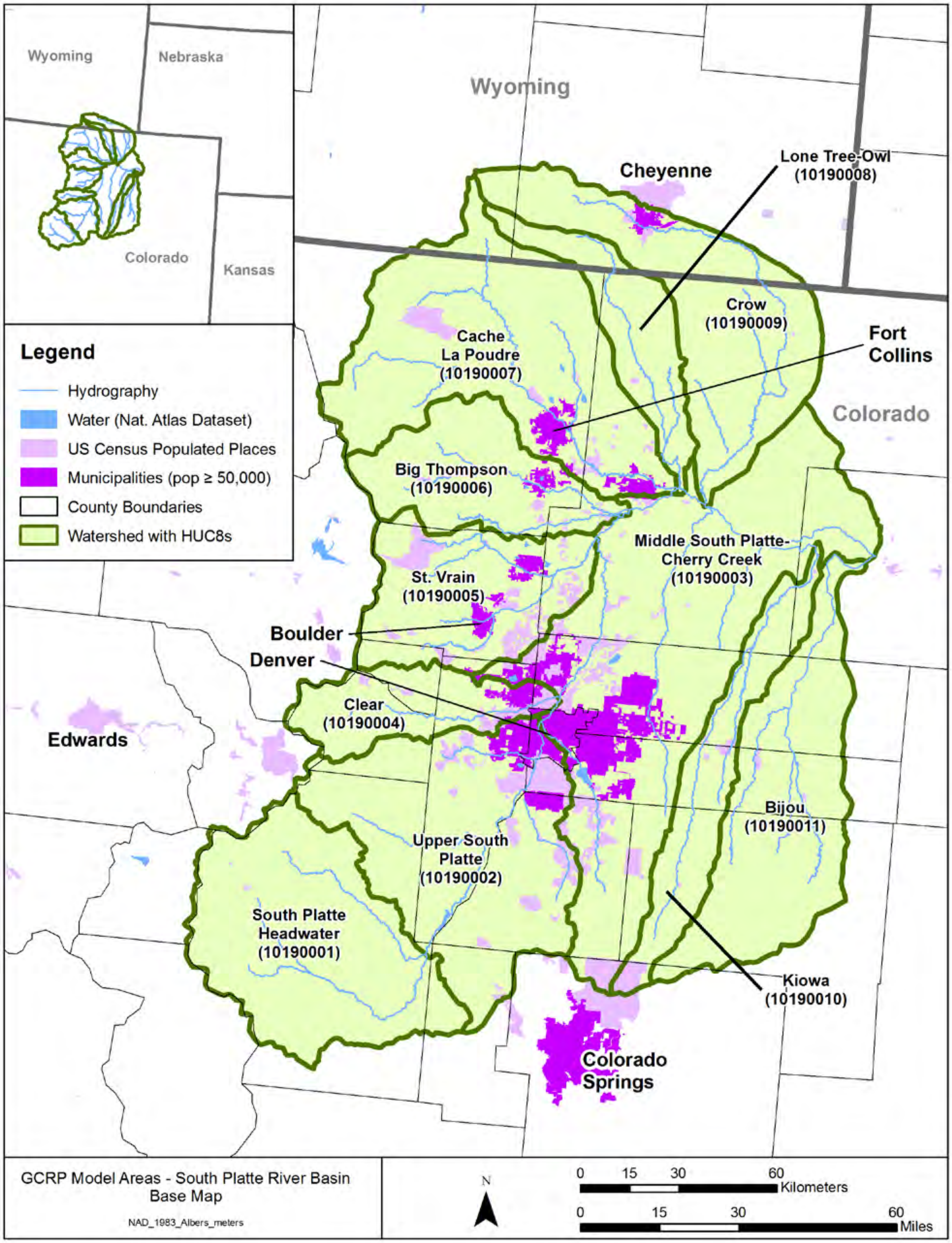

Figure 3-18. South Platte River basin study area.

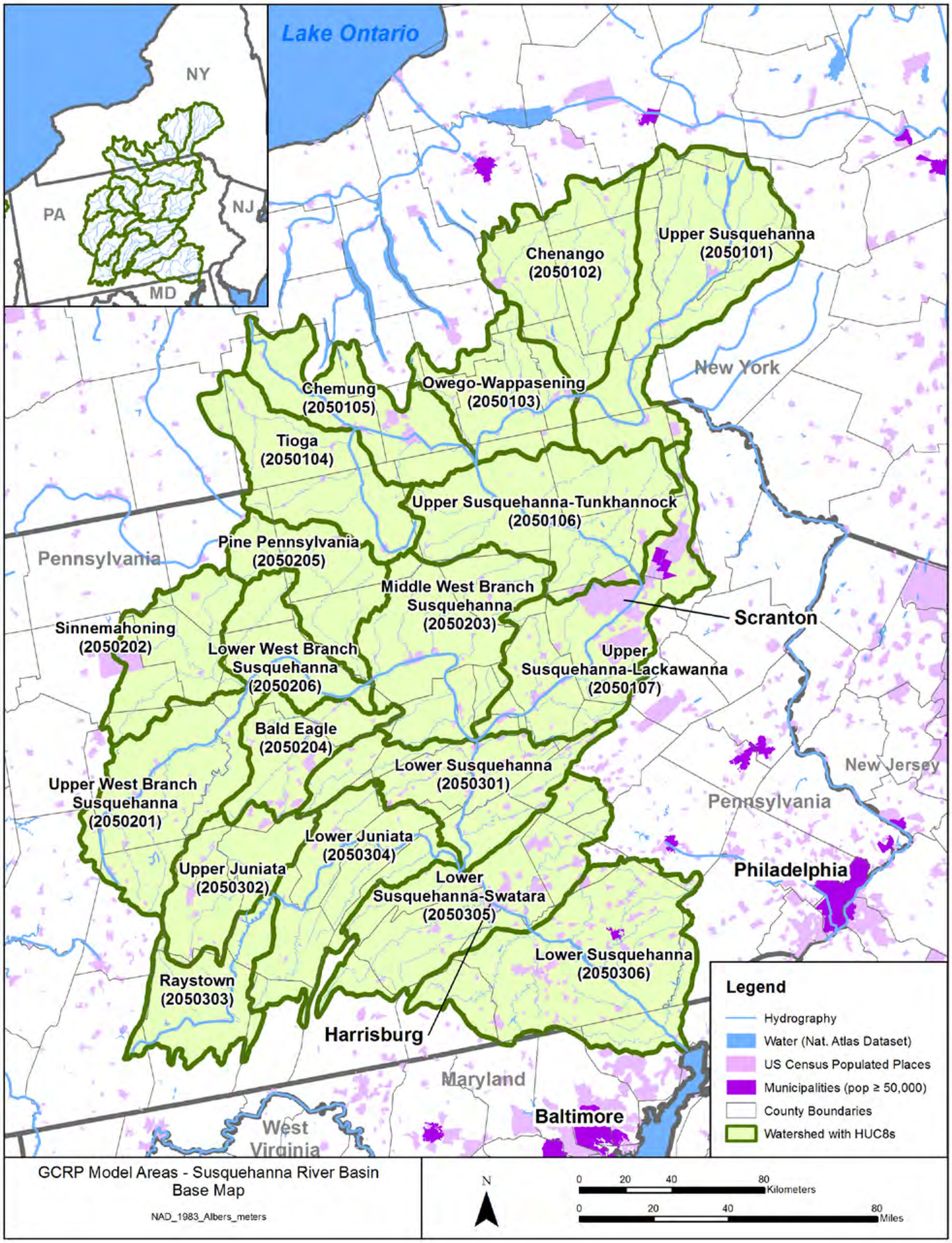

Figure 3-19. Susquehanna River basin study area.

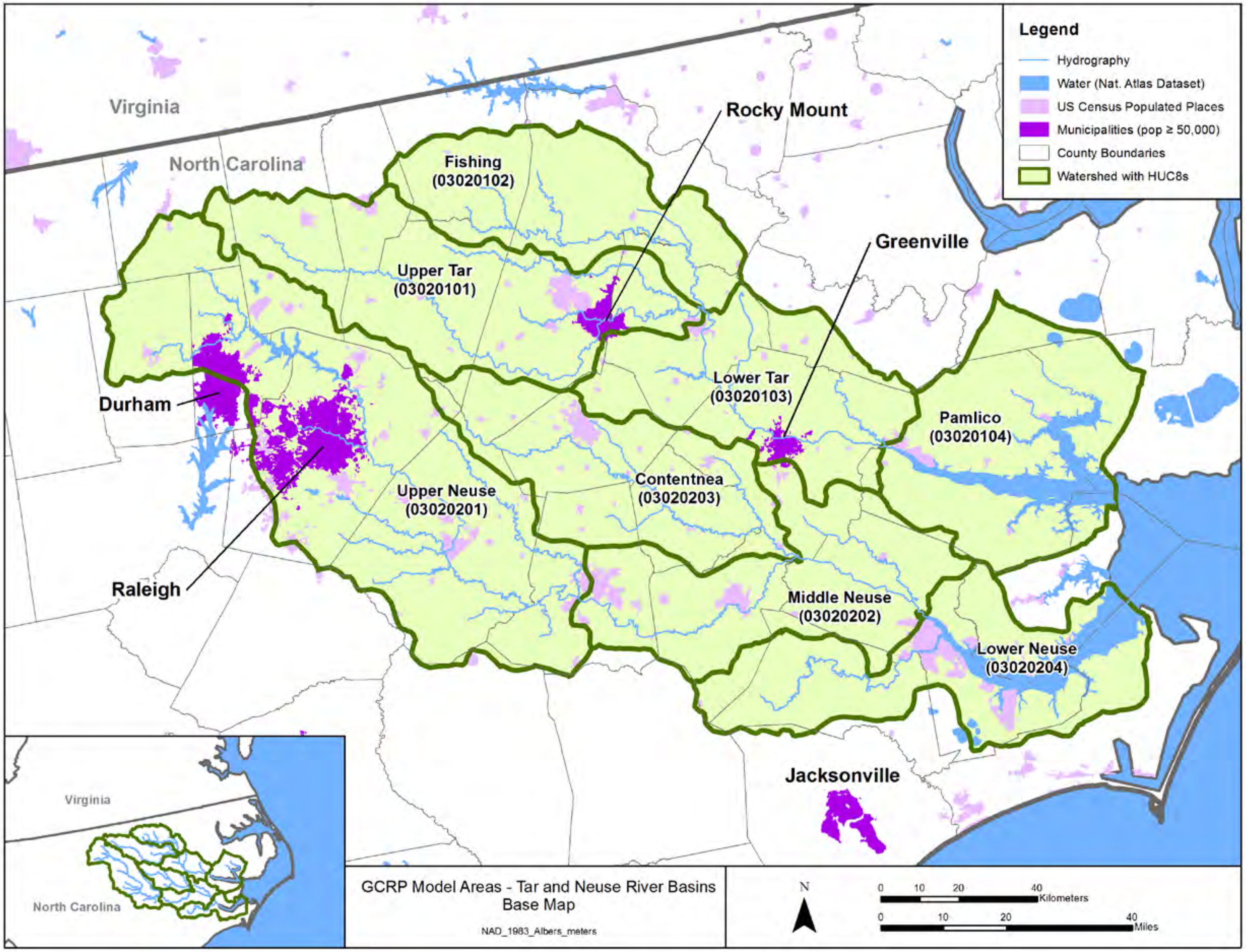

Figure 3-20. Tar and Neuse River basins study area.

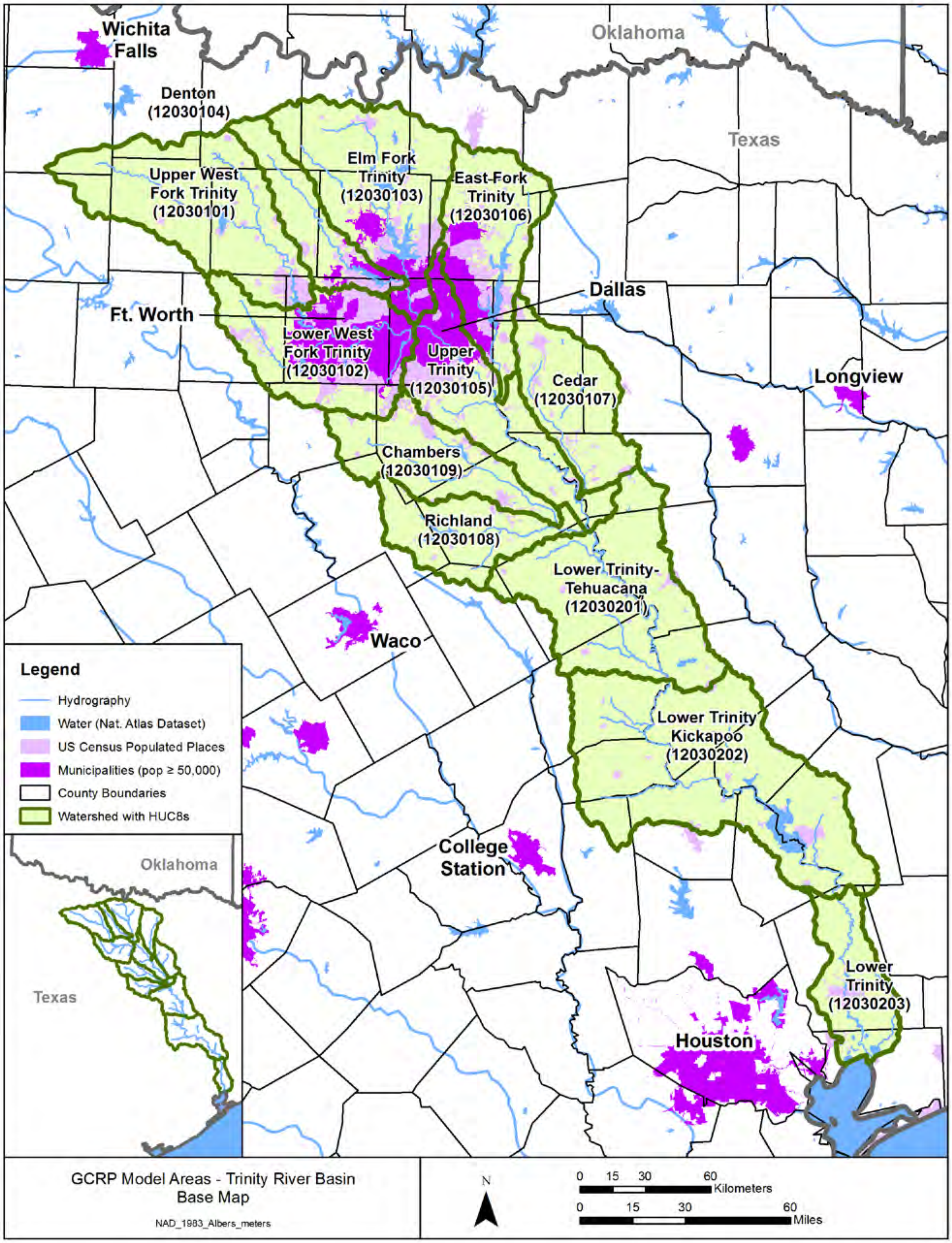

Figure 3-21. Trinity River basin study area.

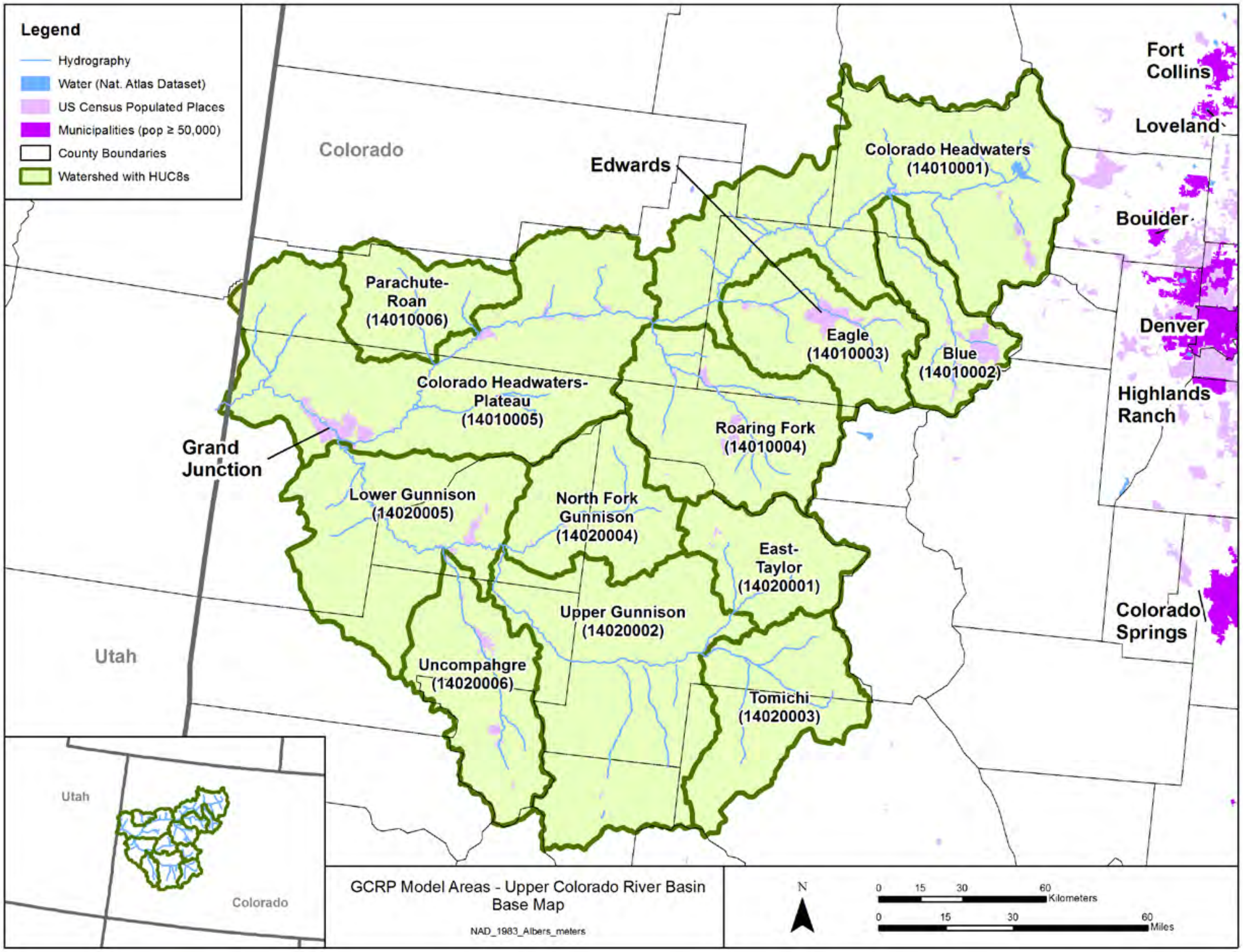

Figure 3-22. Upper Colorado River basin study area.

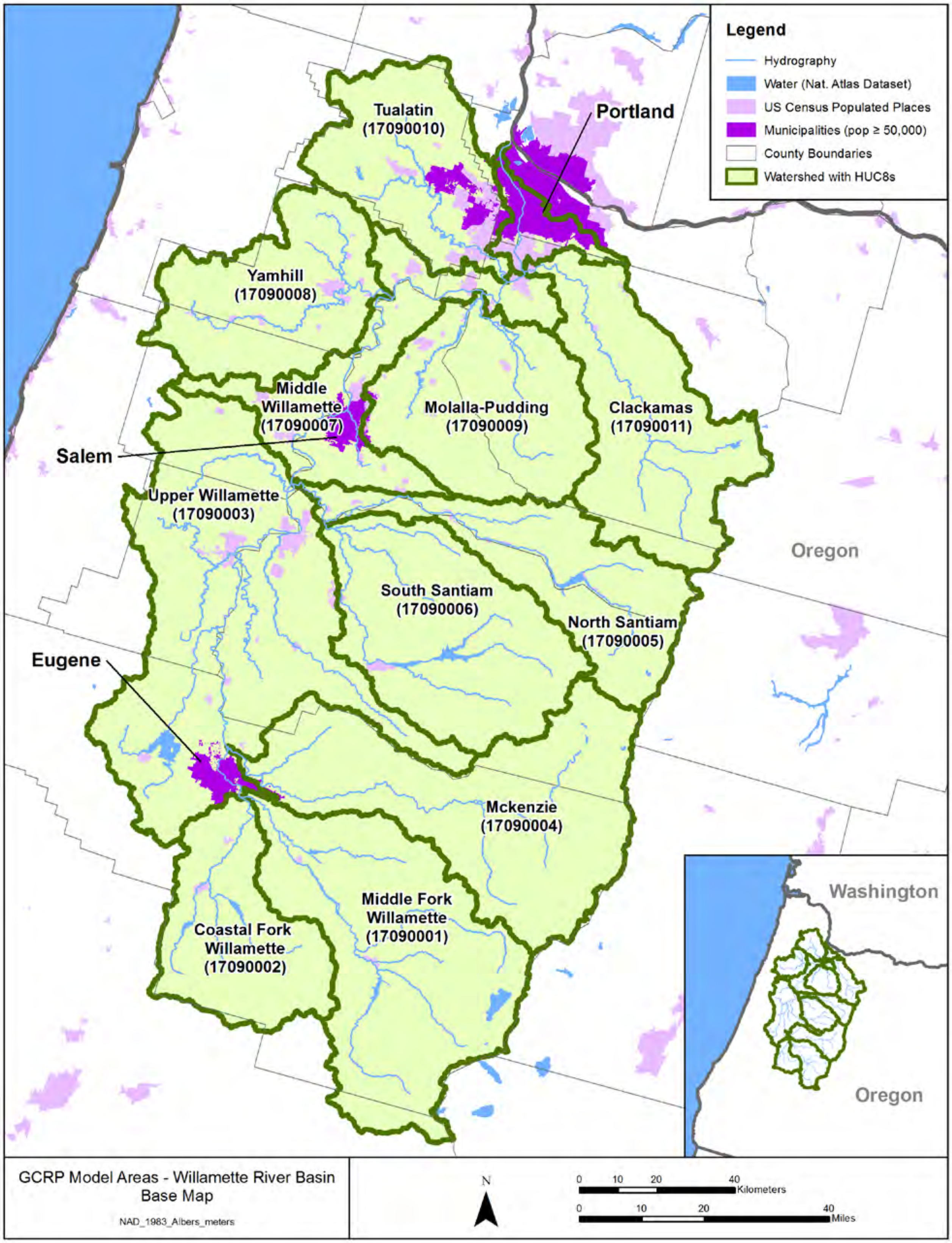

Figure 3-23. Willamette River basin study area.

4. MODELING APPROACH

This study uses dynamic watershed models to simulate the watershed response to potential mid-21st century climate change scenarios, urban and residential development scenarios, and combined climate change and urban development scenarios. Watershed models were developed for 20 large-scale study areas (approximately HUC-4 scale) located throughout the contiguous United States and Alaska. The study also evaluates the sensitivity of modeling results to different methodological choices for assessing climate change impacts, such as the use of climate change scenarios based on different methods of downscaling GCM projections and the use of different watershed models.

A watershed model is a useful tool for providing a quantitative linkage between external forcing and in-stream response. It is essentially a series of algorithms applied to watershed characteristics and meteorological data to simulate naturally occurring, land-based processes over an extended period, including hydrology and pollutant transport. Many watershed models are also capable of simulating in-stream processes. After a model has been set up and calibrated for a watershed, it can be used to quantify the existing loading of pollutants from subbasins or from different land-use categories and can also be used to assess the effects of a variety of management scenarios.

Five of the 20 sites were selected as “pilot” sites: the Minnesota River watershed (Minn), the Apalachicola-Chattahoochee-Flint River watersheds (ACF), the Willamette River watershed (Willa), the Salt/Verde/San Pedro River watershed (Ariz), and the Susquehanna River watershed (Susq). Pilot sites were selected in part due to previous experiences of the study team in applying watershed models in these areas, and in part because they provide a representative cross section of the full set of 20 study areas from a regional, meteorological, geographic, and land-use perspective. Pilot sites were used for testing and comparing model development and application methods, as well as for evaluating the sensitivity of modeling results to different types of climate change scenarios and use of different watershed models. Analysis of the pilot site results led to the selection of a reduced, more streamlined approach for the remaining 15 sites using one watershed model and a reduced set of climate change scenarios.

Two watershed models were selected for initial application to the five pilot study sites: HSPF (Bicknell et al., 2001, 2005) and SWAT (Neitsch et al., 2005). Each of these models has been widely used for hydrologic and water quality applications for regulatory purposes, such as the development of pollutant load allocations under the Total Maximum Daily Load (TMDL) provisions of the Clean Water Act. Both models are also in the public domain with open-source code, enabling ready replication of results. They both provide dynamic simulation with a subdaily or daily time step and can be built from readily available spatial coverages, but are sufficiently efficient to allow implementation of multiple runs for model calibration or scenario application purposes. Both models have also been used in previous studies of watershed responses to climate change (e.g., Taner et al., 2011; and Tong et al., 2011 for HSPF; Luo et al., 2013; Wilson and Weng, 2011; Marshall and Randhir, 2008; and Ficklin et al., 2009 for SWAT).

Application of both HSPF and SWAT to the five pilot watersheds allowed assessment of the variability associated with use of different watershed models in simulating watershed response to climate change. The two model frameworks exhibited similar skill in reproducing observations at the large spatial scales addressed in this project (see Section 4.4.3); however, SWAT is based on a plant growth model that can explicitly represent the impacts of altered temperature, moisture, and CO_2 regimes on plants and the resulting impacts on the water balance and pollutant transport. The analysis of the pilot site results (see Section 6) emphasized the potential importance of these processes. Therefore, the SWAT model was applied in all 20 study areas. HSPF and SWAT are each described in more detail below

4.1. MODEL BACKGROUND

4.1.1. HSPF

The HSPF (Bicknell et al., 2001, 2005) is a comprehensive, dynamic watershed and receiving water quality modeling framework that was originally developed in the mid-1970s. During the past several decades, it has been used to develop hundreds of EPA-approved TMDLs, and it is generally considered among the most advanced hydrologic and watershed loading models available. The hydrologic portion of HSPF is based on the Stanford Watershed Model (Crawford and Linsley, 1966), which was one of the pioneering watershed models developed in the 1960s. The HSPF framework is developed modularly with many different components that can be assembled in different ways, depending on the objectives of a project. The model includes three major modules:

- PERLND for simulating watershed processes on pervious land areas
- IMPLND for simulating processes on impervious land areas
- RCHRES for simulating processes in streams and vertically mixed lakes

All three of these modules include many subroutines that calculate the various hydrologic and water quality processes in the watershed. Many options are available for both simplified and complex process formulations.

HSPF models hydrology as a water balance in multiple surface and subsurface layers and is typically implemented in large watersheds at an hourly time step. The water balance is simulated based on Philip's infiltration (Bicknell et al., 2001, 2005) coupled with multiple surface and subsurface stores (interception storage, surface storage, upper zone soil storage, lower zone soil storage, active groundwater, and inactive [deep] groundwater). Potential evapotranspiration (PET) is externally specified to the model.

As implemented in HSPF, the infiltration algorithms represent both the continuous variation of infiltration rate with time as a function of soil moisture and the areal variation of infiltration over the land segment. The infiltration capacity, the maximum rate at which soil will accept infiltration, is a function of both the fixed and variable characteristics of the watershed. Fixed characteristics include soil permeability and land slopes, while variables are soil surface conditions and soil moisture content. A linear probability function is used to account for spatial variation (Bicknell et al., 2005). The primary parameters controlling infiltration are *INFILT*, an index to mean soil infiltration rate (in/hr) and *LZSN*, the lower soil zone nominal soil moisture storage. Specifically, the mean infiltration capacity over a land segment at any point in time, *IBAR*, is calculated as

$$IBAR = \left[\frac{INFILT}{\left(LZS / LZSN \right)^{INFEXP}} \right] \cdot INFFAC \quad , \tag{4-1}$$

where *LZS* is the current lower soil zone storage, *INFEXP* is an exponent typically set to a value of 2, and *INFFAC* is an adjustment factor to account for frozen ground effects.

Neither *INFILT* nor *LZSN* is directly observable or provided in soils databases and both must be refined in calibration. As *INFILT* is not a maximum rate nor an infiltration capacity term, its values are normally much less than published infiltration rates, soil percolation test results, or permeability rates from the literature (U.S. EPA, 2000).

Sediment erosion in HSPF uses a method that is formally similar to, but distinct from, the universal soil loss equation (USLE) sediment-detachment approach coupled with transport capacity based on overland flow. Nutrients may be simulated at varying levels of complexity, but are most typically represented by either buildup/washoff or sediment potency approaches on the land surface coupled with user-specified monthly concentrations in interflow and groundwater.

Spatially, the watershed is divided into a series of subbasins representing the drainage areas that contribute to each of the stream reaches. The stream network (RCHRES) links the surface runoff and groundwater flow contributions from each of the land segments and subbasins and routes them through water bodies. The stream model includes precipitation and evaporation from the water surfaces as well as streamflow contributions from the watershed, tributaries, and upstream stream reaches. It also simulates a full range of stream sediment and nutrient processes, including detailed representations of scour, deposition, and algal growth.

The version of HSPF used in this study is the Windows interface to Hydrologic Simulation Program—FORTRAN (WinHSPF) as distributed with BASINS version 4.0. WinHSPF is a Windows interface to HSPF and is a component of the EPA's Better Assessment Science Integrating point and Nonpoint Sources (BASINS) Version 4.0 (U.S. EPA, 2001, 2009a, 2009c). WinHSPF itself is a user interface to HSPF that assists the user in building User Control Input (UCI) files (containing model input parameters) from geographic information system (GIS) data (Duda et al., 2001). After the UCI file is built, WinHSPF is used to view, understand, and modify the model representation of a watershed. HSPF can be run from within WinHSPF. The actual model executable engine distributed with BASINS is called WinHSPFLt, which can be run in batch mode independent of the BASINS/WinHSPF interface. The model code for HSPF is stable and well documented. Detailed descriptions of the model theory and user control input are provided in Bicknell et al. (2001, 2005).

WinHSPF also provides access to the Climate Assessment Tool (CAT), which is a component of BASINS 4.0. BASINS CAT facilitates watershed-based assessments of the potential effects of climate variability and change on water and watershed systems (namely streamflow and pollutant loads) using the HSPF model (U.S. EPA, 2009a, 2009b). BASINS CAT is capable of creating climate change scenarios that allow users to assess a wide range of *what if* questions related to climate change.

4.1.2. SWAT

The SWAT model was developed by the U.S. Department of Agriculture to simulate the effect of land management practices on water, sediment, and agricultural chemical yields in large, complex watersheds with varying soils, land use, and management conditions over long periods of time (Neitsch et al., 2005). SWAT requires data inputs for weather, soils, topography, vegetation, and land use to model water and sediment movement, nutrient cycling, and numerous other watershed processes. SWAT is a continuous model appropriate for long-term simulations.

SWAT, as implemented in this study, employs a curve number approach (SCS, 1972) to estimate surface runoff and then completes the water balance through simulation of subsurface flows, evapotranspiration, soil storages, and deep seepage losses. The curve number approach requires a daily time step. PET is typically calculated internally by SWAT based on other weather inputs.

SWAT provides an option for subdaily Green-Ampt infiltration, but this is infrequently used. The curve number approach is popular because parameters are simple and readily available. The curve number approach estimates the depth of daily runoff (Q) from rainfall depth (P), initial abstractions (Ia, depth), a storage parameter (S, depth), and a curve number (CN), as (SCS, 1972):

$$Q = \frac{(P - Ia)^2}{P - Ia + S} \tag{4-2}$$

Ia is typically assumed to be 20% of S (indeed, this is a hard-coded default in SWAT). In units of millimeters for S, this yields:

$$Q = \frac{(P - 0.2S)^2}{(P + 0.8S)}, \quad S = \frac{25{,}400}{CN} - 254 \tag{4-3}$$

The curve number is estimated as a function of land use, cover, condition, hydrologic soil group (HSG), and antecedent soil moisture. SWAT provides capabilities to automatically adjust the *CN* based on soil moisture, plant evapotranspiration, slope, and the presence of frozen ground. The conceptual simplicity of the curve number approach also introduces some potential problems. Specifically, the curve number was developed as a design methodology to estimate average runoff volume of a specific return period, given average total event rainfall of the same return period. It was not designed to predict runoff from specific individual events or runoff from more frequent smaller events, and applicability to continuous simulation is inexact, especially at small spatial scales. For a summary of these issues and their potential implications in continuous simulation modeling, see Garen and Moore (2005).

Sediment yield and erosion are calculated by SWAT using the Modified Universal Soil Loss Equation (MUSLE; Williams, 1975). The MUSLE is based on several factors, including surface runoff volume, peak runoff rate, area of hydrologic response unit (HRU), soil erodibility, land cover and management, support practice, topography, and a coarse fragment factor. MUSLE implicitly combines the processes of sediment detachment and delivery. Nutrient load generation and movement are simulated using overland runoff and subsurface flow.

A key feature of SWAT is the incorporation of an explicit plant growth model, including plant interactions with water and nutrient stores. The transformation of various nitrogen and phosphorus species is simulated in detail in the soil; however, concentrations of nutrients in groundwater discharges are user specified, as in HSPF.

In-stream simulation of sediment in SWAT 2005 includes a highly simplified representation of scour and deposition processes. Nutrient kinetics in receiving waters are based on the numeric representation used in the QUAL2E model but implemented only at a daily time step.

SWAT is generally considered to be an effective tool for watershed simulation that is especially appropriate for estimating streamflow and cumulative pollutant loads in agricultural and rural watersheds (see review by Gassman et al., 2007). Bosch et al. (2011) found that SWAT was an effective tool for estimating hydrology, sediment, and nutrient loads in Lake Erie watersheds, but performed less well in urbanized settings. SWAT has some potential weaknesses relative to HSPF for the simulation of urban lands because it is typically run using a curve number approach at a daily time step while HSPF is typically run at an hourly time step using Philip infiltration. The daily time step is insufficient to resolve details of urban runoff hydrographs that have important implications for stability of small stream channels, while the curve number approach can result in poor resolution of surface versus subsurface flow pathways (Garen and Moore, 2005). The impacts of these differences are, however, believed to be minor at the larger spatial scales addressed in this study.

An important component of the SWAT model is the weather generator (WXGEN). SWAT requires daily values of precipitation, maximum and minimum temperature, solar radiation, relative humidity, and wind speed. The user may read these inputs from a file or generate the values using SWAT's weather generator model based on monthly average data summarized over a number of years (Neitsch et al., 2005). The weather generator model (Sharpley and Williams, 1990) can be used to generate climatic data or to fill in gaps in weather data. The weather generator first independently generates precipitation for the day. Maximum temperature, minimum temperature, solar radiation, and relative humidity are then generated based on the presence or absence of rain for the day. Finally, wind speed is generated independently.

The version of SWAT used in this study is SWAT 2005 as distributed with ArcSWAT 2.1, which was the most recent stable version of SWAT available at the start of this study. ArcSWAT 2.1 is an ArcGIS-ArcView extension and a graphical user input interface for the SWAT watershed model (TAMU, 2010). As with HSPF, the underlying executable code can be run in batch mode independent of the user interface. Unlike HSPF, the SWAT code is continuously evolving, with frequent enhancements and bug fixes. For a detailed description of the version of SWAT used here, see Neitsch et al. (2005).

4.2. MODEL SETUP

Watershed models were configured to simulate each study area as a series of hydrologically connected subbasins. Each study area was subdivided into subbasin-scale modeling units. Continuous simulations of streamflow, total nitrogen, total phosphorus, and total suspended solids were then made for each unit using meteorological, land use, soil, and stream data.

Many study areas are highly managed systems influenced by humans, including dams, water transfers and withdrawals, point source discharges and other factors. Given the difficulty of modeling at the large spatial scale in this study, detailed representation of all management was not possible. The following assumptions were made to simplify modeling among all 20 study areas:

- External boundary conditions (where needed), such as upstream inflows and pollutant loads, are assumed constant.
- Interactions with deep groundwater systems are assumed constant.
- Large-scale shifts in natural cover type in response to climate change are not simulated.
- Point source discharges and water withdrawals are assumed constant at current levels.
- Only large dams that have a significant impact on hydrology at the HUC-8 (subbasin) scale are included in the models. Where these dams are simulated, an approximation of current operating rules (using a target storage approach) is assumed to apply in all future scenarios.
- Human adaptation response to climate change, such as shifts in water use or cropping practices, are not simulated.

The project team consisted of multiple modelers working in different locations. To ensure consistency of results, a common set of procedures and assumptions was established (e.g., see Appendix A). Both HSPF and SWAT were implemented using a HRU approach to upland simulation. An HRU consists of a unique combination of land use/land cover, soil, and land management practice characteristics, and thus represents areas of similar hydrologic response. Individual land parcels included within an HRU are expected to possess similar hydrologic and load generating characteristics and can thus be simulated as a unit. The HRU approach is the default for SWAT but is also good practice with HSPF. Consistent with the broad spatial scale of the models, the land cover component is aggregated into a relatively small number of categories (e.g., forest, wetland, range, grass/pastureland, crop, developed pervious, low-density impervious, and high-density impervious).

Initial preparation of spatial data was done primarily in ArcGIS for the entire study area. Processed GIS inputs were then used in ArcSWAT (which runs as an extension in ArcGIS), and imported into BASINS4 (which uses MapWindow GIS) to complete the setup of SWAT and HSPF, respectively. Spatial data sources are discussed in more detail in Section 4.2.3. Additional initial setup tasks included identification of weather stations, streamflow gaging and water quality monitoring locations, and major watershed features that significantly affect the water balance, such as presence of major lakes, reservoirs, and diversions.

4.2.1. SWAT Setup Process

SWAT model setup used the ArcSWAT extension in ArcGIS. The general procedure for SWAT setup is described below; a more detailed modeling protocol used for this project is included in Appendix A.

Subbasin boundaries and reach hydrography for each study area were generally defined from NHDPlus catchments (U.S. EPA, 2010) aggregated to approximately the HUC-10 spatial scale. The subbasin and reach shapefiles were imported into the SWAT interface and subbasin parameters were calculated automatically.

Study area boundaries were configured to minimize the presence of large reservoirs due to the difficulty of representing operational rules. Models included only major reservoirs that have a significant effect on streamflow at the scale of HUC-8s or greater. Inclusion of reservoirs was left to the discretion of individual modelers; however, the reservoirs included are generally those that drain an area greater than a single HUC-8 and provide a retention time of half a year or greater. If a reservoir was located at the terminus of the model area, it was generally ignored so that the model represented input to, rather than output from, the terminal reservoir. Models include point source discharges from major permitted facilities (greater than 1 million gallons per day [MGD] discharge). It was also necessary to define an upstream boundary condition "point source" for study areas where the model did not extend to the headwaters (e.g., Sacramento River basin).

HRUs were developed from an intersection of land use, slope, and major soils, using the geospatial data sources described in Section 4.2.3. In the HRU analysis, SWAT was used to classify the slopes into two categories: above and below 10%. A single breakpoint was chosen to represent major differences in runoff and erosive energy without creating an unmanageable number of individual HRUs. The State Soil Geographic Database (STATSGO) soils coverage was assigned using the dominant component method in which each soil polygon is represented by the properties of the dominant constituent soil. The NLCD 2001 land use coverage was loaded directly into ArcSWAT without modification. The default NLCD class to SWAT class mapping was appropriate for most areas. Impervious percentage was assigned to developed land-use classes in the SWAT urban database using values calculated from the NLCD impervious coverage. The same assumptions were applied for the future developed land-use classes (i.e., the future classes have the same total and connected impervious fractions as the corresponding existing urban land uses). HRUs were created by overlaying land use, soil, and slope at appropriate cutoff tolerance levels to prevent the creation of large numbers of insignificant HRUs. Land-use classes were retained if they occupied at least 5% of the area of a subbasin (with the exception of developed land uses, which were retained regardless of area). Soils were retained if they occupied at least 10% of the area within a given land use in a subbasin. Slope classes were retained if they occupied at least 5% of the area within a given soil polygon. Land uses, soils, and slope classes that fall below the cutoff value are reapportioned to the dominant classes so that 100% of the watershed area is modeled (Winchell et al., 2008).

The SWAT models were linked to meteorological stations contained in EPA's BASINS 4 meteorological data set (U.S. EPA, 2008). The models used observed time series for precipitation and temperature; other weather data were simulated with the SWAT weather generator, as discussed in Section 4.2.4. Elevation bands were turned on if necessary to account for orographic effects in areas with a sparse precipitation network and significant elevation changes. This was generally appropriate where elevations within subbasins spanned a range of 250 m or more. Daily curve number hydrology with observed precipitation and air temperature was used.

Land management operations were assigned, primarily to account for agricultural practices. For urban lands, the USGS regression method for pollutant load estimation was specified. In-stream water quality options started with program defaults.

The target time period for simulation was 31 water years, with the first year dropped from analysis to account for model spinup (initialization). Some weather stations may have been absent for the spinup year, but SWAT fills in the missing records using the weather generator. The remaining 30 years span a period for which the supplied weather data were complete and included the year 2000 (with the exception of the Loup/Elkhorn basins in Nebraska, for which the simulation period ended in 1999 due to the termination of a number of precipitation gauges before the end of 2000).

4.2.2. HSPF Setup Process

HSPF models were developed on a common basis with the SWAT models using the same geospatial data, but only for the five pilot watersheds. Subbasin boundaries and reach hydrography were defined using the same NHDPlus catchments as the SWAT models. The HRUs for HSPF were calculated from the SWAT HRUs, but differ in that soils were aggregated into hydrologic soil group. Pervious (PERLND) and impervious (IMPLND) land areas are specified and simulated separately in HSPF, whereas SWAT specifies an impervious fraction for different land-use categories.

The WinHSPF interface distributed with BASINS (U.S. EPA, 2001) was used to create the user control input (UCI) and watershed data management (WDM) files. A starter UCI file was prepared that assigned default values for HRUs. Initial parameter values were based on previous modeling where available. For areas without previous modeling, hydrologic parameters were based on recommended ranges in BASINS Technical Note 6 (U.S. EPA, 2000) and related to soil and meteorological characteristics where appropriate. Snowmelt simulation used the simplified degree-day method.

The stage-storage-discharge hydraulic functional tables (FTables) for stream reaches were generated automatically during model creation. The WinHSPF FTable tool calculates the tables using relationships to drainage area. FTables were adjusted in WinHSPF if specific information was available to the modeler. Hydraulic characteristics for major reservoirs and flow/load characteristics for major point sources were defined manually based on available information.

Nutrients on the land surface were modeled as inorganic nitrogen, inorganic phosphorus, and total organic matter. The latter was transformed to appropriate fractions of organic nitrogen and organic phosphorus in the linkage to the stream. The in-stream simulation represented total nitrogen and total phosphorus as general quality constituents subject to removal approximated as an exponential decay process. Initial values for decay rates were taken from studies supporting the USGS SPARROW model (e.g., Alexander et al., 2008).

4.2.3. Watershed Data Sources

The HSPF and SWAT models each use identical geospatial and other input data sources as described below.

4.2.3.1. *Watershed Boundaries and Reach Hydrography*

Subbasin boundaries and reach hydrography (with connectivity) for both SWAT and HSPF were defined using NHDPlus data (U.S. EPA, 2010), which is a comprehensive set of digital spatial data representing the surface water of the United States including lakes, ponds, streams, rivers, canals, and oceans. NHDPlus provided catchment/reach flow connectivity, allowing for creation of large model subbasins with automation. NHDPlus incorporates the National Hydrography Dataset (NHD), the National Elevation Dataset, the NLCD, and the Watershed Boundary Dataset. A MapWindow script was developed to automate (with supervision) the aggregation of NHDPlus catchments/reaches into model subbasins and reaches. The general approach was to first run the aggregation script with a smaller target subbasin size (i.e., create several hundred to a thousand subbasins), then run the script again to create watersheds of the target model size (comparable to the HUC-10 spatial scale). The two-tiered approach has several benefits; it was found to be more time efficient, it allowed for greater control over the final basin size, and it provided a midpoint that could be used to redefine subbasin boundaries to match specified locations, such as gaging stations and dams/diversions.

Each delineated subbasin was conceptually represented with a single stream assumed to be a completely mixed, one-dimensional segment with a constant cross section. For the HSPF model, reach slopes were calculated based on Digital Elevation Model (DEM) data, and stream lengths were measured from the original NHD stream coverage. Assuming representative trapezoidal geometry for all streams, mean stream depth and channel width were estimated using regression curves that relate upstream drainage area to stream dimensions developed for three regions in the Eastern United States. Existing and more detailed models provided additional site-specific information on channel characteristics for some watersheds (e.g., Minnesota River; Tetra Tech, 2008b).

The SWAT model also automatically calculates the initial stream geometric values based on subbasin drainage areas, standard channel forms, and elevation, using relationships developed for numerous areas of the United States. Channel slope is automatically calculated from the DEM.

4.2.3.2. *Elevation*

Topography was represented by digital elevation models (DEMs) with a resolution of 30 meters obtained from USGS' National Elevation Dataset (Gesch et al., 2002). Multiple DEM coverages were grouped and clipped to the extent of the model watershed area (with a 10-mile buffer to allow for unforeseen changes to watershed boundaries).

4.2.3.3. *Land Use and Land Cover*

The SWAT and HSPF models use a common land use platform representing current (calibration) conditions and derived from the 2001 NLCD (Homer et al., 2004, 2007). The 2001 NLCD land cover was used to ensure consistency between all models for the project. The 2001 land use was chosen rather than the 2006 coverage because it is closer in time to the calibration period of the models, which typically runs through 2002/3. The 2001 land use is assumed to apply throughout the baseline model application period.

Some additional processing of the NLCD data was necessary. Several of the land use classes were aggregated into more general categories to provide a more manageable set of HRUs. The developed land classes were kept separate for SWAT but aggregated for HSPF. This is because SWAT assigns percent imperviousness to total developed area, whereas HSPF explicitly separates developed pervious and impervious areas. The regrouping of the NLCD classes for SWAT and HSPF is shown in Table 4-1.

The percent impervious area was specified for each developed land class from the NLCD Urban Impervious data coverage. The NLCD 2001 Urban Imperviousness coverage was clipped to the extent of the model watershed area (with 10-mile buffer) to calculate the impervious area. The percent impervious area was then specified by combining data from the 2001 NLCD Land Cover and Urban Impervious data products. Specifically, average percent impervious area was calculated over the whole basin for each of the four developed land use classes. These percentages were then used to separate out impervious land. The analysis was performed separately for each of the 20 study areas, since regional differences occur. Table 4-2 presents the calculated 2001 impervious areas for each study area.

4.2.3.4. *Soils*

Soils data were implemented using SWAT's built-in STATSGO (USDA, 1991) national soils database. The SWAT model uses the full set of characteristics of dominant soil groups directly, including information on infiltration, water holding capacity, erodibility, and soil chemistry. A key input is infiltration capacity, which is used, among other things, to estimate the runoff curve number. Curve numbers are a function of hydrologic soil group, vegetation, land use, cultivation practice, and antecedent moisture conditions. The Natural Resource Conservation Service (NRCS; SCS, 1972) has classified more than 4,000 soils into four hydrologic soil groups (HSGs) according to their minimum infiltration rate for bare soil after prolonged wetting. The characteristics associated with each HSG are provided in Table 4-3.

In the HSPF setup the HRUs are not based directly on dominant soils; instead, these were aggregated to represent HSGs. The HSGs include special agricultural classes (A/D, B/D, and C/D) in which the first letter represents conditions with artificial drainage and the second letter represents conditions without drainage. The first designator was assumed to apply to all crop land, while the second designator was assumed for all other land uses.

Table 4-1. Regrouping of the NLCD 2001 land-use classes for the HSPF and SWAT models

NLCD class	SWAT class	HSPF class
11 Water[a]	WATR (water)	WATER
12 Perennial ice/snow	WATR (water)	BARREN
21 Developed open space	URLD (Urban Residential—Low Density)	DEVPERV (Developed Pervious) IMPERV (Impervious)
22 Dev. Low Intensity	URMD (Urban Residential—Medium Density)	
23 Dev. Med. Intensity	URHD (Urban Residential—High Density)	
24 Dev. High Intensity	UIDU (Urban Industrial and High Intensity)	
31 Barren Land	SWRN (Range-Southwestern U.S.)	BARREN
41 Forest—Deciduous	FRSD (Forest—Deciduous)	FOREST
42 Forest—Evergreen	FRSE (Forest—Evergreen)	
43 Forest—Mixed	FRST (Forest—Mixed)	
51−52 Shrubland	RNGB (Range—Brush)	SHRUB
71−74 Herbaceous Upland	RNGE (Range—grasses)	GRASS BARREN
81 Pasture/Hay	HAY	GRASS
82 Cultivated	AGRR (Agricultural Land-Row Crops)	AGRI (Agriculture)
91−97 Wetland (emergent)	WETF (Wetlands—Forested), WETL (Wetlands), WETN (Wetlands—Nonforested)	WETL (Wetlands)
98−99 Wetland (nonemergent)	WATR (water)	WATER

[a]Water surface area is usually accounted for as reach area.

Table 4-2. Calculated fraction impervious cover within each developed land class for each study area based on NLCD 2001

Site ID	Open space (%)	Low intensity (%)	Medium intensity (%)	High intensity (%)
ACF	8.04	30.16	60.71	89.90
Ariz	7.37	29.66	53.71	73.85
Cook	10.11	29.79	61.48	87.17
GaFla	7.20	31.87	60.14	87.47
Illin	8.83	32.36	61.24	88.70
LErie	7.30	32.53	60.72	86.75
LPont	7.53	32.91	60.11	88.08
Minn	6.59	29.20	55.01	83.31
Neb	8.34	29.68	60.14	86.59
NewEng	8.22	32.81	60.90	87.25
PowTon	7.42	31.64	59.16	85.99
RioGra	8.76	32.36	60.49	84.32
Sac	5.95	30.02	55.41	81.20
SoCal	7.75	35.39	61.31	88.83
SoPlat	6.41	33.46	60.79	86.76
Susq	6.90	31.26	60.90	85.41
TarNeu	7.17	30.90	61.05	87.31
Trin	7.74	31.65	60.78	89.15
UppCol	9.78	31.89	60.48	87.41
Willa	9.56	32.31	61.49	88.94

Table 4-3. Characteristics of NRCS soil hydrologic groups

Soil group	Characteristics	Minimum infiltration capacity (in/hr)
A	Sandy, deep, well drained soils; deep loess; aggregated silty soils	0.30−0.45
B	Sandy loams, shallow loess, moderately deep and moderately well drained soils	0.15−0.30
C	Clay loam soils, shallow sandy loams with a low permeability horizon impeding drainage (soils with a high clay content), soils low in organic content	0.05−0.15
D	Heavy clay soils with swelling potential (heavy plastic clays), water-logged soils, certain saline soils, or shallow soils over an impermeable layer	0.00−0.05

4.2.3.5. *Point Source Discharges*

The primary objective of this study is to examine relative changes that are potentially associated with changes in climate and land use. From that perspective, point source discharges can be characterized as a nuisance parameter. However, point sources that are large enough relative to receiving waters to affect the observed streamflow and nutrient loads in river systems need to be included to calibrate the models. This is done in a simplified way, and the point sources were then held constant for future conditions, allowing analysis of relative change. Only the major dischargers, typically those with a discharge rate greater than 1 MGD were included in the models. The major dischargers account for the majority of the total flow from all permitted discharges in most watersheds, so the effect on the calibration of omitting smaller sources is relatively small, except perhaps during extreme low streamflow conditions. Data were sought from the EPA's Permit Compliance System database for the major dischargers in the watersheds. Facilities that were missing TN, TP, or total suspended solids (TSS) concentrations were filled with a typical pollutant concentration value from the literature based on Standard Industrial Classification (SIC) code. The major dischargers were represented at long-term average flows, without accounting for changes over time or seasonal variations.

4.2.3.6. *Atmospheric Deposition*

Atmospheric deposition can be a significant source of inorganic nitrogen to watersheds and water bodies. SWAT2005 allows the user to specify wet atmospheric deposition of nitrate nitrogen. This is specified as a constant concentration across the entire watershed. Wet deposition of ammonia and dry deposition of nitrogen is not addressed in the SWAT2005 model.

HSPF allows the specification of both wet and dry deposition of both nitrate nitrogen (NO_3) and ammonium nitrogen (NH_4), and both were included in the model. Dry deposition is specified as a loading series, rather than concentration series. Because wet deposition is specified as a concentration, it will vary in accordance with precipitation changes in future climate scenarios, whereas the dry deposition series (HSPF only) is assumed constant for future scenarios.

Total oxidized nitrogen (NO_x) emissions in the United States remained relatively constant to a first approximation across the model period considered in this study from the early 1970s up through 2002 (U.S. EPA, 2002). There is strong geographic variability in atmospheric deposition, but much smaller year-to-year variability at the national scale over this period (Suddick and Davidson, 2012). The National Acid Deposition Program (NADP; http://nadp.sws.uiuc.edu/) monitors wet deposition across the country and produces yearly gridded maps of NO_3 and NH_4 wet deposition concentrations. Dry deposition rates are monitored (and interpreted with models) by the EPA Clean Air Status and Trends Network (http://epa.gov/castnet/javaweb/index.html). Results for year 2000 were selected as generally representative and each study watershed was characterized by a spatial average wet deposition concentration (and dry deposition loading rate for HSPF). Atmospheric deposition of phosphorus and sediment was not considered a significant potential source and is not addressed in the models.

4.2.3.7. *Impoundments, Diversions, and Withdrawals*

The hydrology of many large watersheds in the United States is strongly impacted by anthropogenic modifications, including large impoundments and withdrawals for consumptive use. It is necessary to take these factors into account to develop a calibrated model. At the same time, these anthropogenic factors constitute a problem for evaluating responses to future changes, as there is no clear basis for evaluating future changes in reservoir operations or water withdrawals. In addition, information on impoundments, withdrawals, and trans-basin water imports is often difficult to obtain. The approach taken in this project is to minimize the importance of impoundments and withdrawals by focusing on relative changes between present and future conditions with these factors held constant. In this way, the results that are presented are estimates of the change that may be anticipated based on changes to meteorological and land use forcing within the subject study area, with other factors held constant. Simulation results do not account for potential future changes in water management.

The general approach adopted for this project was to select study areas by avoiding major human interventions (e.g., reservoirs) in the flow system where possible, to ignore relatively minor interventions, and where necessary to represent significant interventions in a simplified manner. In the first instance, study watersheds were delineated to avoid major reservoirs where possible. For example, the model of the Verde River watershed (Arizona) is terminated at the inflow to Horseshoe Reservoir. In some cases, as in the Sacramento River watershed, an upstream reservoir is treated as a constant boundary condition because information on future reservoir management responses to climate change was not available.

Impoundments, withdrawals, and water imports that do not have a major impact on downstream streamflow were generally omitted from the large scale models. Inclusion or omission of such features was a subjective choice of individual modelers; however, it was generally necessary to include such features if they resulted in a modification of flow at downstream gages on the order of 10% or more. Where these features were included they were represented in a simplified manner: (1) impoundments were represented by simplified (two-season) stage-discharge operating rules, developed either from documented operational procedures or from analysis of monitored discharge; (2) large withdrawals were represented as either annual or monthly constant average rates; and (3) major trans-basin water imports were also represented as either annual or monthly constant average rates depending on availability of data. Use of surface water for irrigation was simulated only in those basins where it was determined during calibration that it was a significant factor in the overall water balance. These simplifying assumptions decrease the quality of model fit during calibration and validation, but provide a stable basis for the analysis of relative response to climate and land-use change within the basin.

More detailed information about the representation of impoundments and other anthropogenic influences on hydrology in each study area are presented in Appendices D through W.

4.2.4. Baseline Meteorology Representation

Time series of observed meteorological data (for both SWAT and HSPF) were obtained from the 2006 BASINS 4 Meteorological Database (U.S. EPA, 2008). The database contains records for 16,000 stations from 1970−2006, set up on an hourly basis, and has the advantage of providing a consistent set of parameters with missing records filled and daily records disaggregated to an hourly time step. The disaggregation was performed using automated scripts that distribute the daily data using one of several nearby hourly stations, using the one whose daily total is closest to the daily value being disaggregated. If the daily total for the hourly stations being used were not within a specified tolerance of the daily value, the daily value was distributed using a triangular distribution centered at the middle of the day. The process involved extensive quality control review; however, the true temporal distribution of precipitation at daily stations is unknown and the automated approach can occasionally result in anomalously high hourly estimates. Both factors introduce some irreducible uncertainty into hydrologic simulations using disaggregated daily precipitation stations.

A typical site-specific watershed project would assemble additional weather data sources to address under-represented areas, but this requires significant amounts of additional quality control and data processing to fill gaps and address accumulated records. It was assumed that the use of the BASINS 2006 data was sufficient to produce reasonable results at the broad spatial scale that is the focus of this project, particularly for evaluating the relative magnitude of change. Significant orographic variability was accounted for through the use of lapse rates because the available stations typically under-represent high mountain areas.

The required meteorological time series for both SWAT and HSPF (as implemented for this project) included precipitation, air temperature, and either calculated PET or time series required to generate PET. SWAT uses daily meteorological data, while HSPF requires hourly data. Stations were selected to provide a common 30-year or more period of record (or one that could be filled from an approximately co-located station).

Table 4-4 presents a summary of annual precipitation and temperature observations for each of the study areas from 1971−2000. For more specific details on the meteorological data used in each of the study areas, refer to the model calibration reports provided in Appendices D through W.

PET is the third major weather time series input to the watershed models. As evapotranspiration is typically the largest outgoing term in the water balance, watershed models are highly sensitive to the specification of PET, particularly for simulating low streamflow conditions and events. Many watershed modeling efforts perform well with simplified approaches to estimating PET, such as the Hamon method (included as an option in the BASINS data set), which depend primarily on air temperature. However, the robustness of watershed model calibrations conducted with simplified PET is suspect under conditions of climate change, since a variety of other factors that influence PET, such as wind speed and cloud cover, are also likely to change. Therefore, we implemented Penman-Monteith PET, which employs a full energy balance (Monteith, 1965; Jensen et al., 1990). The implementation varies slightly between SWAT and HSPF. In SWAT, the full Penman-Monteith method (Allen et al., 2005) is implemented as an internal option in the model and includes feedback from crop height simulated by the plant growth model. For HSPF, Penman-Monteith reference evapotranspiration at each weather station was calculated externally using the SWAT2005 model subroutines with observed precipitation and temperature. In both cases, the additional inputs to the energy balance (solar radiation, wind movement, cloud cover, and relative humidity) were provided by the SWAT weather generator, which relies on monthly conditional probability statistics for each of these inputs. An evaluation of the BASINS meteorological data set indicated substantial amounts of missing data for these inputs (especially for solar radiation and cloud cover); hence, the SWAT weather generator was preferred to enable consistent 30-year simulations. HSPF does not simulate crop growth, so monthly coefficients are incorporated in the model to convert reference crop PET to values appropriate to different crop stages using the Food and Agriculture Organization (FAO) method (Allen et al., 1998).

Table 4-4. Weather station statistics for the 20 study areas (1971−2000)

Model area	Number of precipitation stations	Average annual precipitation total (inches)	Number of temperature stations	Average annual temperature (°F)
Apalachicola-Chattahoochee-Flint Basins	37	54.26	22	63.43
Arizona: Salt, Verde, and San Pedro	29	19.67	25	56.81
Cook Inlet Basin	14	28.50	14	34.16
Georgia-Florida Coastal Plain	51	53.21	37	68.24
Illinois River Basin	72	38.25	47	49.00
Lake Erie Drainages	57	38.15	41	49.10
Lake Pontchartrain Drainage	26	66.33	15	66.64
Minnesota River Basin	39	28.26	32	43.90
Nebraska: Loup and Elkhorn River Basins	81	26.10	31	48.35
New England Coastal Basins	52	48.45	36	46.23
Powder and Tongue River Basins	37	17.70	30	44.15
Rio Grande Valley	53	15.18	41	44.71
Sacramento River Basin	28	37.47	18	57.45
Southern California Coastal Basins	85	20.21	33	61.20
South Platte River Basin	50	16.82	23	43.46
Susquehanna River Basin	60	41.30	27	48.26
Tar and Neuse River Basins	40	49.91	28	59.91
Trinity River Basin	64	40.65	32	64.78
Upper Colorado River Basin	47	16.36	39	41.73
Willamette River Basin	37	58.38	29	51.19

4.3. SIMULATION OUTPUT AND ENDPOINTS

Simulations focused on streamflow, total nitrogen, total phosphorus, and total suspended solids loads. Output from both models was analyzed as daily time series over the 30-year analysis period. Several summary metrics or endpoints were also calculated based on the daily time series. Because of calibration uncertainty inherent in modeling at this scale, estimates of relative change between historical and future simulations are most relevant. In addition to basic streamflow statistics, comparisons are made for 100-year flood peak (fit with Log Pearson type III distribution; USGS, 1982), average annual 7-day low flow, Richards-Baker flashiness index (a measure of the frequency and rapidity of short-term changes in streamflow; Baker et al., 2004), and days to the centroid of mass for the annual streamflow on a water-year basis (i.e., days from previous October 1 at which half of the streamflow for the water year is achieved, an important indicator of changes in the snow accumulation and melt cycle). For the Log Pearson III estimator, use of a regionalized skew coefficient is not appropriate to climate change scenario applications as the regional map represents existing climate. Therefore, the K factor is estimated using the skew coefficient from the model output only, without any weighting with the regional estimate.

Each of the streamflow endpoints discussed in the preceding section has been calculated for each scenario at the output of each HUC-8 contained within a study area. Several other summary measures of the water balance, largely drawn from the work of Hurd et al. (1999), are summarized as averages at the whole-watershed scale. These are the Dryness Ratio (fraction of precipitation that is lost to ET as reported by the SWAT model), Low Flow Sensitivity (expressed as the rate of baseflow generation by shallow groundwater, tile drainage, and lateral subsurface flow pathways in units of cfs/mi^2), Surface Runoff Fraction (the fraction of total streamflow from the uplands that occurs through overland flow pathways), Snowmelt Fraction (the fraction of total streamflow from the uplands that is generated by melting snow), and Deep Recharge Rate (the annual average depth of water simulated as recharging deep aquifers that do not interact with local streams). Table 4-5 provides a summary of streamflow and water quality endpoints evaluated in this study.

The mobilization and transport of pollutants will also be affected by climate and land-use change, both as a direct result of hydrologic changes and through changes in land cover and plant growth. Monthly and annual loads of sediment, phosphorus, and nitrogen are likely the most useful and reliable measures of water quality produced by the analysis. Accordingly, the focus of comparison among scenarios is on monthly and average annual loads for total suspended solids, total nitrogen, and total phosphorus. As with the streamflow simulation, it is more robust to examine relative rather than absolute changes in simulated pollutant loads when comparing scenarios to current conditions. Thus, we also calculate and express results as percent changes. All models are calibrated and validated, but in many cases current loads are imprecisely known due to limited monitoring data.

Because the sediment load in rivers/streams is often dominated by channel adjustment processes, which are highly site specific and occur at a fine spatial scale, it is anticipated that precision in the simulation of sediment and sediment-associated pollutant loads will be relatively low. Nutrient balances can also be strongly affected by biological processes in the channels, which can only be roughly approximated at the scale of modeling undertaken. It should also be noted that the modeling makes the following assumptions that limit uses for absolute (as opposed to relative) simulations of future pollutant loads: (1) external boundary conditions (if needed), such as upstream inflows and pollutant loads, are constant; (2) point source discharges and water withdrawals are assumed constant at current rates; (3) no provision is made for human adaptation in rural land management, such as shifts in crop type in response to climate change; and (4) plant growth responses to climate change are simulated to the extent they are represented in the SWAT plant growth model; however, large-scale shifts in natural cover type in response to climate change are not simulated.

Table 4-5. Summary of streamflow and water quality endpoints

Endpoint	Dimension	Description	Calculation
Future Flow Volume	L^3/t	Average of simulated streamflow volume per unit time	Sum of annual streamflow volume simulated by the watershed model
Average Seven Day Low Flow	L^3/t	Average annual 7-day low streamflow event volume	Lowest 7-day-average streamflow simulated for each year
100 Year Peak Flow	L^3/t	Estimated peak streamflow rate based on annual flow maxima series, Log Pearson III method	Log Pearson III extreme value estimate following USGS (1982), based on simulated annual maxima series
Days to Flow Centroid	*t* (days)	Number of days from the previous October 1 (start of water year) at which half of the streamflow volume for that water year is achieved	Count of days to 50% of simulated total annual streamflow volume for each water year.
Richards-Baker Flashiness Index	dimensionless	Indicator of the frequency and rapidity of short term changes in daily streamflow rates	Analyzed by method given in Baker et al. (2004), applied to daily streamflow series for each year
Dryness Ratio	dimensionless	Fraction of input precipitation lost to ET	Calculated as (precipitation − outflow)/precipitation for consistency with Hurd et al. (1999)
Low Flow Sensitivity	L/t	Rate of baseflow contributions from shallow groundwater, tile drainage, and lateral subsurface flow pathways, depth per unit time	Sum of simulated streamflow from shallow groundwater, tile drainage, and lateral subsurface flow pathways divided by area.
Surface Runoff Fraction	dimensionless	Fraction of streamflow contributed by overland flow pathways	Surface runoff divided by total outflow.
Snowmelt Fraction	dimensionless	Fraction of streamflow contributed by snowmelt	Estimated as water equivalent of simulated snowfall divided by total precipitation
Deep Recharge	L/t	Depth of water recharging deep aquifers per unit time	Total water volume simulated as lost to deep recharge divided by area
AET	L/t	Actual depth of evapotranspiration lost to the atmosphere per unit time	Evapotranspiration simulated by the watershed model
PET	L/t	Theoretical potential evapotranspiration as depth per unit time, assuming moisture not limiting	Potential evapotranspiration simulated by the Penman-Monteith method (Jensen et al., 1990)
Total Suspended Solids (TSS)	mass/*t*	Mass load of suspended sediment exiting stream reach per unit time	Sum of simulated mass exiting a stream reach
Total Phosphorus (TP)	mass/*t*	Mass load of total phosphorus exiting reach per unit time	Sum of simulated mass exiting a stream reach
Total Nitrogen (TN)	mass/*t*	Mass load of total nitrogen exiting stream reach per unit time	Sum of simulated mass exiting a stream reach

4.4. MODEL CALIBRATION AND VALIDATION

The watershed models were calibrated and validated in each of the study areas in accordance with the project Quality Assurance Project Plan (QAPP; see Appendix B). The following section provides a brief summary of calibration and validation methods and results. Detailed description of calibration and validation methods and results for the individual study areas are presented in Appendices D through W.

Calibration refers to the adjustment of model parameters to reproduce or fit simulation results to observed data. Calibration is required for parameters that cannot be deterministically and uniquely evaluated from topographic, climatic, physical, and chemical characteristics of the watershed and compounds of interest. Validation is performed by application of the calibrated model to a different period of observed data to test the robustness of the calibrated parameter set. If the model exhibited a significant degradation in performance in the validation period, the calibration process is repeated until results are considered acceptable.

The calibration and validation approach for the study areas was to first focus on a single HUC-8 within the larger study area (preferably one for which some modeling was already available along with a good record of flow gaging and water quality monitoring data), and then extend the calibration to adjacent areas with modifications as needed to achieve a reasonable fit at multiple spatial scales. Each HUC-8 watershed was generally subdivided into approximately 8 subbasins, approximating the HUC-10 watershed scale.

The base period of observed data used for calibration and validation was approximately 1970 to 2000, with some variation depending on availability of meteorological data, while the base land use was from 2001 NLCD. In watersheds with significant land-use change, moving back too far from 2001 may not provide a firm basis for calibration. Therefore, calibration generally focused on approximately the 1991−2001 time period, although the full 1971−2000 period was used for comparison to future changes. Validation was typically performed on the period before 1991 and/or data from post-1991 at different locations.

4.4.1. Hydrology

The goal of hydrologic calibration for both HSPF and SWAT was to achieve error statistics for total streamflow volume, seasonal streamflow volume, and high and low streamflow within the range recommended by Lumb et al. (1994) and Donigian (2000) while also maximizing the Nash-Sutcliffe coefficient of model fit efficiency (*E*). Standardized spreadsheet tools were developed to help ensure consistency in the calibration and validation process across watersheds, and to provide a standardized set of statistics and graphical comparisons to data. These statistics were used to adjust appropriate model parameters until a good statistical match was shown between the model output and observed data.

Lumb et al. (1994) and Donigian (2000) recommend performance targets for HSPF based on relative mean errors calculated from simulated and observed daily average streamflow. Donigian classified these into qualitative ranges, which were modified slightly in this project for application to both HSPF and SWAT (see Table 4-6). In general, hydrologic calibration endeavored to achieve a “good” level of model fit where possible. It is important to note that the tolerance ranges are intended to be applied to mean values and that individual events or observations may show larger differences and still be acceptable (Donigian, 2000).

Table 4-6. Performance targets for hydrologic simulation (magnitude of annual and seasonal relative mean error) from Donigian (2000)

Model component	Very good (%)	Good (%)	Fair (%)	Poor (%)
1. Error in total volume	≤5	5−10	10−15	>15
2. Error in 50% lowest streamflow volumes	≤5	5−10	10−25	>25
3. Error in 10% highest streamflow volumes	≤10	10−15	15−25	>25
4. Error in storm volume	≤10	10−20	20−30	>30
5. Winter volume error	≤15	15−30	30−50	>50
6. Spring volume error	≤15	15−30	30−50	>50
7. Summer volume error	≤15	15−30	30−50	>50
8. Fall volume error	≤15	15−30	30−50	>50
9. Error in summer storm volumes	≤25	25−50	50−75	>75

The Nash-Sutcliffe coefficient of model fit efficiency (E) is also widely used to evaluate the performance of models that predict time series. Nash and Sutcliffe (1970) define E as:

$$E = 1 - \frac{\sum_{i=1}^{n} \left(O_i - P_i\right)^2}{\sum_{i=1}^{n} \left(O_i - \overline{O}\right)^2}, \qquad 4\text{-}4$$

where O_i and P_i represent members of a set of n paired time series observations and predictions, respectively, and $\overline{O}$ is the mean of the observed values. E ranges from minus infinity to 1.0, with higher values indicating better agreement. The coefficient represents the ratio of the mean square error to the variance in the observed data, subtracted from unity (Wilcox et al., 1990). A value of zero for E indicates that the observed mean is as good a predictor of time series values as the model, while negative values indicate that the observed mean is a better predictor than the model. A value of E greater than 0.7 is often taken as an indicator of a good model fit (Donigian, 2000). Note, however, that the value depends on the time basis on which the coefficient is evaluated. That is, values of E for monthly average streamflow are typically noticeably greater than values of E for daily streamflow, as watershed models, in the face of uncertainty in the representativeness of precipitation records, are often better predictors of interseasonal trends than of intraseasonal variability. Moriasi et al., (2007) recommend a Nash-Sutcliffe E of 0.50 or better (applied to monthly sums) as an indicator of adequate hydrologic calibration when accompanied by a relative error of 25% or less.

A potential problem with the use of E is that it depends on squared differences, making it overly sensitive to extreme values (Legates and McCabe, 1999). This is particularly problematic for sparse time series, such as water quality observations, in which poor estimation of one or a few high outliers may strongly influence the resulting statistic. It is an even greater problem for the comparison of model output to load estimates based on sparse concentration data, as these estimates are themselves highly uncertain (using point-in-time grab samples to represent daily averages and interpolating to unobserved days), further increasing the leverage associated with high outliers.

To address these issues and lessen the effect of outliers, Garrick et al. (1978) proposed use of a baseline adjusted coefficient of model fit efficiency, E_1', which depends on absolute differences rather than squared differences:

$$E_1' = 1 - \frac{\sum_{i=1}^{n} |O_i - P|}{\sum_{i=1}^{n} |O_i - \overline{O}'|} \quad \text{4-5}$$

Garrick's proposed statistic is actually more general, allowing $\overline{O}'$ to be a baseline value that may be a function of time or of other variables, rather than simply the mean. E_1' may be similar to or greater or less than E for a given set of predictions and measurements depending on the type of outliers that are present.

For most watershed models, E is an appropriate measure for the fit of streamflow time series in which complete series of observations are known with reasonable precision. E_1' is a more appropriate and stable measure for the comparison of simulated pollutant loads to estimates based on sparse observed data.

4.4.1.1. *Flow Calibration Adjustments*

HSPF and SWAT hydrology calibration adjustments were made for a range of sensitive model parameters selected to represent key watershed processes affecting runoff (U.S. EPA, 2000; Neitsch et al., 2005; see Tables 4-7 and 4-8, respectively, for selected key parameters most frequently adjusted). The adjustment of other parameters and the degree of adjustment to each parameter vary by watershed. Details are provided in the individual calibration reports for each of the watersheds in Appendices D through W.

Table 4-7. Key hydrology calibration parameters for HSPF

Parameter name	Definition
INFILT	Nominal infiltration rate parameter
AGWRC	Groundwater recession rate
LZSN	Lower zone nominal soil moisture storage
BASETP	ET by riparian vegetation
KMELT	Degree-day melt factor
PET factor	Potential evapotranspiration
DEEPFR	Fraction of groundwater inflow that will enter deep groundwater
LZETP	Lower zone E-T parameter

Table 4-8. Key hydrology calibration parameters for SWAT

Parameter name	Definition
CN	Curve numbers—varied systematically by land use
ESCO	Soil evaporation compensation factor
SURLAG	Surface runoff lag coefficient
ALPHA_BF	Baseflow alpha factor
GW_DELAY	Groundwater delay time
CANMAX	Maximum canopy storage
OV_N, CH_N2, CH_N1	Manning's "*n*" values for overland flow, main channels, and tributary channels
Sol_AWC	Available water capacity of the soil layer, mm water/mm of soil
Bank storage and recession rates	Bank storage and recession rates
Snow parameters SFTMP, SMTMP, SMFMX and SMFMN	Snowfall temperature, snowmelt base temperature, maximum melt rate for snow during year, and minimum melt rate for snow during year
TIMP	Snow pack temperature lag factor
CH_K1	Effective hydraulic conductivity in tributary channel alluvium

4.4.2. Water Quality

The models in this study are designed to simulate total nitrogen, total phosphorus, and total suspended solids. The first objective of calibration was to reduce the relative absolute deviation between simulated and estimated loads to below 25% if possible. The water quality calibration focuses on the replication of monthly loads, as specified in the project QAPP (see Appendix B). While a close match to individual, instantaneous concentration observations cannot be expected given the approach taken in the model simulations of water quality, the calibration also examined the general relationship of observed and predicted concentrations with the intent of minimizing bias relative to streamflow regime or time of year. Comparison to monthly loads presents challenges, as monthly loads are not observed. Instead, monthly loads must be estimated from scattered concentration grab samples and continuous streamflow records. As a result, the monthly load calibration is inevitably based on the comparison of two uncertain numbers. Nonetheless, calibration is able to achieve a reasonable agreement. The direct comparison of estimated and simulated monthly loads was supplemented by detailed examinations of the relationships of streamflow to loads and concentrations, and the distribution of concentration prediction errors versus streamflow, time, and season to help minimize bias in the calibration.

For application on a nationwide basis, it was assumed that total suspended solids and total phosphorus loads will likely exhibit a strong positive correlation to streamflow (and associated erosive processes), while total nitrogen loads, which often have a dominant subsurface loading component, will not (Allan, 1986; Burwell et al., 1975; Follett, 1995). Accordingly, total suspended solids and total phosphorus loads were estimated from observations using a flow-stratified log-log regression approach, while total nitrogen loads were estimated using a flow-stratified averaging estimator, consistent with the findings of Preston et al. (1989).

4.4.2.1. *Water Quality Calibration Adjustments*

Water quality calibration began with sediment transport processes. Observed suspended solids concentrations are the result of multiple processes, including sediment detachment, sediment transport in overland flow, and channel scour and deposition processes. The sediment detachment routines for both SWAT and HSPF were related to USLE parameters available in the soils database. For most basins, calibration focuses on sediment transport in overland flow, using the peak rate or transport rate factors available in both models. Channel scour and deposition processes were modified where needed to achieve a fit to observations or where detailed work with prior models provided a basis for modifying the default parameters.

In HSPF, nitrogen loading from the land surface was simulated as a buildup/washoff process, while phosphorus was simulated as sediment-associated. Both nitrogen and phosphorus also were simulated with dissolved-phase loads from interflow and groundwater discharge. Calibration for nutrients in HSPF primarily addressed adjustments of the buildup/washoff coefficients or sediment potency (concentration relative to sediment load) factors and monthly subsurface discharge concentrations. In SWAT, the nutrient simulation is intimately linked to the plant growth model, but is sensitive to initial nutrient concentrations and the ability of plants to withdraw nutrients from various soil layers. In watersheds where significant channel scour was simulated, the nutrient content of scoured sediment was also an important calibration parameter.

4.4.3. Accuracy of the Watershed Models

The quality of model fit varies with the study area and parameter considered. In general, the full suite of SWAT models for the 20 watersheds—after calibration—provide a good to excellent representation of the water balance at the monthly scale and a fair to good representation of hydrology at the daily scale (see Table 4-9 for the initial calibration site results). The quality of model fit to hydrology as measured at multiple stations (HUC-8 spatial scale and larger) throughout the watershed was, not surprisingly, better when a spatial calibration approach was used. At all calibration and validation sites, the median monthly Nash-Sutcliffe *E* coefficient from the SWAT models was 0.74 for both the pilot and nonpilot study areas. More detailed calibration and validation results for each study area are provided in Appendices D through W.

Less precise model fit to observations resulted in several study areas for various reasons. In addition to differences in individual modeler preferences and skill, Low *E* coefficients in the Rio Grande Valley likely reflect insufficient knowledge of operations of the many reservoirs in the basin. Calibrating watershed hydrology was problematic in systems dominated by large-scale interactions with regional groundwater systems—notably, Verde River in Arizona and the Loup/Elkhorn River system in the Nebraska sandhills. Both HSPF and SWAT use simplistic storage reservoir representations of groundwater in which water can percolate from the soil profile into local shallow groundwater storage, from which it is gradually released following an exponential decay pattern characterized by a recession coefficient. Perennial streamflow in the Verde River is sustained by groundwater discharges of nonlocal origin that derive from the upstream Chino basin. The Loup and Elkhorn Rivers drain highly porous sands where surface runoff is minimal and streamflow in some tributary rivers is nearly constant and only weakly correlated to rainfall patterns (e.g., see Figure 4-1), a situation that is difficult to address in a rainfall-runoff model without linking to a true groundwater simulation model.

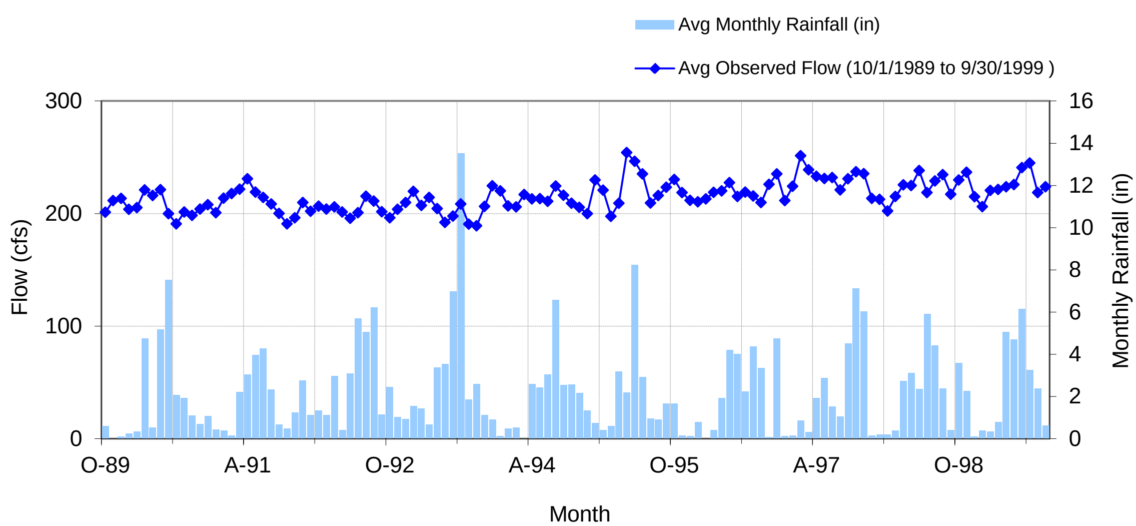

Figure 4-1. Example of weak correlation of rainfall and flow in the Dismal River at Thedford, NE (USGS 06775900) in the Loup River basin.

Different modelers handled the situation in these two regions in different ways. For the Verde River (where both HSPF and SWAT were applied) the regional groundwater inflow was specified as an external forcing time series. This has the advantage of allowing the model calibration to focus on rainfall-runoff events that are responsible for most year-to-year variability in streamflow and most pollutant transport. The major disadvantage is that there is not a clear means to specify how this groundwater forcing might respond to changes in climate. Instead, results for the Verde River show relative changes that would be expected under the assumption that the regional groundwater discharge does not change.

For the Loup and Elkhorn River basins, a reasonable fit to both calibration and validation periods was obtained by specifying extremely slow groundwater recession rates in conjunction with use of the soil crack flow option (which allows a fraction of rainfall to flow directly to groundwater) in the sandhill region. This approach can replicate the major observed features of the water balance, although it does not achieve a high degree of precision in explaining day-to-day variability in observed streamflow. Further, the simulated groundwater discharges are responsive to changes in climate forcing. However, use of this approach comes at a cost due to the way that groundwater is simulated in the SWAT model. Specifically, SWAT simulates baseflow discharge on a given day as a function of discharge on the previous day, modified by the recession coefficient, plus the effects of new recharge to groundwater. Groundwater discharge at the start of the simulation is constrained to be zero. Use of a very slow recession rate gives a reasonable fit to the calibration and validation periods in this study area; however, it also results in very slow convergence of estimated groundwater discharge from the initial zero. This resulted in a situation in which it took approximately 10 years for streamflow to reach levels in line with observations. Thus, simulated streamflow for the early years are often zero. Adding a longer spinup period does not resolve the problem as the low recession rate results in a nonstationary solution in which baseflow continues to gradually increase over time and the simulated streamflow eventually overshoots observations during the calibration period if the spinup period is extended. Due to this issue, change scenario results are presented only for the 20-year calibration and validation periods in the Loup and Elkhorn River study area.

Calibration and validation for water quality is subject to higher uncertainty than streamflow calibration due to limited amounts of monitoring data and a simplified representation of the multiple complex processes that determine in-stream pollutant concentrations. The primary objective of water quality simulation in this project is to assess relative changes in pollutant loads, but loads are not directly observed. Inferring loads from point-in-time concentration data and streamflow introduces another layer of uncertainty into the calibration process. Calibration also examined observed versus predicted concentrations; however, SWAT, as a daily curve number model, does not have a high level of skill in simulating instantaneous concentrations, particularly during high flow events, and is better suited to the simulation of loads at the weekly to monthly scale.

As with the hydrology calibration, the reliability of the models for simulating changes in water quality appears to increase with calibration at multiple locations. In general, it is more difficult to obtain a high level of precision for simulated water quality than for hydrology in a watershed model, as the processes are complex, the data typically sparse, and any errors in hydrology tend to be amplified in the water quality simulation. The water quality calibration is based on loads, but loads are not directly observed. Instead, loads are inferred from sparse concentration monitoring data and streamflow gaging. Thus, both the simulated and "observed" loads are subject to considerable uncertainty. Comparison based on concentrations can also be problematic, as most water quality samples are grab samples that represent points in time and space, whereas model output is integrated over a stream segment and may produce large apparent errors due to small shifts in timing. Finally, most stations at the HUC-8 scale include upstream point sources, which often have a strong influence on low-flow concentrations and load estimates. Limited knowledge about point source loads thus also creates a challenge for the water quality calibration. In most cases, the pollutant load simulations from the SWAT model appear to be in the fair to good range (see Table 4-9)—except in a few cases where parameters were extended from one station to another watershed without adjustment, giving poor results. This suggests limits to the reliability of simulation results in the portions of watersheds for which calibration was not pursued. Nonetheless, simulations of the relative response to climate change and land development scenarios are more reliable than for the actual observed future values—as long as the significant processes that determine pollutant load and transport within a watershed are represented.

HSPF model calibration for the five pilot sites provided a somewhat stronger fit to daily streamflow in four of the five watersheds (see Table 4-10), presumably at least in part due to HSPF's use of subdaily precipitation. In two models, the fit to total suspended solids load was notably worse for HSPF, apparently due to the difficulties in adjusting the more complex channel scour and deposition routines of this model with limited data and on a compressed schedule.

Table 4-9. Summary of SWAT model fit for initial calibration site (20 study areas)

Study area	Initial calibration/ validation watershed	Initial calibration/ validation USGS gage	Hydrology cal./val. yr	Total volume cal./val. (daily and monthly *E*)	Total volume cal./val. (% error)	Water quality cal./val yr	TSS monthly load cal./val. (% error)	TP monthly load cal./val. (% error)	TN monthly load cal./val. (% error)
ACF	Upper Flint River	02349605	1993−2002/ 1983−1992	0.62/0.56 0.88/0.83	7.28/3.33	1999−2002/ 1991−1998	−9/17	−50/−30	−18/9
Ariz	Verde River	09504000	1992−2002/ 1982−1992	0.03/−1.0 0.88/0.32	−2.46/5.68	1993−2002/ 1986−1992	16.9/−42.6	83.5/31.4	−14.4/−15.9
Cook	Kenai River	15266300	1992−2001/ 1982−1991	0.68/0.55 0.80/0.75	−18.96/19.49	1985−2001/ 1972−1984	66.4/64.1	83.2/82.18	57.3/50.4
GaFla	Ochlockonee River	02329000	1992−2002/ 1982−1992	0.71/0.80 0.79/0.90	4.25/−5.54	1992−2002/ 1982−1992	9.5/−6.6	−7.4/−5.8	−8/−5
Illin	Iroquois River	05526000	1992−2001/ 1982−1992	0.70/0.67 0.77/0.71	−16.99/−2.98	1985−2001/ 1978−1984	38/39	5/−1	56/60
LErie	Cuyahoga River	04208000	1990−2000/ 1980−1990	0.61/0.62 0.70/0.73	−3.32/−13.38	1990−2000/ 1980−1990	67.9/69.8	23.9/−12.5	35.8/13.7
LPont	Amite River	07378500	1995−2004/ 1985−1994	0.79/0.69 0.95/0.90	−1.61/−0.93	1984−1994/ ND	9.2/NA	2.4/NA	−8.9/NA
Minn	Cottonwood River	05317000	1992−2002/ 1982−1992	0.79/0.74 0.91/0.83	−5.41/−0.84	1993−2000/ 1986−1992	9.2/9	9.3/−21.6	−8.9/−1.3
Neb	Elkhorn River	06800500	1989−1999/ 1978−1988	0.42/0.52 0.70/0.66	−2.59/−8.81	1990−1995/ 1979−1989	59.6/66.8	24.2/34.9	28.1/18.1
NewEng	Saco River	01066000	1993−2003/ 1983−1993	0.61/0.76 0.71/0.84	1.08/0.67	1993−2003/ 1983−1993	−9/3.2	9.6/−11.5	27.5/26.3
PowTon	Tongue River	06306300	1993−2003/ 1983−1993	0.72/0.7 0.83/0.82	9.26/−9.95	1993−2003/ 1982−2002	−21.8/−3.4	8.8/35.1	3.9/31.5
RioGra	Saguache Creek	08227000	1993−2003/ 1983−1993	0.47/0.07 0.53/0.31	−4.92/32.99	1985−2003/ 1973−1984	57.3/41	−46.9/−653.98	−28.3/−909.1
Sac	Sacramento River	11377100	1992−2001/ 1983−1992	0.75/0.57 0.94/0.92	10.23/10.06	1997−2001/ 1973−1996	−2/−55	−8/−33	−135/−156
SoCal	Santa Ana River	11066460	1991−2001/ 1981−1991	0.63/0.59 0.75/0.68	3.71/1.61	1998−2000/ ND	19/NA	−14.7/NA	−5.5/NA
SoPlat	South Platte River	06714000	1991−2000/ 1981−1990	0.74/0.52 0.86/0.63	9.82/−16.28	1993−2000/ ND	86.6/NA	−14/NA	6.1/NA

Table 4-9. Summary of SWAT model fit for initial calibration site (20 study areas) (continued)

Study area	Initial calibration/ validation watershed	Initial calibration/ validation USGS gage	Hydrology cal./val. yr	Total volume cal./val. (daily and monthly *E*)	Total volume cal./val. (% error)	Water quality cal./val yr	TSS monthly load cal./val. (% error)	TP monthly load cal./val. (% error)	TN monthly load cal./val. (% error)
Susq	Raystown Branch of the Juniata River	02050303	1995−2005/ 1985−1995	0.29/0.42 0.67/0.66	−5.41/16.3	1991−2000/ 1990	−10.1/−33.6	−0.5/−9.2	28.6/43.9
TarNeu	Contentnea Creek	02091500	1993−2003/ 1983−1993	0.68/0.64 0.86/0.74	−3.98/−1.18	1993−2003/ 1983−1993	−19.9/9.9	15.9/5.3	−5.6/5.3
Trin	Trinity River	08066500	1992−2001/ 1982−1991	0.62/0.47 0.74/0.76	−6.88/0.70	1985−2001/ 1972−1984	9.2/−17.4	3/−21.58	−3.8/−31.9
UppCol	Colorado River	09070500	1992−2002/ 1982−1992	0.83/0.78 0.86/0.82	8.18/0.93	1992−2002/ — ND	0.4/NA	47.4/NA	15.1/NA
Willa	Tualatin River	14207500	1995−2005/ 1985−1995	0.49/0.39 0.88/0.81	−4.76/−12.1	1991−1995/ 1986−1990	−12/−7	−114/−105	−72/−66

Table 4-10. Summary of HSPF model fit for initial calibration sites (five pilot study areas)

Study area	Initial calibration/ validation watershed	Initial calibration/ validation USGS gage	Hydrology cal./val. yr	Total volume cal./val. (daily and monthly *E*)	Total volume cal./val. (% error)	Water quality cal./val yr	TSS monthly load cal./val. (% error)	TP monthly load cal./val. (% error)	TN monthly load cal./val. (% error)
ACF	Upper Flint River	02349605	1993−2002/ 1983−1992	0.71/0.65 0.93/0.90	5.50/5.79	1999−2002/ 1991−1998	−117/−78	−59/−23	−30/−22
Ariz	Verde River	09504000	1992−2002/ 1982−1992	0.48/0.45 0.85/0.66	2.43/6.31	1993−2002/ 1986−1992	31/−41	87/66	1.6/−2.7
Minn	Cottonwood River	05317000	1992−2002/ 1982−1992	0.75/0.78 0.69/0.86	1.61/14.78	1993−2002/ 1986−1992	7.5/13.1	23/15.8	15.4/16.2
Susq	Raystown Branch of the Juniata River	02050303	1995−2005/ 1985−1995	0.70/0.55 0.90/0.87	−0.16/−8.0	1991−2000/ 1990	−78.2/−89.7	26.0/21.5	7.0/17.2
Willa	Tualatin River	14207500	1995−2005/ 1985−1995	0.73/0.81 0.96/0.92	−3.92/−9.80	1991−1995/ 1986−1990	3.0/4.8	−1.2/−9.3	2.2/−6.3

5. CLIMATE CHANGE AND URBAN DEVELOPMENT SCENARIOS

Watershed simulations were conducted using SWAT and HSPF in each study area to assess the sensitivity of streamflow, total nitrogen, total phosphorus, and total suspended solids loads to a range of plausible mid-21^{st} century climate change and urban development scenarios. Climate change scenarios are based on downscaled climate model projections for mid-21^{st} century from the NARCCAP and BCSD (Maurer et al., 2007) data sets. Fourteen climate scenarios were applied to the five pilot sites, and a subset of 6 climate scenarios from the NARCCAP archive were applied to the nonpilot sites. Scenarios of urban and residential development were based on projections from EPA's ICLUS project (U.S. EPA, 2009c).

Simulations were conducted to assess the response to climate change scenarios alone, urban and residential development scenarios alone, and combined climate change and urban development scenarios. The following sections discuss the use and implementation of climate change and urban development scenarios in this study.

5.1. SCENARIO-BASED APPROACH

The scientific uncertainties related to our understanding of the physical climate system are large, and they will continue to be large for the foreseeable future. It is beyond our current capabilities to predict with accuracy decadal (and longer) climate changes at the regional spatial scales of relevance for watershed processes (e.g., see Cox and Stephenson, 2007; Stainforth et al., 2007; Raisanen, 2007; Hawkins and Sutton, 2009; among many others). The uncertainties associated with socioeconomic trajectories, technological advances, and regulatory changes that will drive greenhouse gas emissions changes (and land-use changes) are even larger and less potentially tractable.

Faced with this uncertainty, an appropriate strategy is to take a scenario-based approach to the problem of understanding climate change impacts on water quality. A scenario is a plausible description of how the future may develop, based on a coherent and internally consistent set of assumptions about driving forces and key relationships (IPCC, 2007). Scenarios are used in assessments to provide alternative views of future conditions considered likely to influence a given system or activity. By systematically exploring the implications of a wide range of plausible alternative futures, or scenarios, we can reveal where the greatest vulnerabilities lie. This information can be used by decision makers to help understand and guide the development of response strategies for managing climate risk. A critical step in this approach is to create a number of plausible future states that span the key uncertainties in the problem. The goal is not to estimate a single, "most likely" future trajectory for each study watershed, but instead to understand, to the extent feasible, how big an envelope of potential future impacts we are unable to discount and must therefore incorporate into future planning.

Note that for climate change studies, the word "scenario" is often used in the context of the IPCC greenhouse gas storylines. The IPCC emissions scenarios describe alternative development pathways, covering a range of demographic, economic, and technological driving forces that affect greenhouse gas emissions. This can produce some confusion when phrases like "climate change scenarios" are used to refer to the future climates simulated using these greenhouse gas storylines. For the purposes of this study, "scenario" is a generic term that can be applied to any defined future, including a climate future or a land-use future, among others.

5.2. CLIMATE CHANGE SCENARIOS

It is standard practice when assessing climate change impacts to consider an ensemble of climate change scenarios based on different climate models and emissions pathways. Use of a single model run is not considered scientifically rigorous because different GCMs often produce very different results, and there is no consensus in the climate modeling community that any model is comprehensively better or more accurate than the others (e.g., see Gleckler et al., 2008). Different methods of "downscaling" GCM model output to finer spatial scales can also influence the variability among models.

5.2.1. Future Climate Models, Sources, and Downscaling

To sample across this model-based uncertainty, this project focused on six climate change scenarios derived from four GCMs covered by the regional downscaling efforts of the NARCCAP (http://www.narccap.ucar.edu). NARCCAP uses higher-resolution RCMs to dynamically downscale output from four of the GCMs used in the IPCC 4th Assessment Report (IPCC, 2007) to a 50 × 50 km^2 grid over North America. This downscaled output is archived for the two 30-year periods (1971−2000 and 2041−2070) at a temporal resolution of 3 hours. NARCCAP uses the IPCC's A2 greenhouse gas storyline (which at the time of development was a relatively "pessimistic" future greenhouse gas trajectory, but is now more middle-of-the-road compared to current trends and the most recently developed scenarios). We note that, by mid-21st Century, the different IPCC greenhouse gas storylines have not yet diverged much, so impact of the choice of any one particular storyline is diminished compared to later in the century.

At the time we initiated the watershed modeling, six downscaled scenarios were available from NARCCAP, and we are using these six as our common set of climate scenarios across all the 20 watersheds, as listed in Table 5-1.

One of the objectives of this work was to investigate the influence of downscaling approaches on watershed model simulations. To evaluate the sensitivity of our results to downscaling methodology, we ran the watershed models in the five pilot sites with eight additional scenarios (also listed in Table 5-1) derived from the same four GCMs used in NARCCAP: four scenarios interpolated to station locations directly from the GCM output (without downscaling), and four scenarios based on the BCSD statistically downscaled climate projections described by Maurer et al. (2007), and served at: http://gdo-dcp.ucllnl.org/downscaled_cmip3_projections/. The BCSD data provides monthly mean surface air temperature and precipitation rates for the contiguous United States (along with portions of Canada and Northern Mexico) at a horizontal grid spacing of 1/8 degree (roughly 12 × 12 km^2) for the period 1950−2099.

The BCSD climate projections use statistical downscaling to interpret GCMs to a finer resolution based on current observations. The principal potential weakness of this approach is an assumption of stationarity. That is, the assumption is made that the relationship between large-scale precipitation and temperature and local precipitation and temperature in the future will be the same as in the past. Thus, the method can successfully account for orographic effects that are observed in current data, but not for impacts that might result from the interaction of changed wind direction and orographic effects. A second assumption included in the bias-correction step of the BCSD method is that any biases exhibited by a GCM for the historical period will also be exhibited in simulations of future periods.

Table 5-1. Climate models and source of model data used to develop climate change scenarios

Scenario #	Climate model(s) (GCM/RCM)
NARCCAP (dynamically downscaled)	
1	CGCM3/CRCM
2	HadCM3/HRM3
3	GFDL/RCM3
4	GFDL/GFDL hi res
5	CGCM3/RCM3
6	CCSM/WRFP
GCM (without downscaling)	
7	CGCM3
8	HadCM3
9	GFDL
10	CCSM
BCSD (statistically downscaled)	
11	CGCM3
12	HadCM3
13	GFDL
14	CCSM

Model Abbreviations:

CGCM3:	Third Generation Coupled Global Climate Model http://www.ec.gc.ca/ccmac-cccma/default.asp?lang=En&n=4A642EDE-1
HadCM3:	Hadley Centre Coupled Model, version 3 http://www-pcmdi.llnl.gov/ipcc/model_documentation/HadCM3.htm
GFDL:	Geophysical Fluid Dynamics Laboratory GCM http://www-pcmdi.llnl.gov/ipcc/model_documentation/GFDL-cm2.htm
CCSM:	Community Climate System Model http://www-pcmdi.llnl.gov/ipcc/model_documentation/CCSM3.htm
CRCM:	Canadian Regional Climate Model http://www.ec.gc.ca/ccmac-cccma/default.asp?lang=En&n=4A642EDE-1
RCM3:	Regional Climate Model, version 3 http://users.ictp.it/~pubregcm/RegCM3/
HRM3:	Hadley Region Model 3 http://precis.metoffice.com/
WRFP:	Weather Research and Forecasting Model http://www.wrf-model.org/index.php
GFDL hi res:	Geophysical Fluid Dynamics Laboratory 50-km global atmospheric time slice http://www-pcmdi.llnl.gov/ipcc/model_documentation/GFDL-cm2.htm

The BCSD scenarios, while all derived from the A2 climate storyline, do not in all cases use the output of the exact same GCM run that was used to construct the NARCCAP archive. Specifically, the BCSD results for the Geophysical Fluid Dynamics Laboratory global climate model (GFDL) and Third Generation Coupled Global Climate Model (CGCM3) GCMs use exactly the same GCM output as NARCCAP, but BCSD results for Hadley Centre Coupled Model, version 3 (HadCM3) and Community Climate System Model (CCSM) use different runs of the A2 scenario than used by NARCCAP. The HadCM3 run used in NARCCAP was a custom run generated specifically for NARCCAP and has not been downscaled for the BCSD archive. The CCSM run used in NARCCAP is run number 5, which is not available in the CMIP3 archive used by BCSD. Instead, BCSD uses the HadCM3 run 1 and CCSM run 4 from the CMIP3 archive for the A2 scenario. As a result, the most direct comparisons between the NARCCAP and BCSD data sets are for the GFDL and CGCM3 GCM models. However, we still expect comparisons between NARCCAP and BCSD for the HadCM3 and CCSM to provide useful insights when considered along with the GFDL and CGCM3 comparisons. These scenarios were evaluated only at the five pilot study areas.

Scenarios for the five pilot sites also examined use of the direct output from the GCM runs used to drive the NARCCAP downscaling (i.e., no downscaling). Comparison of results from these scenarios to full dynamical downscaling is expected to inform the accuracy with which simpler methods can be used to address watershed response. These scenarios were evaluated only at the five pilot study areas.

Table 5-1 summarizes the climate change scenarios used in this study and also contains a numbering key for shorthand reference to climate scenarios. For example, climate scenario 2 refers to the HadCM3 GCM, downscaled with the Hadley Region Model 3 (HRM3) RCM. All 14 scenarios are applied in the five pilot sites. Only scenarios 1 through 6 are applied for the nonpilot sites.

5.2.2. Translation of Climate Model Projections to Watershed Model Weather Inputs

Even the 50-km NARCCAP scale is relatively coarse for watershed modeling. In this study, meteorological time series for input to the watershed models were created using a “change factor” or “delta change” method (Anandhi et al., 2011). Using this approach, a period of baseline observed weather data was selected for each study area (to which the watershed models have been calibrated), and the data series adjusted or perturbed to represent a specific type of climate change projected by a climate model (i.e., a climate change scenario). The benefits of the change factor approach include its simplicity, elimination of the need for bias correction, and ability to create spatially variable climate change scenarios that maintain the observed historical spatial correlation structure among different watershed locations. Specifically, there is a tendency for GCMs to generate too many low-intensity events and to under-simulate the intensity of heavy events (Sun et al., 2006; Dai, 2006). The frequency and duration of large events can have significant effects on hydrology, pollutant loading, and other watershed processes. Applying the model-derived change factors to the observed precipitation time series mitigates this problem. Limitations of this approach include the inability to adjust the number and timing of precipitation events (e.g., to add precipitation events on dry days), and potential bias introduced through the selection of an arbitrary historical base period as the template for future climate time series. In addition, climate models do not necessarily archive all the meteorological forcing variables required to run watershed models.

Monthly change factors derived from climate models for each climate change scenario were calculated by comparing simulated monthly average values for baseline (1971−2000) and future (2041−2070) climate conditions. It should be noted that the intention is not to simulate the impacts of change in land use and climate that occurred over the decades from 1971 to 2000. Rather, the 1971−2000 meteorological data is assumed to provide a static estimate of natural climate variability under “current” land-use conditions, which are defined by the selection of the 2001 NLCD baseline land cover.

Change statistics from the climate models were interpolated to locations corresponding to each of the BASINS meteorological stations and SWAT weather generator stations used in the watershed models. Change factors were used to perturb existing records of hourly observed precipitation and temperature using the CAT (U.S. EPA, 2009b). CAT permits the sequential modification of weather records to introduce a number of alterations, each reflecting various assumptions concerning the regional manifestations of climate change. Precipitation records can be modified by (1) multiplying all records by an empirical constant reflecting projected climate change to simulate a shift in total precipitation, applied uniformly to all periods and intensity classes, (2) selective application of such a multiplier to specific seasons or months, (3) selective application of the multiplier to a range of months or years within the record, and (4) selective application of the multiplier to storm events of a specific size or intensity class. Modification can be iteratively applied to more than one event size class, allowing changes in frequency and intensity as well as changes in overall volume of precipitation to be represented. Temperature records can be modified by adding or subtracting a constant to all values in the record, or selective application to certain months or years within the record.

The third meteorological time series required by the watershed models is PET, which is calculated based on other meteorological time series as described in Section 5.2.2.3.

The full suite of statistics available to calculate PET using the Penman-Monteith energy balance method is not available for the statistically downscaled model runs or the nondownscaled GCM archives. Data availability is summarized in Table 5-2 and assumptions for creating PET time series in the absence of specific data sets is discussed in Section 5.2.2.3.

It is important to note that using this approach, multiyear climate change scenarios created by perturbing multiple years of historical weather data are representative of a single, future time period and do not represent continuous climatic change during this period (i.e., they are not transient simulations). Instead, the variability in multiyear scenarios created in this way provides a snapshot of the natural variability in climate based on historical conditions.

5.2.2.1. *Temperature Changes*

Monthly variations (deltas) to the temperature time series throughout the entire time period were applied using the BASINS CAT. Monthly adjustments based on each scenario were used and a modified HSPF binary data (WDM) file was created. The temperature time series were adjusted based on an additive change using the monthly deltas (temperature difference in Kelvin [K]) calculated from the 2041−2070 to 1971−2000 climate simulation comparison. Beginning with the HSPF WDM, an automated script then creates the SWAT observed temperature files (daily maximum and daily minimum).

Table 5-2. Climate change data available from each source used to develop climate scenarios

Scenario #	RCM	GCM	Temp.	Prec.	Dew point temp	Solar radiation	Wind speed	Min temp.	Max temp.	Prec. bin data
NARCCAP RCM-downscaled scenarios										
1	CRCM	CGCM3	X	X	X	X	X	X	X	X
2	HRM3	HadCM3	X	X	X	X	X	X	X	X
3	RCM3	GFDL	X	X	X	X	X	X	X	X
4	GFDL hi res	GFDL	X	X	X	X	X	X	X	X
5	RCM3	CGCM3	X	X	X	n/a	X	X	X	X
6	WRFP	CCSM	X	X	X	X	X	X	X	X
Driving GCMs of the NARCCAP and BCSD scenarios (i.e., no downscaling)										
7		CGCM3	X	X	X	X	X	n/a	n/a	n/a
8		HadCM3	X	X	n/a	n/a	n/a	n/a	n/a	n/a
9		GFDL	X	X	n/a	X	X	n/a	n/a	n/a
10		CCSM	X	X	X	X	n/a	n/a	n/a	n/a
BCSD statistically downscaled scenarios										
11		CGCM3	X	X	n/a	n/a	n/a	n/a	n/a	n/a
12		HadCM3	X	X	n/a	n/a	n/a	n/a	n/a	n/a
13		GFDL	X	X	n/a	n/a	n/a	n/a	n/a	n/a
14		CCSM	X	X	n/a	n/a	n/a	n/a	n/a	n/a

Note: X indicates data are available; n/a indicates not available.

5.2.2.2. *Precipitation Changes*

Relative changes in the *frequency* and *intensity* of precipitation events associated with climate change may prove to be more influential in determining future patterns of discharge than changes in overall (annual, seasonal) precipitation. Appendix C provides a summary review of recent literature on potential changes in the precipitation regime, including volume and intensity, and the ability of climate models to simulate these changes.

As a general pattern, warming of the lower atmosphere is projected to lead to a more vigorous hydrologic cycle, characterized by increases in global precipitation, and proportionally larger increases in high-intensity precipitation events (Trenberth et al., 2007). Much of the United States is anticipated to experience an increasing proportion of annual precipitation as larger, more intense events (Kundzewicz et al., 2007; Groisman et al., 2012). Increasing intensity of precipitation could increase direct runoff during events and increase nonpoint source loading of sediment, nutrients, and other pollutants to streams (Gutowski et al., 2008). To ensure that model simulations embody the most important dimensions of climate change affecting watershed response, it is important that climate change scenarios represent potential changes in precipitation intensity-frequency-duration relationships.

The most rigorous approach to applying the downscaled climate scenario results to modification of the existing precipitation series would be to undertake a detailed analysis (by month) of the distribution of precipitation *event* volumes and intensities. Working on an event basis is important because many of the existing precipitation time series in the BASINS meteorological data set are disaggregated from daily totals. However, analyzing volume-event data for each of the climate scenarios for all the precipitation stations was not feasible and the ability of the climate models to correctly simulate event durations is suspect.

Using the change factor method, future climate time series are constructed by applying changes to observed precipitation time series that represent the ratio between historical simulations and future climate simulations in a given climate model. No modifications were made to the number of rainfall events in the observed record. The following approach was developed to apply changes in intensity in the baseline precipitation time series.

Total accumulated precipitation data for different percentile bins (for each station location by month) were provided by NARCCAP for the dynamically downscaled climate change scenarios. The data consisted of total simulated precipitation volume (over 30 years) and the 0−25, 25−50, 50−70, and 70−90, and >90 percentile bins of the 3-hour intensity distribution (relative to the existing intensity distribution). These intensity percentiles yield information on where precipitation intensification occurs, but represent fixed 3-hour windows, not discrete event volumes, as required for the CAT program. Most of the climate scenarios showed increases in precipitation volume in the larger events, while volume in the smaller events remained constant or decreased. The net effect of this was an increase in the proportion of annual precipitation occurring in larger events. Analysis of the comprehensive (percentile, total volume) climate scenario data showed that, for most weather stations, the change in the lower percentiles of the intensity distribution appeared to be relatively small compared to the changes above the 70th percentile. However, in some cases (e.g., in Arizona), there is greater change in the 25−50th percentile bin.

Analyses of observed changes in precipitation during the 20th and early 21st century indicate that more than half of the precipitation increase has occurred in the top 10 or 5% of events (Karl and Knight, 1998; Alexander et al., 2006). However, GCMs have been shown to systematically underestimate the frequency of heavy events in the top few percentages (Trenberth et al., 2003; Sun et al., 2006; Dai, 2006). Therefore, the top 30% range is selected as a compromise that accounts for intensification but remains within the general skill of the climate models.

To account for changes in intensity, climate change scenarios were thus created using the delta method by applying climate change adjustments separately to precipitation events ≥70th percentile and events <70th percentile, while maintaining the appropriate mass balance as described below.

Percentile bin-intensity data were available only for climate scenarios 1 through 6 (RCM-downscaled scenarios). Bin data were not available for climate scenarios 7 through 14 (GCM and statistically downscaled scenarios). Two approaches were developed to account for intensification of precipitation, depending on whether precipitation bin data were available. Each approach is discussed in detail below.

Approach 1: Precipitation Bin Data Are Available

For scenarios where bin data was available (the six NARCCAP scenarios) the following approach was used. For these data, the change in the volume above the 70th percentile intensity can be taken as an *index* of the change in the top 30% of *events*. At the same time, it is necessary to maintain mass balance by honoring the predicted relative change in total volume. This can be accomplished mathematically as follows:

Let the ratio of total volume in a climate scenario (V_2) relative to the baseline scenario volume (V_1) be given by $r = (V_2/V_1)$. Further assume that the total event volume (V) can be decomposed into the top 30% (V_H) and bottom 70% (V_L). These may be related by a ratio $s = V_H/V_L$. To conserve the total volume we must have:

$$V_2 = rV_1 \qquad 5\text{-}1$$

Equation 5-1 can be rewritten to account for intensification of the top 30% of events (V_H) by introducing an intensification parameter, q:

$$V_2 = rV_{L,1} + rV_{H,1} + (rqV_{H,1} - rqV_{H,1}) = [rV_{L,1} - rqV_{H,1}] + [r(1+q)V_{H,1}], \qquad 5\text{-}2$$

Substituting for the first instance of $V_{H,1} = s\ V_{L,1}$ in eq 5-2 yields:

$$V_2 = (r - rqs)V_{L,1} + (r + qr)V_{H,1} \qquad 5\text{-}3$$

In eq 5-3 the first term represents the change in the volume of the lower 70% of events and the second term the change in the top 30%. This provides multiplicative factors that can be applied to event ranges using the BASINS CAT program on a month-by-month basis.

The intensification parameter, q, can be calculated by defining it relative to the lower 70% of values (i.e., from 0 to 70th percentile). Specifically ($r - rqs$), which represents the events below the 70th percentile, can be written as the ratio of the sum of the volumes below the 70th percentile in a climate scenario relative to the sum of the volumes below the 70th percentile for the current condition:

$$(r - rqs) = \frac{(V_{70})_2}{(V_{70})_1} \approx \frac{(Q_{70})_2}{(Q_{70})_1} \qquad 5\text{-}4$$

where $(Q_{70})_1$ and $(Q_{70})_2$ are the sum of the volumes reported up to the 70th percentile for a month for the current condition and future condition respectively.

Solving eq 5-4 for q yields:

$$q = (1 - A/r)/s \qquad 5\text{-}5$$

where A is defined as $A = \frac{(Q_{70})_2}{(Q_{70})_1}$

In sum, for each month at each station the following were calculated:

$r = V_2 / V_1$ from the summary of the climate scenario output,

$\boldsymbol{s = V_H / (V - V_H)}$ from the existing observed precipitation data for the station, sorted into events and postprocessed to evaluate the top 30% (V_H) and bottom 70% (V_L) event volumes. The numerator is calculated as the difference between total volume and the top 30% volume, rather than directly from V_L to correct for analyses in which some scattered precipitation is not included within defined "events." The s value was calculated by month and percentile (for every station, every month) using the observed precipitation time-series data that forms the template for the delta method representation of future climate time series.

$q = (1 - A/r)/s$ where A is obtained from the percentile bin climate scenario output summary

The multiplicative adjustment factors for use in the CAT tool can then be assembled as:

$r\,(1 - qs)$, for the events below the 70th percentile, and
$r\,(1 + q)$, for the events above the 70th percentile.

In addition to the typical pattern of increasing rainfall occurring in large events, this approach is applicable for the cases in which there is a relative increase in the low-percentile intensities. In those cases, the change in the 70th percentile intensity is relatively small and tends to be less than current conditions under the future scenario, resulting in q being a small negative number. In such cases, application of the method results in a decrease in the fraction of the total volume belonging to the larger events, with a shift to the smaller events—thus approximating observed increases in intensity for smaller events.

In general, it is necessary to have $-1 < q < 1/s$ to prevent negative solutions to the multipliers. The condition that $q < 1/s$ is guaranteed to be met by the definition of q (because A/r is always positive); however, the lower bound condition is not guaranteed to be met. Further, the calculation of q from the percentile bin data is at best an approximation of the actual intensification pattern. To address this problem, a further constraint is placed on q requiring that some precipitation must remain in both the high and low ranges after adjustment by requiring $-0.8 < q < 0.8/s$. It should be noted that the cases in which negative solutions arose were rare and mainly occurred for stations located in Arizona in the summer months.

Approach 2: Precipitation Bin Data not Available

For scenarios where bin data were not available (scenarios 7 through 14 based on BCSD and nondownscaled GCM output) the following approach was used. For all these climate scenarios the distribution of volume changes in events of different sizes was not known. However, because the majority of stations in the NARCCAP dynamically downscaled scenarios that had precipitation volume increases also showed strong intensification, it was assumed that any increases in precipitation would occur in the top 30% of events. In the cases where there was a decline in precipitation for a given month, the decreases were applied across all events.

For the case when $r = V_2/V_1 > 1$ (increasing precipitation), the future volume representing the climate scenario (V_2) can be defined as:

$$V_2 = V_{1L} + r^* \cdot V_{1H} \qquad 5\text{-}6$$

where r^* is the change applied to the upper range (>30%), V_H is the volume in the top 30%, and V_L is the volume in the bottom 70% of events.

Rearranging eq 5-6 and expressing $r^* = r + \cdot(r-1) \cdot {}^{V_{1L}}\!/_{V_{1H}}$, the overall change is satisfied, as:

$$V_2 = V_{1L} + r^* \cdot V_{1H} = V_{1L} + r \cdot V_{1H} - V_{1L} + r \cdot V_{1L} = r\,(V_{1H} + V_{1L}) = r \cdot V_1 . \qquad 5\text{-}7$$

Further, as $r > 1$, r^* is always positive.

For the case of $r \leq 1$ (decreasing precipitation), an across-the-board decrease in precipitation was applied as follows:

$$V_2 = r \cdot V_{1L} + r \cdot V_{1H} \qquad 5\text{-}8$$

The adjustment factors can then be assembled as follows:

For the events above the 70th percentile, if
$r > 1$, then use r^*
$r \le 1$, then use r.

For the events below the 70th percentile, if
$r > 1$, then use 1 (no change)
$r \le 1$, then use r.

5.2.2.3. *Potential Evapotranspiration Changes*

Potential evapotranspiration is an important parameter that is sensitive to climate change and urban development. In this study, PET is simulated with the Penman-Monteith energy balance method. In addition to temperature and precipitation, the Penman-Monteith method requires dew point (or relative humidity), solar radiation, and wind as inputs. Because only a few stations have time series for all four additional variables that are complete over the entire 1971−2000 period, these variables are derived from the SWAT 2005 statistical weather generator (Neitsch et al., 2005). This is done internally by SWAT. For HSPF implementation a stand-alone version of the weather generator code was created and used to create time series for each of the needed variables at each BASINS meteorological station based on the nearest SWAT weather generator station after applying an elevation correction.

The SWAT weather generator database (.wgn) contains the statistical data needed to generate representative daily climate data for the different stations. Adjustments to the wgn file parameters were made using monthly change statistics for the NARCCAP dynamically downscaled scenarios. Specifically solar radiation, dew point temperature, and wind speed were adjusted for each scenario (see Table 5-3).

The probability of a wet day following a dry day in the month and the probability of a wet day following a wet day in the month were kept the same as in the original SWAT climate generator file for the station. Climate models showed a systematic bias, likely introduced by the scale mismatch (between a 50-km grid and a station observation) for weather generator parameters like wet day/dry day timing, resulting in too many trace precipitation events relative to observed. Thus it was not possible to use climate models to determine changes in these parameters. Also, an analysis of the dynamically downscaled 3-hourly time series for the Canadian Regional Climate Model (CRCM) downscaling of the CGCM3 GCM at five randomly selected locations in the southeast, southwest, mid-Atlantic, upper Midwest, and Pacific Northwest demonstrated that the probability that a rainy day is followed by a rainy day (transition probability) in the model output did not change significantly at any of the sample locations.

For the BCSD climate scenarios, information on these additional meteorological variables is not available. Many of these outputs are also unavailable from the archived nondownscaled GCM output. For these scenarios it was assumed that the statistical parameters remained unchanged at current conditions. While the lack of change is not physically realistic (e.g., changes in rainfall will be associated with changes in cloud cover and thus with changes in direct solar radiation reaching the land surface), this reflects the way in which output from these models is typically used.

Table 5-3. SWAT weather generator parameters and adjustments applied for scenarios

SWAT wgn file parameter	Description	Adjustment applied
SOLARAV1	Average daily solar radiation for month ($MJ/m^2/day$)	Adjusted based on Surface Downwelling Shortwave Radiation change (%)
DEWPT1	Average daily dew point temperature in month (ºC)	Additive Delta value provided for climate scenario for each month
WNDAV1	Average daily wind speed in month (m/s)	Adjusted based on 10-meter Wind Speed change (%)

Inconsistencies in the available data among different scenarios required special treatment. One of the NARCCAP scenario archives (Scenario 5: CGCM3 downscaled with regional climate model, version 3 [RCM3]) does not include solar radiation, which may be affected by changes in cloud cover. Current condition statistics for solar radiation contained in the weather generator were used for this scenario. This does not appear to introduce a significant bias as the resulting changes in PET fall within the range of those derived from the other NARCCAP scenarios.

Table 5-4 compares the reference crop estimates of Penman-Monteith PET for the five pilot watersheds. This is the PET used directly by the HSPF model, while the SWAT model performs an identical calculation internally, and then adjusts actual evapotranspiration (AET) for crop height and leaf area development. Because PET is most strongly a function of temperature, a fairly consistent increase in PET is simulated for most basins. It can be seen from the figures in Appendix Z, however, that the statistically downscaled and nondownscaled GCM scenarios (scenarios 7−14) that do not include solar radiation, dew point, and wind time series consistent with the simulated precipitation and temperature, generally provide higher estimates of PET than do the dynamically downscaled models. This issue is explored in more detail in Section 6.2.

5.3. URBAN AND RESIDENTIAL DEVELOPMENT SCENARIOS

Watershed simulations were also conducted to assess the sensitivity of study areas to potential mid-21st century changes in urban and residential development.

Table 5-4. Comparison of PET estimation between different downscaling approaches

Scenario type		NARCCAP dynamically downscaled		Nondownscaled GCM	BCSD statistically downscaled	NARCCAP dynamically downscaled		Nondownscaled GCM	BCSD statistically downscaled
Climate scenario		**1. CRCM-CGCM3**	**5.RCM3-CGCM3**	**7. CGCM3**	**11. CGCM3**	**3. RCM3-GFDL**	**4. GFDL (high res)**	**9. GFDL**	**13. GFDL**
ACF (GA, AL, FL)	annual average PET (in)	60.32	58.59	59.85	64.75	60.46	57.16	67.88	65.97
	difference from NARCCAP mean	1.46%	−1.46%	0.67%	8.90%	2.81%	−2.81%	15.42%	12.17%
Minnesota River (MN, SD)	annual average PET (in)	58.57	55.24	56.22	63.90	54.92	60.02	64.99	63.65
	difference from NARCCAP mean	2.92%	−2.92%	−1.21%	12.29%	−4.44%	4.44%	13.08%	10.75%
Salt/Verde/San Pedro (AZ)	annual average PET (in)	83.67	82.89	84.19	85.01	81.32	82.93	86.73	84.74
	difference from NARCCAP mean	0.47%	−0.47%	1.09%	2.07%	−0.98%	0.98%	5.60%	3.18%
Susquehanna (PA, NY, MD)	annual average PET (in)	43.78	42.24	42.91	51.15	43.06	42.69	50.18	50.17
	difference from NARCCAP mean	1.79%	−1.79%	−0.23%	18.94%	0.43%	−0.43%	17.05%	17.02%
Willamette (OR)	annual average PET (in)	44.18	44.51	45.24	50.73	45.44	43.91	49.16	49.17
	difference from NARCCAP mean	−0.37%	0.37%	2.01%	14.41%	1.70%	−1.70%	10.04%	10.06%

5.3.1. ICLUS Urban and Residential Development Scenarios

Projected changes in urban and residential development were acquired from EPA's ICLUS project (U.S. EPA, 2009c). ICLUS has produced seamless, national-scale change scenarios for developed land that are compatible with the assumptions about population growth, migration, and economic development that underlie the IPCC greenhouse gas emissions storylines. ICLUS projections were developed using a demographic model coupled with a spatial allocation model that distributes the population as housing units across the landscape. Specifically, population is allocated to 1-hectare (ha) pixels, by county, using the Spatially Explicit Regional Growth Model (SERGoM). The model is run for the conterminous United States and output is available for each emissions storyline by decade to 2100. The final spatial data sets provide decadal projections of housing density and impervious surface cover as a function of population for the period 2000 through 2100 (U.S. EPA, 2009c).

Data from the ICLUS project are composed of grid-based housing density estimates with 100-m cells, whose values are set equal to *units/ha × 1,000*. Existing housing densities were estimated using a variety of sources and models, and future housing densities developed under various scenarios for each decade through 2100. For the existing housing density grid, two types of "undevelopable" area where residential development was precluded were masked out during the production—a comprehensive spatial data set of protected lands (including land placed in conservation easements), and land assumed to be commercial/industrial under current conditions. Undevelopable commercial/industrial land use was masked out according to the SERGoM method (U.S. EPA, 2009c) that eliminated commercial, industrial, and transportation areas that preclude residential development, identified as "locations (1-ha cells) that had >25% urban/built-up land cover with lower than suburban levels of housing density."

The ICLUS projections used in this study thus do not account for potential growth in commercial/industrial land use. It is also important to note that the ICLUS projections do not explicitly account for changes in rural or agricultural land uses. These categories change in the analysis based on ICLUS only when they convert to developed land.

5.3.2. Mapping ICLUS Housing Density Projections to NLCD Land Use Categories

The ICLUS projections used in this study are for changes in housing density and impervious cover. This data cannot be used directly with the SWAT and HSPF watershed models, which require land use data consistent with the NLCD. It was therefore necessary to translate between ICLUS projections and NLCD land-use classes.

In addition, ICLUS housing density class estimates and the NLCD developed classes do not have a one-to-one spatial relationship because they are constructed on different underlying scales. ICLUS represents housing density based largely on the scale of census block groups. As a result, it represents the overall density within a relatively large geographic area when compared to the 30 × 30 meter resolution of NLCD 2001 land cover and can represent a mix of different NLCD classes. Therefore, land-use changes must be evaluated on a spatially aggregated basis at the scale of model subbasins.

Baseline land use, derived from the 2001 NLCD, contains four developed land classifications (NLCD classes 21 through 24), nominally representing "developed, open space" (less than 20%

impervious), developed, low intensity (20−49% impervious), developed, medium intensity (50−79% impervious), and developed, high intensity (greater than 80% impervious). Impervious fractions within each developed NLCD land-use class were estimated separately for each study area, using the 2001 NLCD Land Cover and Urban Impervious data products. ICLUS land-use change scenarios were implemented by modifying the existing land-use distribution in the watershed models.

ICLUS estimates housing density on a continuous scale. To process the data more efficiently, the data were reclassified into 10 housing density ranges. In each study area, the ICLUS housing density ranges were cross-tabulated with NLCD 2001 classes based on percent imperviousness. It was assumed that the number of housing units changes, but that the characteristic percent impervious values for each NLCD developed class remains constant. The change in land area needed to account for the change in impervious area was then back calculated.

To represent the net change in future land cover, the change in developed land use was added (or subtracted) from the existing totals in each subbasin. Land area was then removed from each undeveloped NLCD class (excluding water and wetlands) according to their relative ratios in each subbasin to account for increases in developed area. If the undeveloped land area was not sufficient to accommodate the projected growth, development on wetlands was allowed. The reductions in undeveloped land were distributed proportionately among modeled soils (in SWAT) or hydrologic soil groups (in HSPF). The new developed lands were then assumed to have the parameters of the most dominant soil and lowest HRU slope in the subbasin. For HSPF, the changed area was implemented directly in the area table of the user control input (.uci) file. For SWAT, the land-use change was implemented by custom code that directly modified the SWAT geodatabase that creates the model input files.

The gains (and losses) in NLCD class interpreted from ICLUS were tabulated separately for each subbasin. In almost every case, the gains far exceeded the losses and a net increase was projected in all four NLCD developed classes. However, in a few cases there was an overall loss of the lowest density NLCD class. This tended to occur when a subbasin was already built out, and ICLUS projected redevelopment at a higher density.

The projected overall changes in developed land for 2050 as interpreted to the NLCD land-cover classes and used for modeling are presented in Table 5-5. Note that even in areas of expected high growth (e.g., the area around Atlanta in the ACF basin), new development by 2050 is expected to constitute only a small fraction of the total watershed area at the scale of the study areas in this project. The highest rate of land-use change in the studied watersheds is Coastal Southern California, at 11.7%. (Note that the ICLUS project does not cover the Cook Inlet watershed in Alaska. Urban and residential development scenarios were thus not evaluated at this study area.)

Table 5-5. ICLUS projected changes in developed land area within different imperviousness classes by 2050

Study area	Change, <20% impervious class (km^2)	Change, 20−49% impervious class (km^2)	Change, 50−79% impervious class (km^2)	Change, >80% impervious class (km^2)	Total change in developed land (km^2)	Increase as percent of study area (%)
ACF	+665.2	+809.7	+212.3	+90.8	+1,778.0	+3.56
Ariz	+92.1	+87.0	+16.0	+1.3	+196.4	+0.51
Cook	ND	ND	ND	ND	ND	ND
GaFla	+873.9	+776.1	+361.5	+102.2	+2,113.8	+4.65
Illin	+353.5	+1,506.6	+447.5	+116.2	+2,424.0	+5.50
LErie	+152.1	+204.8	+51.0	+15.6	+423.4	+1.40
LPont	+307.2	+308.3	+91.4	+23.4	+730.1	+4.82
Minn	+71.3	+142.9	+60.9	+18.5	+293.5	+0.67
Neb	+8.9	+18.7	+4.1	+1.6	+33.2	+0.06
NewEng	+238.6	+327.2	+215.5	+59.2	+840.4	+3.13
PowTon	+1.3	+0.5	+0.1	0.0	+1.9	+0.00
RioGra	+139.0	+228.8	+57.1	+7.4	+432.4	+0.88
Sac	+103.6	+58.1	+29.5	+8.2	+199.3	+0.93
SoCal	+162.0	+1,001.0	+1,089.1	+114.1	+2,466.2	+11.72
SoPlat	+329.4	+1,364.6	+473.5	+83.6	+2,251.1	+5.93
Susq	+211.1	196.2	+69.6	+25.6	+502.5	+0.71
TarNeu	+492.4	+306.6	+107.4	+29.2	+935.6	+3.66
Trin	+978.9	+1,896.7	+891.1	+304.3	+4,071.0	+8.76
UppCol	+56.9	+168.1	+66.3	+8.3	+299.6	+0.65
Willa	+75.8	+193.4	+95.0	+33.3	+397.6	+1.37

Note: The ICLUS project does not cover the Cook Inlet watershed. Results shown are total new developed area, including pervious and impervious fractions.

6. STREAMFLOW AND WATER QUALITY SENSITIVITY TO DIFFERENT METHODOLOGICAL CHOICES: ANALYSIS IN THE FIVE PILOT STUDY AREAS

One goal of this study was to assess the implications of different methodological choices for conducting climate change impacts assessments on the variability of simulation results. Sensitivity studies in the five pilot study areas allow assessment of the variability resulting from the use of different watershed models, and variability resulting from use of climate change scenarios developed using different methods of downscaling GCM output. The five pilot study areas are the Minnesota River, ACF, Susquehanna, Willamette, and Salt/Verde/San Pedro Rivers. In each of these sites, independent simulations were conducted using the SWAT and HSPF watershed models, and in addition to the six dynamically downscaled NARCCAP scenarios, an additional set of climate change scenarios was evaluated, four based on the BCSD statistically downscaled data set, and four based directly on GCMs with no downscaling. This section presents a summary of these results.

6.1. COMPARISON OF WATERSHED MODELS

The magnitude of the additional variability introduced by choice of a hydrologic model is of interest when simulating hydrologic responses to climate change and urban development. Two different watershed models, SWAT and HSPF, were calibrated and applied to the five pilot study areas. Evaluation of different watershed models can be considered an extension of the scenario-based, ensemble approach commonly used in climate change studies. Detailed examination of the calibration of each model in the five pilot study areas and the results of change scenarios conducted with each model are presented in separate sections and the appendices to this report.

HSPF and SWAT take different approaches to watershed simulation and have different structures and algorithms, resulting in different strengths and weaknesses. Most notably, the two models differ in the way that they represent infiltration and plant-climate interactions. SWAT (in standard application mode) simulates rainfall-runoff processes using a curve number approach, operating at a daily time step. The curve number approach first partitions incoming moisture into direct runoff and a remainder that is available for infiltration. In contrast, HSPF simulates rainfall-runoff processes using Green-Ampt infiltration, in which infiltration into the soil is simulated first, with the remainder available for direct runoff or surface storage.

HSPF is typically run at a subdaily time step, usually hourly for large watersheds, and has a more sophisticated representation of runoff, infiltration, and channel transport processes than does SWAT. SWAT's advantage is that it incorporates a plant growth model (including representation of changes in atmospheric CO_2 concentration) and can therefore simulate some of the important feedbacks between plant growth and hydrologic response. Both models simulate evapotranspiration of soil water stores, but HSPF does this using empirical monthly coefficients relative to potential evapotranspiration, while SWAT incorporates a plant growth model that can, in theory, dynamically represent plant transpiration of soil moisture.

6.1.1. Comparison of Model Calibration and Validation Performance

Models were calibrated and validated using multiple measures as summarized previously in this report and described in detail in Appendices D−W. Calibration of both models was conducted in accordance with the modeling QAPP (see Appendix B; Tetra Tech, 2008a) for each of the five pilot study areas. Development and setup of the two watershed models proceeded from a common basis, with both models using the same subbasin delineations, land use coverage (2001 NLCD), soils coverage (STATSGO), hydrography, digital elevation model, impervious area fractions for developed land classes, and point source and dam representations. Other aspects of model setup were designed to be similar, although it was not possible to be identical because of differences in the way the two models conceptualize discretization of the land surface. For instance, hydrologic response units (the fundamental building blocks of the upland simulation) were created as an overlay of land use and HSG for HSPF, while SWAT uses an overlay of land use and STATSGO dominant soil, associating various other properties from the soil database in addition to HSG with the model hydrologic response units. In addition, HSPF simulates impervious surfaces as a separate land use, while SWAT assigns an impervious fraction to an underlying land use.

Calibration/validation locations and observed data series were the same for both models. Further, the calibration of both models was guided by prespecified statistical analyses that were performed using identical spreadsheet setups obtained from a common template. Despite these commonalities, the scope of the modeling effort in this study required that models be developed by different modeling teams, with inevitable differences in results. To reduce the likelihood of bias, model calibration assignments were structured so that the same team did not apply both HSPF and SWAT to a single study area, and each watershed model was implemented by at least three different modeling teams for the pilot studies.

6.1.1.1. *Streamflow Results*

This section examines hydrologic simulations as compared to observed streamflow records based on total volume error and the daily Nash-Sutcliffe coefficient of model fit efficiency. Model performance is first examined in terms of the quality of fit for the initial calibration watershed, followed by similar analyses for the largest-scale downstream watershed. Intercomparisons then provide some insight into model performance relative to temporal change (calibration vs. validation period) and relative to spatial change within each study area (calibration watershed vs. downstream watershed).

Summary results for percent error in total volume and the Nash-Sutcliffe E coefficient for daily streamflow are shown in Tables 6-1 and 6-2, respectively, for the initial calibration site along with the calibration fit for the most downstream gage in the watershed. In general, the quality of model fit is good for both models. In most, but not all cases, the quality of model fit is slightly better (smaller magnitude of percent error, larger E coefficient) for the HSPF simulations (e.g., see Figure 6-1 for the calibration period). This is likely due in large part to the use of daily precipitation in SWAT versus hourly precipitation in HSPF, although the advantage accruing to HSPF is muted by the fact that many of the “hourly” precipitation input series used are actually disaggregated from daily totals. Monthly values of Nash-Sutcliffe E are higher for both models, but attention is called to the daily scale because it better reflects the models’ ability to separate surface and subsurface flow pathways. Note that E is low for the Arizona initial site on the

Verde River because streamflow is dominated by relatively constant deep groundwater discharges.

Table 6-1. Percent error in simulated total streamflow volume for 10-year calibration and validation periods at initial and downstream calibration gages

Study area	Model	Initial site calibration	Initial site validation	Downstream calibration
Apalachicola-Chattahoochee-Flint (ACF)	HSPF	5.50	5.79	16.79
	SWAT	7.28	3.33	16.53
Salt/Verde/San Pedro (Ariz)	HSPF	2.43	6.31	4.48
	SWAT	−2.46	5.68	9.43
Minnesota River (Minn)	HSPF	1.61	14.78	−4.25
	SWAT	−5.41	−0.84	7.89
Susquehanna (Susq)	HSPF	−0.16	−8.00	1.79
	SWAT	−5.41	−16.30	−9.74
Willamette (Willa)	HSPF	−3.92	−9.80	2.58
	SWAT	−4.76	12.10	−4.96

Table 6-2. Nash-Sutcliffe coefficient of model fit efficiency (*E*) for daily streamflow predictions, 10-year calibration and validation periods at initial and downstream calibration gages

Study area	Model	Initial site calibration	Initial site validation	Downstream calibration
Apalachicola-Chattahoochee-Flint (ACF)	HSPF	0.71	0.65	0.72
	SWAT	0.62	0.56	0.64
Salt/Verde/San Pedro (Ariz)	HSPF	0.48	0.45	0.53
	SWAT	0.03	−1.00	0.22
Minnesota River (Minn)	HSPF	0.75	0.78	0.92
	SWAT	0.79	0.74	0.63
Susquehanna (Susq)	HSPF	0.70	0.55	0.77
	SWAT	0.29	0.42	0.45
Willamette (Willa)	HSPF	0.80	0.81	0.88
	SWAT	0.49	0.39	0.67

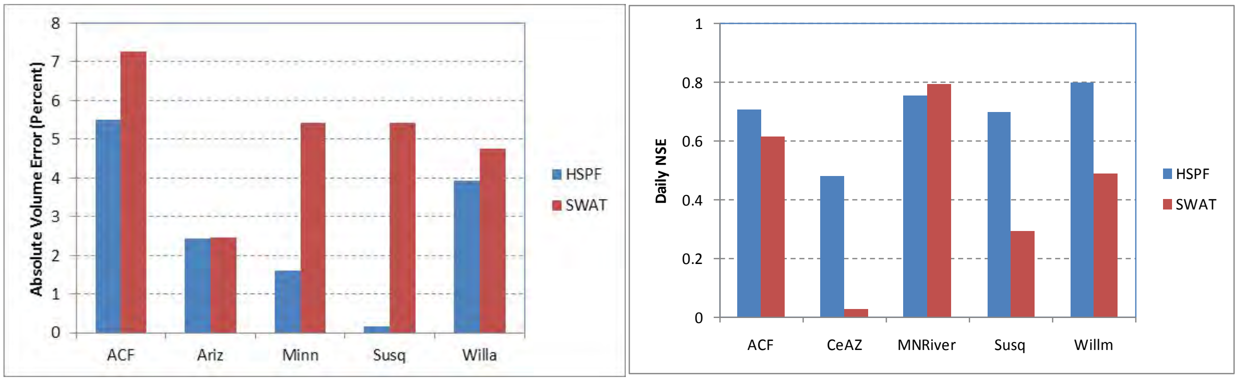

Figure 6-1. Comparison of model calibration fit to streamflow for the calibration initial site.

Note: Figures compare calibration results for HSPF and SWAT. Total volume error is converted to its absolute value.

The ability of the model to assess relative changes in response to altered climate forcing is of paramount importance in this project. Some insight on this topic can be gained by looking at the sensitivity of model fit to temporal and spatial changes in application. Figure 6-2 summarizes the sensitivity to temporal changes by examining the percent error in the calibration period and the validation test. It is interesting to observe that for both the ACF and the Minnesota River, the SWAT model achieved an improvement in total volume error during the validation period. These are the two study areas with the greatest amount of row crop agriculture, and the results may reflect SWAT's ability to reflect changing responses of crops to changes in climate over the last 20 years.

Figure 6-3 examines model sensitivity to spatial scale, comparing performance during the calibration period for the initial calibration target gage (HUC-8 spatial scale) and the most downstream gage in the model (approximately HUC-4 spatial scale). The left panel shows the change in the absolute magnitude of percent error, while the right panel shows the change in *E*. A smaller magnitude of change in total volume error or a larger increase in *E* represents better performance. The changes in total volume errors are generally small, regardless of whether detailed spatial calibration was pursued. In most cases, the models achieved an improvement in *E* in going from the smaller to the larger scale.

6.1.1.2. *Water Quality Results*

The water quality calibration compared simulated monthly loads to monthly load estimates obtained from a stratified regression on (typically sparse) observed data. To compare these results between models, the baseline adjusted E_1' coefficient of model fit efficiency is most appropriate. Results are summarized graphically for the calibration period at the calibration initial site and downstream site in Figures 6-4 through 6-6. For suspended solids and total phosphorus, the performances of the two models are similar, while HSPF appears to provide a somewhat better fit for total nitrogen.

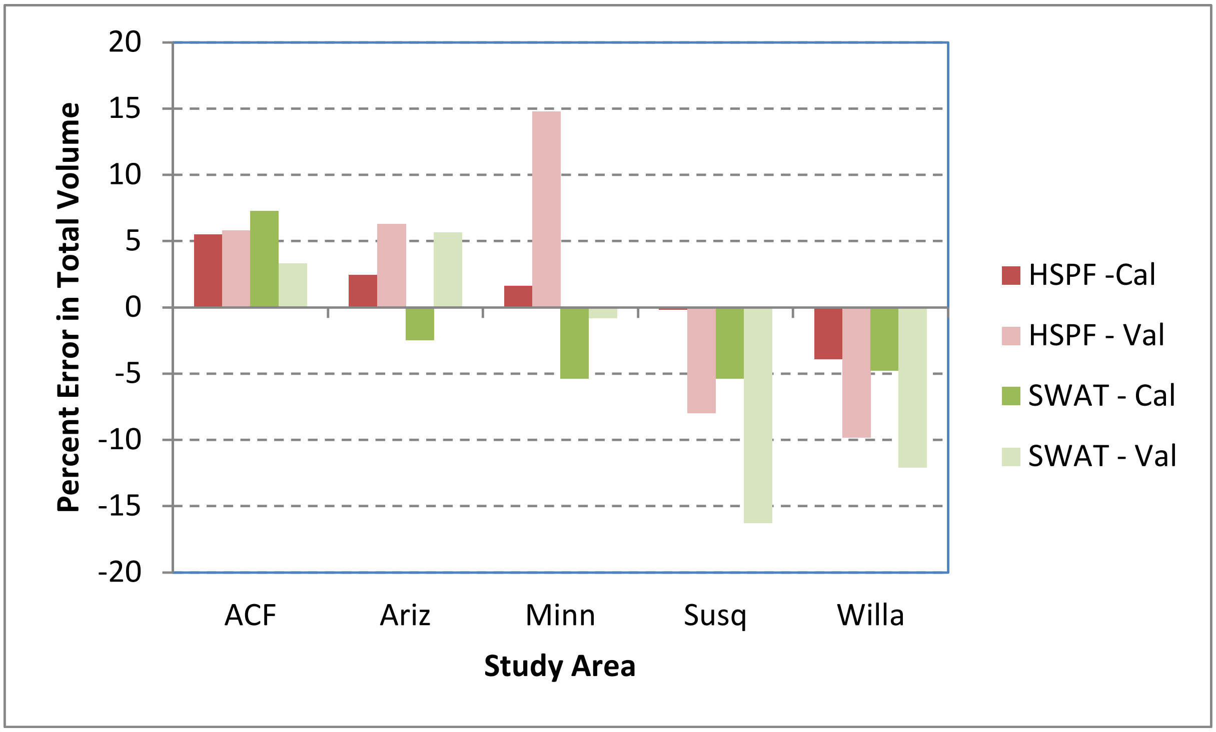

Figure 6-2. Sensitivity of model fit for total streamflow volume to temporal change.

Figure 6-3. Sensitivity of model fit for streamflow to spatial change.

Note: Change in percent total volume error represents the difference in the absolute value of percent error in going from the initial calibration site to a larger scale, typically the furthest downstream site. Change in *E* represents the difference in the Nash-Sutcliffe *E* coefficient in going from the calibration site to the larger-scale site.

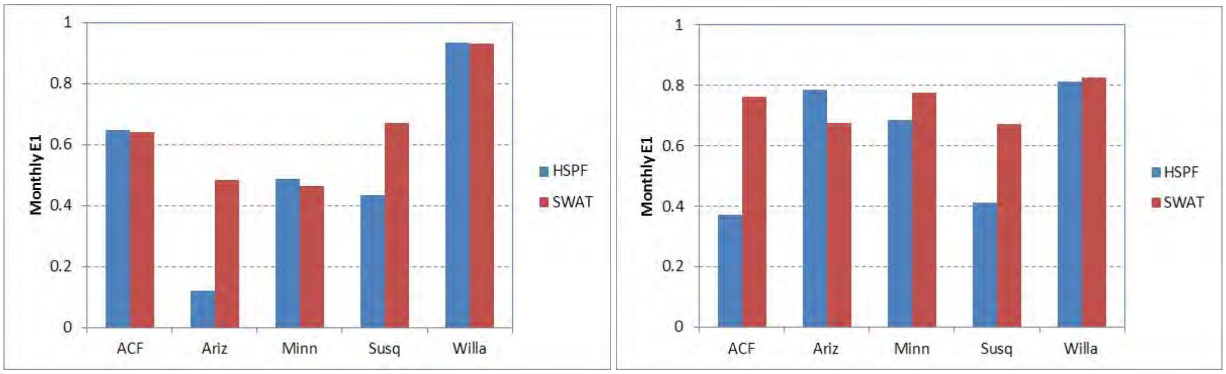

Figure 6-4. Comparison of baseline adjusted model fit efficiency for total suspended solids monthly loads for calibration site (left) and downstream site (right).

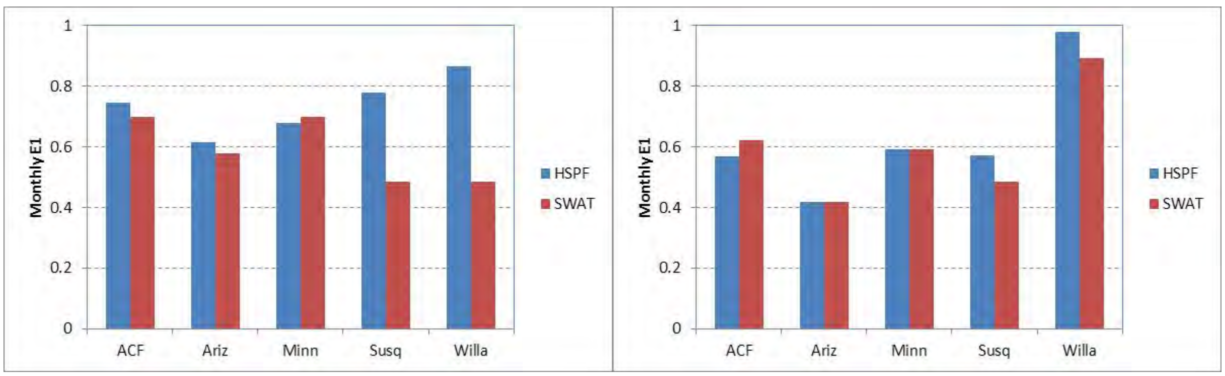

Figure 6-5. Comparison of baseline adjusted model fit efficiency for total phosphorus monthly loads for calibration site (left) and downstream site (right).

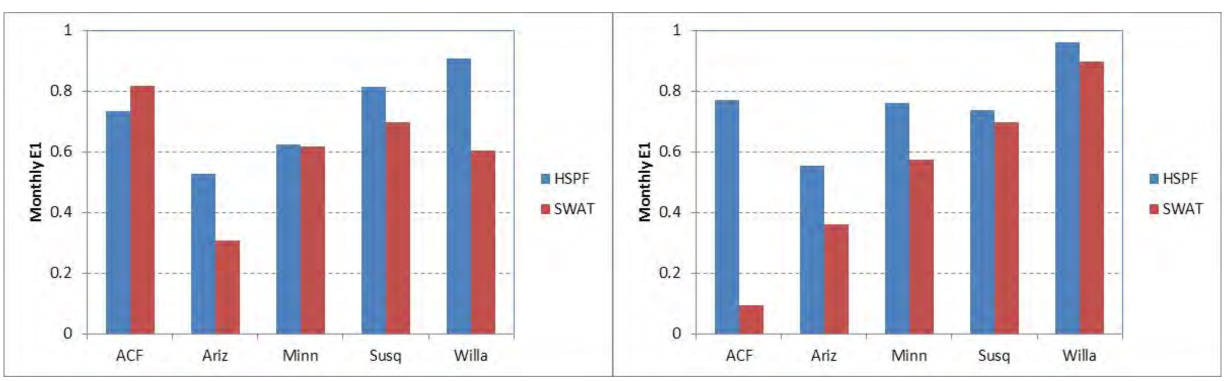

Figure 6-6. Comparison of baseline adjusted model fit efficiency for total nitrogen monthly loads for calibration site (left) and downstream site (right).

6.1.1.3. *Summary of Relative Model Performance*

In general, the HSPF model provides a somewhat better fit to observed streamflow and water quality data for the calibration periods. The effect is most noticeable in the coefficient of model fit efficiency (*E*) for daily streamflow, where the HSPF approach of applying Philip infiltration using hourly precipitation appears to yield an advantage over the SWAT daily curve number method. However, relative performance of the two models is more similar as the analysis moves to the validation period or to other sites for which detailed calibration has not been undertaken. Most importantly, both models appear to be capable of performing adequately.

6.1.2. Comparison of Simulated Changes Using SWAT and HSPF

Figure 6-7 compares HSPF and SWAT simulated changes in mean annual streamflow at the downstream station of each of the five pilot watersheds for all 28 combinations of climate and land-use change scenarios (expressed as a percent of the baseline conditions, representing approximately 1970−2000). In general, the mean annual streamflow results provided by the two models are similar, as is shown quantitatively below. One notable difference is for the Minnesota River where SWAT projects higher flows relative to HSPF under future climate conditions—an issue that is explored further in Section 6.1.3. Note that points plotting close to or on top of each other for a given study site in Figure 6-7 are scenarios representing the same climate change scenario with and without changes in urban development.

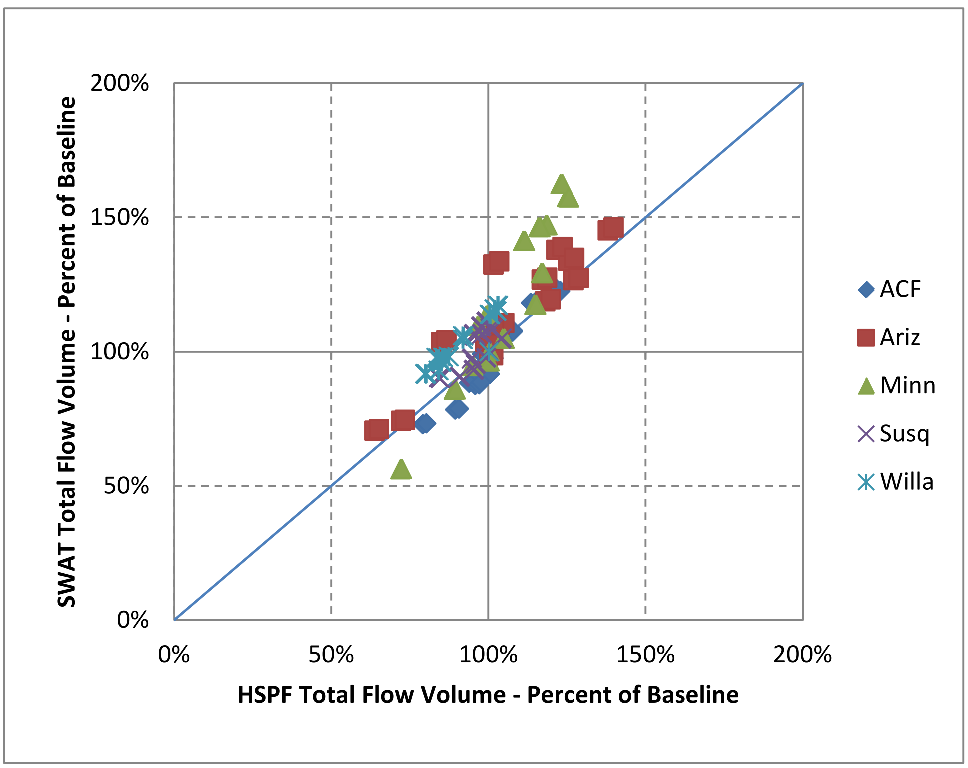

Figure 6-7. SWAT and HSPF simulated changes in total streamflow in pilot watersheds (expressed relative to current conditions).

Table 6-3 provides a statistical comparison of the HSPF and SWAT results at the downstream station. Three types of tests are summarized. The first is a *t*-test on the series of paired means (HSPF and SWAT for each climate and land use scenario), which has a null hypothesis that the mean of the differences between the series is not significantly different from zero. The second test is a two-way analysis of variance (ANOVA) that looks at choice of watershed model (HSPF or SWAT) as blocks and climate scenario as treatment. The null hypotheses for this test are that the difference between series for a given source of variance is zero. The third test is a linear regression on SWAT results as a function of HSPF results. Where the models are in full agreement, the intercept of such a regression should not be significantly different from zero and the slope should not be significantly different from unity.

For mean annual streamflow, both models produce similar results with a high Pearson correlation coefficient. The null hypothesis from the *t*-test that the mean difference is zero cannot be rejected. However, the two-way ANOVA shows that both the choice of watershed model and the climate scenario are significant sources of variability in streamflow, with probability values (*p*-value) well less than 0.1. Together these results suggest that the SWAT and HSPF results are similar in the aggregate, but may contain an underlying systematic shift. A regression analysis shows that the slope coefficient for SWAT and HSPF is 0.93, with a 95% confidence interval that does not overlap 1.0, and an intercept of 1,262 that also does not overlap zero. Thus, SWAT projects a somewhat smaller response to increased rainfall, but results in higher baseflow estimates (likely due to the effects of increased CO_2 on evapotranspiration, as explained further below).

Table 6-3. Statistical comparison of HSPF and SWAT outputs at downstream station for the five pilot sites across all climate scenarios

Measure	Mean annual flow (cfs)	TSS load (*t*/yr)	TP load (*t*/yr)	TN load (*t*/yr)
Paired *t*-test on sample means				
HSPF Mean	20,546	2,398,714	2,748	35,346
SWAT Mean	20.435	2,865,178	3,344	43,275
Pearson Correlation	0.989	0.733	0.644	0.948
t-statistic	0.616	−3.123	−4.783	−7.385
p (two-tail)	0.539	0.002	<0.001	<0.001
Two-way ANOVA on watershed model and climate scenario				
p value—Model	<0.001	0.071	0.006	0.044
p value—Climate	<0.001	0.960	0.999	1.000
Linear regression; SWAT result as a function of HSPF result				
Intercept	1,261.7	141,717	954.0	−1,173.1
Intercept, 95% confidence	695−1,828	−363,064−646,498	431−1,477	−4,194−1,848
Coefficient (slope)	0.933	1.136	0.870	1.257
Coefficient (slope) 95% confidence	0.911−0.956	0.964−1.307	0.702−1.038	1.189−1.326

The comparison for total suspended solids is obscured by the extremely large projected increases under certain scenarios for the Arizona basins (Verde River, in this case). Those increases are mostly due to simulated channel erosion, for which both models are likely to be highly uncertain because future simulated peak flows are outside the range of calibration data. Figure 6-8 shows the simulated total suspended solids results but with the *x*-axis truncated to exclude these extreme results for the Verde River. Results for the other four pilot sites appear generally consistent between models, although simulated increases from SWAT are generally less than those from HSPF for the ACF, Susquehanna, and Willamette. In part this is due to differences in the baseline simulation. For example, HSPF simulations show less channel transport and much smaller total suspended solids loads at the mouth of the Susquehanna than does SWAT for the baseline scenario, resulting in a larger relative change with increased future streamflow. The difference between results for SWAT and HSPF may also reflect the effects of increased atmospheric CO_2 concentration and longer growing periods simulated by SWAT, leading to more litter cover and reduced soil erosion.

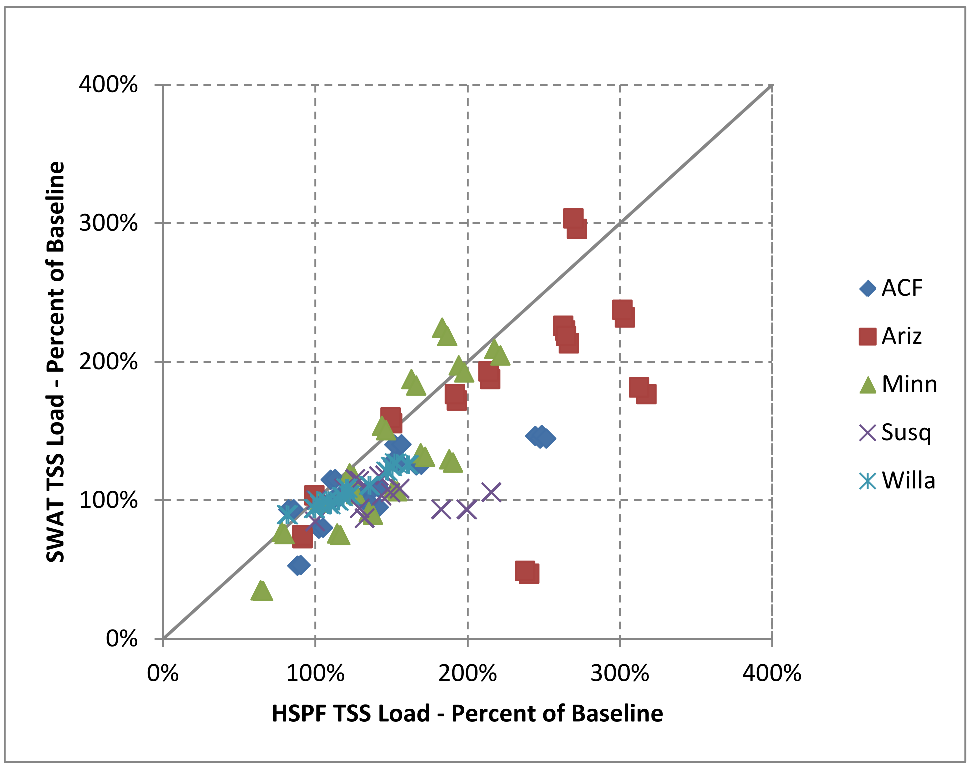

Figure 6-8. SWAT and HSPF simulated changes in TSS at downstream station in pilot watersheds (expressed relative to current conditions).

Note: HSPF simulation for climate scenarios 9 (GFDL, nondownscaled GCM), 10 (CCSM, nondownscaled GCM), 12 (HadCM3, BCSD), and 13 (CCSM, BCSD) yield increases in simulated total suspended solids load of greater than 400% and are omitted from this plot.

For total suspended solids, the baseline load is higher in SWAT than in HSPF for three of the five watersheds; thus the statistical comparison (see Table 6-3) shows a higher mean load from

SWAT, even though the percentage increases are often smaller. The *t*-test on means shows that this difference is highly significant. However, the ANOVA show that neither the model choice nor the climate scenario is a significant explanatory variable for the variance at the 95% confidence level. The regression analysis shows that the intercept is large, but not significantly different from zero, while the slope is not significantly different from 1. Together these statistics indicate that the total suspended solids simulation is subject to considerable uncertainty and that differences between sites are more important than other factors.

Results for total phosphorus are generally similar to those seen for total suspended solids, with much more extreme increases projected by both models for the Verde River (Ariz; see Figure 6-9). HSPF simulations are especially high due to an assumption of phosphorus concentrations in scoured channel sediment. SWAT tends to simulate higher rates of increases for total nitrogen (see Figure 6-10) than does HSPF (likely due to more rapid cycling of organic matter), with the notable exception of the ACF study area. However, it appears that projections of total nitrogen at the downstream end of the ACF may be significantly underestimated in the calibrated SWAT model. Total nitrogen varies little in the Susquehanna model due to small changes in streamflow and significant point source contributions.

For both total nitrogen and total phosphorus the choice of model is a significant factor in the ANOVA and higher mean loads are produced by SWAT. The slope of a regression of SWAT on HSPF is not significantly different from 1 for total phosphorus, consistent with the solids simulation, but the intercept is significantly different from zero, indicating differences in the baseflow simulation of total nitrogen. For total nitrogen, the intercept is not significantly different from zero, but the slope is significantly greater than 1, suggesting that SWAT projects a greater increase in total nitrogen loads under future climate conditions.

In sum, the comparison of relative response to change scenarios indicates that the two models provide generally consistent results for hydrology, with differences that may be in part due to the inclusion of explicit representation of several processes in SWAT (increased atmospheric CO_2, changes in planting time, changes in crop growth and litter production, and changes in nutrient recycling rates) that are not automatically included in HSPF. Water quality results exhibit greater variability between the models, due in large part to the uncertainty inherent in model calibration.

An additional contributing cause to differences in results from the two models is the extent to which spatial calibration of the model was pursued, which was left to modeler judgment. In all study areas, initial calibration and validation was pursued at an "initial calibration" gage and monitoring station at an HUC-8 spatial scale. The calibration results were then carried to the larger study area. At this point, individual modeler preferences introduced some variability into results. Some modelers undertook detailed spatial adjustments to parameters; others extended the initial parameter set with only minor modifications. With more spatial adjustments a higher degree of fit is generally to be expected for model calibration—although this does not necessarily result in better performance in model validation. In general, only limited spatial calibration adjustments beyond the initial parameter set was carried out for the Minnesota River, Susquehanna, and Willamette SWAT models and also for the Susquehanna HSPF model.

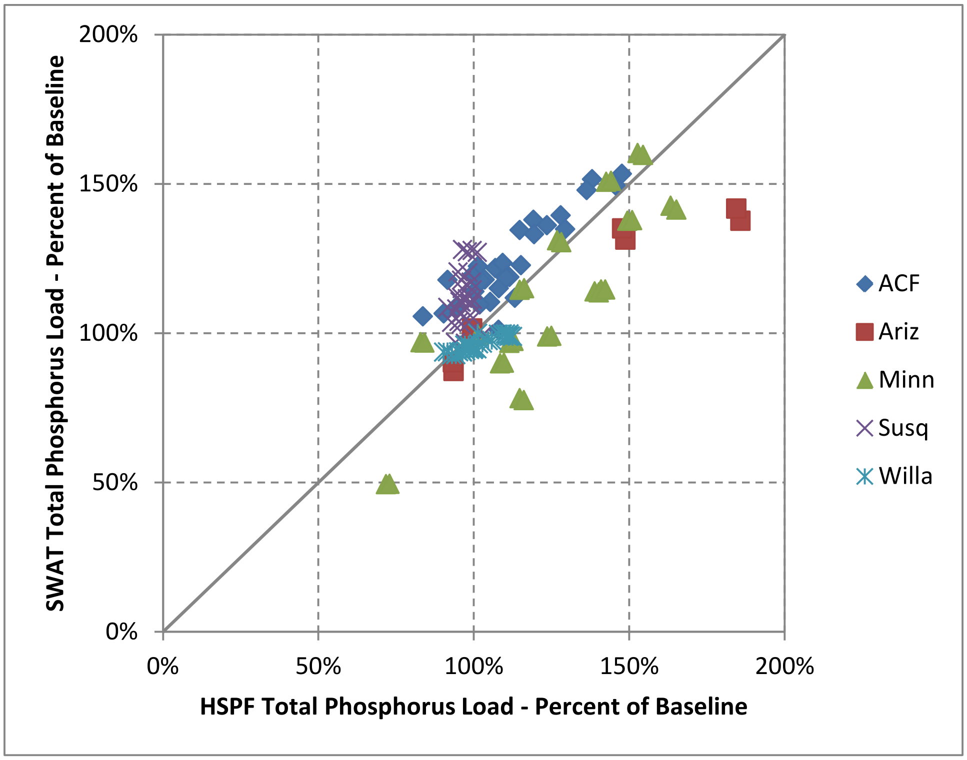

Figure 6-9. SWAT and HSPF simulated changes in total phosphorus load in pilot watersheds (expressed relative to current conditions).

Note: 22 HSPF simulations for Ariz ranging from 200 to 875% are omitted.

Due to the potential influence of modeler choice and skill, it is cautioned that the results should not be interpreted as a true head-to-head comparison of the two models, as the results for any given watershed may be skewed by exogenous factors such as modeler calibration strategy. Instead, it is most relevant to examine relative performance and potential inconsistencies between simulations using the two models.

6.1.3. Sensitivity to Increased Atmospheric CO_2

A key difference between HSPF and SWAT is that SWAT has a dynamic plant growth module with ability to represent changes in atmospheric CO_2 on plant growth and water loss to ET. We performed paired sets of SWAT simulations with and without increased CO_2 for all five pilot sites to assess the sensitivity of streamflow and water quality endpoints to the effects of increased atmospheric CO_2 concentrations.

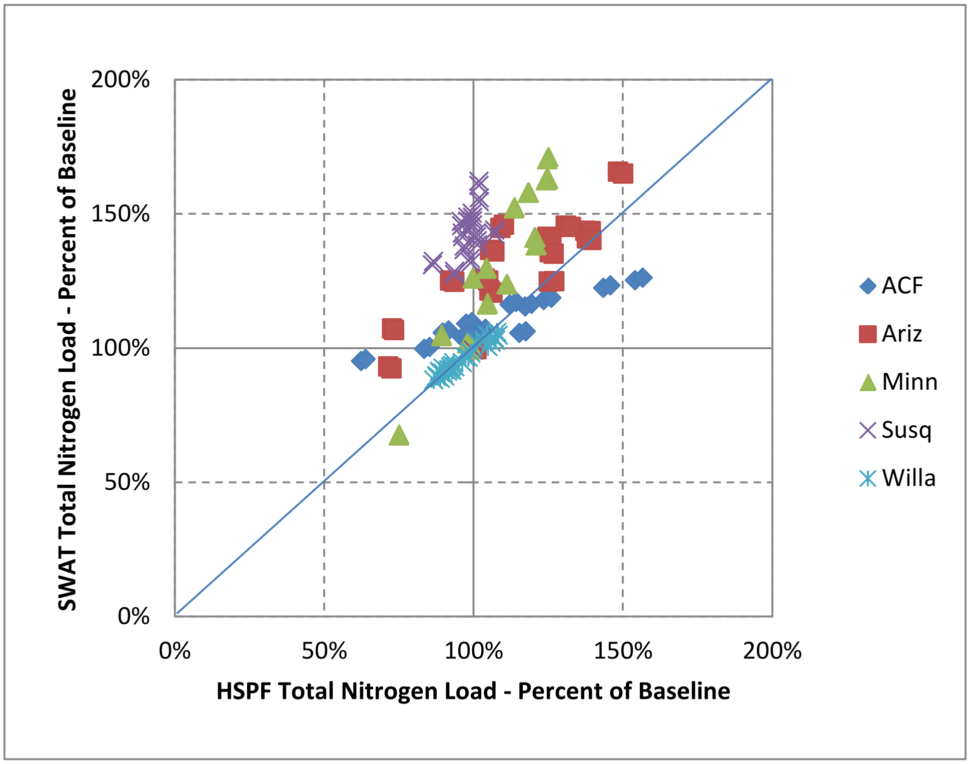

Figure 6-10. SWAT and HSPF simulated changes in total nitrogen load in pilot watersheds (expressed relative to current conditions).

IPCC estimates of future atmospheric CO_2 concentrations under the assumptions of the A2 emissions scenario (the basis of climate and land-use change scenarios in this study) call for an increase from 369 ppmv CO_2 in 2000 to about 532 ppmv (using the ISAM model reference run) or 522 ppmv (using the Bern-CC model reference run) in 2050 (Appendix II in IPCC, 2001). Plants require CO_2 from the atmosphere for photosynthesis. An important effect of increased atmospheric CO_2 is a reduction in the time plant leaf stomata must be open to obtain the CO_2 needed for growth, resulting in reduced water loss as transpiration (Leakey et al., 2009; Cao et al., 2010; Ainsworth and Rogers, 2007). This effect can potentially counterbalance projected increases in transpiration associated with increased air temperatures. It may also reduce water stress on plants, resulting in greater biomass and litter production, which in turn will influence pollutant loads.

In the past it has been argued that these effects, long documented at the leaf and organism level, might not translate to true ecosystem effects. However, recent research, particularly results from the Free-Air CO_2 Enrichment (FACE) experiments (Leakey et al., 2009) suggests that significant reductions in evapotranspiration do occur at the ecosystem level with increased atmospheric CO_2 concentrations. Although there are differences in responses among plant species, with lesser effects with C_4 photosynthesis, the magnitude of the response to CO_2 levels projected by the mid-21st century appears to be on the order of a 10% reduction in evapotranspiration response (e.g., Bernacchi et al., 2007). Further, a recent study by Cao et al. (2010) suggests that up to

25% of the temperature increase projected for North America could result directly from decreased plant evapotranspiration under increased CO_2 concentrations.

SWAT includes a plant growth module that accounts for the effects of changes in atmospheric CO_2 concentration on stomatal conductance using the equation developed by Easterling et al. (1992). Using this approach, increased CO_2 leads to decreased leaf conductance, which in turn results in an increase in the canopy resistance term in the PET calculation. The model also simulates the change in radiation use efficiency of plants as a function of CO_2 concentration using the method developed by Stockle et al. (1992). Figure 6-11 shows the differences between projected mid-21st century streamflow and water quality endpoints in the five pilot sites simulated using SWAT with and without representation of the effects of increased atmospheric CO_2 concentrations (SWAT projections for the six NARCCAP climate scenarios incorporating the ICLUS future land use for each watershed). These simulations suggest increases in mean annual streamflow from 3 to 38% due to increased CO_2, with a median of 11%, in the same range as the results summarized by Leakey et al. (2009). Simulations also suggest increased atmospheric CO_2 results in increased pollutant loads. Total suspended solids loads show increases from 3 to 57%, with a median of 15%. Total phosphorus loads increase from 0 to 29%, with a median of 6%. Total nitrogen loads increase from zero to 34%, with a median of 6%. The large increases in total suspended solids loads indicate that the effects of higher runoff under increased atmospheric CO_2 (largely due to greater soil moisture prior to rainfall events) may outweigh benefits associated with greater ground cover―a finding that could have important land management implications in the midwestern watersheds, including many of the Great Lakes drainages. For the nutrients, the simulated load increases are less than for streamflow and total suspended solids increases. This presumably is due to the fact that increased atmospheric CO_2 concentrations allow greater plant growth per unit of water, resulting in greater uptake and sequestration of nutrients, and thus smaller increases in nutrient loads relative to streamflow and total suspended solids.

The response to increased atmospheric CO_2 concentration varies greatly by study area, with the greatest effect simulated by SWAT for the Minnesota River basin and the smallest effect for the Willamette basin. The large effect in the Minnesota River basin apparently occurs because the land in this basin is predominantly in high-biomass corn-soybean rotation agricultural cropland with precipitation and evapotranspiration in approximate balance. In contrast, the Willamette basin is dominated by evergreen forest and has a moisture surplus for much of the year.

Ficklin et al. (2009), working with the SWAT model in the San Joaquin watershed in California, also showed that increased atmospheric CO_2 could cause a significant relative decrease in simulated evapotranspiration and a corresponding increase in water yield relative to simulations that did not account for increased CO_2. However, Luo et al. (2013) recently suggested that the approach used in SWAT to estimate the effects of CO_2 on evapotranspiration is appropriate only for arable land and may overestimate CO_2-associated reductions from forest, pasture, and range land. This remains an important topic for further investigation.

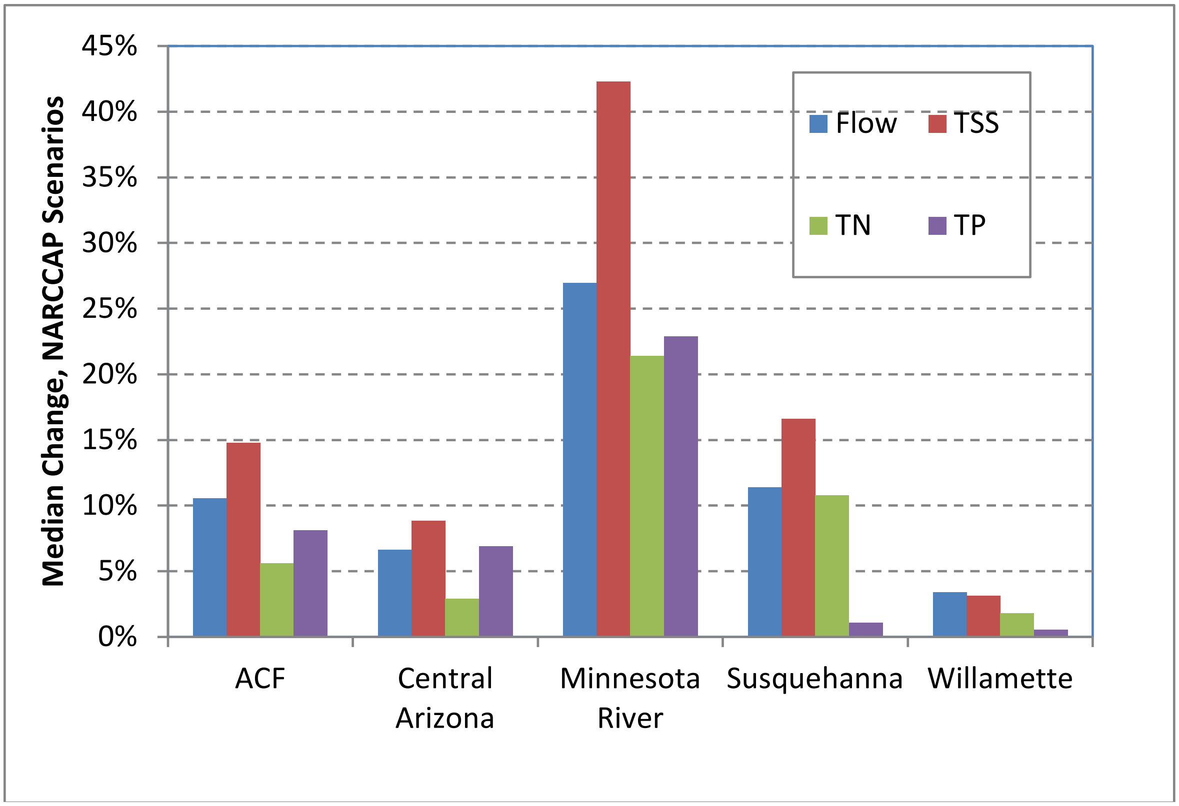

Figure 6-11. Differences between SWAT projections of mid-21st century streamflow and water quality (median across six NARCCAP scenarios) with and without representation of increased atmospheric CO_2.

Note: Figure shows model simulation with increased CO_2 minus projection with CO_2 assumed constant at current levels.

Several important feedback loops other than the CO_2 effect on stomatal conductance are also included in the SWAT plant growth model. First, planting, tillage, fertilization, and harvest timing for crops (and start and end of growth for native plants) is represented by heat unit scheduling relative to existing climate normals, allowing automatic adjustment in timing under a changed temperature regime. Evapotranspiration is also simulated with the full Penman-Monteith method, allowing dynamic simulation of leaf area development and crop height, both of which impact ET. Finally, organic matter residue accumulation and degradation on the land surface are dynamically simulated as a function of plant growth, and the effects of altered cover on land surface erosion are represented.

All these factors are of potential importance in examining response to climate change. In contrast to SWAT, HSPF does not automatically compute these adjustments. Instead, the user would need to estimate changes in monthly parameters such as the lower zone evapotranspiration coefficient (LZETP) and erosion cover externally and bring them into the model. While not well understood, use of calibrated parameters in HSPF without these modifications could introduce error to simulations under climatic conditions different from those during the calibration period.

6.2. SENSITIVITY TO DIFFERENT METHODS OF DOWNSCALING GCM OUTPUT

A variety of methods for downscaling large-scale GCM output to local scale projections are available. Both the selection of an underlying GCM and the choice of downscaling method have a significant influence on the streamflow and water quality simulations. Indeed, in some basins (e.g., Minnesota River, ACF) the difference among watershed model simulations as driven by the six NARCCAP dynamically downscaled scenarios appears to be noticeably greater than the range of model simulations driven by BCSD statistically downscaled or nondownscaled GCM scenarios. The results of the larger ensemble leads to the observation that incorporating additional information, either from dynamic RCMs or via statistical methods, can increase the range of variability of simulated changes.

6.2.1. Climate Model Energy Inputs and PET Estimates

PET is calculated using the Penman-Monteith PET energy balance approach. The BCSD and nondownscaled GCM scenarios do not provide all the required meteorological time series (see Table 5-2 in Section 5.2.1.). As a result, PET for these scenarios was estimated using current climate statistics for solar radiation, dew point, and wind time series. Comparisons presented in Appendix Z suggest that PET estimates for the and GCM scenarios (scenarios 7−14) that do not include solar radiation, dew point, and wind time series that are consistent with the simulated precipitation and temperature are noticeably higher than estimates of PET derived from the dynamically downscaled models that do provide these time series.

A comparison of the effects of data availability on PET calculations can be done through comparison of scenarios that are based on the identical underlying GCM runs for CGCM3 and GFDL that were each dynamically downscaled with two different RCMs (as discussed in Section 5.2.2.). Annual average PET estimates from these pairs are generally close to one another, but may differ by up to 4.5% from their mean (see Table 5-4). For the CGCM3 model, PET generated from the nondownscaled GCM is similar to that from the dynamically downscaled scenarios, but PET calculated from the statistically downscaled scenario is from 2 to 19% higher. This appears to be due to the fact that dew point temperature, which has an important impact on PET, is provided with the CGCM3 GCM but is not available from the BCSD scenarios (see Table 5-2 above). The difference is smallest for the Salt/Verde/San Pedro River basins in Arizona, where dew point temperature is very low and not expected to change much under future climates. In contrast, the GFDL model does not provide dew point temperature from the nondownscaled GCM. For that model, both the nondownscaled and statistically downscaled climate change scenarios produce higher PET estimates than the NARCCAP dynamically downscaled scenarios. As with CGCM3, the smallest effect is seen in the Salt/Verde/San Pedro River basins in Arizona, and the largest effect in the Susquehanna basin, where a greater change in dew point temperature and relative humidity is projected. The observed sensitivity of PET estimates to climate variables other than air temperature and precipitation suggests that simulation of future climates that does not account for changes in the full suite of variables that influence PET could thus introduce significant biases into the simulated water balance. Further investigation of this phenomenon was pursued through use of “degraded” NARCCAP climate scenarios, as described below.

6.2.2. "Degraded" NARCCAP Climate Scenarios

To provide a consistent basis for comparison, all scenarios were created with a common minimum set of variables. Specifically, NARCCAP provided data on changes in precipitation intensity (bin data), solar radiation, wind, and humidity that were not available in the GCM and BCSD based scenarios. The following steps were taken to develop a consistent set of climate scenario input series that differ only in the underlying climate model and downscaling technique:

- Representation of intensification in each of the NARCCAP dynamically downscaled scenarios was based on Approach 2 in Section 5.2.2., which assumes that all increases in precipitation occur in the top 30% of events, rather than using the direct analysis of intensity changes provided by NARCCAP.
- Complete information on changes in weather generator statistics for dew point temperature, solar radiation, and wind speed was removed for the NARCCAP dynamically downscaled scenarios, consistent with the information available for the BCSD scenarios. Incomplete information on these variables provided by the nondownscaled GCMs was also removed. (For the nondownscaled GCMs this affects weather scenarios 7, 9, and 10—see Table 5-2 above).
- Penman-Monteith PET was recalculated with the revised set of climate variables.
- Simulations use current land use to remove land-use change effects.

Note that these simplified or "degraded" NARCCAP scenarios are used only for the comparisons presented in this section. Results presented in subsequent sections of this report use the scenarios that contain all available meteorological information.

Comparison of the PET series generated with full climatological data to the degraded series in which only precipitation and temperature are updated illustrates the effect of including these additional variables (see Table 6-4). Further, the effect of individual meteorological time series is discernible because the original set lacked solar radiation for Scenario 5, dewpoint temperature for Scenario 9, and wind speed for Scenario 10 (see Table 5-2). Dewpoint temperature (which tends to increase in future, warmer climates) has the biggest impact. Including a climate model-simulated dewpoint that is consistent with the scenario temperature and precipitation regime results in a reduction in estimated annual PET of about 11% across all the meteorological stations used for the five pilot watersheds. The effect appears to be greater at higher latitudes. The reduction in PET from including simulated dewpoint is around 10−20% for the Minnesota, New York, Oregon, and Pennsylvania stations, but only 3−10% for the Alabama, Arizona, Florida, and Georgia stations. In contrast, for Scenario 9 (for which dewpoint temperature was not available), the original PET series were on average 1.9% higher than the degraded series. Omission of solar radiation or wind speed results from the climate scenario appears to have at most a minor impact on the estimated PET.

In retrospect, these results suggest that a better approach to simulation of PET in cases where the climate models do not provide dewpoint would be to assume that relative humidity remains constant and recalculate a new dewpoint based on the relative humidity and climate-modified air temperature, thus providing a more physically realistic estimate of vapor pressure deficit.

Table 6-4. Effects of omitting simulated auxiliary meteorological time series on Penman-Monteith reference crop PET estimates for "degraded" climate scenarios

State	Climate Scenario (GCM/RCM)								
	1 CGCM3/ CRCM	**2 HadCM3/ HRM3**	**3 GFDL/ RCM3**	**4 GFDL/ GFDL hi res**	**5 CGCM3/ RCM3**	**6 CCSM/ WRFP**	**7 CGCM3 (not down-scaled)**	**9 GFDL (not down-scaled)**	**10 CCSM (not down-scaled)**
AL	−4.87%	−4.44%	−5.21%	−10.90%	−5.76%	−4.47%	−4.89%	2.66%	−7.11%
AZ	−2.38%	−3.01%	−4.12%	−3.59%	−2.97%	−3.08%	−0.99%	2.69%	−3.02%
FL	−7.14%	−8.48%	−7.45%	−16.69%	−9.04%	−9.02%	−7.35%	2.92%	−10.91%
GA	−9.30%	−7.21%	−7.79%	−18.01%	−10.15%	−7.27%	−8.71%	1.79%	−14.04%
MN	−14.68%	−10.30%	−13.73%	−10.30%	−16.46%	−21.16%	−13.83%	1.68%	−16.46%
NY	−23.27%	−16.99%	−17.68%	−20.62%	−22.95%	−18.30%	−23.01%	−1.29%	−20.48%
OR	−15.82%	−14.28%	−7.75%	−12.90%	−13.67%	−13.29%	−12.73%	0.11%	−10.17%
PA	−17.62%	−12.54%	−14.77%	−18.93%	−18.59%	−13.40%	−17.96%	0.28%	−17.28%
All (%)	−12.53%	−9.93%	−9.97%	−12.62%	−12.86%	−12.48%	−11.37%	1.19%	−12.39%
All (in/yr)	−6.36	−5.27	−5.16	−6.48	−6.42	−6.31	−5.63	0.90	−6.55

Note: Auxiliary time series are solar radiation, dewpoint temperature, and wind. Scenario 5 did not have a solar radiation time series; Scenario 9 did not have a dewpoint temperature time series; Scenario 10 did not have a wind time series. Results are averages across entire study area. See Table 5-1 for details of the climate scenarios.

These results suggest that downscaling approaches that omit dewpoint temperature can introduce significant biases. Specifically, simulation without adjusting for future changes in dewpoint temperature is likely to overestimate PET, leading to an underestimation of soil moisture and streamflow.

6.2.3. Sensitivity of Flow and Water Quality to Approaches for Downscaling GCM Projections

The effect of downscaling approach on the variability of watershed model simulations can be investigated quantitatively by comparing the results from simulations based on degraded NARCCAP, GCM, and BCSD scenarios. Table 6-5 presents results obtained with current land use and the SWAT watershed model (with increased atmospheric CO_2) at the most downstream gage in each study area. Table 6-6 presents detailed results for multiple streamflow and water quality parameters in the Minnesota River study area. Differences among results with different downscaling methods are qualitatively similar for HSPF output (not shown).

Table 6-5. Summary of SWAT-simulated total streamflow in the five pilot study areas for scenarios representing different methods of downscaling

Study area	Downscaling method	Number of scenarios	Median (cms)	Maximum (cms)	Minimum (cms)	CV
Apalachicola-Chattahoochee-Flint (ACF)	NARCCAP	6	710.4	818.8	478.6	0.208
	BCSD	4	675.5	722.0	655.3	0.042
	GCM	4	655.0	750.7	581.3	0.105
Salt/Verde/San Pedro (Ariz)	NARCCAP	6	19.4	24.5	12.9	0.233
	BCSD	4	24.0	28.4	21.3	0.122
	GCM	4	26.0	27.0	19.9	0.131
Minnesota River (Minn)	NARCCAP	6	229.5	274.3	149.4	0.230
	BCSD	4	236.8	286.3	209.7	0.153
	GCM	4	238.3	277.0	124.4	0.301
Susquehanna (Susq)	NARCCAP	6	834.8	855.5	705.6	0.068
	BCSD	4	935.7	948.4	879.2	0.035
	GCM	4	868.7	1,017.1	807.0	0.106
Willamette (Willa)	NARCCAP	6	878.8	951.8	763.6	0.086
	BCSD	4	833.0	1,003.7	800.3	0.108
	GCM	4	843.3	970.7	810.6	0.082

Notes: Results shown are for most downstream station in each study area; coefficient of variation (CV) = standard deviation divided by the mean. Climate scenarios are degraded to a common basis of scenario precipitation and air temperature information only.

Results show considerable variability among climate models and downscaling techniques in different basins and for different streamflow and water quality endpoints. No consistent pattern attributable to downscaling method is evident for the case in which all climate model outputs are evaluated using a common basis of precipitation and air temperature only. As was discussed in Section 6.1.3., the additional information on other meteorological variables can have a profound effect on PET and watershed responses.

It is noteworthy that the dynamically downscaled results may differ significantly from the statistically downscaled results from the same GCM, and that the results may also be quite different when the same GCM is downscaled with a different RCM (e.g., refer to Table 5-1 and compare climate scenarios 1 and 5 for CGCM3, also 3 and 4 for the GFDL). As noted in Section 5.2., direct comparison between NARCCAP and BCSD downscaling of a single GCM can only be reliably undertaken for the GFDL and CGCM3 models, because slightly different GCM runs were used to produce NARCCAP and BCSD results for other GCMs.

Table 6-6. Summary of SWAT-simulated streamflow and water quality in the Minnesota River study area for scenarios representing different methods of downscaling

Endpoint	Downscaling method	Number of scenarios	Median	Maximum	Minimum	CV
Total Streamflow (cms)	NARCCAP	6	229.5	274.3	149.4	0.230
	BCSD	4	236.8	286.3	209.7	0.153
	GCM	4	238.3	277.0	124.4	0.301
100-Yr High Flow (cms)	NARCCAP	6	3,415.4	3,700.2	3,155.7	0.058
	BCSD	4	3,960.2	5,055.0	3,617.6	0.153
	GCM	4	3,565.7	4,432.3	2,508.7	0.227
7 Day Average Low Flow (cms)	NARCCAP	6	27.7	38.5	14.3	0.353
	BCSD	4	25.8	37.9	22.3	0.247
	GCM	4	28.2	37.0	12.9	0.395
Total Suspended Solids (MT/yr)	NARCCAP	6	1,926,166	2,520,444	896,806	0.385
	BCSD	4	2,002,421	2,428,565	1,376,608	0.265
	GCM	4	1,914,800	2,557,634	633,793	0.460
Total Phosphorus (MT/yr)	NARCCAP	6	36,304	42,119	25,843	0.191
	BCSD	4	40,579	44,936	32,451	0.150
	GCM	4	38,747	42,087	21,538	0.264
Total Nitrogen (MT/yr)	NARCCAP	6	2,700	3,283	2,007	0.194
	BCSD	4	3,073	3,453	2,356	0.183
	GCM	4	2,889	3,162	1,489	0.292

MT = metric ton

Notes: Results shown are for most downstream station in each study area; coefficient of variation (CV) = standard deviation divided by the mean. Climate scenarios are degraded to a common basis of scenario precipitation and air temperature information only.

Both the GFDL and CGCM3 A2 scenario runs for 2041−2070 were downscaled with two different NARCCAP RCMs—with one RCM (RCM3) in common between the two. A comparison in terms of the ratio of simulated future mean annual streamflow to simulated current mean annual streamflow, using SWAT, is made in Figure 6-12 for the GFDL and in Figure 6-13 for the CGCM3 model. For both GCMs, the NARCCAP downscaling, BCSD downscaling, and nondownscaled GCM output produce relatively consistent results for the Willamette and Susquehanna basins, but diverge for the Minnesota River. For the Arizona basin, the two different downscaling approaches diverge for the GFDL but not the CGCM3 GCM. Elevated coefficients of variation (CVs) on mean annual streamflow in both the Minnesota River and Arizona basins appear to be largely due to the difference in downscaling results obtained with the GFDL high-resolution regional model, which suggests lower flow than other dynamically downscaled interpretations of the GFDL GCM.

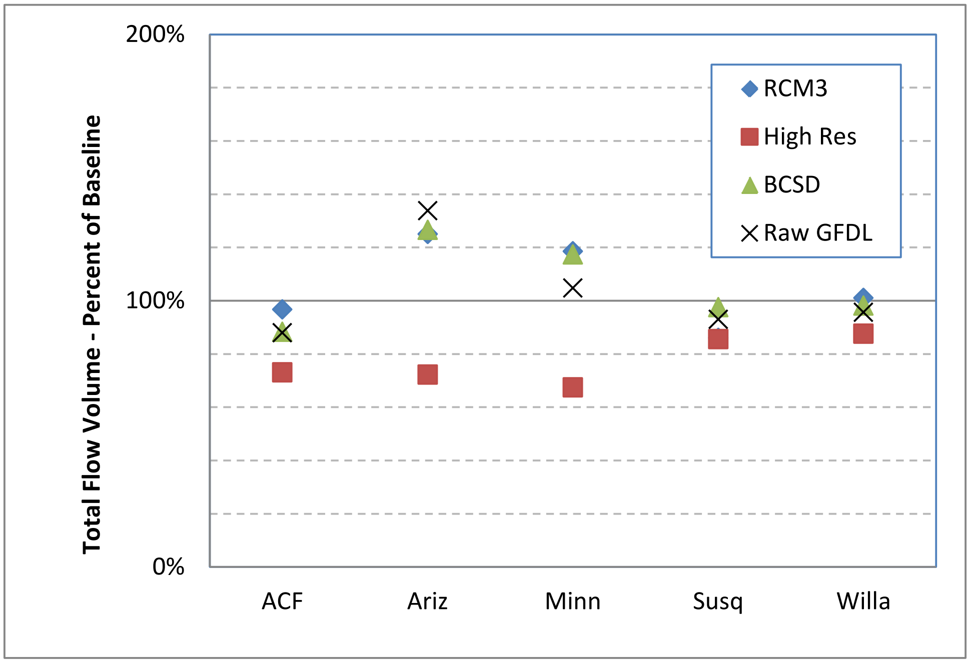

Figure 6-12. Consistency in SWAT model projections of mean annual streamflow at downstream stations with downscaled (NARCCAP, BCSD) and nondownscaled GCM projections of the GFDL GCM.

Note: The climate change scenarios used in this analysis are simplified to include changes only in air temperature and precipitation (variables common to the NARCCAP, BCSD, and GCM data sets) to provide a common basis for comparison.

Figures 6-12 and 6-13 demonstrate that a single GCM may yield rather different results depending on the RCM used for dynamical downscaling. In the current state of the science it does not appear that the use of dynamical downscaling reduces uncertainty; however, use of multiple downscaling approaches helps to inform the potential range of climate futures.

To date, relatively few comparisons of RCM model performance in the NARCCAP data sets have been undertaken. An exception is the study of Wang et al. (2009) for the Intermountain Region of the Western United States. Significant orographic effects in this area lead to a complex combination of precipitation annual and semiannual cycles that form four major climate regimes in this area. Wang et al. compared results from six RCMs over this region to the North American Regional Reanalysis (NARR) precipitation study (Mesinger et al., 2006) and found that each model produces its own systematic bias in the central Intermountain Region where the four different climate regimes meet. All six of the RCMs appeared to produce simulated annual cycles that are too strong and winter precipitation that is too high under current conditions. The BCSD statistical approach can correct this for current conditions; however, the statistical approach would not account for any future large-scale changes in the interaction of the major climate regimes.

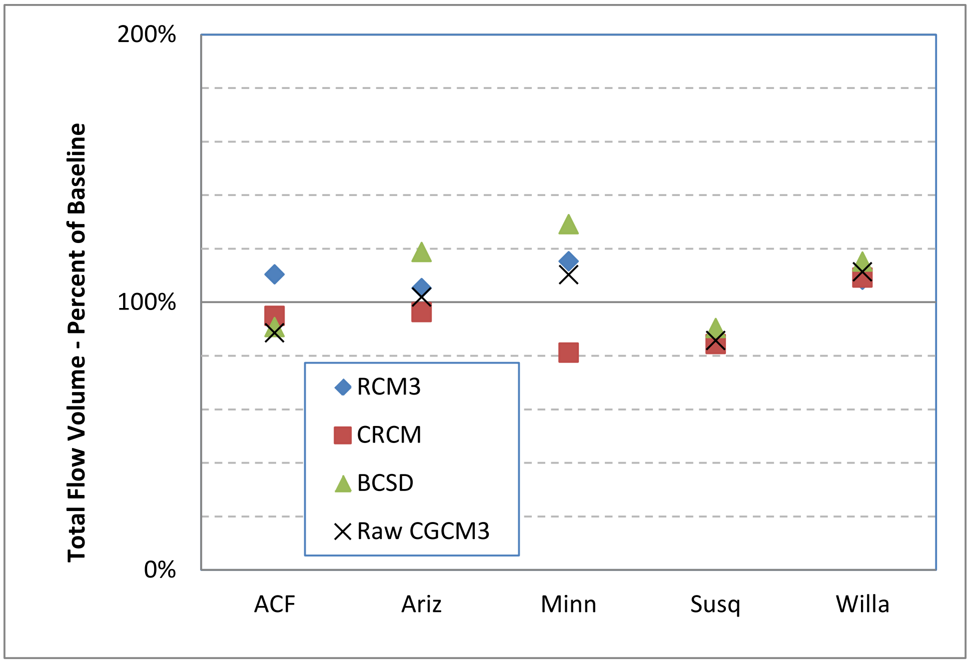

Figure 6-13. Consistency in SWAT model projections of mean annual streamflow at downstream stations with downscaled (NARCCAP, BCSD) and nondownscaled GCM projections of the CGCM3 GCM.

Note: The climate change scenarios used in this analysis are simplified to include changes only in air temperature and precipitation (variables common to the NARCCAP, BCSD, and GCM data sets) to provide a common basis for comparison.

Wang et al. (2009) also demonstrate that the different RCMs are largely consistent in the Cascade Range (OR, WA), where the dominant upper level flow first encounters land, which fits with the reduced level of variability between downscaling methods noted for the Willamette study area. The differences among RCMs reported by Wang et al., and the difference from NARR, are greatest on the windward side of the Rocky Mountains in Colorado and remain large into Arizona. Interestingly, the apparent wet bias of the CRCM and dry bias of most other RCMs relative to NARR in Arizona reported by Wang et al. does not appear to carry through into the future scenarios reported here, suggesting that the RCMs may be providing different simulated solutions to the future interaction of large-scale climate regimes in this area.

In addition to uncertainties in representing climate forcing at the watershed level, as discussed in this section, previous sections have shown that the results are sensitive to the selection of a watershed model, and to modeler skill in calibrating the model. Furthermore, the results are undoubtedly also sensitive to feedback loops that are not incorporated into the models. Results produced in this study thus likely do not span the full range of potential future impacts (even conditional on the A2 storyline) for the reasons given above, among others. Nonetheless, the range of uncertainty is considerable, and generally covers the zero point, as is summarized at selected downstream analysis points shown in Table 6-7.

Table 6-7. Range of SWAT-projected changes in annual streamflow and pollutant loads for combined mid-21st century NARCCAP climate change and ICLUS urban and residential development scenarios

Downstream location	Change in flow (%)	Change in total solids load (%)	Change in total nitrogen load (%)	Change in total phosphorus load (%)
ACF: Apalachicola River Outlet	−26.9 to +23.6	−47.2 to +6.1	−4.6 to +25.6	−6.6 to +73.1
Ariz: Verde River ab Tangle Creek	−29.4 to +26.7	−52.6 to +118.4	−7.2 to +46.6	−32.8 to +63.4
Susq: Susquehanna River Outlet	−10.0 to +11.0	−15.6 to +17.8	+32.1 to +61.9	+6.3 to +28.1
Minn: Minnesota River Outlet	−14.3 to +62.1	−22.9 to +122.9	+4.9 to +71.0	−6.3 to +59.5
Willa: Willamette River Outlet	−8.4 to +15.9	−10.3 to +24.5	−10.9 to +3.3	−13.3 to +4.2

The ranges shown in Table 6-7 suggest that for 2041−2070 conditions it is not possible in most cases to even state the sign of change in watershed response with a high degree of assurance unless one is willing to assert that one of the RCMs is more reliable than another. Rather, the results tell us that the range of potential responses is large.

Based on the analysis presented here, however, the differences in simulation results in our study are largely a result of combined differences in the underlying GCM and the downscaling approach used, and more specifically, largely a result of heterogeneity in simulated precipitation amounts and patterns. For the 2041−2070 timeframe, these warming-induced increases in simulated PET are generally insufficient to overcome this range of variability in projected precipitation. This may not be the case, however, for more distant future simulation periods—given continually increasing temperature and PET, evapotranspiration increases are likely to ultimately exceed the range of variability in projected precipitation in many basins, resulting in more uniform decreases in runoff.

7. REGIONAL SENSITIVITY OF STREAMFLOW AND WATER QUALITY TO CLIMATE CHANGE AND LAND DEVELOPMENT: RESULTS IN ALL 20 WATERSHEDS

This section presents simulation results in all 20 study areas using SWAT. Model simulations evaluate the effects of mid-21st century climate change alone (see Section 7.1.), urban and residential development alone (see Section 7.2.), and the combined effects of climate change and urban development (see Section 7.4) on streamflow, TN, TP, and TSS. Scenarios also assume future increases in atmospheric CO_2. Results are presented for a single representative analysis point in each study area (see Table 7-1). For study areas composed of a single watershed, this is the outlet (pour point) of the entire study area. For study areas composed of multiple, adjacent watersheds draining to the coast, the analysis point reported here is at or near the outlet of the largest river within the study area. Results for additional locations within each study area are presented in Appendix X for the five pilot study areas and in Appendix Y for the other 15 study areas.

Table 7-1. Downstream stations within each study area where simulation results are presented

Study area	Location presenting results
Apalachicola-Chattahoochee-Flint Basins (ACF)	Apalachicola R at outlet
Southern California Coastal (SoCal)	Los Angeles R at outlet
Cook Inlet Basin (Cook)	Kenai R at Soldotna
Georgia-Florida Coastal Plain (GaFla)	Suwanee R at outlet
Illinois River Basin (Illin)	Illinois R at Marseilles, IL
Lake Erie Drainages (LErie)	Maumee R at outlet
Lake Pontchartrain Drainage (LPont)	Amite R at outlet
Nebraska: Loup and Elkhorn River Basin (Neb)	Elkhorn R at outlet
Minnesota River Basin (Minn)	Minnesota R at outlet
Tar and Neuse River Basins (TarNeu)	Neuse R at outlet
New England Coastal Basins (NewEng)	Merrimack R at outlet
Powder and Tongue River Basin (PowTon)	Tongue R at outlet
Rio Grande Valley (RioGra)	Rio Grande R below Albuquerque
Sacramento River Basin (Sac)	Sacramento R at outlet
Arizona: Salt, Verde, and San Pedro (Ariz)	Salt River near Roosevelt
South Platte River Basin (SoPlat)	S. Platte R at outlet
Susquehanna River Basin (Susq)	Susquehanna R at outlet
Trinity River Basin (Trin)	Trinity R at outlet
Upper Colorado River Basin (UppCol)	Colorado R near State Line
Willamette River Basin (Willa)	Willamette R at outlet

7.1. SELECTION OF WATERSHED MODEL FOR USE IN ALL STUDY AREAS

Resource limitations for this study precluded the application of SWAT and HSPF in all 20 study areas. Analyses at Pilot sites were used to select a single model for application in all 20 study areas. Analyses in the Pilot sites show HSPF and SWAT are each capable of providing a good fit to streamflow and pollutant loads for existing conditions. The quality of fit depends in part on the strategy and skill of the individual modeler. In this study, the quality of fit was also influenced by the availability in certain areas of preexisting, calibrated models which were adapted for use as compared to locations where new models were developed and calibration subject to resource limitations.

For the purposes of this study, the SWAT model was considered to have a technical advantage because it can account for the influence of changes in atmospheric CO_2 concentration and other feedback responses of plant growth to climate change. HSPF does not automatically account for these effects. While it uncertain how well SWAT is able to represent the complex processes affecting plant growth, nutrient dynamics, and water budgets under changing climate (see Luo et al., 2013), it was considered important to include some representation of these processes to better understand potential watershed sensitivity to a wide range of conditions. In addition, there are also practical advantages to the choice of SWAT, as the model is somewhat easier to set up and calibrate than is HSPF.

Conversely, the HSPF model proved generally better able to replicate observations during calibration, as shown in Section 6.1.1., although the difference between HSPF and SWAT model performance was small for the selected response variables. HSPF is often able to provide a better fit to streamflow after calibration due to the use of hourly precipitation and a more sophisticated algorithm compared to SWAT's daily curve number approach—although this advantage is diminished by the need to use disaggregated daily total rainfall to drive the models in many areas. Increased accuracy in hydrology—especially the accurate partitioning between surface and subsurface runoff—should also provide increased accuracy in the simulation of sediment yield and the transport of sediment-associated nutrients. However, at the larger watershed scales studied here (HUC-8 and greater), such advantages will tend to diminish as observations reflect the integration of flows and loads from multiple subwatersheds driven by multiple weather stations. Further, SWAT is generally considered to perform better under limited calibration and thus may have an advantage for extension to changed conditions of land use and climate (Gassman et al., 2007).

The file structure of the HSPF model is also considerably more efficient for implementing and running multiple scenarios. SWAT's use of the curve number approach to hydrology and a daily time step can also cause difficulties in representing the full hydrograph and introduces uncertainties into the simulation of erosion and pollutant loading as a function of surface flow (Garen and Moore, 2005). This is a concern in particular for the simulation of urban hydrology at small spatial scales; however, these concerns are of lesser importance at the larger spatial scales that are the focus of this study.

Given that both models were capable of performing adequately, the SWAT model was selected for use in the 15 nonpilot watersheds due to its integrated plant growth model and practical advantages of ease of calibration.

It should be recognized that there are other feedback cycles that are not incorporated in either model, such as the potential for any increased rate of catastrophic forest fires (Westerling et al., 2006), changes to vegetative communities as a result of pests and disease (Berg et al., 2006), and human adaptations such as shifts to different crops and agricultural management strategies (Polsky and Easterling, 2001).

7.2. SENSITIVITY TO CLIMATE CHANGE SCENARIOS

This section presents the results of SWAT simulations in all 20 study areas for climate change scenarios alone (that is, with land use held constant at existing conditions). In general, the different climate scenarios provide a consistent picture of temperature increases by mid-century (on the order of 2 to 3°C or 3 to 6°F), although there do appear to be systematic differences between the scenarios (for example, the NARCCAP scenario using the GFDL model downscaled with RCM3 typically is the coolest scenario for the watersheds studied here). In contrast, changes in precipitation between the historical and future periods differ widely across climate change scenarios, with some producing increases and some decreases in total precipitation.

Projected mid-21st century precipitation, air temperature, PET, and simulated AET (from SWAT) for each of the six NARCCAP climate change scenarios in each study area are shown in Tables 7-2 through 7-5. For Cook Inlet (Alaska) results are shown only for the three NARCCAP scenarios that provide climate projections for this portion of Alaska. The projected future climate annual average as a percent of baseline resulting from each of the six NARCCAP scenarios is shown for precipitation, PET, and AET; absolute change is shown for the annual average temperature. It should be noted that while the projected future average annual temperature increases in all cases, PET does not always increase. This is particularly noticeable in some of the southwestern study areas (e.g., Rio Grande Valley) where at least some future climate scenarios project increases in humidity and cloudiness that offset the temperature impact on PET. While shown here for comparison to PET, AET is a model input, not a model output. AET is driven by PET, but can also be limited by lack of soil moisture and is affected by changes in the seasonal timing of both precipitation and plant growth.

Table 7-2. Average annual precipitation (in/yr and percent of baseline) for current conditions and mid-21st century climate scenarios

Study area	Current conditions	CRCM_ cgcm3 (%)	HRM3_ hadcm3 (%)	RCM3_ gfdl (%)	GFDL_ slice (%)	RCM3_ cgcm3 (%)	WRFP_ ccsm (%)	Median ratio (%)
ACF—Apalachicola-Chattahoochee-Flint Basins	52.14	105.1	114.3	106.2	97.2	111.2	90.4	105.6
Ariz—Arizona: Salt, Verde, and San Pedro	19.38	87.4	94.3	110.4	85.9	98.5	87.9	91.1
Cook—Cook Inlet Basin	24.22	ND	118.3	ND	113.9	ND	122.6	118.3
GaFla—Georgia-Florida Coastal Plain	52.98	101.3	117.3	106.5	95.3	112.0	85.1	103.9
Illin—Illinois River Basin	37.63	101.5	114.2	103.9	104.1	105.3	93.3	104.0
LErie—Lake Erie Drainages	36.88	102.4	114.2	104.9	109.0	104.0	91.7	104.5
LPont—Lake Pontchartrain Drainage	64.76	96.0	109.2	106.4	92.5	100.9	87.8	98.5
Minn—Minnesota River Basin	27.61	102.3	106.7	110.3	97.8	110.7	112.1	108.5
Neb—Nebraska: Loup and Elkhorn River Basins	24.43	99.5	103.4	103.4	86.2	106.3	104.8	103.4
NewEng—New England Coastal Basins	46.42	106.1	113.2	107.7	107.4	104.7	98.1	106.7
PowTon—Powder and Tongue River Basins	13.85	99.1	100.2	104.8	86.5	105.6	120.0	102.5
RioGra—Rio Grande Valley	12.20	89.1	91.1	106.5	90.6	88.3	99.4	90.8
Sac—Sacramento River Basin	35.81	102.3	88.6	95.8	99.6	99.1	96.3	97.7
SoCal—Southern California Coastal Basins	19.62	96.2	117.1	97.0	95.5	99.4	87.6	96.6
SoPlat—South Platte River Basin	15.93	95.4	92.2	97.5	87.1	98.9	101.2	96.5
Susq—Susquehanna River Basin	39.73	106.6	109.2	103.6	105.4	105.7	97.9	105.6
TarNeu—Tar and Neuse River Basins	48.90	99.5	122.3	112.6	103.2	108.0	92.4	105.6
Trin—Trinity River Basin	42.83	94.8	110.4	98.6	83.4	101.8	105.9	100.2
UppCol—Upper Colorado River Basin	15.88	90.3	97.3	108.3	95.7	94.8	95.2	95.4
Willa—Willamette River Basin	55.43	106.5	101.1	97.6	88.4	105.1	94.5	99.4

Table 7-3. Average annual temperature (°F and change from baseline) for current conditions and mid-21st century climate scenarios

Study area	Current conditions	CRCM_ cgcm3	HRM3_ hadcm3	RCM3_ gfdl	GFDL_ slice	RCM3_ cgcm3	WRFP_ ccsm	Median change
ACF—Apalachicola-Chattahoochee-Flint Basins	64.33	+3.81	+4.16	+3.62	+4.49	+3.45	+4.35	+3.98
Ariz—Arizona: Salt, Verde, and San Pedro	56.41	+4.93	+5.19	+4.35	+4.96	+4.75	+4.62	+4.84
Cook—Cook Inlet Basin	33.13	ND	+5.20	ND	+3.99	ND	+5.30	+5.20
GaFla—Georgia-Florida Coastal Plain	68.29	+3.56	+3.99	+3.45	+4.36	+3.32	+3.68	+3.62
Illin—Illinois River Basin	49.57	+5.36	+4.66	+4.38	+4.84	+4.75	+5.36	+4.80
LErie—Lake Erie Drainages	49.13	+5.19	+4.65	+4.29	+4.75	+4.67	+5.11	+4.71
LPont—Lake Pontchartrain Drainage	66.48	+3.77	+4.53	+3.61	+4.13	+3.41	+3.79	+3.78
Minn—Minnesota River Basin	44.18	+5.61	+5.29	+4.01	+5.02	+4.60	+4.90	+4.96
Neb—Nebraska: Loup and Elkhorn River Basins	47.94	+5.20	+5.10	+3.88	+5.09	+4.53	+4.65	+4.87
NewEng—New England Coastal Basins	46.32	+4.97	+4.81	+4.07	+4.12	+4.67	+4.50	+4.58
PowTon—Powder and Tongue River Basins	44.84	+4.77	+4.97	+3.81	+4.71	+4.50	+4.27	+4.61
RioGra—Rio Grande Valley	44.72	+5.13	+5.37	+4.20	+5.84	+5.02	+4.74	+5.08
Sac—Sacramento River Basin	58.23	+4.16	+4.76	+3.75	+3.47	+3.94	+4.06	+4.00
SoCal—Southern California Coastal Basins	61.38	+3.58	+3.97	+3.72	+3.27	+3.98	+3.57	+3.65
SoPlat—South Platte River Basin	45.06	+4.98	+5.20	+4.14	+5.51	+4.93	+4.77	+4.96
Susq—Susquehanna River Basin	48.18	+4.98	+4.98	+4.16	+4.72	+4.59	+4.60	+4.66
TarNeu—Tar and Neuse River Basins	59.93	+4.28	+4.51	+3.83	+4.18	+3.70	+4.14	+4.16
Trin—Trinity River Basin	64.91	+4.35	+4.66	+3.97	+4.45	+3.79	+4.38	+4.36
UppCol—Upper Colorado River Basin	40.80	+5.20	+5.14	+4.13	+5.53	+4.90	+5.04	+5.09
Willa—Willamette River Basin	51.48	+3.79	+4.37	+2.80	+3.03	+3.59	+3.57	+3.58

Table 7-4. Average annual PET (in/yr and percent of baseline) for current conditions and mid-21st century climate scenarios

Study area	Current conditions	CRCM_ cgcm3 (%)	HRM3_ hadcm3 (%)	RCM3_ gfdl (%)	GFDL_ slice (%)	RCM3_ cgcm3 (%)	WRFP_ ccsm (%)	Median ratio (%)
ACF—Apalachicola-Chattahoochee-Flint Basins	62.04	101.2	103.8	101.6	97.5	98.3	105.2	101.4
Ariz—Arizona: Salt, Verde, and San Pedro	81.27	103.6	103.8	100.3	103.0	102.6	106.4	103.3
Cook—Cook Inlet Basin	16.56	ND	106.2	ND	99.7	ND	104.1	104.1
GaFla—Georgia-Florida Coastal Plain	65.82	99.9	101.1	99.6	100.3	98.6	100.6	100.1
Illin—Illinois River Basin	42.91	112.3	110.5	109.3	111.2	110.0	111.2	110.9
LErie—Lake Erie Drainages	45.27	102.0	100.7	99.6	101.1	100.2	101.3	100.9
LPont—Lake Pontchartrain Drainage	59.19	101.4	106.9	103.0	103.9	99.3	101.2	102.2
Minn—Minnesota River Basin	49.36	106.3	110.4	98.6	110.5	99.7	94.2	103.0
Neb—Nebraska: Loup and Elkhorn River Basins	61.94	100.4	100.5	97.0	101.4	98.1	97.9	99.2
NewEng—New England Coastal Basins	43.22	103.3	105.9	100.3	100.6	100.6	101.3	100.9
PowTon—Powder and Tongue River Basins	55.39	101.3	102.7	99.0	102.3	100.3	99.0	100.8
RioGra—Rio Grande Valley	54.48	94.4	100.1	90.4	99.9	95.9	92.6	95.1
Sac—Sacramento River Basin	66.77	99.2	103.0	102.5	98.8	98.8	101.6	100.4
SoCal—Southern California Coastal Basins	64.41	99.2	100.2	99.9	99.0	100.0	99.2	99.6
SoPlat—South Platte River Basin	53.25	102.0	103.4	100.3	104.1	101.9	101.4	102.0
Susq—Susquehanna River Basin	43.81	102.9	107.6	101.2	101.4	99.5	104.9	102.1
TarNeu—Tar and Neuse River Basins	56.38	100.5	100.9	99.2	100.1	99.0	100.1	100.1
Trin—Trinity River Basin	77.27	99.5	100.1	99.0	99.8	98.1	98.7	99.3
UppCol—Upper Colorado River Basin	38.14	106.8	107.7	103.9	108.8	105.8	106.2	106.5
Willa—Willamette River Basin	43.64	97.4	102.0	100.5	98.9	98.6	98.7	98.8

Table 7-5. Average annual SWAT-simulated actual ET (in/yr and percent of baseline) for current conditions and mid-21st century climate scenarios

Study area	Current conditions	CRCM_ cgcm3 (%)	HRM3_ hadcm3 (%)	RCM3_ gfdl (%)	GFDL_ slice (%)	RCM3_ cgcm3 (%)	WRFP_ ccsm (%)	Median ratio (%)
ACF—Apalachicola-Chattahoochee-Flint Basins	32.22	106.1	110.6	106.6	106.2	104.9	102.8	106.2
Ariz—Arizona: Salt, Verde, and San Pedro	14.47	86.8	94.8	102.8	86.3	97.3	89.8	92.3
Cook—Cook Inlet Basin	7.95	ND	109.1	ND	103.6	ND	108.6	108.6
GaFla—Georgia-Florida Coastal Plain	30.86	98.5	101.1	99.7	98.9	99.1	95.0	99.0
Illin—Illinois River Basin	22.90	101.5	103.4	101.3	101.0	101.7	98.9	101.4
LErie—Lake Erie Drainages	22.75	94.4	95.3	96.0	97.2	93.3	90.8	94.9
LPont—Lake Pontchartrain Drainage	29.83	100.1	107.0	101.3	103.4	99.0	98.2	100.7
Minn—Minnesota River Basin	21.64	96.1	99.9	94.9	97.2	95.7	92.7	95.9
Neb—Nebraska: Loup and Elkhorn River Basins	18.00	97.8	101.8	100.6	94.3	98.9	97.9	98.4
NewEng—New England Coastal Basins	23.31	103.3	110.4	103.5	102.5	104.3	104.8	103.9
PowTon—Powder and Tongue River Basins	16.83	93.3	94.9	96.7	83.7	97.2	105.4	95.8
RioGra—Rio Grande Valley	10.32	84.2	87.9	98.0	88.7	85.2	94.7	88.3
Sac—Sacramento River Basin	15.26	99.2	97.6	94.7	97.0	95.9	94.9	96.5
SoCal—Southern California Coastal Basins	8.75	97.2	102.7	92.9	93.7	96.8	94.1	95.5
SoPlat—South Platte River Basin	13.06	96.1	94.0	96.0	90.4	97.1	98.5	96.0
Susq—Susquehanna River Basin	23.73	104.8	108.4	102.6	103.7	102.0	104.8	104.2
TarNeu—Tar and Neuse River Basins	29.48	97.2	99.9	98.0	97.8	97.4	95.6	97.6
Trin—Trinity River Basin	27.58	95.0	99.9	97.0	90.1	96.4	97.8	96.7
UppCol—Upper Colorado River Basin	13.13	91.7	98.0	101.2	98.6	94.0	95.5	96.7
Willa—Willamette River Basin	19.84	87.9	92.9	85.4	82.9	88.7	88.3	88.1

In addition to changes in precipitation amount, this study considers the impacts of changes in precipitation intensity, which may have significant effects on the partitioning between surface and subsurface flows and associated generation of pollutant loads. As described in Section 5.2., a change factor approach was used to modify historical meteorological time series to represent mid-21st century climate futures projected by a variety of downscaled (and nondownscaled) GCM projections. Potential intensification of precipitation is represented by reapportioning the net change in precipitation volume according to GCM forecasts of the distribution of event intensities above and below the 70th percentile of the distribution of current (1971−2000) rainfall events. Under current conditions, the fraction of rainfall volume occurring in events above the 70th percentile ranges from a low of 61% (Cook Inlet and Willamette) to a high of 93% (Southern California Coastal). Projected mid-21st century changes in precipitation intensity from the six NARCCAP scenarios, shown in Table 7-6, are mixed. Across all study areas there is an average increase in the fraction of total volume above the 70th percentile of the current distribution of 1.19 percentage points. However, for most study areas the six NARCCAP scenarios are not in full agreement as to whether intensification of precipitation (as defined relative to the 70th percentile event) will increase. An increase in the volume in high-intensity events is consistently projected across all six of the NARCCAP mid-21st century projections in only six of the 20 study areas (Susq, Minn, Cook, LErie, Illin, and NewEng). Two RCM/GCM combinations (HRM3_hadcm3 = Scenario 2) and (RCM3_cgcm3 = Scenario 5) project increases in intensity in all study areas. No study area is expected to have a decrease in precipitation volume in high intensity events across all NARCCAP scenarios, while six study areas (Cook, Illin, LErie, Minn, NewEng, and Susq) are projected to have an increase in high-intensity events across all six NARCCAP scenarios. By far the largest increases in high-intensity events are projected for the Cook Inlet watershed in Alaska, followed by the Upper Colorado basin.

The simulated watershed responses to mid-21st century climate change scenarios are shown in Tables 7-7 through 7-14. For endpoints other than days to streamflow centroid, the results are displayed as a percentage relative to the current baseline (generally, 1972−2003), allowing comparison across multiple basins with different magnitudes of streamflow and pollutant loads. For Cook Inlet (Alaska), the results are shown only for the three NARCCAP scenarios that provide climate projections for this portion of Alaska.

Table 7-7 summarizes results for total average annual streamflow volume, with results ranging from 62% to 240% of current average flows. Results for 7-day low streamflow and 100-year peak flows (estimated with log-Pearson III fit) are shown in Tables 7-8 and 7-9, respectively. The Kenai River has by far the greatest increase in 7-day low flows because warmer temperatures alter the snow/ice melt regime, while the largest increases in 100-year peak flows are for the Neuse River on the east coast.

Table 7-10 summarizes the estimated change in days to streamflow centroid relative to the start of the water year. Many stations show negative shifts, indicating earlier snowmelt resulting in an earlier center of streamflow mass. In contrast, several stations show positive shifts due to increased summer precipitation.

Results for the Richards-Baker flashiness index (see Table 7-11) show generally small percentage changes, with a few exceptions. Baker et al. (2004) suggest that changes on the order of 10% or more may be statistically significant. It is likely, however, that the focus on larger watersheds reduces the observed flashiness response.

Table 7-6. Changes in precipitation intensity for NARCCAP mid-21st century climate scenarios

	CRCM_cgcm3 (%)	HRM3_hadcm3 (%)	RCM3_gfdl (%)	GFDL_slice (%)	RCM3_cgcm3 (%)	WRFG_ccsm (%)
ACF	3.28	1.35	1.87	−0.68	2.43	−0.12
Ariz	−0.19	0.53	0.03	0.36	0.79	−0.43
Cook	ND	7.51	ND	3.71	ND	4.62
GaFla	2.74	1.60	2.33	−1.23	2.99	−0.89
Illin	1.95	1.56	1.09	0.87	1.25	0.20
LErie	2.25	2.01	1.64	1.81	1.12	0.27
LPont	2.49	0.71	2.50	−0.48	1.61	−0.87
Minn	1.92	1.22	1.94	0.09	1.38	0.43
Neb	1.08	1.56	1.61	−0.12	0.99	0.14
NewEng	2.55	1.51	1.74	0.36	1.21	0.15
PowTon	1.67	1.54	1.66	−1.09	1.59	0.97
RioGra	−0.04	0.96	1.64	0.37	0.91	0.52
Sac	1.87	0.47	0.00	−1.06	2.28	1.42
SoCal	0.24	1.83	−0.76	−0.28	0.29	−0.15
SoPlat	−0.20	0.85	1.13	−0.15	1.27	0.51
Susq	3.28	1.58	2.08	0.41	1.77	0.41
TarNeu	2.59	1.38	1.55	−0.42	1.21	−0.02
Trin	1.32	1.24	0.61	−0.66	0.14	0.46
UppCol	−0.10	1.95	2.36	0.79	2.06	0.71
Willa	2.50	2.59	0.46	−2.63	2.71	0.97

Note: Potential change in precipitation intensity is shown as the change total volume of precipitation event above the 70th percentile of the current (1971−2000) distribution of rainfall event volumes.

Simulated changes in pollutant loads (TN, TP, TSS) are summarized in Tables 7-12 through 7-14. The patterns are generally similar to changes in streamflow. Increases in pollutant loads are suggested for many watersheds, but there are also basins where loads decline, mostly due to reduced flows.

Table 7-7. Simulated total streamflow volume (climate scenarios only; percent relative to current conditions) for selected downstream stations

Station	Study area	CRCM_ cgcm3 (%)	HRM3_ hadcm3 (%)	RCM3_ gfdl (%)	GFDL_ slice (%)	RCM3_ cgcm3 (%)	WRFP_ ccsm (%)	Median (%)
Apalachicola R at outlet	ACF	107	122	108	88	124	73	107
Salt River near Roosevelt	Ariz	80	80	149	75	94	73	80
Kenai R at Soldotna	Cook	ND	154	ND	132	ND	167	154
Suwanee R at outlet	GaFla	114	153	128	92	156	75	121
Illinois R at Marseilles, IL	Illin	94	125	101	102	105	78	101
Maumee R at outlet	LErie	116	150	120	136	122	88	121
Amite R at outlet	LPont	96	110	115	84	106	77	101
Minnesota R at outlet	Minn	109	113	147	86	146	162	130
Elkhorn R at outlet	Neb	117	125	137	68	138	143	131
Merrimack R at outlet	NewEng	108	115	111	111	106	94	109
Tongue R at outlet	PowTon	101	85	140	70	130	240	115
Rio Grande R below Albuquerque	RioGra	72	69	112	66	69	84	71
Sacramento R at outlet	Sac	104	89	98	98	100	99	99
Los Angeles R at outlet	SoCal	92	138	102	103	106	84	103
S. Platte R at outlet	SoPlat	90	74	90	65	107	119	90
Susquehanna R at outlet	Susq	109	106	106	108	111	90	107
Neuse R at outlet	TarNeu	103	158	137	110	125	86	118
Trinity R at outlet	Trin	98	146	106	62	118	134	112
Colorado R near State Line	UppCol	86	95	116	89	92	91	91
Willamette R at outlet	Willa	116	106	105	92	114	98	105

Table 7-8. Simulated 7-day low flow (climate scenarios only; percent relative to current conditions) for selected downstream stations

Station	Study area	CRCM_ cgcm3 (%)	HRM3_ hadcm3 (%)	RCM3_ gfdl (%)	GFDL_ slice (%)	RCM3_ cgcm3 (%)	WRFP_ ccsm (%)	Median (%)
Apalachicola R at outlet	ACF	97	120	105	85	113	64	101
Salt River near Roosevelt	Ariz	58	77	130	87	79	90	83
Kenai R at Soldotna	Cook	ND	267	ND	280	ND	401	280
Suwanee R at outlet	GaFla	104	141	121	95	136	78	113
Illinois R at Marseilles, IL	Illin	85	123	97	91	100	70	94
Maumee R at outlet	LErie	104	184	126	132	128	58	127
Amite R at outlet	LPont	73	106	88	74	89	62	81
Minnesota R at outlet	Minn	115	136	201	81	182	228	159
Elkhorn R at outlet	Neb	119	133	151	48	148	154	140
Merrimack R at outlet	NewEng	110	140	130	118	124	120	122
Tongue R at outlet	PowTon	102	92	145	67	127	235	115
Rio Grande R below Albuquerque	RioGra	81	64	120	62	74	86	77
Sacramento R at outlet	Sac	101	91	95	96	99	93	95
Los Angeles R at outlet	SoCal	96	114	98	98	100	92	98
S. Platte R at outlet	SoPlat	93	87	97	74	102	113	95
Susquehanna R at outlet	Susq	91	120	104	89	107	86	98
Neuse R at outlet	TarNeu	94	170	135	113	125	70	119
Trinity R at outlet	Trin	26	167	64	23	70	85	67
Colorado R near State Line	UppCol	85	94	121	85	91	90	91
Willamette R at outlet	Willa	131	113	108	83	127	102	111

Table 7-9. Simulated 100-year peak flow (log-Pearson III; climate scenarios only; percent relative to current conditions) for selected downstream stations

Station	Study area	CRCM_ cgcm3 (%)	HRM3_ hadcm3 (%)	RCM3_ gfdl (%)	GFDL_ slice (%)	RCM3_ cgcm3 (%)	WRFP_ ccsm (%)	Median (%)
Apalachicola R at outlet	ACF	119	144	110	90	128	94	114
Salt River near Roosevelt	Ariz	119	101	104	68	120	66	102
Kenai R at Soldotna	Cook	ND	132	ND	125	ND	132	132
Suwanee R at outlet	GaFla	130	145	129	94	157	107	130
Illinois R at Marseilles, IL	Illin	120	153	107	99	128	97	114
Maumee R at outlet	LErie	96	106	87	93	93	92	93
Amite R at outlet	LPont	105	150	108	99	105	65	105
Minnesota R at outlet	Minn	84	83	96	88	90	96	89
Elkhorn R at outlet	Neb	126	117	109	92	139	103	113
Merrimack R at outlet	NewEng	114	130	111	138	89	80	112
Tongue R at outlet	PowTon	118	113	133	82	121	146	119
Rio Grande R below Albuquerque	RioGra	90	77	108	66	72	92	83
Sacramento R at outlet	Sac	105	98	125	117	102	131	111
Los Angeles R at outlet	SoCal	83	89	161	95	127	77	92
S. Platte R at outlet	SoPlat	132	127	98	126	151	150	129
Susquehanna R at outlet	Susq	107	130	106	128	172	100	118
Neuse R at outlet	TarNeu	71	292	161	111	224	63	136
Trinity R at outlet	Trin	97	106	107	60	86	106	102
Colorado R near State Line	UppCol	78	84	97	91	94	84	87
Willamette R at outlet	Willa	116	130	114	79	116	95	115

Table 7-10. Simulated changes in the number of days to streamflow centroid (climate scenarios only; relative to current conditions) for selected downstream stations

Station	Study area	CRCM_ cgcm3	HRM3_ hadcm3	RCM3_ gfdl	GFDL_ slice	RCM3_ cgcm3	WRFP_ ccsm	Median
Apalachicola R at outlet	ACF	−2	−2	1	8	−6	1	−1
Salt River near Roosevelt	Ariz	−18	41	28	17	−6	53	22
Kenai R at Soldotna	Cook	ND	−3	ND	−5	ND	−1	−3
Suwanee R at outlet	GaFla	−3	17	25	−8	−5	11	4
Illinois R at Marseilles, IL	Illin	−12	6	−3	−12	−2	−15	−7
Maumee R at outlet	LErie	−2	−4	1	0	10	−8	−1
Amite R at outlet	LPont	−14	13	−24	−7	−6	−11	−9
Minnesota R at outlet	Minn	−13	−19	−6	−15	−3	2	−10
Elkhorn R at outlet	Neb	−12	6	1	−15	−6	2	−2
Merrimack R at outlet	NewEng	−17	−14	−19	−13	−9	−18	−16
Tongue R at outlet	PowTon	−6	−3	1	−16	−4	7	−3
Rio Grande R below Albuquerque	RioGra	25	6	3	11	14	17	13
Sacramento R at outlet	Sac	−4	−7	−4	−1	−3	−8	−4
Los Angeles R at outlet	SoCal	5	48	−3	10	−3	1	3
S. Platte R at outlet	SoPlat	−12	−20	−14	−19	−3	−12	−13
Susquehanna R at outlet	Susq	−18	16	−6	−12	−6	0	−6
Neuse R at outlet	TarNeu	−14	23	30	−12	10	−5	2
Trinity R at outlet	Trin	16	21	30	3	6	37	18
Colorado R near State Line	UppCol	−11	−14	−7	−10	−8	−10	−10
Willamette R at outlet	Willa	3	−8	−1	3	1	8	2

Table 7-11. Simulated Richards-Baker flashiness index (climate scenarios only; percent relative to current conditions) for selected downstream stations

Station	Study area	CRCM_ cgcm3 (%)	HRM3_ hadcm3 (%)	RCM3_ gfdl (%)	GFDL_ slice (%)	RCM3_ cgcm3 (%)	WRFP_ ccsm (%)	Median (%)
Apalachicola R at outlet	ACF	106	125	109	94	125	90	108
Salt River near Roosevelt	Ariz	81	102	121	98	103	119	102
Kenai R at Soldotna	Cook	ND	94	ND	102	ND	96	96
Suwanee R at outlet	GaFla	93	62	76	117	59	187	84
Illinois R at Marseilles, IL	Illin	106	104	103	106	105	104	105
Maumee R at outlet	LErie	99	101	99	100	100	96	100
Amite R at outlet	LPont	105	105	106	104	104	102	104
Minnesota R at outlet	Minn	104	112	107	100	109	108	108
Elkhorn R at outlet	Neb	95	98	94	95	96	94	95
Merrimack R at outlet	NewEng	101	103	99	101	98	93	100
Tongue R at outlet	PowTon	102	108	104	100	103	109	104
Rio Grande R below Albuquerque	RioGra	109	117	95	119	103	106	108
Sacramento R at outlet	Sac	124	103	112	109	116	123	114
Los Angeles R at outlet	SoCal	103	119	100	105	105	99	104
S. Platte R at outlet	SoPlat	99	91	101	87	108	106	100
Susquehanna R at outlet	Susq	107	111	107	110	112	103	109
Neuse R at outlet	TarNeu	96	113	115	98	103	91	101
Trinity R at outlet	Trin	71	68	72	73	69	68	70
Colorado R near State Line	UppCol	101	107	111	105	104	101	105
Willamette R at outlet	Willa	101	105	100	97	101	102	101

Table 7-12. Simulated total suspended solids load (climate scenarios only; percent relative to current conditions) for selected downstream stations

Station	Study area	CRCM_ cgcm3 (%)	HRM3_ hadcm3 (%)	RCM3_ gfdl (%)	GFDL_ slice (%)	RCM3_ cgcm3 (%)	WRFP_ ccsm (%)	Median (%)
Apalachicola R at outlet	ACF	125	146	129	93	144	53	127
Salt River near Roosevelt	Ariz	89	79	184	66	106	74	84
Kenai R at Soldotna	Cook	ND	234	ND	196	ND	244	234
Suwanee R at outlet	GaFla	121	176	138	90	181	74	130
Illinois R at Marseilles, IL	Illin	116	142	115	128	120	90	118
Maumee R at outlet	LErie	123	169	126	153	129	86	128
Amite R at outlet	LPont	100	115	128	83	111	71	106
Minnesota R at outlet	Minn	107	119	187	77	197	225	153
Elkhorn R at outlet	Neb	122	131	147	60	162	162	139
Merrimack R at outlet	NewEng	118	128	117	122	111	85	118
Tongue R at outlet	PowTon	108	84	169	66	153	351	131
Rio Grande R below Albuquerque	RioGra	60	53	114	49	59	71	59
Sacramento R at outlet	Sac	139	94	122	118	99	108	113
Los Angeles R at outlet	SoCal	71	111	81	81	84	65	81
S. Platte R at outlet	SoPlat	91	87	94	80	100	104	93
Susquehanna R at outlet	Susq	117	108	108	115	118	84	112
Neuse R at outlet	TarNeu	106	199	162	115	143	82	129
Trinity R at outlet	Trin	63	124	62	27	83	113	73
Colorado R near State Line	UppCol	80	90	124	82	89	85	87
Willamette R at outlet	Willa	124	111	109	90	121	97	110

Table 7-13. Simulated total phosphorus load (climate scenarios only; percent relative to current conditions) for selected downstream stations

Station	Study area	CRCM_ cgcm3 (%)	HRM3_ hadcm3 (%)	RCM3_ gfdl (%)	GFDL_ slice (%)	RCM3_ cgcm3 (%)	WRFP_ ccsm (%)	Median (%)
Apalachicola R at outlet	ACF	138	152	134	118	148	106	136
Salt River near Roosevelt	Ariz	82	83	155	70	106	88	86
Kenai R at Soldotna	Cook	ND	89	ND	90	ND	113	90
Suwanee R at outlet	GaFla	115	171	135	89	173	76	125
Illinois R at Marseilles, IL	Illin	107	112	107	113	108	99	108
Maumee R at outlet	LErie	118	150	132	148	117	88	125
Amite R at outlet	LPont	113	131	135	94	115	83	114
Minnesota R at outlet	Minn	97	115	151	97	138	160	126
Elkhorn R at outlet	Neb	118	124	138	65	145	147	131
Merrimack R at outlet	NewEng	111	118	111	115	106	94	111
Tongue R at outlet	PowTon	107	86	163	67	148	324	127
Rio Grande R below Albuquerque	RioGra	54	43	127	51	41	67	53
Sacramento R at outlet	Sac	100	86	104	115	95	108	102
Los Angeles R at outlet	SoCal	53	88	71	60	62	54	61
S. Platte R at outlet	SoPlat	90	78	99	72	108	111	95
Susquehanna R at outlet	Susq	128	106	111	127	115	109	113
Neuse R at outlet	TarNeu	112	230	169	120	166	94	143
Trinity R at outlet	Trin	124	163	130	83	135	160	132
Colorado R near State Line	UppCol	79	88	119	81	84	83	84
Willamette R at outlet	Willa	100	98	96	94	100	96	97

Table 7-14. Simulated total nitrogen load (climate scenarios only; percent relative to current conditions) for selected downstream stations

Station	Study area	CRCM_ cgcm3 (%)	HRM3_ hadcm3 (%)	RCM3_ gfdl (%)	GFDL_ slice (%)	RCM3_ cgcm3 (%)	WRFP_ ccsm (%)	Median (%)
Apalachicola R at outlet	ACF	116	125	115	106	122	95	116
Salt River near Roosevelt	Ariz	90	91	142	86	105	84	90
Kenai R at Soldotna	Cook	ND	200	ND	175	ND	223	200
Suwanee R at outlet	GaFla	127	160	135	112	166	85	131
Illinois R at Marseilles, IL	Illin	103	118	106	110	108	93	107
Maumee R at outlet	LErie	128	158	162	191	125	94	143
Amite R at outlet	LPont	123	141	143	106	120	91	121
Minnesota R at outlet	Minn	126	130	163	105	158	171	144
Elkhorn R at outlet	Neb	93	97	145	88	104	107	101
Merrimack R at outlet	NewEng	119	128	117	121	114	101	118
Tongue R at outlet	PowTon	109	91	165	71	148	320	128
Rio Grande R below Albuquerque	RioGra	49	38	125	47	37	64	48
Sacramento R at outlet	Sac	99	89	100	110	98	107	100
Los Angeles R at outlet	SoCal	93	140	131	98	90	101	100
S. Platte R at outlet	SoPlat	86	70	91	63	109	116	89
Susquehanna R at outlet	Susq	162	147	147	156	150	132	149
Neuse R at outlet	TarNeu	111	189	154	118	144	99	131
Trinity R at outlet	Trin	121	165	125	80	136	164	130
Colorado R near State Line	UppCol	73	82	110	76	80	79	80
Willamette R at outlet	Willa	104	97	95	89	103	93	96

For most measures in most watersheds, there is a substantial amount of variability between scenario projections based on different methods of downscaling GCM outputs. This reflects our uncertainty in predicting future climate, especially the future joint distribution of precipitation and potential evapotranspiration that is fundamental to watershed response, and reinforces the need for an ensemble approach for evaluating the range of potential responses.

Climate change could also alter the seasonal dynamics of streamflow and nutrient loading. Seasonal effects are investigated here in summary form through calculation of the ratio of winter (January−March) to summer (July−September) runoff volume averaged over all HUC-8s in a study area. More detailed results showing simulated changes in streamflow by month are presented in Appendices X and Y. The different study areas have very different seasonal runoff volume ratios under current conditions, ranging from a winter:summer low of 0.11 in the Cook Inlet basin to a high of 11 in the Willamette River basin. The average ratios under the mid-21st century NARCCAP climate change scenarios are shown relative to the current ratio in Figure 7-1. In most cases, the future climate scenarios span the current ratio; however, in the case of the South Platte and Upper Colorado study areas, currently dominated by snowmelt runoff from the Rocky Mountains, all future climate scenarios project an increase in the ratio. In some basins the range of future projected seasonal runoff ratios is quite large. For the Salt, Verde, and San Pedro River basins (Ariz) the average future ratios by climate scenario range from 0.8 to 5.4, depending on whether the climate scenario projects greater increases in the summer monsoon or winter rainy period, while in the Lake Erie drainages (LErie) the range is from 1.5 to 7.8. The distribution for each of the six NARCCAP climate scenarios is summarized in Figure 7-2. There are clear differences between the different scenarios, with some projecting a much greater increase in the winter:summer runoff ratio than others.

7.3. SENSITIVITY TO URBAN AND RESIDENTIAL DEVELOPMENT SCENARIOS

This section presents the results of SWAT simulations in all 20 study areas for mid-21st century urban and residential development alone (that is, with climate held constant at existing conditions). Results in the pilot study areas (see Section 6.) suggested that effects of urban and residential development by 2050 on streamflow and pollutant loads is likely to be comparatively small relative to the potential range of impacts associated with climate change. This is largely a reflection of the scale of the analysis: at the scale of large (HUC-4 to HUC-8) watersheds, developed land is rarely a large portion of the total land area. Significant effects may occur in smaller subbasins where extensive new land development occurs.

Over the full extent of individual study areas, current impervious surface area ranges from near zero to 13.8% of the total area, while projected changes (increases) in impervious cover area range from 0 to 5.3% of the total area (see Table 7-15). While several fast-growing metropolitan areas are included within the study areas, the impact of these areas is diminished at larger spatial scales. At the HUC-8 and larger scale, it is not surprising that projected changes in urban and residential development have only a relatively small effect compared to climate change, which affects all portions of a watershed. The largest response of total streamflow volume to land-use change at the full-basin scale is simulated for the Trinity River in Texas, where total flow increased by 6%, while the estimated 100-year peak flow decreased and days to streamflow centroid increased (i.e., later runoff). This reflects increases in development upstream in the Dallas-Fort Worth metropolitan area. A stronger response to land development is seen at smaller spatial scales where development can account for a larger fraction of watershed area. Development effects are also more likely be reflected in high or low streamflow statistics. For example, in the Los Angeles River projected changes in urban and residential development result in little change in model-simulated total streamflow volume, but the 100-year peak flow increases by nearly 25%.

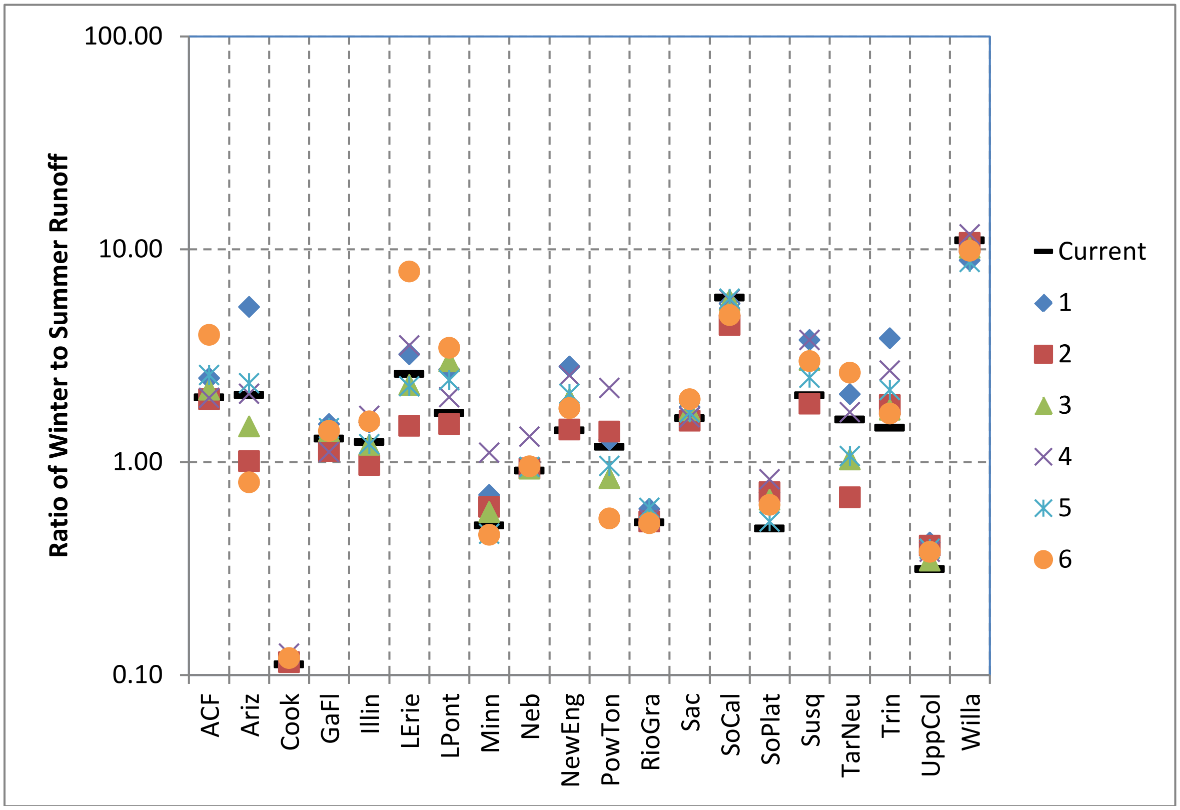

Figure 7-1. Ratio of winter (January−March) to summer (July−September) runoff volume under current and mid-21st century NARCCAP climate scenarios.

Notes: Results are averages over all HUC-8s simulated within a study area. Climate scenarios are (RCM and GCM): (1) CRCM_cgcm3, (2) HRM3_hadcm3, (3) RCM3_gfdl, (4) GFDL High Res_gfdl, (5) RCM3_cgcm3, and (6) WRFP_ccsm.

The simulated watershed responses to projected mid-21st century urban and residential development are shown in (see Table 7-16). Results across all 20 watersheds are small, as would be expected given the small changes in developed lands, when expressed as a fraction of total watershed area, at the scale of modeling in this study. Larger effects are likely in smaller subbasins within the study areas where urban and residential development is concentrated. Note that results are not available for the Kenai River (Cook Inlet, AK study area) because ICLUS projections do not include Alaska.

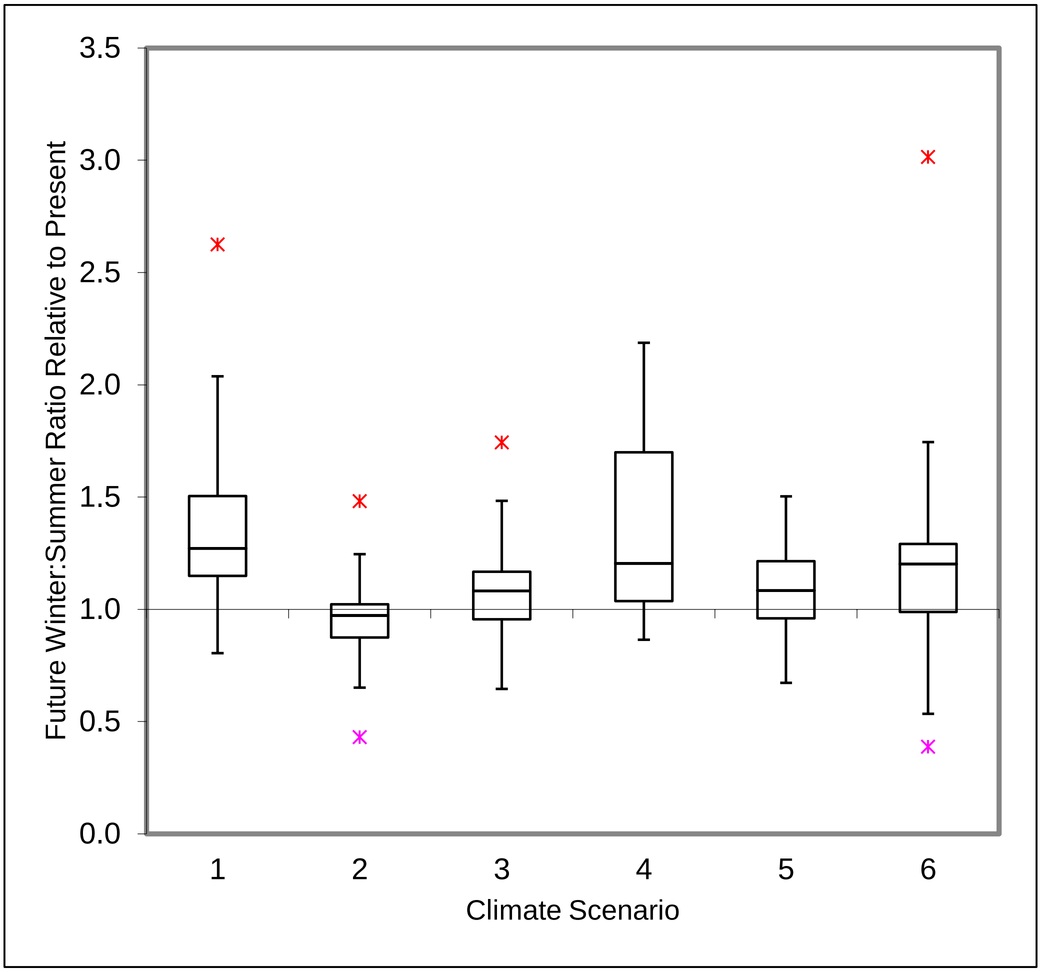

Figure 7-2. Box plots of the distribution of the ratio of winter (January−March) to summer (July−September) runoff volume normalized to the ratio under current conditions.

Notes: The box shows the interquartile range, with median indicated by a horizontal line, and the whiskers extend 1.5 times the interquartile range. Outliers beyond the whiskers are shown by individual points. The data are averages over all HUC-8s simulated within a study area. Climate scenarios are (RCM and GCM): (1) CRCM_cgcm3, (2) HRM3_hadcm3, (3) RCM3_gfdl, (4) GFDL High Res_gfdl, (5) RCM3_cgcm3, and (6) WRFP_ccsm.

7.4. RELATIVE EFFECTS OF CLIMATE CHANGE AND URBAN DEVELOPMENT SCENARIOS

The changes in urban and residential development projected by ICLUS for 2050 suggest changes may be large locally but are small relative to the area of basins modeled in this study (see Table 5-5). Urban and residential development has long been recognized as a source of hydrologic changes and water quality degradation at local scales in developing areas (e.g., U.S. EPA, 1984). The cumulative impacts of development, however, tend to be relatively small at the larger basin scale evaluated in this study simply because only a small fraction of most HUC-4 scale watersheds is developed or projected to be developed by 2050.

Table 7-15. Projected mid-21st century impervious cover changes in study areas from ICLUS for A2 emissions storyline

Study area	Current (2001) impervious cover (%)	Projected mid-21st century impervious cover (%)	Change in impervious cover (%)
ACF	2.04	3.06	1.02
Ariz	0.19	0.30	0.11
Cook	0.24	ND	ND
GaFla	2.50	3.86	1.36
Illin	6.19	8.22	2.03
LErie	3.48	3.88	0.40
LPont	3.24	4.56	1.32
Minn	1.06	1.28	0.22
Neb	0.38	0.39	0.01
NewEng	5.59	6.74	1.15
PowTon	0.08	0.08	0.00
RioGra	0.55	0.81	0.26
Sac	0.73	0.95	0.22
SoCal	13.80	19.11	5.31
SoPlat	2.06	4.27	2.21
Susq	1.50	1.69	0.19
TarNeu	1.70	2.55	0.85
Trin	4.17	7.37	3.20
UppCol	0.37	0.61	0.24
Willa	2.51	3.06	0.55

The relative magnitude of effects from urban development versus climate change in our simulations can be examined by looking at changes in mean annual streamflow. Figure 7-3 compares the HSPF simulated change in mean annual streamflow in the pilot study areas for mid-21st century urban and residential development compared to the six NARCCAP climate change scenarios. The results summarize the range of responses across selected HUC-8 subbasins and calibration locations contained within each study area. Table 7-17 compares the range of SWAT simulated changes in mean annual streamflow in all study locations for mid-21st century urban and residential development and the six NARCCAP climate change scenarios. Results summarize the ranges at the HUC-8 and larger scale within the study areas.

Table 7-16. Simulated response to projected 2050 changes in urban and residential development (percent or days relative to current conditions) for selected downstream stations

Station	Study area	Total flow (%)	7-day low flow (%)	100-yr peak flow (%)	Days to flow centroid	Richards-Baker flashiness (%)	TSS load (%)	TP load (%)	TN load (%)
Apalachicola R at outlet	ACF	100.3	100.4	100.3	−0.1	100.0	100.6	101.1	100.5
Salt River near Roosevelt	Ariz	100.1	100.0	100.2	0.1	100.3	100.2	100.4	100.2
Kenai R at Soldotna	Cook	ND	ND	ND	ND	ND	ND	ND	ND
Suwanee R at outlet	GaFla	100.3	99.9	100.6	0.3	99.5	100.4	108.9	102.5
Illinois R at Marseilles, IL	Illin	102.4	104.0	102.1	1.0	98.4	100.5	100.2	99.2
Maumee R at outlet	LErie	100.5	100.8	101.4	0.2	100.9	100.6	101.3	99.6
Amite R at outlet	LPont	100.8	102.6	101.6	0.2	100.4	98.7	106.8	103.9
Minnesota R at outlet	Minn	100.2	100.3	99.9	0.3	100.1	98.0	99.3	99.5
Elkhorn R at outlet	Neb	100.3	100.3	101.5	0.0	102.8	100.1	100.1	99.8
Merrimack R at outlet	NewEng	100.4	100.5	101.4	0.0	101.3	101.2	103.8	102.0
Tongue R at outlet	PowTon	100.0	100.0	100.0	0.0	100.0	100.0	100.0	100.0
Rio Grande R below Albuquerque	RioGra	100.1	100.1	100.4	0.0	100.2	101.1	95.4	99.6
Sacramento R at outlet	Sac	100.1	100.1	99.9	−0.1	100.4	99.7	102.1	104.7
Los Angeles R at outlet	SoCal	101.4	101.3	114.4	0.0	103.9	106.6	138.2	111.1
S. Platte R at outlet	SoPlat	102.8	100.7	101.1	0.9	103.9	103.9	104.0	103.4
Susquehanna R at outlet	Susq	100.2	100.7	99.7	0.1	100.1	100.2	99.7	99.2
Neuse R at outlet	TarNeu	101.7	105.2	102.1	0.7	99.1	102.3	106.7	103.3
Trinity R at outlet	Trin	106.4	188.1	74.2	3.7	68.8	61.9	110.0	106.2
Colorado R near State Line	UppCol	100.1	100.6	100.3	−0.1	99.8	100.0	100.8	100.2
Willamette R at outlet	Willa	99.9	100.0	100.1	0.0	100.7	99.7	99.9	102.5

Simulations using both HSPF and SWAT show a smaller range of response to projected future changes in urban development than to projected climate change. As discussed previously, at the spatial scale of these simulations projected future changes in developed land were a relatively small fraction of total watershed area. At smaller spatial scales, however, the effects of urban and residential development could be greater. Results for pollutant loads are similar to those for streamflow.

The simulated response to land-use change is also sensitive to model choice—or, more precisely, an interaction between the model and the way in which the ICLUS is interpreted. In the SWAT setup, there are representations of both directly connected (effective) and disconnected impervious area. New developed land use implied by ICLUS is identified to the model as a total area in a given development density class, then subdivided by the model into pervious and impervious fractions using basin-specific estimates of total and effective impervious area. The effective impervious fraction for a given development category is calculated from the 2000 NLCD and assumed invariant. The model then assumes that the effective impervious area has a curve number of 98, while the remaining disconnected impervious area provides a small modification to the curve number assigned to the pervious fraction of the HRU.

In contrast, HSPF has pervious (PERLND) and impervious (IMPLND) land uses, but does not distinguish a separate disconnected impervious class. For HSPF, the new developed area in ICLUS is assigned to the relevant pervious and impervious land-use fractions based on the basin-specific percent imperviousness for the land-use class. In essence, this means that somewhat greater future connected imperviousness is being specified to the HSPF model than is specified to the SWAT model. While the two approaches are rather different, they are consistent with typical modeling practice for the two models.

Several other details of the SWAT modeling process adopted in this study affect results. The approach to implementing changes in urban development in SWAT was to remove land from existing undeveloped and nonexempt land uses and reassign it to new developed classes that have the parameters of the most dominant soil and lowest HRU slope in the subbasin. In some cases (particularly when a subbasin is already largely developed) the dominant soil in the watershed may have characteristics different from the soils and slopes of the remaining undeveloped land. For HSPF, the urban land uses are not associated with a specific soil or HSG.

In addition, a special circumstance occurs in the Willamette SWAT model. In that model, new developed land primarily comes from dense forest cover. The model tends to simulate greater evapotranspiration for urban grass than for intact evergreen forest, which appears to offset increases in total streamflow volume due to increased impervious area.

The effects of land-use change on simulated streamflow extremes can be more dramatic in basins where strong growth is expected, but also tend to be smaller than the range of simulated climate responses. For example, in the ACF basin, land-use change alone can increase the simulated 100-year flood peak by up to 27%, but the range of responses to the six NARCCAP climate scenarios is from 17 to 66%.

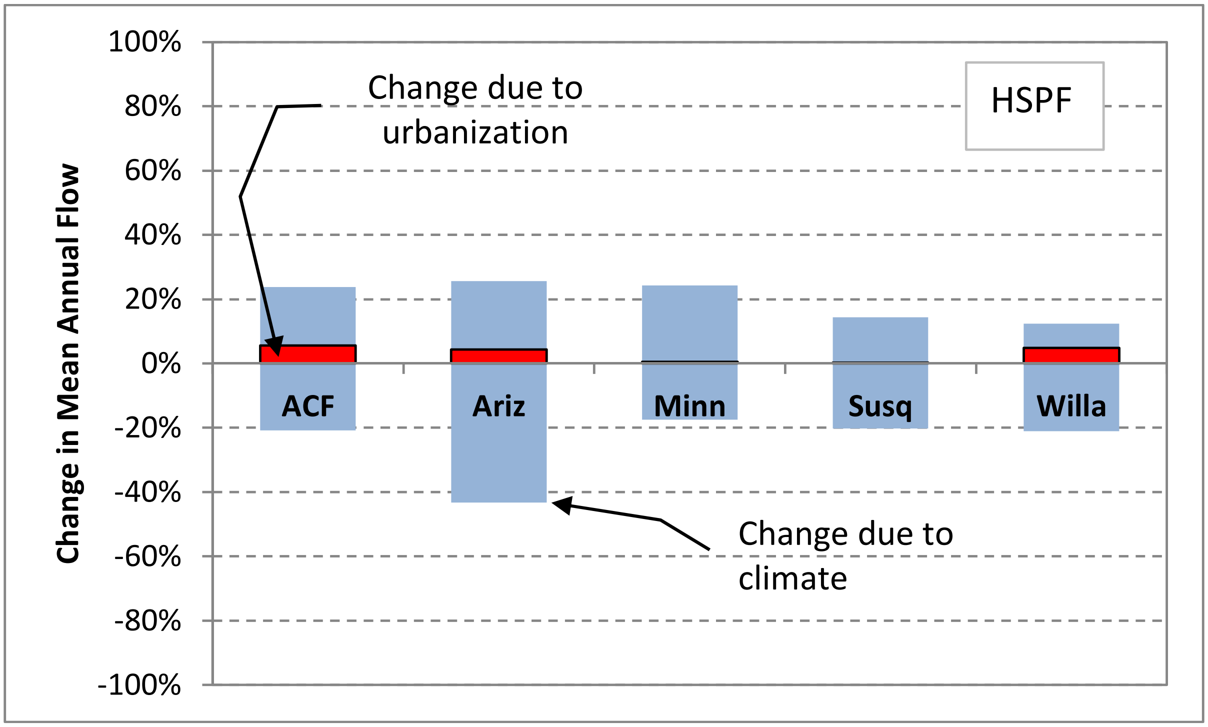

Figure 7-3. Comparison of simulated responses of mean annual streamflow to urban development and climate change scenarios—HSPF model.

Note: The blue area represents the range of responses to the six NARCCAP RCM-downscaled 2050 climate scenarios across the different HUC-8 scale reporting sites (with no change in land use). The red bars represent the maximum response to land-use change among the reporting sites (with no change in climate). Results are shown for Apalachicola River at outlet (ACF), Sat River near Roosevelt (Ariz), Minnesota River at outlet (Minn), Susquehanna River at outlet (Susq), and Willamette River at outlet (Willa).

7.5. SENSITIVITY TO COMBINED CLIMATE CHANGE AND URBAN DEVELOPMENT SCENARIOS

This section presents the results of SWAT simulations in all 20 study areas for the combined effects of mid-21st century climate change and urban and residential development scenarios. Simulation results are generally consistent with results for climate scenarios alone (presented in Section 7.2.) given the relatively small response to projected urban and residential development at the spatial scale of modeling in this study. Results are presented for selected locations in each study area in Tables 7-18 through 7-27. For study sites comprised of a single watershed, results are shown for a downstream outlet. For study sites comprised of multiple adjacent basins results are shown for a single representative basin, typically the largest. These same results for each study area are also shown as scatterplots in Figures 7-4 through 7-24, followed by maps showing the simulated median values for the six NARCCAP scenarios at the HUC-8 scale within study areas. It should be noted that use of the median values alone without taking into account the full range of simulated responses to all scenarios is potentially misleading. Median values are presented here only as an indicator of variability between study areas and should not alone be considered indicative of broad regional trends. It should also be noted that simulation results for

Kenai River in the Cook Inlet basin do not include urban and residential development scenarios. ICLUS projections are not available for the Alaska study area, but are anticipated to be small.

Table 7-17. Simulated range of responses of mean annual streamflow to mid-21st century climate and land-use change at the HUC-8 and larger spatial scale

	Climate Change Response		Land-Use Change Response	
	Minimum (%)	**Maximum (%)**	**Minimum (%)**	**Maximum (%)**
ACF	−45.73	24.84	0.00	0.68
Ariz	−35.29	152.52	0.00	1.48
GaFla	−39.73	69.85	0.01	7.36
Illin	−22.20	34.00	0.00	11.90
LErie	−22.89	72.13	0.00	1.84
LPont	−24.75	21.82	0.00	1.24
Minn	−23.39	85.38	0.00	0.19
Neb	−79.14	72.64	0.00	0.27
NewEng	−12.55	19.80	0.02	0.76
PowTon	−42.49	206.01	0.00	0.00
RioGra	−45.38	19.86	−0.07	0.13
Sac	−20.79	10.29	−0.03	0.47
SoCal	−26.91	62.19	−3.60	6.36
SoPlat	−53.04	59.23	−1.00	2.82
Susq	−23.80	25.79	0.00	0.23
TarNeu	−13.65	61.60	0.28	4.31
Trin	−60.57	125.65	7.09	34.91
UppCol	−20.21	22.93	−0.38	0.47
Willa	−17.51	23.21	−1.18	0.00

Note: Cook Inlet basin is not shown because ICLUS land-use change information is not available. Results based on SWAT simulations for the six NARCCAP climate change scenarios and ICLUS 2050 projected changes in developed land.

The simulated ranges of total streamflow volume changes shown in Figure 7-4 suggest several observations. The first is that increases in streamflow volume for the Kenai River (Cook Inlet basin) are on average larger than for other basins. Perhaps more importantly, for a majority of the basins the different downscaled models do not provide a consistent sign for changes in streamflow for the 2041−2070 period, with some simulating increases and some decreases. The models are in complete agreement as to the sign of change only for Kenai River (increase). It is also worth noting that the Weather Research and Forecasting Model (WRFP) downscaling of the CCSM GCM often seems to be an outlier relative to the other models.

Figure 7-5 shows the median simulated annual streamflow volume (as the median over the six NARCCAP scenarios; expressed as percent of baseline conditions) at the HUC-8 spatial scale for each study area. On this map, a neutral gray tone represents no change from current conditions (100% of current conditions). Browns indicate streamflow volumes less than current, with greater color intensity reflecting lower streamflow; blues represent flow volumes greater than current, with greater intensity reflecting higher flows. Simulated median values suggest a general trend of decreasing streamflow volume in the central Rockies, accompanied by increases in streamflow in the northern plains. Only moderate changes are seen for the west coast and Mississippi Valley, while streamflow volume generally increases on the east coast.

In addition to streamflow volume, changes in the timing and rate of streamflow can also affected by climate change. At a national scale, the number of days to the streamflow centroid—the point at which half the streamflow volume of an average year is achieved (calculated from the October 1 start of the water year)—is a useful measure of changes in the seasonal distribution of streamflow. Figure 7-11 shows that the centroid of streamflow comes earlier in the year in model-simulated response to warmer temperatures for many of the snow-melt dominated basins, particularly Cook Inlet in Alaska and higher elevations in the Rockies, but also for many basins in the southeast. The latter result reflects changes in precipitation timing, with increased winter precipitation and decreased summer precipitation. Several of the western basins have later dates for the streamflow centroid due to a substantial increase in model-simulated spring or summer precipitation relative to winter snowpack that counteracts the effects of earlier snowmelt. Appendices X and Y provide more detailed information about seasonal shifts in streamflow timing in the study areas.

The geographic distribution of 100-year peak flows (Log-Pearson III) fit is displayed in Figure 7-9 and shows considerably more heterogeneity. Simulated peak flows increase in many basins, but show less of a clear pattern (see Figure 7-8). Peak flows tend to decline in the area of the Southwest where total streamflow volumes decline, while the greatest increases are seen in Alaska and the populated areas of the east and west coast. The increase in 100-year peak flows is generally greater (or, in some instances, the reduction less) than the change in total streamflow volume, consistent with the findings of Taner et al. (2011) for Lake Onondaga.

Results also suggest a large (factor of 5) increase in low flows for the Kenai River (see Figure 7-6). This reflects greater dry season melt rates of ice under a warmer climate in Alaska. The models also consistently show large declines in low flows for the Rio Grande Valley.

Table 7-18. Simulated total streamflow volume (climate and land-use change scenarios; percent relative to current conditions) for selected downstream stations

Station	Study area	CRCM_ cgcm3 (%)	HRM3_ hadcm3 (%)	RCM3_ gfdl (%)	GFDL_ slice (%)	RCM3_ cgcm3 (%)	WRFP_ ccsm (%)	Median (%)
Apalachicola R at outlet	ACF	107	122	108	89	124	73	108
Salt River near Roosevelt	Ariz	80	80	149	75	94	73	80
Kenai R at Soldotna	Cook	ND	154	ND	132	ND	167	154
Suwanee R at outlet	GaFla	115	154	128	93	157	75	122
Illinois R at Marseilles, IL	Illin	96	126	103	104	106	79	103
Maumee R at outlet	LErie	117	151	120	136	123	89	122
Amite R at outlet	LPont	96	111	116	85	107	78	102
Minnesota R at outlet	Minn	110	113	147	86	146	162	130
Elkhorn R at outlet	Neb	117	126	137	68	138	143	131
Merrimack R at outlet	NewEng	108	116	111	112	106	94	110
Tongue R at outlet	PowTon	101	85	140	70	130	240	115
Rio Grande R below Albuquerque	RioGra	73	69	112	66	69	84	71
Sacramento R at outlet	Sac	104	89	98	98	100	99	99
Los Angeles R at outlet	SoCal	92	140	104	103	107	85	103
S. Platte R at outlet	SoPlat	92	76	92	67	110	121	92.27
Susquehanna R at outlet	Susq	109	107	106	108	111	90	108
Neuse R at outlet	TarNeu	104	160	138	111	127	88	119
Trinity R at outlet	Trin	102	150	110	66	122	138	116
Colorado R near State Line	UppCol	86	95	116	89	92	91	91
Willamette R at outlet	Willa	116	106	104	92	114	98	105

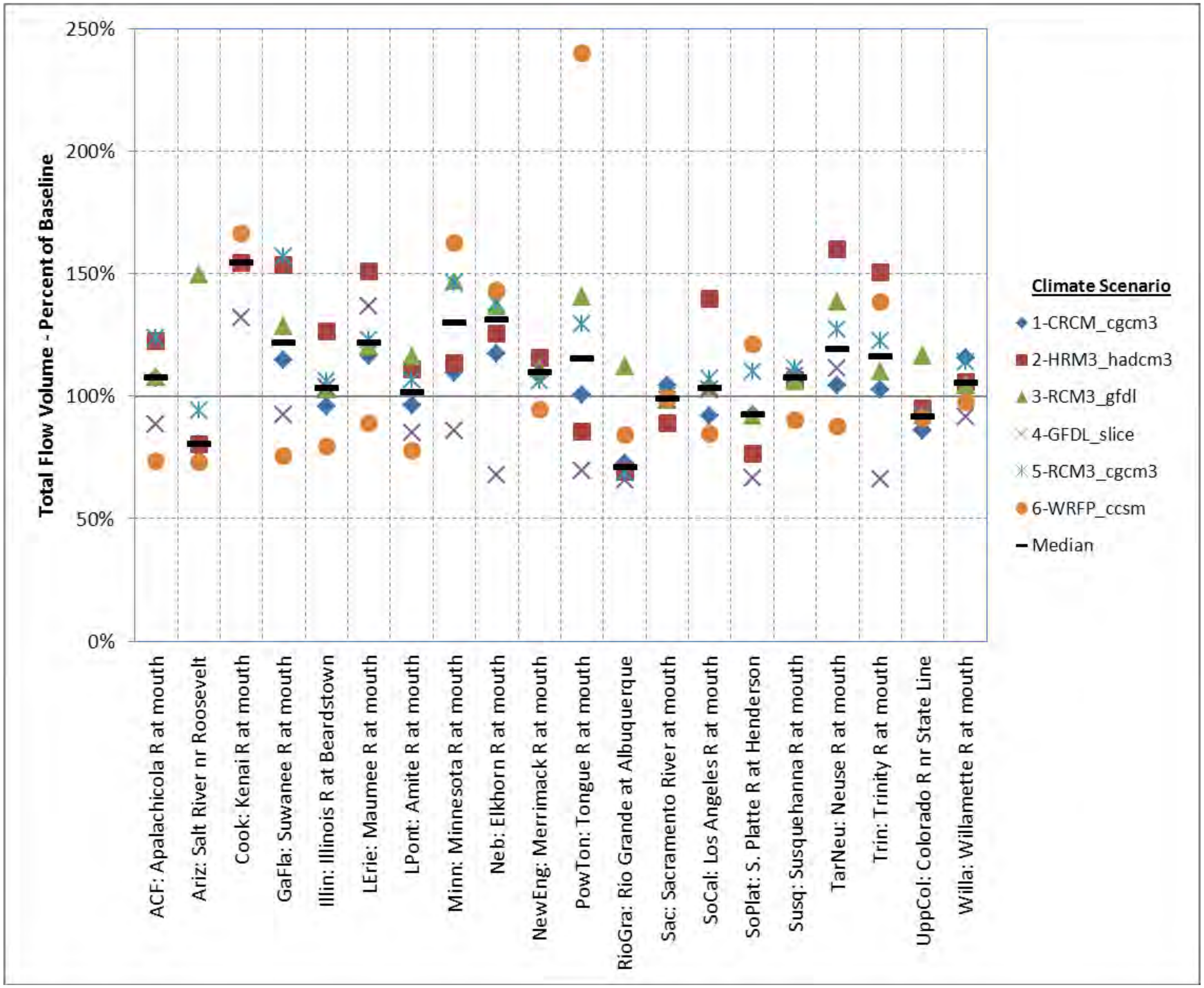

Figure 7-4. Simulated total future streamflow volume relative to current conditions (NARCCAP climate scenarios with urban development) for selected stations.

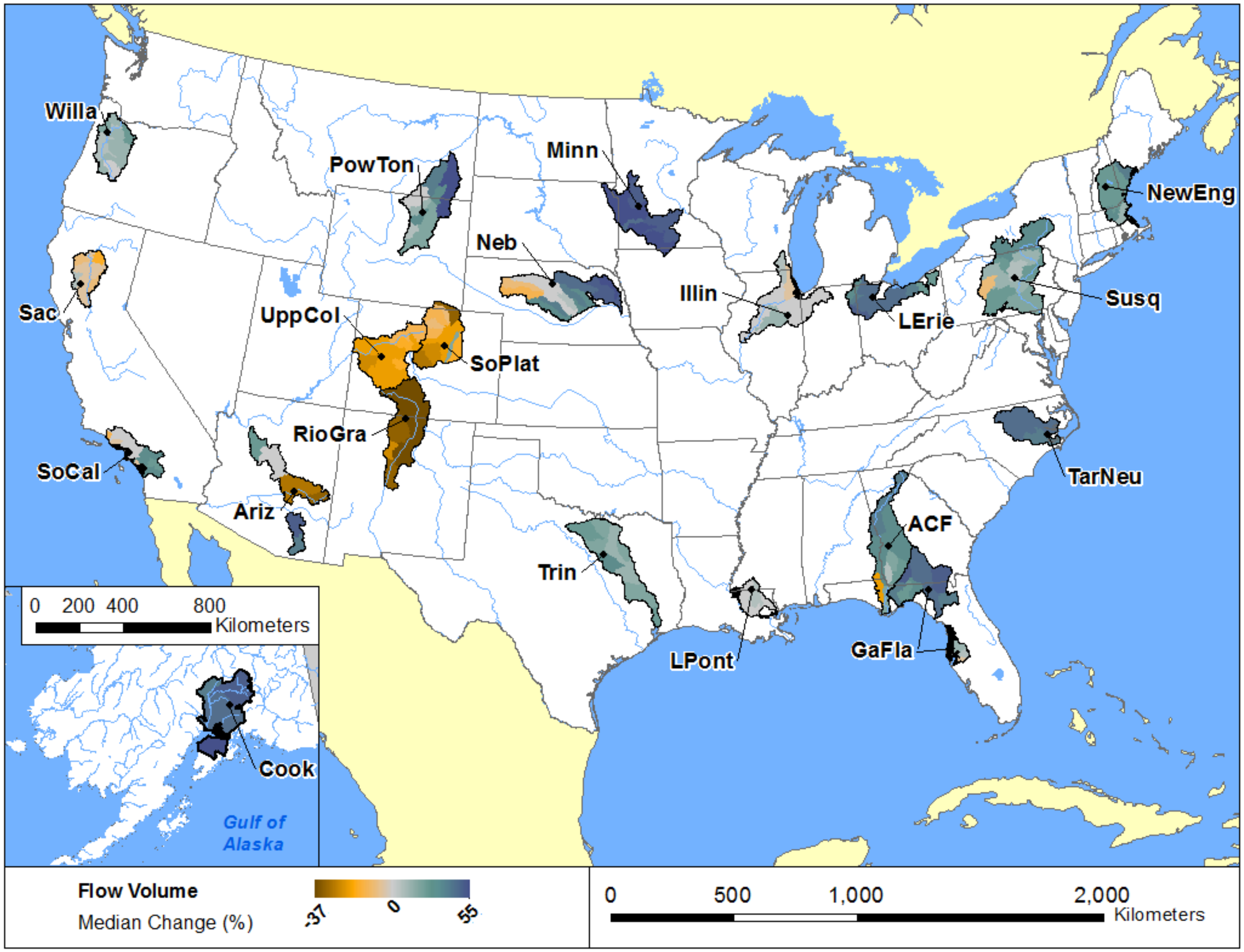

Figure 7-5. Median simulated percent changes in total future streamflow volume for six NARCCAP scenarios relative to current conditions by HUC-8 (median of NARCCAP climate scenarios with urban development).

Note: Cook Inlet results do not include land-use change.

Table 7-19. Simulated 7-day low flow (climate and land-use change scenarios; percent relative to current conditions) for selected downstream stations

Station	Study area	CRCM_ cgcm3 (%)	HRM3_ hadcm3 (%)	RCM3_ gfdl (%)	GFDL_ slice (%)	RCM3_ cgcm3 (%)	WRFP_ ccsm (%)	Median (%)
Apalachicola R at outlet	ACF	98	120	105	86	113	64	101
Salt River near Roosevelt	Ariz	58	77	131	87	79	90	83
Kenai R at Soldotna	Cook	ND	267	ND	280	ND	401	280
Suwanee R at outlet	GaFla	105	141	121	95	136	78	113
Illinois R at Marseilles, IL	Illin	88	126	100	94	103	73	97
Maumee R at outlet	LErie	105	184	127	133	129	59	128
Amite R at outlet	LPont	76	108	91	77	92	64	84
Minnesota R at outlet	Minn	115	137	202	82	182	228	159
Elkhorn R at outlet	Neb	119	133	152	48	148	154	141
Merrimack R at outlet	NewEng	112	141	131	119	125	121	123
Tongue R at outlet	PowTon	102	92	145	67	127	235	115
Rio Grande R below Albuquerque	RioGra	81	64	120	62	74	86	77
Sacramento R at outlet	Sac	101	91	95	96	99	93	95
Los Angeles R at outlet	SoCal	98	115	99	100	101	93	99
S. Platte R at outlet	SoPlat	94	88	98	75	103	114	96
Susquehanna R at outlet	Susq	92	121	105	90	108	87	98
Neuse R at outlet	TarNeu	100	175	139	118	129	74	123
Trinity R at outlet	Trin	33	199	87	36	93	102	90
Colorado R near State Line	UppCol	85	94	122	86	92	91	91
Willamette R at outlet	Willa	131	113	108	82	127	102	111

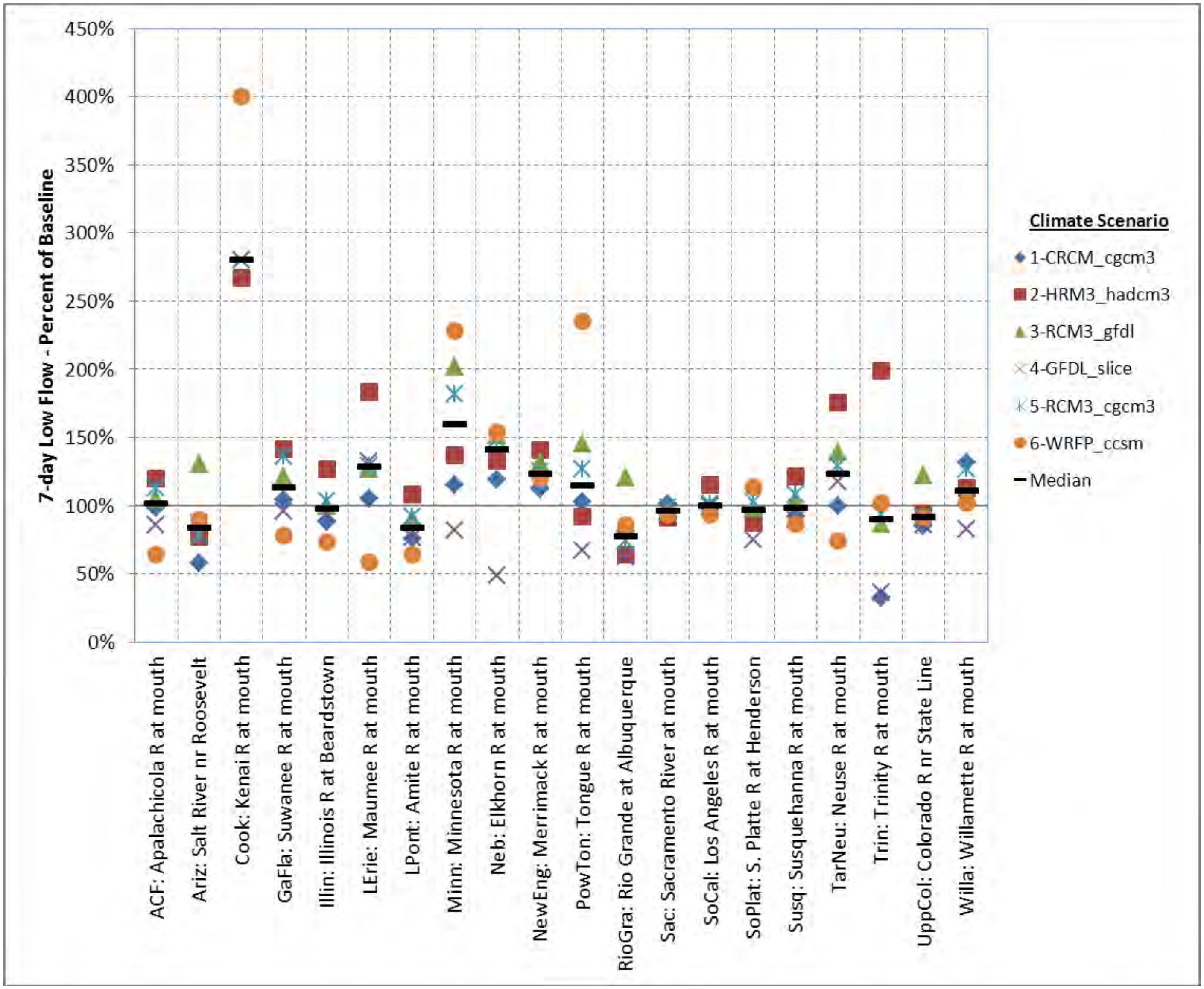

Figure 7-6. Simulated 7-day low flow relative to current conditions (NARCCAP climate scenarios with urban development) for selected downstream stations.

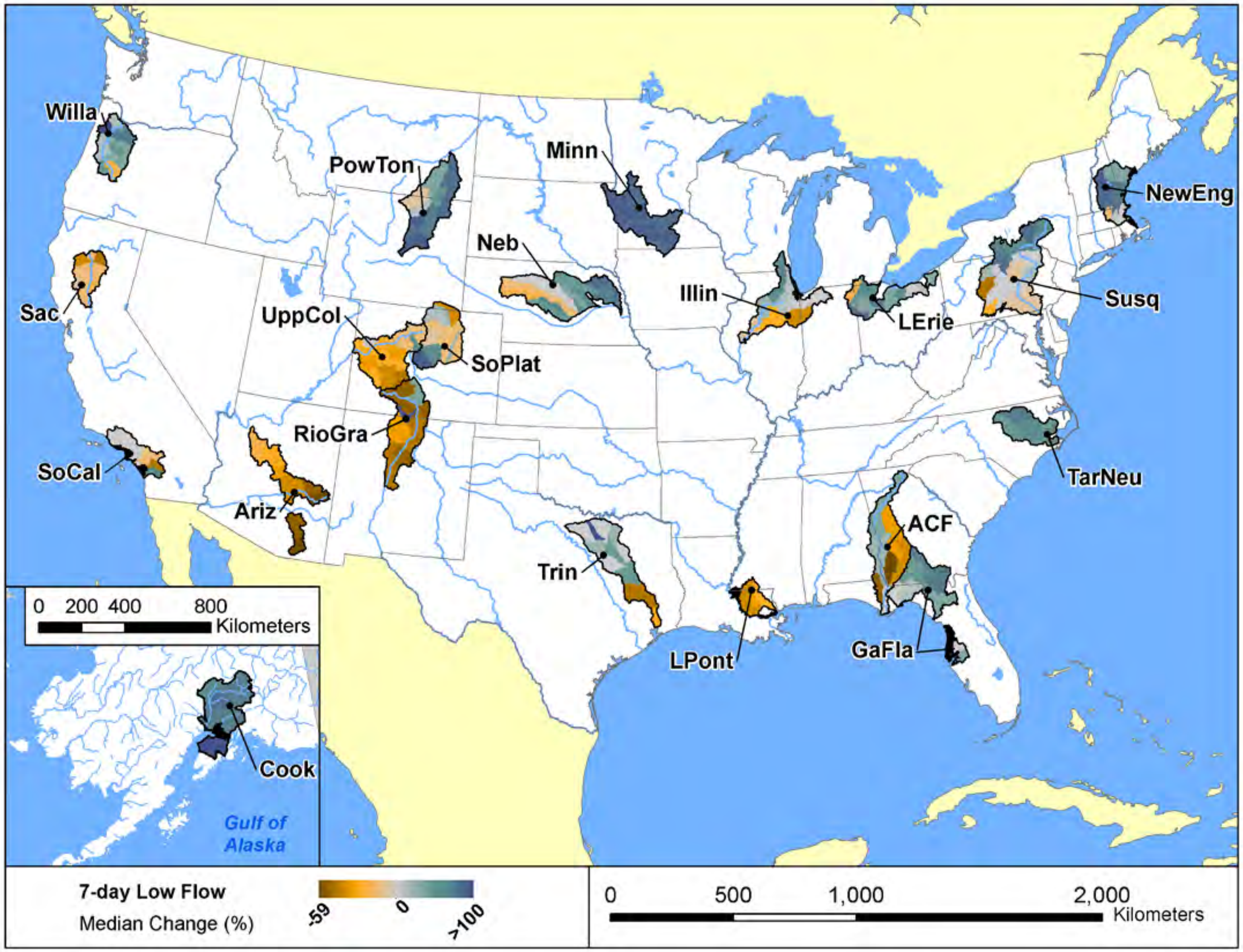

Figure 7-7. Median simulated percent changes in 7-day average low flow volume for six NARCCAP scenarios relative to current conditions by HUC-8 (median of NARCCAP climate scenarios with urban development).

Note: Cook Inlet results do not include land-use change.

Table 7-20. Simulated 100-year peak flow (log-Pearson III; climate and land-use change scenarios; percent relative to current conditions) for selected downstream stations

Station	Study area	CRCM_ cgcm3 (%)	HRM3_ hadcm3 (%)	RCM3_ gfdl (%)	GFDL_ slice (%)	RCM3_ cgcm3 (%)	WRFP_ ccsm (%)	Median (%)
Apalachicola R at outlet	ACF	117	145	110	90	128	94	114
Salt River near Roosevelt	Ariz	119	101	104	68	121	66	102
Kenai R at Soldotna	Cook	ND	132	ND	125	ND	132	132
Suwanee R at outlet	GaFla	131	145	130	95	158	107	130
Illinois R at Marseilles, IL	Illin	121	155	109	103	129	98	115
Maumee R at outlet	LErie	96	107	88	94	94	93	94
Amite R at outlet	LPont	107	152	110	100	107	66	107
Minnesota R at outlet	Minn	84	83	96	87	89	96	88
Elkhorn R at outlet	Neb	128	117	110	93	139	102	114
Merrimack R at outlet	NewEng	116	134	113	141	90	82	115
Tongue R at outlet	PowTon	118	113	133	82	121	146	119
Rio Grande R below Albuquerque	RioGra	90	77	108	66	72	92	83
Sacramento R at outlet	Sac	105	98	122	117	102	131	111
Los Angeles R at outlet	SoCal	100	112	194	124	158	93	118
S. Platte R at outlet	SoPlat	132	126	101	129	163	152	131
Susquehanna R at outlet	Susq	108	130	107	129	173	101	118
Neuse R at outlet	TarNeu	71	294	163	113	227	64	138
Trinity R at outlet	Trin	97	107	108	60	87	107	102
Colorado R near State Line	UppCol	78	83	97	91	93	84	87
Willamette R at outlet	Willa	116	131	114	79	116	95	115

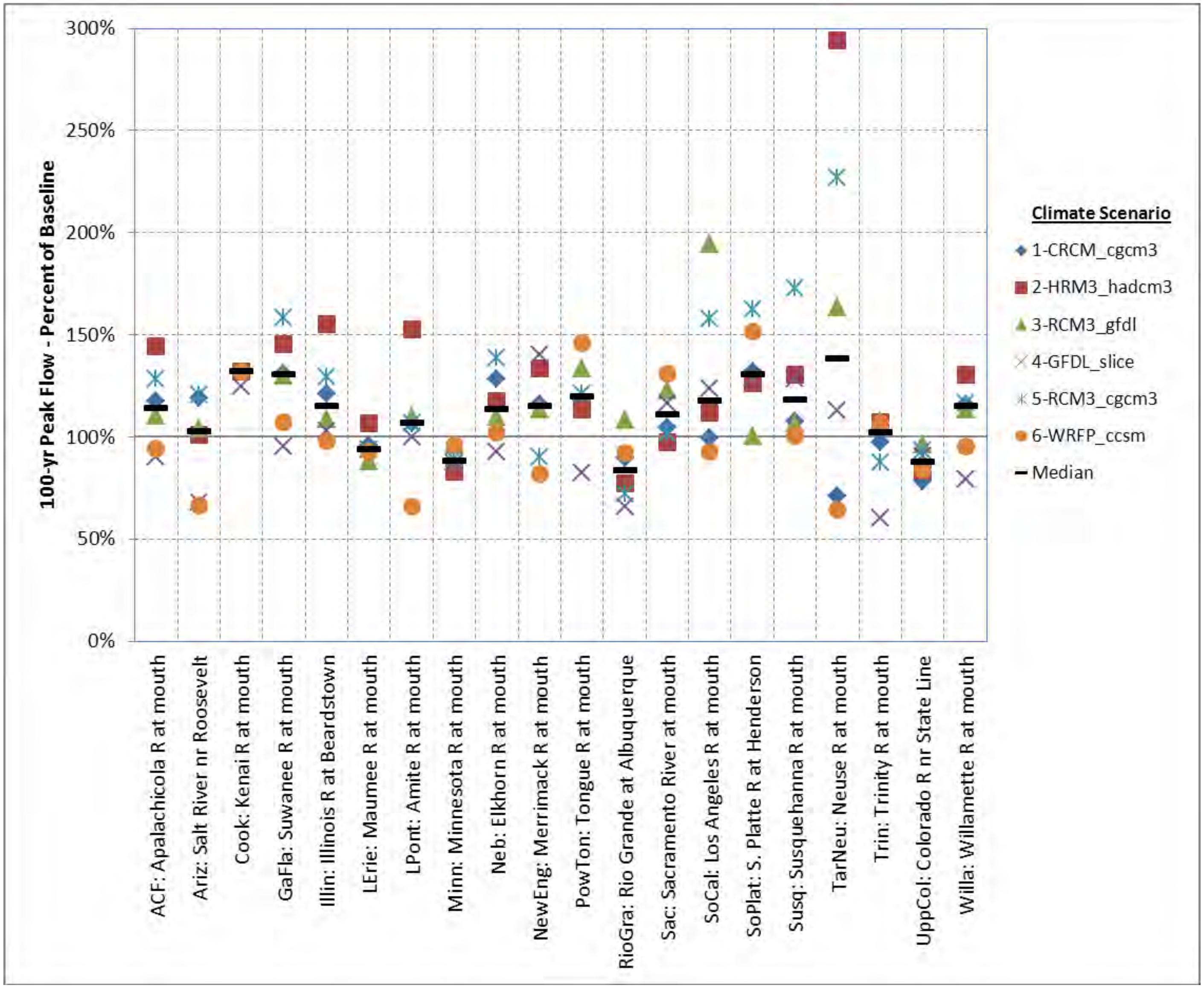

Figure 7-8. Simulated 100-year peak flow relative to current conditions (NARCCAP climate scenarios with urban development) for selected downstream stations.

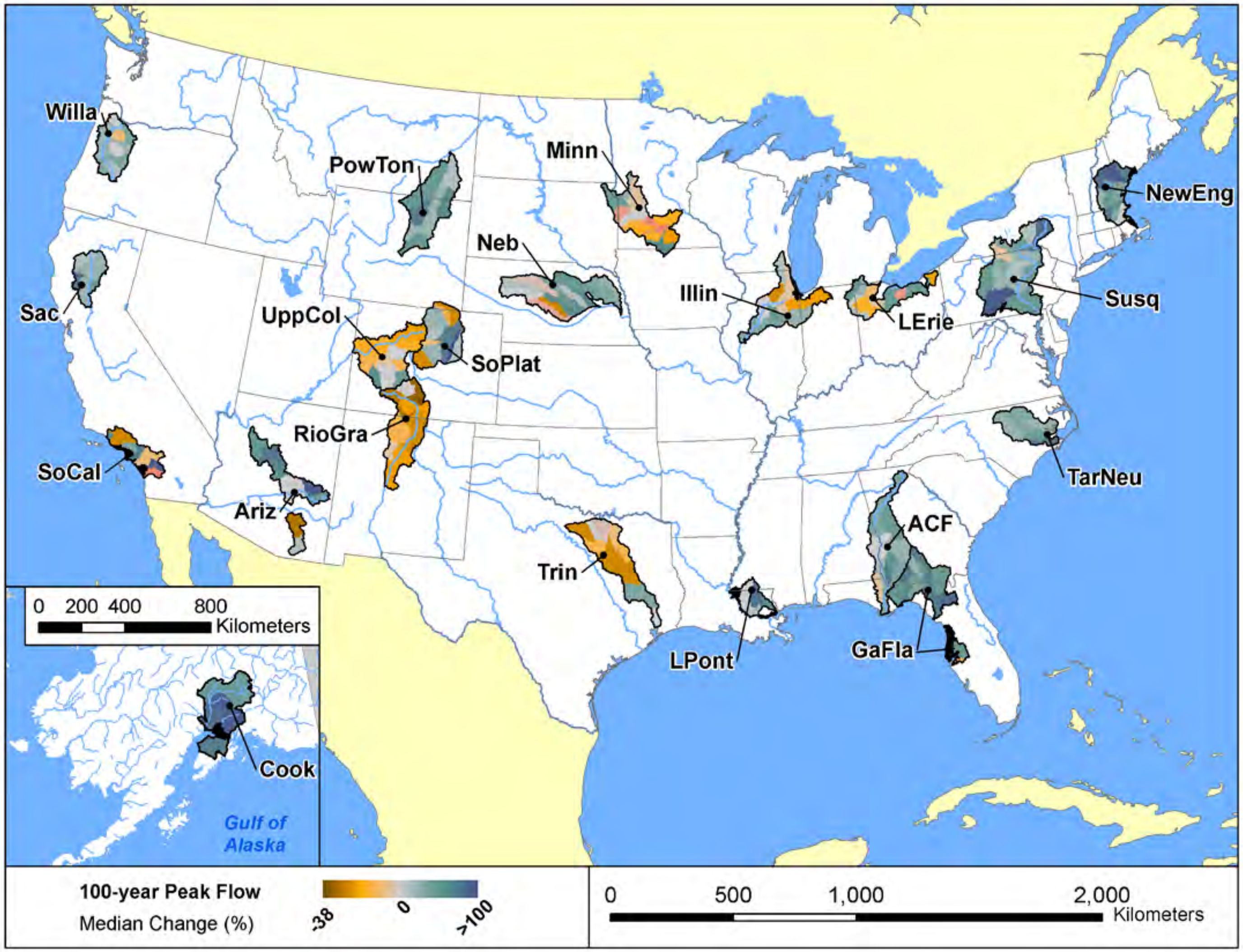

Figure 7-9. Median simulated percent changes in 100-year peak flow for six NARCCAP scenarios relative to current conditions by HUC-8 (median of NARCCAP climate scenarios with urban development).

Note: Cook Inlet results do not include land-use change.

Table 7-21. Simulated change in the number of days to streamflow centroid (climate and land-use change scenarios; relative to current conditions) for selected downstream stations

Station	Study area	CRCM_ cgcm3	HRM3_ hadcm3	RCM3_ gfdl	GFDL_ slice	RCM3_ cgcm3	WRFP_ ccsm	Median
Apalachicola R at outlet	ACF	−2	−2	1	8	−6	1	−1
Salt River near Roosevelt	Ariz	−18	41	28	17	−5	54	22
Kenai R at Soldotna	Cook		−3		−5		−1	−3
Suwanee R at outlet	GaFla	−3	17	25	−8	−5	11	4
Illinois R at Marseilles, IL	Illin	−11	6	−2	−12	−1	−14	−6
Maumee R at outlet	LErie	−2	−4	1	0	10	−8	−1
Amite R at outlet	LPont	−14	14	−23	−7	−5	−11	−9
Minnesota R at outlet	Minn	−13	−19	−6	−15	−3	2	−9
Elkhorn R at outlet	Neb	−12	6	1	−15	−6	2	−2
Merrimack R at outlet	NewEng	−17	−14	−19	−13	−9	−18	−16
Tongue R at outlet	PowTon	−6	−3	1	−16	−4	7	−3
Rio Grande R below Albuquerque	RioGra	25	6	3	11	14	17	13
Sacramento R at outlet	Sac	−4	−7	−4	−1	−3	−8	−4
Los Angeles R at outlet	SoCal	6	48	−3	10	−3	0	3
S. Platte R at outlet	SoPlat	−11	−19	−13	−18	−2	−11	−12
Susquehanna R at outlet	Susq	−18	16	−6	−12	−5	0	−6
Neuse R at outlet	TarNeu	−13	23	31	−11	11	−5	3
Trinity R at outlet	Trin	17	23	31	4	7	25	20
Colorado R near State Line	UppCol	−11	−14	−7	−10	−8	−11	−10
Willamette R at outlet	Willa	3	−8	−1	3	1	8	2

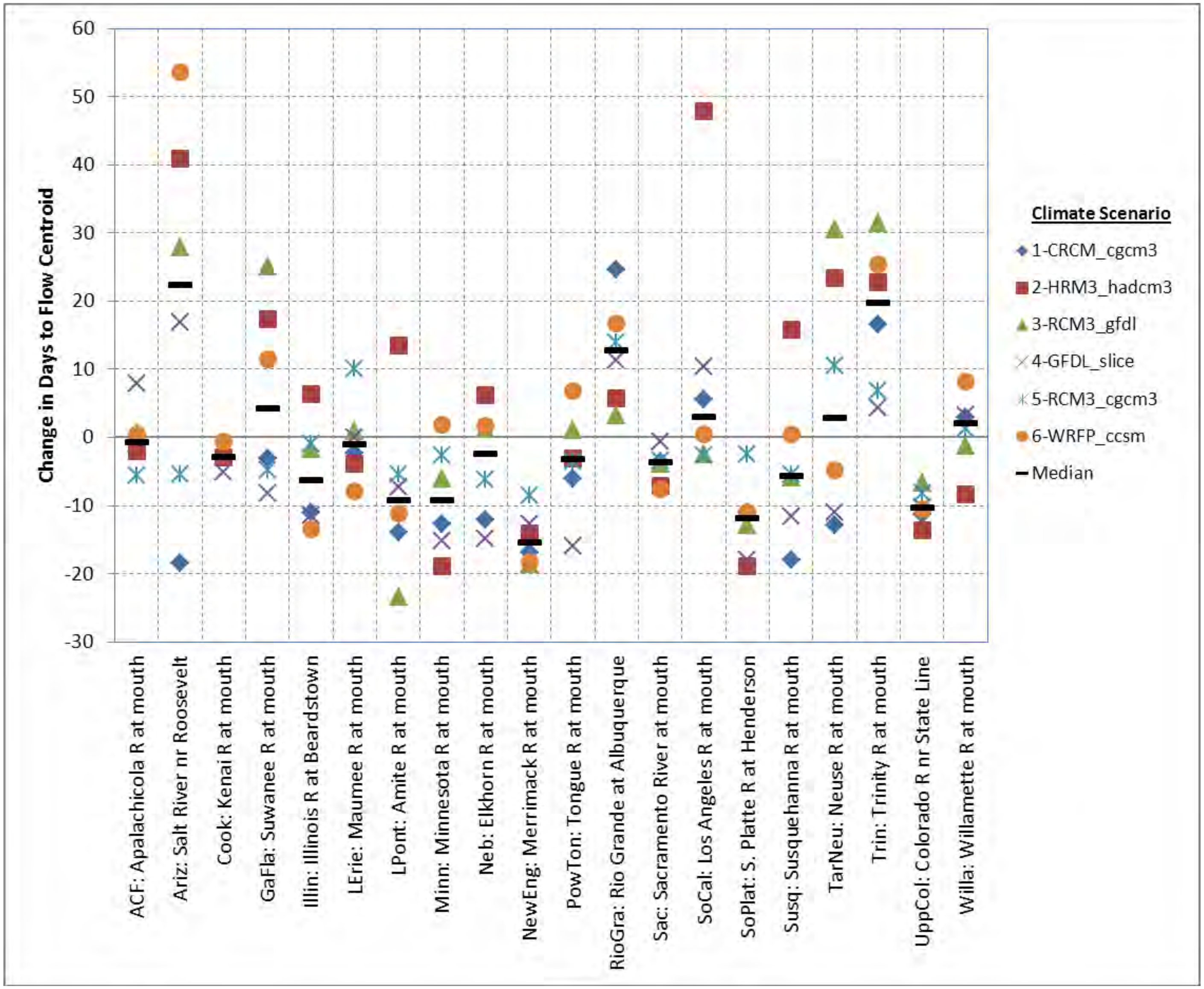

Figure 7-10. Simulated change in days to streamflow centroid relative to current conditions (NARCCAP climate scenarios with urban development) for selected downstream stations.

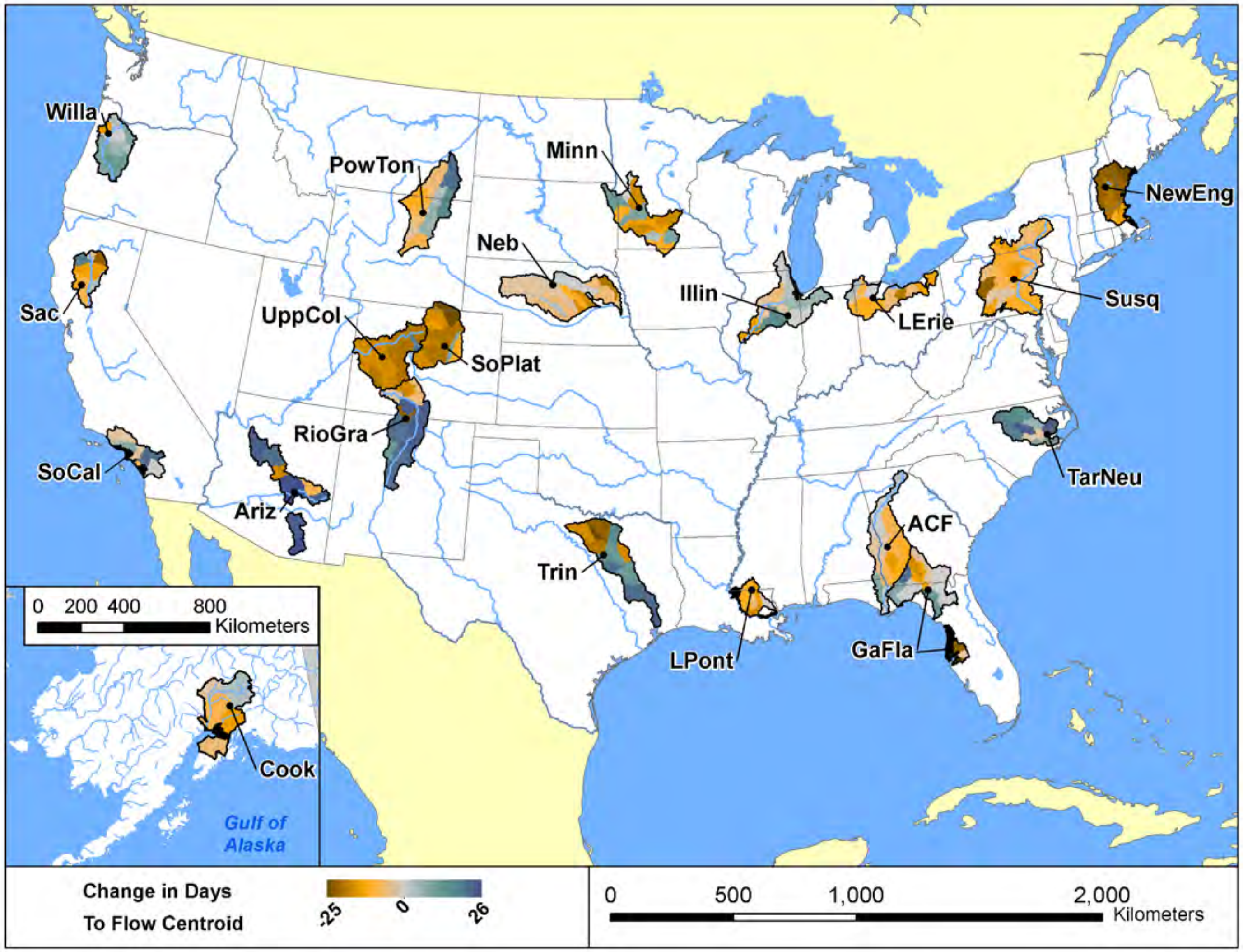

Figure 7-11. Median simulated change in the number of days to streamflow centroid for six NARCCAP scenarios relative to current conditions by HUC-8 (median of NARCCAP climate scenarios with urban development).

Note: Cook Inlet results do not include land-use change.

Table 7-22. Simulated Richards-Baker flashiness index (climate and land-use change scenarios; percent relative to current conditions) for selected downstream stations

Station	Study area	CRCM_ cgcm3 (%)	HRM3_ hadcm3 (%)	RCM3_ gfdl (%)	GFDL_ slice (%)	RCM3_ cgcm3 (%)	WRFP_ ccsm (%)	Median (%)
Apalachicola R at outlet	ACF	106	125	109	94	126	90	107
Salt River near Roosevelt	Ariz	81	103	121	98	103	119	103
Kenai R at Soldotna	Cook	ND	94	ND	102	ND	96	96
Suwanee R at outlet	GaFla	93	62	76	116	59	185	84
Illinois R at Marseilles, IL	Illin	105	103	102	106	105	103	104
Maumee R at outlet	LErie	100	102	100	101	100	97	100
Amite R at outlet	LPont	105	105	106	104	104	102	104
Minnesota R at outlet	Minn	105	112	108	101	109	108	108
Elkhorn R at outlet	Neb	97	101	97	96	98	97	97
Merrimack R at outlet	NewEng	102	104	100	102	99	94	101
Tongue R at outlet	PowTon	102	108	104	100	103	109	104
Rio Grande R below Albuquerque	RioGra	109	117	95	120	103	106	108
Sacramento R at outlet	Sac	124	103	113	109	117	124	115
Los Angeles R at outlet	SoCal	104	125	103	105	108	104	105
S. Platte R at outlet	SoPlat	103	95	105	91	113	110	104
Susquehanna R at outlet	Susq	107	111	107	110	112	103	109
Neuse R at outlet	TarNeu	95	112	114	97	102	90	100
Trinity R at outlet	Trin	71	69	72	73	70	68	70
Colorado R near State Line	UppCol	101	107	111	105	103	101	104
Willamette R at outlet	Willa	102	105	100	98	101	102	102

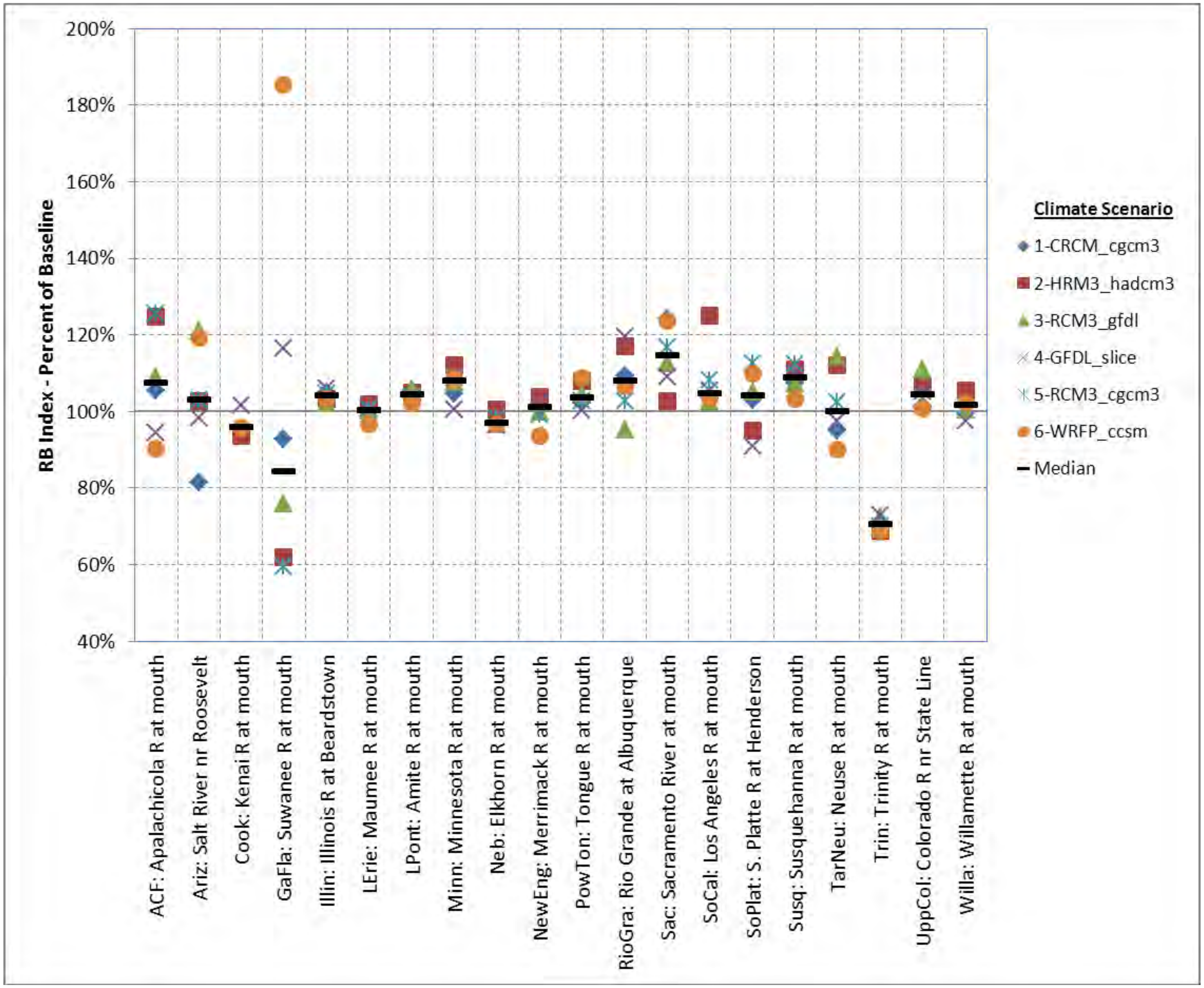

Figure 7-12. Simulated Richards-Baker flashiness index relative to current conditions (NARCCAP climate scenarios with urban development) for selected downstream stations.

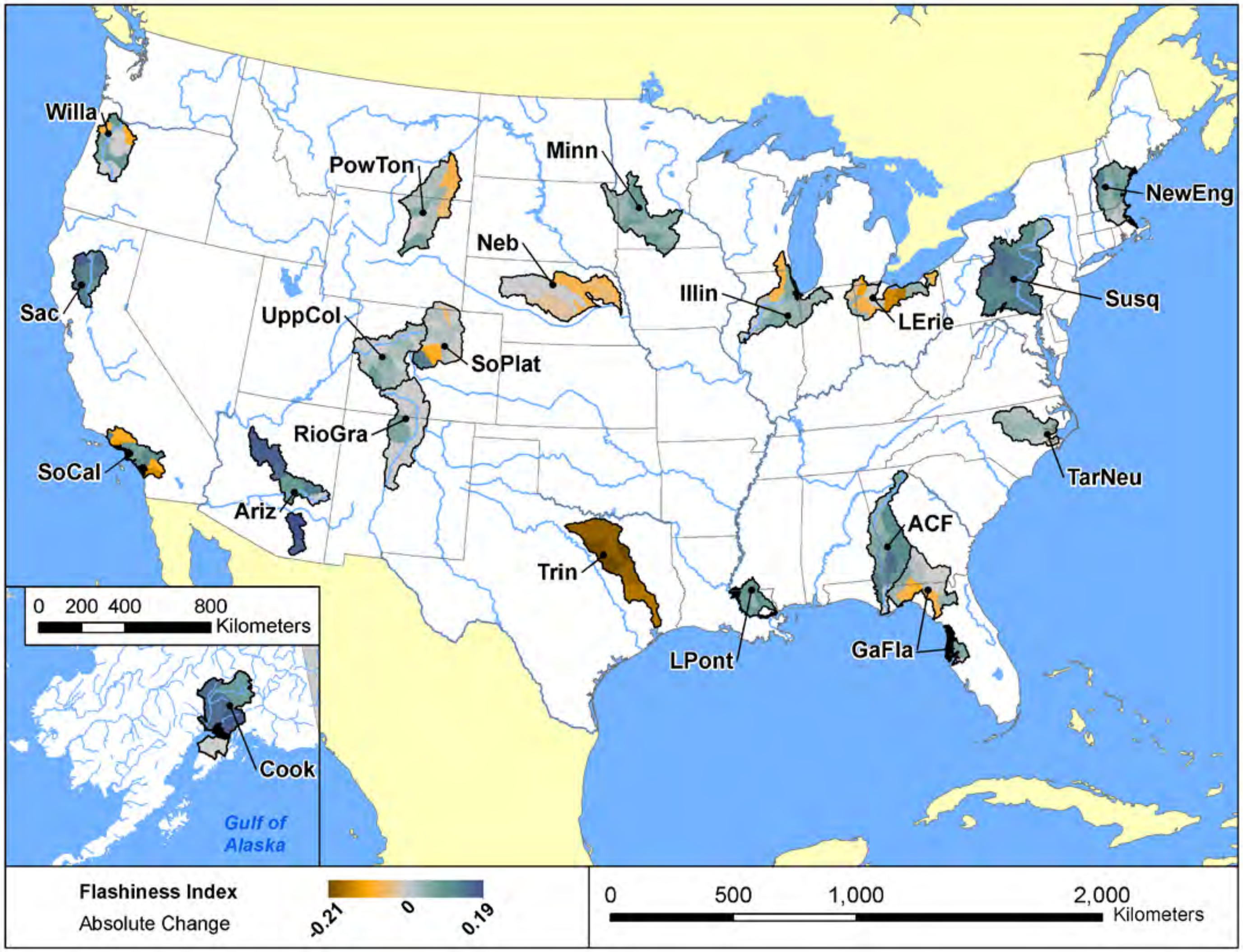

Figure 7-13. Simulated absolute changes in the Richards-Baker flashiness index for six NARCCAP scenarios relative to current conditions by HUC-8 (median of NARCCAP climate scenarios with urban development).

Note: Cook Inlet results do not include land-use change.

Regional differences also occur in the degree of agreement among simulated watershed responses to climate change scenarios. Table 7-23 shows the CV (standard deviation divided by the mean) for SWAT-simulated percentage changes in different streamflow endpoints at the downstream location of each study site for the six NARCCAP scenarios (calculated without land-use change to isolate the impacts of climate). The CV for total streamflow is large at some stations, such as Salt River and Tongue River, indicating poor model agreement on the magnitude of change. Note that CVs on total streamflow are artificially reduced at some stations (e.g., Colorado River, Sacramento River) due to the presence of constant upstream boundary conditions (representing interbasin transfers for the Colorado and releases from an upstream dam on the Sacramento River). The largest divergences among simulated high flows are seen at different stations than the largest divergences among total streamflow volume estimates.

CVs were also calculated reflecting the variability in response across the selected downstream stations for all study areas for each NARCCAP climate change scenario. Table 7-24 shows these values along with the average absolute difference from the median of all scenarios for each NARCCAP scenario. For total streamflow volume, the CCSM downscaled with WRFP has both the greatest station-to-station variability (highest CV) and largest average absolute difference from the median of all six simulations.

Simulated changes in pollutant loads are shown in Tables 7-25 through 7-27, and Figures 7-14 through 7-19. Changes in projected pollutant loads are qualitatively similar to those seen for response to climate change only, but further increased in areas with significant new urban development. In general, projected changes in pollutant loads follow a pattern similar to the changes in total streamflow volume. Total suspended solids loads (see Figure 7-15) increase in most basins, except for declines in the Rocky Mountain and Southwest study areas where overall streamflow decreases. The large increases in solids loads for some basins (especially sand bed rivers in the west) are mostly driven by channel scour. These results should be considered highly uncertain given the simplified approach to channel scour included in SWAT version 2005 and the differences among individual models in calibration to channel scour. The regional pattern for total phosphorus loads is similar, as much of the total phosphorus load is driven by erosion (see Figure 7-17), with the notable exception of the Cook Inlet basin in Alaska. The regional pattern for total nitrogen loads is also generally similar, with some additional variability associated with the interactions of plant growth and erosion (see Figure 7-19).

Changes in the timing of nutrient load delivery may be even more significant for ecological impacts (c.f., Tu, 2009; Wilson and Weng, 2011; Tong et al., 2011; Marshall and Randhir, 2008). Potential ecological impacts of changes in timing of pollutant delivery simulated in the rich data set generated by this study remain to be evaluated.

7.6. WATER BALANCE INDICATORS

Several additional endpoints—identified here as water balance indicators—were calculated for each study area. Water balance indicators are defined in Section 4.3. This section presents results describing the SWAT-simulated changes in these indicators in response to the six mid-21st century NARCCAP climate change and urban development scenarios.

Table 7-28 provides a summary of water balance indicators for each study area. Figures 7-20 through 7-24 show the median values for changes in water balance metrics for simulations using the six NARCCAP climate change scenarios at each study location. As stated previously, median values are presented here only as an indicator of variability within and among study areas and should not alone be considered indicative of broad regional trends. Appendices X and Y provide more detailed results for changes in water balance indicators including analysis at additional locations in each study area.

Table 7-23. Coefficient of variation of SWAT-simulated changes in streamflow by study area in response to the six NARCCAP climate change scenarios for selected downstream stations

Station	Study area	Total flow	100-yr peak	7-day low flow
Apalachicola R at outlet	ACF	0.038	0.037	0.043
Salt River near Roosevelt	Ariz	0.091	0.060	0.067
Kenai R at Soldotna	Cook	0.021	0.001	0.172
Suwanee R at outlet	GaFla	0.089	0.043	0.053
Illinois R at Marseilles, IL	Illin	0.023	0.039	0.033
Maumee R at outlet	LErie	0.035	0.004	0.137
Amite R at outlet	LPont	0.023	0.070	0.029
Minnesota R at outlet	Minn	0.066	0.004	0.198
Elkhorn R at outlet	Neb	0.064	0.024	0.128
Merrimack R at outlet	NewEng	0.005	0.046	0.009
Tongue R at outlet	PowTon	0.293	0.039	0.273
Rio Grande R below Albuquerque	RioGra	0.039	0.028	0.056
Sacramento R at outlet	Sac	0.003	0.016	0.001
Los Angeles R at outlet	SoCal	0.032	0.100	0.005
S. Platte R at outlet	SoPlat	0.044	0.029	0.019
Susquehanna R at outlet	Susq	0.005	0.057	0.017
Neuse R at outlet	TarNeu	0.055	0.534	0.101
Trinity R at outlet	Trin	0.079	0.036	0.378
Colorado R near State Line	UppCol	0.013	0.006	0.020
Willamette R at outlet	Willa	0.008	0.030	0.028

Table 7-24. Coefficient of variation of SWAT-simulated changes in streamflow by NARCCAP climate scenario for selected downstream stations

	Total flow		100-yr peak flow		7-day low flow	
RCM/GCM	CV	Average absolute difference from median (%)	CV	Average absolute difference from median (%)	CV	Average absolute difference from median (%)
CRCM_cgcm3	0.016	14.66	0.032	14.97	0.058	27.95
HRM3_hadcm3	0.068	15.38	0.166	19.76	0.163	23.45
RCM3_gfdl	0.026	19.54	0.035	18.52	0.073	27.32
GFDL_slice	0.049	18.37	0.048	17.56	0.264	20.10
RCM3_cgcm3	0.036	16.06	0.108	25.00	0.068	21.52
WRFP_ccsm	0.167	25.25	0.063	19.83	0.571	31.89

Table 7-25. Simulated total suspended solids load (climate and land-use change scenarios; percent relative to current conditions) for selected downstream stations

Station	Study area	CRCM_ cgcm3 (%)	HRM3_ hadcm3 (%)	RCM3_ gfdl (%)	GFDL_ slice (%)	RCM3_ cgcm3 (%)	WRFP_ ccsm (%)	Median (%)
Apalachicola R at outlet	ACF	126	147	128	93	145	53	127
Salt River near Roosevelt	Ariz	89	79	184	66	106	74	84
Kenai R at Soldotna	Cook	ND	234	ND	196	ND	244	234
Suwanee R at outlet	GaFla	121	177	139	90	182	74	130
Illinois R at Marseilles, IL	Illin	117	142	115	128	121	91	119
Maumee R at outlet	LErie	123	170	127	154	130	87	128
Amite R at outlet	LPont	99	113	125	82	110	70	104
Minnesota R at outlet	Minn	104	117	183	76	192	219	150
Elkhorn R at outlet	Neb	122	131	147	60	162	162	139
Merrimack R at outlet	NewEng	119	129	119	123	112	86	119
Tongue R at outlet	PowTon	108	84	169	66	153	351	131
Rio Grande R below Albuquerque	RioGra	61	54	115	50	60	72	60
Sacramento R at outlet	Sac	138	94	121	118	99	108	113
Los Angeles R at outlet	SoCal	75	121	86	85	90	69	86
S. Platte R at outlet	SoPlat	95	91	98	84	104	108	97
Susquehanna R at outlet	Susq	118	108	109	116	118	85	112
Neuse R at outlet	TarNeu	108	201	164	117	145	84	131
Trinity R at outlet	Trin	64	126	64	28	85	115	74
Colorado R near State Line	UppCol	80	90	124	82	89	85	87
Willamette R at outlet	Willa	124	111	108	89	121	97	110

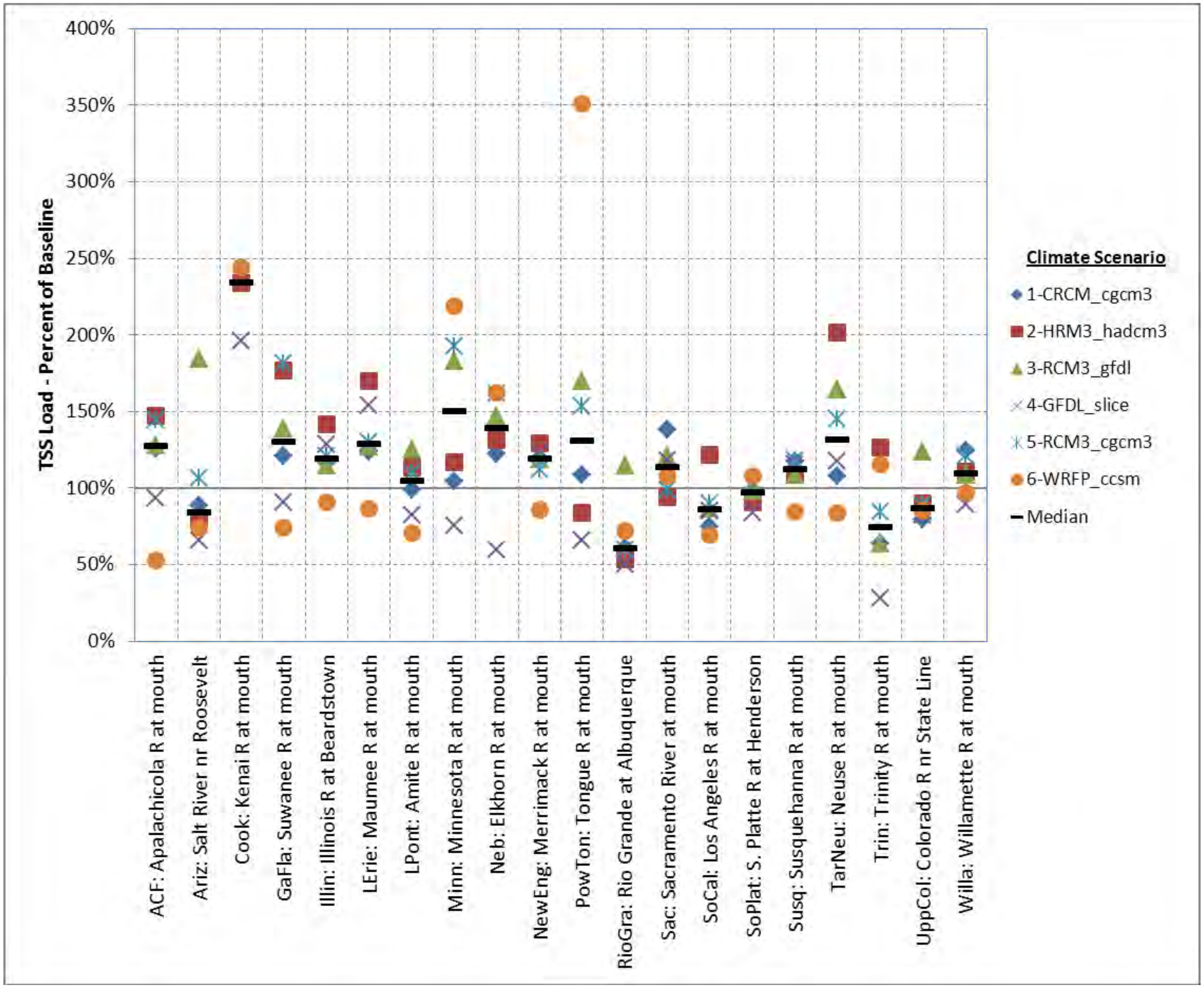

Figure 7-14. Simulated total suspended solids load relative to current conditions (NARCCAP climate scenarios with urban development) for selected downstream stations.

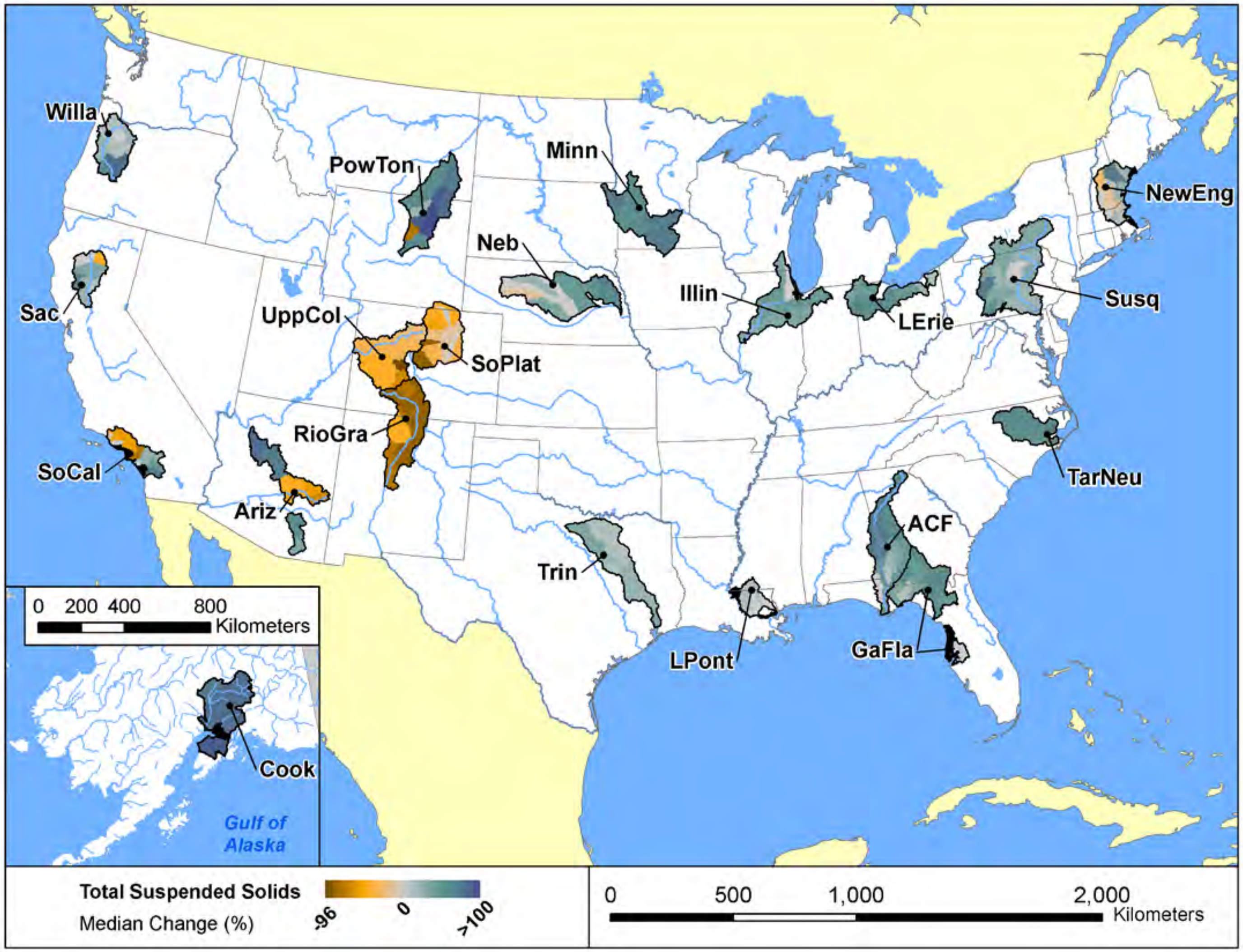

Figure 7-15. Median simulated percent changes in total suspended solids loads for six NARCCAP scenarios relative to current conditions by HUC-8 (median of NARCCAP climate scenarios with urban development) for selected downstream stations.

Note: Cook Inlet results do not include land-use change.

Table 7-26. Simulated total phosphorus load (climate and land-use change scenarios; percent relative to current conditions) for selected downstream stations

Station	Study area	CRCM_ cgcm3 (%)	HRM3_ hadcm3 (%)	RCM3_ gfdl (%)	GFDL_ slice (%)	RCM3_ cgcm3 (%)	WRFP_ ccsm (%)	Median (%)
Apalachicola R at outlet	ACF	139	153	136	119	150	107	138
Salt River near Roosevelt	Ariz	82	84	156	70	107	88	86
Kenai R at Soldotna	Cook	ND	89	ND	90	ND	113	90
Suwanee R at outlet	GaFla	125	190	149	96	189	82	137
Illinois R at Marseilles, IL	Illin	107	112	107	113	108	99	107
Maumee R at outlet	LErie	121	155	136	151	120	89	128
Amite R at outlet	LPont	123	144	147	103	125	89	124
Minnesota R at outlet	Minn	97	115	151	97	138	160	126
Elkhorn R at outlet	Neb	118	124	138	65	145	148	131
Merrimack R at outlet	NewEng	116	125	116	120	111	97	116
Tongue R at outlet	PowTon	107	86	163	67	148	324	127
Rio Grande R below Albuquerque	RioGra	51	40	125	49	37	64	50
Sacramento R at outlet	Sac	102	88	106	117	97	110	104
Los Angeles R at outlet	SoCal	78	128	102	83	89	71	86
S. Platte R at outlet	SoPlat	93	81	104	75	113	115	99
Susquehanna R at outlet	Susq	128	106	110	127	114	108	112
Neuse R at outlet	TarNeu	123	259	184	134	183	103	158
Trinity R at outlet	Trin	148	188	153	98	155	187	154
Colorado R near State Line	UppCol	80	88	120	82	84	84	84
Willamette R at outlet	Willa	100	98	97	94	100	96	97

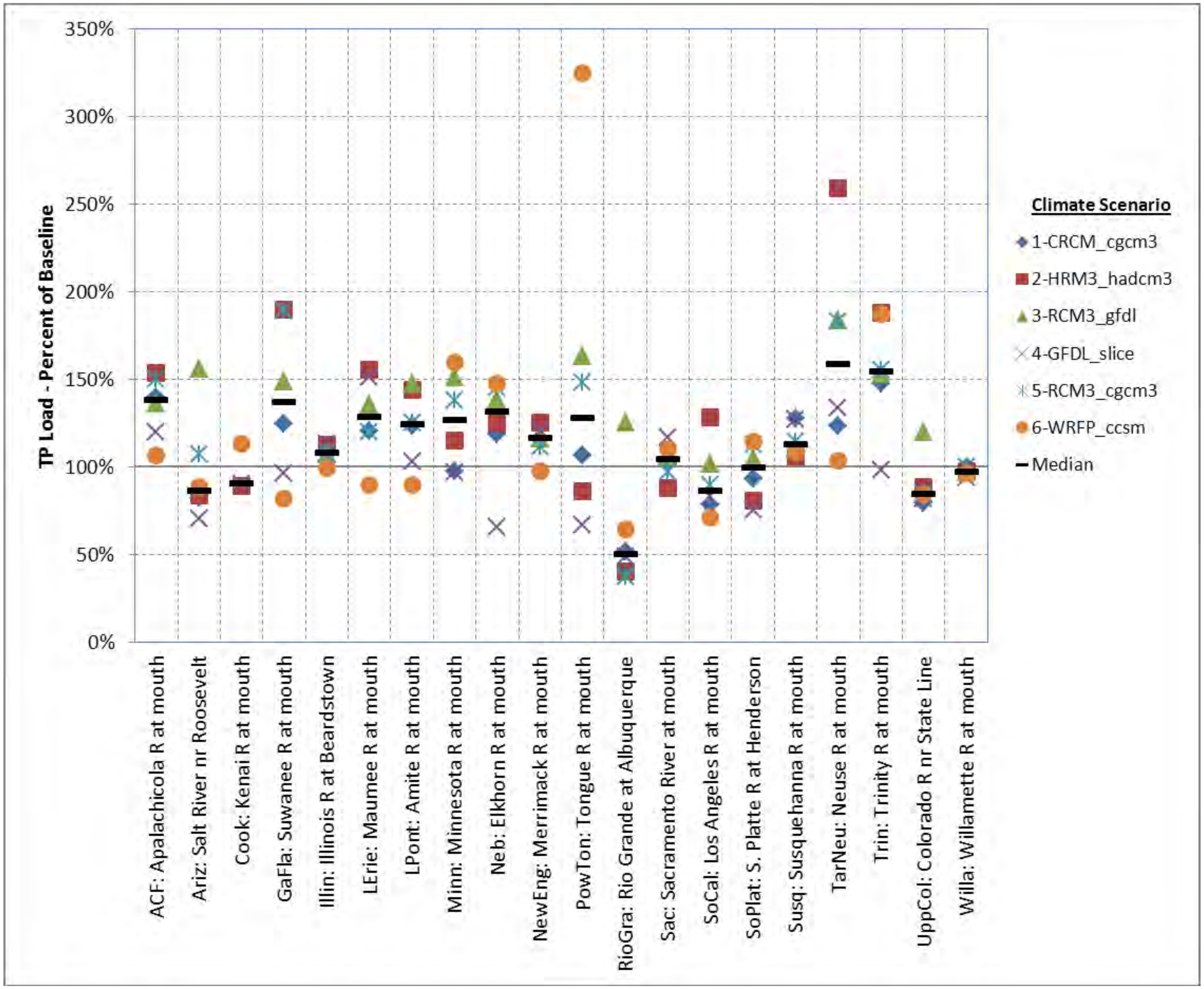

Figure 7-16. Simulated total phosphorus load relative to current conditions (NARCCAP climate scenarios with urban development) for selected downstream stations.

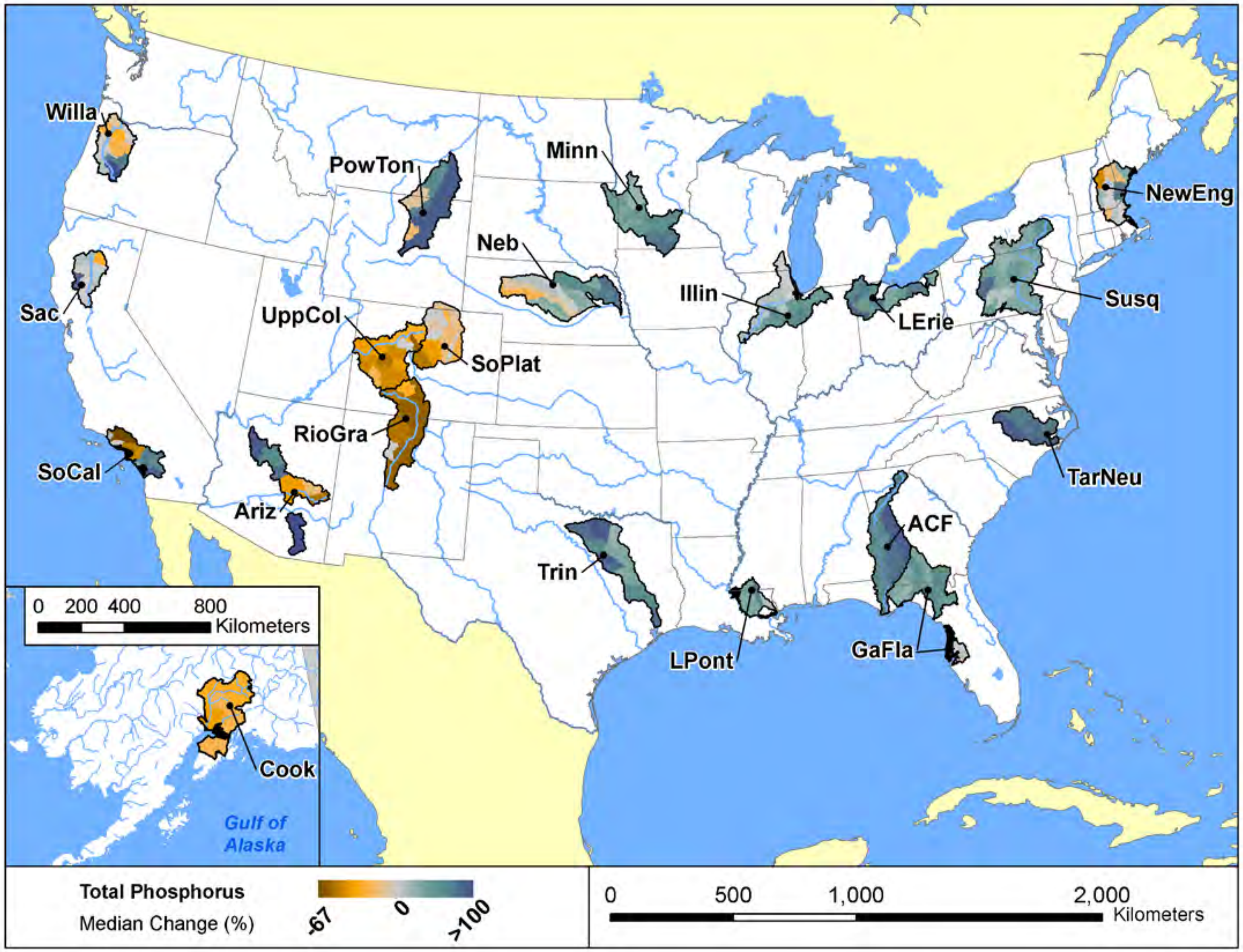

Figure 7-17. Median simulated percent changes in total phosphorus loads for six NARCCAP scenarios relative to current conditions by HUC-8 (median of NARCCAP climate scenarios with urban development).

Note: Cook Inlet results do not include land-use change.

Table 7-27. Simulated total nitrogen load (climate and land-use change scenarios; percent relative to current conditions) for selected downstream stations

Station	Study area	CRCM_ cgcm3 (%)	HRM3_ hadcm3 (%)	RCM3_ gfdl (%)	GFDL_ slice (%)	RCM3_ cgcm3 (%)	WRFP_ ccsm (%)	Median (%)
Apalachicola R at outlet	ACF	117	126	116	107	123	96	117
Salt River near Roosevelt	Ariz	90	91	142	87	105	85	91
Kenai R at Soldotna	Cook	ND	200	ND	175	ND	223	200
Suwanee R at outlet	GaFla	129	167	139	113	171	86	134
Illinois R at Marseilles, IL	Illin	103	117	105	109	107	93	106
Maumee R at outlet	LErie	127	158	161	190	125	94	142
Amite R at outlet	LPont	130	152	153	113	127	95	128
Minnesota R at outlet	Minn	126	130	163	104	158	170	144
Elkhorn R at outlet	Neb	93	97	145	88	104	107	100
Merrimack R at outlet	NewEng	123	131	121	124	116	103	122
Tongue R at outlet	PowTon	109	91	165	71	148	320	128
Rio Grande R below Albuquerque	RioGra	50	38	127	48	37	65	49
Sacramento R at outlet	Sac	104	94	105	113	103	111	104
Los Angeles R at outlet	SoCal	125	159	154	102	96	101	113
S. Platte R at outlet	SoPlat	89	72	95	65	112	120	92
Susquehanna R at outlet	Susq	161	146	146	155	149	131	147
Neuse R at outlet	TarNeu	120	207	166	125	155	105	140
Trinity R at outlet	Trin	140	187	142	93	153	186	148
Colorado R near State Line	UppCol	73	82	111	76	80	79	80
Willamette R at outlet	Willa	106	98	97	91	105	95	97

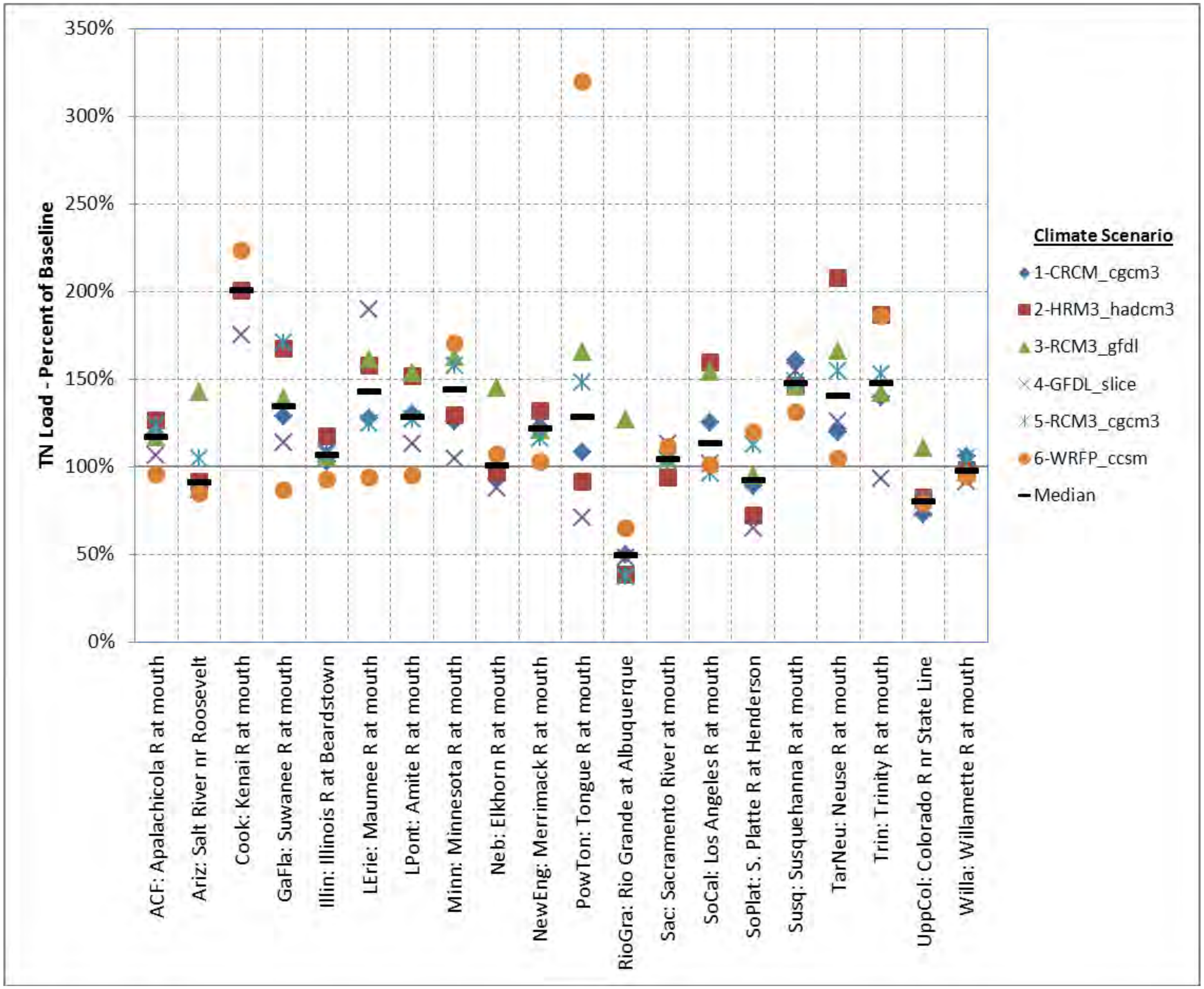

Figure 7-18. Simulated total nitrogen load relative to current conditions (NARCCAP climate scenarios with urban development) for selected downstream stations.

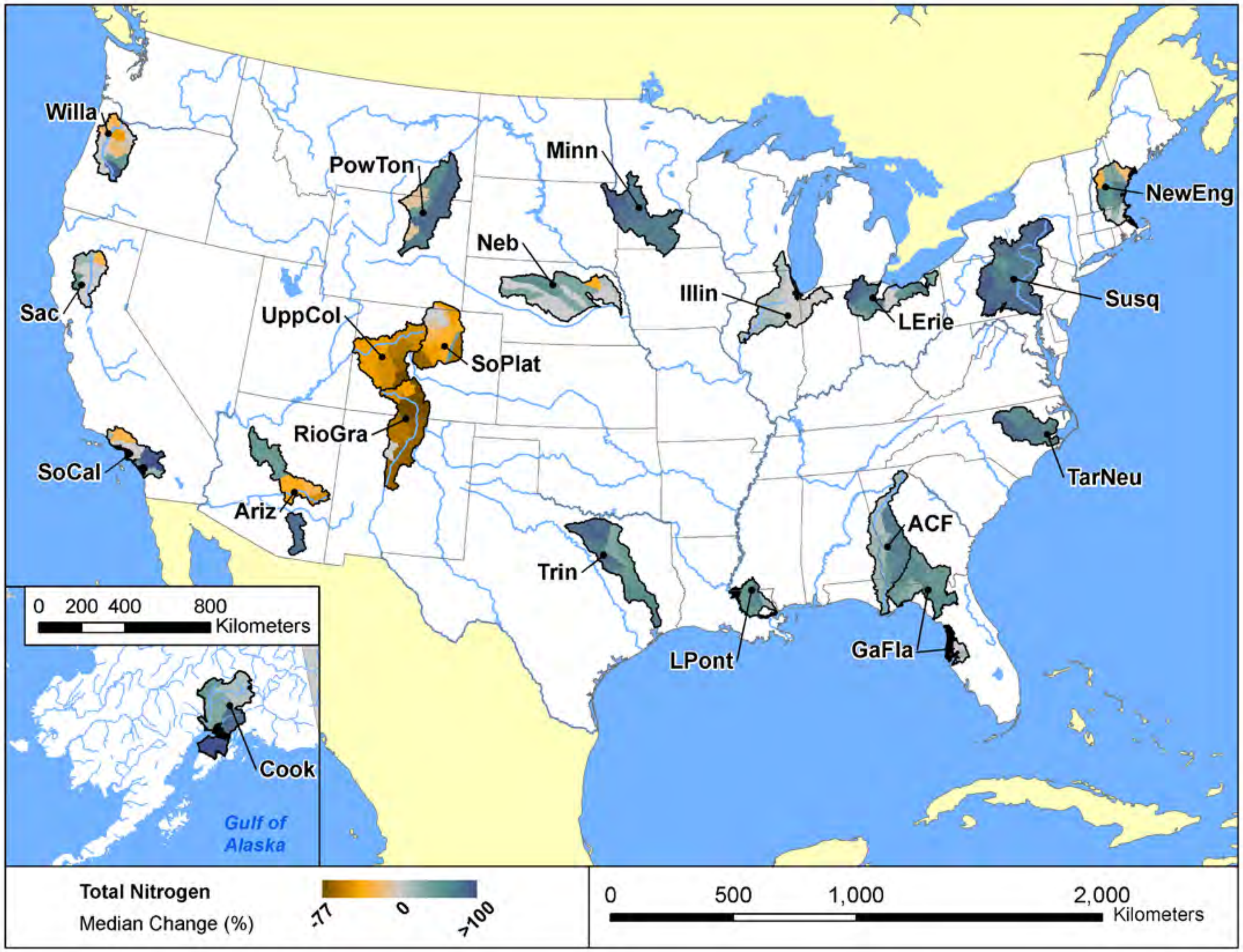

Figure 7-19. Median simulated percent changes in total nitrogen loads for six NARCCAP scenarios relative to current conditions by HUC-8 (median of NARCCAP climate scenarios with urban development).

Note: Cook Inlet results do not include land-use change.

Table 7-28. Simulated percent changes in water balance statistics for study areas (NARCCAP climate with land-use change scenarios; median percent change relative to current conditions)

Study Area	Dryness Ratio (fraction of precipitation lost to ET) (%)	Low Flow Sensitivity (baseflow generation, cfs/mi^2) (%)	Surface Runoff Fraction of Flow (%)	Snowmelt Fraction of Flow (%)	Deep Recharge Rate (depth) (%)
ACF	0	−16	22	−57	−14
Ariz-Salt	1	−10	−5	−46	−15
Ariz-San Pedro	−1	−7	23	−52	−12
Ariz-Verde	−2	−3	7	−50	4
Cook	−8	22	4	−12	−43
GaFla-North	−10	47	−8	−32	39
GaFla-Tampa	−6	8	11	−72	7
Illin	−1	−7	15	−39	−6
LErie	−3	22	−4	−32	20
LPont	−10	59	−14	−22	47
Minn	−5	28	49	−24	24
Neb-Elkhorn	0	3	16	−24	1
Neb-Loup	−3	12	−1	−33	13
NewEng	−1	−6	1	−82	−5
PowTon-Powder	−7	18	−1	−18	NA
PowTon-Tongue	−6	5	6	−17	−8
RioGra	2	−28	3	−1	−28
Sac	0	−4	4	−45	−6
SoCal	−2	−5	7	−54	1
SoPlat	−1	−6	1	−17	NA
Susq	0	−6	16	−31	−5
TarNeu	−8	15	5	−49	15
Trin	−4	−1	2	−43	0
UppCol	1	−8	−4	−15	−16
Willa	−11	5	1	−68	6

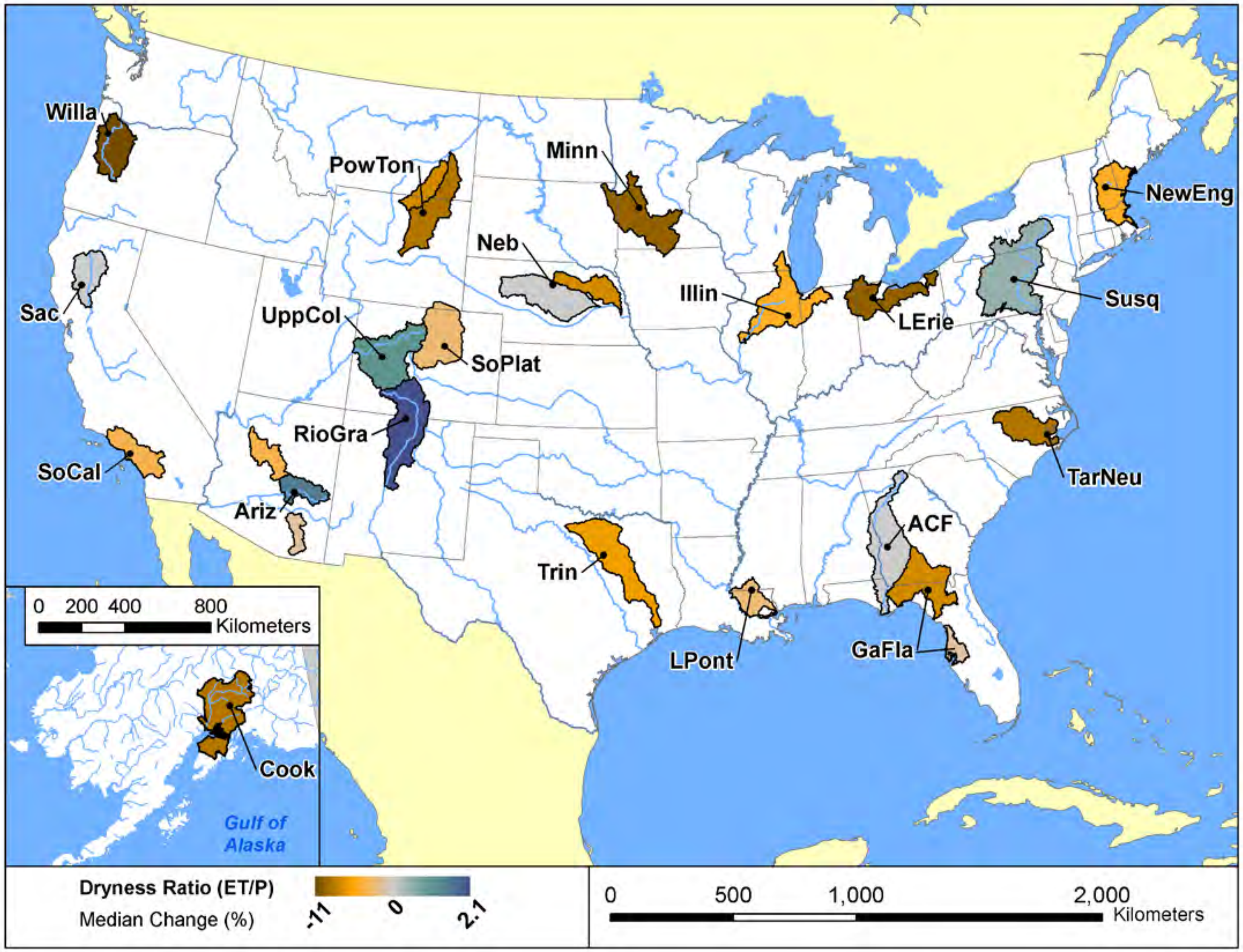

Figure 7-20. Median simulated percent changes in watershed Dryness Ratio for six NARCCAP scenarios relative to current conditions (median of NARCCAP climate scenarios with urban development).

Note: Dryness ratio is the fraction of input precipitation lost to ET. Cook Inlet results do not include land-use change.

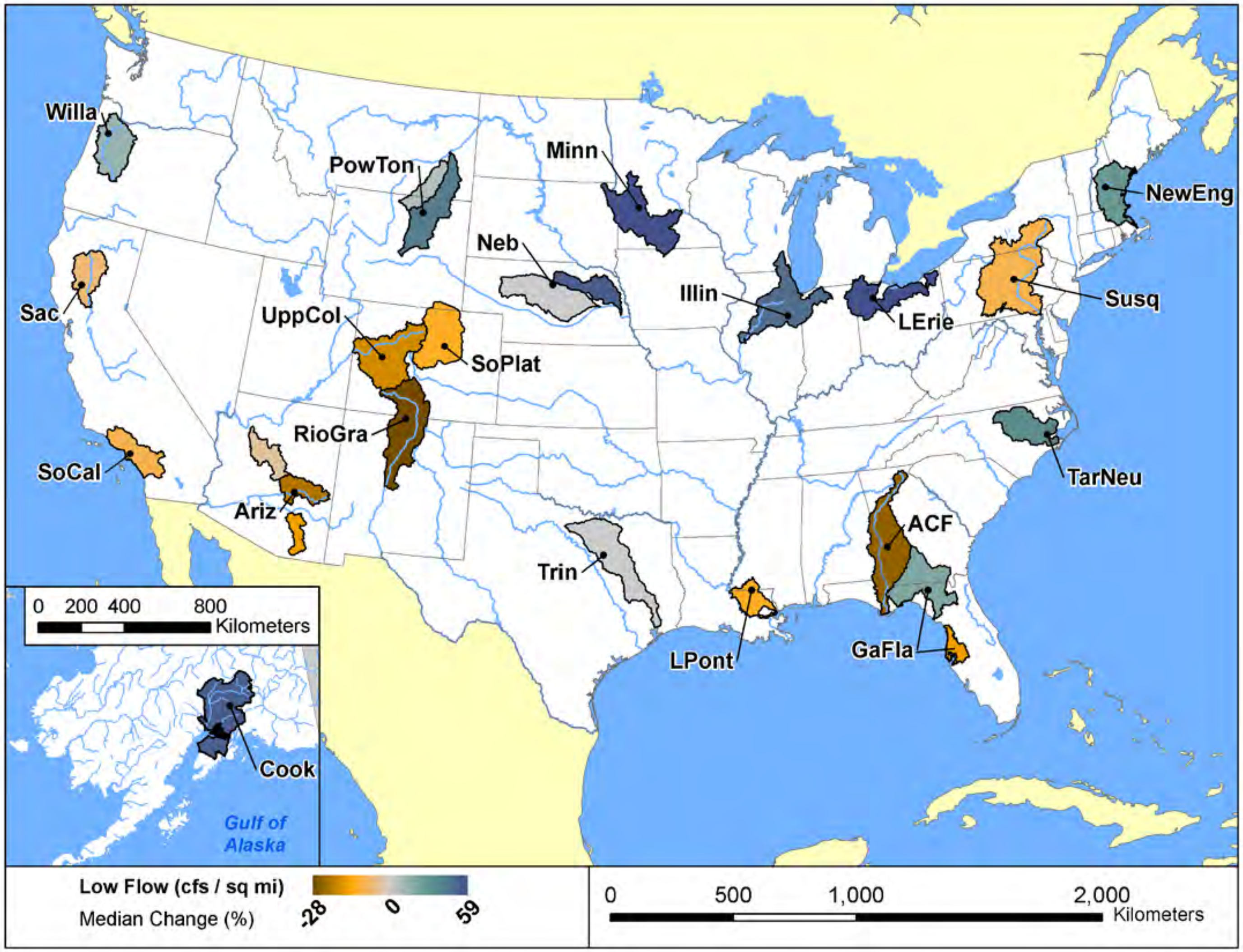

Figure 7-21. Median simulated percent changes in watershed Low Flow Sensitivity for six NARCCAP scenarios relative to current conditions (median of NARCCAP climate scenarios with urban development).

Note: Low Flow Sensitivity is the rate of streamflow generation by baseflow (cfs/mi^2). Cook Inlet results do not include land-use change.

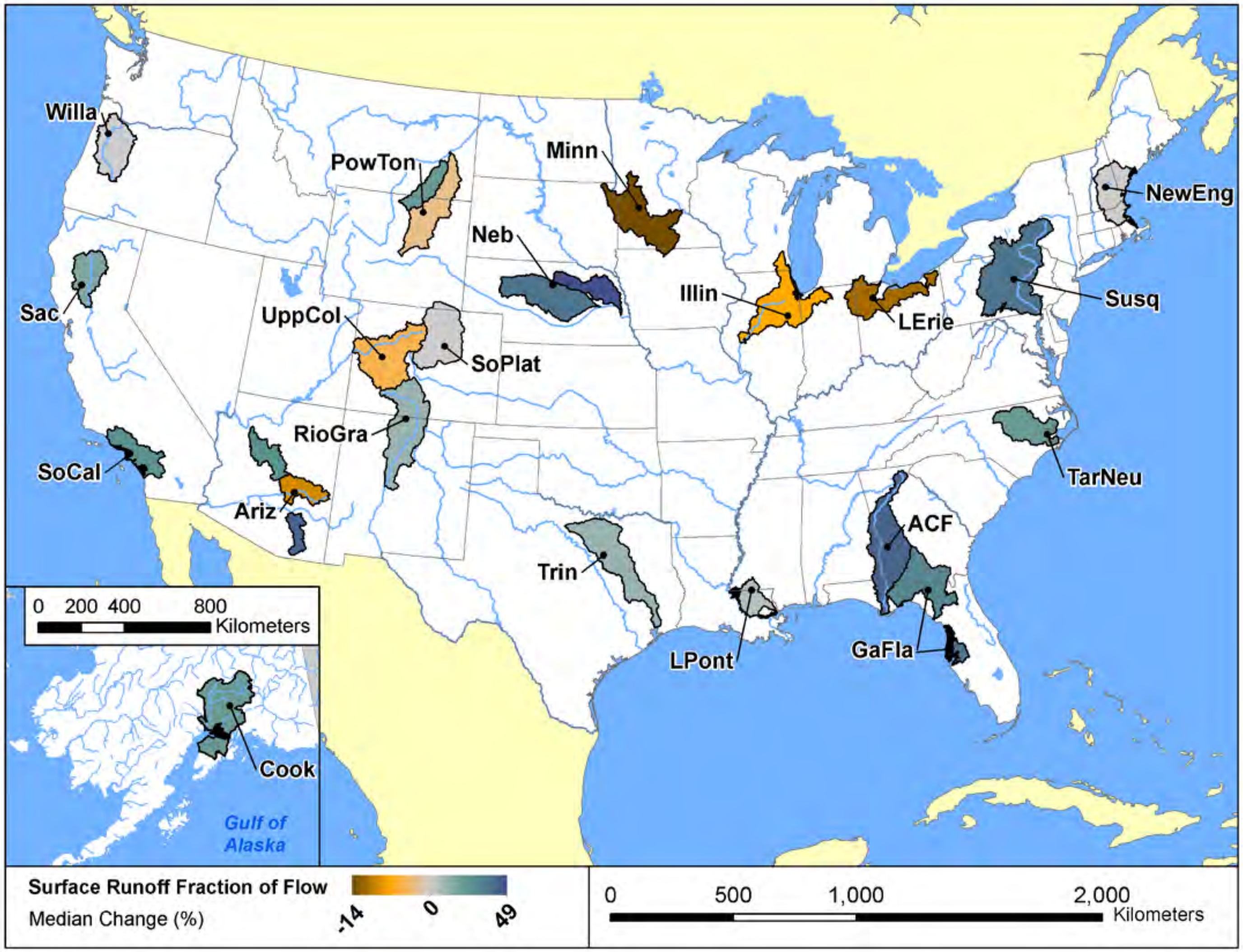

Figure 7-22. Median simulated percent changes in watershed Surface Runoff Fraction for six NARCCAP scenarios relative to current conditions (median of NARCCAP climate scenarios with urban development).

Note: Surface Runoff Fraction is the fraction of streamflow contributed by overland flow pathways. Cook Inlet results do not include land-use change.

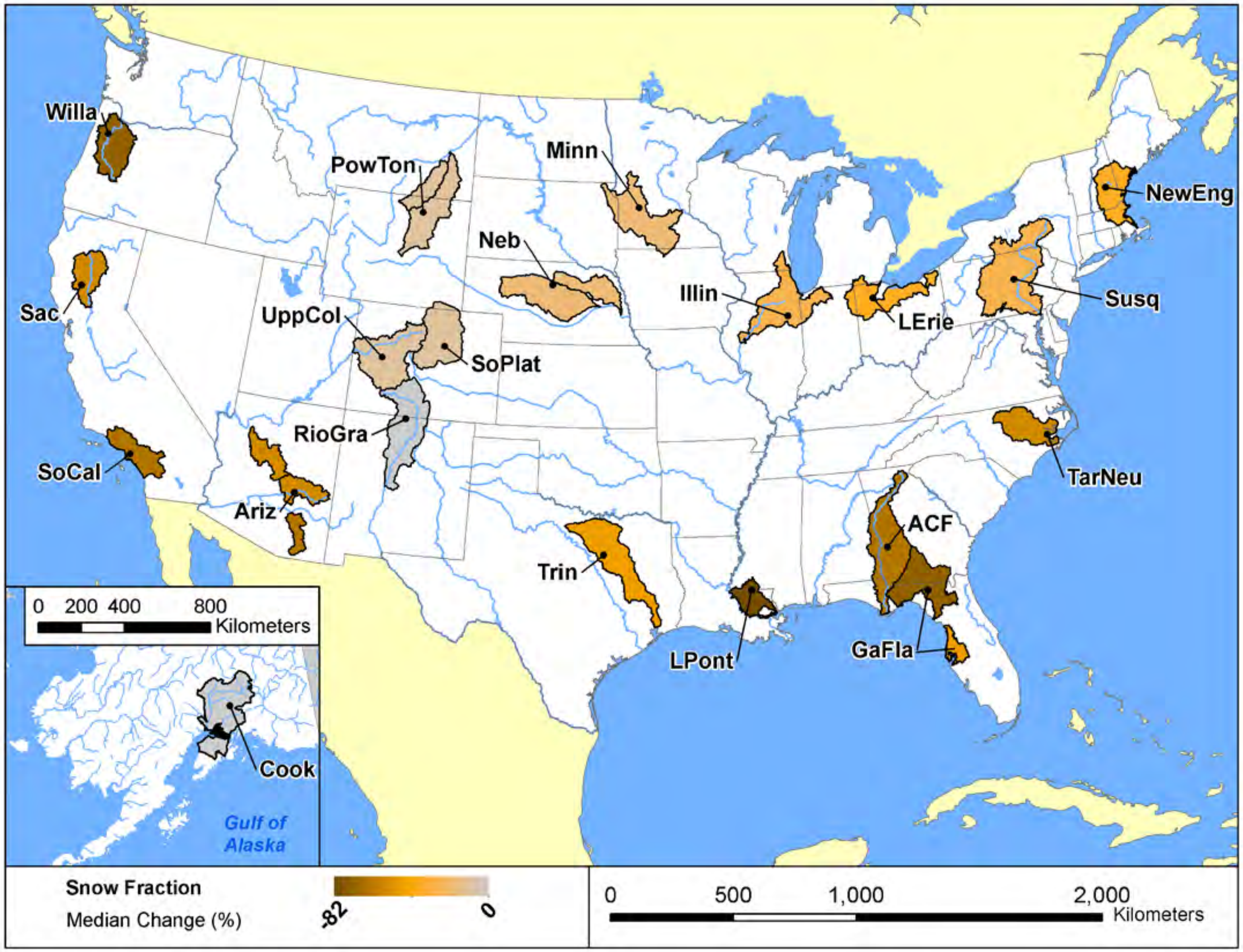

Figure 7-23. Median simulated percent changes in watershed Snowmelt Fraction for six NARCCAP scenarios relative to current conditions (median of NARCCAP climate scenarios with urban development).

Note: Snowmelt Fraction is the fraction of streamflow contributed by snowmelt. Cook Inlet results do not include land-use change.

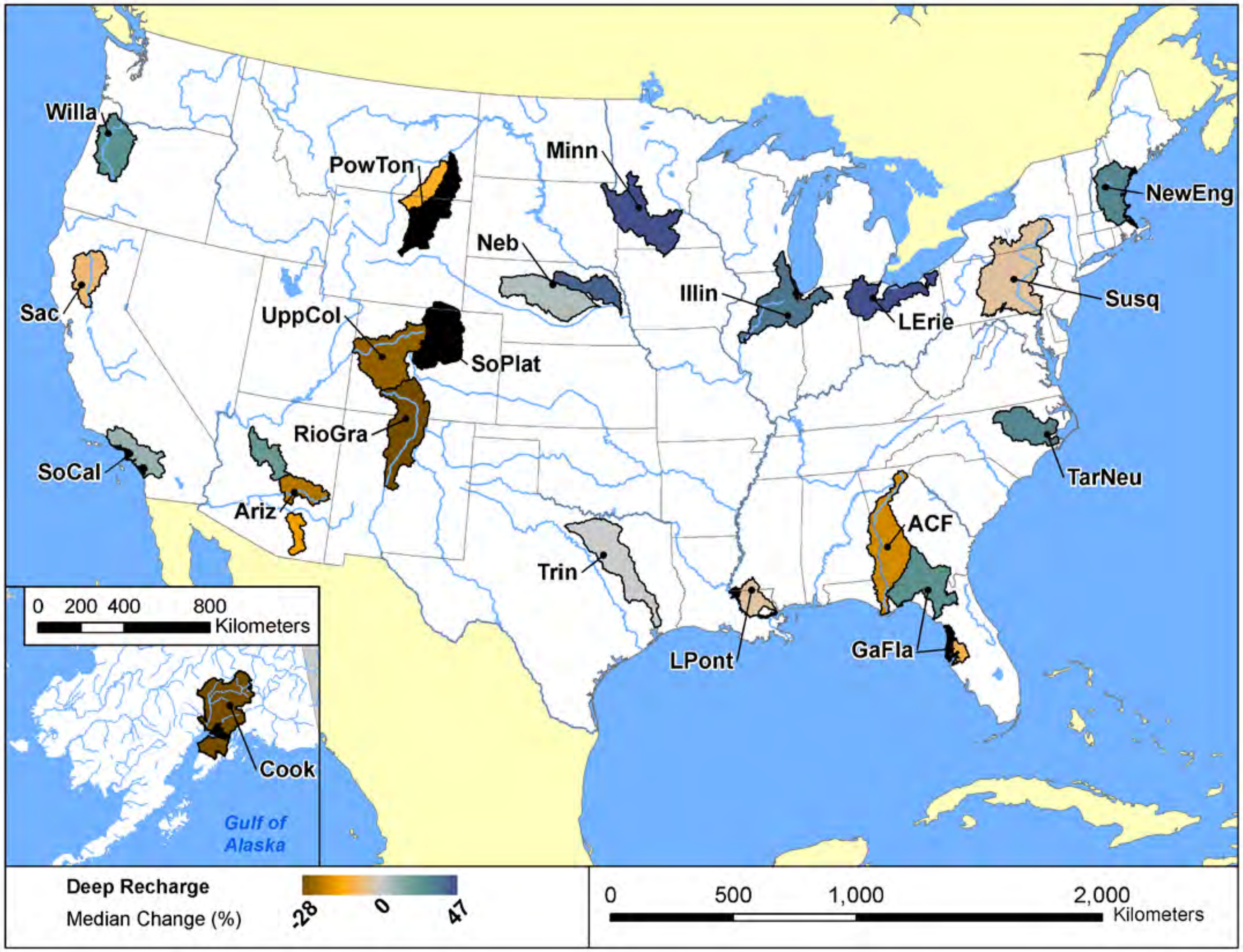

Figure 7-24. Median simulated percent changes in watershed Deep Recharge for six NARCCAP scenarios relative to current conditions (median of NARCCAP climate scenarios with urban development).

Note: Deep Recharge is the depth of water recharging deep aquifers per unit time. Cook Inlet results do not include land-use change. Areas shown in black have no deep recharge simulated.

The water balance summaries are presented as averages over whole watersheds. These are generally consistent with the project study areas, except that several study areas (e.g., Central Nebraska) were simulated using more than one SWAT model and thus show multiple results. Figure 7-20 shows the change in the Dryness Ratio, expressed as the ratio of ET to precipitation. The central tendency of the Dryness Ratio is estimated to increase in the southern Rocky Mountains and adjacent parts of Arizona, consistent with median decreases in simulated mean annual streamflow (see Figure 7-4).

Another aspect of low flows is shown by the Low Flow Sensitivity metric—the average rate of baseflow generation per square mile of watershed area. This metric (see Figure 7-21) decreases in areas for which the Dryness Ratio increases. However, it also decreases in various other watersheds (such as SoCal and ACF) for which there is little change in the Dryness Ratio. Areas where the Low Flow Sensitivity metric decreases may be expected to experience difficulties in maintaining minimum streamflow for aquatic life support or for meeting wasteload dilution expectations.

The Surface Runoff Fraction (the fraction of streamflow contributed by overland flow pathways) increases strongly for various study areas on the east coast and some other areas, mostly due to intensification of rainfall events in climate models (see Figure 7-22). Study areas for which the Surface Runoff Fraction strongly increases, such as ACF and Ariz-San Pedro, are those where the Low Flow Sensitivity decreases despite relatively small changes in the Dryness Ratio.

Snowmelt Fraction, the fraction of runoff that is due to melting snow (see Figure 7-23) declines in all watersheds. The strongest percentage declines (in southern and coastal areas) are somewhat misleading, as these watersheds generally have small amounts of snow. The lesser percentage declines throughout the Rockies are of greater concern to water management in the west.

The combination of a greater fraction of surface runoff in many watersheds coupled with increased dryness and reduced total streamflow in many western watersheds leads to a reduction in projected Deep Recharge (rates of recharge to deep aquifers) in many study areas (see Figure 7-24). The risks are estimated to be particularly acute in the Rockies and the ACF basins. In other areas, increased precipitation in the models counteracts other forces through mid-century, including the critical recharge areas in central Nebraska.

7.7. MODELING ASSUMPTIONS AND LIMITATIONS

Model simualtions in the study provide an improved understanding of streamflow and water quality sensitivity in different regions of the United States to a range of plausible mid-21st century climate change and urban development scnearios. The study also illustrates certain challenges associated with the use of watershed models for conducting scenario-based studies of climate change impacts. In the process, this study adds to our knowledge of how to implement such investigations.

A number of sources of uncertainty must be considered in interpreting results from watershed hydrologic and water quality simulations of response to climate change—including uncertainty in the emissions scenario, uncertainty in the GCM simulations of future climate, uncertainty in the downscaling of these GCM outputs to the local scale, and uncertainty in the watershed models used to translate potential changes in local climate to watershed response. The strong dependence of streamflow and water quality on climate drivers (e.g., temperature, precipitation, etc.) means that accurate weather data is necessary to generate accurate estimates of future flow and water quality conditions. Inherent in the scenario approach to modeling climate futures is uncertainty in knowledge of future climate conditions. It is therefore necessary to choose a range of scenarios that reflect the full, plausible set of future conditions.

Simulation results showed a wide range of watershed responses to differences in climatic forcing. Results suggest the variability resulting from scenarios based on different methods of downscaling with a single GCM can be of the same order of magnitude as the variability among GCMs. In many cases, simulations for scenarios based on different downscaling approaches with a single GCM do not agree even in the direction of projected changes relative to current values. In part, this issue reflects the skill associated with RCM simulations. A recent study by Racherla et al. (2012) investigated the value added by using an RCM (the Weather Research and Forecasting or WRF model) with the GCM GISS-ModelE2 and concluded that the RCM does not achieve holistic improvement in the simulation of seasonally and regionally averaged surface temperature or precipitation for historical data. They further suggested that no strong relationship exists between skill in capturing climatological means and skill in capturing climate change. If RCMs do not add considerable value to the global simulation, the underlying uncertainties can only be reduced by improving the global-scale climate simulations.

As with any study of this type, simulation results are conditional upon the specific methods, models, and scenarios used. The simulated range of response in this study is limited by the particular set of climate model projections available in the NARCCAP archives (the subset of BCSD projections was selected to match those in the NARCCAP set). For example, all climate change scenarios evaluated in this study are based on the IPCC A2 greenhouse gas emissions storyline. While simulations in this study represent a credible set of plausible future climatic conditions, the scenarios evaluated should not be considered comprehensive of all possible futures. A recent summary by Mote et al. (2011) concludes that ensemble scenarios with a limited number of projections taken from the full set of available climate models yields results that differ little from those achieved from larger sets given the current state of science; furthermore, attempting to preselect the “best” models based on measures of model skill does little to refine the estimate of central tendency of projected change. Mote et al. recommend a sample size of approximately ten climate scenarios, which is greater than the six used in this study. Inclusion of additional sources and types of scenarios could alter the ranges of change simulated in this study. Similarly, alternative urban and residential development scenarios would also expand the ensemble range of future responses.

Watershed model simulations developed here also do not consider feedback effects of human and ecological adaptation to change. In essence, the climate-land use-watershed system is considered independent of management and adaptation in this study. At the most direct level, various aspects of human water management such as operation of dams, water use, transboundary water inputs, and point source discharges are considered fixed at present levels. In fact, we know these will change. For instance, a warmer climate is likely to result in increased irrigation withdrawals for crops, while more intense precipitation is likely to result in changes in operating rules for dams. In some cases, the models are driven by fixed upstream boundary conditions (e.g., the Sacramento River model). There was, however, insufficient knowledge of these changes to incorporate them into the scenarios. The analyses thus provide an increased understanding of the marginal changes in watershed responses due to potential changes in climate and urban and residential development, but do not account for the net changes from all factors, including human use and management of water.

At a more sophisticated level, both natural and human communities are likely to adapt to climate changes, influencing the watershed response. The SWAT plant growth model takes into account the effects of changed climate on plant growth as a function of CO_2, temperature, water stress, and nutrient availability. However, it does not take into account changes in the type of land cover that may occur as a result of such stresses—either slowly, as through a gradual shifting of ecological niches, or catastrophically, as might occur through drought-induced forest fires. Human adaptations that affect watershed processes will also occur. For example, crop types (or total area in crops) are likely to change as producers respond to changes in growing season length and water availability (e.g., Polsky and Easterling, 2001). Simulation models are not yet available to provide a credible analysis of such feedback loops at the scale necessary for evaulating watershed responses.

In addition, many of the modeled study areas are highly managed systems influenced by dams, water transfers and withdrawals, and point and nonpoint pollution sources. Given the difficulty inherent in modeling watershed response at the large spatial scale used in this study, detailed representation of all management and operational activities was not possible. Results therefore represent the potential response of watersheds to different change scenarios, but should not be considered quantitative forecasts of future conditions.

7.7.1. Model Calibration

Reliably reproducing the baseline period is important for any study of watershed response to climate change because any biases present in the model calibration are likely to also affect the future simulations of streamflow (Prudhomme and Davies, 2009), possibly with nonlinear amplification. The experiences of this project emphasize the importance (and challenges) of calibration and validation for watershed models. Water quality calibration is particularly challenging due to limited amounts of readily available monitoring data. Additional efforts similar to the one presented here should either focus on watersheds for which well-calibrated models already exist (and the effort of assembling water quality input and monitoring data from multiple sources has already been completed) or allocate sufficient time and budget to conduct detailed, site-specific calibration.

The calibration process can introduce modeler bias, which could be mitigated through use of an automated model calibration scheme. We avoided this option based on past experience with the SWAT and HSPF models in which automated calibration often converges to physically unrealistic model parameter sets. It may, however, be advisable to pursue stepwise, guided model calibration with carefully specified parameter constraints to avoid the effects of user bias, as was done, for example, in recent USGS simulations of watershed-scale streamflow response to climate change using the PRMS model (Hay et al., 2011). PRMS, however, only addresses streamflow and has a much more parsimonious data set than does SWAT or HSPF. Nonetheless, the advantages of controlling for modeler bias may make use of a semiautomated calibration procedure desirable.

The significance of calibration bias is mitigated by focusing on projected changes relative to baseline conditions as compared to actual future values. If biases are consistent and linear between the baseline and future condition, the effect of such biases will tend to cancel out when relative change is calculated. There is, however, no guarantee that biases will be linear. Further testing to evaluate the effects of alternative model calibrations on the simulated response of different study areas would be desirable.

7.7.2. Watershed Model Selection

Simulation results are sensitive to the watershed model applied. In the pilot studies, both HSPF and SWAT appeared capable of providing similar quality of fit to observed streamflow at the large basin scale and to pollutant loads at the monthly scale, while HSPF, using a shorter time step, was better able to resolve streamflow at smaller spatial scales and better able to match observed concentrations when fully calibrated. An important result of model comparisons conducted in this study is the significant effect that increased atmospheric CO_2 concentrations (effects of reduced stomatal conductance that decrease ET) appeared to have on the water balance. SWAT's integrated plant growth model takes this effect into account, whereas HSPF does not.

It is unclear, however, how well SWAT is able to represent the complex processes affecting plant growth, nutrient dynamics, and water budgets under changing climate. For example, as CO_2 levels increase, leaf level reductions in stomatal conductance and evapotranspiration may be offset by increased plant growth and leaf area. The effects of CO_2 on plant growth may also be altered over time due to nutrient limitation (Reich et al., 2006). Further study is required to better understand how climate change will affect these processes. It should also be noted that SWAT (as implemented here, using version SWAT2005) has limitations in its representation of a number of important watershed processes, including simplified simulation of direct runoff using a curve number approach, erosion prediction with MUSLE that does not fully incorporate changes in energy that may occur with altered precipitation regimes, and a simplistic representation of channel erosion processes that appears unlikely to provide a firm foundation for simulating channel stability responses to climate change. More recent versions of SWAT considerably expand the options for simulating channel erosion, but do not appear to be fully validated at this time and are limited by the model's use of a daily time step for hydrology.

These considerations suggest that a more sophisticated watershed model formulation, combining a plant growth model (as in SWAT) with a more detailed hydrologic simulation would be preferable for evaluating watershed responses to climate change. However, even if such a model was available, fully validated, and ready for use, it would likely require a significantly higher level of effort for model implementation and calibration.

Comparison of change scenarios using HSPF and SWAT suggests one must proceed with caution when attempting to estimate even relative aggregate impacts at a national scale through use of watershed models with different underlying formulations. For example, a national synthesis that drew conclusions from a mix of models, some of which did and others of which did not include explicit simulation of effects of increased CO_2 on evapotranspiration, could reach erroneous conclusions regarding the relative intensity of impacts in different geographical areas.

8. SUMMARY AND CONCLUSIONS

This report describes watershed modeling in 20 large, U.S. drainage basins (6,000−27,000 mi^2 or 15,000−60,000 km^2) to characterize the sensitivity of streamflow, nutrient (nitrogen and phosphorus) loading, and sediment loading to a range of potential mid-21st century climate futures, to assess the potential interaction of climate change and urbanization in these basins, and to improve our understanding of methodological challenges associated with integrating existing tools (e.g., climate models, downscaling approaches, and watershed models) and data sets to address these scientific questions. Study areas were selected to represent a range of geographic, hydroclimatic, physiographic, land use, and other watershed attributes. Other important criteria used in site selection included the availability of necessary data for calibration and validation of watershed models, and opportunities for leveraging the availability of preexisting watershed models.

Models were configured by subdividing study areas into modeling units, followed by continuous simulation of streamflow and water quality for these units using meteorological, land use, soil, and stream data. A unique feature of this study is the use of a consistent watershed modeling methodology and a common set of climate and land-use change scenarios in multiple locations across the nation. Models in each study area are developed for current (1971−2000) observed conditions, and then used to simulate results under a range of potential mid-21st century (2041−2070) climate change and urban development scenarios. Watershed modeling was conducted at each study location using the SWAT model and six climate change scenarios based on dynamically downscaled (50×50 km^2) output from four of the GCMs used in the IPCC 4th Assessment Report for the period 2041−2070 archived by the NARCCAP. Scenarios were created by adjusting historical weather series to represent projected changes in climate using a change factor approach. To explore the potential interaction of climate change and urbanization, simulations also include urban and residential development scenarios for each of the 20 study watersheds. Urban and residential development scenarios were acquired from EPA's national-scale ICLUS project.

In a subset of five study areas (the Minnesota River, the Susquehanna River, the Apalachicola-Chattahoochee-Flint, the Salt/Verde/San Pedro, and the Willamette River Basins), additional simulations were conducted to assess the variability in simulated watershed response resulting from use of different watershed models and different approaches for downscaling GCM climate change scenarios. In these study areas, watershed simulations were also run with eight additional scenarios derived from the same four GCMs used in NARCCAP: four scenarios interpolated to station locations directly from the GCM output, and four scenarios based on BCSD statistically downscaled climate projections described by Maurer et al. (2007). In addition, in these five study areas, all scenario simulations were run independently with a second watershed simulation model, the HSPF.

Given the large size of study areas, calibration and validation of all models was completed by first focusing on a single HUC-8 within the larger study area (preferably one with a good record of streamflow gaging and water quality monitoring data), and then extending the calibration to adjacent areas with modifications as needed to achieve a reasonable fit at multiple spatial scales.

Large-scale GCM projections are generally consistent in showing a continued warming trend over the next century (although with sometimes significant regional-scale disagreements in the magnitude of this warming), but offer a much wider range of plausible outcomes in other aspects of local climate—particularly the timing and intensity of precipitation and the energy inputs (in addition to air temperature) that determine potential evapotranspiration—that interact to create watershed responses.

The simulated watershed responses to these changes provide an improved understanding of system sensitivity to potential climate change and urban development scenarios in different regions of the country and provide a range of plausible future hydrologic and water quality change scenarios that can be applied in various planning and scoping frameworks. The results illustrate a high degree of regional variability in the response of different streamflow and water quality endpoints to a range of potential mid-21st century climatic conditions in different regions of the nation. Watershed hydrologic response is determined by the interaction of precipitation and evapotranspiration, while water quality response is largely dependent on hydrology. Comparison of simulations in all 20 study areas for the 2041−2070 time horizon suggest potential streamflow volume decrease in the Rockies and interior southwest, and increases in the east and southeast coasts. Wetter winters and earlier snowmelt are likely in many of the northern and higher elevation watersheds. Higher peak flows will also increase erosion and sediment transport; nitrogen and phosphorus loads are also likely to increase in many watersheds.

Both the selection of an underlying GCM and the choice of downscaling method have a significant influence on the streamflow and water quality simulations. In many cases, the range of simulated responses across the different climate models and downscaling methodologies do not agree in direction. The ultimate significance of any given simulation of future change will depend on local context, including the historical range of variability, thresholds and management targets, management options, and interaction with other stressors. The simulation results in this study do, however, clearly illustrate that the potential streamflow and water quality response in many areas could be large.

Watershed simulations were run in all study areas with and without projected mid-21st century changes in urban and residential development. These results suggest that at the HUC-8 spatial scale evaluated in this study, watershed sensitivity to projected urban and residential development will be small relative to the changes resulting from climate change. It is important, however, to qualify this result. The finest spatial scale reported in this study is that of an 8-digit HUC, and most urbanized areas are located on larger rivers downstream of multiple 8-digit HUCs. Over the whole of individual study areas, urban and residential growth scenarios represented changes in the amount of developed land on the order of <1 to about 12% of total watershed area and increases in impervious surfaces on the order of 0 to 5% of total watershed area. The effects of urban development on adjacent water bodies at higher levels of development are well documented. It is thus likely that at smaller spatial scales within study areas where the relative fraction of developed land is greater, the effects of urbanization will be greater. Identifying the scale at which urbanization effects become comparable to the effects of a changing climate is an important topic for future research.

The simulation results also illustrate a number of methodological issues related to impacts assessment modeling. These include the sensitivities and uncertainties associated with use of different watershed models, different approaches for downscaling climate change simulations from global models, and the interaction between climate change and other forcing factors, such as urbanization and the effects of changes in atmospheric CO_2 concentrations on evapotranspiration. Uncertainty associated with differences in emission scenarios and climate model sensitivities is well known and widely discussed in previous assessments of climate change impacts on water (e.g., IPCC, 2007; Karl et al., 2009). This study illustrates a potentially significant additional sensitivity of watershed simulations to the method selected for downscaling GCM model output. Results of the intercomparison of climate change data sets suggest that the variability between downscaling of a single GCM with different RCMs can be of the same order of magnitude as the ensemble variability between GCMs.

This study also suggests potentially important sensitivity of results to the use of different hydrologic models (HSPF and SWAT in this study), associated with differences in process representation, such as accounting for the influence of increased atmospheric CO_2 on evapotranspiration. One notable insight from these results is that, in many watersheds, climate change (when precipitation amount and/or intensity is altered), increasing urbanization, and increasing atmospheric CO_2 can have similar or additive effects on streamflow and pollutant loading (e.g., a more flashy runoff response with higher high flows and lower low flows). The results, while useful as guidance for designing and conducting similar impacts assessment studies, are only a first step in understanding what are likely highly complex and context-dependent relationships. Further study and evaluation of the implications of these and other questions is necessary for improving the plausibility and relevance of coupled climate-hydrology simulations, and ultimately for informing resource managers and climate change adaptation strategies.

The model simulations in this study contribute to a growing understanding of the complex and context-dependent relationships between climate change, land development, and water in different regions of the nation. As a first order conclusion, results indicate that in many locations future conditions are likely to be different from past experience. In the context of decision making, being aware and planning for this uncertainty is preferable to accepting a position that later turns out to be incorrect. Results also provide a plausible envelope on the range of streamflow and water quality responses to mid-21st century climate change and urban development in different regions of the nation. In addition, in many study areas the simulations suggest a likely direction of change of streamflow and water quality endpoints. This information can be useful in planning for anticipated but uncertain future conditions. The sensitivity studies evaluating different methodological choices help to improve the scientific foundation for conducting climate change impacts assessments, thus building the capacity of the water management community to understand and respond to climate change.

Understanding and responding to climate change is complex, and this study is only an incremental step towards fully addressing these questions. It must be stressed that results are conditional upon the methods, models, and scenarios used in this study. Scenarios represent a plausible range but are not comprehensive of all possible futures. Several of the study areas are also complex, highly managed systems; all infrastructure and operational aspects of water management are not represented in full detail. Finally, changes in agricultural practices, water demand, other human responses, and natural ecosystem changes such as the prevalence of forest fire (e.g., Westerling et al., 2006) or plant disease that will influence streamflow and water quality are not considered in this study. Further study is required to continue to build the scientific foundation for assessing these and other questions relevant to the scientific and watershed management communities.

Successful climate change adaptation strategies will need to encompass practices and decisions to reduce vulnerabilities across a wide range of plausible future climatic conditions. Where system thresholds are known, knowledge of the range of potential changes can help to identify the need to consider future climate change in water planning. Many of these strategies might also help reduce the impacts of other existing stressors. It is the ultimate goal of this study to build awareness of the potential range of future watershed response so that where simulations suggest large and potentially disruptive changes, the management community will respond to build climate resiliency.

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Appendix A
Model Setup Process

1 Overview

This memorandum describes the protocol to ensure an efficient and consistent model setup process to implement the SWAT and HSPF models for the 20 Watersheds study areas.

Modeling in this study addresses large study areas, with an emphasis on relative change for future conditions. A simplified approach is used for land use and soils coverages to the extent possible to make this efficient. SWAT setup and calibration starts from a common land use platform representing current (calibration) conditions.

Simplifying principles include the following:

- Optimize for automated processing, taking advantage of features already built into ArcSWAT.
- Calibrate first for one 8-digit HUC, then extend to whole study area. The calibration HUC should be selected in an area with the greatest availability of hydrology and water quality calibration data. Avoid selecting a calibration HUC8 with complicating features, such as large reservoirs.
- SWAT is set up in the usual way, using an HRU overlay of land use and STATSGO soils.
- Use only weather stations already processed for BASINS 4 and supplied to the team. Account for sparse coverage by using elevation bands in areas of high relief.
- Existing impervious area is identified based on NLCD products.
- HSPF setup is based on the same spatial coverages as SWAT but requires additional processing in the WinHSPF interface.
- HSPF is developed only for the five pilot watersheds.

2 Processing Steps

2.1 Initial Setup

Initial GIS processing has been performed by Tt in ArcGIS for the whole study area. Processed GIS inputs are then used in ArcSWAT (which runs as an extension in ArcGIS).

Watershed Boundaries and Reach Hydrography

Subbasin boundaries and reach hydrography have been created from NHDPlus. In general these delineations should be sufficient for application and isolation of appropriate calibration points. Note that many river "basins" have multiple outlets, notably those adjacent to the Great Lakes or ocean shorelines.

DEM

Mosaic-ed DEMs are supplied for the full extent of the model watershed area. ArcSWAT will create a slope grid during model setup. For some of the study areas (notably those with significant shoreline adjacent to an ocean or Great Lake), the DEM extent does not fully overlap the subbasin extent, due to differences in shoreline representation in the parent spatial files. If the study area has shoreline, or if the SWAT "subbasin delineation" process fails, we recommend the following ArcGIS procedure to fill the DEM NoData "holes".

- In the Single Output Map Algebra tool, use the following statement:
  con(*grid*>0,*grid*,0)
  where *grid* is the name of the DEM.
- Before executing the tool, in the Environments section set the extent to the subbasin shapefile.
- The procedure will replace NoData cells with 0 inside the subbasin extent, but not beyond. The error associated with using 0 is likely to be minimal and not adversely affect model setup.

Land Cover and Soils

1. Clipped NLCD 2001 Land Cover is provided for the extent of the model watershed area. The grid files have been modified to include four reclassified cells in each subbasin. These cells and their values are used as placeholders for updating developed land cover in future scenarios. You must use the land cover grid ending in "*_sw*" for SWAT applications.
2. NLCD 2001 Urban Imperviousness bas been analyzed to calculate developed class impervious area. This is provided in an Excel spreadsheet.
3. STATSGO soils grids are provided with ArcSWAT.

Other Data Provided

4. BASINS4 weather stations in proximity of model watersheds. Weather stations from this set must be used to enable climate updates for the scenarios. The locations are provided within the SWAT precipitation and air temperature input files on the project FTP site. ArcSWAT will create shapefiles for the weather stations during model setup.
5. Locations of major point sources are provided in an Excel file.
6. Shapefiles with locations of long-term gaging stations and water quality monitoring stations.
7. Area-averaged nitrogen wet atmospheric deposition concentration (mg/L as N) for the study area.
8. Area-averaged percent impervious values for each of the NLCD developed classes. The values were developed from an analysis specific to each study area. Both total (FIMP) and directly connected (FCIMP) values are provided.

Other Setup Tasks (to be undertaken by modeler)

1. Identify locations and characteristics of any major reservoirs. Reservoirs included in the model should be kept to the essential minimum of those that are sufficiently significant to the water balance of the simulated area (at the HUC-8 scale or greater) to include explicitly.
2. Identify locations and characteristics of any major features of the watershed affecting water balance (e.g., diversions, upstream areas not modeled, reaches that lose flow to groundwater). Some of these features may best be represented with observed flow series as boundary conditions. Irrigation should be explicitly considered only where needed as a significant part of the basin-scale water balance, e.g. Rio Grande.

Special notes for the Cook Inlet study areas

a. The projection is different from the one used for the lower 48 states. Be sure that all input data used in building the model is in the same projection as the DEM and land cover grid.
b. The DEM is in meters, not cm.
c. No wet atmospheric deposition rates for nitrogen were available, so it can be omitted from the model.
d. The SWAT soils database does not include Alaska, so the user will need to obtain appropriate STATSGO data for the extent of the model area.

2.2 SWAT MODEL SETUP

SWAT model setup follows directly from the initial setup, using the ArcSWAT extension in ArcGIS. The following items should be noted and/or followed during SWAT model setup:

Watershed Delineation

Use the Automatic Watershed Delineation option with the following steps:

1. Open the Watershed Delineation window.
2. Import the DEM for the watershed and choose the z unit as cm.
3. Select the option for using user defined watersheds.
4. Import the subbasin and reach shapefiles subsequently. Create outlets.
5. Click the calculate subbasin parameters button. Please check “Skip Longest flow path calculation” option before calculating subbasin parameters.

6. Once the subbasin parameters have been calculated, add reservoirs, if any. It is desirable to avoid inclusion of reservoirs where possible due to the difficulty in representing operating rules adequately. Therefore, only include significant/major reservoirs that have a major impact on flows. If a reservoir is at the terminus of the model area it may be ignored so that the model represents input to, rather than output from the terminal reservoir.
7. For point sources, only those identified as majors and supplied by Tt are included in the model. Create a GIS coverage of the point sources in the subbasin from the list of majors supplied by Tetra Tech. Bring in the point sources layer to aid manual addition of point sources using the ArcSWAT interface. Define the major point sources at this stage. For some watersheds it will also be necessary to define an upstream boundary condition "point source".
8. Run Watershed Topographic Report for later use.

HRU Analysis

Start with the Land Use/Soils/Slope Definition

1. Save the model often, and make complete backups as you finish major tasks.
2. Use SWAT to classify the slopes into two categories with a breakpoint at 10%.
3. Bring in STATSGO soils with the MUID option.
4. NLCD 2001 land use coverage that is supplied can be loaded directly into ArcSWAT without modification. The default NLCD class to SWAT class mapping is appropriate for most areas; however, there are added future urban land uses (codes 121, 122, 123, and 124). Use the supplied *luc.txt* file to ensure correct mapping. Adjustments to the land use assignment can be made during cover setup, or parameters for SWAT classes adjusted at a later time. The clipped grids distributed for a project include a nominal representation of **all** potential future developed classes in each subwatershed, with near-zero area (e.g., 0.001 ha). This will provide a basis for ready modification to address future land use scenarios.
5. Assign impervious percentage to developed land use classes in the SWAT urban database using the values provided for the study area. The same assumptions must be applied for the future developed land use classes UFRL, UFRM, UFRH, and UFHI, i.e., the future classes will have the same total and connected impervious fractions as the corresponding URLD, URMD, URHD, and UIDU urban land uses. Within ArcSWAT, the impervious values are saved to the main program geodatabase at C:\Program Files\SWAT\SWAT2005.mdb. The corresponding urban.dat file is regenerated from the geodatabase each time the model is run from the ArcGIS interface. This has another important implication: If a given model is ported to a different machine, the SWAT2005.mdb file must also be ported.
6. Proceed to the HRU Definition tab. Create HRUs by overlaying land use, soil, and slope at appropriate cutoff tolerance levels (usually 5% for land use, 10% for soil, and 5% for slope). BE SURE to EXCLUDE all 8 urban land use classes (URLD, URMD, URHD, UIDU, UFRL, UFRM, URFH, and UFHI) from the threshold criteria. This is done on the Land Use Refinement tab.
7. Proceed with standard SWAT model generation ("Write Input Tables") using met data provided on the project FTP site (processed weather series and station locations files). Precipitation and temperature use observed series; other weather data are simulated with the weather generator. It is advisable to screen the precipitation and air temperature files for any gross errors during the simulation time period. While errors are uncommon in the BASINS dataset from which these were derived, they do occur. Outliers and periods of flatlined values have been discovered in the pilot phase of the project, and the met data should be corrected and/or stations removed if gross errors are found.
8. Specify PET option as 1 (Penman/Monteith) in General Watershed Parameters.

9. Turn on elevation bands if necessary to account for orographic effects in areas with a sparse precipitation network and significant elevation changes. This will generally be appropriate where elevations within subbasins span a range of 250 m or more (see Watershed Topographic Report).
10. Assign management operations. The simulation option IURBAN in the mgt files associated with urban land use classes should be left at the default value of 1 (use USGS regression equations).
11. Set instream water quality options; IWQ = 1, and start with program defaults.
12. Use (daily) Curve Number hydrology with observed precipitation and air temperature. Remaining meteorological variables are simulated using the weather generator.
13. Specify atmospheric N wet deposition concentrations.
14. The time period for simulation should be 31 water years. The first year will be dropped from analysis to account for model spinup. The remaining 30 years span a period for which the supplied weather data are complete and include the year 2000 (with the exception of the Nebraska (Loup and Elkhorn River) basins, where the weather data are complete only through 1999). Note that the start of simulation for some of the non-pilot study areas may be one year prior to the complete weather data period. For this spinup year, some weather stations may be absent, but SWAT will fill in the missing records using the weather generator. Save and backup the model at this point.
15. Run the model for the full 31 year period. Due to spin up effects and interaction with the weather generator random number processing, ***all*** model runs (calibration, validation, and scenario application) should use the entire model network and the entire simulation time period. (Initial testing can be done on a subset of the model or a reduced time period; however, it is necessary to run the full model extent and time period to obtain valid final results.)
16. Undertake calibration for target HUC8. After calibration, repeat for remainder of study area. Calibration should first be performed for hydrology, then sediment, then nutrients. Calibration spreadsheet templates are distributed for Hydrology and Water Quality, as described in the next section.

    NOTE: When pursuing calibration through the ArcSWAT interface be sure to use the option to REwrite SWAT input files (and not "Write Input Files"). The latter option will cause default parameters to be reloaded from the geodatabase.

2.2 HSPF MODEL SETUP

BASINS4/HSPF uses primarily two applications – MapWindow GIS and WinHSPF to create, modify and run HSPF UCI files. The following steps should be implemented first for the Calibration HUC8 subbasins, then repeated for the entire model watershed.

1. Prepare a starter.uci file defining default values for PERLND/IMPLND base numbers (see below). Where previous modeling is available, the initial parameter values will be based on that earlier modeling. For areas without previous modeling, hydrologic parameters will be based on recommended ranges in BASINS Technical Note 6 and related to soil and meteorological characteristics where appropriate.
2. Load HSPF land cover/soils grid (as discussed in the GIS Processing Memorandum), DEM, subbasin, and reach file into BASINS4 MapWindow interface.
3. Use Manual Delineation to calculate subbasin and reach parameters.
4. Assign subbasins to model segment groups using the Model Segmentation Specifier Tool. (A segment is a group of subbasins with a unique set of PERLNDs and IMPLNDs. Segments are used primarily for weather station assignment, but may also be used for other factors such as differences in soils, geology, etc.) Assignment will be based on proximity to weather stations, elevation bands,

and any other unique watershed characteristics identified previously. The Tool will generate unique model segments within the HSPF model, using the PERLND/IMPLND numbering scheme shown below.

5. Run the BASINS4 HSPF tool.
    a. General Tab
        i. Land Use Type, assign to LU+HSG grid
        ii. Subbasins and Streams, use subbasin and reach shapefiles developed previously.
        iii. Point sources, using input shapefile developed for watershed.
        iv. Met stations, using input shapefile developed for watershed.
    b. Land Use Tab: assign imperviousness to the developed land use classes using values developed from the impervious area analysis.
    c. Streams Tab: uses default fields
    d. Subbasins Tab: uses default fields.
    e. Point Sources Tab: uses default fields.
    f. Met Stations Tab: uses default fields.
6. Use separate automated processing tool to do the following:
    a. Lump area from the four developed classes into one IMPLND and four PERLND categories.
    b. Assign PERLND/IMPLND model segmentation using a set numbering scheme for the land use classes. Model segments will be implemented in groups of 25 (i.e., PERLND 1, 26, 51, 76, and 101 are all WATER). Ensure that all combinations of base number and segment are represented throughout the model. If necessary, define a nominal area for missing PERLND/IMPLND values in the SCHEMATIC block. Assignments are shown below, first for PERLND, and then IMPLND.

LC_HSG Class	LC_HSG Value	HSPF PERLND Name	HSPF PERLND Base Number
WATER	101	WATER	1
BARREN_D	4	BARREN_D	2
WETL_D	14	WETL_D	3
FOREST_A	21	FOREST_A	5
FOREST_B	22	FOREST_B	6
FOREST_C	23	FOREST_C	7
FOREST_D	24	FOREST_D	8
SHRUB_A	31	SHRUB_A	9
SHRUB_B	32	SHRUB_B	10
SHRUB_C	33	SHRUB_C	11
SHRUB_D	34	SHRUB_D	12
GRASS_A	41	GRASS_A	13
GRASS_B	42	GRASS_B	14
GRASS_C	43	GRASS_C	15
GRASS_D	44	GRASS_D	16
AGRI_A	51	AGRI_A	17
AGRI_B	52	AGRI_B	18

LC_HSG Class	LC_HSG Value	HSPF PERLND Name	HSPF PERLND Base Number
AGRI_C	53	AGRI_C	19
AGRI_D	54	AGRI_D	20
DEVO_A	61	DEVPERV_A	21
DEVO_B	62	DEVPERV_B	22
DEVO_C	63	DEVPERV_C	23
DEVO_D	64	DEVPERV_D	24
DEVL_A	71	DEVPERV_A	21
DEVL_B	72	DEVPERV_B	22
DEVL_C	73	DEVPERV_C	23
DEVL_D	74	DEVPERV_D	24
DEVM_A	81	DEVPERV_A	21
DEVM_B	82	DEVPERV_B	22
DEVM_C	83	DEVPERV_C	23
DEVM_D	84	DEVPERV_D	24
DEVH_A	91	DEVPERV_A	21
DEVH_B	92	DEVPERV_B	22
DEVH_C	93	DEVPERV_C	23
DEVH_D	94	DEVPERV_D	24
(all imperv)			25

7. In WinHSPF, define hydraulic characteristics for major reservoirs and flow/load characteristics for major point sources. This step can be done in common with the corresponding step for SWAT.
8. FTABLES will be generated automatically during model creation. FTABLES can be easily adjusted in WinHSPF if specific information is available to the modeler. The WinHSPF FTABLE tool also includes a way to recalculate FTABLES using relationships developed for three regions in the Eastern United States.
9. Adjust lapse rates as needed to account for elevation bands associated with model segments. Lapse rates are needed for precipitation and air temperature only. For snowmelt, the simplified degree-day method for snowmelt should be employed.
10. Add additional UCI tables as needed, using the WinHSPF interface.
11. Undertake calibration for target HUC8. After calibration, repeat for remainder of study area. Calibration should first be performed for hydrology, then sediment, then nutrients.
12. Nutrients will be modeled as inorganic N, inorganic P, and organic matter. The latter will be transformed to organic N and organic P in the MASS-LINK to the stream. The buildup-washoff approach should be used to simulate land surface processes; it is easy to implement and tools are available to translate storm Event Mean Concentrations (EMCs) to model inputs. The instream simulation should use GQUALS with exponential decay. The project does not have sufficient resources to develop models with a full algal simulation.

3 Calibration and Reporting Procedures

Calibration will be pursued for flow, TSS, TN, and TP sequentially. The water quality calibration focuses on replicating inferred monthly loads, although some attention must be paid to the calibration of concentration as well.

As noted above, calibration starts with a single HUC8. Parameters derived for this site are then extended to the remainder of the watershed. However, experience is that this procedure alone is not adequate to provide reasonable results for the entire study area. Therefore, secondary calibration adjustments should be made at 2-3 additional stations in the watershed, at least one of which should be at a larger spatial scale than HUC8 (if available).

The time period for calibration should generally be the last 10 water years of the simulation. Validation will be applied to the preceding 10 water years (for which fit may be less good due to changes in land use and management relative to the 2001 NLCD). Adjustments can be made based on data availability if necessary.

The hydrologic calibration uses the Hydrocal spreadsheet. A version of this spreadsheet will be provided for the assigned non-pilot study areas. The spreadsheet is already loaded with a list of USGS gages with sufficiently long periods of record. The spreadsheet will automatically download USGS flows from NWIS and will load SWAT simulated flows from the program output. Note that this spreadsheet should be opened in Excel 2003 to ensure proper operation. Most of the functions can be run in Excel 2007 if needed, but, if so, it should be saved in compatibility mode for Excel 2003. The program uses macros, and macro security will need to be set to “Medium” for the program to operate.

User controls for the Hydrocal spreadsheet are located on the Data Management tab. Key results are provided on the Analysis tab. In general, the user should strive to meet the “Recommended Criteria” on the Analysis tab.

Water quality calibration uses the WQUAL-GCRP spreadsheet. This program also uses macros and is now designed for Excel 2007. The water quality calibration takes place at stations for which there are both flow and concentration data and comes pre-loaded with a list of USGS gaging stations. Note that one spreadsheet covers both the calibration and validation periods.

The modeler is responsible for preparing and loading observed water quality data for TSS, TN, and TP on the “Obs” tab. At a minimum use the data available on the USGS NWIS system. (In some cases, previous studies have resulted in creation of more extensive, QA’d data sets that may be used instead.) Pre-processing is required. Duplicate observations on the same day should be pre-averaged. The “TSS” column can be used to store both SSED and TSS data; when both are present on a given day use the SSED results preferentially. A special note is required regarding TN. TN is a calculated value, and USGS reports it directly only in some years. In many other cases the user can construct TN observations by adding TKN plus NO2+NO3 observations. Note that the “Obs” tab contains a column for denoting samples below detection limit (using symbol “<”) for each parameter. For TN, observations should be flagged as non-detect only when both TKN and NO2+NO3 are non-detect. If only one of these is non-detect use one-half the detection limit to create the sum.

After entering the observed data, the main user controls are on the “Interface” tab. After running the macros, key results are shown on the GCRP tab at BH22+. The key interest of EPA is in the prediction of loads. Loads are, of course, not observed, but are estimated using a stratified regression (TSS, TP) or an averaging estimator (TN). The first objective of calibration is to reduce the relative percent deviation between simulated and estimated loads – to below 25% if possible. (This will sometimes not be possible.) However, the user should also examine the diagnostic plots on the TSS, TP, and TN worksheets.

4 Implementing Future Scenarios

Both climate and land use scenarios will be implemented by working directly with the model input files, rather than returning to the GIS interface.

4.1 Climate Scenarios

In both HSPF and SWAT, climate scenarios are readily implemented simply by substituting new meteorological series. We will not assume any feedback between climate changes and HSPF parameters.

4.2 Land Use Scenarios

ICLUS will be used to estimate a change table by subwatershed. In SWAT, the HRU fractions in each HRU file are changed using automation scripts.

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Appendix B
Project Quality Assurance Project Plan Section 8: Model Calibration

This appendix reproduces Section 8.0 of the QAPP which describes model calibration requirements; taken from:

Tetra Tech. (2008) Quality assurance project plan for watershed modeling to evaluate potential impacts of climate and land use change on the hydrology and water quality of major U.S. drainage basins. Prepared for the Office of Research and Development, Global Change Research Program, U.S. Environmental Protection Agency, Washington, DC.

8.0 MODEL SETUP/CALIBRATION

8.1 PROJECT QUALITY OBJECTIVES

EPA emphasizes (USEPA 2000, 2002) a systematic planning process to determine the type and quality of output needed from modeling projects. This begins with a Modeling Needs and Requirements Analysis, which includes the following components:

- Assess the need(s) of the modeling project
- Define the purpose and objectives of the model and the model output specifications
- Define the quality objectives to be associated with model outputs

The first item (needs assessment) is covered in EPA's task order. In essence, simulation models are needed to predict future responses to changes in climate and land use. The existing simulation models HSPF and SWAT are believed to be sufficient to this purpose, and creation of new models is not required.

The second item (define purpose and objectives) is the subject of EPA's Draft Analysis Plan. This proposes both the purpose of the modeling and the specific endpoints to be evaluated as a result of the modeling. At a general level, the objective of this modeling project is to assess the potential effects of climate and land use change on the hydrology and water quality of major U.S. drainage basins; however, this general objective will need to be made more specific to guide development of the modeling effort. The Tt team is tasked with reviewing and commenting on the Analysis Plan as part of this work—and revisions to the existing Analysis Plan could arise as a result of these recommendations. At the end of this review, the Tt team and the EPA COR must agree on the principal study questions to be addressed through the modeling.

The quality objectives for the model(s) follow directly from the purposes and objectives—and can be refined in conjunction with the review of the Analysis Plan. In general, the modeling effort needs to be designed to achieve an appropriate level of accuracy and certainty in answering the principal study questions. This process takes into account the following elements:

- The accuracy and precision needed for the models to predict a given quantity at the application site of interest to satisfy study questions
- The appropriate criteria for making a determination of whether the models are accurate and precise enough on the basis of past general experience combined with site-specific knowledge and completeness of the conceptual models
- How the appropriate criteria would be used to determine whether model outputs achieve the needed quality

EPA's Draft Analysis Plan suggests that the principal study questions to be addressed by the models are changes in (defined on the basis of modeling at a daily time step): (1) the 100-year flood, (2) 7Q10 low flow, (3) runoff center of mass, (4) monthly sediment loads, (5) monthly total nitrogen loads, and (6) monthly total phosphorus loads. This list could be expanded or modified on the basis of the review of the Draft Analysis Plan.

The models will be calibrated and validated to existing (1970–2000) data to establish their credibility for use in forecasting responses to future change. Specific calibration and validation targets for model acceptability (see Sections 8.2 and 8.3) will be selected in light of the intended uses of the model, as identified in the final revisions to the Analysis Plan.

8.2 MODEL CALIBRATION AND VALIDATION

Model calibration is the process of adjusting model inputs in acceptable limits until the resulting predictions give good correlation with observed data. Commonly, calibration begins with the best estimates for model input on the basis of measurements and subsequent data analysis. Results from initial simulations are then used to improve the concepts of the system or to modify the values of the model input parameters. The use of calibrated models, the scientific veracity of which is well defined, is of paramount importance to this project. Because the goal is to be able to assess the potential effects of climate and land use change on the hydrology and water quality of major U.S. drainage basins, model calibration and validation should strive to minimize errors (deviations between model predictions and observed measurement data.).

The Tt Co-TOLs or lead modeler will direct the model calibration efforts. Models are often calibrated through a subjective trial-and-error adjustment of model input data because a large number of interrelated factors influence model output. However, the experience and judgment of the modeler are a major factor in calibrating a model accurately and efficiently. Further, the model should meet pre-specified quantitative measures of accuracy to establish its acceptability in answering the principal study questions.

The model calibration process proceeds through both qualitative and quantitative analyses. Qualitative measures of calibration progress are commonly based on the following:

- Graphical time-series plots of observed and predicted data

- Graphical transect plots of observed and predicted data at a given time interval
- Scatter plots of observed versus predicted values in which the deviation of points from a 45-degree straight line gives a sense of fit
- Tabulation of measured and predicted values and their deviations

After initially configuring the modeling systems, the Tt team will perform model calibration and validation. The watershed models will be calibrated to the best available data, including literature values, and interpolated or extrapolated values using existing field data. If multiple data sets are available, an appropriate time period and corresponding data set will be chosen on the basis of factors characterizing the data set, such as corresponding weather conditions, amount of data, and temporal and spatial variability of data.

A model is considered calibrated when it reproduces data within an acceptable level of accuracy, as described in Section 8.3 and itemized in Table 4 (quantitative measures). A set of parameters used in a calibrated model might not accurately represent field values, and the calibrated parameters might not represent the system under a different set of boundary conditions or hydrologic stresses. Therefore, a model validation period helps establish greater confidence in the calibration and the predictive capabilities of the model. A site-specific model is considered validated if its accuracy and predictive capability have been proven to be within acceptable limits of error independently of the calibration data.

Table 4. General percent error calibration/validation targets for watershed models (applicable to monthly, annual, and cumulative values)

	Relative percent error		
	Very good	Good	Fair
Hydrology/Flow	< 10	10–15	15–25
Sediment	< 20	20–30	30–45
Water Quality/Nutrients	< 15	15–25	25–35

In general, model validation is performed using a data set separate from the calibration data. If only a single time series is available, the series could be split into two subseries, one for calibration and another for validation. If the model parameters are changed during the validation, this exercise becomes a second calibration, and the first calibration needs to be repeated to account for any changes. Representative stations will be used to guide parameter adjustment to get an accurate representation of the conditions of the individual subwatersheds and streams. The calibration and validation process will be documented for inclusion in the technical reports.

8.3 SPECIFIED PERFORMANCE AND ACCEPTANCE CRITERIA

Model Testing

Model testing includes calibration, verification, and validation. The previous section described model calibration and validation. Model verification is the process of testing the model code, including program debugging, to ensure that the model implementation has been done correctly. Testing usually begins with the best estimates for model input on the basis of measurements and subsequent data analyses. Results from initial simulations are then used to improve the concepts of the system or to modify the values of the model input parameters.

For this project, existing tested model code will be used (HSPF and SWAT). Therefore, model verification is required only for new *bridge* code, such as that required to translate climate scenarios into model input.

The Tt team will calibrate the project models using the best available data, including literature values and interpolated or extrapolated existing field data. The model will be considered successfully tested when it reproduces data at an acceptable level of accuracy.

The work proposed for this project, as defined in the Draft Analysis Plan, differs from other, more common applications of watershed models (e.g., for TMDLs) in several ways that affect the calibration strategy:

- Models will be developed at a very large spatial scale (i.e., HUC4 scale) and will be calibrated at a limited number of points, most of which will likely be at the HUC8 scale.
- Models will be developed for multiple watersheds, and calibration will be done by multiple teams of modelers. The different teams should all apply the same calibration metrics.
- Two separate models (HSPF and SWAT) will be developed for some or all the watersheds. A common set of calibration criteria should be applied to both models to facilitate comparison.
- Models are proposed to be developed using a daily time step (based on the scale of the analysis), which will limit the ability to resolve extreme flows.
- Model application is not for regulatory purposes but to inform possible long-term effects of different change scenarios. While calibration to establish model credibility is essential, the ability to correctly simulate relative changes is most important.
- Comparison of observed and predicted values on a frequency-duration plot.

Quantitative acceptance criteria for the models will be selected to reflect the final set of principal study questions in the revised Analysis Plan and incorporated into the QAPP. Given the considerations listed above, quantitative acceptance criteria will be expressed in relative, rather than absolute form. That is, relevant calibration outputs will be ranked on a scale ranging from *poor* to *very good*. Calibration will strive to obtain the best fit possible; however, specific values of quantitative measures will not be proposed to define whether results should be accepted or rejected. Rather, the level of uncertainty determined in calibration and validation will be documented to decision makers to aid in interpretation of results.

The current Draft Analysis Plan references only three measures related to hydrology (100-year flood, 7Q10 low flow, and runoff center of mass); however, accurate representation of the general water balance is required to demonstrate that the model provides a reasonable representation of reality that can serve as a foundation for water quality simulation. Therefore, commonly accepted measures of model hydrologic fit will be applied.

Model simulation of water quality is, in general, more difficult than simulating hydrology, in part because any uncertainty in the hydrologic simulation will propagate into the water quality simulation. In addition, the principal study questions related to water quality contained in the Draft Analysis Plan address loads. Loads are not directly observed but are inferred from point-in-time concentration data and continuous flow data. As a result, *observed* load estimates are subject to considerable uncertainty.

Quantitative measures, sometimes referred to as calibration criteria, include the relative percent error between model predictions and observations as defined generally below:

$$E_{rel} = \frac{\sum |O - P|}{\sum O} \times 100,$$

where E_{rel} = relative error in percent. The relative error is the ratio of the absolute mean error to the mean of the observations and is expressed as a percent. A relative error of zero is ideal. Additional statistics that will be applied include the correlation coefficient (R) and its squared value, the coefficient of determination (R^2), where

$$R = \frac{\sum (O_i - \overline{O}) \cdot (P_i - \overline{P})}{\sqrt{\sum (O_i - \overline{O})^2 \cdot (P_i - \overline{P})^2}} = \frac{\sum O_i \cdot P_i}{\sqrt{\sum O_i^2 \cdot \sum P_i^2}},$$

where the overbar indicates the sample mean.

For hydrology and the water balance, percent error tests will be applied to the following components:

- Total flow volume
- 10 percent high flows
- 50 percent low flows
- Seasonal flow volumes

For water quality, the outcomes of interest defined in the current Draft Analysis Plan are monthly loads. Therefore, similar calculations of relative percent error will be applied to the series of predicted and *observed* monthly loads (where the observed monthly loads will need to be estimated from observed flow and concentration data using an appropriate estimation technique, such as those described in Preston et al. 1989).

These tests are relevant to monthly and annual values. General calibration/validation targets for percent error consistent with current best modeling practices (Donigian 2000) are shown in Table 4.

For hydrology, there is also an interest in extreme high and low flows. Answering this study question requires calibration to daily flows, rather than just monthly and annual values. Figure 3 (also from Donigian 2000) summarizes R and R^2 ranges for the evaluation of daily and monthly flows:

Figure 3. R and R^2 value ranges for model performance

In addition, the Nash-Sutcliffe coefficient of model fit efficiency (COE) will be reported for all calibration and validation runs—although no specific criteria are proposed. This is calculated as

$$COE = 1 - \frac{\sum [O_i - P_i]^2}{\sum [O_i - \overline{O}]^2}.$$

A COE value of one indicates a perfect fit between measured and predicted values for all events. A value of zero indicates that the model fit is not better than using the average value of all the measured data.

Following model calibration, model validation will be conducted using separate, independent portions of the available time series at the calibration stations. Because the Analysis Plan calls for simulating the period 1970–2000, while land use will be based on 2001 NLCD information, the 10-year period from 1991 through 2000 will generally be proposed for calibration, while an earlier period (dependent on data availability) will be used for validation tests. Because the land use distribution during the 1970–1991 period could be different in some regions than during the 1991–2000 period, it is important to note that validation results might not achieve the same quantitative acceptance levels as for calibration.

The Tt team will document model performance over both the calibration and validation period in the technical reports, using the quantitative measures of accuracy documented above (or any additional measures that could be identified in modifications to this QAPP). In addition to measures of accuracy, additional acceptance criteria will include modeling result precision and representativeness:

- Precision of model results: Precision of generated data produced by the model will be examined by performing replicate runs. By confirming that an identical data set is generated when a replicate of the previous model run will rule out numerical instability issues and verify the precision of the model.
- Representativeness of model results: The Tt team technical staff will compare the loadings data and measured environmental concentrations to examine sources and sinks of materials.

An overall assessment of the success of the calibration can be expressed using calibration levels.

Level 1: Quantitative performance measures fall within the *very good* range (highest degree of calibration).

Level 2: Quantitative performance measures fall within the *good* range.

Level 3: Quantitative performance measures fall within the *fair* range.

Level 4: Quantitative performance measures fall within the *poor* range (lowest degree of calibration).

Model Sensitivity Analysis

The sensitivity to variations or uncertainty in input parameters is an important characteristic of a model. Sensitivity analysis is used to identify the most influential parameters in determining the accuracy and precision of model predictions. This information is of importance to the user who must establish required accuracy and precision in model application as a function of data quantity and quality. Sensitivity analysis quantitatively or semi-quantitatively defines the dependence of the model's performance assessment measure on a specific parameter or set of parameters. Sensitivity analysis can also be used to decide how to simplify the model simulation and to improve the efficiency of the calibration process.

Model sensitivity can be expressed as the relative rate of change of selected output caused by a unit change in the input. If the change in the input causes a large change in the output, the model is considered to be sensitive to that input parameter. Sensitivity analysis methods are mostly nonstatistical or even intuitive by nature. Sensitivity analysis is typically performed by changing one input parameter at a time and evaluating the effects on the distribution of the dependent variable. Nominal, minimum, and maximum values are specified for the selected input parameter.

Sensitivity analysis is performed at the beginning of the calibration process to design a calibration strategy. After calibration is completed, a more elaborate sensitivity analysis is performed to quantify the uncertainty in the calibrated model caused by uncertainty in the estimates of the model input parameters.

Informal sensitivity analyses (iterative parameter adjustments) are generally performed during model calibration to ensure that reasonable values for model parameters will be obtained, resulting in acceptable model results. The degree of allowable adjustment of any parameter is usually directly proportional to the uncertainty of its value and is limited to its expected range of values.

8.4 ASSESSMENT AND RESPONSE ACTIONS

The ability of computer code to represent model theory accurately will be ensured by following rigorous programming protocols, including documentation within the source code. Specific tests will be required of all model revisions to ensure that fundamental operations are verified to the extent possible, including testing numerical stability and convergence properties of the model code algorithms, if appropriate. Model results will generally be checked by comparing results to those obtained by other models or by comparing them to hand calculations. Visualization of model results will help determine whether model simulations are realistic. Model calculations will be compared to field data. If adjustments to model parameters are made to obtain a fit to the data, the modelers will provide an explanation and justification that must agree with scientific knowledge and fit within reasonable ranges of process rates as found in the literature.

As described in Section 5.1, non-project-generated data will be used for model development and calibration. The model calibration procedure is discussed in Section 8.2. The DQOs were discussed in Section 7.0 and 8.0 of this document. Modelers will cross-check data for bias, outliers, normality, completeness, precision, accuracy, and other potential problems.

Data generated outside the project will be obtained primarily from quality assured databases maintained by EPA, USGS, and other entities. Additional data may be obtained from either published or nonpublished sources. The published data will have some degree or form of peer review. Typically, modelers examine these data as part of a data quality assessment. Unpublished databases are also examined in light of a data quality assessment. Data provided by EPA or other sources will be assumed to meet precision objectives established by those entities.

The QA program under which this task order will operate includes surveillance, with independent checks of the data obtained from sampling, analysis, and data gathering activities. This process is illustrated in Figure 4.

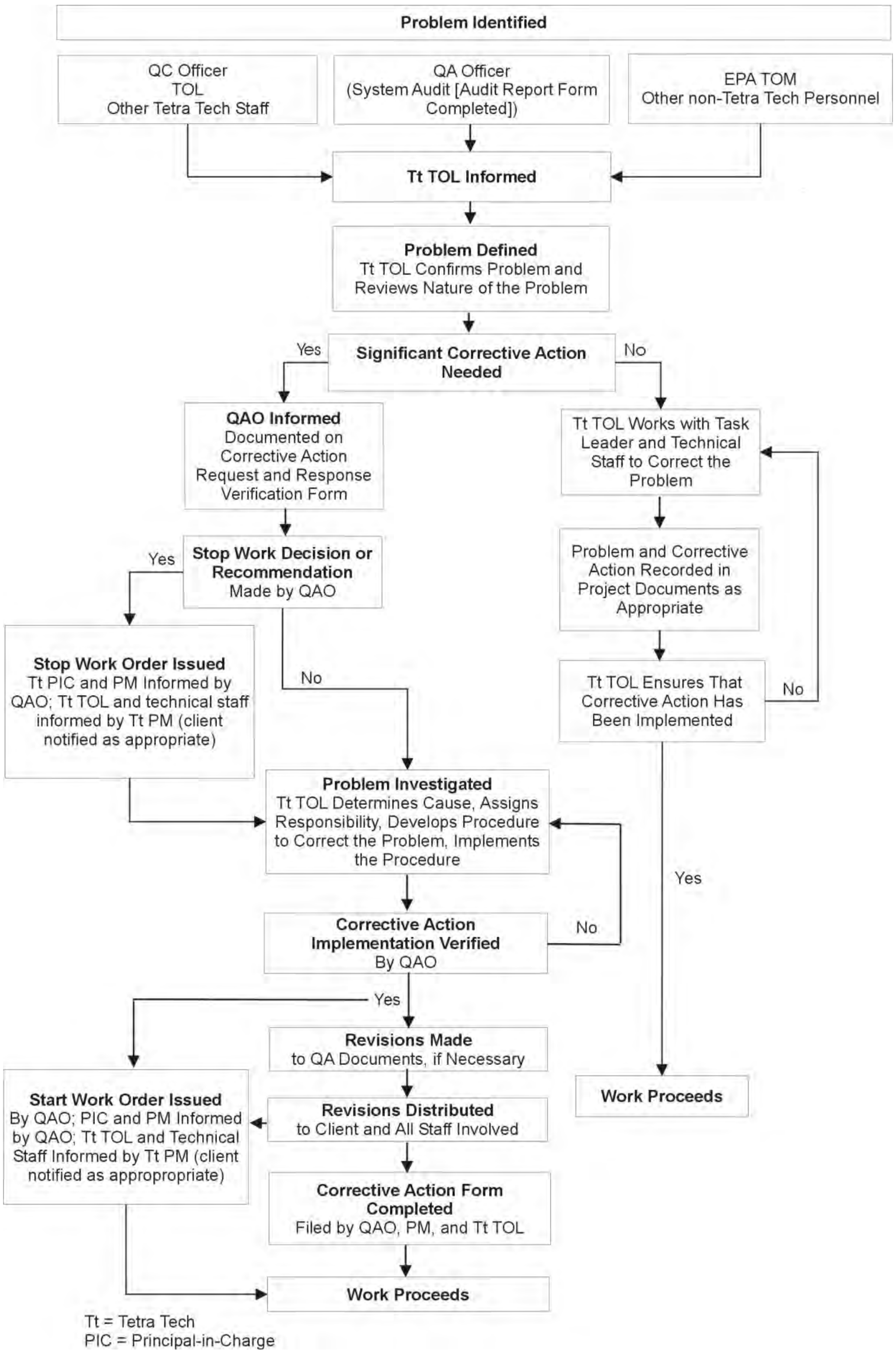

Figure 4. Problem assessment and correction operations

The essential steps in the QA program are as follows:

- Identify and define the problem
- Assign responsibility for investigating the problem
- Investigate and determine the cause of the problem
- Assign and accept responsibility for implementing appropriate corrective action
- Establish the effectiveness of and implement the corrective action
- Verify that the corrective action has eliminated the problem

Many of the possible technical problems can be solved on the spot by staff, for example, by modifying the Initial Technical Approach memorandum or correcting errors or deficiencies in implementation of the approach. Immediate corrective actions are considered SOPs, and they are noted in records for the project. Problems that cannot be solved in this way require more formalized, long-term corrective action.

If quality problems that require attention are identified, Tt will determine whether attaining acceptable quality requires either short- or long-term actions. If a failure in an analytical system occurs (e.g., performance requirements are not met), the Tt team modeling QC officers will be responsible for corrective action and will immediately inform the Tt Co-TOLs or the QAO, as appropriate. Subsequent steps taken will depend on the nature and significance of the problem, as illustrated in Figure 4.

Contract (name) ____________________

Date of Assessment ______________ Request No. ______________

Title (of project or other) ______________________________

Project Leader ______________________ TC# ______________

Other Responsible Personnel ______________________________

Auditor or Initiator of This Corrective Action Request ______________________

Problem Description:

Recommended Action: **Date to Be Completed:**

______________________ ______________
Quality Assurance Officer Date

______________________ ______________
Principal-in-Charge or Program Manager Date

Action Taken: **Date:**

Verification of Completion of Corrective Action:

______________________ ______________
Quality Assurance Officer Date

______________________ ______________
Principal-in-Charge or Program Manager Date

Original form to be filed in QAO File; one copy to be filed in Project File and one copy in Contract File (if corrective action pertains to a project), or one copy to be filed in Contract File (if corrective action pertains to a contract).

Figure 5. Example corrective action request and response verification form

The Tt Co-TOLs have primary responsibility for monitoring the activities of this project and identifying or confirming any quality problems. The Co-TOLs will also bring these problems to the attention of the Tt QAO, who will initiate the corrective action system described above, document the nature of the problem (using a form such as that shown in Figure 5), and ensure that the recommended corrective action is carried out. The Tt QAO has the authority to stop work on the project if problems affecting data quality that will require extensive effort to resolve are identified.

The EPA COR, Tt PGM and Tt Co-TOLs will be notified of major corrective actions and stop work orders. Corrective actions can include the following:

- Reemphasizing to staff the project objectives, the limitations in scope, the need to adhere to the agreed-upon schedule and procedures, and the need to document QC and QA activities
- Securing additional commitment of staff time to devote to the project
- Retaining outside consultants to review problems in specialized technical areas
- Changing procedures

The Tt Co-TOLs may replace a staff member, as appropriate, if it is in the best interest of the project to do so.

Performance audits are quantitative checks on different segments of project activities; they are most appropriate for sampling, analysis, and data-processing activities. The Tt modeling QC officer is responsible for overseeing work as it is performed and periodically conducting internal assessments during the data entry and analysis phases of the project. As data entries, model codes, calculations, or other activities are checked, the Tt modeling QC officer will sign and date a hard copy of the material or complete Tt's standard Technical/Editorial Review Form, as appropriate, and provide it to the Tt Co-TOLs for inclusion in the administrative record. Performance audits will consist of comparisons of model results with observed historical data. Performing control calculations and post-simulation validation of predictions are major components of the QA framework.

The Tt Co-TOLs will perform or oversee the following qualitative and quantitative assessments of model performance periodically to ensure that the model is performing the required task while meeting the quality objectives:

- Data acquisition assessments
- Model calibration studies
- Sensitivity analyses
- Uncertainty analyses
- Data quality assessments
- Model evaluations
- Internal peer reviews

Internal peer reviews will be documented in the project and QAPP files. Documentation will include the names, titles, and positions of the peer reviewers; their report findings; and the project management's documented responses to their findings.

The Tt Co-TOLs will perform surveillance activities throughout the duration of the project to ensure that management and technical aspects are being properly implemented according to the schedule and quality requirements specified in this QAPP. These surveillance activities will include assessing how project milestones are achieved and documented; corrective actions implemented; budgets adhered to; peer reviews performed; data managed; and whether computers, software, and data are acquired in a timely manner.

System audits are qualitative reviews of project activity to check that the overall quality program is functioning and that the appropriate QC measures identified in the QAPP are being implemented. If requested by the EPA COR, and EPA provides additional funding, the Tt QAO or designee will conduct an internal system audit of the project and report the results to the EPA COR and the Tt Co-TOLs.

8.5 DOCUMENTATION AND RECORDS

Thorough documentation of all modeling activities is necessary for interpreting study results. Tt will prepare monthly progress reports that will address task and subtask milestones, deliverables, adherence to schedule, and financial progression at the end of each full month while the task order for this project is still open. Data needs and deadlines for Tt's receipt of information needed to meet the project schedule will also be included in the progress reports and Gantt chart. The progress in meeting modeling QA targets (QA reports) will also be included in the progress reports. Other deliverables will be distributed to project participants as indicated by the EPA COR. Data tables, assumptions and analyses used to develop the models will be recorded and provided to EPA as a separate deliverable. The format of the raw data to be used for model parameters, model input, model calibration, and model output will be converted to the appropriate units, as necessary.

The Tt team will save on an external hard drive all modeling output data from all 20 watersheds as digital computer files in a file directory using a file-naming convention specified by the EPA COR. In addition, the Tt team will save on an external hard drive all scripts, project files, calibration data, and other information used to conduct watershed modeling at each of the 20 study watersheds. Tt will deliver these external hard drives to EPA within 2 weeks of the EPA COR's approval of the final report presenting and discussing the goals, methods, results and conclusions of watershed modeling in all 20 study watersheds (see the schedule in Table 2). Tt will maintain a copy of the project files at the Cincinnati, Ohio and/or Fairfax, Virginia, office for at least 3 years (unless otherwise directed by the EPA COR). The EPA COR and Tt Co-TOLs will maintain files, as appropriate, as repositories for information and data used in models and for preparing any reports and documents during the project. Electronic project files are maintained on network computers and are backed up periodically. The Tt Co-TOLs will supervise the use of project materials. The following information will be included in the electronic project files within Tt and on the external hard drives:

- Any reports and documents prepared
- Contract and task order information
- Electronic copies of model input/output (for model calibration and allocation scenarios)
- Results of technical reviews, model tests, data quality assessments of output data, and audits

- Documentation of response actions during the project to correct model development or implementation problems
- Assessment reports for acquired data
- Statistical goodness-of-fit methods and other rationale used to decide which statistical distributions should be used to characterize the uncertainty or variability of model input parameters
- Communications (memoranda; internal notes; telephone conversation records; letters; meeting minutes; and all written correspondence among the project team personnel, subcontractors, suppliers, or others)
- Maps, photographs, and drawings
- Studies, reports, documents, and newspaper articles pertaining to the project
- Spreadsheet data files including physical measurements, analytical chemistry data, and microbiological data (hard copy and on diskette)

The model application will include complete record keeping of each step of the modeling process. The documentation will consist of reports and files addressing the following items:

- Selection of study watersheds and model calibration points
- Assumptions
- Adjustments
- Parameter values and sources
- Nature of grid, network design, or subwatershed delineation
- Changes and verification of changes made in code
- Actual input used
- Output of model runs and interpretation
- Sensitivity analyses results
- Calibration and validation of the models

Formal reports submitted to EPA that are generated from the data will be maintained in the central file (diskette and hard copy) at Tt's Cincinnati, Ohio, and Fairfax, Virginia, offices. The data reports will include a summary of the types of data collected, sampling dates, and any problems or anomalies observed during sample collection.

8.6 OUTPUT ASSESSMENT AND MODEL USABILITY

Tt team technical staff will review model predictions for reasonableness, relevance, and consistency with the requirements of the model development process through model calibration as described in Section 8.0 of this QAPP. Tt team modeling experts will also determine consistency with the acceptance criteria described in Sections 7.0 and 8.0 of this QAPP. The Tt modeling QC officer will ensure that all steps of the modeling process are performed correctly.

Electronic copies of model input/output for model calibration, data quality assessments of output data, and QA reports will be maintained as part of the project files.

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Appendix C
Climate Change and the Frequency and Intensity of Precipitation Events

Technical Note

By: Charles Rodgers, Stratus Consulting Inc.

This review has been prepared to address issues raised in the context of the preparation of meteorological data used as input to the SWAT and HSPF watershed models. The data preparation process is summarized as follows: The approach selected for this project is to use the U.S. Environmental Protection Agency's (EPA's) BASINS Climate Assessment Tool (CAT; U.S. EPA, 2009) to modify historical meteorological records to reflect the projected impacts of climate change on important meteorological variables. Temperature and precipitation records from the National Oceanic and Atmospheric Administration (NOAA) National Climatic Data Center (NCDC) stations in and surrounding each pilot watershed have been identified, and hourly data covering the period 1970–2000 is being used in the calibration of models and the simulation of historical patterns of discharge. The projected regional impacts of climate change will be obtained from the North American Regional Climate Change Assessment Program (NARCCAP) dynamically downscaled 50 kilometer Regional Climate Model (RCM) output, primarily at monthly resolution. The original proposal was to use 15 General Circulation Model (GCM)-RCM combinations to simulate a range of future projections, although due to restrictions on the likely availability of NARCCAP downscaled data, a combination of NARCCAP, statistically downscaled CMIP3 projections and direct GCM outputs will likely be used. In each instance, the model-projected changes in temperature and precipitation patterns will be used to modify the historical climate records using CAT. The advantages to this approach include the preservation of short-timescale variability and other aspects of time series behavior, and the preservation of inter-site variability and correlation patterns, none of which are feasible using downscaled GCM outputs directly as model inputs.

CAT permits the sequential modification of weather records to introduce a number of alterations, each reflecting various assumptions concerning the regional manifestations of climate change. Precipitation records can be modified by (1) multiplying all records by an empirical constant reflecting projected climate change to simulate a shift in total precipitation, applied uniformly to all periods and intensity classes, (2) selective application of such a multiplier to specific seasons or months, (3) selective application of the multiplier to a range of months or years within the record, (4) selective application of the multiplier to storm events of a specific size or intensity class; and (5) addition or removal of storm events to simulate changes in the frequency of precipitation events (U.S. EPA, 2009). Modification (4) can be iteratively applied to more than one event size class. In summary, changes in frequency and intensity as well as changes in overall precipitation accumulation can be represented using CAT and historical records.

Relative changes in the *frequency* and *intensity* of precipitation events associated with climate change may prove to be more influential in determining future patterns of discharge than projected changes in overall (annual, seasonal) precipitation. In particular, the partitioning of precipitation into re-evaporation, runoff and percolation to groundwater is understood to be sensitive to the intensity and timing of precipitation events. Thus, to ensure that model simulations embody the most important dimensions of projected climate change, particular attention should be paid to precipitation intensity-frequency-duration (IFD) relationships. As a general pattern, the warming of the lower atmosphere is projected to lead to a more vigorous hydrologic cycle, characterized by increases in global precipitation, and proportionally larger increases in high-intensity events (Trenberth et al., 2007). This memorandum is intended to provide a summary review of recent literature to address the following questions: (1) How should precipitation change as a consequence of lower atmosphere warming? (2) What is the historical evidence for increases in precipitation intensity over the United States? (3) What do climate models project with respect to precipitation frequency and intensity? (4) What are the important limitations in these projections? and (5) What are the implications for the development of meteorological time series used in the modeling study?

1. How should precipitation change as a consequence of lower atmosphere warming?

Physical arguments predicting increases in precipitation intensity as a consequence of the warming of the lower atmosphere are presented by Trenberth et al. (2003). The basic argument can be summarized as follows: (1) The primary conditions for precipitation to occur include (a) availability of precipitable moisture in the atmosphere and (b) a mechanism for lifting and cooling parcels of air, leading to condensation and precipitation. (2) Progressive warming of the land surface and lower atmosphere (i.e., climate change) will lead to increases in atmospheric (precipitable) moisture through the positive relationship between air temperature and saturation vapor pressure (moisture-holding capacity). The Clausius-Clapeyron equation quantifies this relationship, and can be used to predict an increase in atmospheric water holding capacity of around 7% per °C at current global mean temperatures.[1] (3) Precipitation, when it occurs, often exceeds the extractable fraction (typically below 30%) of available moisture in the immediate zone of precipitation. This reflects the role of low-level convergence in drawing moist air into convective zones from surrounding areas. Trenberth et al. (2003) calculate that as an approximate global average, a zone of precipitation is supported by a larger region – roughly three to five times the radius of the precipitation zone – from which it draws moisture. Assuming no significant change in the efficiency of precipitation generation (i.e., maximum rate of extraction of water from the atmosphere), the intensity of such events should therefore increase as a function of mean temperature at roughly the same rate as atmospheric water-holding capacity (i.e., around 7% per °C). Finally (4), the increased atmospheric moisture supply also provides additional latent heat

[1] The slope of the saturation vapor pressure curve is around 6% at 300 K and 7.4% at 270 K.

to drive the convective process, further enhancing low-level convergence. Thus, increases in atmospheric temperature lead to proportional increases in precipitation intensity when other conditions required for initiating convective precipitation are present. Trenberth et al. (2003) note that the GCMs supporting the Intergovernmental Panel on Climate Change (IPCC) assessment simulate increases in precipitation of around 1% to 2% per °C.[2] This suggests (assuming these GCMs accurately simulate the atmospheric water balance) that the increase in precipitation intensity predicted by Clausius-Clapeyron (7% per °C) for intense convective events must be compensated for by reductions in the frequency and/or intensity of light to moderate intensity events. The latter hypothesis assumes that the durations of intense precipitation events do not also change significantly as a function of temperature.

2. Historical evidence of increases in precipitation intensity over the United States

If the proposed relationship between increasing air temperatures and precipitation intensity is theoretically sound, then the predicted changes should already be evident due to observed increases in global and U.S. air temperatures. Analysis of instrumental records from 1850–2005 indicates that globally-averaged temperatures have increased by 0.76°C (+/- 0.19°C) over this period, with the most rapid warming occurring in the last 50 years and the steepest increase in global temperatures, equivalent to changes of +0.177°C per decade, occurring over the last 25 years (Trenberth et al., 2007). Within the United States, temperature increases have also been observed at rates exceeding the global average. Present (1993–2008) U.S. temperatures are on average over 1.1°C warmer than during the 1961–1979 period (Karl et al., 2009). Corresponding, increasing trends in evaporation, atmospheric moisture and precipitation, particularly high-intensity precipitation, should thus be in evidence. However, it is not necessarily the case that all of these increases (if observed) should be of the magnitude predicted by Clausius-Clapeyron (7% per °C) since globally, evaporation is controlled by the availability of surface moisture (over land) and by the availability of energy at the earth's surface to drive evaporation and transpiration (Allen and Ingram, 2002).

Evaporation: Among the predicted impacts of a warming lower atmosphere, increases in actual evaporation and transpiration (evapo-transpiration, or ET) have been the most difficult to demonstrate, largely due to the relative absence of long-term records of direct ET measurements (Lettenmaier et al., 2008). Physical theory (the Clausius-Clapeyron equation) predicts an increase in *potential* ET, since a supply of moisture available for ET cannot be assumed. A relatively small number of recent land-based studies in the United States, India, China and Australia that make use of long-term evaporation pan data conclude that actual evaporation rates

2. Trenberth et al. (2003) refer to the GCMs supporting the Third IPCC Assessment (2001).

have *decreased*. One proposed explanation for this paradox is a reduction in incoming solar radiation due to increases in aerosols associated with air pollution (Trenberth et al., 2007). Alternatively, Brutsaert and Parlange (1998) conjecture that as humidity supplied by the surrounding landscape increases, pan evaporation will decrease (a reverse of the "oasis effect"). A synthesis of water balance studies of several major North American watersheds (Walter et al., 2004), in which ET was estimated as the residual of precipitation and discharge, concludes that actual ET has increased over the last 50 years. More direct evidence of a temperature-induced increase in actual evaporation is provided by Yu and Weller (2007). These authors utilized satellite remote sensing and atmospheric model re-analysis to estimate trends in evaporation over the ocean surface, where moisture supply is not limited. They estimate that globally averaged ocean latent heat flux (evaporation) has increased by approximately 10% over the 25-year period 1981–2005. This reflects increases in both atmospheric moisture capacity (Clausius-Clapeyron) and sea surface temperature (SST).

Atmospheric moisture: Clausius-Clapeyron predicts an increase in absolute or specific humidity (q) with increasing temperature, as distinct from relative humidity (RH). Climate model simulations tend to indicate that temperature-related changes in RH are small (Trenberth et al., 2003). Balloon-borne radiosonde has been used to estimate altitude-integrated RH, although time series analysis based on radiosonde is subject to a number of constraints. Specifically, the density of radiosonde observations is low, observations are unavailable over the open ocean and radiosonde sensors have changed over time, confounding efforts to measure decadal-scale changes in atmospheric water content (Dai, 2006b), effectively limiting analysis to the mid-1970s and onward. Nevertheless, Ross and Elliott (1996; 2001) used radiosonde time series records to estimate changes in RH and precipitable water (up to 500 mb) over North America in recent decades. They found that precipitable water has increased by 3% to 7% per decade between 1973 and 1995 over the area ranging from the Caribbean to 45°N, with greater increases in the south and smaller increases in the north. Above 45°N, changes were either uncertain or negative over this period. Ross and Elliott (2001) note also that these changes appear greater and more uniform over North America than over Eurasia.

Dai (2006b) evaluated changes in surface specific q and RH using a much wider range of sensors, located both over land and over ocean. Near-surface measurements do not provide altitude-integrated estimates of q and RH, although the spatial sampling is greatly improved relative to Ross and Elliott (1996; 2001) due to the large number of records (over 15,000 surface and ocean weather stations), and the sensor technology is more consistent over the period of record. Dai (2006b) found that globally averaged specific humidity (q) increased by around 0.06 g kg^{-1} per decade over the 1976–2004 period. This corresponds to roughly 4.9% per degree (°C) of warming over that period, globally averaged. The response of q to temperature increases over water (i.e., not source-limited) was found to be around 5.7% per °C of warming, reasonably consistent with the predictions of Clausius-Clapeyron (7% per °C) at constant RH. By contrast, the response over land is around 4.3% per °C of warming, presumably reflecting spatio-temporal limitations in water available for evaporation. Finally, column-integrated estimates of atmospheric water vapor have been available since 1988 from the special sensor microwave imager (SSM/I). On the basis of SSM/I, Trenberth et al. (2005) estimate that over the period 1988–2003, altitude-integrated atmospheric precipitable water over oceans has increased by around 0.40 mm per decade (1.3%). Variability over the period of analysis was found to reflect variations in SST. Assuming relatively constant RH, the observed trend is reasonably close to the 7% per °C predicted by Clausius-Clapeyron.

Precipitation: Increases in the frequency and intensity of heavy precipitation events over the last several decades are among the most clearly documented changes in recent U.S. climate (Kunkel, 2008). The following studies are representative of several recent studies examining trends in precipitation in the United States and globally. Karl and Knight (1998) found that precipitation over the U.S. increased by around 10% between the 1910s and the 1980s. These authors examined the respective contributions of changes in both frequency and intensity of precipitation to changes in total precipitation. Precipitation events were disaggregated into 20 intensity classes, each encompassing 5% of observed events; and extreme intensity events, defined as precipitation exceeding 2 inches (50.4) mm per day, were also examined. Among their conclusions, Karl and Knight (1998) found that observed increases reflect both increased frequency and intensity of rainfall events. While the frequency of events increased for all intensity (percentile) classes, intensity increased for heavy and extreme precipitation days only, and the proportion of total annual precipitation attributable to these heavy and extreme events has increased relative to more moderate events. Specifically, over half (53%) of the observed increase was due to increases in the upper 10% of events. Karl and Knight (1998) also found that the percentage of total area within the U.S. experiencing extreme precipitation events (> 50.4 mm/day) had increased by roughly 20% between 1910 and the mid-1990s. Kunkel et al. (1999) found statistically significant increasing trends in 1-year and 5-year return period 7-day precipitation events in the United States. However, subsequent work (Kunkel et al., 2003) extended the period of record back to 1895, and the frequency of extreme events in the late 19th-early 20th century was found to be similar to the late 20th Century, suggesting that natural variability cannot be ruled out as an additional factor contributing to the observed late 20th century increases in intensity.

Groisman et al. (2004) examined trends in several climatologic and hydrologic variables for the conterminous U.S. potentially influenced by climate change, including total precipitation, precipitation intensity, temperature and streamflow. Heavy precipitation events, defined as the upper 5% of daily events, increased by 14% over the period 1908–2002. Very heavy events (upper 1 %) increased by 20% over this period, and extreme events (upper 0.1 %) by 21%. The most significant increases occurred in the upper and lower Midwest for annual events, the upper Midwest and Great Lakes areas for summer events, and in New England for winter events. Similar results are presented in the global analysis of Groisman et al. (2005) for the period 1910–1999, who found that while total annual precipitation volumes over the United States increased by 1.2% per decade over the period 1970–1999, the share of annual precipitation associated with extreme events (defined as above) increased by 14% per decade over this period. These authors note that "*...practically the entire nationwide increase in heavy and very heavy precipitation occurred during the last three decades*" (p. 1328). Alexander et al. (2006), examining global precipitation statistics for the period 1951–2003, reached similar conclusions, specifically, that the contribution to total annual precipitation from very wet days, defined as the upper 5% of daily precipitation events, has increased over this period, even in many areas where total precipitation has decreased.

3. Model projections of trends in precipitation intensity

Evaporation and transpiration are in many circumstances controlled by factors other than the moisture-holding capacity of the atmosphere, including availability of moisture supply over land areas and energy available to drive the ET process (e.g., Allen and Ingram, 2002). Thus, GCMs generally predict increases in the global hydrologic cycle that are more modest than the 7% per °C predicted by Clausius-Clapeyron (Trenberth et al., 2003). Sun et al. (2007) have summarized changes in total global precipitation, precipitation frequency, intensity, fraction of precipitation from convective events and other related variables as projected by 17 of the most recent generation of GCMs from the Program for Climate Model Diagnosis and Intercomparison (PCMDI), used in the IPCC AR4 (2007), for emissions [Special Report on Emissions Scenarios SRES] scenarios B1 (low), A1B (medium) and A2 (high). Ensemble results, averaged over models and scenarios, indicate that global mean precipitation is projected to increase by around 1.2% per °C, and latent heat flux (evaporation) by a comparable amount, although global precipitable water is projected to increase by around 9.1% per °C. These results indicate that the atmospheric state variable (atmospheric precipitable water) responds approximately as predicted by Clausius-Clapeyron (consistent with relatively small increases in average RH), while atmospheric water fluxes (ET, precipitation) are constrained by other factors. Sun et al. (2007) report that overall, the frequency of (daily) precipitation events is projected to decrease, and the intensity of events to increase on average, consistent with Trenberth et al. (2003). However, the frequency of *heavy* precipitation events is projected to increase, indicating a more dramatic reduction in the frequency of light precipitation events. Thus, heavy (20–50 mm day^{-1}) and very heavy (> 50 mm day^{-1}) precipitation events are projected to contribute a disproportionately increasing share of total precipitation, through the combined effects of increased frequency and increased magnitude, with frequency effects more influential than intensity effects. These projected impacts are most pronounced under SRES scenario A2 (high emissions). These authors acknowledge that the (simulated) increases in intensity may not be fully captured in an analysis based on daily precipitation totals, since high-intensity events are often of shorter duration.

Tebaldi et al. (2006) have also examined model-simulated changes in extreme events, encompassing both temperature and precipitation events, on the basis of nine GCMs included in the IPCC AR4 (2007). These authors use a set of indicators of precipitation intensity proposed by

Frich et al. (2002) including the following: (1) frequency of days with precipitation exceeding 10 mm, (2) maximum 5-day precipitation total, (3) mean precipitation intensity (total precipitation divided by number of days with precipitation exceeding 1 mm) and (4) fraction of total precipitation due to events exceeding the 95th percentile. Significant increases in each of these four indices were projected by the GCMs evaluated, although not all trends were statistically significant. Significant (increasing) trends were associated with mid- to high latitudes in the Northern Hemisphere as well as some tropical areas within South America and Africa. Tebaldi et al. (2006) conclude that "Models (also) agree with observations over the historical period that there is a trend towards a world characterized by intensified precipitation, with a greater frequency of heavy-precipitation and high-quantile events, although with substantial geographic variability" (p. 206).

4. **How well do GCMs capture the frequency-intensity relationships observed in actual precipitation?**

In evaluating the model-generated evidence that precipitation intensity is likely to increase as a consequence of increasing tropospheric temperatures, it is important to recognize that many GCMs display well-documented biases with regard to precipitation frequency and intensity. Specifically, there is a tendency for GCMs to generate too many low-intensity events, and to under-simulate the intensity of heavy events. There are several possible reasons for this (since there are several convective precipitation parameterization schemes in use) although problems associated with the simulation of the diurnal cycle appear to play an important role (Dai, 1999; Trenberth et al., 2003). If conditions for the onset of moist convection in models are biased or poorly specified, convection occurs too early in the diurnal cycle, weaker convection results in less vigorous precipitation, and the removal of atmospheric moisture reduces the likelihood of more intense convective events subsequently (Trenberth et al., 2003).

Sun et al. (2006) compared the performance of 18 coupled Atmosphere-Ocean General Circulation Models (AOGCMs) used in the IPCC AR4 (2007) in simulating precipitation with historic observational data. Most of the models were found to greatly overestimate the frequency of summer (June-August) light precipitation events in the Northern Hemisphere, although the frequency of heavy precipitation events was simulated with greater skill, each subject to regional variations. Sun et al. (2006) summarize their observations as follows: "For *light* precipitation, most of the models greatly *overestimate the frequency* but reproduce the observed patterns of intensity relatively well. For *heavy* precipitation, most of the models roughly reproduce the observed frequency but *underestimate the intensity*" (p. 928, emphasis in original). *Light precipitation* is defined as 1–10 mm day^{-1} and *heavy precipitation* as >10 mm day^{-1}. These authors emphasize the importance of getting precipitation "right for the right reasons" since surface runoff, evaporation and soil moisture are all highly sensitive to precipitation IFD relationships. Dai (2006a) also examines the performance of 18 models from the PCMDI (AR4) ensemble with respect to the characterization of precipitation. Dai's (2006a) study emphasizes model skill in simulating precipitation via the distinct convective and stratiform mechanisms, noting that (in GCMs) stratiform precipitation is a grid-scale process while convective precipitation is a subgrid-scale process. Model performance is compared to the Tropical Rainfall Measuring Mission (TRMM) observational data. Among other results, Dai (2006a) found that the models examined derived too much of total precipitation (28%–38%) from light precipitation (1–5 mm day^{-1}) relative to TRMM data (19%), and far too little (0–2%) from very heavy precipitation (> 50 mm day^{-1}) (7% for TRMM). Model replication of TRMM results were best for moderate events, defined as 10–20 mm day^{-1}. Dai (2006a) concludes that "…the newest generation of Coupled Ocean-Atmosphere General Circulation Models (CGCMs) still rains too frequently, as in previous generations (…), mostly within the 1–10 mm day^{-1} categories, while heavy precipitation (> 20 mm day^{-1}) occurs too rarely" (p. 4622).

5. Implications for the ORD modeling study

On the basis of literature reviewed here, several observations can be made. First, the importance of getting IFD relationships right cannot be over-emphasized. Analysis of historical data indicates that changes in the distribution of precipitation between light- and heavy-intensity events are quantitatively greater than changes in overall precipitation at annual or seasonal levels in many regions, and projected runoff estimates are likely to be quite sensitive to these IFD relationships. Second, model-generated projections of precipitation are characterized by documented biases with respect to precipitation intensity and frequency. This suggests that the *relative changes* in precipitation IFD relationships should be used as the basis for adjusting historical precipitation records in CAT rather than their absolute levels.

NARCCAP has to date provided summaries of three GCM-RCM downscaled products intended for use in modifying the historical gauge records. These datasets include changes in monthly precipitation accumulation, and changes in the contributions of precipitation by intensity class for 25%, 50%, 70%, and 90% percentile classes. While this data is extremely useful, it is recommended that we obtain a number of representative output series at finer time resolution – down to 3-hourly as output by NARCCAP RCMs. Ideally, we would obtain series that sample from at least three of the climatic zones associated with the pilot watersheds, and including the upper Midwest (Minnesota) in particular, since many of the greatest observed changes in precipitation intensity have occurred in this region. These time series would be processed to obtain estimates of the change in frequency of events, by event size class, to support the appropriate use of CAT. As emphasized above, the "deltas" (changes in projection period relative to base period) would be the basis for CAT transformations rather than the projections themselves, which potentially contain biases, as discussed.

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Appendix D
Model Configuration, Calibration and Validation

Basin: Apalachicola-Chattahoochee-Flint (ACF)

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Watershed Background

The Apalachicola-Chattahoochee-Flint (ACF) River basin lies in Georgia, Alabama, and Florida, empties into the Gulf of Mexico at Apalachicola Bay (Figure 1). It is comprised of 12 HUC8 cataloging units, and stretches across parts of three geological physiographic provinces. The ACF basin along with the Alabama-Coosa-Tallapoosa (ACT) River basin, are the central focus of water war that has been ongoing for over 20 years. The states of Georgia, Alabama, and Florida have been involved in a legal controversy over the fair management of the waters that these states share (Alabama River Alliance 2007).

Approximately 64 percent of the basin is forested. Approximately 25 percent of these forests are timberlands used for manufacturing wood products. Agricultural land represents a mix of cropland, pasture, orchards, and areas of confined feeding for poultry and livestock production. The dominant agricultural land use in the Piedmont Province is pasture and confined feeding for dairy or livestock production. Most of the poultry operations in the ACF River basin are concentrated in the upper part of the Chattahoochee River basin. Row-crop agriculture, orchards, and silviculture are most common in the Coastal Plain areas. Common crops in the watershed include peanuts, corn, soybeans, wheat, and cotton. The largest concentration of urban land in the basin is in the Atlanta area. Nearly 90 percent of the total population in the basin lives in Georgia, and nearly 75 percent live in the Atlanta metropolitan area.

The ACF River basin is characterized by a warm and humid, temperate climate. Precipitation is greatest in the mountains and near the Gulf of Mexico, lowest in the center of the basin. Average annual precipitation in the basin is about 55 inches, but ranges from a low of 45 inches in the east-central part of the basin to a high of 60 inches in the Florida panhandle. Throughout the ACF River basin, low flows usually occur from September to November and peak flows usually occur from January to April when rainfall is high and evapotranspiration is low.

The watershed is underlain by five major aquifer systems: crystalline rock aquifers in the Blue Ridge and Piedmont physiographic provinces, and four aquifer systems in the Coastal Plain physiographic province. Watershed hydrology is influenced by 16 reservoirs, 13 of which are on the Chattahoochee River. These reservoirs play a major role in controlling flow and influencing the quality of water in the watershed (Couch 1993).

Water Body Characteristics

Chattahoochee River

The Chattahoochee River is 430 miles long, drains an area of 8,770 mi^2, and has an average discharge of 11,500 cubic feet per second (cfs). The river begins in the Blue Ridge Province in the mountainous region of northeast Georgia, which is characterized by steep topography and relatively high precipitation and runoff. Annual precipitation ranges from 53 to 70 inches and annual runoff from 27 to 37 inches. The part of the Chattahoochee River watershed in the Blue Ridge Province is underlain by crystalline rock, and surface water in the area is siliceous and low in natural mineral content (Couch 1993).

Thirteen of 16 dams on mainstem locations in the ACF River basin are on the Chattahoochee River. Dam construction in the watershed began in the early 1800s on the Chattahoochee River above the Fall Line at Columbus, Georgia, to take advantage of natural gradients for power production. Pronounced decreases in the frequency of high and low flows have occurred since the start of operation of Buford Dam, which forms Lake Sidney Lanier. Lake Sidney Lanier, West Point Lake, and Lake Walter F. George provide most water storage available to regulate flows in the watershed. Lake Sidney Lanier alone provides 65 percent of conservation storage, although it drains only 5 percent of the ACF River basin. In addition, West Point Lake and Lake Walter F. George provide 18 and 14 percent, respectively, of the watershed's conservation storage (USGS 2008).

Throughout most of its length, the Chattahoochee River is controlled by hydropeaking hydroelectric plants, which contribute to power supply during peak periods of electric demand. From Cornelia, Georgia all the way down to Lake Seminole, the hydrograph shows the influence of hydropeaking operations and these operations can result in daily stage fluctuations of 4 feet or more (USGS 2008).

In contrast to the mainstem Chattahoochee River, many tributaries remain free flowing. Flows of tributaries in forested watersheds are represented by Snake Creek and flows typical of urban watersheds are represented by Peachtree Creek. Similar to most Piedmont streams, both streams have higher sustained flows during winter months and show response to storm events throughout the year. However, sharper peaks in the hydrography of Peachtree Creek reflect greater influence of impervious land cover in the urban watershed (USGS 2008).

Flint River

The Flint River, which is 340 miles long and drains an area of 8,460 mi^2, has an average discharge of 9,800 cfs and begins in the Piedmont Province near Atlanta's Hartsfield International Airport. In the upper part of the Flint River watershed annual precipitation ranges from 44 to 59 inches, and annual runoff ranges from 10 to 39 inches. The upper part of the Flint River watershed is characterized by both broad and narrow ridges separated by narrow valleys. Natural surface water quality in the part of the watershed in the Piedmont Province is similar to that in the Blue Ridge Province, but the water generally has higher concentrations of dissolved minerals and higher turbidity (Couch 1993, Cherry 1961).

Most of the larger tributaries in the ACF River basin are located in the Coastal Plain Province part of the Flint River watershed. These tributaries include Ichawaynochaway Creek, Chickasawhatchee Creek, Kinchafoonee Creek , and Muckalee Creek.

Apalachicola River

The Chattahoochee and Flint Rivers flow through the Piedmont and Coastal Plain Provinces to their confluence at Lake Seminole where they form the Apalachicola River. The parts of these river watersheds that lie in the Coastal Plain Province are underlain by unconsolidated sediments consisting of sand, gravel, and clay. Surface water tends to be siliceous in the upper part of the Coastal Plain Province but is predominantly carbonate in southwestern Georgia where it is in contact with limestone. Rainfall in the lower Chattahoochee and Flint River watersheds ranges from 43 to 55 inches, annually. Rainfall in this area is rapidly absorbed by the permeable soils, and annual runoff ranges from 12 to 28 inches (Couch 1993).

The Apalachicola River is 106 miles long and drains an area of about 2,400 mi^2 in the lower Coastal Plain Province. Because of the low gradient of the lower Coastal Plain Province, the channel of the Apalachicola River meanders through a wide, swampy floodplain. The floodplain ranges in width from 0.6 miles below Lake Seminole to 5 miles near its mouth, where the Apalachicola River flows through a system of distributaries to the Apalachicola Bay. The Apalachicola River has an average discharge of 26,000 cfs (Couch 1993).

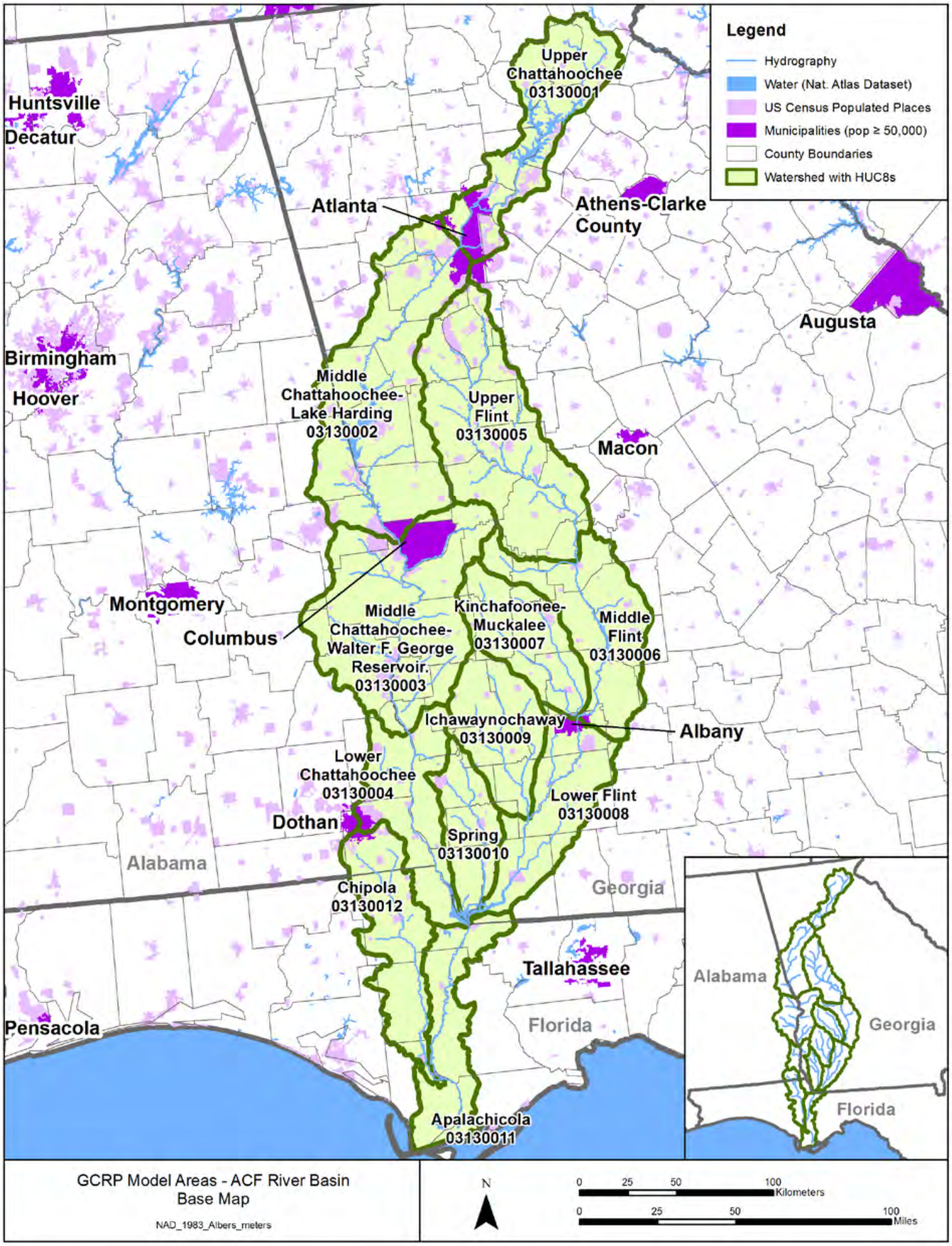


Figure 1. Location of the Apalachicola-Chattahoochee-Flint (ACF) River basin.

Soil Characteristics

The ACF River basin contains parts of the Blue Ridge, Piedmont, and Coastal Plain physiographic provinces that extend throughout the southeastern United States. Similar to much of the Southeast, the watershed's physiography reflects a geologic history of mountain building in the Appalachian Mountains, and long periods of repeated land submergence in the Coastal Plain Province. Physiography within the major provinces is not homogeneous and has been subdivided by the states of Alabama, Florida, and Georgia. Although similar physiography may extend across state boundaries, districts may be assigned different names by state geologists in each state (USGS 2008).

Three major soil orders, ultisols, entisols, and spodosols, and more than 50 soil series are present in the ACF River basin. Ultisols are characterized by sandy or loamy surface horizons and loamy or clayey subsurface horizons. These deeply weathered soils are derived from underlying acid crystalline and metamorphic rocks. Entisols are young soils with little or no change from parent material and with poorly developed subhorizons. These soils are frequently infertile and droughty because they are deep, sandy, well-drained, and subject to active erosion. Spodosols are characterized by a thin sandy subhorizon underlaying the A horizon. This sandy subhorizon is cemented by organic matter and aluminum. The ACF River basin is similar to much of the southeastern coastal plain in the dominance of ultisols. Entisols are found at and below the Fall Line and in the Dougherty Plain; and spodosols are found in the Gulf Coast Lowlands (USGS 2008).

The 20 Watershed study utilized STATSGO soil survey hydrologic soil group (HSG) information during model set-up. The descriptions of each hydrologic soil group are provided below.

Group A Soils Have low runoff potential and high infiltration rates even when thoroughly wetted. They consist chiefly of deep, well to excessively drained sands or gravels and have a high rate of water transmission.

Group B Soils Have moderate infiltration rates when wet and consist chiefly of soils that are moderately deep to deep, moderately well to well drained, and moderately fine to moderately course textures.

Group C Soils Have low infiltration rates when thoroughly wetted and consist chiefly of soils having a layer that impedes downward movement of water with moderately fine to fine structure.

Group D Soils Have high runoff potential, very low infiltration rates and consist chiefly of clay soils with high swelling potential, soils with a permanent water table, soils with a claypan or clay layer at or near the surface and shallow soils over nearly impervious material.

The ACF basin has all four HSGs in the watershed. The Upper and Middle Chattahoochee and most of the Upper Flint watersheds are dominated by hydrologic type B soils. As both rivers reach and cross over the Fall Line, the boundary between the Piedmont and Coastal Plain physiographic provinces, they flow through an area dominated by HSG A soils. As the two rivers come together near Lake Seminole the soil distribution is equally split between HSG A and B soils. The southernmost extents of the Apalachicola River are dominated by hydrologic soil type D.

Land Use Representation

Land use/cover in the watershed is based on the 2001 NLCD coverage (Figure 2). The 2001 NLCD land cover was used in order to generate consistency amongst all models for the 20 Watershed project.

Chattahoochee River Watershed

The Chattahoochee River watershed above Lake Sidney Lanier is dominated by forested land with a majority of the remaining land being pasture. As the Chattahoochee River flows out of Buford Dam to the southwest the dominant land use starts shifting to urban. As the Chattahoochee River nears and flows through the Atlanta metro area, land use is almost entirely urban. After leaving the Atlanta Metro area, land use shifts back to forest dominance, but with a greater amount of pasture than the area above Lake Sidney Lanier. Continuing down the Chattahoochee and across the Fall Line, the dominant land use is still forest, but wetland areas begin to increase while pasture areas begin to decrease. After the Chattahoochee leaves Lake Walter F. George, agriculture and forest become equally dominant with wetlands still being prevalent. This land use/land cover pattern continues until the Chattahoochee empties into Lake Seminole.

Flint River Watershed

The most northern portions of the Flint River watershed are almost entirely urban. As the Flint River flows south the land use shifts to predominately pasture and then to forest. Once the Flint River crosses the Fall Line, agriculture become increasingly prevalent but there is still a good portion of forest and an increase in wetlands. The land uses of major tributaries to the Flint River are also chiefly comprised of agriculture, forest, and wetlands. The Flint River immediately above Lake Seminole is mostly agriculture with a small portion of pasture and forest.

Apalachicola River Watershed

The Apalachicola River immediately below Lake Seminole is comprised of mostly forest, scrub land and pasture. As the Apalachicola River flows south, the land use is almost entirely dominated by wetlands until the river empties into the Gulf of Mexico. The Chipola, a major tributary to the Apalachicola River, is chiefly comprised of pasture and barren lands to the north and forest and wetlands to the south.

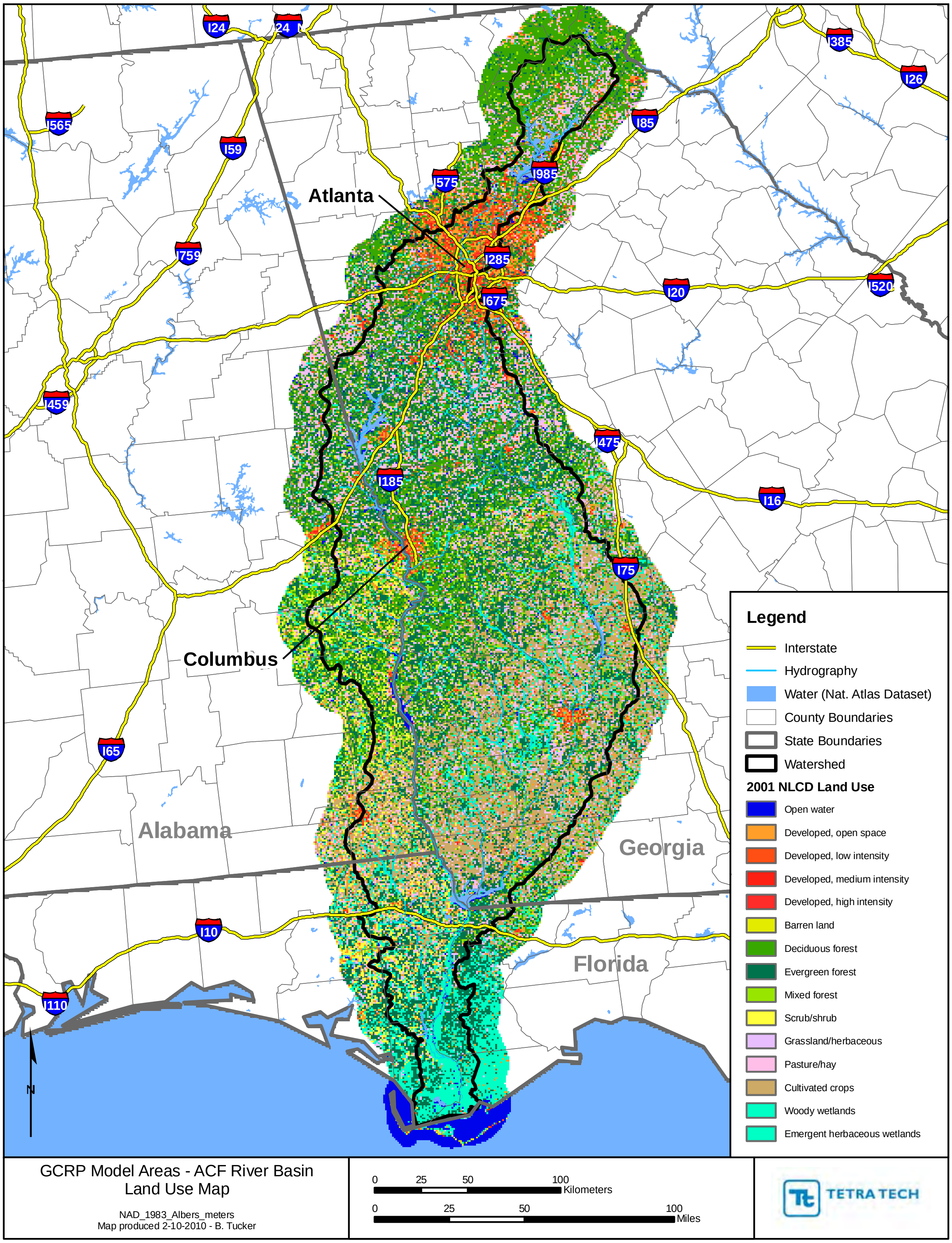


Figure 2. Land use in the ACF River basin.

NLCD land cover classes were aggregated according to the scheme shown in Table 1 for representation in the 20 Watershed model, and then overlain with the soils HSG grid. Pervious and impervious lands are specified separately for HSPF, so only one developed pervious class is used, along with an impervious class. HSPF simulates impervious land areas separately from pervious land. Impervious area distributions were also determined from the NLCD Urban Impervious data coverage. Specifically, percent impervious area was calculated over the entire watershed for each of the four developed land use classes. These percentages were then used to separate out impervious land. NLCD impervious area data products are known to underestimate total imperviousness in rural areas. However, the model requires properly connected impervious area, not total impervious area, and the NLCD tabulation is assumed to provide a reasonable approximation of connected impervious area. Different developed land classes are specified separately in SWAT. The WATER, BARREN, DEVPERV, and WETLAND classes are not subdivided by HSG in HSPF; SWAT uses the built-in HRU overlay mechanism in the ArcSWAT interface. The distribution of land use in the watershed is summarized in Table 2.

Table 1. Aggregation of NLCD land cover classes

NLCD Class	Comments	SWAT class	HSPF (after processing)
11 Water	Water surface area usually accounted for as reach area	WATR	WATER
12 Perennial ice/snow		WATR	BARREN, Assume HSG D
21 Developed open space		URLD	DEVPERV; IMPERV
22 Dev. Low Intensity		URMD	
23 Dev. Med. Intensity		URHD	
24 Dev. High Intensity		UIDU	
31 Barren Land		SWRN	BARREN (D)
41 Forest	Deciduous	FRSD	FOREST (A,B,C,D)
42 Forest	Evergreen	FRSE	
43 Forest	Mixed	FRST	
51-52 Shrubland		RNGB	SHRUB (A,B,C,D)
71-74 Herbaceous Upland		RNGE	GRASS (A,B,C,D), BARREN (D)
81 Pasture/Hay		HAY	GRASS (A,B,C,D)
82 Cultivated		AGRR	AGRI (A,B,C,D)
91-97 Wetland	Emergent & woody wetlands	WETF, WETL, WETN	WETLAND, Assume HSG D
98-99 Wetland	Aquatic bed wetlands (not emergent)	WATR	WATER

Table 2. Land use distribution for the ACF River basin (2001 NLCD) (mi^2)

HUC 8 watershed	Open water	Developed land[a]				Barren land	Forest	Shrubland	Pasture/Hay	Cultivated	Wetland	Total
		Open Space	Low density	Medium density	High density							
Upper Chattahoochee **03130001**	66.6	226.5	150.0	53.8	30.5	10.8	804.8	56.8	176.0	0.1	9.5	1,585.5
Middle Chattahoochee Lake Harding **03130002**	82.8	218.6	127.1	29.9	15.6	23.0	1,809.3	246.5	388.1	1.3	98.7	3,040.9
Middle Chattahoochee Walter F. George Reservoir **03130003**	75.9	116.5	56.7	14.8	6.0	9.7	1,707.5	385.0	157.9	142.8	164.2	2,837.0
Lower Chattahoochee **03130004**	8.7	41.4	10.2	2.3	0.8	0.9	470.5	138.1	94.8	294.0	70.3	1,132.1
Upper Flint **03130005**	28.3	143.7	79.6	21.9	15.0	16.3	1,454.6	227.5	376.2	79.6	192.3	2,635.0
Middle Flint **03130006**	17.3	62.6	20.7	3.9	1.6	1.6	618.3	126.6	120.4	416.2	164.9	1,554.1
Kinchafoonee Muckalee **03130007**	4.0	40.0	13.0	3.1	1.5	0.8	506.4	97.1	83.9	232.7	117.7	1,100.1
Lower Flint **03130008**	6.1	62.5	27.4	6.5	3.3	1.7	455.7	125.9	82.2	348.5	95.1	1,214.9
Ichawaynochaway **03130009**	4.6	31.4	5.6	1.1	0.2	0.8	411.6	90.6	82.0	303.9	172.3	1,104.0
Spring[b] **03130010**	36.6	33.5	8.9	1.4	0.4	0.8	257.6	73.3	70.1	347.5	127.5	957.7
Apalachicola **03130011**	14.8	25.9	2.3	0.6	0.1	0.6	335.7	61.4	25.7	35.8	339.5	842.2
Chipola **03130012**	10.4	68.4	7.6	2.2	0.6	1.0	412.7	231.4	100.7	194.2	250.4	1,279.6
Total	356.1	1,071.0	509.0	141.4	75.6	68.1	9,244.8	1,860.1	1,758.2	2,396.6	1,802.5	19,283.2

[a]The percent imperviousness applied to each of the developed land uses is as follows: open space (8.04%), low density (30.16%), medium density (60.71%), and high density(89.9%).
[b]Delineation for Lake Seminole crossed HUC8 boundaries so whole watershed is represented in Spring HUC8.

The HSPF model is set up on a hydrologic response unit (HRU) basis. For HSPF, HRUs were formed from an intersection of land use and hydrologic soil group, and then further subdivided by precipitation gage. Average slopes (which tend to correlate with soils) were calculated for each HRU. Slopes in most of the watershed are relatively mild (1-5 percent), therefore HSPF HRU's were not further subdivided by slope. The three HRUs above Lake Lanier have average slopes of 15-24 percent, but since there were already three HRU's for four delineated subwatersheds it was not further divided. The water land use area was adjusted to prevent double counting with area described in HSPF reaches. SWAT HRUs are formed from an intersection of land use and SSURGO major soils.

Point Sources

Facilities permitted under the National Pollutant Discharge Elimination System (NPDES) are, by definition, considered point sources. For all models in the 20 Watershed application, it was assumed that minor dischargers (below 1.0 MGD) were insignificant and, therefore, not included in the model setup and simulation. Data were sought from the PCS database for the major dischargers in the ACF River basin and reflect the time period from 1991-2006. Facilities that were missing total nitrogen, total phosphorus, or total suspended solids (TSS) concentrations were filled with a typical pollutant concentration value from literature based on Standard Industrial Classification (SIC) classification. For the 20 Watershed application, the assumption was to use constant point source flows and concentrations, for the entire simulation period, for each major discharge facility in the watershed. Figure 3 presents the locations of the major point sources included in the models.

During the water quality calibration, it was noticed that assumptions used for total phosphorus at some facilities were too high. An investigation into the point sources that had assumed values for total phosphorus was conducted. It was found that point sources with assumed values for total phosphorus, that were too high, were water pollution control plants (WPCP) and the assumed total phosphorus concentration for those facilities was 7 mg/L. A new assumed value was needed for these facilities. The new assumed value was 1.5 mg/L, which is an average of the total phosphorus concentration for WPCP's that do monitor for total phosphorus. It is assumed that 1.5 mg/L is a much better estimate of the true total phosphorus concentration coming out of WPCP's in the ACF basin. The new assumed value was also applied to the SWAT simulation. Both the HSPF and SWAT models used the exact same flows and concentrations for each of the major point sources included in the simulations for the ACF basin.

Table 3. Major point source discharges in the ACF River basin

NPDES ID	Name	Design flow (MGD)*	Observed flow (MGD) (1991-2006 average)
AL0000817	MEADWESTVACO COATED BOARD INC	40.00	22.34
AL0022209	PHENIX CITY WWTP	7.75	3.32
AL0022764	DOTHAN CITY OF OMUSSEE WWTP	7.12	3.97
AL0023159	LANETT CITY OF WWTP	5.00	1.90
AL0024619	SOUTHERN NUCLEAR OPERATNG CO	0.16	0.52
AL0024724	EAST AL WATER LOWER VALLEY WTP	4.00	2.83
AL0059218	OPELIKA CITY OF EASTSIDE WWTP	1.00	0.70
AL0061671	EUFAULA CITY OF	2.70	1.75
AL0072737	DOTHAN CITY CYPRESS WWTP NEW	3.00	1.32
FL0002283	GULF PWR SCHOLZ STEAM	129.60	3.24
FL0026867	BLOUNTSTOWN-STP	1.50	0.57
FL0031402	FL STATE HOSPITAL	1.30	0.71
GA0000973	COLUMBUS WATER WKS-FT.BENNING	4.60	11.71
GA0001112	SCOVILL FASTENERS, INC.		0.26
GA0001198	USAF PLT #6 - LOCKHEED MARTIN		1.63
GA0001201	GA. PACIFIC CORP (GREAT S.P)		32.60

NPDES ID	Name	Design flow (MGD)*	Observed flow (MGD) (1991-2006 average)
GA0001619	MERCK & CO -FLINT RVR PLNT		1.13
GA0020052	WEST POINT WPCP	1.00	0.64
GA0020079	THOMASTON-BELL CREEK WPCP	2.00	1.01
GA0020168	GAINESVILLE (LINWOOD DRIVE)	2.70	2.03
GA0020486	MONTEZUMA WPCP #2	1.95	0.30
GA0020516	COLUMBUS (SOUTH WPCP)	42.00	30.35
GA0021156	GAINESVILLE FLAT CR WPCP	10.20	6.45
GA0021326	DAWSON WPCP	2.50	1.29
GA0021458	ATLANTA (UTOY CREEK WRC)	40.00	29.50
GA0021482	ATLANTA (R.M. CLAYTON WPCP)	100.00	80.00
GA0021504	CORNELIA WPCP	3.00	2.33
GA0023167	BUFORD SOUTHSIDE WPCP	2.00	1.11
GA0024040	ATLANTA (SOUTH RIVER WRC)	48.00	35.31
GA0024333	FULTON CO-BIG CREEK WPCP	24.00	21.09
GA0024503	CORDELE WPCP	5.00	2.66
GA0024678	BAINBRIDGE WPCP	2.50	1.32
GA0025381	FULTON CO-CAMP CREEK WPCP	13.00	12.47
GA0025585	BLAKELY WPCP	1.32	1.01
GA0026077	DAHLONEGA WPCP	1.44	0.51
GA0026140	COBB CO-SUTTON WPCP	40.00	30.62
GA0026158	COBB CO.-SO. COBB WPCP	40.00	24.50
GA0026433	GWINNETT CO (CROOKED CRK WPCP)	36.00	23.52
GA0030121	THOMASTON-TOWN BRANCH WPCP	2.00	0.97
GA0030341	DOUGLASVILLE SOUTHSIDE WPCP	3.25	2.48
GA0030686	FULTON CO-JOHNS CREEK WPCP	7.00	5.73
GA0030791	GRIFFIN POTATO CR WPCP	2.00	1.41
GA0031721	NEWNAN WAHOO WPCP	3.00	1.66
GA0033511	DECATUR CO-IND. AIRPARK WPCP	1.50	0.38
GA0035777	PEACHTREE CTY (LINE CRK WPCP)	2.00	1.44
GA0035807	FAYETTEVILLE-WHITEWTER CR WPCP	3.75	1.88
GA0036951	LAGRANGE WPCP (LONG CANE CRK)	12.50	5.91
GA0037222	ALBANY (WPCP NO 2)	32.00	18.05
GA0038369	CLAYTON COUNTY (SHOAL CRK)	4.40	1.73
GA0046019	CUMMING WPCP	2.00	1.30
GA0046655	PEACHTREE CTY (ROCKAWAY WPCP)	4.00	1.66
GA0047201	DOUGLASVILLE (SWEETWATER CRK.)	3.00	1.39
GA0047767	AMERICUS MILL CRK, WPCP	4.40	2.73

*Note: Facilities that do not list a design flow are large industrial facilities. These industrial facilities have different permitting in the state of Georgia and these permits do not report a design flow.

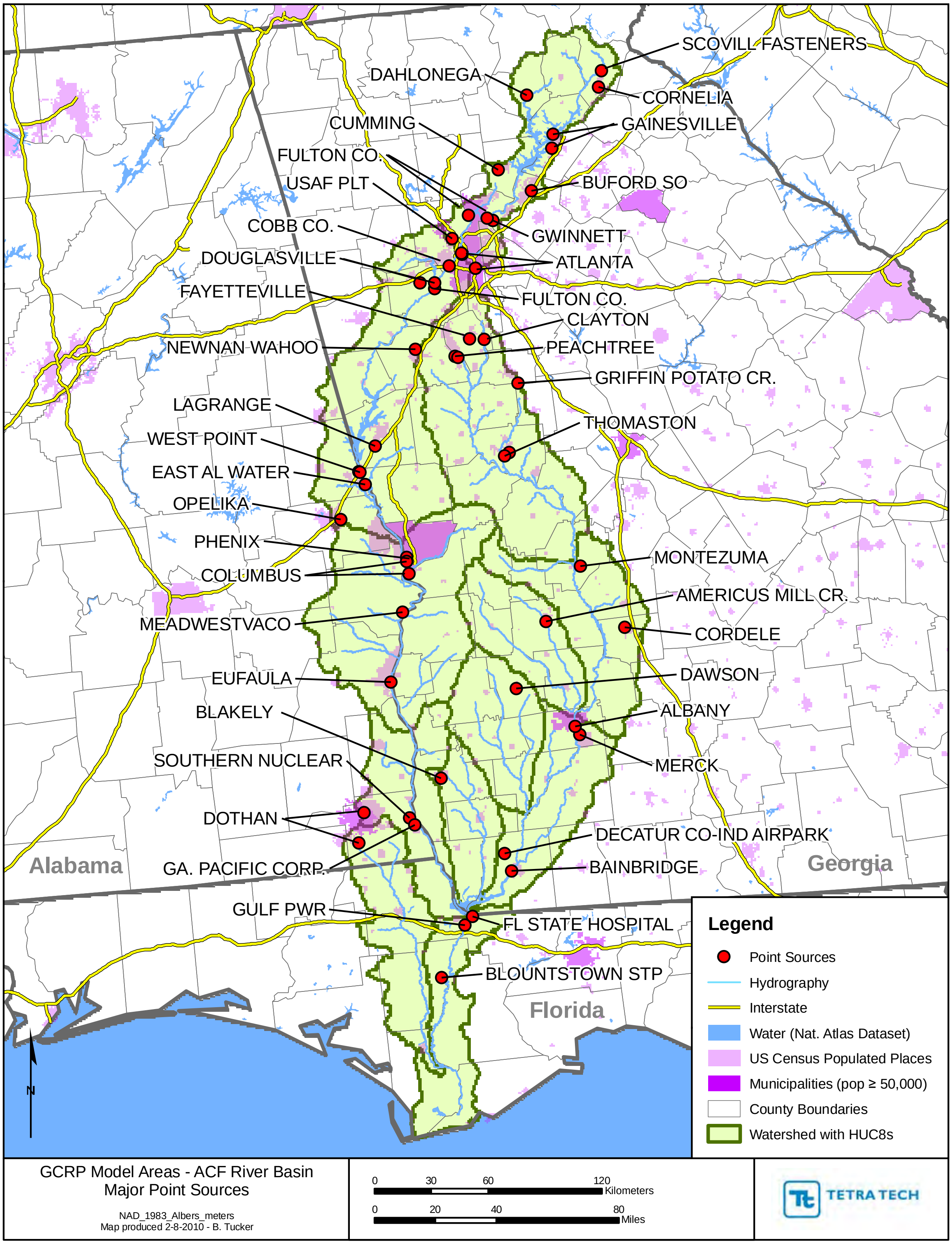


Figure 3. Major point sources in the ACF River basin.

Meteorological Data

The required meteorological data series for the 20 Watershed study are precipitation, air temperature, and potential evapotranspiration. The 20 Watershed model does not include water temperature or algal simulation and uses a degree-day method for snowmelt. These are drawn from the BASINS4 Meteorological Database (USEPA 2008), which provides a consistent, quality-assured set of nationwide data with gaps filled and records disaggregated. Scenario application will require simulation over 30 years, so the available stations are those with a common 30-year period of record (or one that can be filled from an approximately co-located station). A total of 37 precipitation stations were identified for use in the ACF basin model with a common period of record of 10/1/1972-9/30/2002 (Table 4 and Figure 4). Temperature records were sparse; where these were absent, temperature was taken from nearby stations with an elevation correction. For each weather station, Penman-Monteith reference evapo-transpiration was calculated for use in HSPF using observed precipitation and temperature coupled with SWAT weather generator estimates of solar radiation, wind movement, cloud cover, and relative humidity.

For the 20 Watershed model applications, SWAT uses daily meteorological data, while HSPF requires hourly data. It is important to note that a majority of the meteorological stations available for the ACF basin are Cooperative Summary of the Day stations that do not report sub-daily data. The BASINS4 dataset already has versions of the daily data that have been disaggregated to an hourly time step using template stations. For each daily station, this disaggregation was undertaken in reference to a single disaggregation template. Occasionally, this automated procedure provides undesirable results, particularly when the total rainfall for the day is very different between the subject station and the disaggregation template. This yields a small number of hourly precipitation intensity estimates that are unrealistically high (e.g., much greater than the 100-year 1-hour event for the region). This has only a small impact on the watershed-scale hydrologic calibration as gages are influenced by rainfall from multiple weather stations, but can introduce significant problems for the prediction of erosion and sediment loads.

Table 4. Precipitation stations for the ACF River basin model

COOP ID	Name	Latitude	Longitude	Temperature	Elevation (ft)
GA094230	HELEN	34.6997	-83.7261	Yes	1440
GA092283	CORNELIA	34.5181	-83.5286	Yes	1470
GA091998	CLERMONT 4 WSW	34.4503	-83.855	No	1281
GA092408	CUMMING 1 ENE	34.2214	-84.1222	No	1306
GA096407	NORCROSS	33.9483	-84.2219	No	1030
GA090444	ATLANTA BOLTON	33.8236	-84.4983	No	885
GA092791	DOUGLASVILLE 4 S	33.7006	-84.7303	No	1002
GA090451	ATLANTA HARTSFIELD INTERNATIONAL	33.63	-84.4417	Yes	1010
GA096335	NEWNAN 4NE	33.4428	-84.7886	Yes	920
GA093570	FRANKLIN	33.2758	-85.0992	No	790
GA094949	LA GRANGE	33.065	-85.0294	Yes	715
GA099506	WOODBURY	32.9839	-84.5889	No	790
GA099291	WEST POINT	32.8694	-85.1892	Yes	575
GA098661	THOMASTON 2 S	32.8664	-84.3175	Yes	672
GA098535	TALBOTTON	32.6856	-84.5192	Yes	686
GA091425	BUTLER	32.6525	-84.1858	No	446
GA092166	COLUMBUS METRO AP	32.5161	-84.9422	Yes	392
GA091372	BUENA VISTA	32.3178	-84.5203	No	646
GA095979	MONTEZUMA	32.2903	-84.0314	No	327
AL015397	MIDWAY	32.0597	-85.4953	No	556
GA090253	AMERICUS 3 SW	32.0503	-84.2753	Yes	490
GA095394	LUMPKIN 2 SE	32.0306	-84.7753	Yes	485
AL012730	EUFAULA WILDLIFE REF	32.0086	-85.0919	Yes	215

COOP ID	Name	Latitude	Longitude	Temperature	Elevation (ft)
GA092266	CORDELE	31.9847	-83.7758	Yes	308
GA092570	DAWSON	31.7819	-84.4497	No	355
GA092450	CUTHBERT	31.7672	-84.7931	Yes	461
AL010008	ABBEVILLE	31.5703	-85.2483	Yes	456
GA093028	EDISON	31.5664	-84.7339	Yes	294
GA090140	ALBANY 3 SE	31.5339	-84.1489	Yes	180
GA090979	BLAKELY	31.3811	-84.9508	Yes	268
AL012377	DOTHAN	31.1942	-85.3708	No	275
GA091500	CAMILLA 3 SE	31.1903	-84.2036	Yes	175
GA092153	COLQUITT 2 W	31.1681	-84.7664	Yes	153
GA090586	BAINBRIDGE INT PAPER	30.8228	-84.6175	No	190
FL081544	CHIPLEY	30.7836	-85.4847	Yes	130
FL089795	WOODRUFF DAM	30.7219	-84.8742	No	107
FL089566	WEWAHITCHKA	30.1192	-85.2042	Yes	42

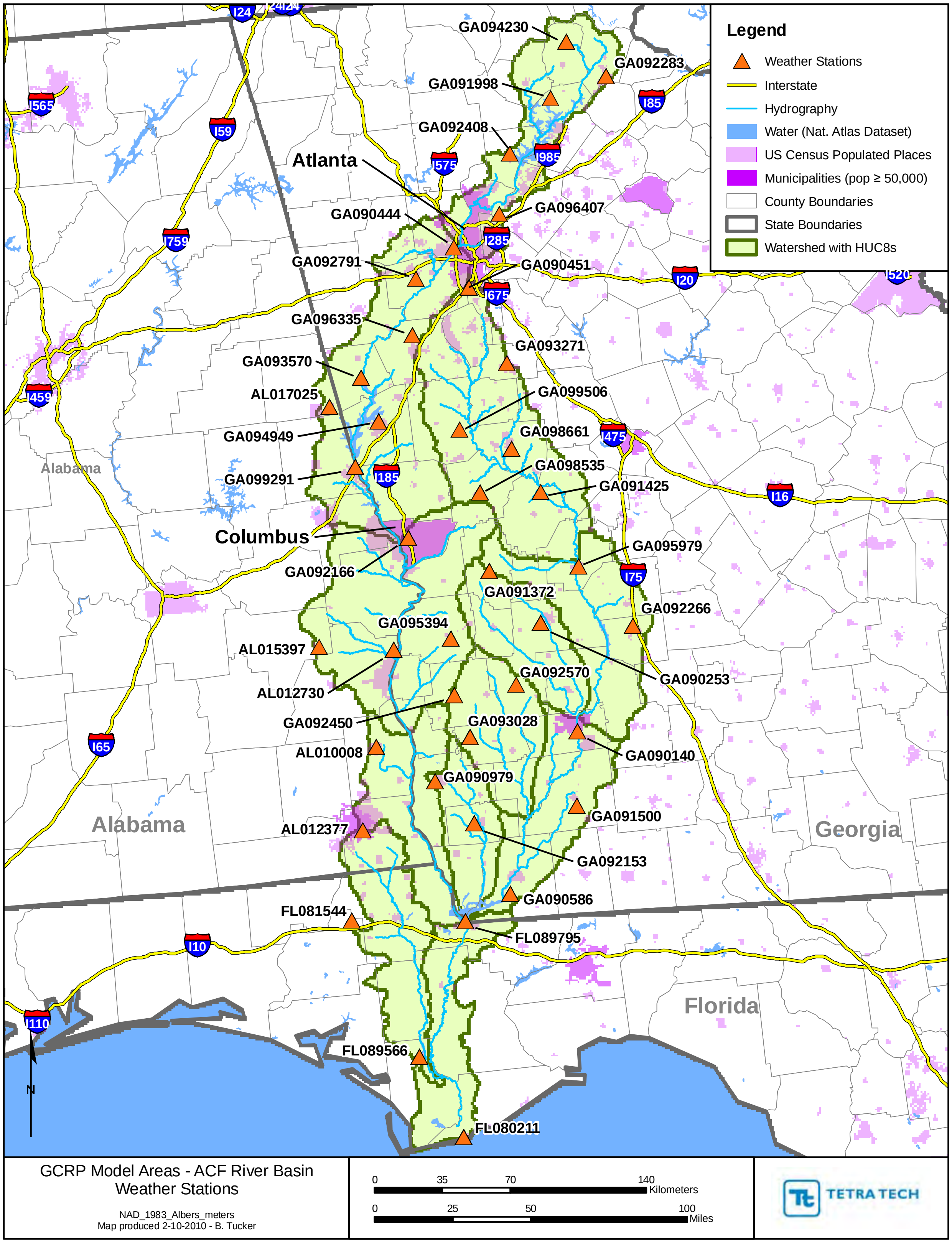


Figure 4. Weather stations for the ACF River basin model.

Watershed Segmentation

The ACF River basin was divided into 101 subwatersheds for the purposes of modeling (Figure 5). The initial calibration watershed (Upper Flint HUC) is highlighted. Each of the subwatershed delineations represents roughly a HUC 10 scale watershed. Each of the major reservoirs in the ACF basin was delineated so that the each dam outlet represents an individual watershed outlet. The delineations were done this way to ensure that any individual lake was contained in one watershed and that the watershed was only represented by one outlet. The ACF 20 Watershed model encompasses the complete watershed and does not require specification of any boundary conditions for application.

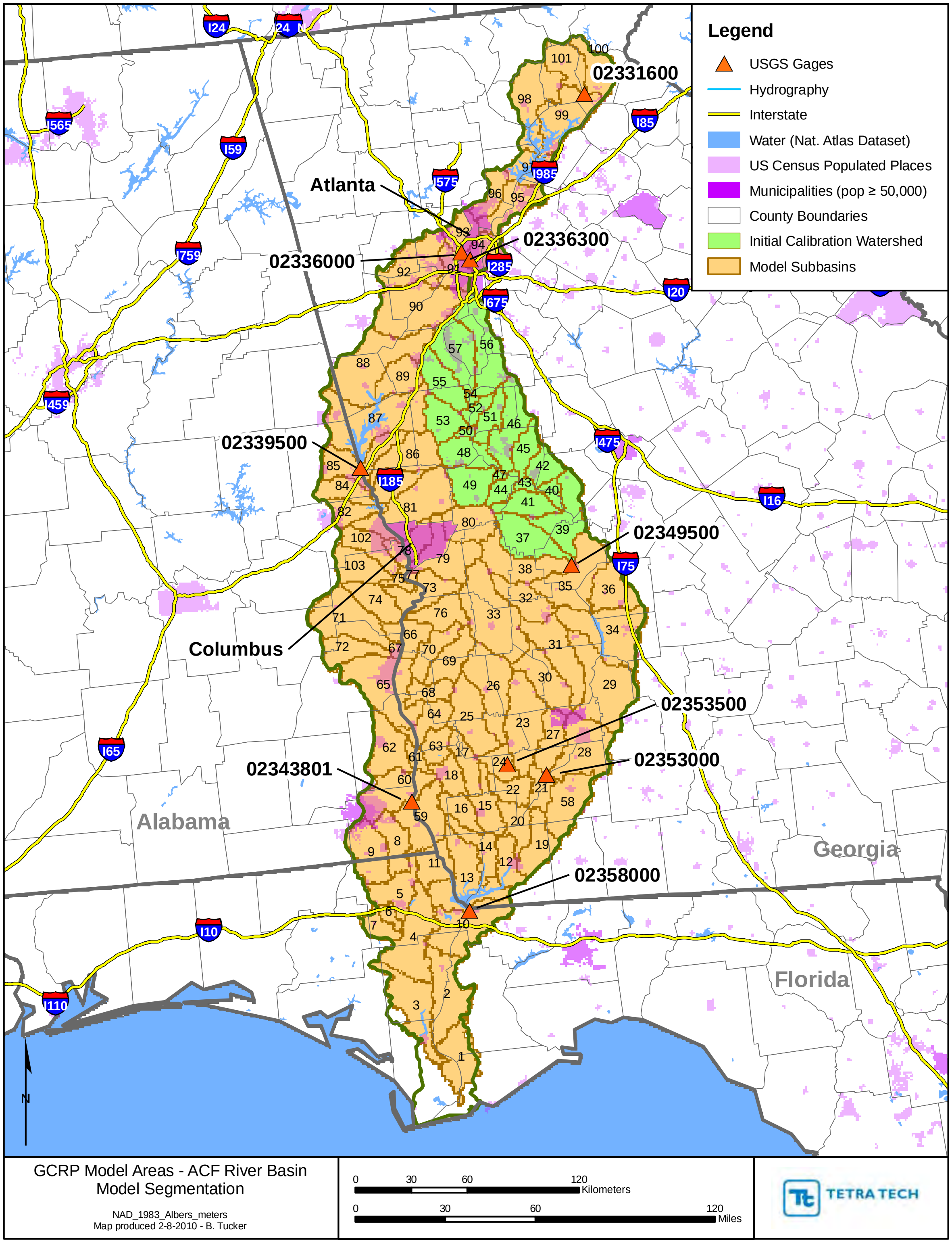


Figure 5. Model segmentation and USGS stations utilized for the ACF River basin.

Note: SWAT subwatershed numbering is shown; the HSPF model for this watershed uses the same subwatershed boundaries with an alternative internal numbering scheme.

Calibration Data and Locations

The ACF basin was selected as an early pilot site application because of previous modeling experience in parts of the watershed and the state of Georgia. The specific site chosen for initial calibration was the Flint River at GA 26, near Montezuma, Georgia (USGS 02349605) (Table 5). This is a flow and water quality monitoring location that approximately coincides with the pour point of the Upper Flint (03130005) 8-digit HUC (Figure 5). This location was selected for several reasons: 1) there is a good set of flow and water quality data available, 2) previous modeling efforts in nearby HUC8's were successful, and 3) investigations of land use, drainage area, and percentage of drainage area controlled by flow control structures, compared with other USGS gage locations in the ACF basin, identified this gage as the best possible choice.

There were an additional eight sites chosen for the whole ACF basin to check the performance of the model. These sites were chosen based on subwatershed delineation boundaries, land use, drainage area, flow control structures, data completeness and location. The eight additional sites are in Table 5 and shown spatially in Figure 5. The idea was to have some locations that were un-impacted by upstream flow control structures and additionally also have some locations downstream of major reservoirs to check the model performance of the reservoir simulation.

Three of the chosen sites were located at the outfall of two delineated subwatersheds. In reality, these gages are slightly downstream of a tributary joining the mainstem. These sites were Flint River at Montezuma, Georgia, Chattahoochee River near Cornelia, Georgia, and Flint River at Newton, Georgia. It is easy to add two flows together to get the theoretical flow at the sampling location but two water quality concentrations cannot be summed to get the theoretical concentration. In order to generate a theoretical concentration, constituent masses must be added together and then divide by the summed volumes to determine what the water quality concentration would be. Accordingly, in the SWAT application, constituent masses from two reaches were added together, and then divided by the summed volumes to determine constituent concentration. The HSPF application, dealt with this by combining the watersheds internally and generating one time series that represented the hydrology and water quality where these subwatersheds merge. This method makes the assumption that the main stem and tributary waters have fully mixed at the sampling location.

The gage for Peachtree Creek is not at the outlet of the subwatershed for Peachtree Creek. Both HSPF and SWAT applications utilized an area weighting approach for this gage. The USGS published drainage area was 66 percent of the drainage area of the subwatershed delineated for Peachtree Creek, so a multiplier of 0.66 was applied to the time series at the output of Peachtree Creek. Although this is not exact, theoretically it should be close to reality at the sampling location, because land use differences are insignificant for this watershed (90 percent urban).

The water quality data found in the NAWQA database for the chosen calibration and validation locations were limited in certain situations. Therefore, additional data were utilized from Georgia Environmental Protection Division (EPD). Due to earlier modeling work done in the state, these data were readily available, vetted and included in the water quality data for calibration and validation. While combining the NAWQA and EPD datasets there was some overlap on a few dates. The data from both datasets were compared and they always agreed on constituent values. It was decided to keep the NAWQA data and remove the EPD data. Georgia EPD submits their monitoring data to NAWQA and in general the additional EPD data contributed to lengthening the period of record available for calibration and validation.

Many of the locations chosen for calibration and validation did not specifically monitor for all constituents making up total nitrogen. Many times reported values were only for ammonia and nitrate+nitrite. The sum of those two constituents does not represent total nitrogen because it is missing the component for organic nitrogen. Because of this, the data available for total nitrogen were very limited. An approach was developed to bolster the amount of total nitrogen data available for calibration and validation. The NAWQA database was investigated for sampling dates that reported total nitrogen, ammonia, and nitrate+nitrite. These sampling dates and data were extracted and a regression analysis of total nitrogen vs. ammonia+nitrate+nitrite was performed. The regression had an R^2 vale of 0.80. Because the fit was high, the regression was applied to the ammonia+nitrate+nitrite value and the result was an estimated value of total nitrogen based on two of the three components making up total nitrogen. For the 20 Watershed application, it was assumed that an estimated value for total nitrogen was better than having no value at all.

A database containing NAWQA, EPD, and calculated total nitrogen values was compiled and used in both the SWAT and HSPF modeling applications. This ensured the data that both models were calibrated to were consistent.

Table 5. Calibration and validation locations in the ACF River basin

Station Name	USGS ID	Drainage area (mi^2)	Hydrology calibration	Water quality calibration
FLINT RIVER AT MONTEZUMA, GA	USGS02349605	2,900.00	X	X
CHATTAHOOCHEE RIVER NEAR CORNELIA, GA	USGS02331600	315	X	X
PEACHTREE CREEK AT ATLANTA, GA	USGS02336300	86.8	X	X
CHATTAHOOCHEE RIVER AT ATLANTA, GA	USGS02336000	1,450	X	X
ICHAWAYNOCHAWAY CREEK AT MILFORD, GA	USGS02353500	620	X	X
CHATTAHOOCHEE RIVER AT WEST POINT, GA	USGS02339500	3,550	X	X
CHATTAHOOCHEE RIVER NEAR COLUMBIA, AL	USGS02343801	8,210	X	X
FLINT RIVER AT NEWTON, GA	USGS02353000	5,740	X	X
APALACHICOLA RIVER AT CHATTAHOOCHEE FLA	USGS02358000	17,200.00	X	

For hydrology, the model calibration period was set to calendar years 1993-2002 (from within the 30-year period of record for modeling). The end date is constrained by the common period of the set of 20 Watershed meteorological stations available for the watershed, and a ten year calibration period was desired. Hydrologic validation was then performed on Calendar Years 1983-1992. Water quality calibration used calendar years 1999-2002, because all gages had a decent set of data during that time period. Water quality validation was limited to 1986-1998, as very sparse data were available prior to 1986. Some of the stations didn't have observed water quality data prior to 1991. In these situations, the validation period represents all data available prior to January 1, 1999.

HSPF Modeling

Initial hydrologic parameterization for the Upper Flint calibration focus area came from a Loading Simulation Program – C++ (LSPC) model created for the Upper Oconee watershed in north central Georgia (HUC 03070101). LSPC is a comprehensive data management and modeling system that is capable of representing both flow and water quality loading from nonpoint and point sources and simulating in-stream processes. It is capable of simulating flow, sediment, metals, nutrients, pesticides, and other conventional pollutants, as well as temperature and pH for pervious and impervious lands and waterbodies. LSPC and HSPF use the same parameterization, therefore, an LSPC model was chosen for initial parameterization assignments.

The LSPC model used for initial parameterization and the HSPF model set up for the 20 Watershed study differed in land use representation as well as soils/HRU representation. The LSPC models utilized a much more detailed land use that was develop by the state of Georgia called Georgia Land Use Trends (GLUT). Additionally, in the LSPC model, subwatersheds were assigned to hydrologic soil groups by utilizing the hydrologic soil group that had the greatest area within the subwatershed. Using this method the Upper Oconee watershed did not have any hydrologic soil groups A or D. Therefore, the LSPC model was investigated to ensure the most representative land use and soil type parameterization was transferred to the HSPF 20 Watershed model. Technical Note 6 (USEPA 2000) was utilized to establish initial parameterization for infiltration rates in areas that had hydrologic soil groups A and D in the 20 Watershed application that.

Upon initial hydrologic parameterization of the focus area, both a model for the Upper Oconee watershed and a model for the Lake Lanier watershed were investigated as potential starting points. The Upper Oconee watershed parameterization did a much better job of representing measured flow than did those for the Lake Lanier watershed parameters. At this point it was realized that parameterization assigned to the calibration focus area probably will not work for all areas in the ACF basin.

The calibration focus area represents 7 HRUs. After calibrating the 7 HRUs, the calibrated parameterization was transferred to the remaining 30 HRUs. Three locations, un-affected by upstream impoundments, therefore only affected by parameterization, were selected to check the results with the focus area parameterization. These three locations were Chattahoochee River near Cornelia, Georgia (USGS 02331600), Peachtree Creek at Atlanta, Georgia (USGS 02336300), and Ichawaynochaway Creek at Milford, Georgia (USGS 02353500). All three of these locations had a poor simulation of the observed hydrology. Because of the poor hydrologic simulation, additional calibration was completed at each of the three locations.

The area contributing to Peachtree Creek at Atlanta, Georgia (USGS 02336300) was utilized as an urban area calibration. Land use at this location is roughly 79 percent urban. Since calibration at this location, entirely revolved around the urban land use, the calibrated results were transferred to all other urban areas throughout the ACF basin.

The area contributing to Chattahoochee River near Cornelia, Georgia (USGS 02331600) was parameterized with the Lake Lanier TMDL LSPC model, and is represented by two HRUs in the HSPF 20 Watershed model. The initial parameterization was adjusted slightly, to account for the indirect transfer of land use associated parameters, from the more detailed LSPC model to the 20 Watershed model. The calibrated parameters at this location were transferred to one more HRU, immediately downstream. The area represented by these parameters is closely associated with the area of the ACF basin that is in the Blue Ridge Geographic Province (Figure 6.)

The area contributing to Ichawaynochaway Creek at Milford, Georgia (USGS 02353500) was used to represent hydrologic conditions for the HRUs in the Coastal Plain Province. To calibrate the area contributing to this gage, the calibration focus area parameterization was adjusted until the simulated hydrology closely resembled the observed hydrology. Since adjustment was needed for multiple parameters on multiple land uses it was decided that this gage would represent the hydrology of the Coastal Plain Province (Figure 6.)

The initial calibration focus area parameters were supplied for all other HRUs and this represents the Piedmont Province (Figure 6.)

In summary, after realizing that parameterization assigned to the calibration focus area will not work for all areas in the ACF basin an approach needed to be developed for assigning parameters for each HRU. After each area that wasn't influenced by major impoundments was calibrated separate of the others it was decided that each of the calibration areas would represent either the geologic province that each was contained in or in the case of the Peachtree Creek gage, the dominant land use. Essentially, there are three parameter groups assigned by geologic province and the urban land use is parameterized the same throughout the model.

After the parameter mapping was complete for all three geologic provinces the calibration turned to reservoir representation and operation. There is a more detailed discussion about the challenges faced during modeling reservoirs in the HSPF Assumptions section of this report.

Once the hydrology calibration was complete for the whole ACF basin, the focus turned to sediment and water quality representation. Initial parameterization for sediment and water quality simulation was taken from a LSPC model developed for the Lake Allatoona watershed. The Lake Allatoona TMDL model was utilized rather than the Lake Lanier TMDL or Upper Oconee watershed LSPC models because the Lake Allatoona model utilized the same general water quality approach that is utilized for the 20 Watershed application. The water quality simulation also generally reflected the need to assign parameters by geologic province, therefore, water quality was calibrated at the same locations as hydrology and the parameterization was transferred to the same HRUs as the hydrology parameters.

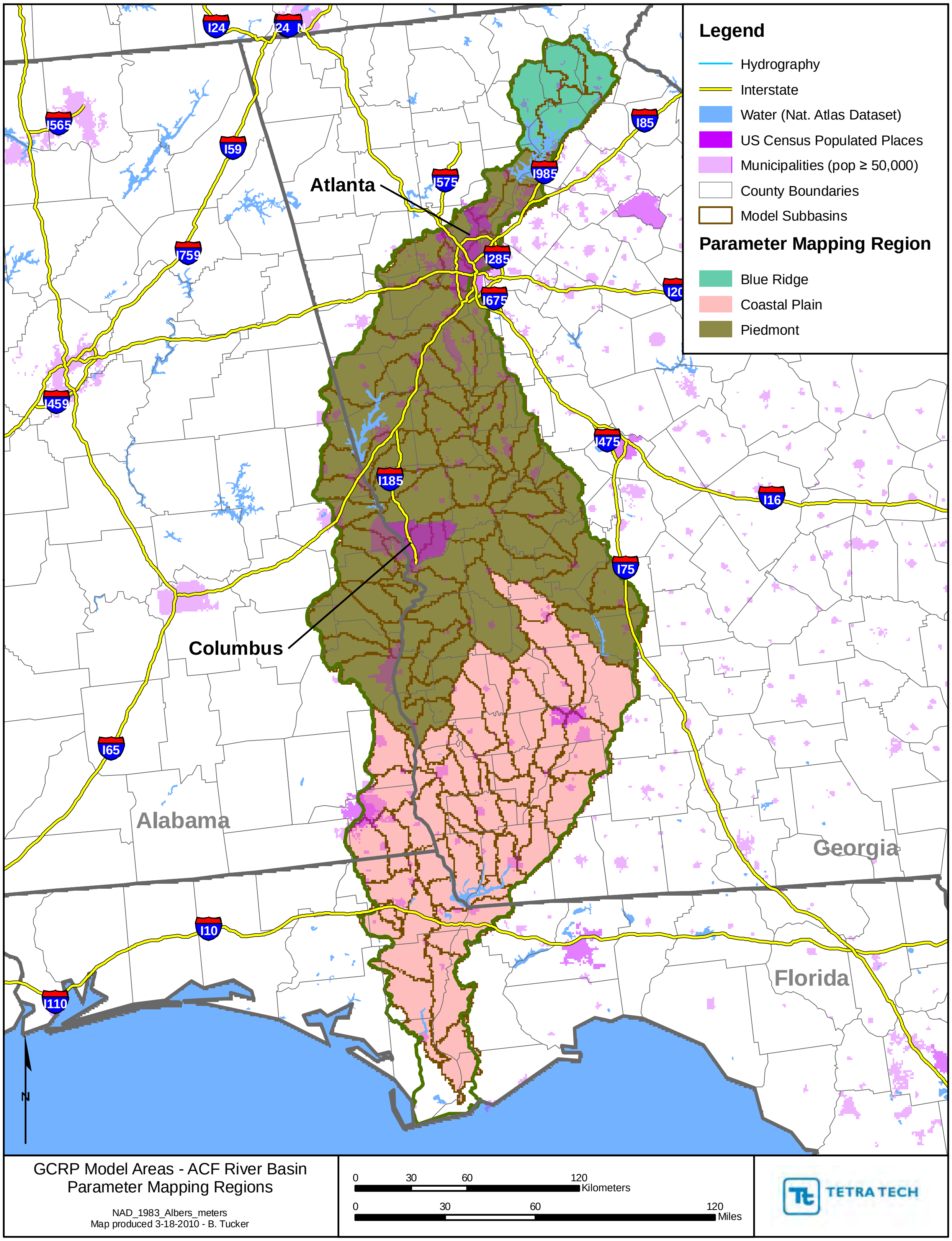


Figure 6. Parameter mapping utilized in the HSPF ACF River basin model.

Changes Made to Base Data Provided

No changes were made to the meteorological or land use base data. The impoundments of Lake Blackshear and Lake Seminole created an odd subwatershed connectivity when developed by BASINS. These two lakes both have large tributaries contributing to them and BASINS delineated the watersheds by having all of the individual tributaries pouring into the next downstream watershed. This made it difficult to represent the dam operation. The connectivity was modified so that there was only one watershed representing the outflow of each impoundment. The upstream subwatersheds, for all of the tributaries entering the lakes, were adjusted to pour into the subwatershed containing the lake. This change was also made in the SWAT model. Before this change was added, the HSPF model was in operation with the original connectivity, and BASINS generated f-tables. The simulation results below both of the lakes, for both original and updated connectivity, showed very similar results. This suggests that the update to the connectivity should not pose any problems.

As discussed earlier in the Point Sources section, an amendment was made to WPCP's that had default values assigned for total phosphorus. Additionally, as discussed earlier, GaEPD data were used to supplement the observed water quality data found in the NAWQA database.

Assumptions

Reservoirs

The Chattahoochee and the Flint Rivers represent two very different types if rivers. The Chattahoochee River has many impoundments while the Flint River has one of the longest unimpeded stretches of flow in the United States. The base data supplied point coverage for nine dams in the ACF basin and each was at the outlet of a delineated subwatershed. Three of those given dams were assumed to operate as run of the river (Oliver, Bartlett's Ferry, and George W. Andrews) and they were not included in the simulation. Table 6 identifies the dams and corresponding reservoirs represented in the ACF basin 20 Watershed model.

Table 6. Reservoirs represented in the ACF basin model

Dam Name	Other Name	River	Owner
Buford	Lake Sidney Lanier	Chattahoochee	USACE
West Point	West Point Lake	Chattahoochee	USACE
Walter F George Lock, Dam, Powerhouse	Eufala	Chattahoochee	USACE
Crisp County (Warwick)	Lake Blackshear	Flint	Crisp County Power Commission
Muckafoonee Creek Dam	Lake Worth	Flint	Georgia Power Company
Jim Woodruff Dam	Lake Seminole	Flint	USACE

All of the Army Corps of Engineers' (USACE) lakes simulated in the model have data published including elevation, inflow, discharge, and power generation, since the facility became operational (USACE 2010). The USACE has also made available a graph of the area capacity curve for each of the lakes. For the 20 Watershed application, it was assumed that the best representation of the reservoirs was to try to simulate them without supplying time series operations or boundary conditions. If time series operations were supplied, it would be difficult to predict what the boundary condition would be in the future. Therefore, the area-capacity curves were developed into an f-table, consistent with Technical Note 1 (USEPA 2007) and supplied for the subwatershed containing the lake. By having the controlling feature on the lake be an f-table future climatic conditions will not be affected by boundary conditions of the past.

Elevation-Storage relationships were not available for Lake Blackshear and Lake Worth. Research was done to look for the average depth and average surface area for each of the lakes. This information was utilized to come up with a reservoir of similar size and storage by using the stage-storage-discharge relationships tool in the HSPF BMP Toolkit on the EPA website.

One of the biggest challenges was trying to represent reservoir operations with only an f-table. When the model was first set up, the focus was on calibrating to areas un-impacted by flow control devices, and the reservoirs simply had the f-table created by BASINS. The hydrology results at the gages used to check reservoir operations actually looked pretty decent considering lake storage and dam releases were not accounted for. F-tables were developed and inserted into the model for all reservoirs included in the simulation. The physical relationship between surface area and storage was left unchanged and reservoir calibration focused on assigning a discharge to a particular depth of water. When there were elevation and discharge data available, they were used as a guideline for assignment of the outflow for a particular depth. The results on the mainstem Flint River changed very little but the results on the mainstem Chattahoochee changed drastically and the simulation became very poor. Much work was done on the Chattahoochee River simulation to try to represent the reservoirs properly. Since the reservoirs are highly controlled by peaking hydro electric operations and targeted elevations based on the season, the approach used for the 20 Watershed application did not do a very good job at representing observed flows below the dams on the Chattahoochee River. Much of the error on the Chattahoochee can be attributed to the improper operation of Buford Dam. The discharges at Buford Dam impact the discharges at all other dams on the Chattahoochee and this is also the case in the 20 Watershed model.

Withdrawals

It is not known what water withdrawals by municipal and industrial facilities will look like in the future, therefore, they were not included in the 20 Watershed model application. Recent court rulings suggest that current withdrawals below Buford dam may change in as little as three years.

Irrigation

Irrigation in the Lower Flint, its tributaries, and the Lower Chattahoochee is used quite extensively when needed. The model, for the 20 Watershed application, is not using the irrigation module. HSPF requires that a land use be associated with irrigation and applying irrigation to all agricultural land may greatly over estimate the amount of irrigation that is actually taking place. Additionally, no one knows what agricultural irrigation may look like in the future. There have been numerous studies commissioned in the past decade to look into the amount of irrigation in the state of Georgia. A majority of the irrigation is from groundwater sources and this would represent new water to the HSPF model. It was assumed that an irrigation component would not benefit the model for the 20 Watershed application.

Snow Simulation

Previous modeling experience in Georgia did not utilize snow simulation. The model for the 20 Watershed application is to include snow simulation using the degree-day method for snowmelt. With no previous models to obtain initial parameters for snow simulation, the initial parameters needed to be developed. Technical Note 6 (USEPA 2000) was used as a guideline for parameterization. The parameters for the physical properties of each HRU are assigned by HRU but all other snow simulation parameters are the same for each HRU. These values are assumed to be appropriate and the initial parameterization was not adjusted.

Hydrology Calibration

As explained above, the starting parameters for ACF 20 Watershed application came from an LSPC model for the Upper Oconee watershed. Differences amongst the model set up between the LSPC application and HSPF 20 Watershed application meant that not all parameters in the LSPC application were directly transferrable to the HSPF 20 Watershed application. When it did not make sense to utilize parameters from the LSPC model, Technical Note 6 (USEPA 2000) was utilized to determine a good starting value. The parameters from the Upper Oconee watershed simulated flows in the range of the observed flows but minor adjustments needed to be made to better fit the simulated flows to the observed flows. Calibration adjustments focused on the following parameters:

- INFILT (index to mean soil infiltration rate): The LSPC model did not represent hydrologic soil groups A or D. A representative value was obtained from Technical Note 6 (USEPA 2000). Very minor modifications were made to these estimated values because the calibration focus area is dominated by B and C soils. Additionally, INFILT was adjusted slightly by land use to account for the land use differences between the LSPC model and the HSPF 20 Watershed model. INFILT values for the hydrologic soil groups are in the range of those stated in Technical note 6.
- AGWRC (Groundwater recession rate): Adjusted slightly in order to replicate groundwater recession in the observed data.
- LZSN (lower zone nominal soil moisture storage): This was increased slightly upward due to baseflow contributions severely tapering off during extreme dry weather. The changes to INFILT and AGWRC resulted in small modifications in this parameter.
- BASETP (ET by riparian vegetation): Even with the modifications mentioned above, simulation of low flows was not that good. It was assumed that the Flint River watershed has a greater amount of riparian vegetation than that of the Upper Oconee watershed. Slightly increasing the BASETP value made the simulation of low flows much better.

Initial calibrations were performed for the upper Flint River, comparing model results to data from USGS 02349605, and are summarized in Figures 7 through 13 and Tables 7 and 8. The model fit is of high quality but always simulates a little bit high. This could be because municipal and industrial withdrawals were not included in the in the simulation. None of the metrics fall out of those set for the 20 Watershed study. The model calibration period was set to calendar years 1993-2002.

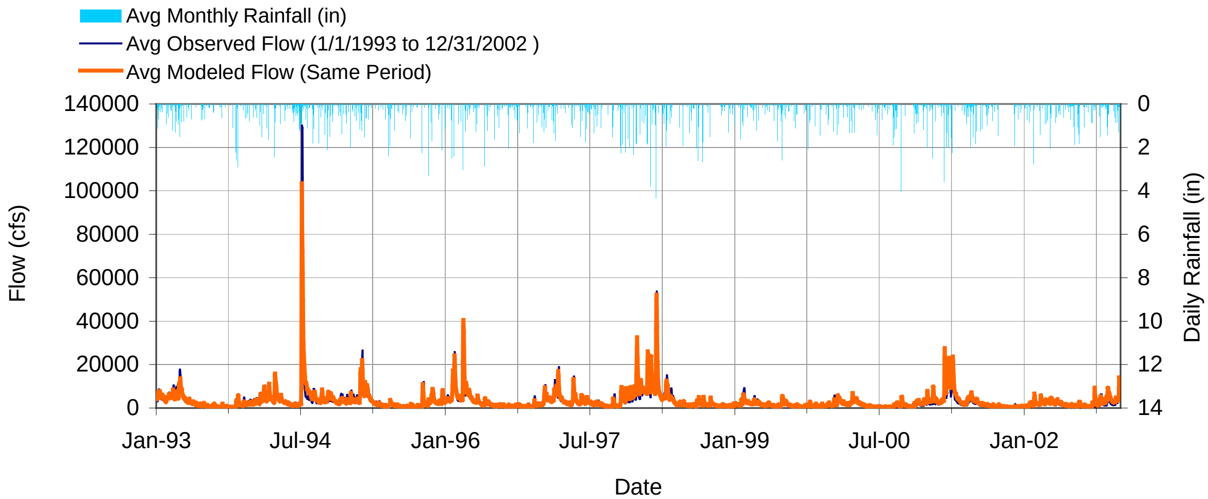


Figure 7. Mean daily flow at USGS 02349605 Flint River at Ga 26, near Montezuma, GA – calibration period (HSPF).

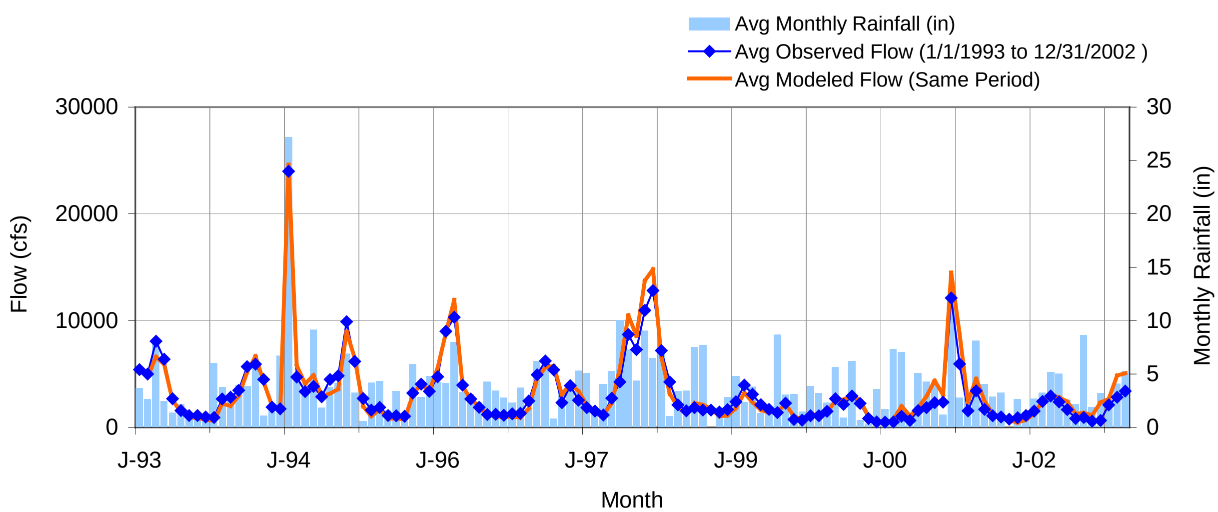
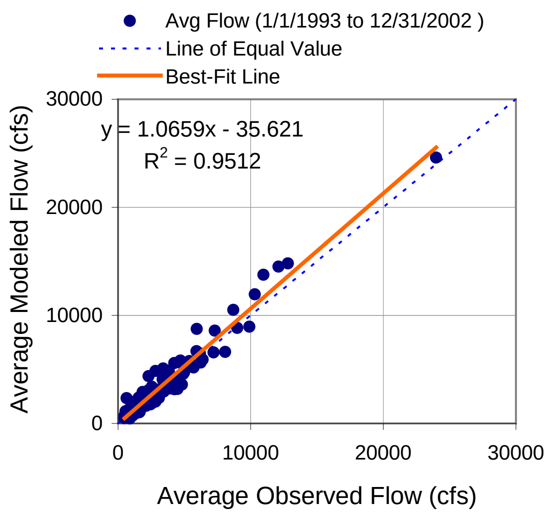


Figure 8. Mean monthly flow at USGS 02349605 Flint River at Ga 26, near Montezuma, GA – calibration period (HSPF).



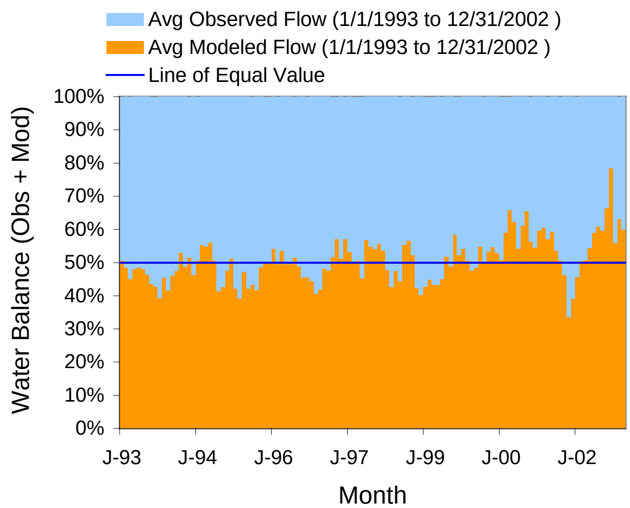
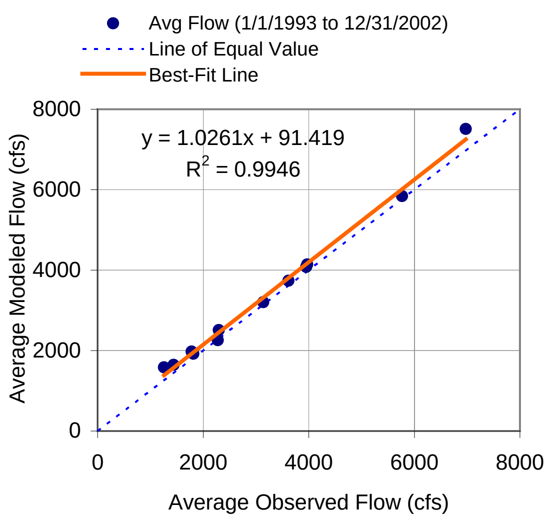


Figure 9. Monthly flow regression and temporal variation at USGS 02349605 Flint River at Ga 26, near Montezuma, GA – calibration period (HSPF).



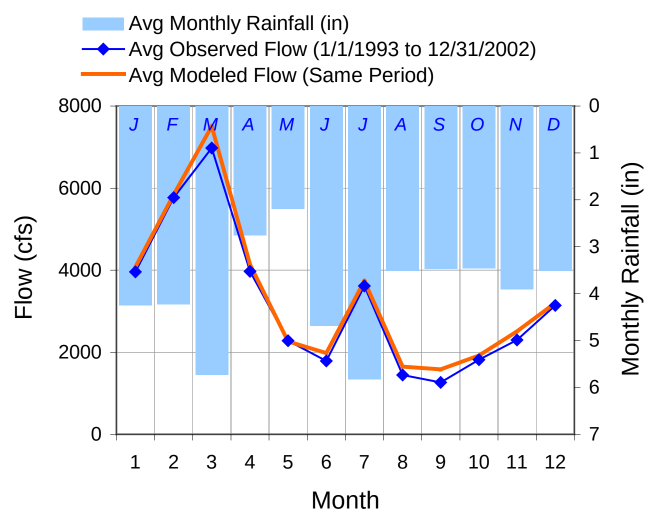


Figure 10. Seasonal regression and temporal aggregate at USGS 02349605 Flint River at Ga 26, near Montezuma, GA – calibration period (HSPF).

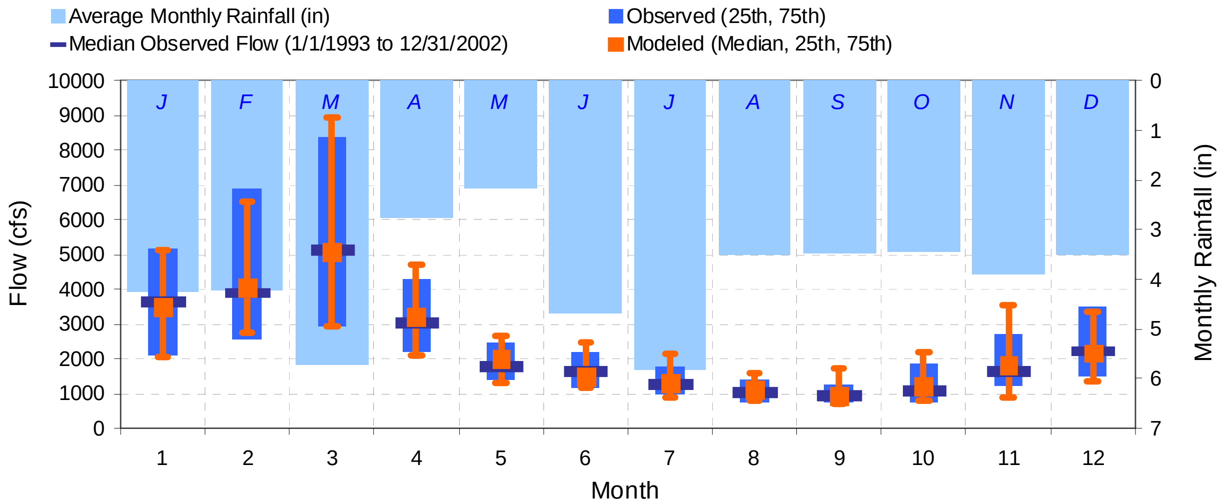


Figure 11. Seasonal medians and ranges at USGS 02349605 Flint River at Ga 26, near Montezuma, GA – calibration period (HSPF).

Table 7. Seasonal summary at USGS 02349605 Flint River At Ga 26, near Montezuma, GA – calibration period (HSPF)

MONTH	OBSERVED FLOW (CFS)				MODELED FLOW (CFS)			
	MEAN	MEDIAN	25TH	75TH	MEAN	MEDIAN	25TH	75TH
Jan	3955.13	3665.00	2110.00	5155.00	4080.88	3477.76	2037.87	5135.68
Feb	5767.27	3915.00	2572.50	6887.50	5840.28	4036.36	2764.25	6514.59
Mar	6976.42	5150.00	2932.50	8377.50	7509.10	5064.71	2921.96	8921.61
Apr	3970.93	3065.00	2210.00	4297.50	4138.24	3192.51	2099.52	4715.87
May	2277.06	1810.00	1400.00	2470.00	2259.06	2007.62	1330.76	2653.59
Jun	1783.49	1670.00	1180.00	2170.00	1976.13	1497.68	1168.42	2453.92
Jul	3617.54	1290.00	977.25	1765.00	3734.42	1309.40	880.28	2131.87
Aug	1440.71	1035.00	752.00	1420.00	1646.45	1108.31	803.03	1567.80
Sep	1260.28	964.00	770.50	1252.50	1584.54	917.93	712.46	1731.82
Oct	1816.83	1105.00	775.75	1855.00	1920.32	1202.58	785.75	2195.35
Nov	2297.06	1660.00	1220.00	2685.00	2506.66	1807.51	878.28	3533.72
Dec	3137.85	2240.00	1490.00	3497.50	3202.84	2167.47	1344.21	3347.46

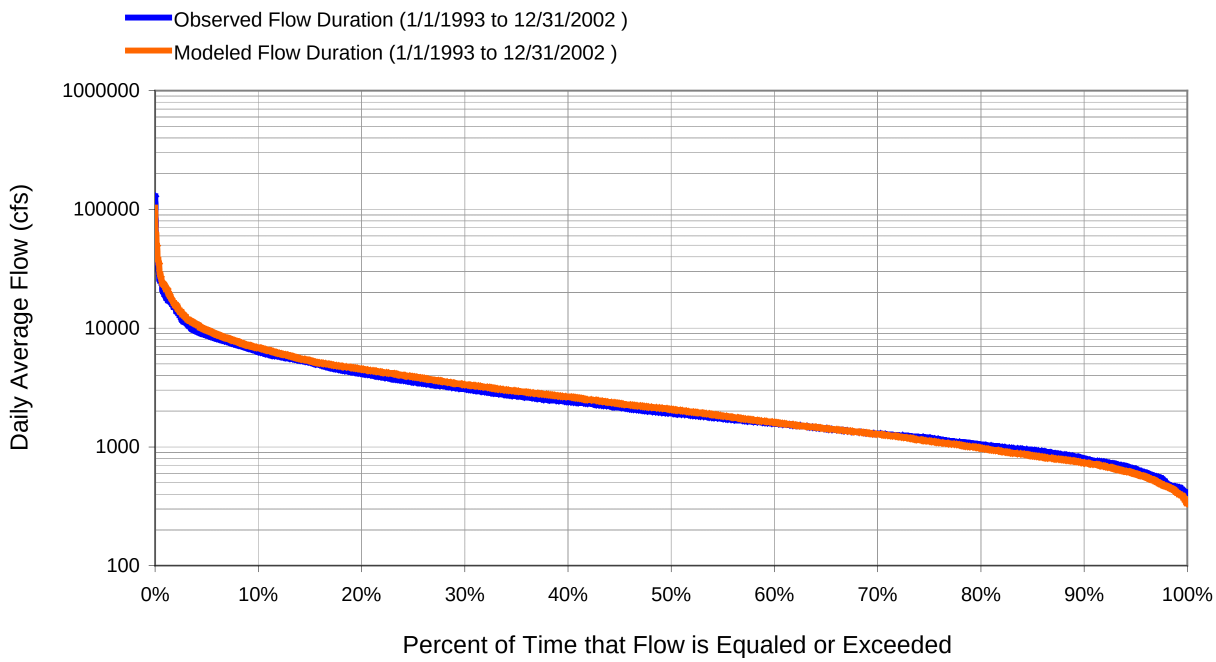


Figure 12. Flow exceedence at USGS 02349605 Flint River at Ga 26, near Montezuma, GA – calibration period (HSPF).

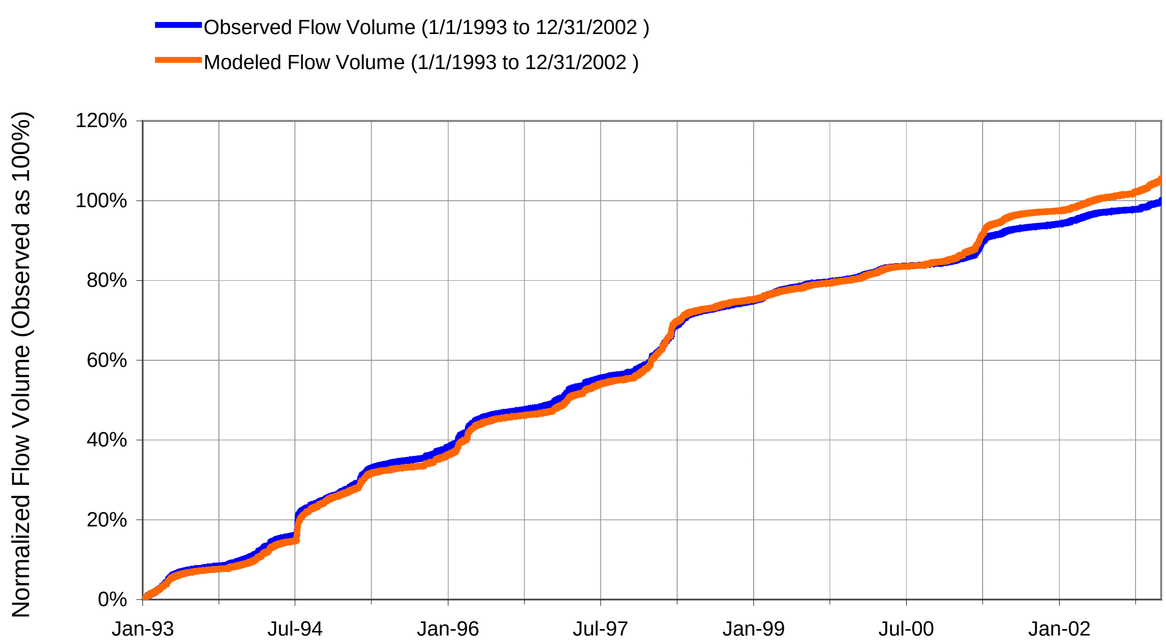


Figure 13. Flow accumulation at USGS 02349605 Flint River at Ga 26, near Montezuma, GA – calibration period (HSPF).

Table 8. Summary statistics at USGS 02349605 Flint River At Ga 26, near Montezuma, GA – calibration period (HSPF)

HSPF Simulated Flow		Observed Flow Gage	
REACH OUTFLOW FROM DSN 1001 10-Year Analysis Period: 1/1/1993 - 12/31/2002 Flow volumes are (inches/year) for upstream drainage area		USGS 02349605 FLINT RIVER AT GA 26, NEAR MONTEZUMA, GA Hydrologic Unit Code: 3130006 Latitude: 32.29305556 Longitude: -84.0436111 Drainage Area (sq-mi): 2920	
Total Simulated In-stream Flow:	**15.61**	Total Observed In-stream Flow:	**14.80**
Total of simulated highest 10% flows:	**6.10**	Total of Observed highest 10% flows:	**5.74**
Total of Simulated lowest 50% flows:	**2.71**	Total of Observed Lowest 50% flows:	**2.75**
Simulated Summer Flow Volume (months 7-9):	**2.73**	Observed Summer Flow Volume (7-9):	**2.48**
Simulated Fall Flow Volume (months 10-12):	**2.98**	Observed Fall Flow Volume (10-12):	**2.83**
Simulated Winter Flow Volume (months 1-3):	**6.67**	Observed Winter Flow Volume (1-3):	**6.39**
Simulated Spring Flow Volume (months 4-6):	**3.23**	Observed Spring Flow Volume (4-6):	**3.10**
Total Simulated Storm Volume:	**4.86**	Total Observed Storm Volume:	**4.80**
Simulated Summer Storm Volume (7-9):	**1.00**	Observed Summer Storm Volume (7-9):	**1.02**

Errors (Simulated-Observed)	*Error Statistics*	*Recommended Criteria*
Error in total volume:	5.50	10
Error in 50% lowest flows:	-1.49	10
Error in 10% highest flows:	6.32	15
Seasonal volume error - Summer:	10.14	30
Seasonal volume error - Fall:	5.17	30
Seasonal volume error - Winter:	4.48	30
Seasonal volume error - Spring:	4.21	30
Error in storm volumes:	1.25	20
Error in summer storm volumes:	-2.14	50
Nash-Sutcliffe Coefficient of Efficiency, E:	0.707	Model accuracy increases
Baseline adjusted coefficient (Garrick), E':	0.568	as E or E' approaches 1.0
Monthly NSE	0.934	

>> Clear

Hydrology Validation

Validation for the Upper Flint calibration focus area was performed at the same location but for calendar years 1983-1992. Results are presented in Figures 14 through 20 and Tables 9 and 10. Similarly to the calibration years, the validation years' model fit is of high quality but always simulates a little bit high. None of the metrics fall out of the range set for the 20 Watershed study. The model validation period was set to calendar years 1983-1992.

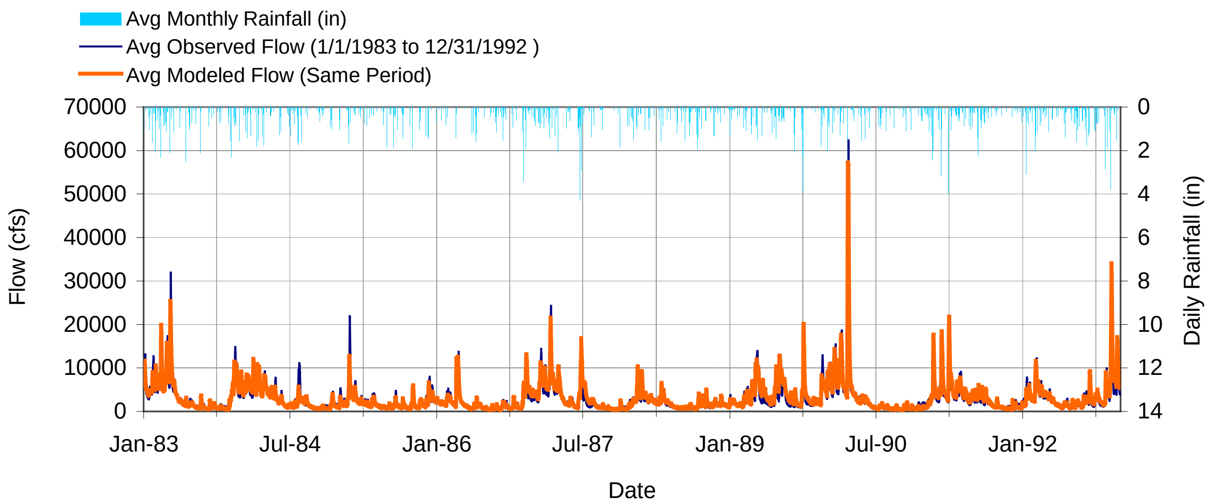


Figure 14. Mean daily flow at USGS 02349605 Flint River at Ga 26, near Montezuma, GA – validation period (HSPF).

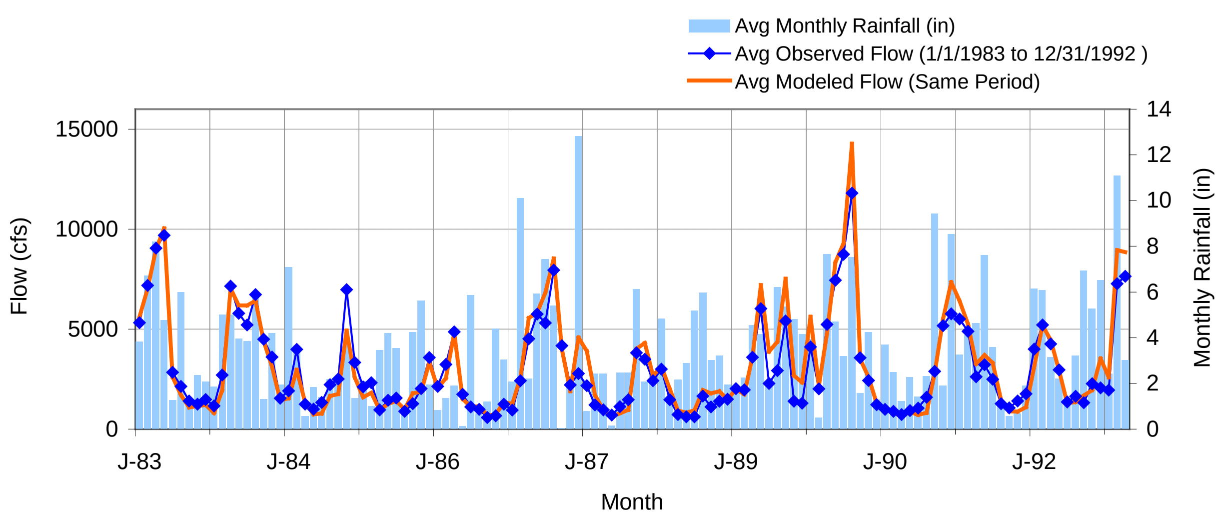


Figure 15. Mean monthly flow at USGS 02349605 Flint River at Ga 26, near Montezuma, GA – validation period (HSPF).

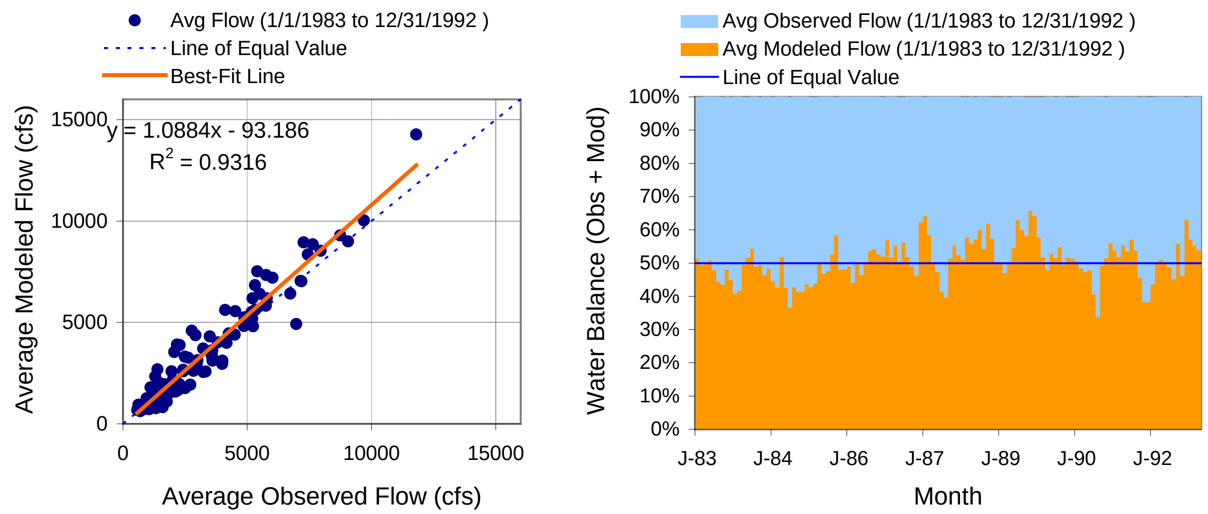


Figure 16. Monthly flow regression and temporal variation at USGS 02349605 Flint River at Ga 26, near Montezuma, GA – validation period (HSPF).

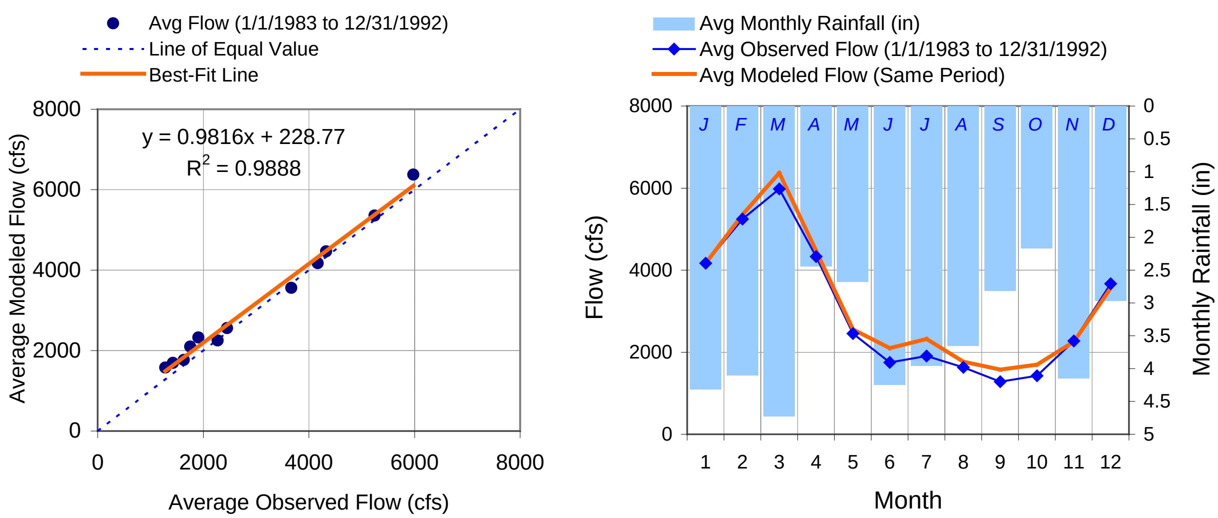


Figure 17. Seasonal regression and temporal aggregate at USGS 02349605 Flint River at Ga 26, near Montezuma, GA – validation period (HSPF).

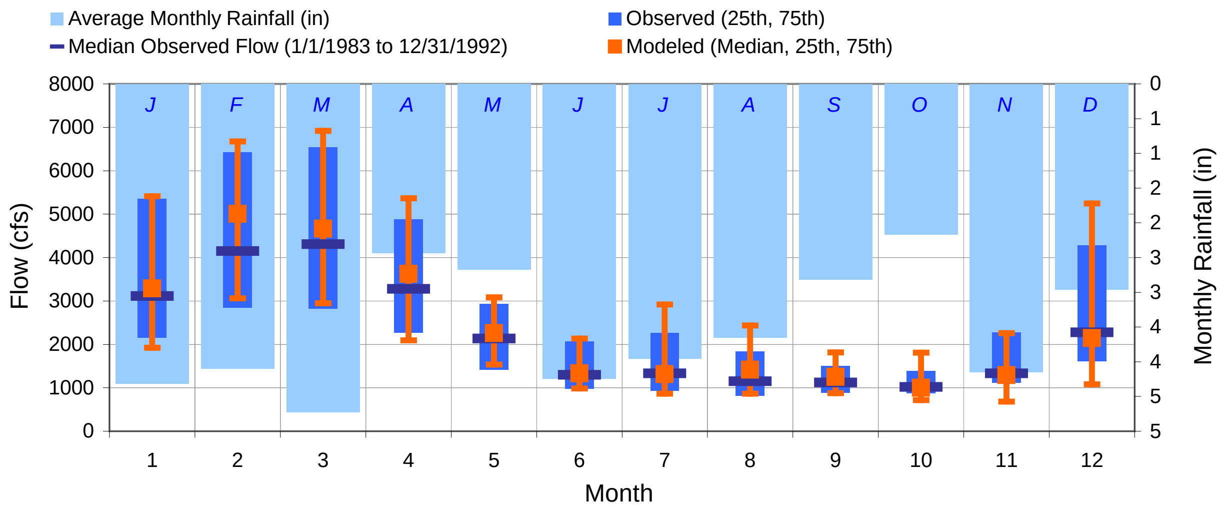


Figure 18. Seasonal medians and ranges at USGS 02349605 Flint River at Ga 26, near Montezuma, GA – validation period (HSPF).

Table 9. Seasonal summary at USGS 02349605 Flint River at Ga 26, near Montezuma, GA – validation period (HSPF)

MONTH	OBSERVED FLOW (CFS)				MODELED FLOW (CFS)			
	MEAN	MEDIAN	25TH	75TH	MEAN	MEDIAN	25TH	75TH
Jan	4168.00	3115.00	2152.50	5350.00	4169.05	3287.48	1922.32	5410.41
Feb	5242.97	4150.00	2850.00	6430.00	5353.14	5008.00	3062.19	6675.95
Mar	5976.65	4310.00	2830.00	6542.50	6371.53	4667.85	2944.79	6916.63
Apr	4328.17	3275.00	2277.50	4880.00	4468.43	3626.93	2094.33	5365.85
May	2451.47	2135.00	1420.00	2937.50	2557.55	2256.24	1533.87	3083.22
Jun	1753.24	1300.00	986.75	2072.50	2100.76	1331.44	985.52	2134.09
Jul	1908.70	1330.00	927.50	2257.50	2323.54	1314.50	866.44	2921.29
Aug	1632.54	1150.00	816.50	1830.00	1765.46	1414.88	867.56	2433.92
Sep	1283.93	1120.00	881.75	1500.00	1577.80	1249.76	876.51	1816.29
Oct	1425.06	1020.00	869.50	1390.00	1695.02	1001.13	717.97	1808.37
Nov	2275.14	1330.00	1120.00	2277.50	2252.76	1293.90	680.19	2259.65
Dec	3667.95	2275.00	1602.50	4277.50	3559.80	2145.93	1079.64	5244.57

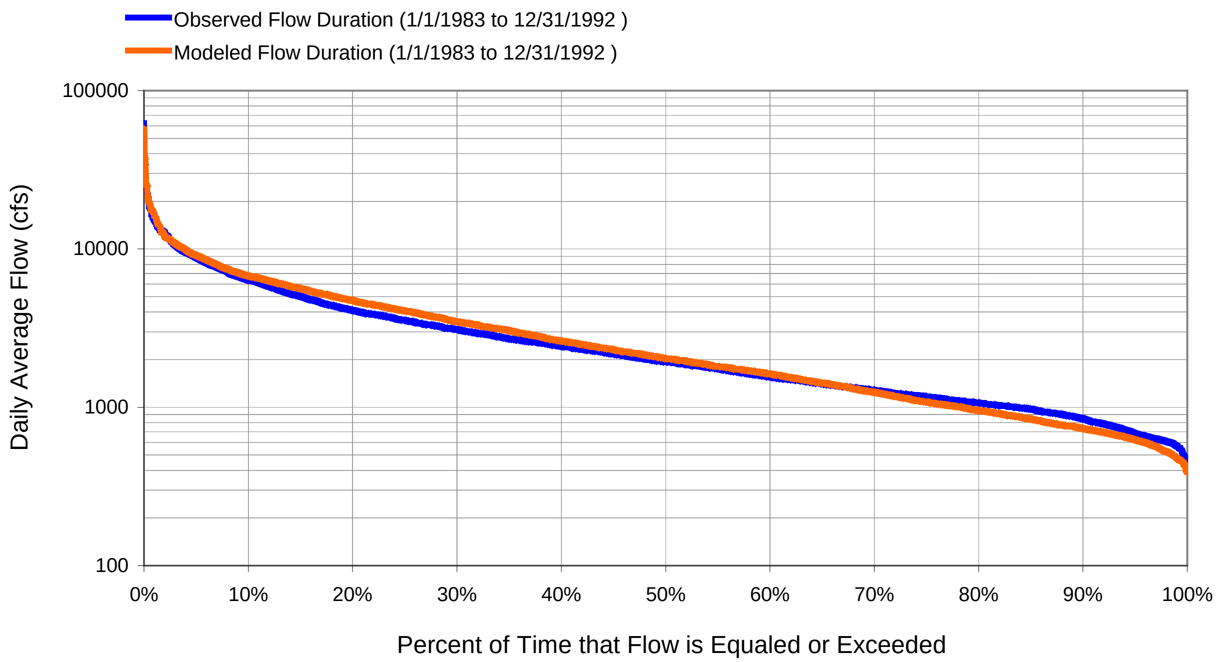


Figure 19. Flow exceedence at USGS 02349605 Flint River at Ga 26, near Montezuma, GA – validation period (HSPF).

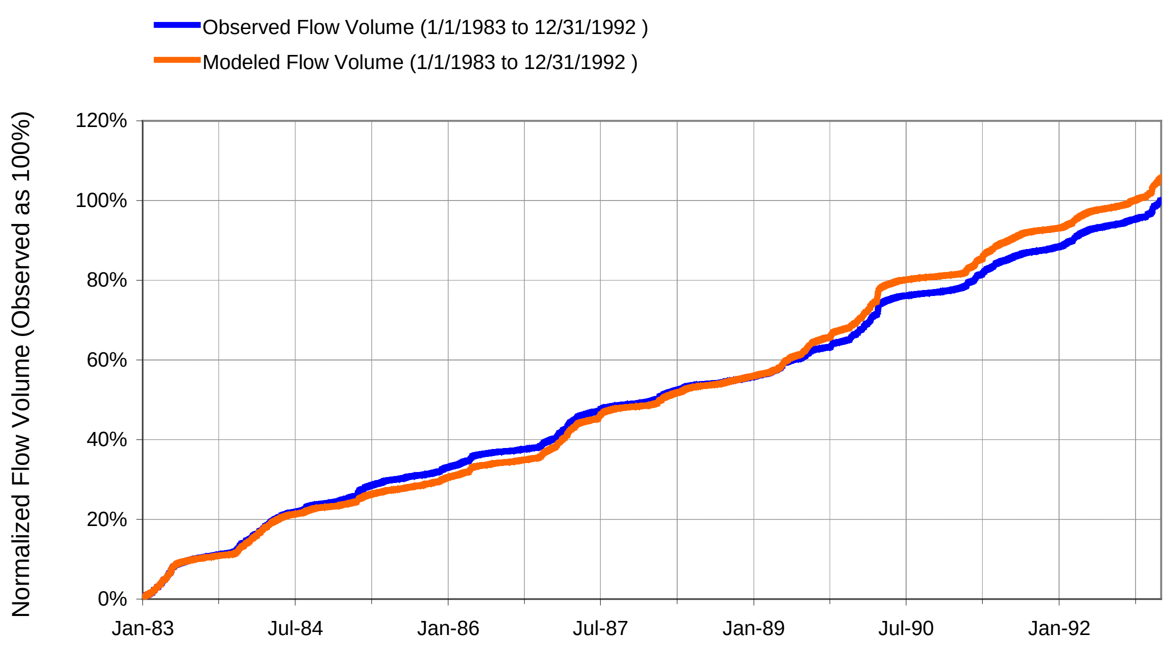


Figure 20. Flow accumulation at USGS 02349605 Flint River at Ga 26, near Montezuma, GA – validation period (HSPF).

Table 10. Summary statistics at USGS 02349605 Flint River at Ga 26, near Montezuma, GA – validation period (HSPF)

HSPF Simulated Flow		Observed Flow Gage	
REACH OUTFLOW FROM DSN 1001 10-Year Analysis Period: 1/1/1983 - 12/31/1992 Flow volumes are (inches/year) for upstream drainage area		USGS 02349605 FLINT RIVER AT GA 26, NEAR MONTEZUMA, GA Hydrologic Unit Code: 3130006 Latitude: 32.29305556 Longitude: -84.0436111 Drainage Area (sq-mi): 2920	
Total Simulated In-stream Flow:	**14.76**	Total Observed In-stream Flow:	**13.95**
Total of simulated highest 10% flows:	**5.05**	Total of Observed highest 10% flows:	**4.87**
Total of Simulated lowest 50% flows:	**2.70**	Total of Observed Lowest 50% flows:	**2.78**
Simulated Summer Flow Volume (months 7-9):	**2.22**	Observed Summer Flow Volume (7-9):	**1.89**
Simulated Fall Flow Volume (months 10-12):	**2.94**	Observed Fall Flow Volume (10-12):	**2.88**
Simulated Winter Flow Volume (months 1-3):	**6.09**	Observed Winter Flow Volume (1-3):	**5.89**
Simulated Spring Flow Volume (months 4-6):	**3.52**	Observed Spring Flow Volume (4-6):	**3.29**
Total Simulated Storm Volume:	**4.30**	Total Observed Storm Volume:	**4.42**
Simulated Summer Storm Volume (7-9):	**0.55**	Observed Summer Storm Volume (7-9):	**0.51**

Errors (Simulated-Observed)	*Error Statistics*	*Recommended Criteria*		
Error in total volume:	5.79	10		
Error in 50% lowest flows:	-3.16	10		
Error in 10% highest flows:	3.69	15		
Seasonal volume error - Summer:	17.40	30		
Seasonal volume error - Fall:	1.92	>> 30	Clear	
Seasonal volume error - Winter:	3.33	30		
Seasonal volume error - Spring:	6.93	30		
Error in storm volumes:	-2.74	20		
Error in summer storm volumes:	9.14	50		
Nash-Sutcliffe Coefficient of Efficiency, E:	0.651	Model accuracy increases		
Baseline adjusted coefficient (Garrick), E':	0.551	as E or E' approaches 1.0		
Monthly NSE	0.899			

Hydrology Results for Larger Watershed

As discussed above, the parameters from the calibration focus were not fully transferrable to other gages in the ACF basin. Therefore, at each of the gages un-impacted by flow control devices, an additional level of calibration was performed. Please refer to the discussion and Figure 6 for details on how the additional calibration areas' parameterization was assigned to the other areas in the watershed.

As stated above, the Upper Chattahoochee borrowed parameterization from a model done for the Lake Lanier TMDL. Due to careful transferring of parameters there wasn't any adjustment made to achieve calibration. The model fit was of high quality in the TMDL model and also has a very high goodness of fit in the 20 Watershed model. The statistics for Upper Chattahoochee gage are within the range defined for the 20 Watershed application. The calibration and validation results for this region are shown in Tables 11 and 12 (station 02331600).

The Ichawaynochaway Creek subwatershed did not have a model to borrow parameterization from. The calibrated results of the calibration focus area were assigned and then adjusted until the simulated flows closely matched the observed flows. All of the parameters adjusted were for the baseflow component of the simulation. Baseflow was being simulated too high so the goal was to lower the amount of baseflow reaching the stream. This was achieved through increasing the amount of ET satisfied by riparian vegetation and direct evaporation from groundwater. The model fit is fairly good except for the extreme low flows. The high simulation of the extreme low flows may be explained by not having simulated irrigation. The calibration and validation results for this region are shown in Tables 13 and 14 (station 02353500).

As discussed in the Assumptions section for Reservoirs, the simulation at all gages on the mainstem Chattahoochee, below Lake Lanier, is very poor. The approach taken to simulate the reservoirs in the ACF did not simulate Lake Lanier very well, but simulation of the other reservoirs was acceptable. This could be because the reservoirs other than Lake Lanier are mostly managed as inflow equals outflow and the discharges at Lake Lanier usually control most of the inflow. Once the Chattahoochee and Flint converge and leave Lake Seminole, the simulation and model fit is once again of high quality and shown for the calibration period in Figures 21 through 27 and Tables 11 and 12.

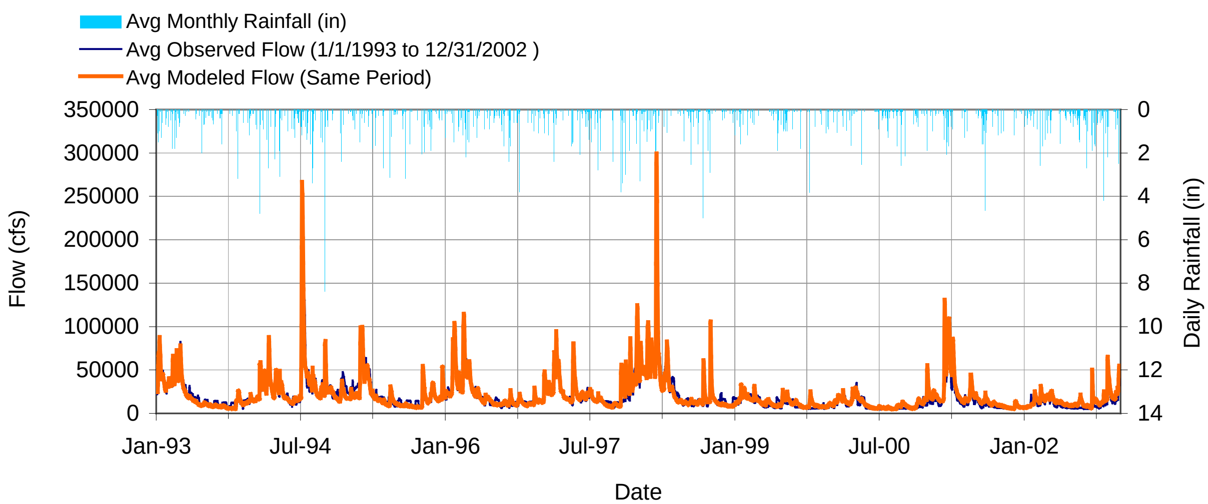


Figure 21. Mean daily flow: Model DSN 9001 vs. USGS 02358000 Apalachicola River At Chattahoochee, FL– calibration period (HSPF).

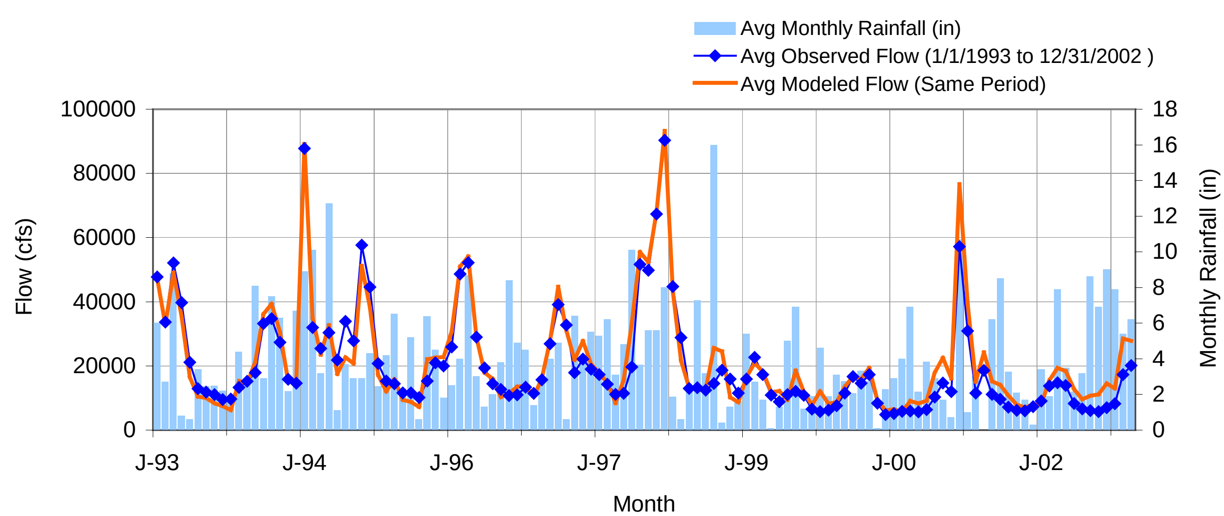


Figure 22. Mean monthly flow: Model DSN 9001 vs. USGS 02358000 Apalachicola River At Chattahoochee, FL– calibration period (HSPF).

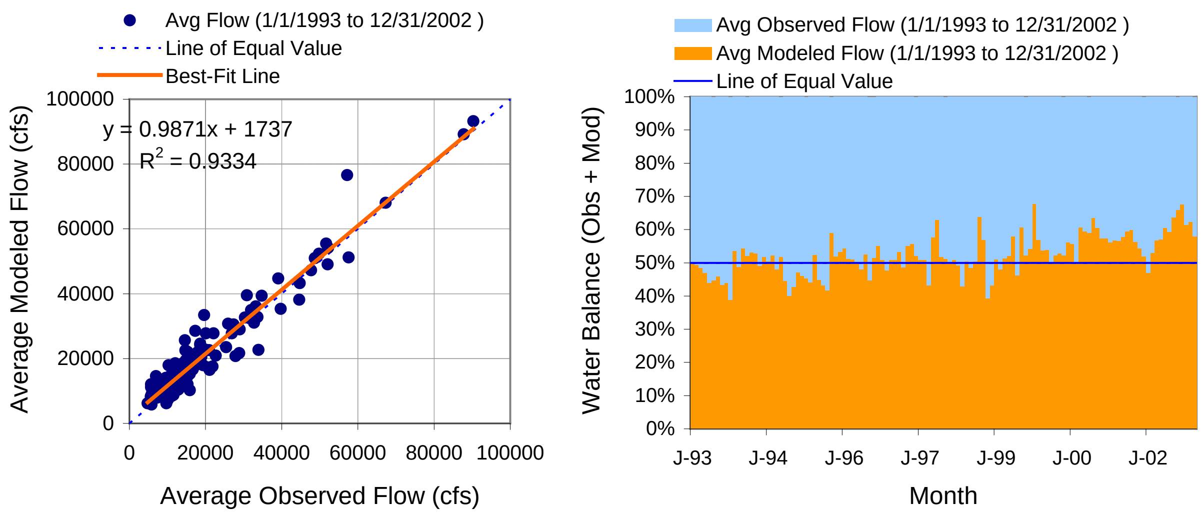


Figure 23. Monthly flow regression and temporal variation: Model DSN 9001 vs. USGS 02358000 Apalachicola River At Chattahoochee, FL– calibration period (HSPF).

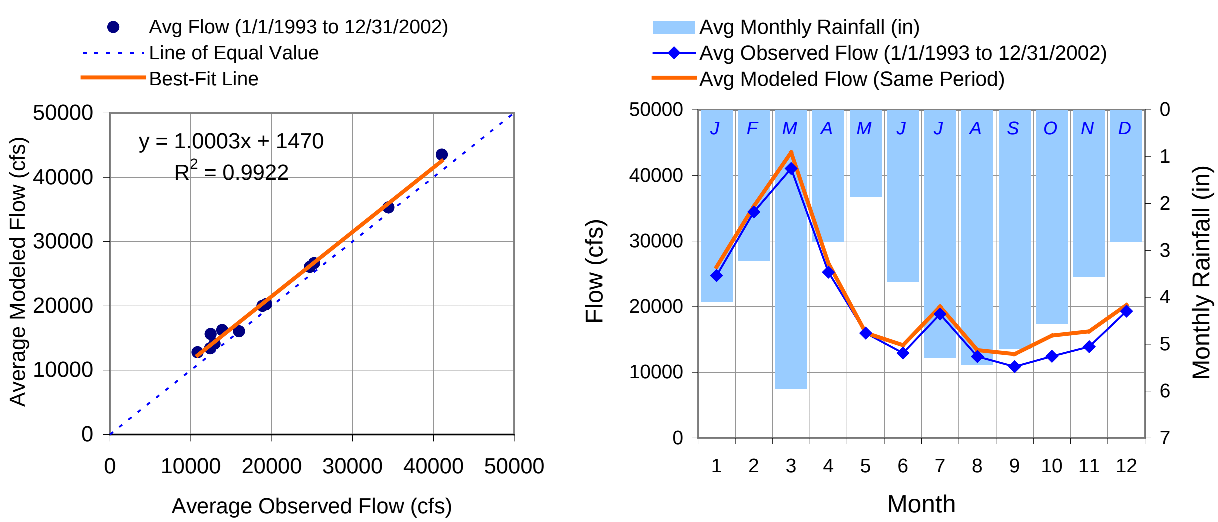


Figure 24. Seasonal regression and temporal aggregate: Model DSN 9001 vs. USGS 02358000 Apalachicola River At Chattahoochee, FL– calibration period (HSPF).

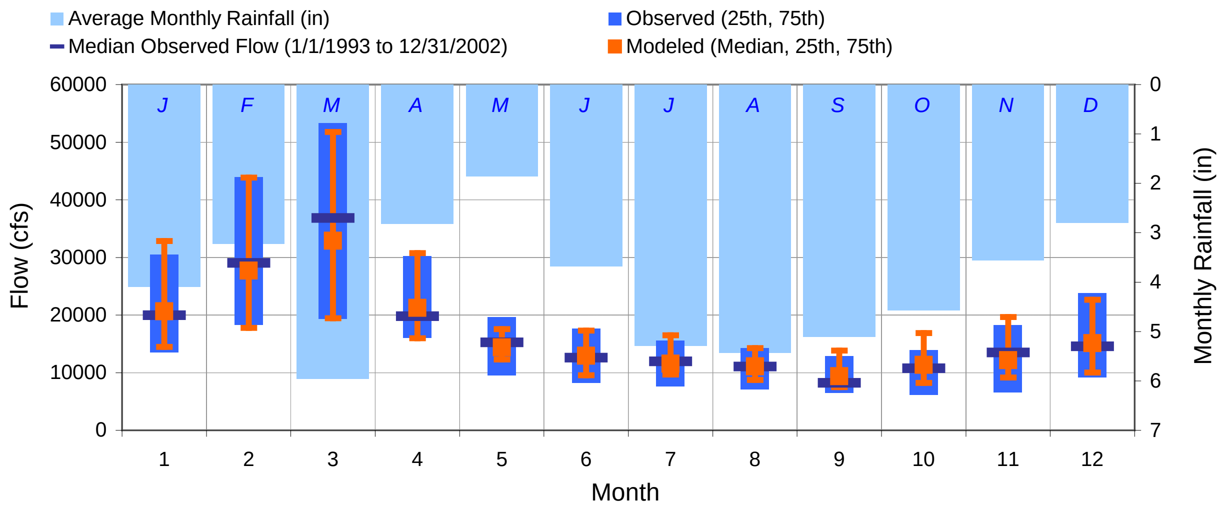


Figure 25. Seasonal medians and ranges: Model DSN 9001 vs. USGS 02358000 Apalachicola River At Chattahoochee, FL– calibration period (HSPF).

Table 11. Seasonal summary: Model DSN 9001 vs. USGS 02358000 Apalachicola River At Chattahoochee, FL– calibration period (HSPF).

MONTH	OBSERVED FLOW (CFS)				MODELED FLOW (CFS)			
	MEAN	MEDIAN	25TH	75TH	MEAN	MEDIAN	25TH	75TH
Jan	24730.16	19950.00	13500.00	30475.00	26069.98	20647.35	14491.39	32838.93
Feb	34453.44	29050.00	18275.00	43900.00	35291.43	27706.10	17766.08	43841.35
Mar	41056.97	36850.00	19300.00	53300.00	43511.83	32896.58	19444.48	51756.70
Apr	25249.20	19800.00	16000.00	30250.00	26617.77	21242.91	15995.22	30764.85
May	15972.58	15250.00	9570.00	19675.00	16032.37	14369.52	12295.58	17570.34
Jun	12939.23	12600.00	8237.50	17600.00	14124.72	12931.98	9530.52	17294.53
Jul	18873.90	11950.00	7665.00	15575.00	20000.73	11560.84	9687.78	16487.60
Aug	12411.87	11050.00	7102.50	14300.00	13379.10	11102.23	8740.66	14248.45
Sep	10850.80	8235.00	6530.00	12900.00	12790.03	9367.20	7476.25	13854.01
Oct	12458.10	10750.00	6112.50	13900.00	15607.91	11368.60	8238.77	16874.80
Nov	13896.10	13500.00	6557.50	18250.00	16250.34	12148.80	9171.31	19639.35
Dec	19332.77	14550.00	9150.00	23800.00	20267.76	15105.64	10019.73	22663.99

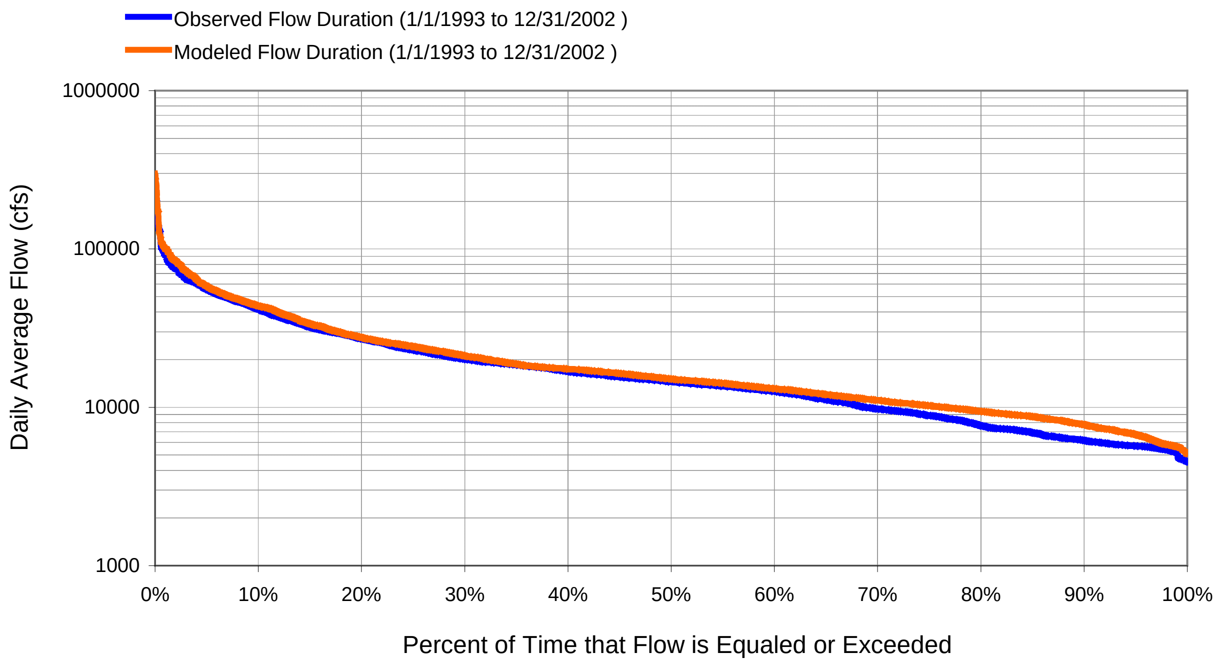


Figure 26. Flow exceedence: Model DSN 9001 vs. USGS 02358000 Apalachicola River At Chattahoochee, FL– calibration period (HSPF).

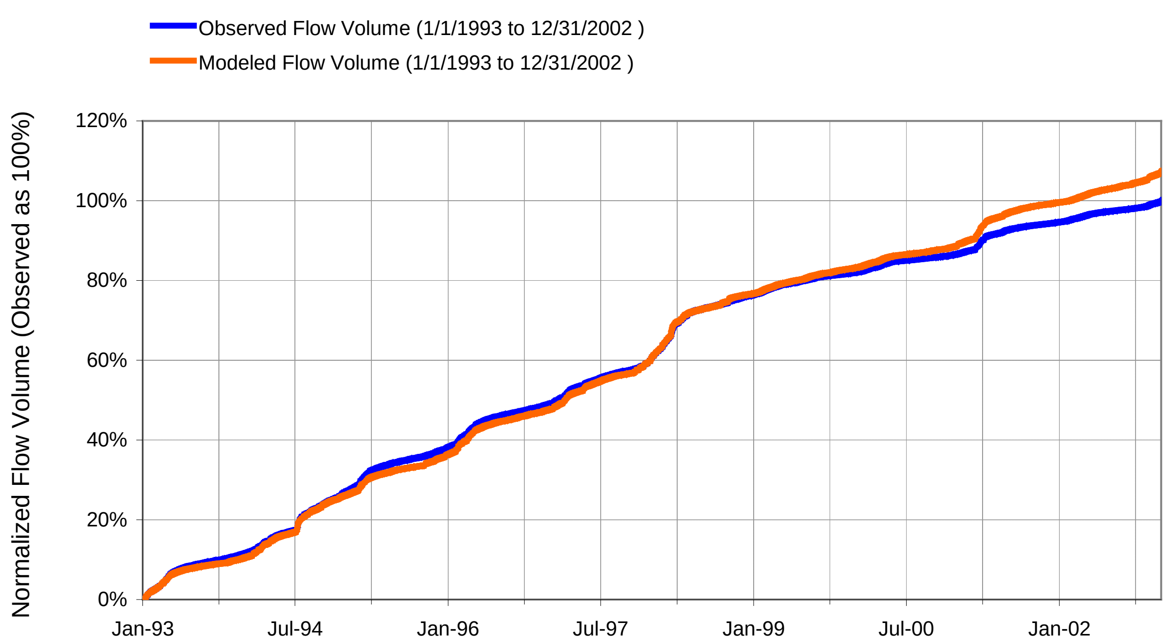


Figure 27. Flow accumulation: Model DSN 9001 vs. USGS 02358000 Apalachicola River At Chattahoochee, FL– calibration period (HSPF).

Table 12. Summary statistics: Model DSN 9001 vs. USGS 02358000 Apalachicola River At Chattahoochee, FL– calibration period (HSPF).

HSPF Simulated Flow		Observed Flow Gage	
REACH OUTFLOW FROM DSN 9001 10-Year Analysis Period: 1/1/1993 - 12/31/2002 Flow volumes are (inches/year) for upstream drainage area		USGS 02358000 APALACHICOLA RIVER AT CHATTAHOOCHEE FLA Hydrologic Unit Code: 3130011 Latitude: 30.7010251 Longitude: -84.8590871 Drainage Area (sq-mi): 17200	
Total Simulated In-stream Flow:	**17.06**	Total Observed In-stream Flow:	**15.89**
Total of simulated highest 10% flows:	**5.55**	Total of Observed highest 10% flows:	**5.11**
Total of Simulated lowest 50% flows:	**4.09**	Total of Observed Lowest 50% flows:	**3.65**
Simulated Summer Flow Volume (months 7-9):	**3.07**	Observed Summer Flow Volume (7-9):	**2.80**
Simulated Fall Flow Volume (months 10-12):	**3.46**	Observed Fall Flow Volume (10-12):	**3.03**
Simulated Winter Flow Volume (months 1-3):	**6.82**	Observed Winter Flow Volume (1-3):	**6.51**
Simulated Spring Flow Volume (months 4-6):	**3.72**	Observed Spring Flow Volume (4-6):	**3.55**
Total Simulated Storm Volume:	**4.27**	Total Observed Storm Volume:	**3.71**
Simulated Summer Storm Volume (7-9):	**0.72**	Observed Summer Storm Volume (7-9):	**0.64**

Errors (Simulated-Observed)	*Error Statistics*	*Recommended Criteria*		
Error in total volume:	7.35	10		
Error in 50% lowest flows:	12.13	10		
Error in 10% highest flows:	8.50	15		
Seasonal volume error - Summer:	9.50	30		
Seasonal volume error - Fall:	14.07	>> 30		Clear
Seasonal volume error - Winter:	4.69	30		
Seasonal volume error - Spring:	4.78	30		
Error in storm volumes:	15.09	20		
Error in summer storm volumes:	12.02	50		
Nash-Sutcliffe Coefficient of Efficiency, E:	0.769	Model accuracy increases		
Baseline adjusted coefficient (Garrick), E':	0.575	as E or E' approaches 1.0		
Monthly NSE	0.922			

The calibration and validation statistical measurements, at all USGS gages used in the ACF basin for the 20 Watershed project, are shown in Tables 13 and 14 respectively.

Table 13. Summary statistics (percent error) for all stations – calibration period 1993-2002 (HSPF)

Station	02349605	02331600	02336300	02353500	02336000	02339500	02343801	02353000	02358000
Error in total volume:	5.50	0.14	17.16	3.93	24.16	15.40	16.79	8.33	7.35
Error in 50% lowest flows:	-1.49	3.09	2.56	17.11	59.65	74.07	49.13	4.70	12.13
Error in 10% highest flows:	6.32	4.62	6.29	9.69	-7.60	-0.36	8.63	14.97	8.50
Seasonal volume error - Summer:	10.14	2.28	1.30	1.33	8.20	9.33	11.54	16.06	9.50
Seasonal volume error - Fall:	5.17	6.04	19.26	-8.97	42.13	19.50	26.84	7.59	14.07
Seasonal volume error - Winter:	4.48	4.19	27.56	9.57	16.81	9.17	10.78	7.54	4.69
Seasonal volume error - Spring:	4.21	-10.90	13.02	9.42	35.91	27.67	24.10	4.65	4.78
Error in storm volumes:	1.25	-0.25	8.76	6.61	-56.00	-70.75	-37.96	4.85	15.09
Error in summer storm volumes:	-2.14	-28.59	3.05	-34.98	-62.85	-87.05	-60.30	12.41	12.02
Daily Nash-Sutcliffe Coefficient of Efficiency, E:	0.707	0.640	0.536	0.339	0.539	0.591	0.717	0.607	0.769
Monthly Nash-Sutcliffe Coefficient: of	0.934	0.862	0.477	0.652	0.683	0.821	0.858	0.928	0.922

Station	02349605	02331600	02336300	02353500	02336000	02339500	02343801	02353000	02358000
Efficiency									

Table 14. Summary statistics (percent error) for all stations – validation period 1983-1992 (HSPF)

Station	02349605	02331600	02336300	02353500	02336000	02339500	02343801	02353000	02358000
Error in total volume:	5.79	-8.32	13.73	1.19	12.01	10.86	13.28	6.91	2.21
Error in 50% lowest flows:	-3.16	-4.98	4.87	-1.92	47.20	80.89	37.90	-1.14	-9.05
Error in 10% highest flows:	3.69	-6.88	3.05	6.48	-14.34	-5.02	7.57	11.27	8.49
Seasonal volume error - Summer:	17.40	-9.94	5.82	23.48	-2.55	6.67	13.98	17.92	3.55
Seasonal volume error - Fall:	1.92	-4.13	19.78	-14.67	8.67	-1.60	8.04	7.94	1.33
Seasonal volume error - Winter:	3.33	-2.73	19.85	-3.02	22.43	16.08	14.33	4.62	4.57
Seasonal volume error - Spring:	6.93	-17.08	7.49	7.15	19.52	21.34	15.92	3.64	-1.81
Error in storm volumes:	-2.74	-22.55	6.12	-0.18	-61.77	-74.01	-56.18	-10.57	20.87
Error in summer storm volumes:	9.14	-50.35	7.78	-22.89	-71.06	-87.14	-77.18	-23.32	-5.49
Daily Nash-Sutcliffe Coefficient of Efficiency, E:	0.651	0.696	0.553	0.385	0.479	0.566	0.698	0.682	0.707
Monthly Nash-Sutcliffe Coefficient: of	0.899	0.865	0.654	0.652	0.845	0.797	0.858	0.890	0.914

Station	02349605	02331600	02336300	02353500	02336000	02339500	02343801	02353000	02358000
Efficiency									

An additional check was done on the reservoirs of the Chattahoochee River mainstem. Observed and modeled reservoir elevations were compared by using a histogram approach. This check ensured that the storage contained within a reservoir was accounted for even though the flow calibration downstream of the reservoir didn't simulate well. These comparisons were performed for the time period from January 1993 to December 2002. All lake elevation simulations closely compared to the observed elevations except for Lake Lanier (Figures 28 through 31).

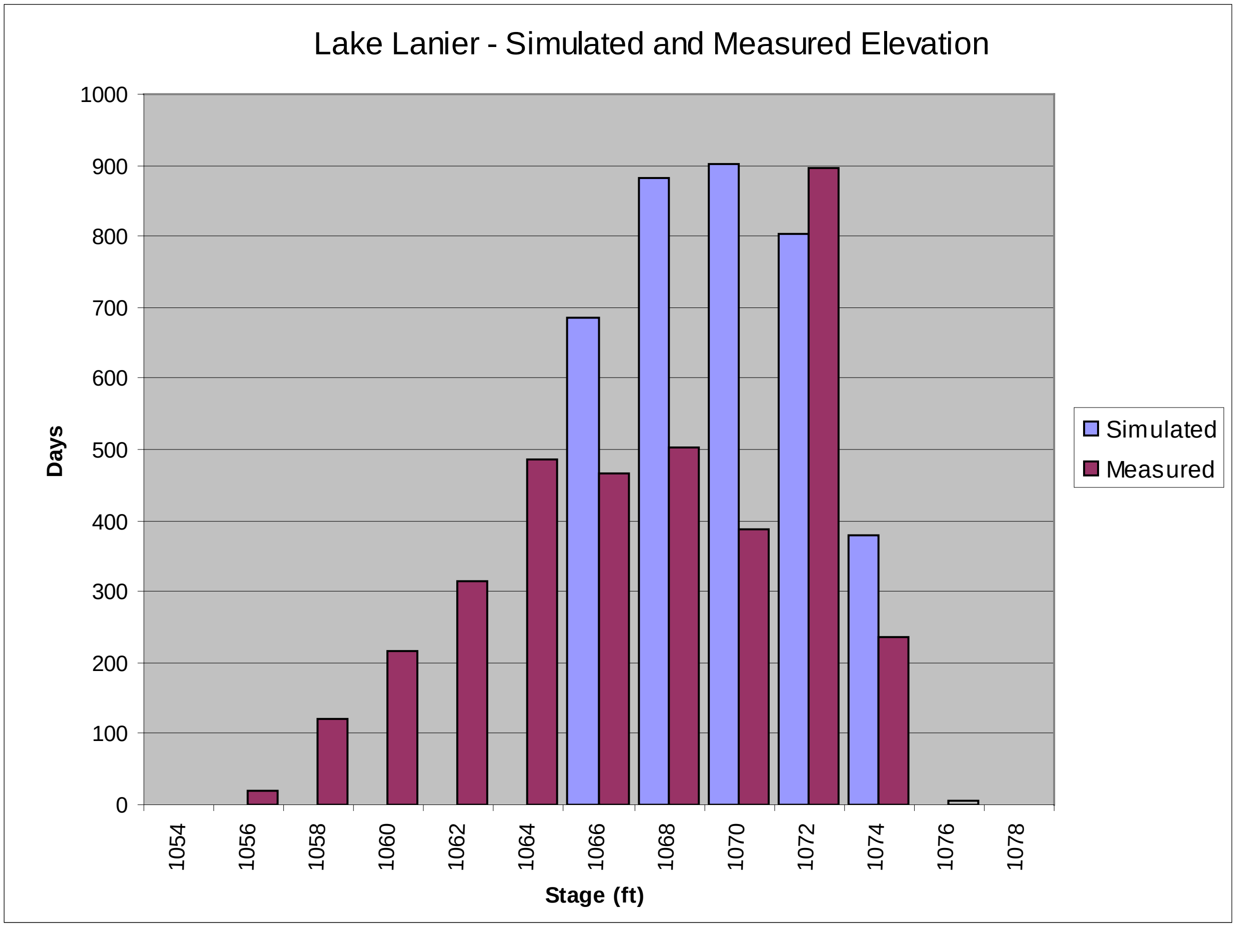


Figure 28. Histogram of simulated and measured elevation for Lake Lanier from 1/1/1993 to 12/31/2002.

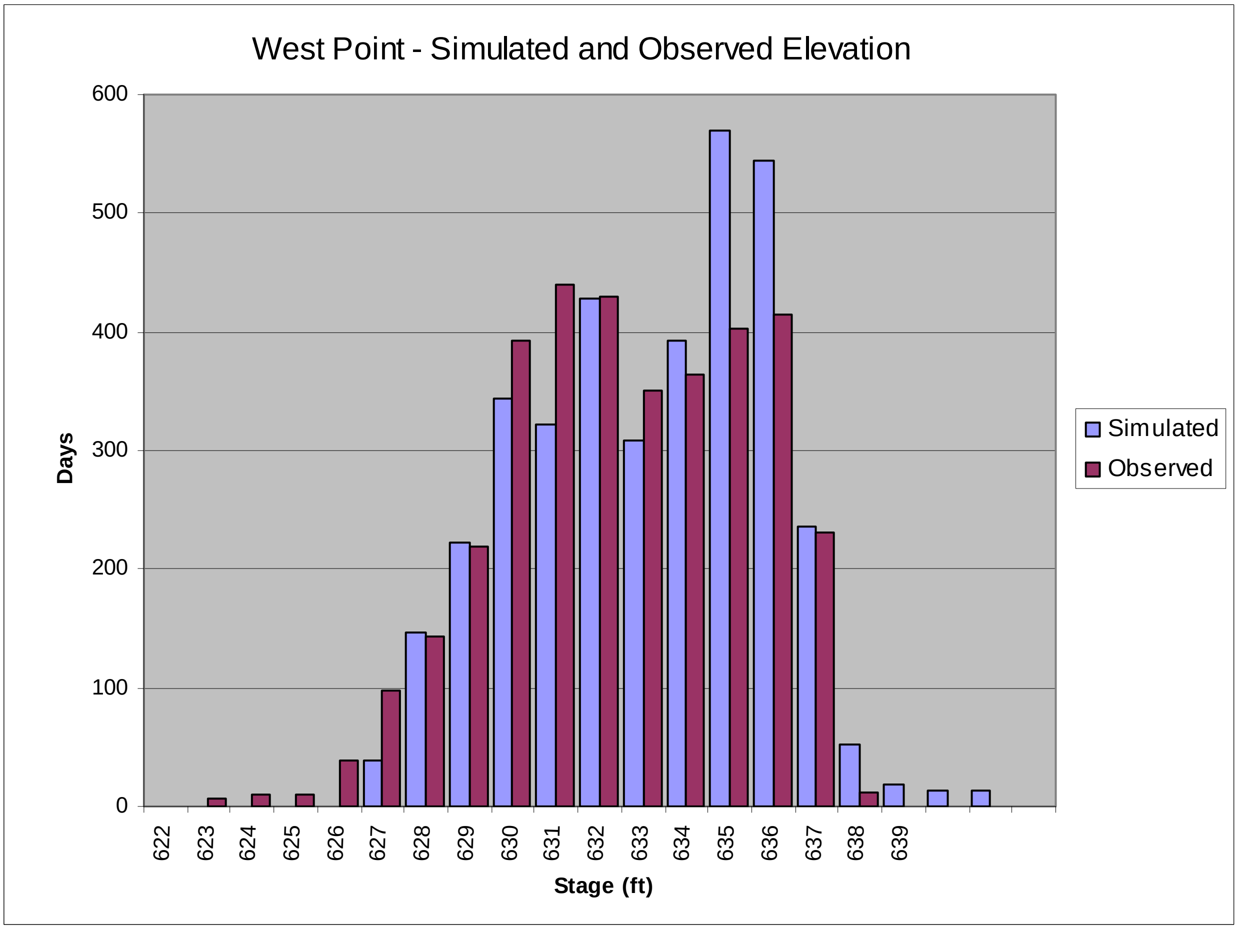


Figure 29. Histogram of simulated and measured elevation for West Point Lake from 1/1/1993 to 12/31/2002.

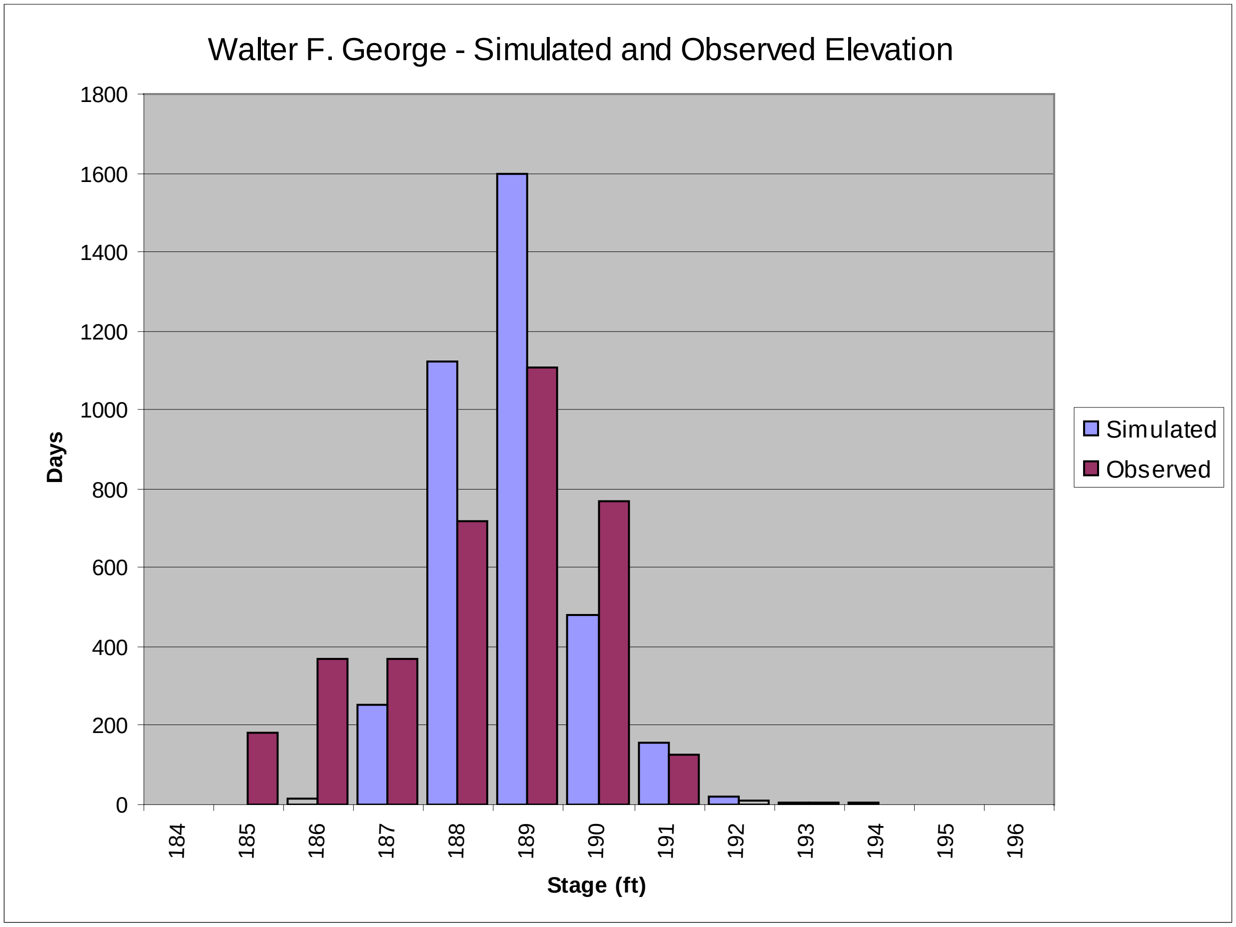


Figure 30. Histogram of simulated and measured elevation for Lake Walter F. George from 1/1/1993 to 12/31/2002.

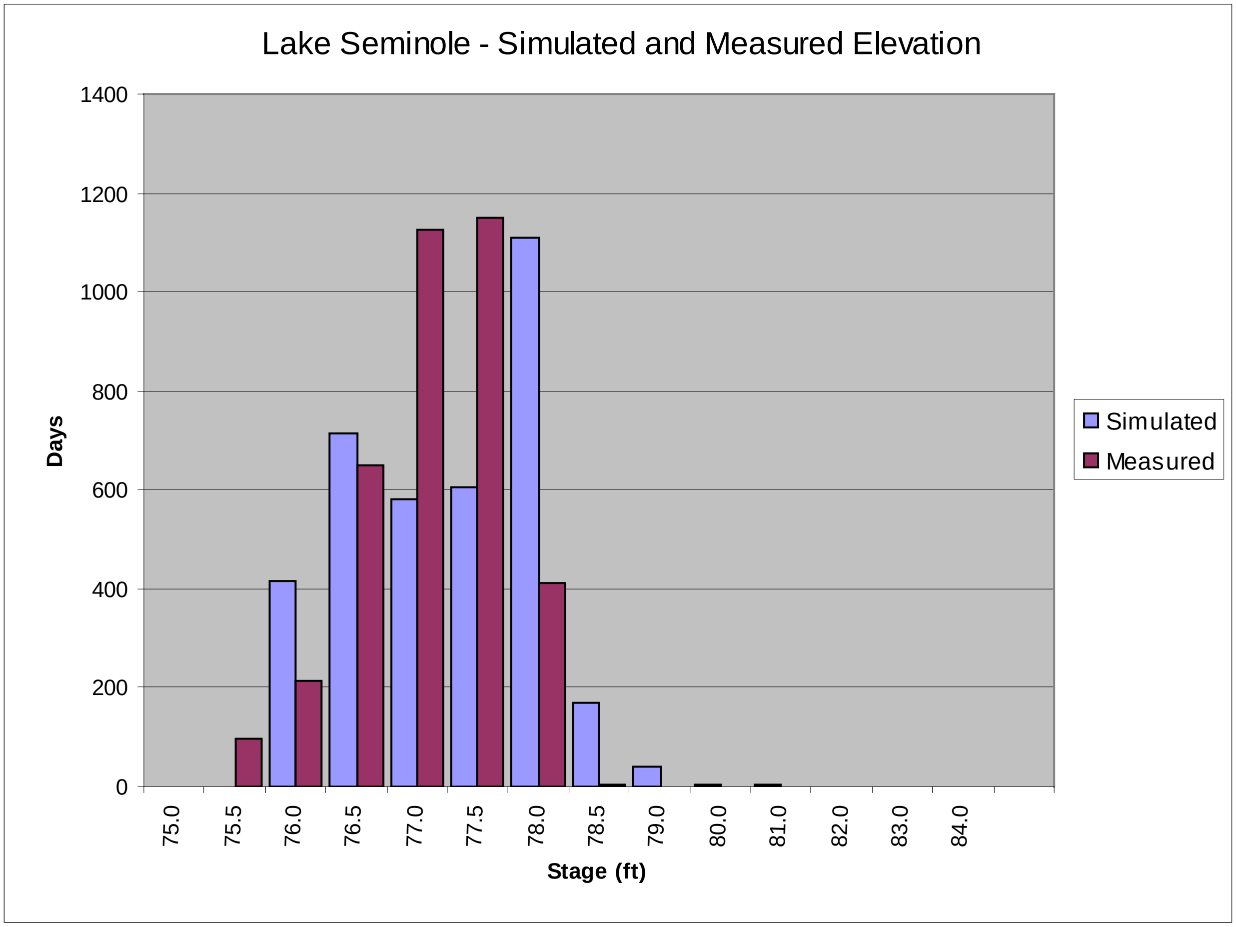


Figure 31. Histogram of simulated and measured elevation for Lake Seminole from 1/1/1993 to 12/31/2002.

Water Quality Calibration and Validation

The 20 Watershed models are designed to provide water quality simulation for total suspended solids (TSS), total nitrogen, and total phosphorus. TSS is simulated with the standard HSPF approach (USEPA 2006). In contrast to TSS, total nitrogen and total phosphorus are simulated in this application in a simplistic fashion, as HSPF general quality constituents (GQUALs) subject to an exponential decay rate during transport.

The water quality calibration focuses on the replication of monthly loads, as specified in the project QAPP. Given the approach to water quality simulation in the 20 Watershed model, a close match to individual concentration observations cannot be expected. Comparison to monthly loads presents challenges, as monthly loads are not observed. Instead, monthly loads must be estimated from scattered concentration grab samples and continuous flow records. As a result, the monthly load calibration is inevitably based on the comparison of two uncertain numbers. Nonetheless, calibration is able to achieve a reasonable agreement. Further, the load comparisons were supported by detailed examinations of the relationships of flows to loads and concentrations and the distribution of concentration prediction errors versus flow, time, and season, as well as standard time series plots.

For application on a nationwide basis, the 20 Watershed protocols assume that TSS and total phosphorus loads will likely exhibit a strong positive correlation to flow (and associated erosive processes), while total nitrogen loads, which often have a dominant groundwater component, will not. Accordingly, TSS and total phosphorus loads were estimated from observations using a flow-stratified log-log regression approach, while total nitrogen loads were estimated using a flow-stratified averaging estimator, consistent with the findings of Preston et al. (1989).

Similarly to hydrology, initial calibration and validation of water quality was done on the Upper Flint River, comparing model results to data from USGS 02349605. The initial calibration used calendar years 1999-2002 for calibration and calendar years 1991-1998 for validation as there were no data available prior to 1992 for this gage. As stated above, initial water quality parameters were obtained from an LSPC model for a TMDL done for the Lake Allatoona watershed in North Georgia. The Lake Allatoona watershed LSPC model was parameterized with values from literature, information collected in the field, and from previous modeling work done in the state of Georgia. With the exception of shrub lands, both the TMDL model and 20 Watershed model had similar land uses. Shrub lands had parameters assigned from forest lands since these two land uses should behave similarly to each other.

Time series of simulated and estimated TSS loads at the Upper Flint gage for both periods are shown in Figure 32 and statistics for the two periods are provided separately in Table 15. Results of the TSS calibration are generally acceptable. Visually, the model is roughly simulating the trends contained in the observed data but the loading estimates are on the high side. The statistics performed on the comparison between the simulated results and observed data also indicate that TSS loading is slightly high. The key statistic in the table (consistent with the QAPP) is the relative percent error, which shows the error in the prediction of monthly load normalized to the estimated load. The table also shows the relative average absolute error, which is the average of the relative magnitude of errors in individual monthly load predictions. This number is inflated by outlier months in which the simulated and estimated loads differ by large amounts (which may be as easily due to uncertainty in the estimated load due to limited data) and the third statistic, the relative median absolute error, is likely more relevant and shows acceptable agreement.

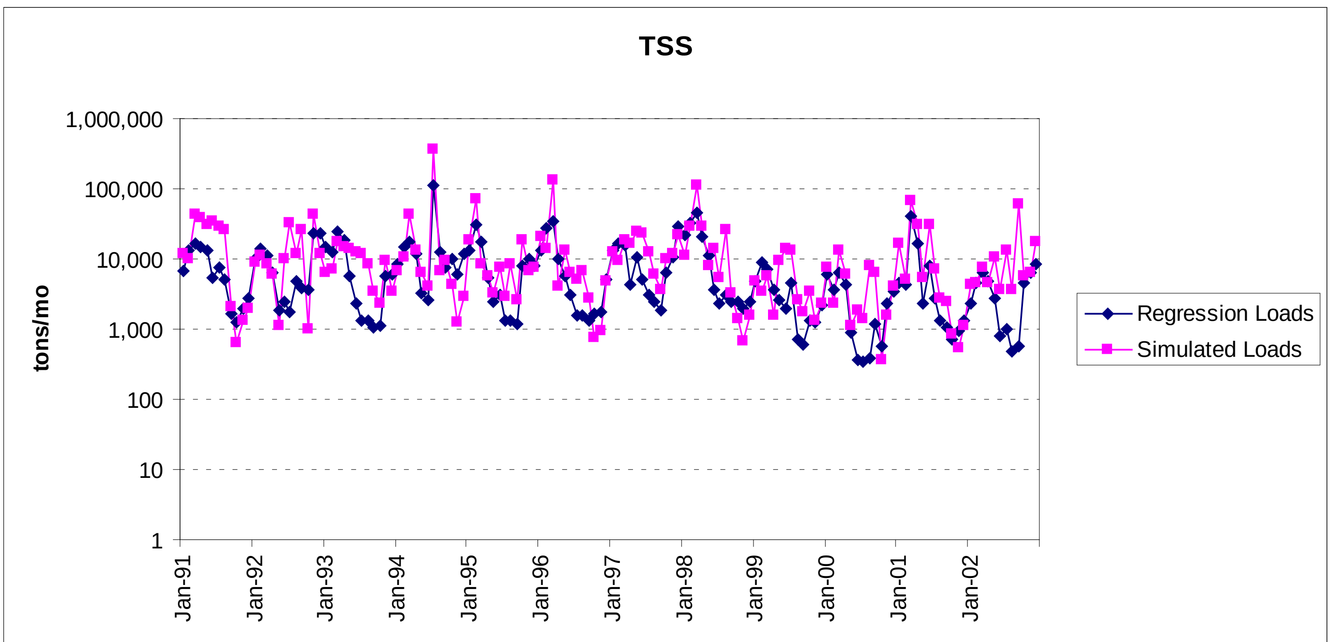


Figure 32. Fit for monthly load of TSS USGS 02349605 Flint River at Ga 26, near Montezuma, GA (HSPF).

Table 15. Model fit statistics (observed minus predicted) for monthly TSS loads using stratified regression

Statistic	Calibration period (1999-2002)	Validation period (1991-1998)
Relative Percent Error	-117%	-78%
Relative Average Absolute Error	129%	110%
Relative Median Absolute Error	38.1%	44.5%

A variety of other diagnostics were also pursued to ensure agreement between the model and observations. These are available in full in the calibration spreadsheets, but a few examples are provided below. First, load-flow power plots were compared for individual days (Figures 33 and 34). These confirm that the relationship between flow and load is consistent across the entire range of observed flows, for both the calibration and validation periods.

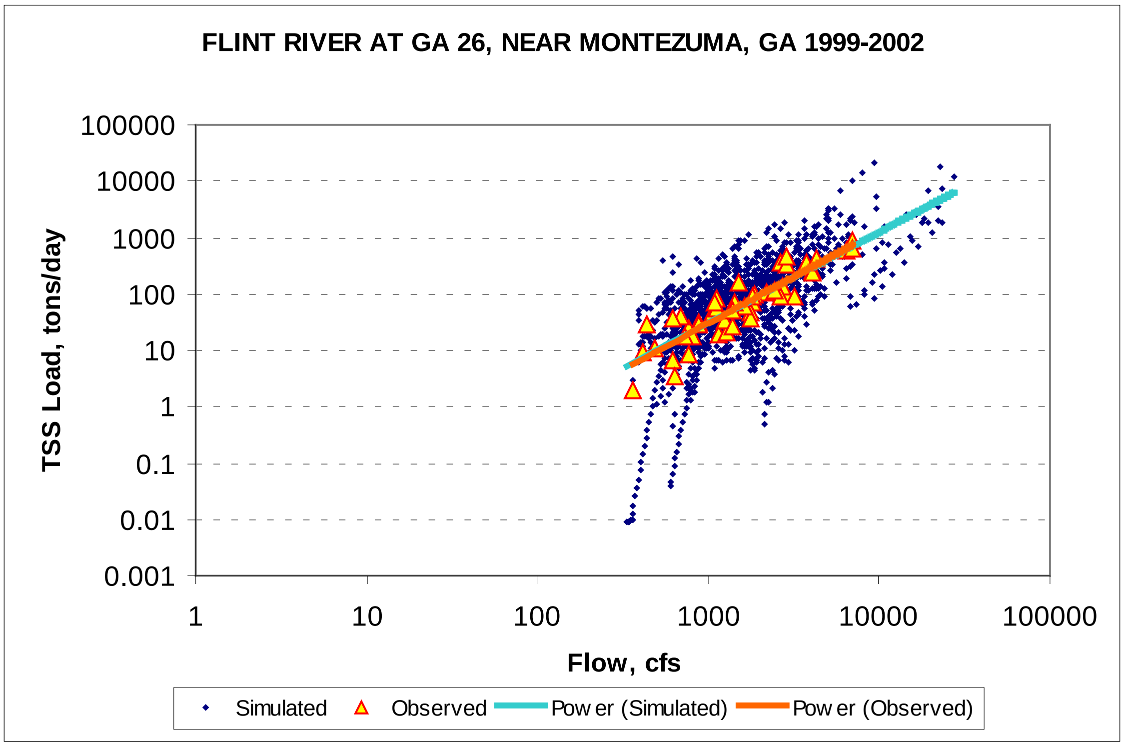


Figure 33. Power plot for observed and simulated TSS at USGS 02349605 Flint River at Ga 26, near Montezuma, GA – calibration period (HSPF).

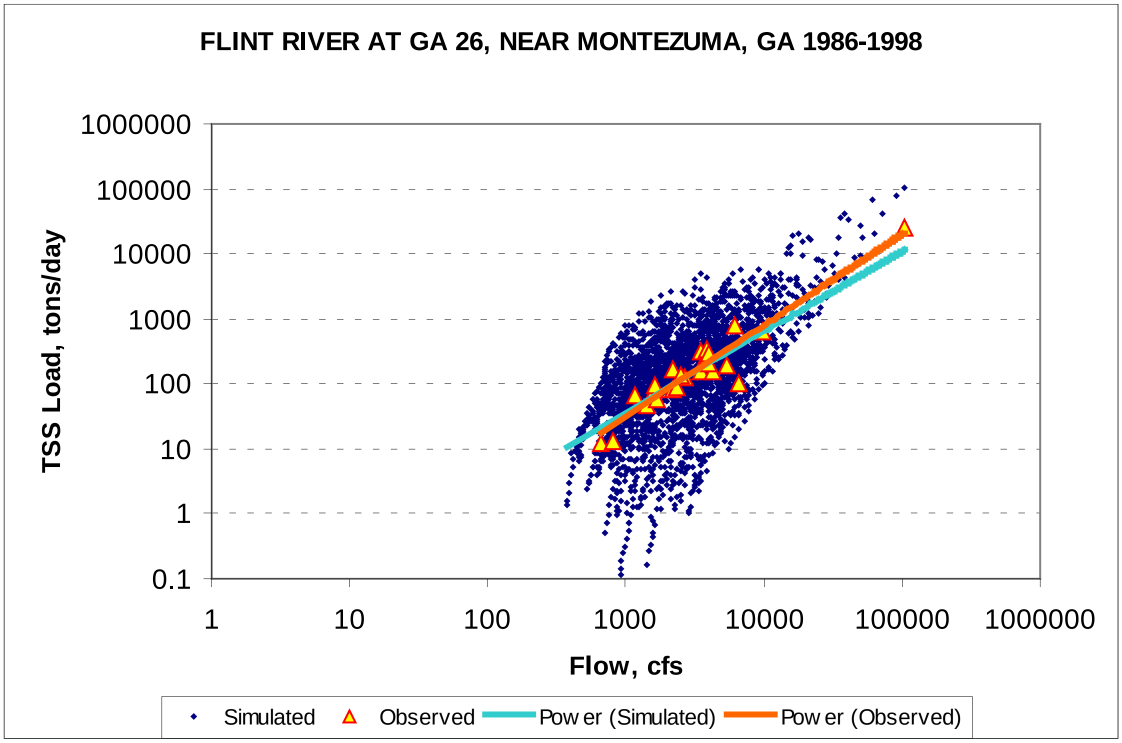


Figure 34. Power plot for observed and simulated TSS at USGS 02349605 Flint River at Ga 26, near Montezuma, GA – validation period (HSPF).

Standard time series plots (Figure 35) show that observed and simulated concentrations achieve good agreement, although individual observations may deviate. Plots of concentration error versus flow and versus month (not shown) were used to guard against hydrologic and temporal bias. Finally, statistics on concentration (Table 16) show that acceptable median errors are achieved for the calibration period.

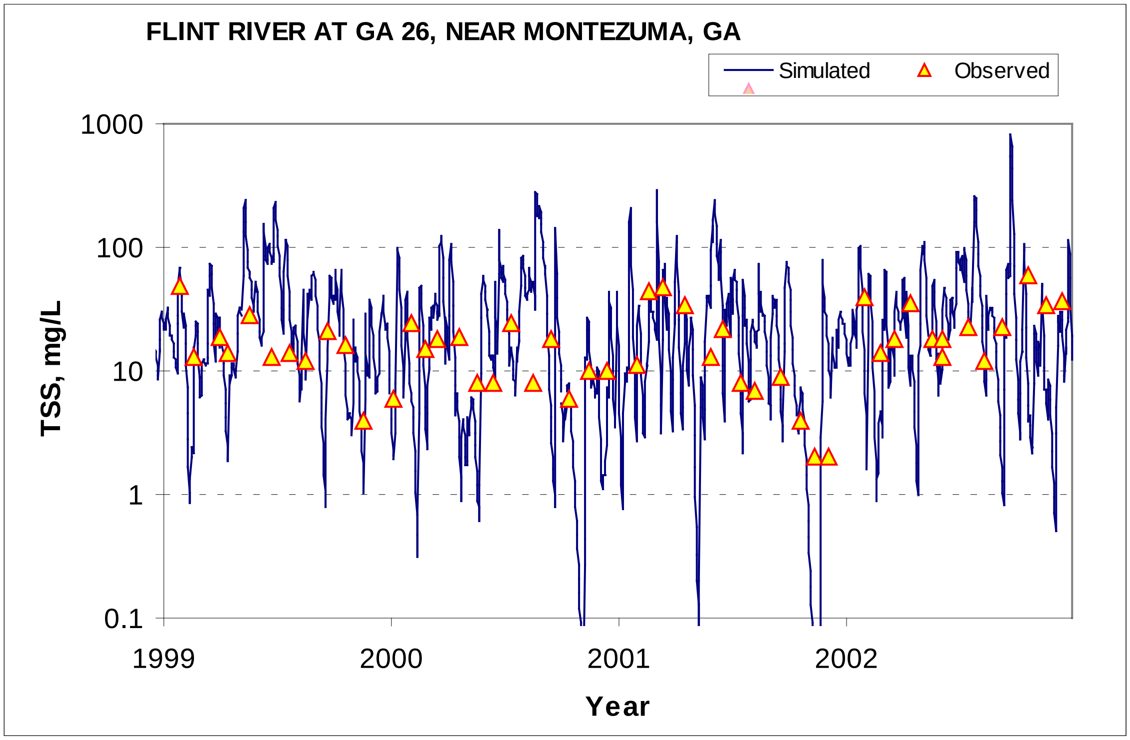


Figure 35. Time series plot of TSS concentration at USGS 02349605 Flint River at Ga 26, near Montezuma, GA – calibration period (HSPF).

Table 16. Relative errors (observed minus predicted), TSS concentration at USGS 02349605 Flint River at Ga 26, near Montezuma, GA (HSPF).

Statistic	Calibration period (1999-2002)	Validation period (1991-1998)
Count	49	24
Concentration Average Error	3.30%	-97.85%
Concentration Median Error	19.78%	-33.27%

The general quality constituent parameters in the Lake Allatoona TMDL model for total phosphorus were essentially directly transferred to the 20 Watershed model. As stated earlier, shrub land was parameterized similarly to forested lands. The model simulates total phosphorus from the uplands as having both sediment-associated and buildup-washoff components. The sediment-associated component of the surface load reflects mineral phosphorus, while the buildup-washoff component addresses organic phosphorus.

Initial parameter assignments for phosphorus for the Upper Flint calibration focus area performed well. Minor adjustments were made to the interflow and groundwater component. The same percent adjustment was made to all land uses in order to keep the land use associated loading rates, developed in the TMDL model, intact. All streams in the calibration focus area were supplied with the same first order decay rate. This decay rate was obtained from the TMDL model and is consistent with other modeling work conducted throughout the state of Georgia. Adjustment was not made to this parameter while calibration was performed on the calibration focus area.

Monthly loading series for total phosphorus are shown in Figure 36 and load statistics are summarized in Table 17. In general, the observed and simulated total phosphorus loads attain an acceptable match for both the calibration and validation periods. There are a few locations where the simulation is not trending and the simulated loads are higher than the observed loads. These errors are most likely attributed to the error in the TSS simulation during the same time period.

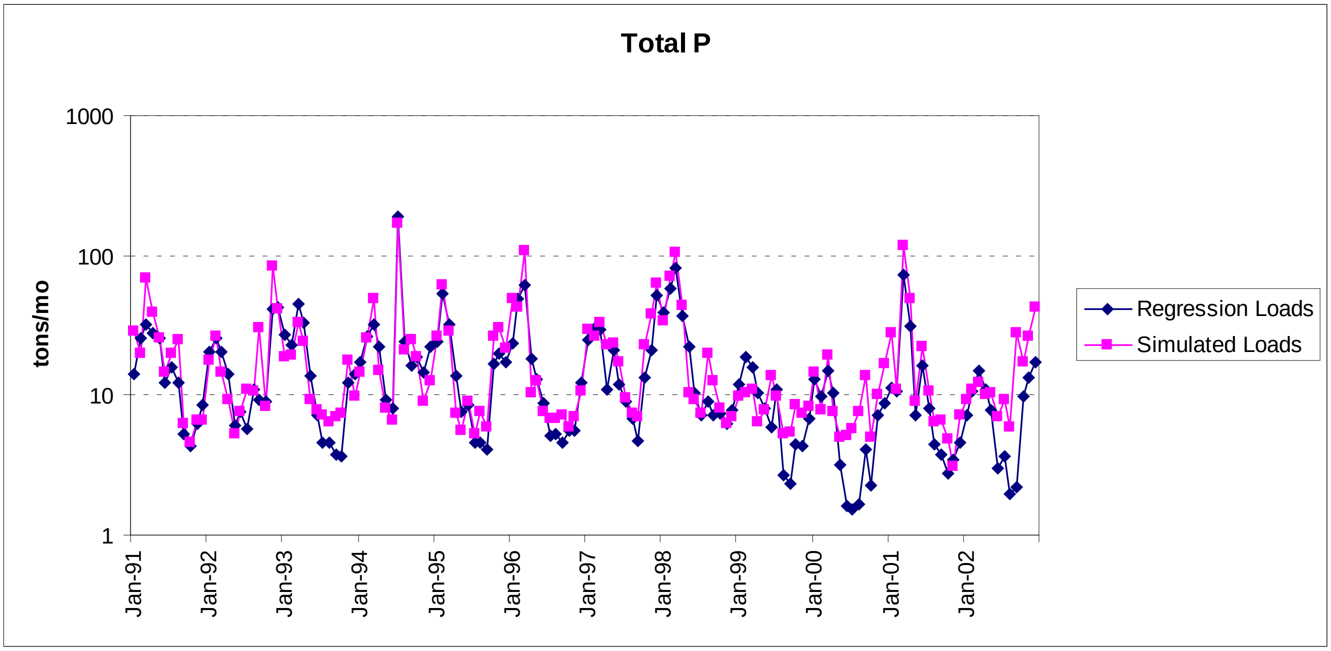


Figure 36. Fit for monthly load of total phosphorus at USGS 02349605 Flint River at Ga 26, near Montezuma, GA (HSPF).

Table 17. Model fit statistics (observed minus predicted) for monthly total phosphorus loads using stratified regression

Statistic	Calibration period (1999-2002)	Validation period (1986-1998)
Relative Percent Error	-59%	-23%
Average Absolute Error	69%	35%
Median Absolute Error	35.3%	18.5%

As with TSS, additional diagnostics for total phosphorus included flow-load power plots (Figures 37 and 38), time series plots (Figure 39) and analysis of concentration errors (Table 18). All show acceptable agreement.

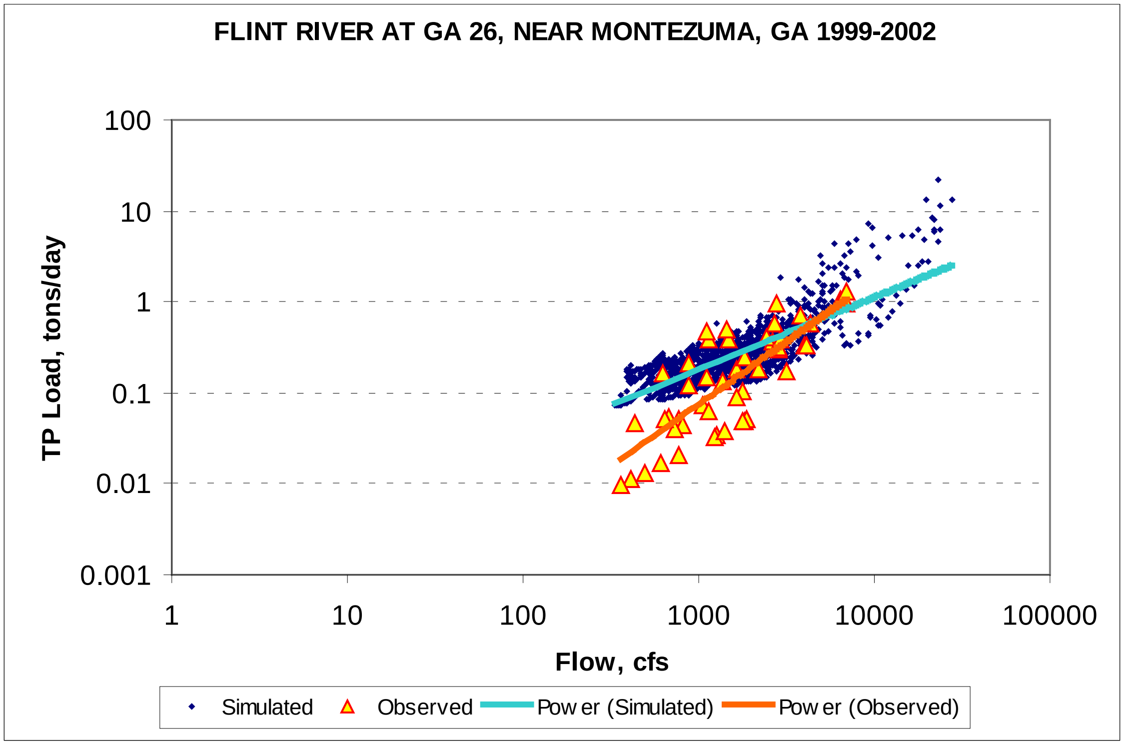


Figure 37. Power plot for observed and simulated total phosphorus at USGS 02349605 Flint River at Ga 26, near Montezuma, GA – calibration period (HSPF).

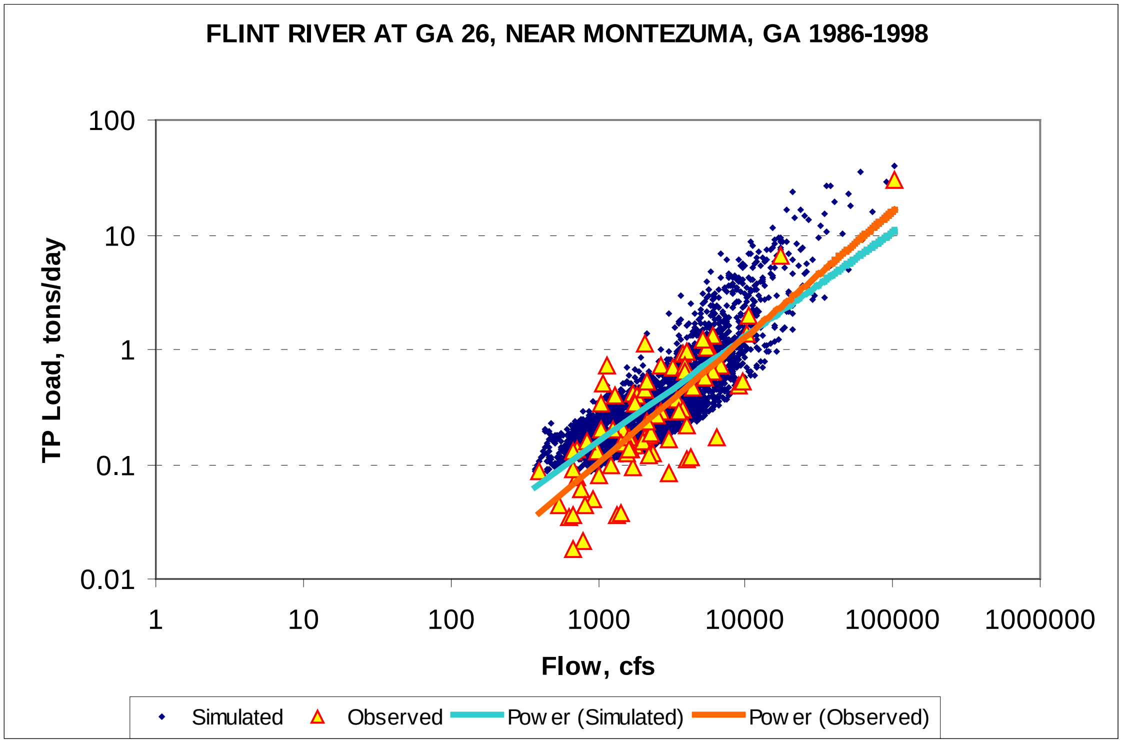


Figure 38. Power plot for observed and simulated total phosphorus at USGS 02349605 Flint River at Ga 26, near Montezuma, GA – validation period (HSPF).

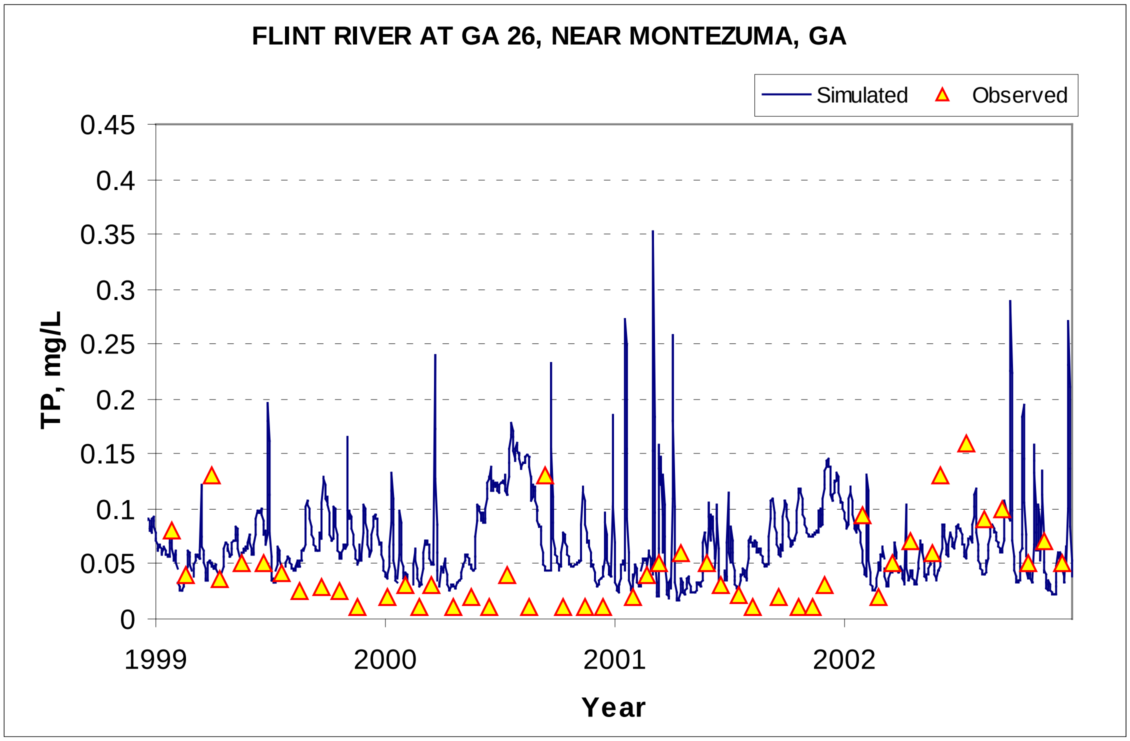


Figure 39. Time series plot of total phosphorus concentration at USGS 02349605 Flint River at Ga 26, near Montezuma, GA – calibration period (HSPF).

Table 18. Relative errors (observed minus predicted), total phosphorus concentration at USGS 02349605 Flint River at Ga 26, near Montezuma, GA (HSPF)

Statistic	Calibration period (1999-2002)	Validation period (1986-1998)
Count	48	80
Concentration Average Error	-31.2%	-2.2%
Concentration Median Error	-26.5%	-12.5%

As discussed above in the Calibration Data and Locations section of this report, the number of measured total nitrogen observations was very limited for the ACF. The approach used to estimate the observed total nitrogen should give reasonable values for total nitrogen since two of the three components making up total nitrogen were measured. Similarly to total phosphorus, total nitrogen parameters in the Lake Allatoona TMDL model were easily transferred to the 20 Watershed model. Also, similarly to total phosphorus, initial interflow and groundwater total nitrogen concentrations were adjusted for all land uses together in order to keep the land use associated loading rates, developed in the TMDL model, intact.

Results for total nitrogen are summarized in Figures 40 through 43 and Tables 19 and 20, following the same format as total phosphorus. The results are acceptable, and generally better than those for total phosphorus. This is because nitrogen is not sediment-associated, therefore, problems with sediment are not reflected in the calibration for total nitrogen.

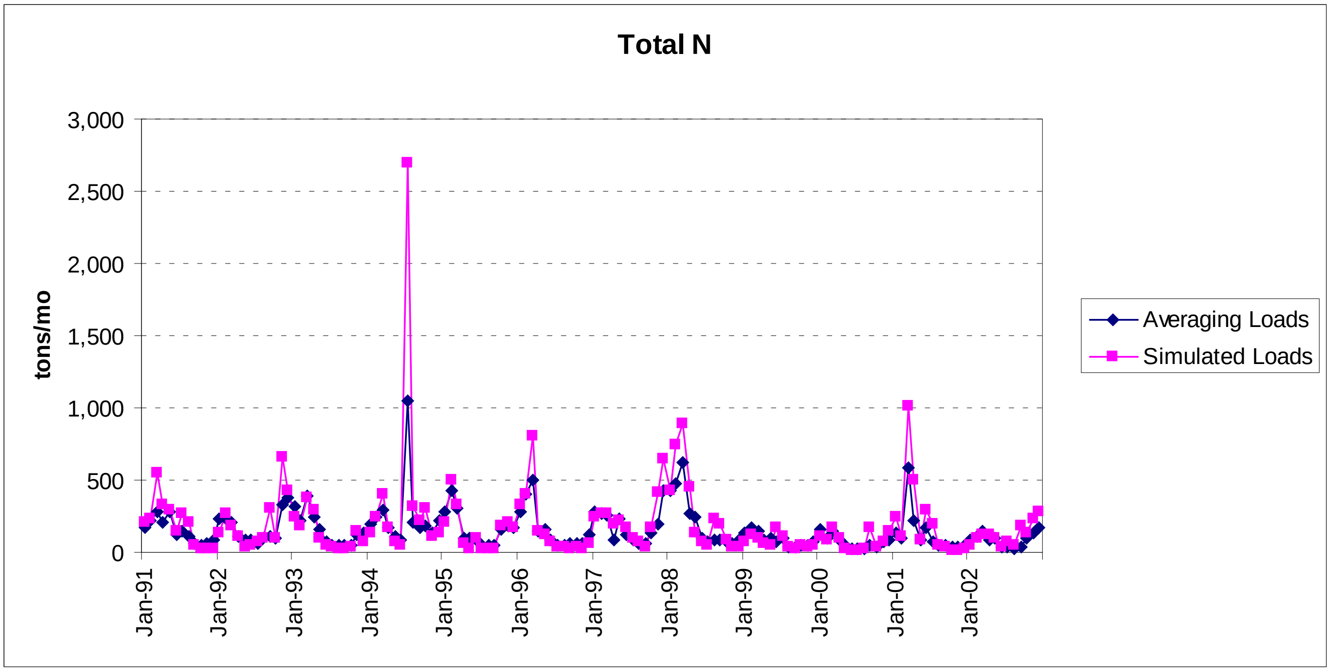


Figure 40. Fit for monthly load of total nitrogen at USGS 02349605 Flint River at Ga 26, near Montezuma, GA (HSPF).

Table 19. Model fit statistics (observed minus predicted) for monthly total nitrogen loads using averaging estimator (HSPF)

Statistic	Calibration period (1999-2002)	Validation period (1986-1998)
Relative Percent Error	-30%	-22%
Average Absolute Error	54%	42%
Median Absolute Error	26.1%	18.2

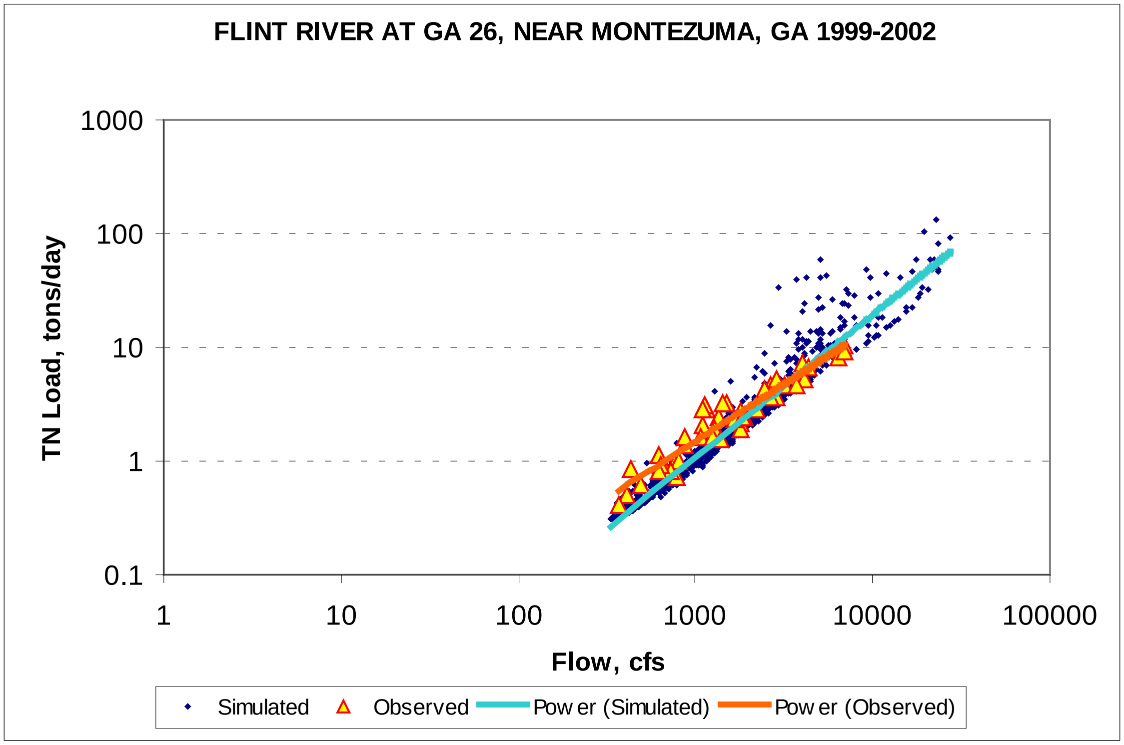


Figure 41. Power plot for observed and simulated total nitrogen at USGS 02349605 Flint River at Ga 26, near Montezuma, GA – calibration period (HSPF).

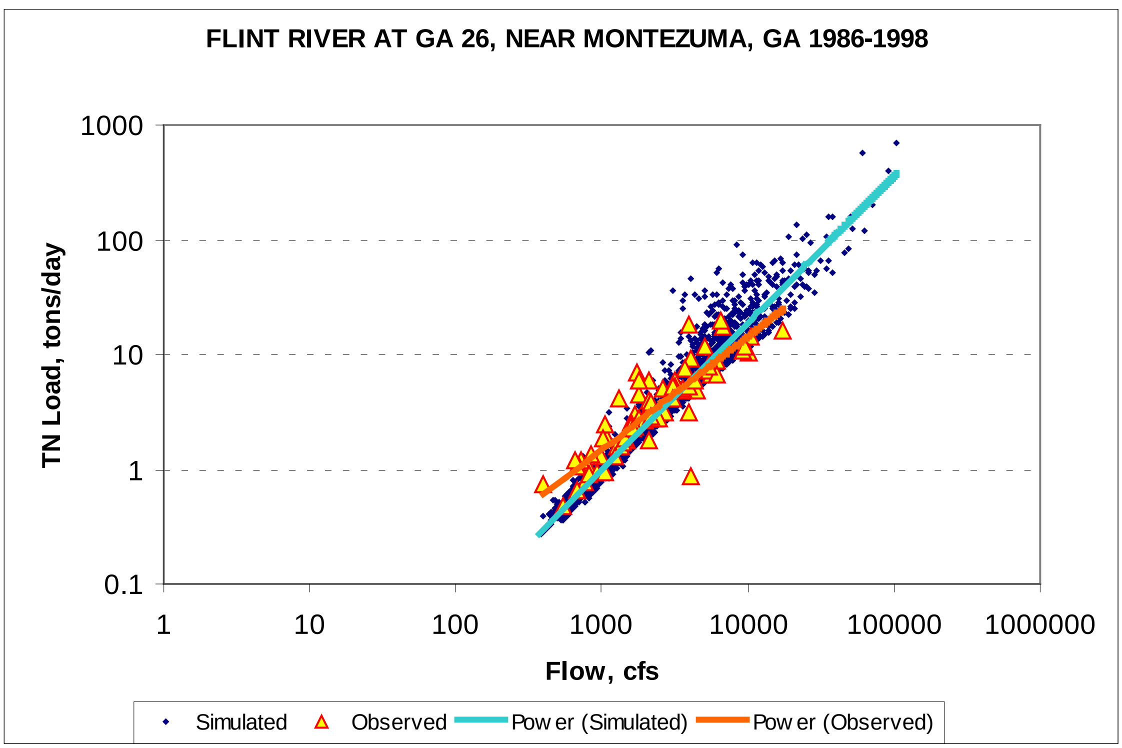


Figure 42. Power plot for observed and simulated total nitrogen at USGS 02349605 Flint River at Ga 26, near Montezuma, GA – validation period (HSPF).

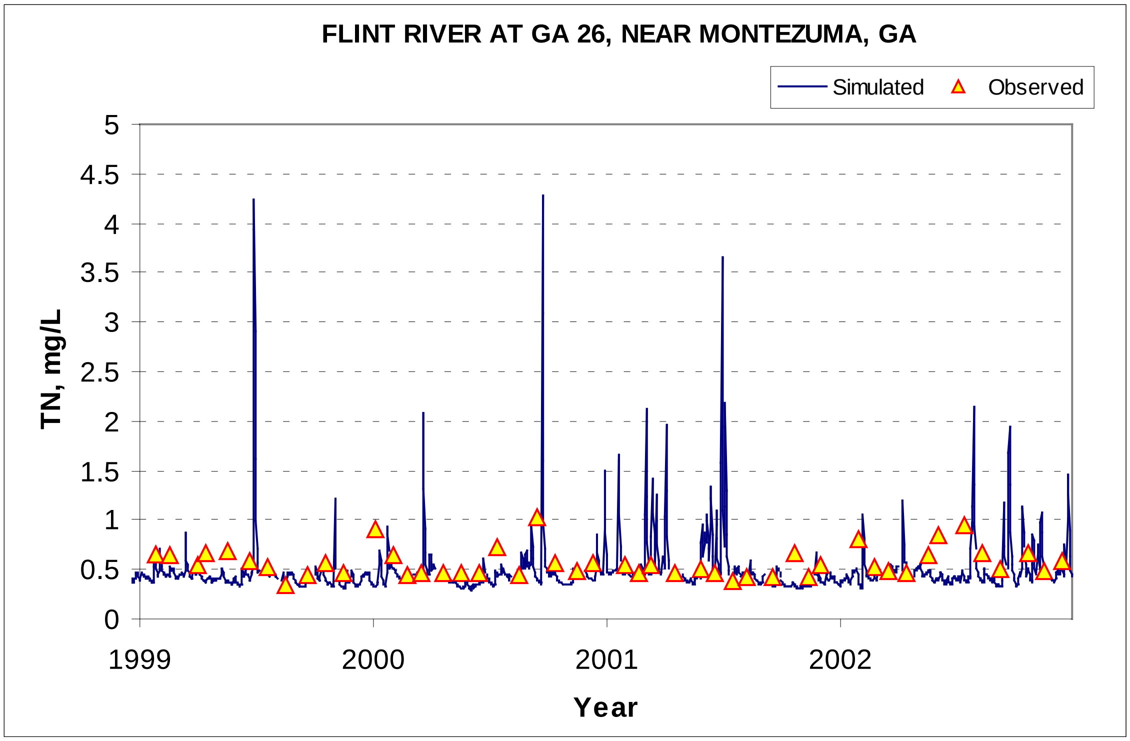


Figure 43. Time series plot of total nitrogen concentration at USGS 02349605 Flint River at Ga 26, near Montezuma, GA – calibration period (HSPF).

Table 20. Relative errors (observed minus predicted), total nitrogen concentration at USGS 02349605 Flint River at Ga 26, near Montezuma, GA (HSPF)

Statistic	Calibration period (1999-2002)	Validation period (1986-1998)
Count	48	76
Concentration Average Error	25.5%	27.2%
Concentration Median Error	19.3%	14.7%

Water Quality Results for Larger Watershed

Similar to hydrology, the Upper Flint water quality parameterization was not directly transferrable to other areas of the watershed. The Upper Flint parameters were utilized as starting parameters at the other calibration locations. Once those locations reasonably agreed with the observed data, they were transferred to other parts of the watershed, as with the hydrology calibration. The decay rates assigned to the streams in the calibration focus area were also assigned to all streams in the ACF basin.

Upon initial water quality parameterization mapping, the water quality simulation below the reservoirs was checked. At this point the simulation suggested that each of the reservoirs consumed all of the nitrogen and phosphorus entering the reservoir and the water leaving the reservoir was free of all total nitrogen and total phosphorus. This was taken to mean that due to longer residence time within reservoir reaches, the first order decay rate applied to the reservoirs was too high. Total nitrogen and total phosphorus first order decay rates were lowered until the simulation below each of the reservoirs better matched the observed water quality. This resulted in decay rates that were an order of magnitude lower than those applied to the other stream reaches. HSPF assumes that the water within a reach is both vertically and horizontally mixed; therefore it does not take into account nutrient transformations and cycling occurring within a reservoir. The lowered decay rate was utilized as a parameter to capture nutrient dynamics within the reservoirs, therefore they decay rate was the only parameter adjusted in order to get a reasonable representation of water quality below the reservoirs.

Summary statistics for the water quality calibration and validation at all stations in the watershed are provided in Tables 21 and 22. The results of the water quality calibration and validation are much better at some gages than others. The gages that are simulating poorly are probably doing so because of a lack of data to reasonably construct observed monthly loadings. Another source of error that can balloon error statistics is poor hydrology simulation at some of the monitoring locations. These two errors coupled together can severely impact the error statistics presented.

Table 21. Summary statistics for water quality (observed minus predicted) for all stations – calibration period 1999-2002 (HSPF)

Station	02349605	02331600	02336300	02353500	02336000	02339500	02343801	02353000
Relative Percent Error TSS Load	-117%	-4%	74%	-438%	-215%	-141%	34%	-63%
TSS Concentration Median Percent Error	19.78%	16.73%	10.16%	-38.90%	1.72%	-120.07%	28.57%	-64.66%
Relative Percent Error TP Load	-59%	-1%	24%	-205%	-77%	-272%	-202%	-82%
TP Concentration Median Percent Error	-26.5%	12.8%	-13.8%	-224.5%	-40.1%	-759.0%	-1107.9%	-89.2%
Relative Percent Error TN Load	-30%	-25%	-38%	-38%	-35%	2%	3%	32%
TN Concentration Median Percent Error	19.3%	4.2%	16.8%	46.7%	35.8%	46.4%	54.8%	53.1%

Table 22. Summary statistics for water quality (observed minus predicted) for all stations – validation period 1986-1998 (HSPF)

Station	02349605	02331600	02336300	02353500	02336000	02339500	02343801	02353000
Relative Percent Error TSS Load	-78%	90%	89%	-570%	18%	-7%	84%	-77%
TSS Concentration Median Percent Error	-33.3%	7.2%	3.5%	-103.8%	6.7%	-36.9%	8.0%	-1.0%
Relative Percent Error TP Load	-23%	53%	47%	-94%	-16%	-64%	54%	-22%
TP Concentration Median Percent Error	-12.5%	43.6%	5.9%	-17.0%	-9.1%	-85.2%	-499.6%	-26.1%
Relative Percent Error TN Load	-22%	-8%	-21%	-20%	10%	25%	7%	16%
TN Concentration Median Percent Error	14.7%	1.3%	20.7%	32.7%	20.0%	-28.2%	31.2%	-39.9%

SWAT Modeling

Changes Made to Base Data Provided

As mentioned in the above section for the HSPF model, no changes were made to the meteorological or land use base data for the SWAT model. However, an error in the connectivity of reaches was found in the predefined reach file, which was rectified. The impoundments of Lake Blackshear and Lake Seminole have large tributaries contributing to them. The pre-defined reach file had reaches of the upstream tributaries draining into the next downstream reach rather than into the reach within the subwatershed containing the lakes. This made the contributing drainage areas for these lakes incorrect. The connectivity was modified so that the tributaries pour into the reaches within the subwatersheds containing the lakes. Incorrect connectivity of reaches would pose a problem because of the incorrect drainage area contributing flow to the impoundments. In the SWAT model, reservoirs are modeled to be simulated at the outlet of the subwatershed in which they are located and receive flow from all the upstream drainage area.

Assumptions

Reservoirs

Jim Woodruff Dam, Muckafoonee Creek Dam, West Point, and Buford (Table 6) reservoirs were represented in the ACF basin 20 Watershed SWAT model. Pertinent reservoir information including surface area and storage at principal (normal) and emergency spillway levels for the reservoirs modeled were obtained from the National Inventory of Dams (NID) database (USACE 1982). The SWAT model provides four options to simulate reservoir outflow: 1) measured daily outflow, 2) measured monthly outflow, 3) average annual release rate for uncontrolled reservoir, and 4) controlled outflow with target release. Keeping the goals of the 20 Watershed climate change impact evaluation application, it was assumed that the best representation of the reservoirs was to simulate them without supplying time series of outflow records. Therefore, a target release approach was used in the GCRP-SWAT model. The average release rate was estimated using the outflow data available at the (USACE 2010). The number of days to reach target storage was assumed to be 90 days for all lakes except Lake Worth, which was assumed to be 10 days.

Irrigation

Croplands occupy about eight percent of the total watershed area. It was found that irrigation occurred on about 5.5 percent of the total watershed area with 4.18 percent being irrigated by groundwater and 1.35 percent being irrigated by surface water (Hook 2009). To simulate irrigation in the SWAT model, the auto-irrigation feature was used in the management set-up on those HRUs that represented cotton and peanut crops.

Hydrology Calibration

The SWAT model setup for the ACF basin was set up fresh, with no prior-existing SWAT model for the watershed. The model calibration period was set to calendar years 1993-2002.

Consistent with the HSPF modeling efforts, the specific site chosen for initial calibration was the Flint River at GA 26, near Montezuma, GA (USGS 02349605) (Table 5). Most of the calibration efforts were geared toward getting a closer match between simulated and observed flows at the outlet of the calibration focus area. Initially, the parameters set for this area were applied across the watershed and the model performance was verified at other stations. Model performance was not the same as it was for the calibration focus area, mostly due to the dominance of different land uses in different parts of the watershed. In response to the variations in spatial characteristics of the subwatersheds, a systematic adjustment of parameters individually, by land use type has been adopted and the same adjustment is applied throughout the watershed. Observed data at other gaging stations with the dominance of a different land use type was used to adjust the corresponding parameters. For example, at the gaging station that drains predominantly urban land, the area was used to set the parameters for the urban land areas.

It is acknowledged that a hydrologic/water quality model can be precisely calibrated, given the degree of freedom, resources, time, and data. Keeping in view the interests of this project, which are to study the land use change and climate change impacts on flow and water quality, a site specific calibration was deliberately not attempted. To some extent, the limitation of this approach is that the local differences in soil, weather, management, and hydrology is not thoroughly accounted for. This approach will provide an idea of the model performance when it is not spatially-tightly calibrated and what to expect when transferring the parameters to other ungaged watersheds or to watersheds where detailed modeling is not practical due to limited resources.

Land Use / Soil / Slope Definition

A 5/10/5 percent threshold was used for land use/soil/slope in the SWAT model while defining the HRUs. The cropland HRUs were split into cotton, peanuts, and corn in proportions of 48, 30, and 22 percent, respectively. Further these classes and the urban (including current and future urban class types) classes were exempt from applying the thresholds.

The calibration focus area represents 21 subwatersheds that, together, consist of 1,342 HRUs. The parameters were adjusted within the practical range to obtain a reasonable fit between the simulated and measured flows in terms of Nash-Sutcliffe modeling efficiency and the high flow and low flow components as well as the seasonal flows. The general land use characteristics of the watershed were represented well in the calibration focus area. Two other locations: one predominantly forested (Chattahoochee River near Cornelia, GA; USGS 02331600) and the other, predominantly urban (Peachtree Creek at Atlanta, GA; USGS 02336300), were chosen to set the parameters for forest and urban areas, respectively. These parameters were then applied across the entire watershed. There is essentially one set of parameters for a land use type for the entire watershed.

During calibration, parameters were carefully adjusted such that different components of streamflow contribution were adequately simulated. For instance, the observed and simulated baseflow and surface runoff contributions to streamflow, as well as seasonal flows, matched well. Reasonable estimations of actual ET and crop yields were also given consideration.

Calibration adjustments focused on the following parameters:

- Curve numbers (varied systematically by land use)
- ESCO (soil evaporation compensation factor)
- SURLAG (surface runoff lag coefficient)
- Groundwater “revap” rates
- Baseflow factor
- GW_DELAY (groundwater delay time)
- GWQMN (threshold depth of water in the shallow aquifer required for return flow to occur)
- RevapMN (threshold depth of water in the shallow aquifer required for “revap” or percolation to the deep aquifer to occur
- CANMAX (maximum canopy storage)
- Manning’s “n” value for overland flow, main channels, and tributary channels
- Sol_AWC (available water capacity of the soil layer, mm water/mm of soil)

Initial calibrations were performed for the Flint River at GA 26, near Montezuma, GA and are summarized in Figures 44 through 50 and Tables 23 and 24. As evidenced through the time series plots and the Nash-Sutcliffe modeling efficiency, the model performed well in simulating the timing and magnitude of streamflow for various seasons.

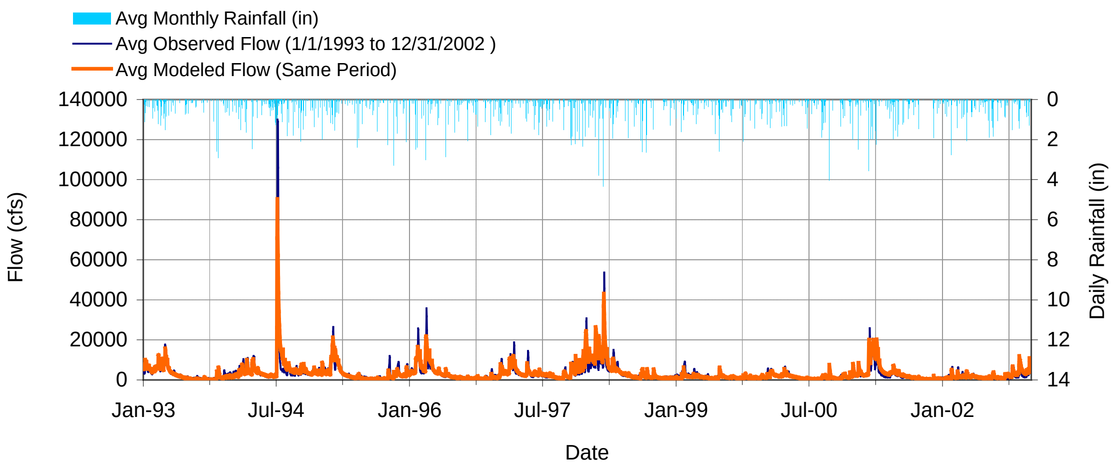


Figure 44. Mean daily flow at USGS 02349605 Flint River at Ga 26, near Montezuma, GA – calibration period (SWAT).

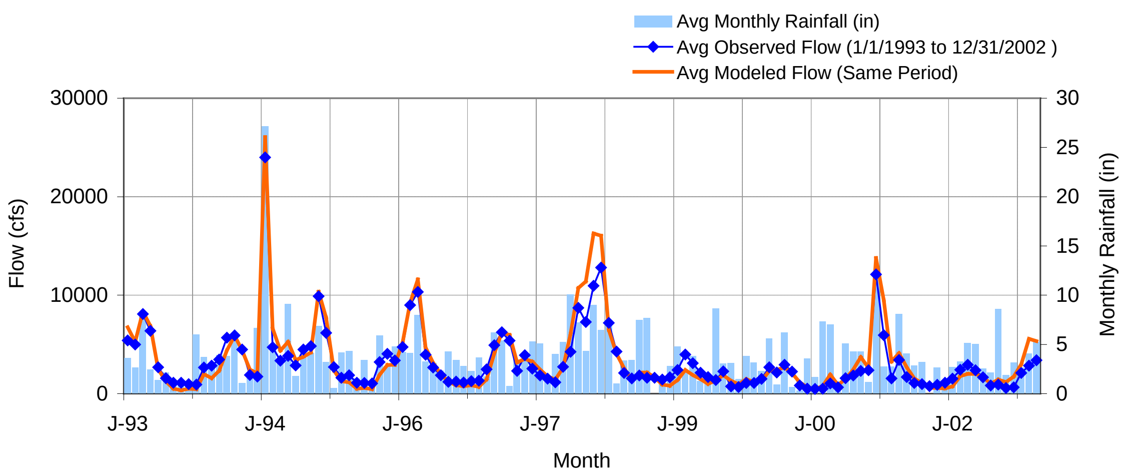


Figure 45. Mean monthly flow at USGS 02349605 Flint River at Ga 26, near Montezuma, GA – calibration period (SWAT).

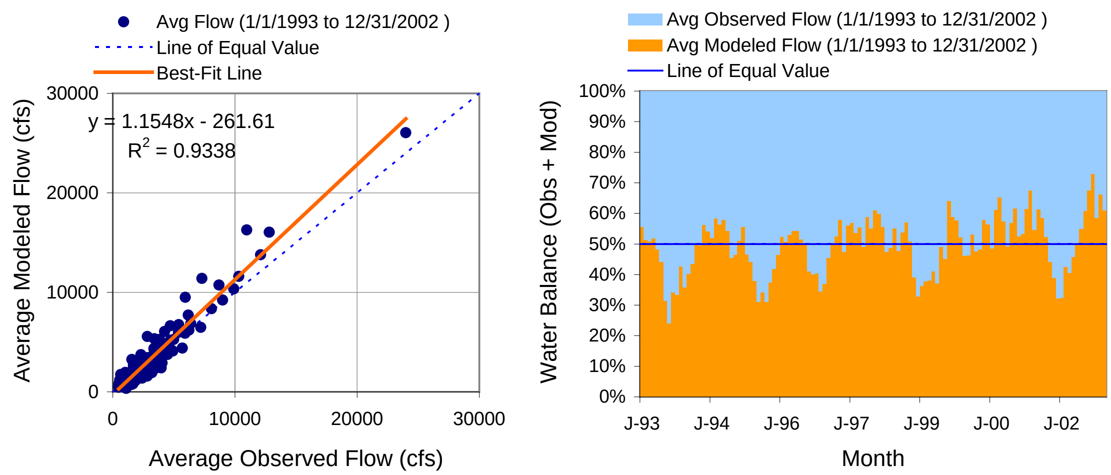


Figure 46. Monthly flow regression and temporal variation at USGS 02349605 Flint River at Ga 26, near Montezuma, GA – calibration period (SWAT).

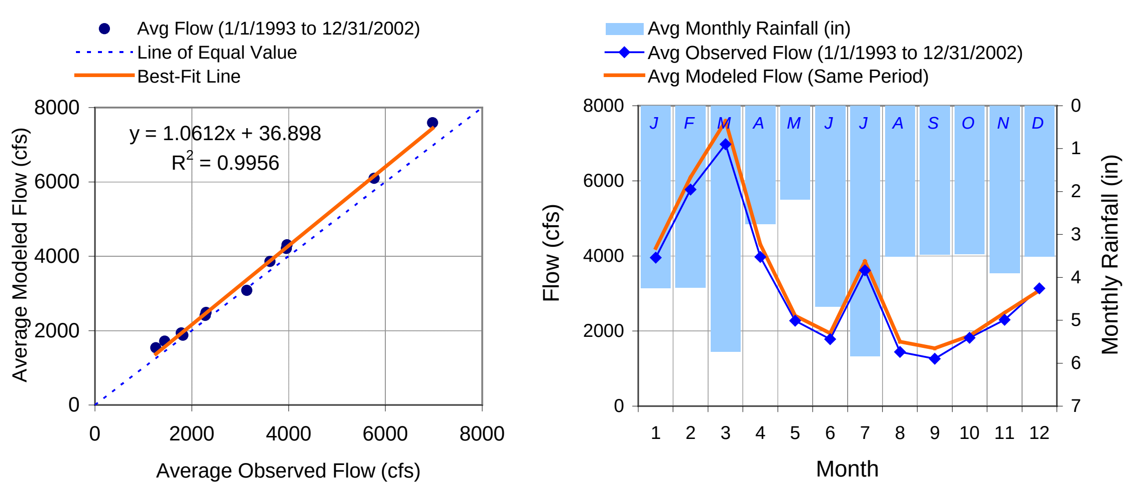


Figure 47. Seasonal regression and temporal aggregate at USGS 02349605 Flint River at Ga 26, near Montezuma, GA – calibration period (SWAT).

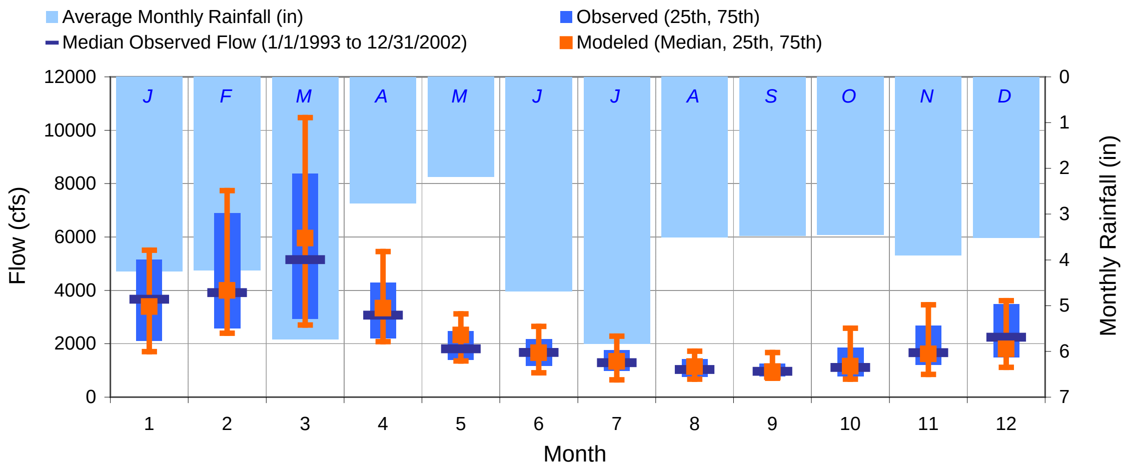


Figure 48. Seasonal medians and ranges at USGS 02349605 Flint River at Ga 26, near Montezuma, GA – calibration period (SWAT).

Table 23. Seasonal summary at USGS 02349605 Flint River at Ga 26, near Montezuma, GA – calibration period (SWAT)

MONTH	OBSERVED FLOW (CFS)				MODELED FLOW (CFS)			
	MEAN	MEDIAN	25TH	75TH	MEAN	MEDIAN	25TH	75TH
Jan	3955.13	3665.00	2110.00	5155.00	4206.77	3393.41	1700.42	5504.55
Feb	5767.27	3915.00	2572.50	6887.50	6093.10	3996.73	2395.72	7738.14
Mar	6976.42	5150.00	2932.50	8377.50	7590.84	5958.04	2700.58	10476.33
Apr	3970.93	3065.00	2210.00	4297.50	4303.82	3329.58	2078.74	5450.56
May	2277.06	1810.00	1400.00	2470.00	2405.19	2322.73	1358.75	3121.85
Jun	1783.49	1670.00	1180.00	2170.00	1937.85	1659.04	909.57	2654.73
Jul	3617.54	1290.00	977.25	1765.00	3856.12	1342.07	644.18	2287.50
Aug	1440.71	1035.00	752.00	1420.00	1715.12	1139.52	673.31	1722.66
Sep	1260.28	964.00	770.50	1252.50	1538.55	957.90	710.14	1670.33
Oct	1816.83	1105.00	775.75	1855.00	1874.05	1162.76	673.08	2586.26
Nov	2297.06	1660.00	1220.00	2685.00	2484.96	1619.56	854.25	3456.35
Dec	3137.85	2240.00	1490.00	3497.50	3082.68	1810.72	1116.26	3611.32

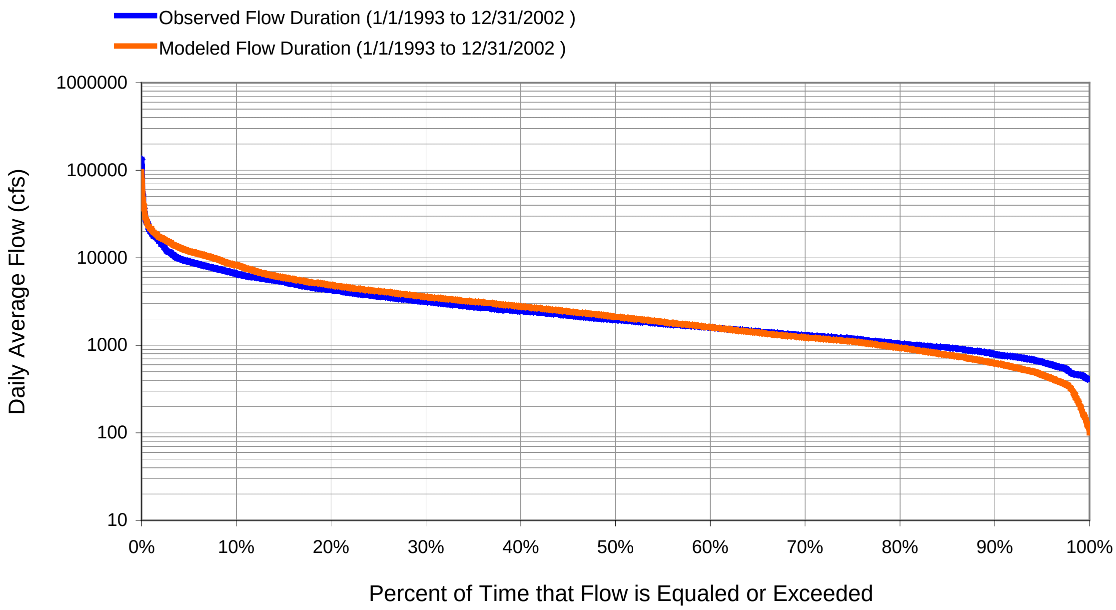


Figure 49. Flow exceedence at USGS 02349605 Flint River at Ga 26, near Montezuma, GA – calibration period (SWAT).

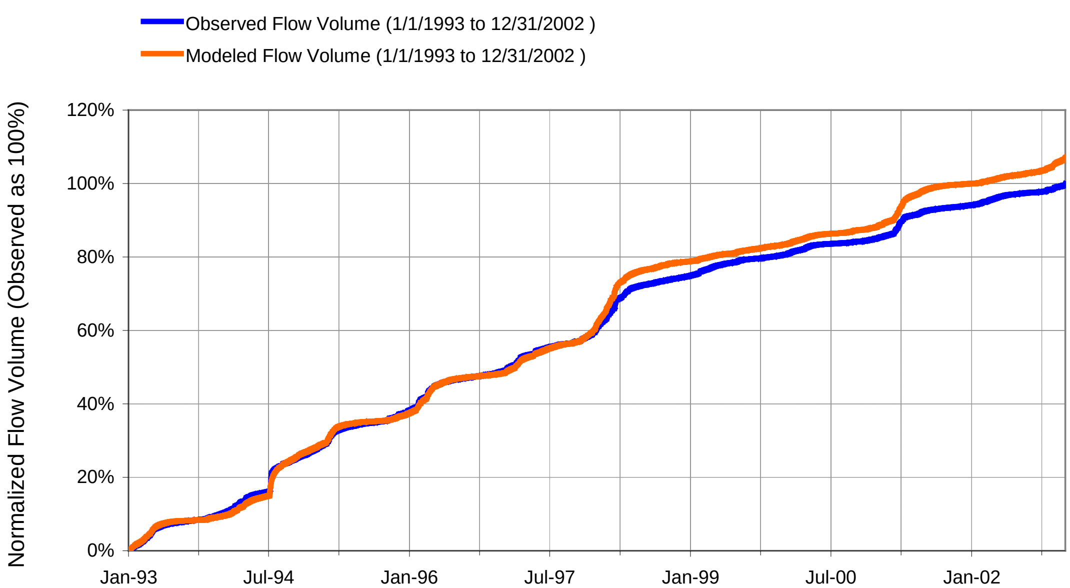


Figure 50. Flow accumulation at USGS 02349605 Flint River at Ga 26, near Montezuma, GA – calibration period (SWAT).

Table 24. Summary statistics at USGS 02349605 Flint River at Ga 26, near Montezuma, GA – calibration period (SWAT)

SWAT Simulated Flow		Observed Flow Gage	
REACH OUTFLOW FROM OUTLET 38 10-Year Analysis Period: 1/1/1993 - 12/31/2002 Flow volumes are (inches/year) for upstream drainage area		USGS 02349605 FLINT RIVER AT GA 26, NEAR MONTEZUMA, GA Hydrologic Unit Code: 3130006 Latitude: 32.29305556 Longitude: -84.0436111 Drainage Area (sq-mi): 2920	
Total Simulated In-stream Flow:	**15.88**	Total Observed In-stream Flow:	**14.80**
Total of simulated highest 10% flows:	**6.39**	Total of Observed highest 10% flows:	**5.74**
Total of Simulated lowest 50% flows:	**2.49**	Total of Observed Lowest 50% flows:	**2.75**
Simulated Summer Flow Volume (months 7-9):	**2.79**	Observed Summer Flow Volume (7-9):	**2.48**
Simulated Fall Flow Volume (months 10-12):	**2.91**	Observed Fall Flow Volume (10-12):	**2.83**
Simulated Winter Flow Volume (months 1-3):	**6.85**	Observed Winter Flow Volume (1-3):	**6.39**
Simulated Spring Flow Volume (months 4-6):	**3.33**	Observed Spring Flow Volume (4-6):	**3.10**
Total Simulated Storm Volume:	**4.22**	Total Observed Storm Volume:	**4.80**
Simulated Summer Storm Volume (7-9):	**0.90**	Observed Summer Storm Volume (7-9):	**1.02**

Errors (Simulated-Observed)	*Error Statistics*	*Recommended Criteria*
Error in total volume:	7.28	10
Error in 50% lowest flows:	-9.39	10
Error in 10% highest flows:	11.34	15
Seasonal volume error - Summer:	12.46	30
Seasonal volume error - Fall:	2.56	30
Seasonal volume error - Winter:	7.19	30
Seasonal volume error - Spring:	7.64	30
Error in storm volumes:	-12.03	20
Error in summer storm volumes:	-12.28	50
Nash-Sutcliffe Coefficient of Efficiency, E:	0.624	Model accuracy increases
Baseline adjusted coefficient (Garrick), E':	0.442	as E or E' approaches 1.0
Monthly NSE	0.876	

>> Clear

Hydrology Validation

Consistent with HSPF modeling efforts, validation for the Upper Flint calibration focus area was performed at the same location but for calendar years 1983-1992. Results are presented in Figures 51 through 57 and Tables 25 and 26. Although, the Nash-Sutcliffe modeling efficiency is not as good as it was for the calibration period, the model performance was adequate for the validation period. None of the metrics fall out of the range set for the 20 Watershed study.

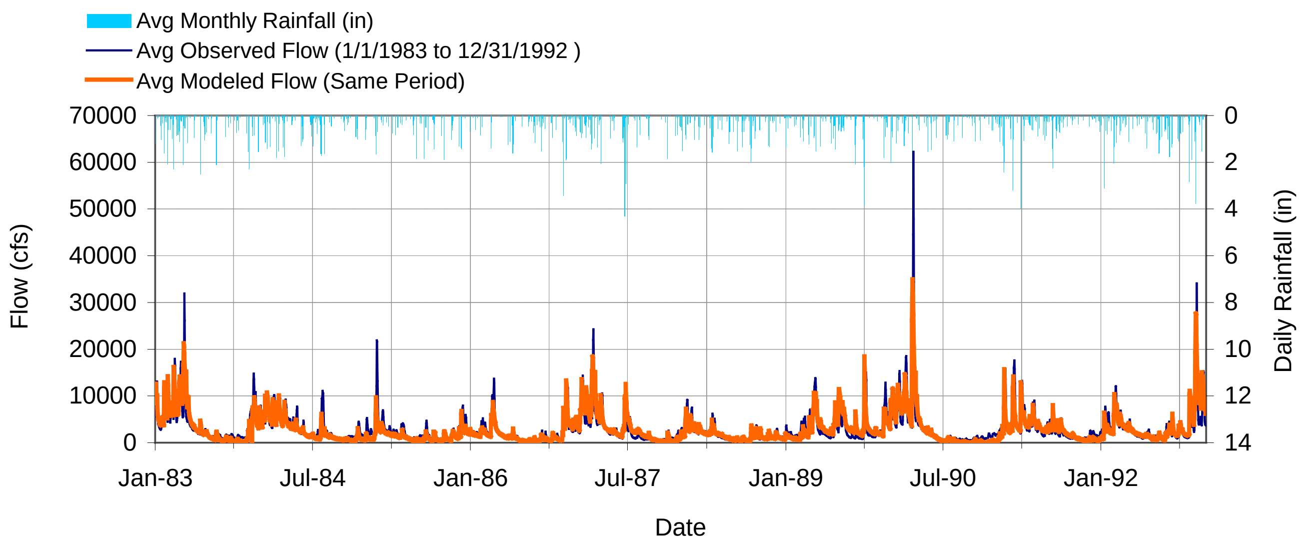


Figure 51. Mean daily flow at USGS 02349605 Flint River at Ga 26, near Montezuma, GA – validation period (SWAT).

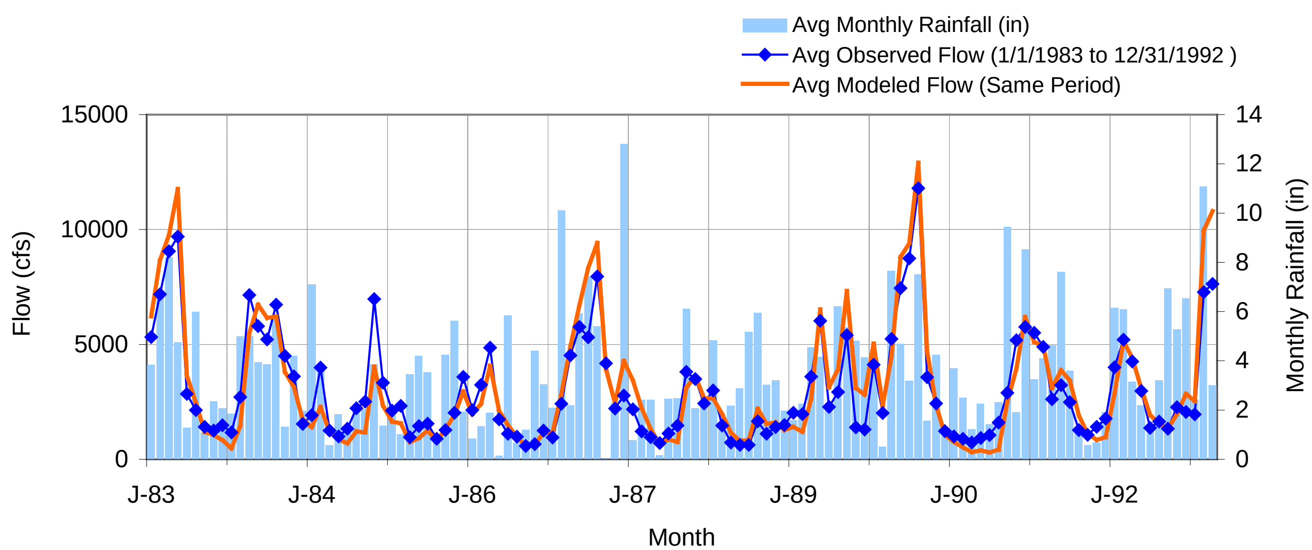


Figure 52. Mean monthly flow at USGS 02349605 Flint River at Ga 26, near Montezuma, GA – validation period (SWAT).

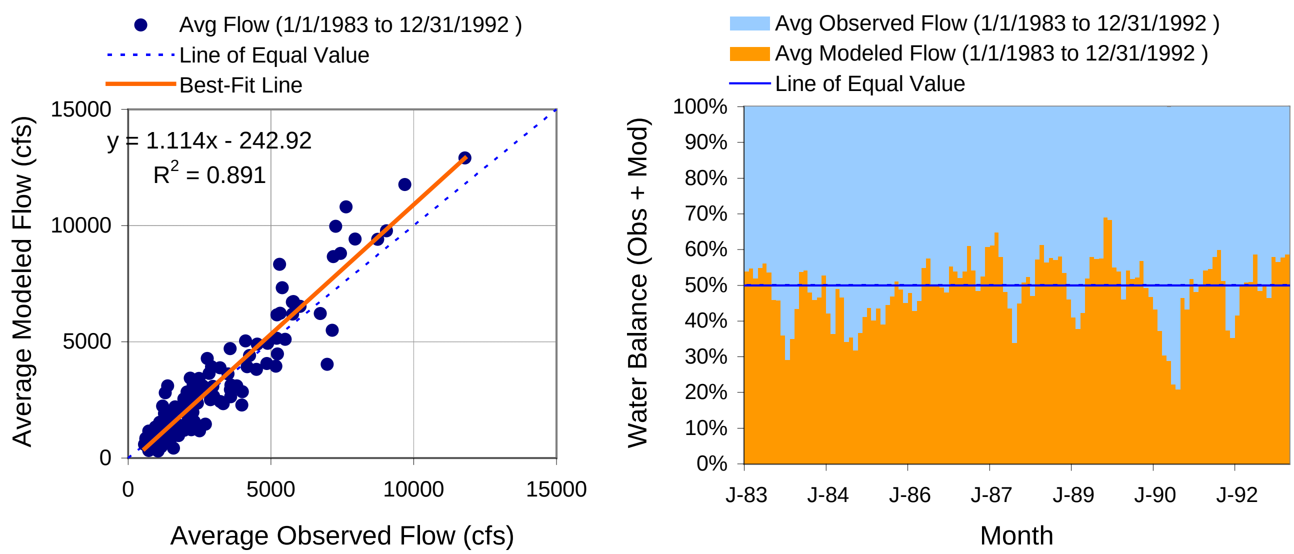


Figure 53. Monthly flow regression and temporal variation at USGS 02349605 Flint River at Ga 26, near Montezuma, GA – validation period (SWAT).

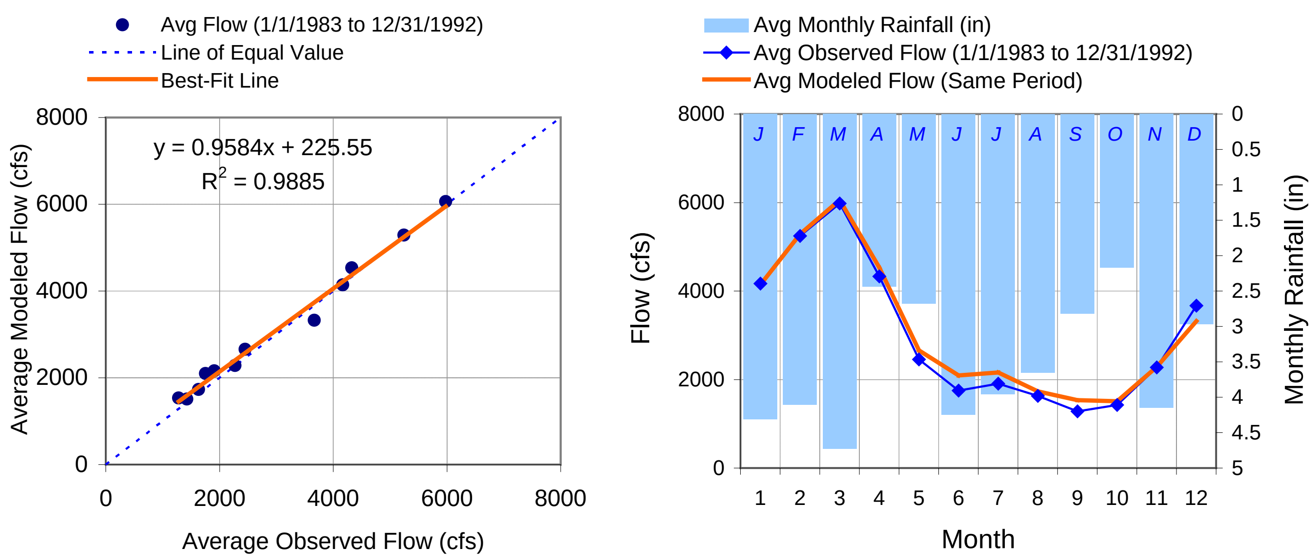


Figure 54. Seasonal regression and temporal aggregate at USGS 02349605 Flint River at Ga 26, near Montezuma, GA – validation period (SWAT).

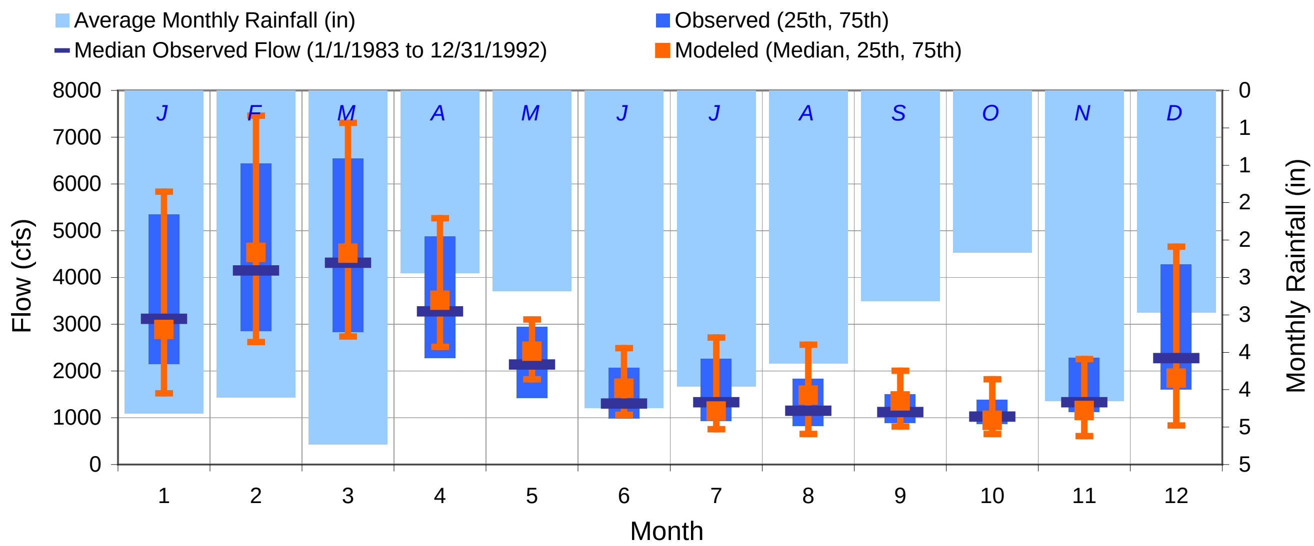


Figure 55. Seasonal medians and ranges at USGS 02349605 Flint River at Ga 26, near Montezuma, GA – validation period (SWAT).

Table 25. Seasonal summary at USGS 02349605 Flint River at Ga 26, near Montezuma, GA – validation period (SWAT)

MONTH	OBSERVED FLOW (CFS)				MODELED FLOW (CFS)			
	MEAN	MEDIAN	25TH	75TH	MEAN	MEDIAN	25TH	75TH
Jan	4168.00	3115.00	2152.50	5350.00	4143.78	2886.66	1525.30	5836.80
Feb	5242.97	4150.00	2850.00	6430.00	5285.84	4532.61	2618.46	7460.70
Mar	5976.65	4310.00	2830.00	6542.50	6060.01	4515.09	2739.77	7304.52
Apr	4328.17	3275.00	2277.50	4880.00	4531.12	3509.51	2517.97	5265.76
May	2451.47	2135.00	1420.00	2937.50	2658.75	2418.76	1824.58	3102.27
Jun	1753.24	1300.00	986.75	2072.50	2095.76	1629.70	1060.96	2490.67
Jul	1908.70	1330.00	927.50	2257.50	2160.97	1141.19	757.51	2715.43
Aug	1632.54	1150.00	816.50	1830.00	1732.26	1482.31	655.52	2563.83
Sep	1283.93	1120.00	881.75	1500.00	1534.60	1359.25	812.62	2005.97
Oct	1425.06	1020.00	869.50	1390.00	1509.13	945.55	654.00	1823.54
Nov	2275.14	1330.00	1120.00	2277.50	2284.09	1154.11	608.47	2252.94
Dec	3667.95	2275.00	1602.50	4277.50	3322.66	1848.91	833.94	4660.44

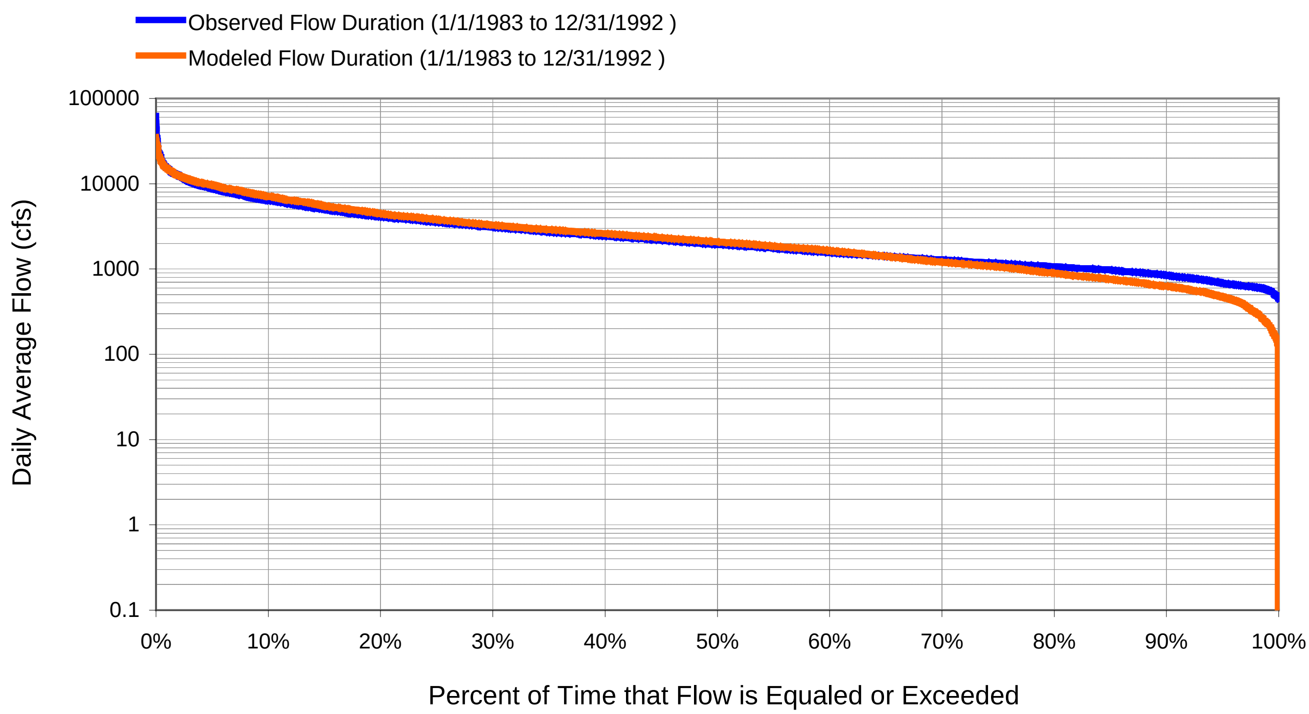


Figure 56. Flow exceedence at USGS 02349605 Flint River at Ga 26, near Montezuma, GA – validation period (SWAT).

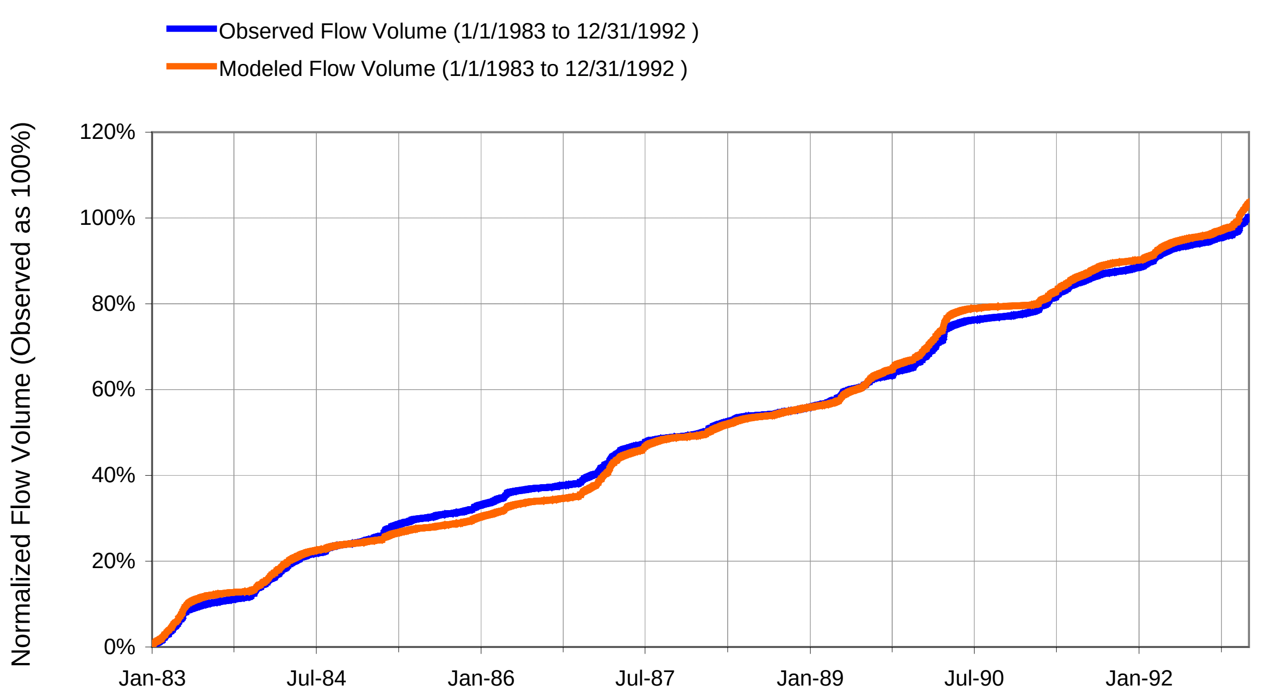


Figure 57. Flow accumulation at USGS 02349605 Flint River at Ga 26, near Montezuma, GA – validation period (SWAT)

Table 26. Summary statistics at USGS 02349605 Flint River at Ga 26, near Montezuma, GA – validation period (SWAT)

SWAT Simulated Flow		Observed Flow Gage			
REACH OUTFLOW FROM OUTLET 37 10-Year Analysis Period: 1/1/1983 - 12/31/1992 Flow volumes are (inches/year) for upstream drainage area		USGS 02349605 FLINT RIVER AT GA 26, NEAR MONTEZUMA, GA Hydrologic Unit Code: 3130006 Latitude: 32.29305556 Longitude: -84.0436111 Drainage Area (sq-mi): 2920			
Total Simulated In-stream Flow:	**14.42**	Total Observed In-stream Flow:			**13.95**
Total of simulated highest 10% flows:	**5.01**	Total of Observed highest 10% flows:			**4.87**
Total of Simulated lowest 50% flows:	**2.57**	Total of Observed Lowest 50% flows:			**2.78**
Simulated Summer Flow Volume (months 7-9):	**2.12**	Observed Summer Flow Volume (7-9):			**1.89**
Simulated Fall Flow Volume (months 10-12):	**2.78**	Observed Fall Flow Volume (10-12):			**2.88**
Simulated Winter Flow Volume (months 1-3):	**5.93**	Observed Winter Flow Volume (1-3):			**5.89**
Simulated Spring Flow Volume (months 4-6):	**3.58**	Observed Spring Flow Volume (4-6):			**3.29**
Total Simulated Storm Volume:	**3.67**	Total Observed Storm Volume:			**4.42**
Simulated Summer Storm Volume (7-9):	**0.46**	Observed Summer Storm Volume (7-9):			**0.51**
Errors (Simulated-Observed)	*Error Statistics*	*Recommended Criteria*			
Error in total volume:	3.33	10			
Error in 50% lowest flows:	-7.57	10			
Error in 10% highest flows:	2.89	15			
Seasonal volume error - Summer:	12.43	30			
Seasonal volume error - Fall:	-3.46	>> 30		Clear	
Seasonal volume error - Winter:	0.66	30			
Seasonal volume error - Spring:	8.82	30			
Error in storm volumes:	-16.93	20			
Error in summer storm volumes:	-10.04	50			
Nash-Sutcliffe Coefficient of Efficiency, E:	0.559	Model accuracy increases			
Baseline adjusted coefficient (Garrick), E':	0.444	as E or E' approaches 1.0			
Monthly NSE	0.833				

Hydrology Results for Larger Watershed

Calibration and validation results at all gages are summarized in Tables 29 and 30. As discussed above, a detailed spatial calibration was not conducted for the GCRP-SWAT model of the ACF basin. The parameterization is identical across the entire watershed, although, measured flow and water quality data at other stations (other than the calibration focus area) where land use dominance occurred were used to set the corresponding parameters. A better model fit could perhaps be achieved if the model was more tightly calibrated but this was not attempted deliberately keeping in view the intended bigger scope of the project.

In general, the model performance was good, as noticed from the Nash-Sutcliffe modeling efficiency statistics, except for forest and urban dominated subwatersheds. The model over-predicted flow in winter months and under-predicted flow in spring months. Also, the Ichawaynochaway Creek subwatershed (station 02353500) simulation statistics are relatively lower than those at the other stations. The model over-predicted high flows and under-predicted low flows. The simulated peak flows correlated well with the observed high rainfall events; however, watershed response, as noticed from the measured streamflows, didn't result in such high flows.

All the reservoir parameters were set such that inflow equals outflow and this approach worked well for all reservoirs except Lake Lanier. Similar to the HSPF results, after the confluence of Chattahoochee and Flint rivers and downstream of Lake Seminole, the simulation and the model fit greatly improved as shown in Figures 58 through 64 and Tables 27 and 28.

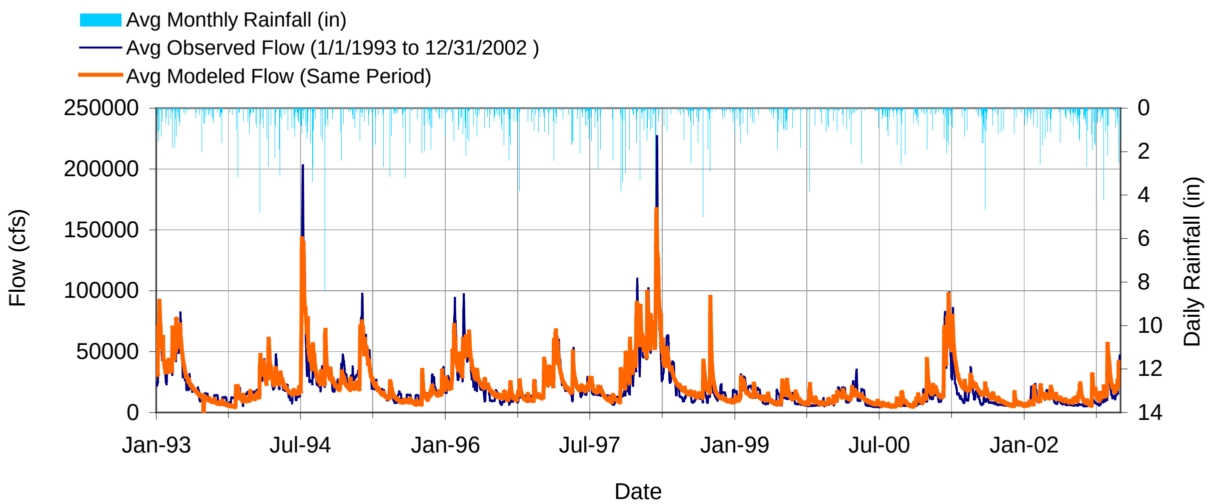


Figure 58. Mean daily flow at USGS 02358000 Apalachicola River at Chattahoochee, FL– calibration period (SWAT)

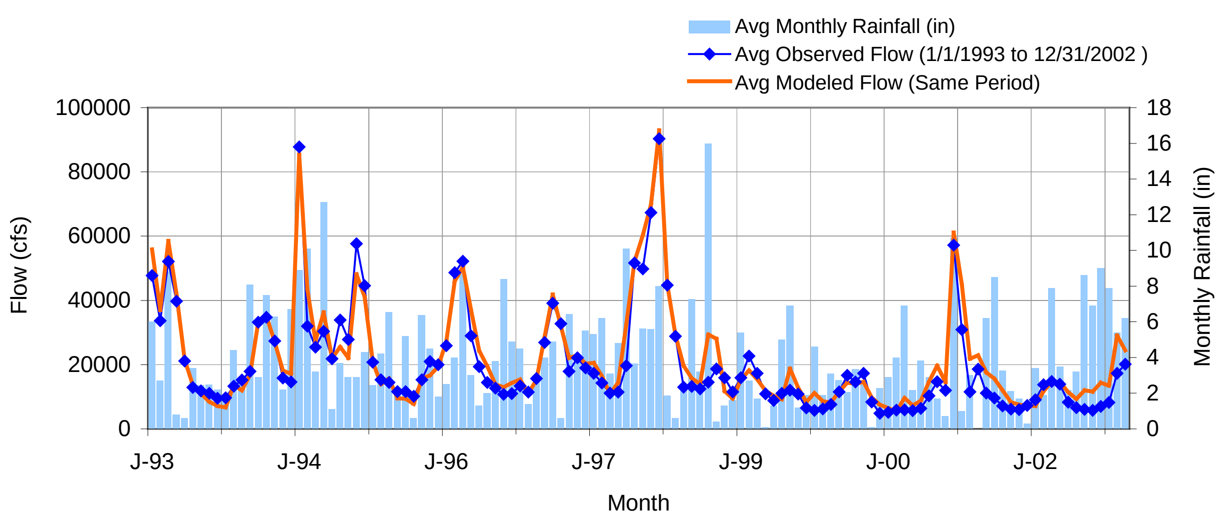


Figure 59. Mean monthly flow at USGS 02358000 Apalachicola River at Chattahoochee, FL– calibration period (SWAT)

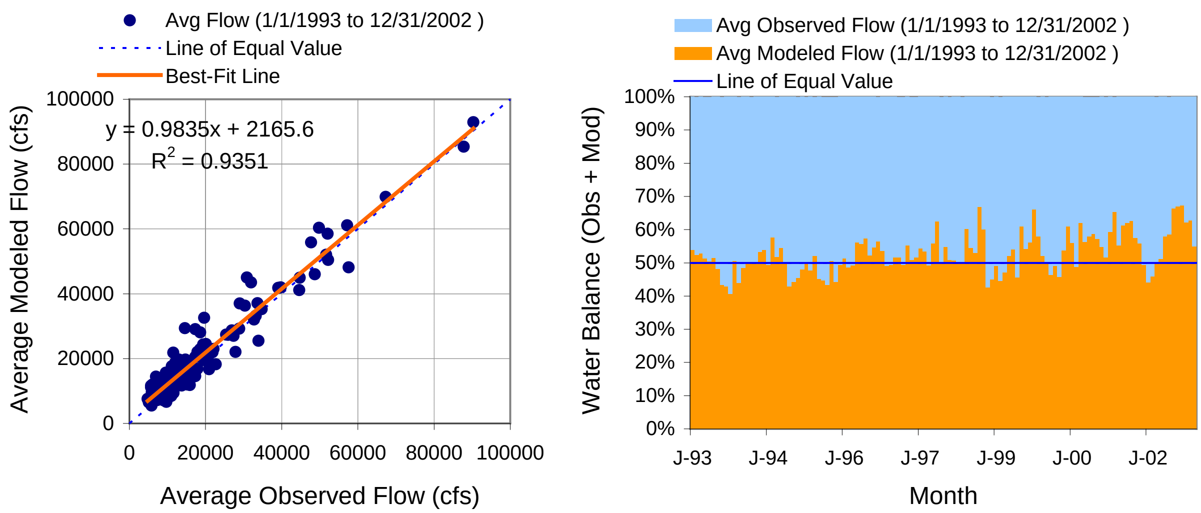


Figure 60. Monthly flow regression and temporal variation at USGS 02358000 Apalachicola River at Chattahoochee, FL– calibration period (SWAT)

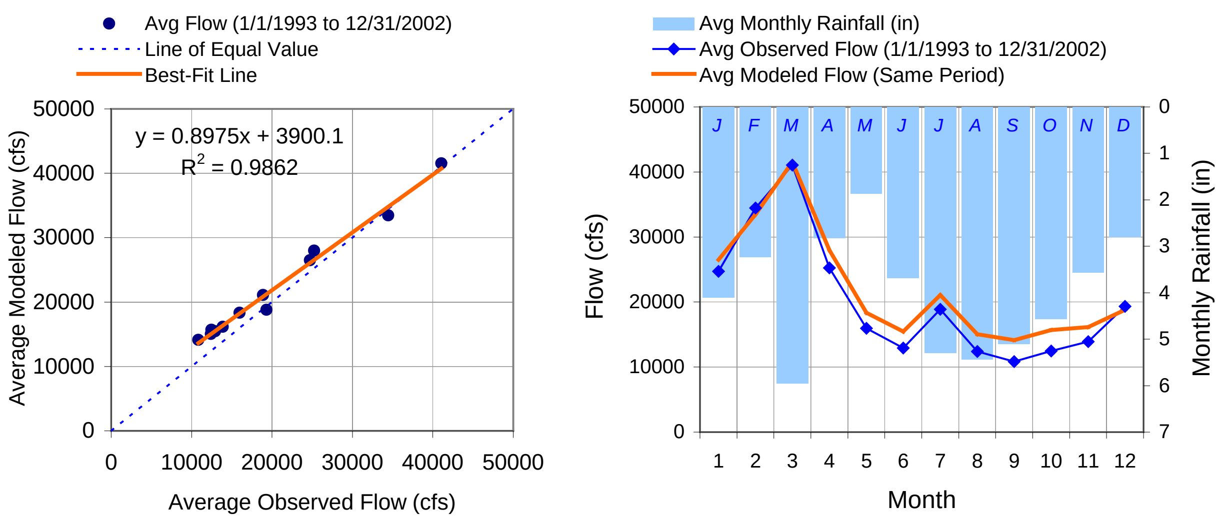


Figure 61. Seasonal regression and temporal aggregate at USGS 02358000 Apalachicola River at Chattahoochee, FL– calibration period (SWAT)

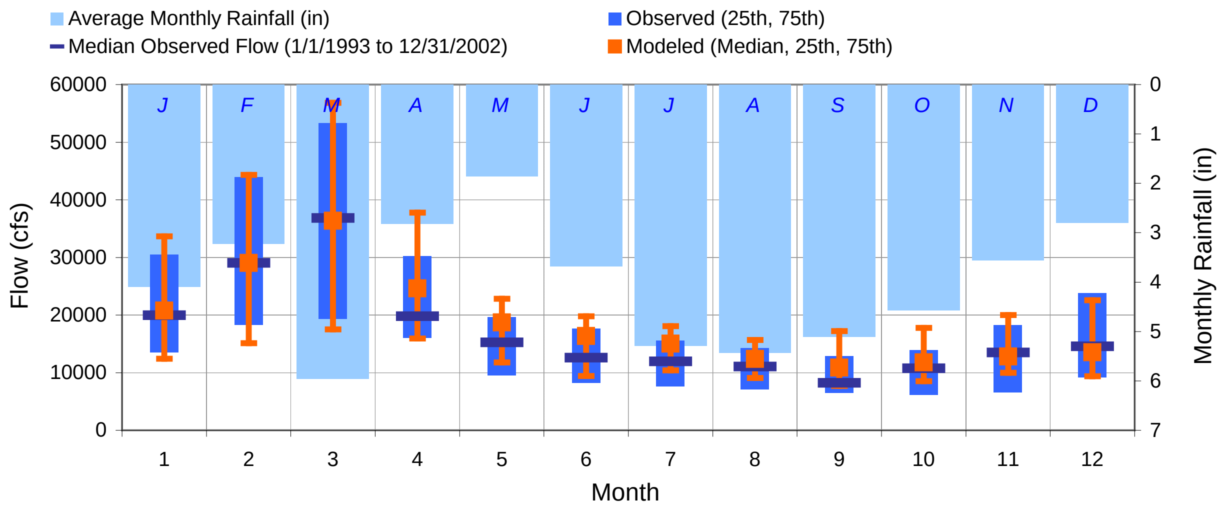


Figure 62. Seasonal medians and ranges at USGS 02358000 Apalachicola River at Chattahoochee, FL– calibration period (SWAT)

Table 27. Seasonal summary at USGS 02358000 Apalachicola River at Chattahoochee, FL– calibration period (SWAT)

MONTH	OBSERVED FLOW (CFS)				MODELED FLOW (CFS)			
	MEAN	MEDIAN	25TH	75TH	MEAN	MEDIAN	25TH	75TH
Jan	24730.16	19950.00	13500.00	30475.00	26487.83	20770.32	12429.88	33656.64
Feb	34453.44	29050.00	18275.00	43900.00	33462.26	29041.02	15105.85	44319.91
Mar	41056.97	36850.00	19300.00	53300.00	41547.96	36338.79	17536.38	56838.96
Apr	25249.20	19800.00	16000.00	30250.00	27986.54	24610.79	15952.52	37760.21
May	15972.58	15250.00	9570.00	19675.00	18337.31	18704.41	11760.67	22816.81
Jun	12939.23	12600.00	8237.50	17600.00	15481.95	16359.52	9413.12	19775.33
Jul	18873.90	11950.00	7665.00	15575.00	21090.83	15028.16	10404.58	18080.23
Aug	12411.87	11050.00	7102.50	14300.00	15037.00	12370.73	9075.87	15658.52
Sep	10850.80	8235.00	6530.00	12900.00	14122.01	10885.75	7701.25	17196.48
Oct	12458.10	10750.00	6112.50	13900.00	15677.74	11788.04	8509.07	17775.64
Nov	13896.10	13500.00	6557.50	18250.00	16163.41	12783.91	9989.64	20016.35
Dec	19332.77	14550.00	9150.00	23800.00	18812.57	13546.71	9380.46	22589.03

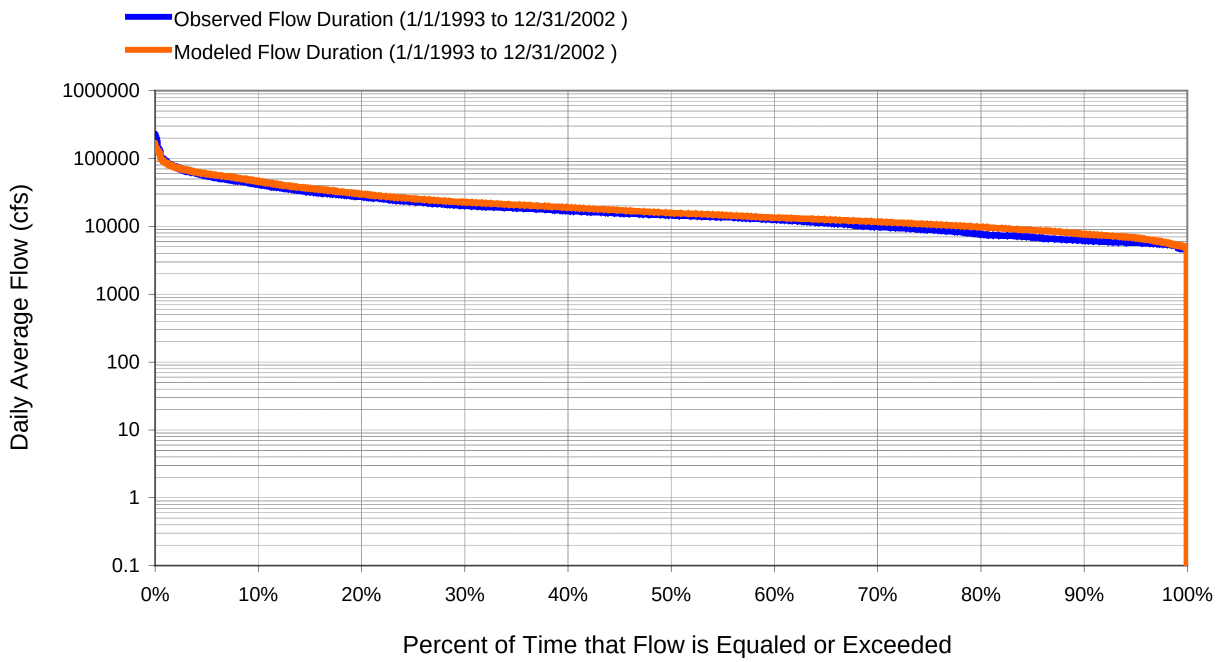


Figure 63. Flow exceedence at USGS 02358000 Apalachicola River at Chattahoochee, FL– calibration period (SWAT)

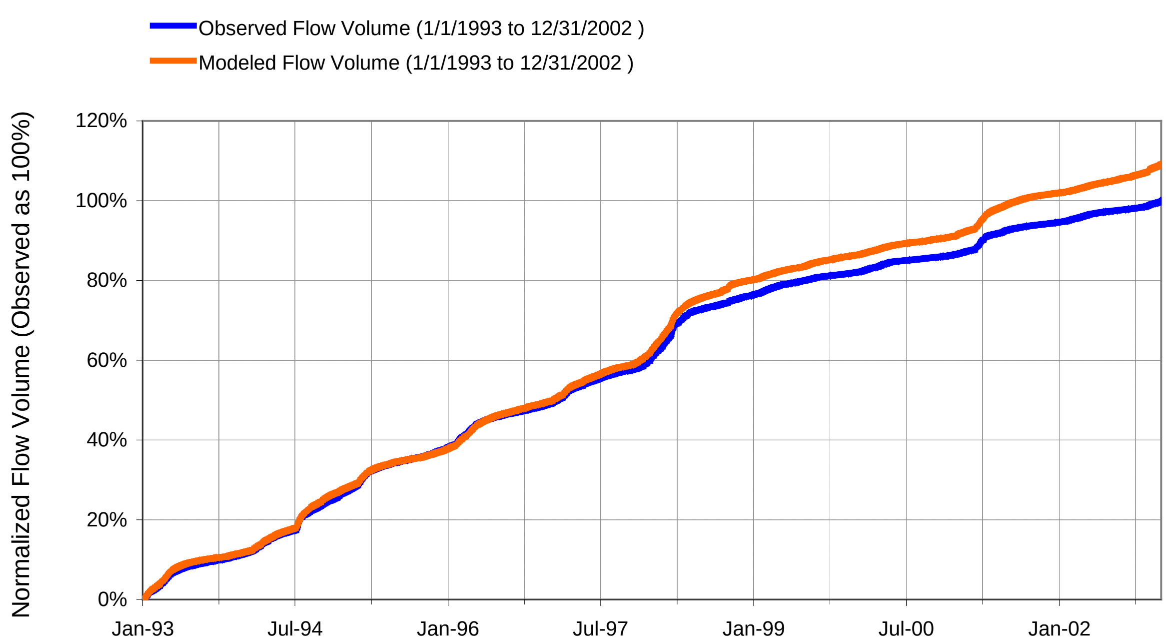


Figure 64. Flow accumulation at USGS 02358000 Apalachicola River at Chattahoochee, FL– calibration period (SWAT)

Table 28. Summary statistics at USGS 02358000 Apalachicola River at Chattahoochee, FL–calibration period (SWAT)

SWAT Simulated Flow		Observed Flow Gage			
REACH OUTFLOW FROM OUTLET 13 10-Year Analysis Period: 1/1/1993 - 12/31/2002 Flow volumes are (inches/year) for upstream drainage area		USGS 02358000 APALACHICOLA RIVER AT CHATTAHOOCHEE FLA Hydrologic Unit Code: 3130011 Latitude: 30.7010251 Longitude: -84.8590871 Drainage Area (sq-mi): 17200			
Total Simulated In-stream Flow:	**17.35**	Total Observed In-stream Flow:			**15.89**
Total of simulated highest 10% flows:	**5.19**	Total of Observed highest 10% flows:			**5.11**
Total of Simulated lowest 50% flows:	**4.21**	Total of Observed Lowest 50% flows:			**3.65**
Simulated Summer Flow Volume (months 7-9):	**3.34**	Observed Summer Flow Volume (7-9):			**2.80**
Simulated Fall Flow Volume (months 10-12):	**3.36**	Observed Fall Flow Volume (10-12):			**3.03**
Simulated Winter Flow Volume (months 1-3):	**6.60**	Observed Winter Flow Volume (1-3):			**6.51**
Simulated Spring Flow Volume (months 4-6):	**4.05**	Observed Spring Flow Volume (4-6):			**3.55**
Total Simulated Storm Volume:	**3.13**	Total Observed Storm Volume:			**3.71**
Simulated Summer Storm Volume (7-9):	**0.62**	Observed Summer Storm Volume (7-9):			**0.64**
Errors (Simulated-Observed)	*Error Statistics*	*Recommended Criteria*			
Error in total volume:	9.16	10			
Error in 50% lowest flows:	**15.49**	**10**			
Error in 10% highest flows:	1.57	15			
Seasonal volume error - Summer:	19.16	30			
Seasonal volume error - Fall:	10.82	>> 30		Clear	
Seasonal volume error - Winter:	1.39	30			
Seasonal volume error - Spring:	14.12	30			
Error in storm volumes:	-15.66	20			
Error in summer storm volumes:	-3.56	50			
Nash-Sutcliffe Coefficient of Efficiency, E:	0.793	Model accuracy increases			
Baseline adjusted coefficient (Garrick), E':	0.543	as E or E' approaches 1.0			
Monthly NSE	0.919				

Table 29. Summary statistics (percent error) for all stations – calibration period 1993-2002 (SWAT)

Station	02349605	02331600	02336300	02336000	02353500	02339500	02343801	02353000	02358000
Error in total volume:	7.28	1.74	-10.17	17.52	5.89	6.26	16.53	10.45	9.16
Error in 50% lowest flows:	-9.39	-44.46	-22.69	34.07	-20.35	33.88	62.17	-2.48	15.49
Error in 10% highest flows:	11.34	28.59	-27.08	-10.28	37.75	-7.29	-10.00	16.02	1.57
Seasonal volume error - Summer:	12.46	9.11	26.93	-4.30	0.78	-8.34	28.70	17.53	19.16
Seasonal volume error - Fall:	2.56	22.61	-15.44	25.99	-2.69	0.51	19.75	1.02	10.82
Seasonal volume error - Winter:	7.19	16.05	10.95	13.79	25.04	5.34	-2.93	9.50	1.39
Seasonal volume error - Spring:	7.64	-27.05	-24.11	37.03	-21.27	25.48	41.14	15.31	14.12
Error in storm volumes:	-12.03	71.60	-38.66	-69.57	25.40	-75.17	-52.52	-48.51	-15.66
Error in summer storm volumes:	-12.28	107.67	-49.29	-77.02	-10.26	-82.70	-58.88	-42.31	-3.56
Daily Nash-Sutcliffe Coefficient of Efficiency, E:	0.624	0.358	0.334	0.489	0.335	0.542	0.642	0.697	0.793
Monthly Nash-Sutcliffe Coefficient of Efficiency, E:	0.876	0.560	0.336	0.631	0.532	0.837	0.837	0.830	0.919

Table 30. Summary statistics (percent error) for all stations – validation period 1983-1992 (SWAT)

Station	02349605	02331600	02336300	02336000	02353500	02339500	02343801	02353000	02358000
Error in total volume:	3.33	-4.33	-12.32	5.62	1.03	0.92	11.47	6.48	2.17
Error in 50% lowest flows:	-7.57	-49.69	-23.46	18.44	-38.73	36.21	50.10	-7.51	-7.83
Error in 10% highest flows:	2.89	26.93	-29.96	-16.50	35.73	-12.47	-10.38	5.33	-2.31
Seasonal volume error - Summer:	12.43	-13.83	-18.32	-15.29	14.60	-11.16	25.32	21.21	9.39
Seasonal volume error - Fall:	-3.46	9.43	-12.56	-3.92	-15.20	-15.65	1.66	-0.29	-3.96
Seasonal volume error - Winter:	0.66	11.99	-3.15	23.35	9.61	12.01	1.04	3.04	1.04
Seasonal volume error - Spring:	8.82	-27.97	-18.51	18.15	-11.43	15.39	27.43	8.68	3.84
Error in storm volumes:	-16.93	56.71	-40.06	-73.11	26.32	-77.02	-65.86	-52.34	-8.64
Error in summer storm volumes:	-10.04	66.81	-43.98	-81.91	14.15	-83.37	-76.19	-52.71	-6.41
Daily Nash-Sutcliffe Coefficient of Efficiency, E:	0.559	0.347	0.420	0.369	0.222	0.481	0.599	0.685	0.770
Monthly Nash-Sutcliffe Coefficient of Efficiency, E:	0.833	0.578	0.587	0.484	0.543	0.758	0.829	0.785	0.901

Water Quality Calibration and Validation

Initial calibration and validation of water quality was done on the Flint River near Montezuma (USGS02349605), using calendar years 1999-2002 for calibration and calendar years 1991-1998 for validation. As with hydrology, calibration was performed on the later period as this better reflects the land use included in the model. The start of the validation period is constrained by data availability.

Calibration adjustments for sediment focused on the following parameters:

- PRF (Peak rate adjustment factor for sediment routing in the main channel)
- SPCON and SPEXP (Linear and Exponent parameters for estimating maximum amount of sediment that can be reentrained during channel sediment routing)
- RSDCO (Residue decomposition coefficient)
- USLE-P (USLE equation support practice factor

Simulated and estimated sediment loads at the Montezuma station for both periods are shown in Figures 65 through 68 and statistics for the two periods are provided separately in Tables 31 and 32. The key statistic in Table 31 is the relative percent error, which shows the error in the prediction of monthly load normalized to the estimated load. Table 31 also shows the relative average absolute error, which is the average of the relative magnitude of errors in individual monthly load predictions. This number is inflated by outlier months in which the simulated and estimated loads differ by large amounts (that may be as easily due to uncertainty in the estimated load due to limited data as to problems with the model) and the third statistic, the relative median absolute error, is likely more relevant and shows good agreement.

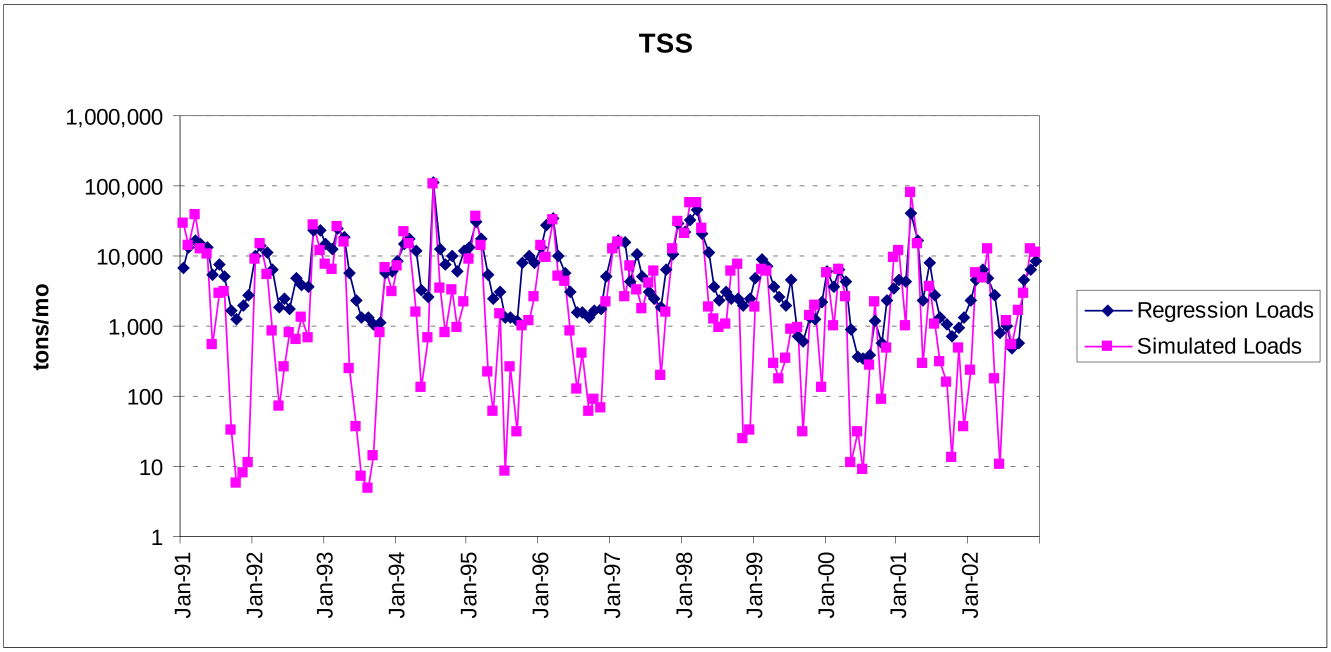


Figure 65. Fit for monthly load of TSS at USGS 02349605 Flint River at Ga 26, near Montezuma, GA – calibration period (SWAT).

Table 31. Model fit statistics (observed minus predicted) for monthly TSS loads using stratified regression at USGS 02349605 Flint River at Ga 26, near Montezuma, GA (SWAT)

Statistic	Calibration period (1999-2002)	Validation period (1991-1998)
Relative Percent Error	-9%	17%
Relative Average Absolute Error	66%	42%
Relative Median Absolute Error	39.1%	25.8%

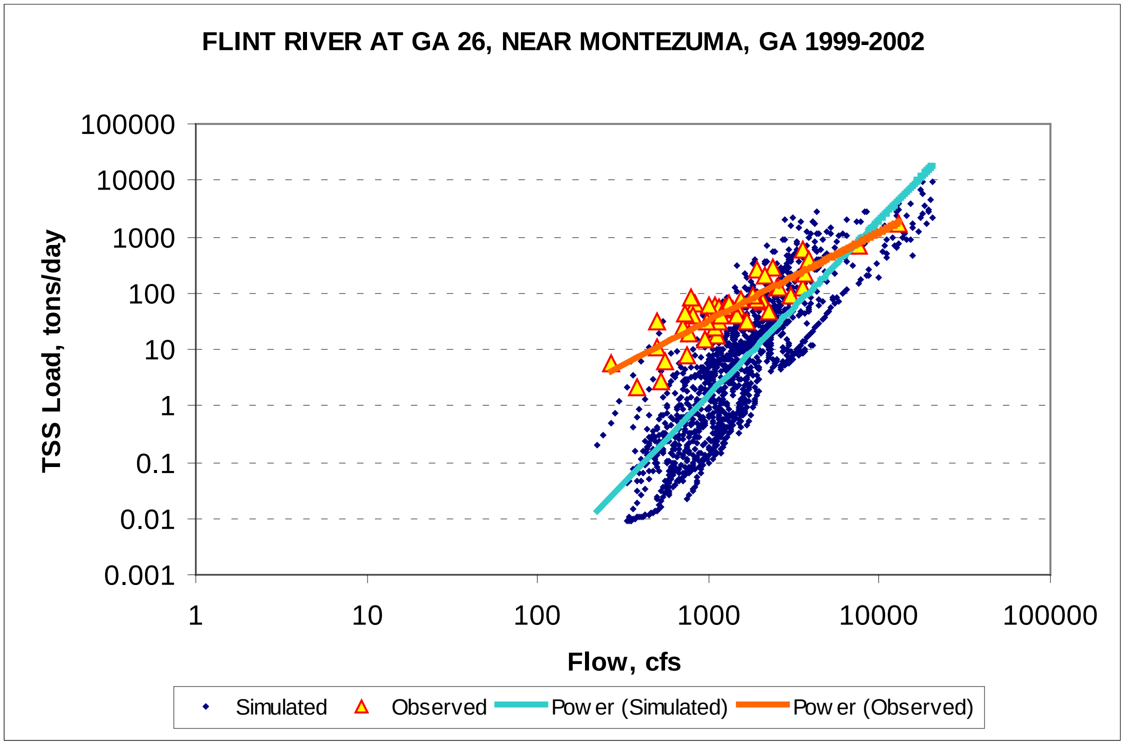


Figure 66. Power plot for observed and simulated TSS at USGS 02349605 Flint River at Ga 26, near Montezuma, GA – calibration period (SWAT).

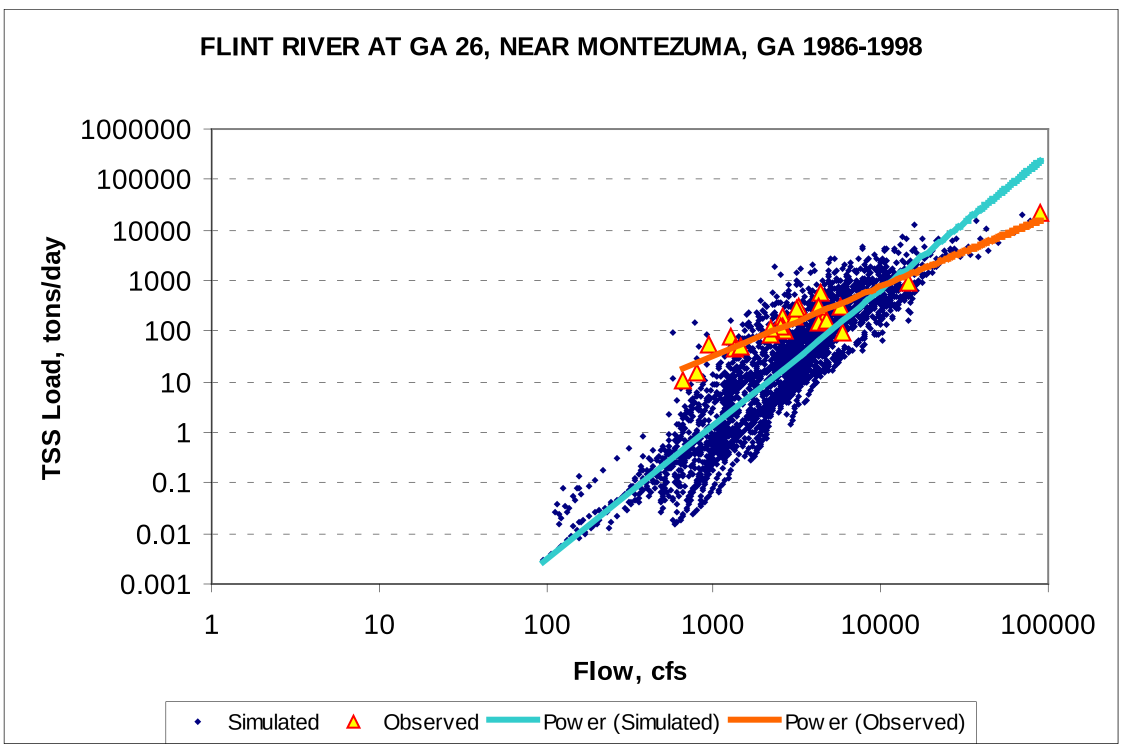


Figure 67. Power plot for observed and simulated TSS at USGS 02349605 Flint River at Ga 26, near Montezuma, GA – validation period (SWAT).

A low baseflow recession factor used in the calibrated model setup allowed streamflow to reach very low values, which in turn simulated numerous days with extremely low sediment values as seen in Figure 68.

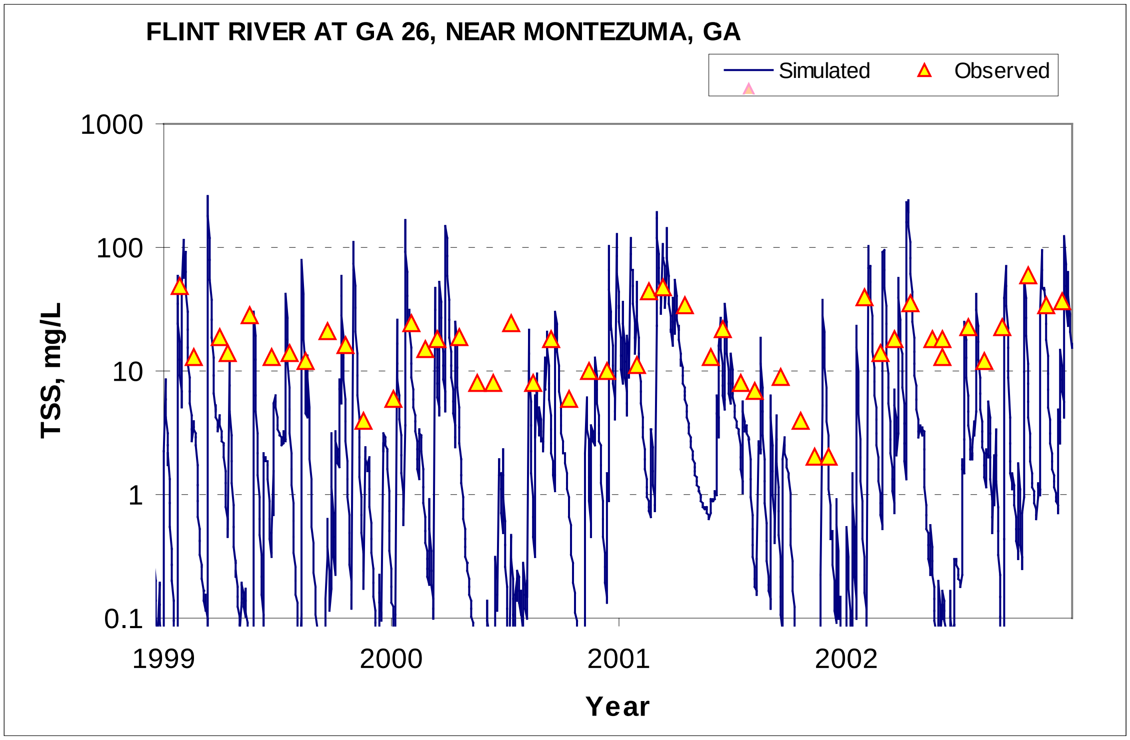


Figure 68. Time series plot of TSS concentration at USGS 02349605 Flint River at Ga 26, near Montezuma, GA (SWAT).

Table 32. Relative errors (observed minus predicted), TSS concentration at USGS 02349605 Flint River at Ga 26, near Montezuma, GA (SWAT)

Statistic	Calibration period (1999-2002)	Validation period (1991-1998)
Count	49	24
Concentration Average Error	63.01%	60.61%
Concentration Median Error	64.14%	52.79%

Calibration adjustments for total phosphorus and total nitrogen focused on the following parameters:

- PPERCO (phosphorus percolation coefficient)
- NPERCO (nitrogen percolation coefficient)
- PHOSKD (phosphorus soil partitioning coefficient)
- HLIFE_NGW (half life of nitrate in the shallow aquifer)
- SOL_CBN1 (organic carbon in the first soil layer)
- QUAL2E parameters such as algal, organic nitrogen, and organic phosphorus settling rate in the reach, benthic source arte for dissolved phosphorus and NH4-N in the reach, fraction of algal biomass that is nitrogen and phosphorus, Michaelis-Menton half-saturation constant for nitrogen and phosphorus

In general, the match between observed and measured total phosphorus and total nitrogen was acceptable. Total phosphorus and total nitrogen calibration results are presented in Figures 69 through 76 and Tables 33 through 36.

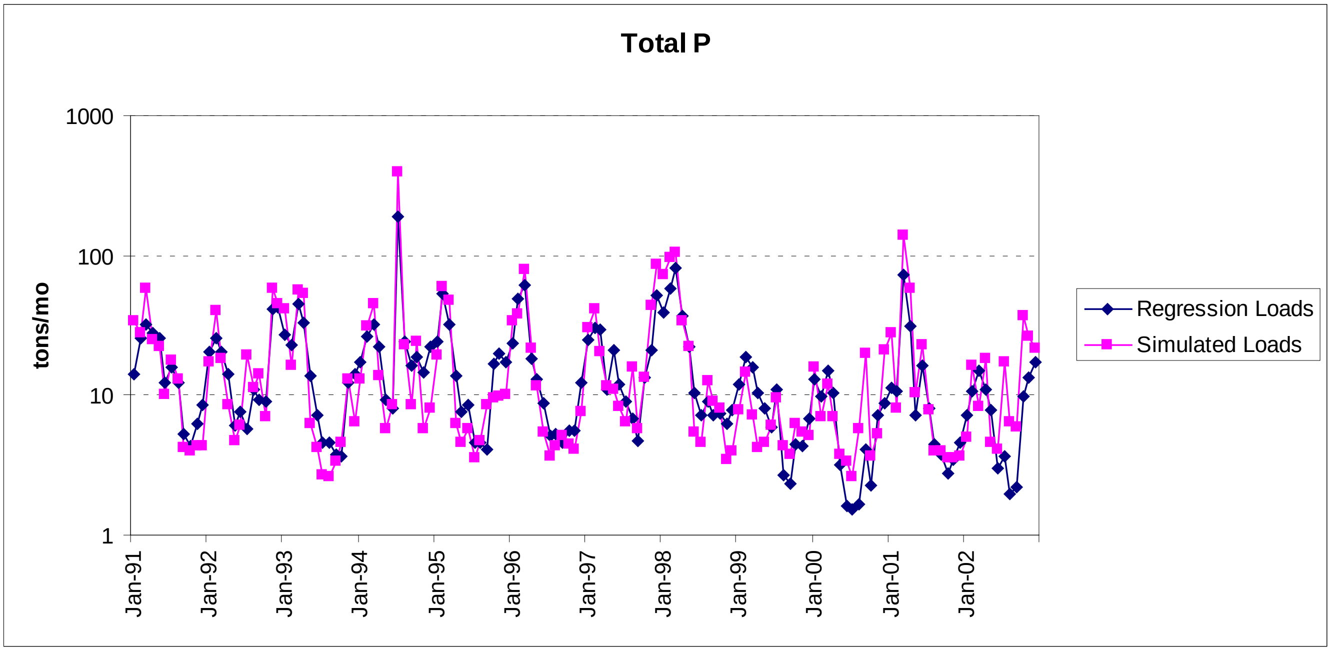


Figure 69. Fit for monthly load of total phosphorus at USGS 02349605 Flint River at Ga 26, near Montezuma, GA (SWAT).

Table 33. Model fit statistics (observed minus predicted) for monthly total phosphorus loads using stratified regression at USGS 02349605 Flint River at Ga 26, near Montezuma, GA (SWAT)

Statistic	Calibration period (1999-2002)	Validation period (1991-1998)
Relative Percent Error	-50%	-30%
Average Absolute Error	72%	49%
Median Absolute Error	31.8%	18.9%

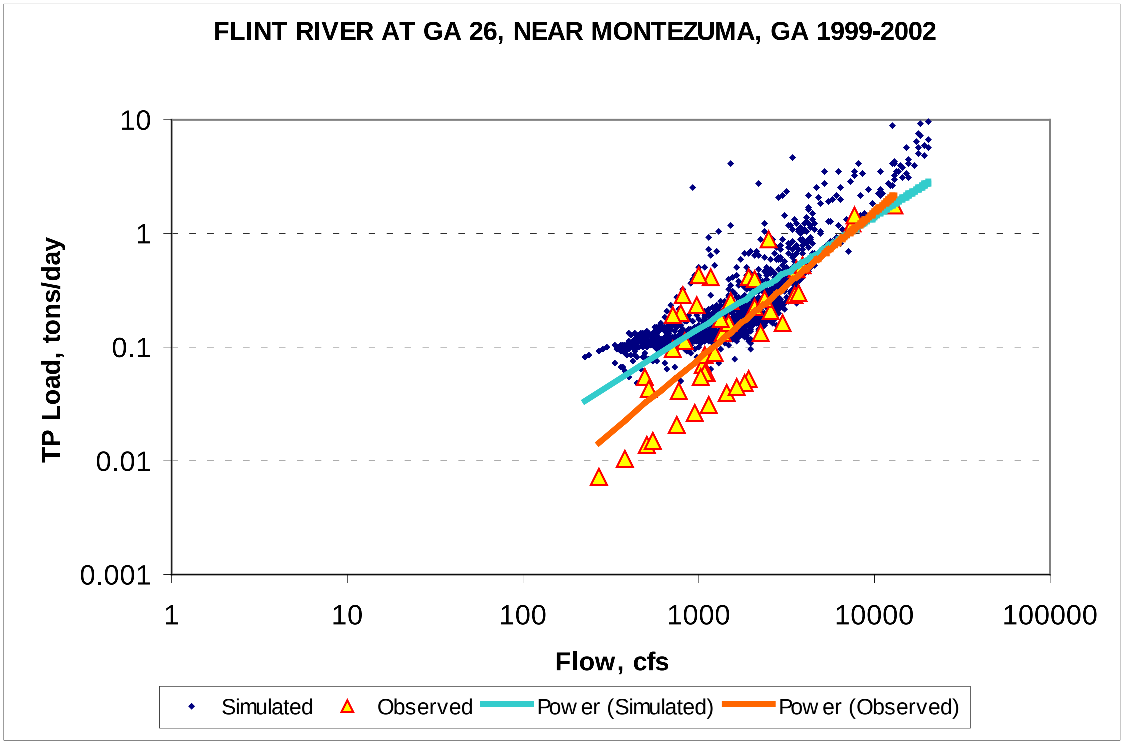


Figure 70. Power plot for observed and simulated total phosphorus at USGS 02349605 Flint River at Ga 26, near Montezuma, GA – calibration period (SWAT).

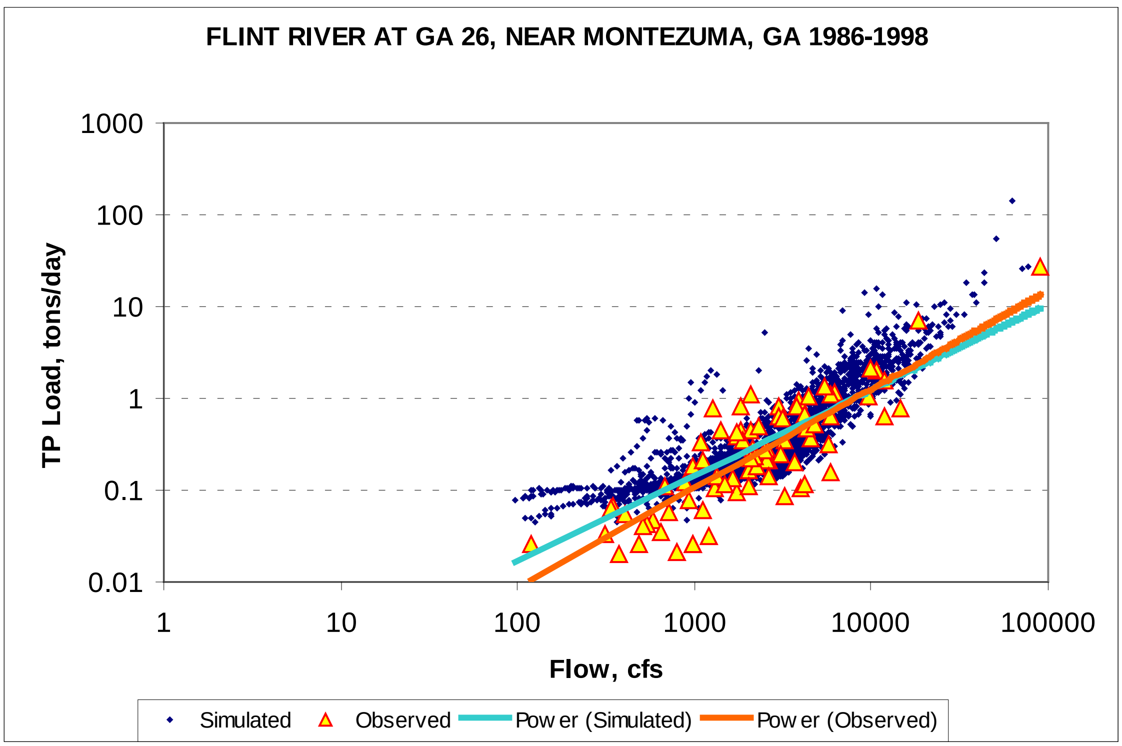


Figure 71. Power plot for observed and simulated total phosphorus at USGS 02349605 Flint River at Ga 26, near Montezuma, GA – validation period (SWAT).

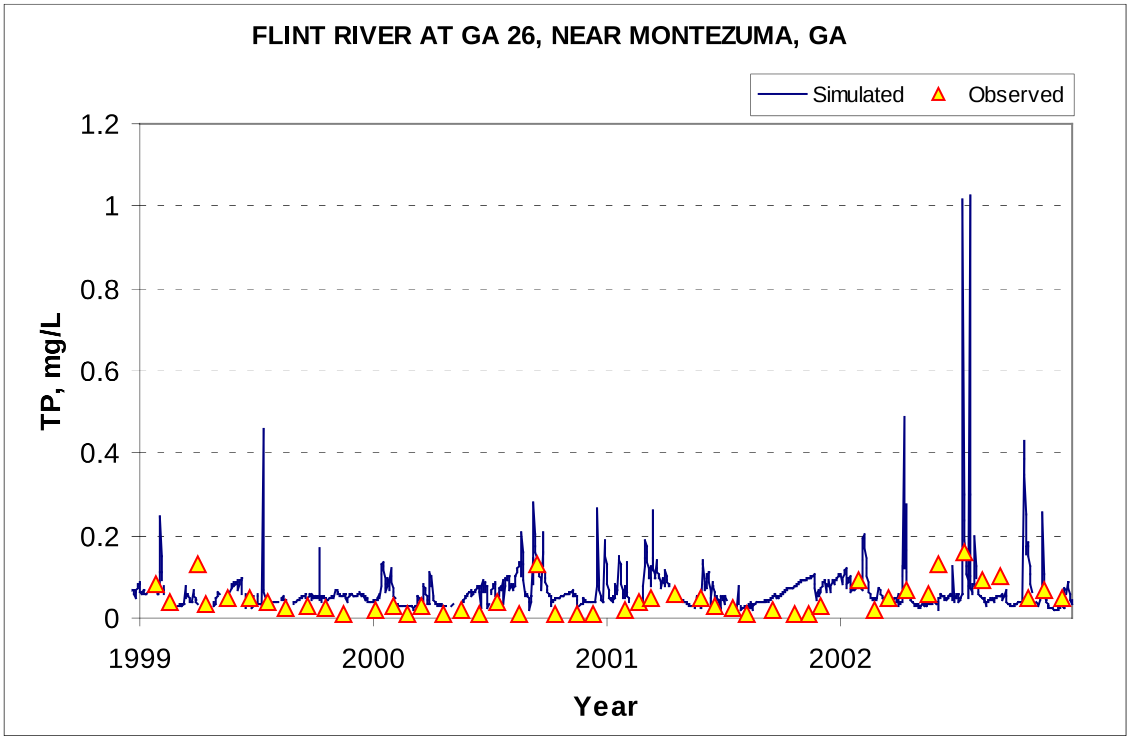


Figure 72. Time series plot of total phosphorus concentration at USGS 02349605 Flint River at Ga 26, near Montezuma, GA (SWAT).

Table 34. Relative errors (observed minus predicted), total phosphorus concentration, USGS 02349605 Flint River at Ga 26, near Montezuma, GA (SWAT)

Statistic	Calibration period (1999-2002)	Validation period (1991-1998)
Count	48	80
Concentration Average Error	-32.67%	-8.3%
Concentration Median Error	-41.28%	-11.99%

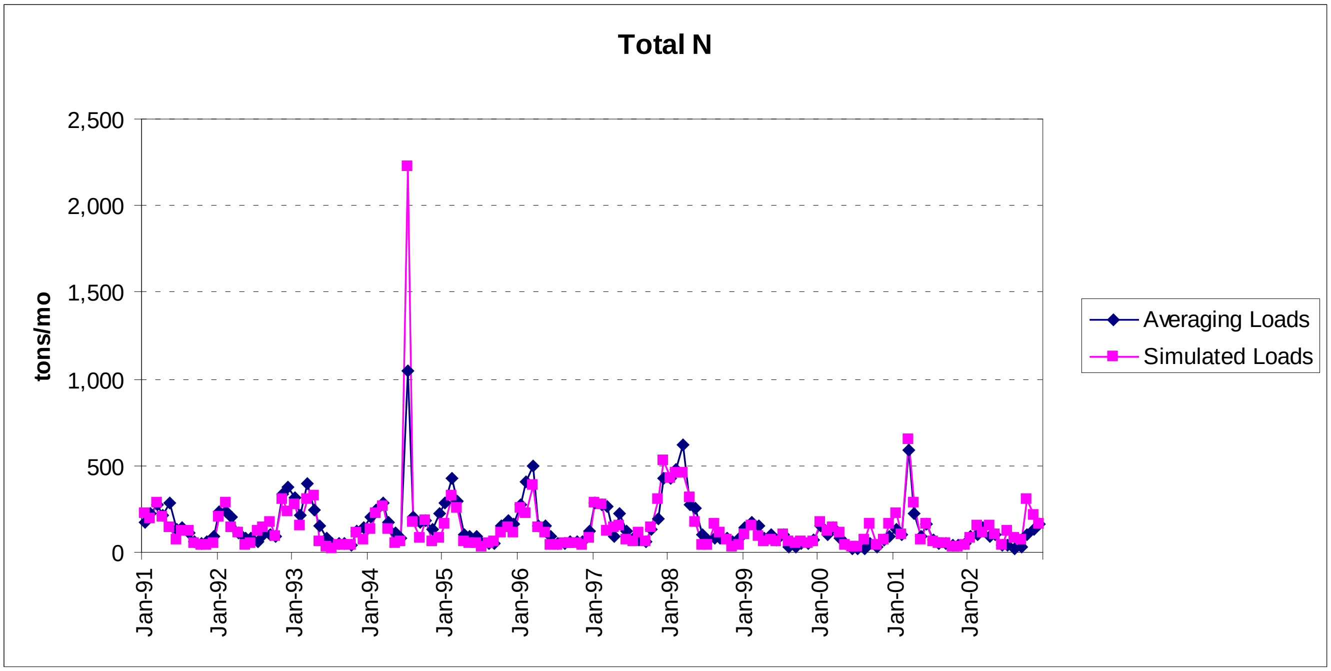


Figure 73. Fit for monthly load of total nitrogen at USGS 02349605 Flint River at Ga 26, near Montezuma, GA (SWAT).

Table 35. Model fit statistics (observed minus predicted) for monthly total nitrogen loads using averaging estimator at USGS 02349605 Flint River at Ga 26, near Montezuma, GA (SWAT)

Statistic	Calibration period (1999-2002)	Validation period (1991-1998)
Relative Percent Error	-18%	9%
Average Absolute Error	31%	30%
Median Absolute Error	15.7%	19.9%

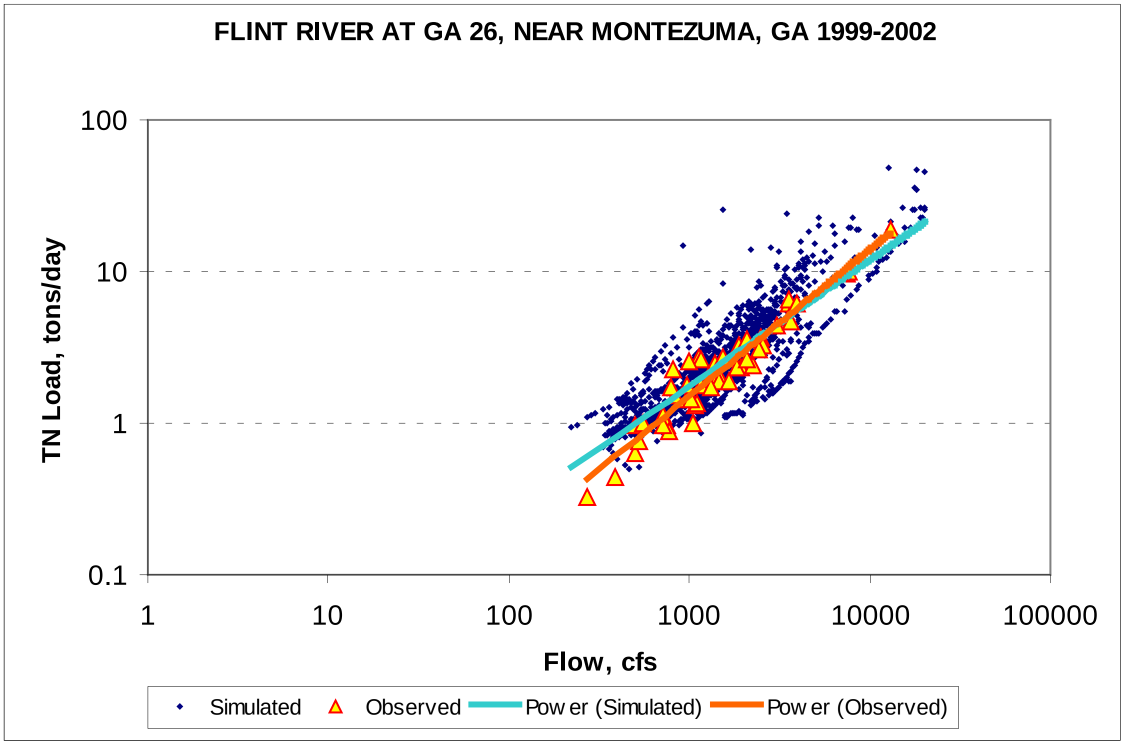


Figure 74. Power plot for observed and simulated total nitrogen at USGS 02349605 Flint River at Ga 26, near Montezuma, GA – calibration period (SWAT).

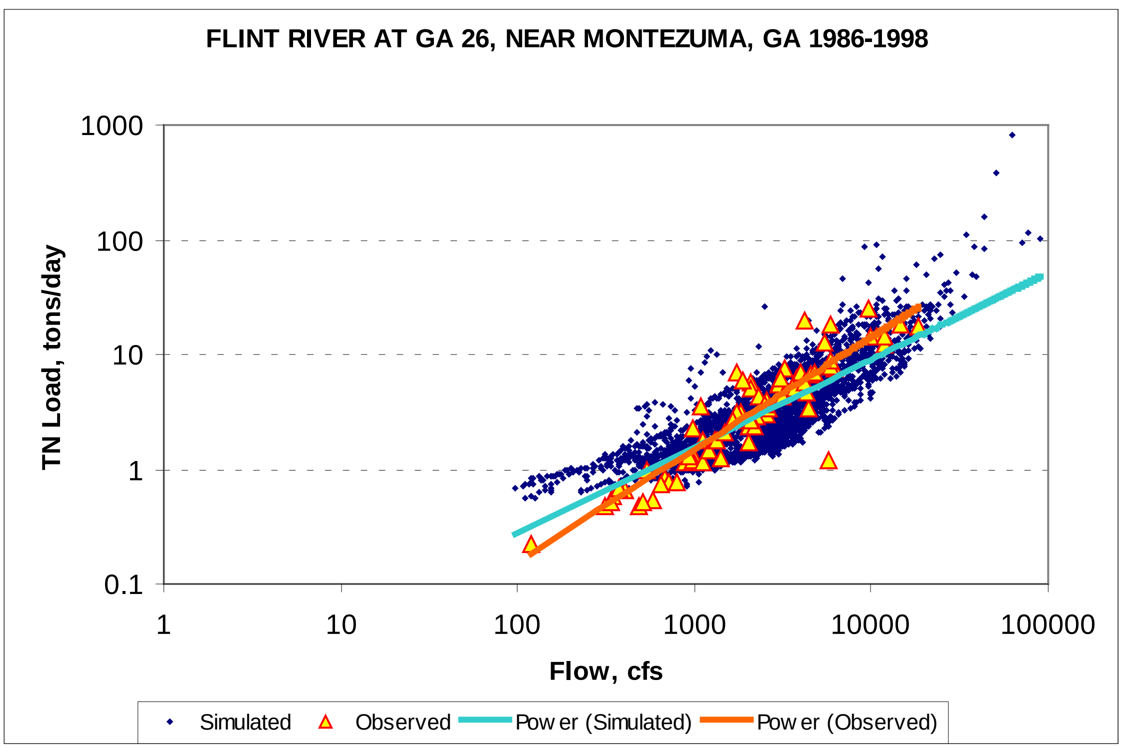


Figure 75. Power plot for observed and simulated total nitrogen at USGS 02349605 Flint River at Ga 26, near Montezuma, GA – validation period (SWAT).

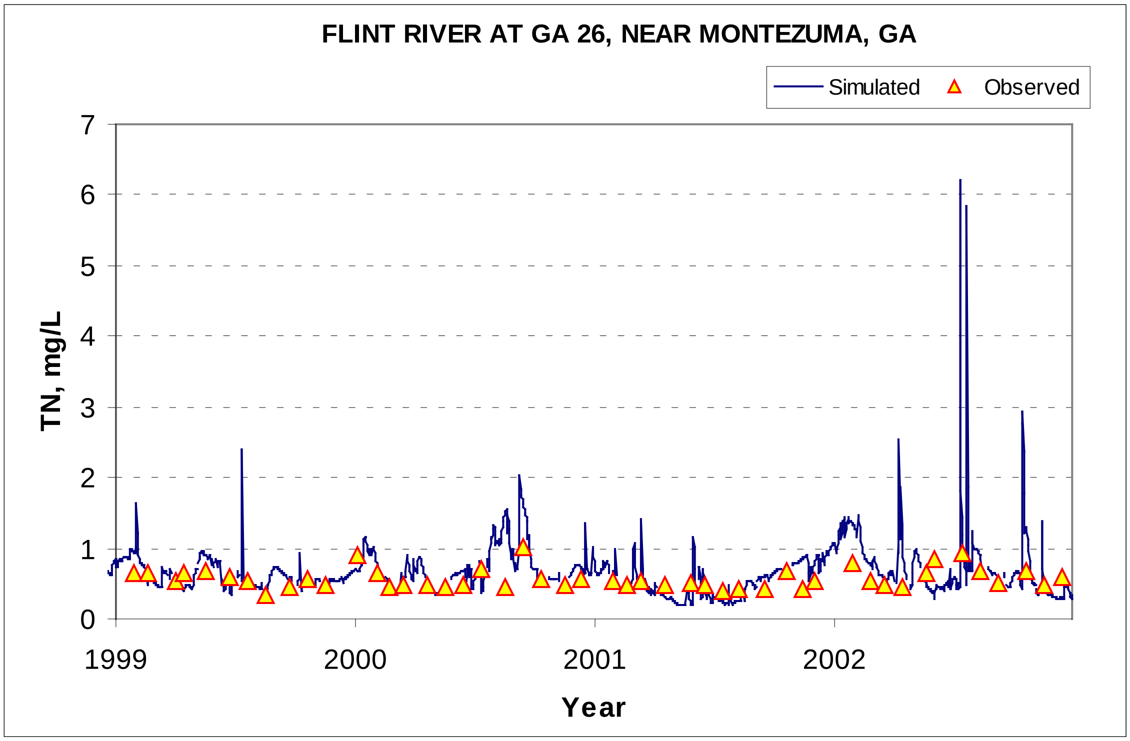


Figure 76. Time series plot of total nitrogen concentration at USGS 02349605 Flint River at Ga 26, near Montezuma, GA (SWAT).

Table 36. Relative errors (observed minus predicted), total nitrogen concentration, USGS 02349605 Flint River at Ga 26, near Montezuma, GA (SWAT)

Statistic	Calibration period (1999-2002)	Validation period (1991-1998)
Count	48	76
Concentration Average Error	-14.52%	2.26%
Concentration Median Error	-10.44%	8.07%

Water Quality Results for Larger Watershed

As with hydrology, the Flint River watershed parameters for water quality were directly transferred to other portions of the watershed. In general, simulated sediment was low and simulated total phosphorus and total nitrogen was high at most of the stations. Ortho phosphorus and mineral nitrogen made up most of the total phosphorus and total nitrogen as organic components corresponded to the sediment fraction. Summary statistics for the water quality calibration and validation at other stations in the watershed are provided in Tables 37 and 38, respectively.

Table 37. Summary statistics (observed minus predicted) for water quality for all stations – calibration period 1999-2002 (SWAT)

Station	02349605	02331600	02336300	02336000	02353500	02339500	02343801	02353000
Relative Percent Error TSS Load	-9	37	91	-3	33	71	83	66
TSS Concentration Median Percent Error	64.1	-26.0	-20.4	3.2	41.9	16.9	32.6	33.7
Relative Percent Error TP Load	-50	25	40	-29	-305	-317	-85	-45
TP Concentration Median Percent Error	-41.3	0.0	-21.6	-56.4	-124.5	-1136.7	-814.9	-24.8
Relative Percent Error TN Load	-18	13	-59	-117	0	-606	-310	26
TN Concentration Median Percent Error	-10.4	54.3	15.8	-46.1	63.9	-461.8	-335.7	25.8

Table 38. Summary statistics (observed minus predicted) for water quality for all stations – validation period 1986-1998 (SWAT)

Station	02349605	02331600	02336300	02336000	02353500	02339500	02343801	02353000
Relative Percent Error TSS Load	17	91	93	33	42	87	95	65
TSS Concentration Median Percent Error	53.8	0.9	1.7	14.4	89.9	54.9	31.1	33.8
Relative Percent Error TP Load	-30	62	18	14	-177	-59	72	-10
TP Concentration Median Percent Error	-12.0	46.6	11.2	2.8	-15.1	-134.0	-291.1	-12.1
Relative Percent Error TN Load	9	44	-75	-52	14	-280	-144	37
TN Concentration Median Percent Error	8.1	59.7	37.4	-50.3	70.6	-467.1	-229.4	20.2

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Appendix E
Model Configuration, Calibration and Validation

Basin: Arizona: Salt, Verde, and San Pedro Rivers (Ariz)

Contents

Tables

Figures

Watershed Background

The Arizona (Salt, Verde, and San Pedro) basins are located in central and southern Arizona in EPA Region 9 (Cordy et al. 2000). The watershed includes large parts of two hydrologic provinces—the Central Highlands in the north and the Basin and Range Lowlands in the south. Five major river systems drain the area: the Gila, Salt, Verde, Santa Cruz and San Pedro Rivers. The selected model area includes perennial portions of the Salt and Verde River basins (in HUC 1506) that lie upstream of major impoundments, along with the San Pedro River (HUC 1505), for a total of 10 HUC8s with an area of 14,910 mi^2 (Figure 1 and Figure 2).

Land cover is primarily desert scrub and rangeland at low elevations with sparse forest at higher elevations (USGS, 2004; Cordy et al., 2000). The two major population centers of Arizona, Phoenix and Tucson, are located just downstream of the model area, while portions of Flagstaff, Prescott, and several smaller towns are within the Verde River watershed. Population growth is resulting in increasing demands on the limited water resources of the area. The climate is arid to semiarid and is characterized by variability from place to place as well as large differences in precipitation from one year to the next. Precipitation can be three times greater in wet years than in dry years.

The Verde and Salt River watersheds are in the Central Highlands hydrologic province, characterized by mountainous terrain with shallow, narrow intermountain basins. Forests and rangeland cover most of the area. The largest town in the province is Prescott and other small rural towns dot the region. Most of the perennial streams in the study area are in the Central Highlands. These streams derive their flow from precipitation in the mountains and from rainfall and snowmelt along the northeastern border of the basins. Many of the major streams with headwaters in the Central Highlands are perennial in their upper reaches but are captured for water supply for metropolitan Phoenix, power generation, and flood control before they reach the Basin and Range Lowlands.

The San Pedro watershed is in the Basin and Range Lowlands hydrologic province. The Basin and Range Lowlands are characterized by ephemeral streams, the largest water demands, and reliance on groundwater. Deep, broad alluvial basins separated by mountain ranges of small areal extent characterize this hydrologic province. There is very little natural streamflow because of an average annual rainfall of less than 10 to 15 inches except at the highest elevations. With the exception of some small, higher elevation streams and sections of the San Pedro River, most perennial streams in the Basin and Range Lowlands are dependent on treated wastewater effluent for their year-round flow. Water use in the Basin and Range Lowlands represents 96 percent of all water use in the Arizona basins. Agriculture is the largest water user. Because of the general lack of surface water resources in the Basin and Range Lowlands, groundwater is relied upon heavily to meet agricultural and municipal demands.

The lower portions of the rivers in the Arizona basins have been extensively engineered for water supply purposes (e.g., the Salt River Project) and also contain many reaches that flow only intermittently. Larger reservoirs are problematic for scenario simulations as future demands and reservoir management are not fully known, while intermittent streams are difficult to calibrate and can present problems for model performance. Therefore, the portions of the watershed chosen for simulation are upstream of major reservoirs and focus on perennial streams. The resulting three distinct study areas are the Verde, Salt, and San Pedro rivers (Figure 1 and Figure 2).

Water Body Characteristics

Verde River

The first area of study is the Verde River watershed upstream of Horseshoe Reservoir (Figure 1). The Verde River watershed comprises approximately 6,577 square miles (mi^2), while the area upstream of the northern end of Horseshoe Reservoir contains approximately 5,563 mi^2. The watershed trends south-southeast from Fraziers Well, immediately south of the Colorado River watershed and the Grand Canyon National Park to its confluence with the Salt River on the east side of Phoenix. The study area ranges in elevation from over 11,000 feet (ft) where it drains a portion of Humphreys Peak north of Flagstaff to around 2,100 ft at the confluence of the Verde River with Horseshoe Reservoir.

The Verde Valley, which descends into the Central Highland province, is bounded by the Mogollon Rim to the north and northeast and by the Black Hills to the southwest (Owen-Joyce and Bell 1983). The headwaters of the Verde River are considered to be just below Sullivan Lake, an impoundment of Big Chino Wash. Upstream of this point lies a large drainage area that is dominated by intermittent flow (HUC 15060201). Within the Upper Verde watershed (HUC 15060202) from Sullivan Lake to Camp Verde, the Verde River flows through rugged country and drains high mountains to the north and east. Perennial flow in the Verde River is usually considered to start at the confluence with Granite Creek, just below Sullivan Lake. Granite Creek and its two tributaries originate in the mountainous area outside of Prescott. All three of these tributaries are dammed to provide water to the city of Prescott and the Chino Valley Irrigation District. Flow in Granite Creek is ephemeral at the point of confluence with the Verde River; however, about 25 percent of the baseflow in the Verde River at this point is believed to derive from groundwater transport out of the Granite Creek drainage (ADWR 2000).

The baseflow in the upper reaches of the Verde River is supported by groundwater discharges between Granite Creek and Paulden (Owen-Joyce and Bell 1983). From Paulden to Sycamore Creek the river gains additional groundwater discharges, primarily at Mormon Pocket. Sycamore Creek is an important tributary of the Verde River, draining the area west of Flagstaff, and has a spring-fed baseflow. The net result of these groundwater sources is a nearly constant baseflow of around 75 to 80 cfs at Clarkdale.

Groundwater throughout the Big Chino subwatershed occurs under both confined and unconfined conditions. Groundwater levels range from above surface due to confined conditions to over 200 feet below surface, with a depth to water in most wells of less than 80 ft (Schwab 1995). The major source of recharge for the Big Chino subwatershed is infiltration of runoff from the mountain fronts and flow within the major washes. Only a small percentage of the annual precipitation in the subwatershed reaches the groundwater table because the majority occurs in high intensity summer storm events and is lost as surface runoff, evaporation and transpiration by vegetation (Schwab 1995).

ADWR (2000) examined water budgets for 1996-97 for the Big Chino subwatershed plus the uppermost part of the Verde River to the USGS gage at Paulden and concluded that there was no net change in the groundwater storage. Inflows were estimated to be 26,760 acre-feet from natural recharge plus 8,010 acre-feet from incidental anthropogenic recharge. Of the total discharges, 19,050 acre-feet (55 percent) occurred as flow in the Verde River near Paulden and the remainder as groundwater pumpage.

An additional important factor in the hydrology of the Verde River watershed, particularly upstream of Paulden, is the construction of numerous stock pond impoundments used to capture surface runoff to support cattle ranching. These impoundments may act as recharge basins, but impede the flow of runoff that would otherwise have occurred. A survey of small impoundments upstream of Camp Verde was conducted in 1996. Approximately 2,635 impoundments ranging in size from 0.1 acres to approximately 350 acres in surface area were identified (ADWR 2000). No estimate of recharge has been calculated for these impoundments and no determination of the impact from restricting and/or impounding the natural runoff has ever been studied.

Salt River

The Salt River (including Tonto Creek) lies immediately to the east of the Verde River watershed and shares many similar characteristics. The model simulates these streams down to Roosevelt Reservoir (Figure 1). Like the Verde River watershed, the Salt River and Tonto Creek watersheds have high relief and are bounded by the Mogollon Rim. However, unlike the Verde watershed, these watersheds have less in the way of teleconnections to deep groundwater. Perennial springs are important in the upper reaches of the Salt; however, most of the water discharged by these springs appears to derive from local sources. The Salt River watershed also has much less human influence than the Verde, with only 1.5 percent of the land area in private ownership. The bulk of the watershed is under tribal or US Forest Service ownership.

San Pedro River

The San Pedro River, a tributary of the Gila River, flows northward from the Arizona-Mexico border (Figure 2). The watershed consists of a large alluvial valley flanked by mountain ranges. The river is perennial in the southern (upstream) reaches, but only intermittent in the northern (downstream) reaches. As with the Verde River and Salt River watersheds, precipitation and temperature vary strongly with elevation, with most of the precipitation occurring at the higher elevations. The perennial portions of the river support important desert riparian forest habitat, and most of this section is contained within the San Pedro Riparian National Conservation Area.

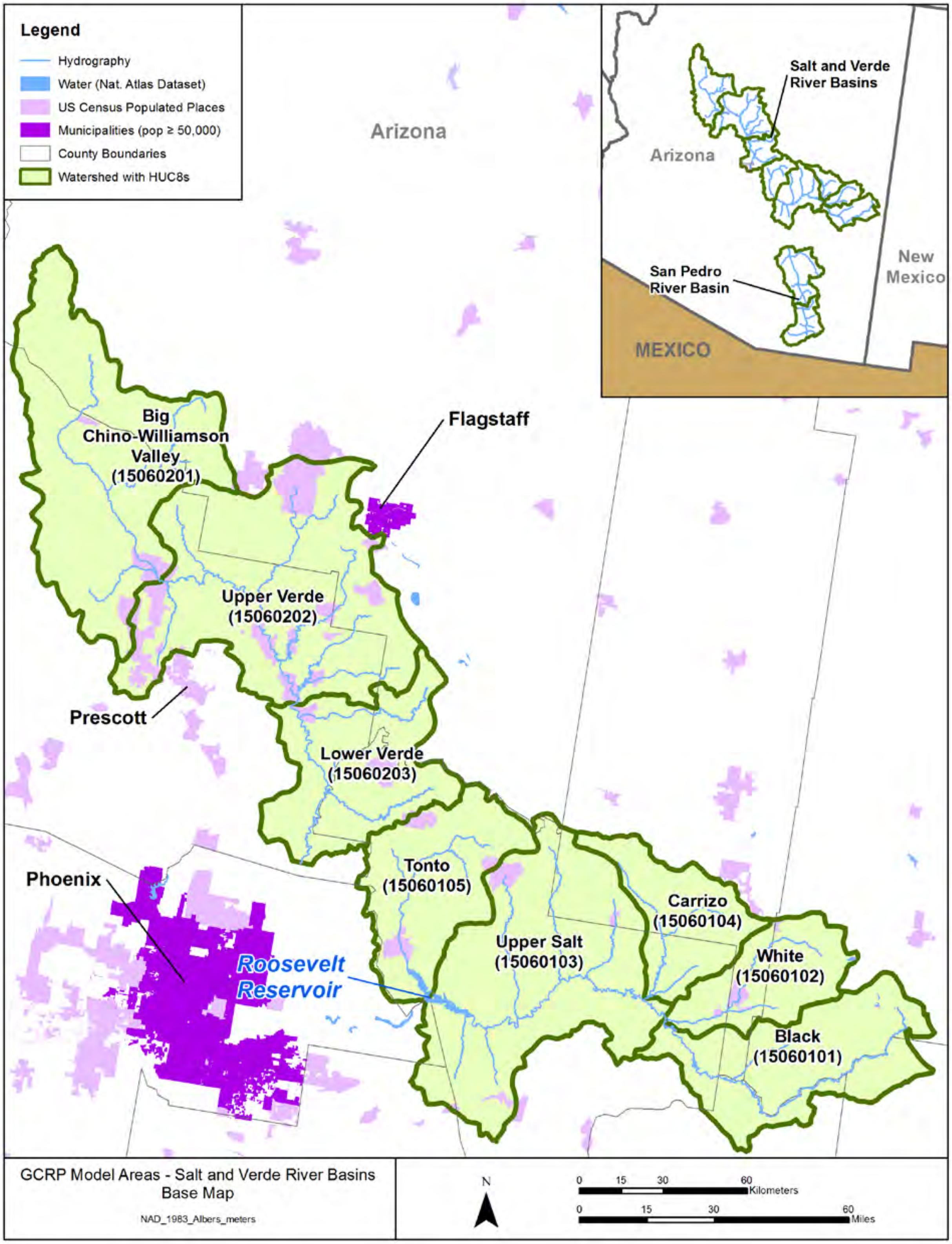

Figure 1. The Arizona basins – Verde and Salt River sections.

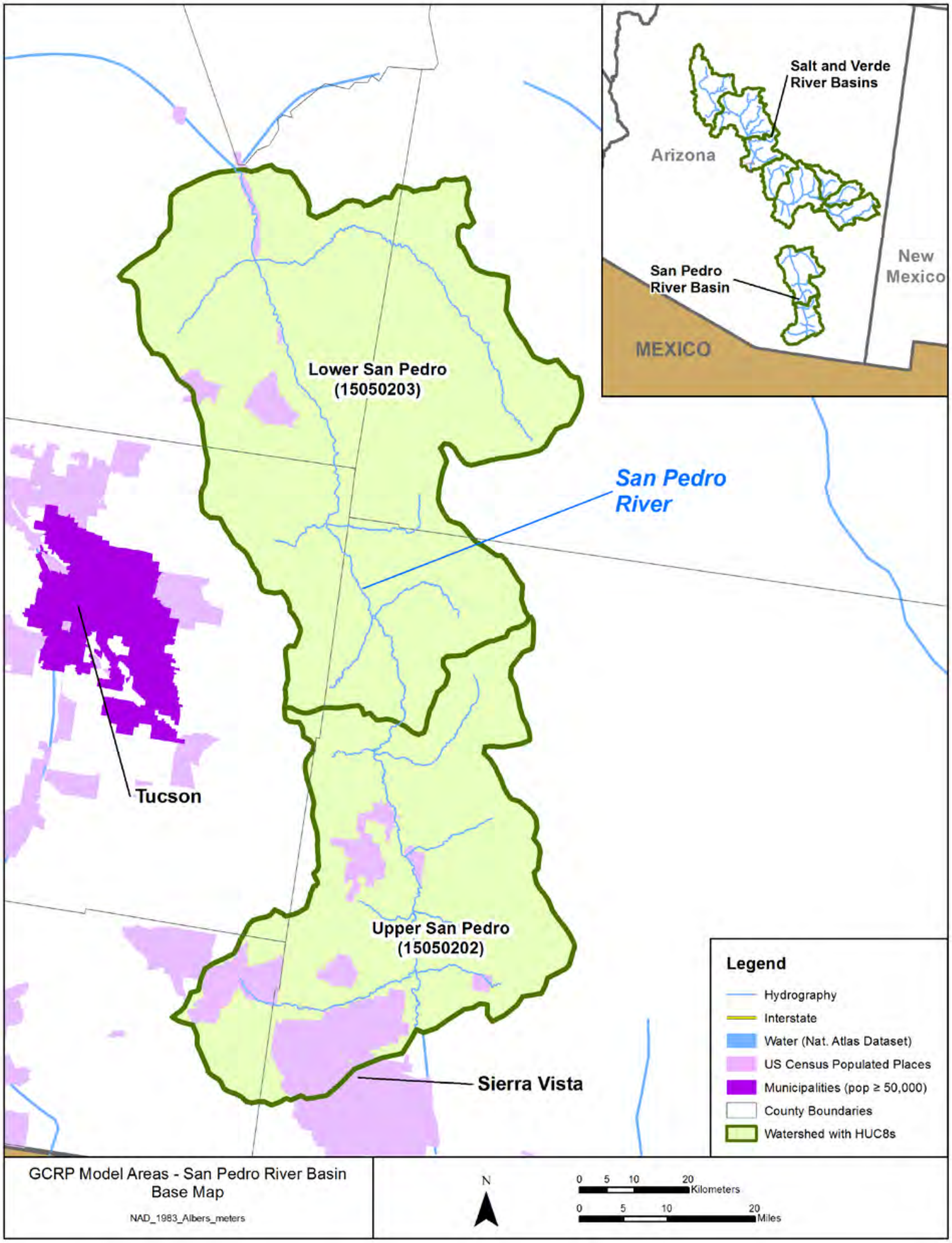

Figure 2. The Arizona basins – San Pedro River section.

Soil Characteristics

The hydrology of the Arizona Basin is strongly influenced by the soils and underlying geology of the watershed. These in turn reflect the complex geologic history of Arizona, which includes periods of marine inundation, volcanism, and uplift.

One of the most important characteristics of soils for watershed modeling is their hydrologic soil group (HSG). The 20 Watershed study utilized STATSGO soil survey HSG information during model set-up. Soils are classified into four hydrologic groups (SCS 1986), separated by runoff potential, as follows:

- A Low runoff potential and high infiltration rates even when thoroughly wetted. Chiefly deep, well to excessively drained sands or gravels. High rate of water transmission (> 0.75 cm/hr).
- B Moderate infiltration rates when thoroughly wetted. Chiefly moderately deep to deep, moderately well to well drained soils with moderately fine to moderately coarse textures. Moderate rate of water transmission (0.40—0.75 cm/hr).
- C Low infiltration rates when thoroughly wetted. Chiefly soils with a layer that impedes downward movement of water, or soils with moderately fine to fine texture. Low rate of water transmission (0.15—0.40 cm/hr).
- D High runoff potential. Very low infiltration rates when thoroughly wetted. Chiefly clay soils with a high swelling potential, soils with a permanent high water table, soils with a claypan or clay layer at or near the surface, or shallow soils over nearly impervious material. Very low rate of water transmission (0—0.15 cm/hr).

The soils in the Verde River watershed are predominantly hydrologic group B soils while soils in the San Pedro River watershed are predominantly hydrologic group C soils. The Salt River watershed contains almost equal amounts of B, C, and D soils with a slight dominance of B soils.

Land Use Representation

Land use in the watershed is based on the 2001 National Land Cover Database (NLCD) coverage (Figure 3 and Figure 4) and is predominantly scrub/shrub chaparral blending into Sonoran paloverde at lower elevations and pinyon-juniper evergreen forest at higher elevations. Only a few small municipalities are located in the study watersheds and much of the land is in federal ownership.

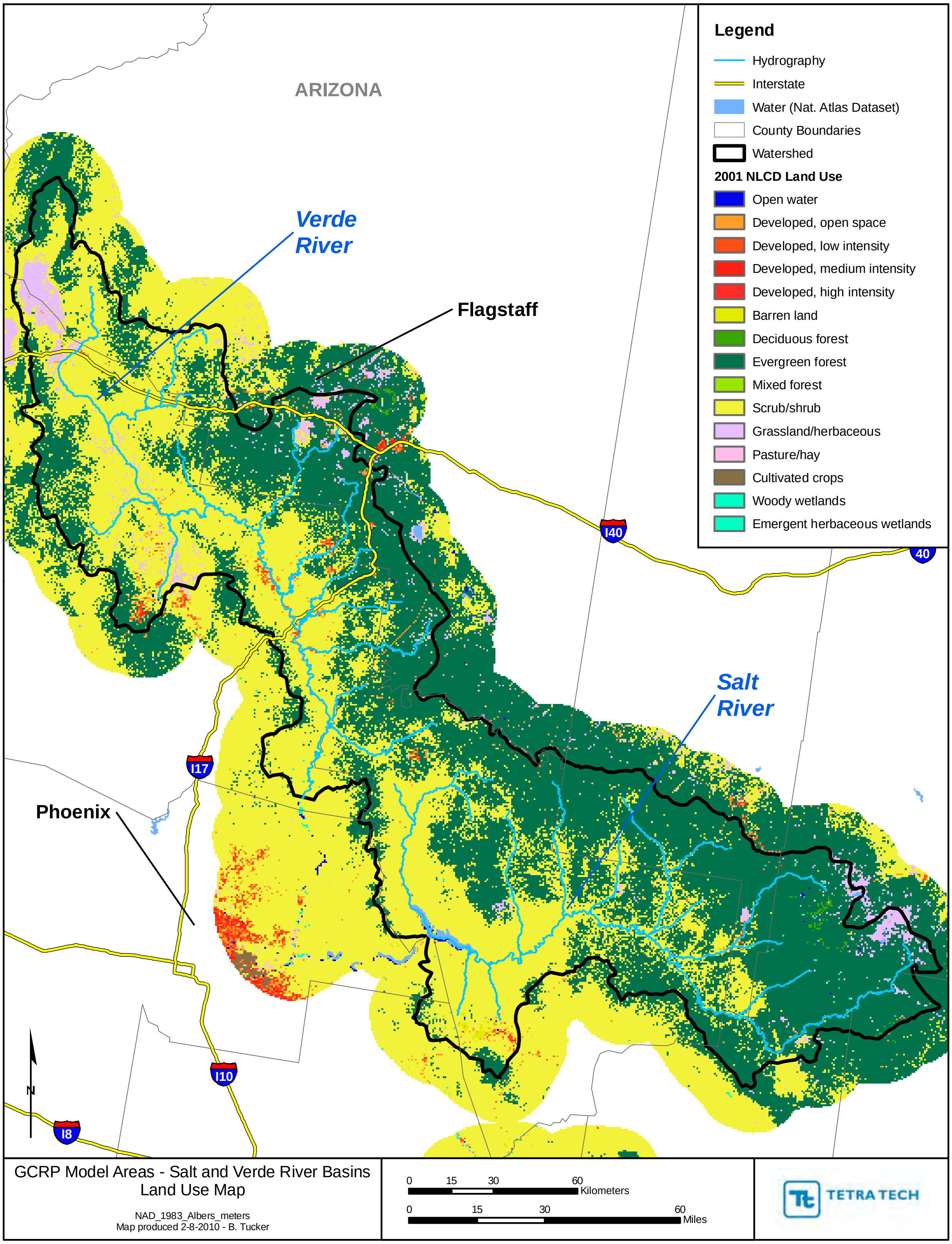

Figure 3. Land use in the Arizona basin – Verde and Salt River section.

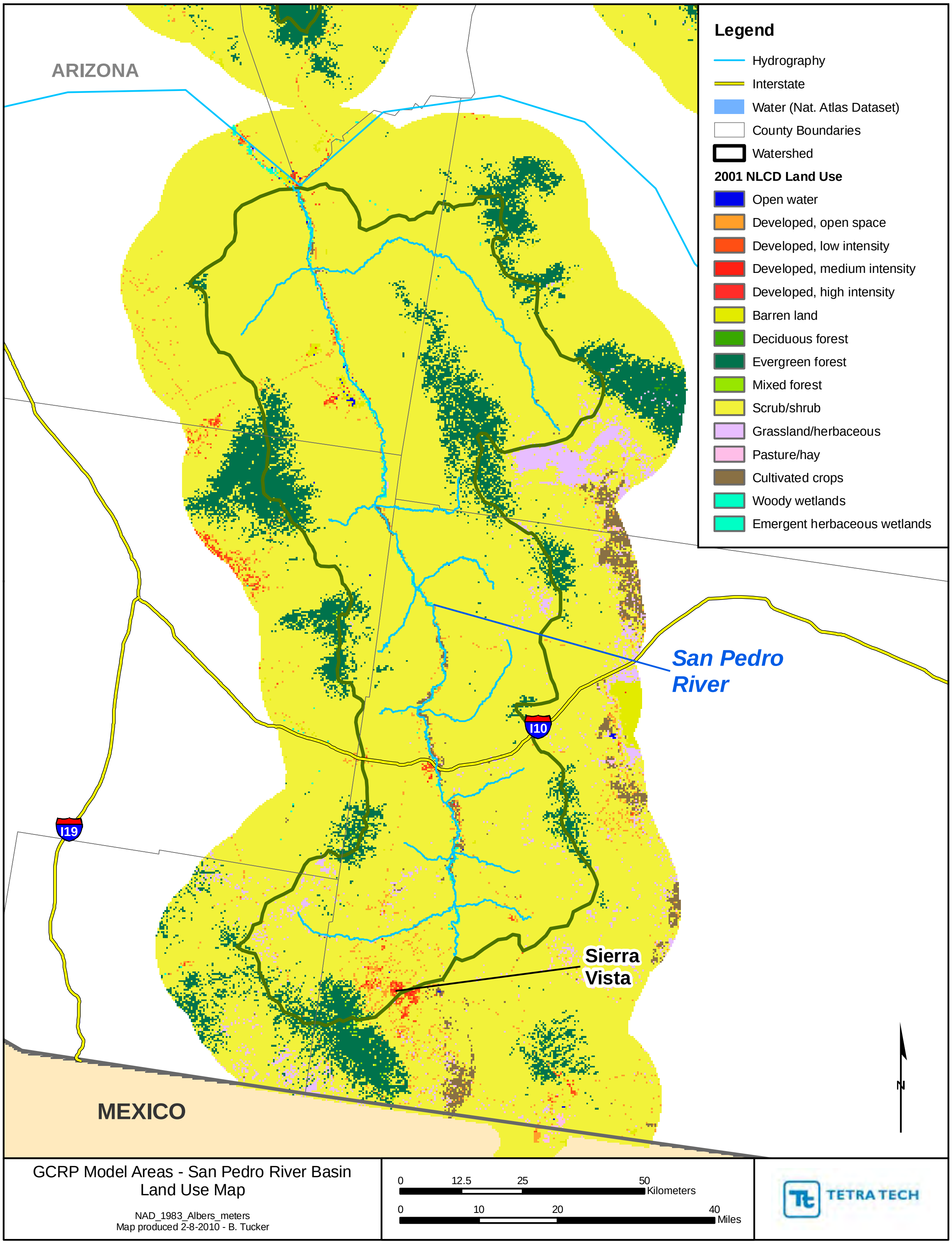

Figure 4. Land use in the Arizona basin – San Pedro River section.

NLCD land cover classes were aggregated according to the scheme shown in Table 1 then overlain with the soils HSG grid. Minor land uses with less than 5 percent coverage within a subwatershed were reassigned to more dominant classes. Pervious and impervious lands are specified separately for HSPF, so only one developed pervious class is used, along with an impervious class. HSPF simulates impervious land areas separately from pervious land. Impervious area distributions were also determined from the NLCD Urban Impervious data coverage. Specifically, percent impervious area was calculated over the whole basin for each of the four developed land use classes. These percentages were then used to separate out impervious land. NLCD impervious area data products are known to underestimate total imperviousness in rural areas. However, the model properly requires connected impervious area, not total impervious area, and the NLCD tabulation is assumed to provide a reasonable approximation of connected impervious area. Different developed land classes are specified separately in SWAT. In HSPF the WATER, BARREN, DEVPERV, and WETLAND classes are not subdivided by HSG; SWAT uses the built-in HRU overlay mechanism in the ArcSWAT interface.

Table 1. Aggregation of NLCD land cover classes

NLCD Class	Comments	SWAT class	HSPF (after processing)
11 Water	Water surface area usually accounted for as reach area	WATR	WATER
12 Perennial ice/snow		WATR	BARREN, Assume HSG D
21 Developed open space		URLD	DEVPERV; IMPERV
22 Dev. Low Intensity		URMD	
23 Dev. Med. Intensity		URHD	
24 Dev. High Intensity		UIDU	
31 Barren Land		SWRN	BARREN (D)
41 Forest	Deciduous	FRSD	FOREST (A,B,C,D)
42 Forest	Evergreen	FRSE	
43 Forest	Mixed	FRST	
51-52 Shrubland		RNGB	SHRUB (A,B,C,D)
71-74 Herbaceous Upland		RNGE	GRASS (A,B,C,D), BARREN (D)
81 Pasture/Hay		HAY or GRASS	GRASS (A,B,C,D)
82 Cultivated		AGRR	AGRI (A,B,C,D)
91-97 Wetland	Emergent & woody wetlands	WETF, WETL, WETN	WETLAND, Assume HSG D
98-99 Wetland	Aquatic bed wetlands (not emergent)	WATR	WATER

The distribution of land use in the watershed is summarized in Table 2. Note that the small areas in crop and hay production along the Verde mainstem and elsewhere do not meet the 5 percent threshold requirement in SWAT and are thus not explicitly included in the model; instead, the developed pervious land use implicitly includes those areas in crop production for SWAT.

Table 2. Land use distribution for the Arizona basins (2001 NLCD) (mi^2)

HUC 8 watershed	Open Water	Developed[a]				Barren Land	Forest	Shrubland	Pasture/Hay	Cultivated	Wetland	Total
		Open space	Low Density	Medium Density	High Density							
Upper San Pedro **15050202**	0.1	19.2	4.9	1.2	0.2	0.4	64.2	1,129.2	1.5	9.9	4.5	1,235.2
Lower San Pedro **15050203**	1.4	8.3	2.2	0.3	0.1	6.6	179.1	1,791.7	1.5	7.5	12.5	2,011.2
Black **15060101**	1.8	1.8	0.2	0.0	0.0	0.6	1,026.3	217.9	0.0	0.0	2.0	1,250.7
White **15060102**	1.6	4.5	1.2	0.2	0.0	0.5	537.2	89.9	0.1	0.0	3.2	638.4
Upper Salt **15060103**	16.7	10.4	5.1	1.4	0.3	14.0	950.1	1,251.9	0.7	0.0	4.7	2,255.2
Carrizo **15060104**	0.0	2.7	0.2	0.0	0.0	1.4	586.4	118.5	0.0	0.0	0.4	709.8
Tonto **15060105**	0.0	4.6	1.2	0.1	0.0	0.6	443.7	494.9	0.3	0.0	1.9	947.1
Big Chino-Williamson Valley **15060201**	0.1	11.8	3.5	0.2	0.0	3.8	615.8	1,514.8	1.4	0.0	0.9	2,152.4
Upper Verde **15060202**	1.2	48.0	25.1	5.3	0.6	15.3	1,256.8	1,143.2	2.5	0.0	6.1	2,504.1
Lower Verde **15060203**	0.3	9.8	4.0	0.4	0.1	1.0	582.0	601.3	1.9	0.0	4.6	1,205.4
Total	23.2	121.2	47.7	9.0	1.3	44.3	6,241.7	8,353.2	10.0	17.4	40.7	14,909.6

[a]The percent imperviousness applied to each of the developed land uses is as follows: open space (7.37%), low density (29.66%), medium density (53.71%), and high density (73.85%).

The HSPF model is set up on a hydrologic response unit (HRU) basis. For HSPF, HRUs were formed from an intersection of land use and hydrologic soil group, then further subdivided by precipitation gage and slope. SWAT HRUs were formed from an intersection of land use and SSURGO major soils.

Topography

The Salt, Verde, and San Pedro River watersheds are characterized by high relief (Figure 5) and precipitation and temperature vary greatly with elevation. The largest precipitation amounts and lowest temperatures occur at the high elevations along the Mogollon Rim on the north and east sides of the Salt and Verde River watersheds.

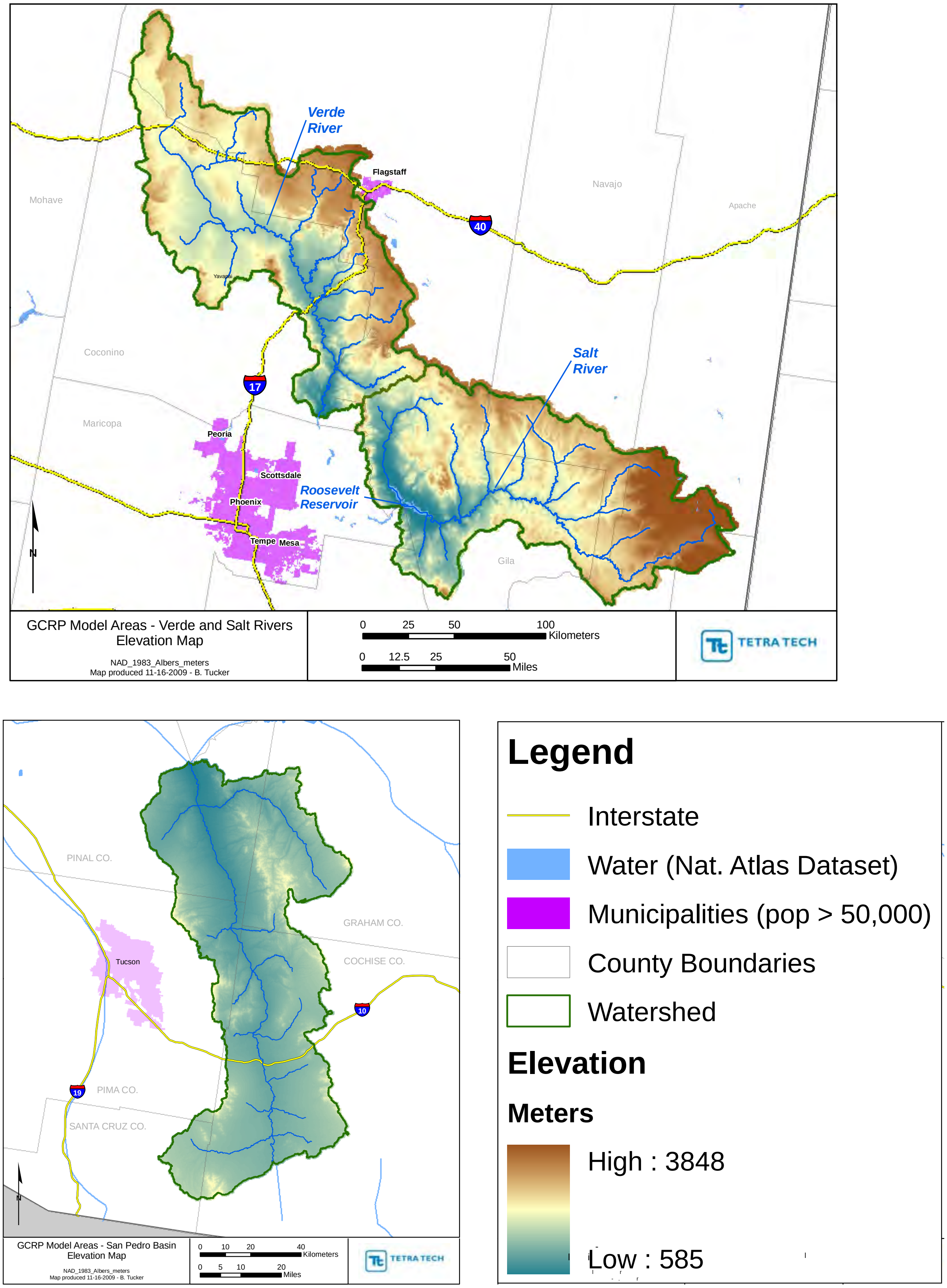

Figure 5. Topography of the Arizona Basins.

Point Sources

Only the two major dischargers with a design flow greater than 1 MGD are included in the simulation (Table 3 and Figure 6). These dischargers are Page Springs Fish Hatchery and the Pinal Creek Wastewater Treatment Plant (WWTP) in Globe, Arizona. Because of the arid climate and low population in the study watersheds, much of the wastewater that is generated is either used for irrigating golf courses or discharged to ephemeral washes that lack a direct surface connection to the river system.

Table 3. Major point source discharges in the Arizona basins

NPDES ID	Name	Design Flow (MGD)	Observed Flow (MGD) (1991-2006 average)
AZ0021245	Page Springs Fish Hatchery (AZ Game and Fish Department)	20.35	21.92
AZ0020249	Pinal Creek WWTP (City of Globe, AZ)	1.20	12.54

The discharges from Page Springs Fish Hatchery to Oak Creek are largely composed of natural groundwater. Some of this groundwater arises within the local subwatershed, and is thus already accounted for in the model. To prevent double-counting of this water, the reported discharges were reduced significantly to provide an approximate match to observed base flows in Oak Creek.

Several other smaller discharges reported in the study area were determined to be used primarily for irrigation or discharge to dry washes, do not cause live stream discharges and so are not explicitly included in the model. The San Jose WWTP major discharge at Bisbee, Arizona is in part used for irrigation, but also discharges to Greenbush Draw, tributary to the San Pedro. However, it enters the San Pedro upstream of the modeled area.

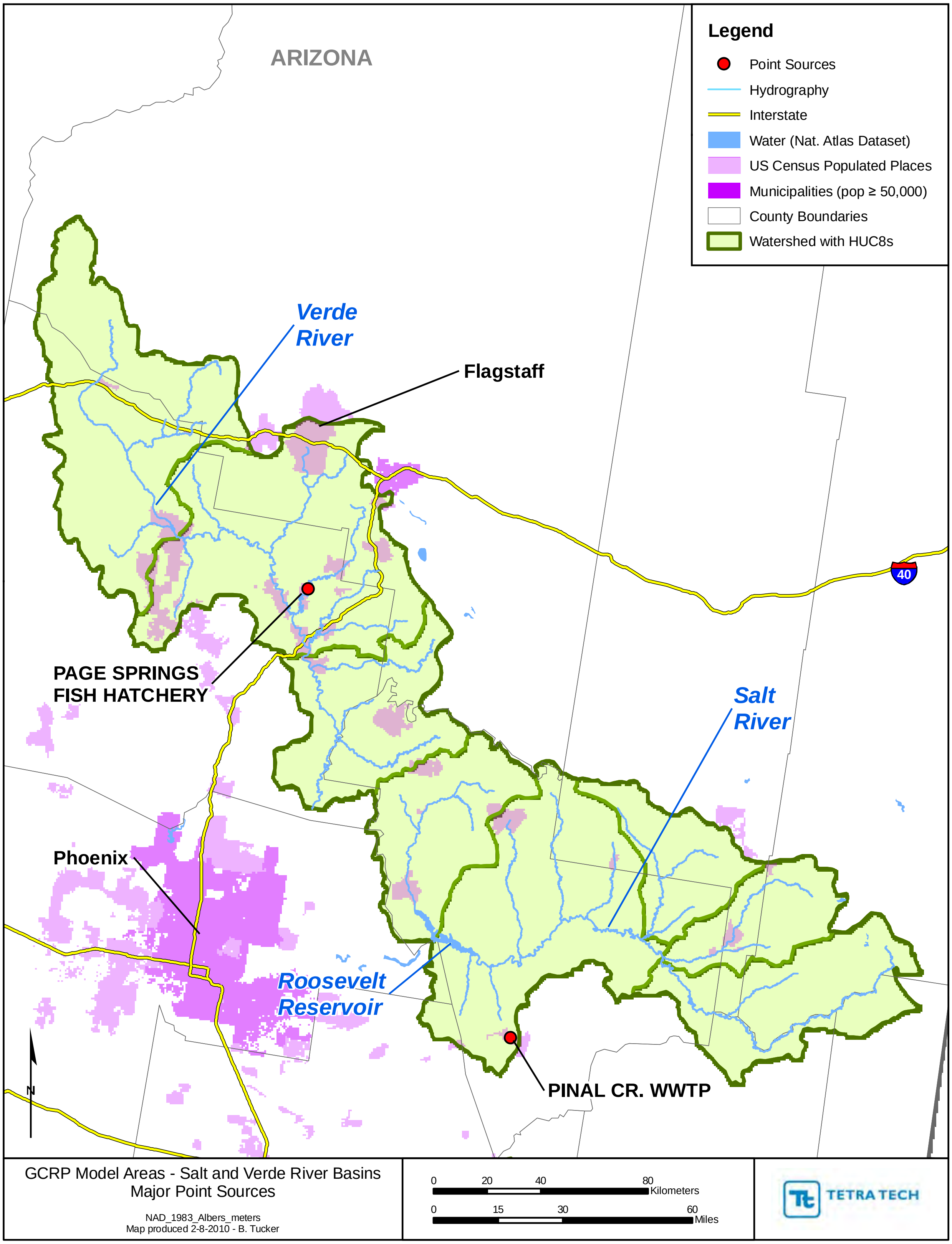

Figure 6. Major point sources in the Arizona basins.

Meteorological Data

The required meteorological data series for the 20 Watershed study are precipitation, air temperature, and potential evapotranspiration. The 20 Watershed model does not include water temperature or algal simulation and uses a degree-day method for snowmelt. These meteorological data are drawn from the BASINS4 Meteorological Database (USEPA 2008), which provides a consistent, quality-assured set of nationwide data with gaps filled and records disaggregated. Scenario application will require simulation over 30 years, so the available stations are those with a common 30-year period of record (or one that can be filled from an approximately co-located station) that covers the year 2001. A total of 29 precipitation stations were identified for use in the Arizona basins model with a common period of record of 10/1/1972-9/30/2002 (Table 4 and Figure 7 and Figure 8). Temperature records are sparser; where these are absent, temperature is taken from nearby stations with an elevation correction. For each weather station, Penman-Monteith reference evapotranspiration was calculated for use in HSPF using observed precipitation and temperature coupled with SWAT weather generator estimates of solar radiation, wind movement, cloud cover, and relative humidity.

For the 20 Watershed model applications, SWAT uses daily meteorological data, while HSPF requires hourly data. It is important to note that a majority of the meteorological stations available for the Arizona basins are Cooperative Summary of the Day stations that do not report sub-daily data. The BASINS4 dataset already has versions of the daily data that have been disaggregated to an hourly time step using template stations. For each daily station, this disaggregation was undertaken in reference to a single disaggregation template. Occasionally, this automated procedure provides undesirable results, particularly when the total rainfall for the day is very different between the subject station and the disaggregation template.

Table 4. Precipitation stations for the Arizona models

COOP ID	Name	Latitude	Longitude	Temperature	Elevation (ft)
AZ020159	Alpine	33.8493	-109.146	X	8049
AZ020487	Ash Fork 3	35.199	-112.488		5074
AZ020670	Beaver Creek	34.6418	-111.783	X	3523
AZ020683	Benson 6 SE	31.8803	-110.24	X	1125
AZ020808	Black River Pumps	33.4783	-109.751	X	6065
AZ021231	Canelo 1 NW	31.559	-110.529		1527
AZ021330	Cascabel	32.3208	-110.413	X	959
AZ021614	Childs	34.3495	-111.698	X	2650
AZ021654	Chino Valley	34.757	-112.456	X	4749
AZ021870	Cochise 4 SSE	32.059	-109.89	X	1274
AZ022140	Coronado NM Hdqtrs	31.3457	-110.254	X	1598
AZ023010	Flagstaff AP	35.1442	-111.666	X	7003
AZ023828	Happy Jack RS	34.7433	-111.413	X	7478
AZ024453	Jerome	34.7523	-112.111	X	4950
AZ025512	Miami	33.4045	-110.87	X	3559
AZ026323	Payson	34.2315	-111.339	X	4907
AZ026601	Pinetop 2E	34.1243	-109.921		7200
AZ026653	Pleasant Valley RS	34.099	-110.944	X	5048
AZ026796	Prescott	34.5706	-112.432	X	5202
AZ026840	Punkin Center	33.8557	-111.306	X	2326

COOP ID	Name	Latitude	Longitude	Temperature	Elevation (ft)
AZ027281	Roosevelt 1 WNW	33.6731	-111.15	X	2204
AZ027530	San Manuel	32.6014	-110.633	X	1055
AZ027708	Sedona	34.8957	-111.764	X	4218
AZ027716	Seligman	35.3323	-112.879	X	5248
AZ028619	Tombstone	31.7057	-110.056	X	1405
AZ028650	Tonto Creek Fish Hatchery 2	34.3839	-111.097		6389
AZ029158	Walnut Creek	34.9282	-112.809	X	5087
AZ029271	Whiteriver 1 SW	33.8169	-109.983	X	5120
AZ029359	Williams	35.2407	-112.19	X	6747

Orographic effects on precipitation and temperature are important throughout the region. This is addressed through use of the elevation bands option and the imposition of precipitation and temperature lapse rates in the SWAT model. All SWAT model subwatersheds are assigned at least one elevation band, and multiple elevation bands are used when the interquartile range of elevations within a subwatershed exceeds 375 m. For HSPF, whenever the precipitation station was located outside or near the edge of a model segment, a multiplier was applied to the data based on the ratio of the estimated median annual rainfall from isohyetal information and the long term annual average for the station. The evaporation data appeared to be estimates of pan evaporation, and ranged from 70 to 100 inches per year. They were therefore adjusted by a factor of 0.7 to reduce them to potential evapotranspiration. Some of the multipliers were adjusted slightly during the hydrology calibration.

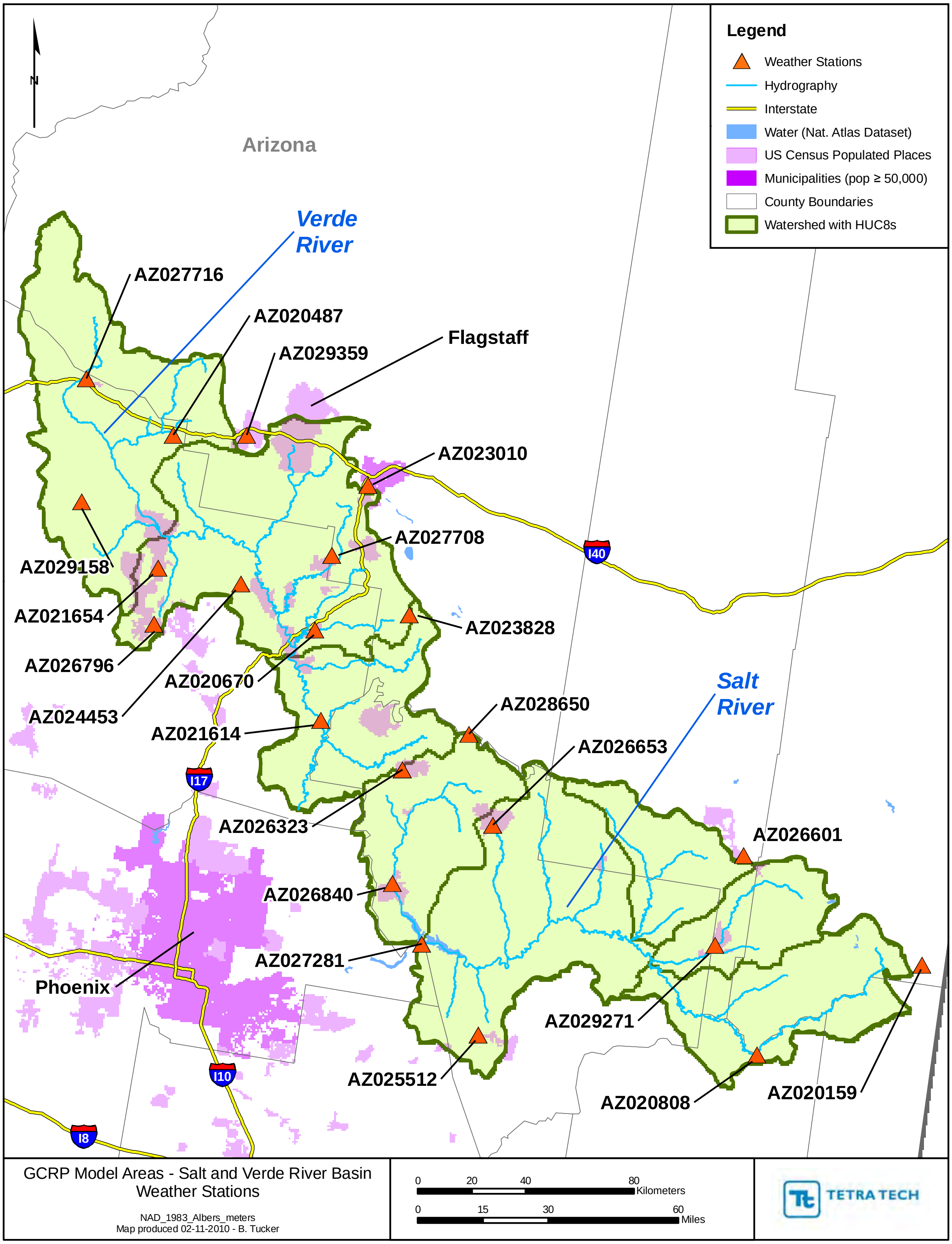

Figure 7. Weather stations for the Arizona basins model – Verde and Salt River section.

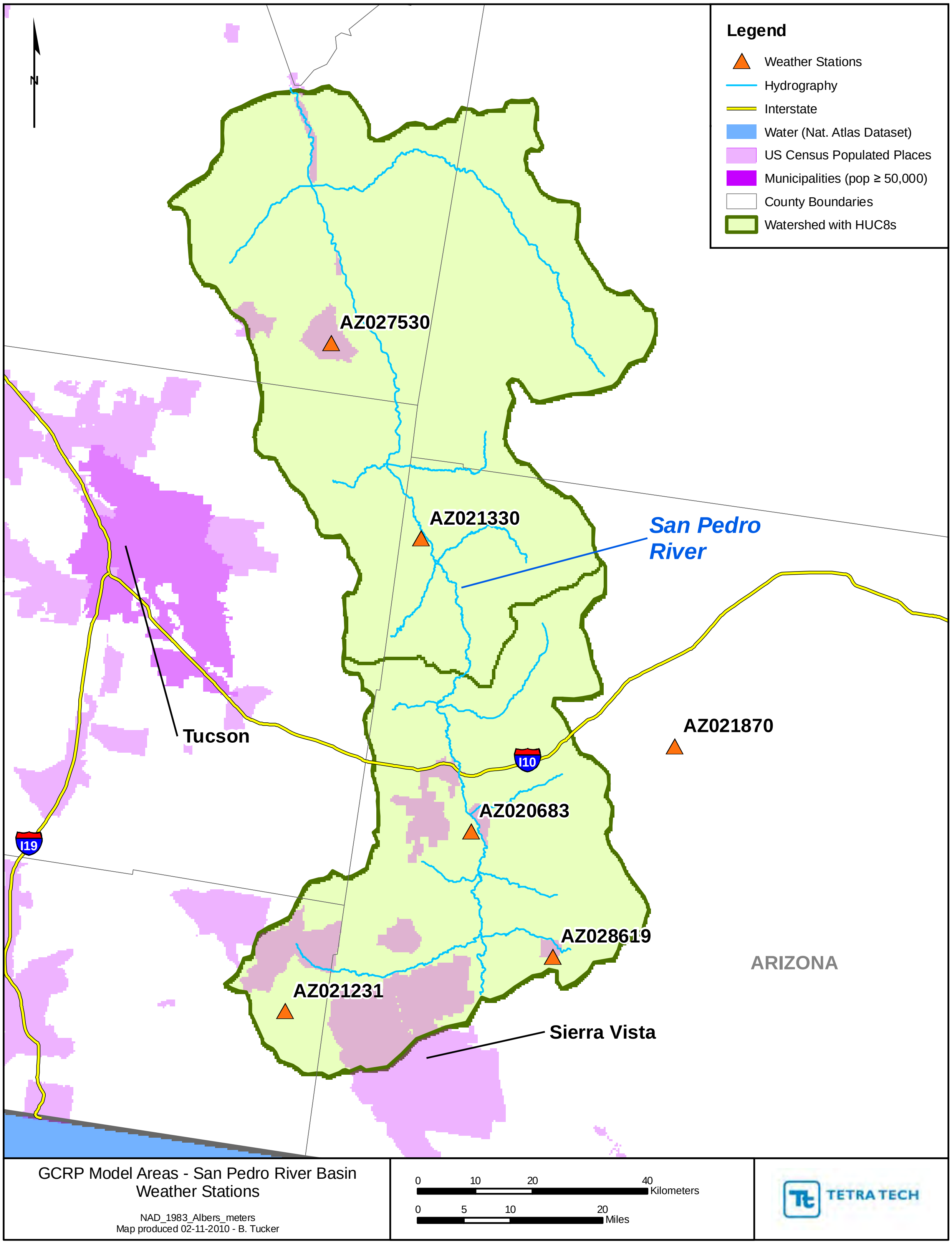

Figure 8. Weather stations for the Arizona basins model – San Pedro River section.

Watershed Segmentation

The Arizona basins were divided into 81 subwatersheds for the purposes of modeling (Figure 9 and Figure 10) – 30 in the Verde, 28 in the Salt, and 23 in the San Pedro river models. Initial calibration was conducted on the Verde River at Clarkdale. However, the parameters derived at this station were not fully transferable to other portions of the watershed, and additional calibration was conducted at multiple gage locations.

The Verde and Salt River models encompass entire watersheds upstream of major reservoirs – thus upstream boundary conditions are not required. However, for the Verde River watershed, boundary conditions are needed to account for the large influx of deep groundwater (much of it ultimately derived from infiltration many miles away in the Chino watershed) that enters the river in the reach near Paulden, Arizona.

The San Pedro River watershed extends into Mexico; however, the geospatial and meteorological data used to build the 20 Watershed models do not cover Mexico. Therefore, the San Pedro is simulated with an upstream boundary condition at the USGS gage on the San Pedro River at Charleston, Arizona (09471000). This is the most upstream gage with near complete records for the simulation period; the gage at Palominas (09470500), although closer to the Mexican border, has long periods of missing records.

Major reservoirs are generally avoided in the model setup; however, it is also necessary to account for storage in smaller reservoirs and stock ponds. For SWAT, these are specified using the Ponds option, based on information in ADWR (2009) and, for the Verde watershed, Tetra Tech (2001). Significant pond storage is considered in subwatersheds 11, 13, 15, 16, 17, 18, 19, 23, 25, 26, and 27 for the Verde River watershed. In the Salt River watershed there are reservoirs with nominal storage capacity near 25,000 acre feet in subwatersheds 20 and 21, although the normal capacity is only a fraction of this total. As these are headwater subwatersheds, these reservoirs are also treated as ponds. No reservoirs or ponds are simulated in the San Pedro watershed.

It should be noted that Sullivan Lake, at the head of the perennial portion of the Verde River watershed (subwatershed 14), intercepts flows out of the Chino watershed and has a significant impact on the progression of flood waves downstream. This lake is not directly represented in the model due to lack of information on storage characteristics.

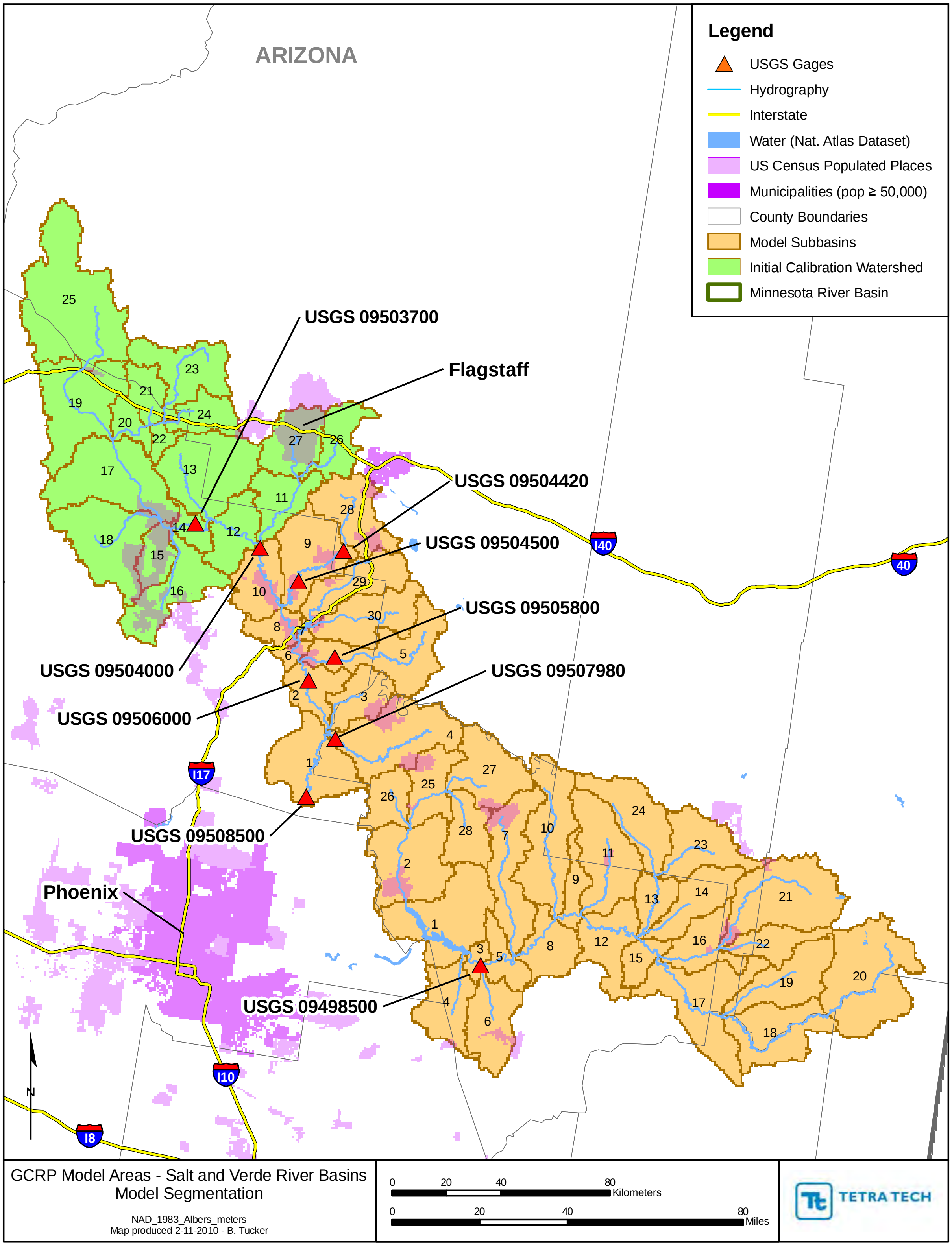

Figure 9. Model segmentation USGS stations utilized for the Arizona basins – Verde and Salt River section.

Note: SWAT subwatersheds numbering is shown; the HSPF model for this watershed uses the same subwatershed boundaries with an alternative internal numbering scheme.

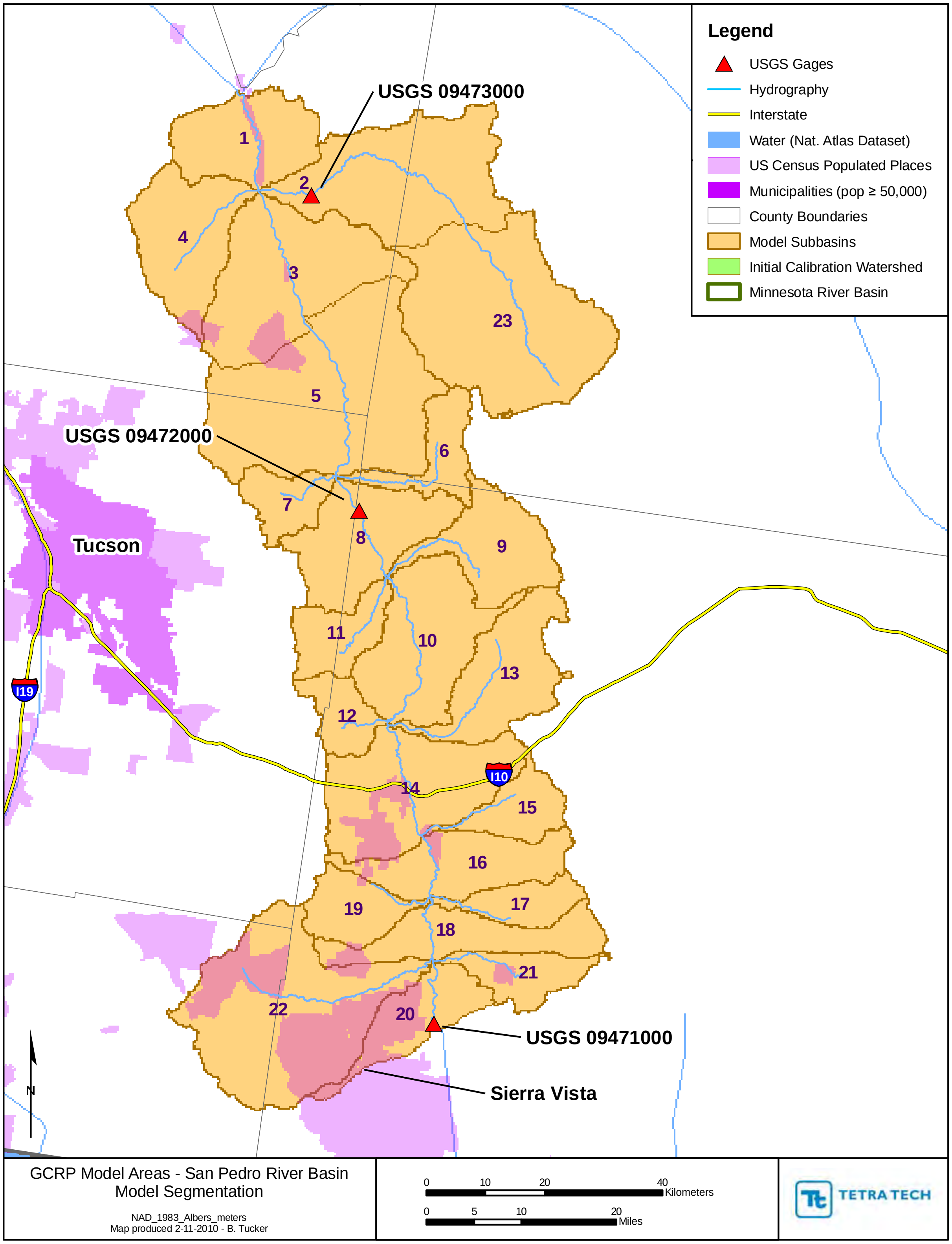

Figure 10. Model segmentation USGS stations utilized for the Arizona basins – San Pedro River section.

Note: SWAT subwatersheds numbering is shown; the HSPF model for this watershed uses the same subwatershed boundaries with an alternative internal numbering scheme.

Calibration Data and Locations

The site selected for initial calibration was the Verde River near Clarkdale, AZ (USGS gage 09504000); however, calibration and validation were pursued at multiple locations (Table 5, Figure 9 and Figure 10).

Table 5. Calibration and validation locations in the Arizona basins

Station name	USGS ID	Drainage area (mi^2)	Hydrology calibration	Water quality calibration
San Pedro River near Redington, AZ	09472000	2,927	X	
Aravaipa Creek near Mammoth,AZ	09473000	537	X	
Salt River near Roosevelt, AZ	09498500	4,306	X	X
Verde River near Paulden, AZ	09503700	2,507	X	
Verde River near Clarkdale, AZ	09504000	3,503	X	X
Oak Creek near Cornville, AZ	09504500	355	X	
West Clear Creek near Camp Verde, AZ	09505800	241	X	
Verde River near Camp Verde, AZ	09506000	5,009	X	X
East Verde River near Childs, AZ	09507980	331	X	
Verde River below Tangle Creek	09508500	5,858	X	X

The model hydrology calibration period was set to Water Years 1993-2002, with some variation according to gage variability. The end date was constrained by the common period of the set of 20 Watershed meteorological stations available for the watershed, and a 10 year calibration period was desired. Calibration was done on the later data, because of concerns that there may have been changes in land use and management over time. Hydrologic validation was then performed on Water Years 1983-1992. Water quality calibration used calendar years 1993-2002, while validation used 1986-1992, as limited data were available prior to 1986.

Other Relevant Features

Along the mainstem of the Verde River between Clarkdale and Camp Verde and on several tributaries there are substantial water diversions to support riparian agricultural production, primarily hay. ADWR (2000) identifies 24 diversion structures on the Verde River proper from near Clarkdale to below Camp Verde, 32 diversions along Oak Creek, and 12 diversions along Wet Beaver Creek, as well as several in other locations, and estimates that the total agricultural diversion amount between Perkinsville and Horseshoe Reservoir (most of it occurring in the Verde Valley, Oak Creek, and Wet Beaver Creek) amounts to 31,668 acre-feet per year. Very little of the water diverted for irrigation returns as surface flow (Owen-Joyce and Bell 1983); however, a substantial portion may return as subsurface flow. The water applied from these diversions is represented as irrigation applications in the model. During development of the previous SWAT model for the Verde it was found that a direct linkage of irrigation applications to river withdrawals did not provide satisfactory results and indeed tended to cause model instability. Therefore, the withdrawals and irrigation are uncoupled in the model: irrigation is represented as nominally occurring from an external source, while withdrawals from the river are specified separately as a consumptive use that occurs during the April-September growing season. Consumptive use withdrawals are applied to Verde model subwatersheds 6, 8, 9, 10, and 30. The status of agricultural diversions in the Salt and San Pedro watersheds is not fully known; however, growing season diversions from the river are assigned to improve flow closure, being assigned to subwatershed 8 in the San Pedro watershed and subwatershed 5 in the Salt River watershed.

A separate representation is used for the Prescott Valley area of the Verde River watershed model (subwatershed 16). Here, agriculture is supported by water stored in two small reservoirs (Granite and Willow). For this subwatershed, irrigation is represented as linked to and derived from water stored in these reservoirs (represented as ponds in the SWAT model).

Special notes are required regarding the East Verde River (Verde model subwatershed 4). The town of Payson, Arizona obtains its municipal supply from groundwater, which is pumped from the alluvium of the East Verde. The groundwater supply appears to be directly connected to surface water, and causes the East Verde to go dry at times. However, there is also a source of imported water in the East Verde, as water is brought from across the Mogollon Rim divide and discharged into the East Verde to augment Payson supplies. Detailed documentation was not obtained. For the purposes of the 20 Watershed model it is assumed that the imported water is essentially all consumed by Payson. Therefore, the stream is simulated as a losing reach, but the imported water is not explicitly simulated. Payson's wastewater discharges leave the watershed, and are primarily used for golf course irrigation in the Tonto Creek watershed (subwatershed 26 in the Salt River model).

HSPF Modeling

Changes Made to Base Data Provided

No changes were made to the meteorological or land use base data. Similar to the SWAT modeling, the Globe, Arizona point source total nitrogen and total phosphorus concentrations were reduced, since the recommended concentrations did not permit a reasonable calibration of total nitrogen and total phosphorus at the Roosevelt station.

Assumptions

An important feature of the Arizona basins is the complex interaction of surface and groundwater. As noted earlier, neither SWAT nor HSPF is capable of providing a detailed, process-based simulation of groundwater flow. It is therefore assumed that interactions with groundwater can be handled with the following simplifying assumptions:

- The local (within subwatershed) accumulation and discharge of shallow groundwater is adequately addressed by HSPF's active groundwater formulation.
- Discharges to streams from deep groundwater are represented as constant point sources, with discharge rates set based on flow information on major springs identified in the Arizona Water Atlas (ADWR 2009). This means that the model cannot account for seasonal variability in deep groundwater discharge, nor can it evaluate how such discharges may evolve in response to climate change.
- Losses to groundwater from stream reaches in alluvial basins are simulated based on channel conductivity. This makes such losses a function of flow and depth in the affected reaches. The HSPF model formulation, which is incorporated in the stream reach FTABLEs as a volume-based loss term does not take into account changes in local groundwater head; instead, the loss occurs continuously.

In the Verde River watershed, irrigation withdrawals and applications were modeled (similarly to the SWAT model) in the Verde Valley between Clarkdale and Camp Verde based on information provided in ADWR (2009). A total of 31,668 ac-ft/yr is withdrawn during April-September from selected reaches based on the relative amounts of grass and developed area in the reach watersheds. The HSPF irrigation module was used to apply this water to the grass and developed PERLND's using a constant application of 0.11 inches/day during the April-September period.

Hydrology Calibration

The starting parameters for the Arizona HSPF model were developed from an HSPF model of the San Francisco Bay area watersheds, particularly watersheds in eastern Alameda County. After the starting parameters were inserted into the model input files, average annual potential evapotranspiration values were computed and compared to published values. Through this process it was determined the input potential evapotranspiration time series should be reduced by multipliers, since the computation of these time series produced more PET on an average annual basis than the published values indicate. The default multipliers used for PET were 0.70; however, some of the multipliers were adjusted slightly during the hydrology calibration. Calibration adjustments focused on the following parameters:

- LZSN (lower zone nominal storage): LZSN was generally reduced from the initial values to shift flows to the wet period and reduce them in the summer. It was also used to increase total runoff.

- INFILT (index to mean soil infiltration rate): Infiltration was generally decreased from the high initial values to increase storm peaks, reduce low flows, and increase surface runoff.
- DEEPFR (fraction of groundwater inflow that will enter deep groundwater): small values of DEEPFR were used to attempt to reduce low flows and to reduce total flow volume. In the Salt River, the initial low values were not adjusted. In the Verde River at Paulden, DEEPFR was increased to a high value to represent the recharge losses in the Chino Basin; some of this groundwater returns to the river below the Paulden gage.
- BASETP (ET by riparian vegetation): Generally BASETP was increased over the initial values in order to provide some ET by riparian vegetation and improved the simulation of low flows.
- LZETP (lower zone E-T parameter): LZETP was generally increased to reduce flow, particularly the low flows, and to reduce total volumes.
- AGWRC (Groundwater recession rate): AGWRC was typically reduced from the initial values to help reproduce the brief, sudden storms that are experienced in the Arizona basin.

Obtaining a high quality fit to hydrology in the Arizona basin is difficult with HSPF due to the importance of groundwater, which is simplistically represented in the model. As in the SWAT model, the specification of groundwater discharges as constant values and the simulation of reach losses by channel conductivity without feedback from local groundwater elevations both introduce uncertainty.

Initial calibrations were performed for the two Verde River gages at Paulden and Clarkdale. The calibration period was set to the 10 water years from 10/01/1992 to 09/30/2002. The results at Clarkdale are summarized in Figures 11 through 17 and Tables 6 and 7. The fit at Clarkdale is fairly good, although the summer storm volumes are over-simulated. Predictions at Clarkdale are largely determined by model fit upstream at Paulden, where flows about 95 percent of the time consist of approximately constant base flow. Spring peaks occasionally push through from the Chino subwatershed. Accuracy in simulating these peaks is primarily affected by lack of an accurate representation of the hydraulic behavior of Sullivan Lake, and somewhat caused by the necessity of specifying constant values for channel conductivity to account for transmission losses, when in fact these loss rates are likely much reduced during the spring wet period. Parameter modifications to improve the peak spring flows out of the Chino subwatershed result in significant over-prediction of summer storm events.

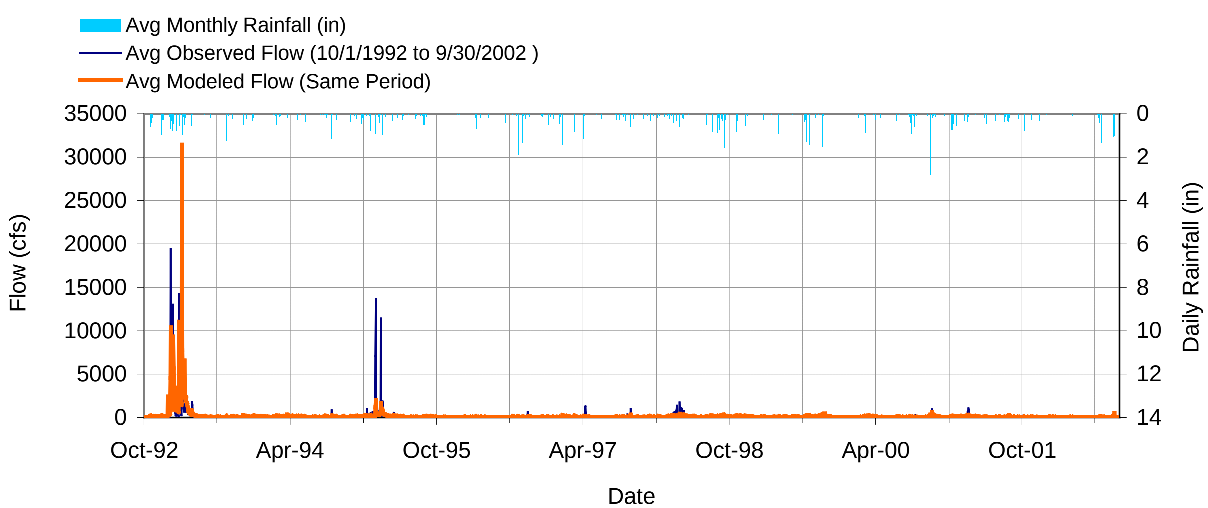

Figure 11. Mean daily flow at USGS 09504000 Verde River near Clarkdale, AZ – calibration period (HSPF).

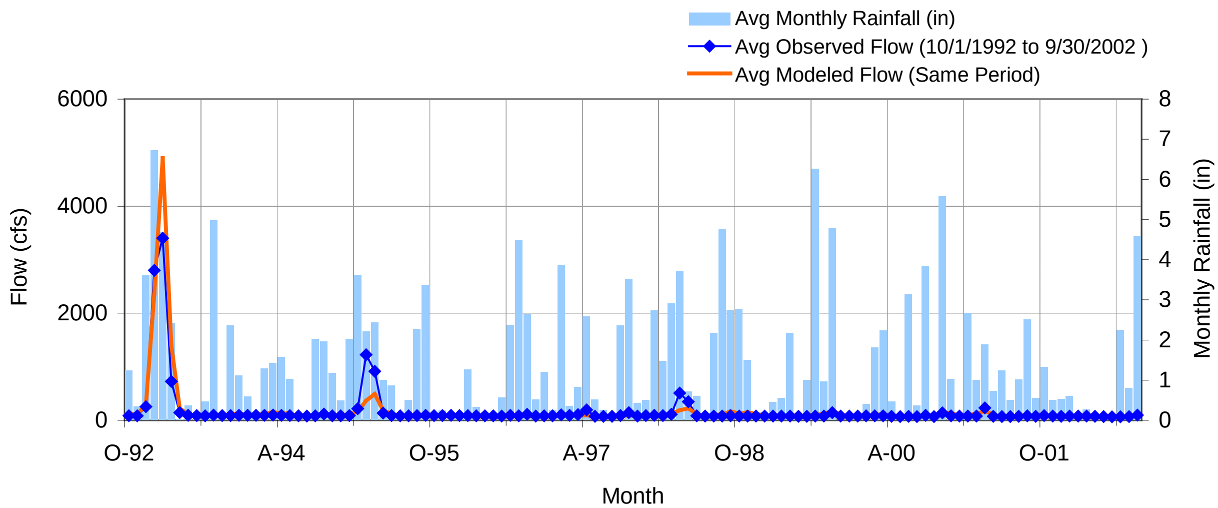

Figure 12. Mean monthly flow at USGS 09504000 Verde River near Clarkdale, AZ – calibration period (HSPF).

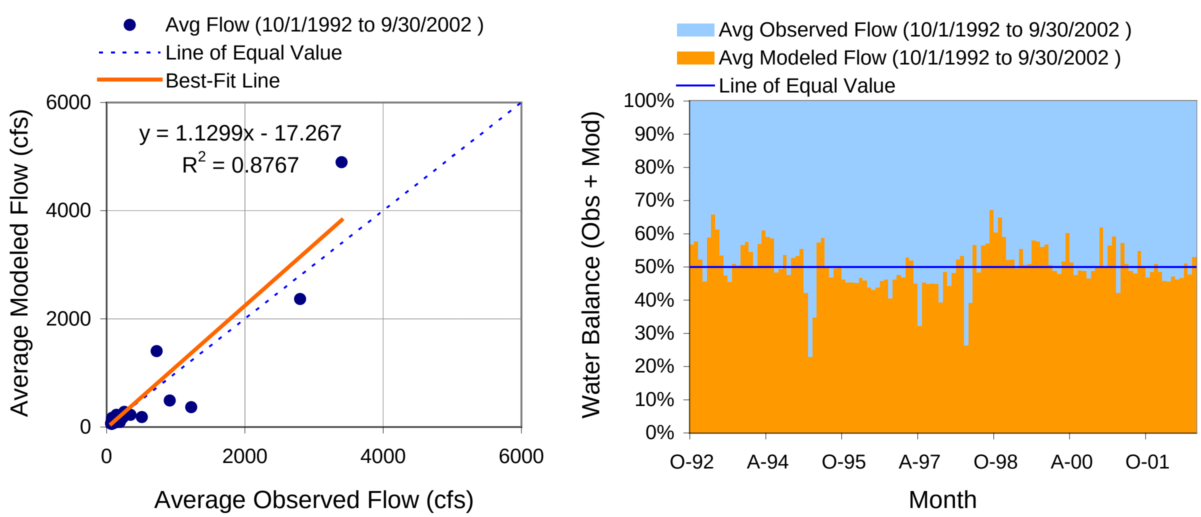

Figure 13. Monthly flow regression and temporal variation at USGS 09504000 Verde River near Clarkdale, AZ – calibration period (HSPF).

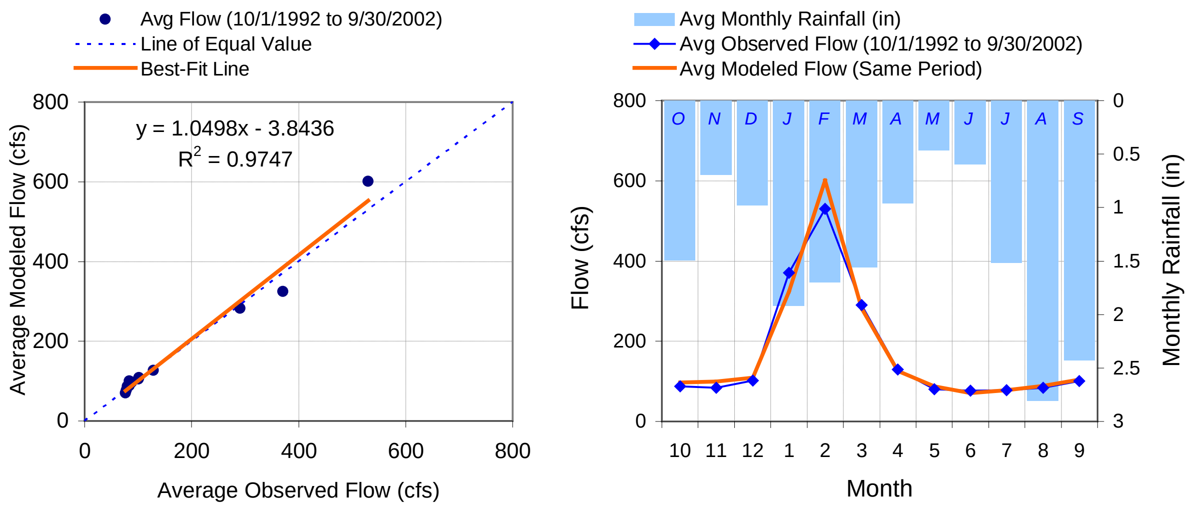

Figure 14. Seasonal regression and temporal aggregate at USGS 09504000 Verde River near Clarkdale, AZ – calibration period (HSPF).

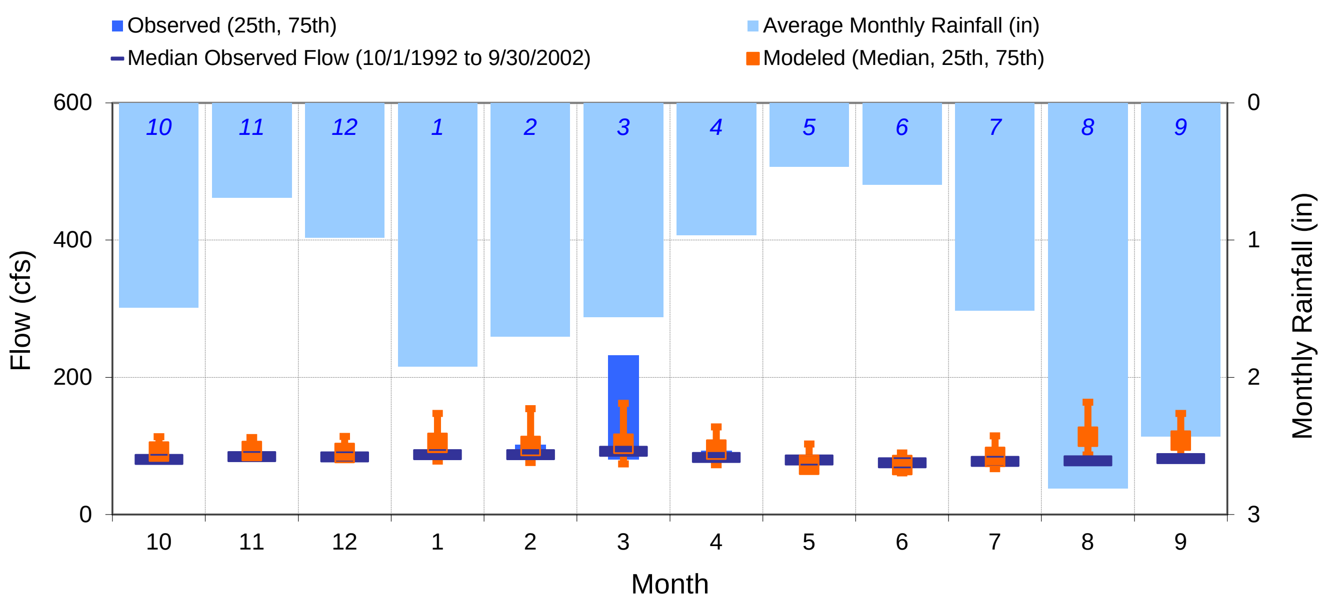

Figure 15. Seasonal medians and ranges at USGS 09504000 Verde River near Clarkdale, AZ – calibration period (HSPF).

Table 6. Seasonal summary at USGS 09504000 Verde River near Clarkdale, AZ – calibration period (HSPF)

MONTH	OBSERVED FLOW (CFS)				MODELED FLOW (CFS)			
	MEAN	MEDIAN	25TH	75TH	MEAN	MEDIAN	25TH	75TH
Oct	87.85	80.00	77.00	84.00	96.91	82.51	71.73	99.47
Nov	84.09	84.00	78.00	89.00	99.66	85.28	72.52	120.36
Dec	101.70	83.50	80.00	90.00	108.76	81.17	75.07	108.70
Jan	370.90	87.00	81.00	93.00	324.23	90.51	74.56	122.50
Feb	529.79	87.00	80.00	101.50	600.69	101.20	78.14	136.39
Mar	290.55	92.00	80.00	232.00	282.20	120.53	74.05	227.47
Apr	129.11	83.00	77.00	93.00	126.31	100.56	72.53	157.49
May	79.98	79.00	72.00	87.00	87.10	73.67	62.50	108.75
Jun	76.29	75.00	69.00	81.00	70.29	68.05	59.97	76.39
Jul	78.20	77.00	71.00	82.00	77.73	69.49	64.23	78.65
Aug	83.85	78.00	75.00	84.00	88.43	79.82	69.25	97.29
Sep	100.71	81.00	73.00	85.00	104.90	83.32	70.17	112.11

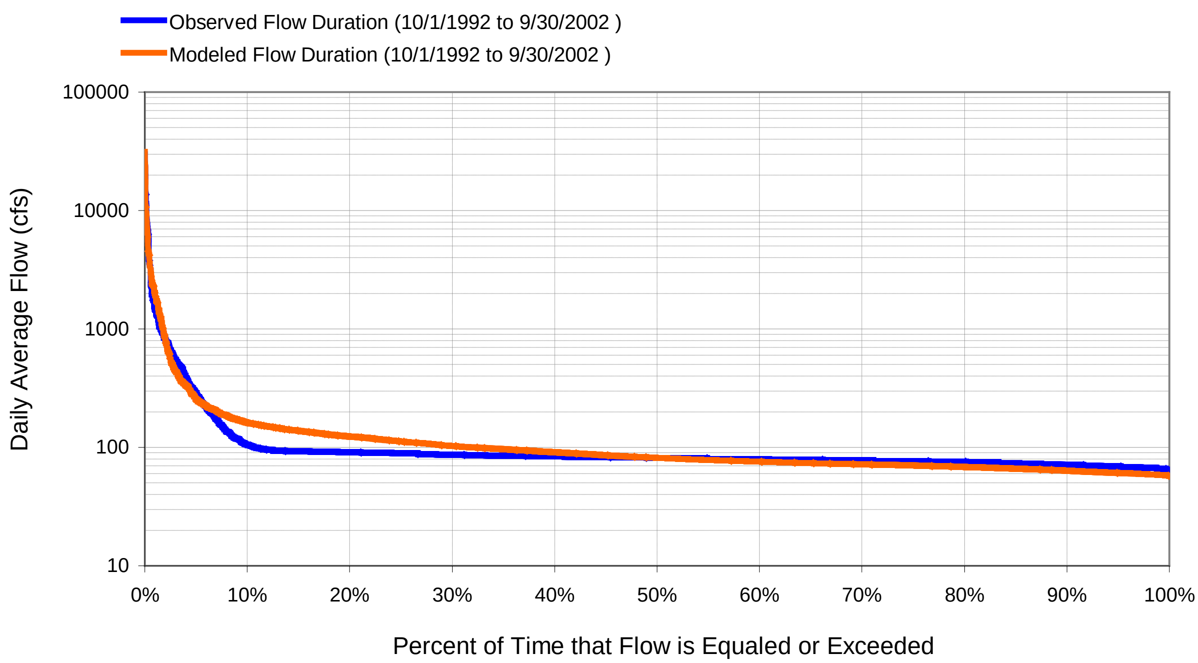

Figure 16. Flow exceedance at USGS 09504000 Verde River near Clarkdale, AZ – caalibration period (HSPF).

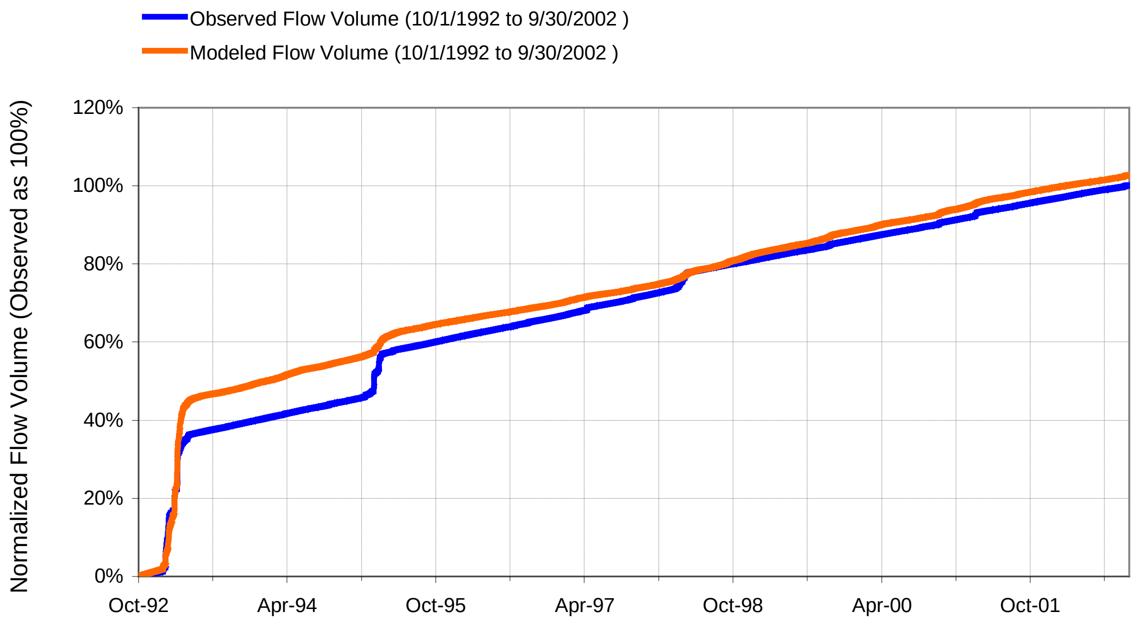

Figure 17. Flow accumulation at USGS 09504000 Verde River near Clarkdale, AZ – calibration period (HSPF).

Table 7. Summary statistics at USGS 09504000 Verde River near Clarkdale, AZ – calibration period (HSPF)

HSPF Simulated Flow		Observed Flow Gage	
REACH OUTFLOW FROM DSN 101 10-Year Analysis Period: 10/1/1992 - 9/30/2002 Flow volumes are (inches/year) for upstream drainage area		USGS 09504000 VERDE RIVER NEAR CLARKDALE, AZ Hydrologic Unit Code: 15060202 Latitude: 34.8522416 Longitude: -112.065994 Drainage Area (sq-mi): 3503	
Total Simulated In-stream Flow:	**0.66**	Total Observed In-stream Flow:	**0.64**
Total of simulated highest 10% flows:	**0.35**	Total of Observed highest 10% flows:	**0.36**
Total of Simulated lowest 50% flows:	**0.14**	Total of Observed Lowest 50% flows:	**0.15**
Simulated Summer Flow Volume (months 7-9):	**0.09**	Observed Summer Flow Volume (7-9):	**0.09**
Simulated Fall Flow Volume (months 10-12):	**0.10**	Observed Fall Flow Volume (10-12):	**0.09**
Simulated Winter Flow Volume (months 1-3):	**0.38**	Observed Winter Flow Volume (1-3):	**0.38**
Simulated Spring Flow Volume (months 4-6):	**0.09**	Observed Spring Flow Volume (4-6):	**0.09**
Total Simulated Storm Volume:	**0.25**	Total Observed Storm Volume:	**0.29**
Simulated Summer Storm Volume (7-9):	**0.02**	Observed Summer Storm Volume (7-9):	**0.01**

Errors (Simulated-Observed)	*Error Statistics*	*Recommended Criteria*
Error in total volume:	2.43	10
Error in 50% lowest flows:	-7.64	10
Error in 10% highest flows:	-1.58	15
Seasonal volume error - Summer:	3.15	30
Seasonal volume error - Fall:	11.52	30
Seasonal volume error - Winter:	0.83	30
Seasonal volume error - Spring:	-0.50	30
Error in storm volumes:	-15.79	20
Error in summer storm volumes:	44.47	50
Nash-Sutcliffe Coefficient of Efficiency, E:	0.481	Model accuracy increases
Baseline adjusted coefficient (Garrick), E':	0.485	as E or E' approaches 1.0
Monthly NSE	0.803	

Hydrology Validation

Like the SWAT modeling, validation for the Verde River near Clarkdale was performed for the period 10/1/1982 through 9/30/1992. Results are presented in Figures 18 through 24 and Tables 8 and 9. The HSPF validation results are fair, but are generally worse than during the calibration period. In particular, the storm peak volumes are under-predicted, likely due to the effort to reduce summer storm peaks in the calibration.

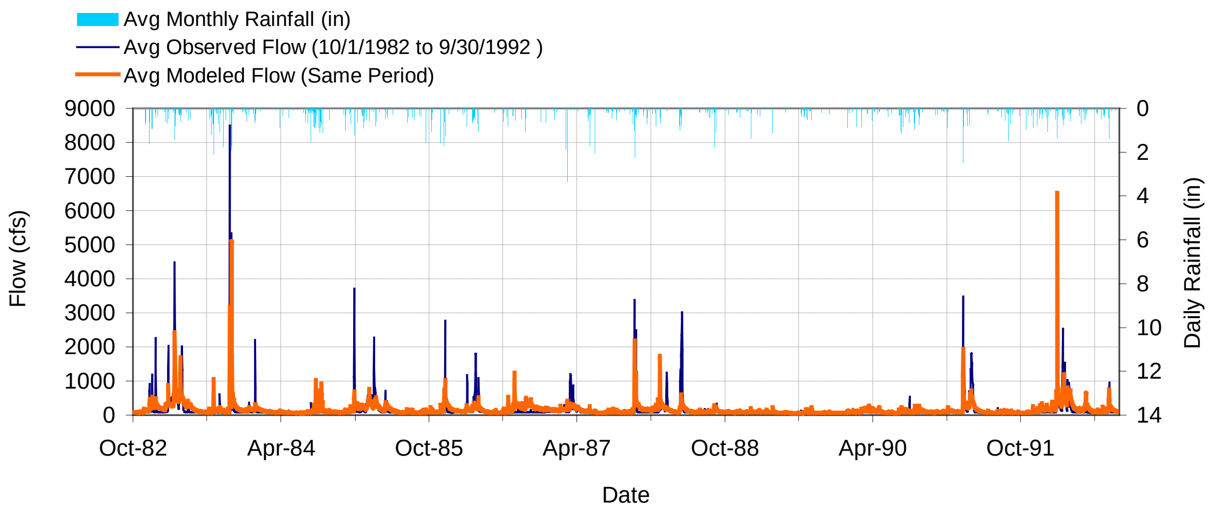

Figure 18. Mean daily flow at USGS 09504000 Verde River near Clarkdale, AZ – validation period (HSPF).

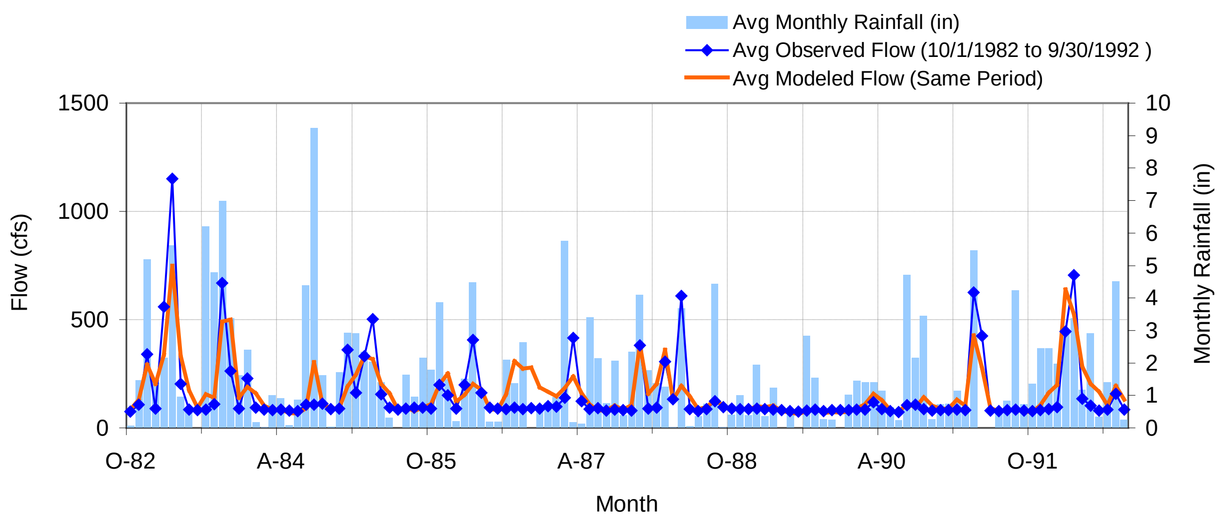

Figure 19. Mean monthly flow at USGS 09504000 Verde River near Clarkdale, AZ – validation period (HSPF).

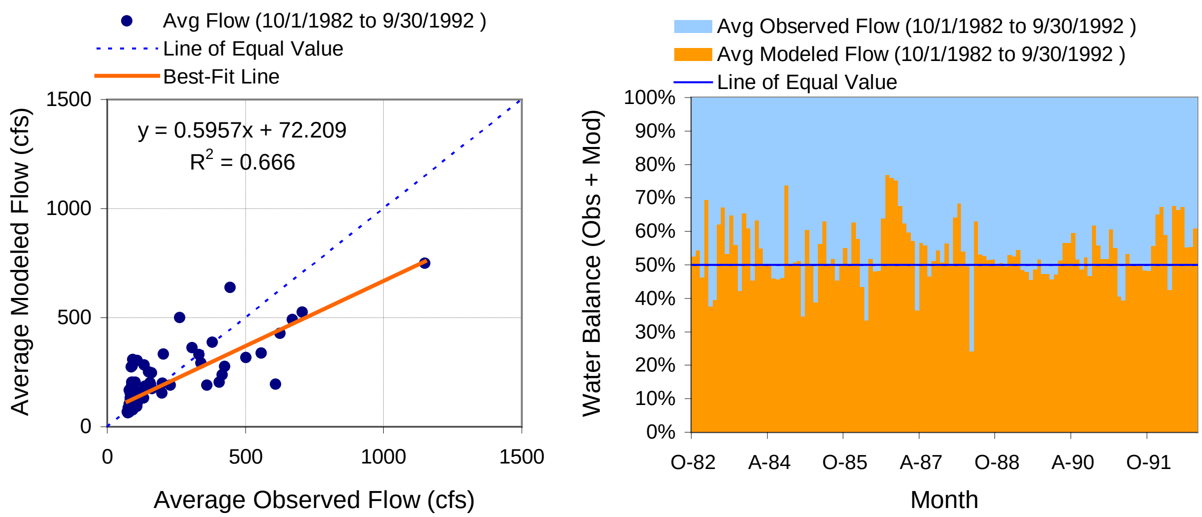

Figure 20. Monthly flow regression and temporal variation at USGS 09504000 Verde River near Clarkdale, AZ – validation period (HSPF).

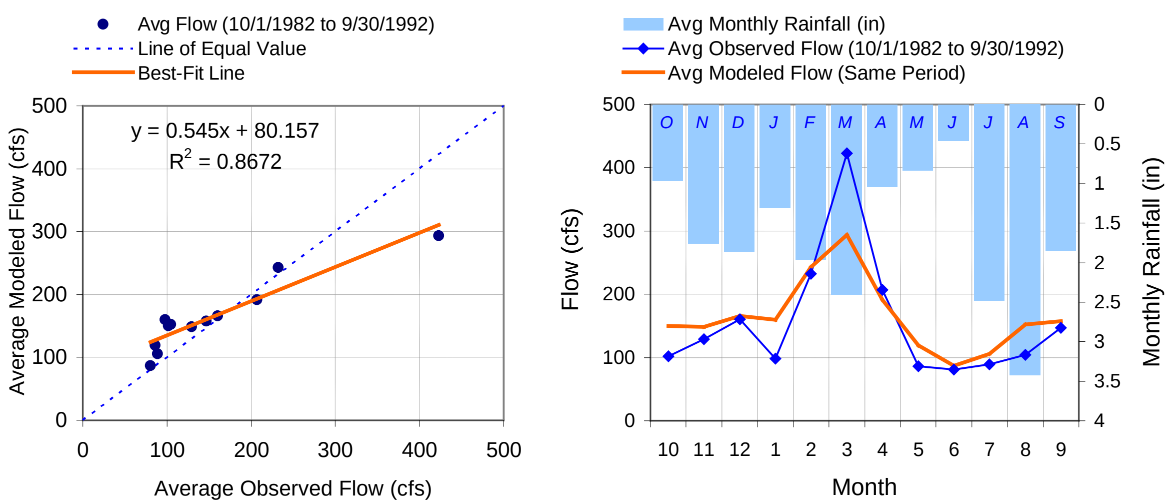

Figure 21. Seasonal regression and temporal aggregate at USGS 09504000 Verde River near Clarkdale, AZ – validation period (HSPF).

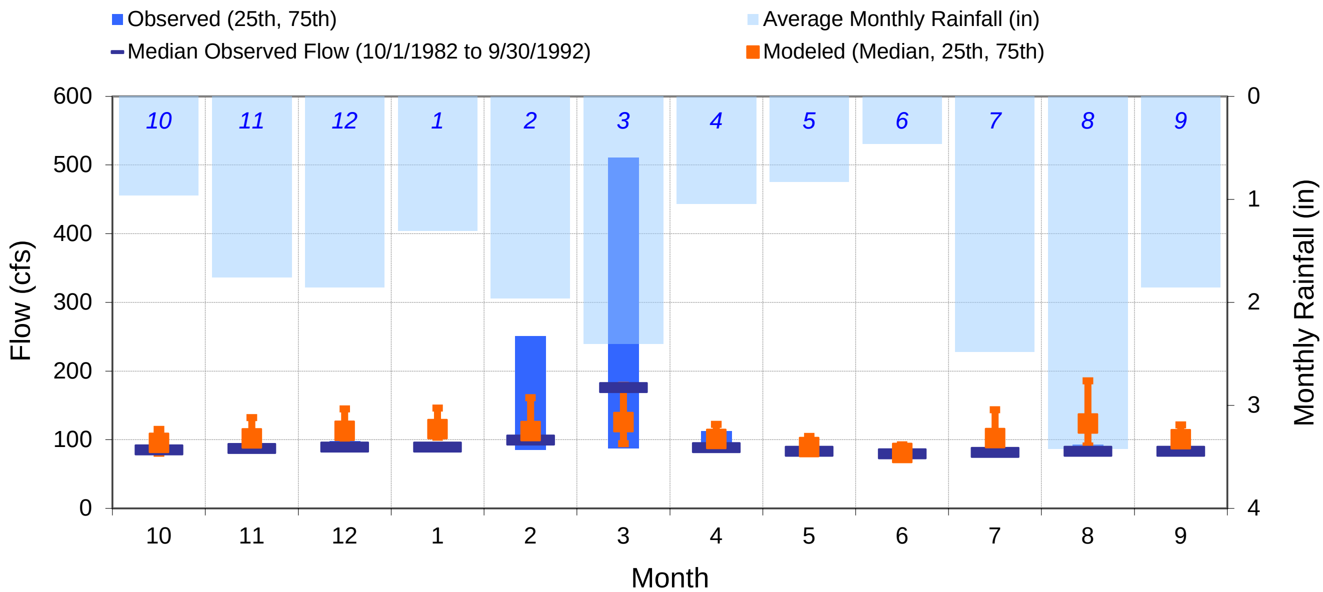

Figure 22. Seasonal medians and ranges at USGS 09504000 Verde River near Clarkdale, AZ – validation period (HSPF).

Table 8. Seasonal summary at USGS 09504000 Verde River near Clarkdale, AZ – validation period (HSPF)

MONTH	OBSERVED FLOW (CFS)				MODELED FLOW (CFS)			
	MEAN	MEDIAN	25TH	75TH	MEAN	MEDIAN	25TH	75TH
Oct	101.69	85.00	79.00	88.00	150.26	89.46	80.07	122.85
Nov	129.11	87.00	84.00	89.00	148.72	105.69	81.49	160.11
Dec	160.55	89.00	85.00	98.00	165.82	151.17	88.08	189.05
Jan	97.85	89.00	86.00	94.75	159.89	143.90	116.52	188.96
Feb	232.11	99.00	85.00	251.00	242.85	156.86	99.85	273.47
Mar	422.76	175.50	87.00	510.50	293.60	219.66	118.37	364.94
Apr	206.73	88.00	83.00	113.00	191.47	149.35	98.93	249.64
May	86.31	83.00	80.00	88.00	119.35	99.69	76.30	136.06
Jun	80.68	79.00	76.75	85.00	86.81	75.84	68.37	89.21
Jul	89.01	81.00	77.00	86.75	105.71	87.23	76.53	109.19
Aug	104.45	83.00	79.00	93.00	152.50	102.41	80.53	154.85
Sep	146.81	83.00	79.00	89.00	157.50	95.00	78.80	132.27

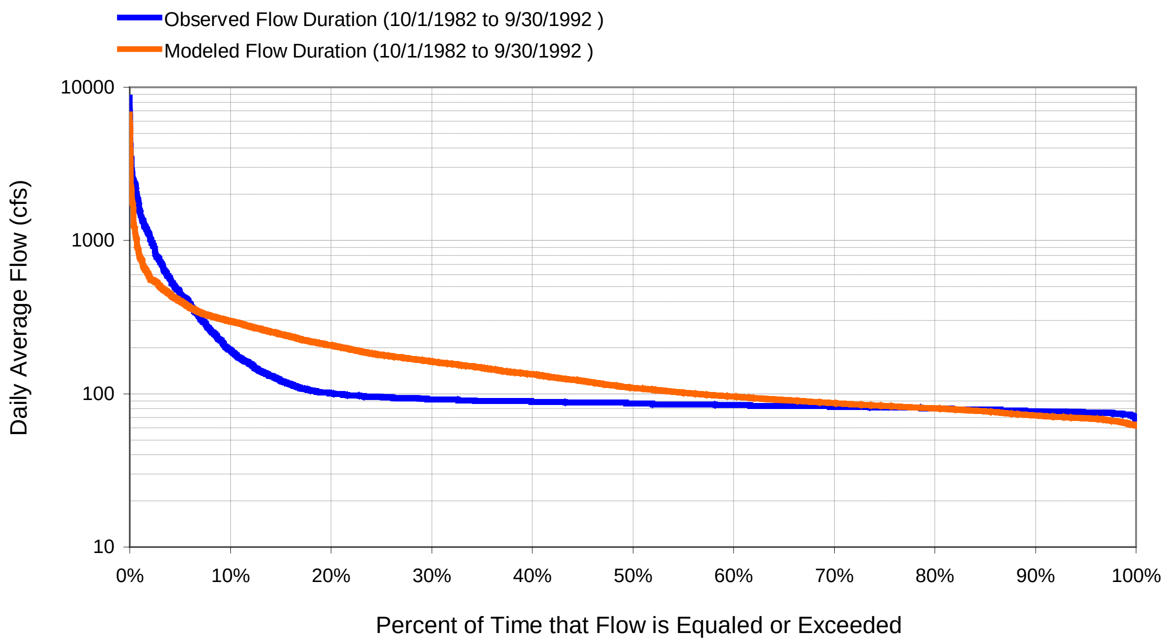

Figure 23. Flow exceedance at USGS 09504000 Verde River near Clarkdale, AZ – validation period (HSPF).

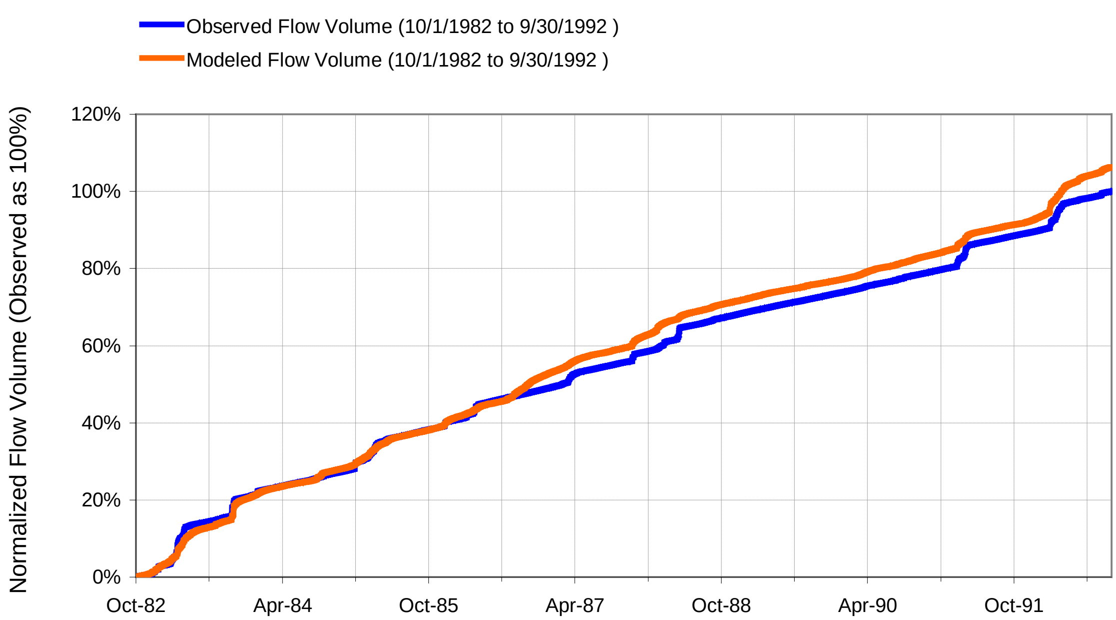

Figure 24. Flow accumulation at USGS 09504000 Verde River near Clarkdale, AZ – validation period (HSPF).

Table 9. Summary statistics at USGS 09504000 Verde River near Clarkdale, AZ – validation period (HSPF)

HSPF Simulated Flow		Observed Flow Gage	
REACH OUTFLOW FROM DSN 101 10-Year Analysis Period: 10/1/1982 - 9/30/1992 Flow volumes are (inches/year) for upstream drainage area		USGS 09504000 VERDE RIVER NEAR CLARKDALE, AZ Hydrologic Unit Code: 15060202 Latitude: 34.8522416 Longitude: -112.065994 Drainage Area (sq-mi): 3503	
Total Simulated In-stream Flow:	**0.64**	Total Observed In-stream Flow:	**0.60**
Total of simulated highest 10% flows:	**0.21**	Total of Observed highest 10% flows:	**0.29**
Total of Simulated lowest 50% flows:	**0.16**	Total of Observed Lowest 50% flows:	**0.16**
Simulated Summer Flow Volume (months 7-9):	**0.14**	Observed Summer Flow Volume (7-9):	**0.11**
Simulated Fall Flow Volume (months 10-12):	**0.15**	Observed Fall Flow Volume (10-12):	**0.13**
Simulated Winter Flow Volume (months 1-3):	**0.22**	Observed Winter Flow Volume (1-3):	**0.24**
Simulated Spring Flow Volume (months 4-6):	**0.13**	Observed Spring Flow Volume (4-6):	**0.12**
Total Simulated Storm Volume:	**0.17**	Total Observed Storm Volume:	**0.23**
Simulated Summer Storm Volume (7-9):	**0.05**	Observed Summer Storm Volume (7-9):	**0.03**

Errors (Simulated-Observed)	*Error Statistics*	*Recommended Criteria*		
Error in total volume:	6.31	10		
Error in 50% lowest flows:	3.34	10		
Error in 10% highest flows:	**-27.25**	**15**		
Seasonal volume error - Summer:	22.38	30		
Seasonal volume error - Fall:	18.80	>> 30	Clear	
Seasonal volume error - Winter:	-7.82	30		
Seasonal volume error - Spring:	6.64	30		
Error in storm volumes:	**-27.53**	**20**		
Error in summer storm volumes:	39.20	50		
Nash-Sutcliffe Coefficient of Efficiency, E:	0.451	Model accuracy increases		
Baseline adjusted coefficient (Garrick), E':	0.325	as E or E' approaches 1.0		
Monthly NSE	0.655			

Hydrology Results for Larger Watershed

As described above, parameters determined through calibration to the Verde River near Paulden and Clarkdale gages were not fully transferable to other gages in the watershed. Hydrology calibration was performed at a total of 10 gages in the Arizona basins – 6 in the Verde River watershed, 1 in the Salt River watershed, and 2 in the San Pedro River watershed. Only the gage at Roosevelt provides a long period of record for the Salt River watershed. The mainstem gage for the San Pedro River does not provide a rigorous calibration test because its flow is largely determined by the upstream boundary condition. Therefore, calibration was also performed on perennial Aravaipa Creek. The San Pedro gages ceased operation in 1995; therefore calibration was pursued over an earlier time period without a separate validation test.

Calibration results at all gages are summarized in Table 10 and are generally of similar quality to the fit obtained on the Verde River near Clarkdale. The generally close match between observed and predicted flow at the Salt River gage is shown in Figures 25 through 31 and Tables 11 and 12. Results of the validation exercise are summarized in Table 13. In general, the quality of fit during the validation period is similar to that in the calibration period, with some reductions in fit for some of the seasonal volume error terms, and also some improvements. The model is judged to be useful for scenario evaluation.

Table 10.Summary statistics (percent error) for all stations – calibration period WY 1992-2002 (HSPF)

Station	09472000 San Pedro nr Redington (1972-95)*	09473000 Aravaipa Crk nr Mammoth (1972-95)	09498500 Salt River nr Roosevelt	09503700 Verde River nr Paulden	09504000 Verde River nr Clarkdale	09504500 Oak Creek nr Cornville	09505800 W Clear Cr nr Camp Verde	09506000 Verde River nr Camp Verde	09507980 E Verde River nr Childs	09508500 Verde R below Tangle Cr
Error in total volume:	8.73	-2.49	4.48	9.41	2.43	2.64	7.50	-2.41	1.00	-5.03
Error in 50% lowest flows:	NA*	-3.74	2.24	8.37	-7.64	-12.56	-7.97	-34.63	64.01	-17.25
Error in 10% highest flows:	-5.26	1.89	7.56	5.57	-1.58	0.51	2.60	6.79	-1.53	-2.42
Seasonal volume error - Summer:	22.67	-0.61	20.18	20.17	3.15	-5.58	-3.67	-34.15	-4.49	-19.87
Seasonal volume error - Fall:	8.64	-7.68	11.78	15.98	11.52	24.57	13.45	-5.83	2.62	0.44
Seasonal volume error - Winter:	-3.27	2.64	2.79	5.12	0.83	7.67	1.00	6.53	1.47	-1.97
Seasonal volume error - Spring:	25.98	-11.01	-1.82	9.84	-0.50	-33.23	37.02	-18.47	-0.25	-14.97
Error in storm volumes:	-4.82	-13.40	30.67	-12.00	-15.79	-18.12	-33.88	-10.81	-11.92	-16.42
Error in summer storm volumes:	11.07	-3.99	21.62	111.20	44.47	-8.02	-44.53	-42.63	-57.76	-36.53
Daily Nash-Sutcliffe Coefficient, E:	0.574	0.553	0.529	0.624	0.481	0.078	0.451	0.661	0.689	0.703
Monthly Nash-Sutcliffe Coefficient, E:	0.908	0.425	0.930	0.835	0.803	0.443	0.803	0.803	0.946	0.921

*Note that median flow for the San Pedro River nr Redington is 0.

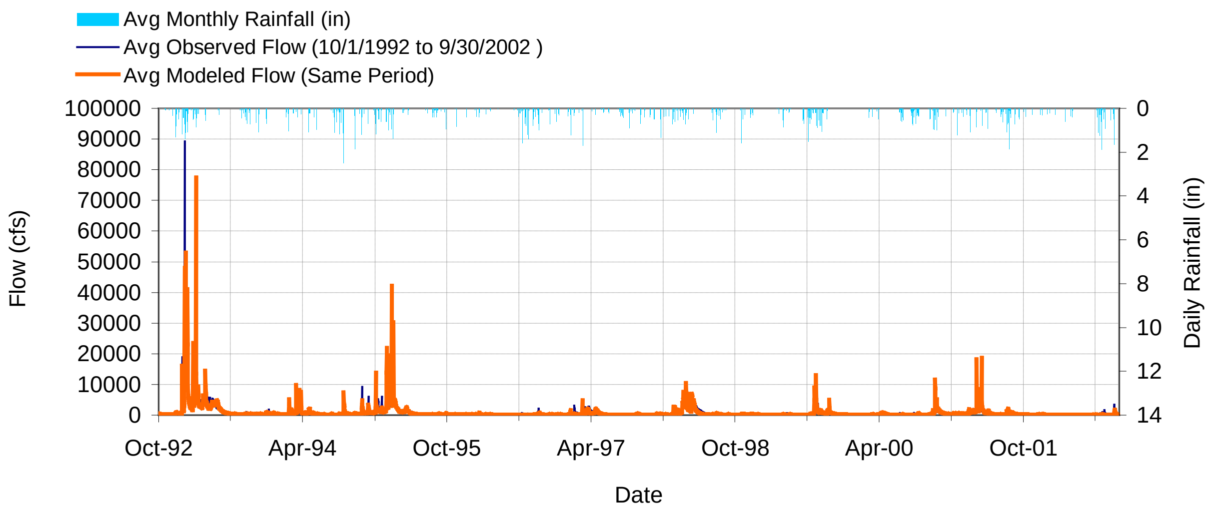

Figure 25. Mean daily flow at USGS 09498500 Salt River near Roosevelt, AZ – calibration period (HSPF).

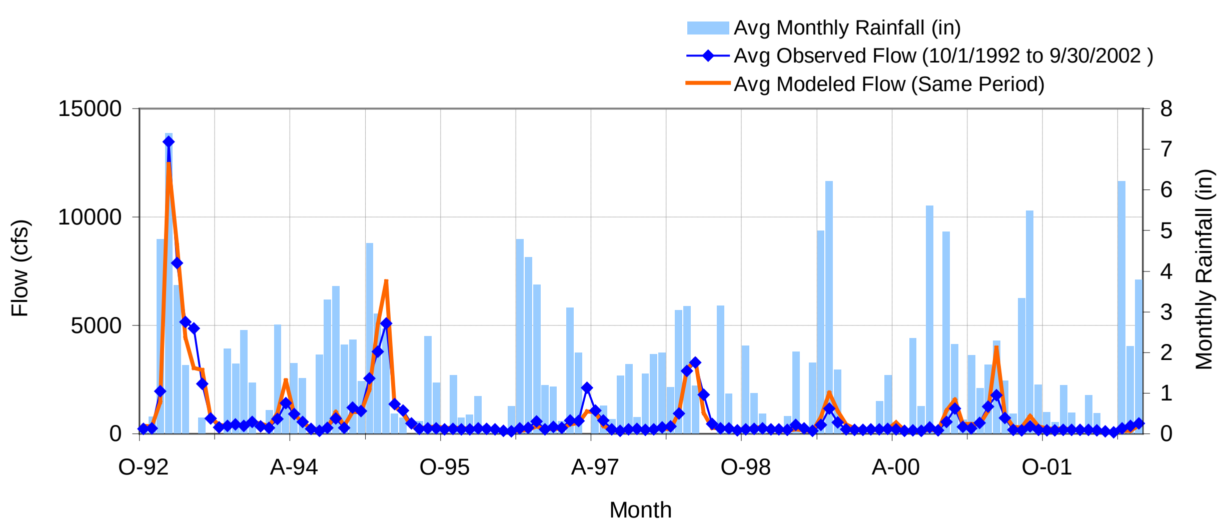

Figure 26. Mean monthly flow at USGS 09498500 Salt River near Roosevelt, AZ – calibration period (HSPF).

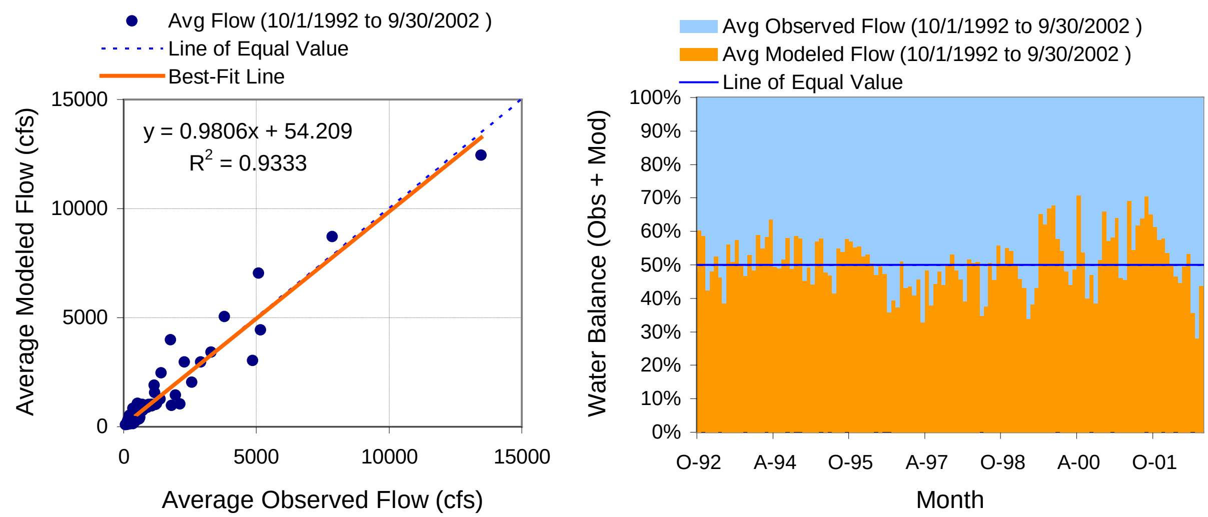

Figure 27. Monthly flow regression and temporal variation at USGS 09498500 Salt River near Roosevelt, AZ – calibration period (HSPF).

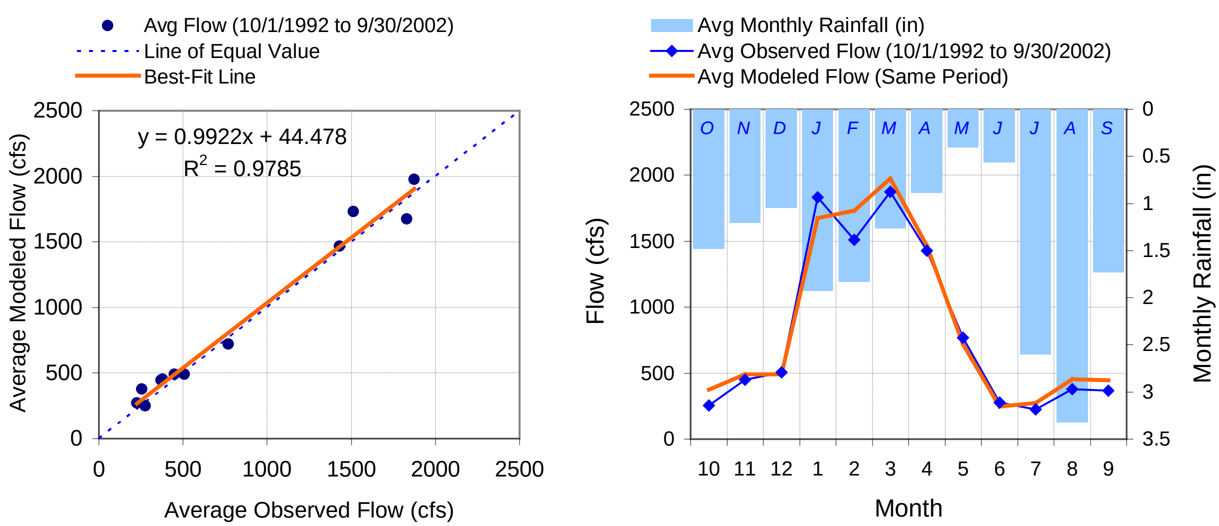

Figure 28. Seasonal regression and temporal aggregate at USGS 09498500 Salt River near Roosevelt, AZ – calibration period (HSPF).

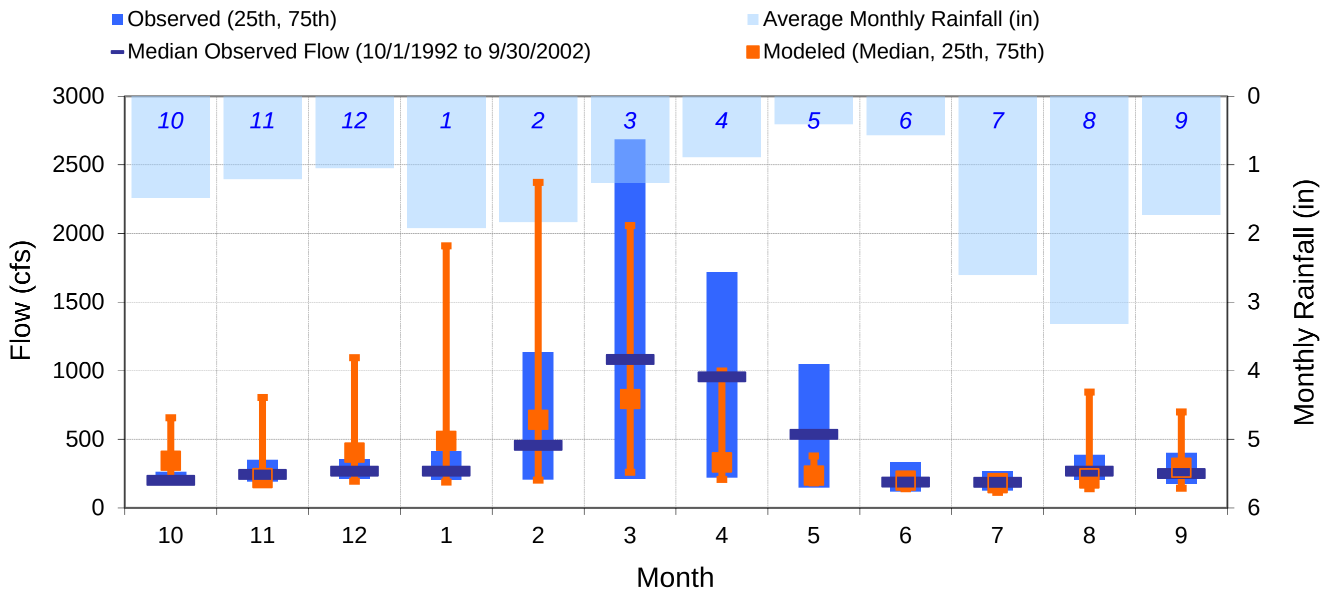

Figure 29. Seasonal medians and ranges at USGS 09498500 Salt River near Roosevelt, AZ – calibration period (HSPF).

Table 11.Seasonal summary at USGS 09498500 Salt River near Roosevelt, AZ – calibration period (HSPF)

MONTH	OBSERVED FLOW (CFS)				MODELED FLOW (CFS)			
	MEAN	MEDIAN	25TH	75TH	MEAN	MEDIAN	25TH	75TH
Oct	256.42	200.50	168.25	264.00	376.63	271.58	214.51	372.78
Nov	450.48	243.00	195.00	352.75	490.17	278.03	229.85	404.40
Dec	507.61	267.50	210.00	356.25	490.28	291.03	228.54	484.15
Jan	1831.48	267.00	204.00	413.25	1674.43	251.55	204.76	491.75
Feb	1511.59	455.50	206.00	1135.00	1731.21	340.99	182.31	1074.86
Mar	1875.51	1080.00	211.50	2682.50	1974.34	725.57	200.23	2429.07
Apr	1429.55	953.50	224.00	1722.50	1465.01	750.52	218.88	1974.37
May	768.86	535.00	150.25	1047.50	718.83	397.70	136.42	761.58
Jun	277.08	187.50	121.00	335.25	247.91	194.37	104.06	307.05
Jul	226.12	185.50	129.25	269.50	272.76	193.92	123.47	274.39
Aug	377.92	267.50	205.50	389.50	452.19	229.13	158.00	366.45
Sep	368.88	249.50	174.00	402.25	444.35	316.73	198.86	415.12

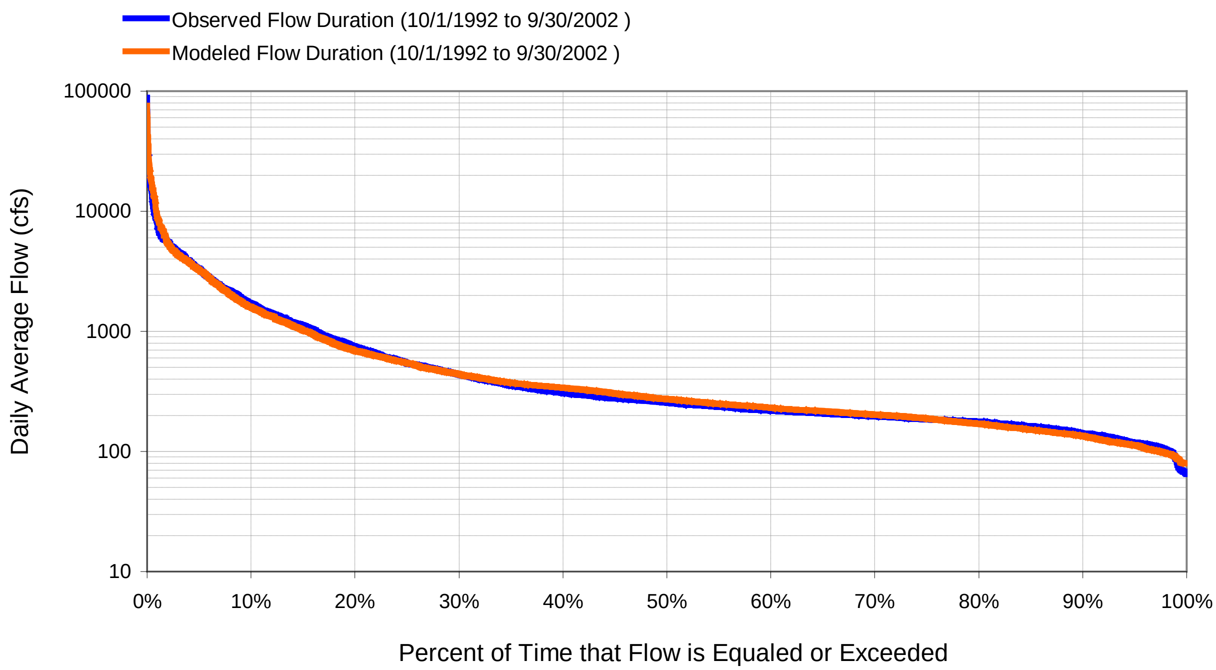

Figure 30. Flow duration at USGS 09498500 Salt River near Roosevelt, AZ – calibration period (HSPF).

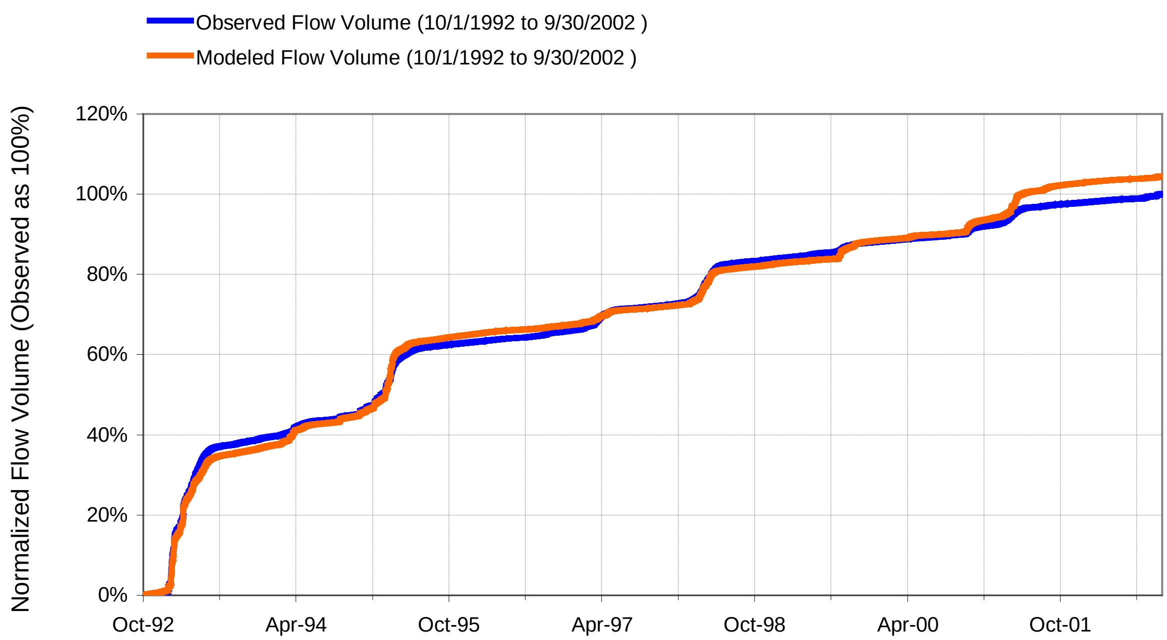

Figure 31. Flow accumulation at USGS 09498500 Salt River near Roosevelt, AZ – calibration period (HSPF).

Table 12.Summary statistics at USGS 09498500 Salt River near Roosevelt, AZ – calibration period (HSPF)

HSPF Simulated Flow		Observed Flow Gage			
REACH OUTFLOW FROM DSN 103 10-Year Analysis Period: 10/1/1992 - 9/30/2002 Flow volumes are (inches/year) for upstream drainage area		USGS 09498500 SALT RIVER NEAR ROOSEVELT, AZ Hydrologic Unit Code: 15060103 Latitude: 33.6194949 Longitude: -110.9215037 Drainage Area (sq-mi): 4306			
Total Simulated In-stream Flow:	**2.70**	Total Observed In-stream Flow:			**2.59**
Total of simulated highest 10% flows:	**1.67**	Total of Observed highest 10% flows:			**1.56**
Total of Simulated lowest 50% flows:	**0.29**	Total of Observed Lowest 50% flows:			**0.29**
Simulated Summer Flow Volume (months 7-9):	**0.31**	Observed Summer Flow Volume (7-9):			**0.26**
Simulated Fall Flow Volume (months 10-12):	**0.36**	Observed Fall Flow Volume (10-12):			**0.32**
Simulated Winter Flow Volume (months 1-3):	**1.40**	Observed Winter Flow Volume (1-3):			**1.36**
Simulated Spring Flow Volume (months 4-6):	**0.64**	Observed Spring Flow Volume (4-6):			**0.65**
Total Simulated Storm Volume:	**1.22**	Total Observed Storm Volume:			**0.94**
Simulated Summer Storm Volume (7-9):	**0.11**	Observed Summer Storm Volume (7-9):			**0.09**
Errors (Simulated-Observed)	*Error Statistics*	*Recommended Criteria*			
Error in total volume:	4.48	10			
Error in 50% lowest flows:	2.24	10			
Error in 10% highest flows:	7.56	15			
Seasonal volume error - Summer:	20.18	30			
Seasonal volume error - Fall:	11.78	>> 30		Clear	
Seasonal volume error - Winter:	2.79	30			
Seasonal volume error - Spring:	-1.82	30			
Error in storm volumes:	**30.67**	**20**			
Error in summer storm volumes:	21.62	50			
Nash-Sutcliffe Coefficient of Efficiency, E:	0.529	Model accuracy increases			
Baseline adjusted coefficient (Garrick), E':	0.539	as E or E' approaches 1.0			
Monthly NSE	0.930				

Table 13.Summary statistics for all stations – validation period WY 1982-1992 (HSPF)

Station	09498500 Salt River nr Roosevelt	09503700 Verde River nr Paulden	09504000 Verde River nr Clarkdale	09504500 Oak Creek nr Cornville	09505800 W Clear Cr nr Camp Verde	09507980 E Verde River nr Childs	09508500 Verde R below Tangle Cr
Error in total volume:	-7.09	8.35	6.31	15.32	-9.69	31.18	-6.93
Error in 50% lowest flows:	-9.03	5.07	3.34	3.54	-9.99	8.49	-21.11
Error in 10% highest flows:	6.64	-11.57	-27.25	-9.47	-17.07	45.18	-13.91
Seasonal volume error - Summer:	16.38	-4.29	22.38	61.67	-26.78	-17.15	24.90
Seasonal volume error - Fall:	4.66	13.22	18.80	15.76	-37.41	28.39	-10.34
Seasonal volume error - Winter:	-26.48	16.64	-7.82	6.84	7.66	65.55	-5.86
Seasonal volume error - Spring:	1.49	8.64	6.64	12.03	-17.93	-26.11	-25.48
Error in storm volumes:	16.98	-14.00	-27.53	-17.61	-51.19	34.57	-16.03
Error in summer storm volumes:	40.28	-20.94	39.20	86.24	-74.51	-43.69	78.31
Daily Nash-Sutcliffe Coefficient of Efficiency, E:	0.354	0.443	0.451	0.545	0.232	-0.119	0.510
Monthly Nash-Sutcliffe Coefficient of Efficiency, E	0.786	0.614	0.320	0.755	0.655	0.335	0.809

Water Quality Calibration and Validation

The 20 Watershed models are designed to provide water quality simulation for total suspended solids (TSS), total nitrogen, and total phosphorus. The water quality calibration focuses on the replication of monthly loads, as specified in the project QAPP. Given the simplified approach to water quality simulation in the 20 Watershed model a close match to individual concentration observations cannot be expected. However, comparison to monthly loads presents challenges, as monthly loads are not observed. Instead, monthly loads must be estimated from scattered concentration grab samples and continuous flow records. Such estimation presents some uncertainty because it depends on the degree and form in which concentration and flow are correlated with one another. Further, the bulk of the load of sediment and sediment-associated phosphorus is likely to move through the system in a limited number of high flow events, which usually have not been monitored. As a result, the monthly load calibration is inevitably based on the comparison of two uncertain numbers. Nonetheless, calibration is able to achieve a fair agreement. The load comparisons were supported by detailed examinations of the relationships of flows to loads and concentrations and the distribution of concentration prediction errors versus flow, time, and season, as well as standard time series plots.

For application on a nationwide basis, the 20 Watershed protocols assume that TSS and total phosphorus loads will likely exhibit a strong positive correlation to flow (and associated erosive processes), while total nitrogen loads, which often have a dominant groundwater component, will not. Accordingly, TSS and total phosphorus loads were estimated from observations using a flow-stratified log-log regression approach, while total nitrogen loads were estimated using a flow-stratified averaging estimator, consistent with the findings of Preston et al. (1989).

Water quality calibration and validation was done on the Verde River near Clarkdale, using 1993-2002 for calibration and 1986-1992 for validation. As with hydrology, calibration was performed on the later period as this better reflects the land use included in the model. The start of the validation period is constrained by data availability.

TSS calibration was performed by adjusting the coefficients in the soil detachment (KRER) and soil washoff (KSER) equations along with changes to the seasonal vegetation COVER. Furthermore, it was necessary to model scour of the soil matrix (i.e., gully erosion) in addition to losses of detached sediment. The washoff of detached sediment did not provide sufficient sediment losses to calibrate the model without severely degrading the channel bed.

Time series of simulated and estimated TSS loads at the Clarkdale station for both periods are shown in Figure 32 and statistics for the two periods are provided separately in Table 14. Visually, the model is roughly simulating the trends contained in the observed data. The key statistic in Table 14 (consistent with the QAPP) is the relative percent error, which shows the error in the prediction of monthly load normalized to the estimated load. Table 14 also shows the relative average absolute error, which is the average of the relative magnitude of errors in individual monthly load predictions. This number is inflated by outlier months in which the simulated and estimated loads differ by large amounts (which may be as easily due to uncertainty in the estimated load due to limited data as to problems with the model) and the third statistic, the relative median absolute error, is likely more relevant and shows good agreement.

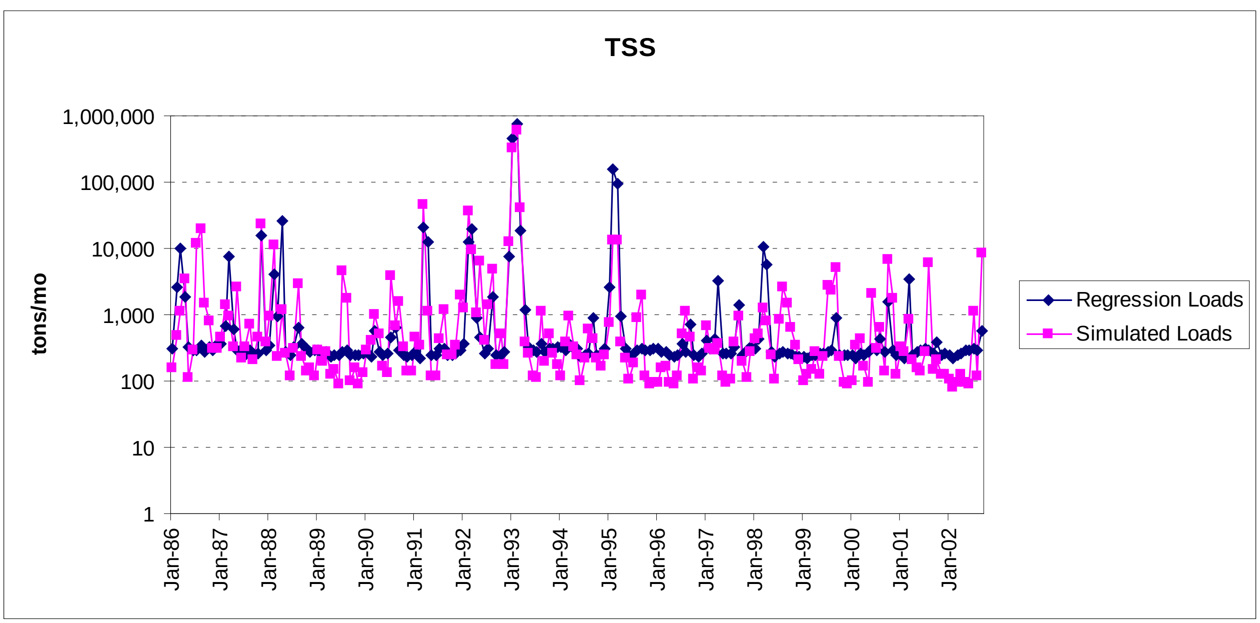

Figure 32. Fit for monthly load of TSS at USGS 09504000 Verde River near Clarkdale, AZ (HSPF).

Table 14. Model fit statistics (observed minus predicted) for monthly sediment loads using stratified regression at USGS 09504000 Verde River near Clarkdale, AZ (HSPF)

Statistic	Calibration period (1993-2002)	Validation period (1986-1992)
Relative Percent Error	31%	-41%
Relative Average Absolute Error	40%	123%
Relative Median Absolute Error	1.1%	8.5%

Several other diagnostics were also examined to evaluate agreement between the model and observations. These are available in full in the calibration spreadsheets, but a few examples are provided below. First, load-flow power plots were compared for individual days (Figures 33 and 34). These show that the relationship between flow and load is reasonably consistent across the entire range of observed flows, for both the calibration and validation periods.

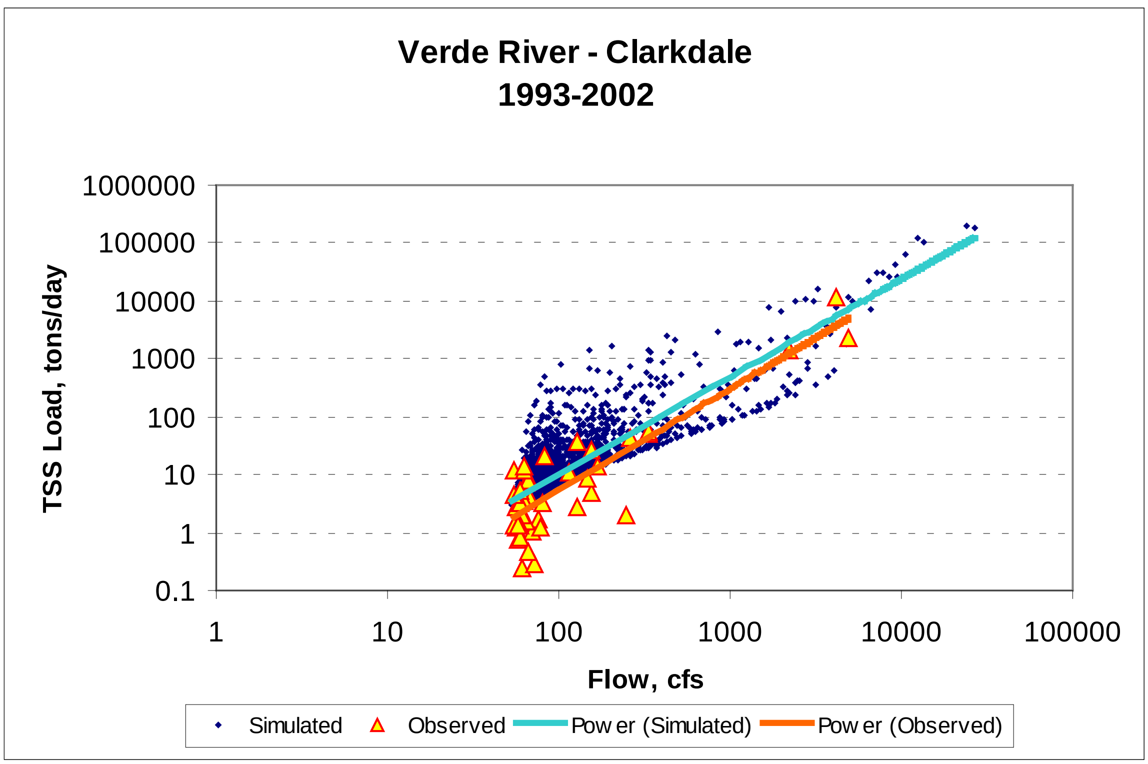

Figure 33. Power plot for observed and simulated TSS at USGS 09504000 Verde River near Clarkdale, AZ – calibration period (HSPF).

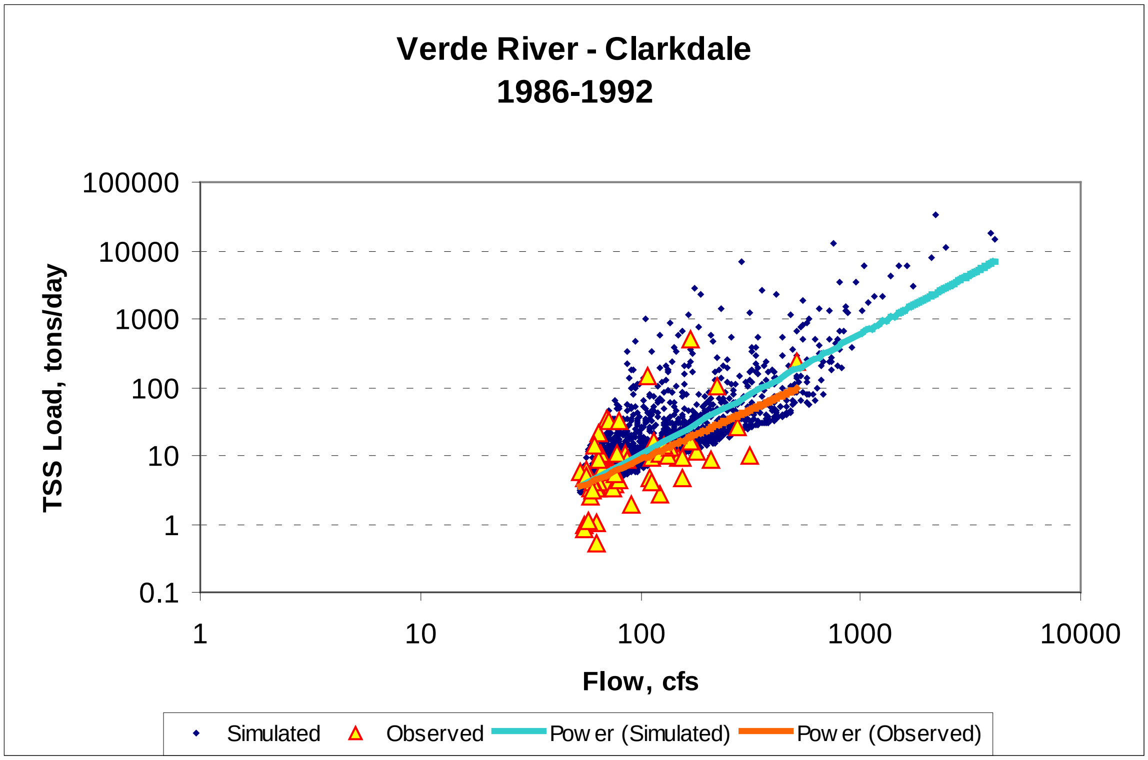

Figure 34. Power plot for observed and simulated TSS at USGS 09504000 Verde River near Clarkdale, AZ – validation period (HSPF).

A standard time series plot (Figure 35) shows that observed and simulated concentrations achieve at best a fair agreement, and the model may deviate substantially from individual observations. However, the concentration statistics (Table 15) show that reasonably low median errors are achieved.

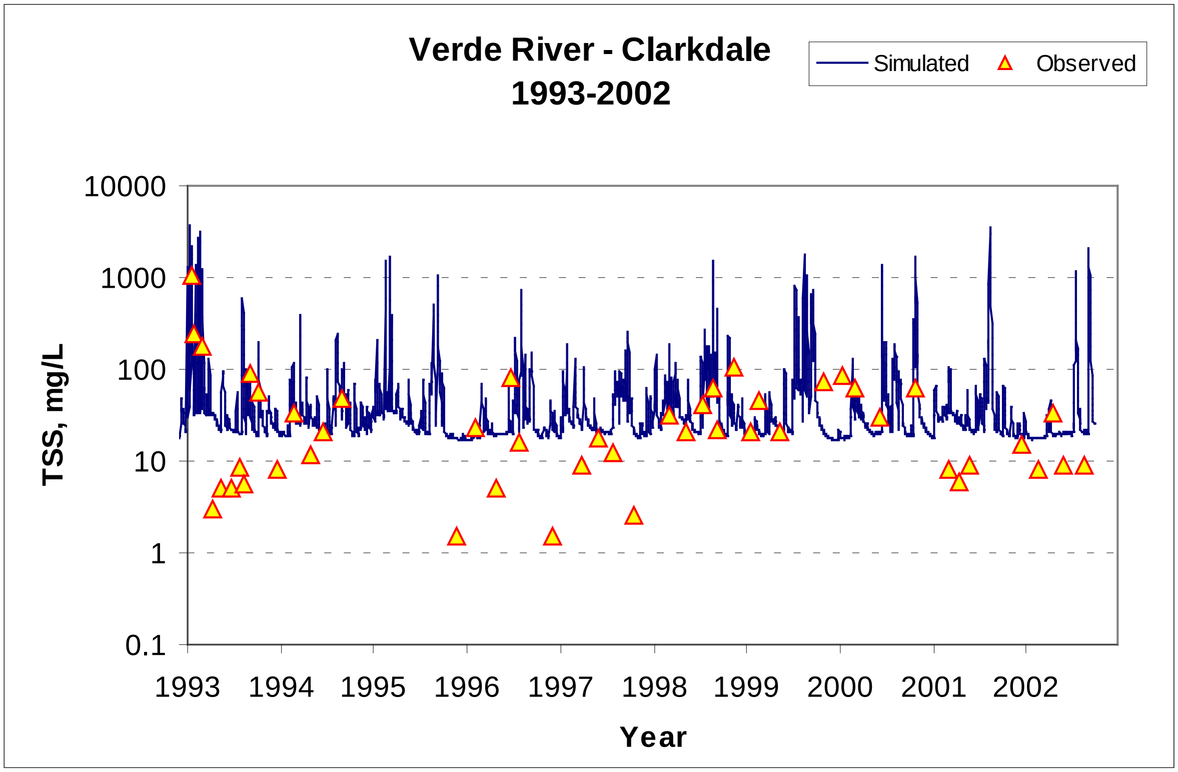

Figure 35. Time series plot of TSS concentration at USGS 09504000 Verde River near Clarkdale, AZ (HSPF).

Table 15. Relative errors (observed minus predicted) for TSS concentration at USGS 09504000 Verde River near Clarkdale, AZ (HSPF).

Statistic	Calibration period (1993-2002)	Validation period (1986-1992)
Count	47	62
Concentration Average Error	-104%	7.3%
Concentration Median Error	-19%	-1.0%

For simulation of total phosphorus, calibration was performed primarily through adjustment of the potency factors and the subsurface concentrations. Total nitrogen calibration was accomplished primarily by adjusting the subsurface concentrations and secondarily by the accumulation-washoff parameters. Monthly loading time series for total phosphorus are shown in Figure 36 and the load statistics are summarized in Table 16. The model reproduces the general trend in monthly loads, but is significantly lower than the peak loads predicted by the regression method, resulting in high relative percent errors for both the calibration and validation periods. It should be noted that the available data are limited, particularly for high flow events. Thus, the estimates of "observed" load are also subject to considerable uncertainty.

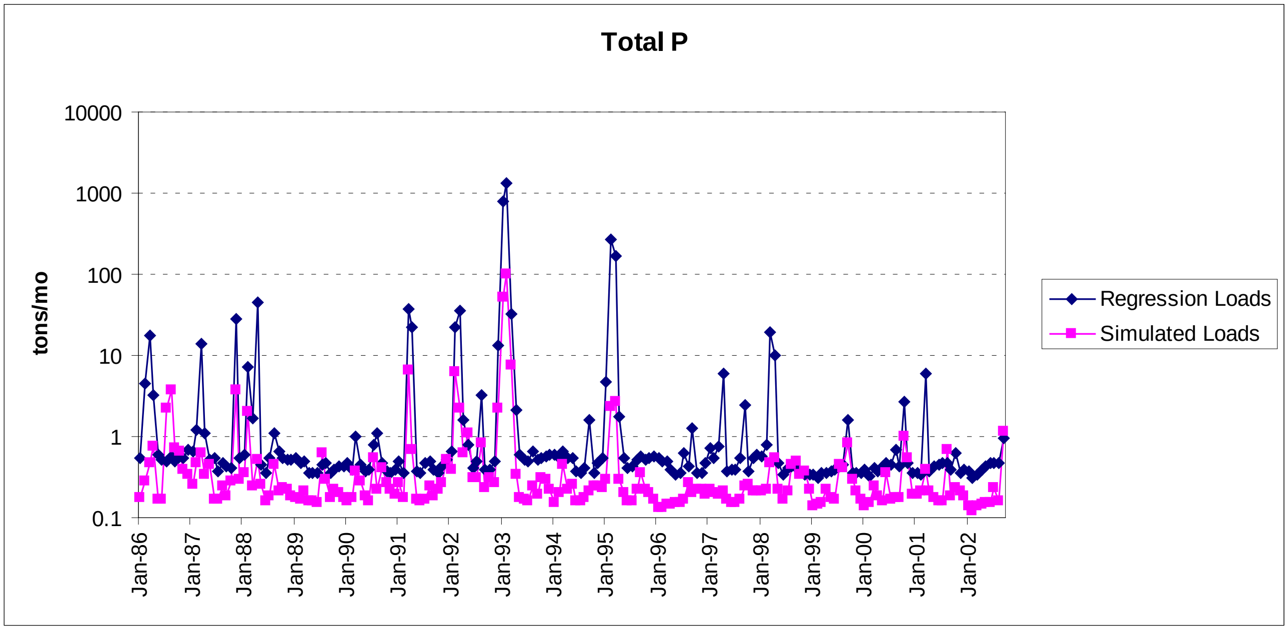

Figure 36. Fit for monthly load of total phosphorus at USGS 09504000 Verde River near Clarkdale, AZ (HSPF).

Table 16. Model fit statistics (observed minus predicted) for monthly total phosphorus loads using stratified regression

Statistic	Calibration period (1993-2002)	Validation period (1986-1992)
Relative Percent Error	87%	66%
Average Absolute Error	87%	78%
Median Absolute Error	0.6%	5.1%

Additional diagnostics for total phosphorus included flow-load power plots (Figures 37 and 38), concentration time series plots (Figure 39) and analysis of concentration errors (Table 17). While these show approximate agreement, the model often overpredicts total phosphorus concentrations under lower flow conditions.

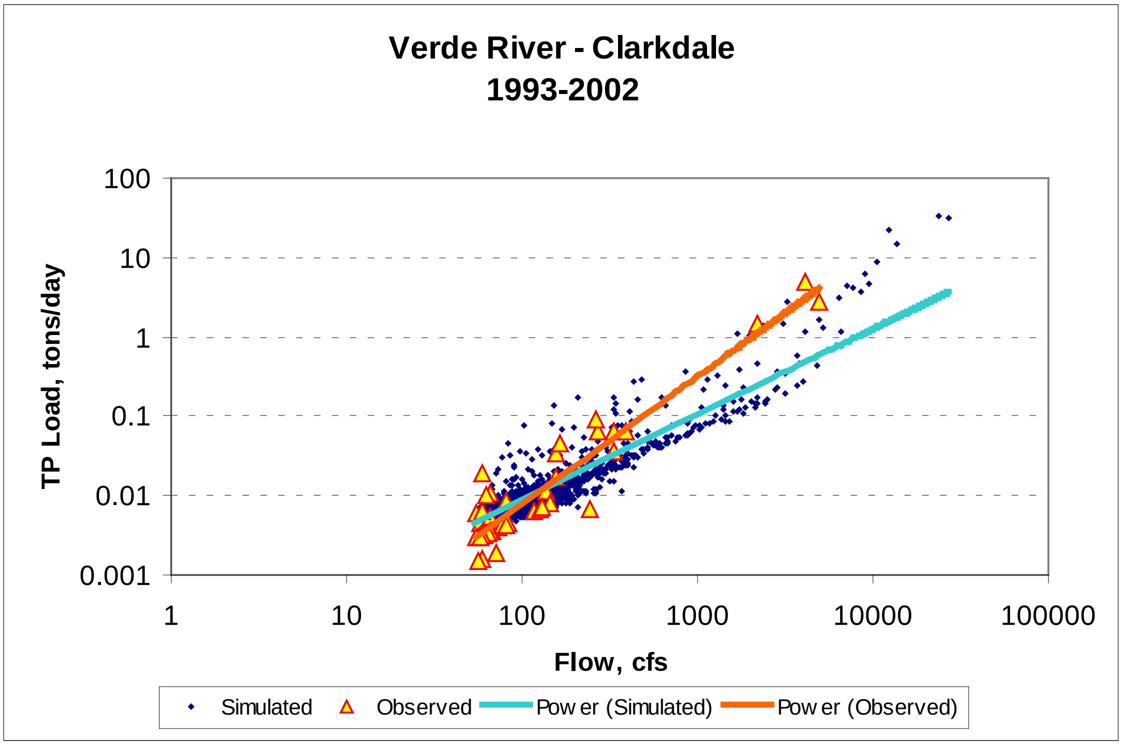

Figure 37. Power plot for observed and simulated total phosphorus at USGS 09504000 Verde River near Clarkdale, AZ – calibration period (HSPF).

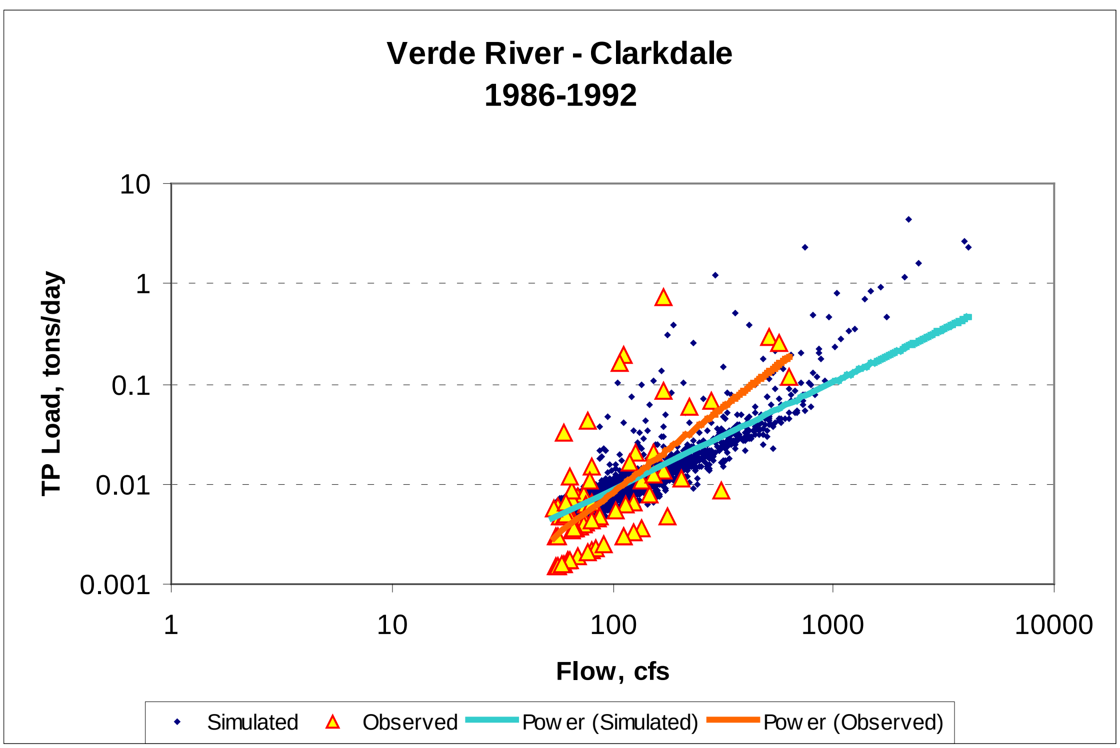

Figure 38. Power plot for observed and simulated total phosphorus at USGS 09504000 Verde River near Clarkdale, AZ – validation period (HSPF).

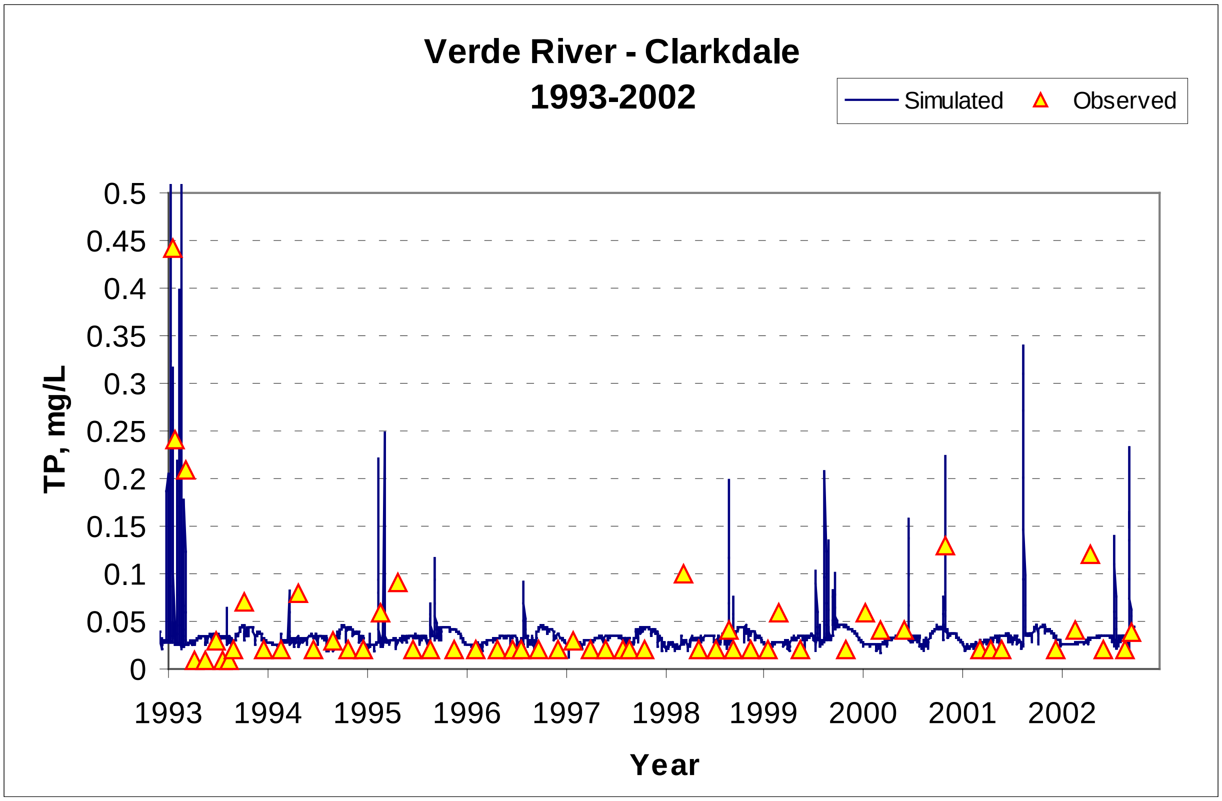

Figure 39. Time series plot of total phosphorus concentration at USGS 09504000 Verde River near Clarkdale, AZ (HSPF).

Table 17. Relative errors (observed minus predicted) for total phosphorus concentration at USGS 09504000 Verde River near Clarkdale, AZ (HSPF)

Statistic	Calibration period (1993-2002)	Validation period (1986-1992)
Count	57	75
Concentration Average Error	16%	54%
Concentration Median Error	-23%	-8.5%

Fewer data are available for total nitrogen because many sampling events omitted one or more nitrogen species. This increases the uncertainty of the comparison. Results for total nitrogen are summarized in Figures 40 through 43 and Tables 18 and 19 following the same format as total phosphorus. The loading results are fair, and are generally better than those obtained for total phosphorus; however, there is significant uncertainty in the prediction of individual total nitrogen observations. Total nitrogen concentrations at base flow are generally over-predicted.

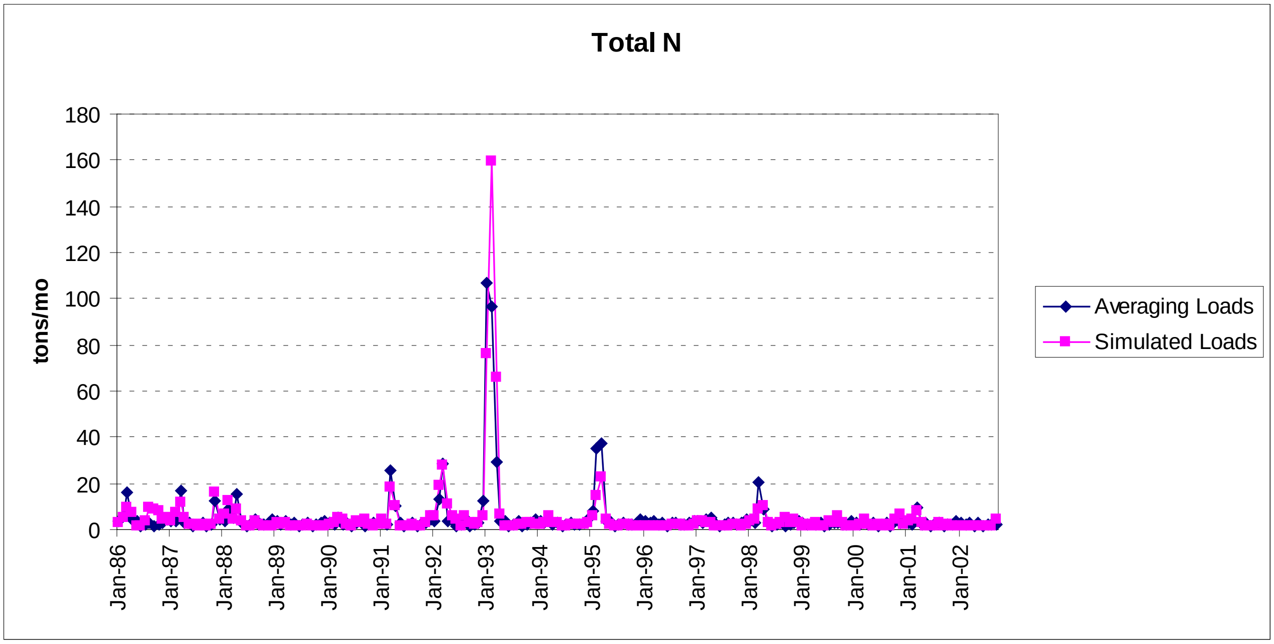

Figure 40. Fit for monthly load of total nitrogen at USGS 09504000 Verde River near Clarkdale, AZ (HSPF).

Table 18. Model fit statistics (observed minus predicted) for monthly total nitrogen loads using averaging estimator (HSPF)

Statistic	Calibration period (1993-2002)	Validation period (1986-1992)
Relative Percent Error	1.6%	-2.7%
Average Absolute Error	45%	37%
Median Absolute Error	17%	18%

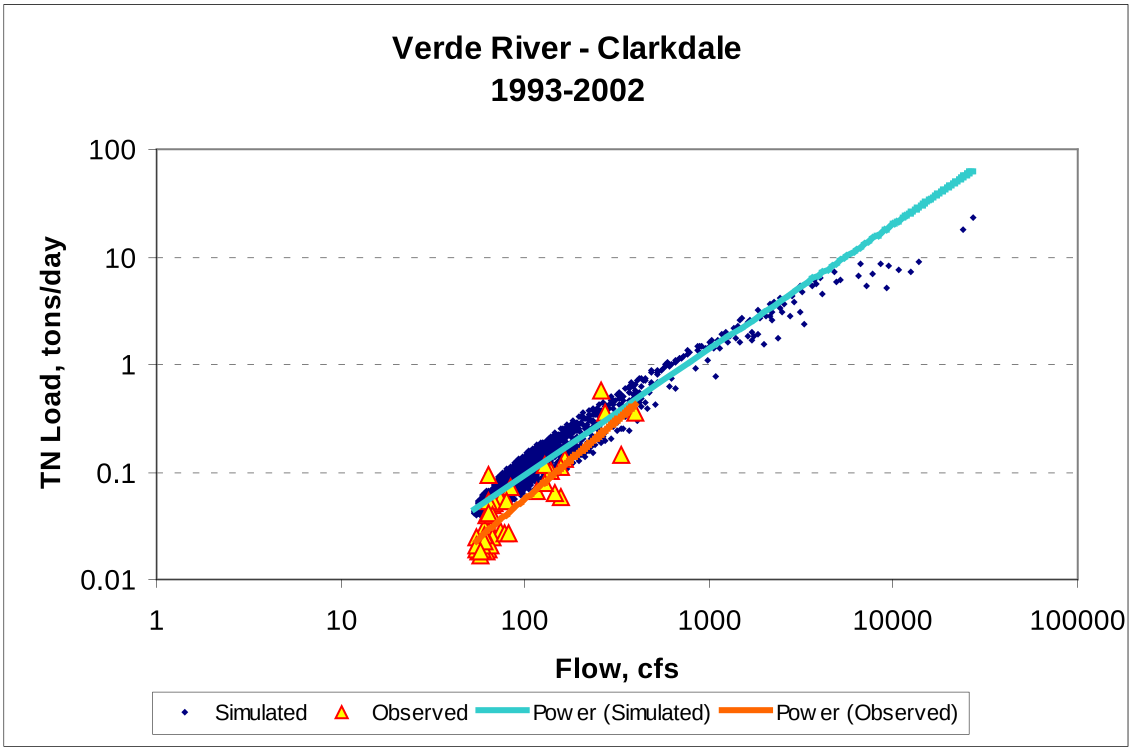

Figure 41. Power plot for observed and simulated total nitrogen at USGS 09504000 Verde River near Clarkdale, AZ – calibration period (HSPF).

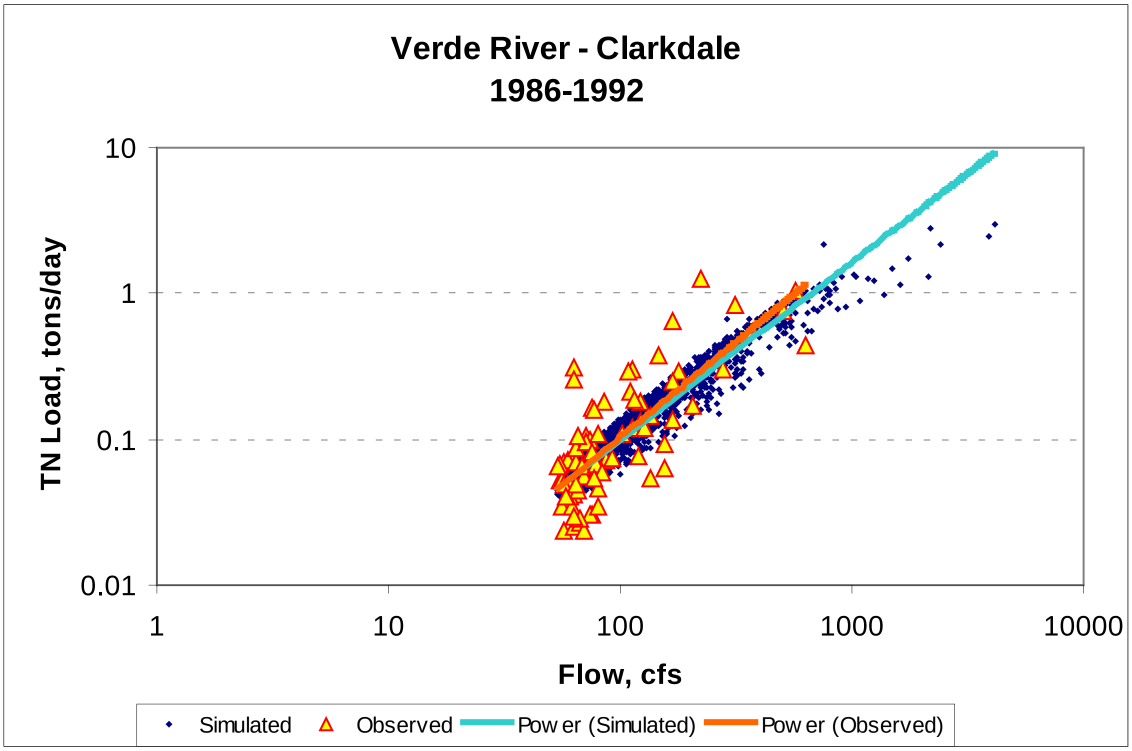

Figure 42. Power plot for observed and simulated total nitrogen at USGS 09504000 Verde River near Clarkdale, AZ – validation period (HSPF).

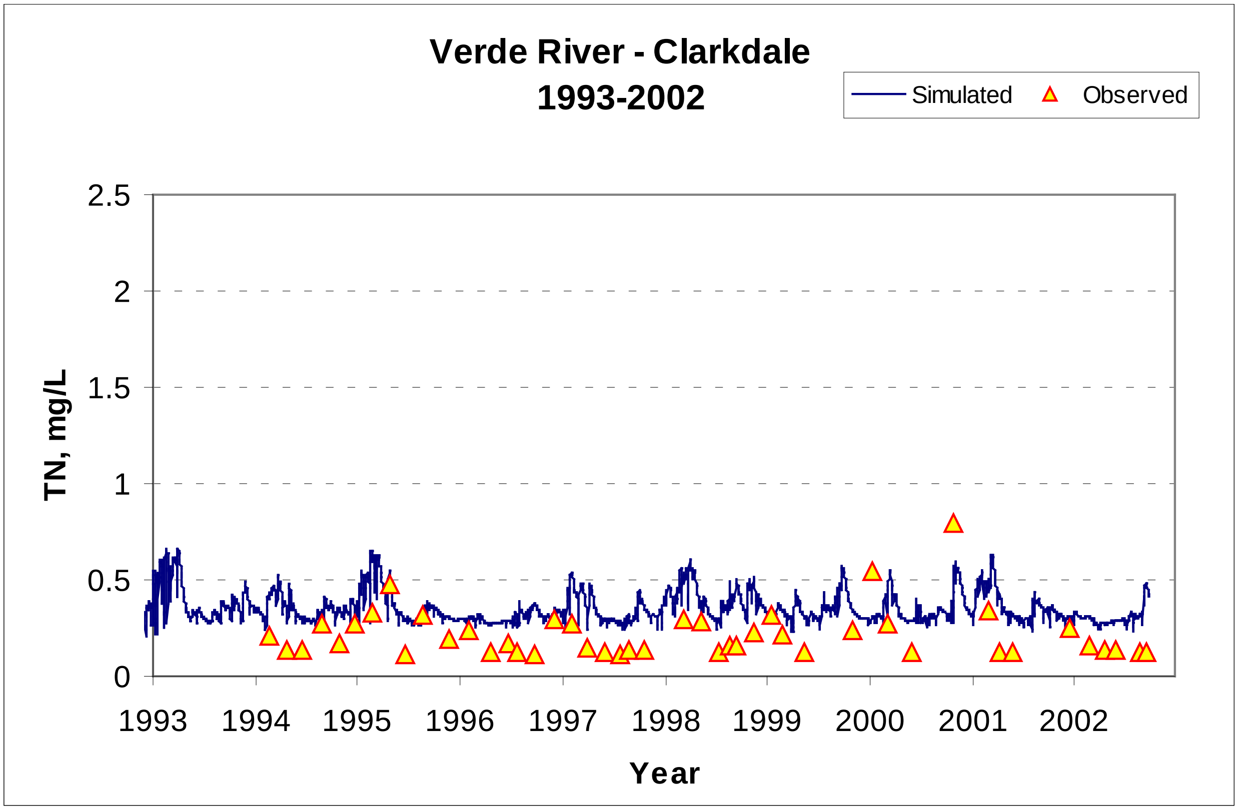

Figure 43. Time series plot of total nitrogen concentration at USGS 09504000 Verde River near Clarkdale, AZ (HSPF).

Table 19. Relative errors (observed minus predicted) for total nitrogen concentration at USGS 09504000 Verde River near Clarkdale, AZ (HSPF)

Statistic	Calibration period (1993-2002)	Validation period (1986-1992)
Count	46	75
Concentration Average Error	-63%	22%
Concentration Median Error	-70%	1.9%

Water Quality Results for Larger Watershed

Summary statistics for the water quality calibration and validation at two other stations in the watershed (i.e., Salt River near Roosevelt and Verde River below Tangle Creek) are provided in Tables 20 and 21 along with the Clarkdale statistics. Water quality was not calibrated at the Camp Verde station on the Verde River because of the lack of observed data at that location. And no water quality calibration was done in the San Pedro River. In most cases, total nitrogen loads are better predicted than total phosphorus and TSS loads. Simulated TSS and total phosphorus loads in the Verde River are lower than those estimated from observations, but this may reflect, in part, the uncertainty in the regression-based load estimates as water quality observations during high flows are sparse. Water quality results in the Salt River are generally better than the Verde River.

Table 20. Summary statistics (observed minus predicted) for water quality for all stations – calibration period 1993-2002 (HSPF)

Station	09498500 Salt River nr Roosevelt	09504000 Verde River nr Clarkdale	09508500 Verde River below Tangle Cr
Relative Percent Error TSS Load	-10	31	81
TSS Concentration Median Percent Error	0.80	-19	-5.6
Relative Percent Error TP Load	-29	87	75
TP Concentration Median Percent Error	-0.53	-23	-17
Relative Percent Error TN Load	-8.2	1.6	-2.7
TN Concentration Median Percent Error	-3.5	-70	-64

Table 21. Summary statistics (observed minus predicted) for water quality for all stations – validation period 1986-1992 (HSPF)

Station	09498500 Salt River nr Roosevelt	09504000 Verde River nr Clarkdale	09508500 Verde River below Tangle Cr
Relative Percent Error TSS Load	4.8	-41	2.1
TSS Concentration Median Percent Error	1.8	-1.0	-28
Relative Percent Error TP Load	52	78	46
TP Concentration Median Percent Error	8.9	-8.5	-12
Relative Percent Error TN Load	10	-2.7	10
TN Concentration Median Percent Error	-21	1.9	-15

SWAT Modeling

A SWAT model already exists for the Verde River portion of the watershed (Tetra Tech 2001). This model was calibrated for hydrology and nutrients. The existence of this earlier model provides a useful basis for parameter initialization, and is one of the reasons that the Arizona basins were selected as a pilot site. However, there are also significant differences to the 20 Watershed model. Because of these differences in approach the two models are substantively different, and not all model parameters are transferable. Nonetheless, the earlier model does provide important insights and parameter starting values that are incorporated into the 20 Watershed model.

A key aspect of the Arizona basins models is the intimate linkage of surface and groundwater hydrology. Perennial flow in various river segments is supported by groundwater discharge that, in the case of the Verde watershed, may arise from distant teleconnections. Many of the river reaches in alluvial valleys also lose flow to groundwater, at least on a seasonal basis. Both SWAT and HSPF models include simplified mass-balance accounting of groundwater at a local (subwatershed) scale, but neither model contains a detailed simulation of surface and groundwater interactions. In SWAT, the presence of deep groundwater discharges derived from sources outside a model subwatershed can be addressed through specification of these inflows as point sources. This is adequate for calibration, but there is no provision in the model for direct consideration of how these sources may change in the face of climate change. SWAT also provides for simulation of losing river reaches through specification of a rate of bed conductivity. This approach does not account for interaction with the seasonal water table. In many cases, alluvial river reaches may gain from groundwater during the wet season when water tables are high and lose to the alluvial aquifer during dry seasons. SWAT is, however, constrained to simulation of these interactions solely as a bed conductivity rate. This means that the behavior of seasonally losing reaches can only be roughly approximated in the model.

Changes Made to Base Data Provided

No changes were made to the meteorological or land use base data. For the Globe, Arizona point source it is clear that phosphorus concentrations downstream during baseflow conditions are much less than would be expected from the estimated phosphorus load from this WWTP. This may be due to a rapid loss of phosphorus in the near field immediately downstream of the discharge, likely due to settling of particulate matter. Discounting total phosphorus load in the effluent to 1/8 of the nominal value provided resolved this problem during calibration.

Assumptions

A key feature of the Arizona basins is the complex interaction of surface and groundwater. As noted above, neither SWAT nor HSPF is capable of providing a detailed, process-based simulation of groundwater flow. It is therefore assumed that interactions with groundwater can be handled with the following simplifying assumptions:

- The local (within a subwatershed) accumulation and discharge of shallow groundwater is adequately addressed by SWAT's linear storage reservoir formulation.
- Discharges to stream from deep groundwater are represented as constant point sources, with discharge rates set based on flow information on major springs identified in the Arizona Water Atlas (ADWR 2009). This means that the model cannot account for seasonal variability in deep groundwater discharge, nor can it evaluate how such discharges may evolve in response to climate change.
- Losses to groundwater from stream reaches in alluvial basins are simulated based on channel conductivity. This makes such losses a function of flow, wetted perimeter, and travel time in the affected reaches. The SWAT model formulation does not take into account changes in local groundwater head; instead, the loss occurs continuously. In addition, SWAT partitions channel losses to deep groundwater and bank storage using a fixed ratio.

Hydrology Calibration

Obtaining a high quality fit to hydrology in the Arizona basins is difficult with SWAT due to the importance of groundwater interaction terms, which are simplistically addressed in the model. The specification of groundwater discharges as constant values and the simulation of reach losses by channel conductivity without feedback from local groundwater elevations both introduce uncertainty. In addition, the model formulation requires specification of several factors at a global level, not allowing for spatial variability, including the fraction of transmission losses assigned to deep groundwater (TRNSRCH), the intensity of direct evaporation from the channel (EVRCH), and the parameters controlling snow melt.

Calibration adjustments focused on the following parameters:

- Curve numbers (varied systematically by land use)
- ESCO (soil evaporation compensation factor)
- Reach conductivity
- Bank storage and recession rates
- Groundwater “revap” rates

Initial calibrations were performed for the Verde River at Clarkdale and are summarized in Figures 44 through 50 Tables 22 and 23. The fit is fair at best, although the total volume errors are small. However, predictions at Clarkdale are largely determined by model fit upstream at Paulden, where flows about 95 percent of the time consist of approximately constant baseflow. Spring peaks occasionally push through from the Chino watershed. Accuracy in simulating these peaks appears to be affected by 1) lack of an accurate representation of the hydraulic behavior of Sullivan Lake, and 2) the necessity of specifying constant values for channel conductivity to account for transmission losses, when in fact these loss rates are likely much reduced during the spring wet period. Modifications to increase spring flows out of the Chino watershed rapidly results in severe over-prediction of response to summer storm events. The Nash-Sutcliffe coefficient is near zero because flows tend to remain approximately constant during dry periods.

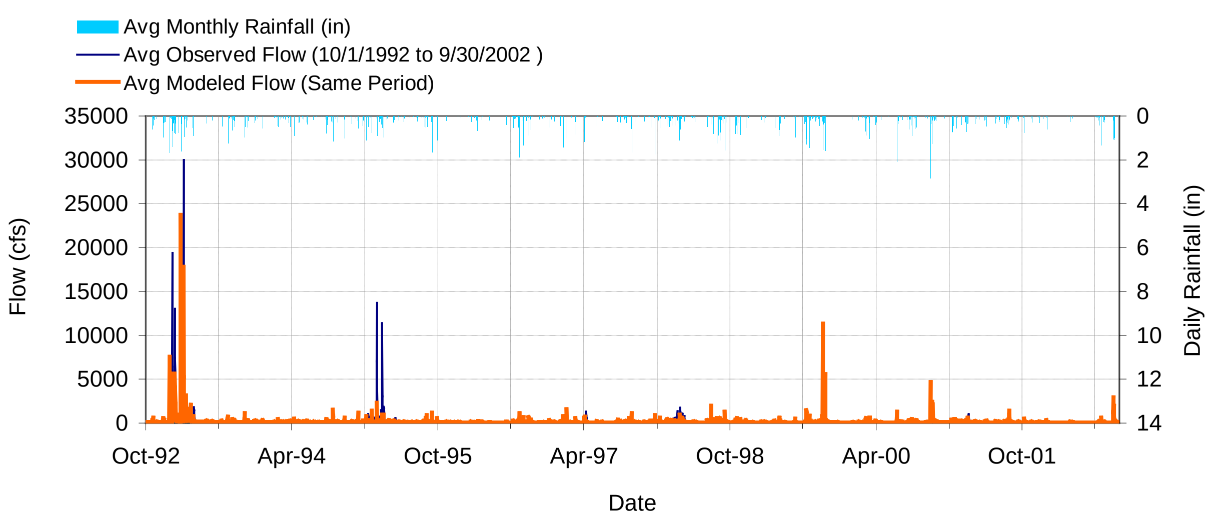

Figure 44. Mean daily flow at USGS 09504000 Verde River near Clarkdale, AZ – calibration period (SWAT).

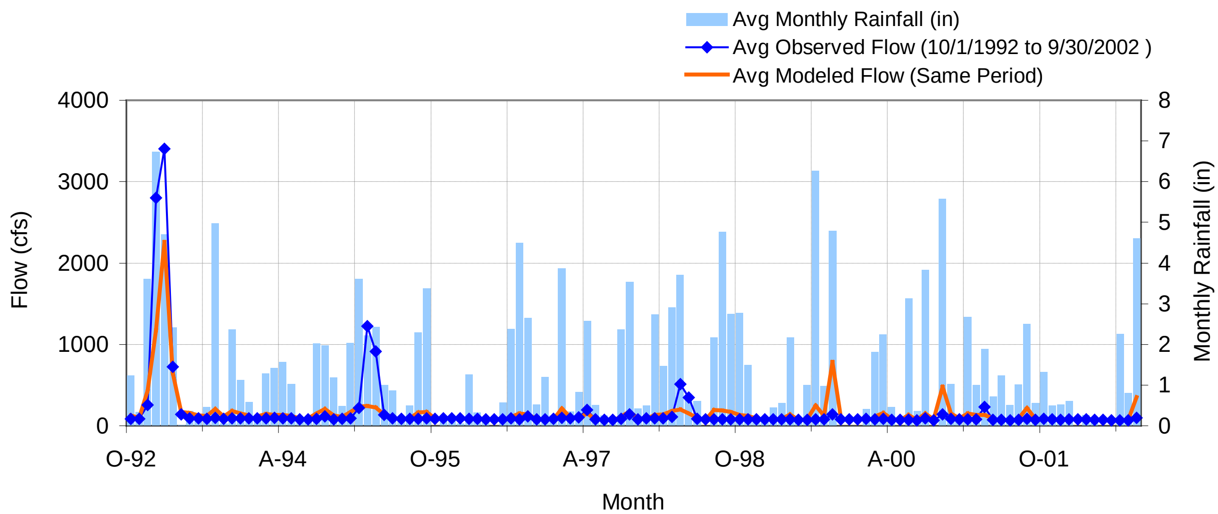

Figure 45. Mean monthly flow at USGS 09504000 Verde River near Clarkdale, AZ – calibration period (SWAT).

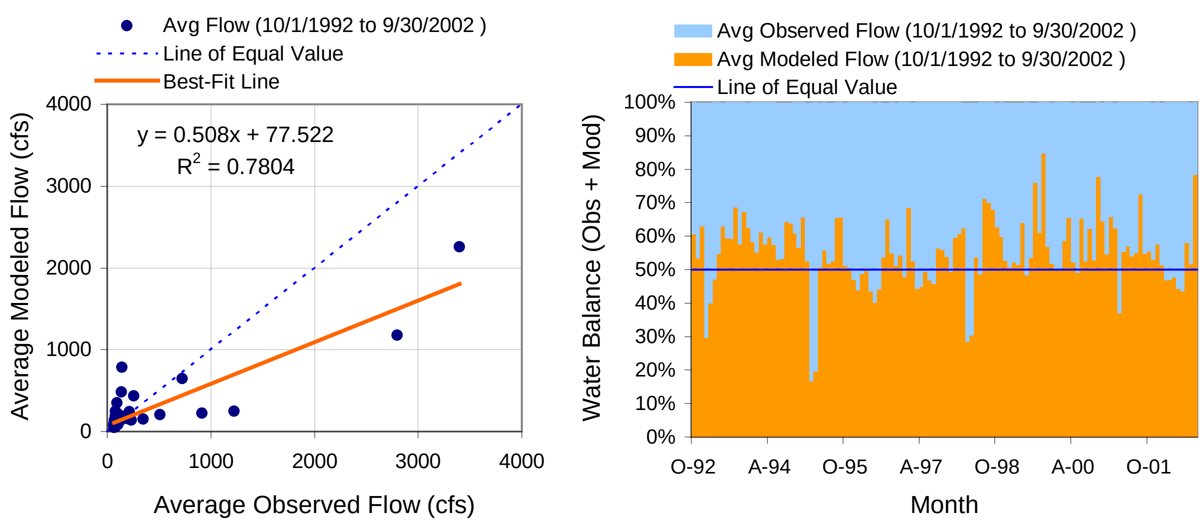

Figure 46. Monthly flow regression and temporal variation at USGS 09504000 Verde River near Clarkdale, AZ – calibration period (SWAT).

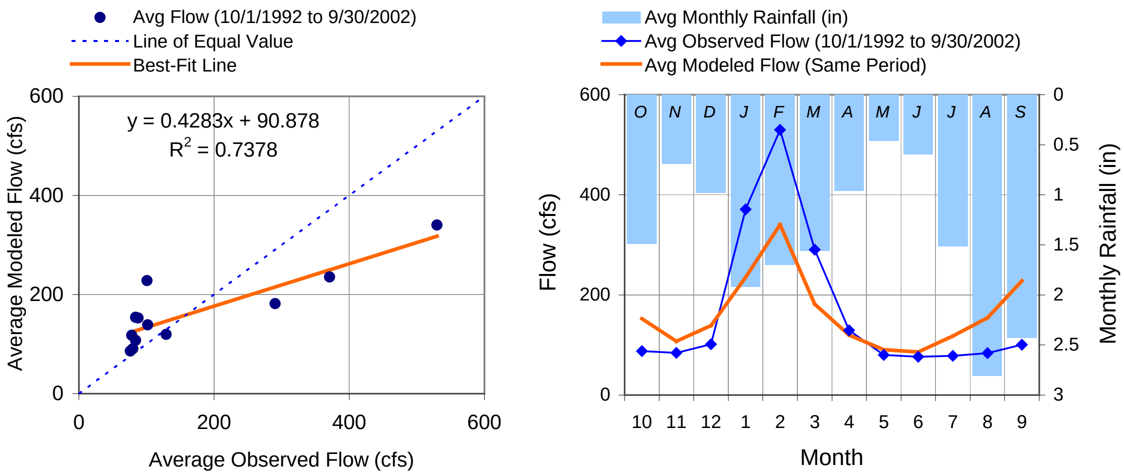

Figure 47. Seasonal regression and temporal aggregate at USGS 09504000 Verde River near Clarkdale, AZ – calibration period (SWAT).

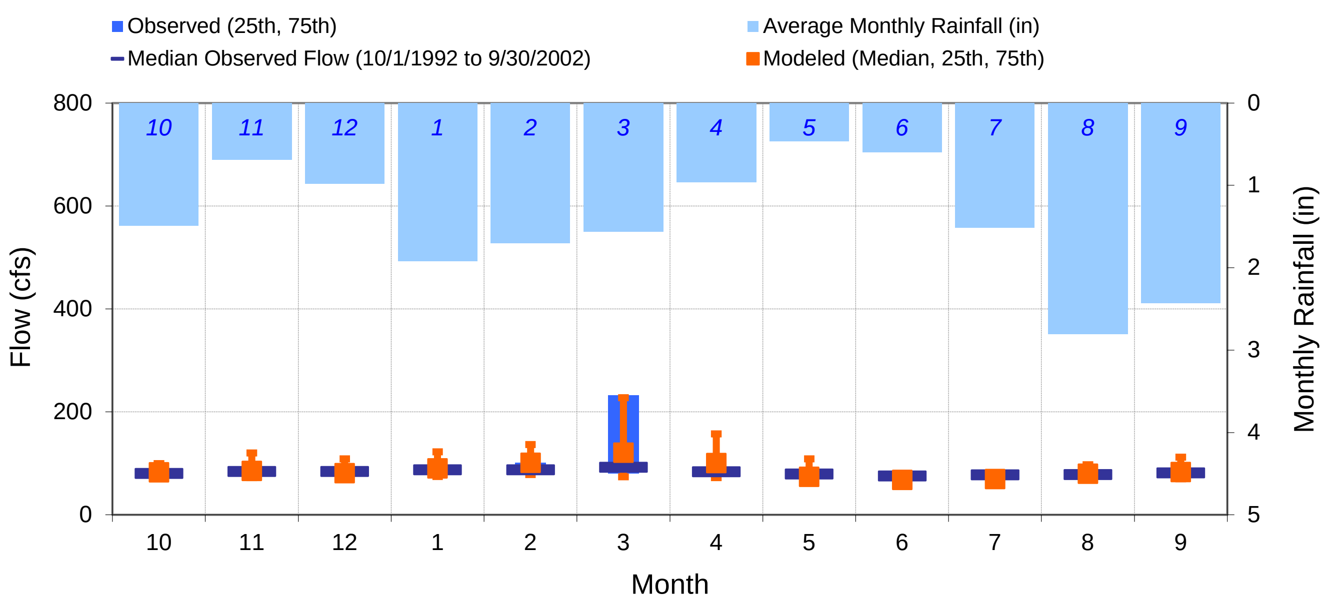

Figure 48. Seasonal medians and ranges at at USGS 09504000 Verde River near Clarkdale, AZ – calibration period (SWAT).

Table 22. Seasonal summary at USGS 09504000 Verde River near Clarkdale, AZ – calibration period (SWAT)

MONTH	OBSERVED FLOW (CFS)				MODELED FLOW (CFS)			
	MEAN	MEDIAN	25TH	75TH	MEAN	MEDIAN	25TH	75TH
Oct	87.85	80.00	77.00	84.00	152.63	91.66	82.39	113.64
Nov	84.09	84.00	78.00	89.00	107.60	92.48	82.01	112.22
Dec	101.70	83.50	80.00	90.00	138.79	89.91	80.83	114.00
Jan	370.90	87.00	81.00	93.00	235.56	104.44	78.08	147.50
Feb	529.79	87.00	80.00	101.50	340.35	99.91	76.04	154.28
Mar	290.55	92.00	80.00	232.00	181.43	103.13	73.67	161.90
Apr	129.11	83.00	77.00	93.00	119.69	94.57	72.58	127.94
May	79.98	79.00	72.00	87.00	90.37	72.78	64.29	102.97
Jun	76.29	75.00	69.00	81.00	86.15	72.08	60.86	89.61
Jul	78.20	77.00	71.00	82.00	117.83	84.24	66.98	114.69
Aug	83.85	78.00	75.00	84.00	154.15	113.30	86.81	163.60
Sep	100.71	81.00	73.00	85.00	228.15	107.68	79.88	147.35

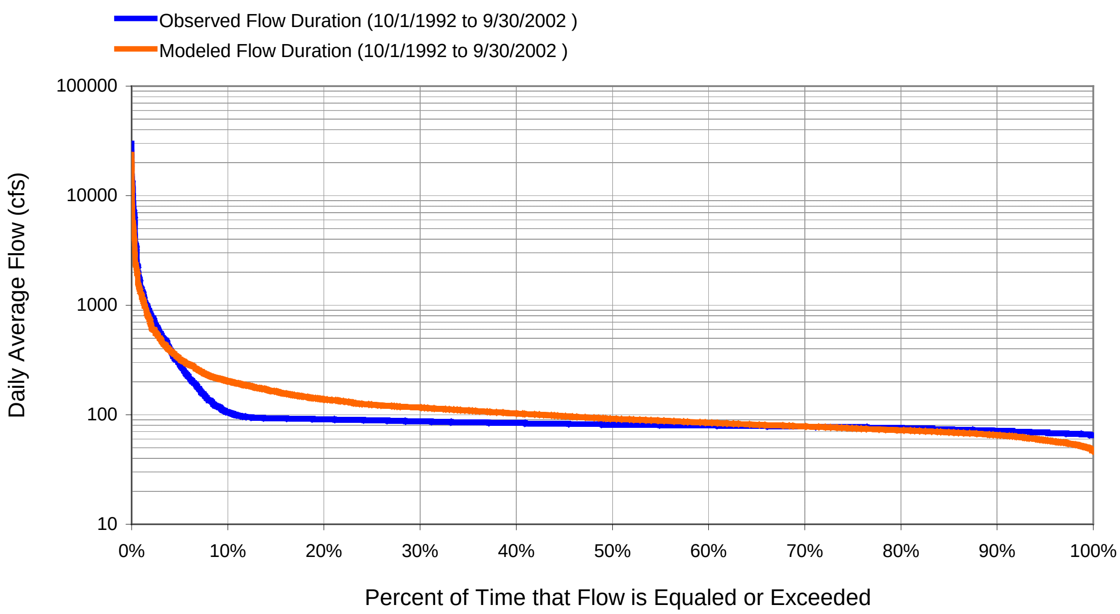

Figure 49. Flow exceedance at USGS 09504000 Verde River near Clarkdale, AZ – calibration period (SWAT).

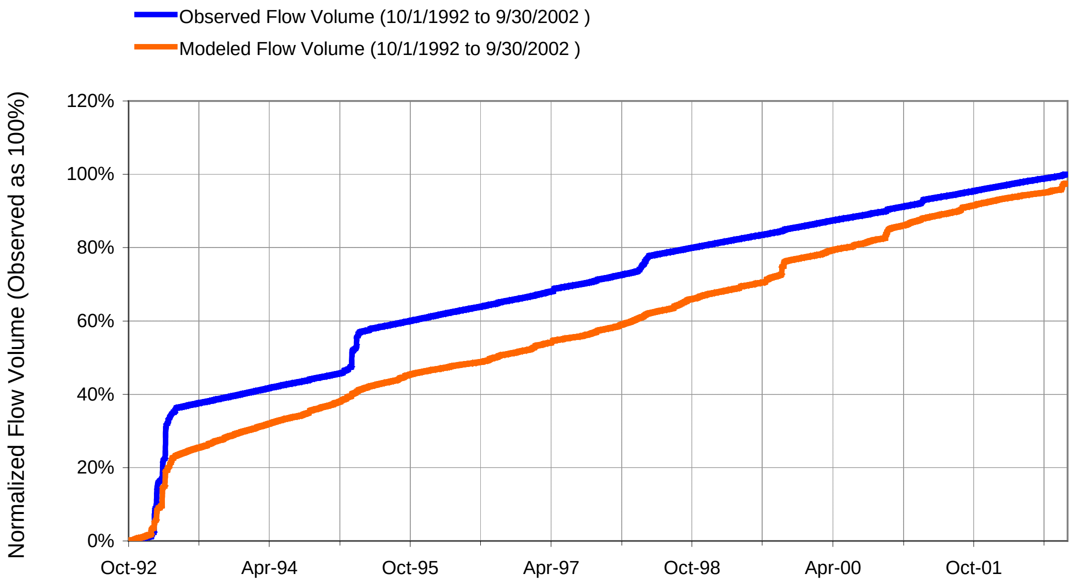

Figure 50. Flow accumulation at USGS 09504000 Verde River near Clarkdale, AZ – calibration period (SWAT).

Table 23. Summary statistics at USGS 09504000 Verde River near Clarkdale, AZ – calibration period (SWAT)

SWAT Simulated Flow		**Observed Flow Gage**	
REACH OUTFLOW FROM OUTLET 10		USGS 09504000 VERDE RIVER NEAR CLARKDALE, AZ	
10-Year Analysis Period: 10/1/1992 - 9/30/2002 Flow volumes are (inches/year) for upstream drainage area		Hydrologic Unit Code: 15060202 Latitude: 34.8522416 Longitude: -112.065994 Drainage Area (sq-mi): 3503	
Total Simulated In-stream Flow:	**0.63**	Total Observed In-stream Flow:	**0.64**
Total of simulated highest 10% flows:	**0.29**	Total of Observed highest 10% flows:	**0.36**
Total of Simulated lowest 50% flows:	**0.14**	Total of Observed Lowest 50% flows:	**0.15**
Simulated Summer Flow Volume (months 7-9):	**0.16**	Observed Summer Flow Volume (7-9):	**0.09**
Simulated Fall Flow Volume (months 10-12):	**0.13**	Observed Fall Flow Volume (10-12):	**0.09**
Simulated Winter Flow Volume (months 1-3):	**0.24**	Observed Winter Flow Volume (1-3):	**0.38**
Simulated Spring Flow Volume (months 4-6):	**0.10**	Observed Spring Flow Volume (4-6):	**0.09**
Total Simulated Storm Volume:	**0.28**	Total Observed Storm Volume:	**0.29**
Simulated Summer Storm Volume (7-9):	**0.08**	Observed Summer Storm Volume (7-9):	**0.01**

Errors (Simulated-Observed)	*Error Statistics*	*Recommended Criteria*		
Error in total volume:	-2.46	10		
Error in 50% lowest flows:	-1.74	10		
Error in 10% highest flows:	**-19.34**	**15**		
Seasonal volume error - Summer:	**89.89**	**30**		
Seasonal volume error - Fall:	**46.00**	>> **30**		Clear
Seasonal volume error - Winter:	**-36.45**	**30**		
Seasonal volume error - Spring:	3.88	30		
Error in storm volumes:	-3.32	20		
Error in summer storm volumes:	**593.89**	**50**		
Nash-Sutcliffe Coefficient of Efficiency, E:	0.030	Model accuracy increases		
Baseline adjusted coefficient (Garrick), E':	0.236	as E or E' approaches 1.0		
Monthly NSE	0.685			

Hydrology Validation

Validation for the Verde River near Clarkdale was performed for the period 10/1/1982 through 9/30/1992. Results are presented in Figures 51 through 57 and Table 24 and 25. The validation results are generally similar to those of the calibration period, and indeed are better on some statistics, indicating that the model is not over-fit to the specific conditions of the calibration period.

It is important to recognize that the validation uses the 2001 land use as a static representation. While the watershed has remained largely in National Forest, Indian Reservations and unoccupied rangeland, important temporal changes have occurred as a result of intermittent wildfires. Areas of recent burns typically have decreased evapotranspiration and increased direct runoff. These, however, are not represented in the model. In addition, the PET estimates for the 20 Watershed model use SWAT weather generator statistics for solar radiation, cloud cover, wind, and relative humidity – essentially assuming that the central tendency of these factors has not changed over time.

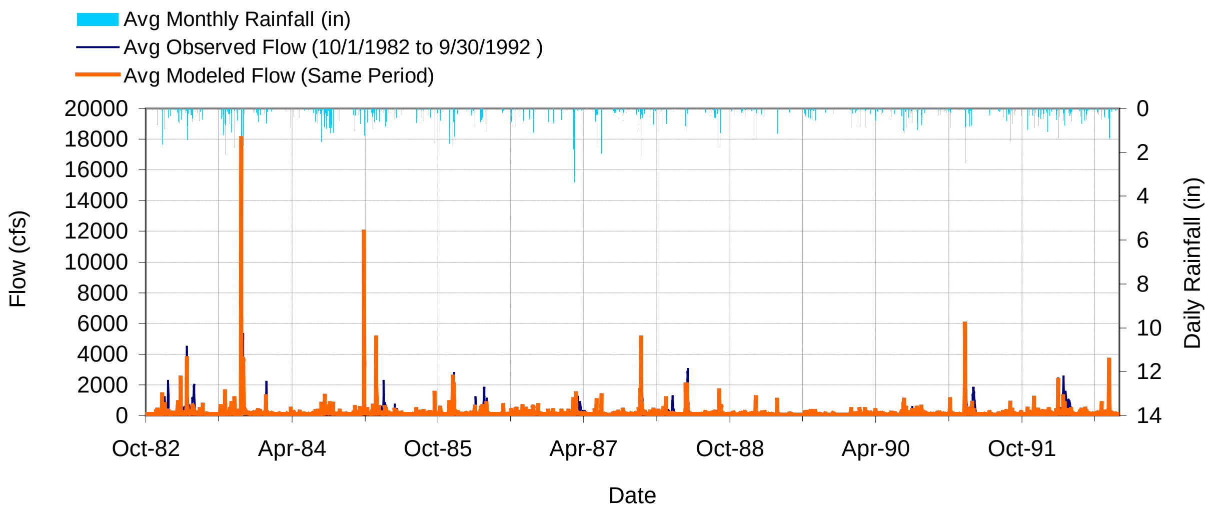

Figure 51. Mean daily flow at USGS 09504000 Verde River near Clarkdale, AZ – validation period (SWAT).

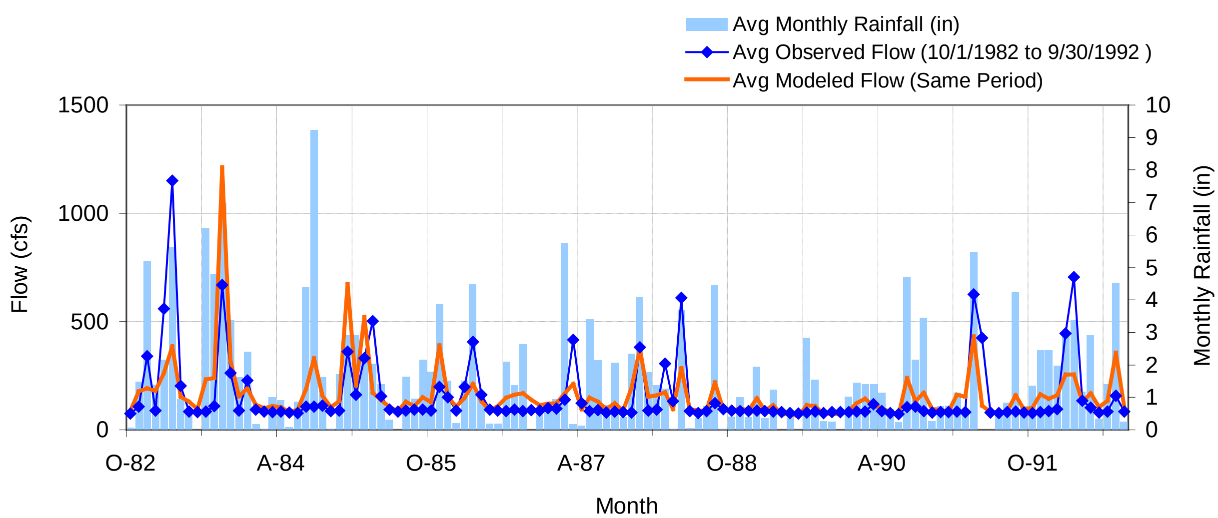

Figure 52. Mean monthly flow at USGS 09504000 Verde River near Clarkdale, AZ – validation period (SWAT).

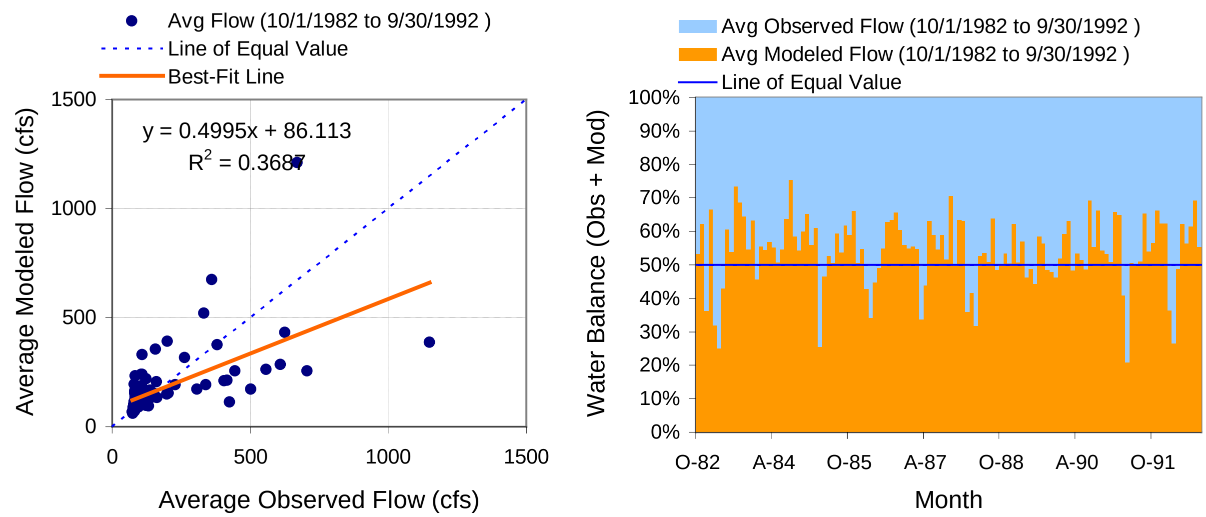

Figure 53. Monthly flow regression and temporal variation at USGS 09504000 Verde River near Clarkdale, AZ – validation period (SWAT).

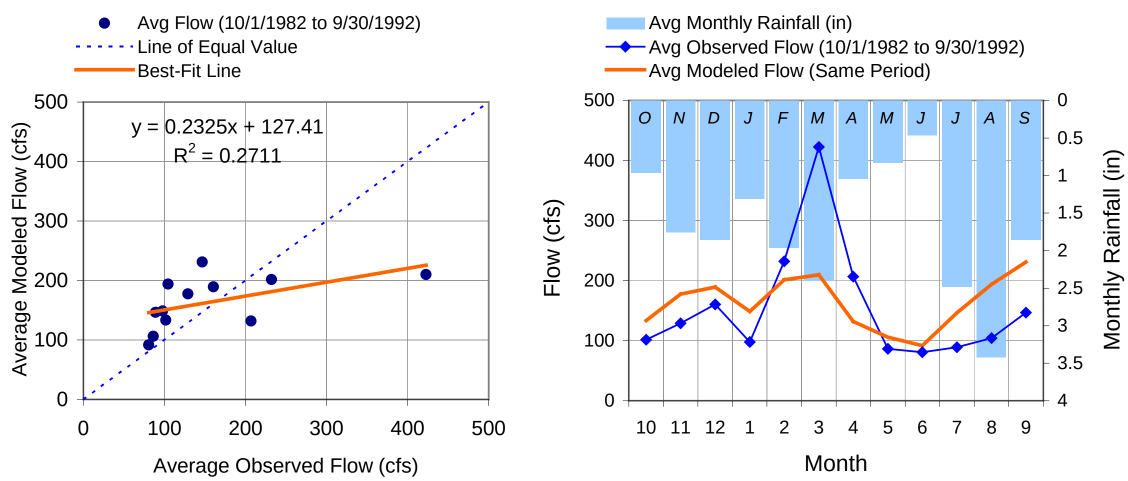

Figure 54. Seasonal regression and temporal aggregate at USGS 09504000 Verde River near Clarkdale, AZ – validation period (SWAT).

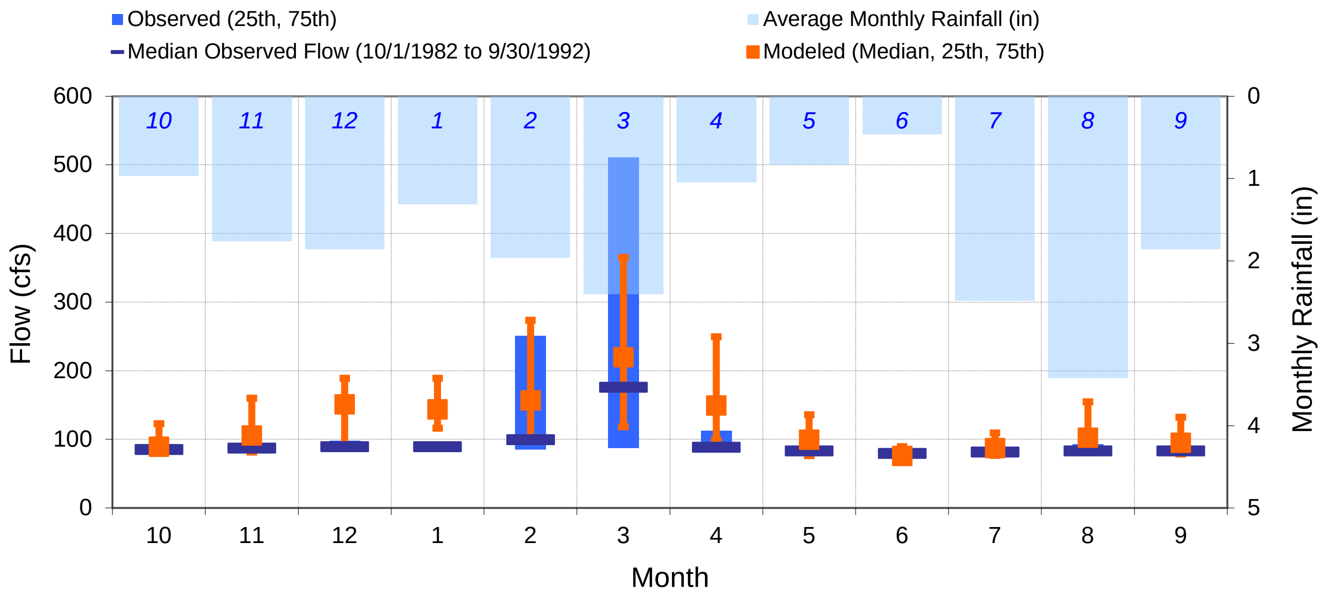

Figure 55. Seasonal medians and ranges at USGS 09504000 Verde River near Clarkdale, AZ – validation period (SWAT).

Table 24. Seasonal summary at USGS 09504000 Verde River near Clarkdale, AZ – validation period (SWAT)

MONTH	OBSERVED FLOW (CFS)				MODELED FLOW (CFS)			
	MEAN	MEDIAN	25TH	75TH	MEAN	MEDIAN	25TH	75TH
Oct	101.69	85.00	79.00	88.00	133.41	95.42	80.47	115.23
Nov	129.11	87.00	84.00	89.00	177.41	102.19	85.14	132.23
Dec	160.55	89.00	85.00	98.00	189.36	113.19	93.62	145.09
Jan	97.85	89.00	86.00	94.75	148.63	115.42	103.86	146.28
Feb	232.11	99.00	85.00	251.00	201.41	112.81	98.46	161.08
Mar	422.76	175.50	87.00	510.50	209.87	125.61	94.45	179.31
Apr	206.73	88.00	83.00	113.00	131.86	101.34	88.26	122.62
May	86.31	83.00	80.00	88.00	106.03	89.26	80.14	104.86
Jun	80.68	79.00	76.75	85.00	91.66	80.87	72.39	92.45
Jul	89.01	81.00	77.00	86.75	146.37	102.31	82.18	143.73
Aug	104.45	83.00	79.00	93.00	194.00	123.61	91.04	185.62
Sep	146.81	83.00	79.00	89.00	230.93	100.94	84.97	121.65

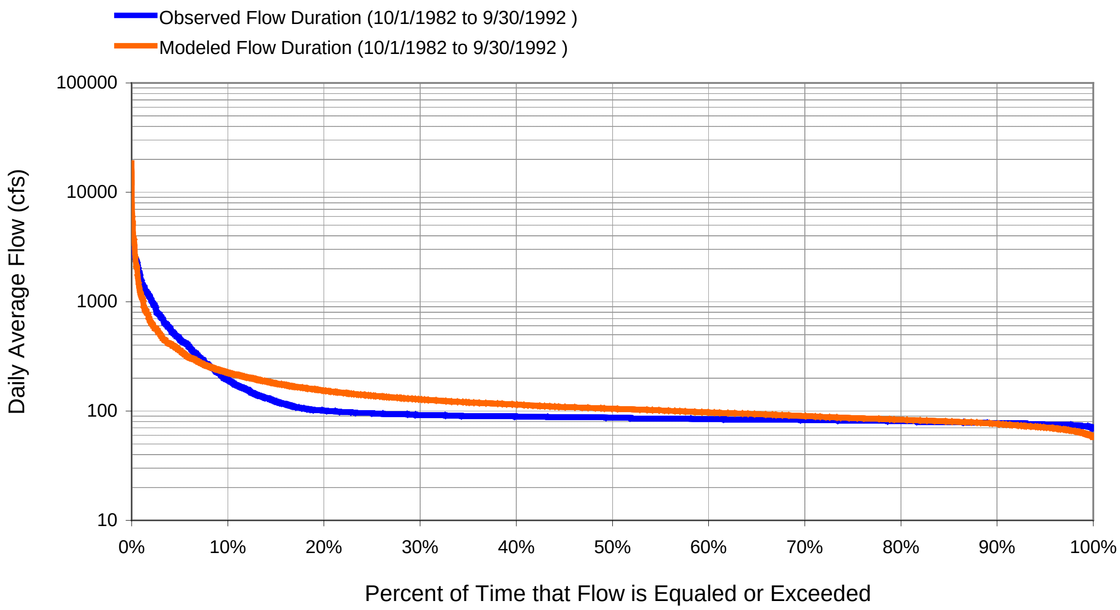

Figure 56. Flow exceedance at USGS 09504000 Verde River near Clarkdale, AZ – validation period (SWAT).

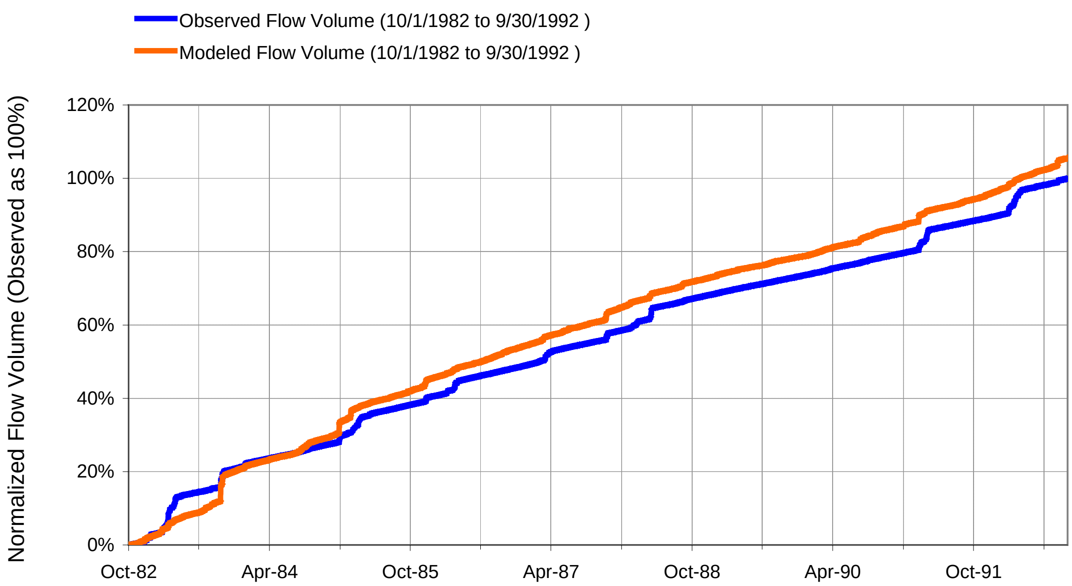

Figure 57. Flow accumulation at USGS 09504000 Verde River near Clarkdale, AZ – validation period (SWAT).

Table 25. Summary statistics at USGS 09504000 Verde River near Clarkdale, AZ – validation period (SWAT)

SWAT Simulated Flow		Observed Flow Gage	
REACH OUTFLOW FROM OUTLET 10		USGS 09504000 VERDE RIVER NEAR CLARKDALE, AZ	
10-Year Analysis Period: 10/1/1982 - 9/30/1992 Flow volumes are (inches/year) for upstream drainage area		Hydrologic Unit Code: 15060202 Latitude: 34.8522416 Longitude: -112.065994 Drainage Area (sq-mi): 3503	
Total Simulated In-stream Flow:	**0.63**	Total Observed In-stream Flow:	**0.60**
Total of simulated highest 10% flows:	**0.26**	Total of Observed highest 10% flows:	**0.29**
Total of Simulated lowest 50% flows:	**0.16**	Total of Observed Lowest 50% flows:	**0.16**
Simulated Summer Flow Volume (months 7-9):	**0.19**	Observed Summer Flow Volume (7-9):	**0.11**
Simulated Fall Flow Volume (months 10-12):	**0.16**	Observed Fall Flow Volume (10-12):	**0.13**
Simulated Winter Flow Volume (months 1-3):	**0.18**	Observed Winter Flow Volume (1-3):	**0.24**
Simulated Spring Flow Volume (months 4-6):	**0.11**	Observed Spring Flow Volume (4-6):	**0.12**
Total Simulated Storm Volume:	**0.26**	Total Observed Storm Volume:	**0.23**
Simulated Summer Storm Volume (7-9):	**0.10**	Observed Summer Storm Volume (7-9):	**0.03**

Errors (Simulated-Observed)	*Error Statistics*	*Recommended Criteria*		
Error in total volume:	5.68	10		
Error in 50% lowest flows:	5.17	10		
Error in 10% highest flows:	-9.70	15		
Seasonal volume error - Summer:	**68.04**	**30**		
Seasonal volume error - Fall:	27.70	>> 30	Clear	
Seasonal volume error - Winter:	-25.96	30		
Seasonal volume error - Spring:	-11.56	30		
Error in storm volumes:	12.44	20		
Error in summer storm volumes:	**197.67**	**50**		
Nash-Sutcliffe Coefficient of Efficiency, E:	-0.996	Model accuracy increases		
Baseline adjusted coefficient (Garrick), E':	0.121	as E or E' approaches 1.0		
Monthly NSE	0.320			

Hydrology Results for Larger Watershed

As described above, parameters determined through calibration to the Verde River near Clarkdale gage were not fully transferable to other gages in the watershed. Therefore, calibration was pursued at a total of 10 gages in the Arizona basins – six in the Verde River watershed, one in the Salt River watershed, and two in the San Pedro River watersheds. Only the gage at Roosevelt provides a long period of record for the Salt River watershed. The mainstem gage for the San Pedro River does not provide a rigorous calibration test because its flow is largely determined by the upstream boundary condition. Therefore, calibration was also pursued on perennial Aravaipa Creek. The two San Pedro gages ceased operation in 1995; therefore calibration was pursued over an earlier time period without a separate validation test.

Calibration results at all gages are summarized in Table 26 and are generally of similar quality to the fit obtained on the Verde River near Clarkdale. The fit for the East Verde River is believed to be relatively poor due to the influences of Payson water withdrawals. The generally close match between observed and predicted flow at the Salt River gage is shown in Figures 58 through 64 and Tables 27 and 28. Results of the validation exercise are summarized in Table 29. In general, the quality of fit during the validation period is similar to that in the calibration period. Thus, the model is judged to be useful for scenario evaluation.

Table 26. Summary statistics (percent error) at all stations – calibration period WY 1992-2002 (SWAT)

Station	09472000 San Pedro nr Redington (1972-95)*	09473000 Aravaipa Crk nr Mammoth (1972-95)	09498500 Salt River nr Roosevelt	09503700 Verde River nr Paulden	09504000 Verde River nr Clarkdale	09504500 Oak Creek nr Cornville	09505800 W Clear Cr nr Camp Verde	09506000 Verde River nr Camp Verde	09507980 E Verde River nr Childs	09508500 Verde R below Tangle Cr
Error in total volume:	-6.74	3.46	9.43	9.15	-2.46	-2.63	9.45	7.68	-6.21	1.68
Error in 50% lowest flows:	NA*	-1.25	-7.16	-1.14	-1.74	-17.90	-10.22	8.49	56.51	-17.85
Error in 10% highest flows:	-7.97	2.62	4.52	8.65	-19.34	-10.31	7.29	-5.00	-6.56	-7.27
Seasonal volume error - Summer:	-4.82	53.40	58.85	110.89	89.89	96.08	49.24	100.98	156.62	96.88
Seasonal volume error - Fall:	8.09	-3.31	103.52	56.82	46.00	27.01	26.17	44.07	58.54	47.60
Seasonal volume error - Winter:	-20.25	-10.77	6.95	-24.75	-36.45	-22.05	2.87	-13.37	-35.02	-19.30
Seasonal volume error - Spring:	-7.04	7.82	-51.64	-1.39	3.88	-4.10	2.23	3.38	0.08	-7.60
Error in storm volumes:	1.49	-27.95	16.40	19.48	-3.32	-10.98	21.24	9.94	17.92	16.89
Error in summer storm volumes:	-3.89	73.05	103.32	875.65	593.89	205.71	96.30	153.62	338.25	262.34
Daily Nash-Sutcliffe Coefficient of Efficiency, E:	-0.362	0.629	0.222	-0.864	0.030	0.454	-0.021	0.225	0.311	0.250
Monthly Nash-Sutcliffe Coefficient of Efficiency, E:	0.690	0.717	0.783	0.777	0.320	0.728	0.804	0.880	0.736	0.860

* Note that median flow for the San Pedro River nr Redington is 0.

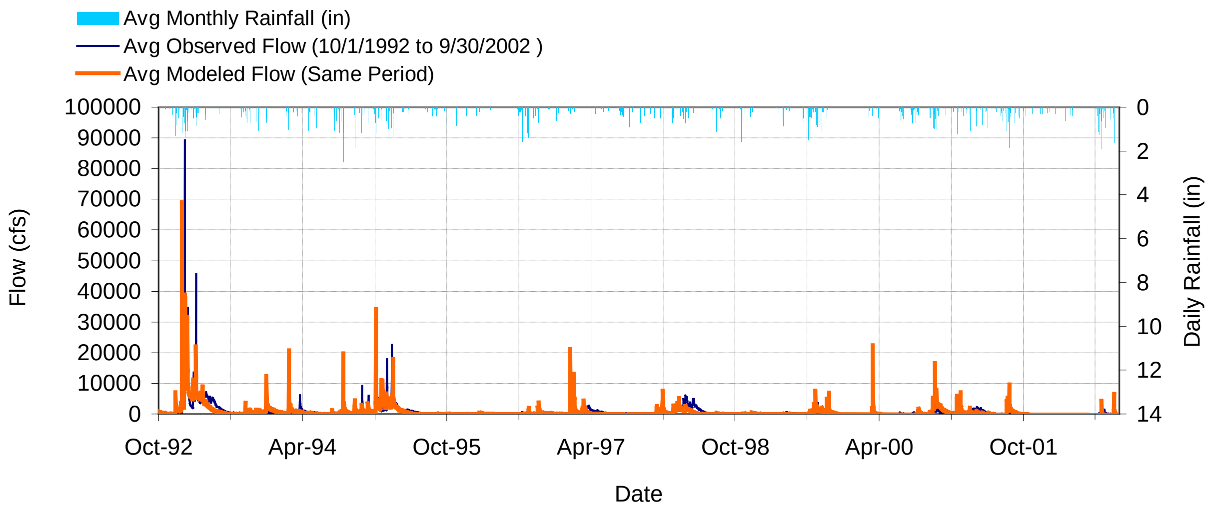

Figure 58. Mean daily flow at USGS 09498500 Salt River near Roosevelt, AZ – calibration period (SWAT).

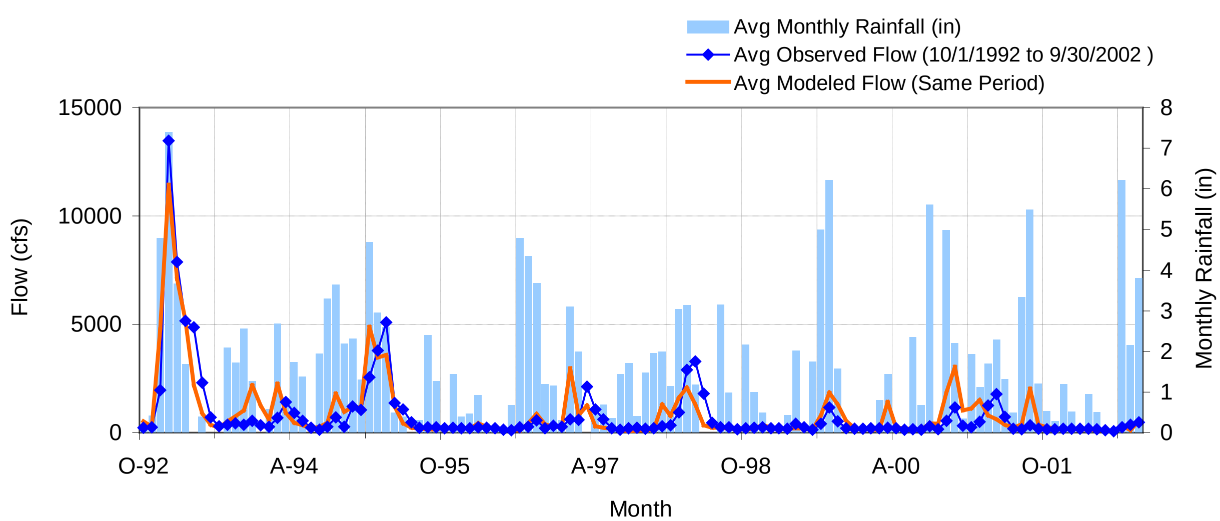

Figure 59. Mean monthly flow at USGS 09498500 Salt River near Roosevelt, AZ – calibration period (SWAT).

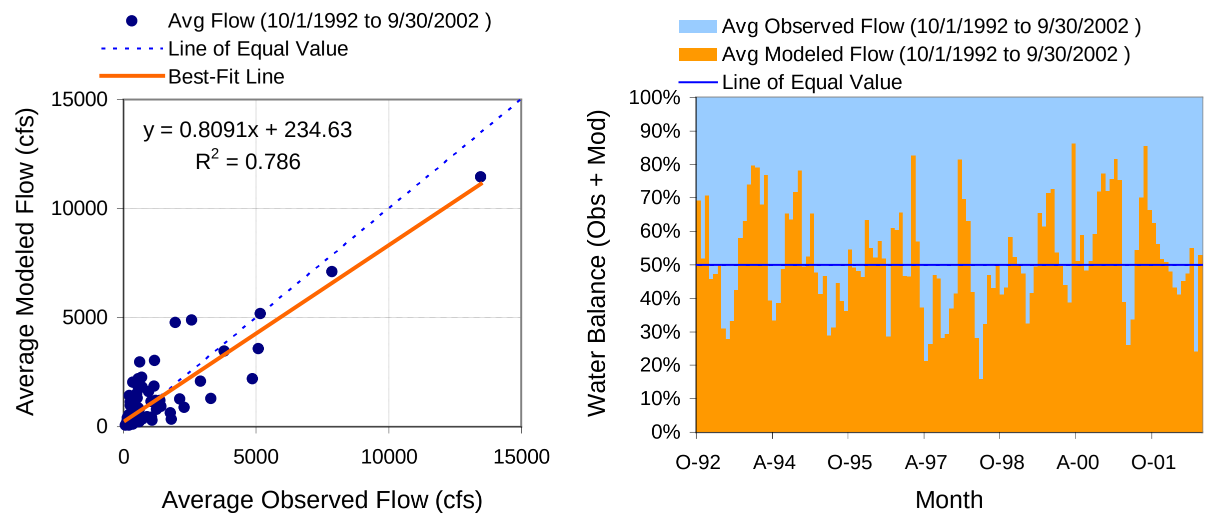

Figure 60. Monthly flow regression and temporal variation at USGS 09498500 Salt River near Roosevelt, AZ – calibration period (SWAT).

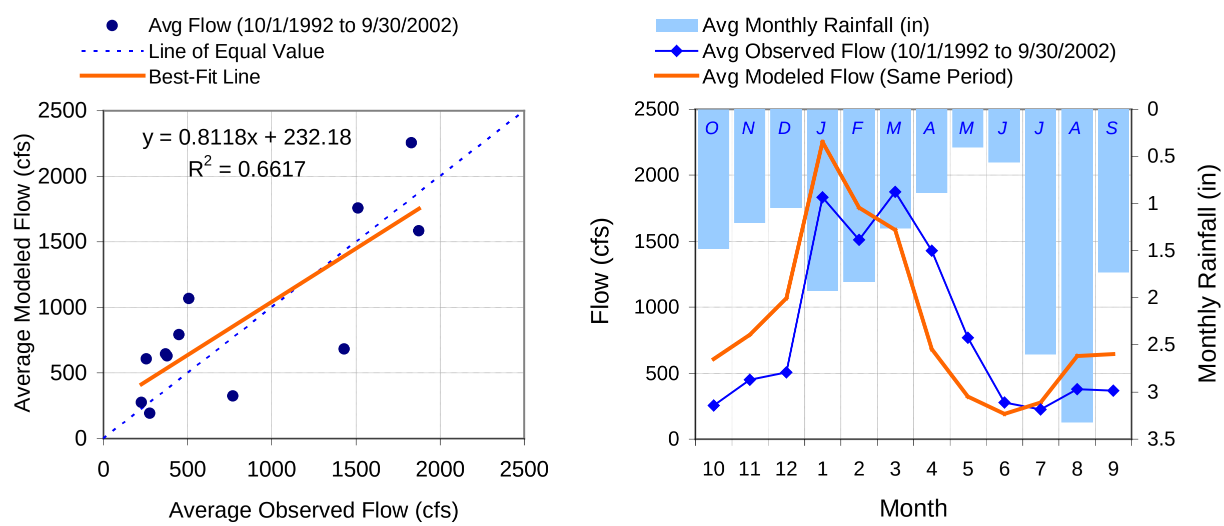

Figure 61. Seasonal regression and temporal aggregate at USGS 09498500 Salt River near Roosevelt, AZ – calibration period (SWAT).

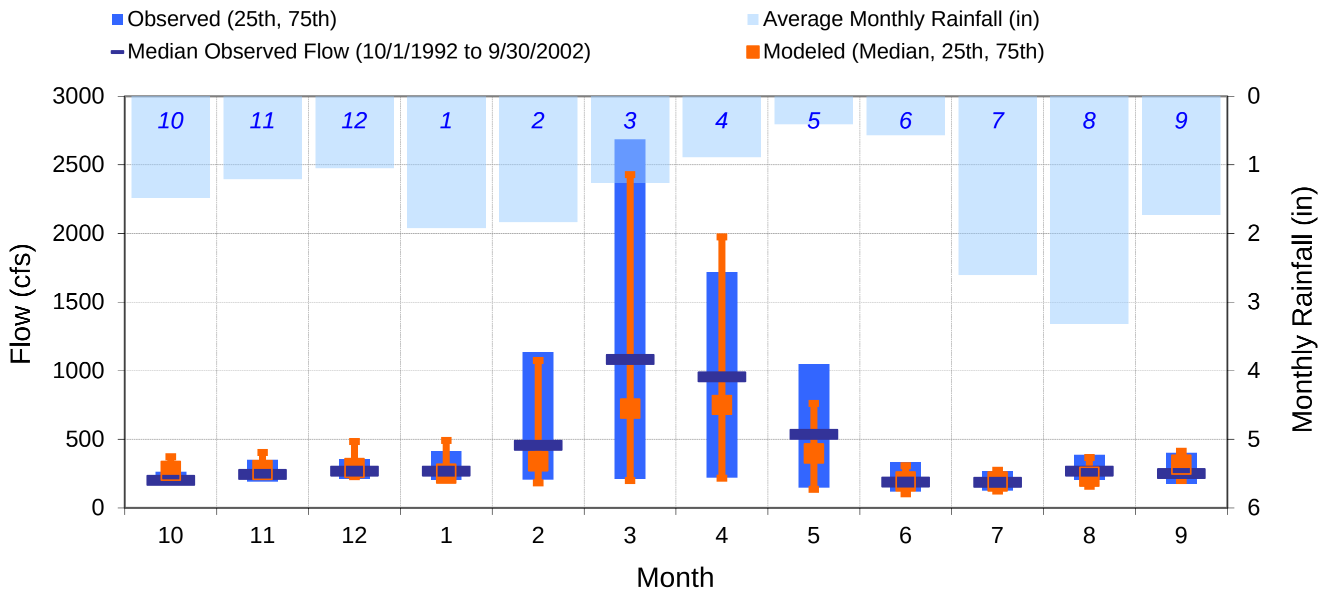

Figure 62. Seasonal medians and ranges at USGS 09498500 Salt River near Roosevelt, AZ – calibration period (SWAT).

Table 27.Seasonal summary at USGS 09498500 Salt River near Roosevelt, AZ – calibration period (SWAT)

MONTH	OBSERVED FLOW (CFS)				MODELED FLOW (CFS)			
	MEAN	MEDIAN	25TH	75TH	MEAN	MEDIAN	25TH	75TH
Oct	256.42	200.50	168.25	264.00	608.17	344.34	198.53	657.22
Nov	450.48	243.00	195.00	352.75	791.68	218.51	204.55	804.13
Dec	507.61	267.50	210.00	356.25	1067.82	403.31	196.21	1094.30
Jan	1831.48	267.00	204.00	413.25	2253.82	489.18	188.76	1909.69
Feb	1511.59	455.50	206.00	1135.00	1755.74	642.09	204.73	2372.74
Mar	1875.51	1080.00	211.50	2682.50	1584.27	794.67	261.51	2058.55
Apr	1429.55	953.50	224.00	1722.50	683.25	331.92	207.45	998.65
May	768.86	535.00	150.25	1047.50	324.01	236.85	184.00	380.12
Jun	277.08	187.50	121.00	335.25	191.56	199.95	141.41	225.64
Jul	226.12	185.50	129.25	269.50	275.63	180.78	113.41	207.08
Aug	377.92	267.50	205.50	389.50	628.63	216.21	140.01	844.51
Sep	368.88	249.50	174.00	402.25	643.08	293.31	144.25	699.35

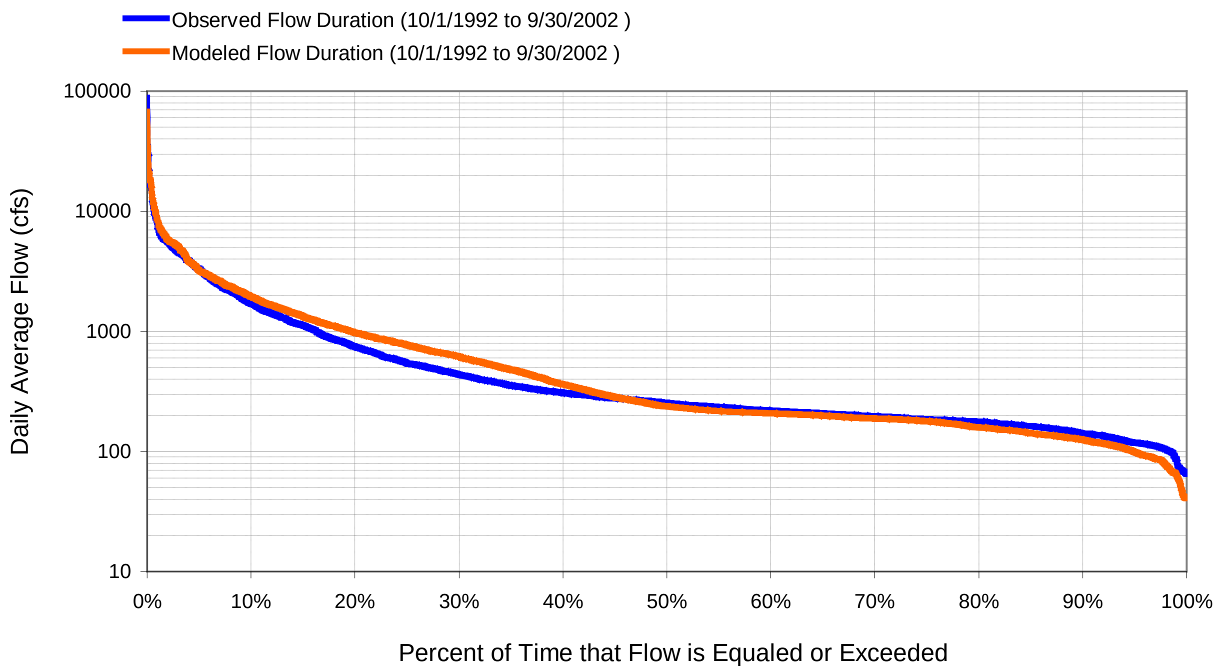

Figure 63. Flow exceedence at USGS 09498500 Salt River near Roosevelt, AZ – calibration period (SWAT).

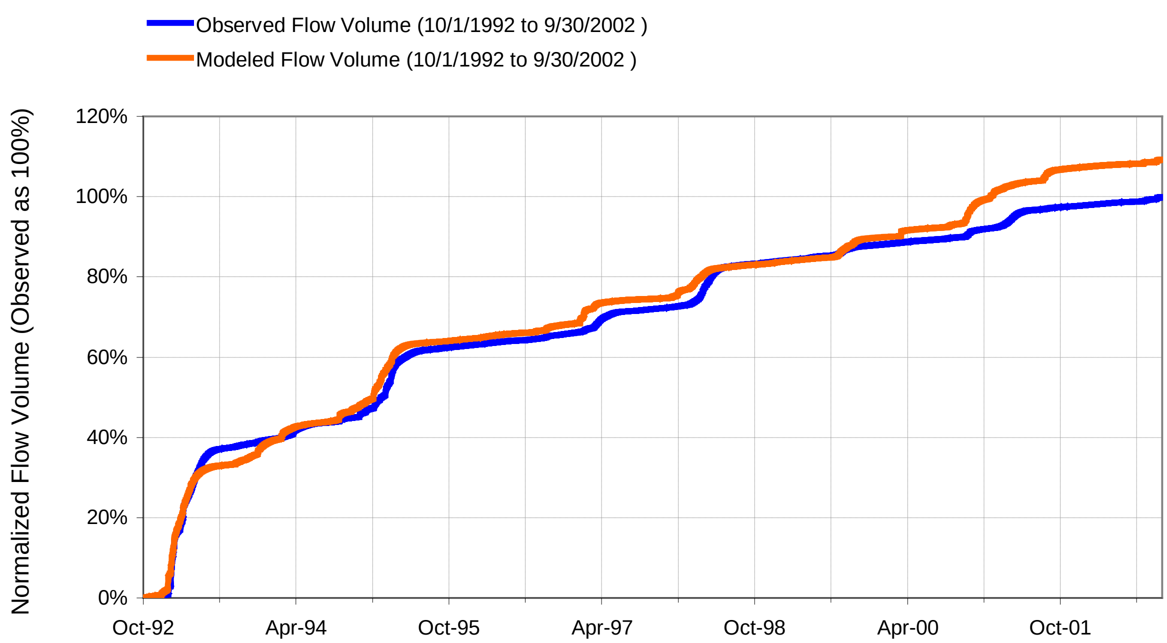

Figure 64. Flow accumulation at USGS 09498500 Salt River near Roosevelt, AZ – calibration period (SWAT).

Table 28. Summary statistics at USGS 09498500 Salt River near Roosevelt, AZ – calibration period (SWAT)

SWAT Simulated Flow		Observed Flow Gage		
REACH OUTFLOW FROM OUTLET 3 10-Year Analysis Period: 10/1/1992 - 9/30/2002 Flow volumes are (inches/year) for upstream drainage area		USGS 09498500 SALT RIVER NEAR ROOSEVELT, AZ Hydrologic Unit Code: 15060103 Latitude: 33.6194949 Longitude: -110.9215037 Drainage Area (sq-mi): 4306		
Total Simulated In-stream Flow:	**2.83**	Total Observed In-stream Flow:		**2.59**
Total of simulated highest 10% flows:	**1.63**	Total of Observed highest 10% flows:		**1.56**
Total of Simulated lowest 50% flows:	**0.27**	Total of Observed Lowest 50% flows:		**0.29**
Simulated Summer Flow Volume (months 7-9):	**0.41**	Observed Summer Flow Volume (7-9):		**0.26**
Simulated Fall Flow Volume (months 10-12):	**0.65**	Observed Fall Flow Volume (10-12):		**0.32**
Simulated Winter Flow Volume (months 1-3):	**1.46**	Observed Winter Flow Volume (1-3):		**1.36**
Simulated Spring Flow Volume (months 4-6):	**0.31**	Observed Spring Flow Volume (4-6):		**0.65**
Total Simulated Storm Volume:	**1.09**	Total Observed Storm Volume:		**0.94**
Simulated Summer Storm Volume (7-9):	**0.18**	Observed Summer Storm Volume (7-9):		**0.09**
Errors (Simulated-Observed)	*Error Statistics*	*Recommended Criteria*	*Run (n-1)*	*Run (n-2)*
Error in total volume:	9.43	10	2.65	5.65
Error in 50% lowest flows:	-7.16	10	3.27	13.54
Error in 10% highest flows:	4.52	15	-3.14	-2.75
Seasonal volume error - Summer:	**58.85**	**30**	**73.05**	**86.02**
Seasonal volume error - Fall:	**103.52**	>> **30**	**77.83**	Clear **91.08**
Seasonal volume error - Winter:	6.95	30	0.17	0.25
Seasonal volume error - Spring:	**-51.64**	**30**	**-57.34**	**-57.27**
Error in storm volumes:	16.40	20	5.26	5.60
Error in summer storm volumes:	**103.32**	**50**	**110.10**	**112.10**
Nash-Sutcliffe Coefficient of Efficiency, E:	0.222	Model accuracy increases	0.363	0.360
Baseline adjusted coefficient (Garrick), E':	0.314	as E or E' approaches 1.0	0.335	0.317
Monthly NSE	0.783			

Table 29. Summary statistics at all stations – validation period WY 1982-1992 (SWAT)

Station	09498500 Salt River nr Roosevelt	09503700 Verde River nr Paulden	09504000 Verde River nr Clarkdale	09504500 Oak Creek nr Cornville	09505800 W Clear Cr nr Camp Verde	09507980 E Verde River nr Childs	09508500 Verde R below Tangle Cr
Error in total volume:	-1.76	38.73	5.68	15.80	-0.57	23.55	7.96
Error in 50% lowest flows:	-18.12	-2.09	5.17	13.08	-28.71	1.12	11.91
Error in 10% highest flows:	-2.86	78.10	-9.70	-3.77	-0.02	53.33	-2.37
Seasonal volume error - Summer:	58.01	50.18	68.04	197.59	18.18	141.05	157.67
Seasonal volume error - Fall:	54.85	67.27	27.70	24.82	-10.18	45.31	17.43
Seasonal volume error - Winter:	-0.60	31.00	-25.96	-16.44	11.25	-6.66	-17.53
Seasonal volume error - Spring:	-60.95	-1.16	-11.56	-8.90	-33.19	-18.58	-30.60
Error in storm volumes:	6.42	108.63	12.44	18.06	34.57	91.61	19.33
Error in summer storm volumes:	99.23	107.87	197.67	370.81	-9.73	310.39	332.99
Daily Nash-Sutcliffe Coefficient of Efficiency, E:	-0.072	-2.028	-0.996	-0.061	-1.666	-1.193	-0.191
Monthly Nash-Sutcliffe Coefficient of Efficiency, E:	0.446	-0.034	0.320	0.395	-0.161	0.736	0.441

Water Quality Calibration and Validation

The 20 Watershed models are designed to provide water quality simulation for total suspended solids (TSS), total nitrogen, and total phosphorus. The water quality calibration focuses on the replication of monthly loads, as specified in the project QAPP. Given the simplified approach to water quality simulation in the 20 Watershed model a close match to individual concentration observations cannot be expected. However, comparison to monthly loads presents challenges, as monthly loads are not observed. Instead, monthly loads must be estimated from scattered concentration grab samples and continuous flow records. Such estimation is fraught with uncertainty because it depends on the degree and form in which concentration and flow are correlated with one another. Further, the bulk of the load of sediment and sediment-associated phosphorus is likely to move through the system in a limited number of high flow events that typically are not monitored. As a result, the monthly load calibration is inevitably based on the comparison of two uncertain numbers. Nonetheless, calibration is able to achieve a fair agreement. The load comparisons were supported by detailed examinations of the relationships of flows to loads and concentrations and the distribution of concentration prediction errors versus flow, time, and season, as well as standard time series plots.

For application on a nationwide basis, the 20 Watershed protocols assume that sediment and phosphorus loads will likely exhibit a strong positive correlation to flow (and associated erosive processes), while total nitrogen loads, which often have a dominant groundwater component, will not. Accordingly, sediment and phosphorus loads were estimated from observations using a flow-stratified log-log regression approach, while total nitrogen loads were estimated using a flow-stratified averaging estimator, consistent with the findings of Preston et al. (1989).

Initial calibration and validation of water quality was done on the Verde River near Clarkdale, using 1993-2002 for calibration and 1986-1992 for validation. As with hydrology, water quality calibration was performed on the later period as this better reflects the land use included in the model. The start of the validation period was constrained by data availability.

Sediment concentrations in larger, higher-order alluvial streams are largely determined by channel scour, deposition, and transport capacity rather than by upland sediment load. The SWAT representation of these channel processes is rather simplistic. First, the maximum transport capacity concentration (C_{mx}) is determined as $C_{mx} = SPCON \cdot V_{pk}^{SPEXP}$, where V_{pk} is the peak velocity, estimated by a simple ratio to the average rate of flow, and SPCON and SPEXP are user-defined parameters. When the predicted sediment concentration in the reach exceeds C_{mx} the excess is assumed to settle out. If the predicted sediment concentration in the reach is less than C_{mx}, additional sediment may be scoured from the channel to make up the difference, depending on the channel erodibility factor, K_{ch} (cm/hr/Pa). There is no provision for the different transport characteristics of different sediment size fractions. Further, the SPCON and SPEXP parameters are specified at the global level and do not vary by reach. As a result, the ability of SWAT to match individual TSS observations is rather limited.

By judicious adjustment of the SPCON, SPEXP, and K_{ch} parameters combined with the SWAT default MUSLE representation of upland sediment yield a reasonable representation of sediment load can be obtained. Time series of simulated and estimated sediment loads at the Clarkdale station for both periods are shown in Figure 65 and statistics for the two periods are provided separately in Table 30. The key statistic in the table is the relative percent error, which shows the error in the prediction of monthly load normalized to the estimated load. The table also shows the relative average absolute error, which is the average of the relative magnitude of errors in individual monthly load predictions. This number is inflated by outlier months in which the simulated and estimated loads differ by large amounts (which may be as easily due to uncertainty in the estimated load due to limited data as to problems with the model) and the third statistic, the relative median absolute error, is likely more relevant and shows good agreement.

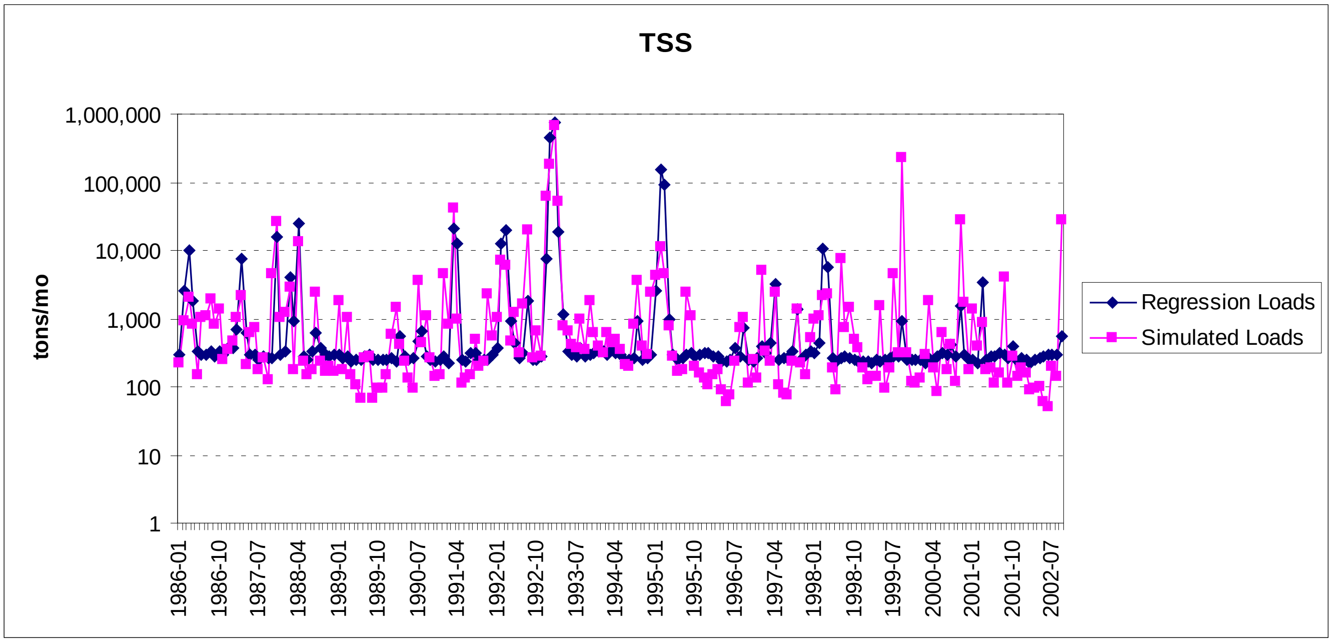

Figure 65. Fit for monthly load of TSS at USGS 09504000 Verde River near Clarkdale, AZ (SWAT).

Table 30. Model fit statistics (observed minus predicted) for monthly sediment loads using stratified regression at USGS 09504000 Verde River near Clarkdale, AZ (SWAT)

Statistic	Calibration period (1993-2002)	Validation period (1986-1992)
Relative Percent Error	16.9%	-42.6%
Relative Average Absolute Error	64%	122%
Relative Median Absolute Error	0.5%	0.8%

A variety of other diagnostics were also examined to evaluate agreement between the model and observations. These are available in full in the calibration spreadsheets, but a few examples are provided below. First, load-flow power plots were compared for individual days (Figures 66 and 67). These show that the relationship between flow and load is reasonably consistent across the entire range of observed flows, for both the calibration and validation periods.

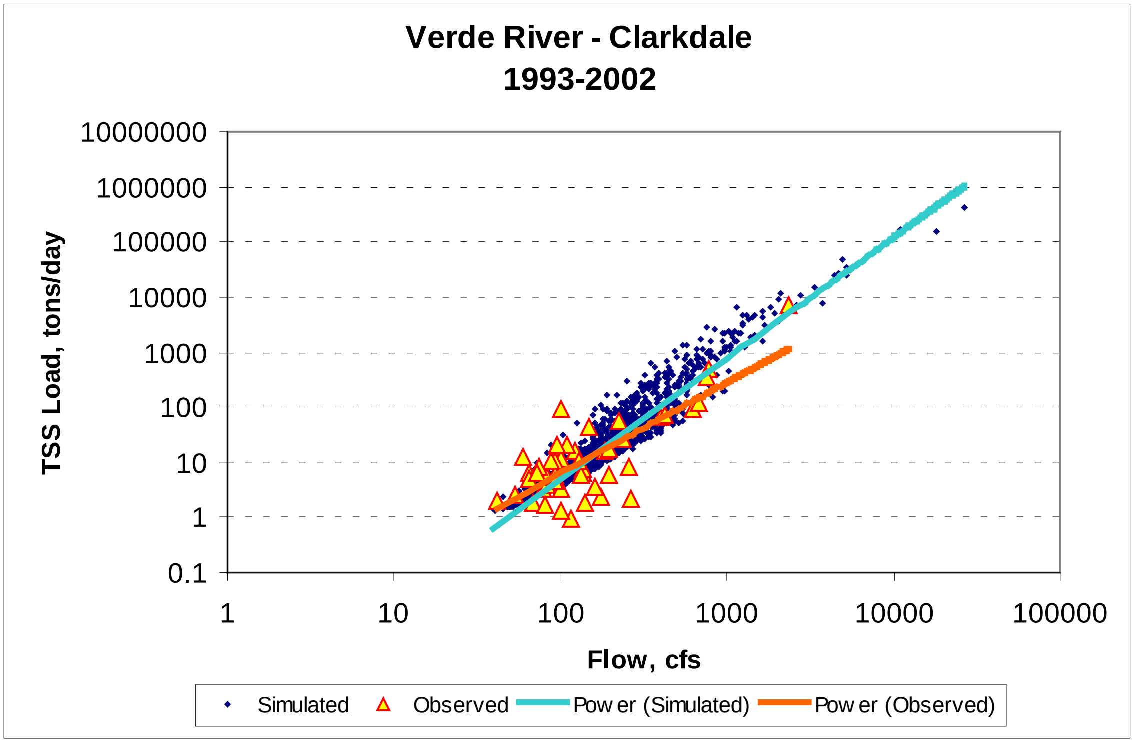

Figure 66. Power plot for observed and simulated TSS at USGS 09504000 Verde River near Clarkdale, AZ – calibration period (SWAT).

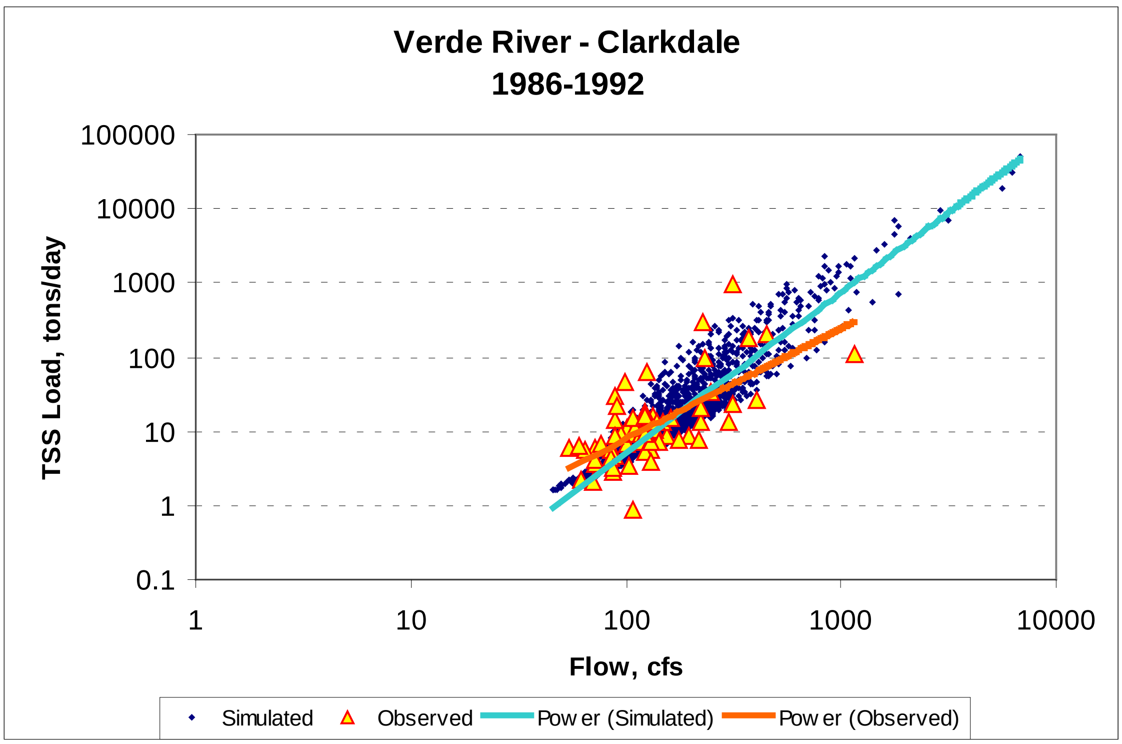

Figure 67. Power plot for observed and simulated TSS at USGS 09504000 Verde River near Clarkdale, AZ – validation period (SWAT).

Standard time series plots (Figure 68) show that observed and simulated concentrations achieve at best a fair agreement, and the model may deviate substantially from individual observations. However, statistics on concentration (0) show that low median errors are achieved (Table 31).

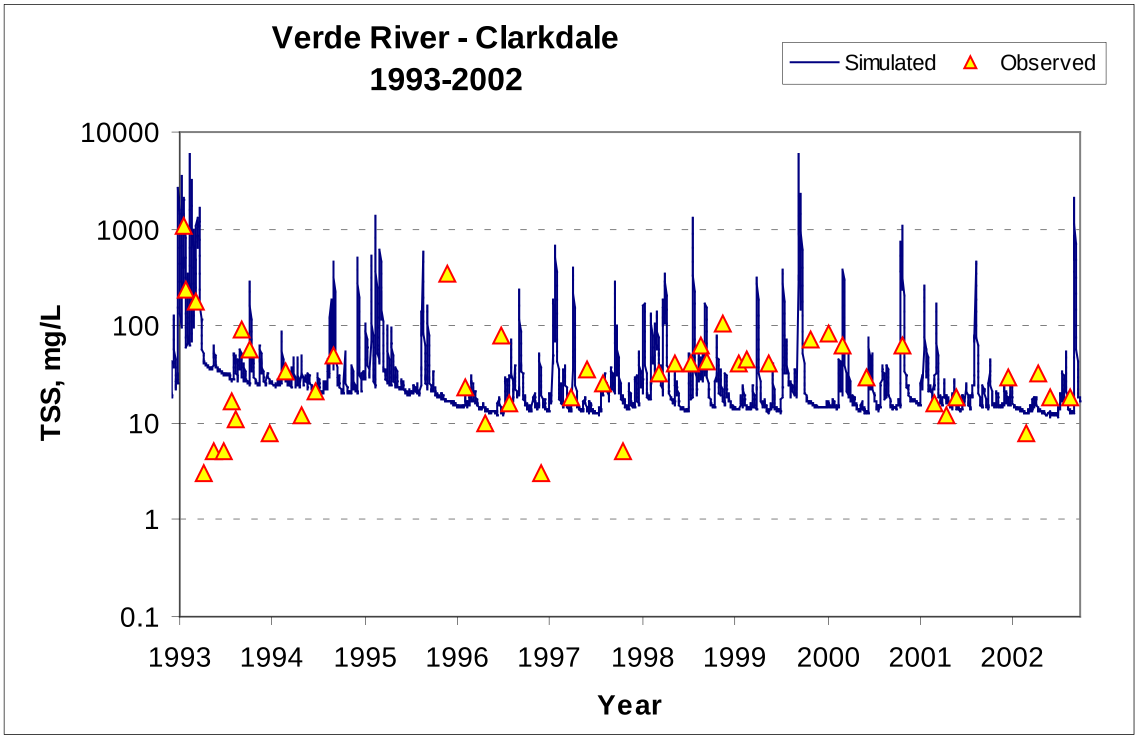

Figure 68. Time series plot of TSS concentration at USGS 09504000 Verde River near Clarkdale, AZ (SWAT).

Table 31. Relative errors (observed minus predicted) for TSS concentration at USGS 09504000 Verde River near Clarkdale, AZ (SWAT)

Statistic	Calibration period (1993-2002)	Validation period (1986-1992)
Count	47	62
Concentration Average Error	-22%	32%
Concentration Median Error	3.3%	9.3%

For simulation of total phosphorus and total nitrogen, calibration was advanced primarily through adjustment of the PPERCO and NPERCO coefficients. Monthly loading series for total phosphorus are shown in Figure 69 and load statistics are summarized in Table 32. The model reproduces the general trend in monthly loads, but is significantly lower than the peak loads predicted by the regression method, resulting in high relative percent errors for both the calibration and validation periods. It should be noted that the available data are limited, particularly for high flow events. Thus, the estimates of "observed" load are also subject to considerable uncertainty.

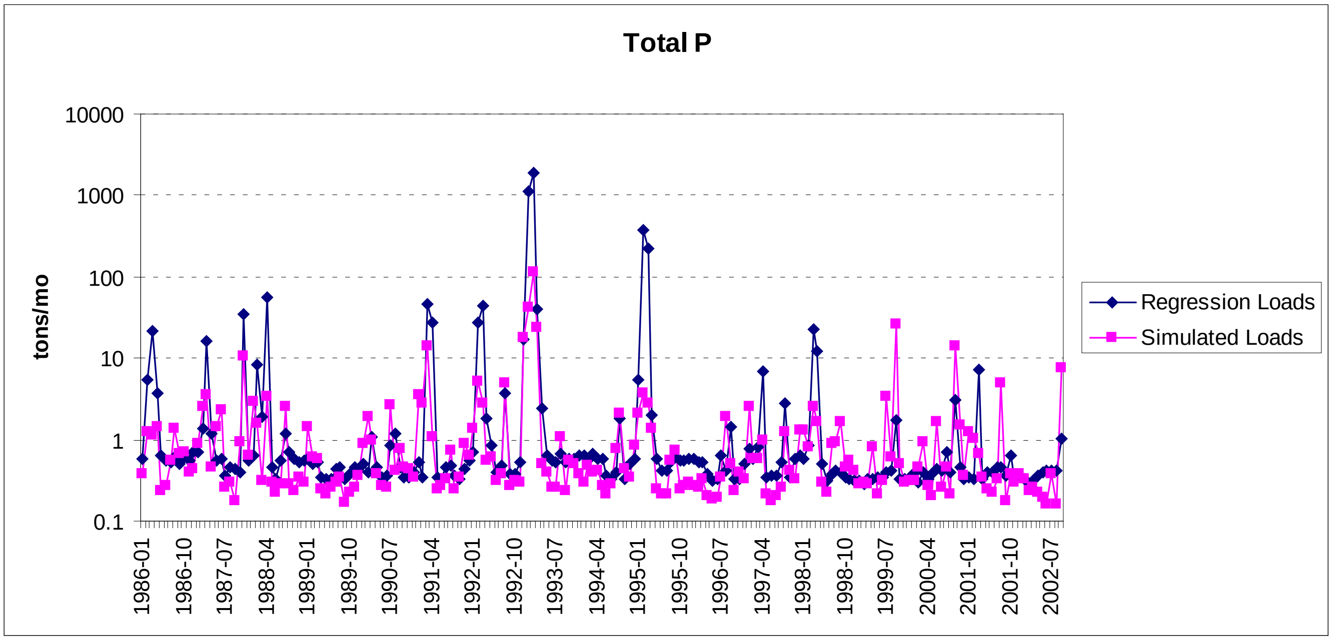

Figure 69. Fit for monthly load of total phosphorus at USGS 09504000 Verde River near Clarkdale, AZ (SWAT).

Table 32. Model fit statistics (observed minus predicted) for monthly total phosphorus loads using stratified regression (SWAT)

Statistic	Calibration period (1993-2002)	Validation period (1986-1992)
Relative Percent Error	83.5%	31.4%
Average Absolute Error	93%	83%
Median Absolute Error	0.3%	13.1%

As with TSS, additional diagnostics for total phosphorus included flow-load power plots (Figures 70 and 71), time series plots (Figure 72) and analysis of concentration errors (Table 33). While these show approximate agreement, the model often overpredicts total phosphorus concentrations under lower flow conditions, although not on a consistent basis.

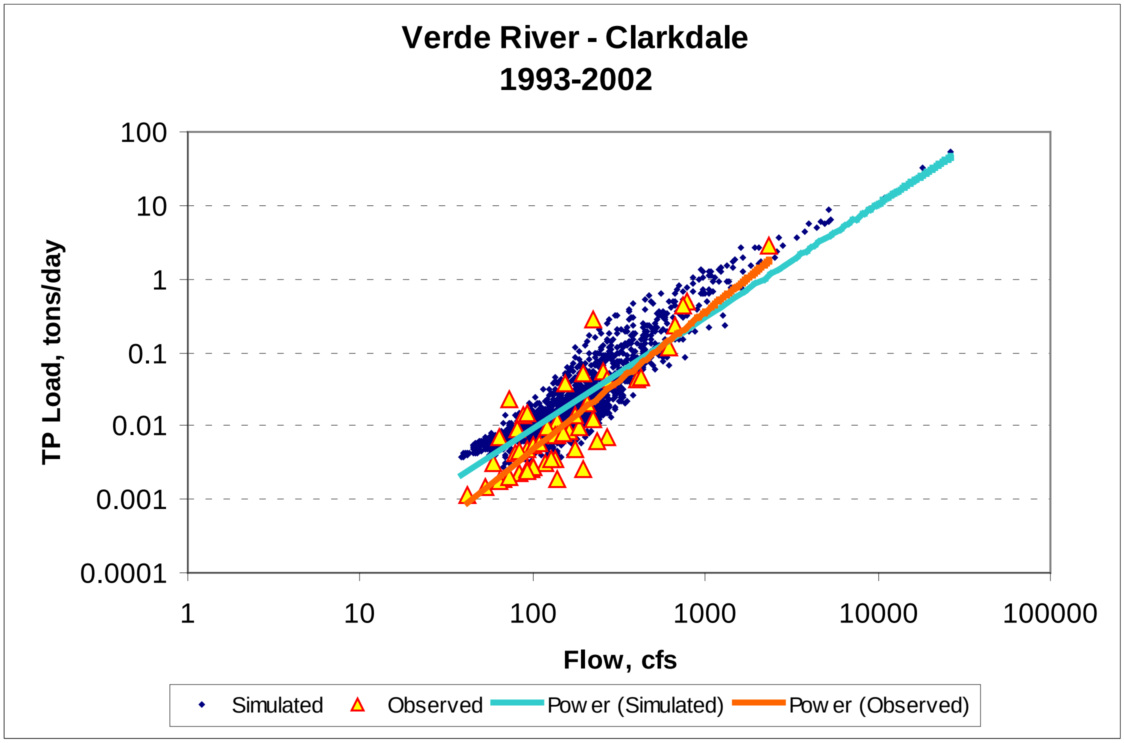

Figure 70. Power Plot for Observed and Simulated total phosphorus at USGS 09504000 Verde River near Clarkdale, AZ – calibration period (SWAT).

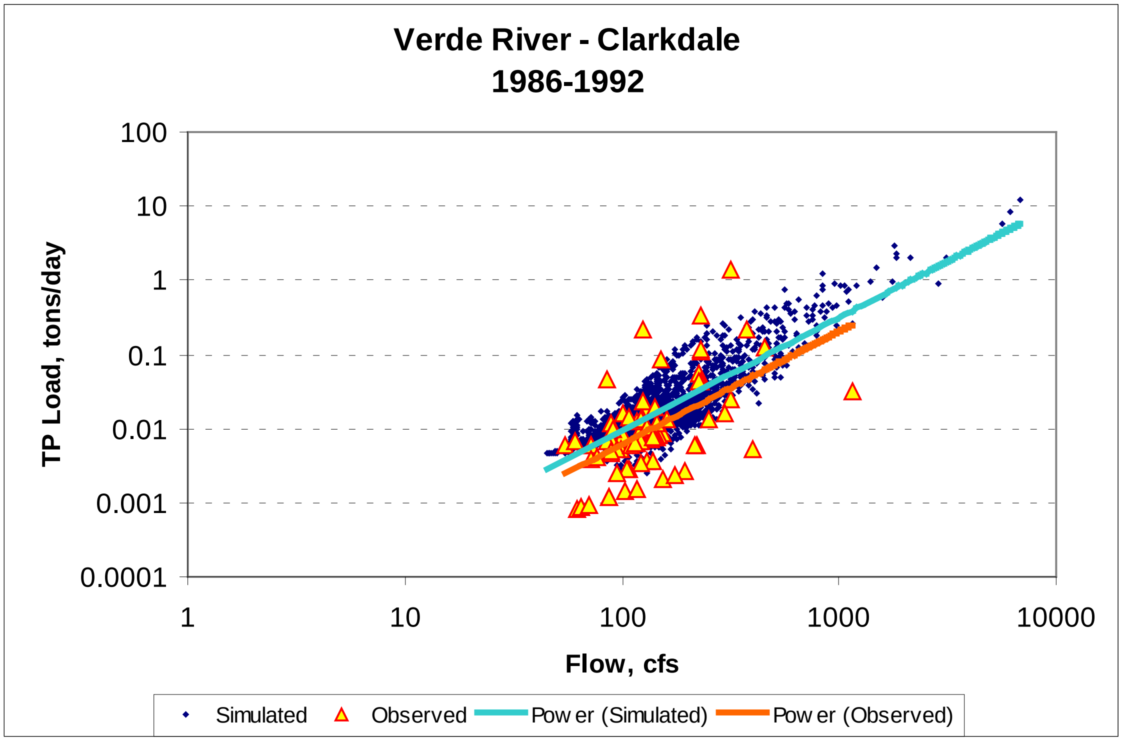

Figure 71. Power plot for observed and simulated total phosphorus at USGS 09504000 Verde River near Clarkdale, AZ – validation period (SWAT).

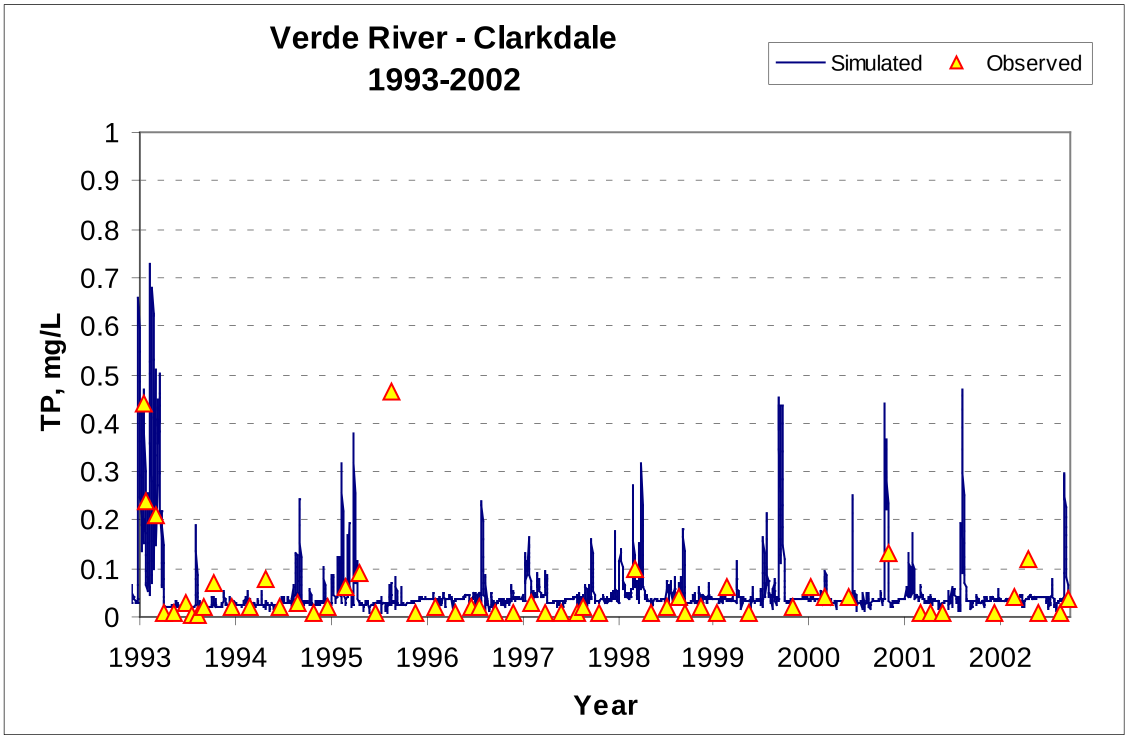

Figure 72. Time series plot of total phosphorus concentration at USGS 09504000 Verde River near Clarkdale, AZ (SWAT).

Table 33. Relative errors (observed minus predicted) for total phosphorus concentration at USGS 09504000 Verde River near Clarkdale, AZ (SWAT)

Statistic	Calibration period (1993-2002)	Validation period (1986-1992)
Count	57	75
Concentration Average Error	-11%	31%
Concentration Median Error	-33%	-17%

For total nitrogen, fewer data are available because many sampling events omitted one or more nitrogen species. This increases the uncertainty of the comparison. Results for total nitrogen are summarized in Figures 73 through 76 and Tables 34 and 35, following the same format as total phosphorus. The loading results are acceptable, and generally better than those obtained for total phosphorus. However, there is significant uncertainty in the prediction of individual nitrogen observations.

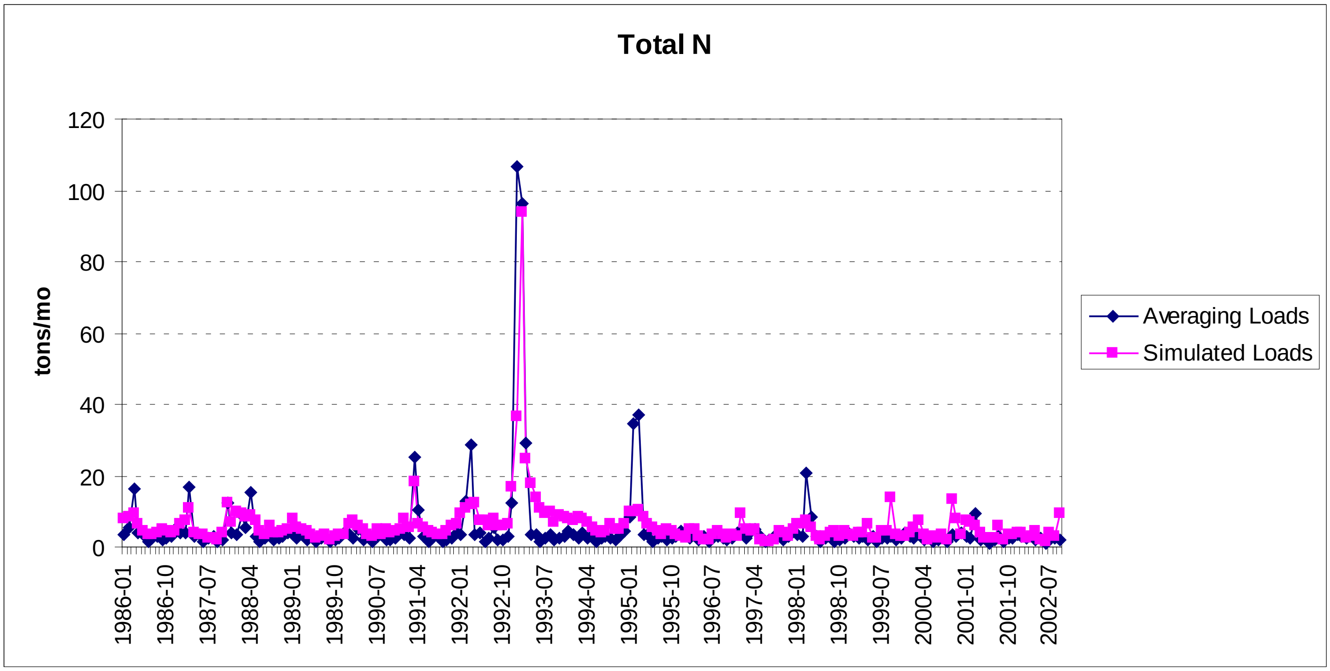

Figure 73. Fit for monthly load of total nitrogen at USGS 09504000 Verde River near Clarkdale, AZ (SWAT).

Table 34. Model fit statistics (observed minus predicted) for monthly total nitrogen loads using averaging estimator (SWAT)

Statistic	Calibration period (1993-2002)	Validation period (1986-1992)
Relative Percent Error	-14.4%	-15.9%
Average Absolute Error	84%	67%
Median Absolute Error	13%	48%

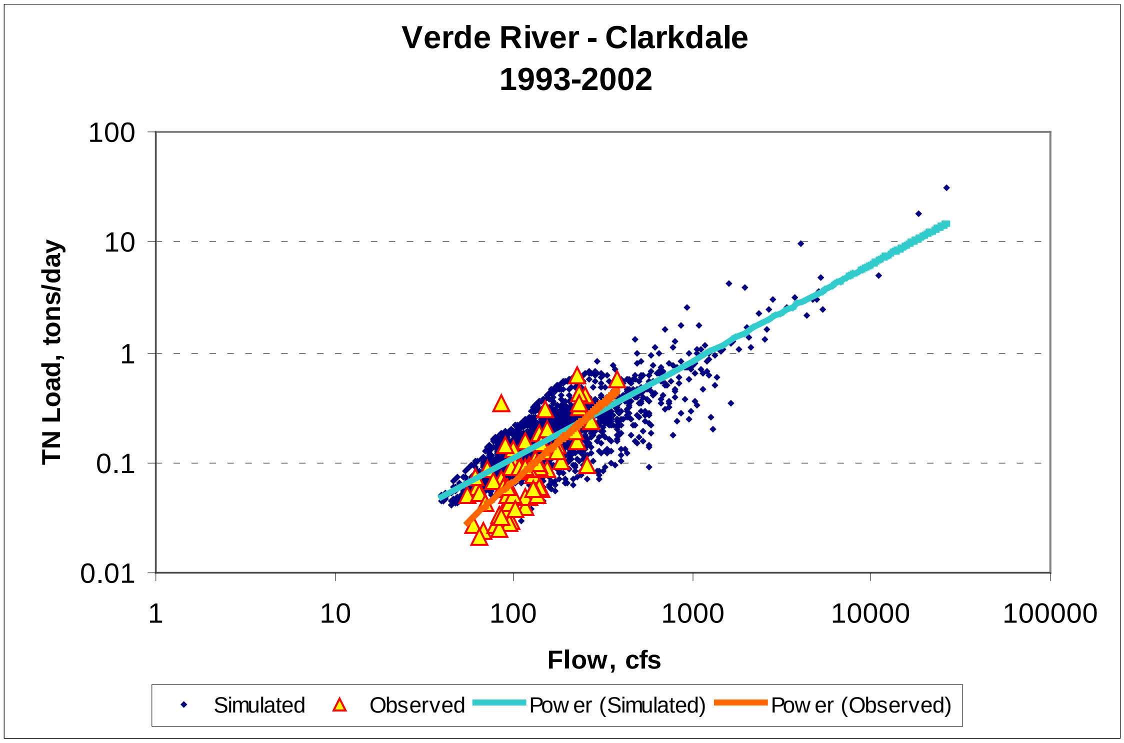

Figure 74. Power plot for observed and simulated total nitrogen at USGS 09504000 Verde River near Clarkdale, AZ – calibration period (SWAT).

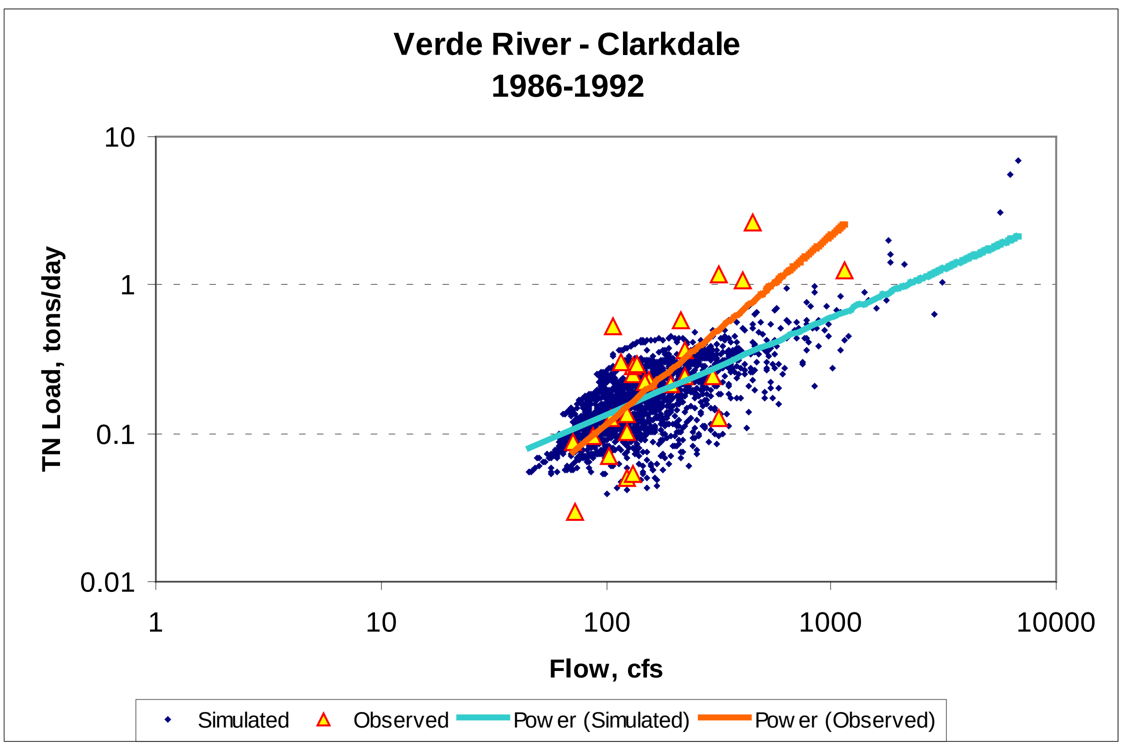

Figure 75. Power plot for observed and simulated total nitrogen at USGS 09504000 Verde River near Clarkdale, AZ – validation period (SWAT).

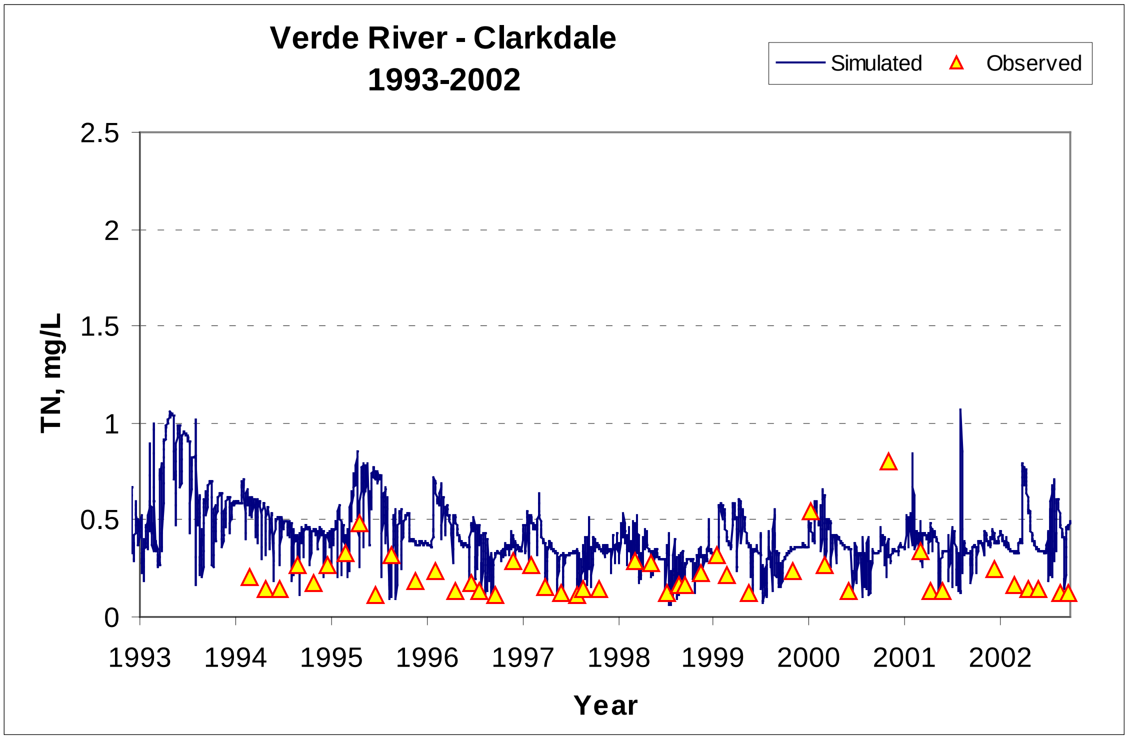

Figure 76. Time series plot of total nitrogen concentration at USGS 09504000 Verde River near Clarkdale, AZ (SWAT).

Table 35. Relative errors (observed minus predicted) for total nitrogen concentration at USGS 09504000 Verde River near Clarkdale, AZ (SWAT)

Statistic	Calibration period (1993-2002)	Validation period (1986-1992)
Count	46	75
Concentration Average Error	-83%	1.3%
Concentration Median Error	-90%	-18%

Water Quality Results for Larger Watershed

Summary statistics for the water quality calibration and validation at other stations in the watershed are provided in Tables 36 and 37, respectively. In most cases, nitrogen loads are better predicted than phosphorus and TSS loads. In a majority of cases simulated TSS and total phosphorus loads are lower than those estimated from observations, but this may reflect in part the uncertainty in the regression-based load estimates as water quality observations during high flows are sparse.

Table 36. Summary statistics (observed minus predicted) for water quality at all stations – calibration period 1993-2002 (SWAT)

Station	09498500 Salt River nr Roosevelt	09504000 Verde River nr Clarkdale	09508500 Verde River below Tangle Cr
Relative Percent Error TSS Load	41.1	16.9	17.7
TSS Concentration Median Percent Error	-15	3.4	2.0
Relative Percent Error TP Load	61.0	83.5	33.8
TP Concentration Median Percent Error	-2	-33	-19.9
Relative Percent Error TN Load	9.5	-14.4	17.0
TN Concentration Median Percent Error	-4	-90	-60

Table 37. Summary statistics (observed minus predicted) for water quality at all stations – validation period 1986-1992 (SWAT)

Station	09498500 Salt River nr Roosevelt	09504000 Verde River nr Clarkdale	09508500 Verde River below Tangle Cr
Relative Percent Error TSS Load	-0.6	-42.6	-55.1
TSS Concentration Median Percent Error	-16	9.3	0.35
Relative Percent Error TP Load	54.2	31.4	-41.4
TP Concentration Median Percent Error	-18	-17	-5.8
Relative Percent Error TN Load	18.0	-15.9	-20.3
TN Concentration Median Percent Error	-36	-18	-13

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Appendix F
Model Configuration, Calibration and Validation

Basin: Susquehanna River

Contents

Tables

Figures

Watershed Background

Water Body Characteristics

The Susquehanna River drains about 27,500 mi^2 in the states of New York, Pennsylvania, and Maryland and includes a total of 19 HUC8s in HUC 2050 (Figure 1). The watershed makes up 43 percent of the Chesapeake Bay's drainage area and consists of six major subwatersheds (Chemung, Upper Susquehanna, West Branch Susquehanna, Middle Susquehanna, Juniata, and Lower Susquehanna). The Susquehanna River flows about 444 miles from its headwaters at Otsego Lake in Cooperstown, New York to Havre de Grace, Maryland, where the river flows into the Chesapeake Bay. The river is the largest tributary to the Chesapeake Bay, providing 50 percent of its freshwater flows (SRBC 2008).

The Susquehanna River watershed includes three physiographic provinces: the Appalachian Plateau, the Valley and Ridge, and the Piedmont Provinces. The Appalachian Plateau Province is characterized by high, flat-topped hills and deep valleys cut by the Susquehanna River and its tributaries. The Valley and Ridge physiographic province contains steep mountains and ridges separated by valleys. The Piedmont physiographic province consists of uplands and lowlands. The Piedmont physiographic province generally has terrain that is gently rolling to hilly.

Sixty-nine percent of the watershed is forested. However, the well-drained areas with rolling hills and valleys in the southern part of the watershed contain most of the population and some of the most productive agricultural land in the US. Groundwater maintains the base flow of perennial streams during periods of little or no precipitation and constitutes an average of 50 percent of the flow of most streams at other times.

The U.S. Army Corps of Engineers (USACE) operates and maintains 13 dams and reservoirs that are located in all six major subwatersheds. USACE also regulates the operation of a state of Pennsylvania reservoir (George B. Stevenson) in the West Branch Susquehanna subwatershed for the purpose of flood damage reduction. These 14 reservoirs provide most of the floodwater storage in the watershed. The Natural Resources Conservation Service and the state of Pennsylvania have also constructed reservoirs in the watershed that reduce flood damages; however, these reservoirs are typically smaller in scale than the USACE reservoirs.

In addition to the many flood storage dams and reservoirs, there are 20 major electric power generating plants located in the Susquehanna River watershed that use water resources in their operation. Many of these hydroelectric dams are located in the lower Susquehanna watershed. Just below Harrisburg, Pennsylvania the Susquehanna River flows through a series of gorges dammed by hydroelectric power facilities. There are also 13 approved water diversions from the Susquehanna River watershed.

The Susquehanna River basin has a continental type of climate. The average annual temperature in the basin ranges from about 44 degrees in the northern part of the basin to about 53 degrees in the southern part. Average annual precipitation is about 40 inches over the entire basin and ranges from 33 inches in the northern part of the basin to 46 inches in the southern part. Virtually all the major streams experience their highest flows in March, April, and May, when melting snows combine with spring rains. These three months account for about one-half of the yearly runoff. Flows are lowest in these streams during the summer and early fall months, with most streams falling to their lowest levels in September. The Susquehanna River basin is one of the country's most flood prone areas. Generally, floods occur each year somewhere in the basin, and major floods can occur in all seasons of the year, and a major flood occurs on average every 13 years.

Groundwater flow maintains the base flow of perennial streams during periods of little or no precipitation and constitutes an average of 50 percent of the flow of most streams at other times. The use of groundwater resources in the basin is extensive. Groundwater plays a critical role in supplying drinking water and maintaining economic viability. Outside of the major population centers, drinking water supplies are heavily dependent on groundwater wells. Approximately 20 percent of the basin population is served by public water suppliers that use groundwater as a source.

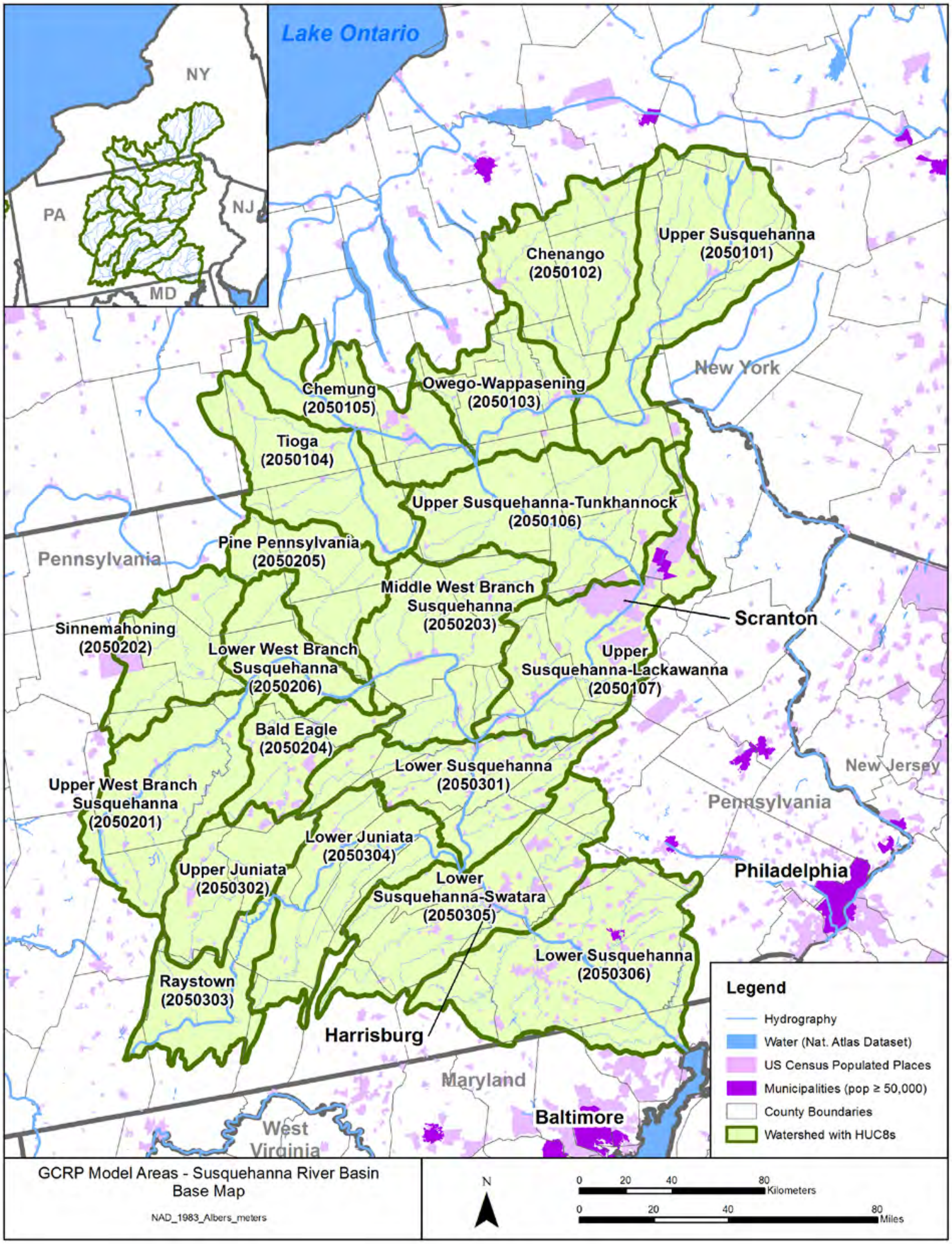


Figure 1. Location of the Susquehanna River watershed.

Soil Characteristics

One of the most important characteristics of soils for watershed modeling is their hydrologic soil group (HSG). The 20 Watershed study utilized STATSGO soil survey HSG information during model set-up. Soils are classified into four hydrologic groups (SCS 1986), separated by runoff potential, as follows:

Group A Soils	Have low runoff potential and high infiltration rates even when thoroughly wetted. They consist chiefly of deep, well to excessively drained sands or gravels and have a high rate of water transmission.
Group B Soils	Have moderate infiltration rates when wet and consist chiefly of soils that are moderately deep to deep, moderately well to well drained, and moderately fine to moderately course textures.
Group C Soils	Have low infiltration rates when thoroughly wetted and consist chiefly of soils having a layer that impedes downward movement of water with moderately fine to fine structure.
Group D Soils	Have high runoff potential, very low infiltration rates and consist chiefly of clay soils with high swelling potential, soils with a permanent water table, soils with a claypan or clay layer at or near the surface and shallow soils over nearly impervious material.

The Susquehanna River watershed contains all four HSGs in the watershed. However, soils in the watershed, as described in STATSGO soil surveys, fall primarily into HSGs B (moderately high infiltration capacity) and C (low infiltration capacity). Hydrologic group C soils dominate the northern portion of the watershed while a mixture of B and C soils dominate the southern portion of the watershed.

Land Use Representation

Land use/cover in the watershed is based on the 2001 National Land Cover Database (NLCD) coverage and is predominantly forested with some agricultural and developed land (Figure 2). Agriculture and pasture are more predominant in the downstream, eastern portions of the watershed. Urban development is found throughout the watershed; however, the major concentration is in the eastern portions of the watershed.

NLCD land cover classes were aggregated according to the scheme shown in Table 1 for representation in the 20 Watershed model, then overlain with the soils HSG grid. Pervious and impervious lands are specified separately for HSPF, so only one developed pervious class is used, along with an impervious class. HSPF simulates impervious land areas separately from pervious land. Impervious area distributions were also determined from the NLCD Urban Impervious data coverage. Specifically, percent impervious area was calculated over the whole basin for each of the four developed land use classes. These percentages were then used to separate out impervious land. NLCD impervious area data products are known to underestimate total imperviousness in rural areas. However, the model properly requires connected impervious area, not total impervious area, and the NLCD tabulation is assumed to provide a reasonable approximation of connected impervious area. Different developed land classes are specified separately in SWAT. In HSPF the WATER, BARREN, DEVPERV, and WETLAND classes are not subdivided by HSG; SWAT uses the built-in HRU overlay mechanism in the ArcSWAT interface.

The distribution of land use in the watershed is summarized in Table 2.

Table 1. Aggregation of NLCD land cover classes

NLCD Class	Comments	SWAT class	HSPF (after processing)
11 Water	Water surface area usually accounted for as reach area	WATR	WATER
12 Perennial ice/snow		WATR	BARREN, Assume HSG D
21 Developed open space		URLD	DEVPERV; IMPERV
22 Dev. Low Intensity		URMD	
23 Dev. Med. Intensity		URHD	
24 Dev. High Intensity		UIDU	
31 Barren Land		SWRN	BARREN (D)
41 Forest	Deciduous	FRSD	FOREST (A,B,C,D)
42 Forest	Evergreen	FRSE	
43 Forest	Mixed	FRST	
51-52 Shrubland		RNGB	SHRUB (A,B,C,D)
71-74 Herbaceous Upland		RNGE	GRASS (A,B,C,D), BARREN (D)
81 Pasture/Hay		HAY	GRASS (A,B,C,D)
82 Cultivated		AGRR	AGRI (A,B,C,D)
91-97 Wetland	Emergent & woody wetlands	WETF, WETL, WETN	WETLAND, Assume HSG D
98-99 Wetland	Aquatic bed wetlands (not emergent)	WATR	WATER

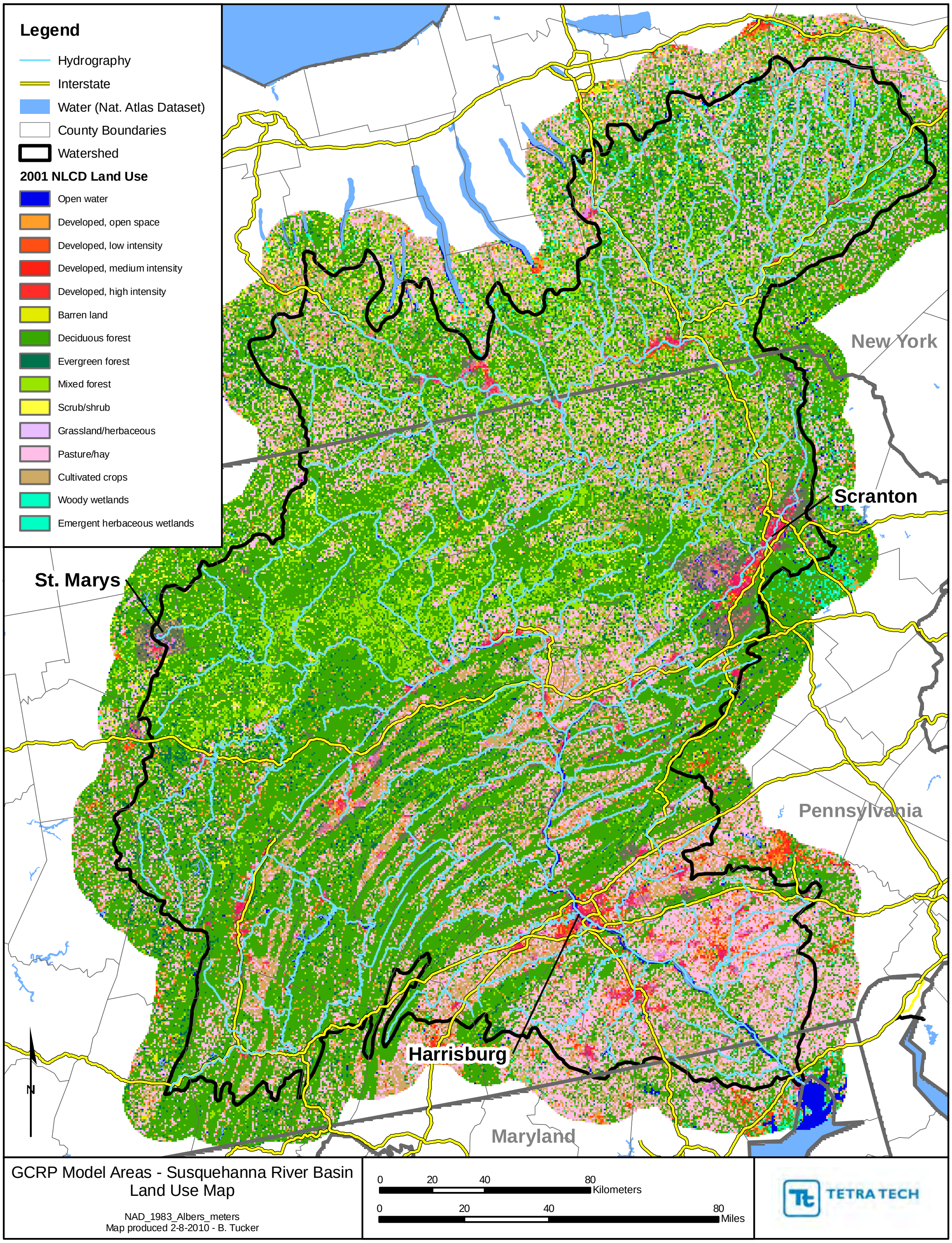


Figure 2. Land use in the Susquehanna River watershed.

Table 2. Land use distribution for the Susquehanna River watershed (2001 NLCD, mi2)

HUC 8 watershed	Open water	Developed[a] Open space	Low density	Medium density	High density	Barren land	Forest	Shrubland	Pasture/Hay	Cultivated	Wetland	Total
02050101	29.7	89.0	18.1	5.7	1.5	0.5	1,345.3	73.0	459.3	163.0	104.6	2,289.7
02050102	13.2	56.8	14.3	4.8	1.1	1.7	909.5	75.2	319.1	146.5	65.0	1,607.3
02050103	7.8	45.3	18.3	6.9	1.7	0.5	659.5	25.0	200.8	56.5	23.7	1,046.1
02050104	7.3	47.4	7.1	2.5	0.5	2.7	833.2	39.8	299.3	137.3	6.0	1,383.2
02050105	9.2	55.7	18.1	5.9	1.2	1.2	704.5	45.4	196.1	152.5	22.1	1,211.8
02050106	24.3	88.2	9.4	2.9	0.7	1.9	1,177.4	29.0	340.7	314.0	18.1	2,006.7
02050107	32.4	117.5	60.5	42.9	12.1	11.8	1,083.8	23.7	230.2	126.1	22.9	1,764.0
02050201	10.6	90.3	14.7	2.5	0.5	30.1	1,229.8	32.9	147.0	36.2	1.9	1,596.7
02050202	1.4	12.1	1.7	0.5	0.1	2.5	921.2	56.5	27.9	2.8	7.3	1,033.8
02050203	5.6	12.8	2.3	0.9	0.1	2.1	728.9	18.6	21.1	7.7	3.1	803.2
02050204	4.4	45.9	19.0	4.5	1.5	1.4	543.1	0.0	64.8	70.0	0.1	754.6
02050205	2.4	16.9	2.4	0.7	0.2	2.1	816.2	42.0	68.0	25.9	4.3	981.0
02050206	14.1	80.6	23.6	8.5	2.1	2.3	1,170.3	33.1	282.9	184.5	7.8	1,809.9
02050301	32.8	87.1	24.7	7.8	2.4	9.3	860.0	0.0	219.9	201.7	3.0	1,448.7
02050302	3.3	54.4	26.5	8.6	3.5	1.8	688.8	0.0	101.9	102.2	0.1	991.1
02050303	17.3	51.5	12.6	2.9	0.8	1.4	655.6	0.0	140.8	78.8	0.0	961.7
02050304	12.4	72.7	18.0	4.1	1.1	0.3	1,019.2	0.0	185.0	137.2	0.7	1,450.7
02050305	33.5	139.6	113.1	35.6	15.1	3.5	858.3	0.0	391.9	273.5	12.3	1,876.5
02050306	51.5	109.8	99.7	40.4	16.0	23.0	603.5	0.0	1,015.3	489.1	39.4	2,487.5
Total	313.2	1,273.6	504.1	188.6	62.5	100.0	16,808.1	494.4	4,712.1	2,705.6	342.2	27,504.3

[a]The percent imperviousness applied to each of the developed land uses is as follows: open space (6.90%), low density (31.26%), medium density (60.90%), and high density (85.41%).

Point Sources

There are numerous point source discharges in the watershed. For the purposes of 20 Watershed modeling, only the 147 major dischargers with a design flow greater than 1 MGD are included in the simulation (Table 3 and Figure 3). The major dischargers account for the majority of the facilities, so the effect of the omitted sources distributed throughout the watershed will be relatively small, except during extreme low flow conditions. The major dischargers are represented at long-term average flows, without accounting for changes over time or seasonal variations.

Data from 1991-2006 were compiled from the PCS database and the median total nitrogen, total phosphorus, and TSS values were estimated. The facilities that were missing a total nitrogen, total phosphorus, and TSS concentration value were filled with a typical pollutant concentration value from literature (Tetra Tech 1990) based on the SIC classification. The median concentrations for the nutrient species were estimated based on the values reported in the Chesapeake Bay Phase 5 Model documentation (USEPA 2010).

Table 3. Major point source discharges in the Susquehanna River watershed

NPDES ID	Name	Design flow (MGD)	Observed flow (MGD) (1991-2006 average)
MD0002518	EXELON POWER GENERATION	47.74	0.00
NY0003824	AEROSPACE OPERATIONS	1.35	0.22
NY0003859	AES HICKLING, LLC	77.34	1.10
NY0003867	AES - JENNISON, LLC	65.34	0.03
NY0003875	AES WESTOVER	101.90	0.44
NY0004057	SYSTEMS INTEGRATION - OWEGO	1.61	0.62
NY0004081	MOTOR COMPONENTS, LLC	0.93	3.00
NY0004138	OSG NORWICH PHARMACEUTICALS	0.80	0.08
NY0004146	WOODS CORNER PLANT	0.30	0.07
NY0004243	KERRY BIO-SCIENCE	2.30	0.39
NY0020672	HAMILTON (V) WPCP	0.85	0.53
NY0021423	NORWICH (C) WWTP	2.20	2.14
NY0021431	BATH (V) WWTP	1.00	0.74
NY0022357	ALFRED (V) WWTP	0.98	0.60
NY0022730	OWEGO (T) SD#1	0.50	0.67
NY0023591	COOPERSTOWN (V) STP	0.52	0.65
NY0023647	HORNELL (C) WPCP	4.00	2.94
NY0023906	ERWIN (T) STP	0.80	0.64
NY0024414	BINGHAMTON-JOHNSON (C) JNT STP	20.00	22.20
NY0025712	PAINTED POST (V) STP	0.50	0.25

NPDES ID	Name	Design flow (MGD)	Observed flow (MGD) (1991-2006 average)
NY0025721	CORNING (C) STP	2.13	1.56
NY0025798	OWEGO WPCP #2	2.00	1.14
NY0027561	LE ROY R SUMMERSON WWTF	10.00	6.96
NY0027669	ENDICOTT (V) WPCP	10.00	7.48
NY0029262	OWEGO (V) STP	1.00	0.57
NY0029271	SIDNEY (V) WWTP	1.70	0.62
NY0031151	ONEONTA (C) WWTP	4.00	2.47
NY0035742	CHEMUNG CO ELMIRA SD STP	12.00	7.49
NY0036986	CHEMUNG CO SD#1 STP	9.50	7.94
PA0007498	WISE FOODS INC	0.59	0.24
PA0007919	CASCADES TISSUE GROUP - PA INC	1.25	1.56
PA0008231	GOLD MILLS INC	2.00	17.94
PA0008265	APPLETON PAPERS INC - SPRING M	4.84	4.45
PA0008281	PPL BRUNNER ISLAND LLC	621.00	6.46
PA0008303	ISG STEELTON LLC	27.60	28.01
PA0008419	MERCK & CO INC	12.20	8.70
PA0008443	PPL MONTOUR LLC	0.46	8.44
PA0008451	SUNBURY GENERATION LLC	3.38	6.50
PA0008508	BURLE BUSINESS PARK LP	0.32	0.11
PA0008575	WIREROPE WORKS INC	0.07	0.05
PA0008869	PH GLATFELTER CO	13.70	28.27
PA0008885	PROCTER & GAMBLE PRODUCTS CO	7.60	7.68
PA0008923	CORNING ASAHI VIDEO PROD CO	1.97	1.27
PA0009024	OSRAM SYLVANIA PRODUCTS INC	1.22	0.93
PA0009164	STANDARD STEEL LLC	1.45	15.56
PA0009202	CERRO METAL PRODUCTS CO	0.23	2.36
PA0009229	NORFOLK SOUTHERN RAILWAY CO -	0.50	0.24
PA0009253	UNITED DEFENSE LP	0.03	0.03
PA0009270	DEL MONTE CORP	0.67	0.41
PA0009733	EXELON GENERATION CO LLC - PEA	0.05	0.12
PA0009920	AMERGEN ENERGY CO LLC - THREE	81.02	20.07
PA0010031	RELIANT ENERGY MID-ATLANTIC PO	0.01	0.70

NPDES ID	Name	Design flow (MGD)	Observed flow (MGD) (1991-2006 average)
PA0010430	HANOVER FOODS CORP	0.23	0.18
PA0013862	CORIXA CORP	0.32	0.18
PA0020273	MILTON REGIONAL SEW AUTH	3.42	78.54
PA0020320	LITITZ SEW AUTH	3.85	2.62
PA0020486	BELLEFONTE BORO	3.22	2.21
PA0020567	NORTHUMBERLAND SEW AUTH	1.13	11.68
PA0020664	MIDDLETOWN BORO AUTH	2.20	1.32
PA0020826	DOVER TWP	8.00	3.71
PA0020885	MECHANICSBURG BORO	2.08	1.05
PA0020893	MANHEIM BORO	1.14	6.29
PA0020923	NEW OXFORD MUN AUTH	1.79	1.11
PA0021067	MOUNT JOY BORO AUTH	1.53	0.78
PA0021571	MARYSVILLE BORO COUNCIL	1.25	0.80
PA0021687	WELLSBORO MUN AUTH	2.00	1.07
PA0021814	MANSFIELD BORO MUN AUTH	1.00	0.53
PA0021890	NEW HOLLAND BORO	1.34	0.96
PA0022209	BEDFORD BORO MUN AUTH	1.50	0.79
PA0022535	MILLERSBURG AREA AUTH	1.00	0.47
PA0023108	ELIZABETHTOWN BORO	3.00	2.10
PA0023248	BERWICK AREA JNT SEW AUTH	3.70	1.38
PA0023531	DANVILLE BORO	3.62	2.13
PA0023558	ASHLAND BORO	1.30	12.19
PA0023744	NORTHEASTERN YORK CO SEW AUTH	1.70	0.73
PA0024040	HIGHSPIRE BORO	2.00	1.11
PA0024287	PALMYRA BORO STP	1.42	0.83
PA0024325	MUNCY BORO MUN AUTH	1.40	0.76
PA0024406	MOUNT CARMEL MUN AUTH	1.50	1.01
PA0024431	DILLSBURG AREA AUTH	1.53	0.68
PA0024759	CURWENSVILLE MUN AUTH	0.75	0.41
PA0024902	UPPER ALLEN TWP BRD OF COMMRS	1.10	5.81
PA0025933	LOCK HAVEN CITY	3.75	2.29
PA0026077	CARLISLE BORO	4.63	3.34

NPDES ID	Name	Design flow (MGD)	Observed flow (MGD) (1991-2006 average)
PA0026107	WYOMING VALLEY SAN AUTH	32.00	24.07
PA0026123	COLUMBIA MUN AUTH	2.00	0.80
PA0026191	HUNTINGTON BORO	5.90	2.50
PA0026239	UNIVERSITY AREA JOINT AUTH -	6.00	4.62
PA0026263	YORK CITY SEW AUTH	26.00	10.66
PA0026280	LEWISTOWN BORO	2.82	1.70
PA0026310	CLEARFIELD MUN AUTH	4.50	3.46
PA0026361	LOWER LACKAWANNA VLY SAN AUTH	6.00	3.36
PA0026441	LEMOYNE BORO	2.09	1.72
PA0026484	DERRY TWP MUN AUTH - CLEARWATE	5.00	3.48
PA0026492	SCRANTON CITY SEW AUTH	20.00	13.03
PA0026557	SUNBURY CITY MUN AUTH	4.20	3.40
PA0026620	MILLERSVILLE BORO	1.85	0.65
PA0026654	NEW CUMBERLAND BORO	1.25	3.98
PA0026727	TYRONE BORO	9.00	5.97
PA0026735	SWATARA TWP AUTH	6.30	3.71
PA0026743	LANCASTER CITY	29.73	19.72
PA0026808	SPRINGETTSBURY TWP	15.00	10.04
PA0026875	HANOVER BOROUGH	5.50	4.16
PA0026921	GREATER HAZELTON JNT SEW AUTH	8.90	7.20
PA0027014	ALTOONA CITY AUTH - EAST	8.00	6.77
PA0027022	ALTOONA CITY AUTH - WEST	9.00	8.03
PA0027049	WILLIAMSPORT SAN AUTH-WEST	3.92	2.89
PA0027057	WILLIAMSPORT SAN AUTH-CENTRAL	10.50	7.38
PA0027065	LACKAWANNA RIVER BASIN SEW AUT	6.00	2.78
PA0027090	LACKAWANNA RIVER BASIN SAN AUT	7.00	5.28
PA0027171	BLOOMSBURG MUN AUTH	4.29	2.58
PA0027189	LOWER ALLEN TWP AUTH	6.25	4.38
PA0027197	HARRISBURG AUTHORITY	37.70	25.06
PA0027316	LEBANON CITY	8.00	5.31
PA0027324	SHAMOKIN-COAL TWP JNT SEW AUTH	7.00	3.74
PA0027405	EPHRATA BORO AUTH - WWTP #1	3.80	2.56

NPDES ID	Name	Design flow (MGD)	Observed flow (MGD) (1991-2006 average)
PA0027553	PINE CREEK MUN AUTH	1.30	39.24
PA0028142	PA NATIONAL GUARD - FORT INDIA	1.00	1.84
PA0028461	MIFFLINBURG BORO	1.40	0.77
PA0028576	CLARKS SUMMIT - S ABINGTON JSA	2.50	2.38
PA0028665	JERSEY SHORE BORO	1.05	0.69
PA0028681	KELLY TWP MUN AUTH	3.75	14.25
PA0028746	HAMPDEN TWP	1.76	1.30
PA0030643	SHIPPENSBURG BORO	3.30	1.79
PA0032883	DUNCANSVILLE BORO	1.22	0.73
PA0034576	TOWANDA MUN AUTH	1.16	0.75
PA0037150	PENN TWP BOARD OF COMMISSIONER	4.20	1.75
PA0037966	MOSHANNON VALLEY JT SEW AUTH	1.73	1.53
PA0038415	EAST PENNSBORO TWP	3.70	3.03
PA0042269	LANCASTER AREA SEW AUTH	15.00	7.52
PA0043257	NEW FREEDOM BORO AUTH	7.20	2.17
PA0043273	HOLLIDAYSBURG SEW AUTH	6.00	3.46
PA0043681	VALLEY JOINT SEW AUTH	2.25	1.04
PA0044661	LEWISBURG AREA JOINT SEW AUTH	2.42	1.30
PA0045985	MOUNTAINTOP AREA JNT SAN AUTH	4.16	2.64
PA0047325	PPL SUSQUEHANNA LLC	0.08	0.11
PA0062219	FRACKVILLE AREA MUN AUTH	1.40	1.05
PA0070041	MAHANOY CITY SEW AUTH	1.38	0.57
PA0070386	SHENANDOAH MUN SEW AUTH	2.00	1.35
PA0080314	HAMPDEN TWP - ROTH LANE	4.65	2.11
PA0083011	NEWBERRY TWP MUN AUTH	1.30	0.53
PA0087181	EPHRATA BORO AUTH - WWTP #2	2.30	1.24
PA0110582	EASTERN SNYDER CO REG AUTH	2.80	1.62
PA0110965	MID-CENTRE COUNTY AUTH	1.00	10.99
PA0111759	CARGILL MEAT SOLUTIONS CORP	0.80	0.56
PA0208779	CLEARFIELD LEATHER INC DBA WIC	0.12	0.13
PA0209228	LYCOMING CO WATER & SEWER AUTH	1.50	0.61
PA0228818	FIRST QUALITY TISSUE LLC	3.95	1.63

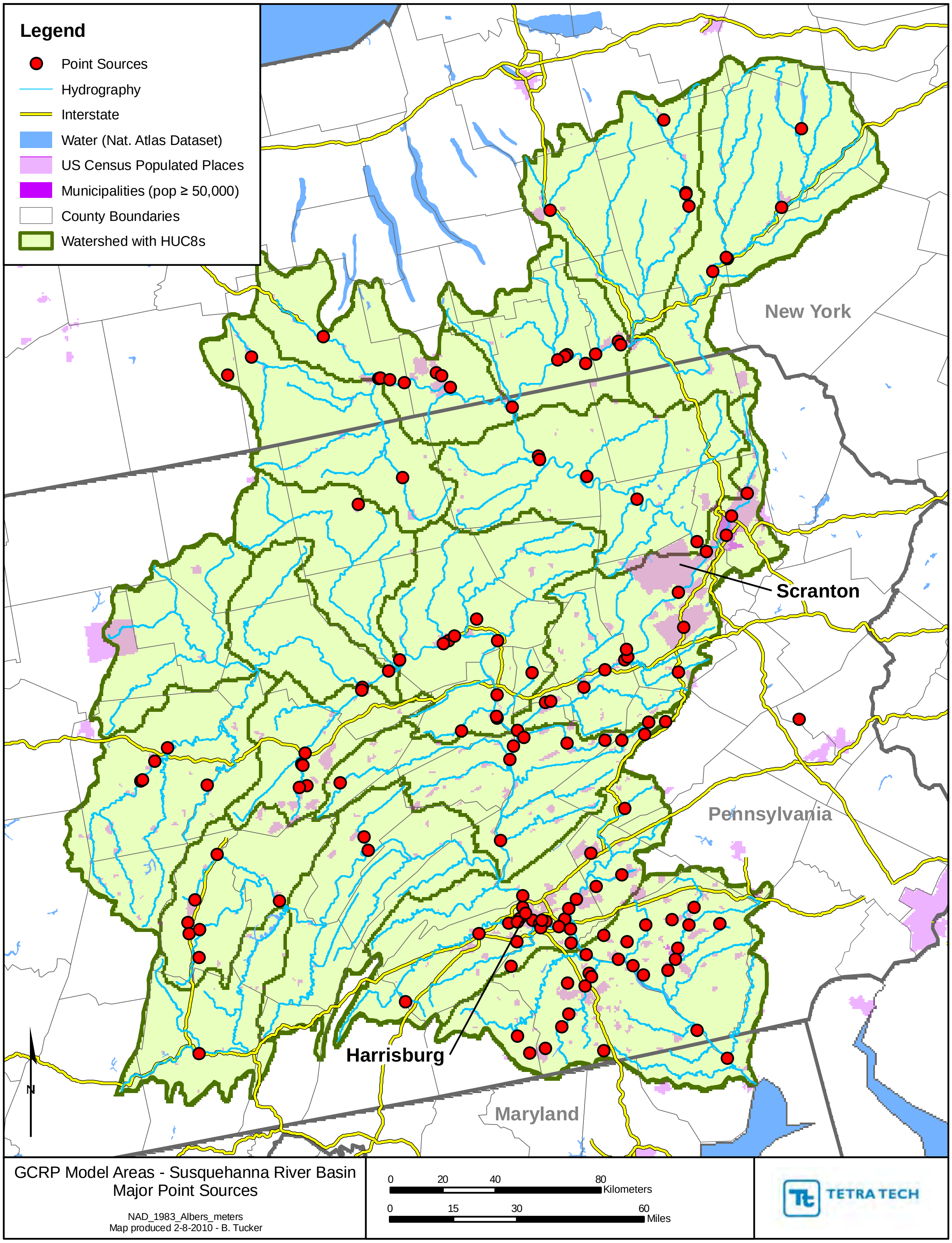


Figure 3. Major point sources in the Susquehanna River watershed.

Meteorological Data

The required meteorological data series for the 20 Watershed model simulations are precipitation, air temperature, and potential evapotranspiration (PET). The 20 Watershed model does not include water temperature or algal simulation and uses a degree-day method for snowmelt, so additional meteorological variables such as solar radiation are needed only for the calculation of PET. These meteorological data are drawn from the BASINS4 Meteorological Database (USEPA 2008), which provides a consistent, quality-assured set of nationwide data with gaps filled and records disaggregated. Scenario application will require simulation over 30 years, so the available stations are those with a common 30-year period of record (or one that can be filled from an approximately co-located station) that covers the year 2001. A total of 62 precipitation stations were identified for use in the Susquehanna River model with a common period of record of 2/1/1972-3/31/2004 for the entire watershed (Table 4 and Figure 4). The majority of the stations are available through at least 9/30/2005. Temperature records are sparser; where these are absent temperature is taken from nearby stations with an elevation correction. For each weather station, Penman-Monteith reference evapotranspiration was calculated for use in HSPF using observed precipitation and temperature coupled with SWAT weather generator estimates of solar radiation, wind movement, cloud cover, and relative humidity.

SWAT uses daily meteorological data for the 20 Watershed model applications, while HSPF requires hourly data. It is important to note that a majority of the meteorological stations available for the Susquehanna River watershed are Cooperative Summary of the Day stations that do not report sub-daily data. The BASINS4 dataset already has versions of the daily data that have been disaggregated to an hourly time step using template stations.

Table 4. Precipitation stations for the Susquehanna River watershed model

COOP ID	Name	Latitude	Longitude	Temperature	Elevation (ft)
NY300085	ALFRED	42.2614	-77.7850	Yes	1,770
NY300270	ARNOT FOREST	42.2670	-76.6330	No	1,200
NY300448	BATH	42.3500	-77.3500	Yes	1,120
NY300687	BINGHAMTON WSO AP	42.2078	-75.9814	Yes	1,600
NY301168	CANDOR 2 SE	42.1947	-76.3133	No	920
NY301173	CANISTEO 1 SW	42.2667	-77.6167	No	1,155
NY301424	CHEPACHET	42.9097	-75.1108	No	1,320
NY301752	COOPERSTOWN	42.7150	-74.9283	Yes	1,200
NY302454	EAST SIDNEY	42.3333	-75.2333	No	1,155
NY302610	ELMIRA	42.1000	-76.8000	Yes	844
NY303979	HORNBY	42.2330	-77.0500	No	1,795
NY303983	HORNELL ALMOND DAM	42.3500	-77.7000	No	1,325
NY304772	LINDLEY 2 N	42.0500	-77.1333	No	1,040
NY305512	MORRISVILLE 6 SW	42.8333	-75.7333	Yes	1,300
NY306085	NORWICH	42.5011	-75.5194	Yes	1,020
NY307195	ROCKDALE	42.3833	-75.4000	No	1,030
NY308498	THURSTON	42.2000	-77.3330	No	1,620
NY309442	WHITNEY POINT DAM	42.3500	-75.9670	No	1,040

COOP ID	Name	Latitude	Longitude	Temperature	Elevation (ft)
PA360140	ALTOONA 3 W	40.4950	-78.4667	Yes	1,320
PA360147	ALVIN R BUSH DAM	41.3670	-77.9330	Yes	930
PA360457	BEAR GAP	40.8236	-76.4983	No	900
PA360482	BEAVERTOWN 1 NE	40.7667	-77.1500	No	540
PA360656	BIGLERVILLE	39.9356	-77.2578	Yes	720
PA360725	BLAIN 5SW	40.3000	-77.5833	No	820
PA360763	BLOSERVILLE 1 N	40.2636	-77.3639	Yes	700
PA361087	BUFFALO MILLS	39.9461	-78.6458	No	1,310
PA361480	CLARENCE	41.0456	-77.9453	No	1,390
PA361833	COVINGTON 2 WSW	41.7331	-77.1167	No	1,745
PA361961	CURWENSVILLE LAKE	40.9500	-78.5330	No	1,165
PA362013	DANVILLE	40.9483	-76.6036	No	475
PA362245	DRIFTWOOD	41.3419	-78.1403	No	820
PA362629	EMPORIUM	41.5067	-78.2275	Yes	1,040
PA362721	EVERETT	40.0136	-78.3653	Yes	1,000
PA363130	GALETON	41.7356	-77.6519	No	1,345
PA364047	HONEY BROOK 2 SSE	40.0789	-75.8975	No	665
PA364763	LANCASTER 2 NE FILT PLANT	40.0500	-76.2742	No	270
PA364778	LANDISVILLE 2 NW	40.1167	-76.4333	Yes	360
PA364853	LAURELTON CENTER	40.9017	-77.2139	Yes	800
PA364896	LEBANON 2 W	40.3333	-76.4667	Yes	450
PA364992	LEWISTOWN	40.5869	-77.5697	Yes	460
PA365344	MAHANOY CITY 2 N	40.8344	-76.1353	No	1,710
PA365915	MONTROSE	41.8667	-75.8500	Yes	1,420
PA366289	NEW PARK	39.7350	-76.5061	No	800
PA366916	PHILIPSBURG 8 E	40.9167	-78.0667	No	1,945
PA367409	RENOVO	41.3297	-77.7381	Yes	660
PA367727	RUSHVILLE	41.7833	-76.1167	No	870
PA367730	SABINSVILLE 3 SE	41.8422	-77.4747	No	1,999
PA367931	SELINSGROVE 2 S	40.7831	-76.8611	Yes	420
PA368057	SHICKSHINNY 3 N	41.2000	-76.1500	No	780
PA368073	SHIPPENSBURG	40.0500	-77.5167	Yes	680
PA368449	STATE COLLEGE	40.7933	-77.8672	Yes	1,170

COOP ID	Name	Latitude	Longitude	Temperature	Elevation (ft)
PA368491	STILLWATER	41.6830	-75.4830	No	1,650
PA368692	SUSQUEHANNA	41.9483	-75.6050	No	910
PA368905	TOWANDA 1 S	41.7506	-76.4428	Yes	750
PA368959	TROY 1 NE	41.7833	-76.7833	No	1,110
PA369408	WELLSBORO 4 SW	41.7003	-77.3894	Yes	1,818
PA369705	WILKES BARRE SCRANTON WSO AP	41.3389	-75.7267	Yes	930
PA369714	WILLIAMSBURG	40.4667	-78.2000	No	840
PA369728	WILLIAMSPORT RGNL AP	41.2433	-76.9217	Yes	520
PA369823	WOLFSBURG	40.0417	-78.5278	No	1,185
PA369933	YORK 3 SSW PUMP STN	39.9167	-76.7500	Yes	390
PA369950	YORK HAVEN	40.1167	-76.7167	No	310

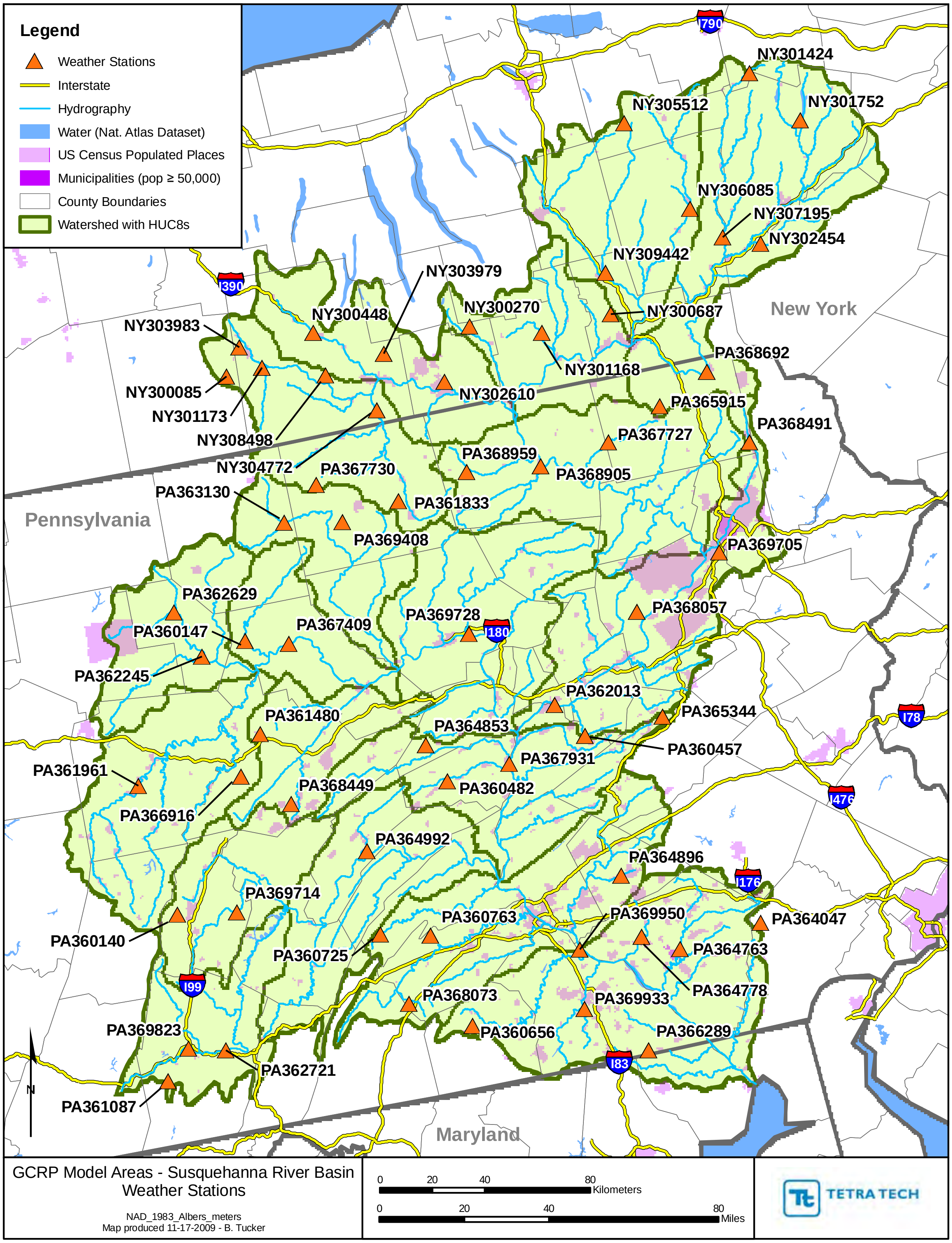


Figure 4. Weather stations for the Susquehanna River watershed model.

Watershed Segmentation

At about 27,000 square miles, the Susquehanna River basin is one of the largest modeling areas considered for the 20 Watershed project. It encompasses a complete drainage area, with no need for upstream boundary conditions. There is also an existing detailed HSPF model of the basin (the Chesapeake Bay Model or CBM; USEPA 2010). Watershed segmentation for the Susquehanna River basin is based on the segmentation used in the CBM, resulting in 278 subbasins for modeling (Figure 5). The initial calibration watershed (Raystown Branch Juniata River) is highlighted.

The model subbasins approximate the HUC-10 scale, but are subdivided as needed to account for the connection of tributaries and location of flow gages. The subbasins range in size from 1.04 to 516 mi^2.

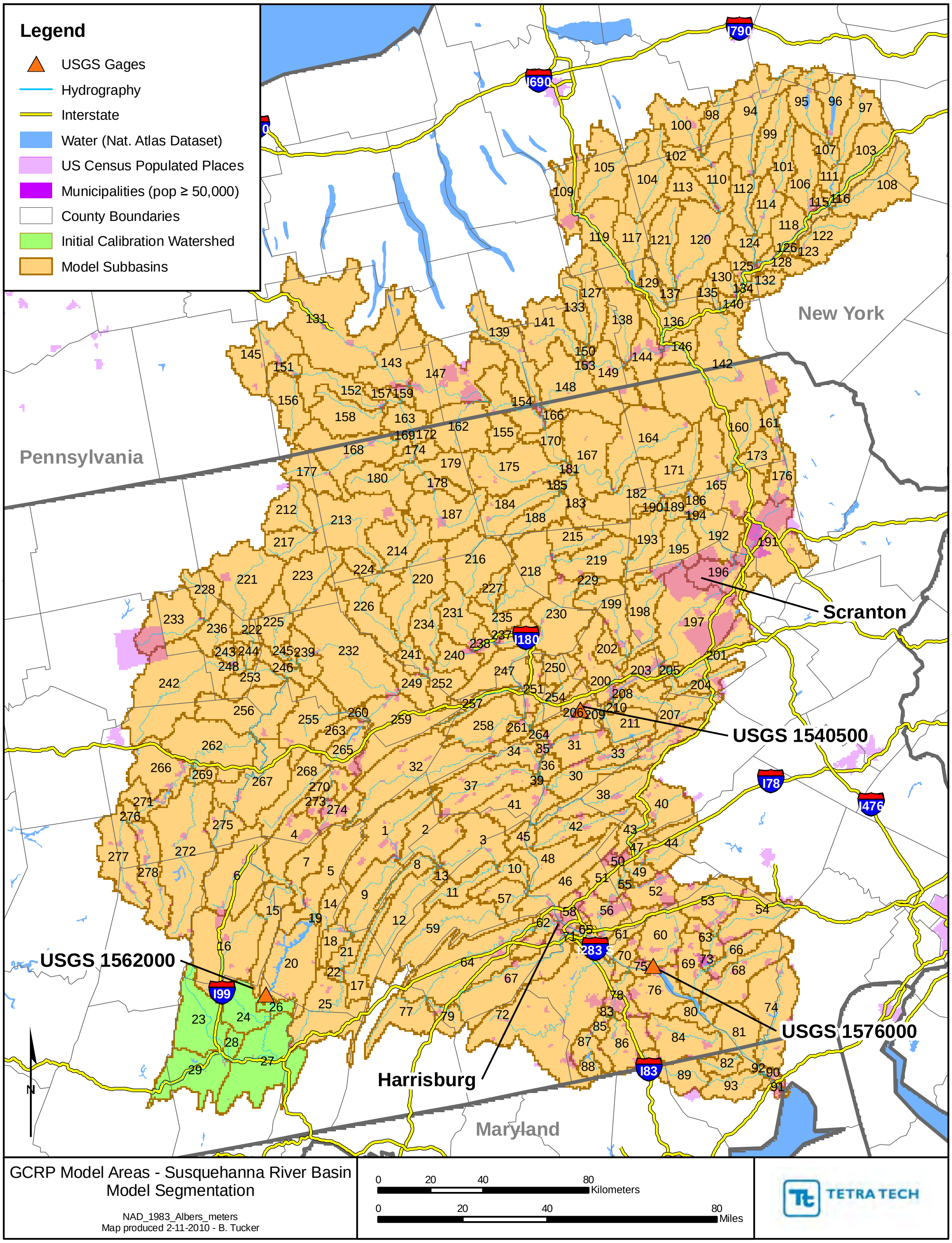


Figure 5. Model segmentation and USGS stations utilized for the Susquehanna River watershed.

Calibration Data and Locations

The Susquehanna River was selected as a pilot site because of extensive previous experience with the CBM. Given the existence of this calibrated model, the approach to the Susquehanna pilot study was to start from parameters derived from the existing model, evaluate the parameterization through detailed application to an initial calibration focus area, then evaluate the quality of the fit through comparison to data at two monitoring points representing the larger watershed. Spatial calibration at multiple locations was not pursued. It should be noted, however, that the 20 Watershed approach is based on a different land use coverage and uses different weather data and, in particular, a different estimator of PET (Penman-Monteith PET using local temperature and weather generator insolation and auxiliary variables for 20 Watershed versus Hamon PET in the Phase 5 CBM and Penman pan evaporation at first-order weather stations in early versions of the CBM). These differences may result in systematic differences in model parameters.

Three sites with known high quality flow gaging and water quality data were selected for both hydrology and water quality calibration (Table 5). The first of these (Raystown Branch Juniata River) was selected for initial calibration, with subsequent adjustments based on comparison to data at two stations on the mainstem Susquehanna.

Table 5. Calibration and validation locations in the Susquehanna River watershed

Station Name	USGS ID	Drainage Area (mi^2)	Hydrology Calibration	Water Quality Calibration
Raystown Branch Juniata River at Saxton, PA	01562000	756	X	X
Susquehanna River at Danville, PA	01540500	11,220	X	X
Susquehanna River at Marietta, PA	01576000	25,990	X	X

The model hydrology calibration period for Raystown Branch Juniata River was set to Water Years 1995-2005, while the mainstem stations use Water Years 1993-2003 to fall within the common period of record of the weather data. Calibration was done on the later data due to concerns that there have been significant changes in land use and agricultural management practices since the 1980s. Hydrologic validation was then performed on the 10 water years prior to the calibration period. The bulk of available water quality data are from the early 1990s. Therefore, water quality calibration used calendar year periods beginning in 1991, with earlier data reserved for validation.

HSPF Modeling

Initial hydrologic parameterization for the Susquehanna River calibration focus area came from the Chesapeake Bay Program's (CBP) model for the Susquehanna River watershed (CBM). The CBM has undergone a series of revisions over many years, with the most current version of the model being known as Phase 5 (USEPA 2010). The Phase 5 parameters were obtained from the CBP and reviewed. Through this process it was identified that the CBM set for Phase 5 was much more complex than that used for a typical HSPF model, with parameters and land use categories provided in a multi-file database, with values changing over the time span of the simulation. In the CBP Phase 5 model, HSPF input sequences are developed through an elaborate scripting scheme, with multiple HSPF input sequences developed for more than 20 land use categories (including various agricultural management practices) and multiple time spans to determine flows and loads on a unit area basis. These unit area flows and loads are then combined through scripts to create input for an in-stream simulation.

The complexity of the Phase 5 model far exceeded the constraints of this study, so rather than using the Phase 5 parameters, it was decided to parameterize Susquehanna River watershed model using the previous version of the CBM, Phase 4. The Phase 4 parameters are readily available, as they are incorporated into the BASINS companion program HSPFParm, and these parameters are available in a format directly akin to that needed by HSPF. The six pervious (forest, high till cropland, low till cropland, pasture, urban, and hay) and two impervious (animal/feedlot and urban) land use categories of the Phase 4 model are more analogous to the categories of the Susquehanna model for this study.

Even using the simpler Phase 4 model from the CBP, there was no one-to-one correlation between land use categories of the CBM and this study. The Phase 4 model of the Susquehanna River watershed consisted of 12 land segments in 4 UCI files, and these parameters needed to be applied to the 21 land uses in this project. Moreover, for this project the land use categories explicitly represented hydrologic soil groups, while the CBM parameters did not. A method was developed for creating the Susquehanna model parameters for this study from these Phase 4 parameters, where approximate average values were applied from the CBP Upper Susquehanna simulations for model section 020501, from the CBP Western Branch Susquehanna simulation for model section 020502, and from the Lower Susquehanna simulation for model section 020503. Since there was no explicit representation of hydrologic soil groups in the CBM, parameter values were assigned the same values across each of the Susquehanna model soil classifications. For example, the CBM forest parameters for the Lower Susquehanna were applied to the land use categories Forest_A through Forest_D in the model parameters for 020503.

The USGS gage on the Raystown Branch of the Juniata River at Saxton, PA (USGS 02050303) was used as the primary calibration location, while the gages on the Susquehanna River at Danville, PA (USGS 01540500), on the West Branch Susquehanna River at Lewisburg, PA (USGS 01553500), and on the Susquehanna River at Marietta, PA (USGS 01576000) were used as additional calibration checks. Calibrated parameters from the Raystown Branch gage were applied to the Lower Susquehanna portion of the study area (020503), while calibration adjustments for the Danville and Lewisburg gages were applied to the Upper and Western sections of the study area respectively (020501 and 020502). The Susquehanna River at Marietta, PA (USGS 01576000), the most downstream of the gages, was used to verify that the calibration parameters applied at the two upstream gages were applicable to the entire watershed.

Once the hydrology calibration was complete for the entire Susquehanna River watershed, the focus turned to sediment and water quality representation. Extracting parameters from the CBP Susquehanna model for sediment and water quality was even less straightforward than that for hydrology parameters, since the CBM used the more complicated NITR and PHOS modules of the HSPF pervious land simulation operations. Initial parameterization for sediment and water quality simulation was taken from the loadings used to set up the Willamette model in this 20 Watershed study, adjusted based on the parameters from the CBP Phase 4 model where available.

Changes Made to Base Data Provided

No changes were made to the meteorological, point source, or land use base data.

Assumptions

Reservoirs

While there are many dams in the study area, their influence was not explicitly included in the study. The largest of the reservoirs are on the Susquehanna River near the outlet of the study area, well below the USGS gage on the Susquehanna River at Marietta. This USGS gage on the Susquehanna River at Marietta was selected for use in calibration because it is the most downstream main stem gage that is still upstream of the influence of the major reservoirs. While one would assume the major main stem reservoirs influence the flow and water quality exiting the Susquehanna River at the outlet, for this model the impacts of these reservoirs are assumed to be implicitly represented through the tabular representation of reach hydrologic response (FTables).

The primary intention of the 20 Watershed simulations is to examine relative changes in response of large watersheds. Information is not available to specify future time series of operations or boundary conditions for these reservoirs. Therefore, representation of the reservoirs through the stage-discharge relationships expressed in the FTables provides the most useful basis for evaluating relative changes in response.

Withdrawals and Point Sources

A variety of water withdrawals occur in the Susquehanna, but these have a relatively small effect on the overall water balance. In addition, future changes in water withdrawals are not known. Therefore, withdrawals were not included in the 20 Watershed model application. In contrast to withdrawals, point sources must be included for model water quality calibration because they represent a significant fraction of nutrient loads in the system. Existing major point source flows and loads are represented in the model, but will be held at current levels for simulation of future conditions to better isolate the potential direct impacts of climate and land use change.

Snow Simulation

The Susquehanna HPSF model includes snow simulation using the degree-day method for snowmelt. The initial values extracted from the Chesapeake Bay Program Model are assumed to be appropriate and the initial parameterization was not adjusted.

Hydrology Calibration

As explained above, the starting parameters for the Susquehanna HSPF model came from a Chesapeake Bay Program model of the Susquehanna River watershed. Once the starting parameters were inserted into the model input files, average annual precipitation and potential evapotranspiration values were computed and compared to published values. Through this process it was determined the input potential evapotranspiration time series should be reduced by multipliers, since the computation of these time series produced more PET on an average annual basis than the published values indicate. The multipliers used for PET were 0.75 for the Lower Susquehanna and Western Branch, and 0.8 for the Upper Susquehanna. Calibration adjustments focused on the following parameters:

- BASETP (ET by riparian vegetation): The model was significantly oversimulating the 50 percent low flows at the primary calibration location. Slightly increasing the BASETP value provided some ET by riparian vegetation and thus improved the simulation of low flows.

- DEEPFR (fraction of groundwater inflow which will enter deep groundwater): Adding a modest amount of DEEPFR above the primary calibration location improved the overall water balance and improved the simulation of low flows.
- INFILT (index to mean soil infiltration rate): In the upper portions of the study area the peak flows were simulating too low, while the low flows were simulating too high. Decreasing INFILT for the upper portions of the watershed shifted flows to a faster response, increasing the peaks and reducing the low flows.
- AGWRC (Groundwater recession rate): Adjusted slightly in order to replicate groundwater recession in the observed data.

Initial calibration was performed at the USGS gage on the Raystown Branch of the Juniata River at Saxton, PA (USGS 02050303), and is summarized in Figures 6 through 12 and Tables 6 and 7. The model fit is of high quality overall, but simulates low on the lowest 10 percent of flows. This could be due to something not accounted for in the model, such as reservoir operations or other discharges. Given that these low flows are not critical to the purposes of this study, the issue is being noted as an area with potential further refinement. None of the metrics fall beyond the range of those set for the 20 Watershed study. The model calibration period was set to the 10 water years from 10/01/1995 to 09/30/2005.

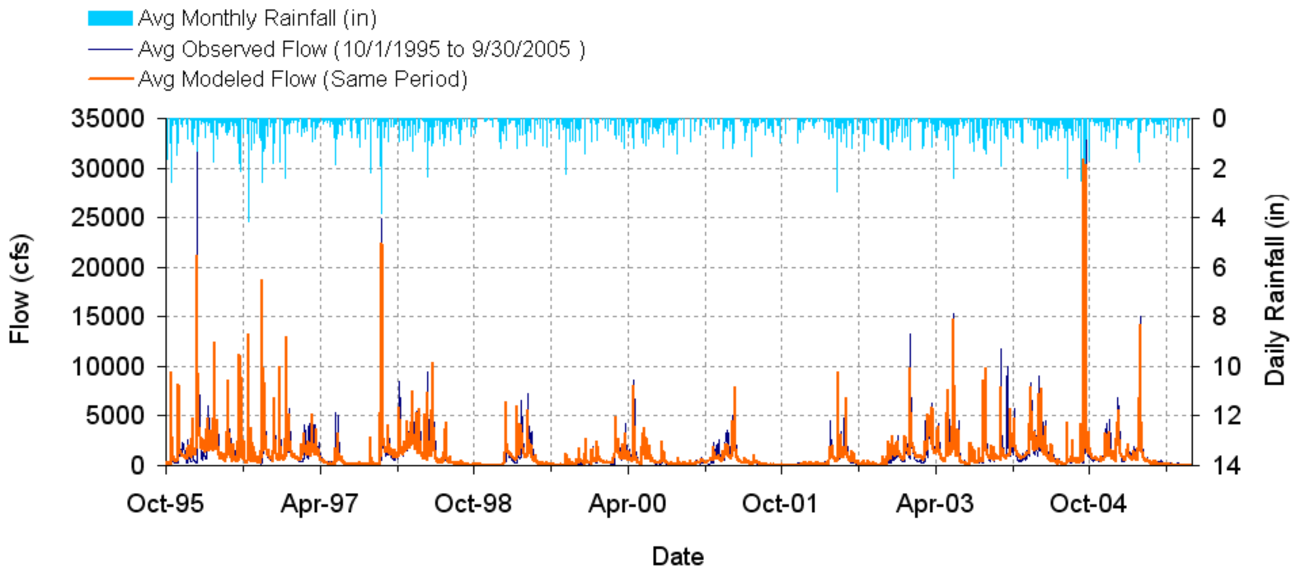


Figure 6. Mean daily flow at USGS 01562000 Raystown Branch Juniata River at Saxton, PA – calibration period (HSPF).

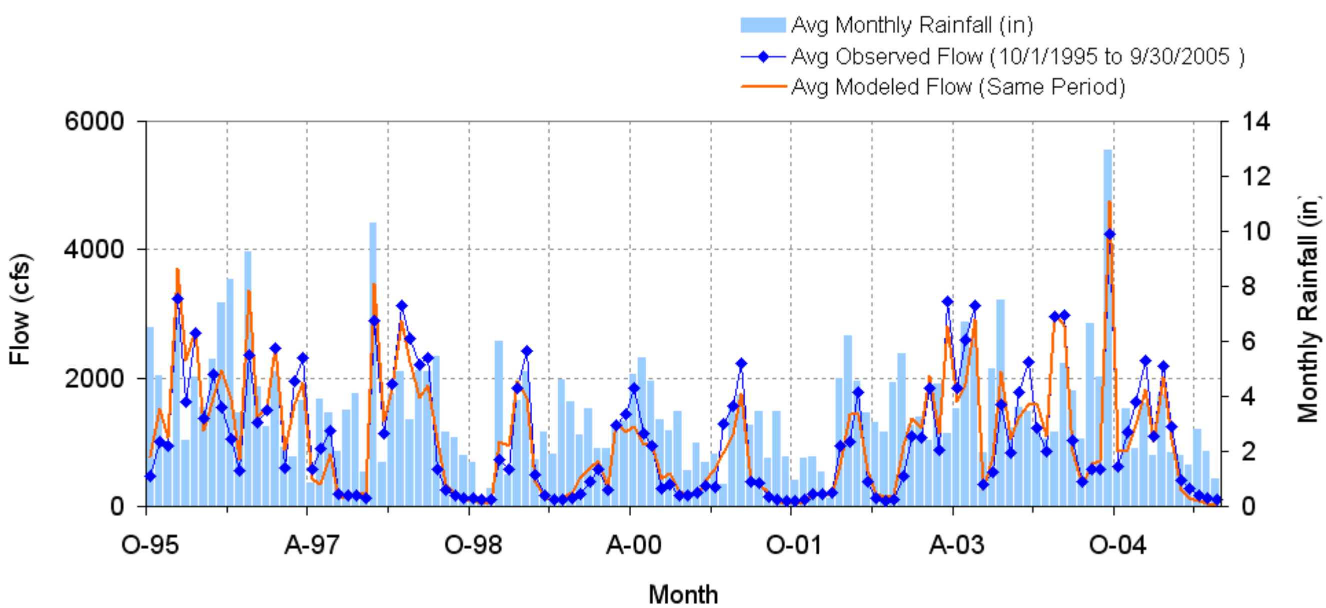
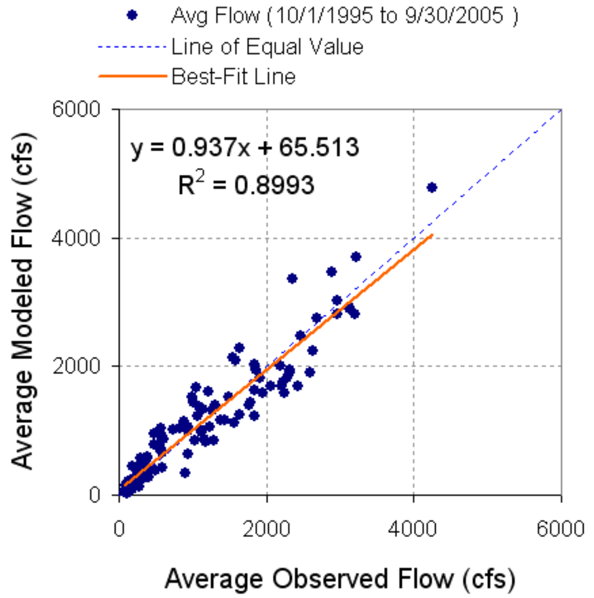


Figure 7. Mean monthly flow at USGS 01562000 Raystown Branch Juniata River at Saxton, PA – calibration period (HSPF).



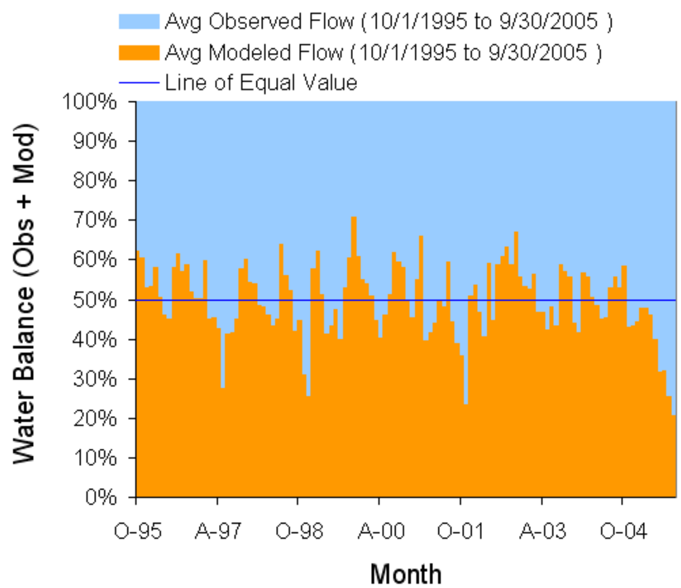
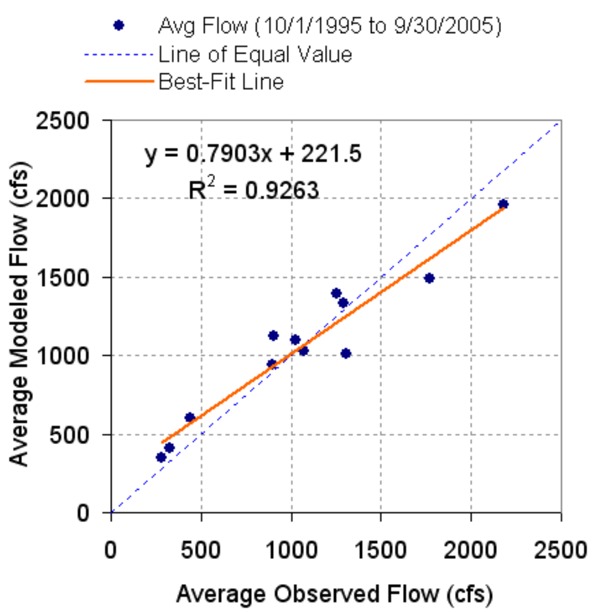


Figure 8. Monthly flow regression and temporal variation at USGS 01562000 Raystown Branch Juniata River at Saxton, PA – calibration period (HSPF).



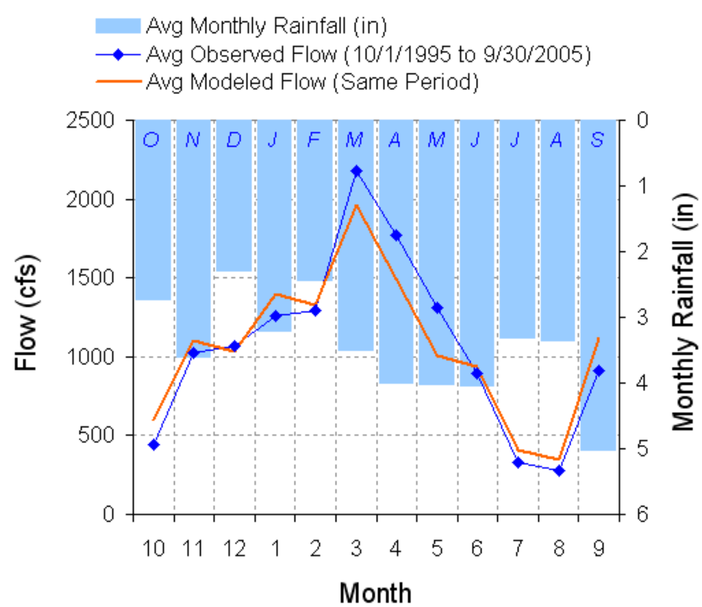


Figure 9. Seasonal regression and temporal aggregate at USGS 01562000 Raystown Branch Juniata River at Saxton, PA – calibration period (HSPF).

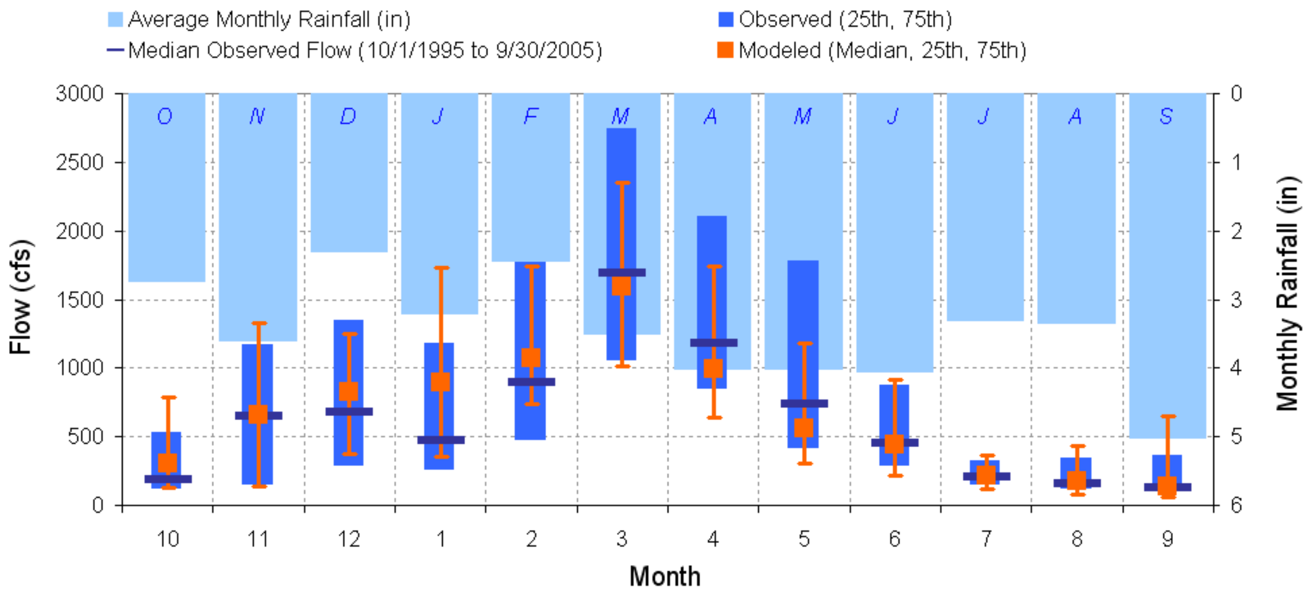


Figure 10. Seasonal medians and ranges at USGS 01562000 Raystown Branch Juniata River at Saxton, PA – calibration period (HSPF).

Table 6. Seasonal summary at USGS 01562000 Raystown Branch Juniata River at Saxton, PA – calibration period (HSPF)

MONTH	OBSERVED FLOW (CFS)				MODELED FLOW (CFS)			
	MEAN	MEDIAN	25TH	75TH	MEAN	MEDIAN	25TH	75TH
Oct	438.69	187.00	119.00	530.75	599.79	301.11	128.74	788.27
Nov	1024.44	647.50	149.75	1170.00	1101.45	658.92	138.80	1324.27
Dec	1071.22	682.00	280.75	1350.00	1029.71	830.45	374.78	1250.32
Jan	1255.25	475.00	260.00	1180.00	1394.02	892.68	351.51	1730.37
Feb	1290.35	900.00	470.00	1775.00	1330.42	1074.05	739.83	1743.98
Mar	2177.77	1690.00	1052.50	2742.50	1963.58	1594.05	1008.22	2348.98
Apr	1771.52	1180.00	843.75	2102.50	1490.45	989.11	640.38	1736.15
May	1310.00	739.50	414.00	1777.50	1010.40	563.51	303.89	1180.35
Jun	895.83	448.00	287.50	879.00	939.20	441.19	220.33	910.95
Jul	326.40	207.00	146.00	324.00	407.92	216.08	114.91	368.66
Aug	278.62	157.50	115.25	339.75	345.53	174.23	74.24	430.05
Sep	907.63	124.50	104.00	360.25	1120.57	133.58	62.75	649.56

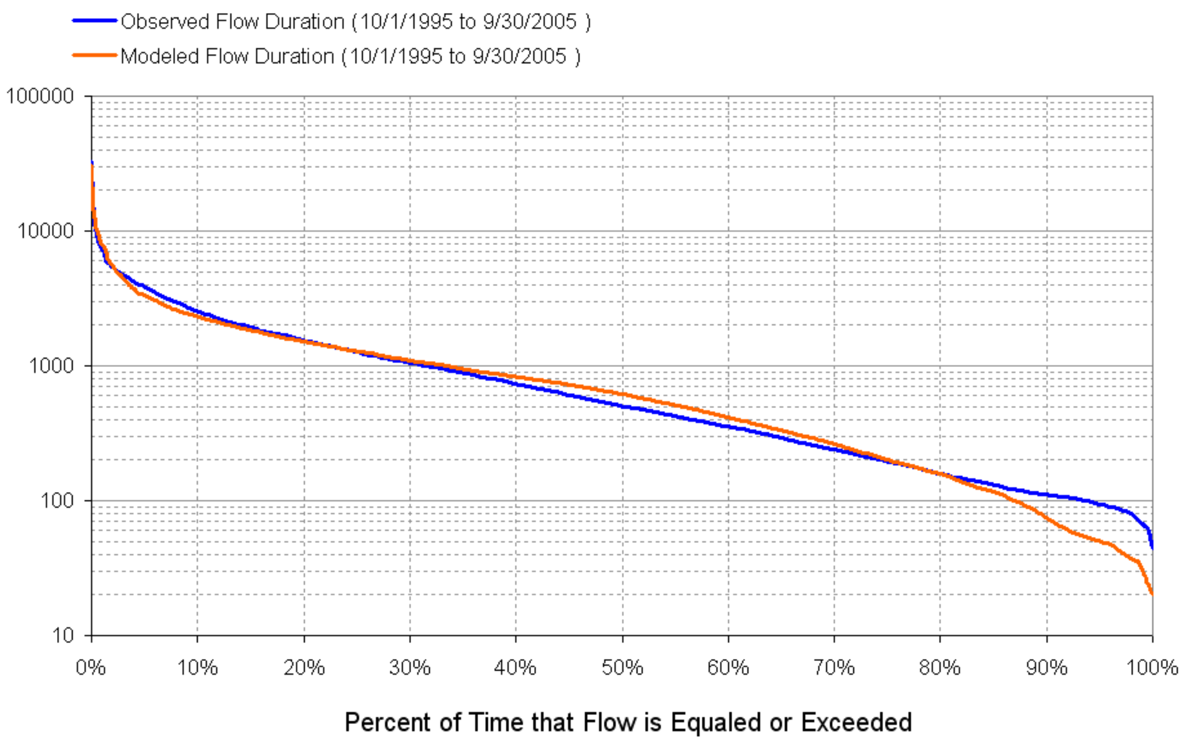


Figure 11. Flow exceedence at USGS 01562000 Raystown Branch Juniata River at Saxton, PA – calibration period (HSPF).

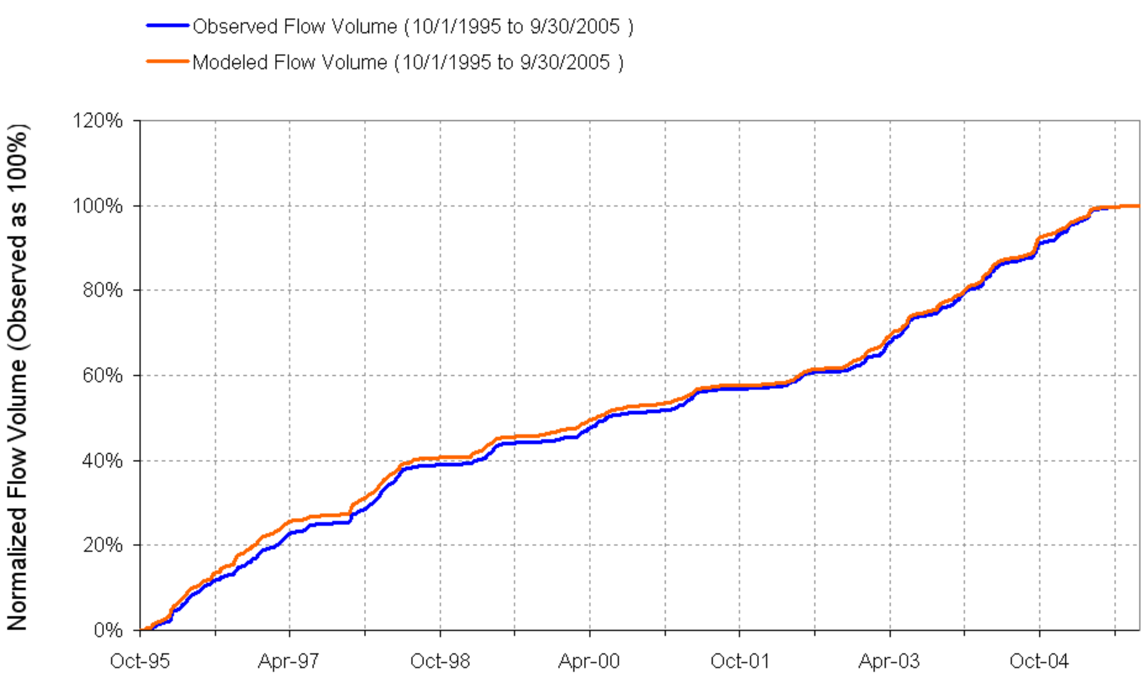


Figure 12. Flow accumulation at USGS 01562000 Raystown Branch Juniata River at Saxton, PA – calibration period (HSPF).

Table 7. Summary statistics at USGS 01562000 Raystown Branch Juniata River at Saxton, PA – calibration period (HSPF)

HSPF Simulated Flow		Observed Flow Gage		
REACH OUTFLOW FROM DSN 101		USGS 01562000 Raystown Branch Juniata River at Saxton, PA		
10-Year Analysis Period: 10/1/1995 - 9/30/2005 Flow volumes are (inches/year) for upstream drainage area		Hydrologic Unit Code: 2050303 Latitude: 40.21591249 Longitude: -78.2652901 Drainage Area (sq-mi): 756		
Total Simulated In-stream Flow:	**19.01**	Total Observed In-stream Flow:		**19.04**
Total of simulated highest 10% flows:	**8.15**	Total of Observed highest 10% flows:		**8.48**
Total of Simulated lowest 50% flows:	**2.19**	Total of Observed Lowest 50% flows:		**2.05**
Simulated Summer Flow Volume (months 7-9):	**2.80**	Observed Summer Flow Volume (7-9):		**2.26**
Simulated Fall Flow Volume (months 10-12):	**4.11**	Observed Fall Flow Volume (10-12):		**3.81**
Simulated Winter Flow Volume (months 1-3):	**6.97**	Observed Winter Flow Volume (1-3):		**7.03**
Simulated Spring Flow Volume (months 4-6):	**5.13**	Observed Spring Flow Volume (4-6):		**5.93**
Total Simulated Storm Volume:	**7.78**	Total Observed Storm Volume:		**7.83**
Simulated Summer Storm Volume (7-9):	**1.62**	Observed Summer Storm Volume (7-9):		**1.16**
Errors (Simulated-Observed)	*Error Statistics*	*Recommended Criteria*		
Error in total volume:	-0.16	10		
Error in 50% lowest flows:	6.72	10		
Error in 10% highest flows:	-3.92	15		
Seasonal volume error - Summer:	23.90	30		
Seasonal volume error - Fall:	7.76	>> 30	Clear	
Seasonal volume error - Winter:	-0.84	30		
Seasonal volume error - Spring:	-13.61	30		
Error in storm volumes:	-0.63	20		
Error in summer storm volumes:	39.10	50		
Nash-Sutcliffe Coefficient of Efficiency, E:	0.698	Model accuracy increases		
Baseline adjusted coefficient (Garrick), E':	0.552	as E or E' approaches 1.0		
Monthly NSE	0.898			

Hydrology Validation

Validation for the Susquehanna River calibration focus was performed at the same gage (USGS 01562000 Raystown Branch Juniata River at Saxton, PA) but for the water years 10/01/1985 to 09/30/1995. Results are presented in Figures 13 through 19 and Tables 8 and 9. Similar to the calibration years, the validation years' model fit is of high quality, although the validation simulates the summer storm volumes somewhat high while undersimulating the overall storm volume. This may in part reflect differences in land use and management practices relative to the 200 NLCD. The remaining metrics fall within the acceptable range set for the 20 Watershed study.

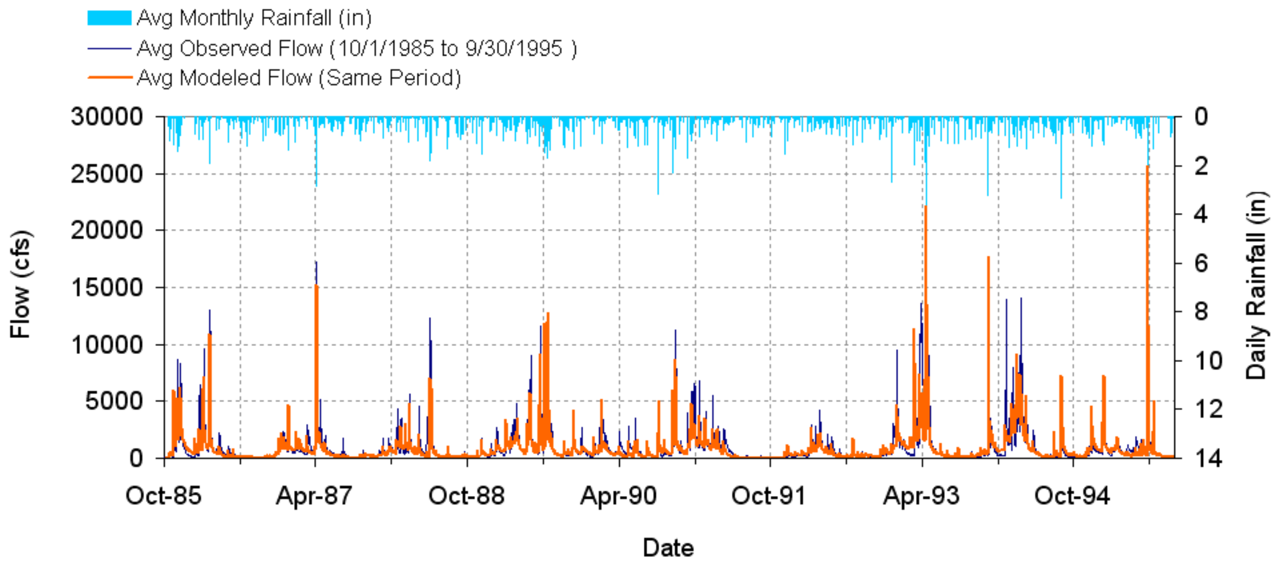


Figure 13. Mean daily flow at USGS 01562000 Raystown Branch Juniata River at Saxton, PA – validation period (HSPF).

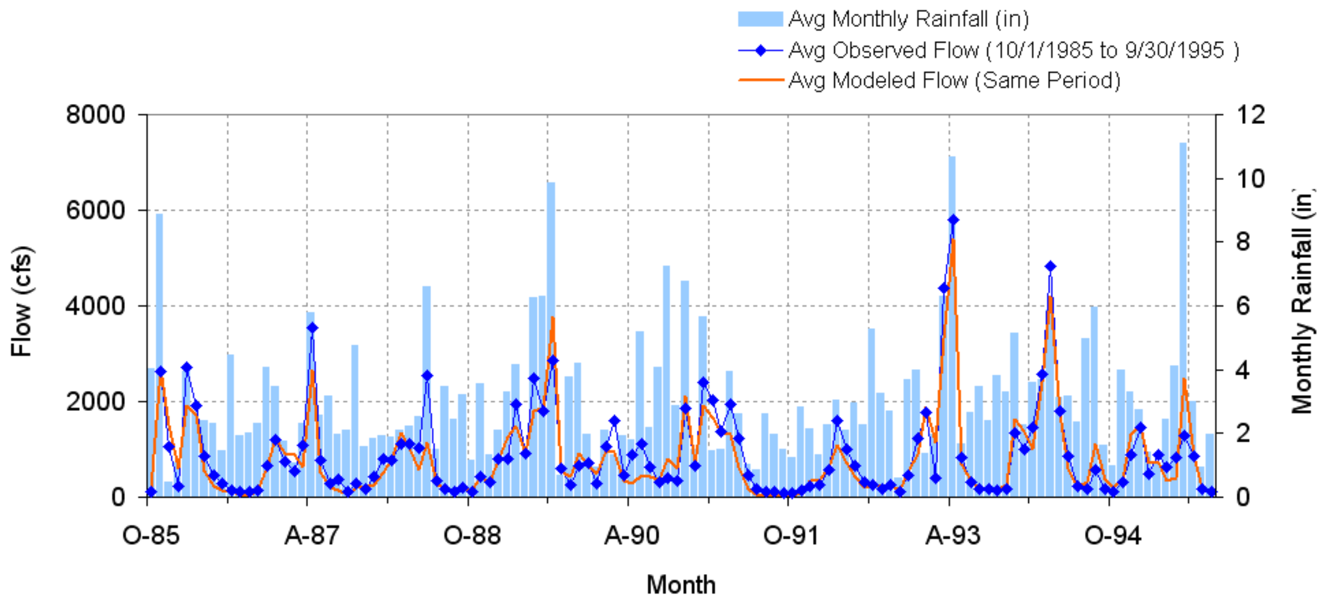
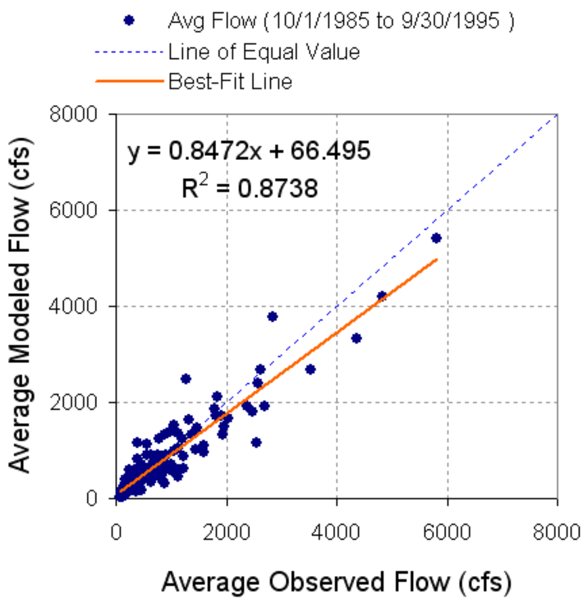


Figure 14. Mean monthly flow at USGS 01562000 Raystown Branch Juniata River at Saxton, PA – validation period (HSPF).



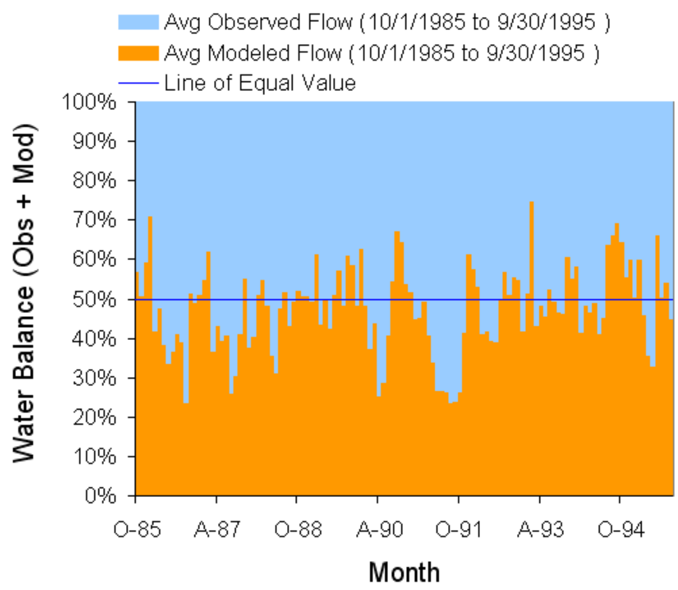
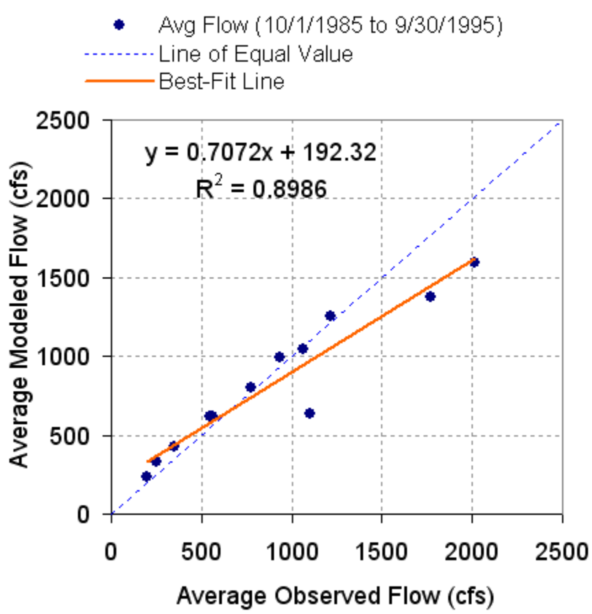


Figure 15. Monthly flow regression and temporal variation at USGS 01562000 Raystown Branch Juniata River at Saxton, PA – validation period (HSPF).



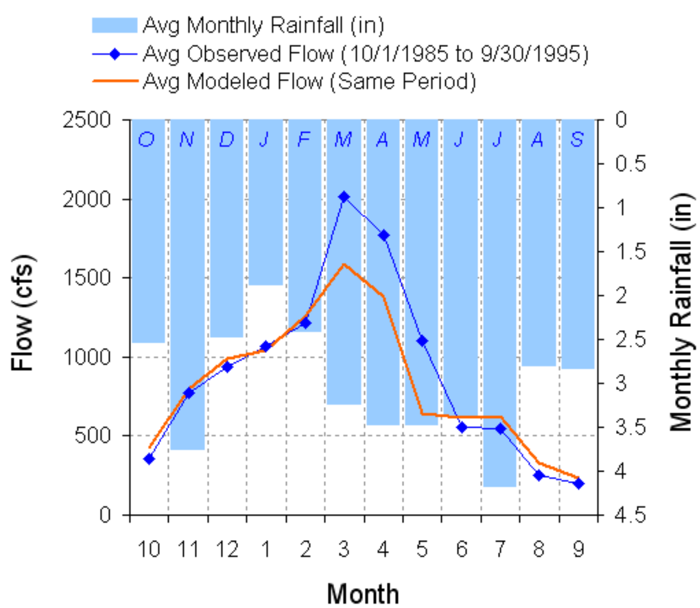


Figure 16. Seasonal regression and temporal aggregate at USGS 01562000 Raystown Branch Juniata River at Saxton, PA – validation period (HSPF).

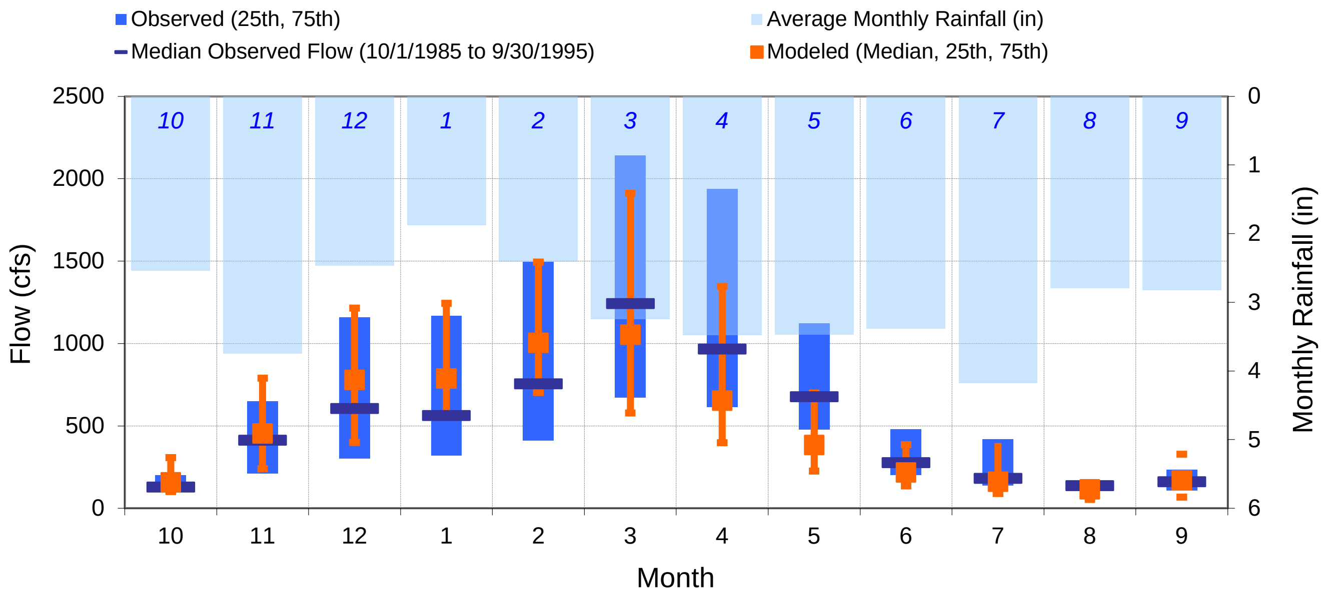


Figure 17. Seasonal medians and ranges at USGS 01562000 Raystown Branch Juniata River at Saxton, PA – validation period (HSPF).

Table 8. Seasonal summary at USGS 01562000 Raystown Branch Juniata River at Saxton, PA – validation period (HSPF)

MONTH	OBSERVED FLOW (CFS)				MODELED FLOW (CFS)			
	MEAN	MEDIAN	25TH	75TH	MEAN	MEDIAN	25TH	75TH
Oct	351.63	128.00	104.00	200.00	429.02	157.78	101.27	307.10
Nov	771.90	411.00	211.75	649.00	798.12	454.17	239.35	790.07
Dec	936.58	603.50	302.50	1157.50	993.77	779.69	399.19	1215.70
Jan	1063.43	562.00	322.50	1167.50	1044.74	787.94	549.18	1243.93
Feb	1214.57	754.00	410.00	1495.00	1256.37	1003.08	702.93	1494.87
Mar	2016.51	1240.00	670.75	2140.00	1591.71	1053.09	578.34	1910.94
Apr	1772.93	965.00	613.50	1935.00	1379.12	653.23	398.61	1345.43
May	1102.77	676.00	479.25	1122.50	638.99	384.81	225.71	698.65
Jun	559.15	275.50	201.00	479.50	619.87	217.91	135.17	385.61
Jul	545.15	180.00	138.00	418.00	621.12	160.93	89.83	396.62
Aug	252.88	136.00	108.00	216.75	328.81	115.81	54.58	259.23
Sep	195.59	160.00	107.75	233.50	231.64	169.21	67.62	328.28

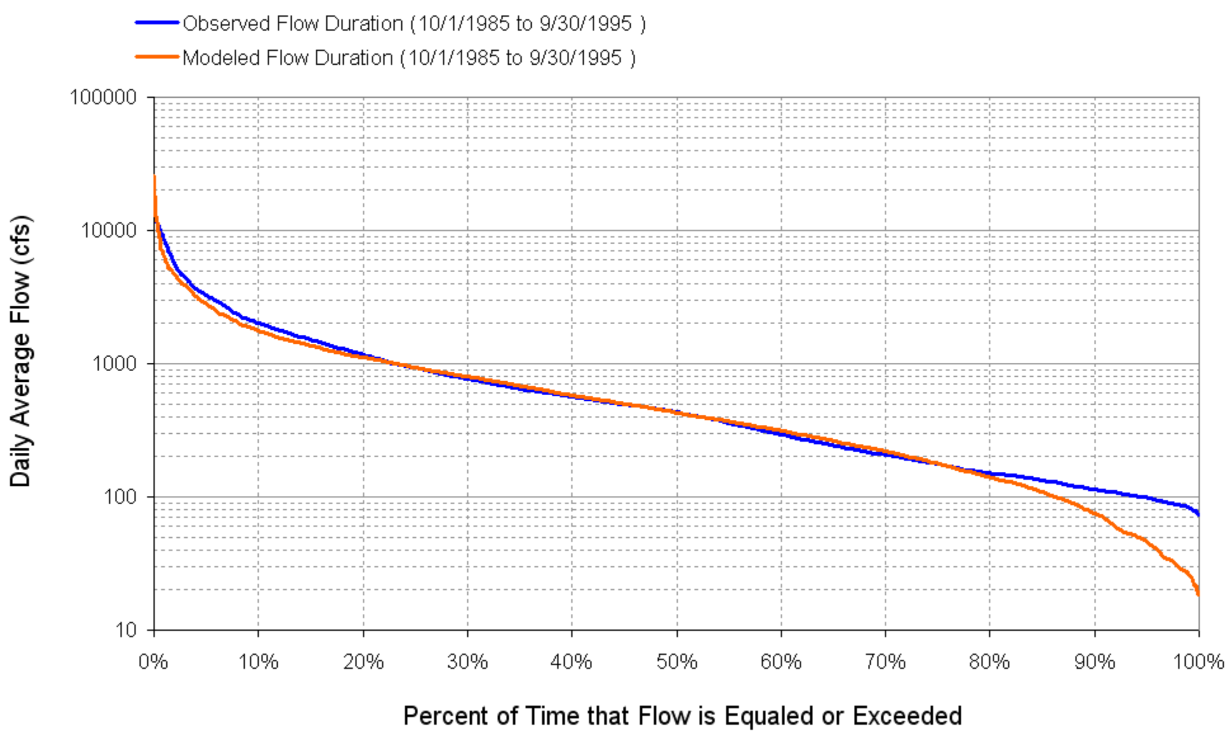


Figure 18. Flow exceedence at USGS 01562000 Raystown Branch Juniata River at Saxton, PA – validation period (HSPF).

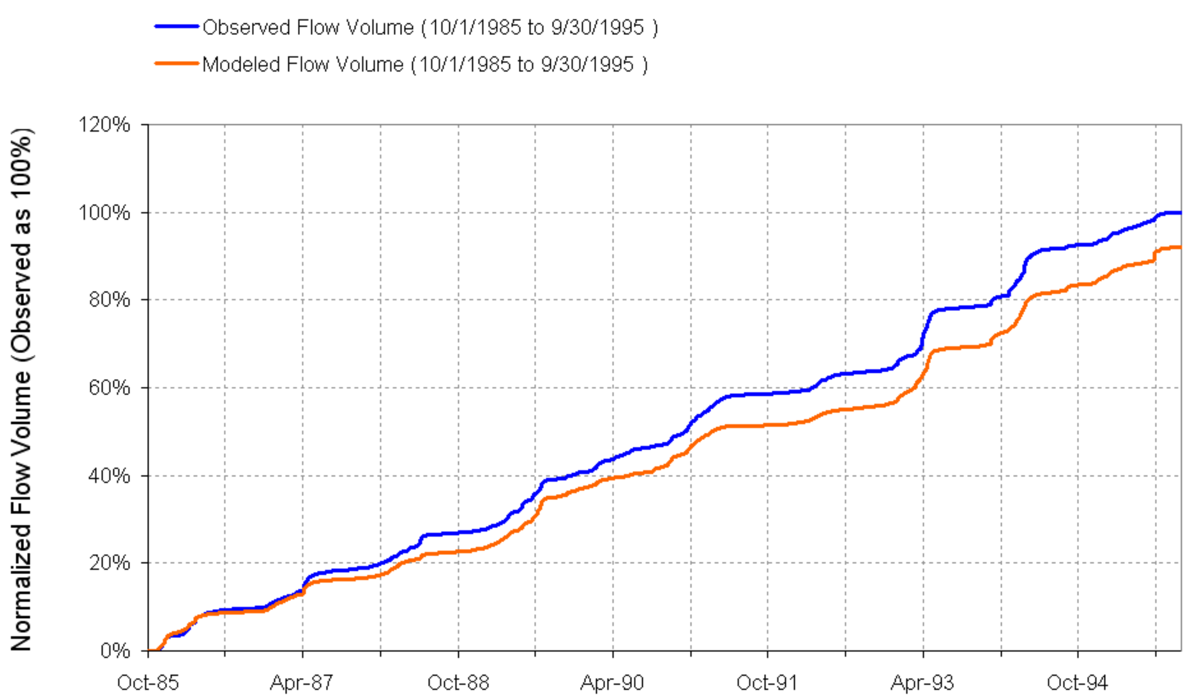


Figure 19. Flow accumulation at USGS 01562000 Raystown Branch Juniata River at Saxton, PA – validation period (HSPF).

Table 9. Summary statistics at USGS 01562000 Raystown Branch Juniata River at Saxton, PA – validation period (HSPF)

HSPF Simulated Flow		Observed Flow Gage	
REACH OUTFLOW FROM DSN 101 10-Year Analysis Period: 10/1/1985 - 9/30/1995 Flow volumes are (inches/year) for upstream drainage area		USGS 01562000 Raystown Branch Juniata River at Saxton, PA Hydrologic Unit Code: 2050303 Latitude: 40.21591249 Longitude: -78.2652901 Drainage Area (sq-mi): 756	
Total Simulated In-stream Flow:	**14.83**	Total Observed In-stream Flow:	**16.12**
Total of simulated highest 10% flows:	**6.77**	Total of Observed highest 10% flows:	**7.77**
Total of Simulated lowest 50% flows:	**1.74**	Total of Observed Lowest 50% flows:	**1.82**
Simulated Summer Flow Volume (months 7-9):	**1.79**	Observed Summer Flow Volume (7-9):	**1.51**
Simulated Fall Flow Volume (months 10-12):	**3.35**	Observed Fall Flow Volume (10-12):	**3.10**
Simulated Winter Flow Volume (months 1-3):	**5.76**	Observed Winter Flow Volume (1-3):	**6.38**
Simulated Spring Flow Volume (months 4-6):	**3.93**	Observed Spring Flow Volume (4-6):	**5.12**
Total Simulated Storm Volume:	**5.52**	Total Observed Storm Volume:	**6.49**
Simulated Summer Storm Volume (7-9):	**0.85**	Observed Summer Storm Volume (7-9):	**0.54**

Errors (Simulated-Observed)	*Error Statistics*	*Recommended Criteria*		
Error in total volume:	-8.00	10		
Error in 50% lowest flows:	-4.61	10		
Error in 10% highest flows:	-12.82	15		
Seasonal volume error - Summer:	18.92	30		
Seasonal volume error - Fall:	7.86	>> 30		Clear
Seasonal volume error - Winter:	-9.69	30		
Seasonal volume error - Spring:	-23.40	30		
Error in storm volumes:	-14.91	20		
Error in summer storm volumes:	**56.16**	**50**		
Nash-Sutcliffe Coefficient of Efficiency, E:	0.553	Model accuracy increases		
Baseline adjusted coefficient (Garrick), E':	0.512	as E or E' approaches 1.0		
Monthly NSE	0.868			

Hydrology Results for Larger Watershed

Since the calibration location above represents only a small portion of the drainage area for this project, results near the outlet of the entire watershed were examined at the Susquehanna River at Marietta, PA USGS gage (01576000). The results at this gage look fairly good as well. The simulated output is just a little high on the low flows and a little high on the summer volumes. A few of the metrics were exceeded, but most of the metrics fall within the acceptable range set for the 20 Watershed study including a daily Nash-Sutcliffe of 0.77 at the Marietta gage. The calibration results at the Susquehanna River at Marietta, PA USGS gage (01576000) are presented in Figures 20 through 26 and Tables 10 and 11. The calibration and validation statistical measurements at all USGS gages used in the Susquehanna River watershed for the 20 Watershed project are shown in Tables 12 and 13, respectively.

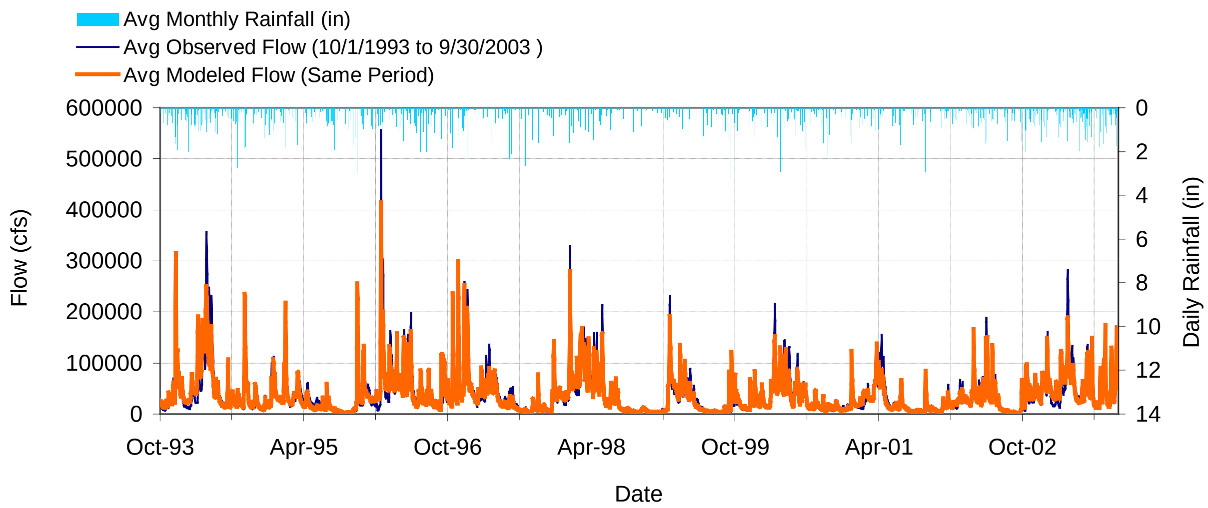


Figure 20. Mean daily flow at USGS 01576000 Susquehanna River at Marietta, PA – calibration period (HSPF).

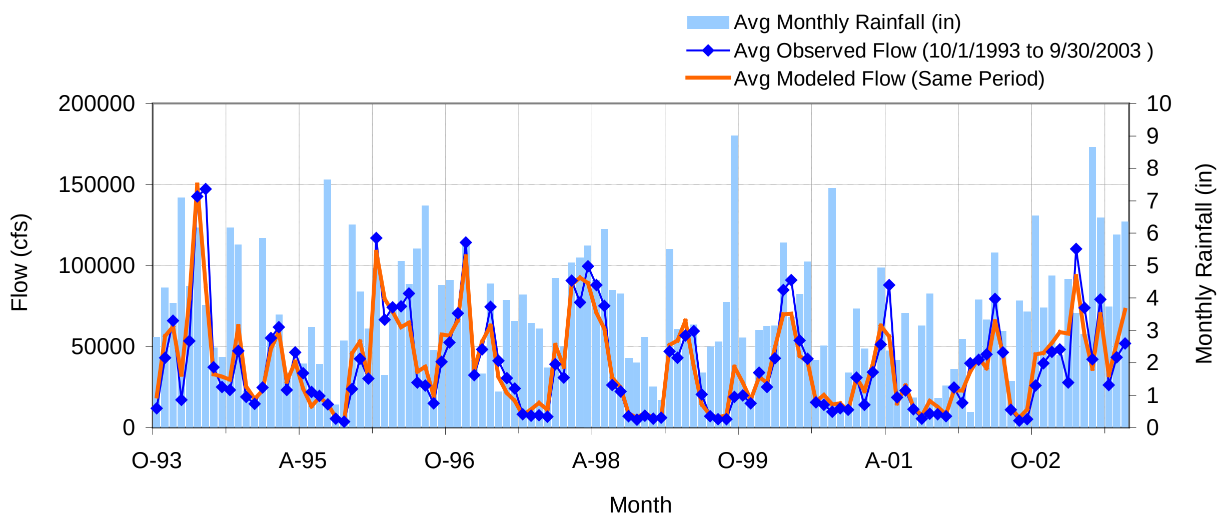


Figure 21. Mean monthly flow at USGS 01576000 Susquehanna River at Marietta, PA – calibration period (HSPF).

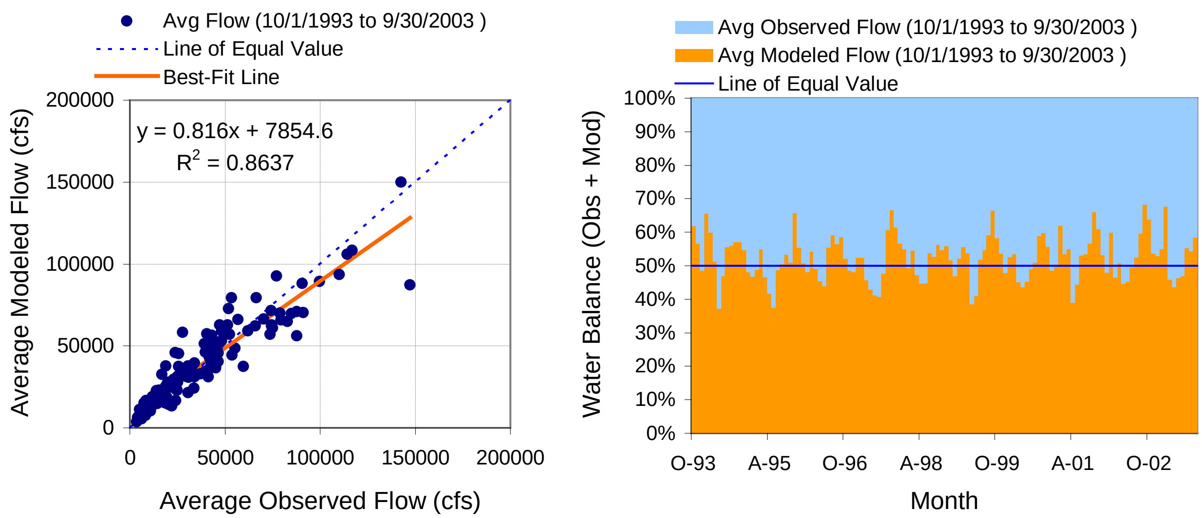


Figure 22. Monthly flow regression and temporal variation at USGS 01576000 Susquehanna River at Marietta, PA – calibration period (HSPF).

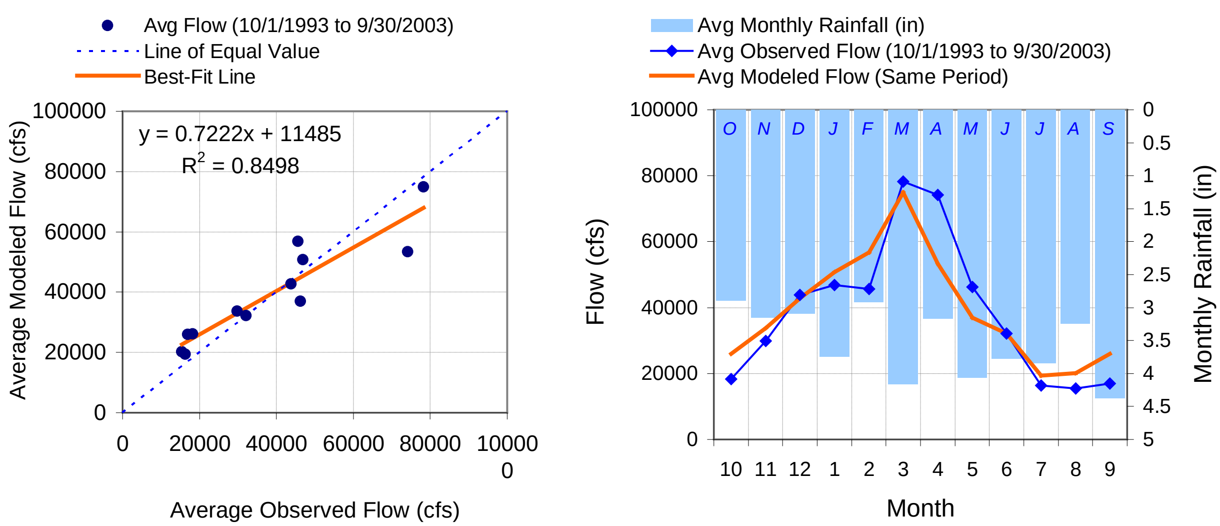


Figure 23. Seasonal regression and temporal aggregate at USGS 01576000 Susquehanna River at Marietta, PA – calibration period (HSPF).

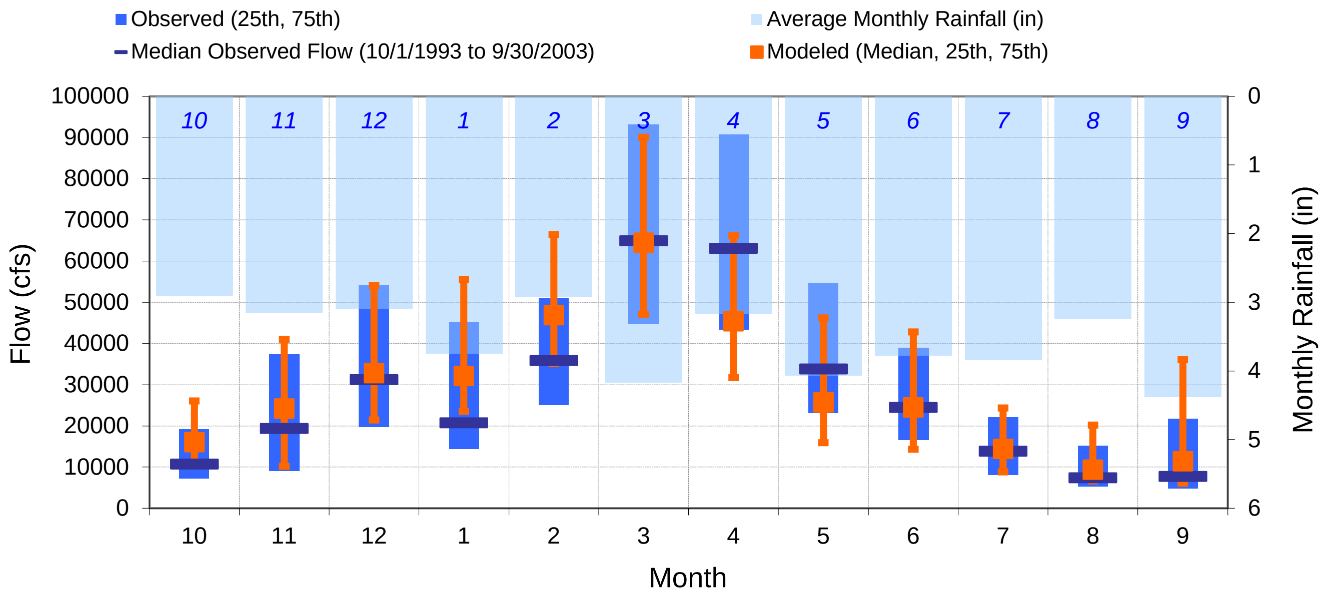


Figure 24. Seasonal medians and ranges at USGS 01576000 Susquehanna River at Marietta, PA – calibration period (HSPF).

Table 10. Seasonal summary at USGS 01576000 Susquehanna River at Marietta, PA – calibration period (HSPF)

MONTH	OBSERVED FLOW (CFS)				MODELED FLOW (CFS)			
	MEAN	MEDIAN	25TH	75TH	MEAN	MEDIAN	25TH	75TH
Oct	18258.39	10650.00	7305.00	19225.00	26039.03	16034.54	11020.63	26062.98
Nov	29811.13	19300.00	9002.50	37325.00	33731.91	24238.21	10179.07	40953.88
Dec	43879.65	31150.00	19700.00	54050.00	42761.05	32769.07	21414.73	54042.56
Jan	46873.61	20700.00	14425.00	45175.00	50733.93	32088.13	23521.55	55480.61
Feb	45647.16	35800.00	25050.00	50975.00	56828.16	46881.28	35098.74	66429.31
Mar	78282.90	64900.00	44725.00	93150.00	74939.27	64475.93	47051.59	90047.35
Apr	74228.00	63000.00	43400.00	90750.00	53288.33	45390.82	31740.68	66146.48
May	46236.13	33750.00	23100.00	54575.00	36901.17	25714.54	15935.99	46244.86
Jun	32080.10	24450.00	16575.00	38925.00	32128.54	24520.57	14349.20	42832.37
Jul	16327.52	13800.00	8122.50	22075.00	19391.00	14448.96	8844.17	24338.26
Aug	15446.55	7330.00	5292.50	15175.00	20184.23	9362.29	6647.42	20176.83
Sep	16977.37	7645.00	4757.50	21650.00	26001.69	11403.96	6133.33	36050.57

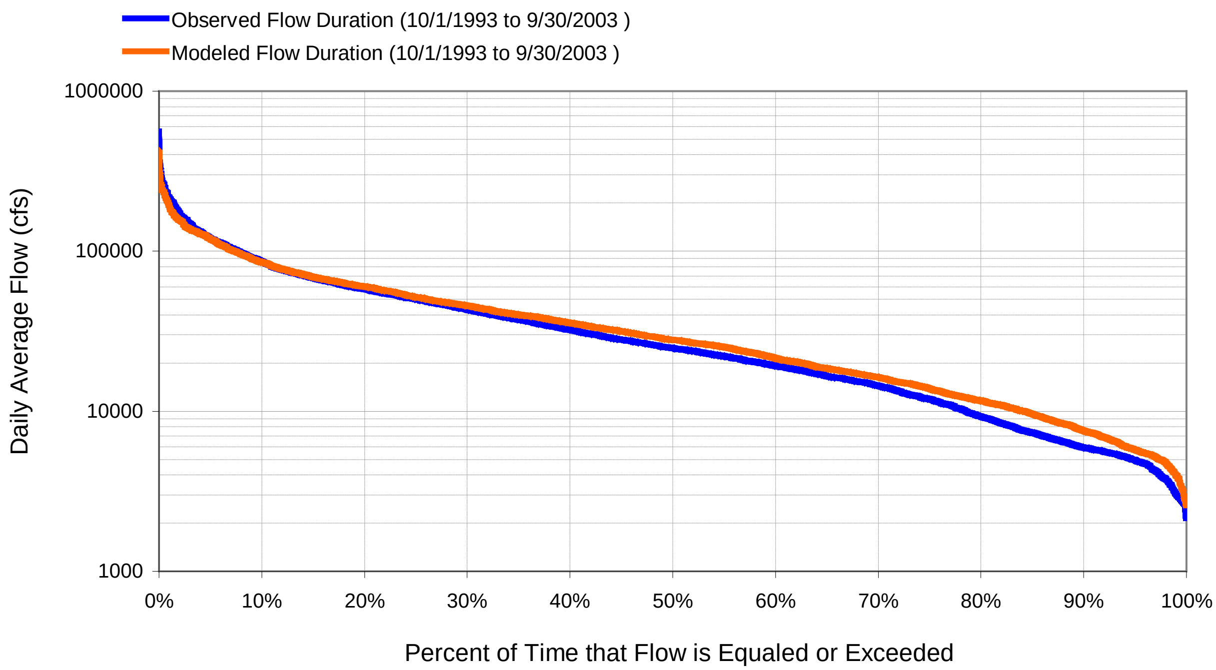


Figure 25. Flow exceedence at USGS 01576000 Susquehanna River at Marietta, PA – calibration period (HSPF).

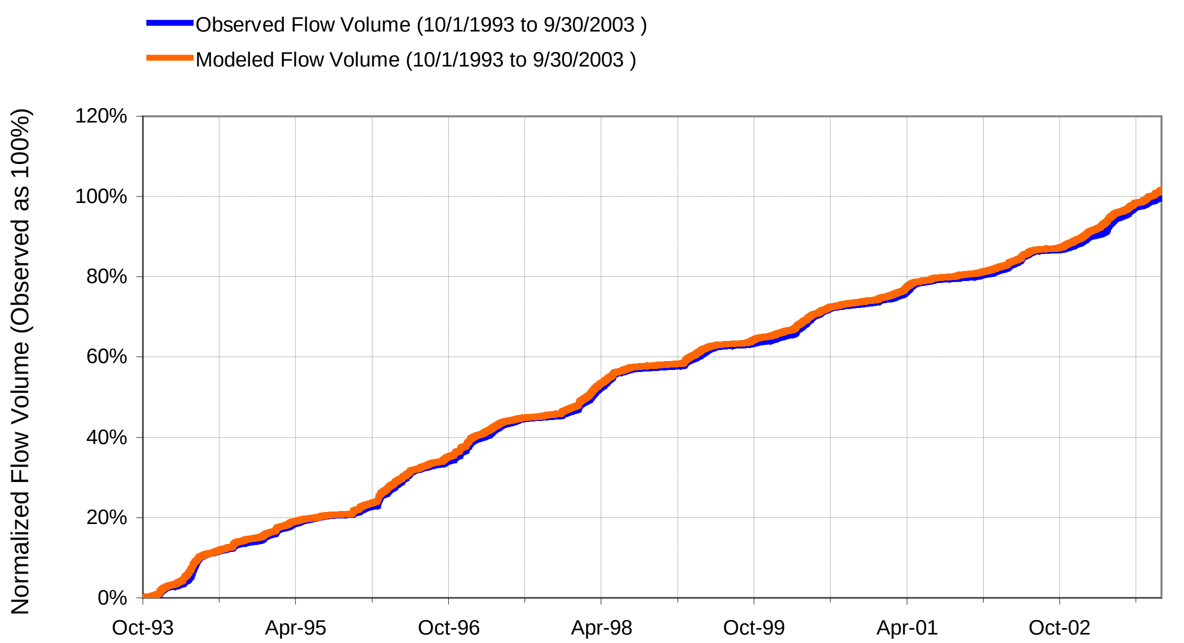


Figure 26. Flow accumulation at USGS 01576000 Susquehanna River at Marietta, PA – calibration period (HSPF).

Table 11. Summary statistics at USGS 01576000 Susquehanna River at Marietta, PA – calibration period (HSPF)

HSPF Simulated Flow		Observed Flow Gage	
REACH OUTFLOW FROM DSN 101 10-Year Analysis Period: 10/1/1993 - 9/30/2003 Flow volumes are (inches/year) for upstream drainage area		USGS 01576000 Susquehanna River at Marietta, PA Hydrologic Unit Code: 2050306 Latitude: 40.0545413 Longitude: -76.5307992 Drainage Area (sq-mi): 25990	
Total Simulated In-stream Flow:	**20.55**	Total Observed In-stream Flow:	**20.19**
Total of simulated highest 10% flows:	**6.79**	Total of Observed highest 10% flows:	**7.31**
Total of Simulated lowest 50% flows:	**3.76**	Total of Observed Lowest 50% flows:	**3.27**
Simulated Summer Flow Volume (months 7-9):	**2.87**	Observed Summer Flow Volume (7-9):	**2.14**
Simulated Fall Flow Volume (months 10-12):	**4.50**	Observed Fall Flow Volume (10-12):	**4.04**
Simulated Winter Flow Volume (months 1-3):	**7.87**	Observed Winter Flow Volume (1-3):	**7.39**
Simulated Spring Flow Volume (months 4-6):	**5.30**	Observed Spring Flow Volume (4-6):	**6.62**
Total Simulated Storm Volume:	**7.51**	Total Observed Storm Volume:	**7.32**
Simulated Summer Storm Volume (7-9):	**1.19**	Observed Summer Storm Volume (7-9):	**0.76**

Errors (Simulated-Observed)	*Error Statistics*	*Recommended Criteria*		
Error in total volume:	1.79	10		
Error in 50% lowest flows:	**14.99**	**10**		
Error in 10% highest flows:	-7.21	15		
Seasonal volume error - Summer:	**34.30**	**30**		
Seasonal volume error - Fall:	11.49	>> 30	Clear	
Seasonal volume error - Winter:	6.41	30		
Seasonal volume error - Spring:	-19.82	30		
Error in storm volumes:	2.72	20		
Error in summer storm volumes:	**56.64**	**50**		
Nash-Sutcliffe Coefficient of Efficiency, E:	0.771	Model accuracy increases		
Baseline adjusted coefficient (Garrick), E':	0.582	as E or E' approaches 1.0		
Monthly NSE	0.861			

Table 12. Summary statistics (percent error) for all stations – calibration period (HSPF)

Station	01562000 Raystown Branch Juniata River at Saxton, PA (1995-2005)	01540500 Susquehanna River at Danville, PA (1993-2003)	01576000 Susquehanna River at Marietta, PA (1993-2003)
Error in total volume:	-0.16	6.67	1.79
Error in 50% lowest flows:	6.72	25.34	14.99
Error in 10% highest flows:	-3.92	-4.71	-7.21
Seasonal volume error - Summer:	23.9	45.64	34.30
Seasonal volume error - Fall:	7.76	14.79	11.49
Seasonal volume error - Winter:	-0.84	13.54	6.41
Seasonal volume error - Spring:	-13.61	-15.66	-19.82
Error in storm volumes:	-0.63	7.37	2.72
Error in summer storm volumes:	39.10	75.91	56.64
Daily Nash-Sutcliffe Coefficient of Efficiency, E:	0.698	0.786	0.771
Monthly Nash-Sutcliffe Coefficient of Efficiency, E	0.898	0.837	0.861

Table 13. Summary statistics (percent error) for all stations – validation period (HSPF)

Station	01562000 Raystown Branch Juniata River at Saxton, PA (1985-1995)	01540500 Susquehanna River at Danville, PA (1983-1993)	01576000 Susquehanna River at Marietta, PA (1983-1993)
Error in total volume:	-8.00	2.12	-1.64
Error in 50% lowest flows:	-4.61	30.70	18.99
Error in 10% highest flows:	-12.82	-13.14	-13.32
Seasonal volume error - Summer:	18.92	54.06	35.02
Seasonal volume error - Fall:	7.86	13.13	15.62
Seasonal volume error - Winter:	-9.69	8.76	2.93
Seasonal volume error - Spring:	-23.40	-23.37	-27.27
Error in storm volumes:	-14.91	0.31	-1.26
Error in summer storm volumes:	56.16	85.91	64.86
Nash-Sutcliffe Coefficient of Efficiency, E:	0.553	0.714	0.665
Baseline adjusted coefficient (Garrick), E':	0.868	0.782	0.777

Water Quality Calibration and Validation

The 20 Watershed models are designed to provide water quality simulation for total suspended solids (TSS), total nitrogen, and total phosphorus. TSS is simulated with the standard HSPF approach (USEPA 2006). In contrast to TSS, total nitrogen and total phosphorus are simulated in this application in a simplistic fashion, as HSPF general quality constituents (GQUALs) subject to an exponential decay rate during transport.

The water quality calibration focuses on the replication of monthly loads, as specified in the project QAPP. Given the approach to water quality simulation in the 20 Watershed model, a close match to individual concentration observations cannot be expected. Comparison to monthly loads presents challenges, as monthly loads are not observed. Instead, monthly loads must be estimated from scattered concentration grab samples and continuous flow records. As a result, the monthly load calibration is inevitably based on the comparison of two uncertain numbers. Nonetheless, calibration is able to achieve a reasonable agreement. Further, the load comparisons were supported by detailed examinations of the relationships of flows to loads and concentrations and the distribution of concentration prediction errors versus flow, time, and season, as well as standard time series plots.

For application on a nationwide basis, the 20 Watershed protocols assume that TSS and total phosphorus loads will likely exhibit a strong positive correlation to flow (and associated erosive processes), while total nitrogen loads, which often have a dominant groundwater component, will not. Accordingly, TSS and total phosphorus loads were estimated from observations using a flow-stratified log-log regression approach, while total nitrogen loads were estimated using a flow-stratified averaging estimator, consistent with the findings of Preston et al. (1989).

Similar to hydrology, initial calibration of water quality was done on the Raystown Branch Juniata River at Saxton, PA, comparing model results to data from USGS 01562000. The calibration used the time period 1991-2000 and 1990 was used for validation.

Results of the TSS calibration are generally acceptable. Visually, the model is roughly simulating the trends contained in the observed data. A variety of other diagnostics were also pursued to ensure agreement between the model and observations. These are available in full in the calibration spreadsheets, but a few examples are provided below. Figure 27 presents the monthly load of TSS. Load-flow power plots were compared for individual days (Figures 28 and 29). This confirms that the relationship between flow and load is consistent across the entire range of observed flows, for both the calibration and validation periods. Tables 14 and 15 provide model statistics and relative errors for the TSS calibration and validation periods.

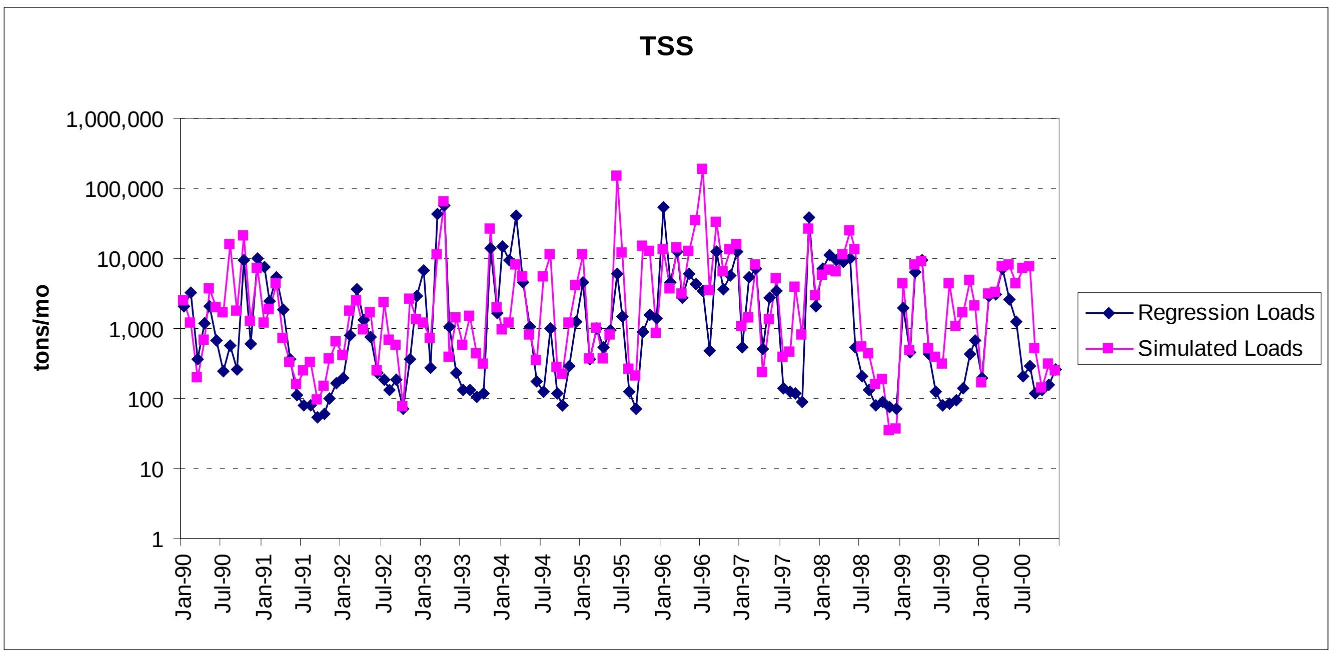


Figure 27. Fit for monthly load of TSS at Raystown Branch Juniata River at Saxton, PA (HSPF).

Table 14. Model fit statistics (observed minus predicted) for monthly sediment loads using stratified regression – USGS 01562000 Raystown Branch Juniata River at Saxton, PA (HSPF)

Statistic	Calibration period (1991-2000)	Validation period (1990)
Relative Percent Error	-78.2%	-89.7%
Relative Average Absolute Error	146%	124%
Relative Median Absolute Error	20.3%	58.3%

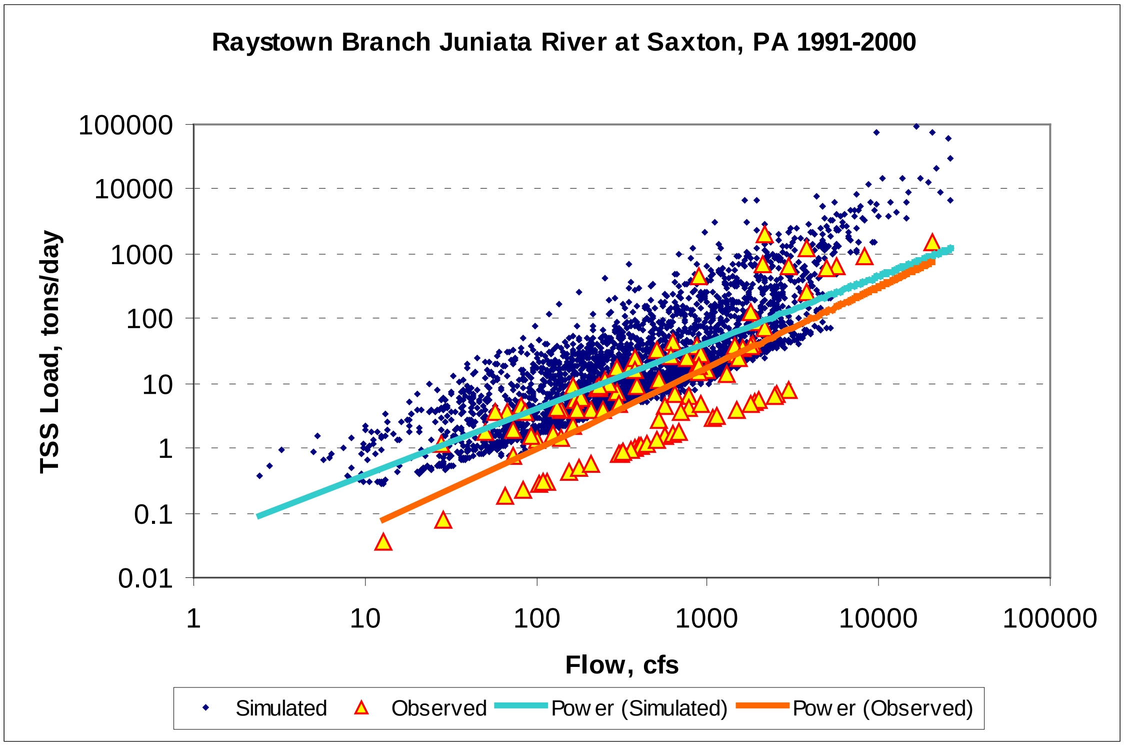


Figure 28. Power plot for observed and simulated TSS at Raystown Branch Juniata River at Saxton, PA – calibration period (HSPF).

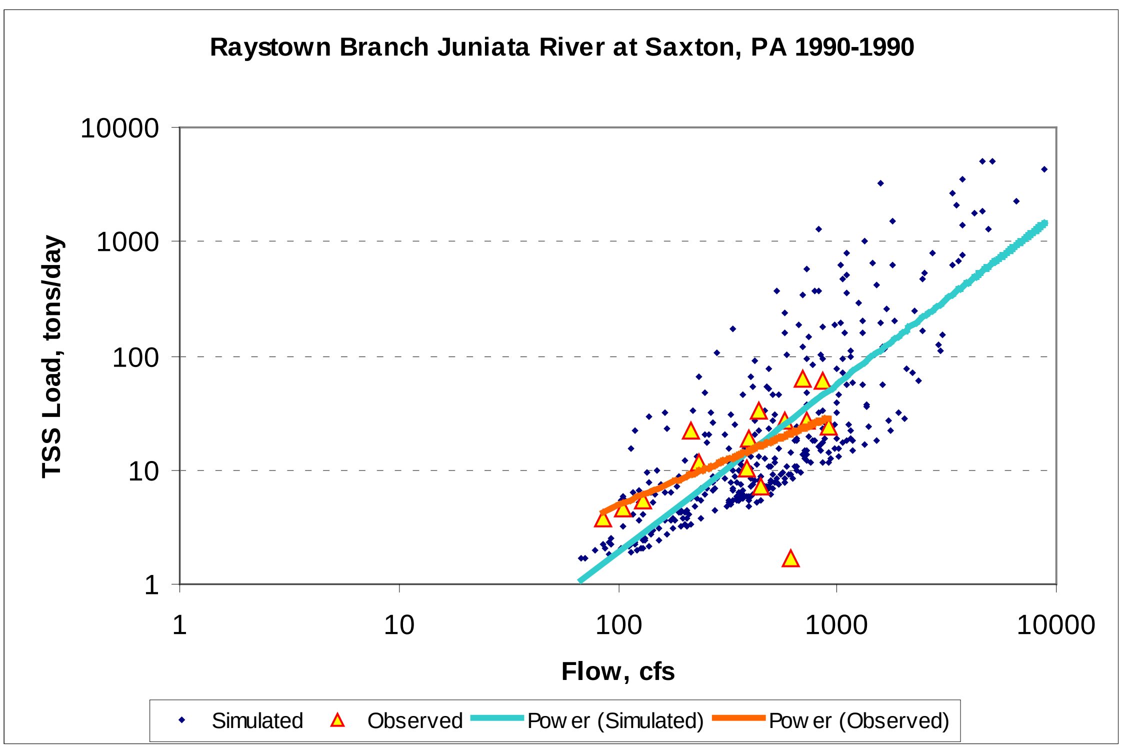


Figure 29. Power plot for observed and simulated TSS at Raystown Branch Juniata River at Saxton, PA – validation period (HSPF).

Standard time series plots (Figure 30) show that observed and simulated concentrations achieve good agreement, although individual observations may deviate. Plots of concentration error versus flow and versus month (not shown) were used to guard against hydrologic and temporal bias.

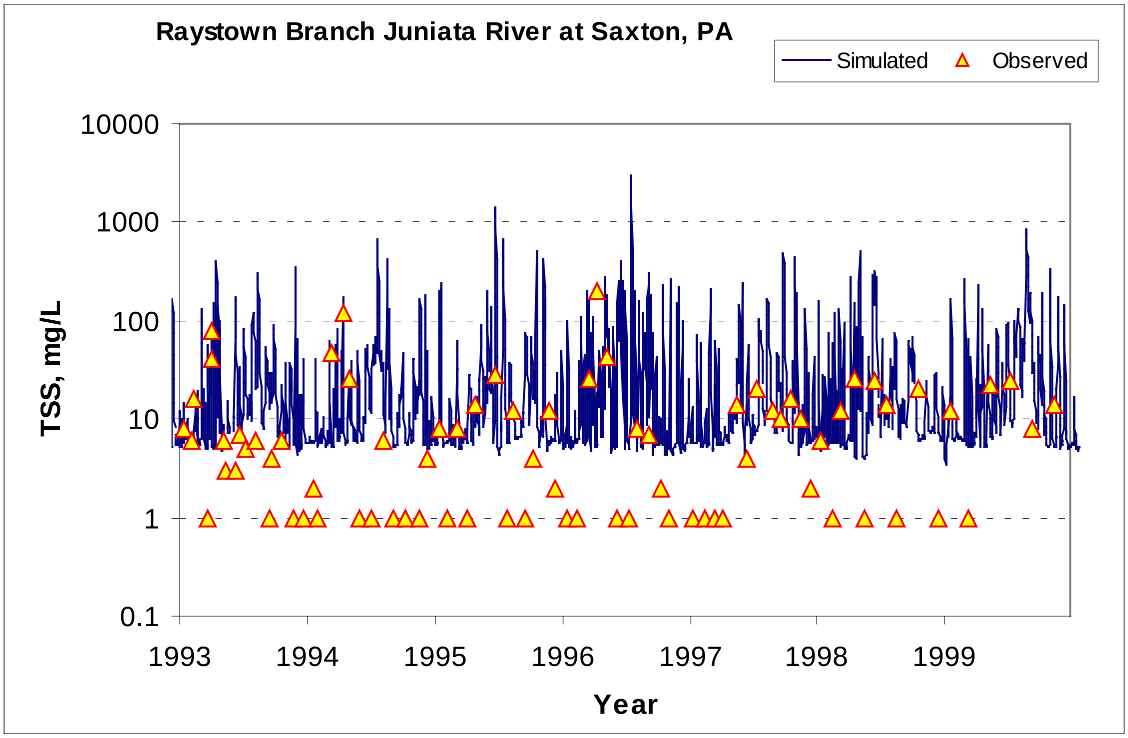


Figure 30. Time series plot of TSS concentration at Raystown Branch Juniata River at Saxton, PA - calibration period (HSPF).

Table 15. Relative errors,(observed minus simulated) for TSS concentrations at USGS 01562000 Raystown Branch Juniata River at Saxton, PA (HSPF)

Statistic	Calibration period (1991-2000)	Validation period (1990)
Count	106	15
Concentration Average Error	-138.4%	-30.82%
Concentration Median Error	-29.73%	24.63%

The total phosphorus load calibration performed well for the Susquehanna River watershed calibration focus area. Adjustments were made to the accumulation rate and storage limits for the impervious surfaces. In general, the observed and simulated total phosphorus loads attained an acceptable match for the simulation period (Figure 31). As with TSS, additional diagnostics for total phosphorus included flow-load power plots (Figures 32 and 33) and time series plots (Figure 34). All show acceptable agreement. Tables 16 and 17 provide model statistics and relative errors for the total phosphorus calibration and validation periods. In contrast to load, phosphorus concentrations are generally over-estimated (observed minus simulated concentration less than zero). This is due to an over-estimation of observed phosphorus concentrations at low flows that may be due to the simplistic representation of point source discharges in the model.

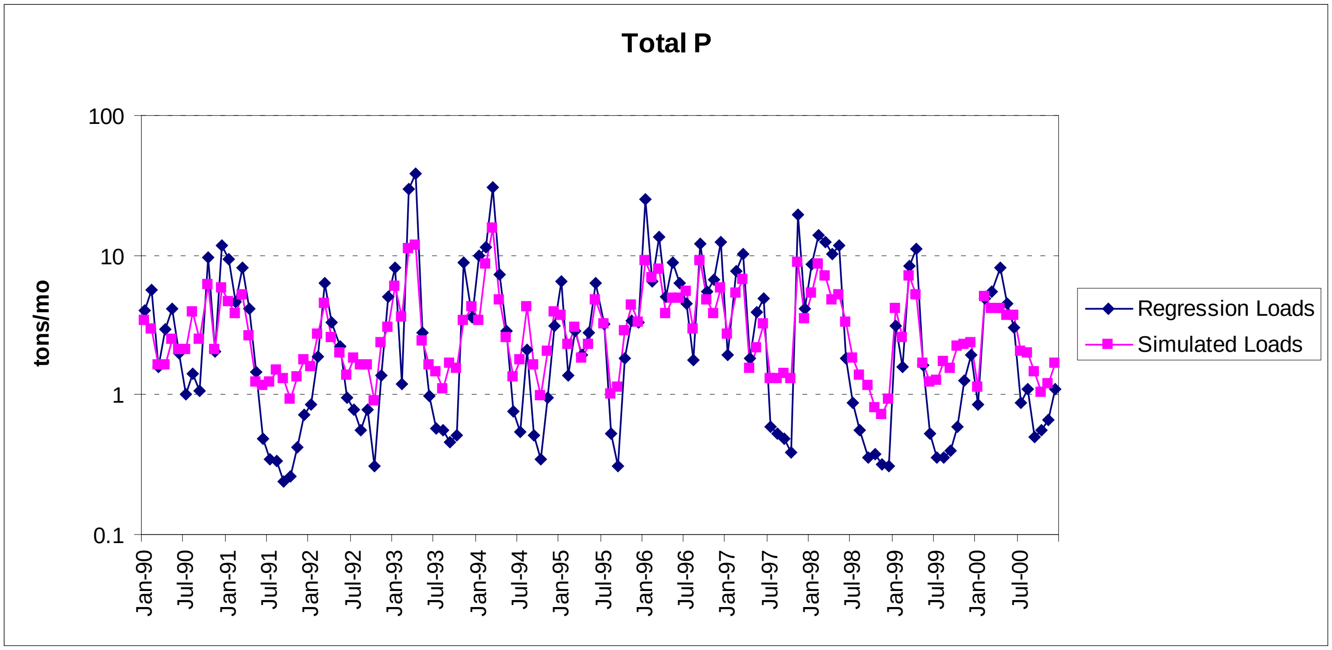


Figure 31. Fit for monthly load of total phosphorus at Raystown Branch Juniata River at Saxton, PA (HSPF).

Table 16. Model fit statistics (observed minus predicted) for monthly total phosphorus loads using stratified regression – USGS 01562000 Raystown Branch Juniata River at Saxton, PA (HSPF)

Statistic	Calibration period (1991-2000)	Validation period (1990)
Relative Percent Error	26.0%	21.5%
Relative Average Absolute Error	49%	45%
Relative Median Absolute Error	22.7%	35.4%

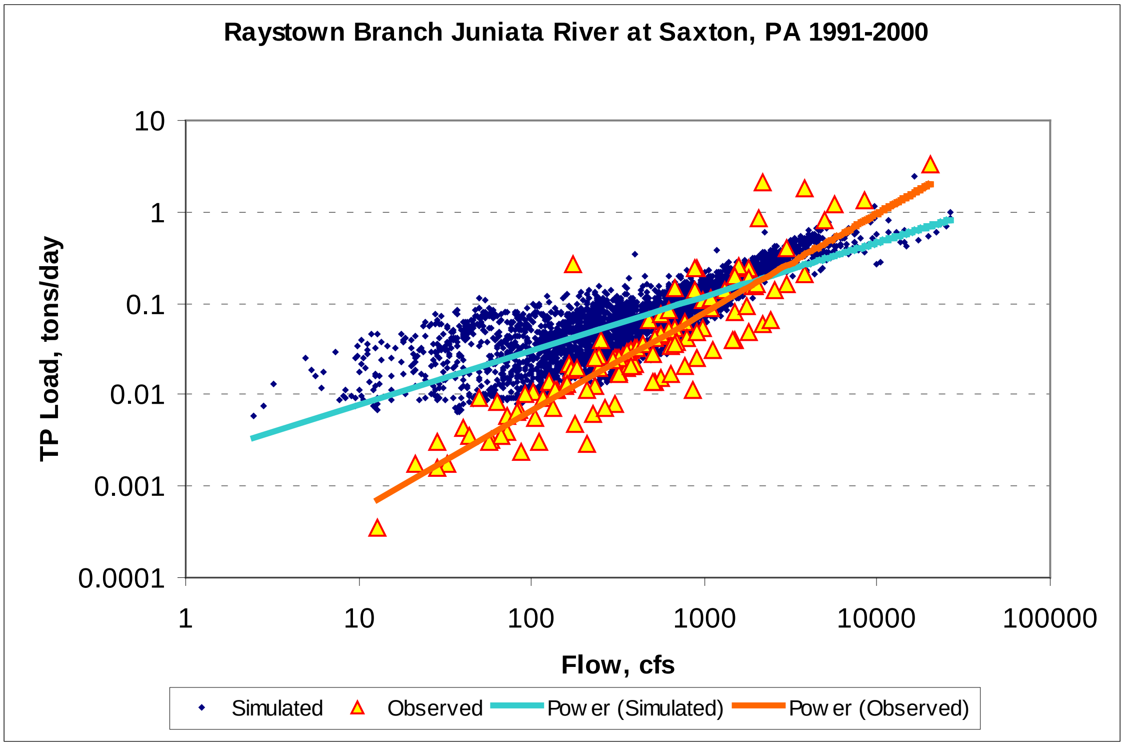


Figure 32. Power plot for observed and simulated total phosphorus at Raystown Branch Juniata River at Saxton, PA – calibration period (HSPF).

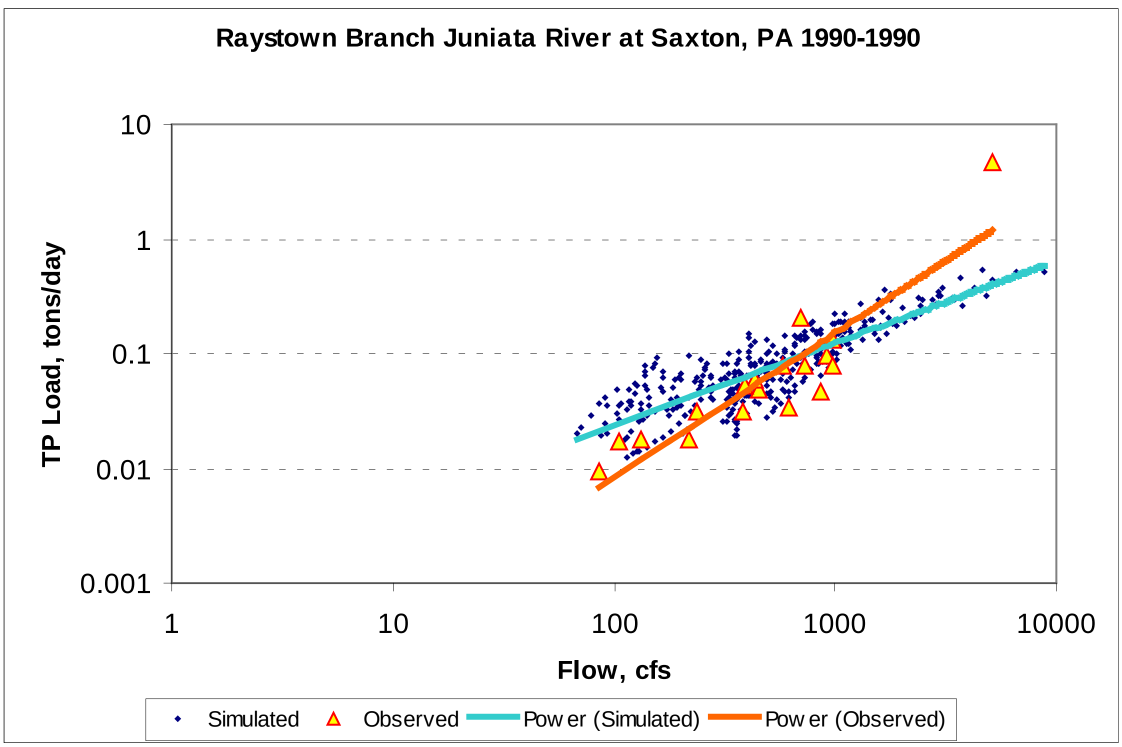


Figure 33. Power plot for observed and simulated total phosphorus at Raystown Branch Juniata River at Saxton, PA – validation period (HSPF).

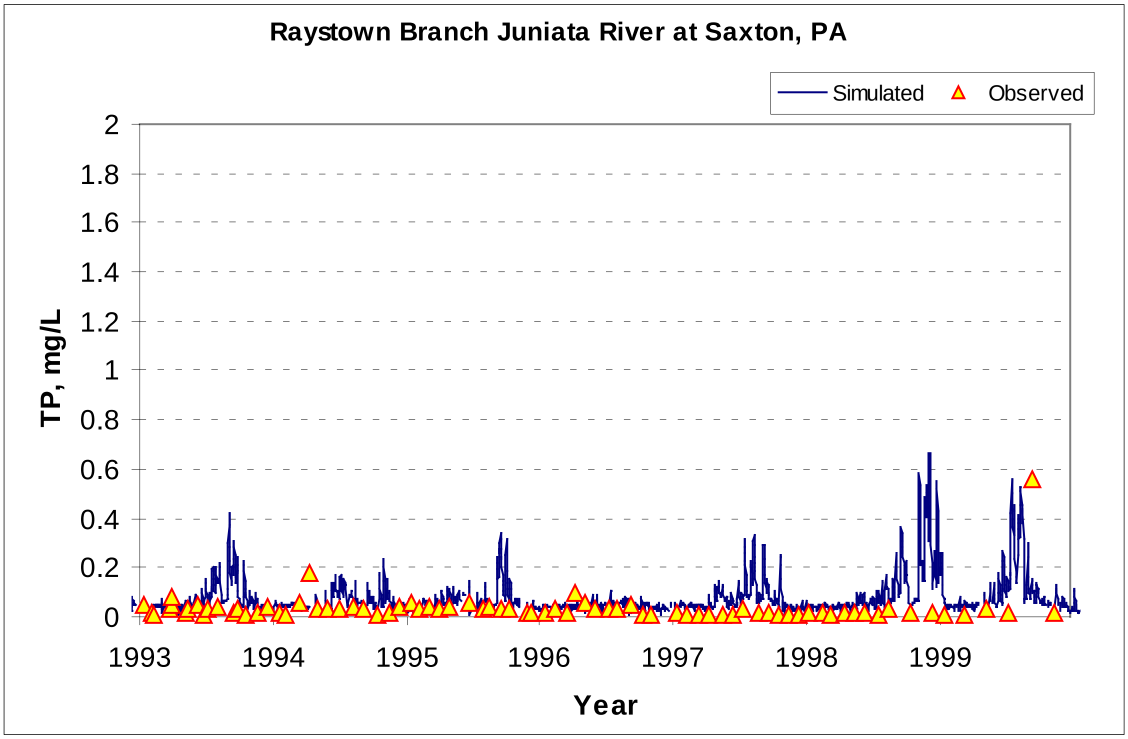


Figure 34. Time series plot of total phosphorus concentration, at Raystown Branch Juniata River at Saxton, PA (HSPF).

Table 17. Relative errors (observed minus simulated) for total phosphorus concentrations at USGS 01562000 Raystown Branch Juniata River at Saxton, PA (HSPF)

Statistic	Calibration period (1990-1990)	Validation period (1990)
Count	122	18
Concentration Average Error	-121.72%	-0.88%
Concentration Median Error	-50.63%	-12.24%

Results for total nitrogen are summarized in Figures 35 through 38. The results are acceptable, and generally better than those for total phosphorus. This is due to total nitrogen not being sediment associated, therefore, problems with sediment are not reflected in the calibration for total nitrogen. Tables 18 and 19 provide model statistics and relative errors for the total nitrogen calibration and validation periods.

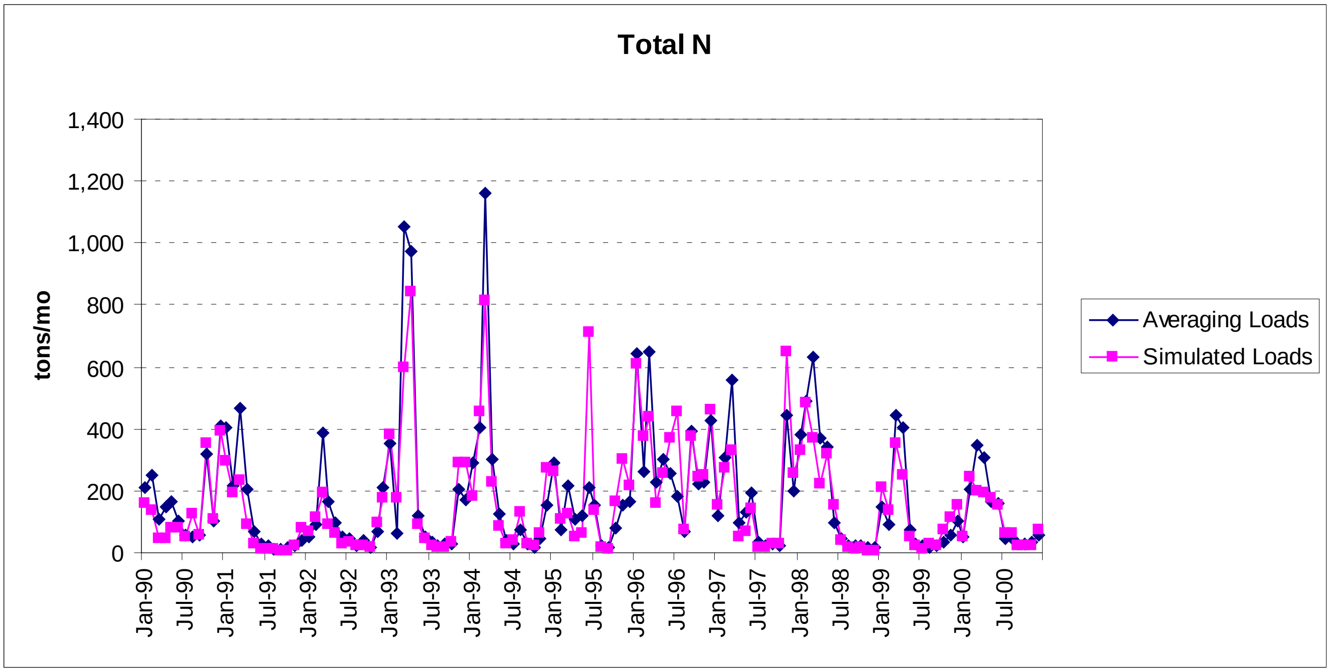


Figure 35. Fit for monthly load of total nitrogen at Raystown Branch Juniata River at Saxton, PA (HSPF).

Table 18. Model fit statistics (observed minus predicted) for monthly total nitrogen loads using averaging estimator – USGS 01562000 Raystown Branch Juniata River at Saxton, PA (HSPF)

Statistic	Calibration period (1991-2000)	Validation period (1990)
Relative Percent Error	7.0%	17.2%
Relative Average Absolute Error	34%	29%
Relative Median Absolute Error	16.8%	26.2%

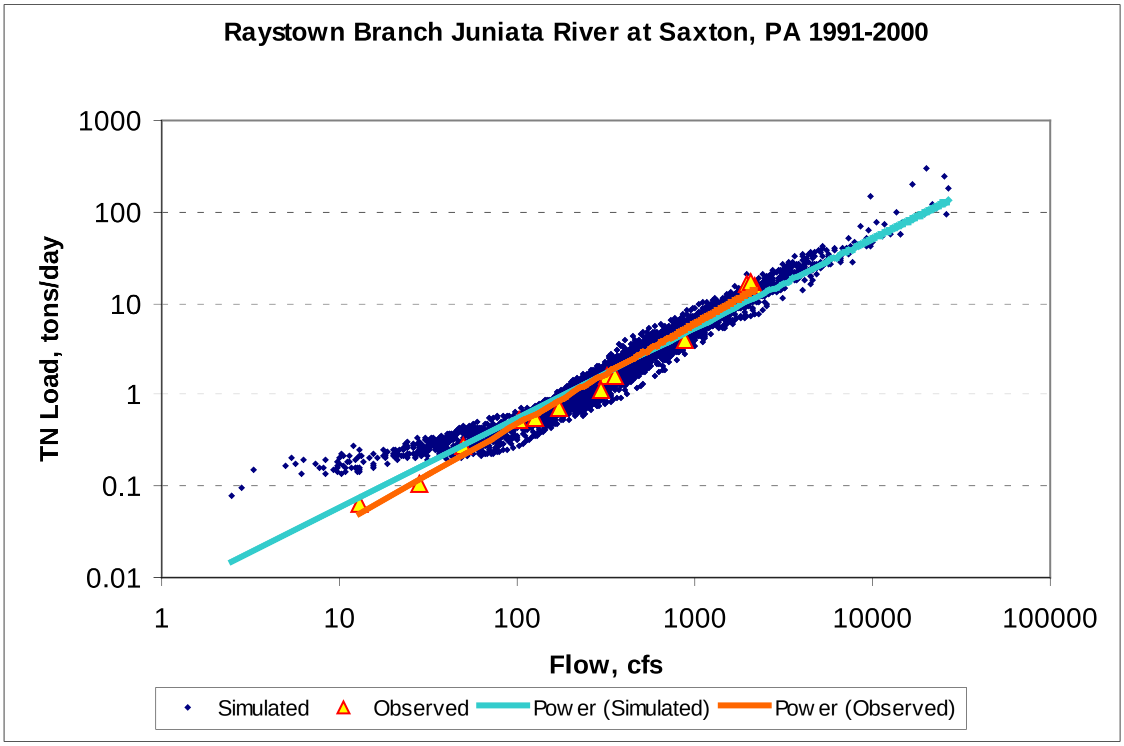


Figure 36. Power plot for observed and simulated total nitrogen at Raystown Branch Juniata River at Saxton, PA – calibration period (HSPF).

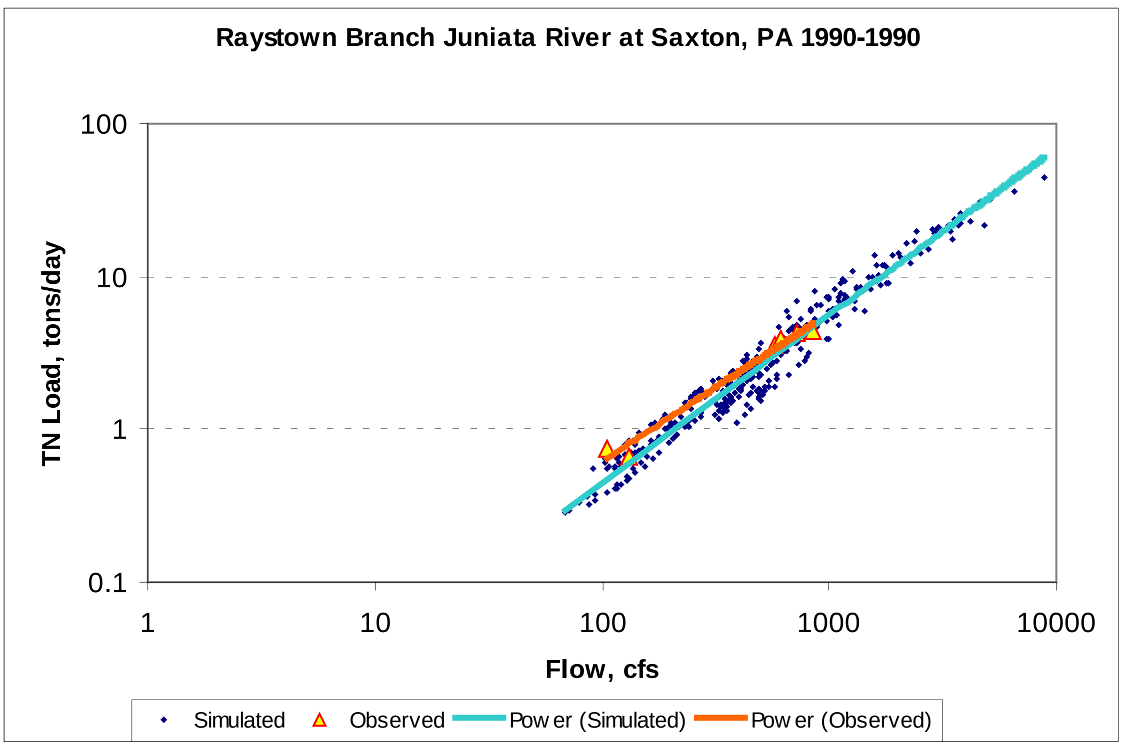


Figure 37. Power plot for observed and simulated total nitrogen at Raystown Branch Juniata River at Saxton, PA – validation period (HSPF).

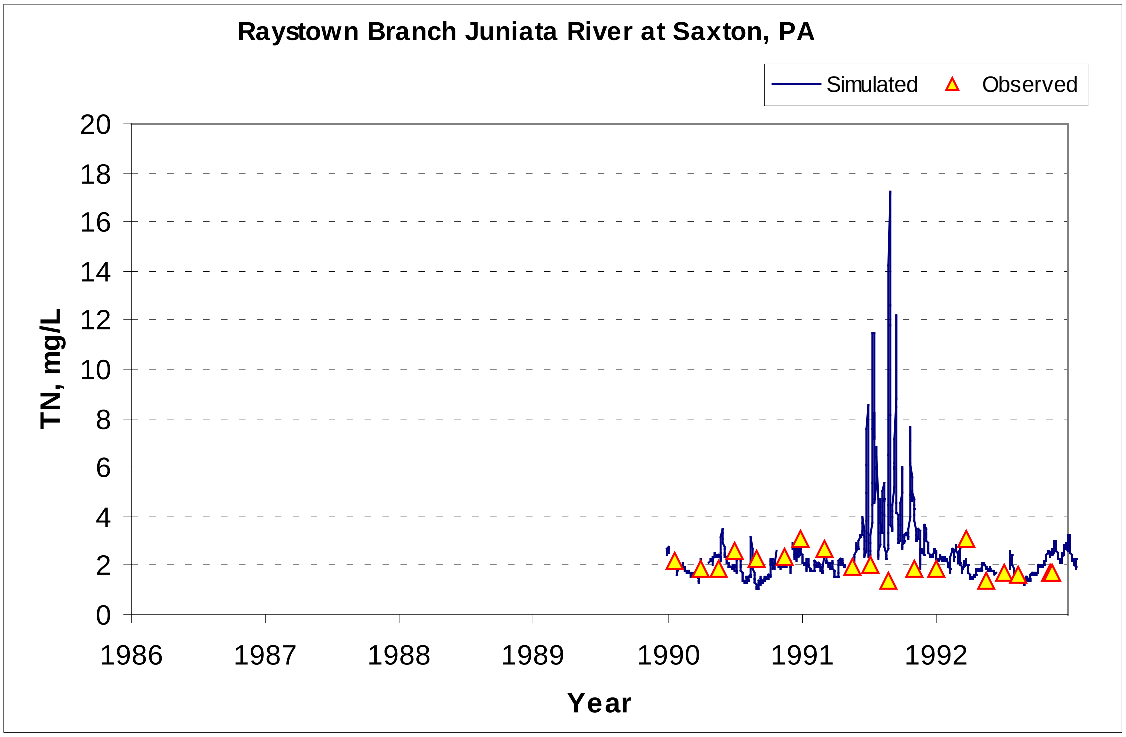


Figure 38. Time series plot of total nitrogen concentration, at Raystown Branch Juniata River at Saxton, PA (HSPF).

Table 19. Relative errors (observed minus simulated) for total nitrogen concentration at USGS 01562000 Raystown Branch Juniata River at Saxton, PA (HSPF)

Statistic	Calibration period (1991-2000)	Validation period (1990)
Count	13	6
Concentration Average Error	-22.89%	11.10%
Concentration Median Error	-22.60%	7.42%

Water Quality Results for Larger Watershed

As with hydrology, the Raystown Branch Juniata River (USGS 01562000) watershed parameters for water quality were directly transferred to other portions of the watershed. Summary statistics for the water quality calibration and validation at other stations in the watershed are provided in Tables 20 and 21, respectively.

Table 20. Summary statistics for water quality for all stations – calibration period (HSPF)

Station	01576000 Susquehanna River at Marietta, PA (1991-1995)	01540500 Susquehanna River at Danville, PA (1991-1994)	01562000 Raystown Branch Juniata River at Saxton, PA (1991-2000)
Relative Percent Error TSS Load	26.5%	27.5%	-78.2%
TSS Concentration Median Error	-24.8%	-6.3%	-29.7%
Relative Percent Error TP Load	44.0%	50.0%	26.0%
TP Concentration Median Error	-1.0%	24.6%	-50.6%
Relative Percent Error TN Load	-14.4%	6.2%	7.0%
TN Concentration Median Error	-34.8%	-4.8%	-22.6%

Table 21. Summary statistics for water quality for all stations – validation period (HSPF)

Station	01576000 Susquehanna River at Marietta, PA (1980-90)	01540500 Susquehanna River at Danville, PA (1986-90)	01562000 Raystown Branch Juniata River at Saxton, PA (1990)
Relative Percent Error TSS Load	-0.6%	-11.1%	-89.7%
TSS Concentration Median Error	-27.3%	-11.2%	24.6%
Relative Percent Error TP Load	38.8%	40.5%	21.5%
TP Concentration Median Error	5.1%	20.7%	-12.2%
Relative Percent Error TN Load	-7.1%	10.0%	17.2%
TN Concentration Median Error	-17.2%	5.9%	7.4%

SWAT Modeling

The SWAT model for the Susquehanna River watershed was set up with the ArcSWAT Version 2.3.3 interface using the subwatersheds and stream network layers obtained from CBP, and other geospatial coverages described above for the HSPF model. The precipitation and temperature data were preprocessed from BASINS Weather Data Management (WDM) files to obtain the daily values.

The SWAT modeling process started with hydrology calibration, followed by calibration of sediment, and then calibration of nitrogen and phosphorous. The USGS gage on the Raystown Branch of the Juniata River at Saxton, PA (USGS 02050303) was used as the initial calibration location. The parameters were then transferred to the entire Susquehanna River watershed and results were evaluated at the gages on the Susquehanna River at Danville, PA (USGS 01540500) and on the Susquehanna River at Marietta, PA (USGS 01576000). While hydrology parameters were readily transferrable, water quality parameters, especially those related to sediment needed some adjustment at the larger watershed scale.

Changes Made to Base Data Provided

No changes were made to the meteorological or land use base data for the SWAT model.

Assumptions

Though there are a number of reservoirs present in Susquehanna River watershed, they are located below the calibration and validation locations. Hence the information regarding these reservoirs was not specifically addressed in the SWAT model, consistent with the approach used for HSPF.

The point source data were specified for all the major active point sources in the Susquehanna study area. The point source flows and concentrations for each facility in the watershed were assumed to be constant throughout the simulation period. The data from the time period from 1991-2006 were compiled from the PCS database and the median values were estimated. The facilities that were missing a total nitrogen, total phosphorus, and TSS concentration value were filled with a typical pollutant concentration value from literature (Typical Pollutant Concentration for NCPDI Discharge Categories -Improving Point Source Loading Data for Reporting National Water Quality Indicators) prepared for Jim Horne, EPA/OWM (Tetra Tech 1990) based on the SIC classification. All POTWs were assumed to have secondary treatment. The median concentrations for the nutrient species were estimated based on the values reported in Cheaspake Bay Phase 5 Model report for species relationship for point sources and used in the model.

Hydrology Calibration

Similar to HSPF, hydrology calibration was performed at the USGS gage on the Raystown Branch of the Juniata River at Saxton, PA (USGS 01562000). Though some adjustments are made at the major watershed level, a spatial calibration approach was not adopted for Susquehanna River watershed SWAT modeling. The calibration efforts were geared toward getting a closer match between simulated and observed flows at the outlet of the calibration focus area and to limit the error statistics within the acceptable ranges listed in the QAPP.

Land Use / Soil / Slope definition

A 5/10/5 percent threshold was used for land use/soil/slope in the SWAT model while defining the HRUs. Urban (including current and future urban class types) classes were exempt from applying the thresholds.

Elevation Bands

The topographical analysis of Susquehanna River watersheds showed a significant range of elevations within some individual modeling subwatersheds. This is likely to result in orographic variability in precipitation. Eight elevation bands were used to account for the orographic effects on temperature and precipitation.

Calibration Parameters

The initial values of the parameters were set by ArcGIS based on various geospatial datasets and the defaults set in the SWAT database. During the calibration process, adjustments were focused on the following parameters:

- ICN (Daily curve number calculation method) – In order to make the CN less dependent on the soil moisture content and more dependent on the antecedent conditions, the ICN was set to 1 (CN as function or ET)
- FFCB (Initial soil water storage expressed as a fraction of field capacity water content)
- CN_FROZ (Frozen curve number active)
- Tlaps (Temperature laps rate)
- Plaps (Preciptation laps rate)
- ALAI_MIN (Minimum leaf area index for plant during dormant period)
- CurYr_Mat (Current age of trees)
- LAI_Ini (Initial leaf area index)
- EPCO (Plant uptake compensation factor)
- CN (Curve Number)
- TIMP (Snow pack temperature lag factor)
- ESCO (Soil evaporation compensation factor)
- CANMX (Maximum canopy storage)
- Alpha_bf (Baseflow alpha factor)
- GW_Delay (Groundwater delay)
- GWQMN (Threshold depth of water in the shallow aquifer for return flow to occur)
- REVAPMN (Threshold depth of water in the shallow aquifer for revap to occur)
- GW_REVAP (Groundwater revap coefficient)
- SURLAG (Surface runoff lag time)
- CH_K1 (Effective hydraulic conductivity in tributary channel alluvium)
- CH_K2 (Effective hydraulic conductivity in main channel alluvium)
- SFTMP (Snowfall temperature)
- SMTMP (Snow melt base temperature)
- SMFMX (Maximum melt rate for snow during year)
- SMFMN (Minimum melt rate for snow during year)
- CNCOEFF (Plant ET curve number coefficient)
- CH_N2 (Manning's n value for the main channel)
- CH_N1 (Manning's "n" value for the tributary channels)
- HRU_Slope (Average slope steepness)
- Slsubbsn (Average slope length)

Initial calibrations were performed for the Raystown Branch of the Juniata River, comparing model results to data from USGS 01562000 (Raystown Branch Juniata River At Saxton, PA), and are summarized in Figures 39 through 45 and Tables 22 and 23. The model fit is of good quality, but summer volumes are over estimated. The model calibration period was set to the 10 water years from 10/01/1995 to 09/30/2005.

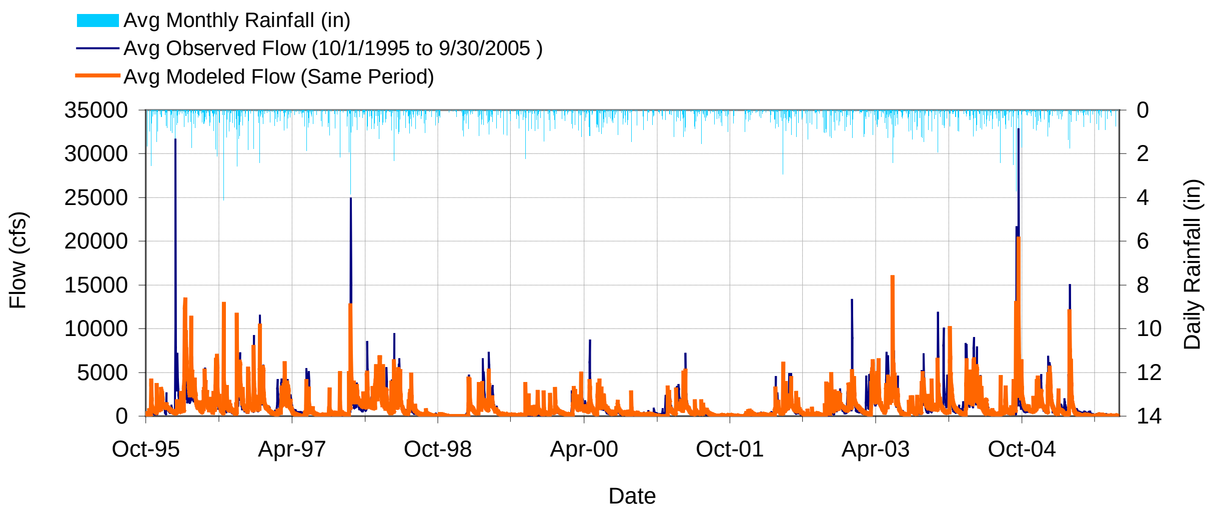


Figure 39. Mean daily flow at USGS 01562000 Raystown Branch Juniata River at Saxton, PA – calibration period (SWAT).

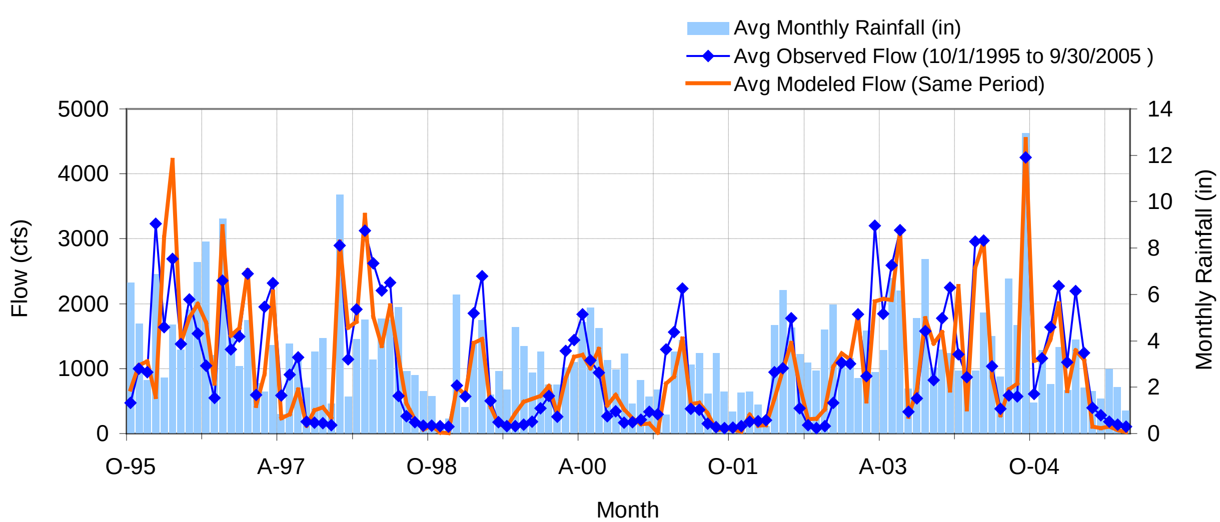


Figure 40. Mean monthly flow at USGS 01562000 Raystown Branch Juniata River at Saxton, PA – calibration period (SWAT).

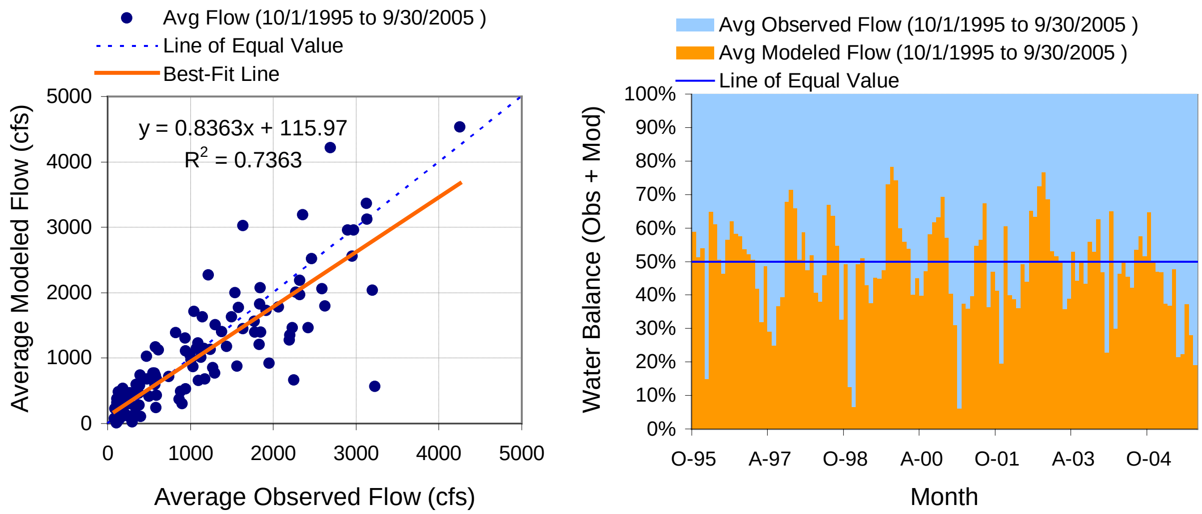


Figure 41. Monthly flow regression and temporal variation at USGS 01562000 Raystown Branch Juniata River at Saxton, PA – calibration period (SWAT).

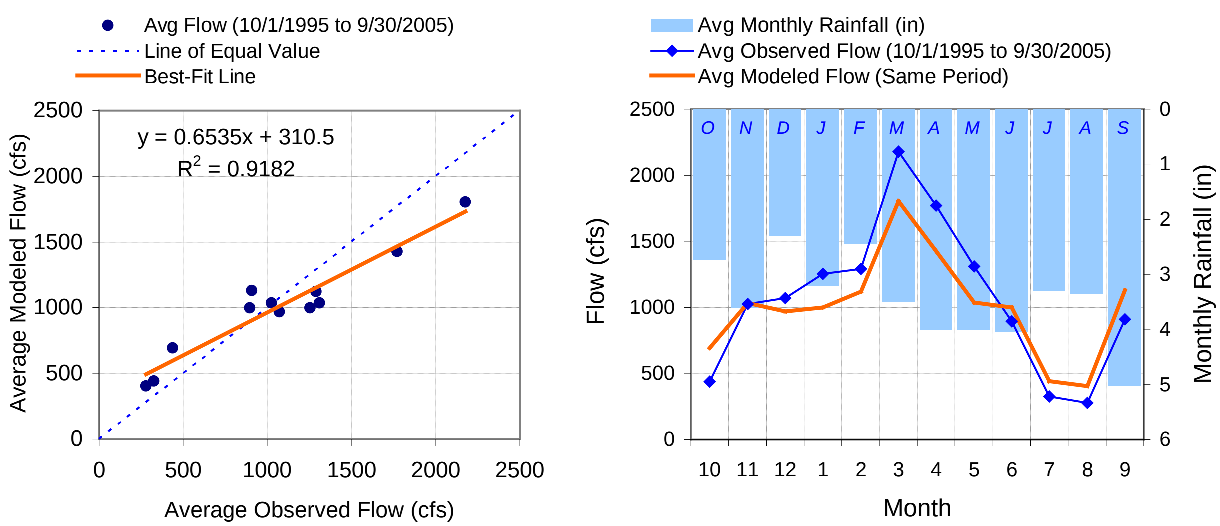


Figure 42. Seasonal regression and temporal aggregate at USGS 01562000 Raystown Branch Juniata River at Saxton, PA – calibration period (SWAT).

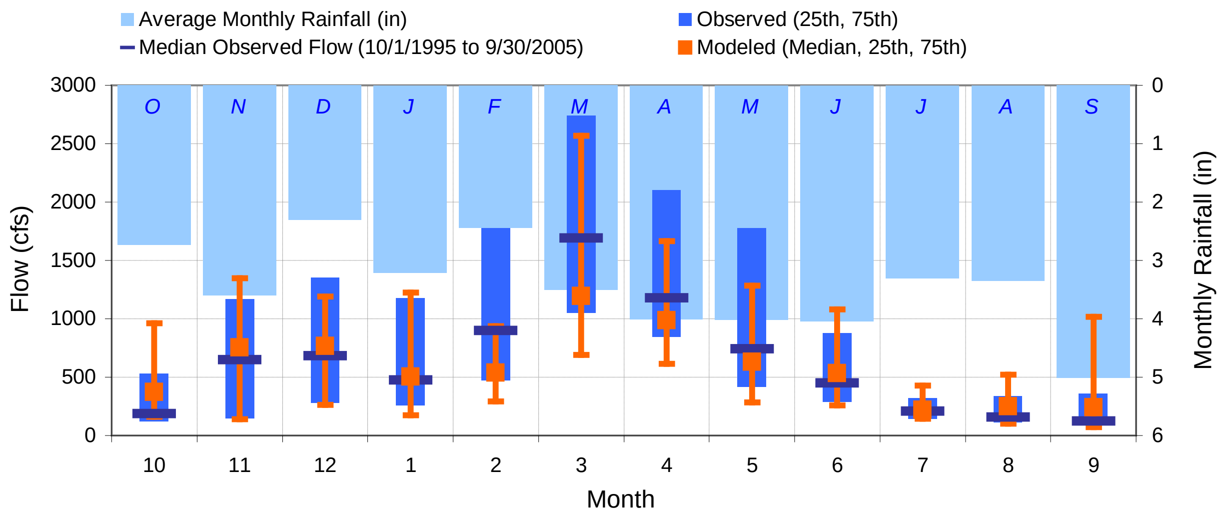


Figure 43. Seasonal medians and ranges at USGS 01562000 Raystown Branch Juniata River at Saxton, PA – calibration period (SWAT).

Table 22. Seasonal summary at USGS 01562000 Raystown Branch Juniata River at Saxton, PA – calibration period (SWAT)

MONTH	OBSERVED FLOW (CFS)				MODELED FLOW (CFS)			
	MEAN	MEDIAN	25TH	75TH	MEAN	MEDIAN	25TH	75TH
Oct	438.69	187.00	119.00	530.75	692.82	371.51	162.66	959.94
Nov	1024.44	647.50	149.75	1170.00	1034.60	754.67	141.71	1346.72
Dec	1071.22	682.00	280.75	1350.00	969.20	765.27	263.19	1190.02
Jan	1255.25	475.00	260.00	1180.00	998.54	505.18	171.86	1224.18
Feb	1290.35	900.00	470.00	1775.00	1120.65	539.96	290.45	935.31
Mar	2177.77	1690.00	1052.50	2742.50	1804.98	1195.40	691.99	2568.17
Apr	1771.52	1180.00	843.75	2102.50	1425.47	986.87	613.33	1666.15
May	1310.00	739.50	414.00	1777.50	1035.99	630.37	283.51	1281.83
Jun	895.83	448.00	287.50	879.00	999.51	535.90	258.19	1082.22
Jul	326.40	207.00	146.00	324.00	440.54	222.43	144.38	426.51
Aug	278.62	157.50	115.25	339.75	404.37	249.52	100.82	519.83
Sep	907.63	124.50	104.00	360.25	1129.77	239.93	73.81	1015.30

Figure 44. Flow exceedence at USGS 01562000 Raystown Branch Juniata River at Saxton, PA – calibration period (SWAT).

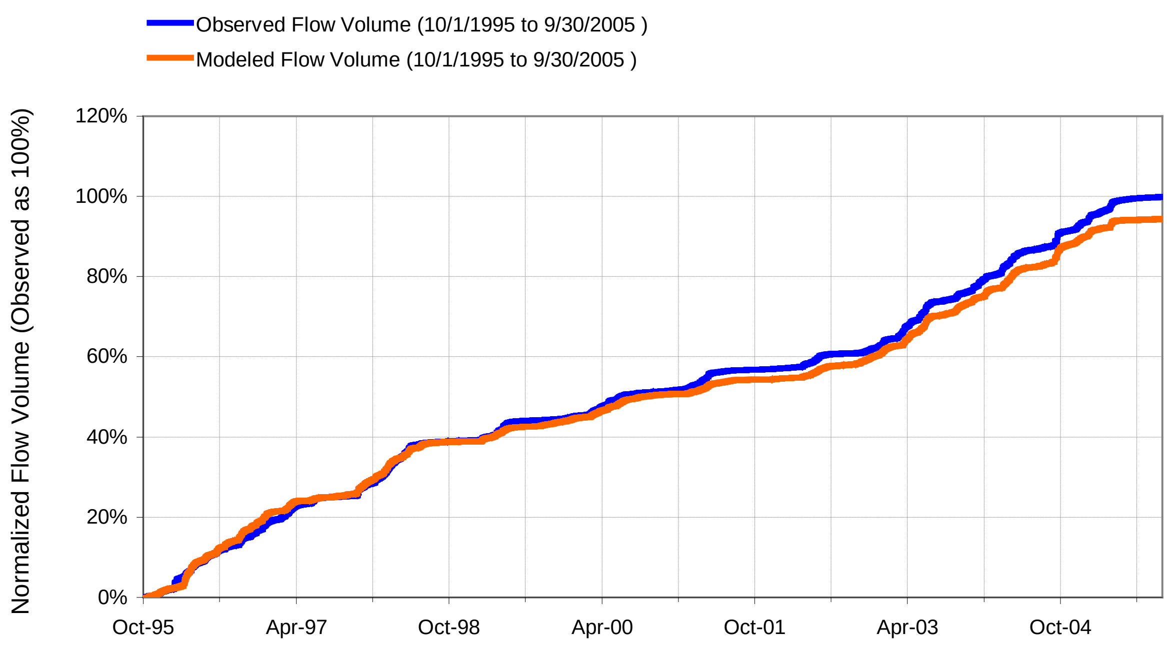


Figure 45. Flow accumulation at USGS 01562000 Raystown Branch Juniata River at Saxton, PA – calibration period (SWAT).

Table 23. Summary statistics at USGS 01562000 Raystown Branch Juniata River at Saxton, PA – calibration period (SWAT)

SWAT Simulated Flow		Observed Flow Gage	
REACH OUTFLOW FROM OUTLET 26 10-Year Analysis Period: 10/1/1995 - 9/30/2005 Flow volumes are (inches/year) for upstream drainage area		USGS 01562000 Raystown Branch Juniata River at Saxton, PA Hydrologic Unit Code: 2050303 Latitude: 40.21591249 Longitude: -78.2652901 Drainage Area (sq-mi): 756	
Total Simulated In-stream Flow:	**18.01**	Total Observed In-stream Flow:	**19.04**
Total of simulated highest 10% flows:	**7.87**	Total of Observed highest 10% flows:	**8.48**
Total of Simulated lowest 50% flows:	**1.94**	Total of Observed Lowest 50% flows:	**2.05**
Simulated Summer Flow Volume (months 7-9):	**2.96**	Observed Summer Flow Volume (7-9):	**2.26**
Simulated Fall Flow Volume (months 10-12):	**4.06**	Observed Fall Flow Volume (10-12):	**3.81**
Simulated Winter Flow Volume (months 1-3):	**5.83**	Observed Winter Flow Volume (1-3):	**7.03**
Simulated Spring Flow Volume (months 4-6):	**5.16**	Observed Spring Flow Volume (4-6):	**5.93**
Total Simulated Storm Volume:	**6.86**	Total Observed Storm Volume:	**7.83**
Simulated Summer Storm Volume (7-9):	**1.30**	Observed Summer Storm Volume (7-9):	**1.16**

Errors (Simulated-Observed)	*Error Statistics*		*Recommended Criteria*		
Error in total volume:	-5.41		10		
Error in 50% lowest flows:	-5.67		10		
Error in 10% highest flows:	-7.15		15		
Seasonal volume error - Summer:	**30.66**		**30**		
Seasonal volume error - Fall:	6.47	>>	30		Clear
Seasonal volume error - Winter:	-17.01		30		
Seasonal volume error - Spring:	-13.07		30		
Error in storm volumes:	-12.43		20		
Error in summer storm volumes:	11.80		50		
Nash-Sutcliffe Coefficient of Efficiency, E:	0.294		Model accuracy increases		
Baseline adjusted coefficient (Garrick), E':	0.395		as E or E' approaches 1.0		
Monthly NSE	0.669				

Hydrology Validation

Hydrology validation for the Susquehanna River watershed model was performed at the same gage location but for the period 10/1/1985 through 9/30/1995. Results are presented in Figure 49 through 52 and Tables 24 and 25. The validation achieves a reasonable coefficient of model fit efficiency, but many of statistics show that simulated values were underestimated compared to the observed values.

In general, the sign of the errors in the validation period are similar to those in the calibration period, but the discrepancies are larger. Additional factors that may have contributed to the difference in the flows between the calibration and validation period are:

- Drainage area of the observed USGS gage is about 6% higher than that of the calibration watershed.
- Increase in urban impervious surface areas between the 1980s and present.

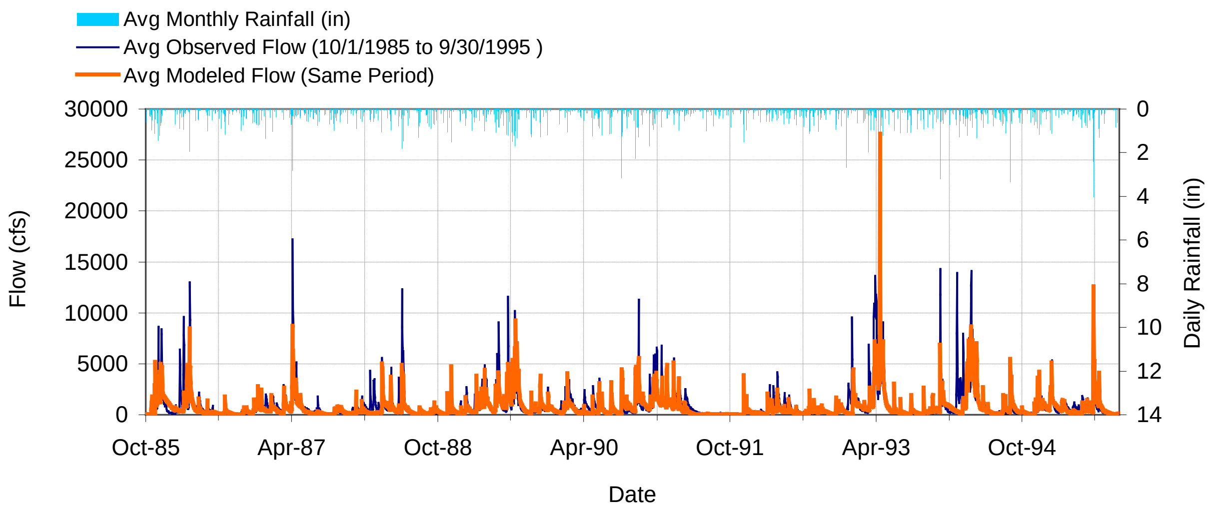


Figure 46. Mean daily flow at USGS 01562000 Raystown Branch Juniata River at Saxton, PA – validation period (SWAT).

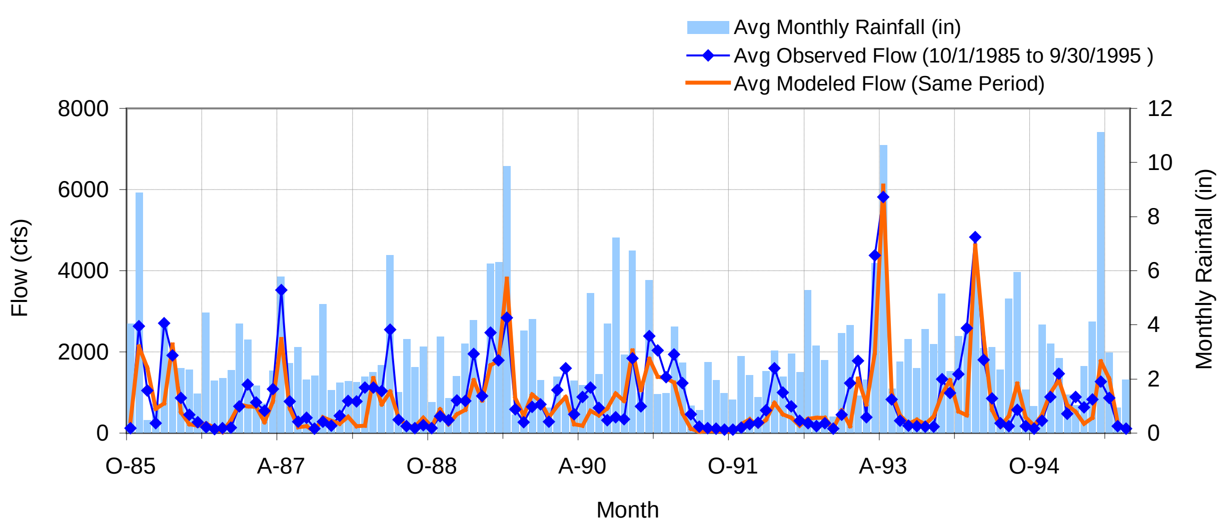


Figure 47. Mean monthly flow at USGS 01562000 Raystown Branch Juniata River at Saxton, PA – validation period (SWAT).

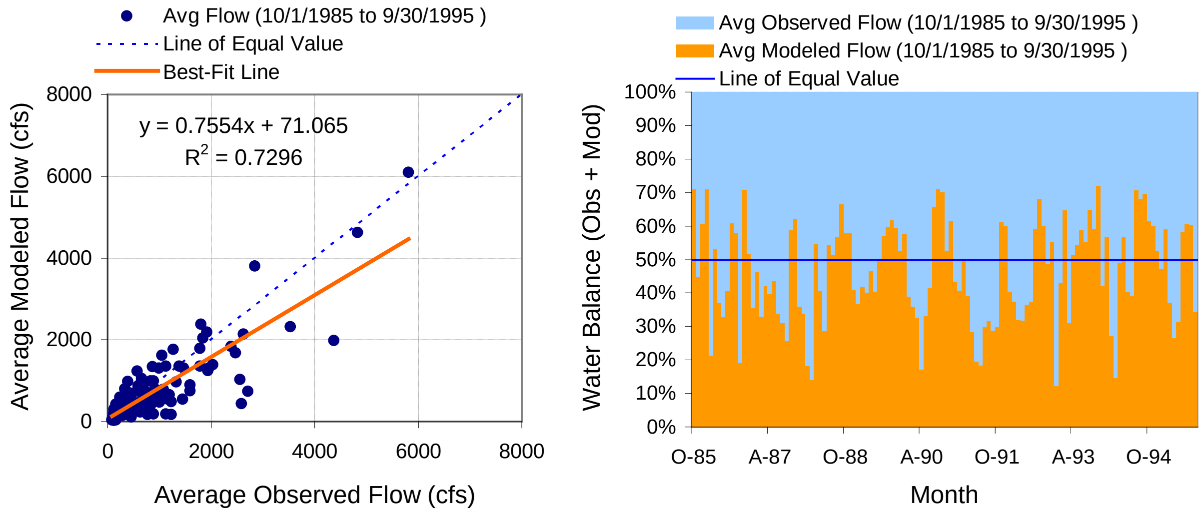


Figure 48. Monthly flow regression and temporal variation at USGS 01562000 Raystown Branch Juniata River at Saxton, PA – validation period (SWAT).

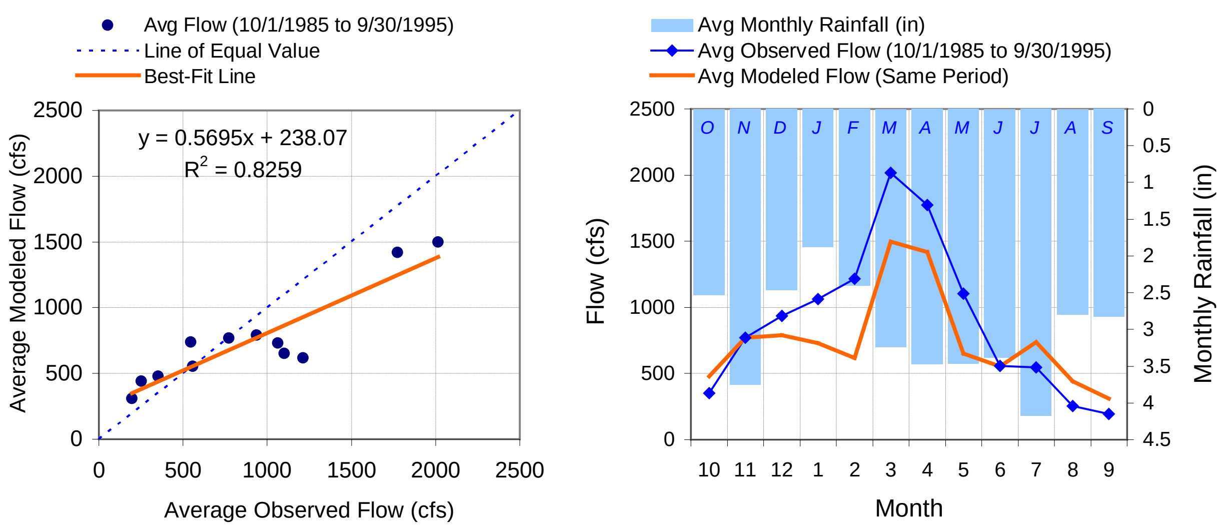


Figure 49. Seasonal regression and temporal aggregate at USGS 01562000 Raystown Branch Juniata River at Saxton, PA – validation period (SWAT).

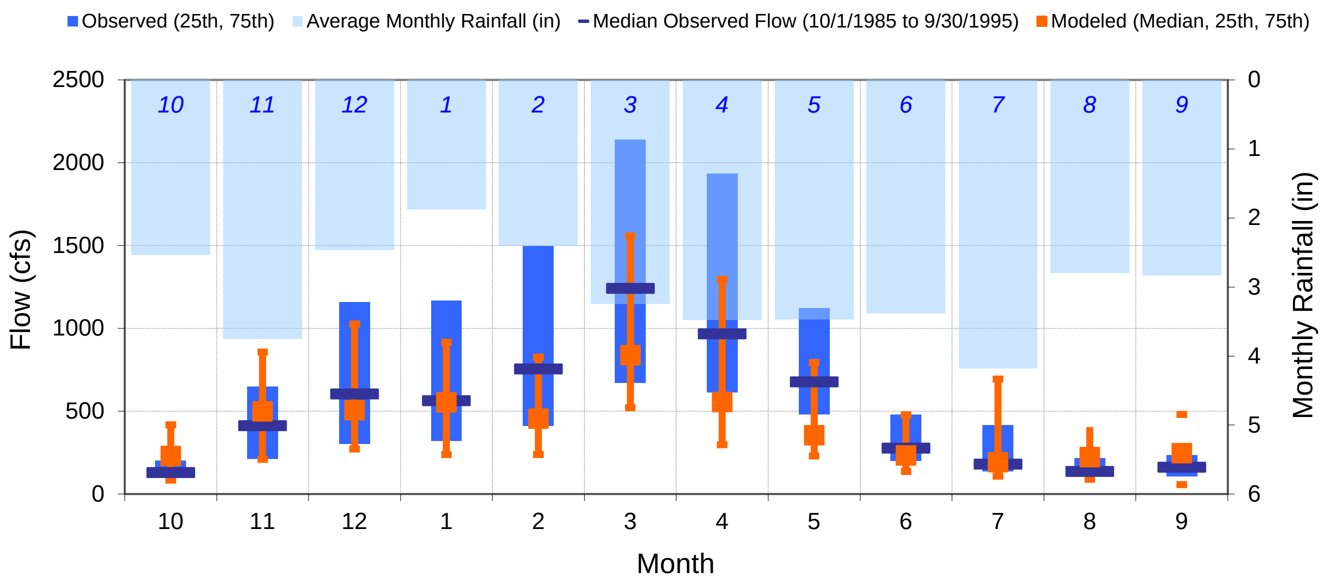


Figure 50. Seasonal medians and ranges at USGS 01562000 Raystown Branch Juniata River at Saxton, PA – validation period (SWAT).

Table 24. Seasonal summary at USGS 01562000 Raystown Branch Juniata River at Saxton, PA – validation period (SWAT)

MONTH	OBSERVED FLOW (CFS)				MODELED FLOW (CFS)			
	MEAN	MEDIAN	25TH	75TH	MEAN	MEDIAN	25TH	75TH
Oct	351.63	128.00	104.00	200.00	479.66	229.97	83.68	417.42
Nov	771.90	411.00	211.75	649.00	769.29	500.41	209.87	857.53
Dec	936.58	603.50	302.50	1157.50	790.68	506.59	271.91	1027.22
Jan	1063.43	562.00	322.50	1167.50	731.64	553.91	238.23	916.06
Feb	1214.57	754.00	410.00	1495.00	615.95	454.68	238.94	827.25
Mar	2016.51	1240.00	670.75	2140.00	1497.03	838.37	522.30	1559.50
Apr	1772.93	965.00	613.50	1935.00	1417.56	554.79	298.14	1296.67
May	1102.77	676.00	479.25	1122.50	652.39	355.80	230.15	793.79
Jun	559.15	275.50	201.00	479.50	552.94	232.64	136.75	476.75
Jul	545.15	180.00	138.00	418.00	739.08	192.13	108.06	694.82
Aug	252.88	136.00	108.00	216.75	441.53	223.70	89.30	404.09
Sep	195.59	160.00	107.75	233.50	310.53	246.34	56.63	481.69

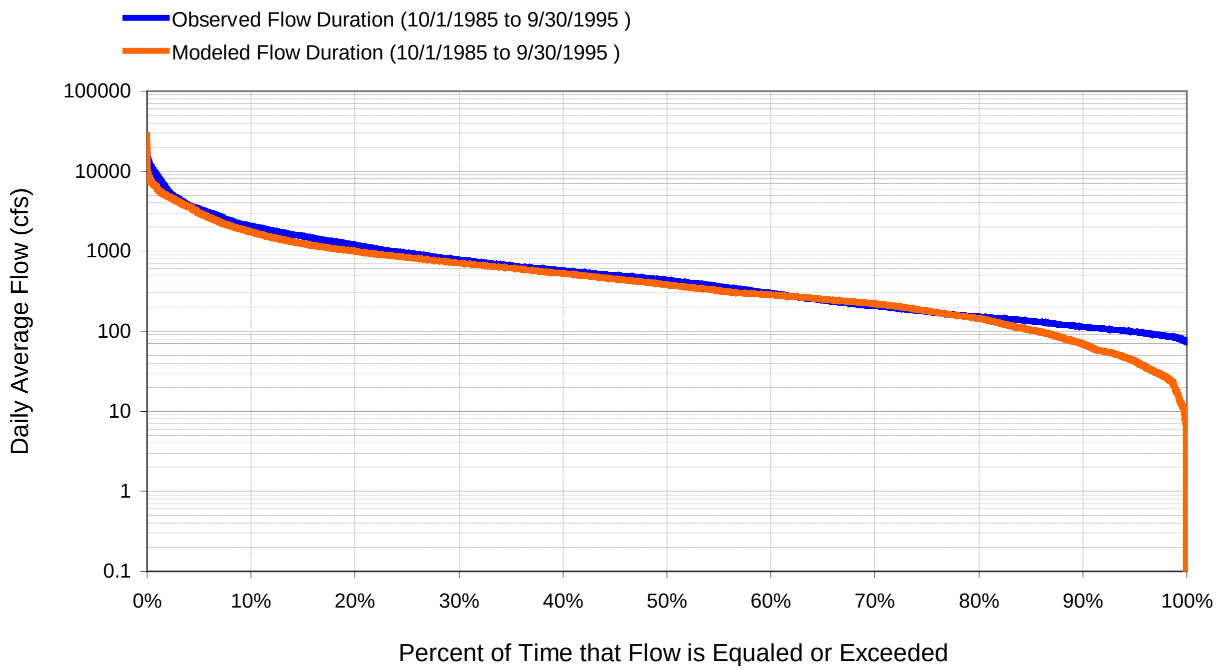


Figure 51. Flow exceedence at USGS 01562000 Raystown Branch Juniata River at Saxton, PA – validation period (SWAT).

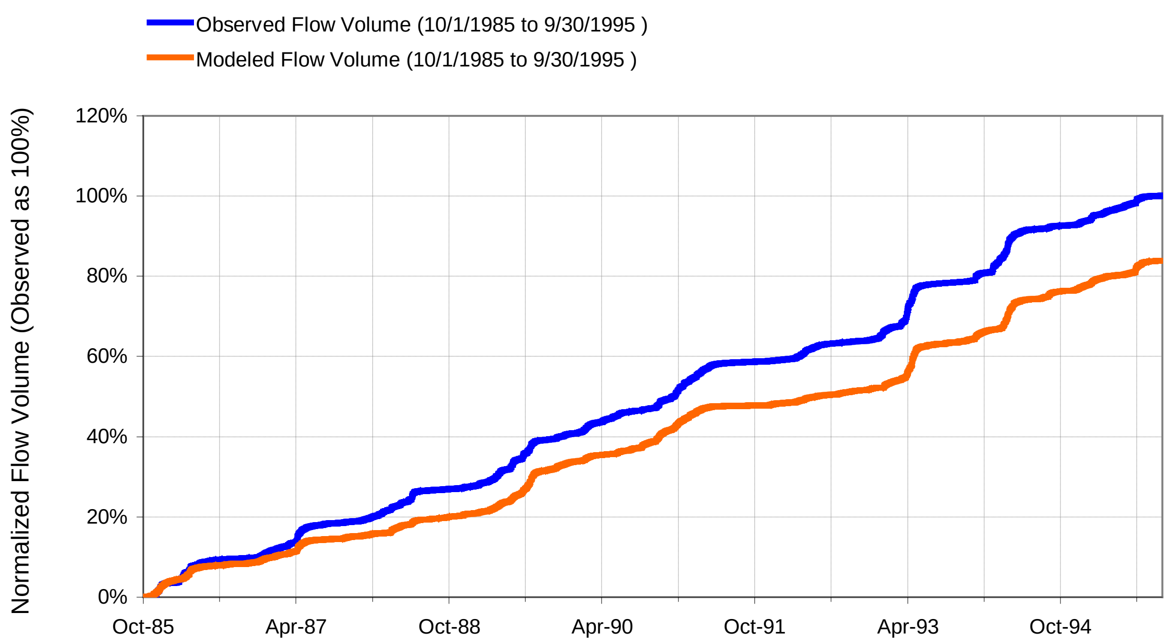


Figure 52. Flow accumulation at USGS 01562000 Raystown Branch Juniata River at Saxton, PA – validation period (SWAT).

Table 25. Summary statistics at USGS 01562000 Raystown Branch Juniata River at Saxton, PA – validation period (SWAT)

SWAT Simulated Flow		Observed Flow Gage	
REACH OUTFLOW FROM OUTLET 26		USGS 01562000 Raystown Branch Juniata River at Saxton, PA	
10-Year Analysis Period: 10/1/1985 - 9/30/1995 Flow volumes are (inches/year) for upstream drainage area		Hydrologic Unit Code: 2050303 Latitude: 40.21591249 Longitude: -78.2652901 Drainage Area (sq-mi): 756	
Total Simulated In-stream Flow:	**13.49**	Total Observed In-stream Flow:	**16.12**
Total of simulated highest 10% flows:	**6.35**	Total of Observed highest 10% flows:	**7.77**
Total of Simulated lowest 50% flows:	**1.59**	Total of Observed Lowest 50% flows:	**1.82**
Simulated Summer Flow Volume (months 7-9):	**2.26**	Observed Summer Flow Volume (7-9):	**1.51**
Simulated Fall Flow Volume (months 10-12):	**3.07**	Observed Fall Flow Volume (10-12):	**3.10**
Simulated Winter Flow Volume (months 1-3):	**4.25**	Observed Winter Flow Volume (1-3):	**6.38**
Simulated Spring Flow Volume (months 4-6):	**3.90**	Observed Spring Flow Volume (4-6):	**5.12**
Total Simulated Storm Volume:	**4.60**	Total Observed Storm Volume:	**6.49**
Simulated Summer Storm Volume (7-9):	**0.77**	Observed Summer Storm Volume (7-9):	**0.54**

Errors (Simulated-Observed)	*Error Statistics*	*Recommended Criteria*
Error in total volume:	**-16.30**	**10**
Error in 50% lowest flows:	**-12.87**	**10**
Error in 10% highest flows:	**-18.30**	**15**
Seasonal volume error - Summer:	**50.02**	**30**
Seasonal volume error - Fall:	-1.00	30
Seasonal volume error - Winter:	**-33.35**	**30**
Seasonal volume error - Spring:	-23.82	30
Error in storm volumes:	**-29.17**	**20**
Error in summer storm volumes:	42.83	50
Nash-Sutcliffe Coefficient of Efficiency, E:	0.415	Model accuracy increases
Baseline adjusted coefficient (Garrick), E':	0.383	as E or E' approaches 1.0
Monthly NSE	0.664	

>> Clear

Hydrology Results for Larger Watershed

The parameters determined for the Raystown Branch of the Juniata River gage were transferred to the remainder of the watershed without detailed spatial calibration. Tests of calibration and validation were pursued at a total of three gages throughout the watershed, all of them at the outlet of 8-digit HUCs. Calibration results were generally acceptable at all gages, as summarized in Table 26. The match between observed and predicted flow corresponding to the largest watershed of the three gages (USGS 01576000, Susquehanna River at Marietta) is shown in Figures 53 through 59 and Tables 27 and 28. Validation results were also generally in the acceptable range for all the gages, as summarized in Table 29. It appears, however, that there are some systematic biases in the model, including under-prediction of the 10 percent highest flows and winter flows, coupled with over-prediction of summer flows

Table 26. Summary statistics (percent error) for all stations – calibration period (SWAT)

Station	01576000 Susquehanna River at Marietta, PA (1993-2003)	01540500 Susquehanna River at Danville, PA (1993-2003)	01562000 Raystown Branch Juniata River at Saxton, PA (1995-2005)
Error in total volume:	-9.74	-4.51	-5.41
Error in 50% lowest flows:	2.03	5.90	-5.67
Error in 10% highest flows:	-19.80	-11.24	-7.15
Seasonal volume error - Summer:	15.58	11.96	30.66
Seasonal volume error - Fall:	-2.46	-4.24	6.47
Seasonal volume error - Winter:	-31.54	-38.92	-17.01
Seasonal volume error - Spring:	1.99	26.18	-13.07
Error in storm volumes:	-22.08	-29.54	-12.43
Error in summer storm volumes:	9.52	-12.84	11.80
Daily Nash-Sutcliffe Coefficient of Efficiency, E:	0.451	0.327	0.294
Monthly Nash-Sutcliffe Coefficient of Efficiency,	0.669	0.573	0.669

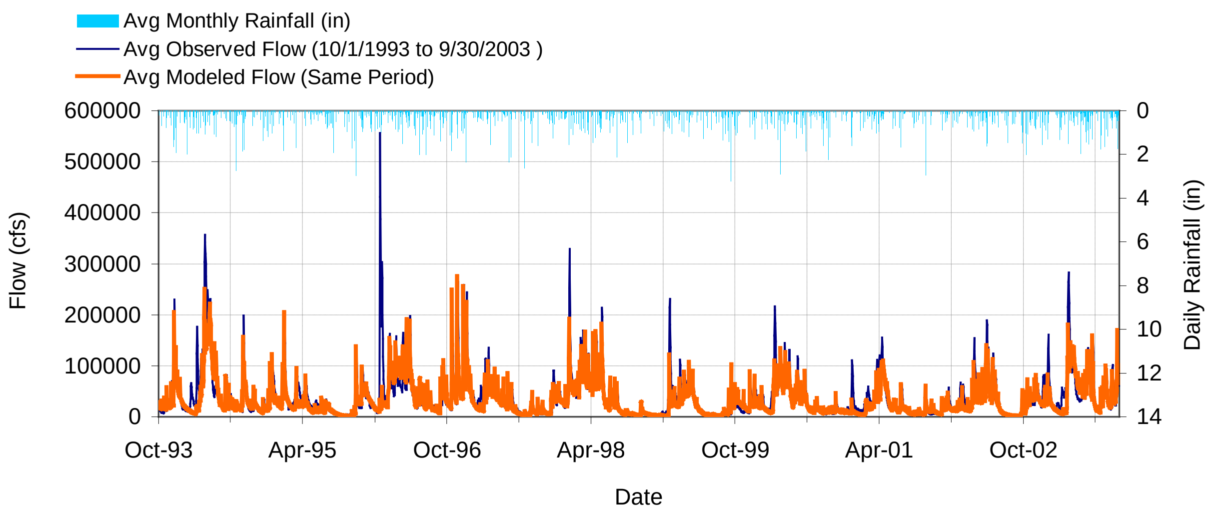


Figure 53. Mean daily flow at USGS 01576000 Susquehanna River At Marietta, PA – calibration period (SWAT).

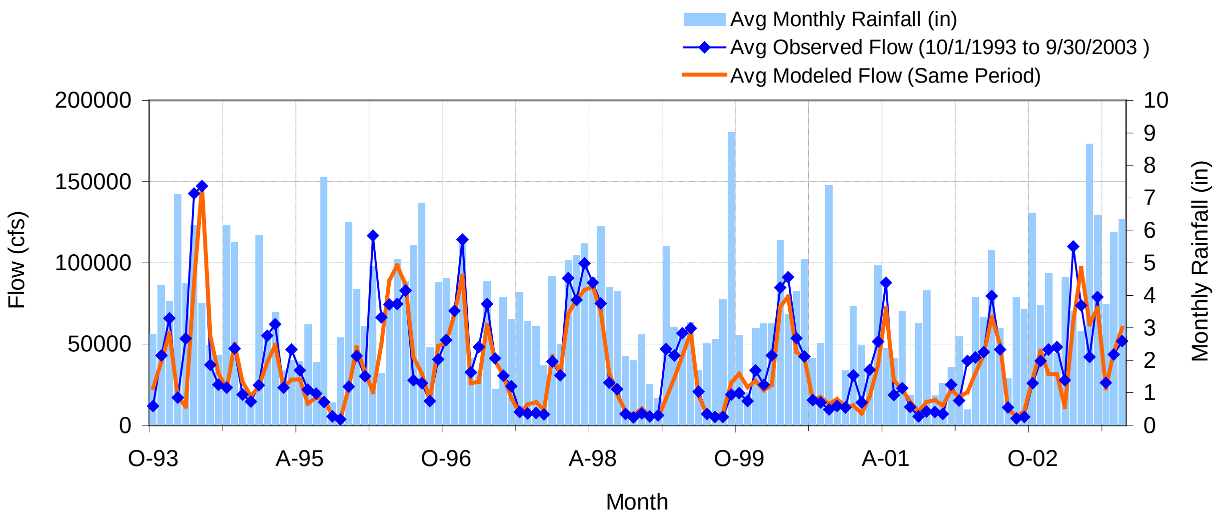
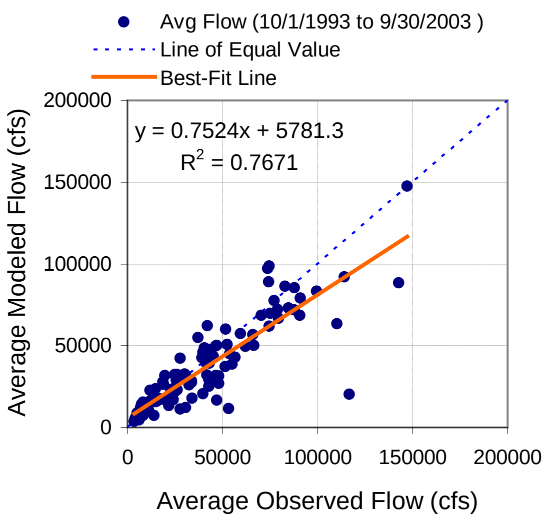


Figure 54. Mean monthly flow at USGS 01576000 Susquehanna River at Marietta, PA – calibration period (SWAT).



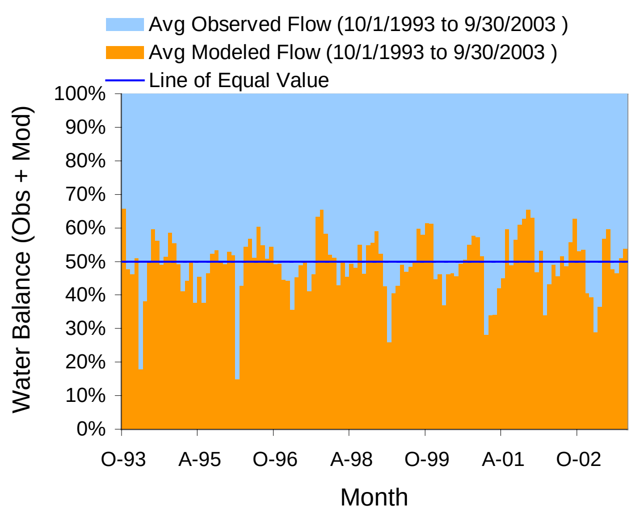


Figure 55. Monthly flow regression and temporal variation at USGS 01576000 Susquehanna River at Marietta, PA – calibration period (SWAT).

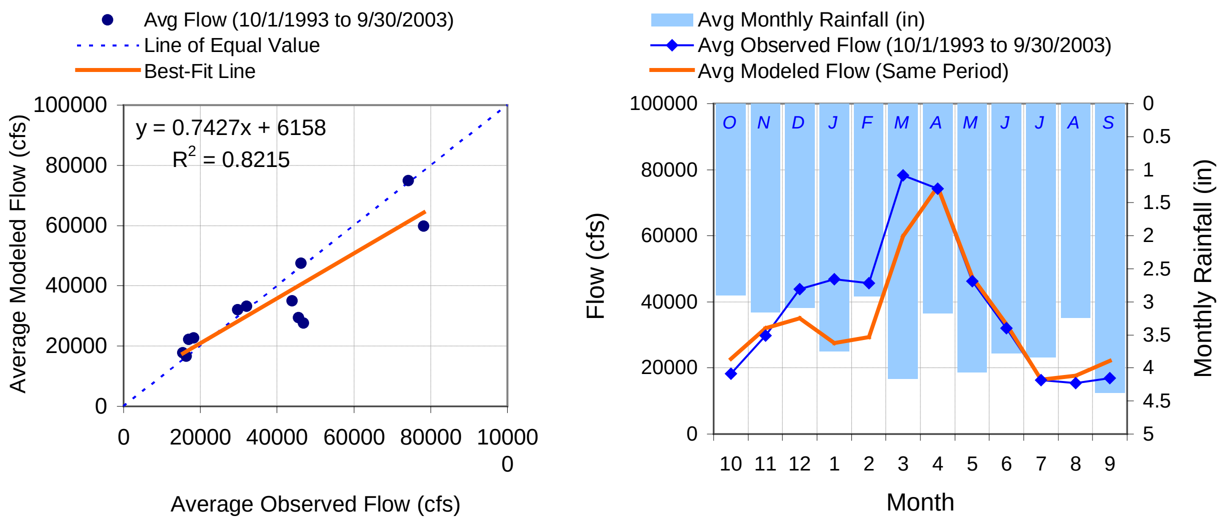


Figure 56. Seasonal regression and temporal aggregate at USGS 01576000 Susquehanna River at Marietta, PA – calibration period (SWAT).

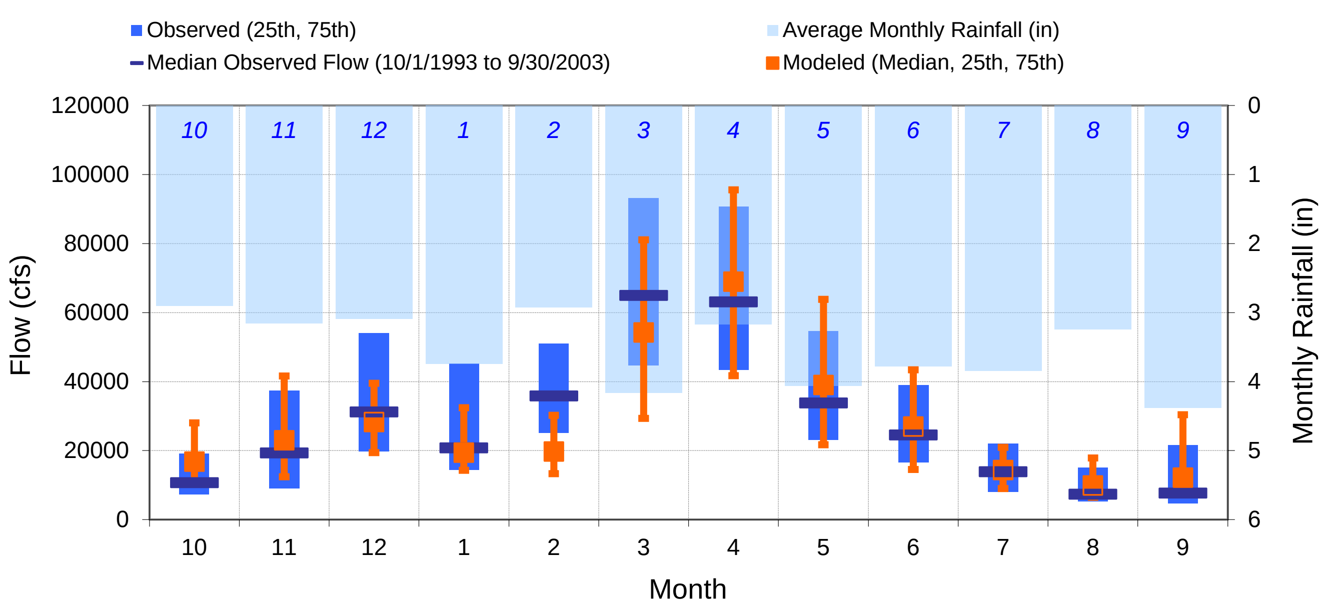


Figure 57. Seasonal medians and ranges at USGS 01576000 Susquehanna River at Marietta, PA – calibration period (SWAT).

Table 27. Seasonal summary at USGS 01576000 Susquehanna River at Marietta, PA – calibration period (SWAT)

MONTH	OBSERVED FLOW (CFS)				MODELED FLOW (CFS)			
	MEAN	MEDIAN	25TH	75TH	MEAN	MEDIAN	25TH	75TH
Oct	18258.39	10650.00	7305.00	19225.00	22700.72	16857.46	11114.41	28029.25
Nov	29811.13	19300.00	9002.50	37325.00	32093.73	22972.19	12402.51	41600.68
Dec	43879.65	31150.00	19700.00	54050.00	34985.85	28272.92	19425.72	39499.45
Jan	46873.61	20700.00	14425.00	45175.00	27590.78	19412.47	14285.67	32425.04
Feb	45647.16	35800.00	25050.00	50975.00	29342.81	19732.07	13347.18	30222.29
Mar	78282.90	64900.00	44725.00	93150.00	59826.28	54243.33	29365.91	81082.47
Apr	74228.00	63000.00	43400.00	90750.00	74819.70	68934.23	41733.11	95561.49
May	46236.13	33750.00	23100.00	54575.00	47504.67	39005.05	21727.35	63884.23
Jun	32080.10	24450.00	16575.00	38925.00	33247.00	26980.41	14564.65	43437.04
Jul	16327.52	13800.00	8122.50	22075.00	16522.99	14343.05	8986.70	20941.60
Aug	15446.55	7330.00	5292.50	15175.00	17697.63	9907.53	6522.62	17877.17
Sep	16977.37	7645.00	4757.50	21650.00	22211.19	12176.50	7015.26	30420.94

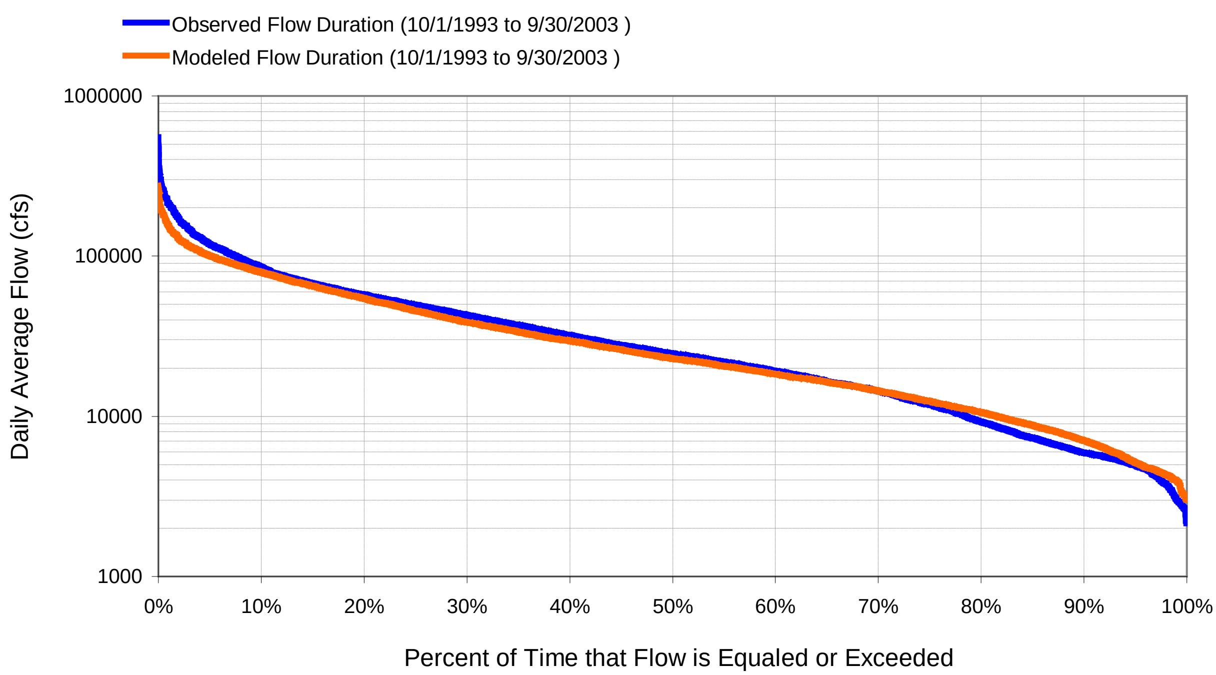


Figure 58. Flow exceedence at USGS 01576000 Susquehanna River at Marietta, PA – calibration period (SWAT).

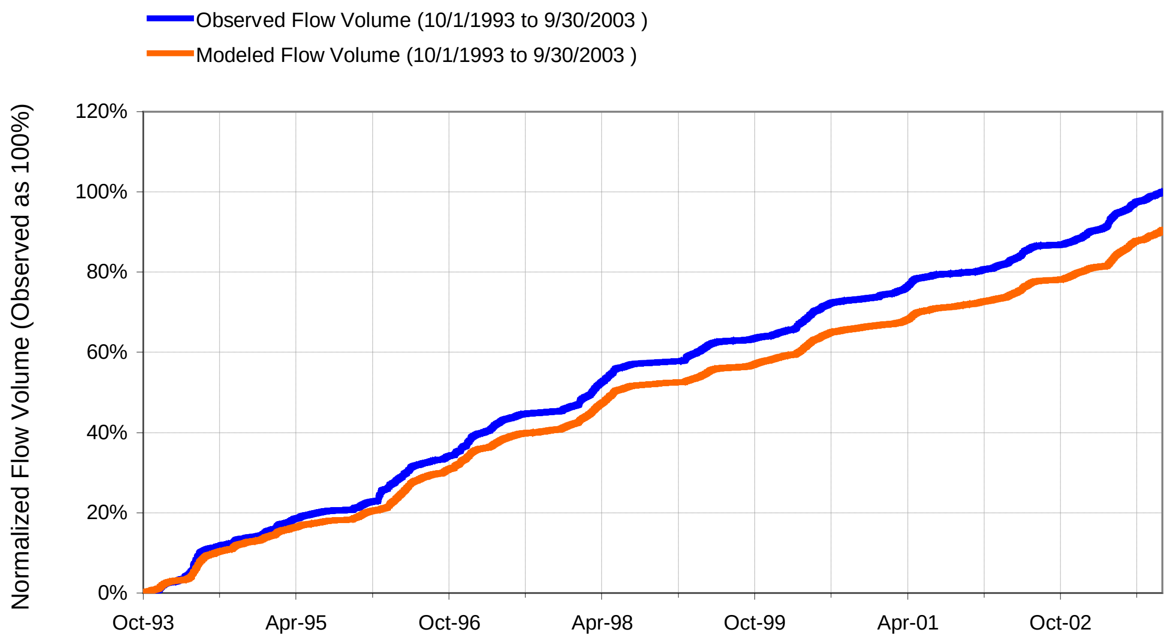


Figure 59. Flow accumulation at USGS 01576000 Susquehanna River at Marietta, PA – calibration period (SWAT).

Table 28. Summary statistics at USGS 01576000 Susquehanna River at Marietta, PA – calibration period (SWAT)

SWAT Simulated Flow		Observed Flow Gage	
REACH OUTFLOW FROM OUTLET 75		USGS 01576000 Susquehanna River at Marietta, PA	
10-Year Analysis Period: 10/1/1993 - 9/30/2003 Flow volumes are (inches/year) for upstream drainage area		Hydrologic Unit Code: 2050306 Latitude: 40.0545413 Longitude: -76.5307992 Drainage Area (sq-mi): 25990	
Total Simulated In-stream Flow:	**18.22**	Total Observed In-stream Flow:	**20.19**
Total of simulated highest 10% flows:	**5.86**	Total of Observed highest 10% flows:	**7.31**
Total of Simulated lowest 50% flows:	**3.34**	Total of Observed Lowest 50% flows:	**3.27**
Simulated Summer Flow Volume (months 7-9):	**2.47**	Observed Summer Flow Volume (7-9):	**2.14**
Simulated Fall Flow Volume (months 10-12):	**3.94**	Observed Fall Flow Volume (10-12):	**4.04**
Simulated Winter Flow Volume (months 1-3):	**5.06**	Observed Winter Flow Volume (1-3):	**7.39**
Simulated Spring Flow Volume (months 4-6):	**6.75**	Observed Spring Flow Volume (4-6):	**6.62**
Total Simulated Storm Volume:	**5.70**	Total Observed Storm Volume:	**7.32**
Simulated Summer Storm Volume (7-9):	**0.84**	Observed Summer Storm Volume (7-9):	**0.76**

Errors (Simulated-Observed)	*Error Statistics*	*Recommended Criteria*
Error in total volume:	-9.74	10
Error in 50% lowest flows:	2.03	10
Error in 10% highest flows:	**-19.80**	**15**
Seasonal volume error - Summer:	15.58	30
Seasonal volume error - Fall:	-2.46	30
Seasonal volume error - Winter:	**-31.54**	**30**
Seasonal volume error - Spring:	1.99	30
Error in storm volumes:	**-22.08**	**20**
Error in summer storm volumes:	9.52	50
Nash-Sutcliffe Coefficient of Efficiency, E:	0.451	Model accuracy increases
Baseline adjusted coefficient (Garrick), E':	0.443	as E or E' approaches 1.0
Monthly NSE	0.641	

>> Clear

Table 29. Summary statistics (percent error) for all stations – validation period (SWAT)

Station	01576000 Susquehanna River at Marietta, PA (1983-1993)	01540500 Susquehanna River at Danville, PA (1983-1993)	01562000 Raystown Branch Juniata River at Saxton, PA (1985-1995)
Error in total volume:	-15.17	-10.17	-16.30
Error in 50% lowest flows:	1.37	1.84	-12.87
Error in 10% highest flows:	-24.62	-17.11	-18.30
Seasonal volume error - Summer:	22.63	17.20	50.02
Seasonal volume error - Fall:	-8.86	-11.29	-1.00
Seasonal volume error - Winter:	-34.95	-40.55	-33.35
Seasonal volume error - Spring:	-12.26	9.55	-23.82
Error in storm volumes:	-28.54	-36.20	-29.17
Error in summer storm volumes:	29.42	-15.18	42.83
Nash-Sutcliffe Coefficient of Efficiency, E:	0.485	0.372	0.415
Baseline adjusted coefficient (Garrick), E':	0.657	0.573	0.664

Water Quality Calibration and Validation

Initial calibration and validation of water quality was done on data from the Raystown Branch Juniata River at Saxton (USGS 01562000), using 1991-2000 for calibration and 1990 for validation. As with hydrology, calibration was performed on the later period as this better reflects the land use included in the model. The start of the validation period is constrained by data availability.

Calibration adjustments for sediment focused on the following parameters:

- SPCON (Linear parameters for estimating maximum amount of sediment that can be re-entrained during channel sediment routing)
- SPEXP (Exponent parameter for calculating sediment re-entrained in channel sediment routing)
- CH_COV (Channel cover factor)
- CH_EROD (Channel erodibility factor)

Various plots that compare TSS simulated by SWAT against the observed data are shown in Figures 60 through 63. The comparison statistics are provided in Tables 30 and 31. The fit to monthly sediment loads is generally better than that obtained with the HSPF model. However, the correlation between observed and predicted concentrations is weak – in part because many of the observed data are reported as less than a detection limit of 2 mg/L (plotted at 1 mg/L in Figure 63).

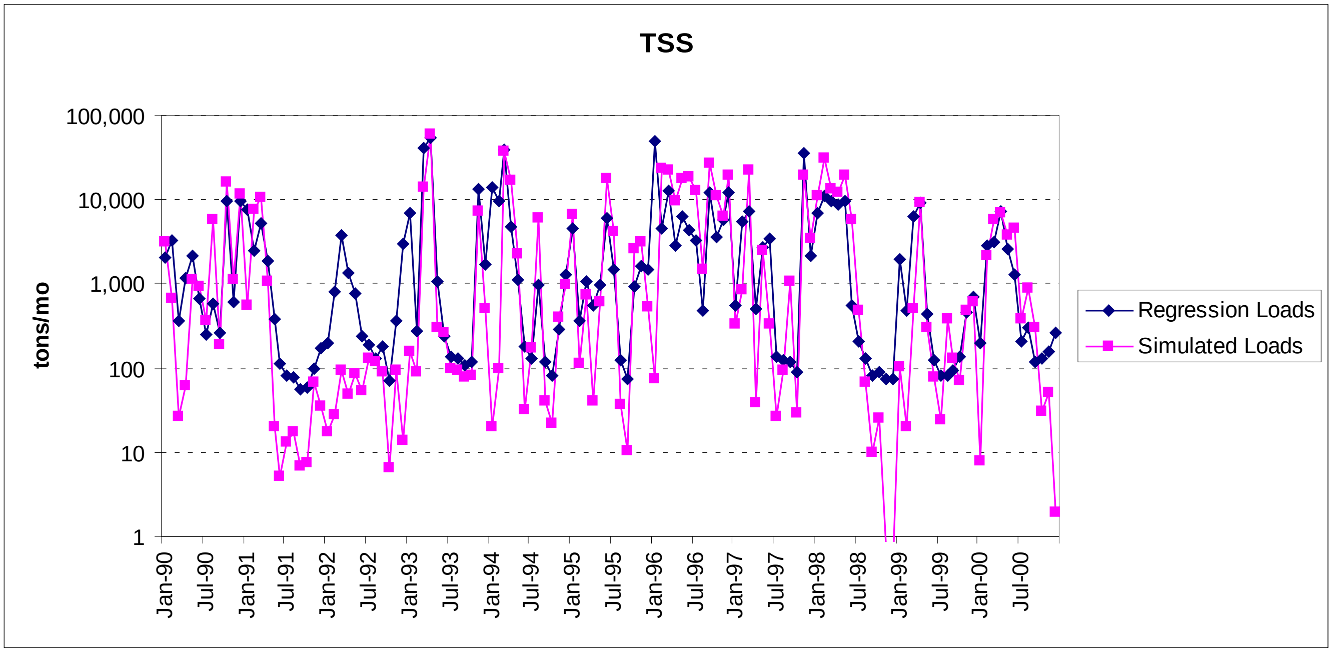


Figure 60. Fit for monthly load of TSS at USGS 01562000 Raystown Branch Juniata River at Saxton, PA (SWAT).

Table 30. Model fit statistics (observed minus predicted) for monthly sediment loads using stratified regression – USGS 01562000 Raystown Branch Juniata River at Saxton, PA (SWAT)

Statistic	Calibration period (1991-2000)	Validation period (1990)
Relative Percent Error	-10.1%	-33.6%
Relative Average Absolute Error	80%	67%
Relative Median Absolute Error	11.1%	41.1%

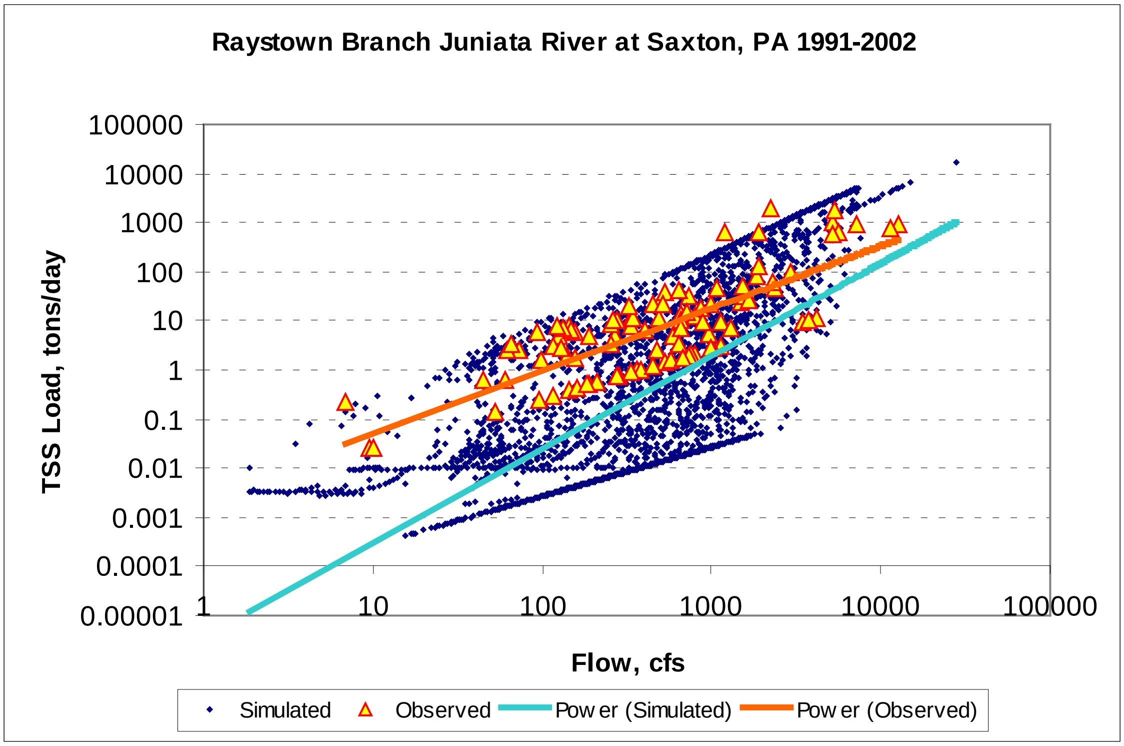


Figure 61. Power plot for observed and simulated TSS at USGS 01562000 Raystown Branch Juniata River at Saxton, PA – calibration period (SWAT).

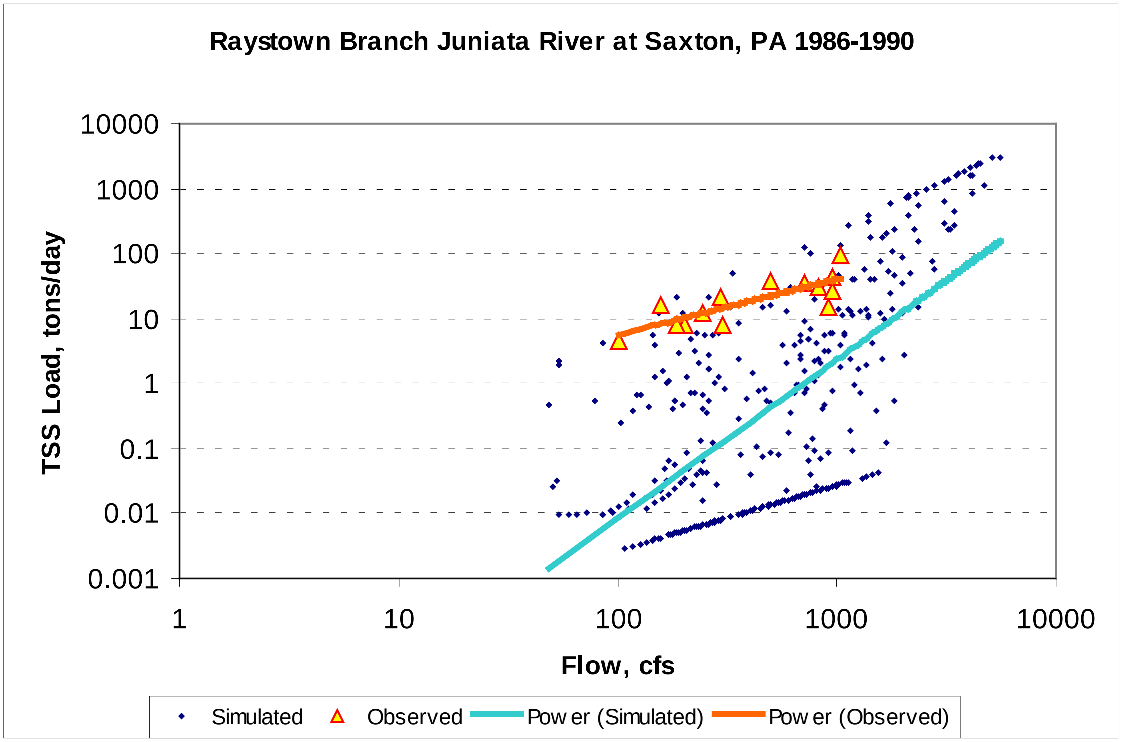


Figure 62. Power plot for observed and simulated TSS at USGS 01562000 Raystown Branch Juniata River at Saxton, PA – validation period (SWAT).

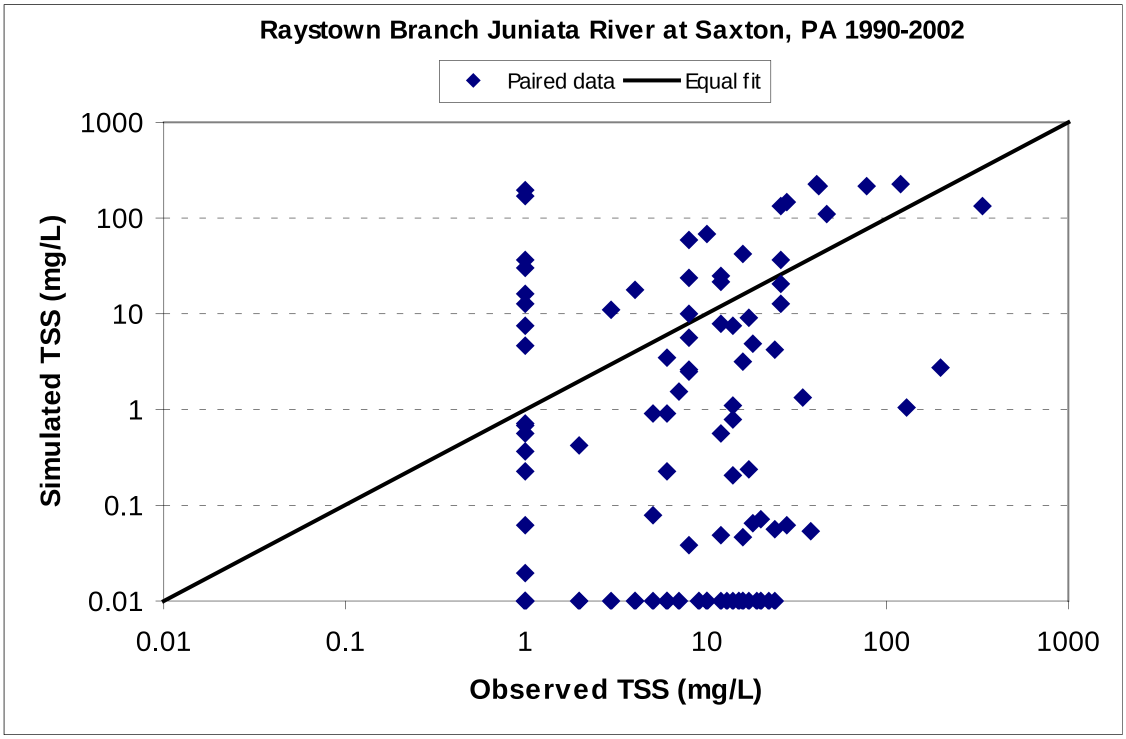


Figure 63. Correlation between observed and predicted TSS concentration at USGS 01562000 Raystown Branch Juniata River at Saxton, PA (SWAT).

Table 31. Relative errors (observed minus simulated) for TSS concentrations at USGS 01562000 Raystown Branch Juniata River at Saxton, PA (SWAT)

Statistic	Calibration period (1991-2000)	Validation period (1990)
Count	106	14
Concentration Average Error	-26.49%	73.88%
Concentration Median Error	12.04%	73.84%

Calibration adjustments for the simulation of total phosphorus and total nitrogen focused on the following parameters:

- PHOSKD (phosphorus soil partitioning coefficient)
- NPERCO (nitrogen percolation coefficient)
- PPERCO (phosphorus percolation coefficient)
- SOL_NO3 (initial nitrate concentration in soil layers)
- SOL_ORGN (initial organic nitrogen concentration in soil layers)
- SOL_SOLP (initial soluble phosphorus concentration in soil layers)
- SOL_ORGP (initial organic phosphorus concentration in soil layers)

Various plots that compare total phosphorous simulated by SWAT against the observed data are shown in Figures 64 through 67. The comparison statistics are provided in Tables 32 and 33. Similarly, the results corresponding to total nitrogen are shown in Figures 68 though 71 and Tables 34 and 35. The model representation of total load is generally acceptable, although better for phosphorus than for nitrogen. As with the HSPF application, phosphorus loads and concentrations tend to be overestimated at lower flows, likely as a result of the simplified representation of point sources.

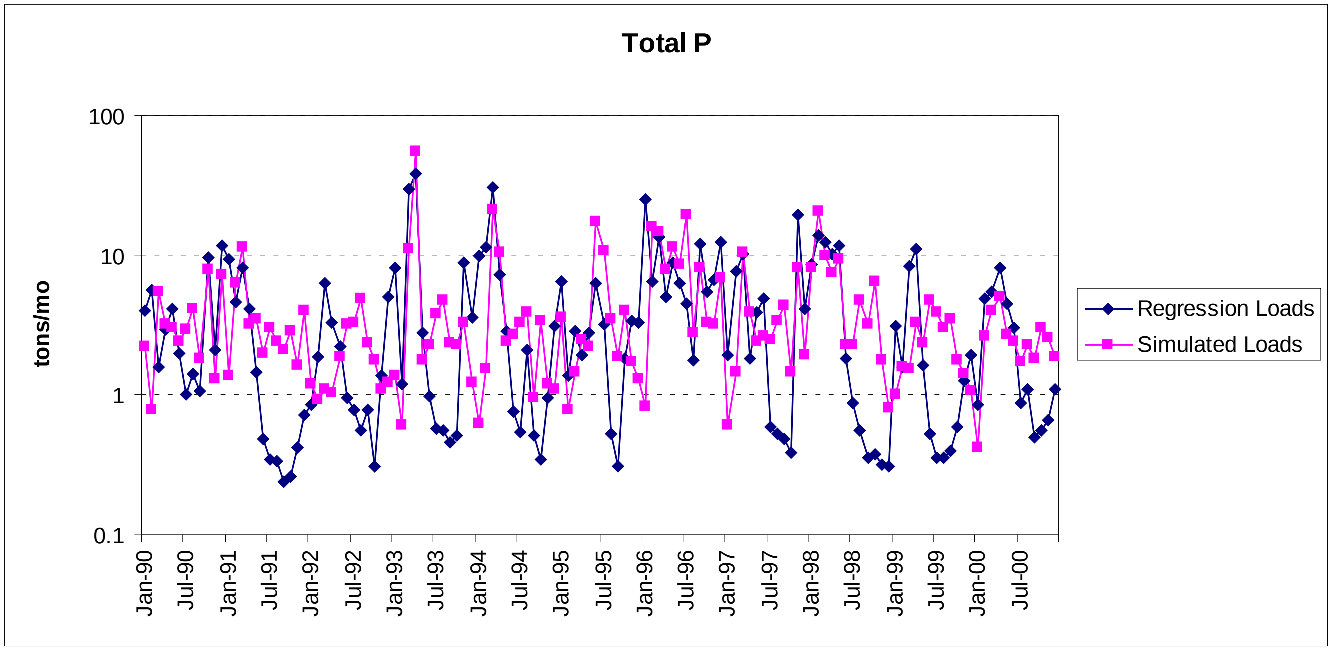


Figure 64. Fit for monthly load of total phosphorous at USGS 01562000 Raystown Branch Juniata River at Saxton, PA (SWAT).

Table 32. Model fit statistics (observed minus predicted) for monthly phosphorus loads using stratified regression – USGS 01562000 Raystown Branch Juniata River at Saxton, PA (SWAT)

Statistic	Calibration period (1991-2000)	Validation period (1990)
Relative Percent Error	-0.5%	9.2%
Average Absolute Error	73%	54%
Median Absolute Error	48.6%	44.6%

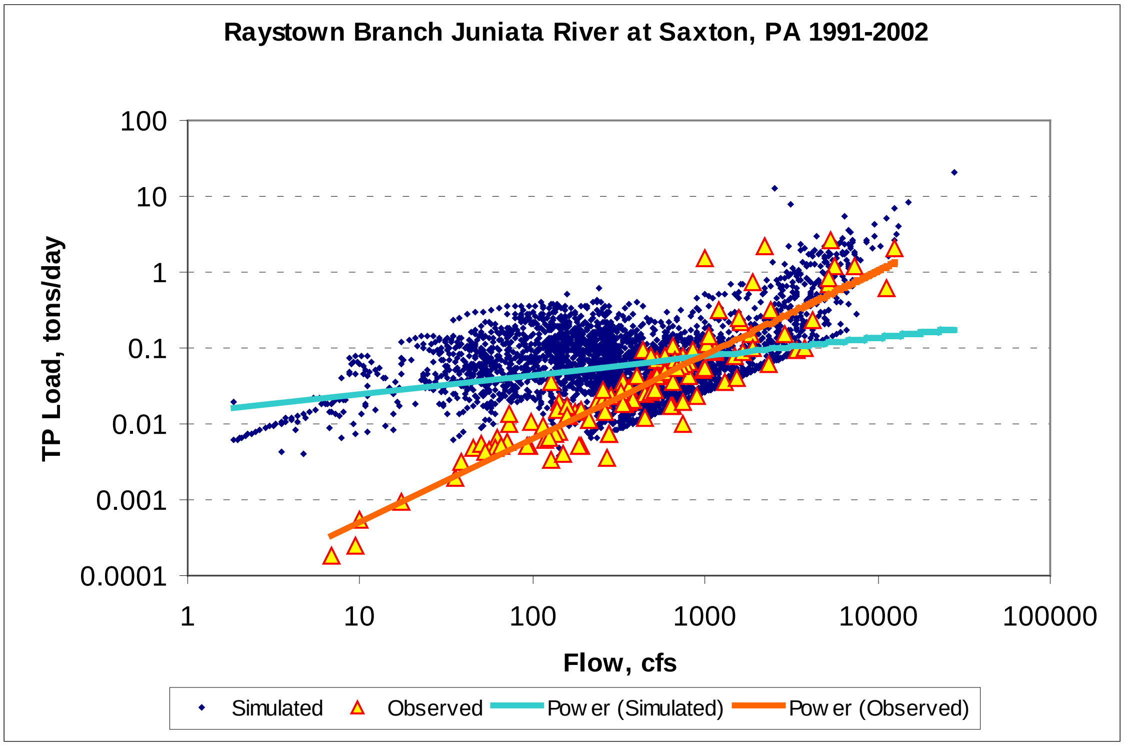


Figure 65. Power plot for observed and simulated total phosphorus at USGS 01562000 Raystown Branch Juniata River at Saxton, PA – calibration period (SWAT)

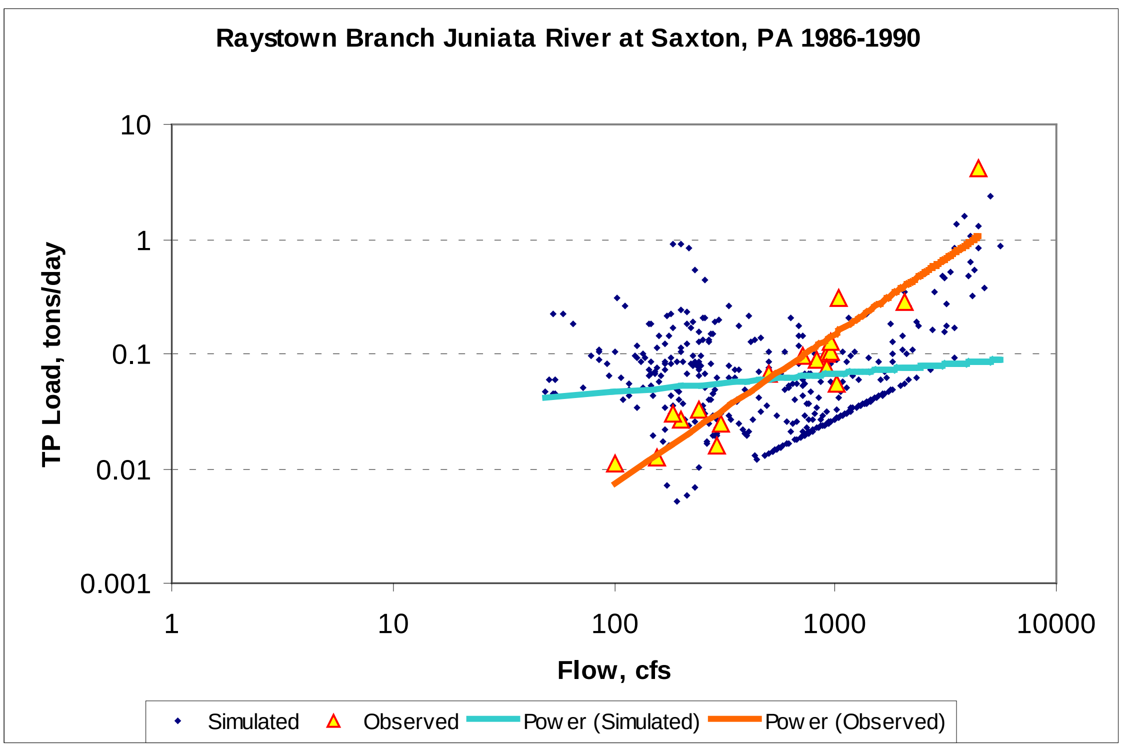


Figure 66. Power plot for observed and simulated total phosphorus at USGS 01562000 Raystown Branch Juniata River at Saxton, PA – validation period (SWAT)

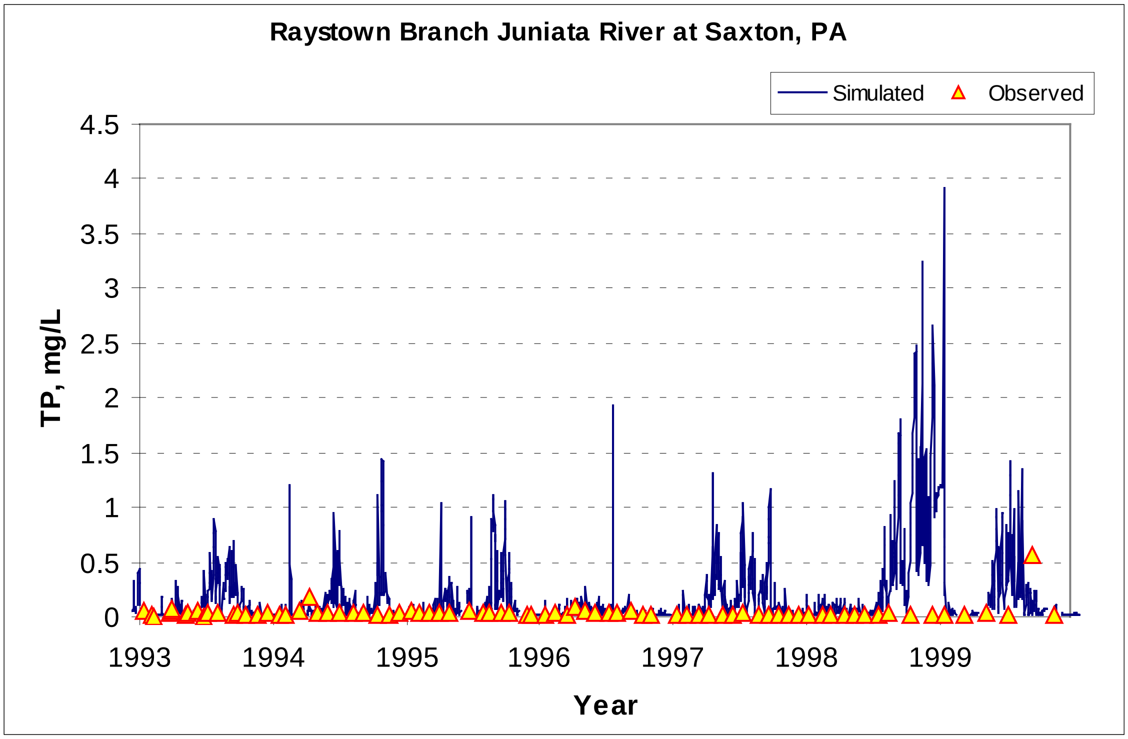


Figure 67. Time series plot of total phosphorus concentration at USGS 01562000 Raystown Branch Juniata River at Saxton, PA (SWAT).

Table 33. Relative errors (observed minus predicted), total phosphorus concentration, USGS 01562000 Raystown Branch Juniata River at Saxton, PA (SWAT)

Statistic	Calibration period (1991-2000)	Validation period (1990)
Count	122	18
Concentration Average Error	-377.89%	-58.65%
Concentration Median Error	-71.74%	-9.69%

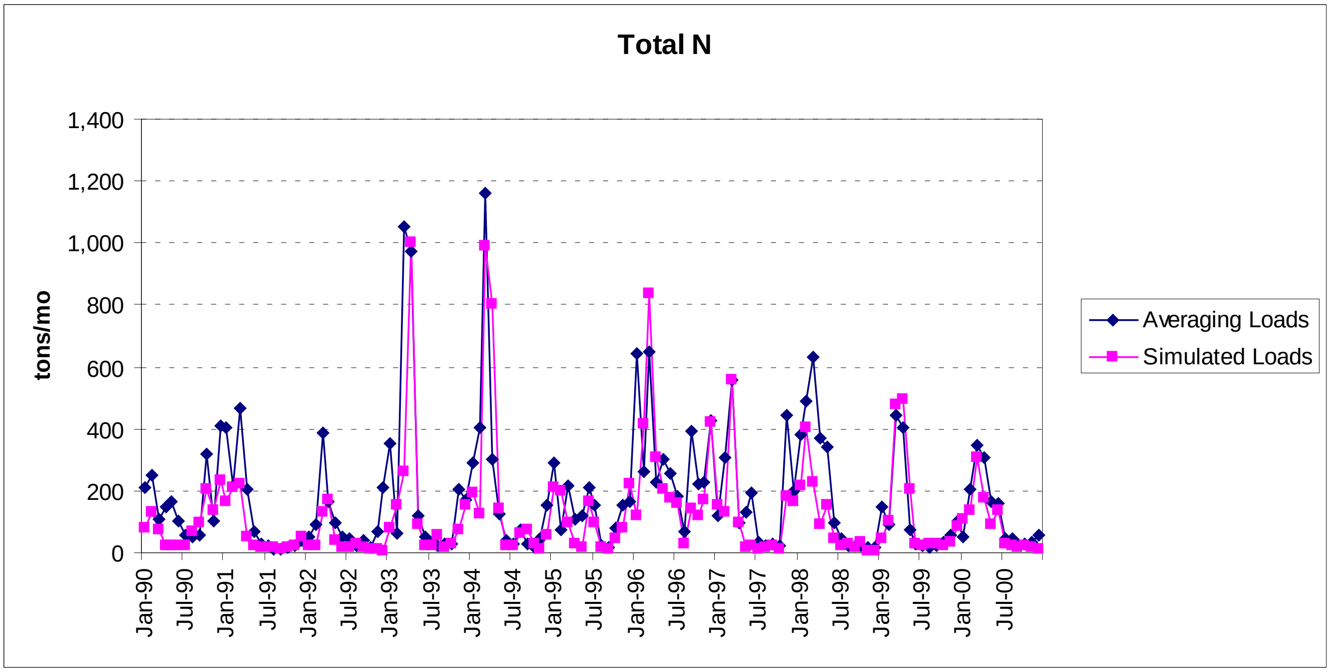


Figure 68. Fit for monthly load of total nitrogen at USGS 01562000 Raystown Branch Juniata River at Saxton, PA (SWAT)

Table 34. Model fit statistics (observed minus predicted) for monthly total nitrogen loads using averaging estimator – USGS 01562000 Raystown Branch Juniata River at Saxton, PA (SWAT)

Statistic	Calibration period (1991-2000)	Validation period (1990)
Relative Percent Error	28.6%	43.9%
Average Absolute Error	45%	53%
Median Absolute Error	19.7%	58.3%

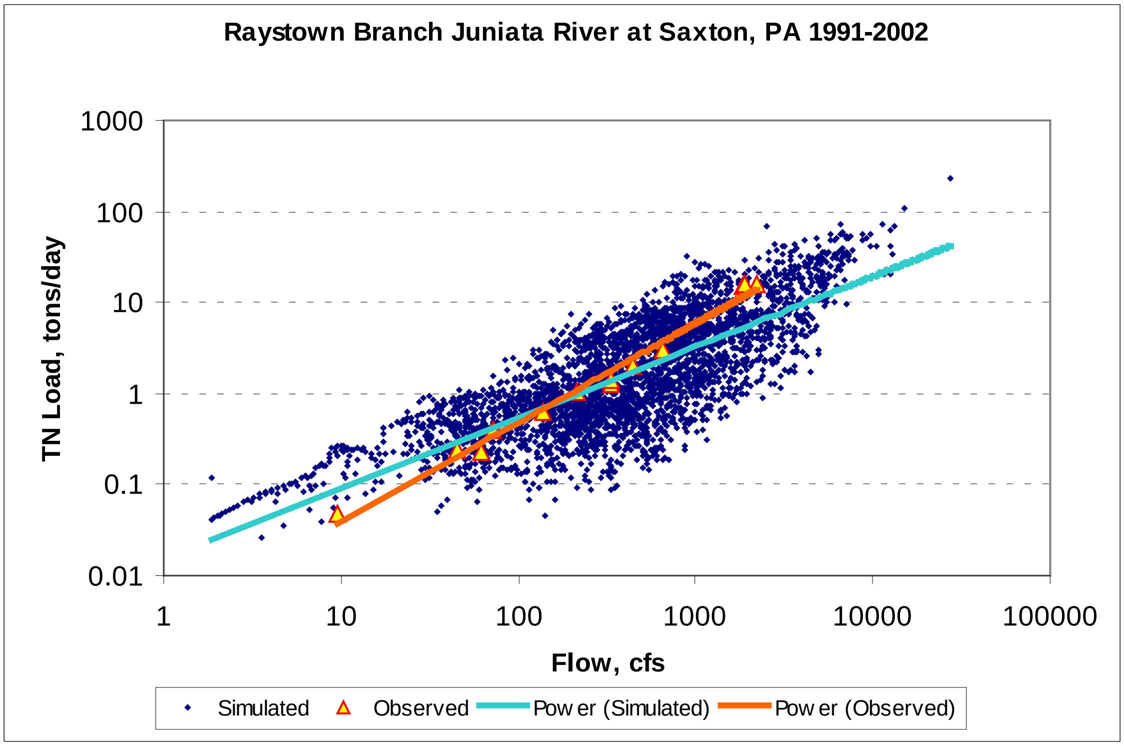


Figure 69. Power plot for observed and simulated total nitrogen at USGS 01562000 Raystown Branch Juniata River at Saxton, PA – calibration period (SWAT).

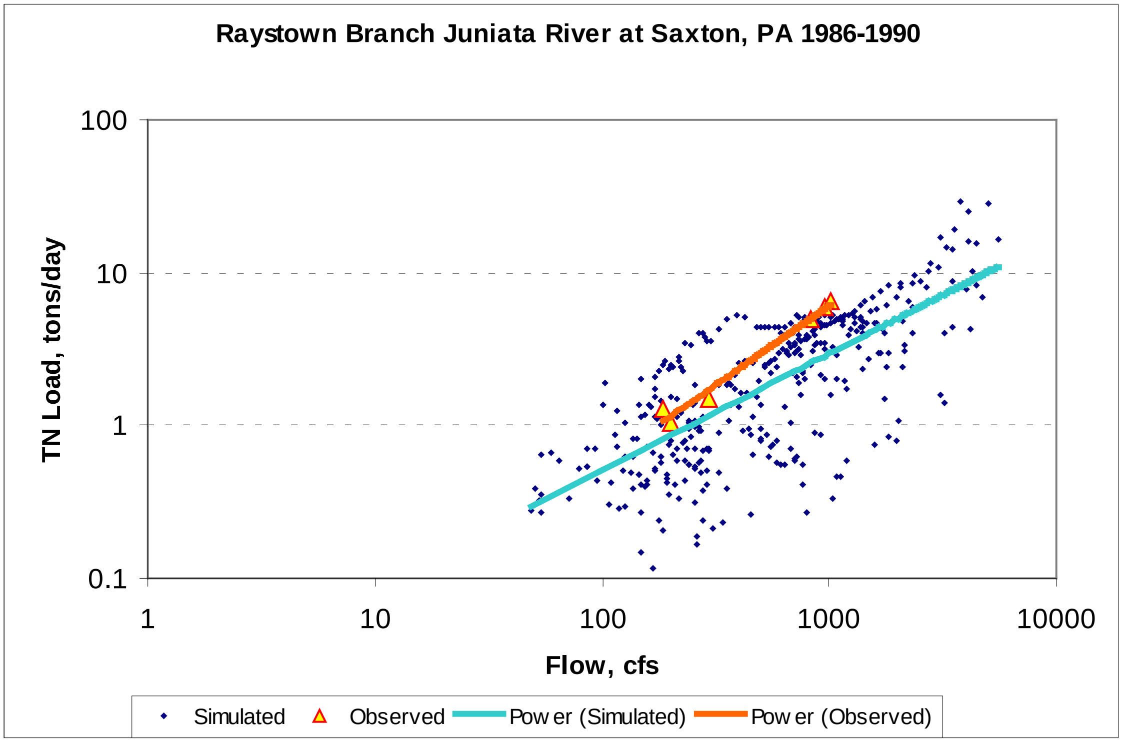


Figure 70. Power plot for observed and simulated total nitrogen at USGS 01562000 Raystown Branch Juniata River at Saxton, PA – validation period (SWAT).

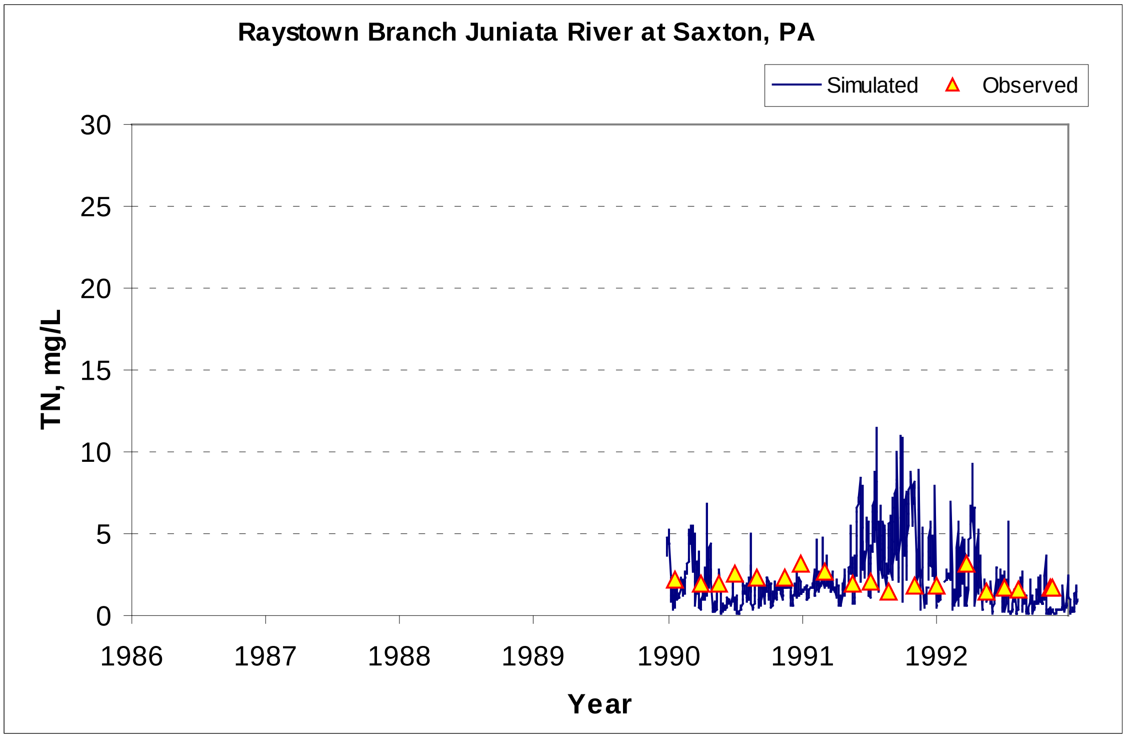


Figure 71. Time series plot of total nitrogen concentration at USGS 01562000 Raystown Branch Juniata River at Saxton, PA (SWAT).

Table 35. Relative errors (observed minus predicted), total nitrogen concentration, USGS 01562000 Raystown Branch Juniata River at Saxton, PA (SWAT)

Statistic	Calibration period (1991-2002)	Validation period (1990)
Count	13	6
Concentration Average Error	-13.82%	32.07%
Concentration Median Error	21.58%	36.92%

Water Quality Results for Larger Watershed

Similar to hydrology calibration, water quality results were compared at other gages. Note that in contrast to the HSPF model, water quality for the SWAT model for Susquehanna River at Marietta, PA was calibrated to the stratified regression monthly load estimates for the entire 1991-2005 period, although the observed data stop with 1995. Summary statistics for the water quality calibration and validation at other stations in the watershed are provided in Tables 36 and 37.

Table 36. Summary statistics for water quality for all stations – calibration period (SWAT)

Station	01576000 Susquehanna River at Marietta, PA (1991-1995)	01540500 Susquehanna River at Danville, PA (1991-1994)	01562000 Raystown Branch Juniata River at Saxton, PA (1991-2000)
Relative Percent Error TSS Load	25.2%	28.4%	-10.1%
TSS Concentration Median Error	-34.0%	-19.9%	12.04%
Relative Percent Error TP Load	-11.4%	22.6%	-0.5%
TP Concentration Median Error	-23.2%	-2.4%	71.74%
Relative Percent Error TN Load	-14.0%	-1.6%	28.6%
TN Concentration Median Error	-39.2%	-7.8%	21.6%

Table 37. Summary statistics for water quality for all stations – validation period (SWAT)

Station	01576000 Susquehanna River at Marietta, PA (1980-1990)	01540500 Susquehanna River at Danville, PA (1986-1990)	01562000 Raystown Branch Juniata River at Saxton, PA (1990)
Relative Percent Error TSS Load	15.2%	17.1%	-33.6%
TSS Concentration Median Error	-22.8%	-3.4%	-73.8%
Relative Percent Error TP Load	0.9%	10.9%	9.2%
TP Concentration Median Error	-21.2%	-21.9%	9.7%
Relative Percent Error TN Load	-0.1%	15.7%	43.9%
TN Concentration Median Error	-16.6%	16.0%	36.9%

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Appendix G
Model Configuration, Calibration and Validation

Basin: Minnesota River (Minn)

Contents

Tables

Figures

Watershed Background

Water Body Characteristics

The Minnesota River (HUC 0702) constitutes 12 HUC8s, covering about 16,900 mi^2, predominantly in the Western Corn Belt ecoregion (Figure 1). The Minnesota River Basin is located primarily in southern Minnesota with headwaters in South Dakota and is tributary to the Upper Mississippi River. Major cities include Mankato and Minneapolis, MN.

Most of the watershed was originally native prairie and pothole wetlands. Intensive agricultural development began in the mid to late 19th century, and the watershed is now part of the corn belt, with the majority of the land area converted to corn-soybean rotation and other types of agriculture. Conversion of many parts of the watershed to agriculture required enhancement of drainage through ditches and subsurface tile drains. These drainage ditches and tile drains have resulted in a strong alteration of the hydrology by human modifications.

Precipitation, evapotranspiration, and air temperature exhibit a gradient from southwest to northeast, with a warmer, wetter climate to the southeast and a colder, drier climate to the northwest. Topography is flat to gently rolling, except in the area of the high bluffs adjoining the Minnesota River mainstem, created by glacial runoff. The dominant land use in the watershed is row crop agriculture (72 percent; mostly in corn / soybean rotation), with another 6 percent in pasture and hay. The surficial geology of the watershed consists of glacial till, moraines, and lake deposits and in its natural state was poorly drained with numerous lakes and wetlands. This topography was largely drained to establish agriculture and the use of tile drainage is now prevalent in the watershed.

The maximum streamflow occurs in spring and early summer as a result of rain and melting snow. Streamflow variation is greatest during late summer and fall, when precipitation ranges from drought conditions to locally heavy rains. Streamflow varies least during winter, when groundwater discharge to streams is dominant. Flow from the upper portions of the Minnesota River is influenced by Lac qui Parle, a U.S. Army Corps of Engineers impoundment of the Minnesota River near Montevideo, MN.

Water quality in the basin is affected by agricultural activities and point sources. The combination of extensive corn production and tile drainage results in a high risk of nitrogen export. Erosion, sedimentation, and turbidity problems are also frequent in the basin; however, analysis of radionuclide data suggests that only about a third of the sediment transported in stream channels is derived from upland sheet and rill erosion, with the remainder coming from gullies (often associated with tile drain outfalls), bank erosion, and bluff collapse.

The watershed does not contain major reservoirs. However, there are a number of smaller lakes and reservoirs that influence flow in this low gradient terrain. As stated above, the Minnesota River's headwaters are located at Big Stone Lake, a natural lake with multiple outlets. The river proceeds through a series of impoundments in the upper reaches to Lac qui Parle, a US Army Corps of Engineers impoundment upstream of Montevideo, Minnesota. Irrigation and groundwater pumping in the watershed are generally small (although irrigation is somewhat more important in the western portions of the watershed). These factors are ignored for the purposes of the 20 Watershed model.

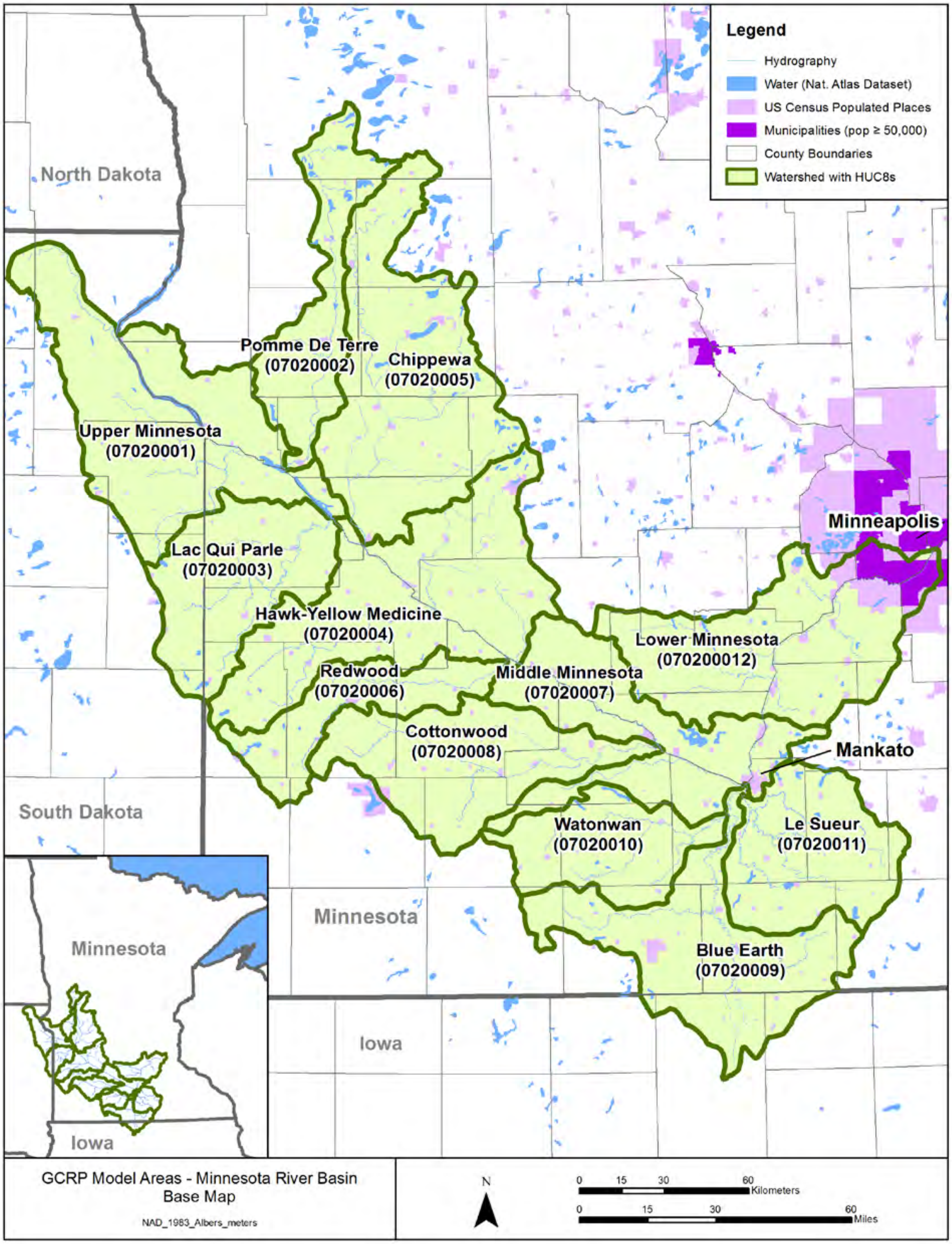

Figure 1. Location of the Minnesota River watershed.

Soil Characteristics

Soils in the watershed, as described in STATSGO soil surveys, fall primarily into hydrologic soil groups (HSGs) B (moderately high infiltration capacity) and D (low infiltration capacity). However, these designations are believed to be somewhat misleading in the Minnesota River watershed, as most agricultural activity benefits from subsurface tile drainage, which has been extensively installed since the 19th century. It is our impression that soils in the basin have received a rating as HSG B primarily because of pre-existing drainage and would more likely be classified as B/D (moderately high surface infiltration with a restricting layer) in its absence. This was substantiated by a previously-developed HSPF model of the basin for TMDL development (Tetra Tech 2008). The TMDL model obtained an excellent fit to basin hydrology without accounting for different HSGs, using parameters typical of HSG D. Therefore, the 20 Watershed HSPF model was constructed with only a small increase in infiltration capacity between group B and group D soils.

The SWAT model relies on a curve number approach rather than direct simulation of infiltration. SWAT uses information drawn directly from the soils data layer to populate the model.

The soil survey data was also used to establish geographic distributions of infiltration rate and available soil water capacity. These were used to index the spatial distribution of infiltration and lower zone soil nominal storage capacities in the 20 Watershed model, as was done in the TMDL model.

Land Use Representation

Land use/cover in the watershed is based on the 2001 National Land Cover Database (NLCD) coverage and is predominantly row crop agriculture (Figure 2). Pasture and wetlands are more predominant in the upstream, western portions of the watershed. A variety of small municipalities are present throughout the watershed; however, major urban development is found only in the downstream Minneapolis-St. Paul metropolitan area.

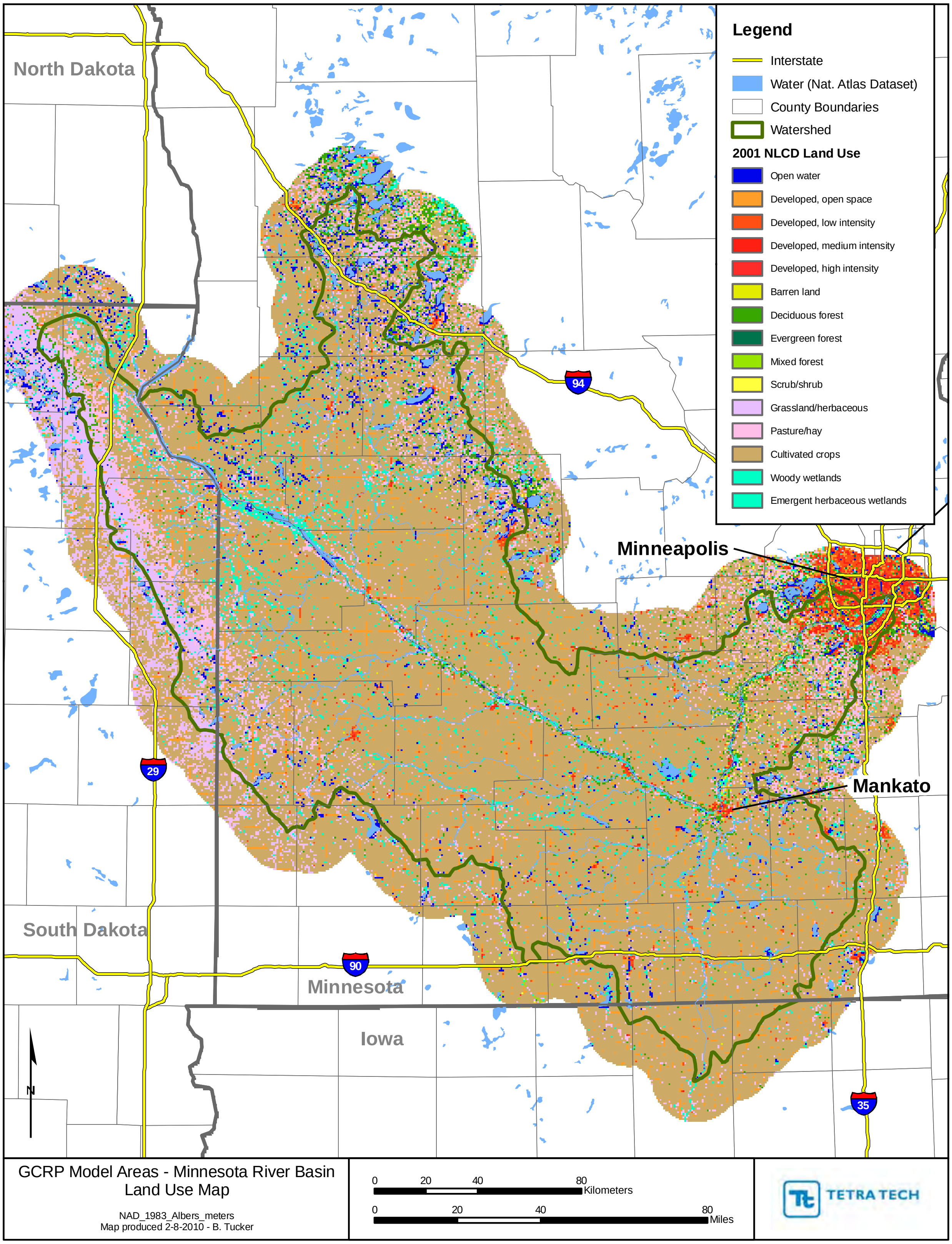

Figure 2. Land use in the Minnesota River watershed.

National Land Cover Database (NLCD) land cover classes were aggregated according to the scheme shown in Table 1 for representation in the 20 Watershed model, then overlain with the soils HSG grid. For HSPF, pervious and impervious lands are specified separately, so only one developed pervious class is used, along with an impervious class. HSPF simulates impervious land areas separately from pervious land. Impervious area distributions were determined from the NLCD Urban Impervious data coverage. Specifically, percent impervious area was calculated over the entire watershed for each of the four developed land use classes. These percentages were then used to separate out impervious land. NLCD impervious area data products are known to underestimate total imperviousness in rural areas; however, the model properly requires connected impervious area, not total impervious area, and the NLCD tabulation is assumed to provide a reasonable approximation of connected impervious area. In SWAT, different developed land classes are specified separately. In HSPF the WATER, BARREN, DEVPERV, and WETLAND classes are not subdivided by HSG; SWAT uses the built-in HRU overlay mechanism in the ArcSWAT interface.

Table 1.Aggregation of NLCD land cover classes

NLCD Class	Comments	SWAT class	HSPF (after processing)
11 Water	Water surface area usually accounted for as reach area	WATR	WATER
12 Perennial ice/snow		WATR	BARREN, Assume HSG D
21 Developed open space		URLD	DEVPERV; IMPERV
22 Dev. Low Intensity		URMD	
23 Dev. Med. Intensity		URHD	
24 Dev. High Intensity		UIDU	
31 Barren Land		SWRN	BARREN (D)
41 Forest	Deciduous	FRSD	FOREST (A,B,C,D)
42 Forest	Evergreen	FRSE	
43 Forest	Mixed	FRST	
51-52 Shrubland		RNGB	SHRUB (A,B,C,D)
71-74 Herbaceous Upland		RNGE	GRASS (A,B,C,D), BARREN (D)
81 Pasture/Hay		HAY	GRASS (A,B,C,D)
82 Cultivated		AGRR	AGRI (A,B,C,D)
91-97 Wetland	Emergent & woody wetlands	WETF, WETL, WETN	WETLAND, Assume HSG D
98-99 Wetland	Aquatic bed wetlands (not emergent)	WATR	WATER

The distribution of land use in the watershed is summarized in Table 2.

Table 2. Land use distribution for the Minnesota River watershed (2001 NLCD) (mi^2)

HUC 8 watershed	Open water	Developed[a] Open space	Low density	Medium density	High density	Barren land	Forest	Shrubland	Pasture/Hay	Cultivated	Wetland	Total
Upper Minnesota **07020001**	90.5	86.7	10.6	3.0	0.7	2.6	36.0	313.8	264.9	1,132.0	175.8	2,116.6
Pomme De Terre **07020002**	77.0	40.7	5.8	1.2	0.3	0.7	47.2	40.7	61.1	560.5	54.6	889.7
Lac Qui Parle **07020003**	16.6	46.5	3.0	0.8	0.3	0.6	9.7	114.4	99.6	707.5	75.9	1,074.9
Hawk-Yellow Medicine **07020004**	31.6	95.5	20.7	4.4	1.1	2.6	35.5	56.7	75.6	1,669.5	92.5	2,085.8
Chippewa **07020005**	123.9	86.3	15.2	1.9	0.6	1.4	94.2	61.2	179.4	1,413.3	110.6	2,088.0
Redwood **07020006**	11.6	35.6	6.8	2.1	0.6	0.9	6.9	43.4	22.1	547.4	21.9	699.4
Middle Minnesota **07020007**	35.8	67.5	19.0	7.9	2.8	4.7	59.3	17.1	40.0	1,082.0	87.0	1,422.8
Cottonwood **07020008**	10.5	63.8	8.3	2.1	0.4	0.7	16.5	26.9	22.5	1,113.5	45.2	1,310.3
Blue Earth **07020009**	22.4	93.2	11.5	2.8	0.9	1.0	13.0	32.3	10.4	1,345.8	39.7	1,573.1
Watonwan **07020010**	12.0	45.9	6.1	1.6	0.3	0.4	9.6	7.9	4.5	745.0	26.6	859.9
Le Sueur **07020011**	22.7	61.6	7.4	1.6	0.6	0.6	16.1	26.9	15.9	918.5	38.5	1,110.4
Lower Minnesota **07020012**	51.3	84.4	88.7	45.8	21.8	0.7	144.2	45.6	202.9	1,011.4	61.3	1,758.1
Total	505.9	807.6	203.3	75.1	30.4	16.9	488.2	786.8	999.0	12,246.4	829.6	16,989.1

[a]The percent imperviousness applied to each of the developed land uses is as follows: open space (6.59%), low density (29.20%), medium density (55.01%), and high density (83.31%).

The HSPF model is set up on a hydrologic response unit (HRU) basis. For HSPF, HRUs were formed from an intersection of land use and hydrologic soil group, then further subdivided by precipitation gage. Because slopes in the basin are relatively mild, HSPF HRUs were not further subdivided by slope. However, average slopes (which tend to correlate with soils) were calculated for each HRU. The water land use area was adjusted to prevent double counting with area described in HSPF reaches. SWAT HRUs are formed from an intersection of land use and SSURGO major soils.

Point Sources

There are numerous point source discharges in the watershed, including approximately 70 mechanical wastewater treatment plants and various industrial discharges. In addition, Minnesota PCA has identified approximately 70 stabilization ponds in the watershed that receive wastewater, primarily serving small communities, and that discharge seasonally to the stream network.

For the purposes of 20 Watershed modeling, only the 13 major dischargers, with a design flow greater than 1 MGD are included in the simulation (Table 3 and Figure 3). The total of all discharges in the basin is believed to be in the range of 100 MGD. The major dischargers account for about 80 percent of that total, so the effect of the omitted sources distributed throughout the watershed will be relatively small, except during extreme low flow conditions. The major dischargers are represented at long-term average flows, without accounting for changes over time or seasonal variations.

Table 3. Major point source discharges in the Minnesota River watershed

NPDES ID	Name	Design flow (MGD)	Observed flow (MGD) (1991-2006 average)
MN0022535	SAINT PETER	4.00	1.04
MN0030171	MANKATO	11.25	6.56
SD0020371	MILBANK - CITY OF	1.50	8.45
MN0020133	MONTEVIDEO	3.00	0.96
MN0022179	MARSHALL	4.50	2.57
MN0057037	MINNESOTA CORN PROCESSORS	2.60	1.31
MN0030066	NEW ULM	6.77	2.55
MN0030112	FAIRMONT	3.90	1.38
MN0025267	WINNEBAGO	1.70	0.40
MN0024759	SAINT JAMES	2.96	1.08
MN0024040	MADELIA	1.31	0.71
MN0029882	METROPOLITAN COUNCIL-BLUE LAKE	42.00	26.44
MN0030007	METROPOLITAN COUNCIL-SENECA	38.00	23.89
MN0020796	WASECA	3.50	1.36
MN0020150	NEW PRAGUE	1.38	0.65
MN0025259	WILLMAR	5.04	3.48

Most of these point sources have reasonably good monitoring for total phosphorus and total suspended solids (TSS), but not for total nitrogen. In many cases, only ammonia nitrogen is monitored. The point sources were initially represented in the model with the median of reported values for total phosphorus and TSS and an assumed total nitrogen concentration of 11.2 mg/L for secondary treatment facilities (Tetra Tech 1999).

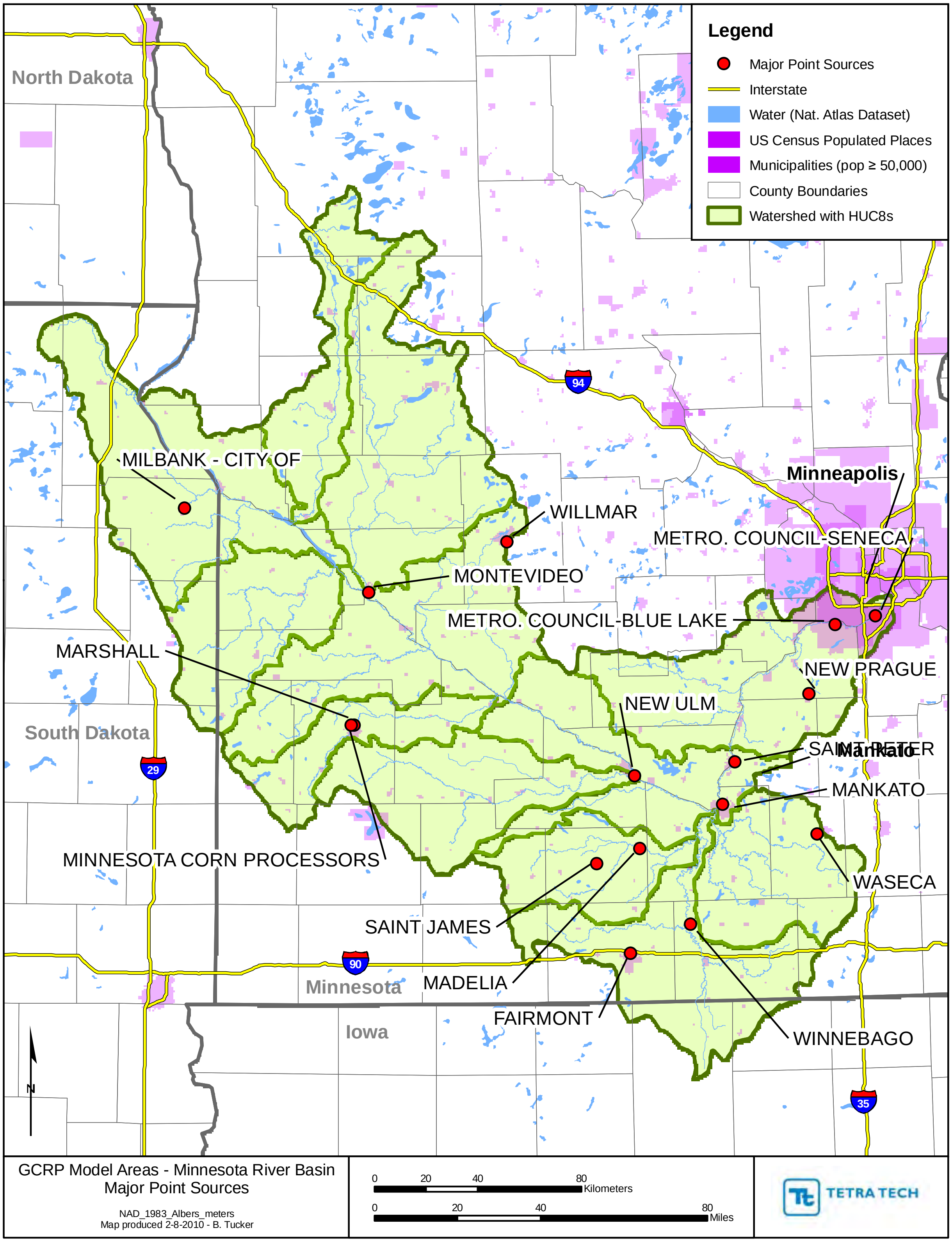

Figure 3. Major point sources in the Minnesota River watershed.

Meteorological Data

The required meteorological data series for the 20 Watershed study are precipitation, air temperature, and potential evapotranspiration. The 20 Watershed model does not include water temperature or algal simulation and uses a degree-day method for snowmelt. These meteorological data are drawn from the BASINS4 Meteorological Database (USEPA 2008), which provides a consistent, quality-assured set of nationwide data with gaps filled and records disaggregated. Scenario application will require simulation over 30 years, so the available stations are those with a common 30-year period of record (or one that can be filled from an approximately co-located station) that covers the year 2001. A total of 39 precipitation stations were identified for use in the Minnesota River model with a common period of record of 10/1/1972-9/30/2002 (Table 4 and Figure 4). Temperature records are sparser; where these are absent temperature is taken from nearby stations with an elevation correction. For each weather station, Penman-Monteith reference evapotranspiration was calculated for use in HSPF using observed precipitation and temperature coupled with SWAT weather generator estimates of solar radiation, wind movement, cloud cover, and relative humidity.

For the 20 Watershed model applications, SWAT uses daily meteorological data, while HSPF requires hourly data. It is important to note that a majority of the meteorological stations available for the Minnesota River watershed are Cooperative Summary of the Day stations that do not report sub-daily data. The BASINS4 dataset already has versions of the daily data that have been disaggregated to an hourly time step using template stations. For each daily station, this disaggregation was undertaken in reference to a single disaggregation template. Occasionally, this automated procedure provides undesirable results, particularly when the total rainfall for the day is very different between the subject station and the disaggregation template. This yields a small number of hourly precipitation intensity estimates that are unrealistically high (e.g., much greater than the 100-yr 1-hour event for the region). This has only a small impact on the basin-scale hydrologic calibration as gages are influenced by rainfall from multiple weather stations, but can introduce significant problems for the prediction of erosion and sediment loads. Perhaps more importantly, past experience makes clear that the available precipitation network is not sufficiently dense to accurately resolve watershed-scale precipitation depths, particularly during summer convective storms (Tetra Tech 2008). This introduces an unavoidable level of uncertainty into the hydrologic calibration.

Table 4. Precipitation stations for the Minnesota River watershed model

COOP ID	Name	Latitude	Longitude	Temperature	Elevation (ft)
IA138270	TITONKA	43.2353	-94.0417	No	1,170
MN210112	ALEXANDRIA CHANDLER FL	45.8686	-95.3942	Yes	1,416
MN210287	ARTICHOKE LAKE	45.3783	-96.1542	Yes	1,075
MN210667	BENSON	45.3167	-95.6167	Yes	1,040
MN210981	BRICELYN	43.5514	-93.8481	No	1,170
MN211263	CANBY	44.7183	-96.2697	Yes	1,243
MN212698	FAIRMONT	43.6447	-94.4656	Yes	1,187
MN212768	FERGUS FALLS	46.2919	-96.1172	Yes	1,250
MN213076	GAYLORD	44.5564	-94.2206	Yes	1,018
MN213174	GLENWOOD 2 WNW	45.6633	-95.4442	Yes	1,198

COOP ID	Name	Latitude	Longitude	Temperature	Elevation (ft)
MN213311	GRANITE FALLS	44.8108	-95.5178	No	910
MN214176	JORDAN 2E	44.6622	-93.5933	Yes	930
MN214546	LAMBERTON SW EXP STN	44.2394	-95.3153	Yes	1,144
MN214994	MADISON SEWAGE PLANT	45.0025	-96.1661	Yes	1,080
MN215073	MANKATO	44.1556	-94.0242	Yes	850
MN215204	MARSHALL	44.4706	-95.7908	Yes	1,152
MN215400	MILAN 1 NW	45.1219	-95.9269	Yes	1,020
MN215435	MINNEAPOLIS/ST PAUL AP	44.8831	-93.2289	Yes	872
MN215563	MONTEVIDEO 1 SW	44.9364	-95.7536	Yes	985
MN215638	MORRIS WC EXP STN	45.5903	-95.8747	Yes	1,140
MN215887	NEW ULM 2 SE	44.3006	-94.4897	Yes	860
MN216152	OLIVIA 3E	44.7628	-94.9297	Yes	1,100
MN216835	REDWOOD FALLS FAA ARPT	44.5472	-95.0822	Yes	1,025
MN217326	ST JAMES FILT PLANT	43.9908	-94.6122	Yes	1,100
MN217405	ST PETER	44.3222	-93.9556	Yes	850
MN217602	SHERBURN 3 WSW	43.6303	-94.7744	Yes	1,320
MN217907	SPRINGFIELD 1 NW	44.2469	-94.9864	Yes	1,066
MN218025	STEWART	44.7344	-94.3425	Yes	1,040
MN218323	TRACY	44.2394	-95.6308	Yes	1,403
MN218429	TYLER	44.2781	-96.1281	No	1,735
MN218520	VESTA	44.5069	-95.4111	No	1,080
MN218692	WASECA EXP STATION	44.0725	-93.5328	Yes	1,153
MN218808	WELLS	43.7333	-93.7333	No	1,197
MN219004	WILLMAR RTC	45.1403	-95.0183	Yes	1,128
MN219046	WINNEBAGO	43.7689	-94.1883	Yes	1,110
SD391777	CLEAR LAKE	44.7506	-96.6906	Yes	1,800
SD395536	MILBANK 2 SSW	45.2061	-96.6361	Yes	1,160
SD397742	SISSETON	45.6667	-97.0419	Yes	1,220
SD399337	WILMOT	45.4081	-96.8600	No	1,160

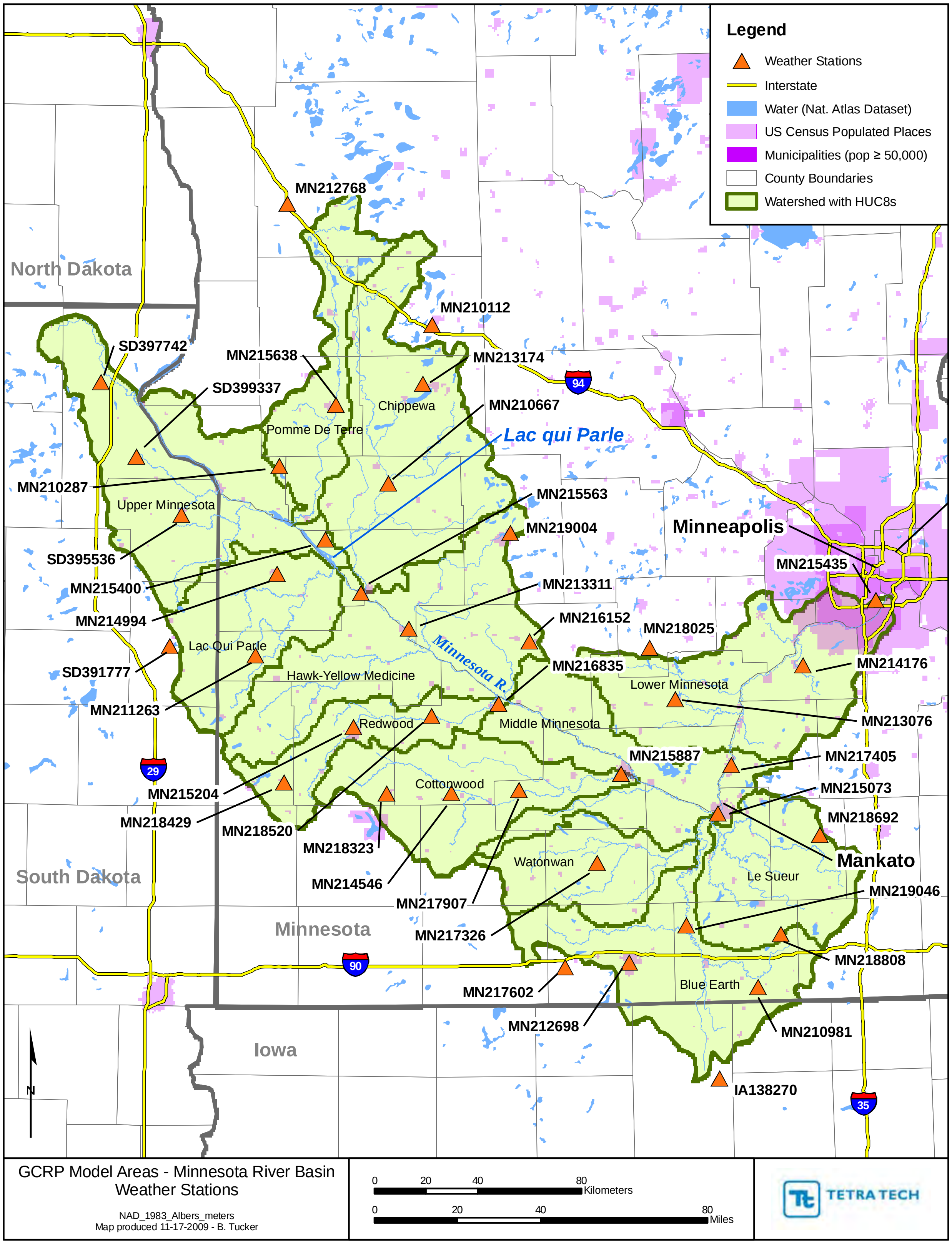

Figure 4. Weather stations for the Minnesota River watershed model.

Watershed Segmentation

The Minnesota River basin was divided into 95 subwatersheds for the purposes of modeling (Figure 5). The initial calibration watershed (Cottonwood River) is highlighted. The model encompasses the complete watershed and does not require specification of any upstream boundary conditions for application. It should be noted, however, that Big Stone Lake (subwatershed 63) is separated from nearby Lake Traverse (which is not part of the watershed) by only a small dike, and Lake Traverse sometimes overflows into Big Stone Lake when winter ice jams are present. This boundary phenomenon is not represented in the model.

The model subwatersheds approximate the HUC-10 scale, but are subdivided as needed to account for the connection of tributaries and location of flow gages. The subwatersheds range in size from 10 to 436 mi^2, with an average size of 178 mi^2.

In developing the HSPF simulation it was noted that the FTable simulation of Lac qui Parle did not perform well for the model validation period. Therefore, for the purposes of HSPF hydrologic validation only, a separate version of the model was created with outflow from Lac qui Parle set as a boundary condition.

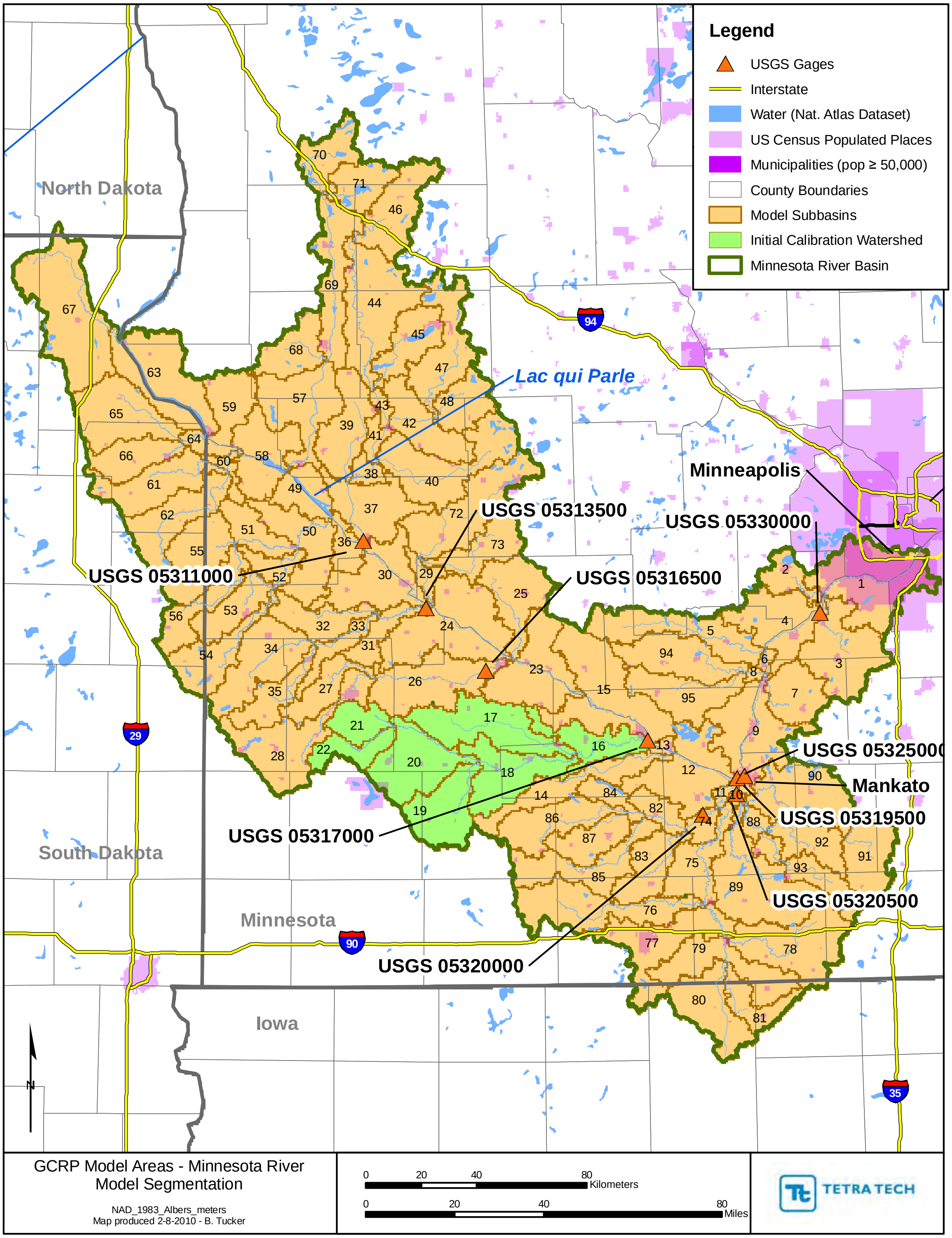

Figure 5. Model segmentation and USGS stations utilized for the Minnesota River watershed.

Note: SWAT subwatersheds numbering is shown; the HSPF model for this watershed uses the same subwatershed boundaries with an alternative internal numbering scheme.

Calibration Data and Locations

The Minnesota River basin was selected as an early pilot site because of extensive previous experience in modeling this watershed. The specific site chosen for initial calibration was the Cottonwood River at New Ulm, a flow and water quality monitoring location that approximately coincides with the mouth of an 8-digit HUC at its outflow to the Minnesota River. The Cottonwood watershed was selected for several reasons: 1) there is a good set of flow and water quality data available, 2) previous modeling efforts were successful, and 3) the watershed lacks major point sources and impoundments.

Previous experience in the watershed indicates that model fit is very sensitive to hydrologic parameter specification – in part because precipitation and ET are, in general, balanced such that minor perturbations in soil moisture persist for long periods of time. In addition, the Minnesota River watershed was an initial test case of procedures; therefore, calibration and validation was pursued at multiple locations (Table 5). Parameters derived on the Cottonwood were not fully transferable to other portions of the Minnesota River watershed, and additional calibration was conducted at multiple gage locations.

Table 5. Calibration and validation locations in the Minnesota River basin

Station Name	USGS ID	Drainage Area (mi^2)	Hydrology Calibration	Water Quality Calibration
Minnesota River at Montevideo, MN	05311000	6,180	X	
Yellow Medicine River at Granite Falls, MN	05313500	664	X	X
Redwood River nr Redwood Falls, MN	05316500	629	X	X
Cottonwood River near New Ulm, MN	05317000	1,300	X	X
Watonwan River near Garden City, MN	05319500	851	X	X
Blue Earth River near Rapidan, MN	05320000	2,410	X	X
LeSueur River near Rapidan, MN	05320500	1,110	X	X
Minnesota River at Mankato, MN	05325000	14,900	X	X
Minnesota River near Jordan, MN	05330000	16,200	X	X

The model hydrology calibration period was set to Water Years 1993-2002 (within the 30-year period of record for modeling). The end date was constrained by the common period of the set of 20 Watershed meteorological stations available for the watershed, and a ten year calibration period was desired. Calibration was done on the later data, due to concerns that there have been significant changes in agricultural management practices and land retirement programs since the 1980s. Hydrologic validation was then performed on Water Years 1983-1992. Water quality calibration used calendar years 1993-2002, while validation used 1986-1992, as limited data were available prior to 1986.

HSPF Modeling

A detailed HSPF model already exists for the portion of the basin between Lac qui Parle and Minnesota River at Jordan, MN (Tetra Tech 2008). This model, which was developed through a number of iterations to support TMDL development, is calibrated for flow, sediment, and nutrients. A particular focus of the calibration effort was on sediment source attribution, using radionuclide data, including detailed calibration for loading from ravines, in-channel processes, and contributions from bluff collapse where tributaries enter the mainstem at the edges of the old glacial River Warren valley.

The existence of this earlier model provides a firm basis for parameter initialization, and is one of the reasons that the Minnesota River was selected as a pilot site. There are significant differences between the 20 Watershed model and the previous TMDL model. In general, the approach adopted for the 20 Watershed large-scale model applications is intended to provide a basis for comparison across the country. Key characteristics of the 20 Watershed model include the following.

- The model is constrained to the land uses identified by NLCD for consistency with applications to other basins. Supplementary refinements to the land use coverage to incorporate information on conservation tillage and manure application were not used in the 20 Watershed model except as a guide to general spatial trends in model parameters.
- The model makes use of the data present in the BASINS4 meteorological data set, with one station assigned per model subwatershed. Patching and disaggregation of the BASINS4 precipitation data sets generally used a single template station, occasionally resulting in very different interpretation of peak events.
- The model uses Penman-Monteith reference evapotranspiration, based on measured precipitation and temperature combined with solar radiation, wind movement, and relative humidity from the SWAT weather generator.
- The model uses the degree-day approach to simulating snowmelt (because measured values of insolation and wind movement are not available at all stations).

The TMDL model does provide important insights and parameter starting values that are incorporated into the 20 Watershed model. Of particular note are the following:

- Tile drainage is a significant component of hydrology in the basin and exhibits a spatial gradient, with the most intensive tiling in the southeastern portion of the watershed. The TMDL model developed an approach to represent tile drainage through the interflow component of HSPF, with values calibrated by 8-digit HUC. This representation is carried forward into the 20 Watershed model.
- Channel hydraulics in the TMDL model (represented through FTables) was developed through use of existing HEC-RAS models, where available. These channel characteristics were carried forward to the 20 Watershed model (for areas covered by HEC-RAS models) by matching channel segments between the two models and adjusting storage volumes to account for differences in reach length.
- Detailed work on sediment source calibration in the TMDL model was carried forward into the 20 Watershed model, including the representation of tillage and sediment loading from bluffs through the HSPF SPECIAL ACTIONS programming capability.

Changes Made to Base Data Provided

No changes were made to the meteorological or land use base data. For the point source data it was known from previous modeling that there is a rapid loss of phosphorus in the near field immediately downstream of various wastewater treatment plant discharges, likely due to settling of particulate matter. This cannot be accurately represented at the scale of the 20 Watershed model and indeed resulted in overprediction of phosphorus concentrations under low flow conditions. Discounting total phosphorus concentration in the effluent by 50 percent resolved this problem during calibration.

Assumptions

Flow in the upper portions of the Minnesota River is influenced by Lac qui Parle, a U.S. Army Corps of Engineers impoundment near Montevideo, Minnesota. The hydrology of Lac qui Parle is complex, as there is a diversion channel at Watson Sag on the Chippewa River (that naturally discharges to the Minnesota River at Montevideo) that diverts high flows, as well as a portion of base flows, upstream into Lac qui Parle. For the TMDL model, significant efforts were made to simulate the operations of the Watson Sag diversion, while Lac qui Parle itself was taken as a boundary condition. For the 20 Watershed model, the basin upstream of Lac qui Parle is simulated directly, while Watson Sag diversion is not explicitly simulated. The original intent was to ignore Lac qui Parle altogether, as the operations of impoundments are difficult to extrapolate to future climate conditions; however, this proved to be a significant detriment to the simulation of flows in the mainstem of the Minnesota River downstream of Lac qui Parle. Therefore, a reservoir storage-discharge representation (FTable) was constructed to approximate the hydraulic behavior of Lac qui Parle, based on reported lake storage and downstream gaged flows. This FTable provides only an approximation of the actual operations of the Lac qui Parle dam, and, together with the omission of the Watson Sag diversion, introduces uncertainty into the representation of mainstem flows.

The other significant dam in the watershed (Rapidan Reservoir on Blue Earth River) is not represented in the 20 Watershed model because accurate data are lacking and the impoundment's storage capacity is greatly diminished by sediment accumulation behind the dam. The many natural lakes in the watershed are also not explicitly represented, although an approximation of their storage was introduced through representation of the water land use. Specifically, the water "upland" land use was assigned characteristics that approximate storage in small natural ponds by assigning a very low slope and a high surface storage capacity, equivalent to approximately 1 inch of runoff from the surrounding drainage area. Surface storage in HSPF is a function of the slope length (SLSUR) and the roughness coefficient (NSUR). As the program limits NSUR to "reasonable" ranges of Mannings coefficient, additional surface storage capacity can be represented only be artificially increasing slope length to a large value. It is also necessary to represent evaporation from these ponds, but HSPF does not include evaporation from surface storage. This is achieved by specifying some upper zone storage capacity, but near zero infiltration rates out of the upper zone. This effectively routes much of the water to evaporation, except when large rainfall events exceed the surface storage plus upper zone storage capacity – which is how a pothole pond in the Minnesota plains behaves.

Another important characteristic of the basin is the widespread presence of subsurface tile drainage. Installation of tile drainage has converted what were predominantly glacial plain outwash depressional wetlands into productive farmland. The presence of tile drains, which include both surface and subsurface inlets, has radically altered the natural hydrology of the area. Surface inlet tile drains, in particular, may also play a significant role in the transport of sediment and pollutants from agricultural land to the river.

It is not feasible to simulate individual tile drain systems at the large basin scale. Further, neither the location nor the total density of tile drainage is known throughout the basin. In most areas, only the public tile drains and ditches are documented in spatial coverages, and the extent of private tile drains is known only for limited areas.

The HSPF model does not contain any routines for the explicit representation of tile drains. In typical applications of HSPF, surface runoff represents the quick flow storm response; interflow represents an intermediate time-scale hydrologic response; and groundwater discharge represents the base flow hydrologic response. In such applications, interflow represents lateral movement of water through the shallow soil profile.

At a gross or basin scale, the net effect of tile drainage is to move water relatively rapidly out of surface storage without direct surface drainage. Accordingly, it is to be expected that tile drainage is best represented in HSPF as an interflow component, with a response time that is somewhat slower than direct surface runoff, but quicker than groundwater discharge, represented by a relatively fast recession coefficient. Accordingly, tile drainage is represented through the interflow inflow and interflow recession parameters in HSPF, as was done for the TMDL model (Tetra Tech 2008). USGS successfully implemented a similar approach for the heavily tiled Heron Lake basin, just south of the Minnesota River drainage (Jones and Winterstein 2000).

The tile drain density has a generally decreasing trend from the southeast to the northwest portions of the basin. Accordingly, interflow inflow rates are also scaled across the basin, using the calibrated values determined by Tetra Tech (2008). These parameters, specified monthly, range from a high of 4 in the Le Sueur River basin to a low of 1.1 in the northwestern portions of the watershed. As shown in Tetra Tech (2008), this results in the models representing interflow ranging up to a maximum of 46 percent of total flow in the Le Sueur basin and provides maximum interflow discharge rates that are consistent with typical drainage coefficients for tile drains.

Hydrology Calibration

As noted above, the starting point for calibration of hydrologic parameters was the existing TMDL model (Tetra Tech 2008); however, differences between the models meant that not all parameters were directly transferable. Therefore, the first focus of calibration was on areas of difference between the model formulations. This included calibrating the degree-day snowmelt representation and adjusting factors related to the different representation of PET. In addition, the model parameters were modified to reflect the HRU representation.

The TMDL model divided cropland into areas with conventional tillage, conservation tillage, and manure application. The 20 Watershed model includes a single cropland class (divided by HSG). Therefore, parameter estimates from the TMDL were converted to initial parameters for the 20 Watershed model by developing weighted averages based on the crop management area distribution in the TMDL model. Similar analyses, based on reported soil properties, were used to extend parameter initial values to the portions of the watershed not covered by the TMDL model. Calibration adjustments focused on the following parameters:

- INFILT (nominal infiltration rate parameter): The TMDL model did not distinguish between HSGs, but was adjusted based on watershed averages of reported soil survey infiltration rates. The resulting INFILT values were generally typical of D soils. The 20 Watershed model includes both D and B soils (although, as noted above, the B classification may be influenced by widespread pre-existing tile drainage). During calibration, the D soils were kept at the values derived from the TMDL model while INFILT for the B soils was adjusted upward as needed to match observations. The resulting final values for the B soils are still generally less than are often cited for B soils (USEPA 2000).
- KMELT (degree-day melt factor): The 20 Watershed model switches to a degree-day approach for snowmelt. This depends on the monthly values of KMELT. These were originally set to values recommended by USACE (1956), then adjusted during calibration.
- AGWRC (active groundwater recession constant): The preceding changes along with the modified form of PET required compensating adjustments in AGWRC.
- PET factor: The 20 Watershed model uses Penman-Monteith reference ET estimates consistent with FAO 56 (Allen et al. 1998), whereas the TMDL model used Penman Pan evaporation. The FAO 56 reference ET calculates ET for a well-watered actively growing grass surface and requires crop factors to convert to actual PET. The reference ET is similar to, but generally less than Penman Pan evaporation, for which pan factors, generally in the range around 0.6-0.8, are needed to convert to model PET. Factors on the Penman-Monteith PET are thus expected to be needed in the model, but will be a little higher than those determined in the previous calibration effort. The previous modeling also determined that these factors tend to vary across the watershed, probably reflecting geographic trends in factors like cloud albedo and opacity. Therefore, new PET factors were assigned during calibration on zonal basis, ranging from 0.71 to 0.935.

Initial calibrations were performed for the Cottonwood River, comparing model results to data from USGS 05317000, and are summarized in Figure 6 through Figure 12 and Table 6 and Table 7. The fit is of high quality for all except the very lowest flows and meets all the recommended criteria – although the fit in the more detailed TMDL model is somewhat better. Potential problems with very low flows likely reflect a combination of factors, including omission of minor point sources and simplified representation of the behavior of small ponds and wetlands.

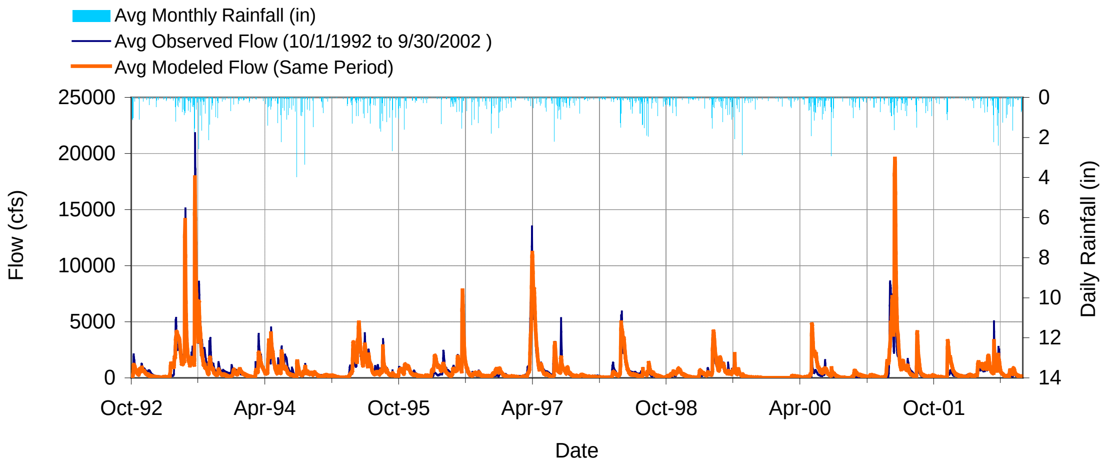

Figure 6. Mean daily flow at USGS 05317000 Cottonwood River near New Ulm, MN - calibration period (HSPF).

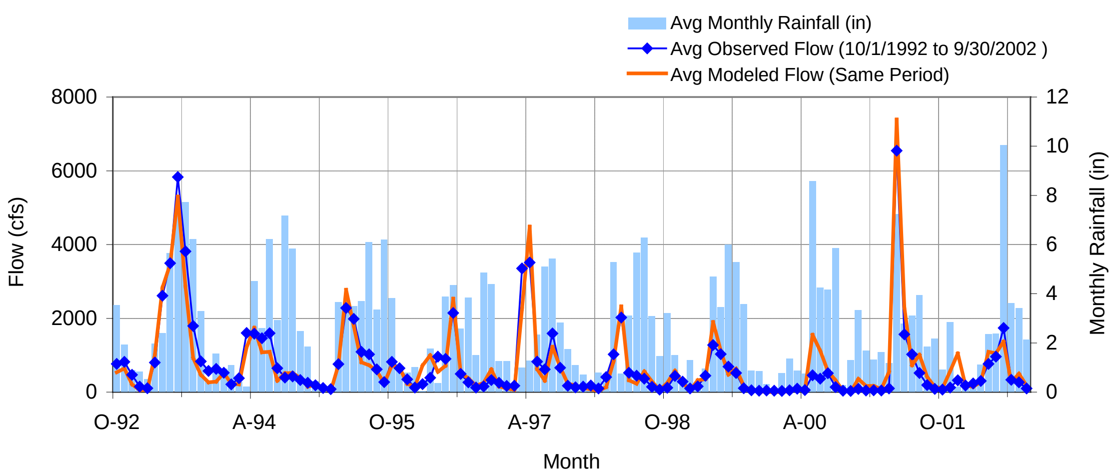

Figure 7. Mean monthly flow at USGS 05317000 Cottonwood River near New Ulm, MN - calibration period (HSPF).

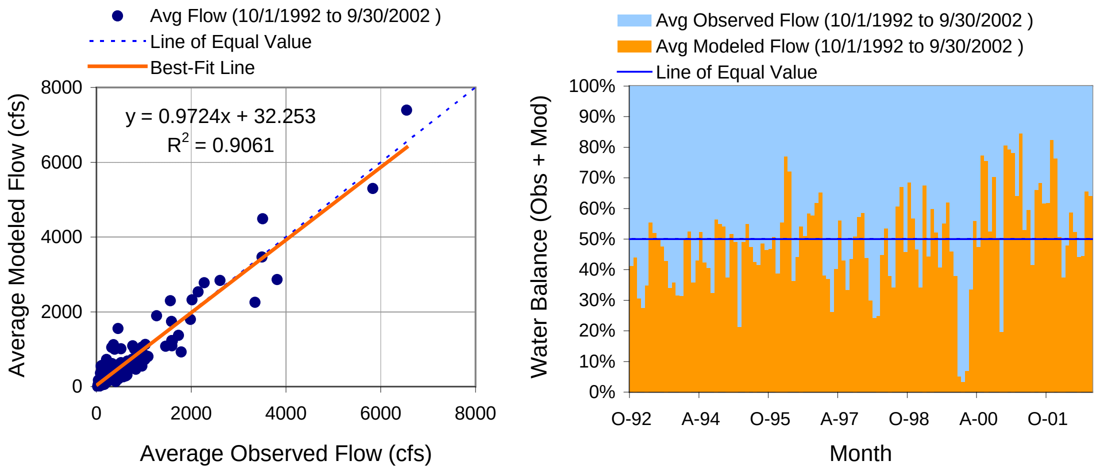

Figure 8. Mean monthly flow regression and temporal variation at USGS 05317000 Cottonwood River near New Ulm, MN - calibration period (HSPF).

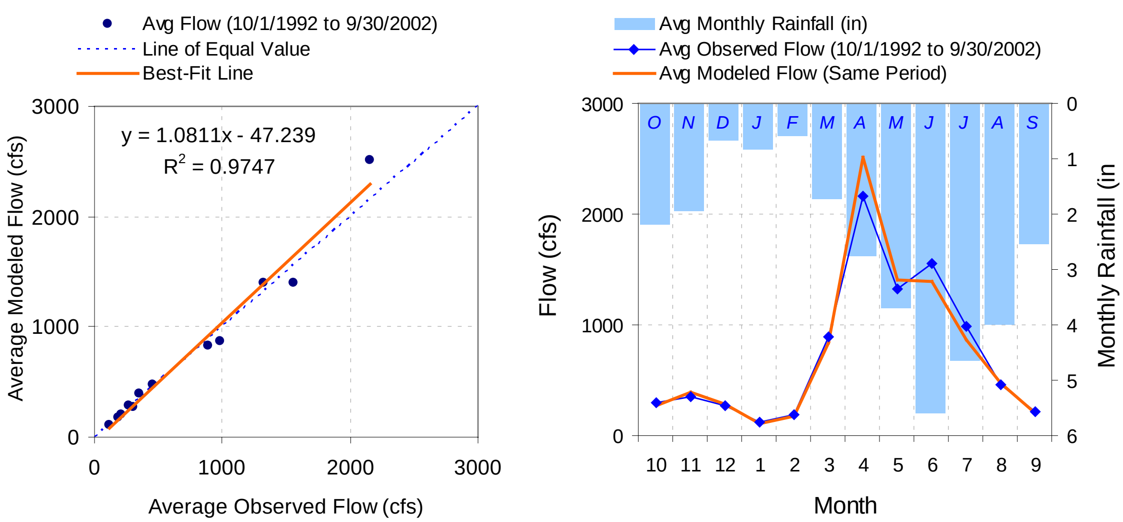

Figure 9. Seasonal regression and temporal aggregate at USGS 05317000 Cottonwood River near New Ulm, MN - calibration period (HSPF).

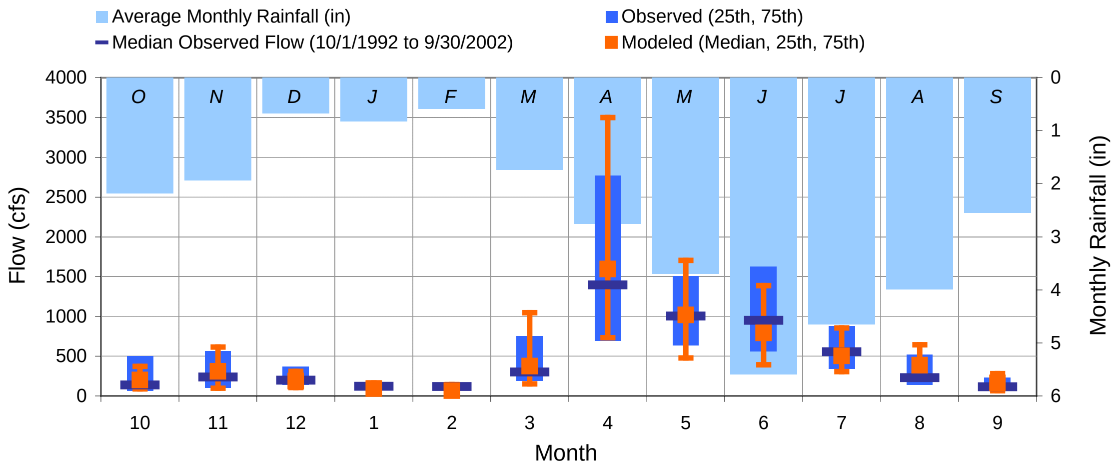

Figure 10. Seasonal medians and ranges at USGS 05317000 Cottonwood River near New Ulm, MN - calibration period (HSPF).

Table 6. Seasonal summary at USGS 05317000 Cottonwood River near New Ulm, MN - calibration period (HSPF)

MONTH	OBSERVED FLOW (CFS)				MODELED FLOW (CFS)			
	MEAN	MEDIAN	25TH	75TH	MEAN	MEDIAN	25TH	75TH
Oct	301.38	137.50	62.25	499.00	272.97	200.96	89.69	372.11
Nov	350.75	237.50	101.25	562.50	397.77	307.86	98.12	615.44
Dec	264.09	198.00	139.25	369.50	283.83	187.17	104.90	307.50
Jan	120.42	120.00	85.25	169.00	107.44	91.30	39.28	163.40
Feb	183.37	116.00	80.00	174.50	178.50	65.86	24.23	144.26
Mar	885.87	300.00	191.25	755.25	833.50	373.98	150.34	1045.37
Apr	2161.06	1395.00	688.00	2767.50	2514.03	1596.32	730.83	3500.30
May	1320.39	1005.00	638.50	1507.50	1403.31	1018.84	477.76	1705.07
Jun	1552.95	950.00	561.25	1625.00	1395.52	792.72	392.66	1387.65
Jul	981.10	554.50	336.00	877.25	868.51	502.40	306.70	853.99
Aug	455.96	228.00	138.00	519.75	476.75	385.70	237.43	643.06
Sep	216.05	114.00	65.00	234.00	207.22	164.22	67.12	280.86

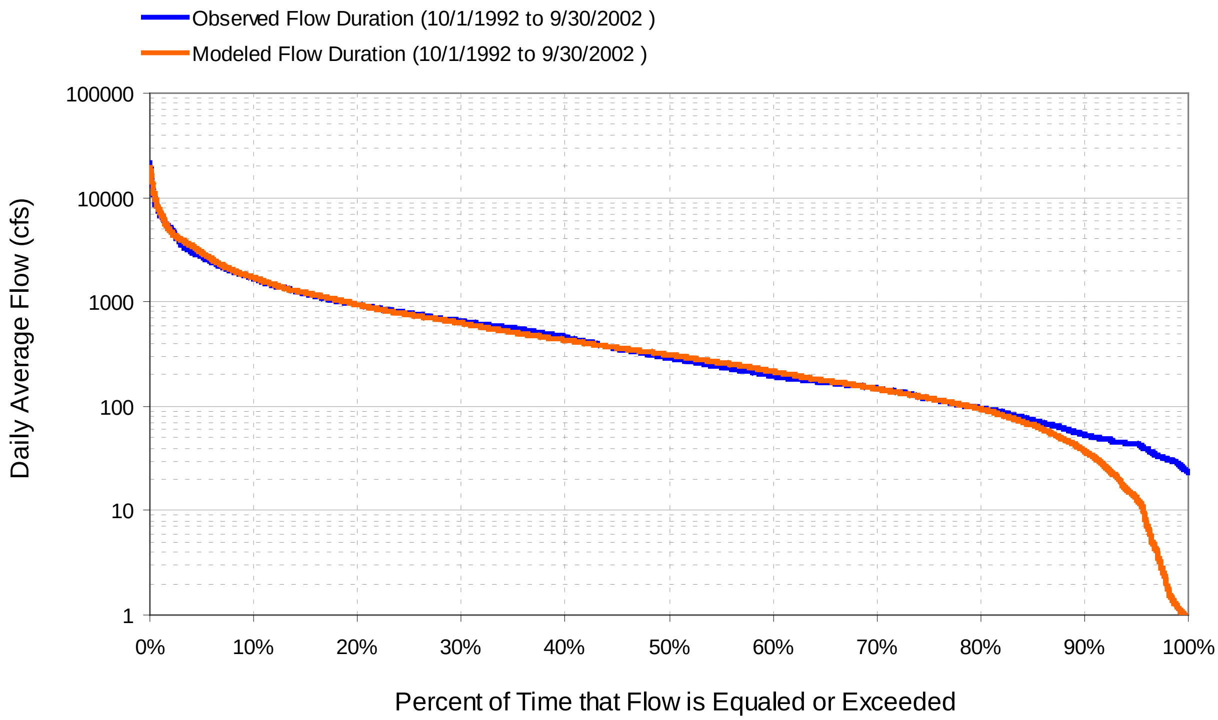

Figure 11. Flow exceedance at USGS 05317000 Cottonwood River near New Ulm, MN - calibration period (HSPF).

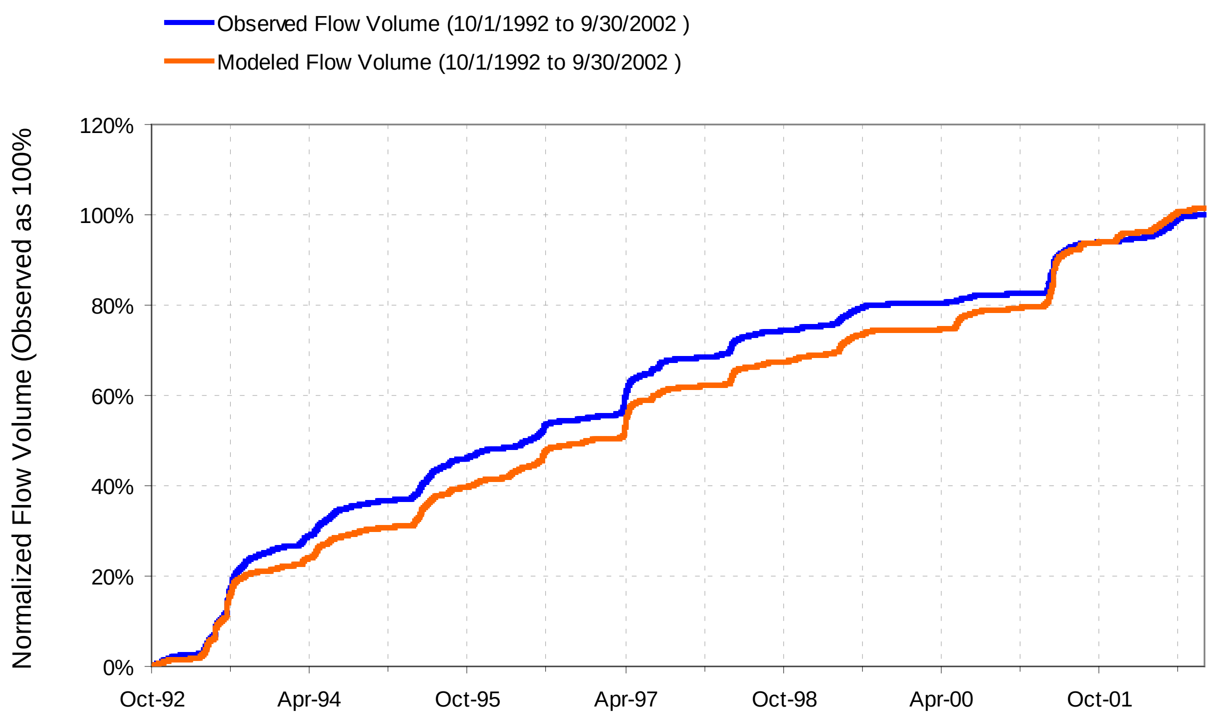

Figure 12. Flow accumulation at USGS 05317000 Cottonwood River near New Ulm, MN - calibration period (HSPF).

Table 7. Summary statistics at USGS 05317000 Cottonwood River near New Ulm, MN - calibration period (HSPF)

HSPF Simulated Flow		Observed Flow Gage	
REACH OUTFLOW FROM DSN 101 10-Year Analysis Period: 10/1/1992 - 9/30/2002 Flow volumes are (inches/year) for upstream drainage area UpperMSd, mod Water; PET 0.9		USGS 05317000 COTTONWOOD RIVER NEAR NEW ULM, MN Hydrologic Unit Code: 7020008 Latitude: 44.29135177 Longitude: -94.4402495 Drainage Area (sq-mi): 1300	
Total Simulated In-stream Flow:	**7.79**	Total Observed In-stream Flow:	**7.66**
Total of simulated highest 10% flows:	**4.09**	Total of Observed highest 10% flows:	**3.92**
Total of Simulated lowest 50% flows:	**0.67**	Total of Observed Lowest 50% flows:	**0.68**
Simulated Summer Flow Volume (months 7-9):	**1.37**	Observed Summer Flow Volume (7-9):	**1.46**
Simulated Fall Flow Volume (months 10-12):	**0.84**	Observed Fall Flow Volume (10-12):	**0.80**
Simulated Winter Flow Volume (months 1-3):	**0.98**	Observed Winter Flow Volume (1-3):	**1.04**
Simulated Spring Flow Volume (months 4-6):	**4.60**	Observed Spring Flow Volume (4-6):	**4.36**
Total Simulated Storm Volume:	**2.61**	Total Observed Storm Volume:	**2.59**
Simulated Summer Storm Volume (7-9):	**0.44**	Observed Summer Storm Volume (7-9):	**0.50**

Errors (Simulated-Observed)	*Error Statistics*	*Recommended Criteria*
Error in total volume:	1.61	10
Error in 50% lowest flows:	-0.73	10
Error in 10% highest flows:	4.26	15
Seasonal volume error - Summer:	-6.09	30
Seasonal volume error - Fall:	4.07	30
Seasonal volume error - Winter:	-5.95	30
Seasonal volume error - Spring:	5.54	30
Error in storm volumes:	0.86	20
Error in summer storm volumes:	-10.51	50
Nash-Sutcliffe Coefficient of Efficiency, E:	0.754	Model accuracy increases
Baseline adjusted coefficient (Garrick), E':	0.589	as E or E' approaches 1.0
Monthly NSE	0.901	

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Hydrology Validation

Validation for the Cottonwood watershed model was performed at the same location as calibration but for the period 10/1/1982 through 9/30/1992. Results are presented in Figure 13 through Figure 19 and Table 8 and Table 9. The validation achieves a high coefficient of model fit efficiency, but is over on both total volume and 50% low volume. Inspection of the figures and tables reveals that median flows are generally over-predicted through the spring and summer.

It is important to recognize that the validation uses the 2001 land use and parameters that are calibrated to land management practices of the 1990s. While the basin has remained largely agricultural, there are a number of differences between the earlier and later periods. These differences include the following:

- Developed impervious surface areas have increased.
- The intensity of tile drainage has increased, with more tile lines with greater capacity installed.
- Cropped areas have changed, with a significant amount of land going out of production and into the Conservation Reserve Program (CRP) and Conservation Reserve Enhancement Program (CREP).
- PET estimates for the 20 Watershed model use SWAT weather generator statistics for solar radiation, cloud cover, wind, and relative humidity – essentially assuming that the central tendency of these factors has not changed over time.

All of these factors may contribute to an increase in the runoff rate for the more recent calibration period, leading to an over-prediction of flows in the validation period.

The TMDL model (Tetra Tech 2008) also included an earlier period validation test, but used a separate land use (ca. 1992) for the earlier period, which accounts for two of these factors, although information was not available on the rate of change in tile drainage intensity. The TMDL model also calculated PET based on observed meteorology, rather than using a weather generator for solar radiation, cloud cover, wind, and relative humidity. Even with these changes it was found in that model that it was necessary to apply higher PET factors for the earlier period to achieve a good hydrologic fit. That adjustment might be compensating for the change in tile drain intensity or it might reflect actual changes in the relationship of actual PET to estimates obtained from solar radiation and cloud cover. Similar discrepancies are found at most other gages in the basin.

Temporal modifications to land use, PET factors, and other parameters were not made for the 20 Watershed model as its purpose is to provide a basis for comparison between current and potential future conditions, where the current condition is characterized by 2001 land use and land management. Therefore, the discrepancies in the validation test are not considered to present a significant bar to application of the model.

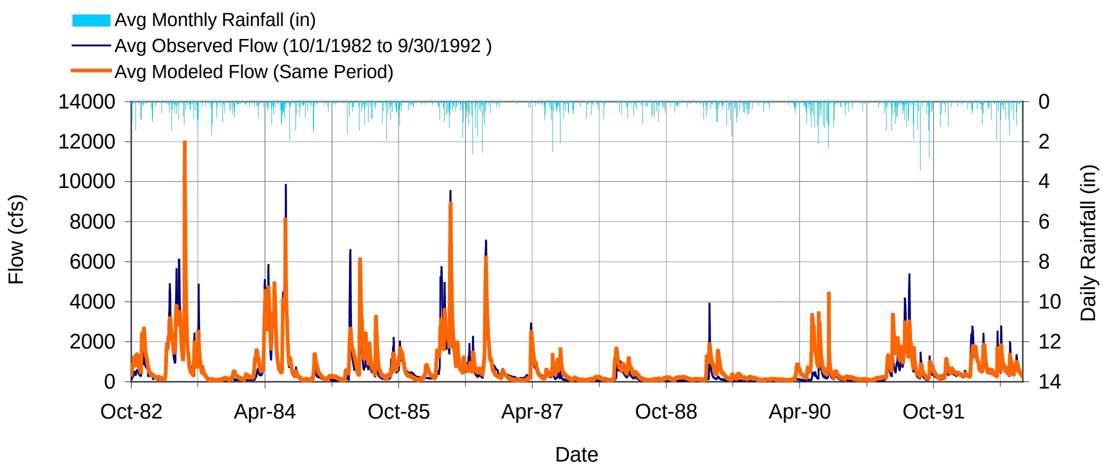


Figure 13. Mean daily flow at USGS 05317000 Cottonwood River near New Ulm, MN - validation period (HSPF).

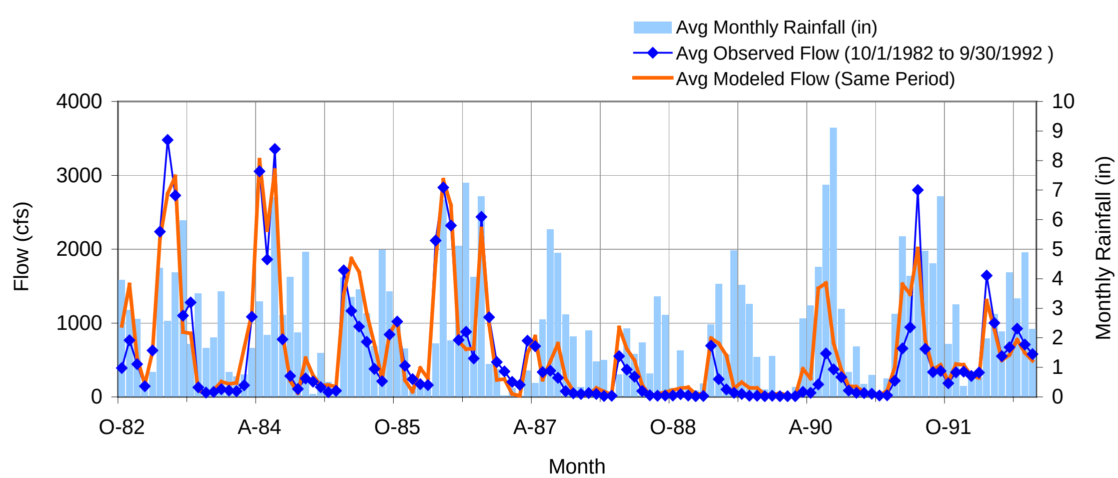


Figure 14. Mean monthly flow at USGS 05317000 Cottonwood River near New Ulm, MN - validation period (HSPF).

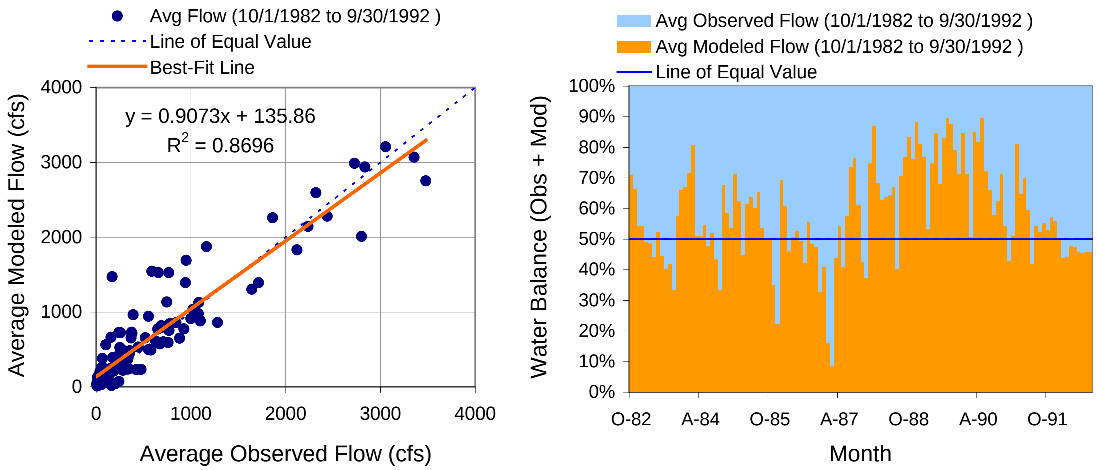


Figure 15. Monthly flow regression and temporal variation at USGS 05317000 Cottonwood River near New Ulm, MN - validation period (HSPF).

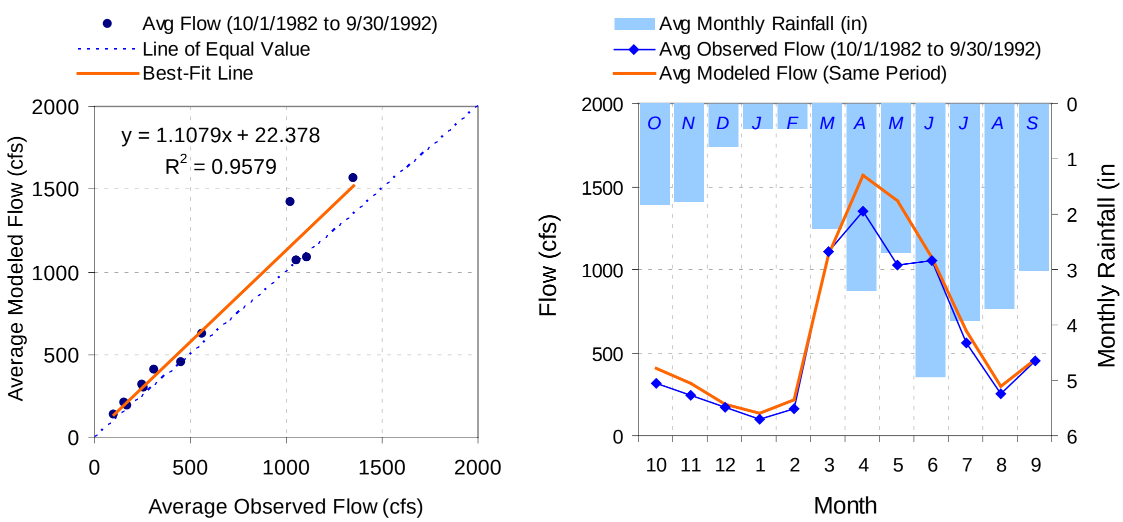


Figure 16. Seasonal regression and temporal aggregate at USGS 05317000 Cottonwood River near New Ulm, MN - validation period (HSPF).

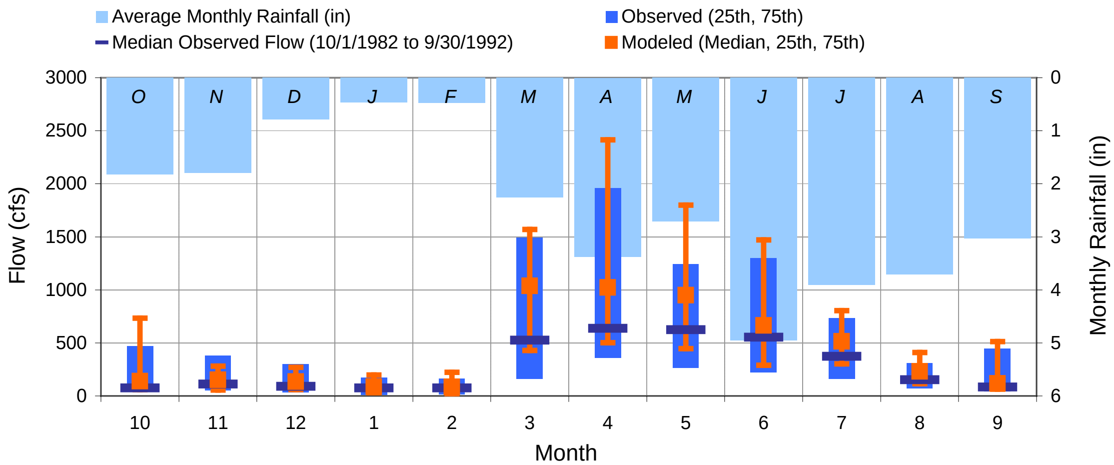


Figure 17. Seasonal medians and ranges at USGS 05317000 Cottonwood River near New Ulm, MN - validation period (HSPF).

Table 8. Seasonal summary at USGS 05317000 Cottonwood River near New Ulm, MN - validation period (HSPF)

MONTH	OBSERVED FLOW (CFS)				MODELED FLOW (CFS)			
	MEAN	MEDIAN	25TH	75TH	MEAN	MEDIAN	25TH	75TH
Oct	311.49	75.50	40.00	467.25	409.43	139.27	59.56	734.36
Nov	246.34	112.00	52.00	380.00	317.71	151.23	54.81	281.15
Dec	170.13	89.00	31.25	300.00	193.45	135.84	60.06	269.57
Jan	98.82	75.00	11.00	172.00	139.56	87.56	30.45	197.78
Feb	158.34	75.00	15.50	166.00	212.14	86.22	21.54	223.51
Mar	1108.68	525.50	162.50	1495.00	1090.13	1037.59	427.82	1570.61
Apr	1354.28	637.50	355.00	1957.50	1565.20	1023.14	501.22	2414.57
May	1023.32	623.00	266.50	1245.00	1417.41	949.90	445.09	1799.84
Jun	1051.98	553.50	222.25	1300.00	1071.80	665.65	289.05	1470.56
Jul	558.86	374.00	160.25	736.50	626.37	514.21	302.17	804.68
Aug	256.15	151.50	71.00	311.50	296.15	231.83	116.57	409.98
Sep	454.86	84.50	46.00	446.00	455.65	117.39	63.86	512.03

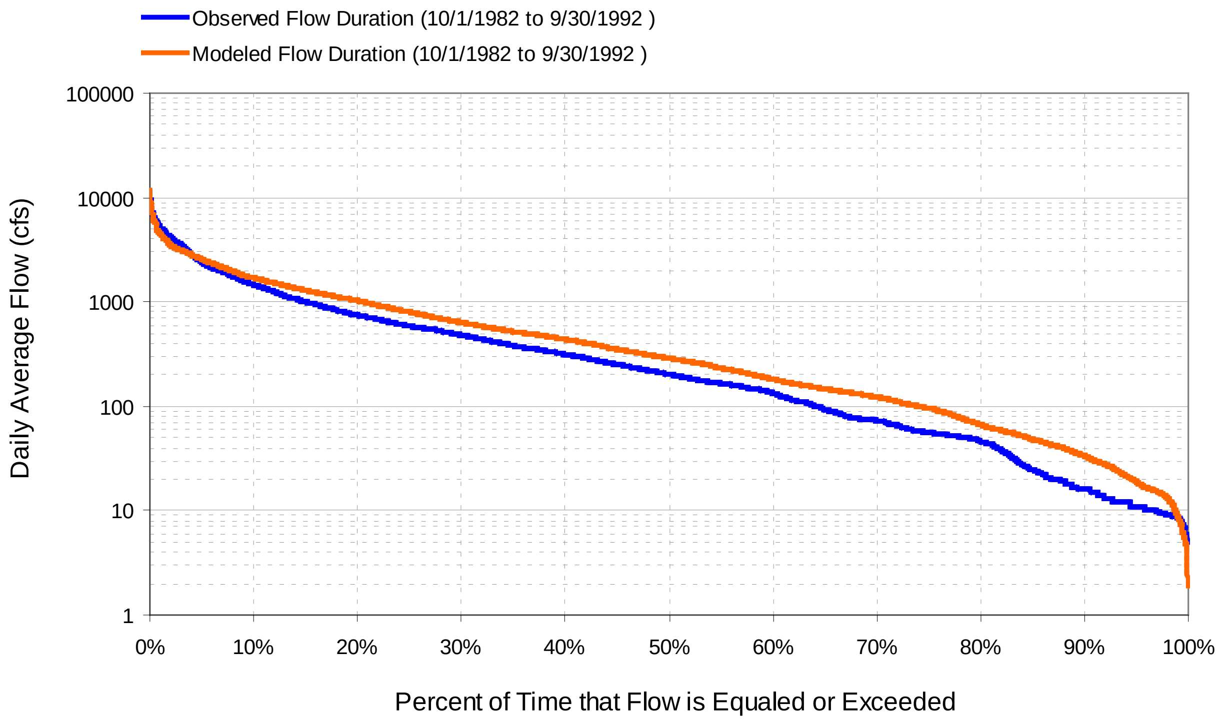


Figure 18. Flow exceedance at USGS 05317000 Cottonwood River near New Ulm, MN - validation period (HSPF).

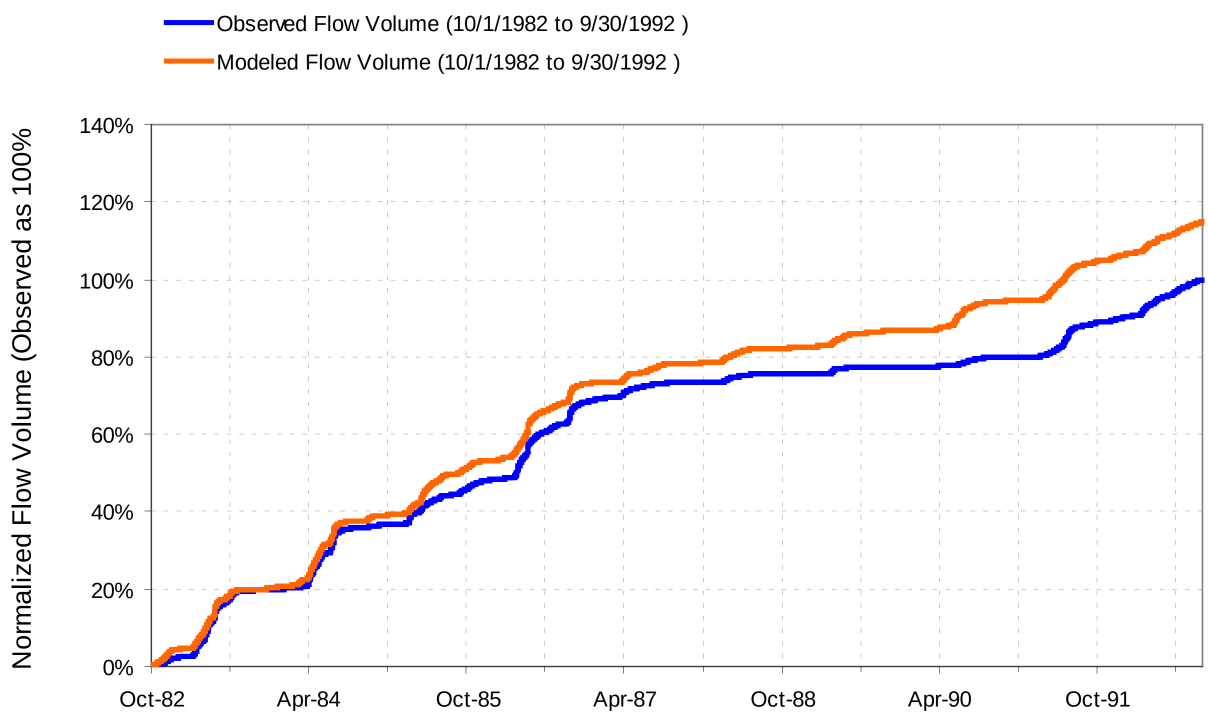


Figure 19. Flow accumulation at USGS 05317000 Cottonwood River near New Ulm, MN - validation period (HSPF).

Table 9. Summary statistics at USGS 05317000 Cottonwood River near New Ulm, MN - validation period (HSPF)

HSPF Simulated Flow		Observed Flow Gage	
REACH OUTFLOW FROM DSN 101 10-Year Analysis Period: 10/1/1982 - 9/30/1992 Flow volumes are (inches/year) for upstream drainage area UpperMSd, mod Water; PET 0.9		USGS 05317000 COTTONWOOD RIVER NEAR NEW ULM, MN Hydrologic Unit Code: 7020008 Latitude: 44.29135177 Longitude: -94.4402495 Drainage Area (sq-mi): 1300	
Total Simulated In-stream Flow:	**6.80**	Total Observed In-stream Flow:	**5.92**
Total of simulated highest 10% flows:	**3.09**	Total of Observed highest 10% flows:	**3.17**
Total of Simulated lowest 50% flows:	**0.57**	Total of Observed Lowest 50% flows:	**0.38**
Simulated Summer Flow Volume (months 7-9):	**1.21**	Observed Summer Flow Volume (7-9):	**1.11**
Simulated Fall Flow Volume (months 10-12):	**0.81**	Observed Fall Flow Volume (10-12):	**0.64**
Simulated Winter Flow Volume (months 1-3):	**1.26**	Observed Winter Flow Volume (1-3):	**1.20**
Simulated Spring Flow Volume (months 4-6):	**3.52**	Observed Spring Flow Volume (4-6):	**2.97**
Total Simulated Storm Volume:	**2.06**	Total Observed Storm Volume:	**2.09**
Simulated Summer Storm Volume (7-9):	**0.40**	Observed Summer Storm Volume (7-9):	**0.45**

Errors (Simulated-Observed)	*Error Statistics*	*Recommended Criteria*		
Error in total volume:	**14.78**	**10**		
Error in 50% lowest flows:	**51.89**	**10**		
Error in 10% highest flows:	-2.54	15		
Seasonal volume error - Summer:	8.63	30		
Seasonal volume error - Fall:	26.43	>> 30	Clear	
Seasonal volume error - Winter:	5.27	30		
Seasonal volume error - Spring:	18.42	30		
Error in storm volumes:	-1.37	20		
Error in summer storm volumes:	-11.91	50		
Nash-Sutcliffe Coefficient of Efficiency, E:	0.779	Model accuracy increases		
Baseline adjusted coefficient (Garrick), E':	0.587	as E or E' approaches 1.0		
Monthly NSE	0.856			

Hydrology Results for Larger Watershed

As described above, parameters determined for the Cottonwood gage were not fully transferable to other gages in the watershed. Therefore, calibration was pursued at a total of nine gages throughout the watershed, including seven gages at the outlet of 8-digit HUCs and two gages on the mainstem. Calibration results were acceptable at all gages (Table 10). The close match between observed and predicted flow volumes at the most downstream available gage (USGS 05330000, Minnesota River near Jordan) are shown in Figure 20 and Figure 21. Additional calibration results are shown in Figures 22 through 26 and Table 11.

Table 10. Summary statistics (percent error): all stations - calibration period (HSPF)

Station	05311000 Minnesota River at Montevideo	05313500 Yellow Medicine River	05316500 Redwood River nr Redwood Falls	05317000 Cottonwood River near New Ulm	05319500 Watonwan River nr Garden City	05320000 Blue Earth River nr Rapidan	05320500 LeSueur River nr Rapidan	05325000 Minnesota River at Mankato	05330000 Minnesota River nr Jordan
Error in total volume:	-7.76	-2.49	0.69	1.61	0.88	-4.35	-0.38	-3.80	-4.25
Error in 50% lowest flows:	-6.49	7.14	9.25	-0.73	5.46	1.58	7.09	-3.29	-7.30
Error in 10% highest flows:	-5.98	2.33	4.12	4.26	-1.37	0.30	4.75	-0.94	-1.25
Seasonal volume error - Summer:	-8.31	-19.71	-4.24	-6.09	5.37	4.45	-9.04	-3.11	-3.21
Seasonal volume error - Fall:	-9.09	-12.80	-4.17	4.07	7.25	-12.99	1.53	-5.15	-6.26
Seasonal volume error - Winter:	-16.82	7.94	8.85	-5.95	-12.48	-17.90	33.10	-7.28	-9.55
Seasonal volume error - Spring:	-5.42	1.52	1.47	5.54	0.90	-3.44	-3.36	-3.17	-3.33
Error in storm volumes:	1.81	10.67	7.14	0.86	5.12	8.79	10.76	12.41	8.85
Error in summer storm volumes:	37.17	8.78	9.86	-10.51	-7.13	12.38	6.76	14.66	7.85
Daily Nash-Sutcliffe Coefficient of Efficiency, E:	0.784	0.573	0.673	0.754	0.728	0.811	0.539	0.899	0.916
Monthly Nash-Sutcliffe Coefficient of Efficiency, E:	0.886	0.851	0.596	0.885	0.888	0.939	0.889	0.954	0.953

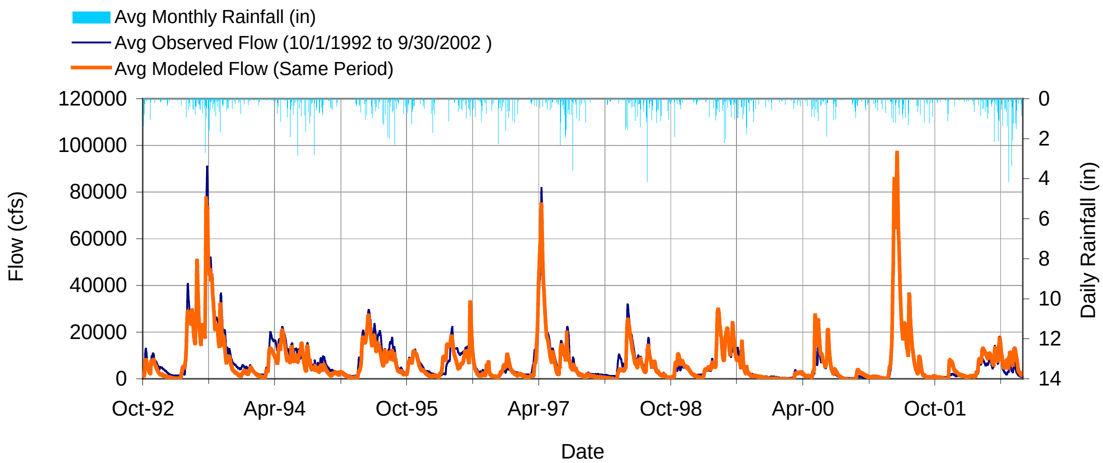


Figure 20. Mean daily flow simulation at USGS 05330000 Minnesota River near Jordan, MN - calibration period (HSPF).

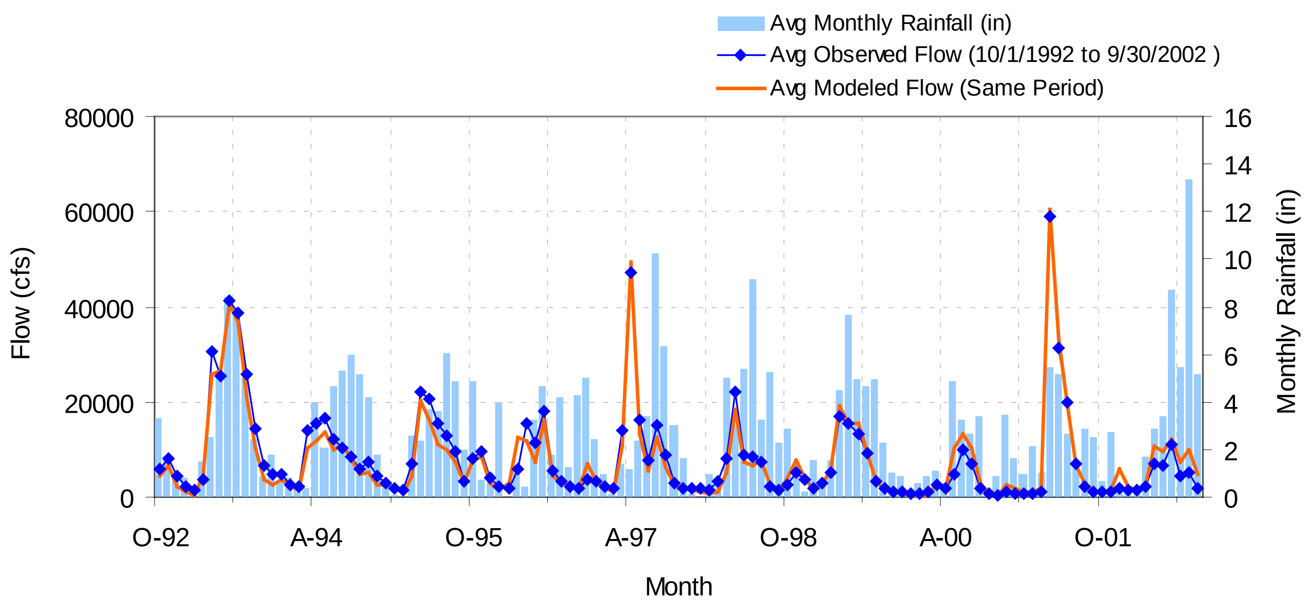
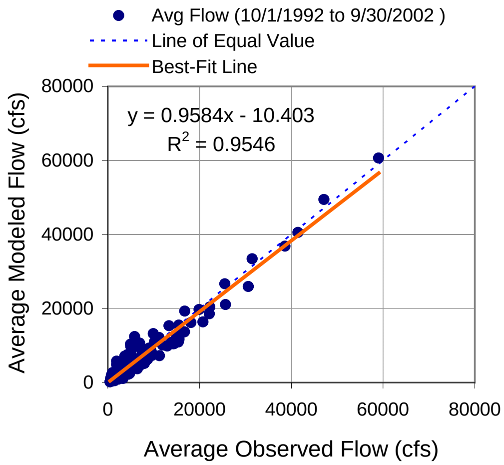


Figure 21. Mean monthly flow simulation at USGS 05330000 Minnesota River near Jordan, MN - calibration period (HSPF).



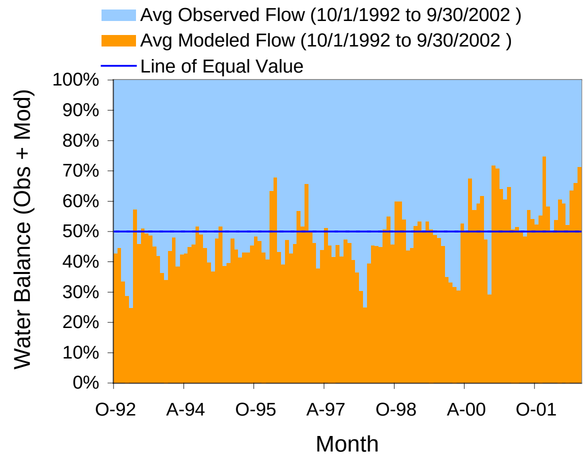
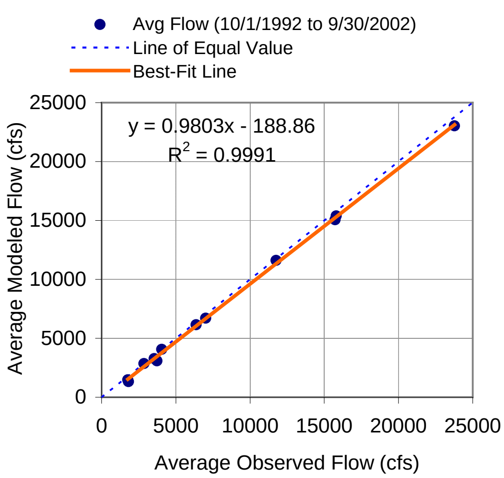


Figure 22. Monthly flow regression and temporal variation at USGS 05330000 Minnesota River near Jordan, MN – calibration period (HSPF).



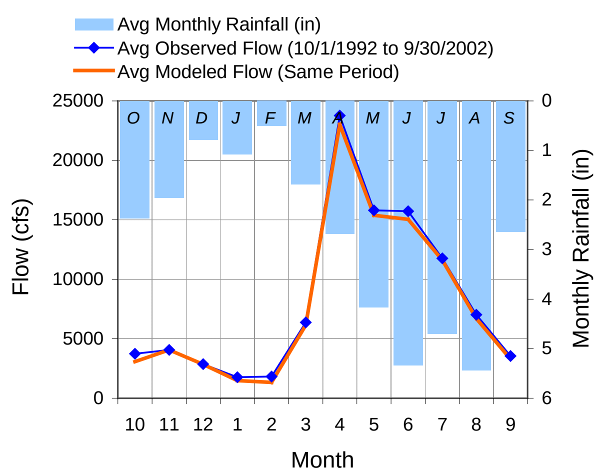


Figure 23. Seasonal regression and temporal aggregate at USGS 05330000 Minnesota River near Jordan, MN – calibration period (HSPF).

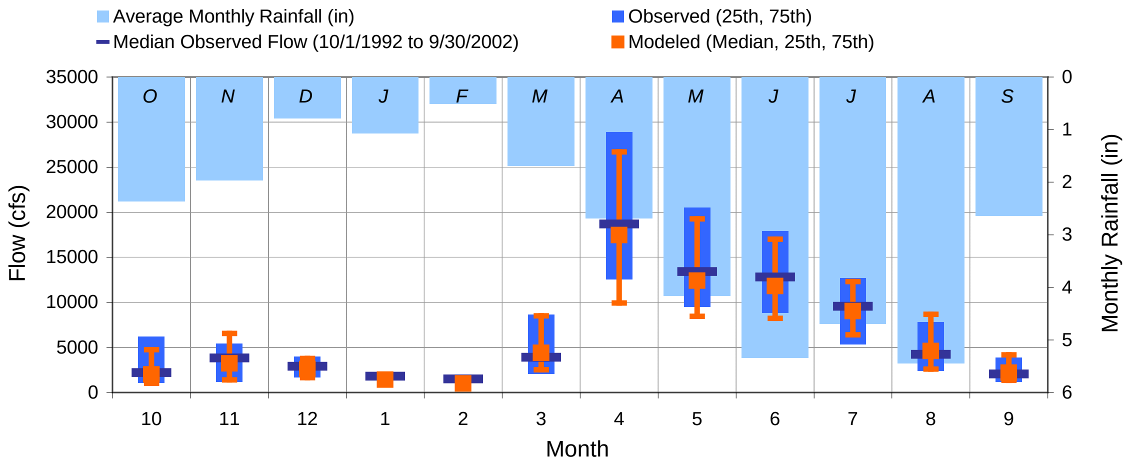


Figure 24. Seasonal medians and ranges at USGS 05330000 Minnesota River near Jordan, MN – calibration period (HSPF).

Table 11. Seasonal summary at USGS 05330000 Minnesota River near Jordan, MN – calibration period (HSPF)

MONTH	OBSERVED FLOW (CFS)				MODELED FLOW (CFS)			
	MEAN	MEDIAN	25TH	75TH	MEAN	MEDIAN	25TH	75TH
Oct	3732.17	2190.00	1082.50	6237.50	3081.52	2001.01	1032.73	4762.72
Nov	4054.61	3825.00	1210.00	5462.50	4059.50	3234.97	1403.38	6562.34
Dec	2858.86	2900.00	1702.50	4000.00	2846.70	2613.94	1647.86	3784.83
Jan	1757.39	1800.00	1392.50	2200.00	1474.05	1435.78	893.52	1978.66
Feb	1811.52	1500.00	1272.50	1900.00	1327.81	989.91	656.04	1398.81
Mar	6364.40	3910.00	2080.00	8627.50	6154.83	4403.41	2529.67	8517.95
Apr	23775.27	18700.00	12550.00	28925.00	23021.23	17473.36	9942.81	26689.60
May	15802.45	13400.00	9470.00	20500.00	15392.60	12413.48	8451.15	19265.36
Jun	15733.60	12800.00	8805.00	17900.00	15049.13	11811.63	8221.43	17020.20
Jul	11756.52	9565.00	5347.50	12675.00	11613.34	9036.76	6415.22	12314.82
Aug	7020.71	4225.00	2377.50	7782.50	6704.00	4601.26	2608.84	8692.04
Sep	3542.37	2040.00	1205.00	3910.00	3279.92	2191.42	1342.62	4185.19

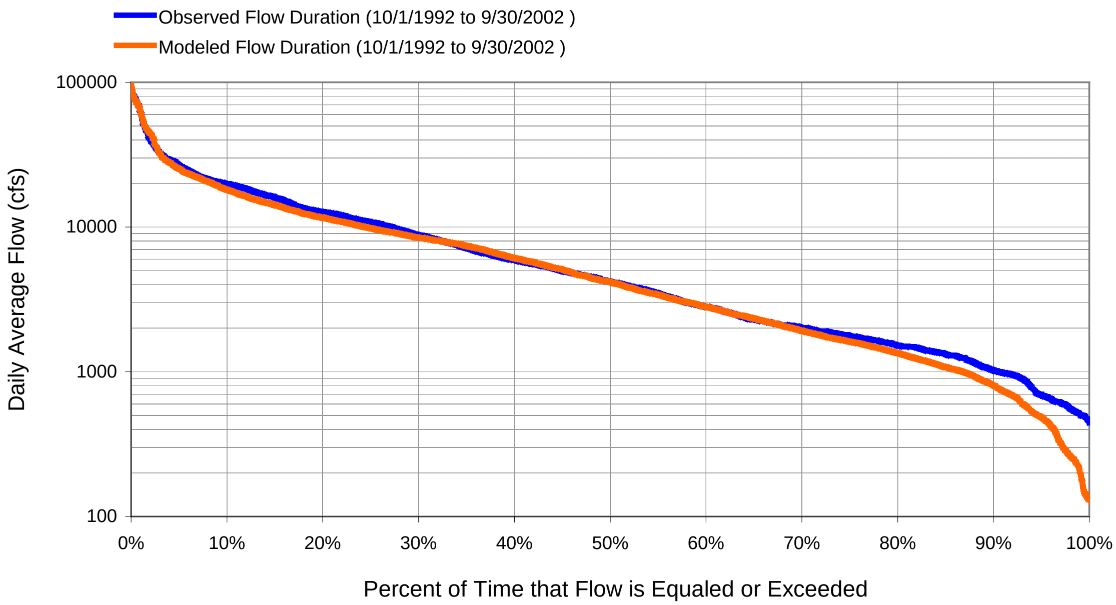


Figure 25. Flow exceedence at USGS 05330000 Minnesota River near Jordan, MN – calibration period (HSPF).

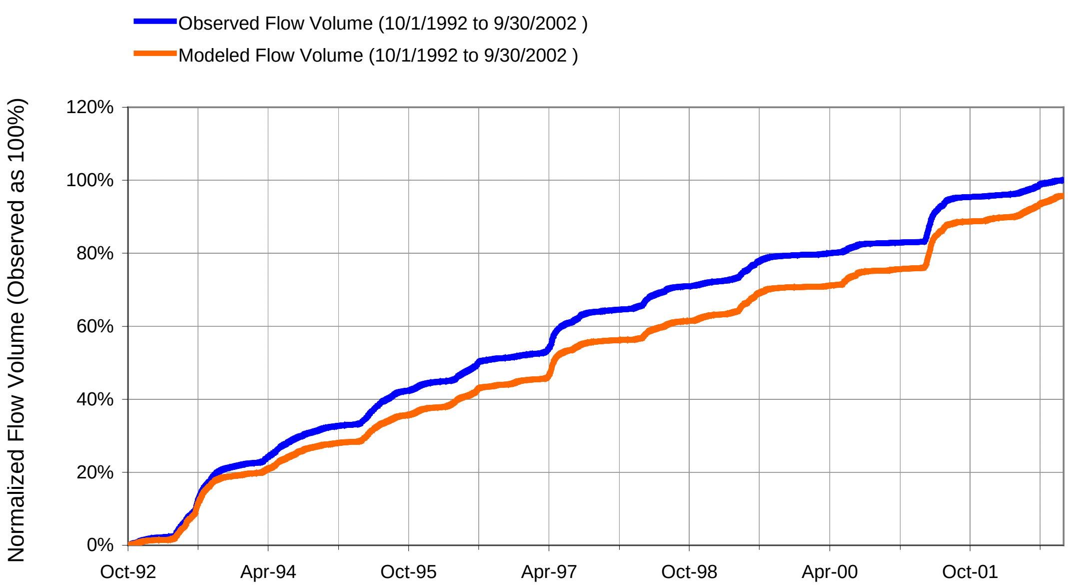


Figure 26. Flow accumulation at USGS 05330000 Minnesota River near Jordan, MN – calibration period (HSPF).

For hydrologic validation, the FTable developed during calibration to represent Lac qui Parle dam did not appear to provide realistic results for the earlier period. Therefore, the model was respecified using gaged flows below Lac qui Parle as a boundary condition. Results of the validation exercise are summarized in Table 12. Problems similar to those experienced on the Cottonwood River were seen at all tributary gages, with overprediction of lower flows in summer. However, as noted above, this is likely due to the use of land use and model parameters that are more reflective of current conditions and is not believed to present a bar to application of the model.

Table 12. Summary statistics: all stations - validation period (HSPF)

Station	05313500 Yellow Medicine River	05316500 Redwood River nr Redwood Falls	05317000 Cottonwood River near New Ulm	05319500 Watonwan River nr Garden City	05320000 Blue Earth River nr Rapidan	05320500 LeSueur River nr Rapidan	05325000 Minnesota River at Mankato	05330000 Minnesota River nr Jordan
Error in total volume:	-3.473	8.55	14.78	13.31	5.11	21.93	-13.43	-9.73
Error in 50% lowest flows:	48.58	74.44	51.89	75.61	67.23	59.34	-2.50	-0.75
Error in 10% highest flows:	-11.24	-11.99	-2.54	-0.33	-7.20	18.94	-17.33	-15.02
Seasonal volume error - Summer:	-20.37	11.63	8.63	29.35	19.13	34.92	-17.07	-13.91
Seasonal volume error - Fall:	22.08	7.22	26.43	21.51	16.11	39.00	-13.92	-11.30
Seasonal volume error - Winter:	-8.64	-1.04	5.27	3.55	-6.63	9.97	-12.26	-9.88
Seasonal volume error - Spring:	-0.22	11.95	18.42	9.93	2.58	19.17	-12.17	-7.27
Error in storm volumes:	5.20	-2.20	-1.37	23.26	12.85	29.98	15.60	14.60
Error in summer storm volumes:	-15.69	-11.47	-11.91	30.61	19.48	61.17	10.28	4.11
Daily Nash-Sutcliffe Coefficient of Efficiency, E:	0.317	0.491	0.779	0.345	0.712	0.374	0.773	0.779
Monthly Nash-Sutcliffe Coefficient of Efficiency, E:	0.714	0.671	0.856	0.598	0.829	0.717	0.830	0.830

Water Quality Calibration and Validation

The 20 Watershed models are designed to provide water quality simulation for TSS, total nitrogen, and total phosphorus. Total suspended solids is simulated with the standard HSPF approach (USEPA 2006), and takes advantage of detailed calibration efforts for the TMDL model (Tetra Tech 2008), which included radionuclide attribution of sediment sources to field, ravine, and channel sources. However, the segmentation of the 20 Watershed model limits the ability to effectively transfer channel erosion and deposition parameters.

In contrast to TSS, total nitrogen and total phosphorus are simulated in this application in a simplistic fashion, as HSPF general quality constituents (GQUALs) subject to an exponential decay rate during transport. This contrasts with the approach in the TMDL model, where individual nutrient species are simulated along with kinetic transformations and algal uptake/release in the stream reaches using the HSPF NUTRX routines. A significant drawback of the GQUAL approach to nutrients is that it is not readily possible to account for the nutrient content of channel bank erosion, which forms an important component of the total phosphorus load in the TMDL model.

The water quality calibration focuses on the replication of monthly loads, as specified in the project QAPP. Given the approach to water quality simulation in the 20 Watershed model a close match to individual concentration observations cannot be expected. However, comparison to monthly loads presents challenges, as monthly loads are not observed. Instead, monthly loads must be estimated from scattered concentration grab samples and continuous flow records. Such estimation inherently includes uncertainty because it depends on the degree and form in which concentration and flow are correlated with one another. Further, the bulk of the load of sediment and sediment-associated phosphorus is likely to move through the system in a limited number of high flow events, which typically have not been monitored. As a result, the monthly load calibration is inevitably based on the comparison of two uncertain numbers. Nonetheless, calibration is able to achieve a reasonable agreement. Further, the load comparisons were supported by detailed examinations of the relationships of flows to loads and concentrations and the distribution of concentration prediction errors versus flow, time, and season, as well as standard time series plots.

For application on a nationwide basis, the 20 Watershed protocols assume that sediment and phosphorus loads will likely exhibit a strong positive correlation to flow (and associated erosive processes), while total nitrogen loads, which often have a dominant groundwater component, will not. Accordingly, sediment and phosphorus loads were estimated from observations using a flow-stratified log-log regression approach, while total nitrogen loads were estimated using a flow-stratified averaging estimator, consistent with the findings of Preston et al. (1989).

As with hydrology, initial calibration and validation of water quality was done on the Cottonwood River, at USGS gage 05317000, using 1993-2002 for calibration and 1986-1992 for validation. As with hydrology, calibration was performed on the later period as this better reflects the land use included in the model. The start of the validation period is constrained by data availability. Initial sediment parameters were transferred from the TMDL model, with area-weighting to account for the change in subwatershed boundaries and the different representation of land use in the 20 Watershed model. It was found that this approach resulted in overestimation of the peak loading at high flows associated with ravine incision. On investigation, it was determined that this was caused by the different methods of processing of rainfall data for the two models. In particular, the approach to disaggregation of daily rainfall totals to hourly rainfall in the BASINS4 meteorological dataset results in greater (and, in some cases, unrealistic) estimates of peak rainfall intensity. As ravine incision depends in a nonlinear fashion on maximum runoff rates this component of the model is highly sensitive to rainfall intensity. This was addressed by reducing the exponent on flow depth (JGER) in the 20 Watershed model and then adjusting the coefficient (KGER) to achieve calibration. Channel scour and deposition critical shear stresses also needed to be adjusted.

Once these changes were made, the sediment model performed well for both the calibration and validation periods. Time series of simulated and estimated sediment loads at the Cottonwood gage for both periods are shown in Figure 27 and statistics for the two periods are provided separately in Table 13. The key statistic in Table 13 (consistent with the QAPP) is the relative percent error, which shows the error in the prediction of monthly load normalized to the estimated load. The table also shows the relative average absolute error, which is the average of the relative magnitude of errors in individual monthly load predictions. This number is inflated by outlier months in which the simulated and estimated loads differ by large amounts (which may be as easily due to uncertainty in the estimated load due to limited data as to problems with the model) and the third statistic, the relative median absolute error, is likely more relevant and shows good agreement.

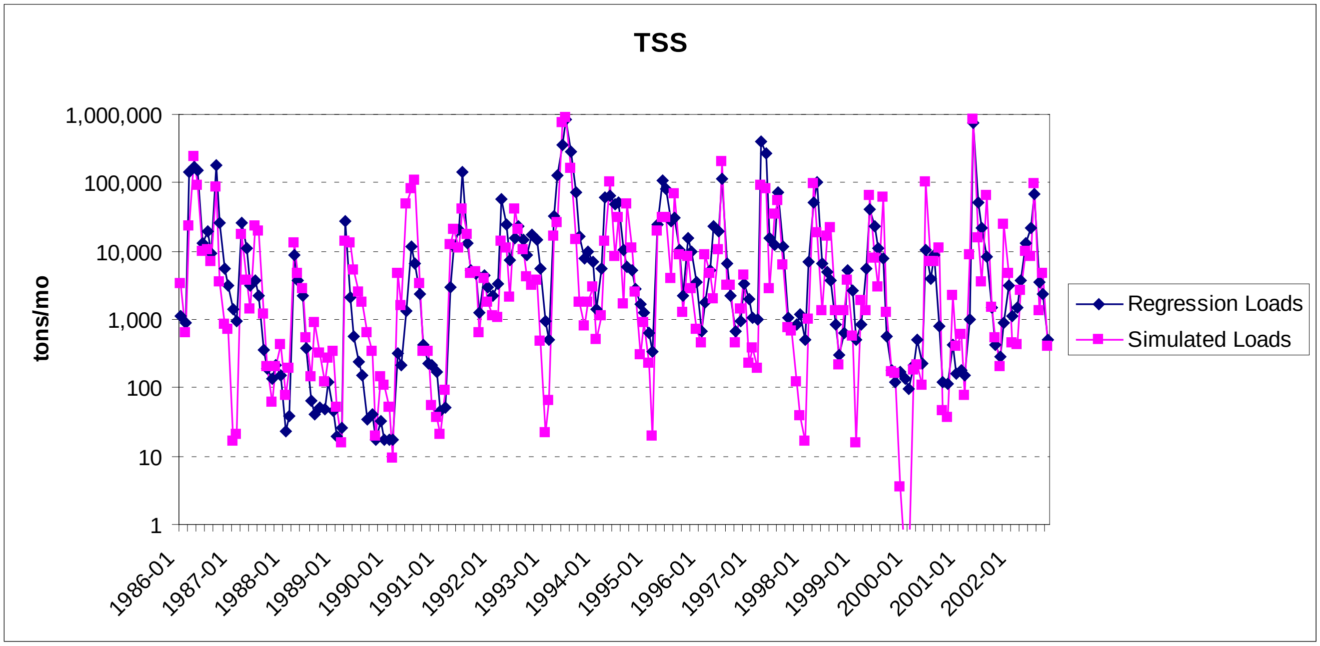


Figure 27. Fit for monthly load of TSS at USGS 05317000 Cottonwood River (HSPF).

Table 13. Model fit statistics (observed minus predicted) for monthly TSS loads using stratified regression (HSPF)

Statistic	Calibration period (1993-2002)	Validation period (1986-1992)
Relative Percent Error	7.5%	13.1%
Relative Average Absolute Error	54%	79%
Relative Median Absolute Error	1.7%	9.9%

A variety of other diagnostics were also pursued to ensure agreement between the model and observations. These are available in full in the calibration spreadsheets, but a few examples are provided below. First, load-flow power plots were compared for individual days (Figure 28 and Figure 29). These confirm that the relationship between flow and load is consistent across the entire range of observed flows, for both the calibration and validation periods.

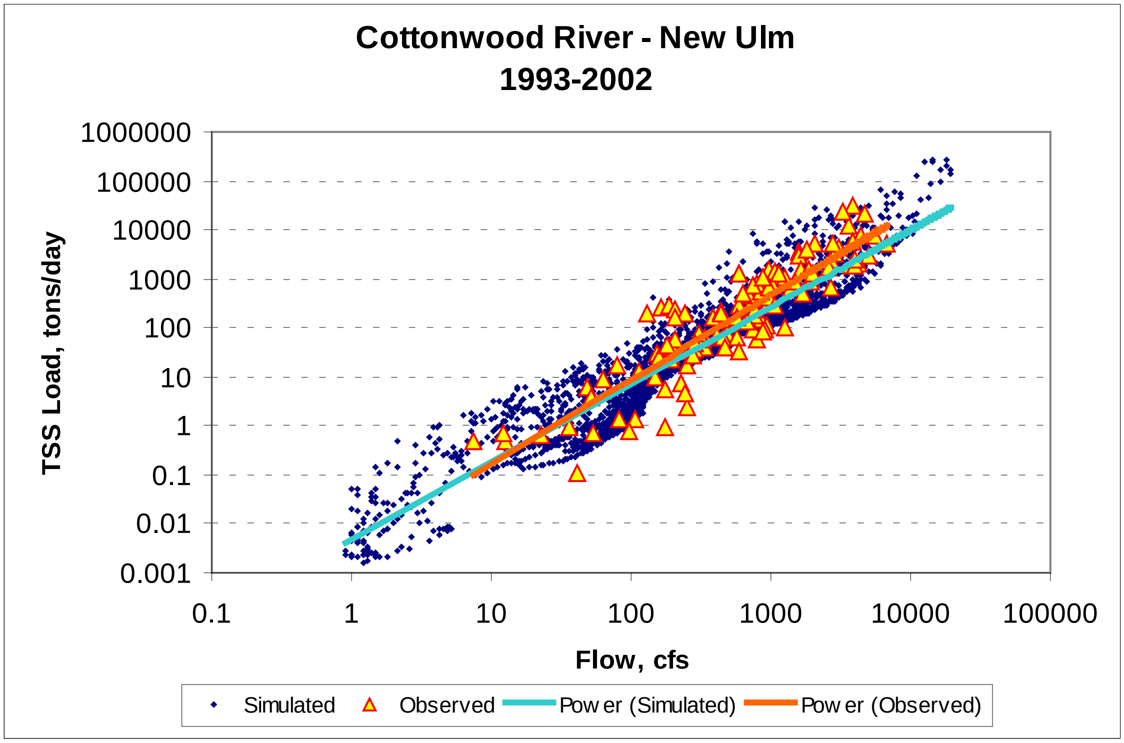


Figure 28. Power plot for observed and simulated TSS at USGS 05317000 Cottonwood River - calibration period (HSPF).

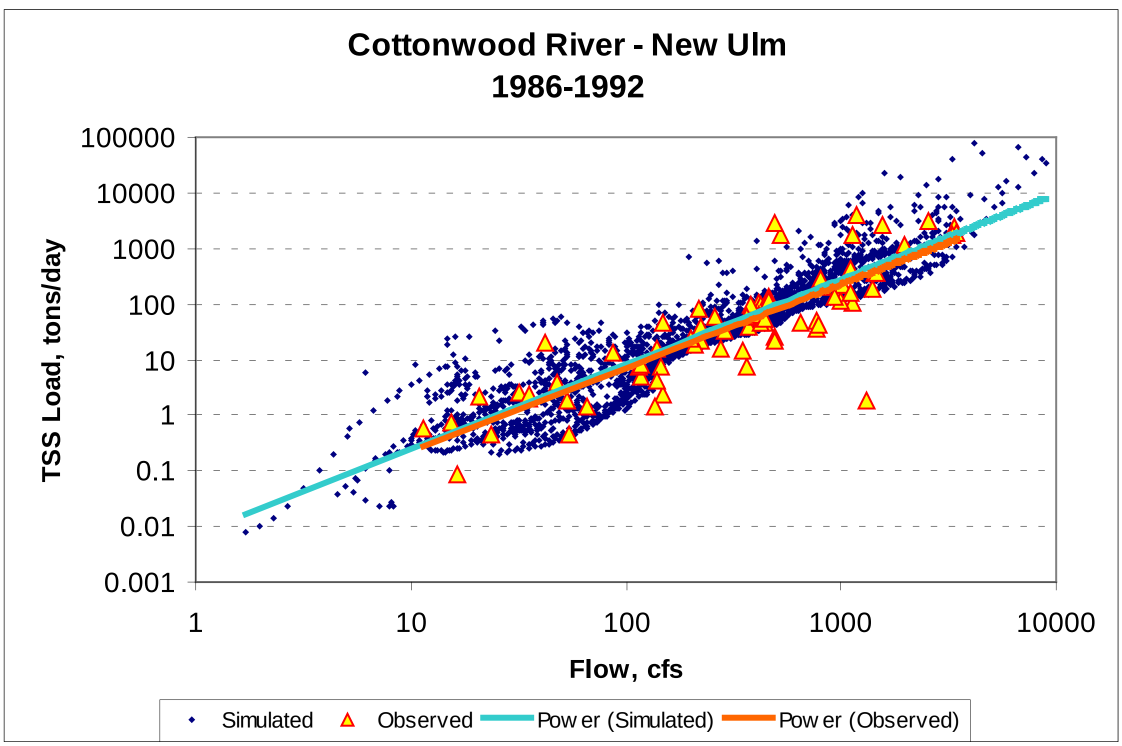


Figure 29. Power plot for observed and simulated TSS at USGS 05317000 Cottonwood River - validation period (HSPF).

Standard time series plots (Figure 30) show that observed and simulated concentrations achieve good agreement, although individual observations may deviate. Plots of concentration error versus flow and versus month (not shown) were used to guard against hydrologic and temporal bias. Finally, statistics on concentration (Table 14) show that low median errors are achieved.

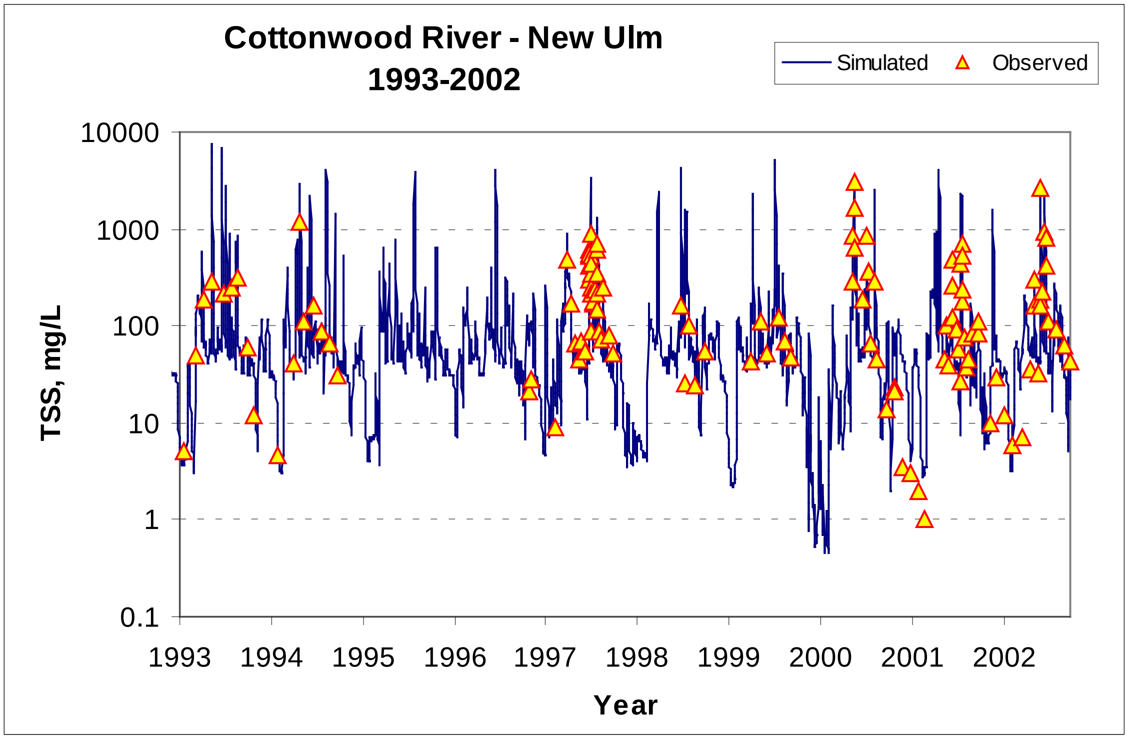


Figure 30. Time series plot of TSS concentration at USGS 05317000 Cottonwood River (HSPF).

Table 14. Relative errors (observed minus predicted), TSS concentration at USGS 05317000 Cottonwood River (HSPF)

Statistic	Calibration period (1993-2002)	Validation period (1986-1992)
Count	121	75
Concentration Average Error	-58.8%	13.1%
Concentration Median Error	0.41%	-2.7%

For simulation of total phosphorus and total nitrogen, the TMDL model parameters, which address individual nutrient species separately, were converted to approximately equivalent parameters on total nutrients using area weighting. The model simulates total phosphorus from the uplands as having sediment-associated (both with sheet and rill erosion and ravine incision) and buildup-washoff components on the land surface along with monthly variable interflow and groundwater components. The sediment-associated component of the surface load reflects mineral phosphorus, while the buildup-washoff component addresses the organic phosphorus. Total nitrogen is simulated with a buildup-washoff component for surface loading, plus monthly variable interflow and groundwater components.

The original parameter set derived in this way did not perform well for the Cottonwood River phosphorus simulation – probably because the process of weighting the parameters related to different agricultural land uses (manured land, conventional tillage, and conservation tillage) assumes linear additivity and independence of hydrologic variation. Calibration was achieved by adjusting downward the sediment potency factors. A similar approach was applied for other subwatersheds, maintaining the spatial variability in loading rates incorporated in the TMDL model.

In-stream, total phosphorus is represented as a simple general quality component, subject to exponential decay. Decay rates were adapted from the most recent version of the SPARROW model (Alexander et al. 2008), which estimates decay coefficients as a function of stream depth, using typical depths for streams of different orders.

Monthly loading series for total phosphorus are shown in Figure 31 and load statistics are summarized in Table 15. In general, the observed and estimated total phosphorus loads attain a good match for both the calibration and validation periods.

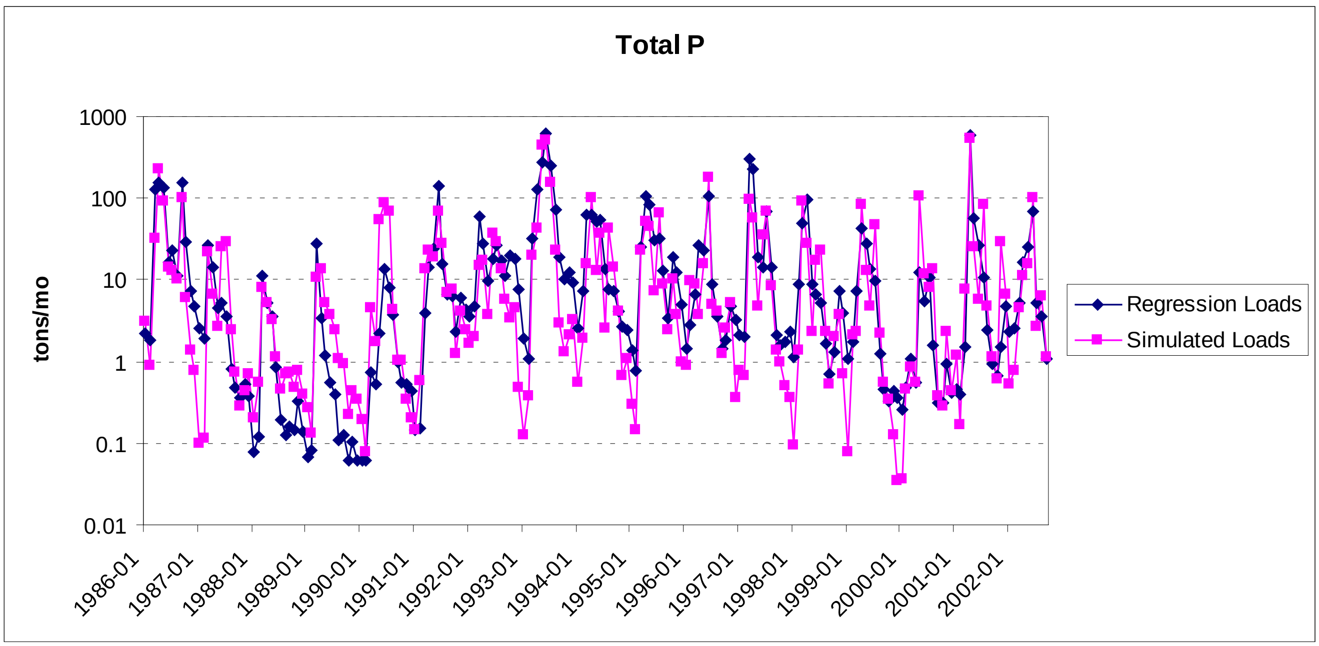


Figure 31. Fit for monthly load of total phosphorus at USGS 05317000 Cottonwood River (HSPF).

Table 15. Model fit statistics (observed minus predicted) for monthly phosphorus loads using stratified regression (HSPF)

Statistic	Calibration period (1993-2002)	Validation period (1986-1992)
Relative Percent Error	23.0%	15.8%
Average Absolute Error	54%	67%
Median Absolute Error	2.5%	13.5%

As with suspended sediment, additional diagnostics for total phosphorus included flow-load power plots (Figure 32 and Figure 33), time series plots (Figure 34) and analysis of concentration errors (Table 16). All show good agreement.

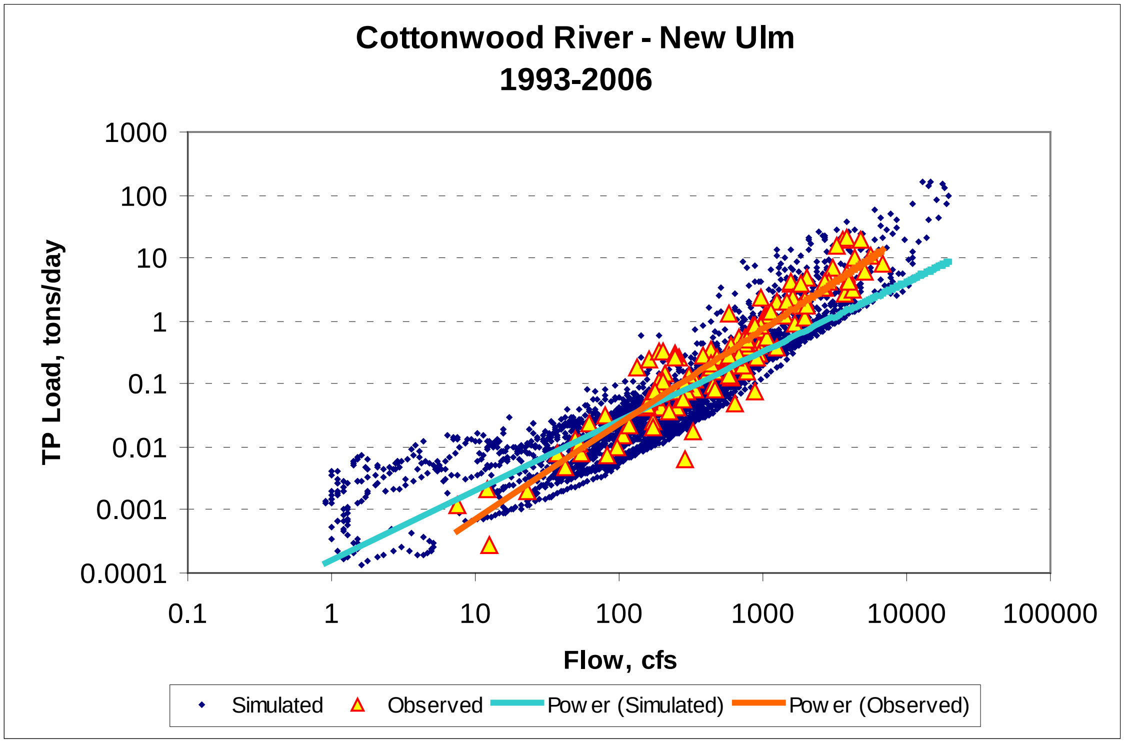


Figure 32. Power plot for observed and simulated total phosphorus at USGS 05317000 Cottonwood River – calibration period (HSPF).

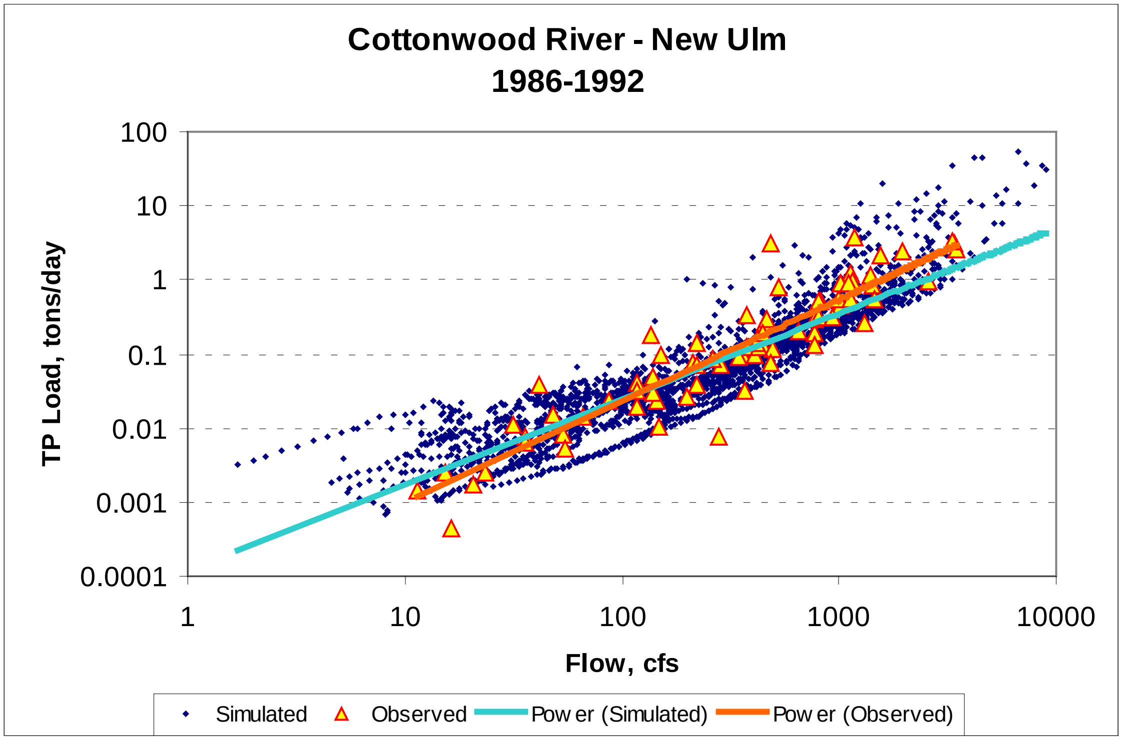


Figure 33. Power plot for observed and simulated total phosphorus at USGS 05317000 Cottonwood River - validation period (HSPF).

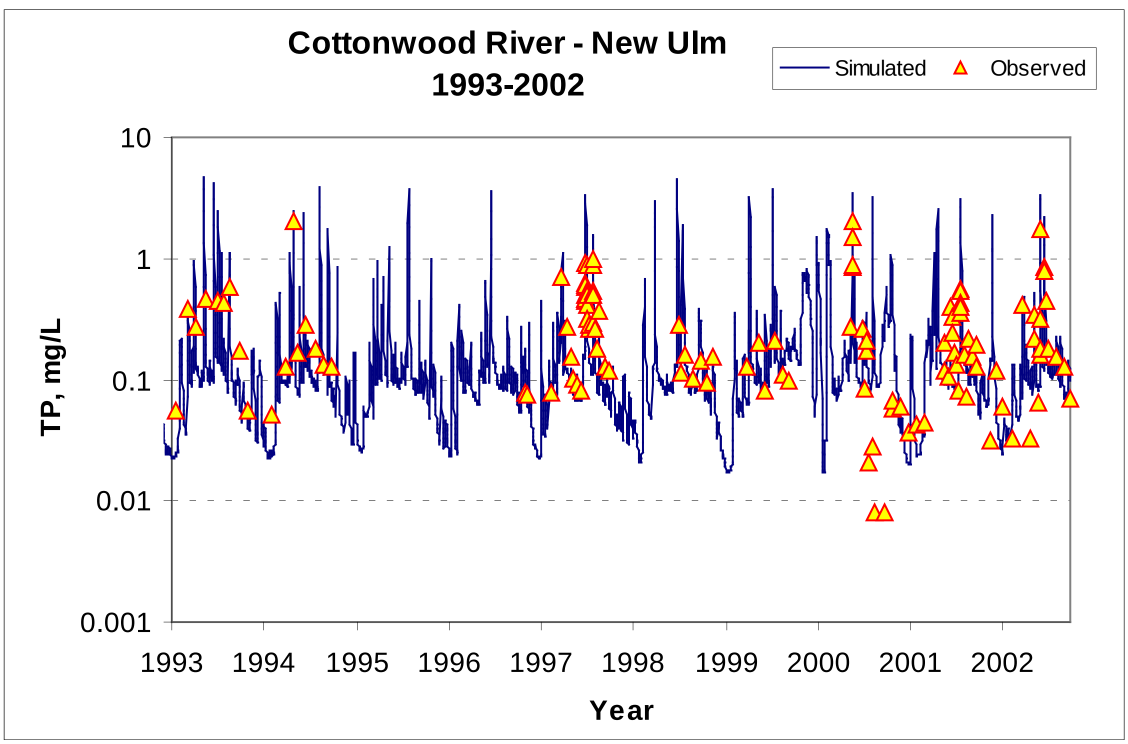


Figure 34. Time series plot of total phosphorus concentration at USGS 05317000 Cottonwood River (HSPF).

Table 16. Relative errors (observed minus predicted), total phosphorus concentration at USGS 05317000 Cottonwood River (HSPF)

Statistic	Calibration period (1993-2002)	Validation period (1986-1992)
Count	123	75
Concentration Average Error	-52.9%	18.0%
Concentration Median Error	5.3%	-0.48%

For total nitrogen fewer data are available because many sampling events omitted one or more nitrogen species. This increases the uncertainty of the comparison. However, development of the TMDL model also revealed that there is large temporal variability in observed total nitrogen concentrations, likely related to seasonal differences in the timing and amount of fertilizer application. (In this watershed, the primary fertilizer applications are of subsurface anhydrous ammonia, which can occur in both spring and fall, along with animal manure.)

During calibration for total nitrogen the major change from the original parameter set was scaling down the buildup-washoff factors. Subsurface concentrations, which represent the major loading pathway for nitrogen, were generally acceptable as previously developed, except that the contribution of organic matter to groundwater nitrogen loading was reduced. As with phosphorus, a similar procedure was applied across all model subwatersheds, retaining the spatial variability in nitrogen loading that was identified in the development of the TMDL model.

Results for total nitrogen are summarized in Figure 35 through Figure 38, Table 17, and Table 18, following the same format as total phosphorus. The results are acceptable, although there is clearly greater uncertainty in the prediction of total nitrogen than in the prediction of total phosphorus.

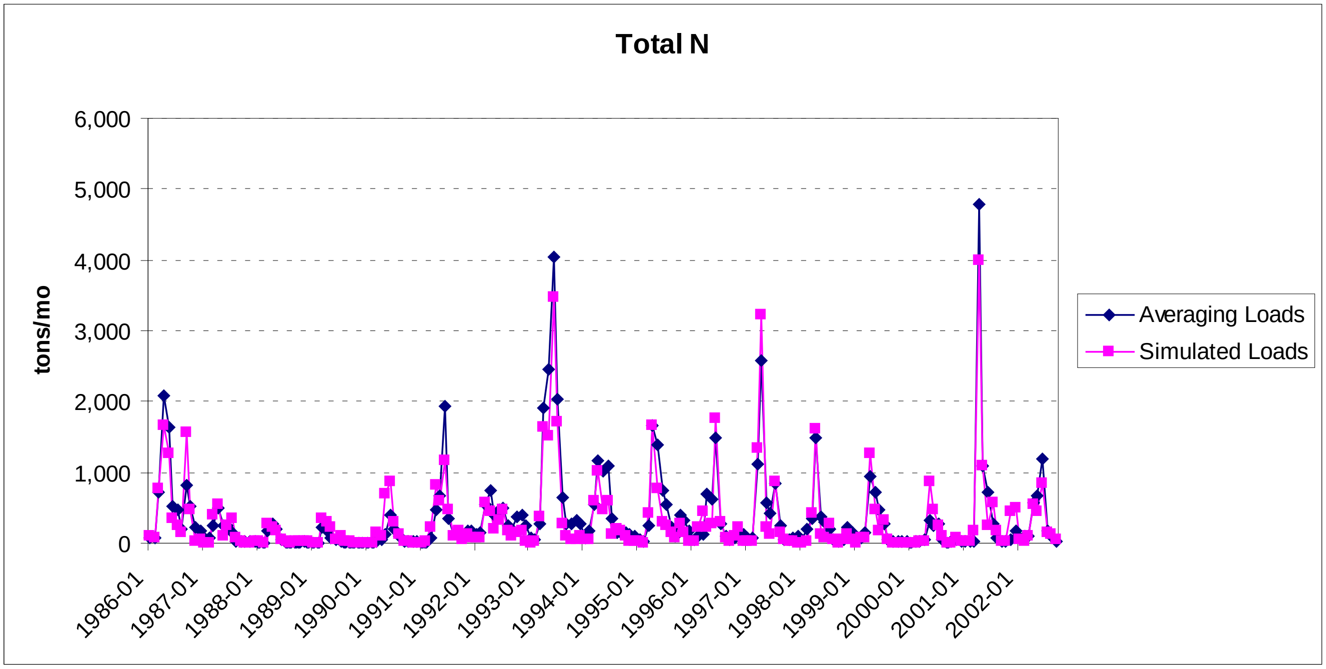


Figure 35. Fit for monthly load of total nitrogen at USGS 05317000 Cottonwood River (HSPF).

Table 17. Model fit statistics (observed minus predicted) for monthly total nitrogen loads using averaging estimator (HSPF)

Statistic	Calibration period (1993-2002)	Validation period (1986-1992)
Relative Percent Error	15.4%	16.2%
Average Absolute Error	35%	43%
Median Absolute Error	5.4%	14.5%

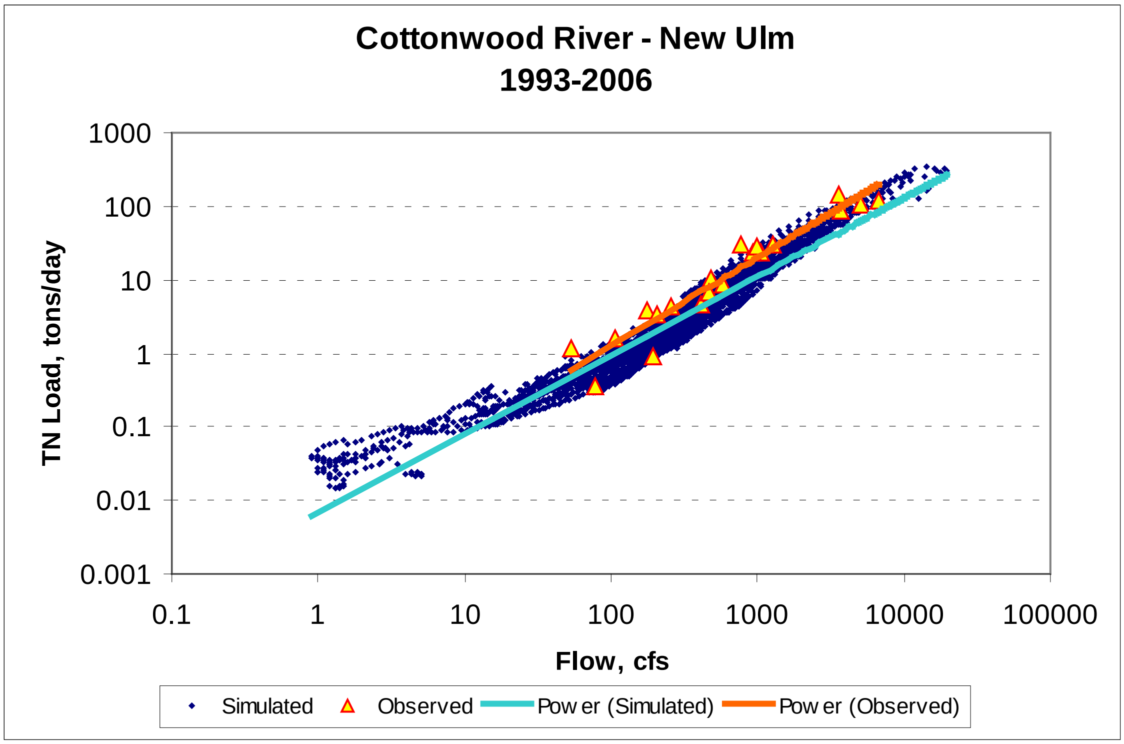


Figure 36. Power plot for observed and simulated total nitrogen at USGS 05317000 Cottonwood River - calibration period (HSPF).

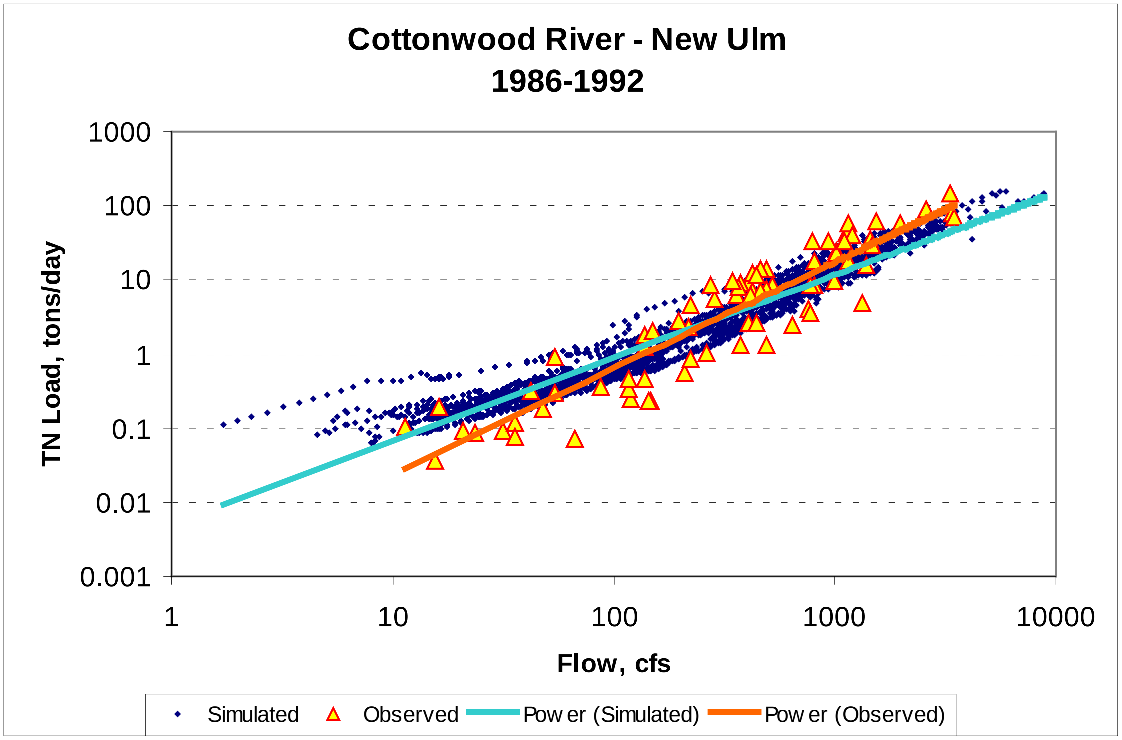


Figure 37. Power plot for observed and simulated total nitrogen at USGS 05317000 Cottonwood River - validation period (HSPF).

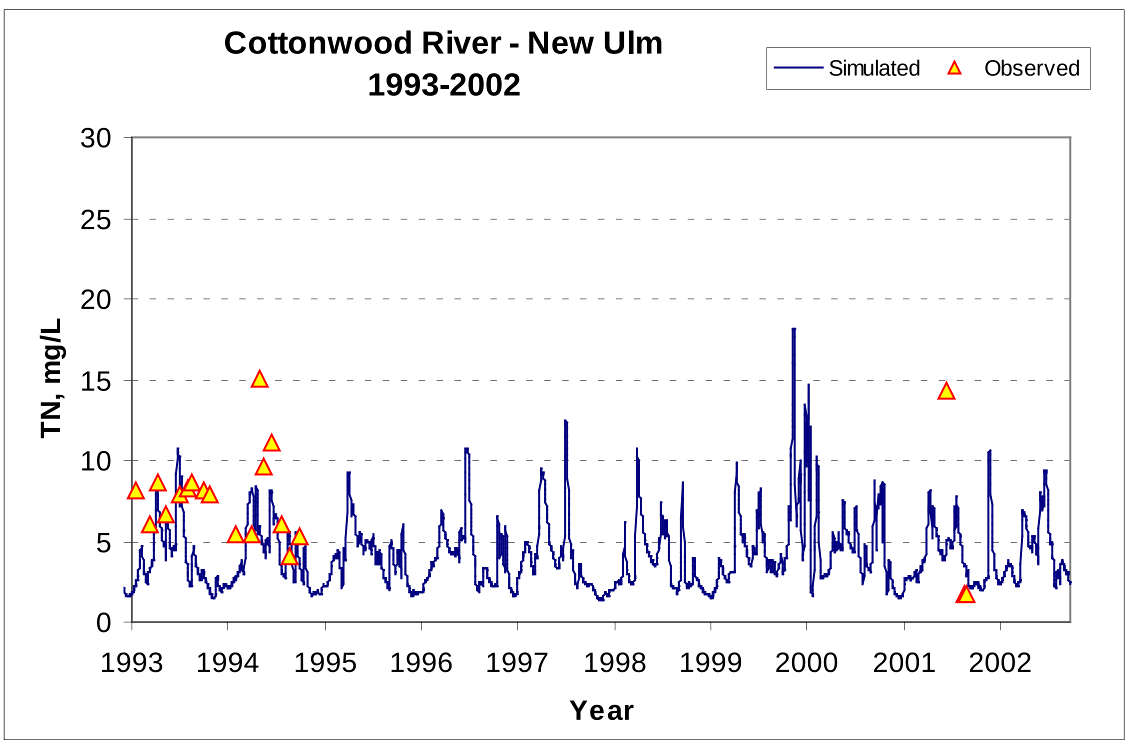


Figure 38. Time series plot of total nitrogen concentration at USGS 05317000 Cottonwood River (HSPF).

Table 18. Relative errors (observed minus predicted), total nitrogen concentration at USGS 05317000 Cottonwood River (HSPF)

Statistic	Calibration period (1993-2002)	Validation period (1986-1992)
Count	20	75
Concentration Average Error	36.6%	25.6%
Concentration Median Error	39.4%	22.2%

Water Quality Results for Larger Watershed

As with hydrology, the Cottonwood parameters for water quality are not directly transferable to other portions of the watershed. It is well established that there are strong spatial gradients in ravine and bank erosion of solids, soil test phosphorus, and subsurface loading of nitrogen, with the highest rates generally in the Blue Earth and Le Sueur basins and the lowest rates in the western watersheds. However, a consistent procedure for translating the parameters of the more detailed TMDL model (Tetra Tech 2008) to the 20 Watershed model provided good results, requiring only relatively minor modifications.

Summary statistics for the water quality calibration and validation at other stations in the watershed are provided in Table 19 and Table 20. The relative percent error on the monthly loads is within 26 percent for all parameters at all stations during the calibration period, with the exception of the mainstem station at Mankato. This station is immediately below the confluence of the Minnesota River and the Blue Earth River (a major source of loading) and it is believed that concentration measurements there are influenced by incomplete mixing, which seems to be borne out by much better fit downstream at Jordan. In contrast, the validation tests underestimate total solids and total phosphorus loads at a number of stations. This is likely due to changes in land use and management over time (including aggressive efforts to increase conservation tillage and decrease erosion), coupled with propagation of errors in the hydrologic simulation.

Table 19. Summary statistics for water quality: all stations - calibration period 1993-2002 (HSPF)

Station	05313500 Yellow Medicine River	05316500 Redwood River nr Redwood Falls	05317000 Cottonwood River near New Ulm	05319500 Watonwan River nr Garden City	05320000 Blue Earth River nr Rapidan	05320500 LeSueur River nr Rapidan	05325000 Minnesota River at Mankato	05330000 Minnesota River nr Jordan
Relative Percent Error TSS Load	-3.8%	2.2%	7.5%	11.4%	-21.6%	2.6%	-3.7%	6.4%
TSS Concentration Median Error	6.5%	8.7%	0.4%	19.5%	4.1%	-1.7%	41.7%	25.8%
Relative Percent Error TP Load	6.9%	10.8%	23.0	2.7%	1.5%	-0.1%	-52.7%	1.3%
TP Concentration Median Error	7.1%	21.2%	5.3%	23.2%	0.53%	1.8%	-6.6%	15.0%
Relative Percent Error TN Load	-21.0%	-7.7%	15.4	-7.2%	-9.0%	14.9%	44.1%	6.5%

TN Concentration Median Error	19.1%	16.7%	39.4%	-4.9%	-10.2%	6.5%	-23.9%	3.1%

Table 20. Summary statistics for water quality: all stations - validation period 1986-1992 (HSPF)

Station	05313500 Yellow Medicine River	05316500 Redwood River nr Redwood Falls	05317000 Cottonwood River near New Ulm	05319500 Watonwan River nr Garden City	05320000 Blue Earth River nr Rapidan	05320500 LeSueur River nr Rapidan	05325000 Minnesota River at Mankato	05330000 Minnesota River nr Jordan
Relative Percent Error TSS Load	-6.4%	-17.0%	13.1%	-46.4%	-25.2%	-36.5%	-37.1%	-6.8%
TSS Concentration Median Error	3.0%	-5.2%	-2.7%	12.7%	ND	11.9%	11.3%	9.1%
Relative Percent Error TP Load	-38.1%	-21.1%	15.8%	-35.0%	-14.0%	-31.7%	-85.3%	-27.3%
TP Concentration Median Error	3.6%	-1.7%	-0.48%	17.6%	ND	-51.9%	-5.1%	29.1%
Relative Percent Error TN Load	-5.0%	-4.9%	6.2%	-14.8%	-19.5%	8.7%	38.6%	-1.2%
TN Concentration Median Error	-43.1%	-12.7%	22.2%	3.2%	ND	29.6%	32.2%	-4.9%

SWAT Modeling

The SWAT model for the Minnesota River basin was set up with the ArcSWAT interface using the same subwatersheds and other geospatial coverages described above for the HSPF model. The SWAT model also uses the same weather data, but at a daily, rather than hourly timestep.

Changes Made to Base Data Provided

No changes were made to the meteorological or land use base data for the SWAT model.

Assumptions

Three major reservoirs occur in the upper portion of the Minnesota River basin. These are Swan Lake, Lac Qui Parle Dam and Big Stone Lake of which only the Lac Qui Parle dam was modeled. Pertinent reservoir information including surface area and storage at principal (normal) and emergency spillway levels for the reservoirs modeled were obtained from the National Inventory of dams (NID) database. The SWAT model provides four options to simulate reservoir outflow: measured daily outflow, measured monthly outflow, average annual release rate for uncontrolled reservoir, and controlled outflow with target release. Keeping in view, the 20 Watershed climate change impact evaluation application, it was assumed that the best representation of the reservoirs was to simulate them without supplying time series of outflow records. Therefore, target release approach was used in the GCRP-SWAT model.

Another important characteristic of the watershed is the widespread presence of subsurface tile drainage. Installation of tile drainage has converted what were predominantly glacial plain outwash depressional wetlands into productive farmland. The presence of tile drains, which include both surface and subsurface inlets, has radically altered the natural hydrology of the area. Surface inlet tile drains, in particular, may also play a significant role in the transport of sediment and pollutants from agricultural land to the river. It is not feasible to simulate individual tile drain systems at the large basin scale. Further, neither the location nor the total density of tile drainage is known throughout the watershed. In most areas, only the public tile drains and ditches are documented in spatial coverages, and the extent of private tile drains is known only for limited areas.

The SWAT model allows for some representation of tile drains in the form of three parameters: depth to the tile drains, time to drain soil to field capacity and tile drain lag time.

Hydrology Calibration

A spatial calibration approach was not adopted for GCRP-SWAT modeling for Upper Mississippi River basin, unlike the HSPF application. However, a systematic adjustment of parameters has been adopted and some adjustments are applied throughout the basin. Most of the calibration efforts were geared towards getting a closer match between simulated and observed flows at the outlet of calibration focus area.

Land Use / Soil / Slope Definition

A 5/10/5 percent threshold was used for land use/soil/slope in the SWAT model while defining the HRUs. The cropland HRUs were split into corn and soybean in the ratio 1:1. Further these classes and the urban (including current and future urban class types) classes were exempt from applying the thresholds.

The calibration focus area (Cottonwood River) represents 7 subwatersheds, which together consists of 349 HRUs. The calibration focus area well represented the general land use characteristics of the overall watershed. Since the

Minnesota River basin has predominantly an agricultural land use, there is essentially one set of parameters for the entire watershed.

The parameters were adjusted within the practical range to obtain reasonable fit between the simulated and measured flows in terms of Nash-Sutcliffe modeling efficiency and the high flow and low flow components as well as the seasonal flows.

The water balance of the whole Minnesota River basin predicted by the SWAT model is as follows:

```
PRECIP =    689.0 MM
SNOW FALL = 102.36 MM
SNOW MELT =    98.01 MM
SUBLIMATION =     4.58 MM
SURFACE RUNOFF Q =    50.96 MM
LATERAL SOIL Q =    1.12 MM
TILE Q =    31.59 MM
GROUNDWATER (SHAL AQ) Q =    67.14 MM
REVAP (SHAL AQ => SOIL/PLANTS) =    3.08 MM
DEEP AQ RECHARGE =     3.70 MM
TOTAL AQ RECHARGE =   73.91 MM
TOTAL WATER YLD =   148.19 MM
PERCOLATION OUT OF SOIL =   71.32 MM
ET =    533.9 MM
PET =   1239.2MM
TRANSMISSION LOSSES =     2.62 MM
```

As is consistent with earlier studies (Tetra Tech, 2008), the baseflow (i.e., the groundwater and the tile Q) component accounts for more than 50 percent of the total water yield.

Calibration adjustments focused on the following parameters:

- FFCB
- SURLAG (surface runoff lag coefficient)
- CNCOEFF
- Baseflow factor
- GW_DELAY (groundwater delay time)
- Manning's "n" value for main channels, and tributary channels
- Sol_AWC (available water capacity of the soil layer, mm water/mm of soil)
- Heat Units to maturity for corn and soybean
- Depth to impervious surface
- BLAI for corn
- Snow parameters SMTMP, SMFMX and SMFMN
- Tile drain parameters (DDRAIN, TDRAIN and GDRAIN)

Initial calibrations were performed for the Cottonwood River, comparing model results to data from USGS 05317000, and are summarized in Figures 39 through 45 and Table 21 and Table 22.

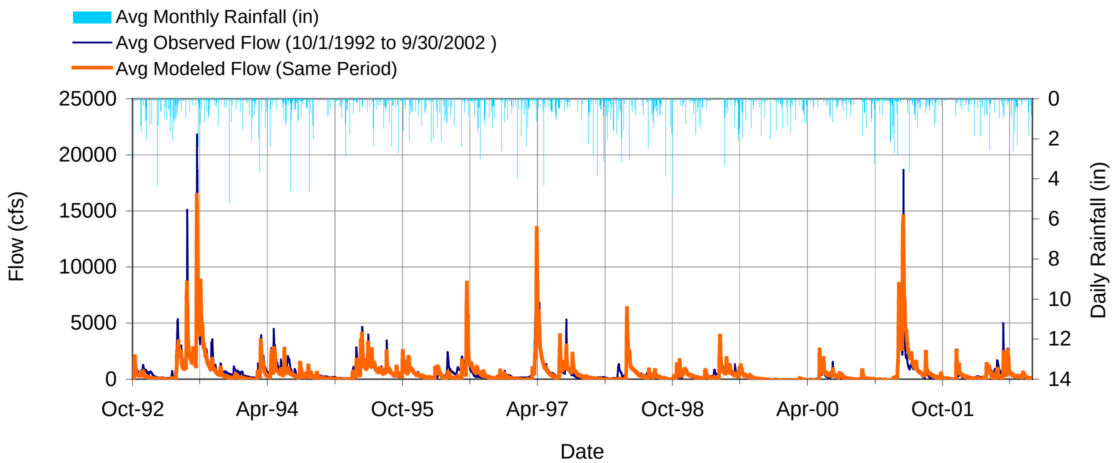


Figure 39. Mean daily flow at USGS 05317000 Cottonwood River near New Ulm, MN – calibration period (SWAT).

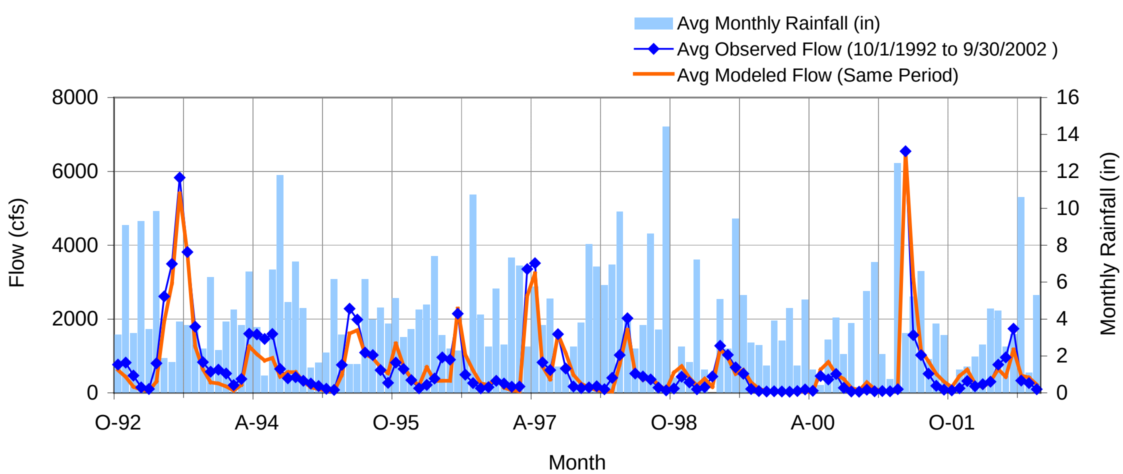
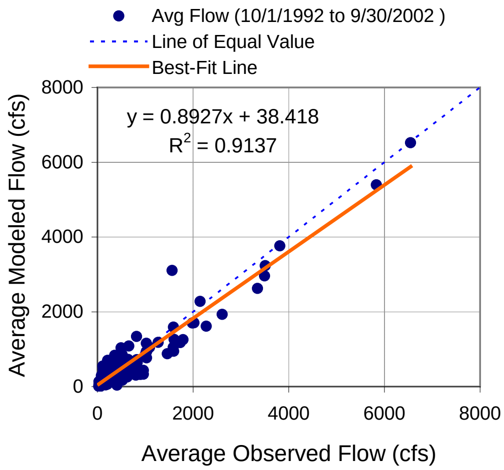


Figure 40. Mean monthly flow at USGS 05317000 Cottonwood River near New Ulm, MN – calibration period (SWAT).



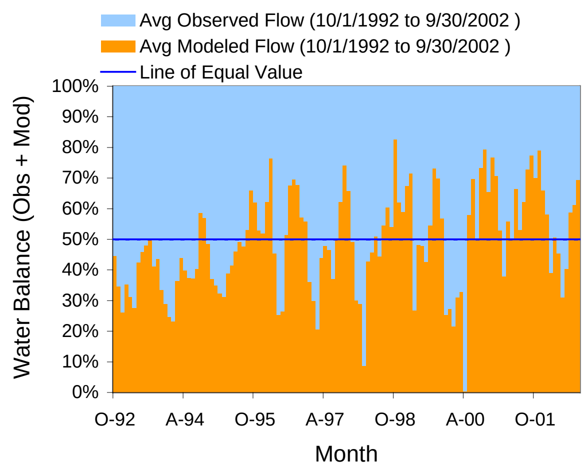
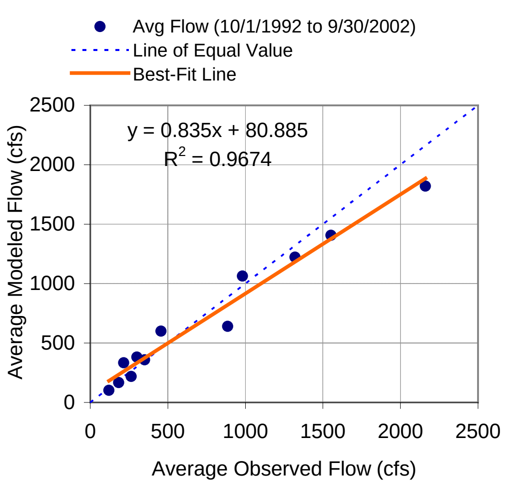


Figure 41. Monthly flow regression and temporal variation at USGS 05317000 Cottonwood River near New Ulm, MN – calibration period (SWAT).



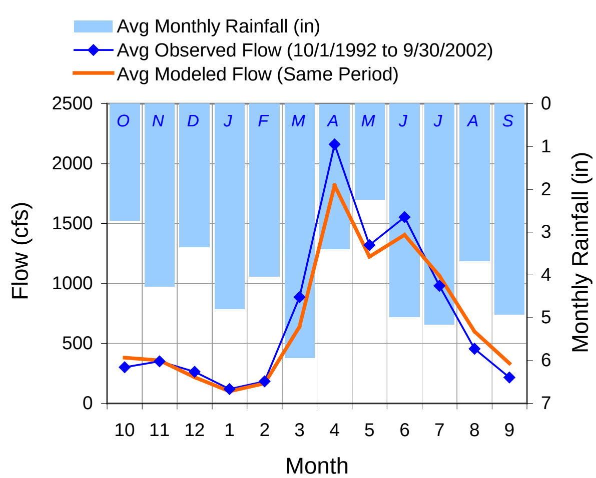


Figure 42. Seasonal regression and temporal aggregate at USGS 05317000 Cottonwood River near New Ulm, MN - calibration period (SWAT).

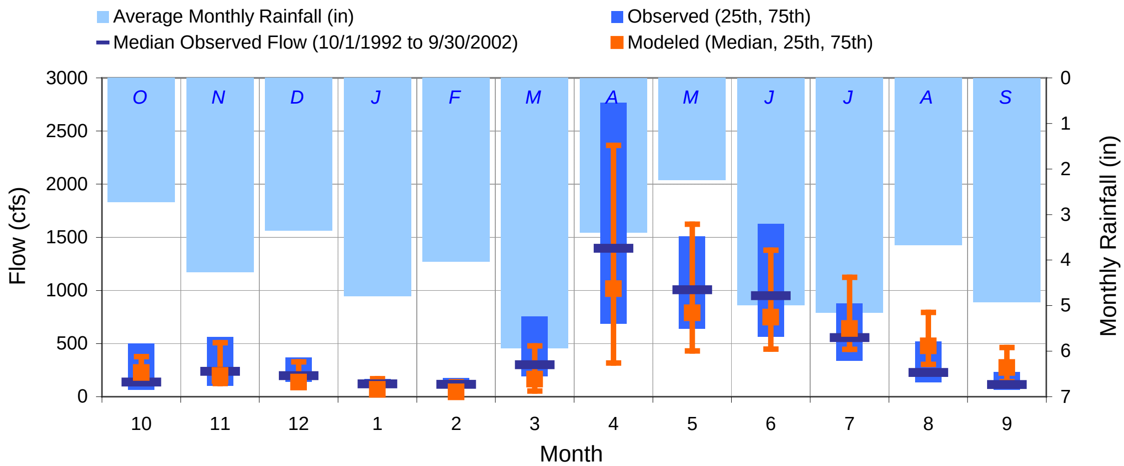


Figure 43. Seasonal medians and ranges at USGS 05317000 Cottonwood River near New Ulm, MN – calibration period (SWAT).

Table 21. Seasonal summary at USGS 05317000 Cottonwood River near New Ulm, MN - calibration period (SWAT)

MONTH	OBSERVED FLOW (CFS)				MODELED FLOW (CFS)			
	MEAN	MEDIAN	25TH	75TH	MEAN	MEDIAN	25TH	75TH
Oct	301.38	137.50	62.25	499.00	381.46	227.46	126.33	377.43
Nov	350.75	237.50	101.25	562.50	359.14	199.53	125.15	508.97
Dec	264.09	198.00	139.25	369.50	218.04	138.01	90.43	328.58
Jan	120.42	120.00	85.25	169.00	101.28	67.56	44.06	168.76
Feb	183.37	116.00	80.00	174.50	167.59	45.34	27.41	141.13
Mar	885.87	300.00	191.25	755.25	639.79	164.53	53.07	478.34
Apr	2161.06	1395.00	688.00	2767.50	1819.87	1015.47	316.98	2365.55
May	1320.39	1005.00	638.50	1507.50	1222.77	788.58	430.93	1623.50
Jun	1552.95	950.00	561.25	1625.00	1406.00	747.96	448.05	1379.83
Jul	981.10	554.50	336.00	877.25	1064.17	641.49	445.58	1123.71
Aug	455.96	228.00	138.00	519.75	599.42	477.98	304.94	792.46
Sep	216.05	114.00	65.00	234.00	333.14	275.54	142.37	463.77

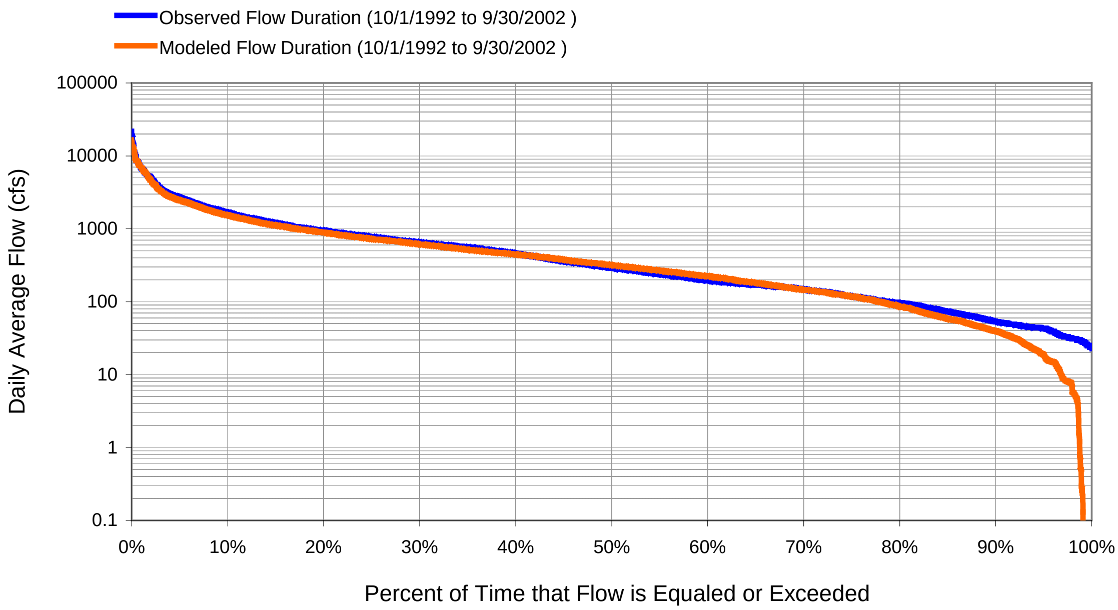


Figure 44. Flow exceedance at USGS 05317000 Cottonwood River near New Ulm, MN - calibration period (SWAT).

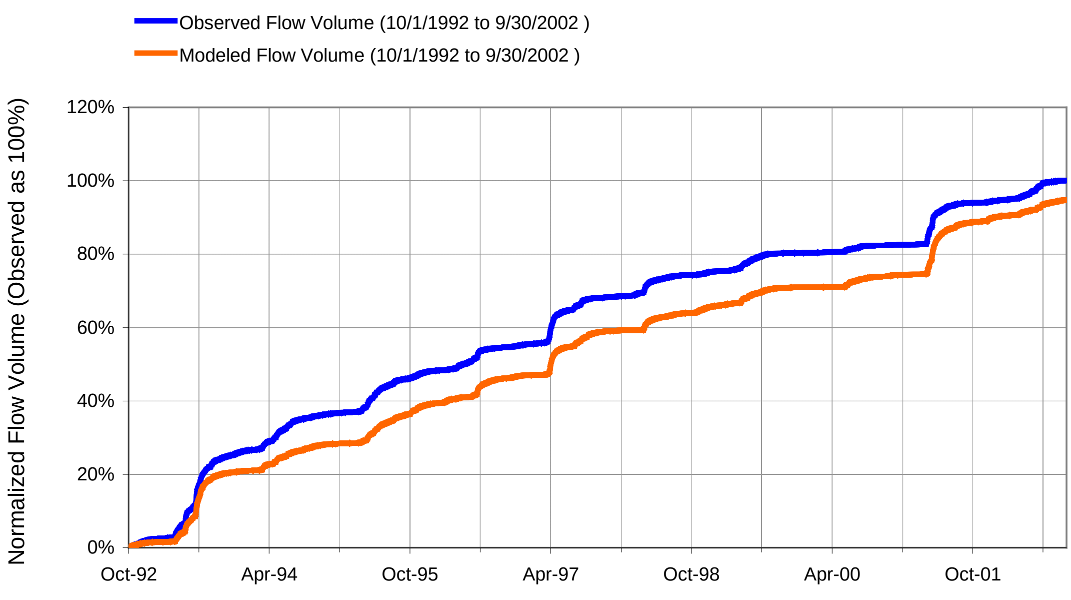


Figure 45. Flow accumulation at USGS 05317000 Cottonwood River near New Ulm, MN - calibration period (SWAT).

Table 22. Summary statistics at USGS 05317000 Cottonwood River near New Ulm, MN - calibration period (SWAT)

HSPF Simulated Flow		Observed Flow Gage	
REACH OUTFLOW FROM DSN 6001 10-Year Analysis Period: 10/1/1992 - 9/30/2002 Flow volumes are (inches/year) for upstream drainage area		USGS 05317000 COTTONWOOD RIVER NEAR NEW ULM, MN Hydrologic Unit Code: 7020008 Latitude: 44.29135177 Longitude: -94.4402495 Drainage Area (sq-mi): 1300	
Total Simulated In-stream Flow:	**7.25**	Total Observed In-stream Flow:	**7.66**
Total of simulated highest 10% flows:	**3.66**	Total of Observed highest 10% flows:	**3.92**
Total of Simulated lowest 50% flows:	**0.68**	Total of Observed Lowest 50% flows:	**0.68**
Simulated Summer Flow Volume (months 7-9):	**1.76**	Observed Summer Flow Volume (7-9):	**1.46**
Simulated Fall Flow Volume (months 10-12):	**0.84**	Observed Fall Flow Volume (10-12):	**0.80**
Simulated Winter Flow Volume (months 1-3):	**0.79**	Observed Winter Flow Volume (1-3):	**1.04**
Simulated Spring Flow Volume (months 4-6):	**3.85**	Observed Spring Flow Volume (4-6):	**4.36**
Total Simulated Storm Volume:	**2.42**	Total Observed Storm Volume:	**2.59**
Simulated Summer Storm Volume (7-9):	**0.43**	Observed Summer Storm Volume (7-9):	**0.50**

Errors (Simulated-Observed)	*Error Statistics*	*Recommended Criteria*
Error in total volume:	-5.41	10
Error in 50% lowest flows:	0.30	10
Error in 10% highest flows:	-6.65	15
Seasonal volume error - Summer:	20.65	30
Seasonal volume error - Fall:	4.66	30
Seasonal volume error - Winter:	-23.83	30
Seasonal volume error - Spring:	-11.60	30
Error in storm volumes:	-6.50	20
Error in summer storm volumes:	-13.60	50
Nash-Sutcliffe Coefficient of Efficiency, E:	0.794	Model accuracy increases
Baseline adjusted coefficient (Garrick), E':	0.580	as E or E' approaches 1.0
Monthly NSE	0.912	

Hydrology Validation

Validation for the Cottonwood model was performed at the same location but for the period 10/1/1982 through 9/30/1992. Results are presented in Figures 46 through 52 and Tables 23 and 24. The validation achieves a high coefficient of model fit efficiency, but is under on 50 percent low volume and over on seasonal volumes for summer and fall.

Factors that may have contributed to the difference in the flows between the calibration and validation period are:

- Increase in urban impervious surface areas.
- Increase in the intensity of tile drainage.
- Cropped areas have changed.
- PET estimates for the 20 Watershed model use SWAT weather generator statistics for solar radiation, cloud cover, wind, and relative humidity – essentially assuming that the central tendency of these factors has not changed over time.

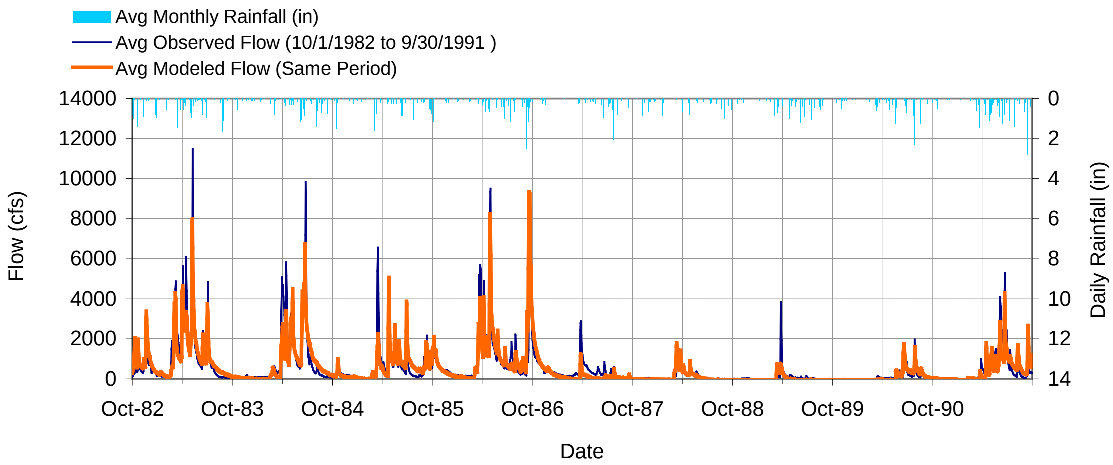


Figure 46. Mean daily flow at USGS 05317000 Cottonwood River near New Ulm, MN – validation period (SWAT).

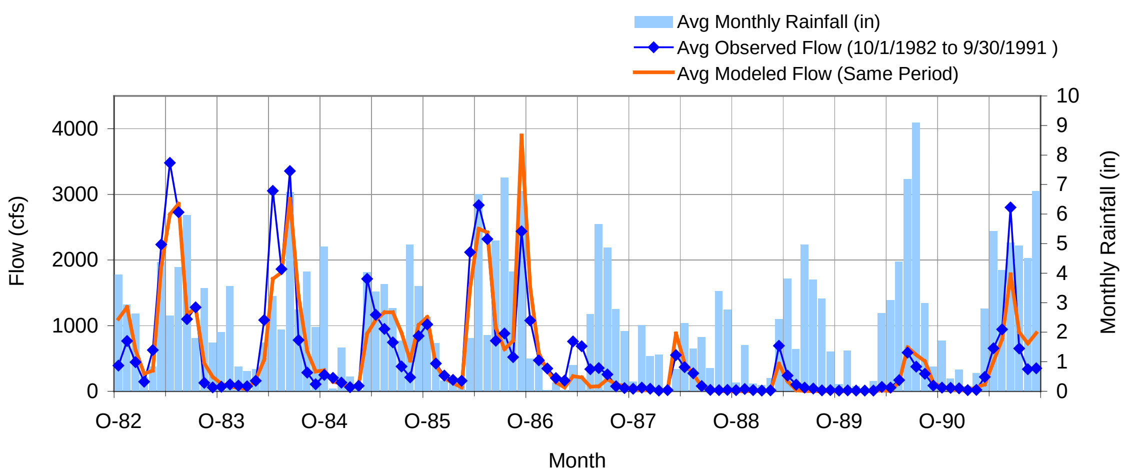


Figure 47. Mean monthly flow at USGS 05317000 Cottonwood River near New Ulm, MN – validation period (SWAT).

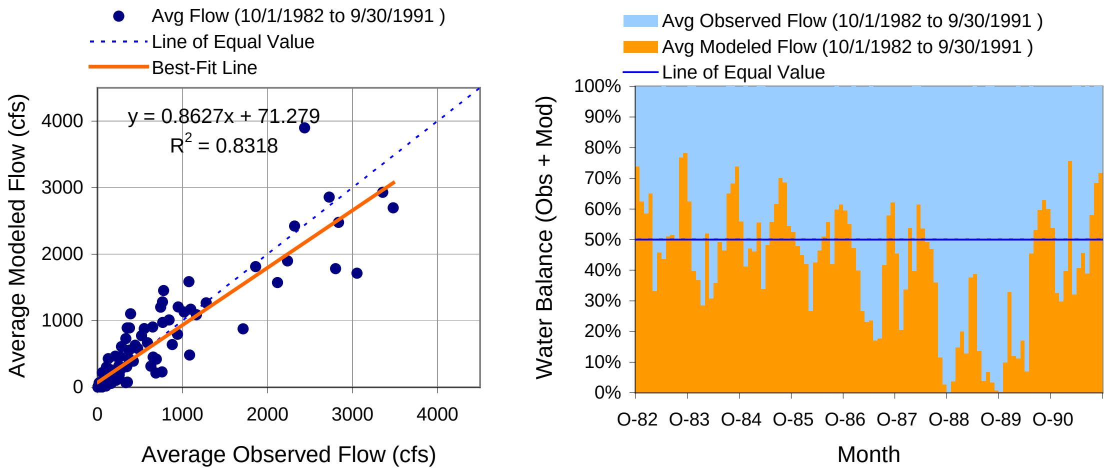


Figure 48. Monthly flow regression and temporal variation at USGS 05317000 Cottonwood River near New Ulm, MN – validation period (SWAT).

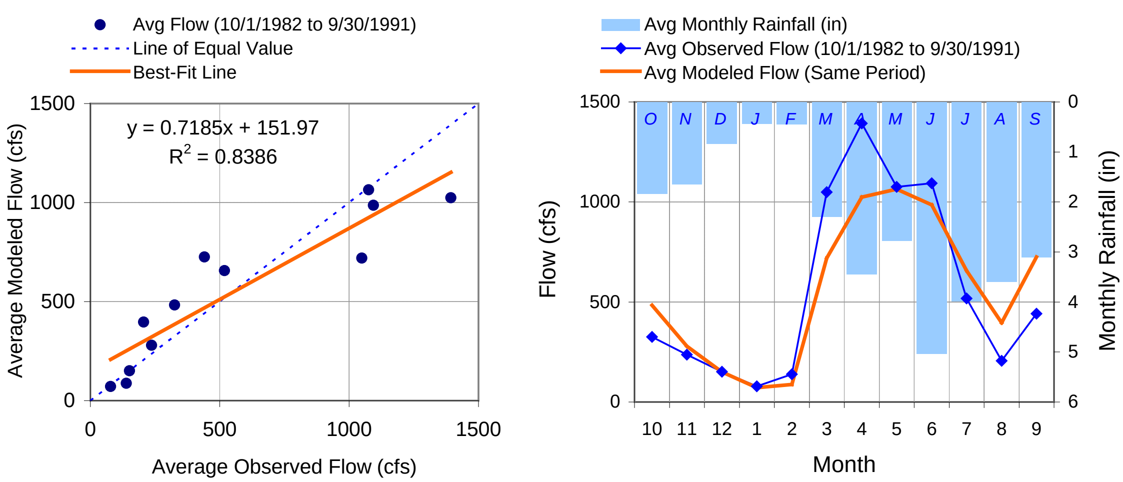


Figure 49. Seasonal regression and temporal aggregate at USGS 05317000 Cottonwood River near New Ulm, MN - validation period (SWAT).

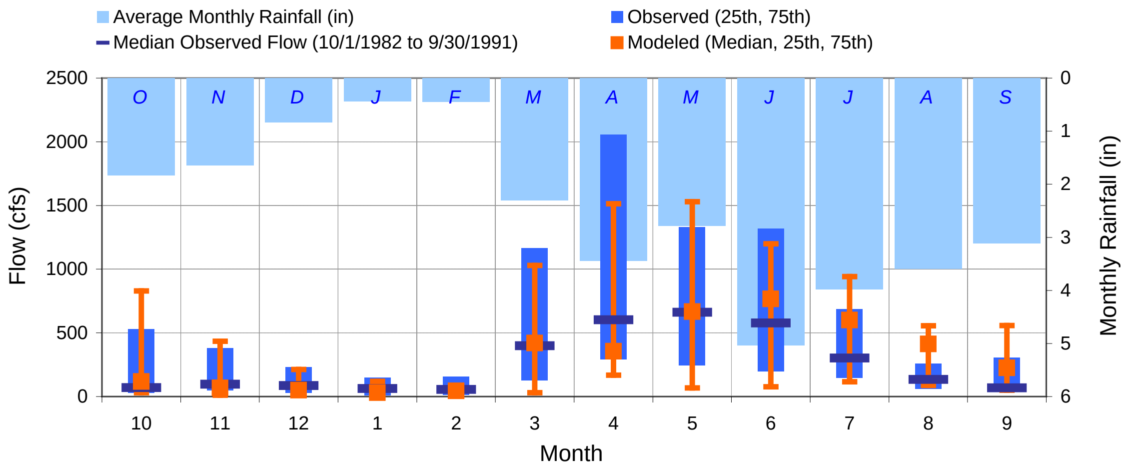


Figure 50. Seasonal medians and ranges at USGS 05317000 Cottonwood River near New Ulm, MN – validation period (SWAT).

Table 23. Seasonal summary at USGS 05317000 Cottonwood River near New Ulm, MN - validation period (SWAT)

MONTH	OBSERVED FLOW (CFS)				MODELED FLOW (CFS)			
	MEAN	MEDIAN	25TH	75TH	MEAN	MEDIAN	25TH	75TH
Oct	325.44	70.00	30.00	530.00	483.16	117.35	29.73	828.48
Nov	236.81	97.00	49.00	378.25	279.00	68.79	11.44	434.99
Dec	151.12	85.00	26.50	231.00	150.35	50.61	14.60	212.47
Jan	78.47	63.00	11.00	148.00	71.41	31.16	8.80	118.92
Feb	138.70	56.00	13.00	158.00	87.25	44.67	5.29	78.17
Mar	1049.35	399.00	128.00	1165.00	719.49	419.19	30.22	1029.60
Apr	1393.56	602.50	293.75	2057.50	1024.55	354.91	168.44	1513.23
May	1075.69	662.00	244.50	1330.00	1064.03	667.09	67.73	1529.65
Jun	1094.19	576.50	198.75	1317.50	985.89	767.21	77.69	1199.11
Jul	518.17	302.00	146.50	684.00	656.53	600.00	116.11	942.20
Aug	205.90	134.00	62.50	260.00	396.61	412.12	87.85	556.21
Sep	441.19	68.50	43.00	305.75	725.22	225.34	49.80	556.82

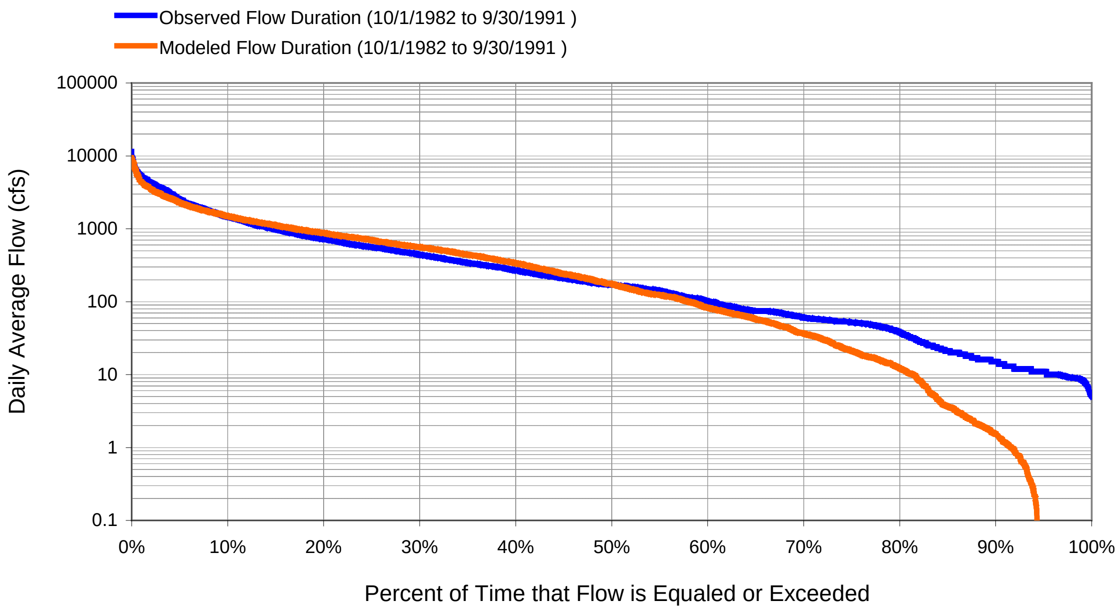


Figure 51. Flow exceedance at USGS 05317000 Cottonwood River near New Ulm, MN - validation period (SWAT).

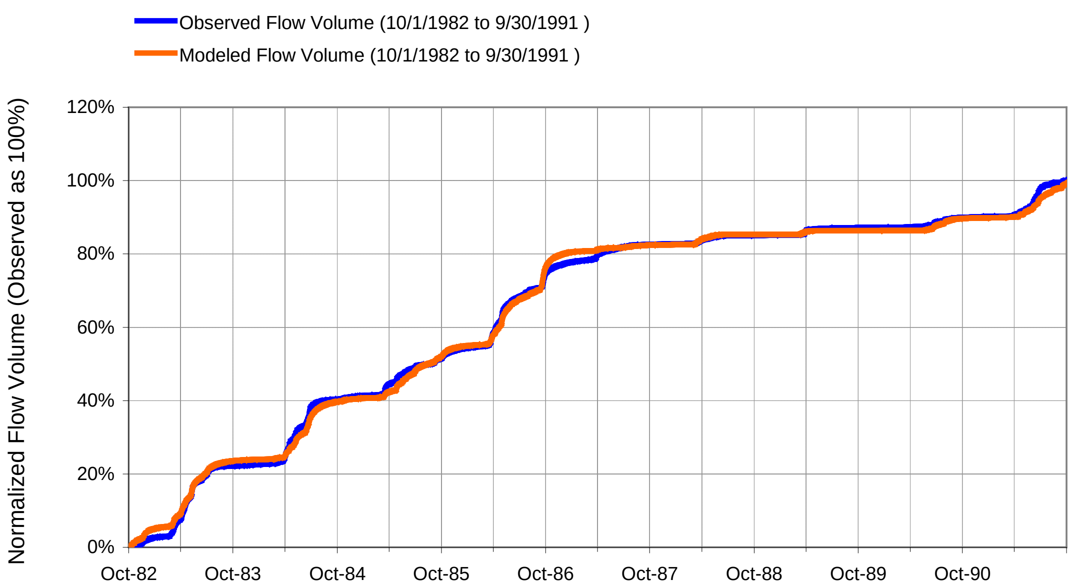


Figure 52. Flow accumulation at USGS 05317000 Cottonwood River near New Ulm, MN - validation period (SWAT).

Table 24. Summary statistics at USGS 05317000 Cottonwood River near New Ulm, MN - validation period (SWAT)

HSPF Simulated Flow		Observed Flow Gage	
REACH OUTFLOW FROM DSN 6001 9-Year Analysis Period: 10/1/1982 - 9/30/1991 Flow volumes are (inches/year) for upstream drainage area		USGS 05317000 COTTONWOOD RIVER NEAR NEW ULM, MN Hydrologic Unit Code: 7020008 Latitude: 44.29135177 Longitude: -94.4402495 Drainage Area (sq-mi): 1300	
Total Simulated In-stream Flow:	**5.80**	Total Observed In-stream Flow:	**5.85**
Total of simulated highest 10% flows:	**2.94**	Total of Observed highest 10% flows:	**3.30**
Total of Simulated lowest 50% flows:	**0.22**	Total of Observed Lowest 50% flows:	**0.32**
Simulated Summer Flow Volume (months 7-9):	**1.56**	Observed Summer Flow Volume (7-9):	**1.02**
Simulated Fall Flow Volume (months 10-12):	**0.80**	Observed Fall Flow Volume (10-12):	**0.63**
Simulated Winter Flow Volume (months 1-3):	**0.77**	Observed Winter Flow Volume (1-3):	**1.11**
Simulated Spring Flow Volume (months 4-6):	**2.67**	Observed Spring Flow Volume (4-6):	**3.09**
Total Simulated Storm Volume:	**1.89**	Total Observed Storm Volume:	**2.10**
Simulated Summer Storm Volume (7-9):	**0.44**	Observed Summer Storm Volume (7-9):	**0.41**

Errors (Simulated-Observed)	*Error Statistics*	*Recommended Criteria*
Error in total volume:	-0.84	10
Error in 50% lowest flows:	**-29.79**	**10**
Error in 10% highest flows:	-10.88	15
Seasonal volume error - Summer:	**52.47**	**30**
Seasonal volume error - Fall:	28.02	30
Seasonal volume error - Winter:	**-30.60**	**30**
Seasonal volume error - Spring:	-13.60	30
Error in storm volumes:	-9.94	20
Error in summer storm volumes:	6.14	50
Nash-Sutcliffe Coefficient of Efficiency, E:	0.740	Model accuracy increases
Baseline adjusted coefficient (Garrick), E':	0.599	as E or E' approaches 1.0
Monthly NSE	0.831	

>> Clear

Hydrology Results for Larger Watershed

As described above, parameters determined for the Cottonwood gage were fully transferable to other gages in the watershed. In addition, calibration and validation was pursued at a total of nine gages throughout the watershed, including seven gages at the outlet of 8-digit HUCs and two gages on the mainstem. Calibration results were acceptable at most gages, as summarized in Table 25. The match between observed and predicted flow volumes at the most downstream available gage (USGS 05330000, Minnesota River near Jordan) are shown in Figures 53 through 58 and Tables 26 and 27.

Table 25. Summary statistics (percent error): all stations - calibration period (SWAT)

Station	05311000 Minnesota River at Montevideo	05313500 Yellow Medicine River	05316500 Redwood River nr Redwood Falls	05317000 Cottonwood River near New Ulm	05319500 Watonwan River nr Garden City	05320000 Blue Earth River nr Rapidan	05320500 LeSueur River nr Rapidan	05325000 Minnesota River at Mankato	05330000 Minnesota River nr Jordan
Error in total volume:	-7.70	19.10	25.84	-5.41	-2.88	-6.46	12.11	16.69	7.89
Error in 50% lowest flows:	22.21	98.49	48.26	0.30	-30.14	-1.22	38.42	40.12	21.60
Error in 10% highest flows:	-15.93	9.44	23.39	-6.65	19.60	-0.02	8.82	14.57	8.10
Seasonal volume error - Summer:	30.78	59.05	56.54	20.65	20.56	25.26	25.23	55.02	38.77
Seasonal volume error - Fall:	15.65	37.01	53.30	4.66	11.22	1.28	32.44	32.84	21.31
Seasonal volume error - Winter:	-19.05	26.86	26.65	-23.83	-9.86	-20.62	52.98	25.76	18.03
Seasonal volume error - Spring:	-23.84	4.67	10.93	-11.60	-12.94	-18.60	-4.87	-2.83	-9.25
Error in storm volumes:	-11.85	13.55	43.78	-6.50	72.02	18.65	20.92	48.13	43.49
Error in summer storm volumes:	23.67	-8.32	31.94	-13.60	34.92	6.89	0.02	45.88	35.70
Daily Nash-Sutcliffe Coefficient of Efficiency, E:	0.637	0.638	0.641	0.794	0.381	0.724	0.688	0.653	0.633
Monthly Nash-Sutcliffe Coefficient of Efficiency, E::	0.801	0.810	0.798	0.912	0.825	0.885	0.845	0.841	0.882

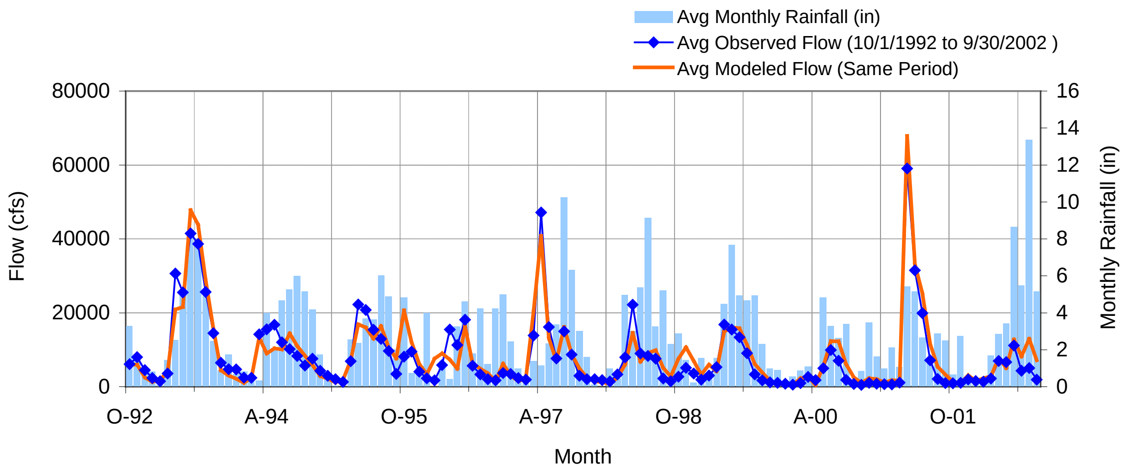
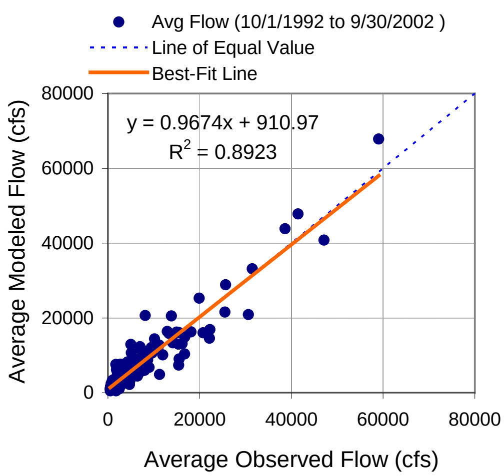


Figure 53. Monthly flow simulation: USGS 05330000 Minnesota River near Jordan, MN - calibration period (SWAT).



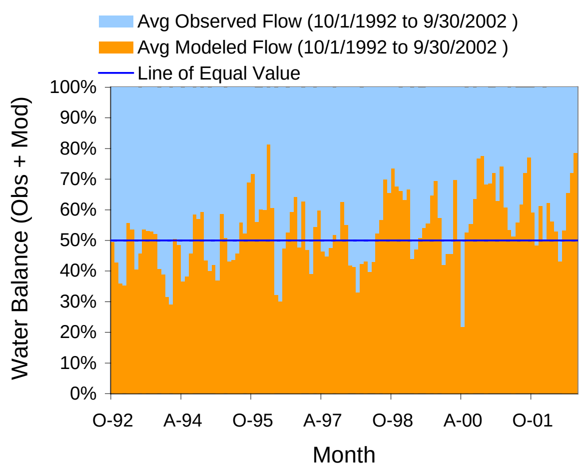
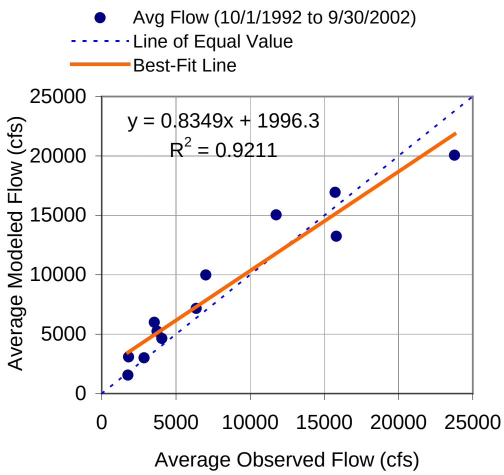


Figure 54. Monthly flow regression and temporal variation at USGS 05330000 Minnesota River near Jordan, MN – calibration period (SWAT).



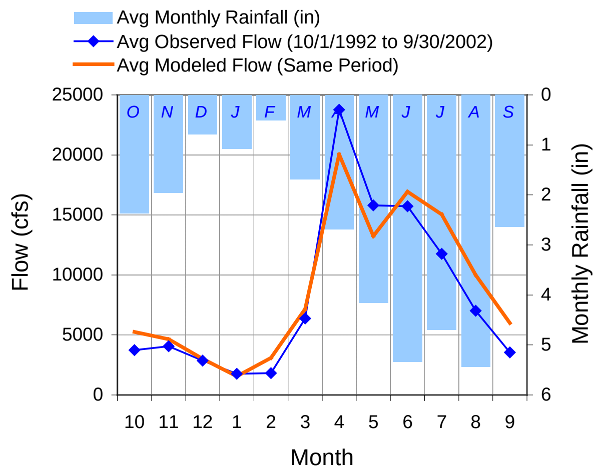


Figure 55. Seasonal regression and temporal aggregate at USGS 05330000 Minnesota River near Jordan, MN – calibration period (SWAT).

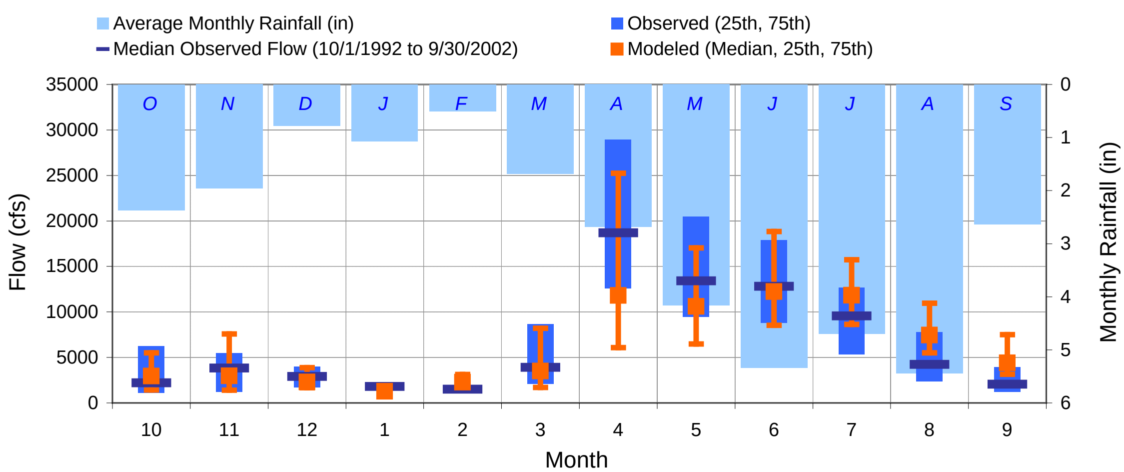


Figure 56. Seasonal medians and ranges at USGS 05330000 Minnesota River near Jordan, MN – calibration period (SWAT).

Table 26. Seasonal summary at USGS 05330000 Minnesota River near Jordan, MN – calibration period (SWAT).

MONTH	OBSERVED FLOW (CFS)				MODELED FLOW (CFS)			
	MEAN	MEDIAN	25TH	75TH	MEAN	MEDIAN	25TH	75TH
Oct	3732.17	2190.00	1082.50	6237.50	5253.33	2954.43	1425.65	5515.27
Nov	4054.61	3825.00	1210.00	5462.50	4640.70	2973.49	1405.61	7576.76
Dec	2858.86	2900.00	1702.50	4000.00	3010.99	2304.81	1684.51	3881.96
Jan	1757.39	1800.00	1392.50	2200.00	1555.88	1265.15	892.75	1712.94
Feb	1811.52	1500.00	1272.50	1900.00	3090.56	2277.97	1606.91	3129.50
Mar	6364.40	3910.00	2080.00	8627.50	7164.26	3503.74	1705.43	8215.07
Apr	23775.27	18700.00	12550.00	28925.00	20056.78	11800.40	6084.72	25252.64
May	15802.45	13400.00	9470.00	20500.00	13244.86	10601.46	6478.48	17027.85
Jun	15733.60	12800.00	8805.00	17900.00	16930.06	12234.77	8519.66	18846.55
Jul	11756.52	9565.00	5347.50	12675.00	15032.51	11823.35	8634.44	15728.27
Aug	7020.71	4225.00	2377.50	7782.50	9987.30	7453.16	5505.56	10963.44
Sep	3542.37	2040.00	1205.00	3910.00	5986.83	4391.38	3145.48	7497.30

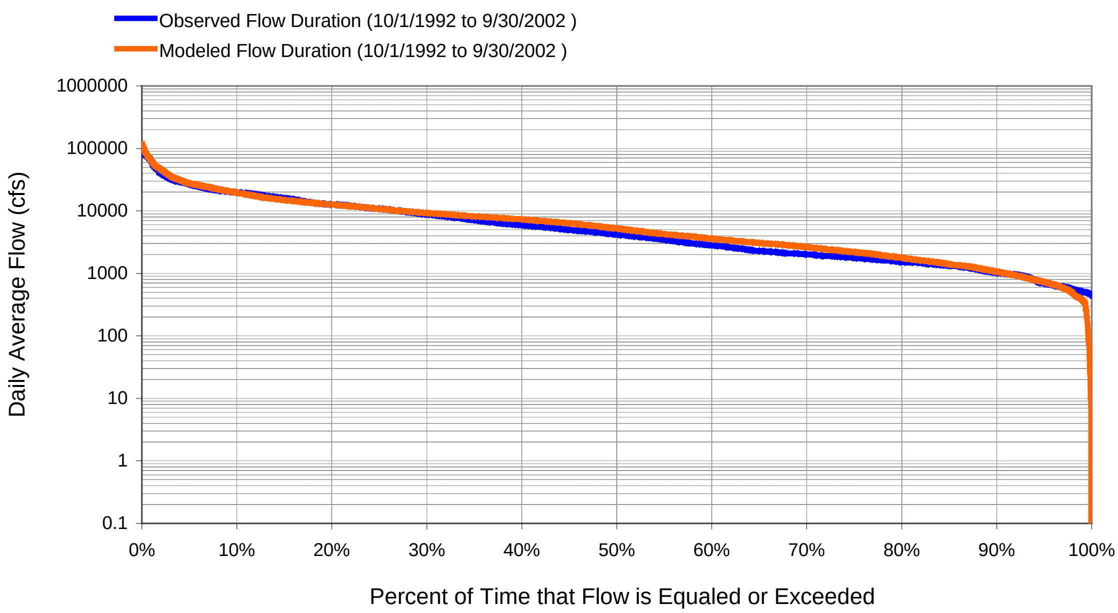


Figure 57. Flow exceedence at USGS 05330000 Minnesota River near Jordan, MN – calibration period (SWAT).

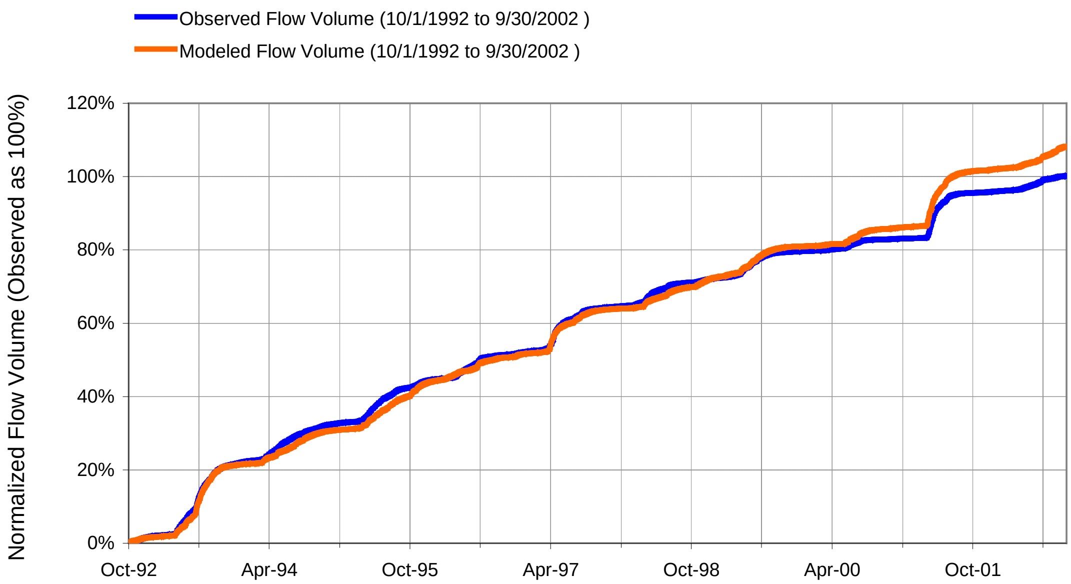


Figure 58. Flow accumulation at USGS 05330000 Minnesota River near Jordan, MN – calibration period (SWAT).

Table 27. Summary statistics at USGS 05330000 Minnesota River near Jordan, MN – calibration period (SWAT).

HSPF Simulated Flow		Observed Flow Gage	
REACH OUTFLOW FROM DSN 6001 10-Year Analysis Period: 10/1/1992 - 9/30/2002 Flow volumes are (inches/year) for upstream drainage area		USGS 05330000 MINNESOTA RIVER NEAR JORDAN, MN Hydrologic Unit Code: 7020012 Latitude: 44.69301845 Longitude: -93.641902 Drainage Area (sq-mi): 16200	
Total Simulated In-stream Flow:	**7.41**	Total Observed In-stream Flow:	**6.87**
Total of simulated highest 10% flows:	**3.01**	Total of Observed highest 10% flows:	**2.79**
Total of Simulated lowest 50% flows:	**0.99**	Total of Observed Lowest 50% flows:	**0.81**
Simulated Summer Flow Volume (months 7-9):	**2.19**	Observed Summer Flow Volume (7-9):	**1.58**
Simulated Fall Flow Volume (months 10-12):	**0.91**	Observed Fall Flow Volume (10-12):	**0.75**
Simulated Winter Flow Volume (months 1-3):	**0.82**	Observed Winter Flow Volume (1-3):	**0.70**
Simulated Spring Flow Volume (months 4-6):	**3.49**	Observed Spring Flow Volume (4-6):	**3.85**
Total Simulated Storm Volume:	**2.06**	Total Observed Storm Volume:	**1.43**
Simulated Summer Storm Volume (7-9):	**0.44**	Observed Summer Storm Volume (7-9):	**0.32**

Errors (Simulated-Observed)	*Error Statistics*	*Recommended Criteria*
Error in total volume:	7.89	10
Error in 50% lowest flows:	**21.60**	**10**
Error in 10% highest flows:	8.10	15
Seasonal volume error - Summer:	**38.77**	**30**
Seasonal volume error - Fall:	21.31	30
Seasonal volume error - Winter:	18.03	30
Seasonal volume error - Spring:	-9.25	30
Error in storm volumes:	**43.49**	**20**
Error in summer storm volumes:	35.70	50
Nash-Sutcliffe Coefficient of Efficiency, E:	0.633	Model accuracy increases
Baseline adjusted coefficient (Garrick), E':	0.502	as E or E' approaches 1.0
Monthly NSE	0.882	

>> Clear

Results of the validation exercise are summarized in Table 28. Problems similar to those experienced on the Cottonwood gage were seen at all the tributary gages, with overprediction of seasonal flows in summer and fall. However, as noted above, this is likely due to the use of land use and model parameters that are more reflective of current conditions and is not believed to present a bar to application of the model.

Table 28. Summary statistics: all stations - validation period (SWAT)

Station	05313500 Yellow Medicine River	05316500 Redwood River nr Redwood Falls	05317000 Cottonwood River near New Ulm	05319500 Watonwan River nr Garden City	05320000 Blue Earth River nr Rapidan	05320500 LeSueur River nr Rapidan	05325000 Minnesota River at Mankato	05330000 Minnesota River nr Jordan
Error in total volume:	11.24	31.84	-0.84	-1.10	-2.66	32.01	38.66	28.58
Error in 50% lowest flows:	20.06	65.19	-29.79	-68.25	13.13	48.38	60.68	34.93
Error in 10% highest flows:	-4.84	10.80	-10.88	23.45	-5.64	24.34	28.42	22.70
Seasonal volume error - Summer:	71.72	127.37	52.47	59.14	50.15	92.70	98.32	72.78
Seasonal volume error - Fall:	54.63	43.60	28.02	22.81	23.23	42.94	57.68	40.65
Seasonal volume error - Winter:	-25.13	1.06	-30.60	-18.95	-24.39	11.05	26.20	18.12
Seasonal volume error - Spring:	-0.75	15.22	-13.60	-18.56	-16.18	19.79	15.14	10.04
Error in storm volumes:	8.05	45.17	-9.94	90.61	25.30	45.02	77.61	74.72
Error in summer storm volumes:	2.96	62.49	6.14	135.92	36.86	59.70	81.05	60.81
Daily Nash-Sutcliffe Coefficient of Efficiency, E:	0.517	0.439	0.740	-0.245	0.636	0.513	0.423	0.421
Monthly Nash-Sutcliffe Coefficient of Efficiency, E:	0.738	0.668	0.831	0.440	0.828	0.657	0.656	0.723

Water Quality Calibration and Validation

Initial calibration and validation of water quality was done on the Cottonwood River (USGS 05317000), using 1993-2002 for calibration and 1986-1992 for validation. As with hydrology, calibration was performed on the later period as this better reflects the land use included in the model. The start of the validation period is constrained by data availability.

Calibration adjustments for sediment focused on the following parameters:

- BIOMIX

- SPCON (Linear parameters for estimating maximum amount of sediment that can be re-entrained during channel sediment routing)
- CH_COV (Channel cover factor)
- CH_EROD (Channel erodibility factor)
- USLE-C (Land surface cover factor).

Simulated and estimated sediment loads at the Cottonwood station for both the calibration and validation periods are shown in Figures 59 through 62 and statistics for the two periods are provided separately in Tables 29 and 30. The key statistic in Table 29 is the relative percent error, which shows the error in the prediction of monthly load normalized to the estimated load. The table also shows the relative average absolute error, which is the average of the relative magnitude of errors in individual monthly load predictions. This number is inflated by outlier months in which the simulated and estimated loads differ by large amounts (which may be as easily due to uncertainty in the estimated load due to limited data as to problems with the model) and the third statistic, the relative median absolute error, is likely more relevant and shows good agreement.

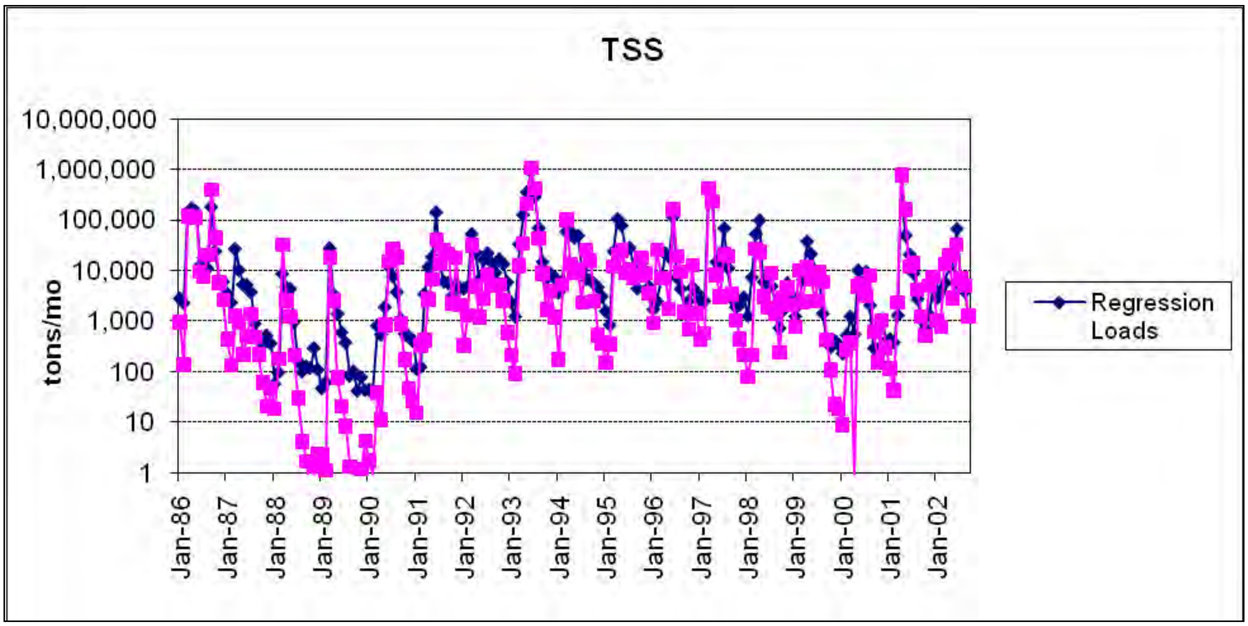


Figure 59. Fit for monthly load of TSS at USGS 05317000 Cottonwood River (SWAT).

Table 29. Model fit statistics (observed minus predicted) for monthly sediment loads using stratified regression at USGS 05317000 Cottonwood River (SWAT)

Statistic	Calibration period (1993-2002)	Validation period (1986-1992)
Relative Percent Error	9.2%	9.0%
Relative Average Absolute Error	36%	65%
Relative Median Absolute Error	9.1%	14.3%

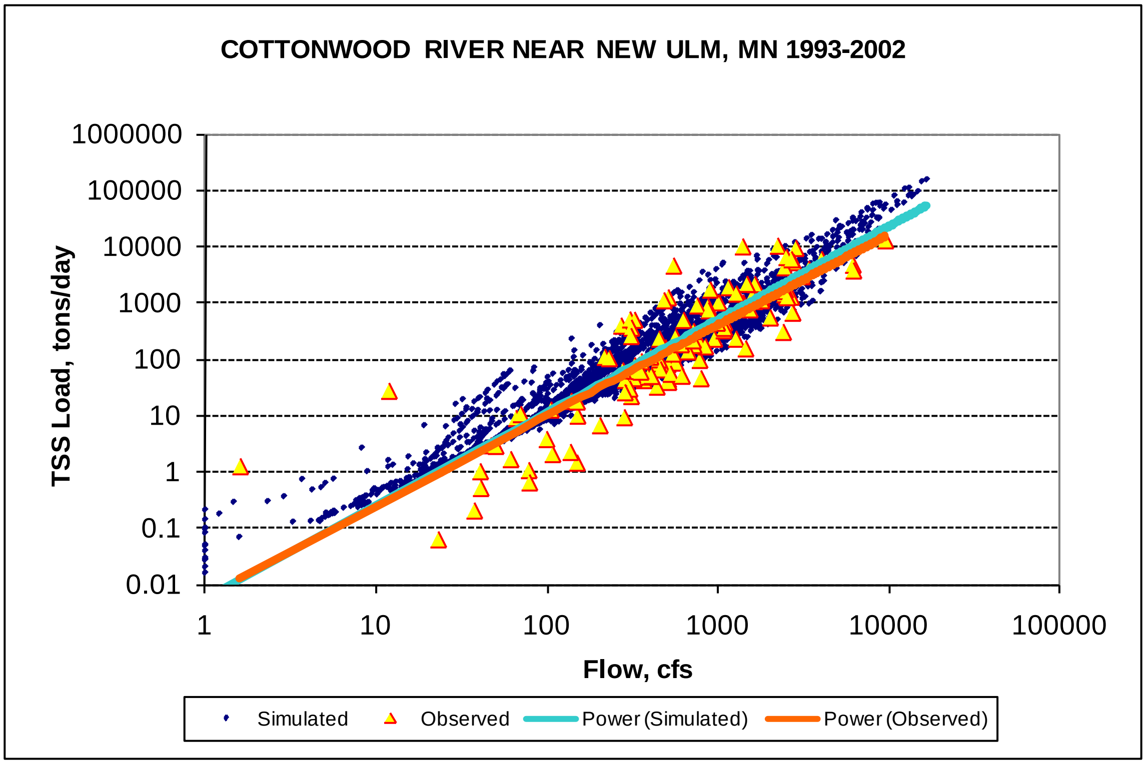


Figure 60. Power plot for observed and simulated TSS at USGS 05317000 Cottonwood River - calibration period (SWAT).

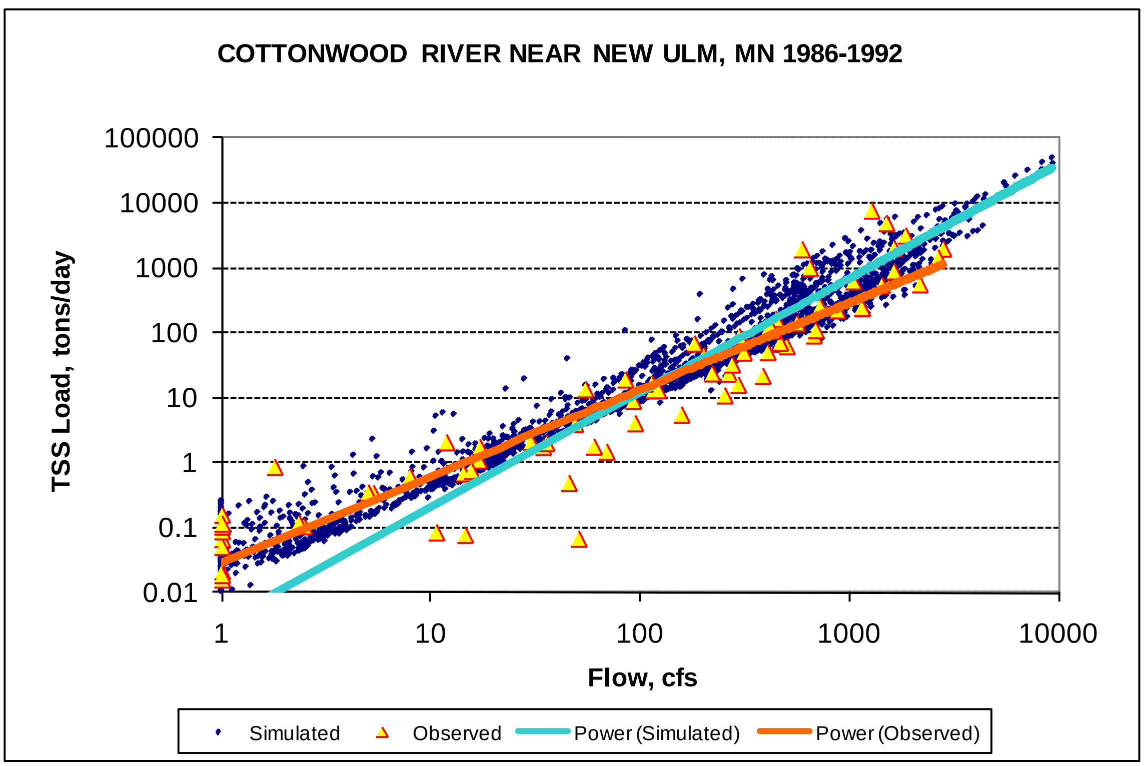


Figure 61. Power plot for observed and simulated TSS at USGS 05317000 Cottonwood River - validation period (SWAT).

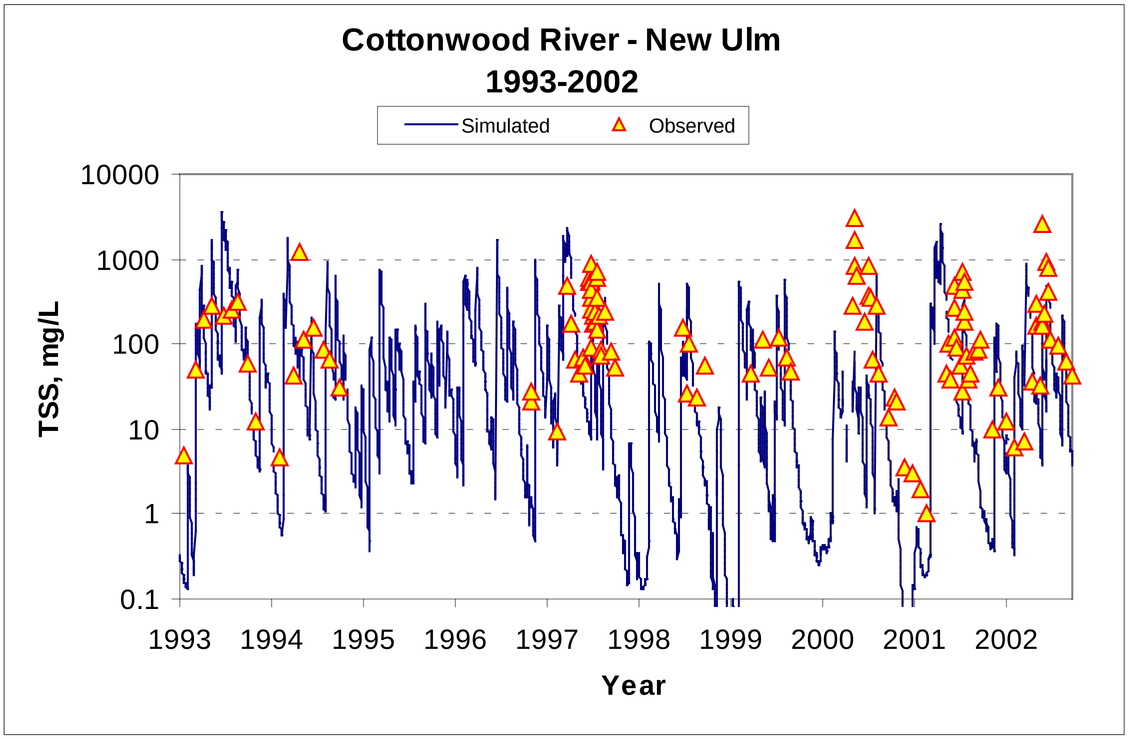


Figure 62. Time series plot of TSS concentration at USGS 05317000 Cottonwood River (SWAT).

Table 30. Relative errors (observed minus predicted), TSS concentration at USGS 05317000 Cottonwood River (SWAT)

Statistic	Calibration period (1993-2002)	Validation period (1986-1992)
Count	121	75
Concentration Average Error	27.69%	13.61%
Concentration Median Error	-2.52%	-4.04%

Calibration adjustments for total phosphorus and total nitrogen focused on the following parameters:

- PHOSKD (Phosphorus soil partitioning coefficient)
- RS4
- PSP
- BC3 and BC4
- SOL_CBN1 (Organic carbon in the first soil layer)
- Michaelis-Menton half-saturation constant for nitrogen and phosphorus
- MUMAX

Results for the phosphorus simulation are shown in Figures 63 through 66 and Tables 31 and 32. Results for the nitrogen simulation are shown in Figures 67 through 70 and Tables 33 and 34. The SWAT fit is generally good, with calibration and validation error statistics similar to those obtained from the HSPF model.

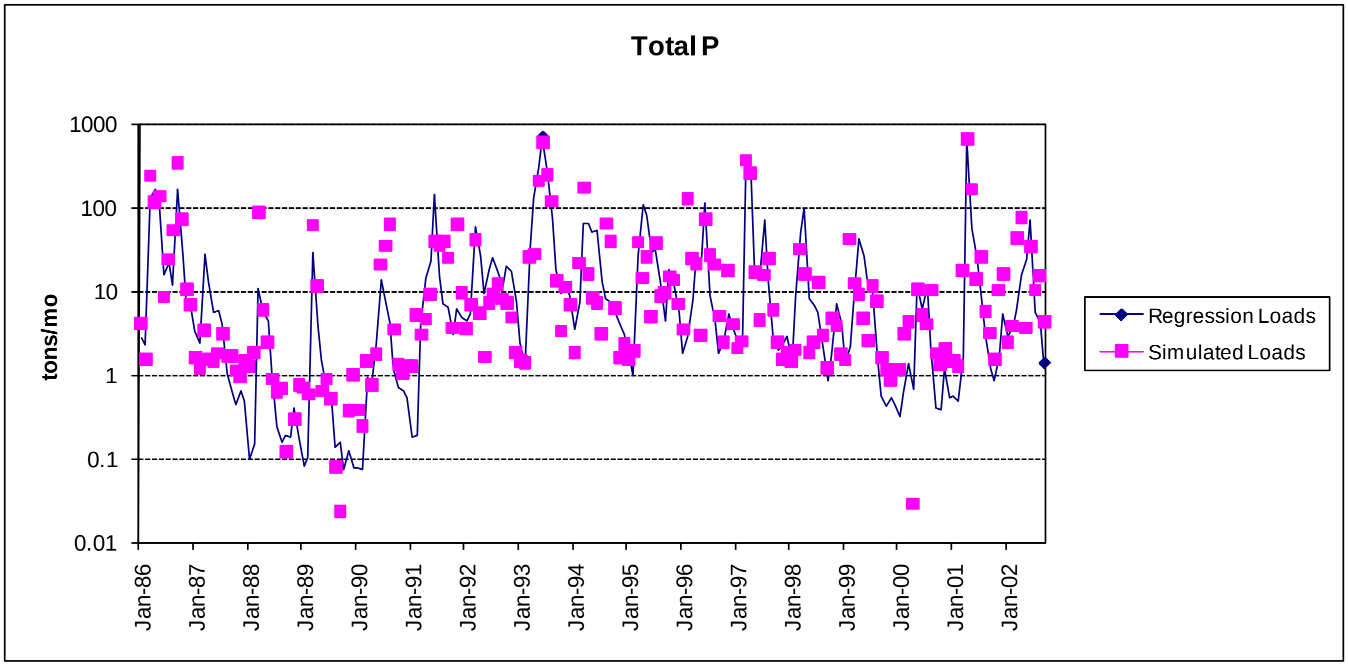


Figure 63. Fit for monthly load of total phosphorus at USGS 05317000 Cottonwood River (SWAT).

Table 31. Model fit statistics (observed minus predicted) for monthly phosphorus loads using stratified regression at USGS 05317000 Cottonwood River (SWAT)

Statistic	Calibration period (1993-2002)	Validation period (1986-1992)
Relative Percent Error	9.3%	-21.6
Average Absolute Error	46%	80%
Median Absolute Error	11.2%	9.3%

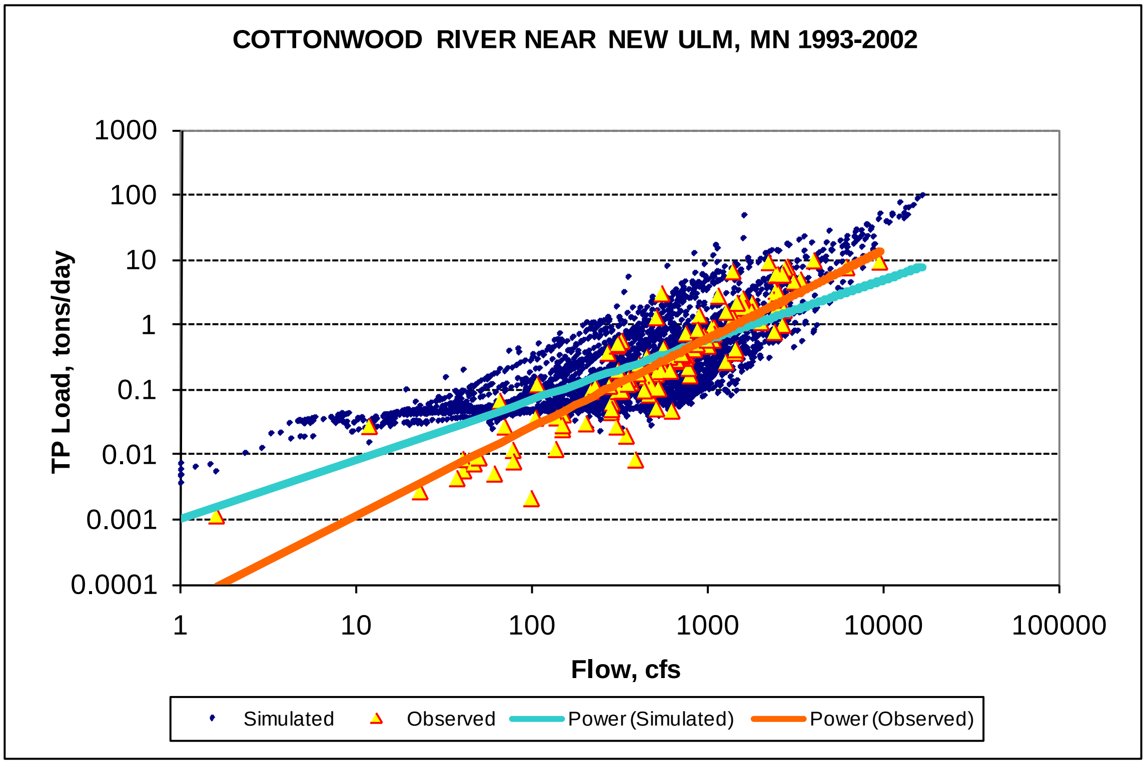


Figure 64. Power plot for observed and simulated total phosphorus at USGS 05317000 Cottonwood River - calibration period (SWAT).

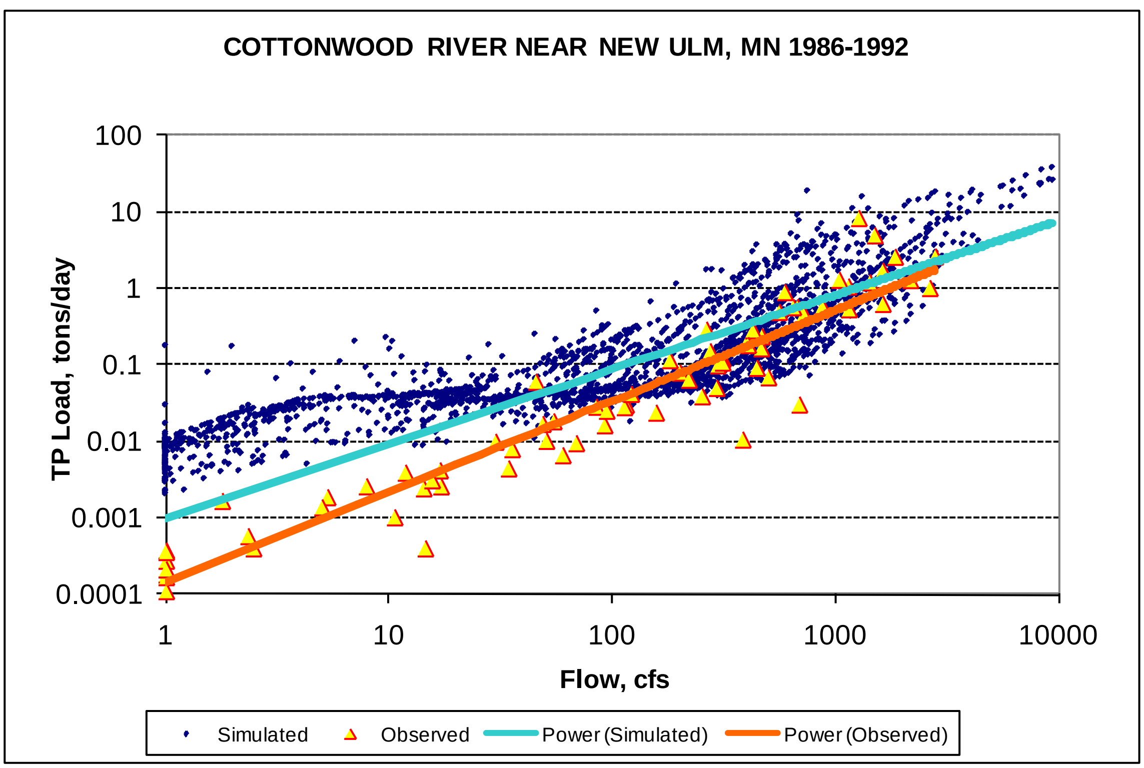


Figure 65. Power plot for observed and simulated total phosphorus at USGS 05317000 Cottonwood River – validation period (SWAT).

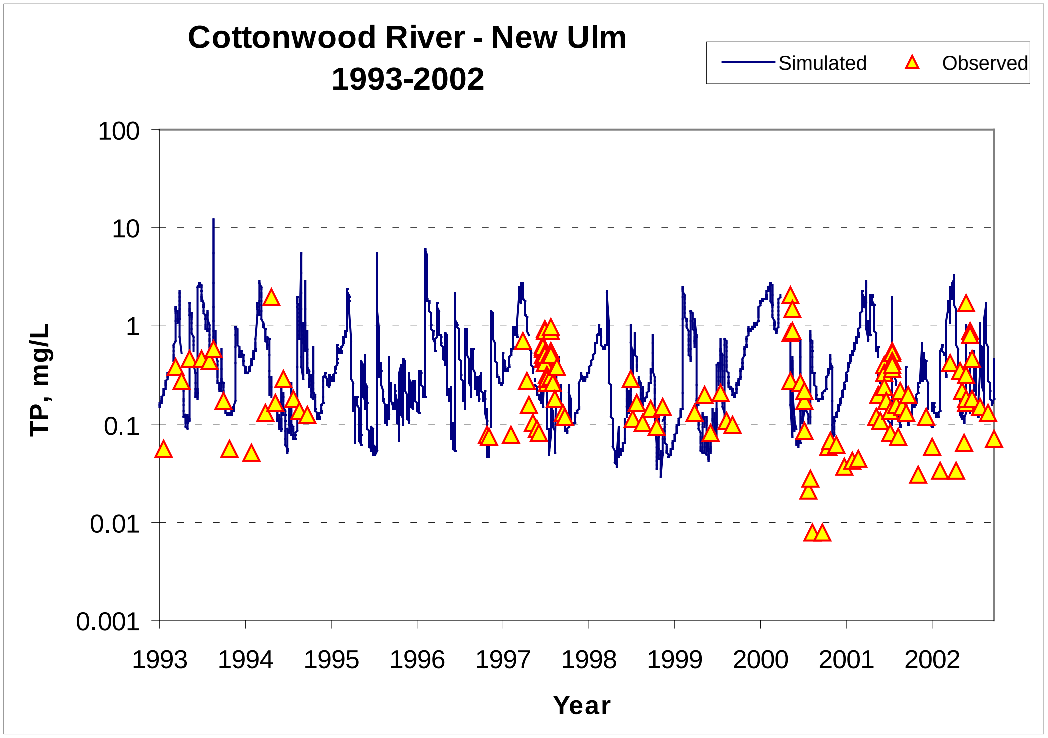


Figure 66. Time series plot of total phosphorus concentration at USGS 05317000 Cottonwood River (SWAT).

Table 32. Relative errors (observed minus predicted), total phosphorus concentration at USGS 05317000 Cottonwood River (SWAT)

Statistic	Calibration period (1993-2002)	Validation period (1986-1992)
Count	123	75
Concentration Average Error	-20.45%	-707.00%
Concentration Median Error	-0.25%	-87.32%

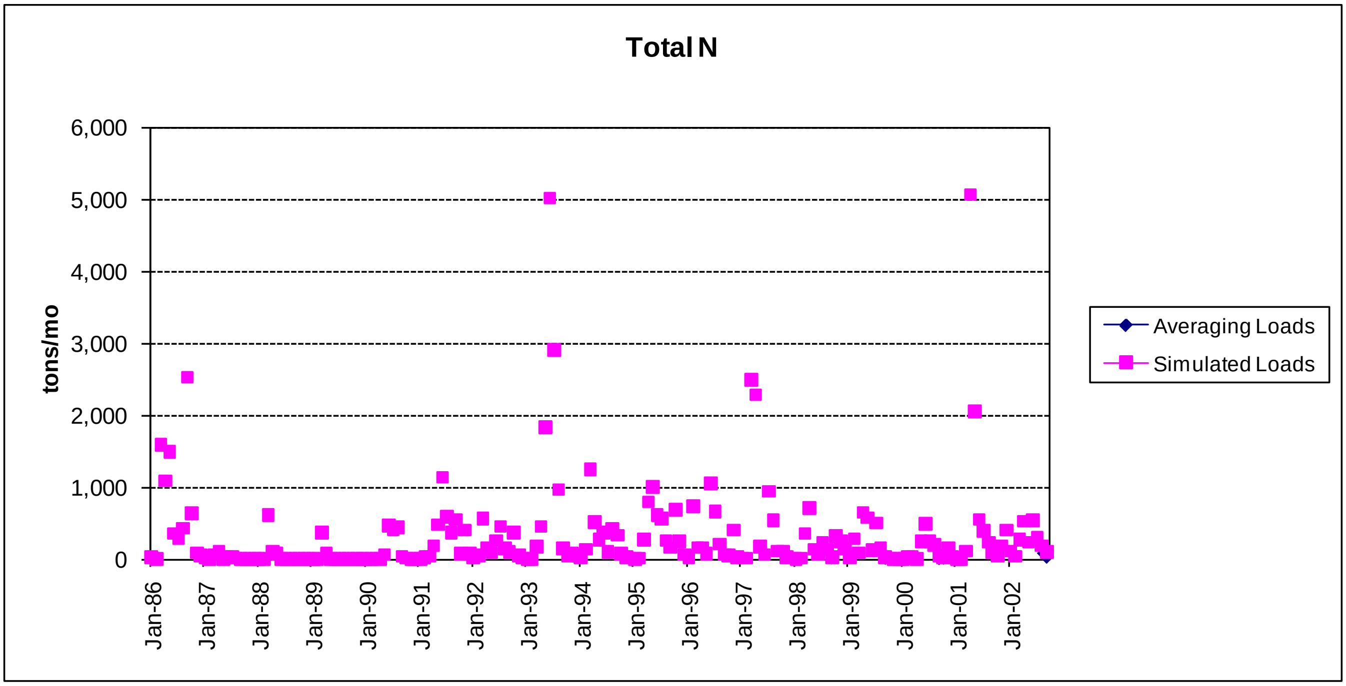


Figure 67. Fit for monthly load of total nitrogen at USGS 05317000 Cottonwood River (SWAT).

Table 33. Model fit statistics (observed minus predicted) for monthly total nitrogen loads using averaging estimator at USGS 05317000 Cottonwood River (SWAT)

Statistic	Calibration period (1993-2002)	Validation period (1986-1992)
Relative Percent Error	-8.9%	-1.3%
Average Absolute Error	54%	65%
Median Absolute Error	24.4%	28.7%

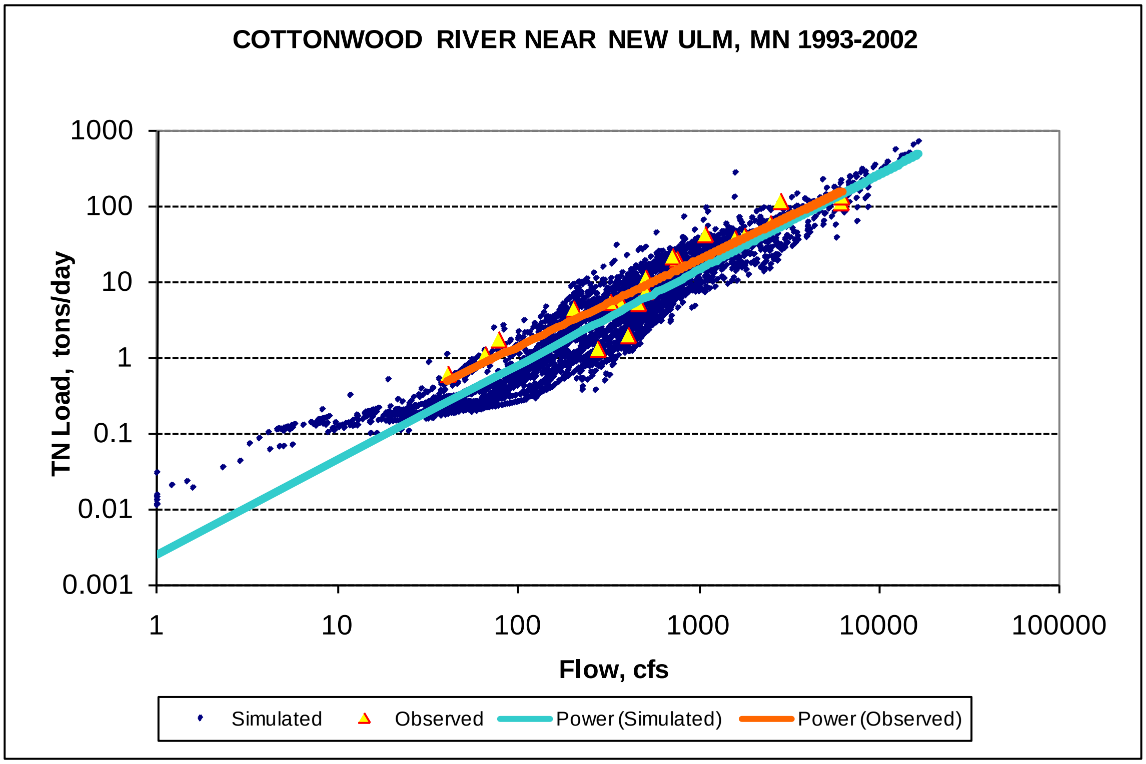


Figure 68. Power plot for observed and simulated total nitrogen at USGS 05317000 Cottonwood River – calibration period (SWAT).

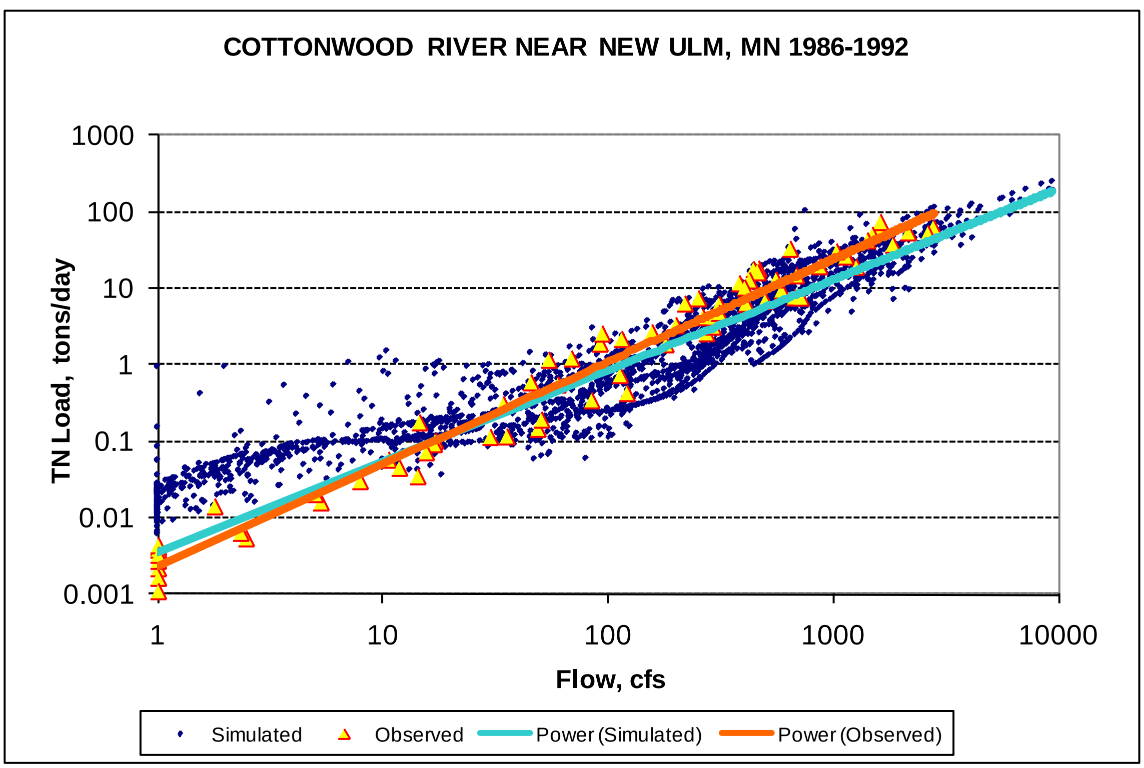


Figure 69. Power plot for observed and simulated total nitrogen at USGS 05317000 Cottonwood River – validation period (SWAT).

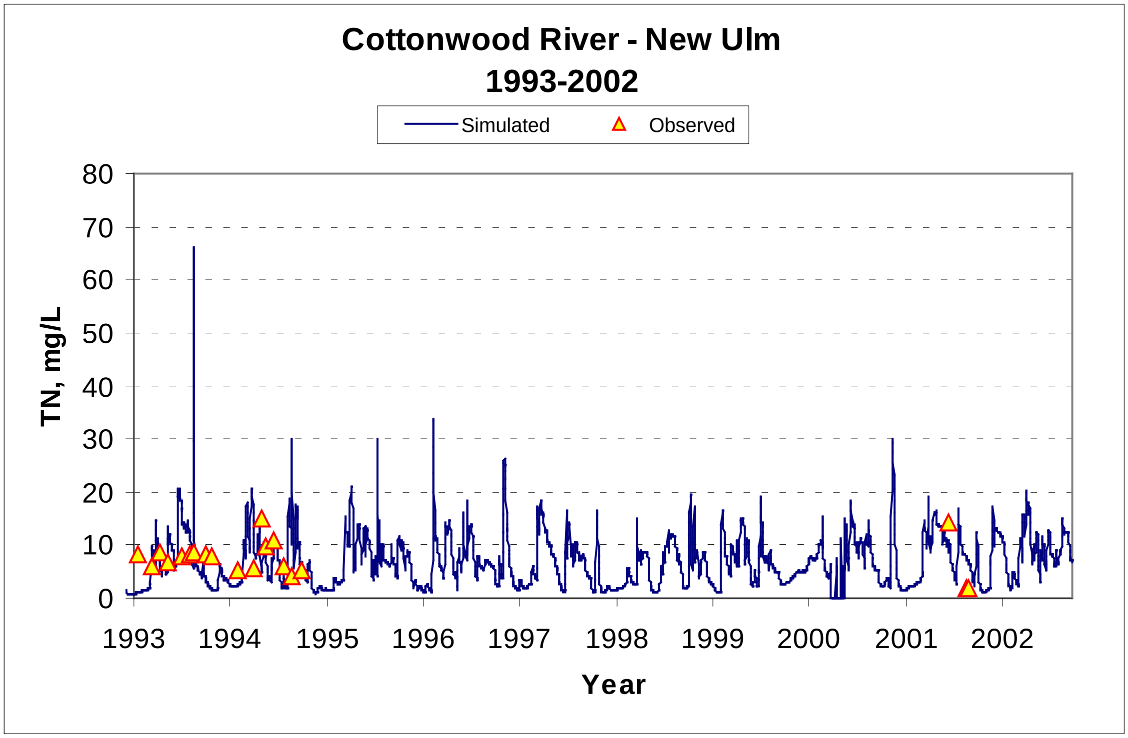


Figure 70. Time series plot of total nitrogen concentration at USGS 05317000 Cottonwood River (SWAT).

Table 34. Relative errors (observed minus predicted), total nitrogen concentration at USGS 05317000 Cottonwood River (SWAT)

Statistic	Calibration period (1993-2002)	Validation period (1986-1992)
Count	20	75
Concentration Average Error	12.65%	-78.90%
Concentration Median Error	31.42%	12.33%

Water Quality Results for Larger Watershed

Water quality results from the larger watershed from the SWAT model appear to be much less precise than those obtained with the HSPF model. This is believed to be largely a result of the calibration strategy adopted for the SWAT application: As with hydrology, the Cottonwood River watershed SWAT model parameters for water quality were directly transferred to other portions of the watershed. In contrast, the HSPF model used a spatial calibration approach. Application of the SWAT model without spatial adjustments resulted in relatively large errors in predicting loads and concentrations at some stations.

Summary statistics for the SWAT water quality calibration and validation at other stations in the watershed are provided in Tables 35 and 36.

Table 35. Summary statistics for water quality at all stations – calibration period 1993-2002 (SWAT)

Station	05313500 Yellow Medicine River	05316500 Redwood River nr Redwood Falls	05317000 Cottonwood River near New Ulm	05319500 Watonwan River nr Garden City	05320000 Blue Earth River nr Rapidan	05320500 LeSueur River nr Rapidan	05325000 Minnesota River at Mankato	05330000 Minnesota River nr Jordan
Relative Percent Error TSS Load	-97.8%	-96.0%	9.2%	-166.7%	-145.1%	-139.8%	-73.1%	-40.7%
TSS Concentration Median Error	7.10%	-3.0%	-2.84%	-11.14%	-31.85%	-28.91%	-41.2%	-20.48%
Relative Percent Error TP Load	-38.3%	-84.0%	9.3%	-58.1%	-54.7%	-65.7%	-13.1%	-5.0%
TP Concentration Median Error	19.53%	-52.87%	-0.25%	-16.19%	-23.38%	-13.37%	-5.65%	-5.99%
Relative Percent Error TN Load	-22.9%	-44.3%	-8.9%	-17.9%	-10.9%	13.4%	9.5%	18.20%
TN Concentration Median Error	29.17%	19.87%	31.42%	38.06%	31.66%	28.4%	42.39%	47.64%

Table 36. Summary statistics for water quality at all stations – validation period 1986-1992 (SWAT)

Station	05313500 Yellow Medicine River	05316500 Redwood River nr Redwood Falls	05317000 Cottonwood River near New Ulm	05319500 Watonwan River nr Garden City	05320000 Blue Earth River nr Rapidan	05320500 LeSueur River nr Rapidan	05325000 Minnesota River at Mankato	05330000 Minnesota River nr Jordan
Relative Percent Error TSS Load	-56.8%	-75.1%	9.0%	-227.1%	-136.3%	-199.8%	-95.1%	-43.2%
TSS Concentration Median Error	-8.60%	-14.87%	-4.04%	-24.78%	-65.75%	-51.33%	-91.48%	-39.50%
Relative Percent Error TP Load	-27.4%	-1142.6%	-21.6%	-174.3%	-60.4%	-143.7%	-39.6%	-31.0%
TP Concentration Median Error	10.04%	-275.32%	-87.32%	-74.48%	-80.91%	-91.5%	-76.07%	-80.93%
Relative Percent Error TN Load	-28.0%	-68.7%	-1.3%	-69.9%	-15.3%	-43.1%	-4.8%	4.2%
TN Concentration Median Error	24.09%	-3.37%	12.33%	21.14%	10.54%	5.29%	10.57%	12.33%

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Appendix H
Model Configuration, Calibration and Validation

Basin: Willamette River (Willa)

Contents

Tables

Figures

Watershed Background

The Willamette River basin is located in northwestern Oregon. The model study area is within HUC 1709, consisting of 11 HUC8s and covering about 11,200 mi^2. The Willamette River is the 13^{th} largest river in the conterminous U.S. in terms of streamflow and produces more runoff per unit area than any of the larger rivers. It discharges to the Columbia River, which flows west to the Pacific Ocean along Oregon's northern border (Figure 1).

The basin is bordered on the west by the Coast Range, where elevations exceed 4,000 ft, and on the east by the Cascade Range, with several peaks higher than 10,000 ft. The Willamette Valley, with elevations near sea level, lies between the two ranges (USGS, 2001). Forested land covers approximately 70 percent of the watershed and dominates the foothills and mountains of the Coast and Cascade Ranges. Agricultural land, mostly cropland, comprises 22 percent of the basin and is located predominantly in the Willamette Valley. About one-third of the agricultural land is irrigated, and most of this is adjacent to the main stem Willamette River in the southern basin or scattered throughout the northern valley. Urban land comprises 6 percent of the watershed and is located primarily in the valley along the main stem Willamette River. The Willamette River flows through Portland, Oregon's largest metropolitan area, before entering the Columbia River.
The Willamette basin is characterized by cool, wet winters and warm, dry summers. About 70-80 percent of the annual precipitation falls from October through March. Most precipitation falls as snow above about the 5,000 ft level of the Cascades; however, the Coast Range and Willamette Valley receive relatively little snow. Mean monthly air temperatures in the valley range from about 3-5^{o} C during January to 17-20^{o} C during August. Although annual precipitation averages 62 inches in the Willamette basin, topography strongly influences its distribution. Yearly amounts range from 40-50 inches in the valley to as much as 200 inches near the crests of the Coast and Cascade Ranges.

More than three-fourths of the water used in the Willamette watershed is surface water. The largest single use is for the irrigation of crops. Public water supply (serving cities, towns, mobile home parks, apartment complexes) is the second largest use. Public supply consists mostly of withdrawals from Cascade streams, including the Bull Run in the Sandy River watershed and the Clackamas, Santiam, and McKenzie Rivers. The small amount of groundwater used for public supply (~10% of the total) comes predominantly from alluvial aquifers located along Cascade streams or along the main stem Willamette River. Most commercial water use is by fish hatcheries, and most industrial use is by pulp-and-paper mills.

Water Body Characteristics

The Willamette River is the 13^{th} largest river in the conterminous U.S. in terms of streamflow and produces more runoff per mi^2 than any of the larger rivers. The Sandy River watershed includes the Bull Run watershed, which is Portland's primary drinking water supply. The Willamette and Sandy Rivers are tributary to the Columbia River, which flows west to the Pacific Ocean along Oregon's northern border. The Willamette River flows through Portland, Oregon's largest metropolitan area, before entering the Columbia River.

Streamflow in the Willamette basin reflects the seasonal distribution of precipitation, with 60-85 percent of runoff occurring from October through March, but less than 10 percent occurring during July and August. Releases from 13 tributary reservoirs are managed for water quality enhancement by maintaining a flow of 6,000 cfs in the Willamette River at Salem during summer months. Flows in the lower Willamette River watershed are dominated by the effects of 13 reservoirs and their associated dams operated by the U.S. Army Corps of Engineers for water supply, flood control, and navigation. These reservoirs control much of the runoff from the southern and eastern mountainous portions of the watershed where precipitation and snow fall are highest. Incorporation of the reservoirs in the model was a significant part of the model development effort.

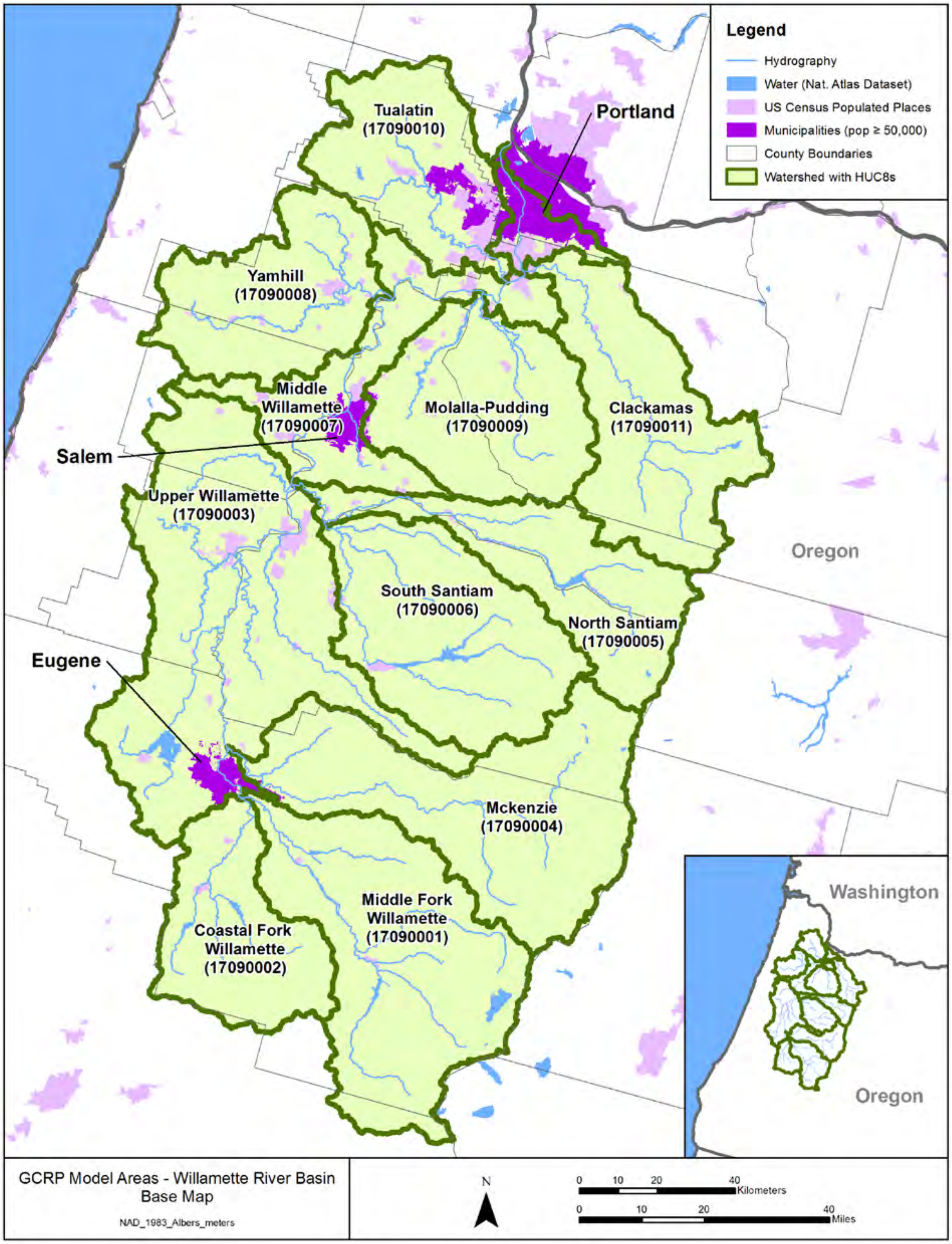

Figure 1. Location of the Willamette River watershed.

Soil Characteristics

One of the most important characteristics of soils for watershed modeling is their hydrologic soil group (HSG). The 20 Watershed study utilized STATSGO soil survey HSG information during model set-up. Soils are classified into four hydrologic groups (SCS 1986), separated by runoff potential, as follows:

A	Low runoff potential and high infiltration rates even when thoroughly wetted. Chiefly deep, well to excessively drained sands or gravels. High rate of water transmission (> 0.75 cm/hr).
B	Moderate infiltration rates when thoroughly wetted. Chiefly moderately deep to deep, moderately well to well drained soils with moderately fine to moderately coarse textures. Moderate rate of water transmission (0.40—0.75 cm/hr).
C	Low infiltration rates when thoroughly wetted. Chiefly soils with a layer that impedes downward movement of water, or soils with moderately fine to fine texture. Low rate of water transmission (0.15—0.40 cm/hr).
D	High runoff potential. Very low infiltration rates when thoroughly wetted. Chiefly clay soils with a high swelling potential, soils with a permanent high water table, soils with a claypan or clay layer at or near the surface, or shallow soils over nearly impervious material. Very low rate of water transmission (0—0.15 cm/hr).

The Willamette River watershed contains all four HSGs, but consists of mostly B, C, and D soils with a dominance of C soils.

Land Use Representation

Land use/cover in the watershed is based on the 2001 National Land Cover Database (NLCD) coverage and is predominantly forest (Figure 2). Most of the developed areas of the watershed are found along the Willamette River with the major urban development near the mouth of the river at the city of Portland.

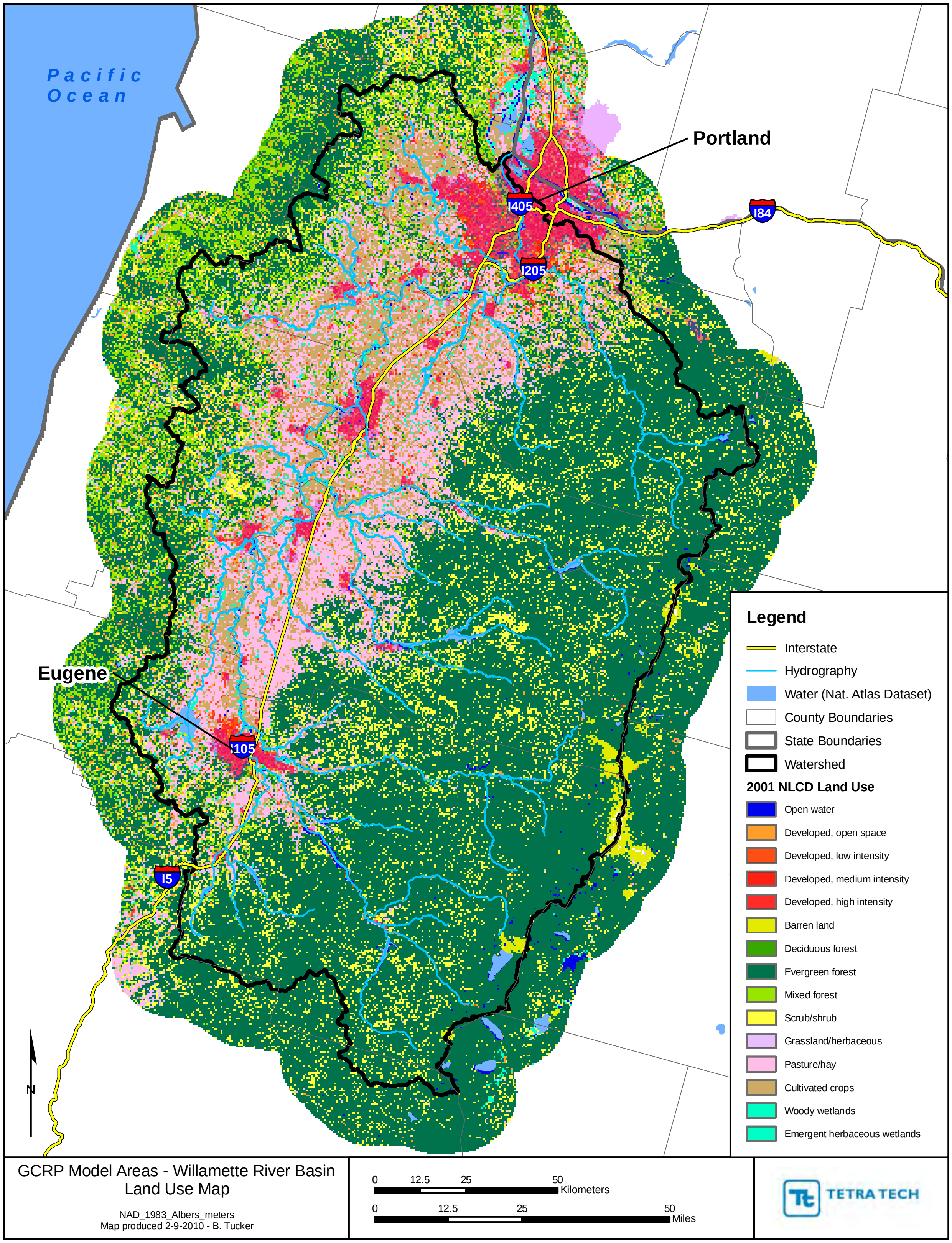

Figure 2. Land use in the Willamette River watershed.

NLCD land cover classes were aggregated according to the scheme shown in Table 1 for representation in the 20 Watershed model, and then overlain with the soils HSG grid. For HSPF, pervious and impervious lands are specified separately, so only one developed pervious class is used, along with an impervious class. HSPF simulates impervious land areas separately from pervious land. Impervious area distributions were determined from the NLCD Urban Impervious data coverage. Specifically, percent impervious area was calculated over the entire watershed for each of the four developed land use classes. These percentages were then used to separate out impervious land. NLCD impervious area data products are known to underestimate total imperviousness in rural areas; however, the model properly requires connected impervious area, not total impervious area, and the NLCD tabulation is assumed to provide a reasonable approximation of connected impervious area. In SWAT, different developed land classes are specified separately. In HSPF the WATER, BARREN, DEVPERV, and WETLAND classes are not subdivided by HSG; SWAT uses the built-in HRU overlay mechanism in the ArcSWAT interface.

Table 1. Aggregation of NLCD land cover classes

NLCD Class	Comments	SWAT class	HSPF (after processing)
11 Water	Water surface area usually accounted for as reach area	WATR	WATER
12 Perennial ice/snow		WATR	BARREN, Assume HSG D
21 Developed open space		URLD	DEVPERV; IMPERV
22 Dev. Low Intensity		URMD	
23 Dev. Med. Intensity		URHD	
24 Dev. High Intensity		UIDU	
31 Barren Land		SWRN	BARREN (D)
41 Forest	Deciduous	FRSD	FOREST (A,B,C,D)
42 Forest	Evergreen	FRSE	
43 Forest	Mixed	FRST	
51-52 Shrubland		RNGB	SHRUB (A,B,C,D)
71-74 Herbaceous Upland		RNGE	GRASS (A,B,C,D), BARREN (D)
81 Pasture/Hay		HAY	GRASS (A,B,C,D)
82 Cultivated		AGRR	AGRI (A,B,C,D)
91-97 Wetland	Emergent & woody wetlands	WETF, WETL, WETN	WETLAND, Assume HSG D
98-99 Wetland	Aquatic bed wetlands (not emergent)	WATR	WATER

The distribution of land use in the watershed is summarized in Table 2.

Table 2. Land use distribution for the Willamette River watershed (2001 NLCD mi²)

HUC 8 watershed	Open water	Snow/ Ice	Developed[a] Open space	Developed[a] Low density	Developed[a] Medium density	Developed[a] High density	Barren land	Forest	Shrubland	Pasture/Hay	Cultivated	Wetland	Total
17090001	26.4	0.0	8.2	2.5	0.9	0.2	12.8	1,111.6	174.2	16.6	10.7	2.9	1,367.0
17090002	4.0	0.0	14.2	5.1	2.1	0.8	1.1	464.6	113.6	42.7	10.4	8.5	667.2
17090003	13.4	0.0	79.3	76.6	34.4	14.1	16.7	615.0	214.7	519.7	220.9	70.6	1,875.5
17090004	7.2	2.5	10.0	3.0	1.5	0.3	41.1	1,059.3	177.0	15.6	13.8	3.6	1,334.8
17090005	8.7	1.0	9.2	4.7	1.0	0.3	8.5	558.0	93.1	38.3	33.5	8.4	764.4
17090006	8.6	0.0	10.0	5.0	1.3	0.3	2.9	673.6	183.6	105.9	42.8	6.0	1,040.0
17090007	11.7	0.0	34.2	63.1	28.5	9.9	2.5	112.1	32.9	215.3	168.5	33.3	712.0
17090008	0.8	0.0	26.7	17.3	4.3	1.6	7.4	333.2	93.3	134.4	132.2	21.2	772.3
17090009	1.8	0.0	18.4	23.1	9.4	3.0	1.7	366.1	99.1	190.5	138.2	22.7	874.0
17090010	1.9	0.0	30.1	69.3	38.5	11.2	8.1	261.1	79.3	79.2	114.6	16.2	709.6
17090011	5.3	0.0	15.4	11.0	3.8	1.7	1.1	716.8	118.2	42.2	25.0	3.6	944.0
17090012	6.4	0.0	11.5	41.0	33.7	15.4	0.4	26.8	1.6	5.9	3.7	2.0	148.4
Total	96.0	3.5	267.1	321.7	159.2	58.8	104.3	6,298.4	1,380.6	1,406.3	914.1	199.1	11,209.1

[a]The percent imperviousness applied to each of the developed land uses is as follows: open space (9.56%), low density (32.31%), medium density (61.49%), and high density (88.94%).

The HSPF model is set up on a hydrologic response unit (HRU) basis. For HSPF, HRUs were formed from an intersection of land use and hydrologic soil group, and then further subdivided by precipitation gage. Average slopes (which tend to correlate with soils) were calculated for each HRU. The water land use area was adjusted to prevent double counting with area described in HSPF reaches. SWAT HRUs are formed from an intersection of land use and SSURGO major soils.

Point Sources

Facilities permitted under the National Pollutant Discharge Elimination System (NPDES) are, by definition, considered point sources. It was assumed that minor dischargers (below 1.0 MGD) were insignificant, therefore, not included in the model setup and simulation. Data were sought from the PCS database for the major dischargers in the Willamette River watershed (Table 3 and Figure 3). Facilities that were missing total nitrogen, total phosphorus, or total suspended solids (TSS) concentrations were filled with a typical pollutant concentration value from literature based on SIC classification (Tetra Tech 1999). Constant point source flows and concentrations were assumed for each major discharge facility in the watershed for the entire simulation period.

During the water quality calibration it was noticed that assumptions used for total phosphorus, at some facilities, were too high. An investigation into the point sources that had assumed values for total phosphorus was conducted. A new assumed value was supplied for these facilities. The modifications made to the total phosphorus values are described in the “Changes to the Base Data” section of this report. The new assumed value was also applied to the SWAT simulation. Both the HSPF and SWAT models used the same flows and concentrations for each of the major point sources included in the simulations for the Willamette River watershed.

Table 3. Major point source discharges in the Willamette River watershed

NPDES ID	Name	Design flow (MGD)	Observed flow (MGD) (1991-2006 average)
OR0026891	PORTLAND,	8.30	15.42
OR0026140	OAK LODGE	4.00	6.29
OR0026221	CLACKAMAS	2.66	19.82
OR0030589	SILTRONIC	--	0.88
OR0031259	TRI-CITY	0.00	17.85
OR0000566[a]	BLUE HERO	--	--
OR0000787[a]	WEST LINN	--	--
OR0020214	CANBY, CI	2.00	1.31
OR0028118[b]	CLEAN WAT	22.60	22.60
OR0029777[c]	CLEAN WAT	39.00	25.00
OR0023345[d]	CLEAN WAT	7.50	5.02
OR0020168[d]	CLEAN WAT	5.00	3.74
OR0020001	WOODBURN,	3.33	4.09
OR0022764	WILSONVIL	2.25	19.03
OR0032352	NEWBERG,	4.00	48.85
OR0000558[a]	VIRGINIA	--	--
OR0026409	SALEM, CI	35.00	51.60
OR0034002	MCMINNVIL	5.60	68.53
OR0020737	DALLAS, C	2.00	5.47
OR0020818	LEBANON,	3.00	3.93
OR0028801	ALBANY, C	8.70	7.28
OR0001112	TDY INDUS	--	2.50
OR0000442	WEYERHAEU	--	--
OR0020427	STAYTON,	1.90	3.47
OR0020346	SWEET HOM	1.38	3.69
OR0026361	CORVALLIS	9.70	13.57
OR0001716	OREGON ME	--	0.73
OR0033405[a]	FORT JAME	--	--
OR0001074[a]	CASCADE P	--	--
OR0000515[a]	WEYERHAEU	--	--
OR0031224	METROPOLI	49.00	36.77
OR0020559	COTTAGE G	1.20	2.78
OR0020656	SILVERTON	2.50	2.84

[a]Paper/pulp mills; discharge was ignored as their withdrawal and discharge are about the same
[b]Due to the upgrading of the treatment plant, total phosphorus concentration in the effluent value considered is 3.6 mg/L prior to 1992 and 0.07 mg/L for 1992 and onward.
[c]Due to the upgrading of the treatment plant, total phosphorus concentration in the effluent value considered is 2.1 mg/L prior to 1992 and 0.07 mg/L for 1992 and onward.
[d]Does not discharge to the river in summer

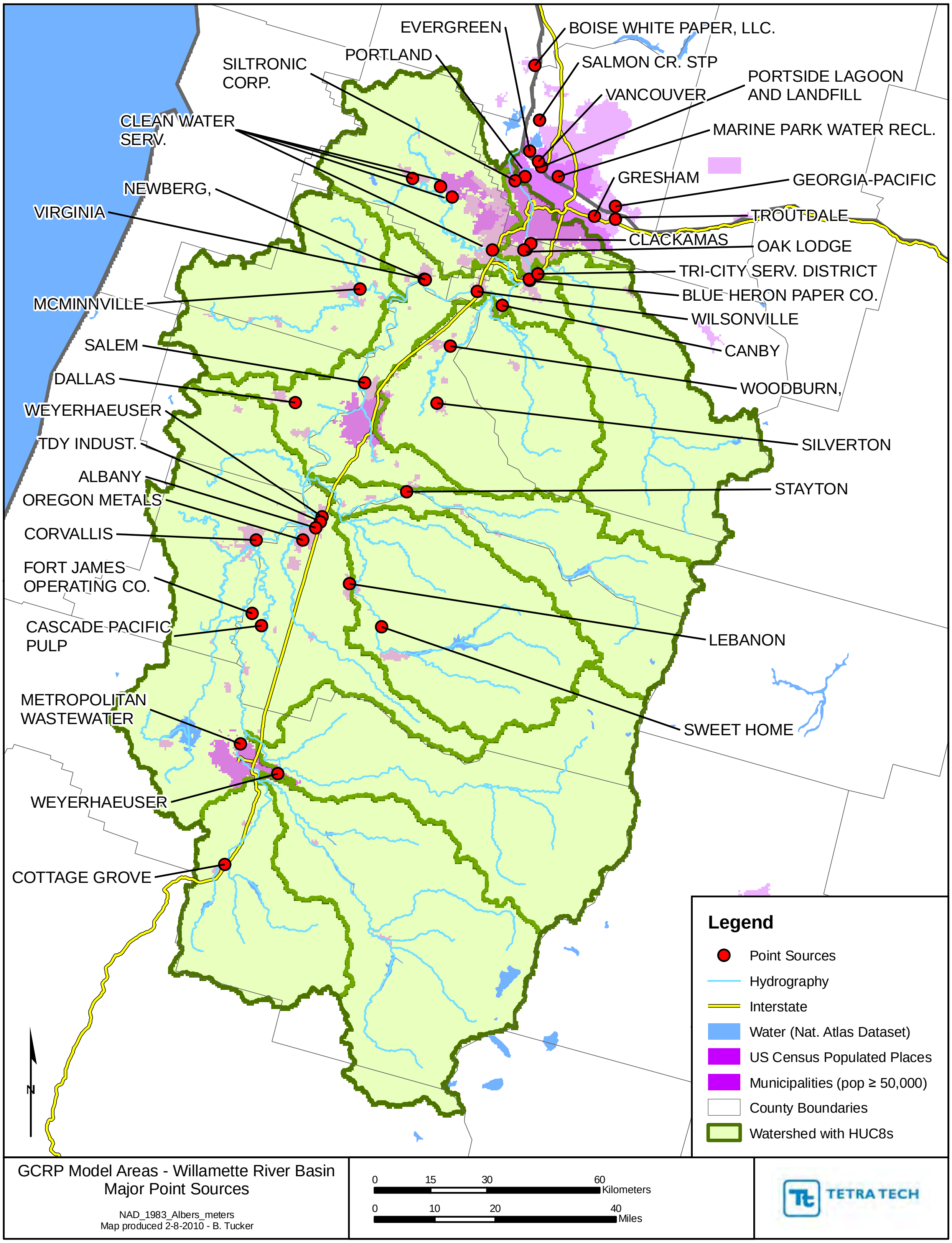

Figure 3. Major point sources in the Willamette River watershed.

Meteorological Data

The required meteorological data series for the 20 Watershed study are precipitation, air temperature, and potential evapotranspiration. The 20 Watershed model does not include water temperature or algal simulation and uses a degree-day method for snowmelt. These are drawn from the BASINS4 Meteorological Database (USEPA 2008), which provides a consistent, quality-assured set of nationwide data with gaps filled and records disaggregated. Scenario application will require simulation over 30 years, so the available stations are those with a common 30-year period of record (or one that can be filled from an approximately co-located station) that covers the year 2001. A total of 40 precipitation stations were identified for use in the Willamette River watershed model with a common period of record (Table 4 and Figure 4). Temperature records are sparser; where these are absent, temperature is taken from nearby stations with an elevation correction. For each weather station, Penman-Monteith reference evapotranspiration was calculated for use in HSPF using observed precipitation and temperature coupled with SWAT weather generator estimates of solar radiation, wind movement, cloud cover, and relative humidity.

For the 20 Watershed model applications, SWAT uses daily meteorological data, while HSPF requires hourly data. It is important to note that a majority of the meteorological stations available for the Willamette River watershed are Cooperative Summary of the Day stations that do not report sub-daily data. The BASINS4 dataset already has versions of the daily data that have been disaggregated to an hourly time step using template stations. For each daily station, this disaggregation was undertaken in reference to a single disaggregation template. Occasionally, this automated procedure provides undesirable results, particularly when the total rainfall for the day is very different between the subject station and the disaggregation template. This yields a small number of hourly precipitation intensity estimates that are unrealistically high (e.g., much greater than the 100-yr 1-hour event for the region). This has only a small impact on the watershed-scale hydrologic calibration as gages are influenced by rainfall from multiple weather stations, but can introduce significant problems for the prediction of erosion and sediment loads.

Table 4. Precipitation stations for the Willamette River watershed model

COOP ID	Name	Latitude	Longitude	Temperature	Elevation (ft)
350595	OR350595	45.4548	-122.8200	Yes	269
350652	OR350652	44.2868	-122.0380	Yes	2,152
351222	OR351222	45.6864	-123.1910	No	157
351433	OR351433	44.3981	-122.4850	Yes	860
351735	OR351735	45.1701	-122.4330	No	679
351862	OR351862	44.6333	-123.1890	Yes	226
351877	OR351877	44.5087	-123.4580	Yes	591
351902	OR351902	43.7178	-123.0570	Yes	830
351914	OR351914	44.1331	-122.2500	No	384
352112	OR352112	44.9464	-123.2910	Yes	289
352292	OR352292	44.7243	-122.2540	Yes	1,220
352345	OR352345	43.7078	-122.7390	No	1,217
352374	OR352374	43.7823	-122.9630	Yes	820
352493	OR352493	45.2743	-122.2010	No	925
352693	OR352693	45.2690	-122.3180	Yes	449
352709	OR352709	44.1279	-123.2200	Yes	354
352805	OR352805	44.8578	-123.4300	Yes	420
352997	OR352997	45.5244	-123.1030	Yes	180
353047	OR353047	44.4139	-122.6720	Yes	551
353705	OR353705	45.3122	-123.3510	No	755
353971	OR353971	44.3525	-122.7840	No	610

COOP ID	Name	Latitude	Longitude	Temperature	Elevation (ft)
354606	OR354606	44.6254	-122.7180	Yes	518
354811	OR354811	44.1001	-122.6880	Yes	676
355050	OR355050	43.9145	-122.7600	Yes	712
355213	OR355213	44.1707	-122.8710	No	545
355221	OR355221	44.6125	-121.9480	Yes	2,474
355384	OR355384	45.2215	-123.1620	Yes	154
356151	OR356151	45.2818	-122.7510	Yes	151
356213	OR356213	43.7429	-122.4430	Yes	1,276
356334	OR356334	45.3553	-122.6050	Yes	167
356749	OR356749	45.5181	-122.6890	Yes	157
357127	OR357127	45.3037	-122.9140	No	515
357500	OR357500	44.9051	-123.0010	Yes	203
357631	OR357631	44.9469	-122.5240	Yes	2,316
357809	OR357809	44.8734	-122.6480	Yes	1,348
357823	OR357823	45.0051	-122.7730	Yes	407
358095	OR358095	44.7895	-122.8140	Yes	427
358466	OR358466	45.1250	-122.0720	Yes	1,119
359083	OR359083	44.5000	-122.8190	No	436
359372	OR359372	45.0832	-123.4890	No	384

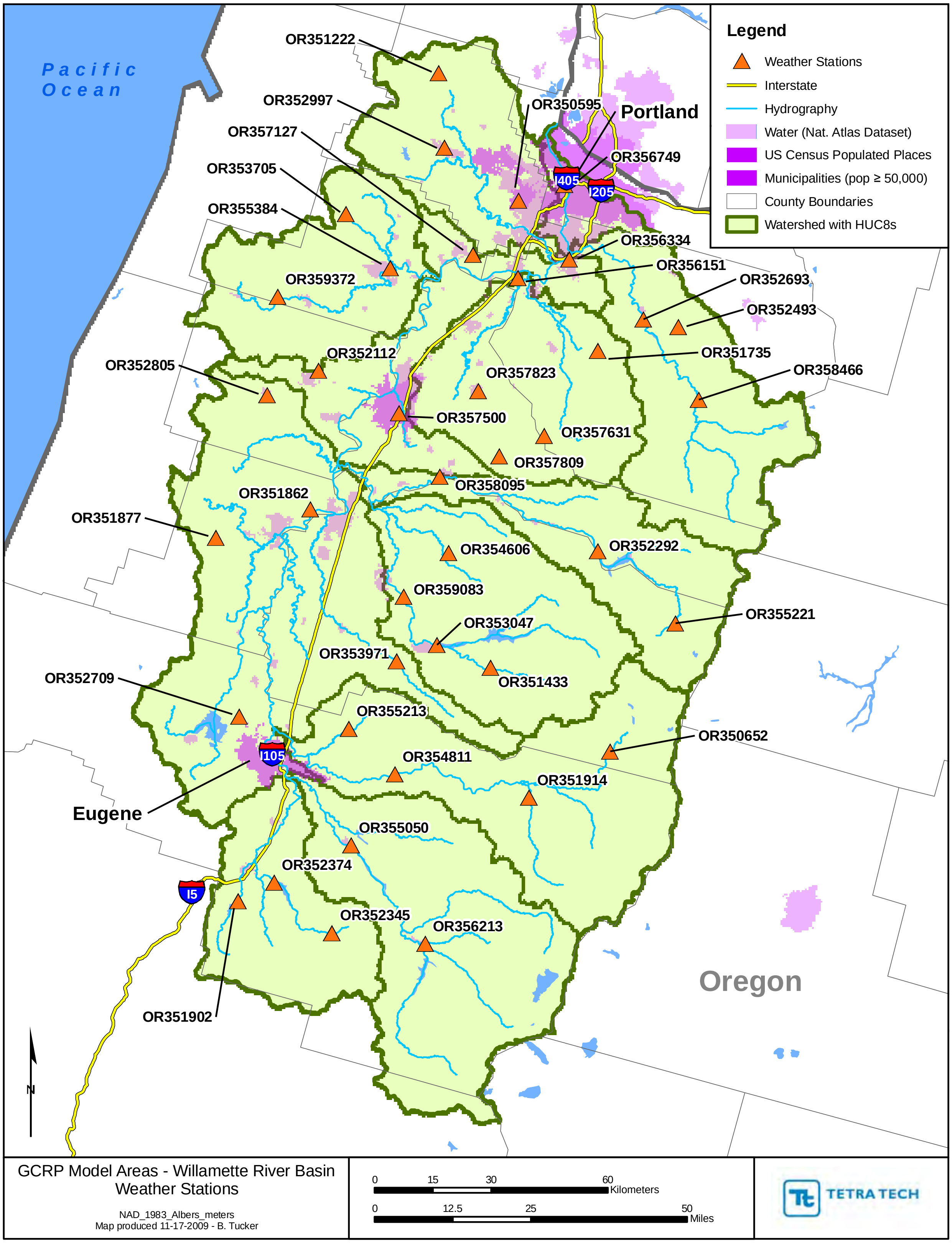

Figure 4. Weather stations for the Willamette River watershed model.

Watershed Segmentation

The Willamette River watershed was divided into 75 subwatersheds for the purposes of modeling (Figure 5). The initial calibration watershed (Tualatin HUC) is highlighted. Each of the subwatershed delineations represents roughly a HUC 10 scale watershed. Each of the major reservoirs in the Willamette watershed was delineated so that each dam outlet represents an individual watershed outlet. The delineations were done this way to ensure that any individual lake was contained in one watershed and that the watershed was only represented by one outlet. The Willamette 20 Watershed model is set for the complete Willamette watershed without any inflow from outside and thus does not require specification of any boundary conditions for application.

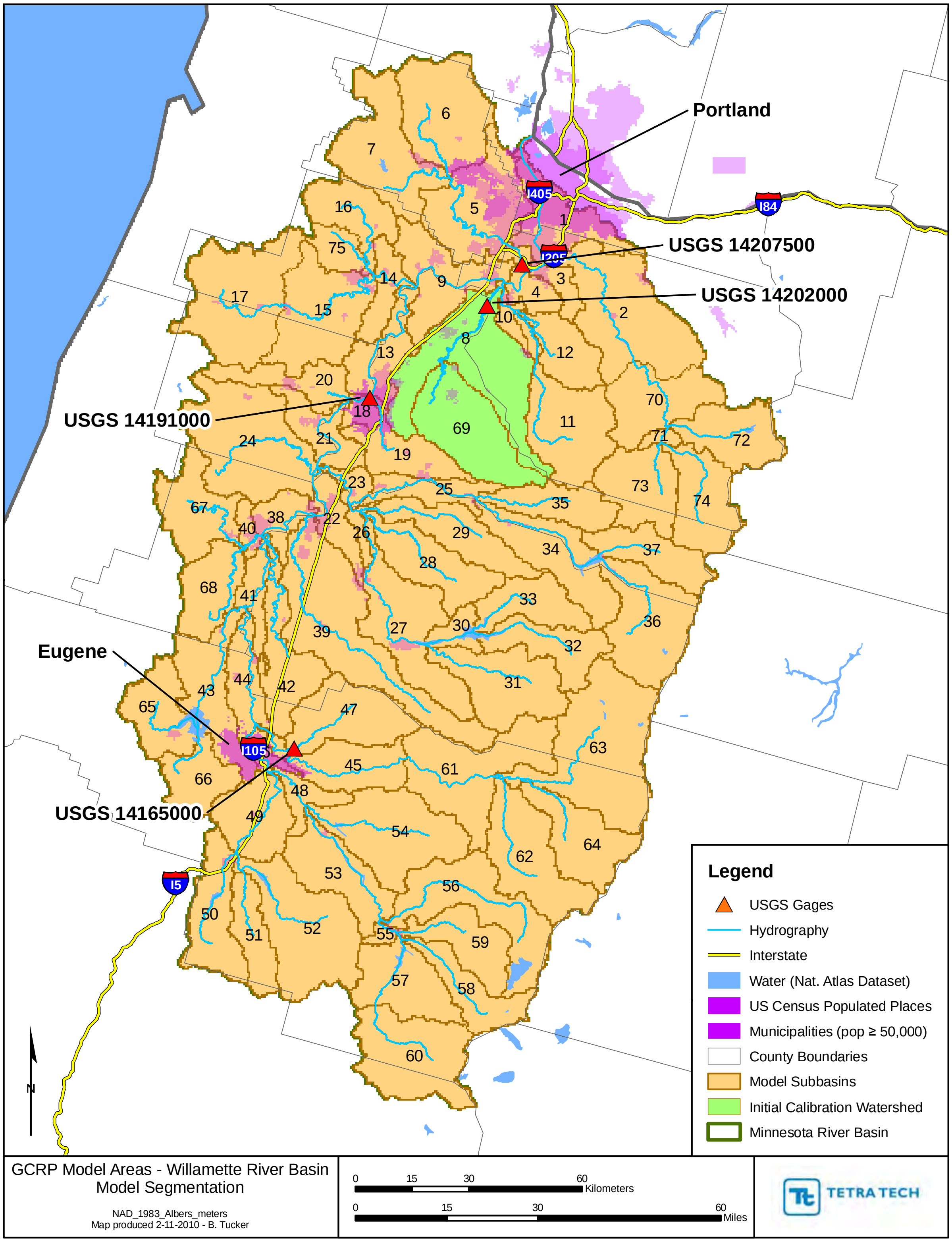

Figure 5. Model segmentation and USGS stations utilized for the Willamette River watershed.
Note: SWAT subwatershed numbering is shown; the HSPF model for this watershed uses the same subwatershed boundaries with an alternative internal numbering scheme.

Calibration Data and Locations

Each of the twelve HUC8s in the watershed was considered as a candidate representative subwatershed for calibration. The objective was to find a HUC8 that resembled the overall characteristics of the Willamette watershed with respect to land use, precipitation and terrain. The USGS gages on the Tualatin River at West Linn, OR (USGS 14207500) and the Pudding River at Aurora, OR (USGS 14202000) were chosen as the primary hydrology and water quality calibration locations. Additional tributary hydrology calibration was performed on the South Yamhill River at McMinnville, OR (USGS 14194150) and the Mohawk (McKenzie) River near Springfield (USGS 14165000). A hydrology calibration check was performed at the USGS gage on the Willamette River at Salem, OR (USGS 14191000), which is the most downstream gage in the watershed that does not include tidal effects. At this location, 43 percent of the tributary area is controlled by the major dams. Therefore, calibration at this location would have been of limited use in developing model parameters. Table 5 presents the calibration and validation locations chosen for the Willamette River watershed.

Table 5. Calibration and validation locations in the Willamette River watershed

Station name	USGS ID	Drainage area (mi^2)	Hydrology calibration	Water quality calibration
Willamette River at Salem, Oregon	14191000	7280	X	
Pudding River at Aurora, Oregon	14202000	479	X	X
Tualatin River at West Linn, Oregon	14207500	706	X	X
Mohawk River near Springfield, Oregon	14165000	177	X	
South Yamhill River at McMinnville	14194150	528	X	

The model calibration period varied based on the availability of data. In general a calibration period of water years 1996 through 2005 was used and a period from water years 1986 through 1995 was used for validation. Water quality data were very limited and the period of coverage was not consistent between the two gages used for water quality calibration in this study. A calibration period of water years 1996 to 2002 and validation period of water years 1993 to 1995 were used for the Pudding gage; whereas, a calibration period of water years 1994-1995 and validation period of water years 1986 to 1993 were used for the Tualatin gage.

HSPF Modeling

Flows in the lower Willamette River watershed are dominated by the effects of 13 reservoirs and their associated dams operated by the U.S. Army Corps of Engineers for water supply, flood control, and navigation. These reservoirs control much of the runoff from the southern and eastern mountainous portions of the watershed where precipitation and snow fall are highest. Incorporation of the reservoirs in the model was a significant part of the model development effort. For the calibration model, the reservoirs were not modeled; the flow at the nearest USGS gage downstream of each reservoir was used as a boundary flow. One main stem gage was used as a hydrology calibration check; however, the flow at this gage was significantly affected by the boundary flows, particularly in the summer months when the boundary flows resulted in a significant overprediction of the observed flow. For the scenario model, the boundary conditions were removed, and the reservoirs were modeled by replacing the default HSPF FTABLEs with more realistic estimates of volume surface area, and spillway outflow rate. U.S. Army Corps of Engineer data were analyzed to develop seasonal storages and minimum flow time series which are specified as inputs to the model. During the simulation, each reservoir receives inflows from upstream areas, and the program computes outflows consisting of the minimum releases plus any water necessary to maintain the storage at or below the seasonal target storage.

Initial hydrologic parameterization for the Willamette calibration focus area came from the King County, Washington HSPF Modeling (Green River Water Quality Assessment and Sammamish-Washington Analysis and Modeling Program) (Bicknell et al. 2005). The King County hydrologic models have been under development for many years, and under the Green River/Sammamish-Washington project were extended to most of the watershed.

Calibrated parameters from the Tualatin River (USGS 14207500) and South Yamhill River (USGS 14194150) were applied to the eastern portions of the study area, while calibration adjustments for the Pudding River (USGS 14202000) were applied to the upper and western sections of the study area. Parameters from the Mohawk River (USGS 14165000) were applied to the southern and southwestern portions of the study area.

Once the hydrology calibration was complete for the entire Willamette watershed, the focus turned to sediment and water quality representation. The starting water quality parameters were again taken from the King County/Seattle HSPF models.

Changes Made to Base Data Provided

No changes were made to the meteorological or land use base data. However, one of the rainfall stations (OR357631) was not used because of unrealistic rainfall in 1996 that significantly skewed the water quality calibration results in the Pudding River subwatershed. A number of changes were made to the point sources. The flow from the six paper mills was changed to zero, since they draw water from the same rivers that they discharge to. These point sources are: OR0000442, OR0000515, OR0000558, OR0000566, OR0000787, and OR0001074. Also, several other point sources discharge to the calibration watersheds. Some of the parameters were determined to be erroneous, and since they caused obvious problems in the calibration in the Tualatin River and Pudding River sub-watersheds, were modified based on information obtained from other sources. Three point sources (OR0020001, OR0020168, and OR0023345) do not discharge to surface waters during the summer, so these three were modified to turn off the discharges between June and September. The discharges of three point sources (OR0028118, OR0029777, and OR0034002) were found to be overestimated by using the “Observed Flow”, and were changed to the “Design Flow”. The total phosphorus concentrations of two point sources were reduced as a result of the use of advanced treatment methods; these are OR0020168 and OR0029777. Summer loads of total phosphorus were substantially overpredicted with the higher values.

Assumptions

Reservoirs

There are 13 dams and 11 major reservoirs in the study area. Figure 6 shows the locations of the dams and the reservoirs in the watershed and Table 6 presents the 11 reservoirs that were included in the HSPF model. Two of the dams (Big Cliff and Dexter) are re-regulation dams that allow the Corps to adjust the downstream flow more smoothly than the releases from the upstream reservoir. The primary tributary calibration sites were chosen in order to avoid effects of these dams. The main stem calibration site on the Willamette at Salem, OR is affected by all of the major dams, so it was only used to check the calibration. The model used for calibration was modified from the original model to include specification of boundary inflows at the USGS gage downstream from each reservoir that provides flow to the Willamette main stem. The final model used for climate scenarios was modified by improving the hydraulic representation of each reservoir, and including a simplified representation of reservoir operation. Fortunately, all of the major reservoirs are operated by the U.S. Army Corps of Engineers, and they are operated in a relatively consistent manner. Seasonally varying target storages and minimum releases were programmed into the model using input time series. HSPF computes the reservoir outflows as the sum of the minimum releases and sufficient water to maintain the actual storage at or below the target storage. While one would assume the reservoirs influence the flow and water quality exiting the Willamette River at the outlet, for this model the impacts of these reservoirs are assumed to be implicitly represented through the modified FTABLES and the simplified operations, which should be applicable under future conditions.

Withdrawals

Because nobody knows what water withdrawals, by municipal and industrial facilities, will look like in the future they were not included in the 20 Watershed model application.

Irrigation

Irrigation is not being explicitly modeled in the Willamette River watershed.

Snow Simulation

The Willamette HPSF model includes snow simulation using the degree-day method for snowmelt. It is modeled in the subwatersheds that have a large area at high elevations, generally above 2,500 feet. The parameter values were extracted from other applications, and minor adjustments were made to ensure that the snow depths and duration were reasonable. No further calibration was performed for snow.

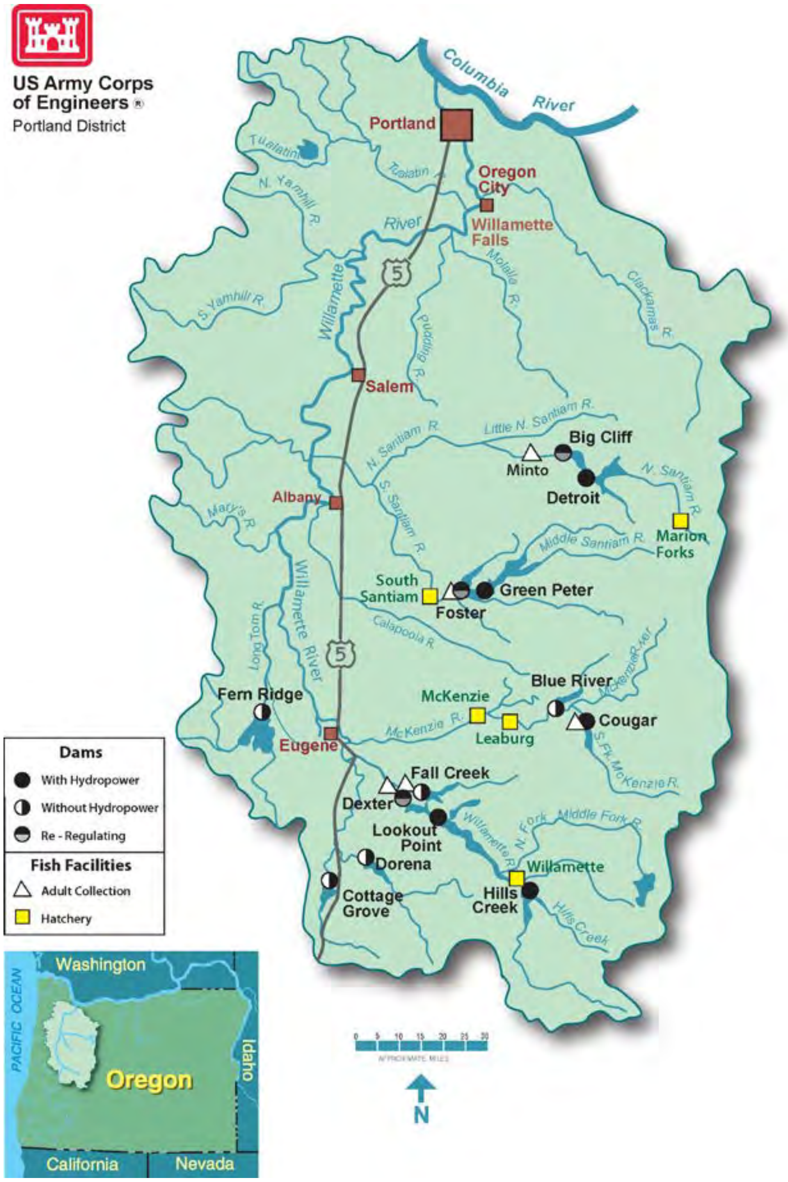

Figure 6. Dams and reservoirs in the Willamette River watershed (Source: USACE 2009).

Table 6. Reservoirs represented in the Willamette River watershed model

Dam Name	Other Name	River	Owner
Fall Creek	Fall Creek Lake	Fall Creek	USACE
Dorena	Dorena Lake	Row River	USACE
Lookout Point	Lookout Point Lake	Middle Fork-Willamette River	USACE
Green Peter	Green Peter	Middle Santiam River	USACE
Foster	Foster Lake	South Santiam River	USACE
Hills Creek	Hills Creek Lake	Middle Fork-Willamette River	USACE
Detroit	Detroit Lake	North Santiam River	USACE
Cottage Grove	Cottage Grove Lake	Coast Fork-Willamette River	USACE
Cougar	Cougar Lake	South Fork-McKenzie River	USACE
Blue River	Blue River Lake	Blue River-McKenzie River	USACE
Fern Ridge	Fern Ridge Lake	Long Tom River	USACE

Hydrology Calibration

As mentioned above, the starting parameters for this Willamette River HSPF model came from the King County, Washington HSPF models. After the starting parameters were inserted into the model input files, average annual potential evapotranspiration values were computed and compared to published values. Through this process it was determined the input potential evapotranspiration time series should be reduced by multipliers, since the computation of these time series produced more PET on an average annual basis than the published values indicate. The default multipliers used for PET were 0.80; however, some of the multipliers were adjusted slightly during the hydrology calibration. Calibration adjustments focused on the following parameters:

- LZSN (lower zone nominal storage): LZSN was reduced to shift flows to the wet period and reduce them in the summer. It was also used to increase total runoff.
- INFILT (index to mean soil infiltration rate): Infiltration was generally decreased from the initial values to increase storm peaks and reduce low flows.
- DEEPFR (fraction of groundwater inflow that will enter deep groundwater): small values of DEEPFR were used to attempt to reduce low flows and to reduce total flow volume.
- BASETP (ET by riparian vegetation): Slightly increasing the BASETP value provided some ET by riparian vegetation and improved the simulation of low flows.
- LZETP (lower zone E-T parameter): LZETP was generally increased to reduce flow, particularly the low flows, and to reduce total volumes.
- AGWRC (Groundwater recession rate)

Initial calibration was performed at the USGS gage on the Tualatin River at West Linn, OR (USGS 14207500), and is summarized in Figures 7 through 13 and Tables 7 and 8. The model fit is of good quality overall, but simulates slightly high on the storm flows as is indicated by the *Error in Storm Volumes* metric. The model calibration period was set to the 10 water years from 10/01/1995 to 09/30/2005.

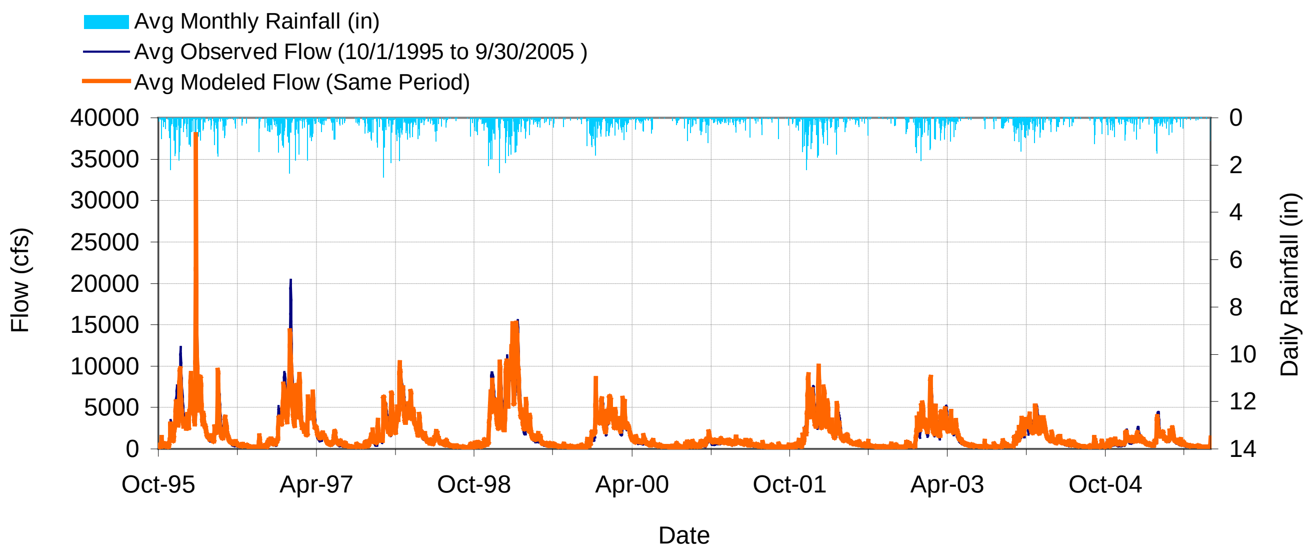

Figure 7. Mean daily flow at USGS 14207500 Tualatin River at West Linn, OR – calibration period (HSPF).

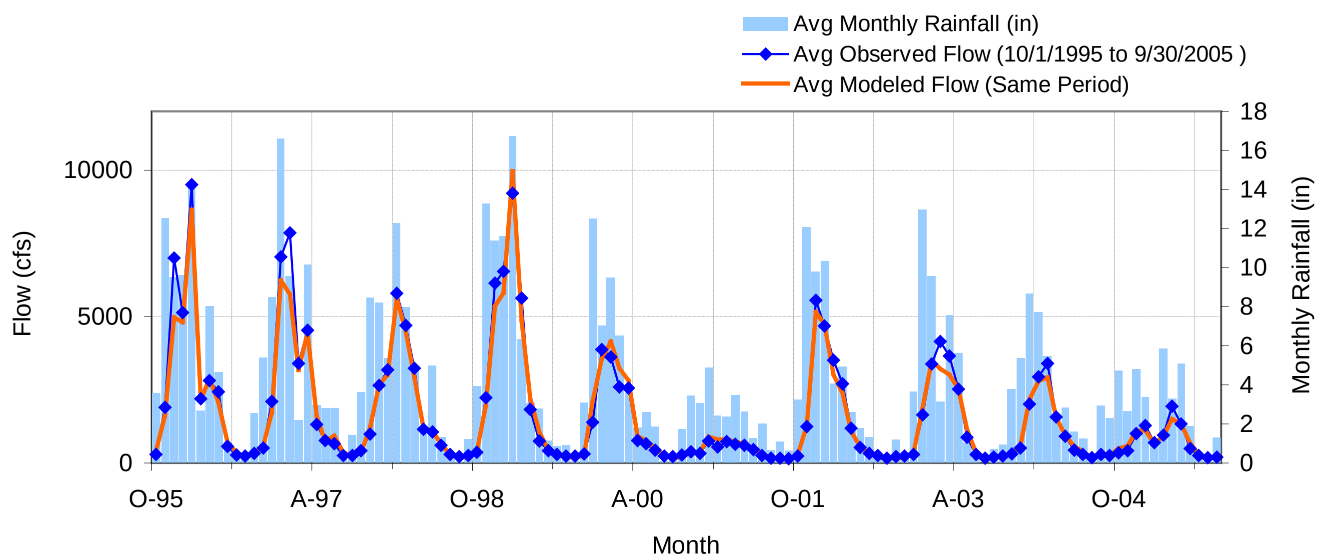

Figure 8. Mean monthly flow at USGS 14207500 Tualatin River at West Linn, OR – calibration period (HSPF).

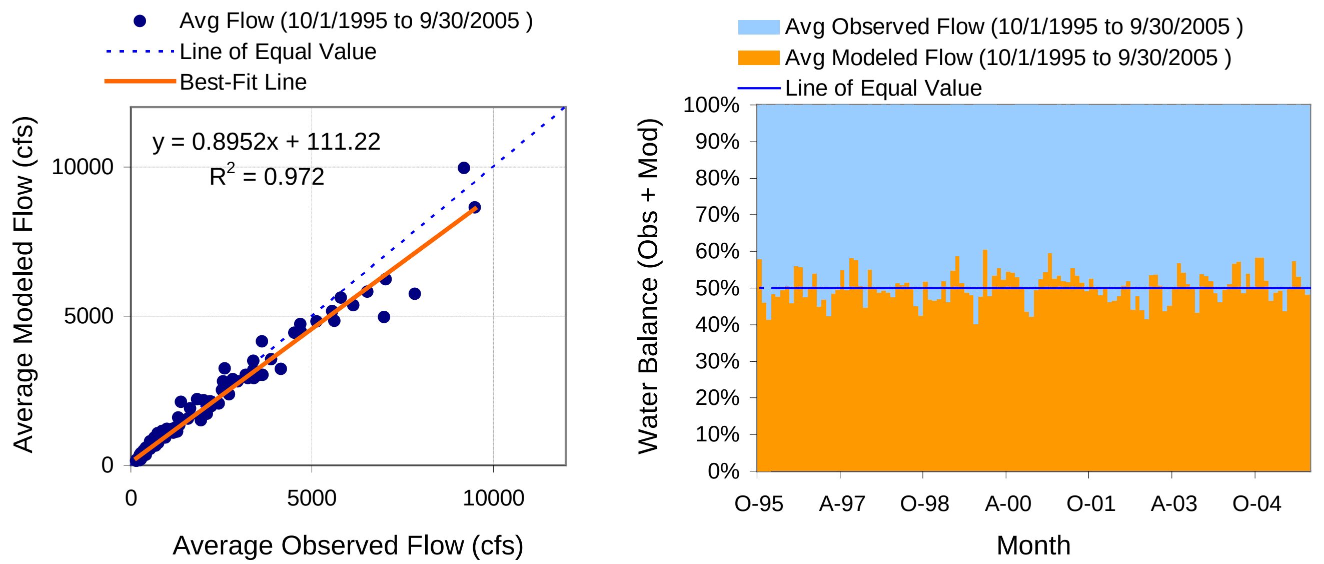

Figure 9. Monthly flow regression and temporal variation at USGS 14207500 Tualatin River at West Linn, OR – calibration period (HSPF).

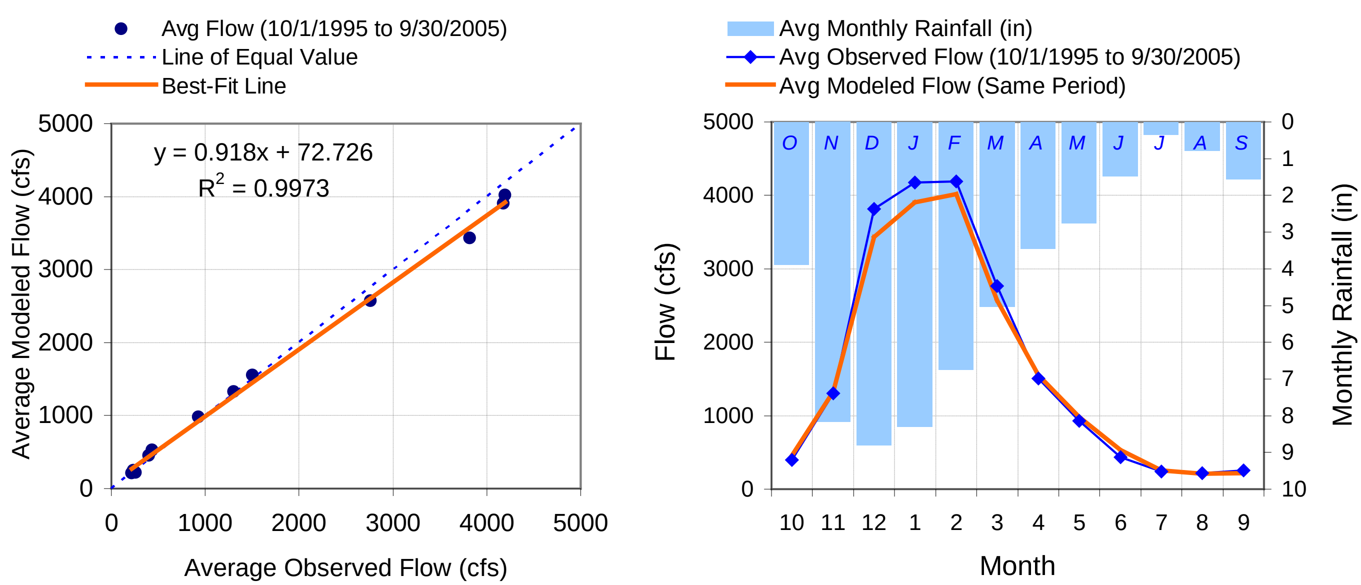

Figure 10. Seasonal regression and temporal aggregate at USGS 14207500 Tualatin River at West Linn, OR – calibration period (HSPF).

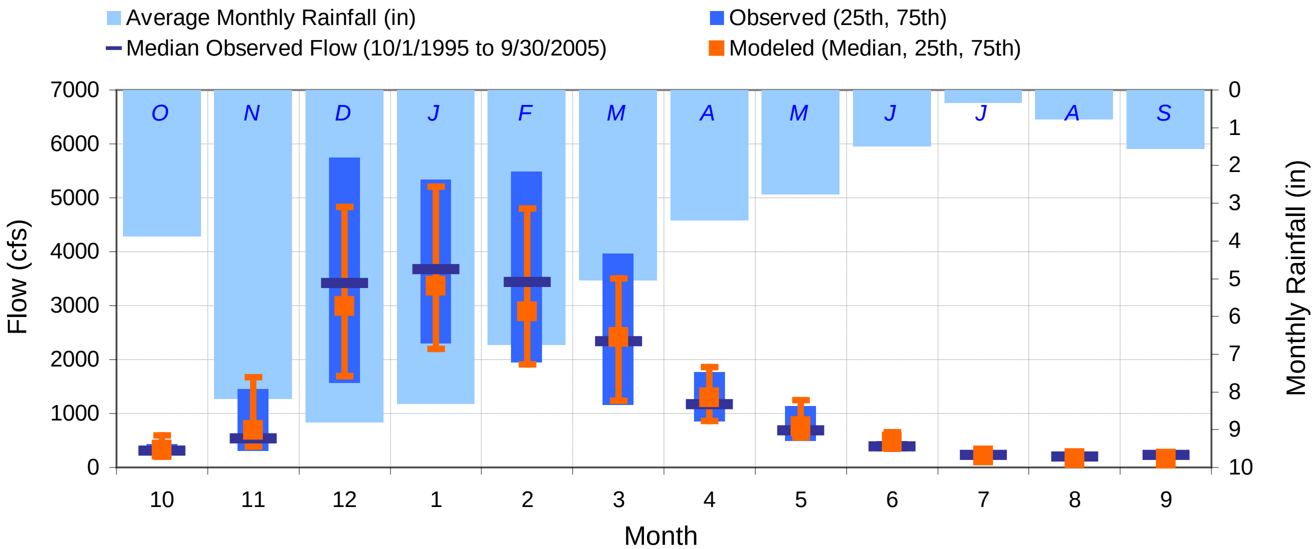

Figure 11. Seasonal medians and ranges at USGS 14207500 Tualatin River at West Linn, OR – calibration period (HSPF).

Table 7. Seasonal summary at USGS 14207500 Tualatin River at West Linn, OR – calibration period (HSPF)

MONTH	OBSERVED FLOW (CFS)				MODELED FLOW (CFS)			
	MEAN	MEDIAN	25TH	75TH	MEAN	MEDIAN	25TH	75TH
Oct	399.00	309.00	234.00	436.75	454.72	329.52	193.65	592.38
Nov	1305.46	534.00	305.75	1460.00	1323.58	697.37	389.21	1674.78
Dec	3817.72	3420.00	1565.00	5747.50	3432.50	2985.78	1690.84	4827.79
Jan	4175.40	3675.00	2297.50	5340.00	3905.86	3369.21	2197.11	5211.28
Feb	4193.04	3440.00	1955.00	5485.00	4018.44	2892.20	1907.41	4798.64
Mar	2763.99	2340.00	1155.00	3962.50	2572.21	2415.34	1238.50	3501.83
Apr	1503.13	1165.00	855.00	1760.00	1551.10	1296.01	858.61	1860.24
May	929.54	681.00	497.25	1140.00	984.03	762.86	557.19	1243.80
Jun	434.30	385.50	295.00	485.00	529.68	479.68	342.37	655.71
Jul	236.99	227.00	187.00	275.50	251.49	222.59	182.91	294.57
Aug	215.16	197.50	171.25	233.75	207.51	170.68	149.20	208.77
Sep	258.55	232.00	197.75	286.25	215.52	156.46	135.63	203.93

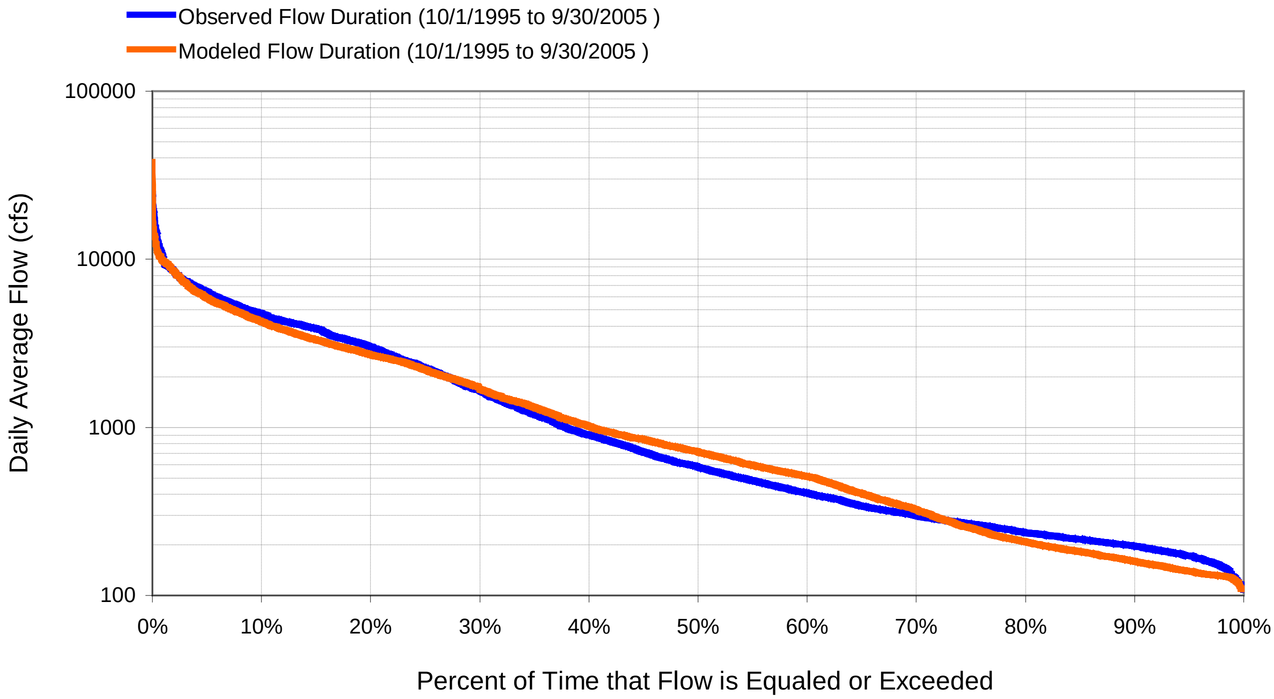

Figure 12. Flow exceedence at USGS 14207500 Tualatin River at West Linn, OR – calibration period (HSPF).

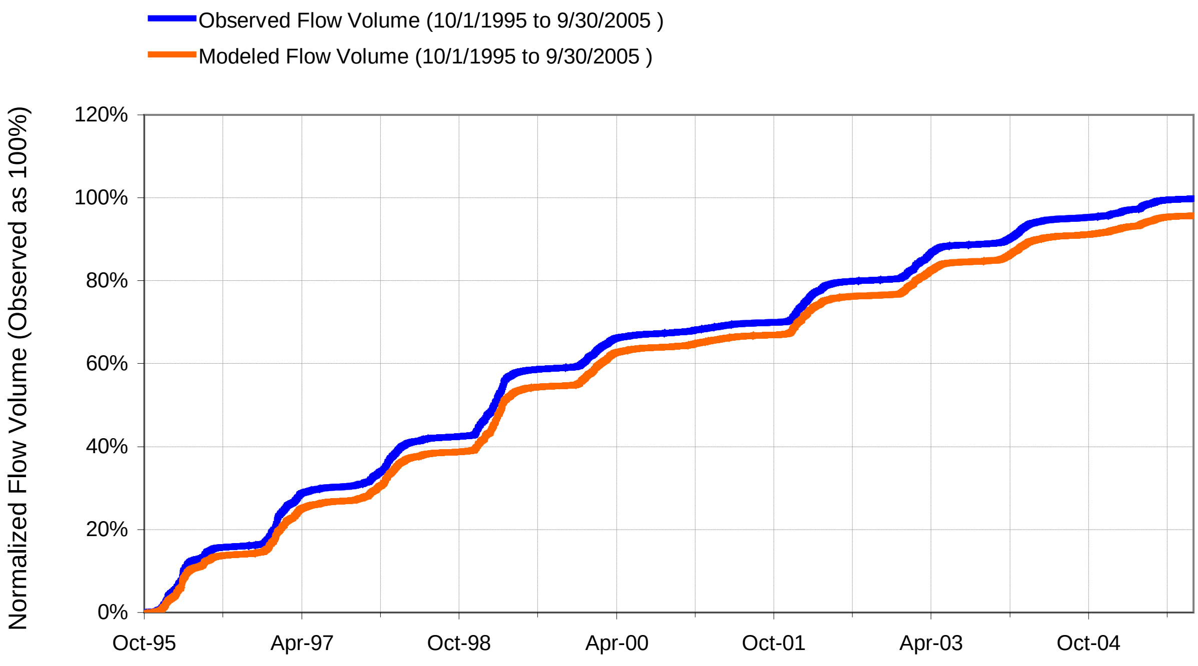

Figure 13. Flow accumulation at USGS 14207500 Tualatin River at West Linn, OR – calibration period (HSPF).

Table 8. Summary statistics at USGS 14207500 Tualatin River at West Linn, OR – calibration period (HSPF)

HSPF Simulated Flow		Observed Flow Gage	
REACH OUTFLOW FROM DSN 14 10-Year Analysis Period: 10/1/1995 - 9/30/2005 Flow volumes are (inches/year) for upstream drainage area		USGS 14207500 TUALATIN RIVER AT WEST LINN, OR Hydrologic Unit Code: 17090010 Latitude: 45.35067559 Longitude: -122.6762044 Drainage Area (sq-mi): 706	
Total Simulated In-stream Flow:	**30.99**	Total Observed In-stream Flow:	**32.25**
Total of simulated highest 10% flows:	**13.03**	Total of Observed highest 10% flows:	**13.96**
Total of Simulated lowest 50% flows:	**3.06**	Total of Observed Lowest 50% flows:	**2.85**
Simulated Summer Flow Volume (months 7-9):	**1.09**	Observed Summer Flow Volume (7-9):	**1.15**
Simulated Fall Flow Volume (months 10-12):	**8.44**	Observed Fall Flow Volume (10-12):	**8.95**
Simulated Winter Flow Volume (months 1-3):	**16.57**	Observed Winter Flow Volume (1-3):	**17.58**
Simulated Spring Flow Volume (months 4-6):	**4.89**	Observed Spring Flow Volume (4-6):	**4.58**
Total Simulated Storm Volume:	**7.59**	Total Observed Storm Volume:	**6.18**
Simulated Summer Storm Volume (7-9):	**0.20**	Observed Summer Storm Volume (7-9):	**0.16**

Errors (Simulated-Observed)	*Error Statistics*	*Recommended Criteria*
Error in total volume:	-3.92	10
Error in 50% lowest flows:	7.28	10
Error in 10% highest flows:	-6.64	15
Seasonal volume error - Summer:	-4.95	30
Seasonal volume error - Fall:	-5.69	30
Seasonal volume error - Winter:	-5.76	30
Seasonal volume error - Spring:	6.89	30
Error in storm volumes:	**22.92**	**20**
Error in summer storm volumes:	27.87	50
Nash-Sutcliffe Coefficient of Efficiency, E:	0.799	Model accuracy increases
Baseline adjusted coefficient (Garrick), E':	0.731	as E or E' approaches 1.0
Monthly NSE	0.965	

>> Clear

Hydrology Validation

Validation for the Willamette River watershed calibration focus area was performed at the same location (Tualatin River) but for water years 10/01/1985 to 09/30/1995. Results are presented in Figures 14 through 20 and Tables 9 and 10. Similar to the calibration years, the validation years' model fit is of good quality, although the validation shows oversimulation of low flows and summer seasonal flows, and undersimulation of the 10 percent highest flows. The rest of the metrics fall within the acceptable range set for the 20 Watershed study.

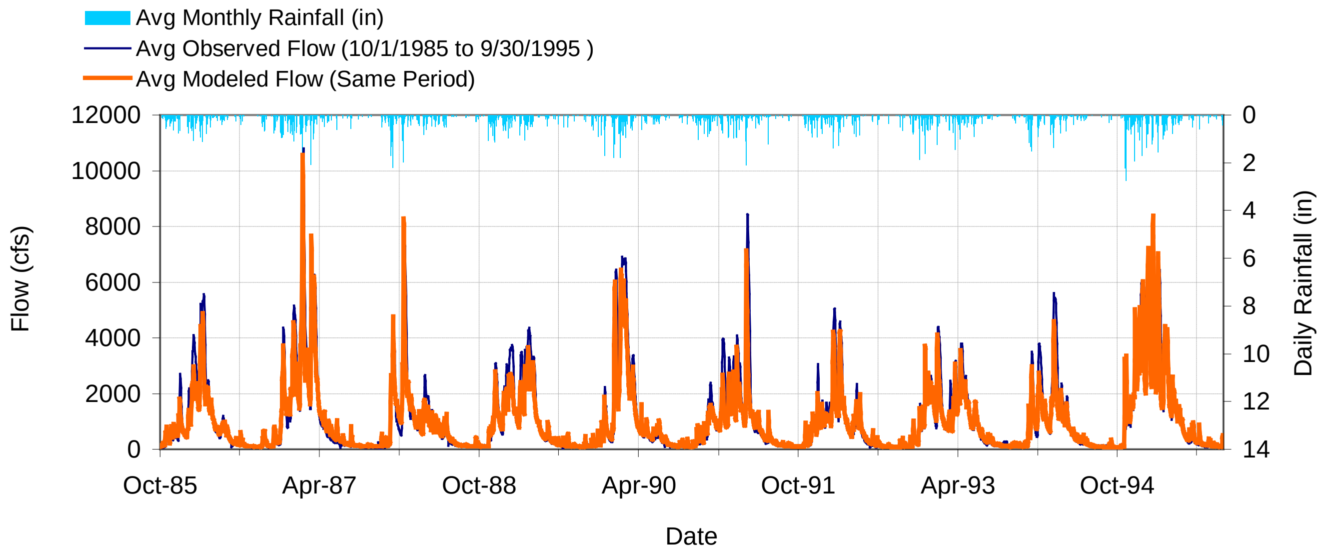

Figure 14. Mean daily flow at USGS 14207500 Tualatin River at West Linn, OR – validation period (HSPF).

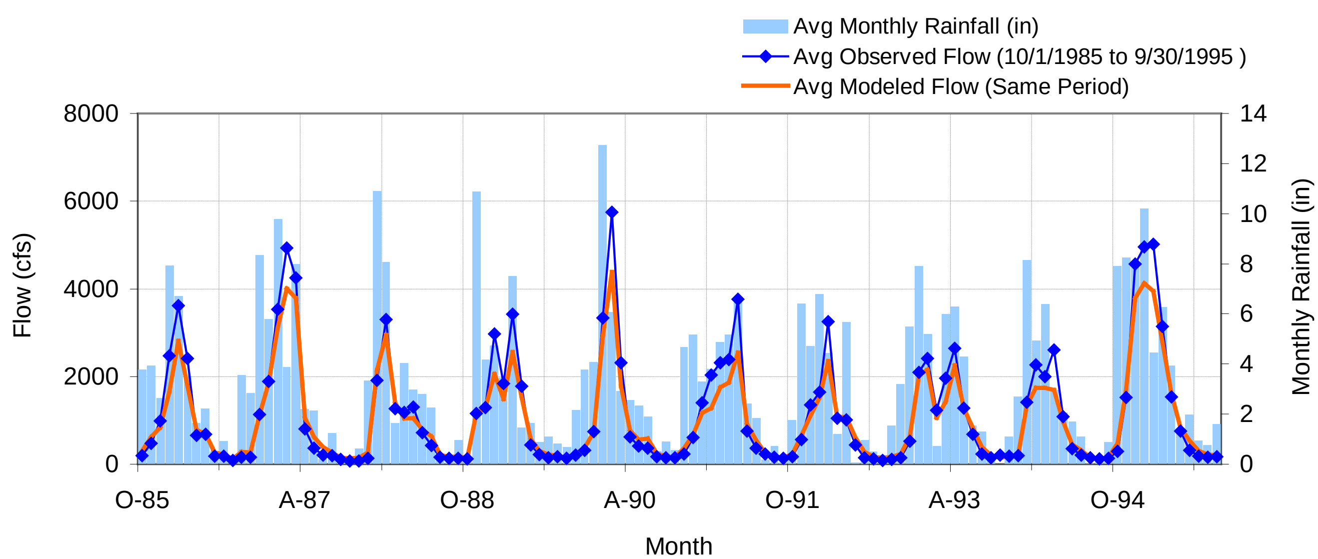

Figure 15. Mean monthly flow at USGS 14207500 Tualatin River at West Linn, OR – validation period (HSPF).

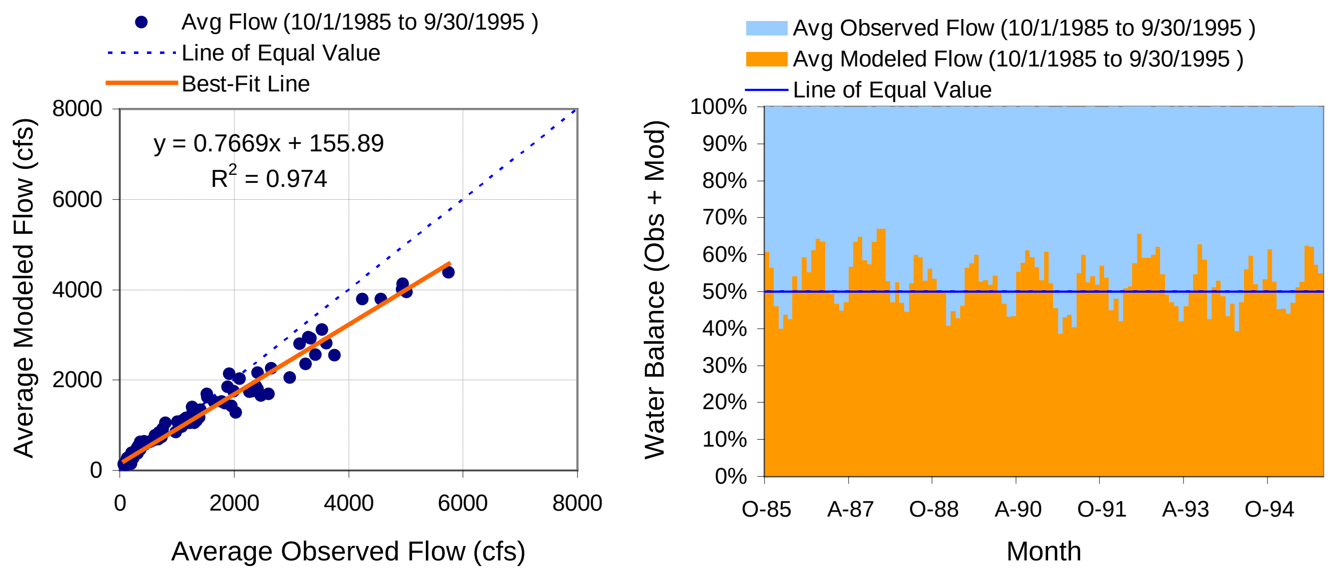

Figure 16. Monthly flow regression and temporal variation at USGS 14207500 Tualatin River at West Linn, OR – validation period (HSPF).

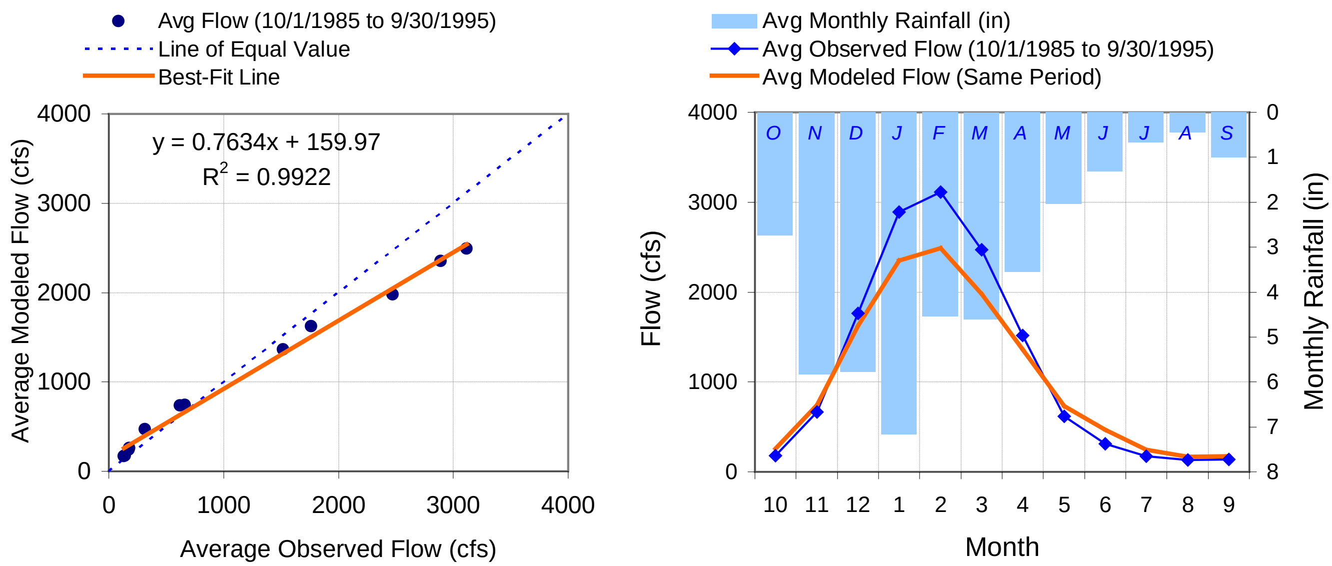

Figure 17. Seasonal regression and temporal aggregate at USGS 14207500 Tualatin River at West Linn, OR – validation period (HSPF).

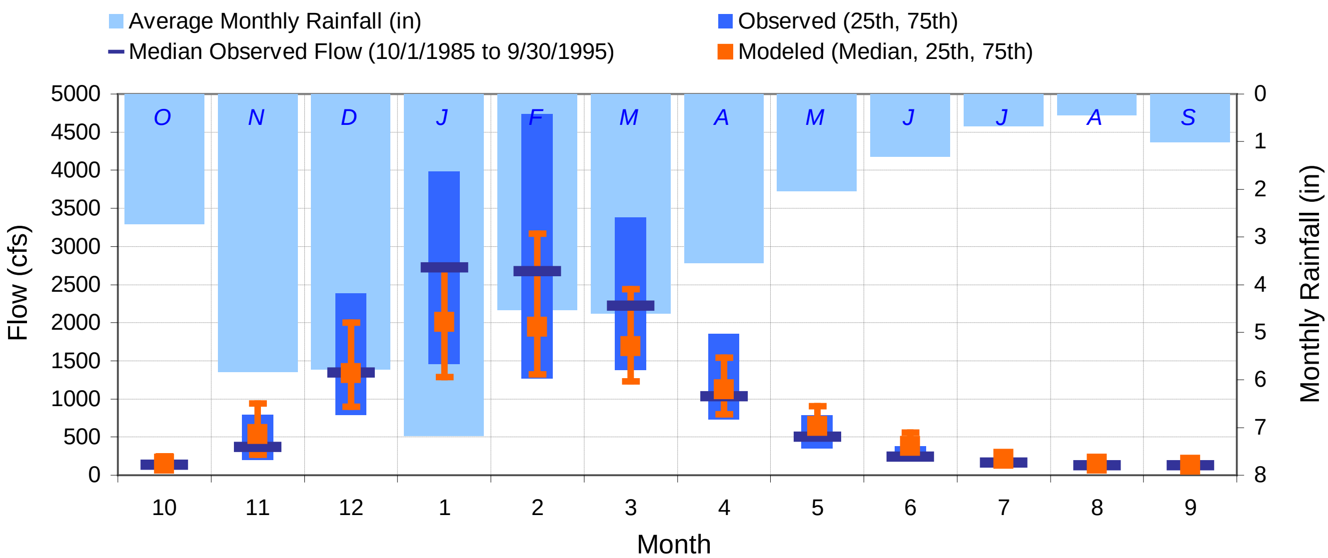

Figure 18. Seasonal medians and ranges at USGS 14207500 Tualatin River at West Linn, OR – validation period (HSPF).

Table 9. Seasonal summary at USGS 14207500 Tualatin River at West Linn – validation period (HSPF)

MONTH	OBSERVED FLOW (CFS)				MODELED FLOW (CFS)			
	MEAN	MEDIAN	25TH	75TH	MEAN	MEDIAN	25TH	75TH
Oct	178.35	132.00	100.00	193.50	257.87	148.30	134.63	250.42
Nov	663.27	369.00	198.00	792.00	742.01	539.33	271.12	940.92
Dec	1762.91	1345.00	786.50	2382.50	1625.28	1334.70	897.16	2002.84
Jan	2892.62	2725.00	1460.00	3985.00	2350.73	2010.52	1285.46	2745.93
Feb	3115.09	2670.00	1262.50	4737.50	2488.82	1947.93	1325.47	3171.78
Mar	2472.13	2220.00	1380.00	3377.50	1980.44	1691.04	1233.37	2442.64
Apr	1520.16	1035.00	731.25	1855.00	1363.78	1124.25	798.68	1542.90
May	618.69	505.50	343.75	788.25	733.54	644.97	488.42	903.26
Jun	313.98	242.00	182.75	382.50	468.21	380.64	293.42	555.62
Jul	173.94	164.50	127.25	211.75	244.29	210.25	169.95	296.58
Aug	131.78	126.50	102.50	158.00	166.56	150.77	131.70	182.07
Sep	140.05	126.50	107.75	162.25	173.33	137.78	127.92	167.28

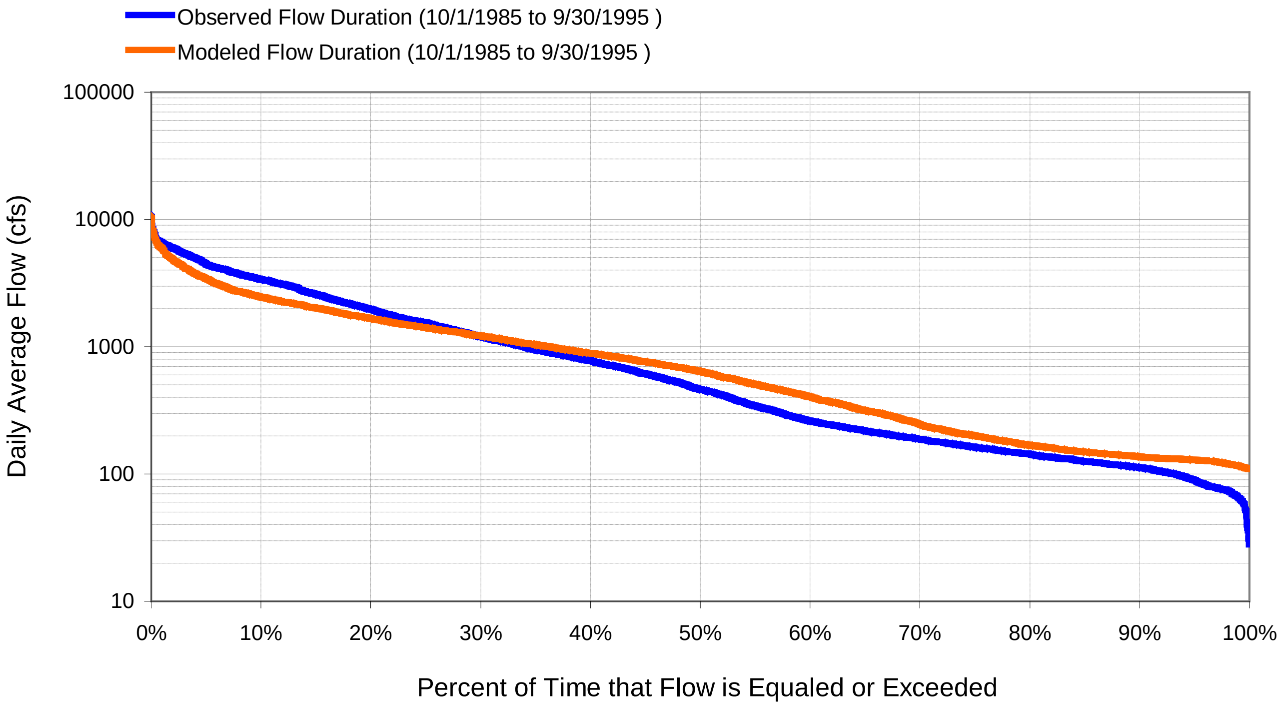

Figure 19. Flow exceedence at USGS 14207500 Tualatin River at West Linn, OR – validation period (HSPF).

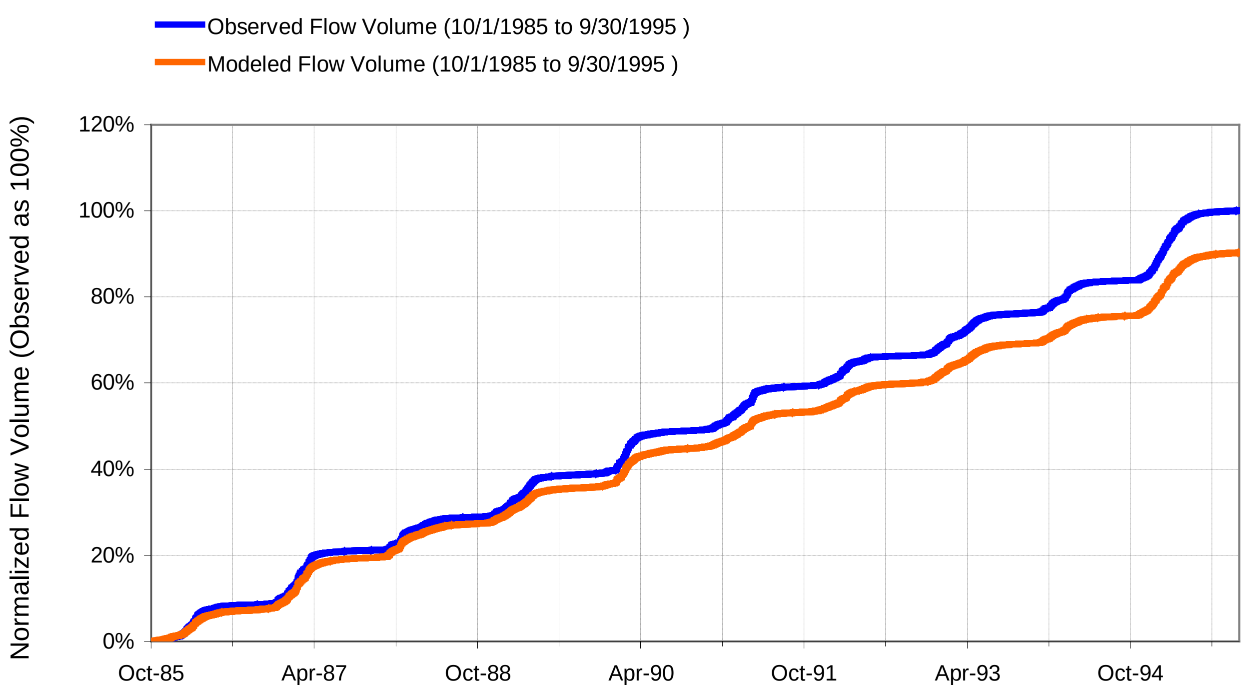

Figure 20. Flow accumulation at USGS 14207500 Tualatin River at West Linn, OR – validation period (HSPF).

Table 10. Summary statistics at USGS 14207500 Tualatin River at West Linn, OR – validation period (HSPF)

HSPF Simulated Flow		Observed Flow Gage	
REACH OUTFLOW FROM DSN 14 10-Year Analysis Period: 10/1/1985 - 9/30/1995 Flow volumes are (inches/year) for upstream drainage area		USGS 14207500 TUALATIN RIVER AT WEST LINN, OR Hydrologic Unit Code: 17090010 Latitude: 45.35067559 Longitude: -122.6762044 Drainage Area (sq-mi): 706	
Total Simulated In-stream Flow:	**20.06**	Total Observed In-stream Flow:	**22.24**
Total of simulated highest 10% flows:	**7.44**	Total of Observed highest 10% flows:	**9.37**
Total of Simulated lowest 50% flows:	**2.53**	Total of Observed Lowest 50% flows:	**1.83**
Simulated Summer Flow Volume (months 7-9):	**0.94**	Observed Summer Flow Volume (7-9):	**0.72**
Simulated Fall Flow Volume (months 10-12):	**4.25**	Observed Fall Flow Volume (10-12):	**4.22**
Simulated Winter Flow Volume (months 1-3):	**10.77**	Observed Winter Flow Volume (1-3):	**13.39**
Simulated Spring Flow Volume (months 4-6):	**4.09**	Observed Spring Flow Volume (4-6):	**3.91**
Total Simulated Storm Volume:	**4.52**	Total Observed Storm Volume:	**4.60**
Simulated Summer Storm Volume (7-9):	**0.14**	Observed Summer Storm Volume (7-9):	**0.12**

Errors (Simulated-Observed)	*Error Statistics*	*Recommended Criteria*		
Error in total volume:	-9.80	10		
Error in 50% lowest flows:	**38.11**	**10**		
Error in 10% highest flows:	**-20.60**	**15**		
Seasonal volume error - Summer:	**31.12**	**30**		
Seasonal volume error - Fall:	0.70	>> 30		Clear
Seasonal volume error - Winter:	-19.56	30		
Seasonal volume error - Spring:	4.71	30		
Error in storm volumes:	-1.77	20		
Error in summer storm volumes:	22.38	50		
Nash-Sutcliffe Coefficient of Efficiency, E:	0.811	Model accuracy increases		
Baseline adjusted coefficient (Garrick), E':	0.702	as E or E' approaches 1.0		
Monthly NSE	0.922			

Hydrology Results for Larger Watershed

Since the Tualatin River calibration location represents only a small portion of the drainage area for this project, results near the outlet of the entire watershed were examined at the Willamette River at Salem, OR (USGS 14191000). This gage is downstream of the large reservoirs in the Willamette River and more than 40 percent of the area at Salem is controlled by dams. Results are presented in Figures 21 through 27 and Tables 11 and 12. The results at the Salem gage look fairly good as well, but are being strongly determined by the input boundary inflows at the dams, particularly during the summer. The simulated output is quite high during the summer, which is manifested in overprediction of the metrics for 50 percent lowest flows, seasonal summer volume, and summer storm volumes. Summer storms are small in this region, and the summer storm volumes are also small; therefore, an error of 0.6 inches produces a large percent difference. The overall storm volumes are overpredicted, which results in exceedance of the metric by a small amount. The remainder of the metrics fall within the acceptable range set for the 20 Watershed study including a daily Nash-Sutcliffe of 0.88 at the Salem gage. Tables 13 and 14 show a summary of the hydrology calibration and validation results for all five locations. In general, the hydrology calibration results on the tributaries were quite good, largely as a result of the calibration efforts at each station. The calibrated parameters were transferred from the tributaries to other non-calibrated portions of the watershed based on location. Since the Salem mainstem gage is so heavily influenced by the reservoirs (as described above), the results at that location are reasonable, but not very useful in concluding that the calibrated parameters are transferrable to the entire watershed.

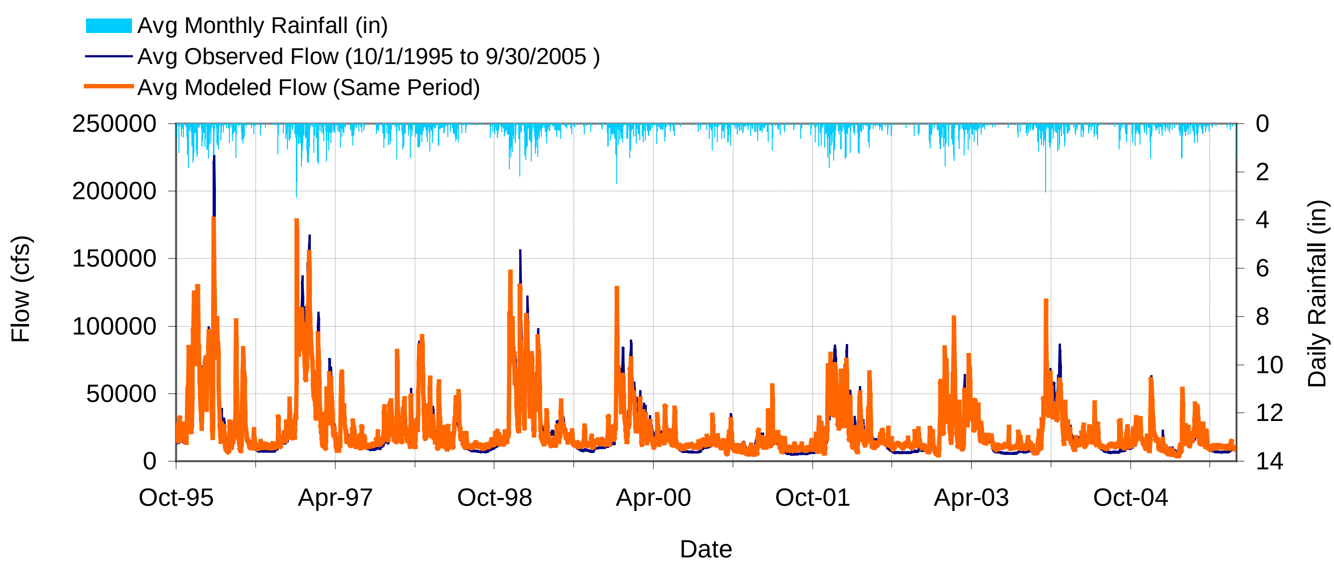

Figure 21. Mean daily flow at USGS 14191000 Willamette River at Salem, OR – calibration period (HSPF).

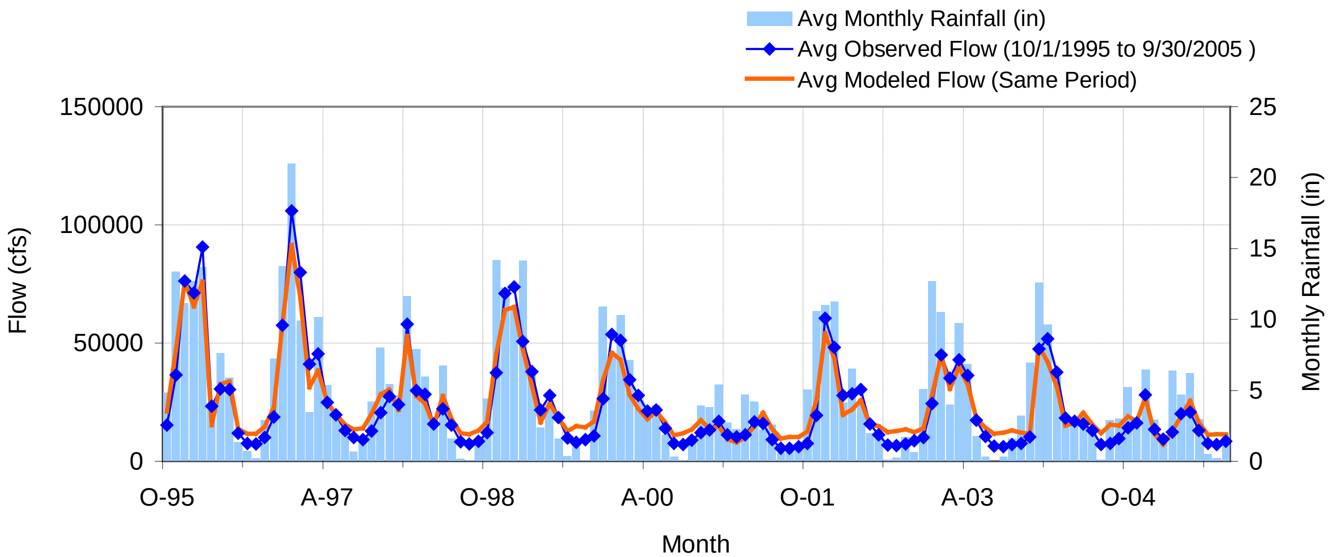

Figure 22. Mean monthly flow at USGS 14191000 Willamette River at Salem, OR – calibration period (HSPF).

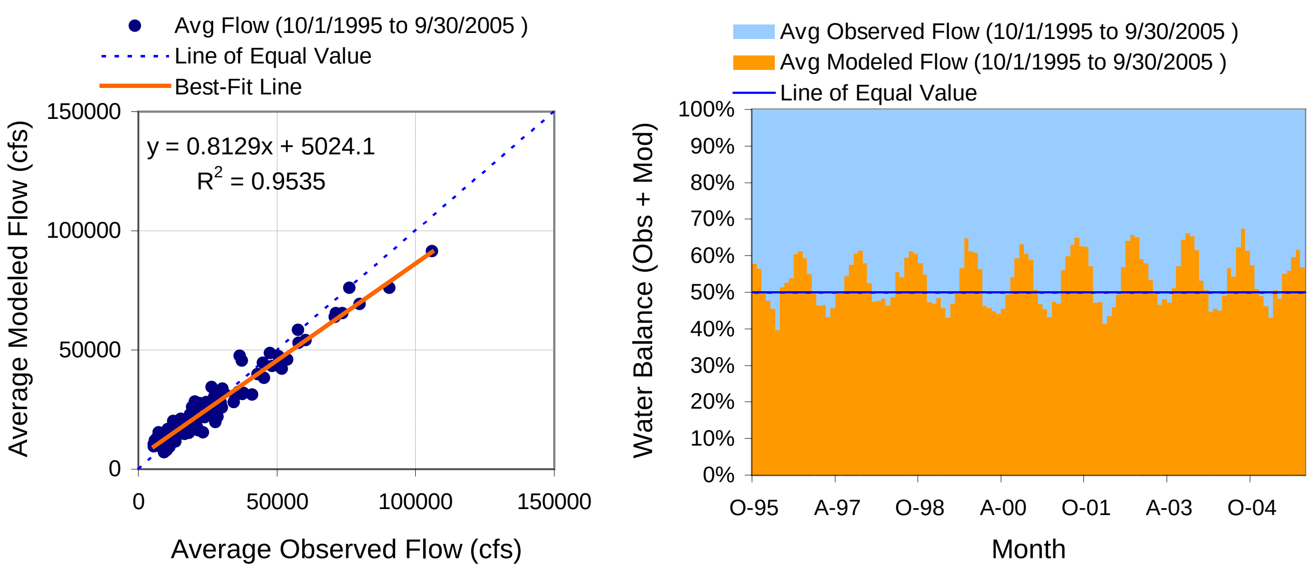

Figure 23. Monthly flow regression and temporal variation at USGS 14191000 Willamette River at Salem, OR – calibration period (HSPF).

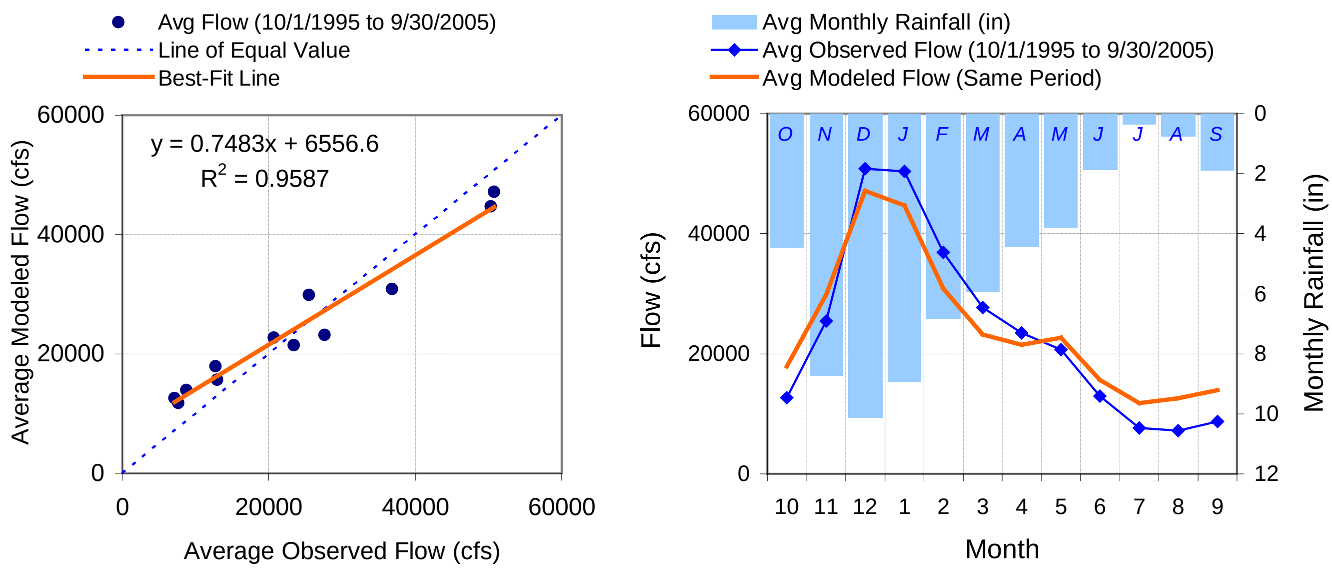

Figure 24. Seasonal regression and temporal aggregate at USGS 14191000 Willamette River at Salem, OR – calibration period (HSPF).

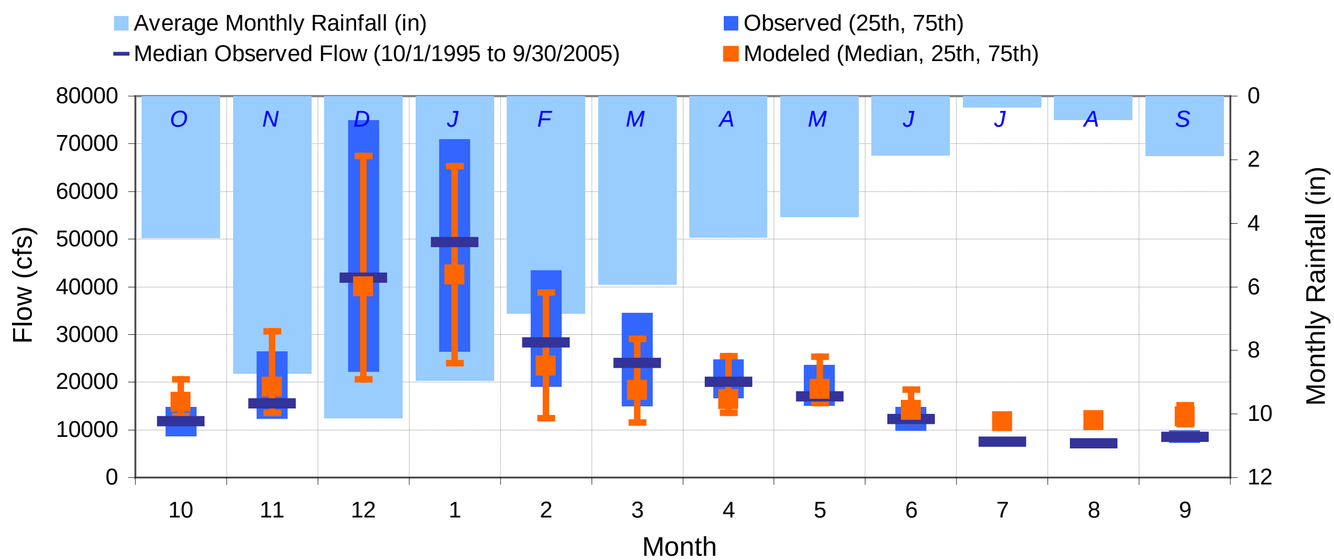

Figure 25. Seasonal medians and ranges at USGS 14191000 Willamette River at Salem, OR – calibration period (HSPF).

Table 11. Seasonal summary at USGS 14191000 Willamette River at Salem, OR – calibration period (HSPF)

MONTH	OBSERVED FLOW (CFS)				MODELED FLOW (CFS)			
	MEAN	MEDIAN	25TH	75TH	MEAN	MEDIAN	25TH	75TH
Oct	12717.87	11800.00	8752.50	14875.00	17880.47	15883.04	12873.57	20553.78
Nov	25500.23	15500.00	12375.00	26525.00	29822.48	19065.62	13575.24	30711.68
Dec	50807.87	41900.00	22175.00	74950.00	47121.03	40022.34	20587.66	67465.45
Jan	50369.00	49350.00	26325.00	70900.00	44675.55	42552.42	24029.88	65317.06
Feb	36872.79	28300.00	19050.00	43500.00	30886.30	23372.96	12456.04	38808.34
Mar	27664.39	23950.00	14950.00	34500.00	23206.99	18325.25	11562.67	29087.93
Apr	23458.33	20000.00	16600.00	24825.00	21472.71	16424.03	13542.39	25476.06
May	20733.55	16950.00	15100.00	23675.00	22704.18	18536.53	15626.60	25378.76
Jun	12950.87	12250.00	9807.50	14825.00	15686.14	14097.00	11904.53	18484.91
Jul	7675.19	7430.00	6780.00	8227.50	11749.44	11749.37	10807.98	12544.74
Aug	7159.26	7110.00	6602.50	7395.00	12563.64	12010.44	11030.47	12990.64
Sep	8761.37	8450.00	7210.00	9847.50	13918.00	12760.73	11221.73	15139.36

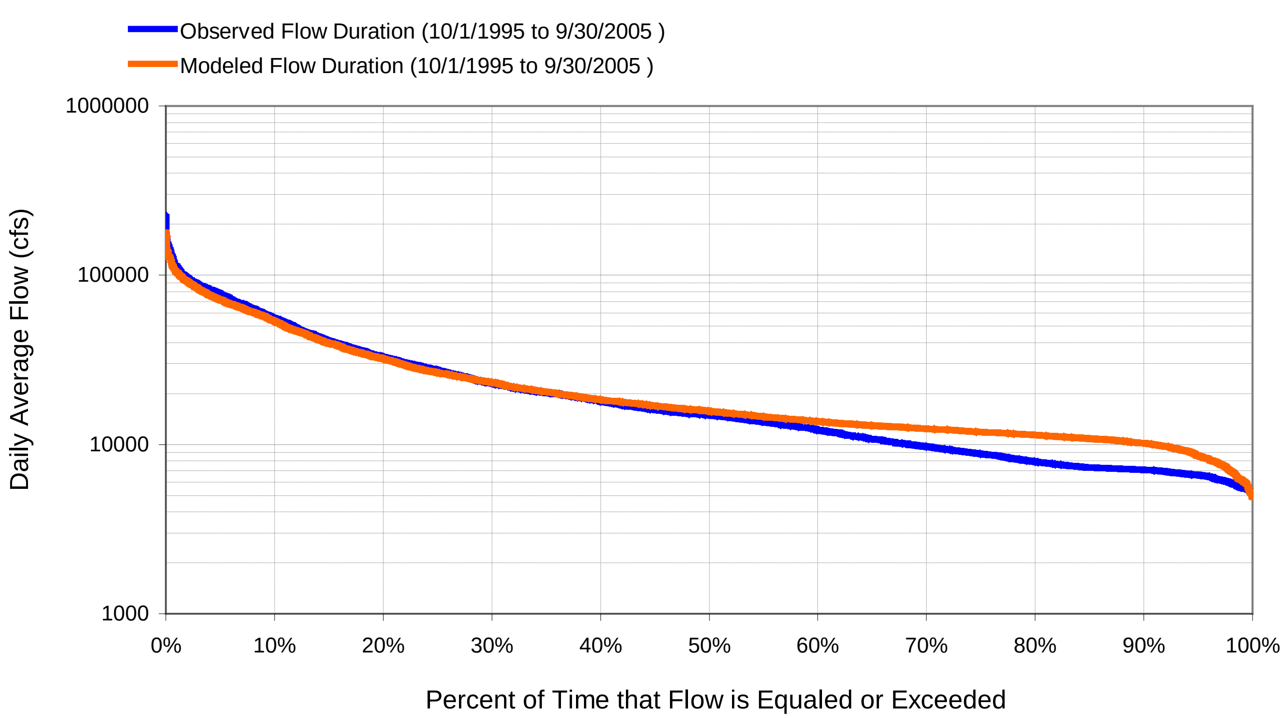

Figure 26. Flow exceedence at USGS 14191000 Willamette River at Salem, OR – calibration period (HSPF).

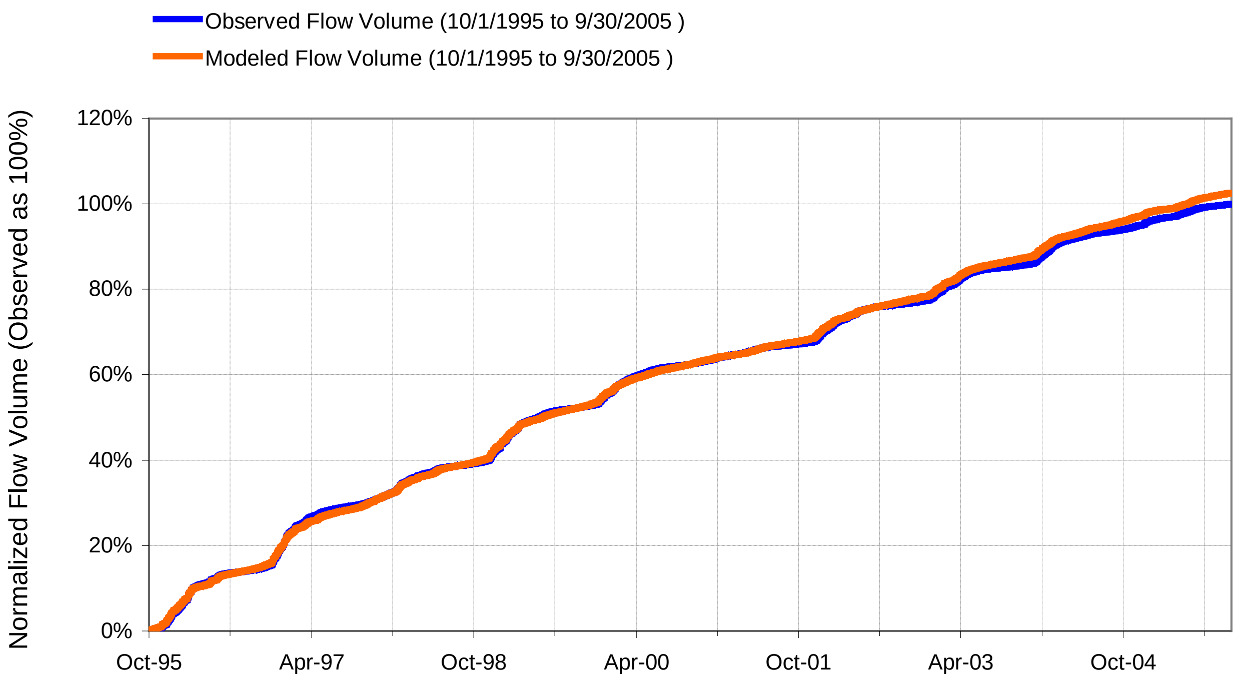

Figure 27. Flow accumulation at USGS 14191000 Willamette River at Salem, OR – calibration period (HSPF).

Table 12. Summary statistics at USGS 14191000 Willamette River at Salem, OR – calibration period (HSPF)

HSPF Simulated Flow		Observed Flow Gage	
REACH OUTFLOW FROM DSN 12 10-Year Analysis Period: 10/1/1995 - 9/30/2005 Flow volumes are (inches/year) for upstream drainage area		USGS 14191000 WILLAMETTE RIVER AT SALEM, OR Hydrologic Unit Code: 17090007 Latitude: 44.9442863 Longitude: -123.0428742 Drainage Area (sq-mi): 7280	
Total Simulated In-stream Flow:	**45.35**	Total Observed In-stream Flow:	**44.21**
Total of simulated highest 10% flows:	**14.60**	Total of Observed highest 10% flows:	**15.55**
Total of Simulated lowest 50% flows:	**11.01**	Total of Observed Lowest 50% flows:	**8.79**
Simulated Summer Flow Volume (months 7-9):	**5.98**	Observed Summer Flow Volume (7-9):	**3.69**
Simulated Fall Flow Volume (months 10-12):	**14.86**	Observed Fall Flow Volume (10-12):	**13.97**
Simulated Winter Flow Volume (months 1-3):	**15.21**	Observed Winter Flow Volume (1-3):	**17.69**
Simulated Spring Flow Volume (months 4-6):	**9.29**	Observed Spring Flow Volume (4-6):	**8.86**
Total Simulated Storm Volume:	**13.95**	Total Observed Storm Volume:	**11.48**
Simulated Summer Storm Volume (7-9):	**0.75**	Observed Summer Storm Volume (7-9):	**0.16**

Errors (Simulated-Observed)	*Error Statistics*	*Recommended Criteria*
Error in total volume:	2.58	10
Error in 50% lowest flows:	**25.19**	**10**
Error in 10% highest flows:	-6.12	15
Seasonal volume error - Summer:	**62.06**	**30**
Seasonal volume error - Fall:	6.42	30
Seasonal volume error - Winter:	-13.98	30
Seasonal volume error - Spring:	4.82	30
Error in storm volumes:	**21.60**	**20**
Error in summer storm volumes:	**364.63**	**50**
Nash-Sutcliffe Coefficient of Efficiency, E:	0.879	Model accuracy increases
Baseline adjusted coefficient (Garrick), E':	0.662	as E or E' approaches 1.0
Monthly NSE	0.932	

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Table 13. Summary statistics (percent error) for all stations – calibration period (HSPF)

Station	14191000 Salem	14207500 West Linn	14202000 Aurora	14194150 McMinnville	14165000 Springfield
Calibration Period:	WY 96-05	WY 96-05	WY 03-05	WY 00-05	WY 99-05
Error in total volume:	2.58	-3.92	6.08	-0.74	-6.41
Error in 50% lowest flows:	25.19	7.28	-13.76	-12.16	-11.20
Error in 10% highest flows:	-6.12	-6.64	2.42	3.88	2.78
Seasonal volume error - Summer:	62.06	-4.95	-2.94	1.19	9.35
Seasonal volume error - Fall:	6.42	-5.69	0.36	9.45	0.24
Seasonal volume error - Winter:	-13.98	-5.76	7.69	-4.63	-8.75
Seasonal volume error - Spring:	4.82	6.89	8.69	-7.70	-11.07
Error in storm volumes:	21.60	22.92	-7.94	6.83	33.01
Error in summer storm volumes:	364.63	27.87	-45.66	-41.57	-38.36
Daily Nash-Sutcliffe Coefficient of Efficiency, E:	0.879	0.799	0.912	0.711	0.674
Monthly Nash-Sutcliffe Coefficient of Efficiency, E:	0.932	0.965	0.970	0.947	0.879

Table 14. Summary statistics (percent error) for all stations – validation period (HSPF)

Station	14191000 Salem	14207500 West Linn	14202000 Aurora	14194150 McMinnville	14165000 Springfield
Calibration Period:	WY 86-95	WY 86-95	WY 94-97	WY 95-99	WY 88-97
Error in total volume:	5.04	-9.80	7.48	-4.52	-4.70
Error in 50% lowest flows:	27.56	38.11	12.54	-19.80	-4.88
Error in 10% highest flows:	-0.59	-20.60	8.10	-4.74	4.68
Seasonal volume error - Summer:	65.84	31.12	38.31	1.81	13.91
Seasonal volume error - Fall:	7.98	0.70	2.36	-2.46	18.51
Seasonal volume error - Winter:	-14.25	-19.56	10.21	-5.28	-14.93
Seasonal volume error - Spring:	7.81	4.71	6.68	-7.98	-13.54
Error in storm volumes:	24.68	-1.77	0.34	-3.10	39.72
Error in summer storm volumes:	298.14	22.38	3.37	-51.72	-39.06
Daily Nash-Sutcliffe Coefficient of Efficiency, E:	0.835	0.811	0.886	0.720	0.467
Monthly Nash-Sutcliffe Coefficient of Efficiency, E:	0.880	0.922	0.973	0.968	0.710

Water Quality Calibration and Validation

The 20 Watershed models are designed to provide water quality simulation for total suspended solids (TSS), total nitrogen, and total phosphorus. TSS is simulated with the standard HSPF approach (USEPA 2006). In contrast to sediment, total nitrogen and total phosphorus are simulated in this application in a simplistic fashion, as HSPF general quality constituents (GQUALs) subject to an exponential decay rate during transport.

The water quality calibration focuses on the replication of monthly loads, as specified in the project QAPP. Given the approach to water quality simulation in the 20 Watershed model, a close match to individual concentration observations cannot be expected. Comparison to monthly loads presents challenges, as monthly loads are not observed. Instead, monthly loads must be estimated from scattered concentration grab samples and continuous flow records. As a result, the monthly load calibration is inevitably based on the comparison of two uncertain numbers. Nonetheless, calibration is able to achieve a reasonable agreement. Further, the load comparisons were supported by detailed examinations of the relationships of flows to loads and concentrations and the distribution of concentration prediction errors versus flow, time, and season, as well as standard time series plots.

For application on a nationwide basis, the 20 Watershed protocols assume that sediment and total phosphorus loads will likely exhibit a strong positive correlation to flow (and associated erosive processes), while total nitrogen loads, which often have a dominant groundwater component, will not. Accordingly, TSS and total phosphorus loads were estimated from observations using a flow-stratified log-log regression approach, while total nitrogen loads were estimated using a flow-stratified averaging estimator, consistent with the findings of Preston et al. (1989).

Water quality calibration was done on the Tualatin River at West Linn, OR, comparing model results to data from USGS 14207500. Calibration and validation were performed for the period with available water quality data, which was 1986-1995. The 1991-1995 time period was used for calibration, and the 1986-1990 period was used for validation. TSS calibration was performed by adjusting the coefficients in the soil detachment (KRER) and soil washoff (KSER) equations along with changes to the seasonal vegetation COVER. Results of the TSS calibration are generally acceptable. The results are shown in Figures 28 through 31 and the statistics of TSS loads and concentrations are shown in Tables 15 and 16, respectively. Visually, the model is roughly simulating the trends contained in the observed data.

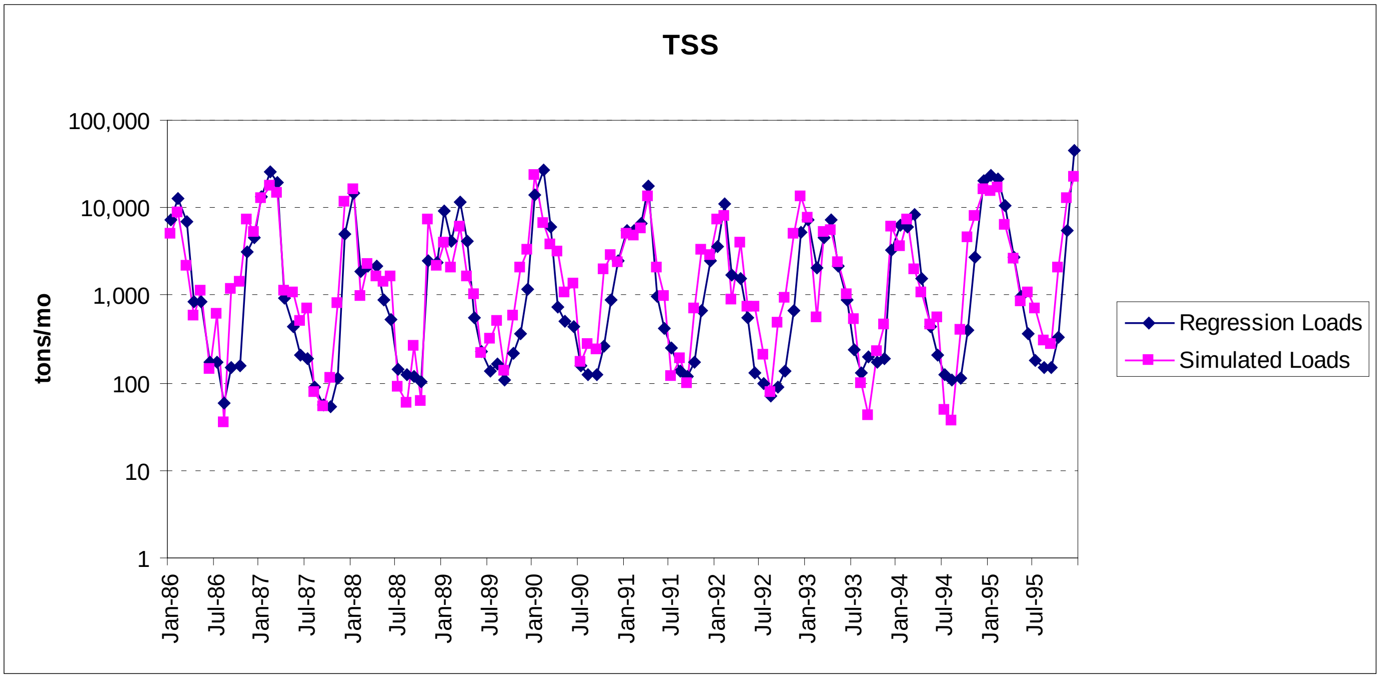

Figure 28. Fit for monthly load of TSS at USGS 14207500 Tualatin River at West Linn, OR (HSPF).

Table 15. Model fit statistics (observed minus predicted) for monthly sediment loads using stratified regression (HSPF)

Statistic	Calibration period (1991-1995)	Validation period (1986-1990)
Relative Percent Error	3%	5%
Relative Average Absolute Error	47%	53%
Relative Median Absolute Error	13.3%	15.9%

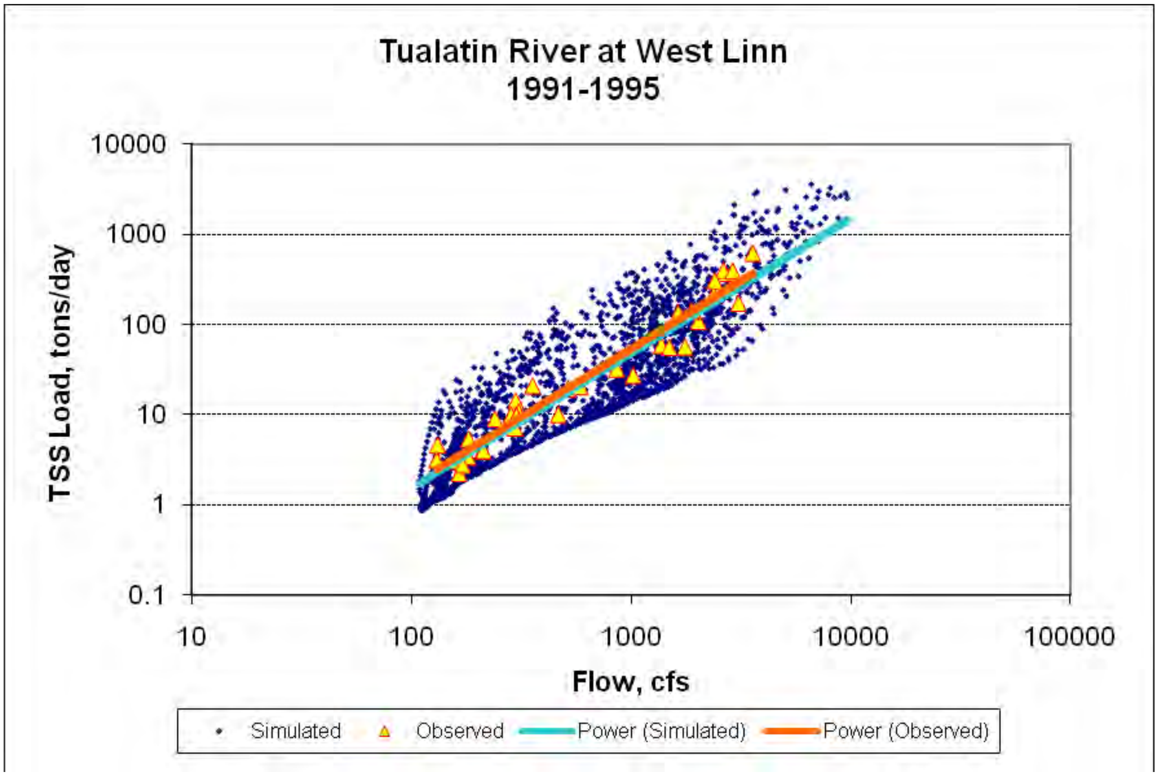

Figure 29. Power plot for observed and simulated TSS at USGS 14207500 Tualatin River at West Linn, OR – calibration period (HSPF).

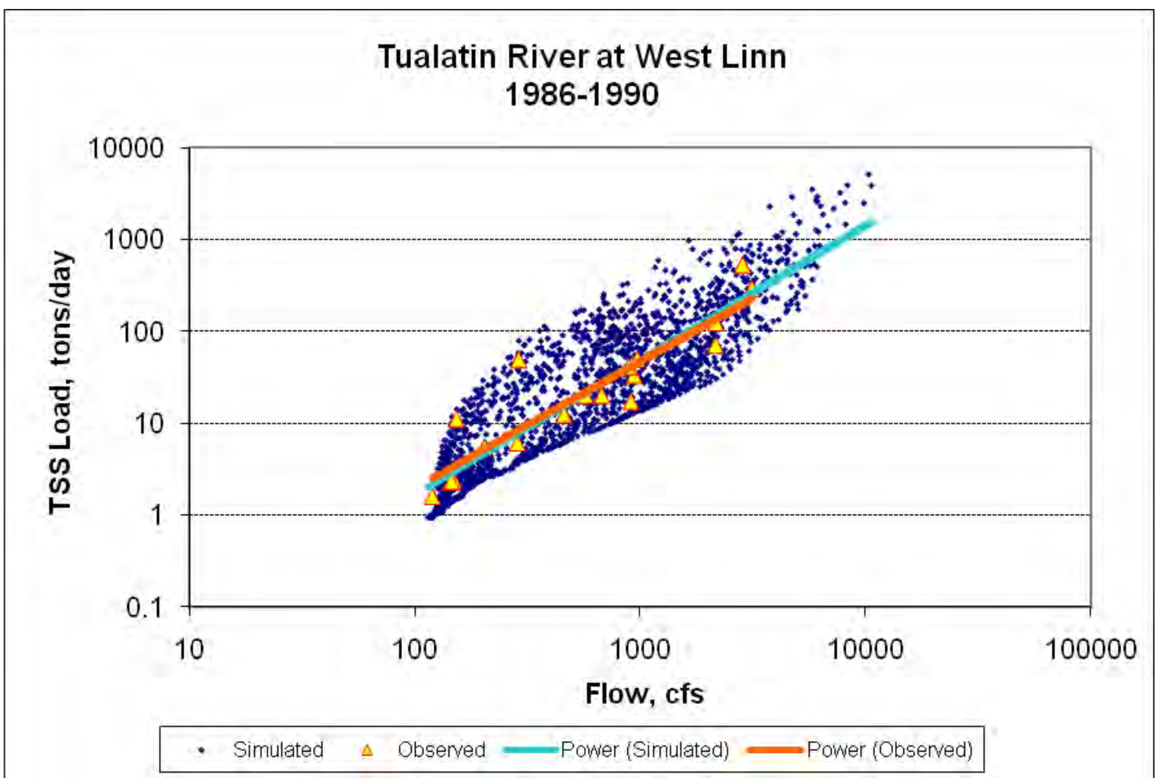

Figure 30. Power plot for observed and simulated TSS at USGS 14207500 Tualatin River at West Linn, OR – validation period (HSPF).

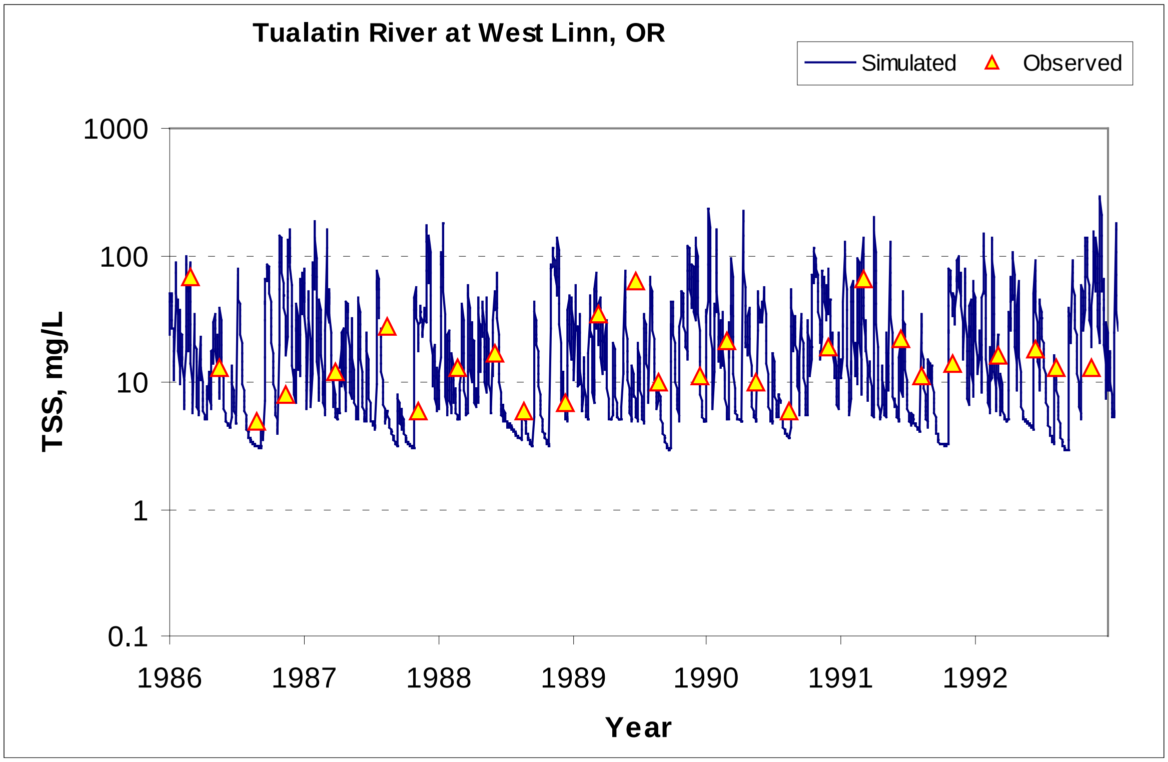

Figure 31. Time series plot of TSS concentration at USGS 14207500 Tualatin River at West Linn, OR – (HSPF).

Table 16. Relative errors (observed minus predicted), TSS concentration, at USGS 14207500 Tualatin River at West Linn, OR (HSPF)

Statistic	Calibration period (1991-1995)	Validation period (1986-1990)
Count	35	29
Concentration Average Error	-40.4%	21.9%
Concentration Median Error	-7.8%	10.0%

The total phosphorus calibration performed well at the Tualatin River location. Adjustments were made to the potency factors and the subsurface concentrations. In general, the observed and simulated total phosphorus loads attain an acceptable match for the simulation period (Figure 32 and Table 17). As with TSS, additional diagnostics for total phosphorus included flow-load power plots (Figures 33 and 34), a time series plot of concentrations (Figure 35), and statistics (Table 18). All show acceptable agreement.

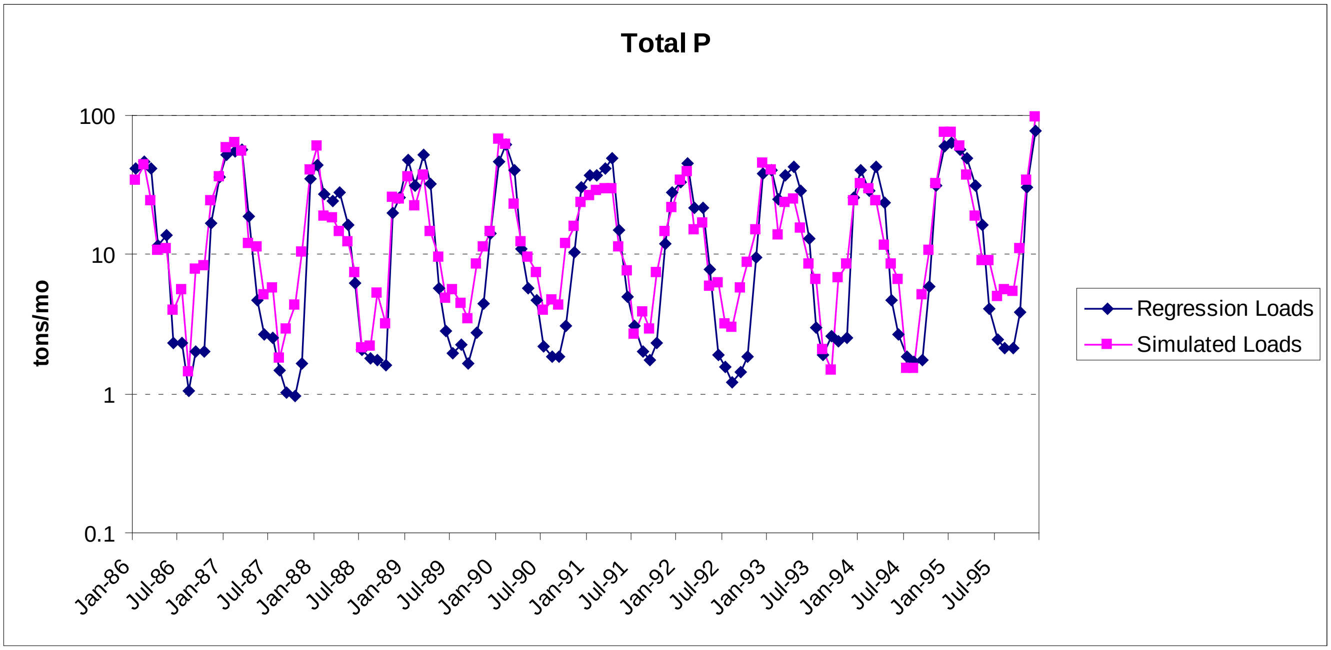

Figure 32. Fit for monthly load of total phosphorus at USGS 14207500 Tualatin River at West Linn, OR (HSPF).

Table 17. Model fit statistics (observed minus predicted) for monthly total phosphorus loads using stratified regression (HSPF)

Statistic	Calibration period (1991-1995)	Validation period (1986-1990)
Relative Percent Error	-1%	-9%
Average Absolute Error	31%	32%
Median Absolute Error	23.0%	21.8%

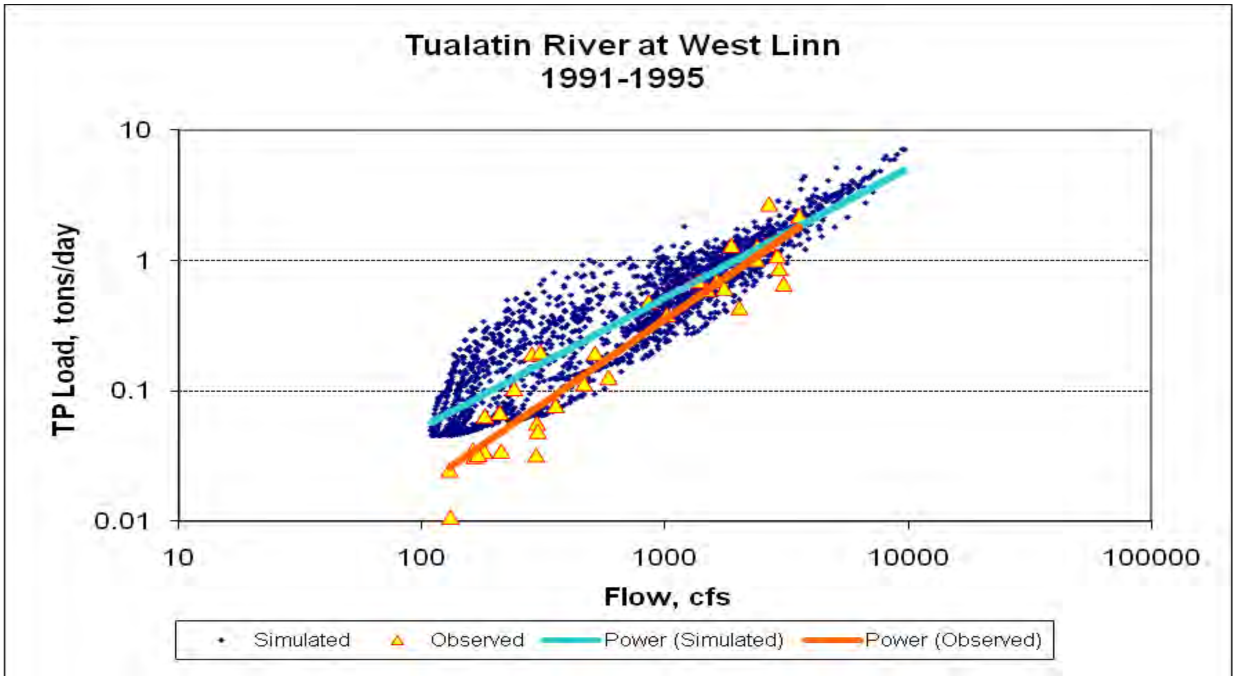

Figure 33. Power plot for observed and simulated total phosphorus at USGS 14207500 Tualatin River at West Linn, OR – calibration period (HSPF).

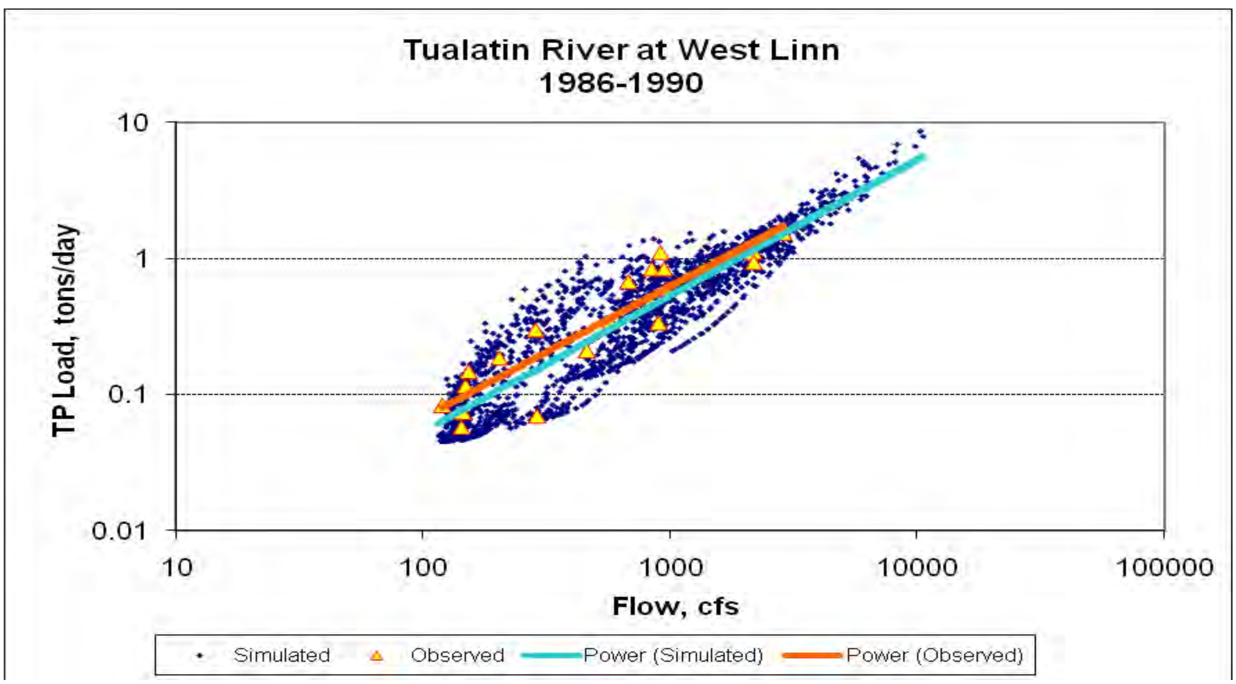

Figure 34. Power plot for observed and simulated total phosphorus at USGS 14207500 Tualatin River at West Linn, OR – validation period (HSPF).

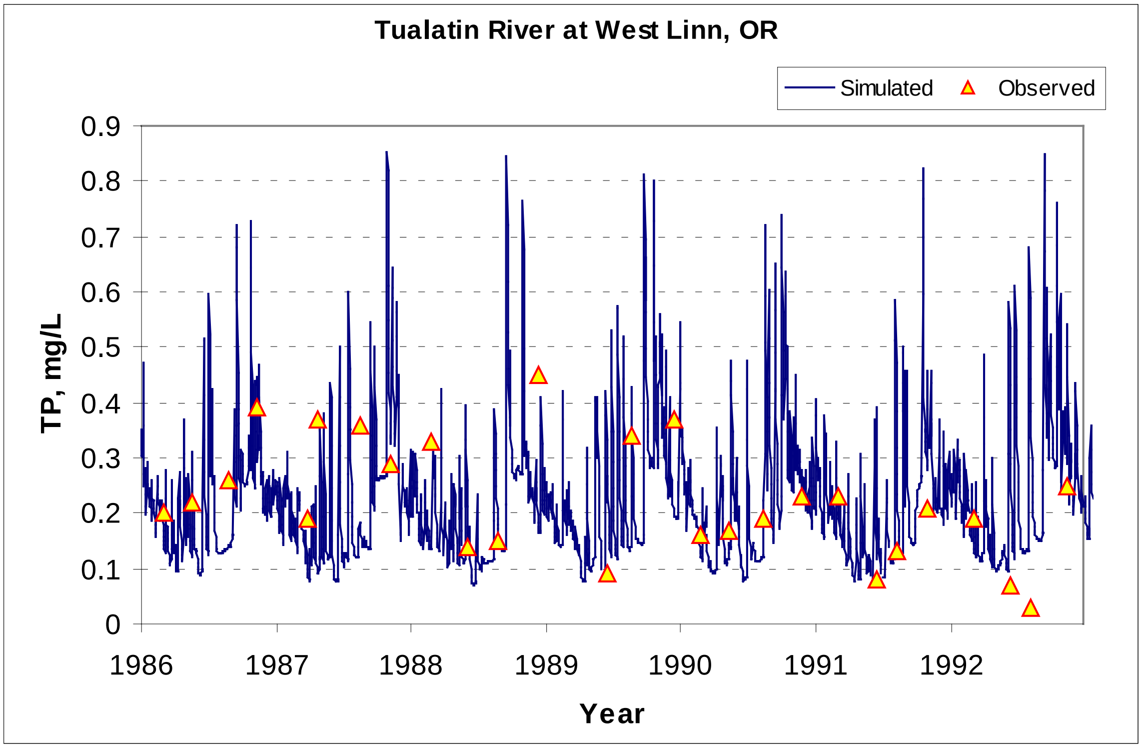

Figure 35. Time series plot of total phosphorus concentration at USGS 14207500 Tualatin River at West Linn, OR (HSPF).

Table 18. Relative errors (observed minus predicted), total phosphorus concentration at USGS 14207500 Tualatin River at West Linn, OR (HSPF)

Statistic	Calibration period (1991-1995)	Validation period (1986-1990)
Count	35	19
Concentration Average Error	-78.8%	26.3%
Concentration Median Error	-59.7%	26.5%

Nitrogen adjustments were made to the seasonally varying accumulation/washoff and subsurface concentrations. Results for total nitrogen are summarized in Figures 36 through 39 and Tables 19 and 20. The results are acceptable, and generally better than those for total phosphorus. This is because nitrogen is not sediment-associated, therefore, problems with sediment are not reflected in the calibration for total nitrogen. A summary of the water quality statistics at the two locations (Tualatin River and Pudding River) are shown in Table 21.

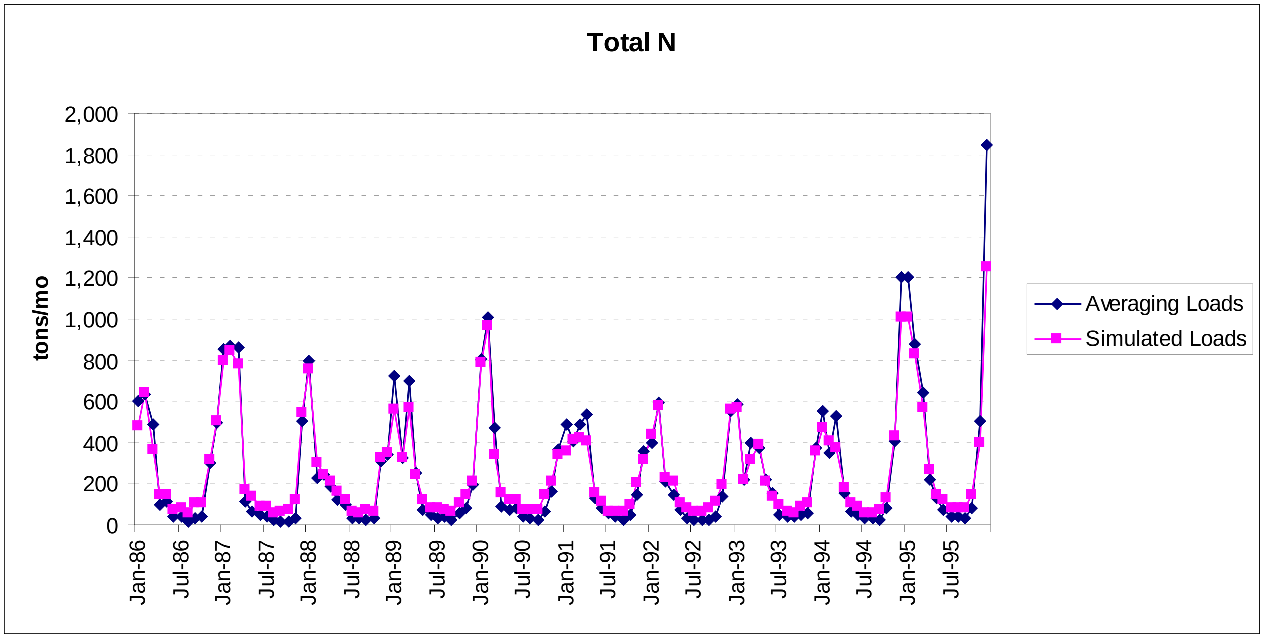

Figure 36. Fit for monthly load of total nitrogen at USGS 14207500 Tualatin River at West Linn, OR (HSPF).

Table 19. Model fit statistics (observed minus predicted) for monthly total nitrogen loads using averaging estimator (HSPF)

Statistic	Calibration period (1991-1995)	Validation period (1986-1990)
Relative Percent Error	2%	-6%
Average Absolute Error	21%	20%
Median Absolute Error	15.5%	17.0%

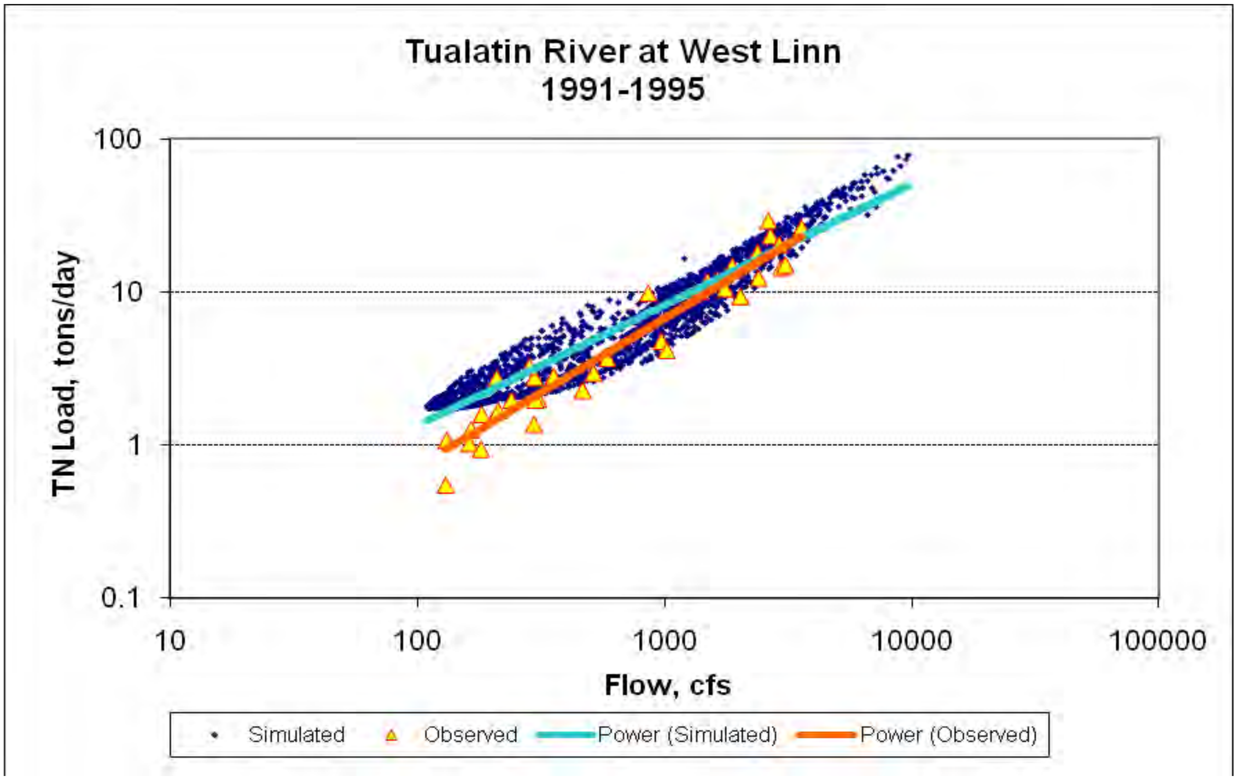

Figure 37. Power plot for observed and simulated total nitrogen at USGS 14207500 Tualatin River at West Linn, OR – calibration period (HSPF).

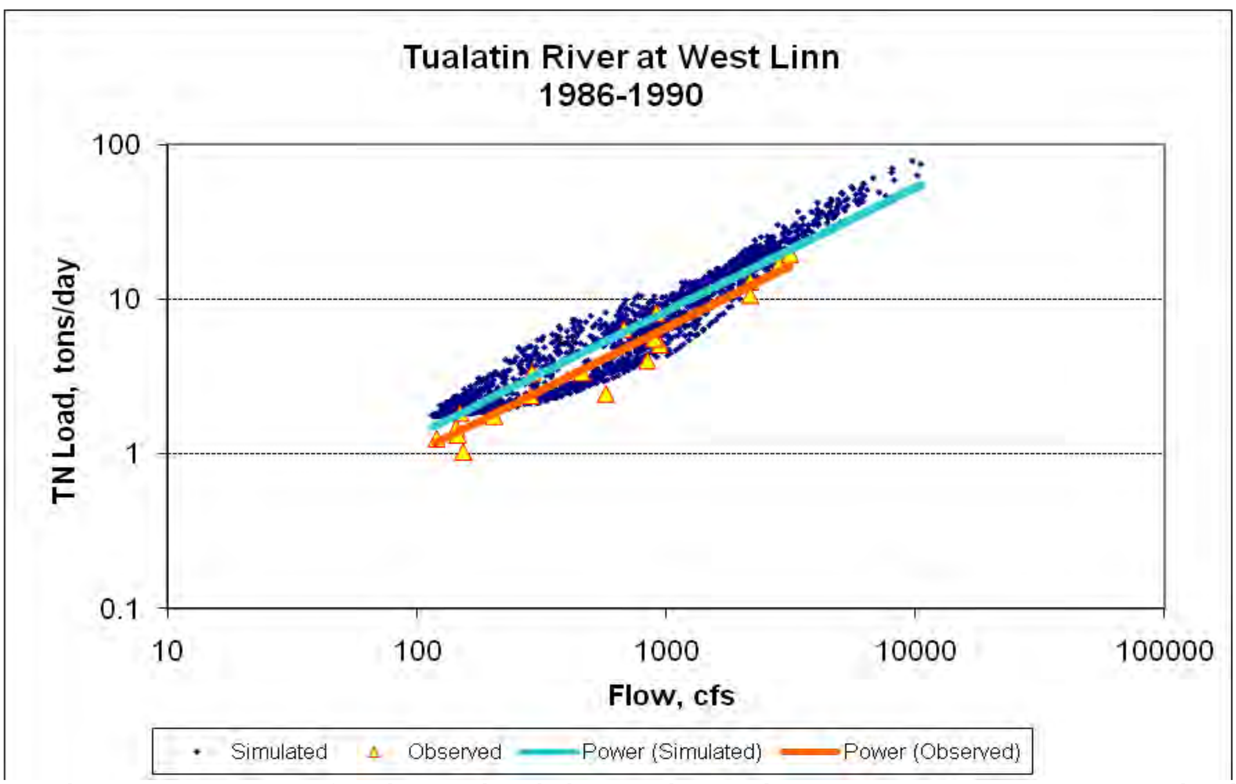

Figure 38. Power plot for observed and simulated total nitrogen at USGS 14207500 Tualatin River at West Linn, OR – validation period (HSPF).

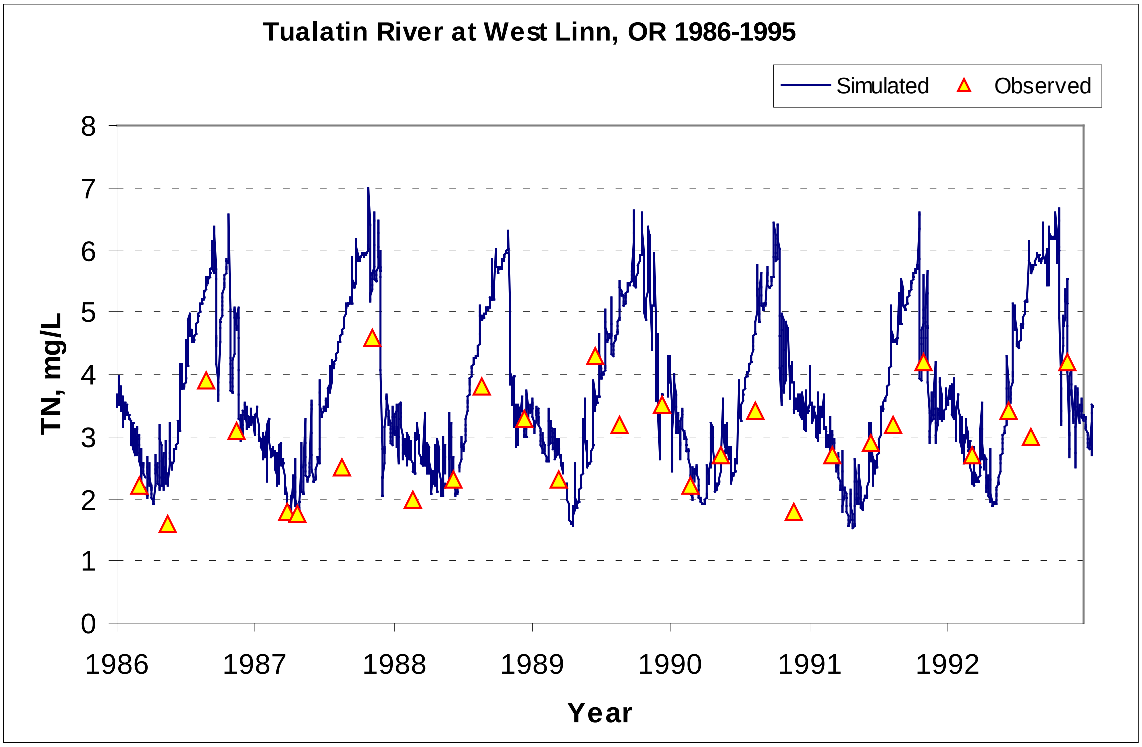

Figure 39. Time series plot of total nitrogen concentration at USGS 14207500 Tualatin River at West Linn, OR (HSPF).

Table 20. Relative errors (observed minus predicted), total nitrogen concentration, USGS 14207500 Tualatin River at West Linn, OR (HSPF)

Statistic	Calibration period (1991-1995)	Validation period (1986-1990)
Count	35	20
Concentration Average Error	-33.5%	-25.6%
Concentration Median Error	-16.8%	-19.2%

Water Quality Results for Larger Watershed

The Tualatin River water quality parameters were transferred to the Pudding River (Aurora) watershed, and further calibration was necessary in the Pudding. A combination of the parameters sets from the Tualatin and Pudding watersheds was transferred to the remaining portions of the watershed. Since there are no other water quality data available in the Willamette watershed, it was not possible to determine whether the parameter set was applicable to the entire watershed. However, the calibration at the two locations was fairly good with respect to the loads (Table 21). As expected, the concentration errors are larger.

Table 21. Summary statistics for water quality for all stations (observed minus predicted) (HSPF)

Station	14207500 West Linn Calibration	14207500 West Linn Validation	14202000 Aurora Calibration	14202000 Aurora Validation
Relative Percent Error TSS Load	3%	5%	1%	20%
TSS Concentration Median Percent Error	-7.8%	10.0%	22.1%	-10.3%
Relative Percent Error TP Load	-1%	-9%	4%	-28%
TP Concentration Median Percent Error	-59.7%	26.5%	-18.2%	38.3%
Relative Percent Error TN Load	2%	-6%	0%	11%
TN Concentration Median Percent Error	-16.8%	-19.2%	16.0%	-12.2%

SWAT Modeling

The USGS gages on the Tualatin River at West Linn, OR (USGS 14207500) and the Pudding River at Aurora, OR (USGS 14202000) were used as the primary hydrology and water quality calibration locations. Additional tributary hydrology calibration was performed on the South Yamhill River at McMinnville, OR (USGS 14194150) and the Mohawk (McKenzie) River near Springfield (USGS 14165000). A hydrology calibration check was performed at the USGS gage on the Willamette River at Salem, OR (USGS 14191000), which is the most downstream gage in the watershed that does not include tidal effects.

Changes Made to Base Data Provided

No changes were made to the input data provided for the SWAT model except for point sources. The flow from the six paper mills was changed to zero, since they draw water from the same rivers that they discharge to. These point sources are: OR0000442, OR0000515, OR0000558, OR0000566, OR0000787, and OR0001074. Several other point sources discharge to the calibration watersheds. Some of the parameters were determined to be erroneous, and since they caused obvious problems in the calibration in the Tualatin and Pudding subwatersheds, were modified based on information obtained from other sources. Three point sources (OR0020001, OR0020168, and OR0023345) do not discharge to surface waters during the summer, so these three were modified to turn off the discharges between June and September. The discharges of three point sources (OR0028118, OR0029777, and OR0034002) were found to be overestimated by using the "Observed Flow" and were changed to the "Design Flow". The total phosphorus concentrations of two point sources were reduced as a result of the use of advanced treatment methods; these are OR0020168 and OR0029777. Summer loads of total phosphorus were substantially overpredicted with the higher values.

Assumptions

Reservoirs

Fall Creek Lake, Dorena Lake, Lookout Point Lake, Green Peter Lake, Foster Lake, Hills Creek Lake, Detroit Lake, Cottage Grove Lake, Cougar Lake, and Fern Ridge Lake (Table 6) were represented in the Willamette River watershed SWAT model. Pertinent reservoir information including surface area and storage at principal (normal) and emergency spillway levels for the reservoirs modeled were obtained from the National Inventory of dams (NID) database (USACE 1982). The SWAT model provides four options to simulate reservoir outflow: 1) measured daily outflow, 2) measured monthly outflow, 3) average annual release rate for uncontrolled reservoir, and 4) controlled outflow with target release. Keeping in view the 20 Watershed climate change impact evaluation application, it was assumed that the best representation of the reservoirs was to simulate them without supplying time series of outflow records. Therefore, a target release approach was used in the GCRP-SWAT model. The number of days to reach target storage was assumed to be 50 days and an average release rate of 50 m^3/s was assumed for all lakes.

Withdrawals

No withdrawals, either by municipal and industrial facilities, were included in the 20 Watershed model application.

Irrigation

Irrigation was not explicitly modeled in the Willamette River watershed.

Hydrology Calibration

The SWAT model setup for the Willamette River watershed 20 Watershed project was set up fresh, with no prior-existing SWAT model for the watershed.

Most of the calibration efforts were geared toward getting a closer match between simulated and observed flows at the outlet of the calibration focus area. Initially, the parameters set for this area were applied across the watershed and the model performance was verified at other stations. This resulted in model performance that was not the same as in the calibration focus area, mostly because of dominance of different land uses in different parts of the watershed. In response to the variations in spatial characteristics of the subwatersheds, a systematic adjustment of parameters, individually, by land use type was adopted and the same adjustment was applied throughout the watershed.

It can be acknowledged that a hydrologic/water quality model can be precisely calibrated, given the degree of freedom, resources, time, and data. Keeping in view the interests of this project, which are to study the land use change and climate change impacts on flow and water quality, a site-specific calibration was deliberately not attempted. To some extent, the limitation of this approach is that the local differences in soil, weather, management, and hydrology is not thoroughly accounted for. This approach will provide an idea of the model performance when it is not spatially-tightly calibrated and what to expect when transferring the parameters to other ungaged watersheds or to watersheds where detailed modeling is not practical due to limited resources.

While adjusting the hydrology and water quality parameters for calibration, crop yields were also checked. The crop yields for wheat, corn, and hay were found to be reasonably close to the reported yield values in the National Agricultural Statistics Service (NASS) database.

Land Use / Soil / Slope Definition

A 5/10/5 percent threshold was used for land use/soil/slope in the SWAT model while defining the HRUs. The cropland HRUs were simulated as 2-year winterwheat-corn-winterwheat rotation with every other year fallow during summer. The hay HRUs were simulated as hay every year with the fourth year being fallow. The urban (including current and future urban class types) classes were exempt from applying the thresholds.

The calibration focus area represents 3 subwatersheds, which together consist of 195 HRUs. The parameters were adjusted within the practical range to obtain a reasonable fit between the simulated and measured flows in terms of Nash-Sutcliffe modeling efficiency and the high flow and low flow components as well as the seasonal flows. The calibration focus area well-represented the general land use characteristics of the overall watershed. The predominantly forested subwatershed (Mohawk River near Springfield, OR; USGS 14165000) was chosen to set the parameters for forest, which were then applied across the entire watershed. There is essentially one set of parameters for a land use type for the entire watershed.

Once the hydrology calibration was complete for the entire Willamette watershed, the water quality calibration was pursued. Similar to hydrology, there is a single set of water quality parameters for the entire Willamette River watershed.

Hydrology calibration adjustments focused on the following parameters:

- Curve numbers (varied systematically by land use)
- ESCO (soil evaporation compensation factor)
- SURLAG (surface runoff lag coefficient)
- Baseflow factor
- GW_DELAY (groundwater delay time)
- Sol_AWC (available water capacity of the soil layer, mm water/mm of soil)

Initial hydrology calibrations were performed for the Tualatin River at West Linn, OR (USGS 14207500) and are summarized in Figures 40 through 46 and Tables 22 and 23. The model calibration period was set to the 10 water years from 10/01/1995 to 09/30/2005. As evidenced through the time series plot, the model performed well in simulating the timing at various seasons. The model overpredicted seasonal spring, summer, and overall storm volumes indicated by the *Error in Storm Volumes* metric.

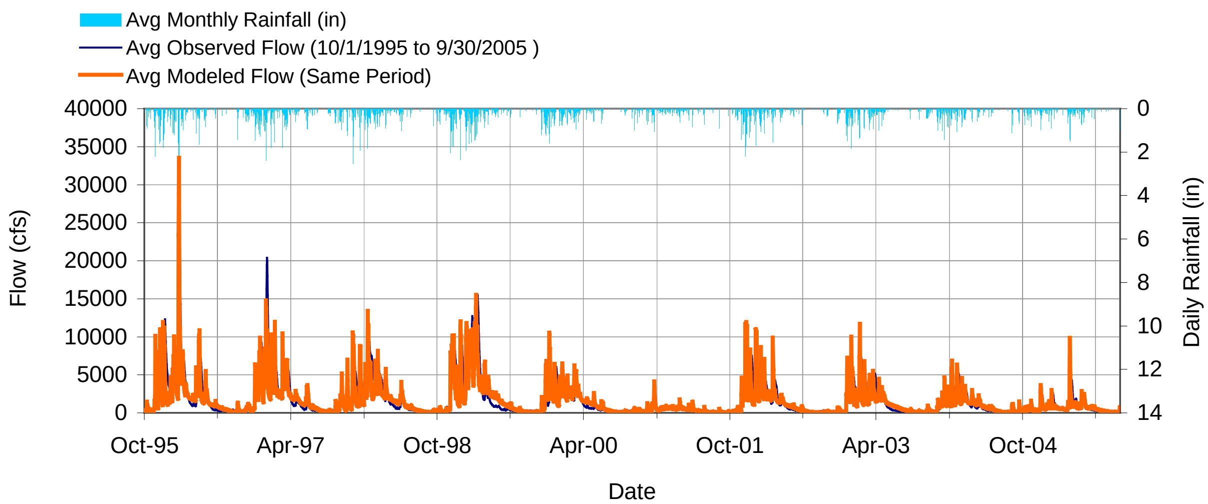

Figure 40. Mean daily flow at USGS 14207500 Tualatin River at West Linn, OR – calibration period (SWAT).

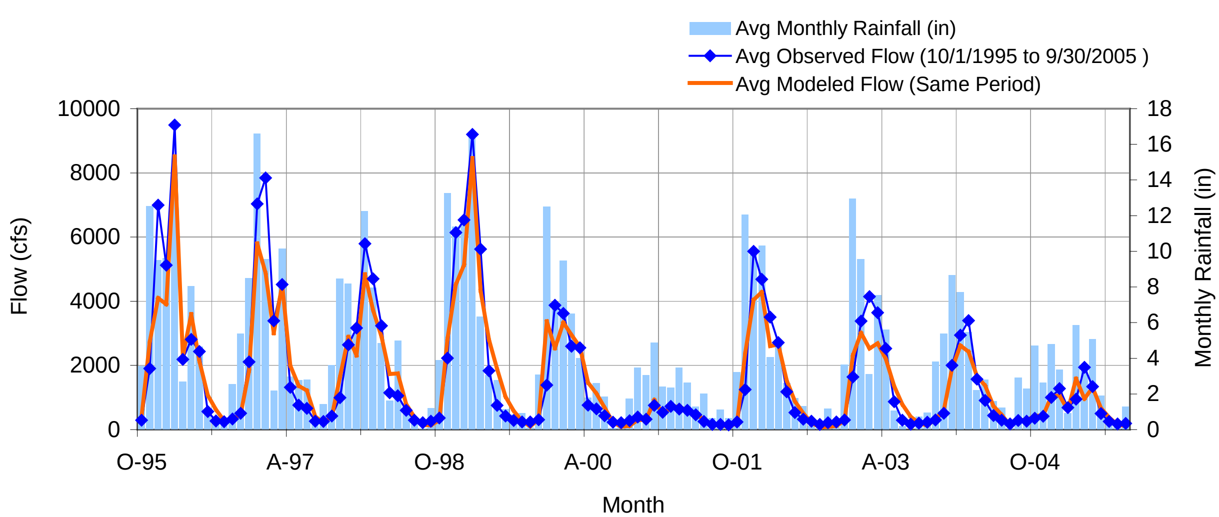

Figure 41. Mean monthly flow at USGS 14207500 Tualatin River at West Linn, OR – calibration period (SWAT).

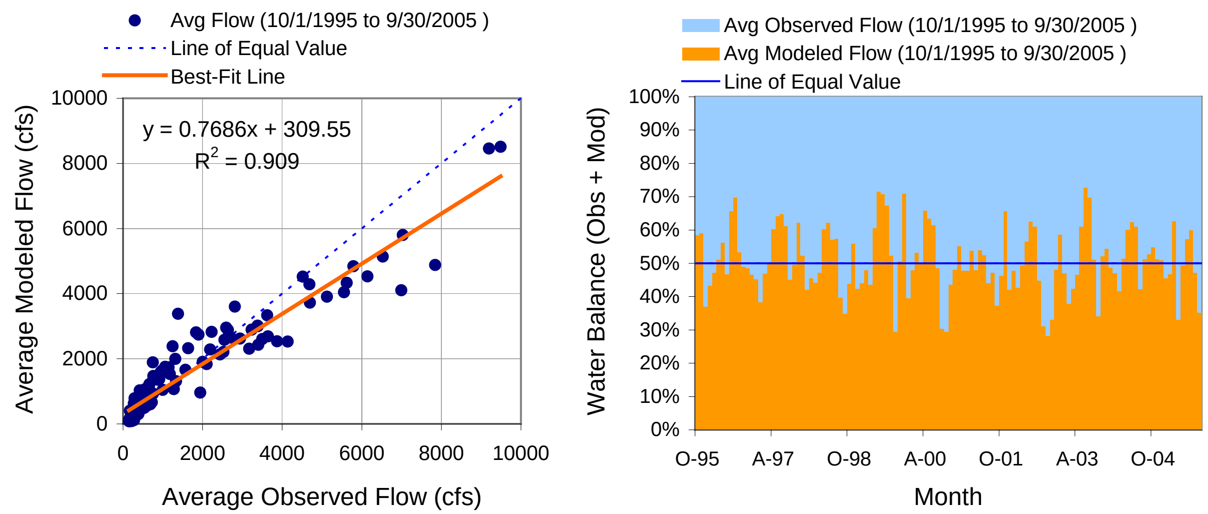

Figure 42. Monthly flow regression and temporal variation at USGS 14207500 Tualatin River at West Linn, OR – calibration period (SWAT).

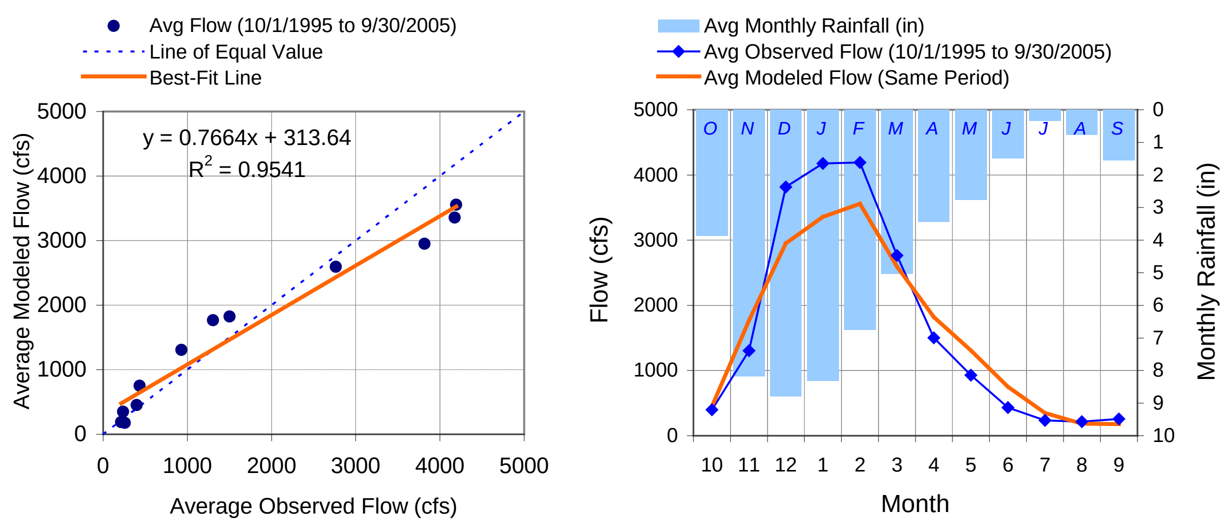

Figure 43. Seasonal regression and temporal aggregate at USGS 14207500 Tualatin River at West Linn, OR – calibration period (SWAT).

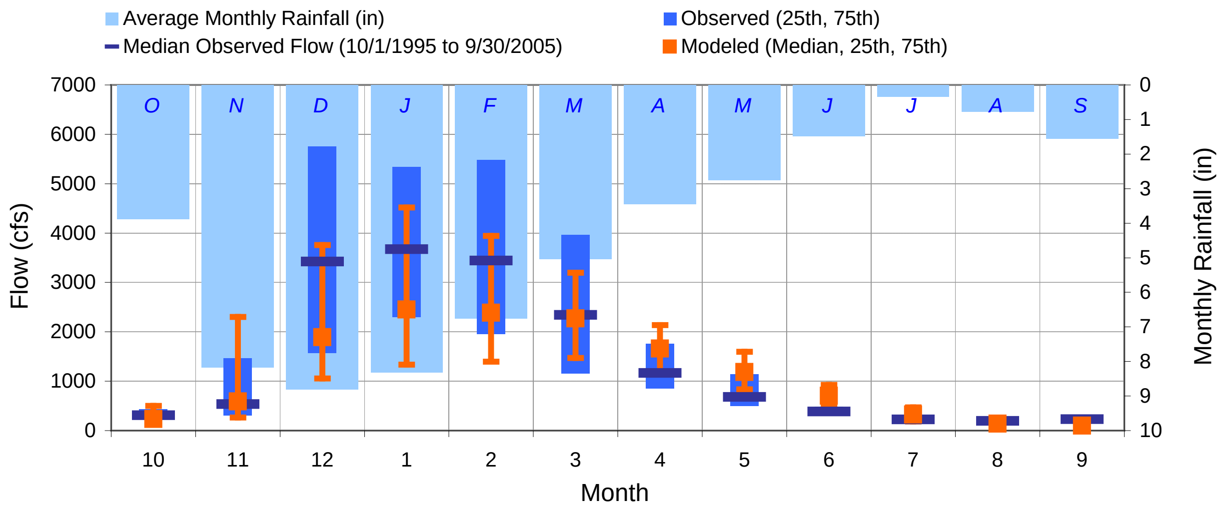

Figure 44. Seasonal medians and ranges at USGS 14207500 Tualatin River at West Linn, OR – calibration period (SWAT).

Table 22. Seasonal summary at USGS 14207500 Tualatin River at West Linn, OR – calibration period (SWAT)

MONTH	OBSERVED FLOW (CFS)				MODELED FLOW (CFS)			
	MEAN	MEDIAN	25TH	75TH	MEAN	MEDIAN	25TH	75TH
Oct	399.00	309.00	234.00	436.75	451.80	233.45	133.30	502.09
Nov	1305.46	534.00	305.75	1460.00	1766.52	591.34	265.80	2302.69
Dec	3817.72	3420.00	1565.00	5747.50	2950.48	1891.63	1053.44	3756.60
Jan	4175.40	3675.00	2297.50	5340.00	3356.79	2452.25	1333.92	4517.63
Feb	4193.04	3440.00	1955.00	5485.00	3557.28	2384.45	1397.75	3944.65
Mar	2763.99	2340.00	1155.00	3962.50	2594.23	2270.38	1469.18	3195.54
Apr	1503.13	1165.00	855.00	1760.00	1822.10	1663.14	1182.51	2135.92
May	929.54	681.00	497.25	1140.00	1307.67	1187.81	835.28	1596.66
Jun	434.30	385.50	295.00	485.00	749.55	705.59	519.57	927.19
Jul	236.99	227.00	187.00	275.50	347.93	325.30	183.15	468.27
Aug	215.16	197.50	171.25	233.75	186.90	138.33	85.99	222.95
Sep	258.55	232.00	197.75	286.25	177.81	98.44	78.28	155.79

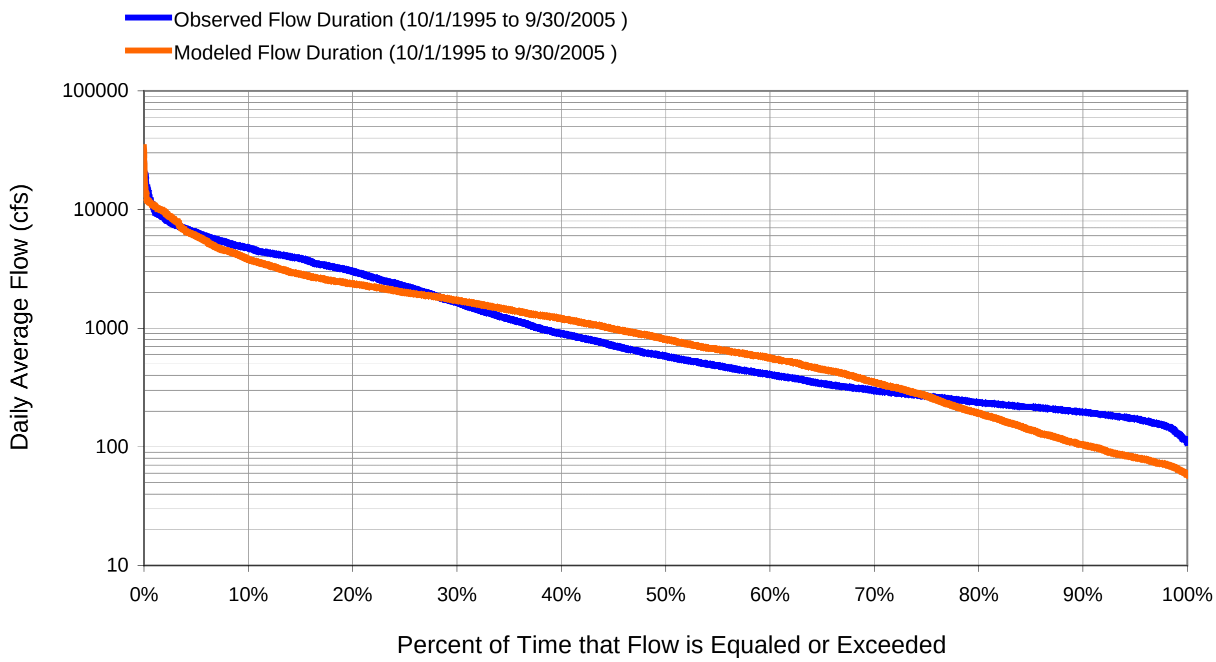

Figure 45. Flow exceedence at USGS 14207500 Tualatin River at West Linn, OR – calibration period (SWAT).

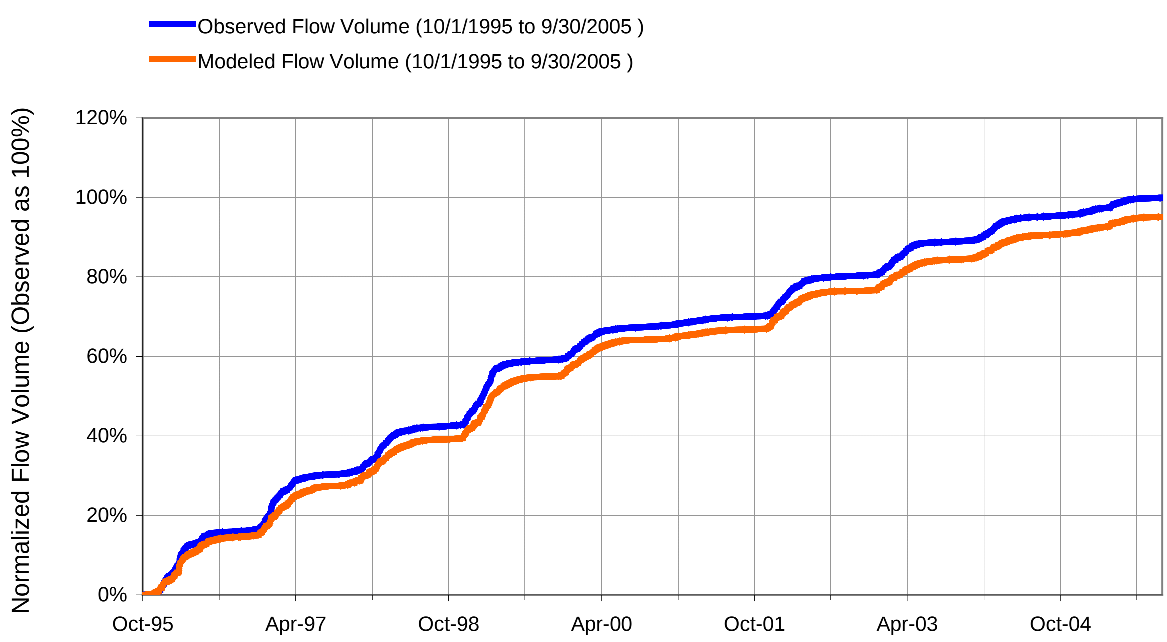

Figure 46. Flow accumulation at USGS 14207500 Tualatin River at West Linn, OR – calibration period (SWAT).

Table 23. Summary statistics: USGS 14207500 Tualatin River at West Linn, OR – calibration period (SWAT)

SWAT Simulated Flow		Observed Flow Gage	
REACH OUTFLOW FROM OUTLET 5 10-Year Analysis Period: 10/1/1995 - 9/30/2005 Flow volumes are (inches/year) for upstream drainage area		USGS 14207500 TUALATIN RIVER AT WEST LINN, OR Hydrologic Unit Code: 17090010 Latitude: 45.35067559 Longitude: -122.6762044 Drainage Area (sq-mi): 706	
Total Simulated In-stream Flow:	**30.72**	Total Observed In-stream Flow:	**32.25**
Total of simulated highest 10% flows:	**13.37**	Total of Observed highest 10% flows:	**13.96**
Total of Simulated lowest 50% flows:	**3.17**	Total of Observed Lowest 50% flows:	**2.85**
Simulated Summer Flow Volume (months 7-9):	**1.22**	Observed Summer Flow Volume (7-9):	**1.15**
Simulated Fall Flow Volume (months 10-12):	**8.33**	Observed Fall Flow Volume (10-12):	**8.95**
Simulated Winter Flow Volume (months 1-3):	**14.99**	Observed Winter Flow Volume (1-3):	**17.58**
Simulated Spring Flow Volume (months 4-6):	**6.18**	Observed Spring Flow Volume (4-6):	**4.58**
Total Simulated Storm Volume:	**10.59**	Total Observed Storm Volume:	**6.18**
Simulated Summer Storm Volume (7-9):	**0.24**	Observed Summer Storm Volume (7-9):	**0.16**

Errors (Simulated-Observed)	*Error Statistics*	*Recommended Criteria*		
Error in total volume:	-4.76	10		
Error in 50% lowest flows:	**11.08**	**10**		
Error in 10% highest flows:	-4.19	15		
Seasonal volume error - Summer:	6.04	30		
Seasonal volume error - Fall:	-6.91	>> 30	Clear	
Seasonal volume error - Winter:	-14.74	30		
Seasonal volume error - Spring:	**35.01**	**30**		
Error in storm volumes:	**71.50**	**20**		
Error in summer storm volumes:	**52.98**	**50**		
Nash-Sutcliffe Coefficient of Efficiency, E:	0.489	Model accuracy increases		
Baseline adjusted coefficient (Garrick), E':	0.505	as E or E' approaches 1.0		
Monthly NSE	0.885			

Hydrology Validation

Consistent with HSPF modeling efforts, validation for the Tualatin River calibration focus area was performed at the same location but for the water years from 10/01/1985 to 09/30/1995. Results are presented in Figures 47 through 53 and Tables 24 and 25. Although, the Nash-Sutcliffe modeling efficiency is not as good as it was for the calibration period, the model performance was adequate for the validation period. The model underestimates total flow volumes while it overestimates low flows and storm volumes. The rest of the metrics fall within the acceptable range set for the 20 Watershed study.

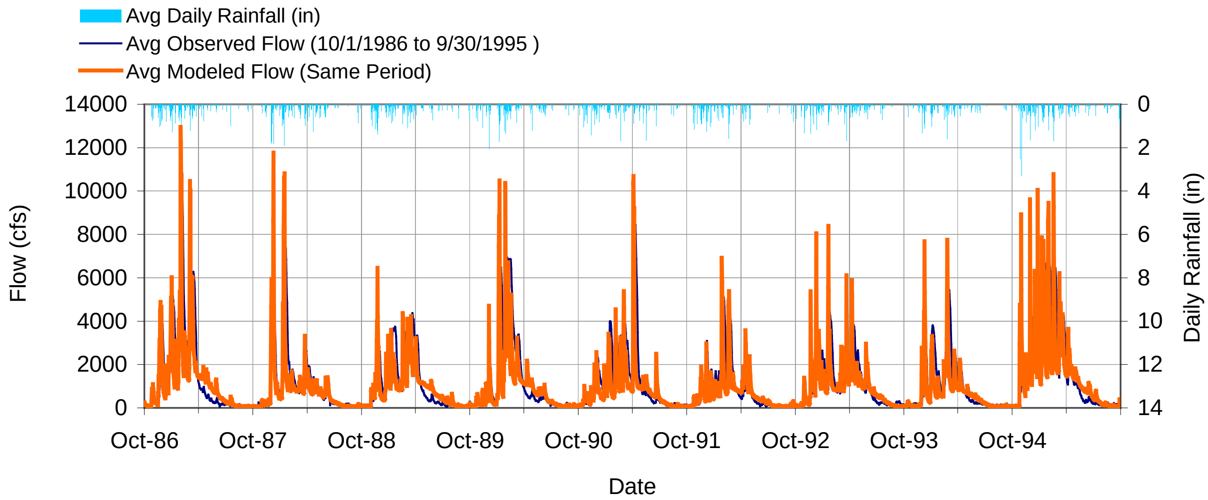

Figure 47. Mean daily flow at USGS 14207500 Tualatin River at West Linn, OR – validation period (SWAT).

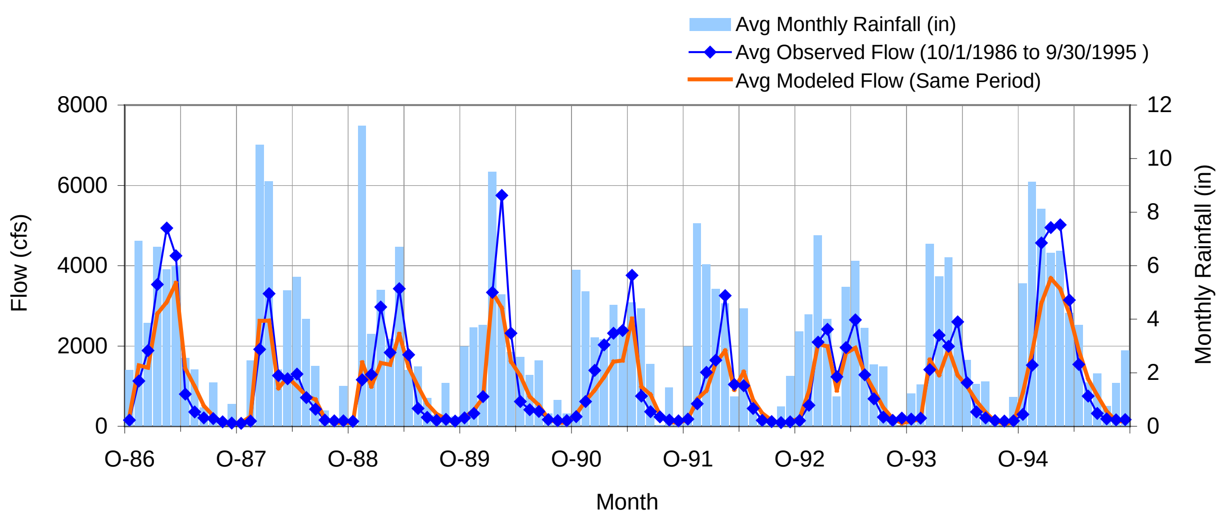

Figure 48. Mean monthly flow at USGS 14207500 Tualatin River at West Linn, OR – validation period (SWAT).

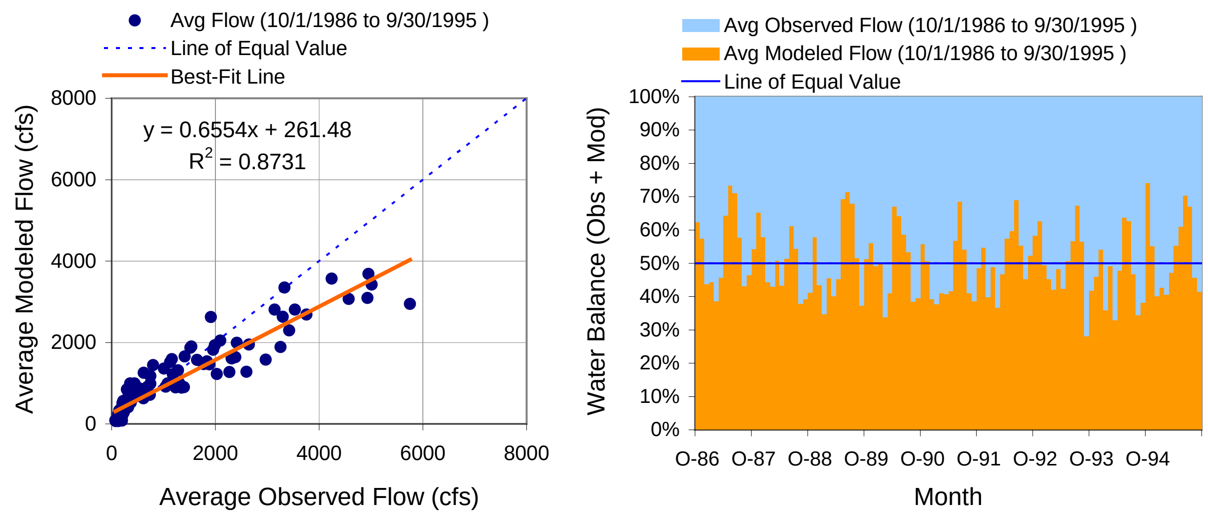

Figure 49. Monthly flow regression and temporal variation at USGS 14207500 Tualatin River at West Linn, OR – validation period (SWAT).

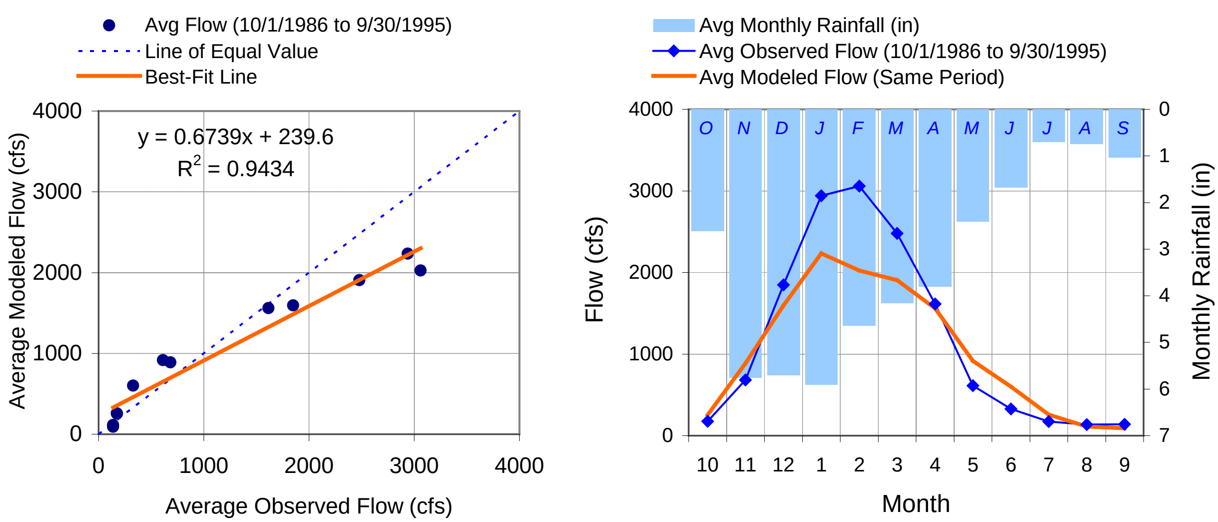

Figure 50. Seasonal regression and temporal aggregate at USGS 14207500 Tualatin River at West Linn, OR – validation period (SWAT).

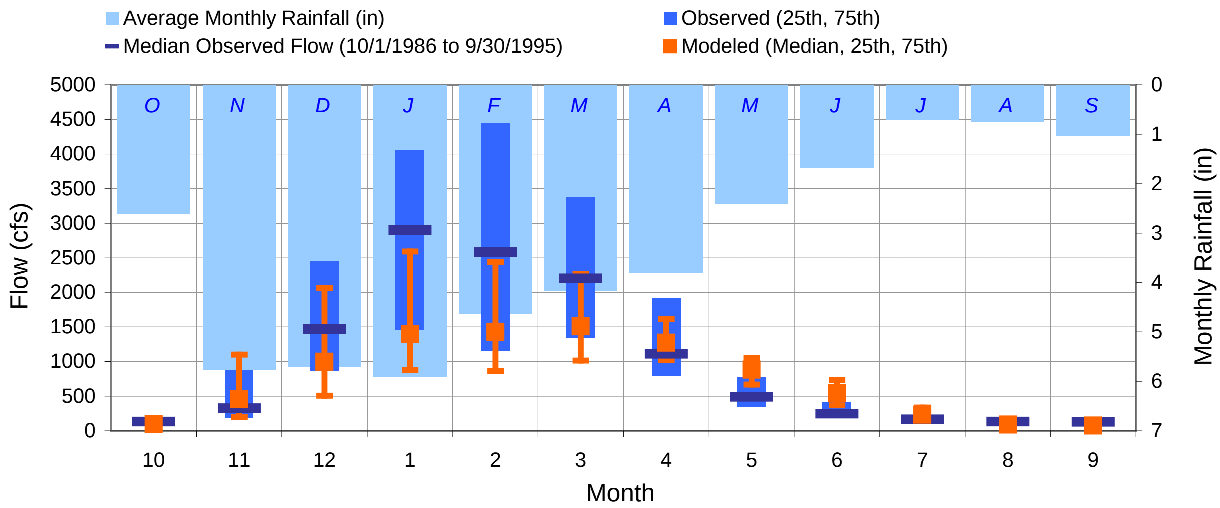

Figure 51. Seasonal medians and ranges at USGS 14207500 Tualatin River at West Linn, OR – validation period (SWAT).

Table 24. Seasonal summary at USGS 14207500 Tualatin River at West Linn, OR – validation period (SWAT)

MONTH	OBSERVED FLOW (CFS)				MODELED FLOW (CFS)			
	MEAN	MEDIAN	25TH	75TH	MEAN	MEDIAN	25TH	75TH
Oct	176.23	133.00	103.00	187.50	253.63	92.74	83.59	157.15
Nov	684.20	324.00	193.00	875.00	887.67	455.03	200.88	1100.85
Dec	1849.41	1470.00	873.00	2450.00	1595.11	996.23	507.82	2060.43
Jan	2939.52	2900.00	1460.00	4055.00	2234.76	1393.87	880.57	2590.33
Feb	3060.41	2580.00	1150.00	4450.00	2025.35	1429.89	865.74	2438.83
Mar	2478.49	2200.00	1335.00	3380.00	1906.07	1506.88	1014.94	2270.91
Apr	1615.37	1110.00	791.00	1917.50	1560.53	1272.74	1025.63	1620.06
May	612.33	491.00	339.50	770.50	915.70	882.87	667.62	1053.08
Jun	328.74	248.00	199.00	410.25	599.41	547.55	367.63	731.63
Jul	173.48	165.00	130.50	211.50	258.61	233.54	149.65	336.11
Aug	137.55	132.00	112.00	159.50	112.11	89.66	72.13	125.44
Sep	138.14	127.00	111.00	158.00	90.80	74.92	66.13	97.54

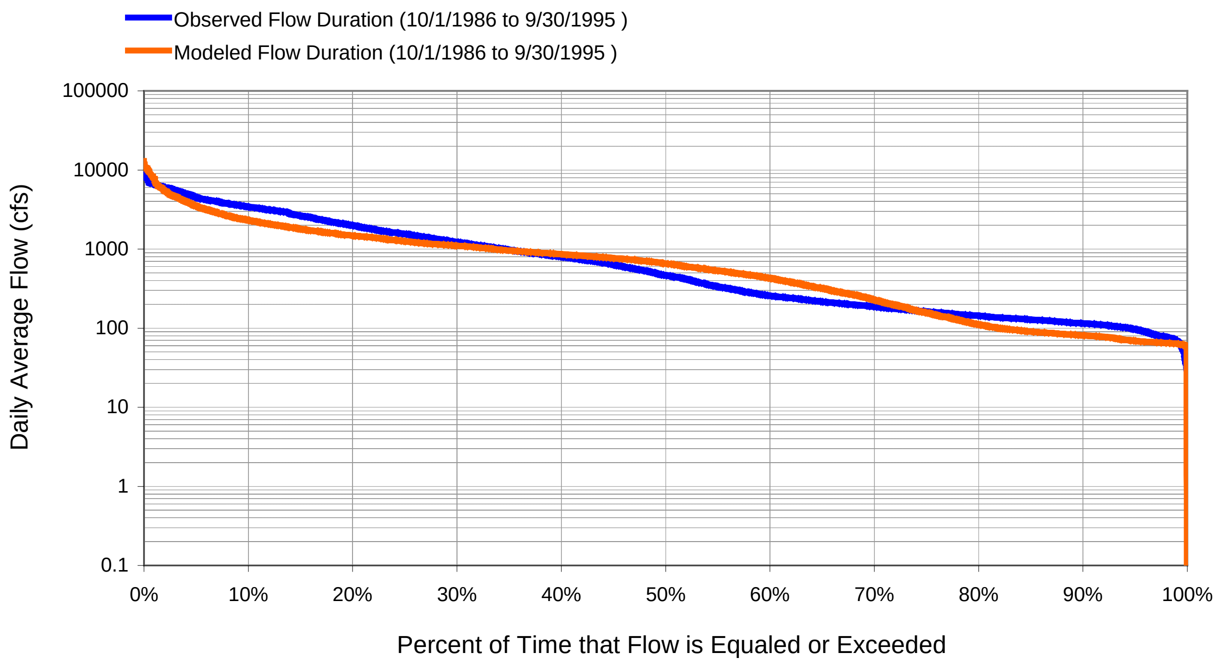

Figure 52. Flow exceedence at USGS 14207500 Tualatin River at West Linn, OR – validation period (SWAT).

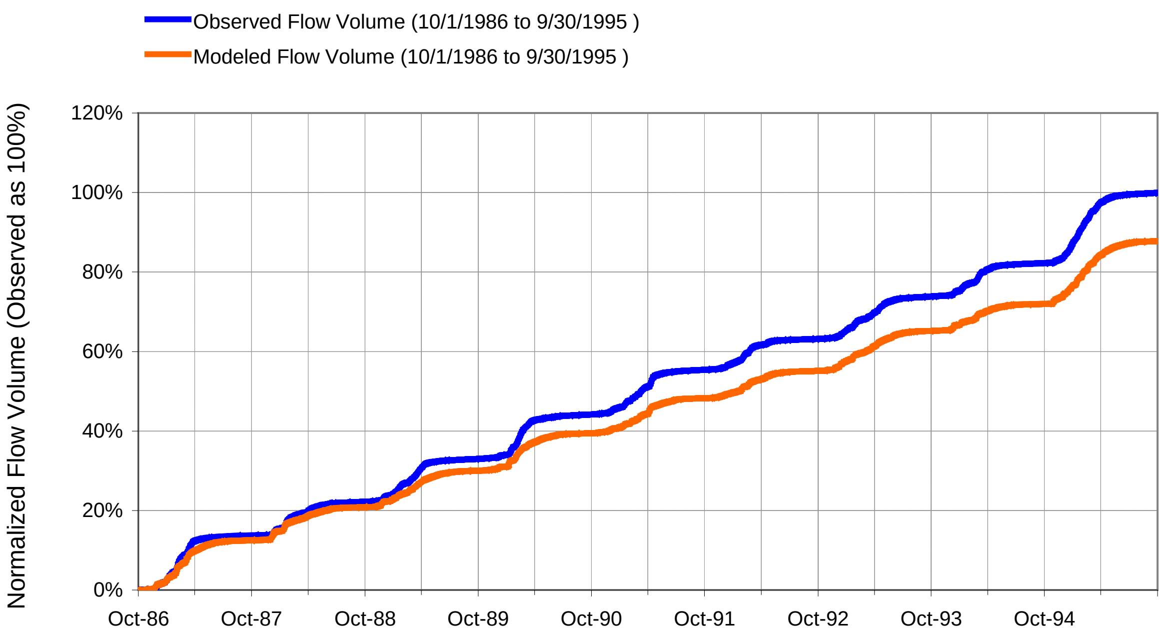

Figure 53. Flow accumulation at USGS 14207500 Tualatin River at West Linn, OR – validation period (SWAT).

Table 25. Summary statistics at USGS 14207500 Tualatin River at West Linn, OR – validation period (SWAT)

SWAT Simulated Flow		Observed Flow Gage	
REACH OUTFLOW FROM OUTLET 5 9-Year Analysis Period: 10/1/1986 - 9/30/1995 Flow volumes are (inches/year) for upstream drainage area		USGS 14207500 TUALATIN RIVER AT WEST LINN, OR Hydrologic Unit Code: 17090010 Latitude: 45.35067559 Longitude: -122.6762044 Drainage Area (sq-mi): 706	
Total Simulated In-stream Flow:	**19.85**	Total Observed In-stream Flow:	**22.59**
Total of simulated highest 10% flows:	**8.29**	Total of Observed highest 10% flows:	**9.50**
Total of Simulated lowest 50% flows:	**2.28**	Total of Observed Lowest 50% flows:	**1.83**
Simulated Summer Flow Volume (months 7-9):	**0.75**	Observed Summer Flow Volume (7-9):	**0.73**
Simulated Fall Flow Volume (months 10-12):	**4.42**	Observed Fall Flow Volume (10-12):	**4.39**
Simulated Winter Flow Volume (months 1-3):	**9.77**	Observed Winter Flow Volume (1-3):	**13.40**
Simulated Spring Flow Volume (months 4-6):	**4.91**	Observed Spring Flow Volume (4-6):	**4.07**
Total Simulated Storm Volume:	**6.95**	Total Observed Storm Volume:	**4.72**
Simulated Summer Storm Volume (7-9):	**0.12**	Observed Summer Storm Volume (7-9):	**0.11**

Errors (Simulated-Observed)	*Error Statistics*	*Recommended Criteria*
Error in total volume:	**-12.10**	**10**
Error in 50% lowest flows:	**24.62**	**10**
Error in 10% highest flows:	-12.81	15
Seasonal volume error - Summer:	3.12	30
Seasonal volume error - Fall:	0.74	30
Seasonal volume error - Winter:	-27.05	30
Seasonal volume error - Spring:	20.54	30
Error in storm volumes:	**47.27**	**20**
Error in summer storm volumes:	4.49	50
Nash-Sutcliffe Coefficient of Efficiency, E:	0.394	Model accuracy increases
Baseline adjusted coefficient (Garrick), E':	0.459	as E or E' approaches 1.0
Monthly NSE	0.807	

>> Clear

Hydrology Results for Larger Watershed

Since the Tualatin River calibration location represents only a small portion of the entire Willamette River watershed, the results near the outlet of the entire watershed were examined at the Willamette River at Salem, OR (USGS 14191000). This gage is downstream of the large reservoirs in the Willamette River watershed. Greater than 40 percent of the area at Salem is controlled by dams. The results are presented in Figures 54 through 60 and Tables 26 and 27. Summer storms are small in this region, and the summer storm volumes are also small; therefore, an error of 0.2 inches produces a large percent difference. Underestimation of low flow is manifested in underestimation of seasonal summer volumes. The remainder of the metrics fall within the acceptable range set for the 20 Watershed study including a daily Nash-Sutcliffe of 0.67 at the Salem gage. Tables 28 and 29 show a summary of the hydrology calibration and validation results for all five locations, respectively.

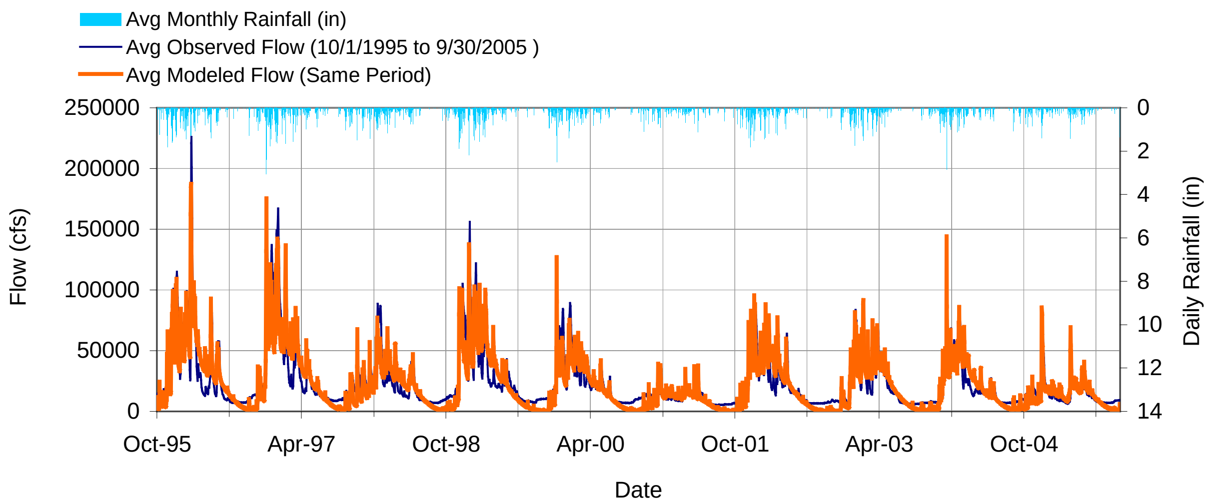

Figure 54. Mean daily flow at USGS 14191000 Willamette River at Salem, OR – calibration period (SWAT).

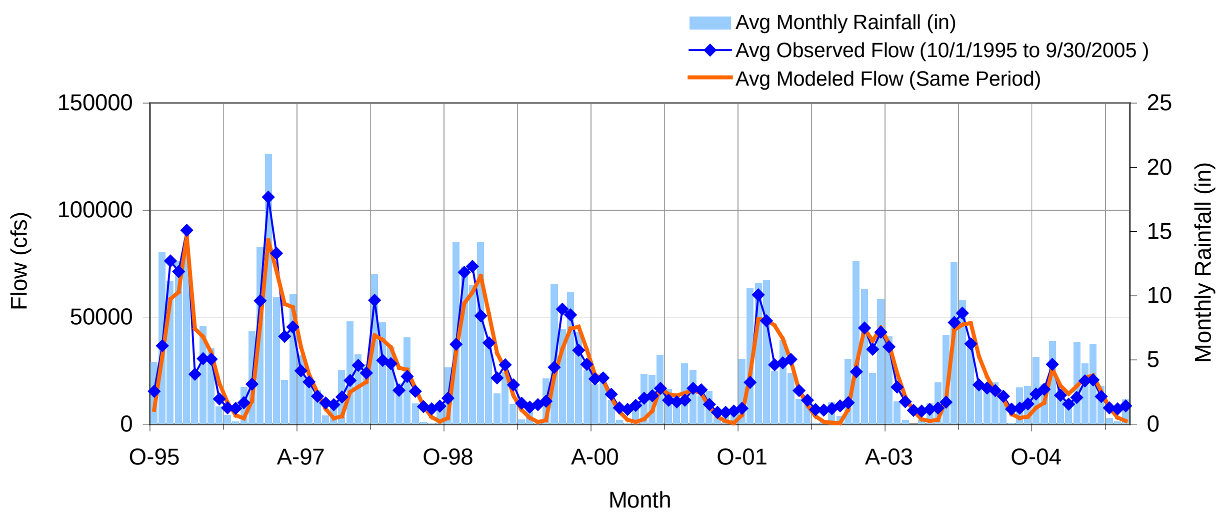

Figure 55. Mean monthly flow at USGS 14191000 Willamette River at Salem, OR – calibration period (SWAT).

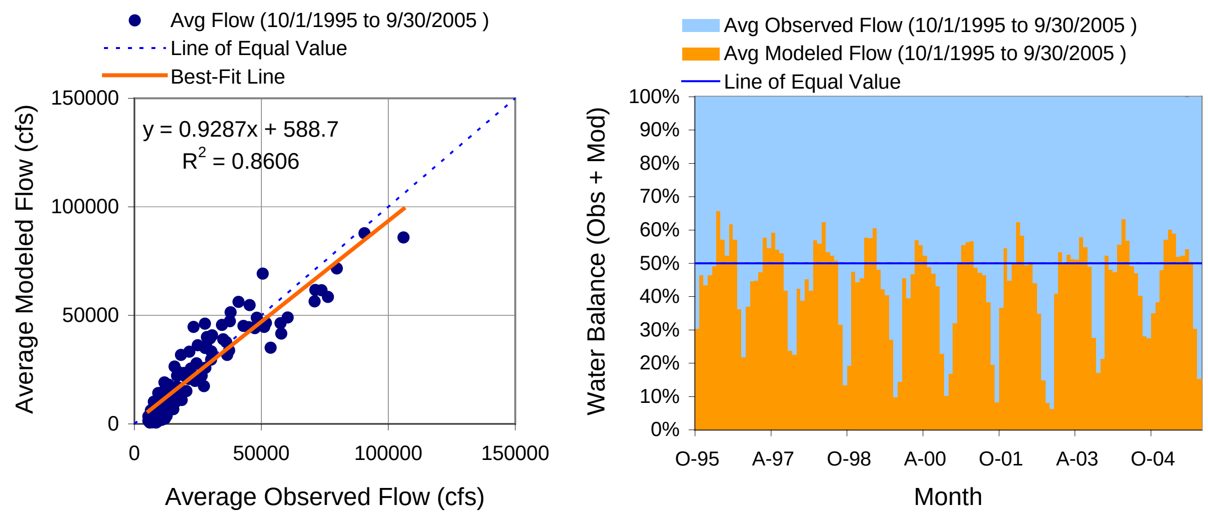

Figure 56. Monthly flow regression and temporal variation at USGS 14191000 Willamette River at Salem, OR – calibration period (SWAT).

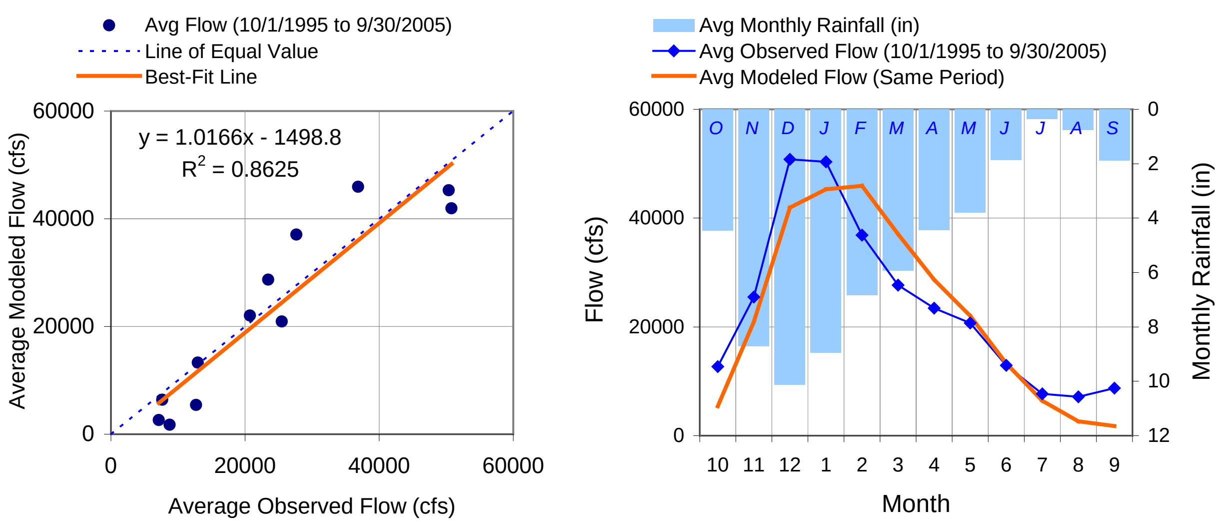

Figure 57. Seasonal regression and temporal aggregate at USGS 14191000 Willamette River at Salem, OR – calibration period (SWAT).

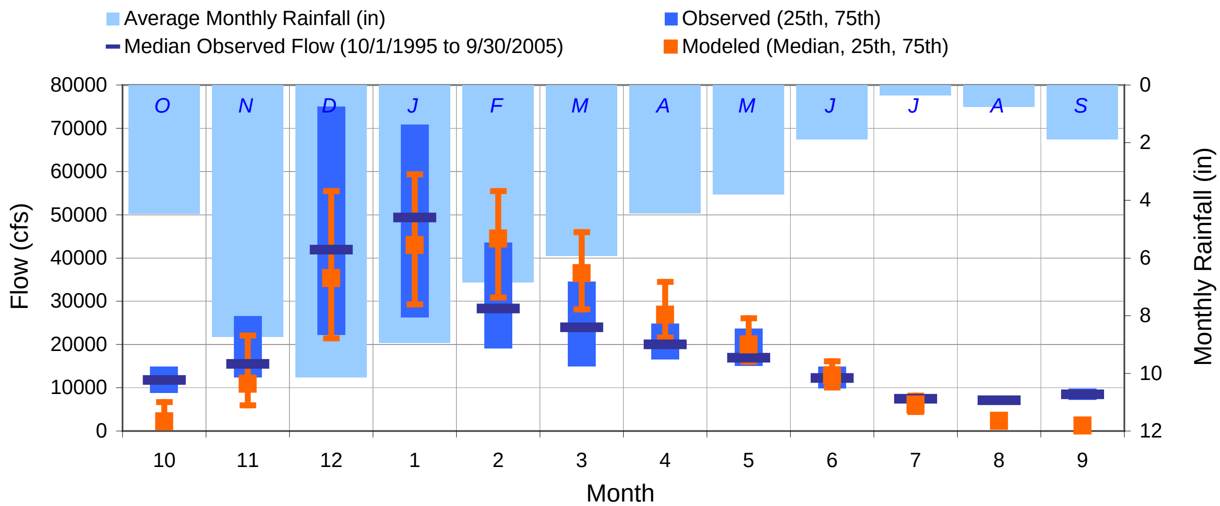

Figure 58. Seasonal medians and ranges at USGS 14191000 Willamette River at Salem, OR – calibration period (SWAT).

Table 26. Seasonal summary at USGS 14191000 Willamette River at Salem, OR – calibration period (SWAT)

MONTH	OBSERVED FLOW (CFS)				MODELED FLOW (CFS)			
	MEAN	MEDIAN	25TH	75TH	MEAN	MEDIAN	25TH	75TH
Oct	12717.87	11800.00	8752.50	14875.00	5439.92	2240.19	905.47	6665.64
Nov	25500.23	15500.00	12375.00	26525.00	20933.37	10921.06	5974.36	22100.80
Dec	50807.87	41900.00	22175.00	74950.00	41930.27	35365.87	21415.70	55488.17
Jan	50369.00	49350.00	26325.00	70900.00	45283.04	42977.95	29260.85	59355.13
Feb	36872.79	28300.00	19050.00	43500.00	45938.63	44496.48	30854.42	55461.68
Mar	27664.39	23950.00	14950.00	34500.00	37075.54	36462.39	28114.89	45953.21
Apr	23458.33	20000.00	16600.00	24825.00	28696.06	26883.29	21591.39	34482.12
May	20733.55	16950.00	15100.00	23675.00	22035.69	20011.06	15987.83	26090.48
Jun	12950.87	12250.00	9807.50	14825.00	13294.29	12840.41	10054.09	16113.20
Jul	7675.19	7430.00	6780.00	8227.50	6400.42	6098.84	4428.46	8161.22
Aug	7159.26	7110.00	6602.50	7395.00	2621.14	2353.02	1650.52	3287.97
Sep	8761.37	8450.00	7210.00	9847.50	1757.98	1243.78	715.39	1834.86

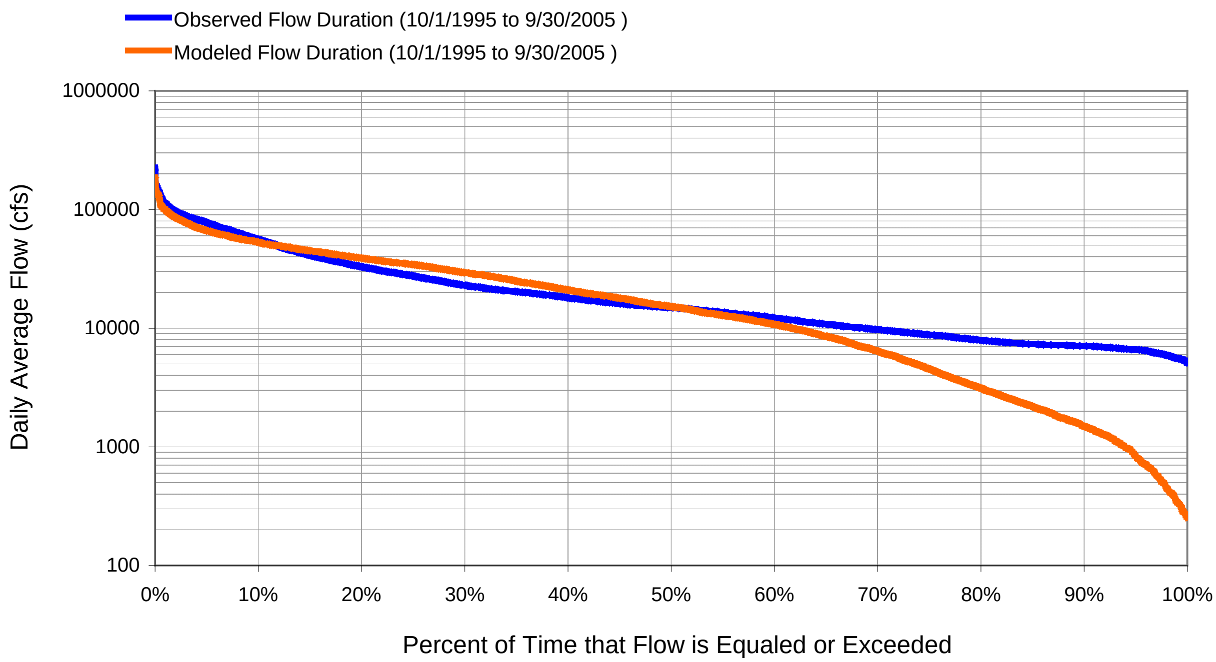

Figure 59. Flow exceedence at USGS 14191000 Willamette River at Salem, OR – calibration period (SWAT).

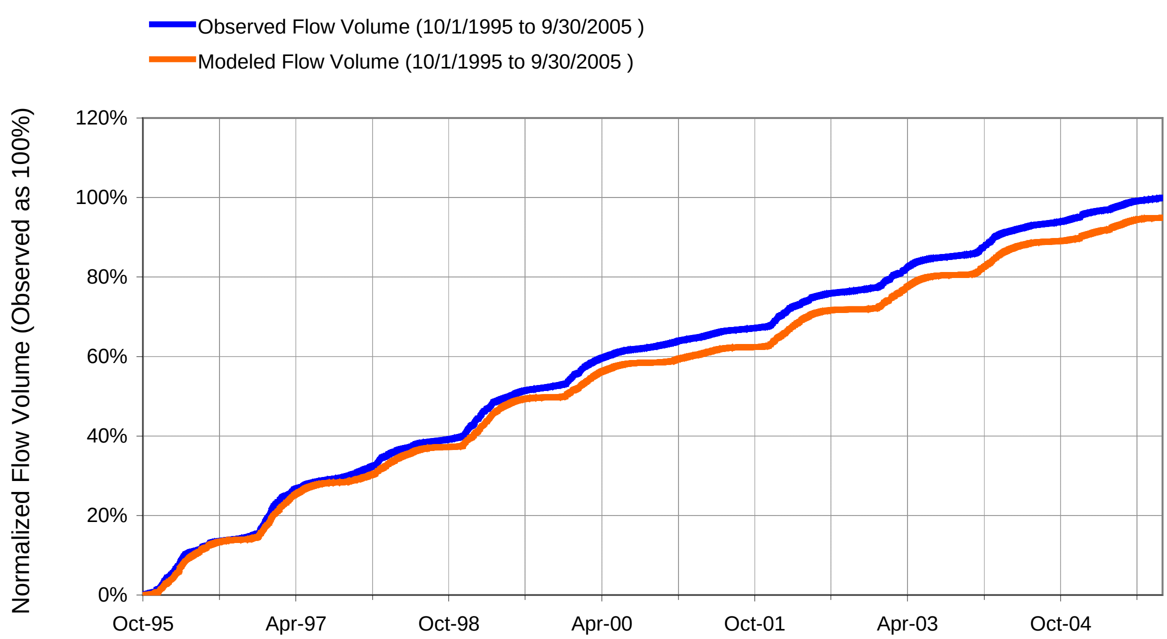

Figure 60. Flow accumulation at USGS 14191000 Willamette River at Salem, OR – calibration period (SWAT).

Table 27. Summary statistics at USGS 14191000 Willamette River at Salem, OR – calibration period (SWAT)

SWAT Simulated Flow		Observed Flow Gage			
REACH OUTFLOW FROM OUTLET 18 10-Year Analysis Period: 10/1/1995 - 9/30/2005 Flow volumes are (inches/year) for upstream drainage area		USGS 14191000 WILLAMETTE RIVER AT SALEM, OR Hydrologic Unit Code: 17090007 Latitude: 44.9442863 Longitude: -123.0428742 Drainage Area (sq-mi): 7280			
Total Simulated In-stream Flow:	**42.01**	Total Observed In-stream Flow:			**44.21**
Total of simulated highest 10% flows:	**13.73**	Total of Observed highest 10% flows:			**15.55**
Total of Simulated lowest 50% flows:	**5.44**	Total of Observed Lowest 50% flows:			**8.79**
Simulated Summer Flow Volume (months 7-9):	**1.70**	Observed Summer Flow Volume (7-9):			**3.69**
Simulated Fall Flow Volume (months 10-12):	**10.71**	Observed Fall Flow Volume (10-12):			**13.97**
Simulated Winter Flow Volume (months 1-3):	**19.68**	Observed Winter Flow Volume (1-3):			**17.69**
Simulated Spring Flow Volume (months 4-6):	**9.92**	Observed Spring Flow Volume (4-6):			**8.86**
Total Simulated Storm Volume:	**10.96**	Total Observed Storm Volume:			**11.48**
Simulated Summer Storm Volume (7-9):	**0.34**	Observed Summer Storm Volume (7-9):			**0.16**
Errors (Simulated-Observed)	*Error Statistics*	*Recommended Criteria*			
Error in total volume:	-4.96	10			
Error in 50% lowest flows:	**-38.08**	**10**			
Error in 10% highest flows:	-11.71	15			
Seasonal volume error - Summer:	**-54.01**	**30**			
Seasonal volume error - Fall:	-23.33	>> 30		Clear	
Seasonal volume error - Winter:	11.28	30			
Seasonal volume error - Spring:	11.98	30			
Error in storm volumes:	-4.51	20			
Error in summer storm volumes:	**109.03**	**50**			
Nash-Sutcliffe Coefficient of Efficiency, E:	0.669	Model accuracy increases			
Baseline adjusted coefficient (Garrick), E':	0.449	as E or E' approaches 1.0			
Monthly NSE	0.852				

Table 28. Summary statistics (percent error) for all stations – calibration period (SWAT)

Station	14191000 Salem	14207500 West Linn	14202000 Aurora	14194150 McMinnville	14165000 Springfield
Calibration Period:	WY 96-05	WY 96-05	WY 03-05	WY 00-05	WY 99-05
Error in total volume:	-4.96	-4.76	-1.06	-31.37	-18.37
Error in 50% lowest flows:	-38.08	9.00	31.57	-17.54	-34.33
Error in 10% highest flows:	-11.71	-4.03	-14.73	-38.63	-15.69
Seasonal volume error - Summer:	-54.01	0.65	71.04	-9.98	-60.43
Seasonal volume error - Fall:	-23.33	-6.72	3.75	-39.84	0.45
Seasonal volume error - Winter:	11.28	-14.57	-12.99	-35.67	-23.92
Seasonal volume error - Spring:	11.98	35.37	11.82	-0.70	-23.90
Error in storm volumes:	-4.51	71.00	5.57	-35.70	-0.30
Error in summer storm volumes:	109.03	52.22	49.05	5.47	2.75
Daily Nash-Sutcliffe Coefficient of Efficiency, E:	0.669	0.489	0.691	0.448	0.663
Monthly Nash-Sutcliffe Coefficient of Efficiency, E:	0.852	0.885	0.910	0.729	0.820

Table 29. Summary statistics (percent error) for all stations – validation period (SWAT)

Station	14191000 Salem	14207500 West Linn	14202000 Aurora	14194150 McMinnville	14165000 Springfield
Calibration Period:	WY 86-95	WY 86-95	WY 94-97	WY 95-99	WY 88-97
Error in total volume:	-5.67	-12.10	1.56	-30.25	-19.42
Error in 50% lowest flows:	-37.51	24.62	63.52	18.59	-30.89
Error in 10% highest flows:	-7.99	-12.81	-10.57	-39.11	-16.44
Seasonal volume error - Summer:	-51.91	3.12	144.28	64.02	-57.17
Seasonal volume error - Fall:	-24.97	0.74	-11.14	-43.35	10.29
Seasonal volume error - Winter:	12.23	-27.05	-7.96	-32.93	-30.79
Seasonal volume error - Spring:	8.57	20.54	48.39	15.41	-29.57
Error in storm volumes:	-5.50	47.27	9.52	-37.44	2.05
Error in summer storm volumes:	79.12	4.49	180.98	25.45	3.44
Daily Nash-Sutcliffe Coefficient of Efficiency, E:	0.534	0.394	0.699	0.451	0.486
Monthly Nash-Sutcliffe Coefficient of Efficiency, E:	0.798	0.807	0.904	0.713	0.667

Water Quality Calibration

Initial water quality calibration and validation was performed for the Tualatin River at Linn, OR (USGS14207500) using water years 1991-1995 for calibration and water years 1986-1990 for validation. As with hydrology, water quality calibration was performed on the later period as this better reflects the land use included in the model. The start of the validation period is constrained by data availability.

Calibration adjustments for TSS focused on the following parameter:

- RSDCO (Residue decomposition coefficient)

Time series of simulated and estimated TSS loads at the Tualatin River gage for both the calibration and validation periods are shown in Figure 61. Statistics for the two periods are provided separately in Table 30. The key statistic in Table 30 is the relative percent error, which shows the error in the prediction of monthly load normalized to the estimated load. Table 30 also shows the relative average absolute error, which is the average of the relative magnitude of errors in individual monthly load predictions. This number is inflated by outlier months in which the simulated and estimated loads differ by large amounts (which may be as easily due to uncertainty in the estimated load due to limited data as to problems with the model) and the third statistic, the relative median absolute error, is likely more relevant and shows good agreement. Additional diagnostics for TSS included flow-load power plots (Figures 62 and 63), a time series plot of concentrations (Figure 64), and statistics (Table 31).

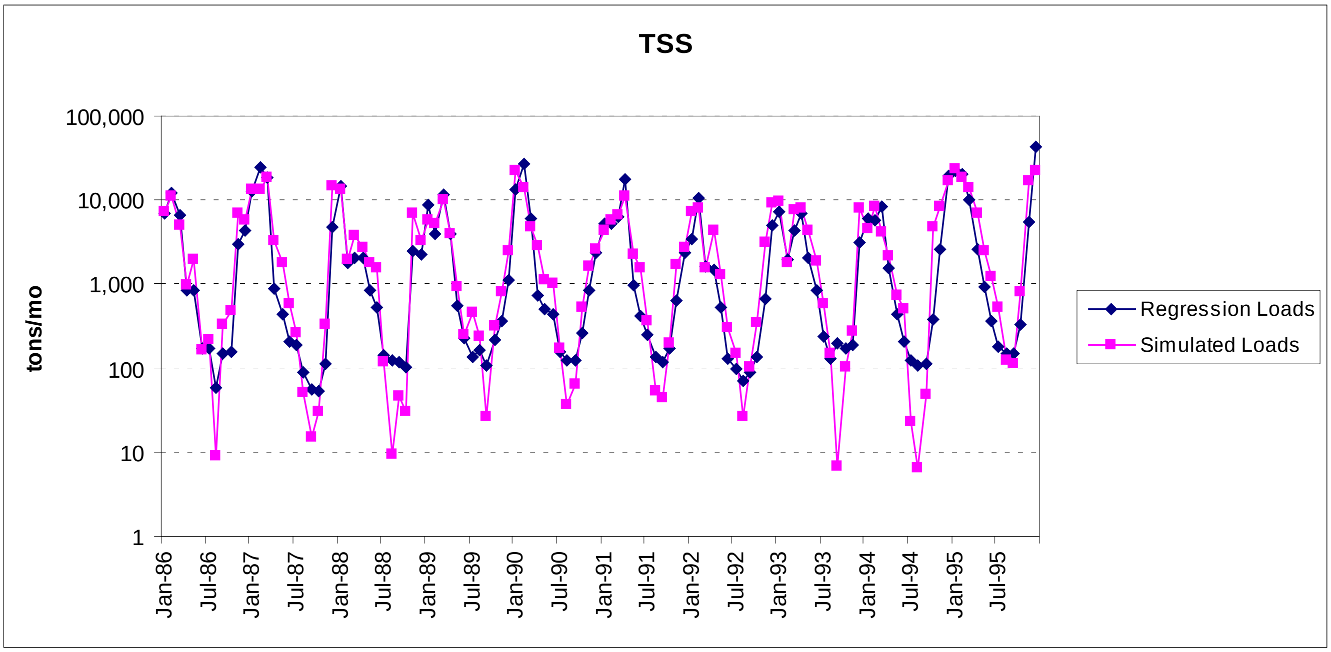

Figure 61. Fit for monthly load of TSS at USGS 14207500 Tualatin River at West Linn, OR (SWAT).

Table 30. Model fit statistics (observed minus predicted) for monthly TSS loads using stratified regression (SWAT)

Statistic	Calibration period (1991-1995)	Validation period (1986-1990)
Relative Percent Error	-12	-7
Relative Average Absolute Error	47	40
Relative Median Absolute Error	17.2	10.5

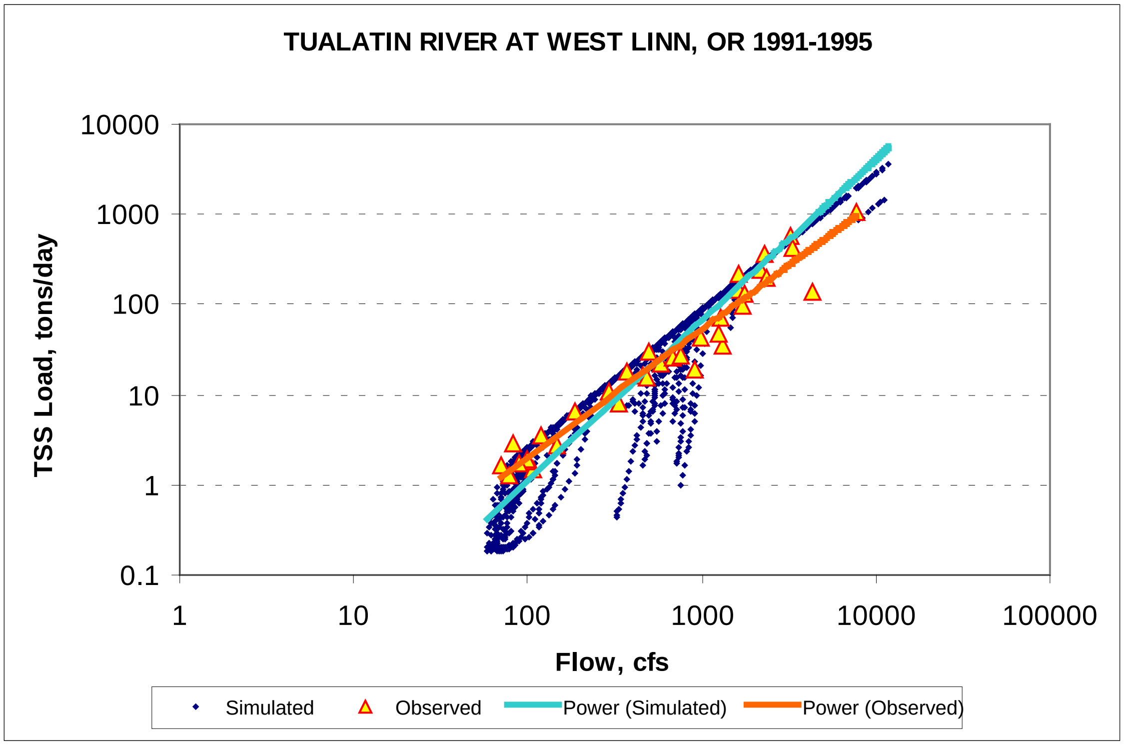

Figure 62. Power plot for observed and simulated TSS at USGS 14207500 Tualatin River at West Linn, OR – calibration period (SWAT).

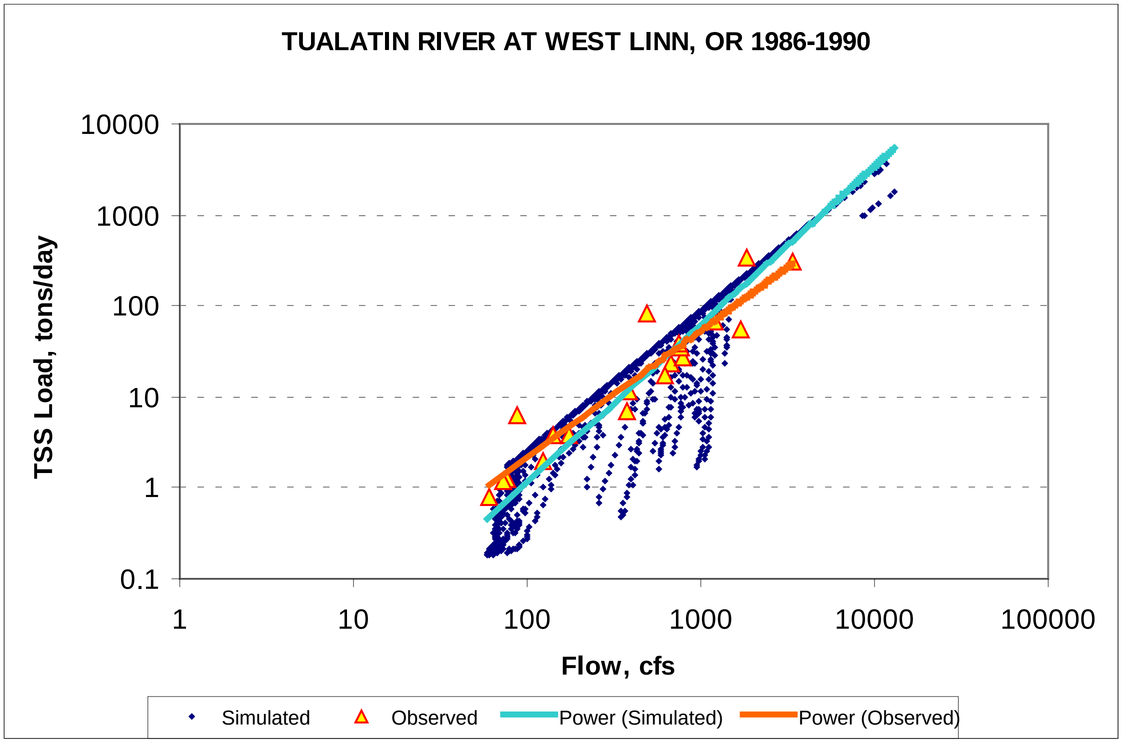

Figure 63. Power plot for observed and simulated TSS at USGS 14207500 Tualatin River at West Linn, OR – validation period (SWAT).

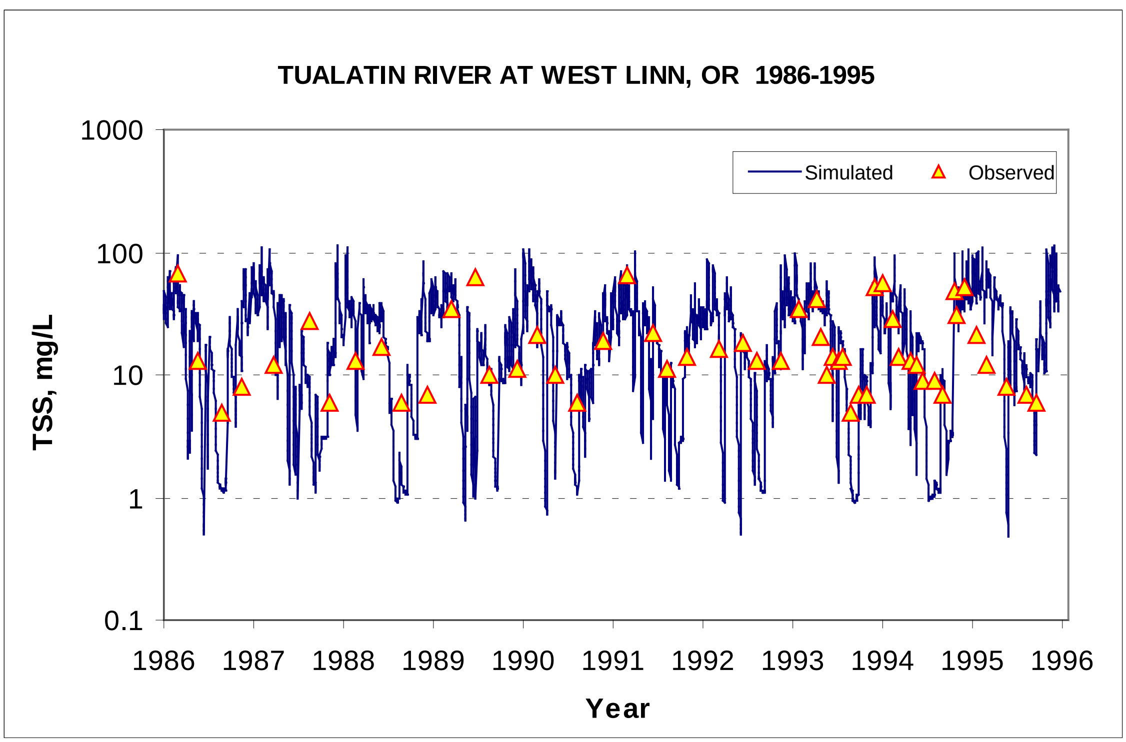

Figure 64. Time series plot of TSS concentration at USGS 14207500 Tualatin River at West Linn, OR (SWAT).

Table 31. Relative errors (observed minus predicted), TSS concentration, at USGS 14207500 Tualatin River at West Linn, OR (SWAT)

Statistic	Calibration period (1991-1995)	Validation period (1986-1990)
Count	35	19
Concentration Average Error	-30.3%	0.06%
Concentration Median Error	10.13%	-22.31%

Calibration adjustments for total phosphorus and total nitrogen focused on the following parameters:

- PPERCO (phosphorus percolation coefficient)
- NPERCO (nitrogen percolation coefficient)
- PHOSKD (phosphorus soil partitioning coefficient)
- HLIFE_NGW (half life of nitrate in the shallow aquifer)
- SOL_CBN1 (organic carbon in the first soil layer)
- QUAL2E parameters such as algal, organic nitrogen, and organic phosphorus settling rate in the reach, benthic source arte for dissolved phosphorus and NH4-N in the reach, fraction of algal biomass that is nitrogen and phosphorus, Michaelis-Menton half-saturation constant for nitrogen and phosphorus

The time series of observed and simulated total phosphorus loads is shown in Figure 65 (monthly loads) and Table 32 (load statistics). As with TSS, additional diagnostics for total phosphorus included flow-load power plots (Figures 66 and 67), a time series plot of concentrations (Figure 68), and statistics (Table 33). In general, total phosphorus for the Willamette River watershed was overestimated by the SWAT model.

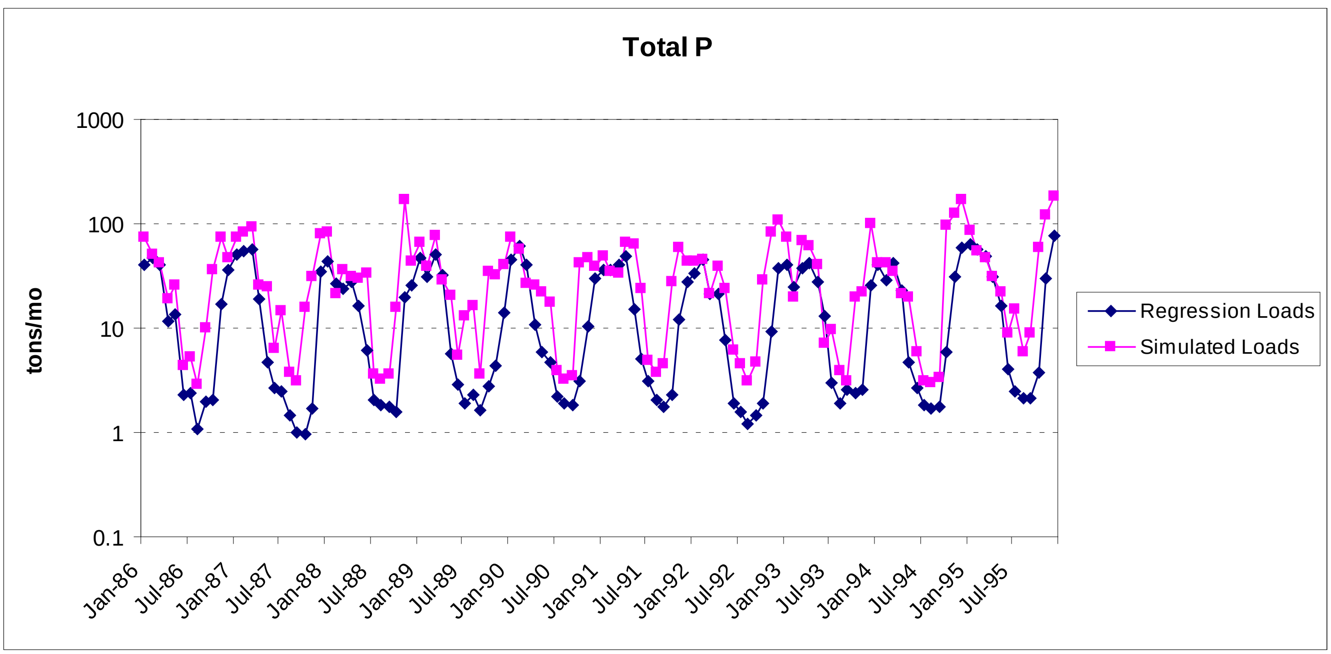

Figure 65. Fit for monthly load of total phosphorus at USGS 14207500 Tualatin River at West Linn, OR (SWAT).

Table 32. Model fit statistics (observed minus predicted) for monthly total phosphorus loads using stratified regression (SWAT)

Statistic	Calibration period (1991-1995)	Validation period (1986-1990)
Relative Percent Error	-114%	-105%
Average Absolute Error	118%	109%
Median Absolute Error	51.7%	79.7%

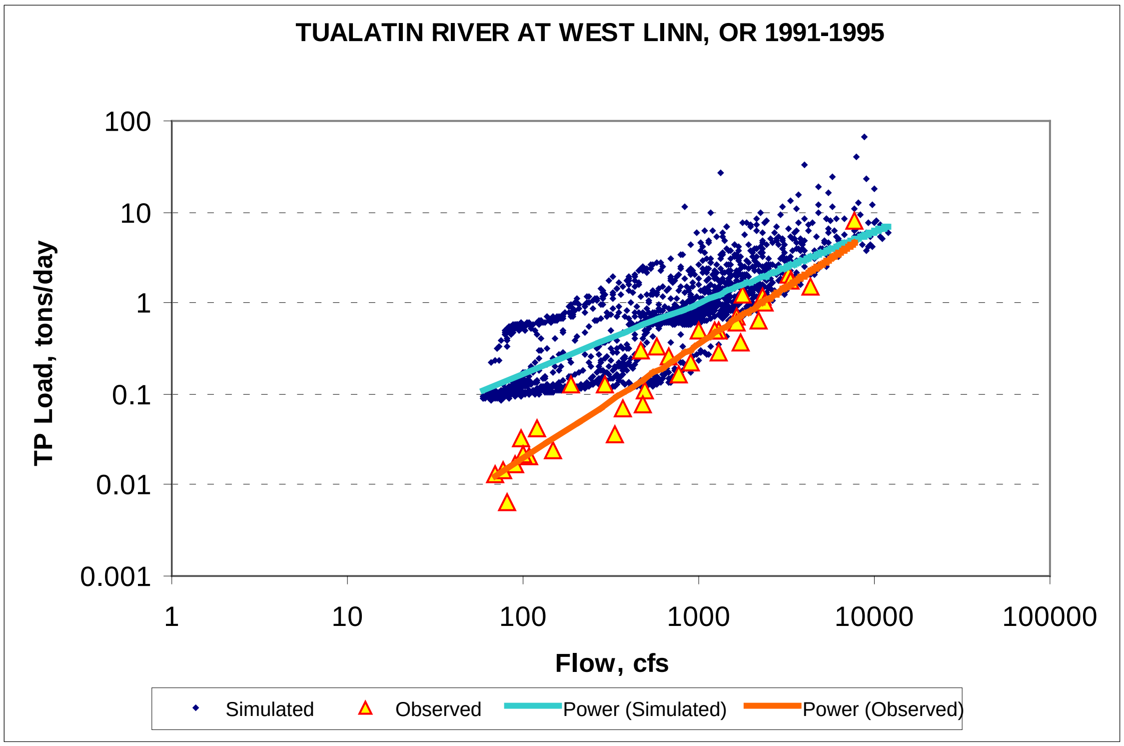

Figure 66. Power plot for observed and simulated total phosphorus at USGS 14207500 Tualatin River at West Linn, OR – calibration period (SWAT).

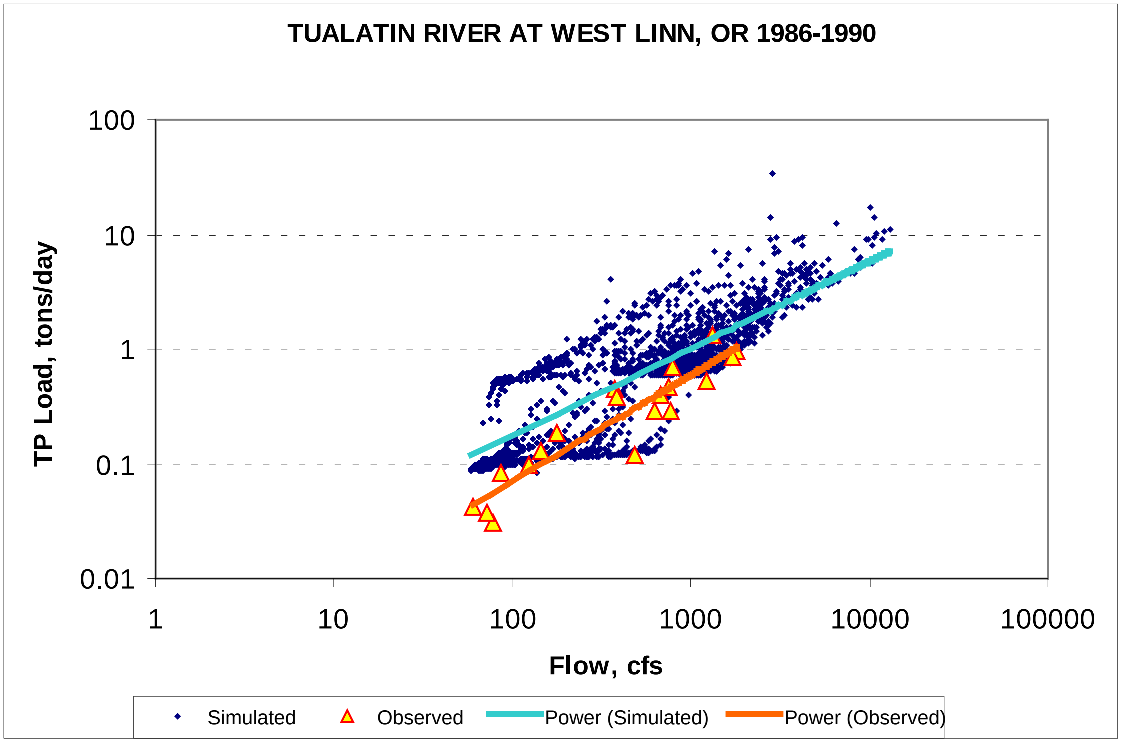

Figure 67. Power plot for observed and simulated total phosphorus at USGS 14207500 Tualatin River at West Linn, OR – validation period (SWAT).

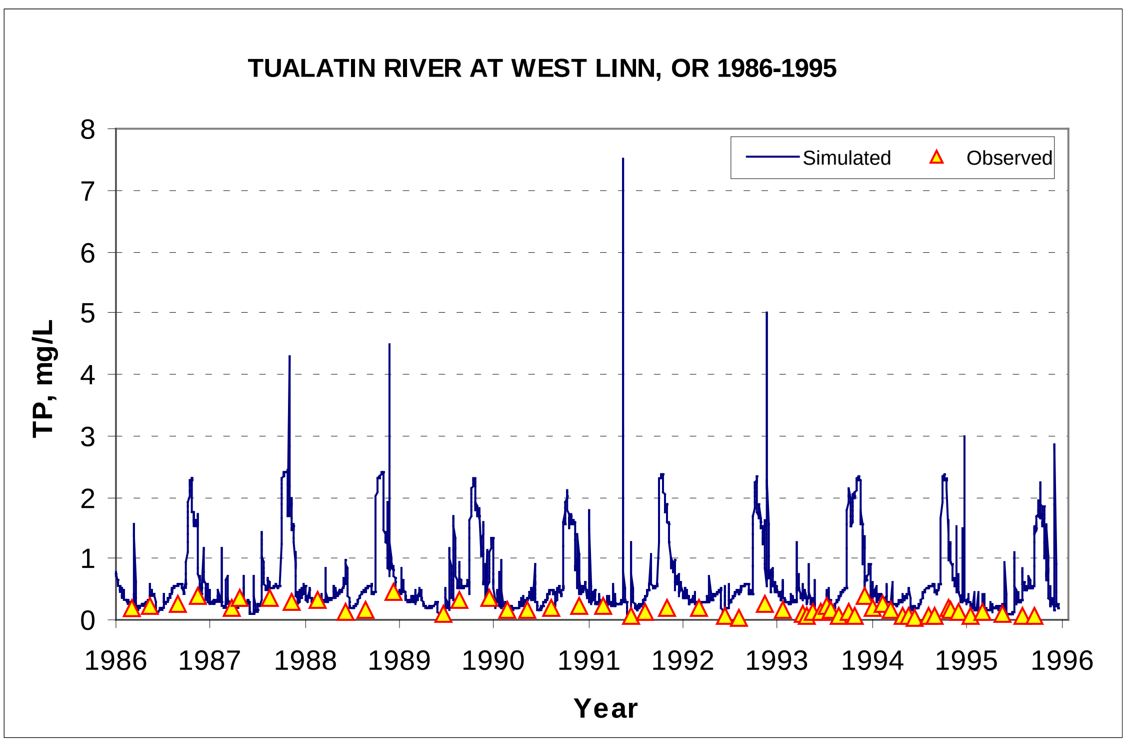

Figure 68. Time series plot of total phosphorus concentration at USGS 14207500 Tualatin River at West Linn, OR (SWAT).

Table 33. Relative errors (observed minus predicted), total phosphorus concentration, at USGS 14207500 Tualatin River at West Linn, OR (SWAT)

Statistic	Calibration period (1991-1995)	Validation period (1986-1990)
Count	35	19
Concentration Average Error	-312.95%	-127.9%
Concentration Median Error	-163.58%	-109.9%

Results for total nitrogen are summarized in Figures 69 through 72 and Tables 34 and 35. Again, total nitrogen loads are overestimated, but are generally better than those for total phosphorus. A summary of the water quality statistics at the two locations (Tualatin River and Pudding River) are shown in Table 36.

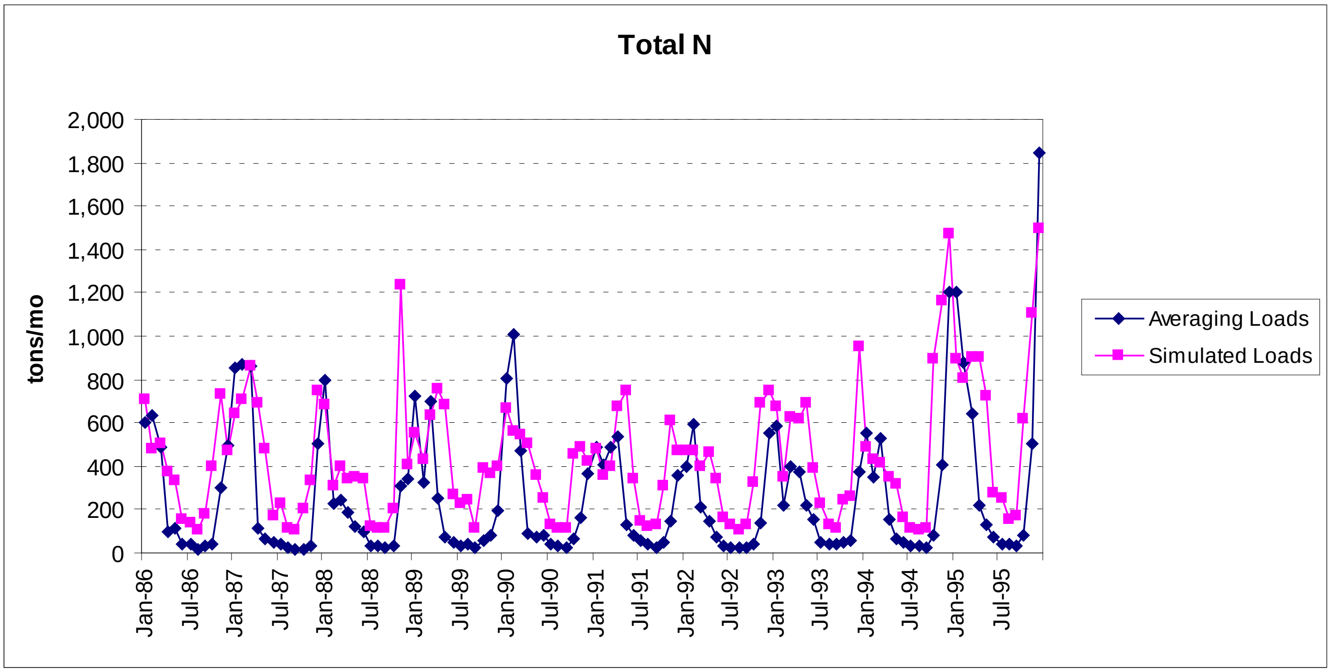

Figure 69. Fit for monthly load of total nitrogen at USGS 14207500 Tualatin River at West Linn, OR (SWAT).

Table 34. Model fit statistics (observed minus predicted) for monthly total nitrogen loads using averaging estimator (SWAT)

Statistic	Calibration period (1991-1995)	Validation period (1986-1990)
Relative Percent Error	-72%	-66%
Average Absolute Error	86%	86%
Median Absolute Error	68.2%	66.3%

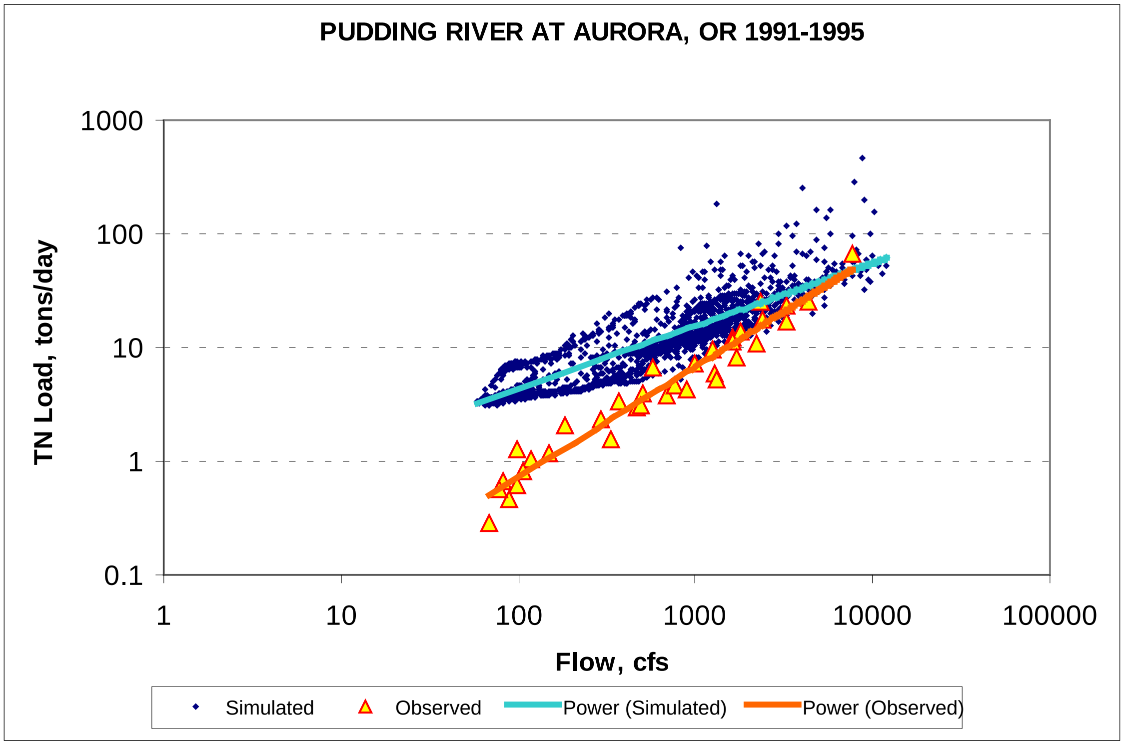

Figure 70. Power plot for observed and simulated total nitrogen at USGS 14207500 Tualatin River at West Linn, OR – calibration period (SWAT).

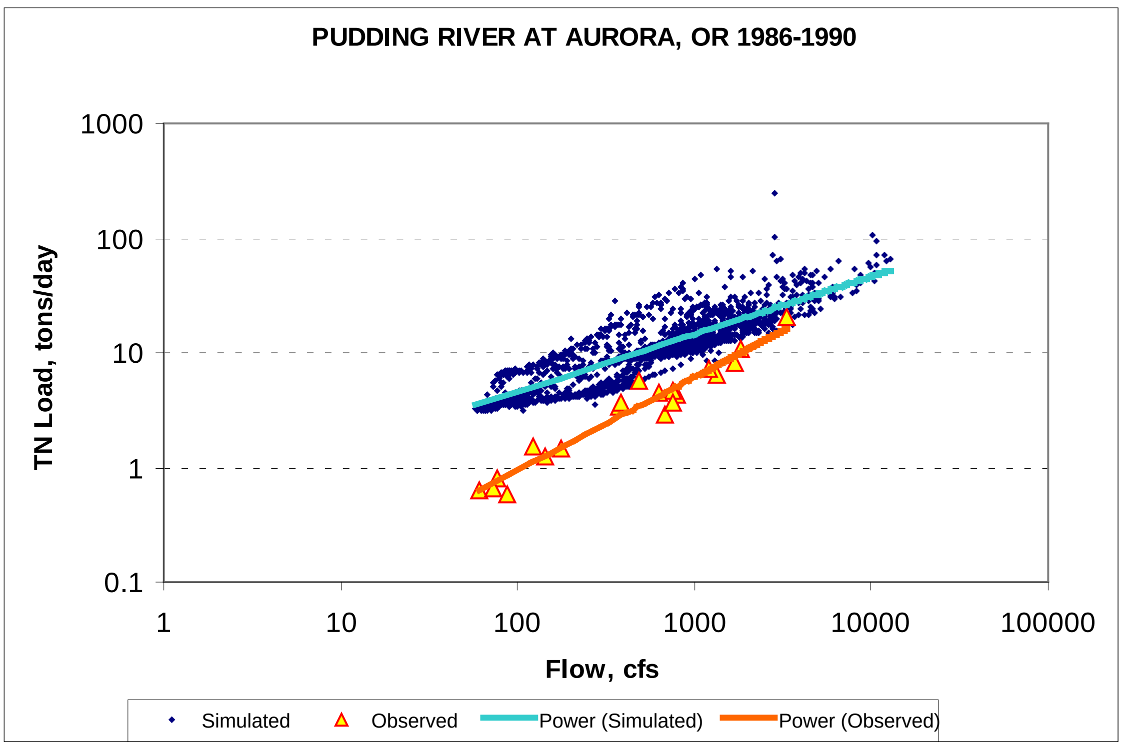

Figure 71. Power plot for observed and simulated total nitrogen at USGS 14207500 Tualatin River at West Linn, OR – validation period (SWAT).

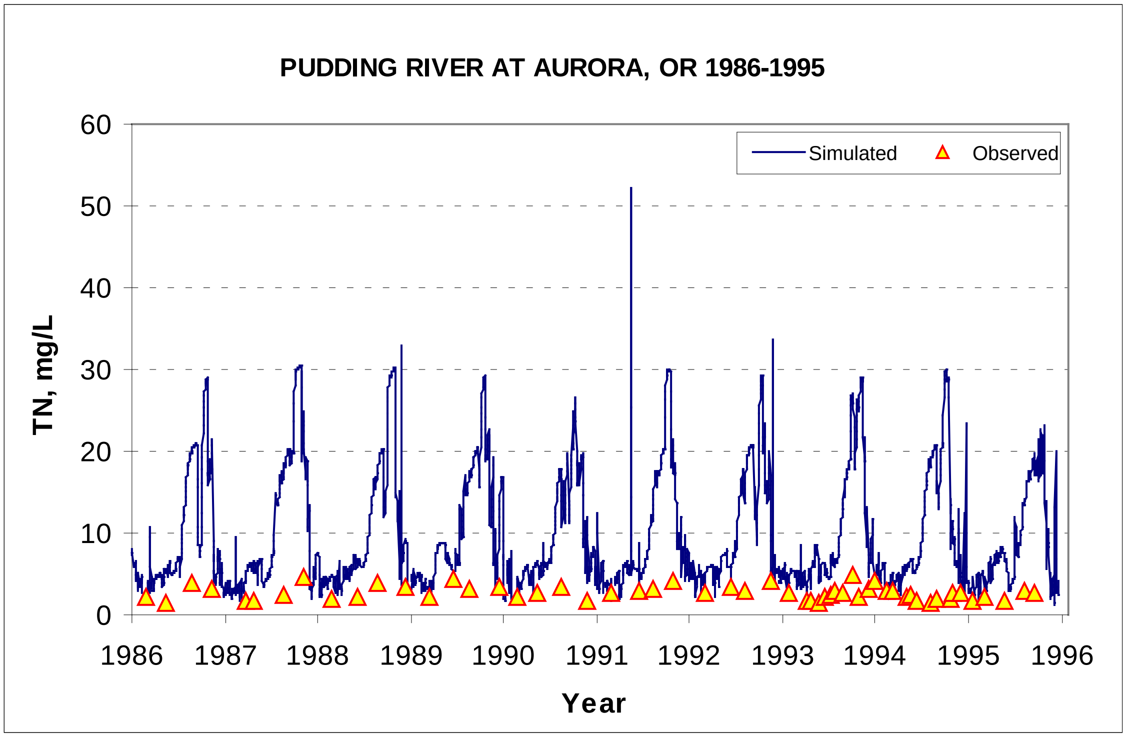

Figure 72. Time series plot of total nitrogen concentration at USGS 14207500 Tualatin River at West Linn, OR (SWAT).

Table 35. Relative errors (observed minus predicted), total nitrogen concentration, at USGS 14207500 Tualatin River at West Linn, OR (SWAT)

Statistic	Calibration period (1991-1995)	Validation period (1986-1990)
Count	35	20
Concentration Average Error	-251.26%	-265.41%
Concentration Median Error	-137.89%	-160.42%

Water Quality Results for Larger Watershed

As with hydrology, the Tualatin River watershed parameters for water quality were directly transferred to other portions of the watershed. This approach resulted in relatively large errors in predicting loads and concentrations at some stations. Summary statistics for the water quality calibration and validation at other stations in the watershed are provided in Table 36.

Table 36. Summary statistics for water quality: all stations (observed minus predicted) (SWAT)

Station	14207500 West Linn Calibration	14207500 West Linn Validation	14202000 Aurora Calibration	14202000 Aurora Validation
Relative Percent Error TSS Load	-12%	-7%	30%	-100%
TSS Concentration Median Percent Error	-10.13%	-22.31%	-13.27%	-43.55%
Relative Percent Error TP Load	-114%	-105%	-30%	-373%
TP Concentration Median Percent Error	-163%	-109.9%	-106.01%	-94.96%
Relative Percent Error TN Load	-72%	-66%	-11%	-218%
TN Concentration Median Percent Error	-137.89%	-160.42%	-42.13%	-165.16%

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Appendix I
Model Configuration, Calibration and Validation

Basin: Lake Pontchartrain Drainage (LPont)

Contents

Tables

Figures

Watershed Background

The Lake Pontchartrain drainage study area was selected as one of the 15 non-pilot application watersheds for the 20 Watershed study. Watershed modeling for the non-pilot areas is accomplished using the SWAT model only, and model calibration and validation results are presented in abbreviated form.

Water Body Characteristics

The Acadian-Pontchartrain NAWQA study area encompasses 26,408 mi^2 in the southern half of Louisiana and includes downstream portions of major rivers, such as the Mississippi with drainage areas far larger than the target size for this project. Therefore, the focus of modeling in this study was the Pontchartrain portion of the study area, including the rivers that drain to Lake Pontchartrain and the cities of New Orleans and Baton Rouge (Figure 1). The resulting model area encompasses over 5,800 mi^2 and seven HUC8s within HUCs 0807 and 0809.The watershed includes the Calcasieu, Mermentau, Vermilion-Teche, Grosse Tete/Verret, Terrebonne, Barataria, and Pontchartrain basins (USGS 2002).

The entire model area is near sea level and frequently impacted by tropical storms from the Gulf of Mexico. The climate is classified as humid subtropical, with an average annual temperature around 70 °F and average annual precipitation of 64 inches per year (USGS, 2002).

Ecosystems and communities in the watershed include cypress-tupelo swamp; freshwater marsh; saltwater marsh; wet prairie; oak cheniers; bottomland hardwood forest; Piney Hills; and longleaf pine savanna. The coastal zone of the watershed is affected by the ocean and its tides. Different wetland types are determined by the salinity of the water in them, which may infiltrate naturally through bayous or reach further inland through canals.

Land uses include a mixture of urban and rapidly urbanizing/industrial areas (12 percent), large areas of mixed forest and pasture (34 percent), wetlands (32 percent) and areas of rice and sugarcane crops (5 percent). Population is rapidly increasing on the north shore of Lake Pontchartrain and surrounding Baton Rouge, causing changes in rainfall-runoff characteristics and quality. Urban streams in the Baton Rouge area are usually channelized, and cleared of woody vegetation to speed drainage during high water.

Surface water in the watershed includes the lower Mississippi delta and wet prairie streams as well as upland streams. Lower Mississippi delta and wet prairie streams tend to have very slow flow, and water can also be pushed upstream by tides or wind causing generally stagnant, backwater conditions. Wetlands develop naturally in poorly drained areas. Streams in the uplands have a moderate flow gradient and sandy, shifting beds that are reshaped quickly in the fast water that is usual for flood conditions.

Modifications to flow include levees, and canals and drainage. Levees are created both naturally during the flooding process (sediment drops out of floodwater next to the waterbody) and by man along many bayous and rivers to reduce floods and to maintain a deeper channel for shipping.

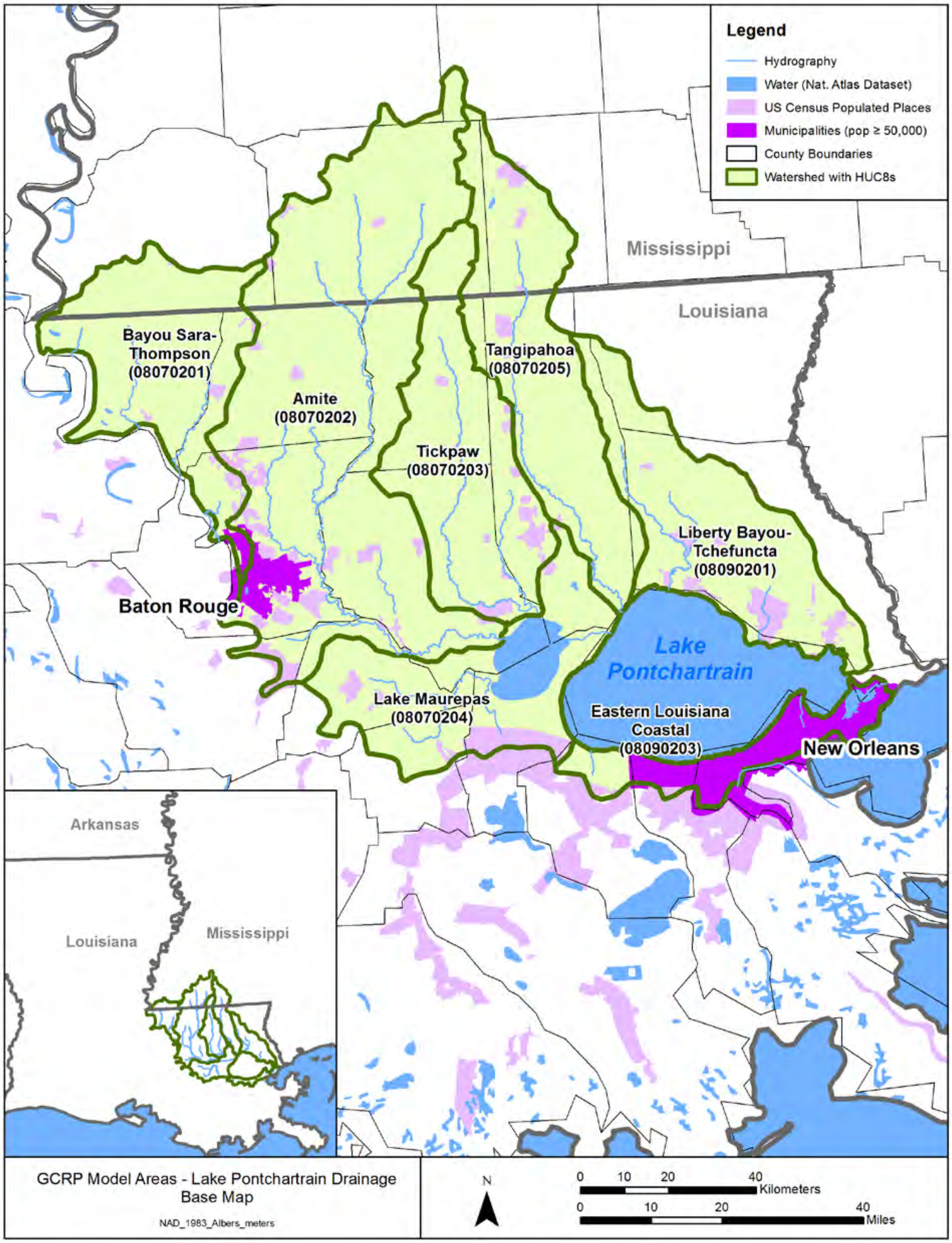


Figure 1. Location of the Pontchartrain watershed

Soil Characteristics

Soils in the watershed, as described in STATSGO soil surveys, fall primarily into hydrologic soil groups (HSGs) C (moderately low infiltration capacity, 58%) and D (low infiltration capacity, 31%). SWAT uses information drawn directly from the soils data layer to populate the model.

Land Use Representation

Land use/cover in the watershed is based on the 2001 National Land Cover Database (NLCD) coverage and is predominantly wetland (32 %) and forest (Figure 2). NLCD land cover classes were aggregated according to the scheme shown in Table 1 for representation in the 20 Watershed model. SWAT uses the built-in hydrologic response unit (HRU) overlay mechanism in the ArcSWAT interface. SWAT HRUs are formed from an intersection of land use and SSURGO major soils. The distribution of land use in the watershed is summarized in Table 2.

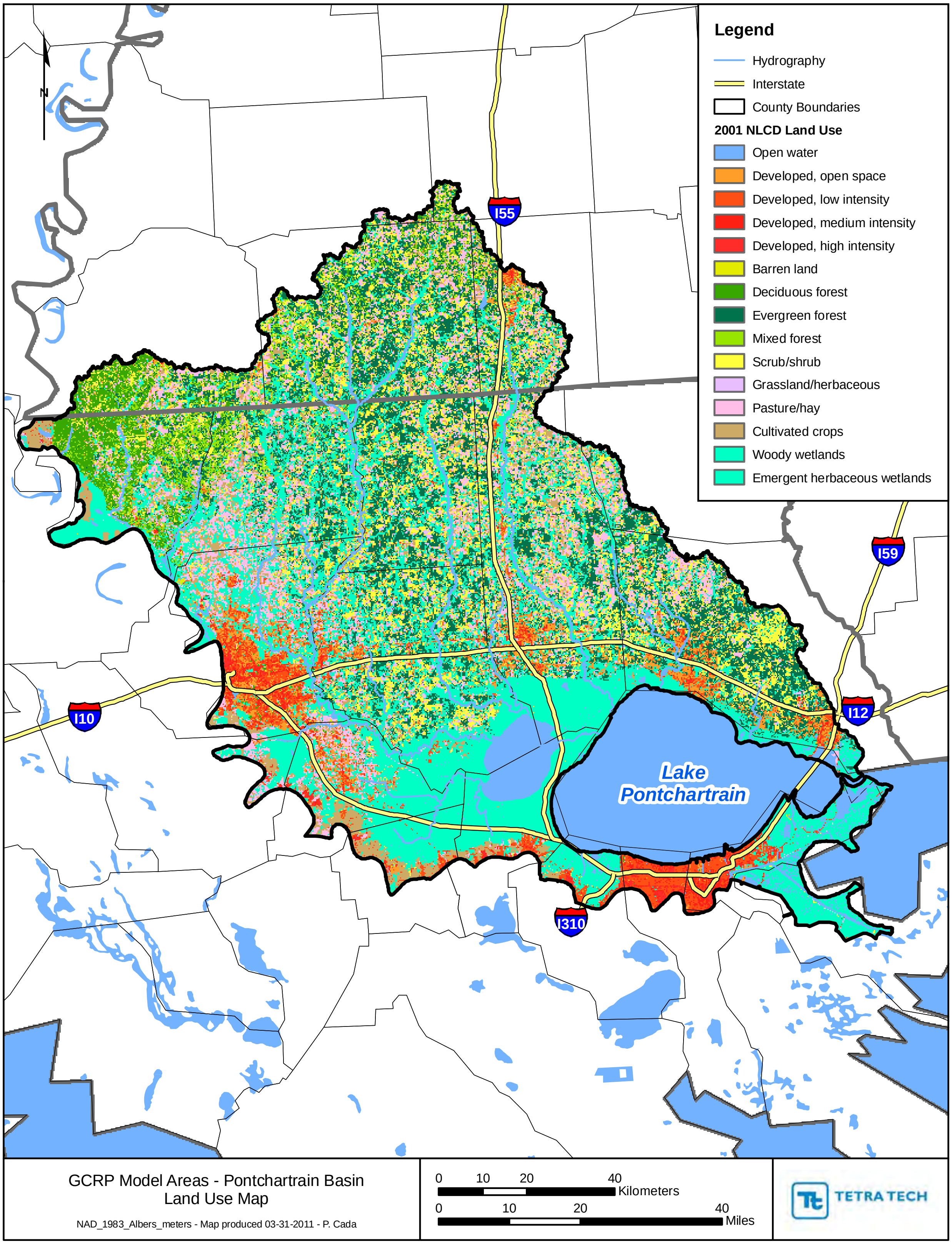


Figure 2. Land use in the Pontchartrain watershed

Table 1. Aggregation of NLCD land cover classes

NLCD Class	Comments	SWAT class
11 Water	Water surface area usually accounted for as reach area	WATR
12 Perennial ice/snow		WATR
21 Developed open space		URLD
22 Dev. Low Intensity		URMD
23 Dev. Med. Intensity		URHD
24 Dev. High Intensity		UIDU
31 Barren Land		SWRN
41 Forest	Deciduous	FRSD
42 Forest	Evergreen	FRSE
43 Forest	Mixed	FRST
51-52 Shrubland		RNGB
71-74 Herbaceous Upland		RNGE
81 Pasture/Hay		HAY
82 Cultivated		AGRR
91-97 Wetland	Emergent & woody wetlands	WETF, WETL, WETN
98-99 Wetland	Aquatic bed wetlands (not emergent)	WATR

Table 2. Land use distribution for the Pontchartrain watershed (2001 NLCD) (mi^2)

HUC 8 watershed	Open water	Developed[a] Open space	Low density	Medium density	High density	Barren land	Forest	Shrubland/ Grassland	Pasture/ Hay	Cultivated	Wetland	Total
Liberty Bayou-Tchefuncta. Louisiana. **08090201**	7.9	28.0	10.7	6.0	3.3	4.2	285.4	77.6	72.9	45.7	153.1	**694.9**
Bayou Sara-Thompson. Louisiana, Mississippi. **08070201**	15.7	113.1	76.7	29.2	5.9	11.0	455.9	296.1	246.5	82.5	551.1	**1,883.8**
Amite. Louisiana, Mississippi. **08070202**	3.1	46.3	15.9	3.4	0.8	1.7	188.8	159.9	66.0	16.7	223.5	**726.0**
Tickpaw. Louisiana, Mississippi. **08070203**	100.3	22.1	41.7	7.0	4.7	0.6	8.7	11.8	30.5	59.8	425.8	**712.9**
Lake Maurepas. Louisiana. **08070204**	7.0	38.7	11.8	2.5	0.7	1.7	201.9	152.6	123.5	46.2	188.9	**775.5**
Tangipahoa. Louisiana, Mississippi. **08070205**	11.6	63.9	23.0	8.4	1.7	1.4	213.0	138.2	63.1	9.8	160.2	**694.3**
Eastern Louisiana Coastal. Louisiana. **08090203**	50.0	3.6	69.8	30.4	18.5	0.5	0.6	2.1	0.7	2.9	185.6	**364.7**
Total	**195.6**	**315.7**	**249.7**	**86.9**	**35.7**	**21.1**	**1,354.3**	**838.3**	**603.1**	**263.6**	**1,888.0**	**5,852.0**

[a]The percent imperviousness applied to each of the developed land uses is as follows: open space (7.53%), low density (32.91%), medium density (60.11%), and high density (88.08%).

Point Sources

There are numerous point source discharges in the watershed. Only the major dischargers, with a design or observed flow greater than 1 MGD are included in the simulation (Table 3). The major dischargers are represented at long-term average flows, without accounting for changes over time or seasonal variations.

Table 3. Major point source discharges in the Pontchartrain watershed

NPDES ID	Name	Design flow (MGD)	Observed flow (MGD) (1991-2006 average)
LA0000841	EXXON CORP-BATON ROUGE RESIN	2.00	0.18
LA0044695	PONCHATOULA, CITY OF	1.00	1.19
LA0002933	OCCIDENTAL CHEMICAL CORP. FKA	1.31	1.99
LA0003191	ENTERGY LOUISIANA,LLC- LITTLE	11.11	0.36
LA0004090	ETHYL CORP-BATON ROUGE	8.68	1.79
LA0005401	EXXON CHEM CO-BATON ROUGE	11.03	5.98
LA0005479	EXXON CHEMICAL AMERICAS	3.90	2.61
LA0005851	ENTERGY GULF STATES, INC-WILLO	8.40	1.71
LA0046361	TAMINCO HIGHER AMINES, INC.	9.31	0.31
LA0045730	DENHAM SPRINGS, CITY OF	2.90	1.58
LA0004464	EXIDE CORP-SCHUYLKILL METALS	3.36	0.27
LA0050962	SHELL CHEMICAL LP-NORCO CYPRES	5.11	0.57
LA0003522	MOTIVA ENTERPRISES, LLC	6.41	11.37
LA0003280	AIR PROD & CHEM INC-NEW ORLEAN	1.17	0.64
LA0005355	EXXON CHEM CO-BATON ROUGE	15.23	1.20
LA0045446	COAST WATERWORKS-EDNE ISLES	0.96	0.85
LA0052256	LOCKHEED MARTIN CORPORATION	13.82	0.21
LA0041718	UOP LLC	4.21	1.70
LA0000914	LION COPOLYMER, LLC	2.70	2.90
LA0006149	FORMOSA PLASTICS-BATON ROUGE	44.92	5.19
LA0032328	HAMMOND CITY OF SOUTH POND	2.50	2.16
LA0038431	AMITE CITY, TOWN OF	0.80	1.20
LA0064092	ST JOHN THE BAPTIST PAR-SD #2L	3.30	0.66
LA0047180	SLIDELL, CITY OF	6.00	4.10
LA0068730	H2O SYSTEMS, INC- GREENLEAVES	4.92	0.52
LA0084336	COVINGTON, CITY OF	1.75	1.62

Most of these point sources have reasonably good monitoring for total suspended solids (TSS), but often lack detailed nutrient monitoring. The point sources without nutrient monitoring were represented in the model with typical nutrient concentrations by SIC code (Tetra Tech 1999).

Meteorological Data

The required meteorological time series for the 20 Watershed SWAT simulations are precipitation and air temperature. The 20 Watershed simulations do not include water temperature simulation and use a degree-day method for snowmelt. SWAT estimates Penman-Monteith potential evapotranspiration using a statistical weather generator for inputs other than temperature and precipitation. These meteorological time series are drawn from the BASINS4 Meteorological Database (USEPA 2008), which provides a consistent, quality-assured set of nationwide data with gaps filled and records disaggregated. Scenario application requires simulation over 30 years, so the available stations are those with a common 30-year period of record (or one that can be filled from an approximately co-located station) that covers the year 2001. A total of 22 precipitation stations were identified for use in the Minnesota River model with a common period of record of 10/1/1973-9/30/2005 (Table 4). Temperature records are sparser; where these are absent temperature is taken from nearby stations with an elevation correction.

Table 4. Precipitation stations for the Pontchartrain watershed model

COOP ID	Name	Latitude	Longitude	Temperature	Elevation (ft)
LA166686	NEW ROADS 5 NE	30.7268	-91.3671	X	14
MS229793	WOODVILLE 4 ESE	31.0929	-91.2327	X	122
LA160549	BATON ROUGE METRO AP	30.5372	-91.1469	X	20
MS225070	LIBERTY 5 W	31.1632	-90.8944	X	105
MS221578	CENTREVILLE	31.0943	-91.0686		113
LA161899	CLINTON 5 SE	30.8178	-90.9732	X	61
LA166911	OAKNOLIA 2 N	30.7531	-90.9938		46
LA163867	GREENWELL SPRINGS	30.5590	-90.9856		18
LA165620	LSU BEN HUR FARM	30.3644	-91.1671	X	6
LA164034	HAMMOND	30.4839	-90.4731	X	27
LA164859	KENTWOOD	30.9434	-90.5117		70
LA167304	PINE GROVE FIRE TOWER	30.7111	-90.7519		58
LA160205	AMITE	30.7094	-90.5250	X	52
LA162534	DONALDSONVILLE 4 SW	30.0717	-91.0275		9
LA167767	RESERVE	30.0565	-90.5802	X	5
MS225614	MCCOMB AIRPORT	31.1829	-90.4707	X	126
LA162151	COVINGTON 4 NNW	30.5273	-90.1114	X	12
LA168539	SLIDELL	30.2651	-89.7697	X	3
LA166660	NEW ORLEANS AP	29.9934	-90.2510	X	1
LA166666	NEW ORLEANS ALGIERS	29.9519	-90.0502	X	1
LA168108	ST BERNARD	29.8722	-89.8299	X	2
LA160021	ABITA SPRINGS FIRE TOWER	30.4397	-90.0464		9

Watershed Segmentation

The Pontchartrain watershed was divided into 37 subwatersheds for the purposes of modeling (Figure 3). The initial calibration watersheds correspond to the USGS gages shown on the figure. The model encompasses only complete watersheds that drain to Lake Pontchartrain or the Mississippi and does not require specification of any upstream boundary conditions for application.

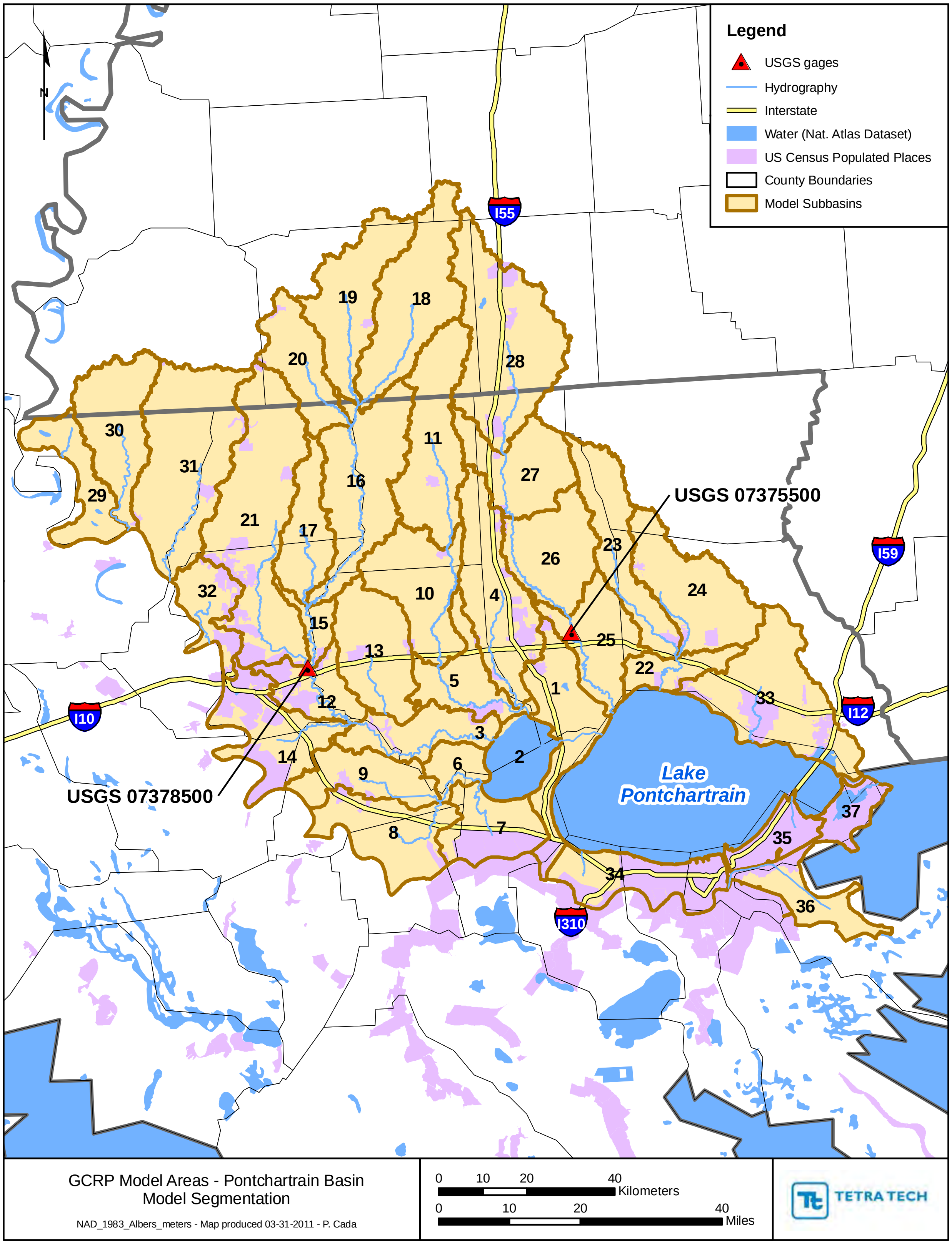


Figure 3. Model segmentation and USGS stations utilized for the Pontchartrain watershed

Calibration Data and Locations

Only limited flow gaging is available in the watershed. The specific site chosen for initial calibration was the Amite River near Denham Springs (USGS 07378500). The Amite watershed was selected because there is a good set of flow and water quality data available and the watershed lacks major point sources and impoundments. Calibration and validation was ultimately pursued at several locations (Table 5). Parameters derived on the Amite were not fully transferable to other portions of the watershed, and additional refinements to the calibration were conducted at the other gage locations.

Table 5. Calibration and validation locations in the Pontchartrain watershed

Station name	USGS ID	Drainage area (mi^2)	Hydrology calibration	Water quality calibration
Amite River near Denham Springs, LA	07378500	1,280	X	X
Tangipahoa River at Robert, LA	07375500	646	X	X
Tickfaw River at Holden, LA	07376000	247	X	

The model hydrology calibration period was set to Water Years 1995-2004 (within the 30-year period of record for modeling). Hydrologic validation was then performed on Water Years 1985-1994. Water quality calibration used available data for calendar years 1984-1999. Insufficient water quality data were available for a separate validation time period.

SWAT Modeling

Assumptions

The modeled portion of the Pontchartrain watershed does not contain major dams or impoundments. It does, however, contain large amounts of low lying land with swamp land cover and high water tables which may not be a good fit for SWAT's curve number approach to hydrology. The watershed is also characterized by the presence of many canals and distributary streams that complicate the flow of water. The USGS gages are located in more upland areas where these issues are of less importance, but the extrapolation of calibration parameters to downstream, swampy areas may be suspect.

Due to the flat topography, the boundary between land and water is often ill-defined in this watershed and is changing over time in response to storms and sea level rise. This modeling exercise does not address the changes in topography and hydrology that have occurred or will occur in the basin; instead, fixed conditions associated with the 2001 NLCD are assumed.

Hydrology Calibration

A partial spatial calibration approach was adopted for GCRP-SWAT modeling for the Pontchartrain watershed, with calibration at three USGS gages with long periods of record. The majority of the calibration effort was geared toward getting a closer match between simulated and observed flows at the outlet of calibration focus area.

The calibration focus area (Amite River) includes seven subwatersheds and is representative of the general land use characteristics of the more upstream portions of the watershed. The parameters were adjusted within the recommended ranges to obtain reasonable fit between the simulated and measured flows in terms of Nash-Sutcliffe modeling efficiency and the high flow and low flow components as well as the seasonal flows.

The average annual water balance of the entire Pontchartrain watershed predicted by the SWAT model over the 32-year simulation period is as follows:

```
PRECIP =   1658.2 MM
SNOW FALL =    8.87 MM
SNOW MELT =     8.74 MM
SUBLIMATION =     0.12 MM
SURFACE RUNOFF Q =   699.14 MM
LATERAL SOIL Q =    2.03 MM
TILE Q =     0.00 MM
GROUNDWATER (SHAL AQ) Q =   158.64 MM
REVAP (SHAL AQ => SOIL/PLANTS) =   29.16 MM
DEEP AQ RECHARGE =   181.07 MM
TOTAL AQ RECHARGE =  368.91 MM
TOTAL WATER YLD =   639.74 MM
PERCOLATION OUT OF SOIL =  155.42 MM
ET =    790.9 MM
PET =   1522.1MM
TRANSMISSION LOSSES =   220.07 MM
```

Hydrologic calibration adjustments focused on the following parameters:

- CN2 (initial SCS runoff curve number for moisture condition II)
- ESCO (soil evaporation compensation factor)
- SURLAG (surface runoff lag coefficient)

- SOL_AWC (available water capacity of the soil layer, mm water/mm of soil)
- ALPHA_BF (baseflow alpha factor, days)
- GW_DELAY (groundwater delay time, days)
- GWQMIN (threshold depth of water in the shallow aquifer required for return flow to occur, mm)
- GW_REVAP (groundwater "revap" coefficient)
- CH_N1 (Manning's "n" value for tributary channels)
- CH_N2 (Manning's "n" value for main channels)
- CH_K1 (Effective hydraulic conductivity in tributary channel alluvium)
- CH_K2 (Effective hydraulic conductivity in main channel alluvium)
- SFTMP (Snowfall temperature)
- SMTMP (Snowmelt base temperature)
- SMFMX (Maximum melt rate for snow during the year)
- SMFMN (Minimum melt rate for snow during the year)

The same general area was modeled with SWAT by Wu and Xu (2006). While the 20 Watershed model did not adopt parameter values directly from this paper, the results and quality of model fit are generally similar.

Calibration was performed for the period of water year 1995 – 2003. Results for the Amite River are summarized in the following figures and table (Figure 4, Figure 5, Figure 6, Figure 7, and Table 6). The overall quality of fit is good to excellent.

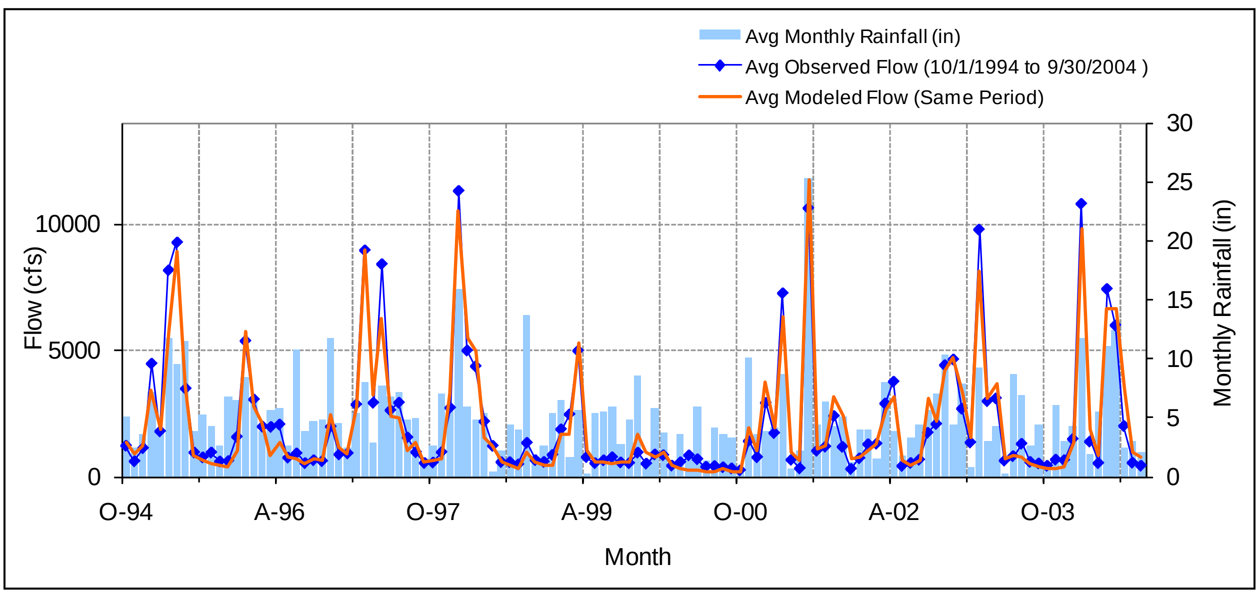


Figure 4. Mean monthly flow at USGS 07378500 Amite River near Denham Springs, LA – calibration period

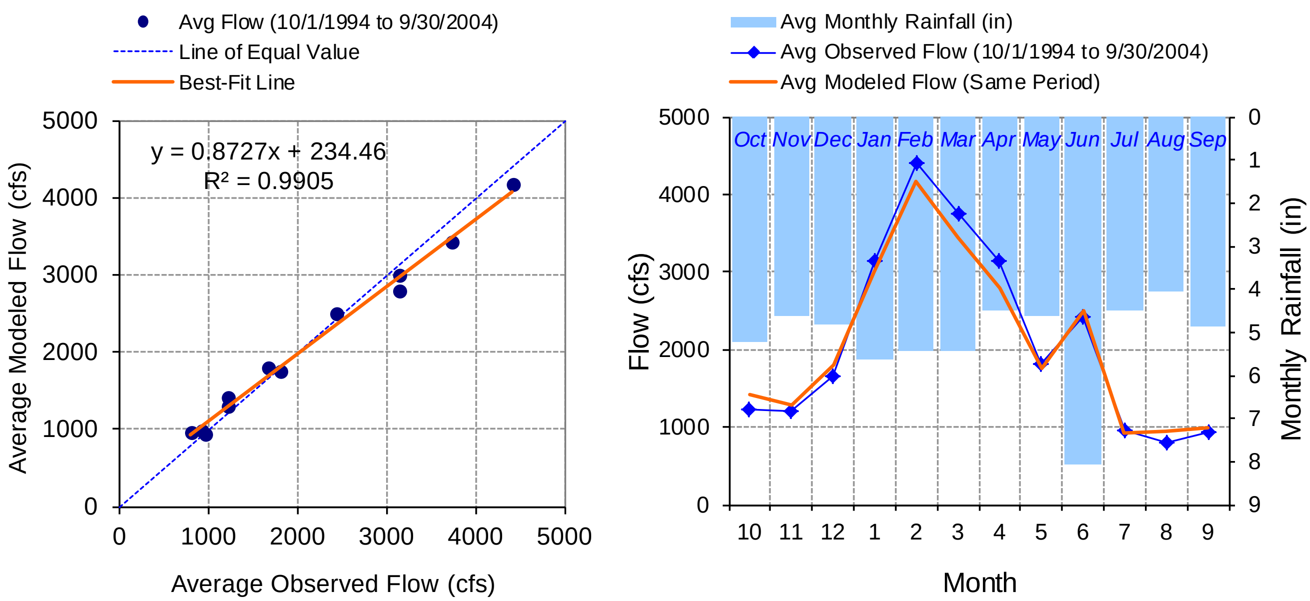


Figure 5. Seasonal regression and temporal aggregate at USGS 07378500 Amite River near Denham Springs, LA - calibration period

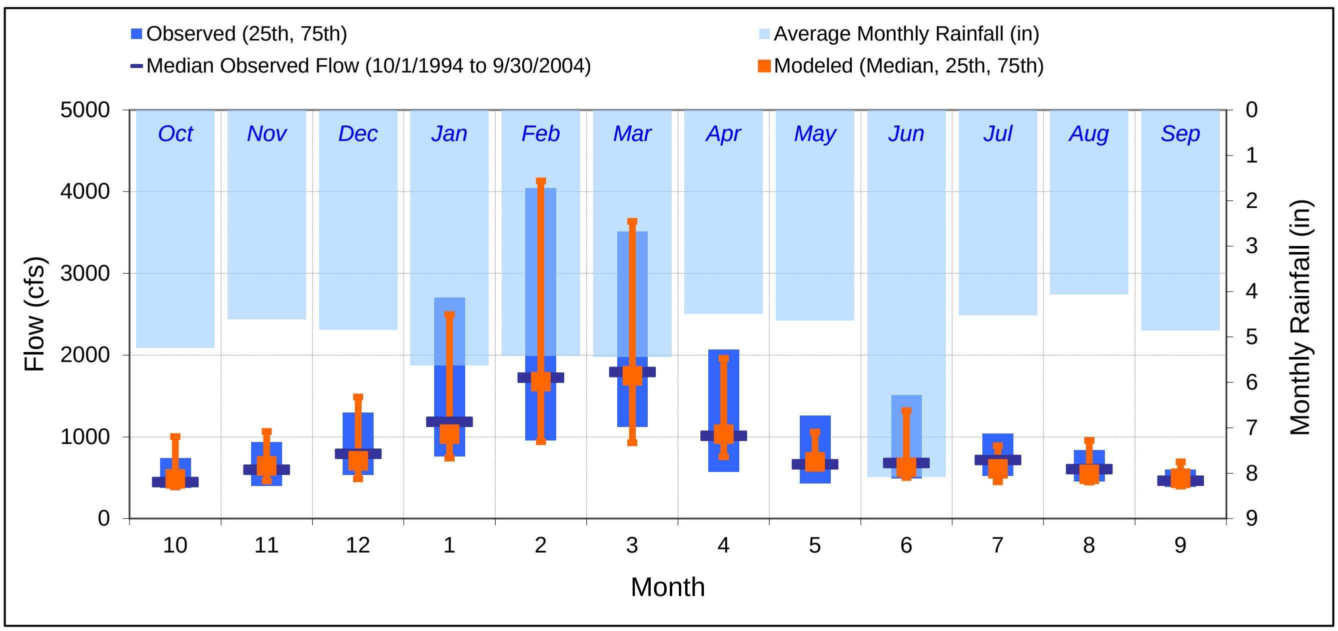


Figure 6. Seasonal medians and ranges at USGS 07378500 Amite River near Denham Springs, LA – calibration period

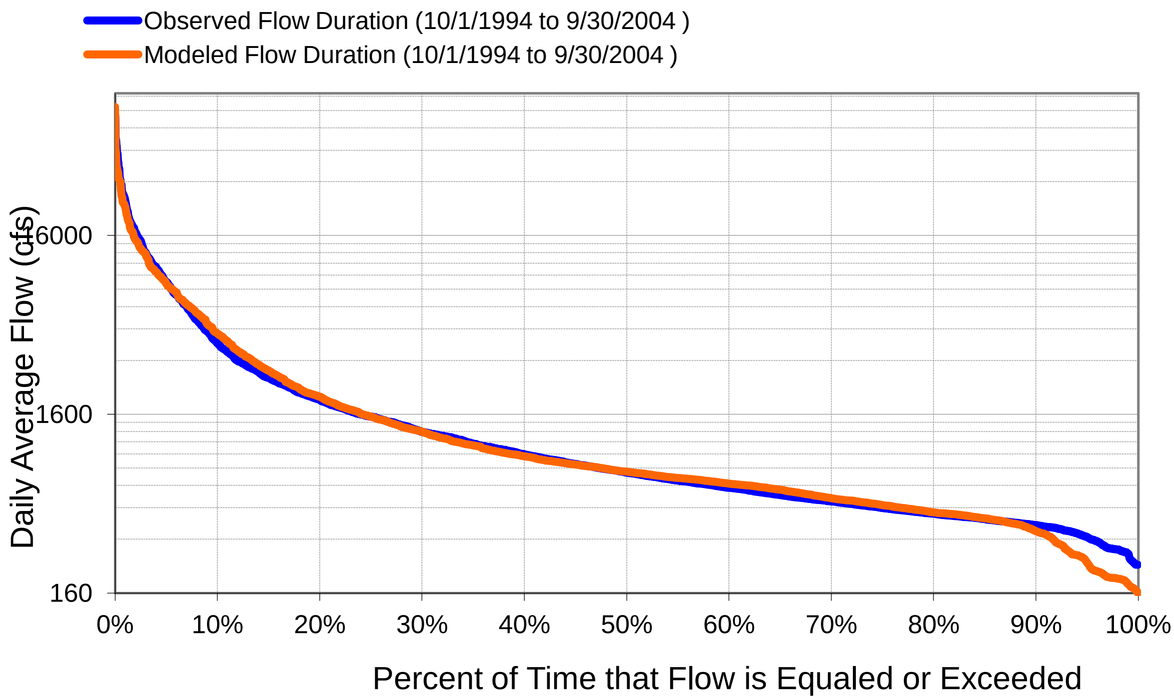


Figure 7. Flow exceedance at USGS 07378500 Amite River near Denham Springs, LA - calibration period

Figure 8. Summary statistics at USGS 07378500 Amite River near Denham Springs, LA - calibration period

SWAT Simulated Flow		Observed Flow Gage	
REACH OUTFLOW FROM OUTLET(S) 15, 21 10-Year Analysis Period: 10/1/1994 - 9/30/2004 Flow volumes are (inches/year) for upstream drainage area		USGS 07378500 Amite River near Denham Springs, LA Hydrologic Unit Code: 8070202 Latitude: 30.464079 Longitude: -90.99038 Drainage Area (sq-mi): 1280	
Total Simulated In-stream Flow:	**21.98**	Total Observed In-stream Flow:	**22.34**
Total of simulated highest 10% flows:	**12.53**	Total of Observed highest 10% flows:	**13.16**
Total of Simulated lowest 50% flows:	**2.62**	Total of Observed Lowest 50% flows:	**2.62**
Simulated Summer Flow Volume (months 7-9):	**2.57**	Observed Summer Flow Volume (7-9):	**2.39**
Simulated Fall Flow Volume (months 10-12):	**4.02**	Observed Fall Flow Volume (10-12):	**3.65**
Simulated Winter Flow Volume (months 1-3):	**9.21**	Observed Winter Flow Volume (1-3):	**9.82**
Simulated Spring Flow Volume (months 4-6):	**6.19**	Observed Spring Flow Volume (4-6):	**6.49**
Total Simulated Storm Volume:	**12.81**	Total Observed Storm Volume:	**13.76**
Simulated Summer Storm Volume (7-9):	**0.97**	Observed Summer Storm Volume (7-9):	**0.93**

Errors (Simulated-Observed)	*Error Statistics*	*Recommended Criteria*		
Error in total volume:	-1.61	10		
Error in 50% lowest flows:	0.29	10		
Error in 10% highest flows:	-4.83	15		
Seasonal volume error - Summer:	7.32	30		
Seasonal volume error - Fall:	10.13	30		
Seasonal volume error - Winter:	-6.17	30		
Seasonal volume error - Spring:	-4.61	30		
Error in storm volumes:	-6.92	20		
Error in summer storm volumes:	4.05	50		
Nash-Sutcliffe Coefficient of Efficiency, E:	0.789	Model accuracy increases		
Baseline adjusted coefficient (Garrick), E':	0.619	as E or E' approaches 1.0		
Monthly NSE	0.950			

>> Clear

Hydrology Validation

Hydrology validation for the Amite River was performed for the period 10/1/1984 through 9/30/1994. Results are presented in Figure 9, Figure 10, Figure 11, Figure 12, and Table 6. The validation also achieves a high quality of fit, but does overpredict the average flows in summer. This is apparently associated with several tropical storms.

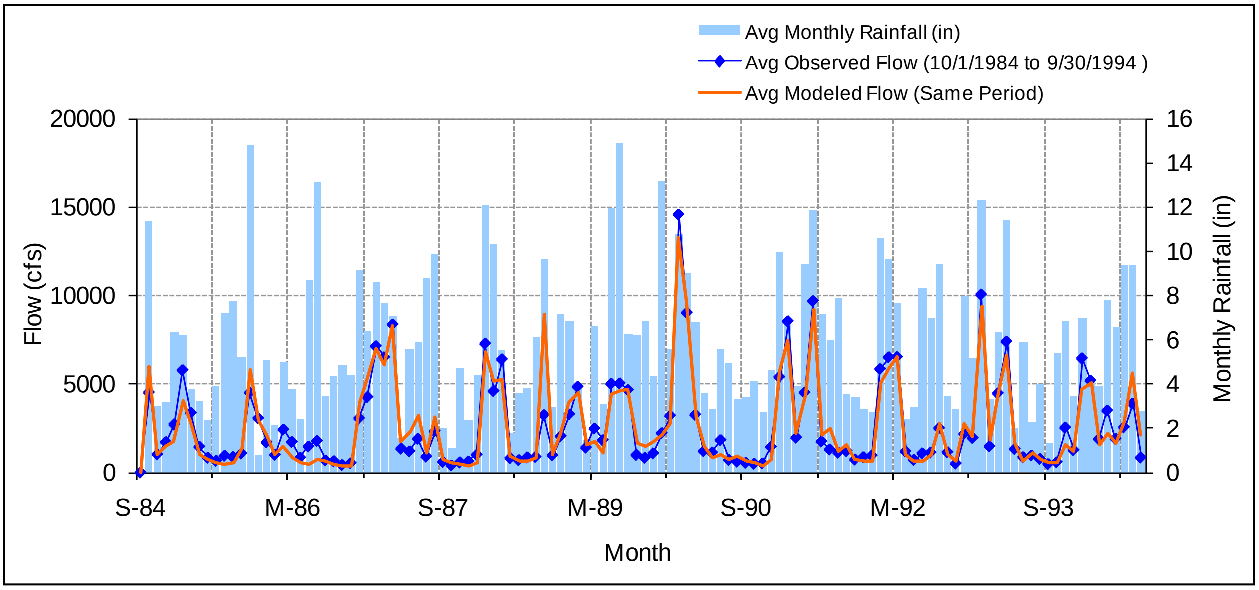
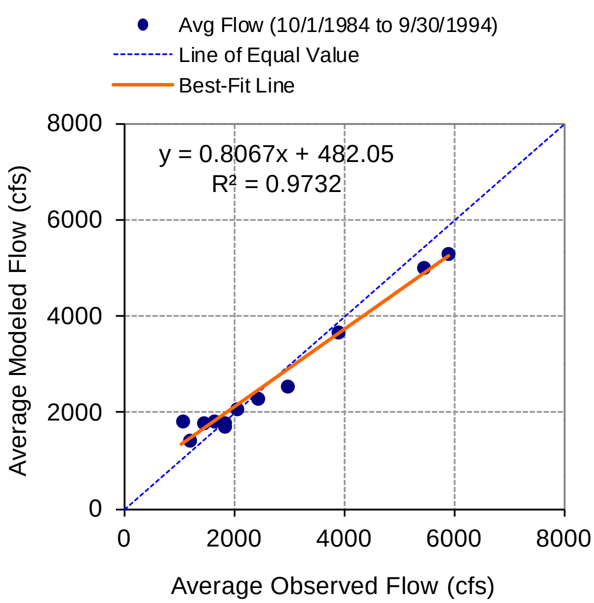


Figure 9. Mean monthly flow at USGS 07378500 Amite River near Denham Springs, LA – validation period



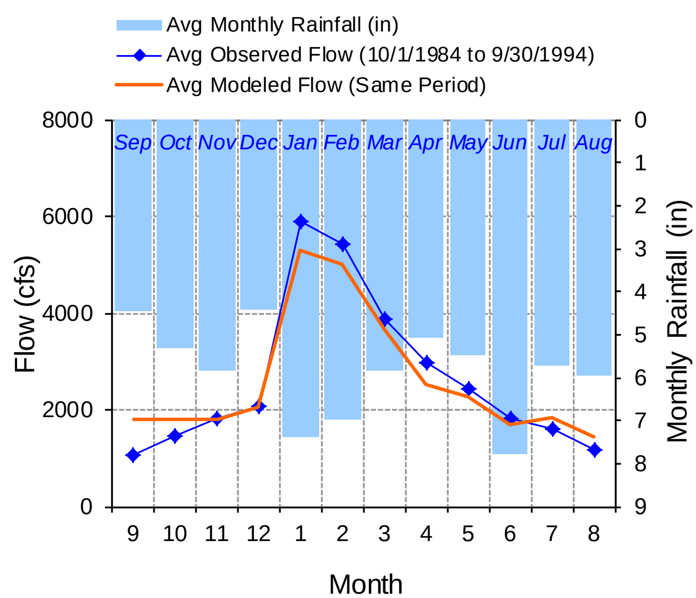


Figure 10. Seasonal regression and temporal aggregate at USGS 07378500 Amite River near Denham Springs, LA - validation period

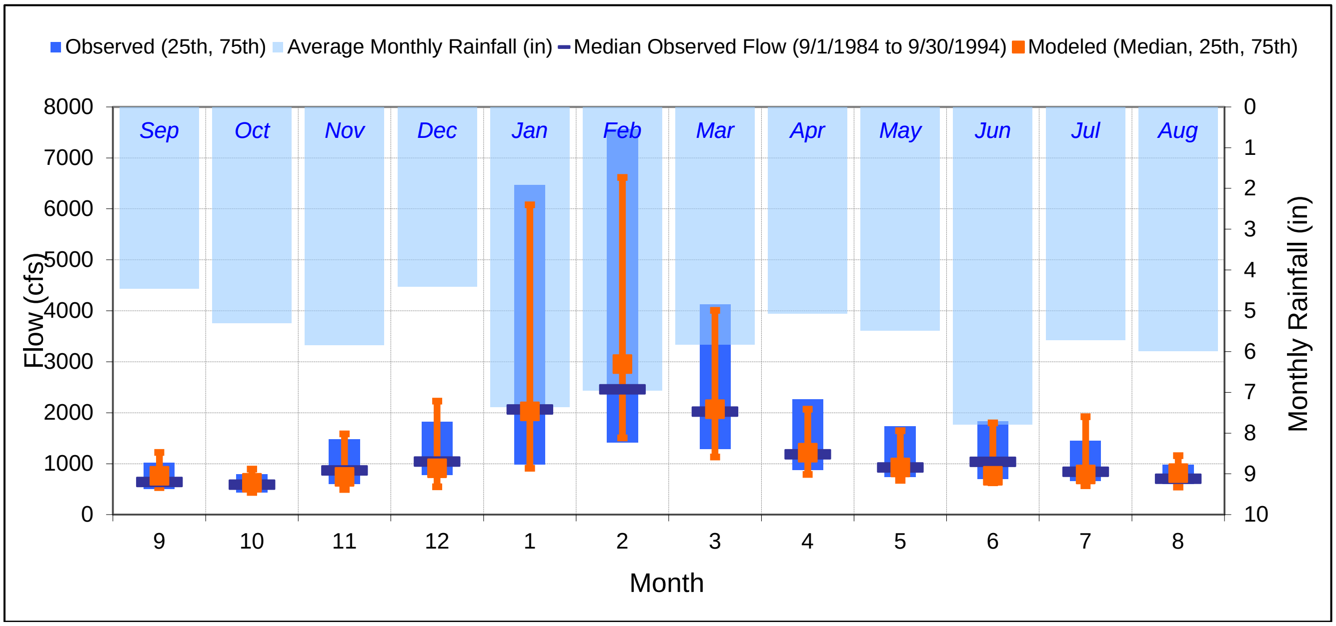


Figure 11. Seasonal medians and ranges at USGS 07378500 Amite River near Denham Springs, LA – validation period

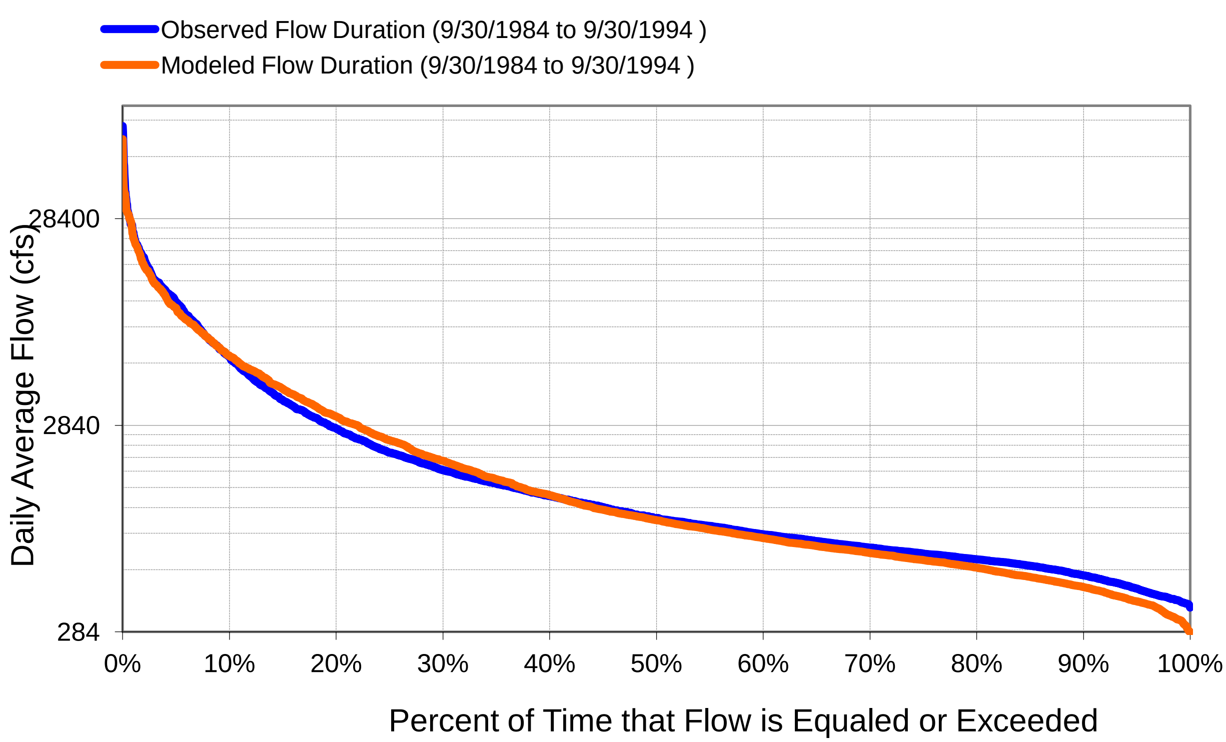


Figure 12. Flow exceedance at USGS 07378500 Amite River near Denham Springs, LA - validation period

Table 6. Summary statistics at USGS 07378500 Amite River near Denham Springs, LA - validation period

SWAT Simulated Flow		Observed Flow Gage	
REACH OUTFLOW FROM OUTLET(S) 15, 21 10-Year Analysis Period: 10/1/1984 - 9/30/1994 Flow volumes are (inches/year) for upstream drainage area		USGS 07378500 Amite River near Denham Springs, LA Hydrologic Unit Code: 8070202 Latitude: 30.464079 Longitude: -90.99038 Drainage Area (sq-mi): 1280	
Total Simulated In-stream Flow:	**27.52**	Total Observed In-stream Flow:	**27.78**
Total of simulated highest 10% flows:	**14.04**	Total of Observed highest 10% flows:	**14.86**
Total of Simulated lowest 50% flows:	**3.38**	Total of Observed Lowest 50% flows:	**3.65**
Simulated Summer Flow Volume (months 7-9):	**4.53**	Observed Summer Flow Volume (7-9):	**3.43**
Simulated Fall Flow Volume (months 10-12):	**5.04**	Observed Fall Flow Volume (10-12):	**4.74**
Simulated Winter Flow Volume (months 1-3):	**12.19**	Observed Winter Flow Volume (1-3):	**13.24**
Simulated Spring Flow Volume (months 4-6):	**5.76**	Observed Spring Flow Volume (4-6):	**6.37**
Total Simulated Storm Volume:	**15.89**	Total Observed Storm Volume:	**16.60**
Simulated Summer Storm Volume (7-9):	**2.25**	Observed Summer Storm Volume (7-9):	**1.57**
Errors (Simulated-Observed)	*Error Statistics*	*Recommended Criteria*	
Error in total volume:	-0.93	10	
Error in 50% lowest flows:	-7.29	10	
Error in 10% highest flows:	-5.54	15	
Seasonal volume error - Summer:	**32.16**	**30**	
Seasonal volume error - Fall:	6.20	30	
Seasonal volume error - Winter:	-7.94	30	
Seasonal volume error - Spring:	-9.49	30	
Error in storm volumes:	-4.31	20	
Error in summer storm volumes:	43.74	50	
Nash-Sutcliffe Coefficient of Efficiency, E:	0.693	Model accuracy increases	
Baseline adjusted coefficient (Garrick), E':	0.567	as E or E' approaches 1.0	
Monthly NSE	0.899		

Hydrology Results for Larger Watershed

In addition to Amite River, calibration and validation was pursued at a two other gages in the watershed. Similar to the Amite River, these are in upland areas; there is no gaging of a single pour point of the watershed. Calibration results were acceptable at all gages (Table 7).

Results of the validation exercise are summarized in Table 8. Problems similar to those experienced on the Amite River gage were seen at all the tributary gages, with overprediction of seasonal flows in summer. However, as noted above, this is likely due to the use of land use and model parameters that are more reflective of current conditions and is not believed to present a bar to application of the model.

Table 7. Summary statistics (percent error): all stations - calibration period

Station	07378500 Amite River near Denham Springs, LA	07375500 Tangipahoa River at Robert, LA	07376000 Tickfaw River at Holden, LA
Error in total volume:	-1.61	2.89	-0.81
Error in 50% lowest flows:	0.29	-8.14	-9.73
Error in 10% highest flows:	-4.83	-5.50	-6.86
Seasonal volume error - Summer:	7.32	20.46	33.29
Seasonal volume error - Fall:	10.13	4.34	13.05
Seasonal volume error - Winter:	-6.17	-0.45	-9.84
Seasonal volume error - Spring:	-4.61	-4.40	-10.75
Error in storm volumes:	-6.92	-12.99	4.38
Error in summer storm volumes:	4.05	18.66	82.23
Nash-Sutcliffe Coefficient of Efficiency, E:	0.789	0.644	0.481
Monthly Nash-Sutcliffe Coefficient	0.950	0.900	0.778

Table 8. Summary statistics: all stations - validation period

Station	07378500 Amite River near Denham Springs, LA	07375500 Tangipahoa River at Robert, LA	07376000 Tickfaw River at Holden, LA
Error in total volume:	-0.93	4.45	-6.39
Error in 50% lowest flows:	-7.29	-4.83	-1.25
Error in 10% highest flows:	-5.54	-4.59	-13.26
Seasonal volume error - Summer:	32.16	20.94	24.25
Seasonal volume error - Fall:	6.20	15.67	1.25
Seasonal volume error - Winter:	-7.94	0.24	-15.19
Seasonal volume error - Spring:	-9.49	-7.16	-8.84
Error in storm volumes:	-4.31	-11.28	-2.76
Error in summer storm volumes:	43.74	23.91	55.01
Nash-Sutcliffe Coefficient of Efficiency, E:	0.693	0.564	0.589
Monthly Nash-Sutcliffe Coefficient	0.899	0.850	0.840

Water Quality Calibration and Validation

Initial calibration of water quality was done on the Amite River (USGS 07378500), using data from 1984 – 1994. Insufficient data were available to support a separate validation period. Instead, the performance of the calibration parameters was checked against limited additional data collected from the Tangipahoa River.

Calibration adjustments for sediment focused on the following parameters:

- SPCON (linear parameter for estimating maximum amount of sediment that can be re-entrained during channel sediment routing)
- SPEXP (exponential parameter for estimating maximum amount of sediment that can be re-entrained during channel sediment routing)
- CH_COV (channel cover factor)
- CH_EROD (channel erodibility factor)
- USLE_P (USLE support practice factor)

Simulated and estimated sediment loads at the Amite River station are shown in Figure 13 and statistics for the two stations are provided in Table 9. The key statistic in Table 10 is the relative percent error, which shows the error in the prediction of monthly load normalized to the estimated load. Table 10 also shows the relative average absolute error, which is the average of the relative magnitude of errors in individual monthly load predictions. This number is inflated by outlier months in which the simulated and estimated loads differ by large amounts (which may be as easily due to uncertainty in the estimated load due to limited data as to problems with the model) and the third statistic, the relative median absolute error, is likely more relevant and shows better agreement. Overall, the model appears to somewhat underpredict TSS due to the estimated loads associated with major storm events.

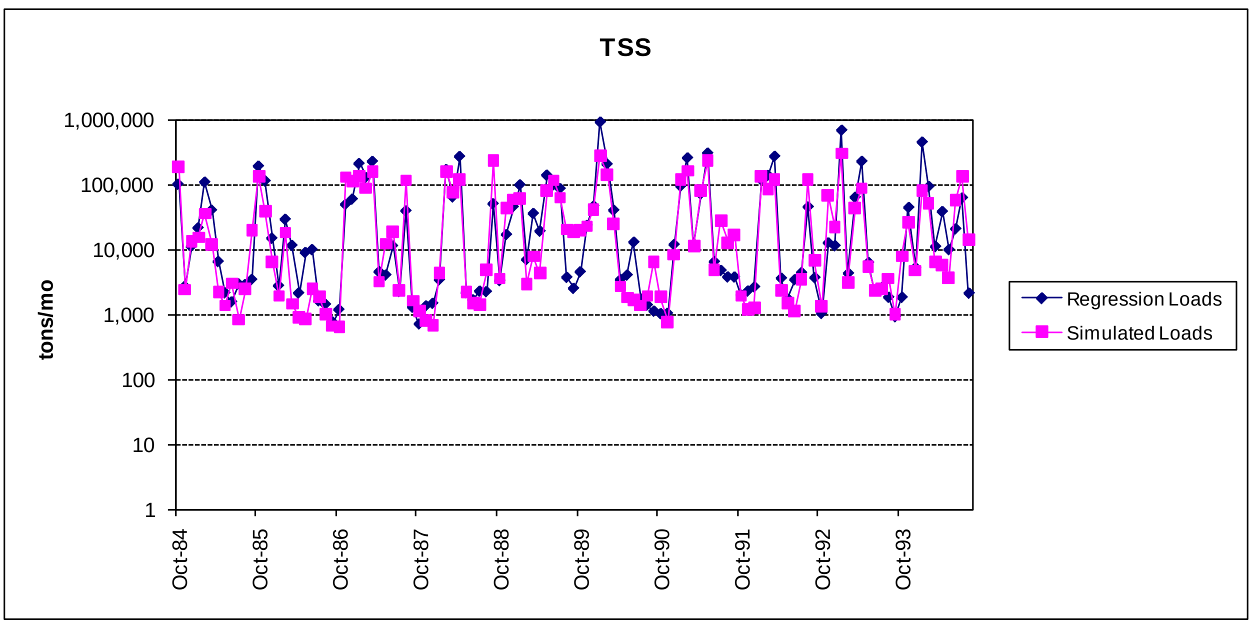


Figure 13. Fit for monthly load of TSS at USGS 07378500 Amite River near Denham Springs, LA

Table 9. Model fit statistics (observed minus predicted) for monthly sediment loads using stratified regression

Statistic	07378500 Amite River near Denham Springs, LA (1984-1994)	07375500 Tangipahoa River at Robert, LA (1984-1999)
Relative Percent Error	9.2%	9.0%
Relative Average Absolute Error	36%	65%
Relative Median Absolute Error	9.1%	14.3%

Calibration adjustments for total phosphorus and total nitrogen focused on the following parameters:

- RHOQ (algal respiration rate at 20^{O} C)
- PHOSKD (phosphorus soil partitioning coefficient)
- PSP (phosphorus availability index)
- RS1 (Local algal settlement rate in the reach at 20^{O} C)
- AL1 (Fraction of algal biomass that is nitrogen)
- AL2 (Fraction of algal biomass that is phosphorus)
- MUMAX (Rate of oxygen uptake per unit NO_2-N oxidation at 20^{O} C)
- RHOQ (Algal respiration rate at 20^{O} C)
- RS2 (benthic source rate for dissolved P in the reach at 20^{O} C)
- RS3 (Benthic source rate for NH_4-N in the reach at 20^{O} C)
- RS5 (organic P settling rate in the reach at 20^{O} C)
- BC4 (rate constant for mineralization of organic P to dissolved P in the reach at 20^{O} C)
- RS4 (rate coefficient for organic N settling in the reach at 20^{O} C)
- CH_ONCO (Channel organic nitrogen concentration)
- CH_OPCO (Channel organic phosphorus concentration)
- SDNCO (Denitrification threshold water content)
- CDN (Denitrification exponential rate constant)

Results for the phosphorus simulation are shown in Figure 14 and Table 10. Results for the nitrogen simulation are shown in Figure 15 and Table 11. The model fit is generally reasonable for nutrients at both stations.

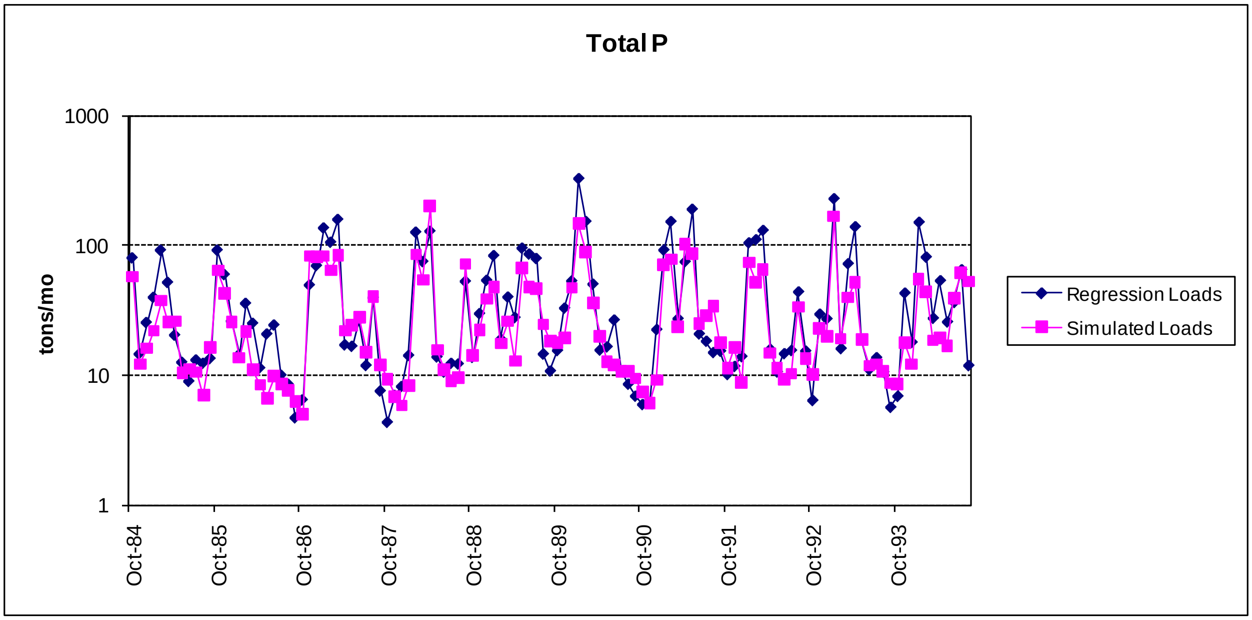


Figure 14. Fit for monthly load of total phosphorus at USGS 07378500 Amite River near Denham Springs, LA

Table 10. Model fit statistics (observed minus predicted) for monthly phosphorus loads using stratified regression

Statistic	07378500 Amite River near Denham Springs, LA (1984-1994)	07375500 Tangipahoa River at Robert, LA (1984-1999)
Relative Percent Error	2.4%	-31.2
Average Absolute Error	46%	84%
Median Absolute Error	13.0%	9.3%

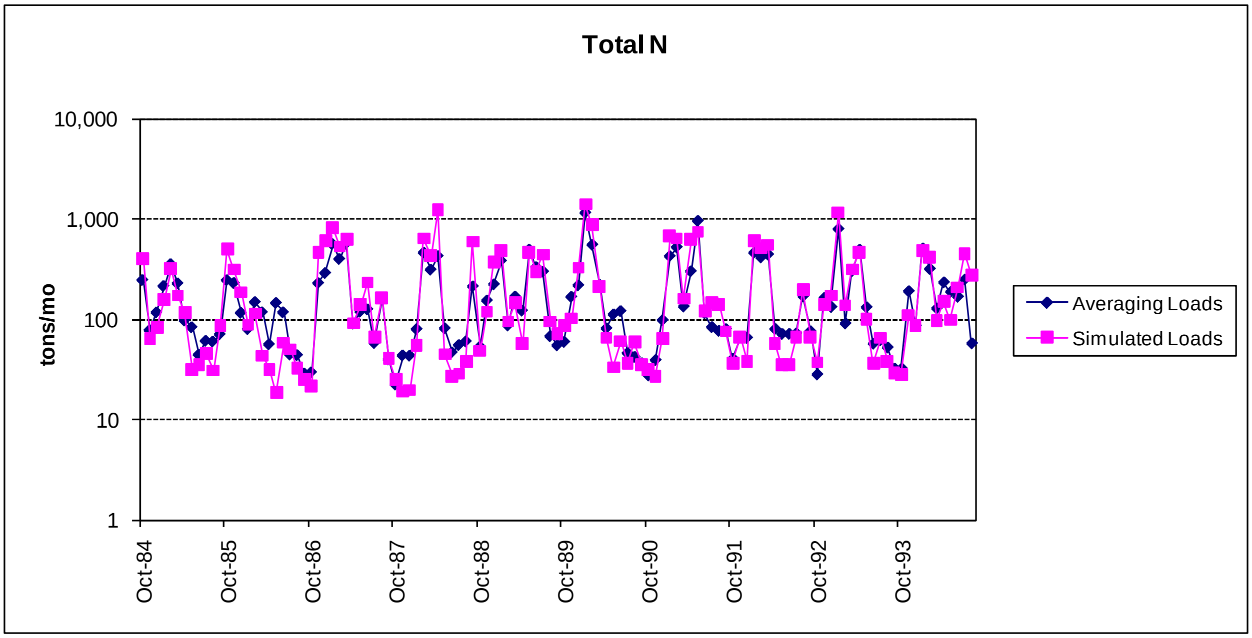


Figure 15. Fit for monthly load of total nitrogen at USGS 07378500 Amite River near Denham Springs, LA

Table 11. Model fit statistics (observed minus predicted) for monthly total nitrogen loads using averaging estimator

Statistic	07378500 Amite River near Denham Springs, LA (1984-1994)	07375500 Tangipahoa River at Robert, LA (1984-1999)
Relative Percent Error	-8.9%	-1.3%
Average Absolute Error	54%	65%
Median Absolute Error	24.4%	28.7%

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Appendix J
Model Configuration, Calibration and Validation

Basin: Tar and Neuse Rivers (TarNeu)

Contents

Tables

Figures

Watershed Background

The Tar and Neuse River basins, within the Albemarle-Pamlico NAWQA study area, were selected as one of the 15 non-pilot application watersheds for the 20 Watershed study. Watershed modeling for the non-pilot areas is accomplished using the SWAT model only, and model calibration and validation results are presented in abbreviated form.

The Tar and Neuse River drainages are located entirely within North Carolina (Figure 1) and drain to two important estuaries (Pamlico and Neuse Estuaries) that have been impacted by excess nutrient loads. The watershed covers an area of 9,972 mi^2 in 8 HUC8s, all within HUC 0302. The watershed is divided between the Piedmont, and Coastal Plain physiographic provinces. Land-surface elevations range from about 885 feet above sea level in the Piedmont northwest of Durham to sea level in the eastern Coastal Plain (McMahon and Lloyd, 1995). Streams descend through the Piedmont province to the Coastal Plain Province (Spruill et al. 1998).

The watershed as a whole is dominated by forested (34 percent) and agricultural crop and pasture land (29 percent). Agricultural land in the study area is used primarily for growing crops (soybeans, corn, wheat, peanuts, tobacco, and cotton) and raising livestock (chickens, turkeys, hogs, and cattle.)

Less than 10 percent of the watershed consists of developed land, primarily in and around the cities of Raleigh, Durham, and Greenville, NC are prominent in the eastern third of the watershed and occupy 13 percent of the study area.

Average annual temperatures in the watershed range from about 58 °F in the western headwaters to slightly more than 62° F along Pamlico Sound in the eastern part of the Coastal Plain. Average annual precipitation ranges from about 44 to about 55 inches per year, but can be much greater in years impacted by tropical storms. The highest average monthly streamflow typically occurs during the months that include the non-growing season when temperatures are low and evapotranspiration rates are low. The lowest average monthly streamflow occurs during the growing season when evapotranspiration rates are high. Groundwater is a significant component of the total water discharged to the Albemarle-Pamlico estuarine system.

The greatest uses of surface water in the Tar and Neuse River drainage basin are for public water supplies and thermoelectric power. Domestic groundwater use and agricultural surface water use are comparable in size, and both are slightly less than groundwater use for public water supplies. Surface water use is highest in areas with large urban populations served by surface water diversions for public water supplies (e.g., Neuse River basin) and in areas with large commercial, industrial, or mining water users (e.g., the Tar-Pamlico River basin). Groundwater use is generally highest in the Coastal Plain.

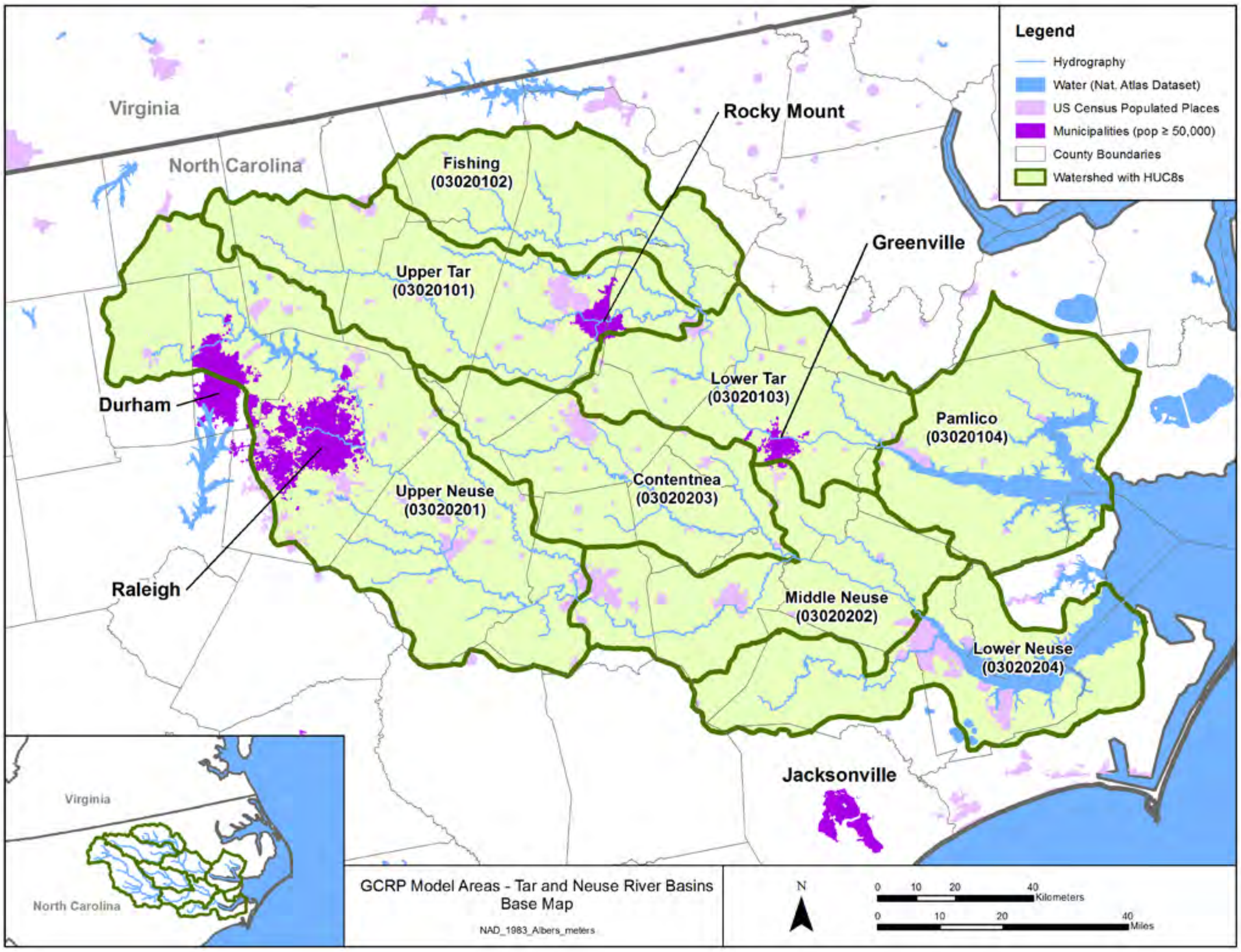

Figure 1. Location of the Tar and Neuse River basins.

Soil Characteristics

Soils in the watershed are described in STATSGO soil surveys. SWAT uses information drawn directly from the soils data layer to populate the model.

Land Use Representation

Land use/cover in the watershed is based on the 2001 National Land Cover Database (NLCD) coverage (Figure 2). NLCD land cover classes were aggregated according to the scheme shown in Table 1 for representation in the 20 Watershed model. SWAT uses the built-in hydrologic response unit (HRU) overlay mechanism in the ArcSWAT interface. SWAT HRUs are formed from an intersection of land use and SSURGO major soils. The distribution of land use in the watershed is summarized in Table 2.

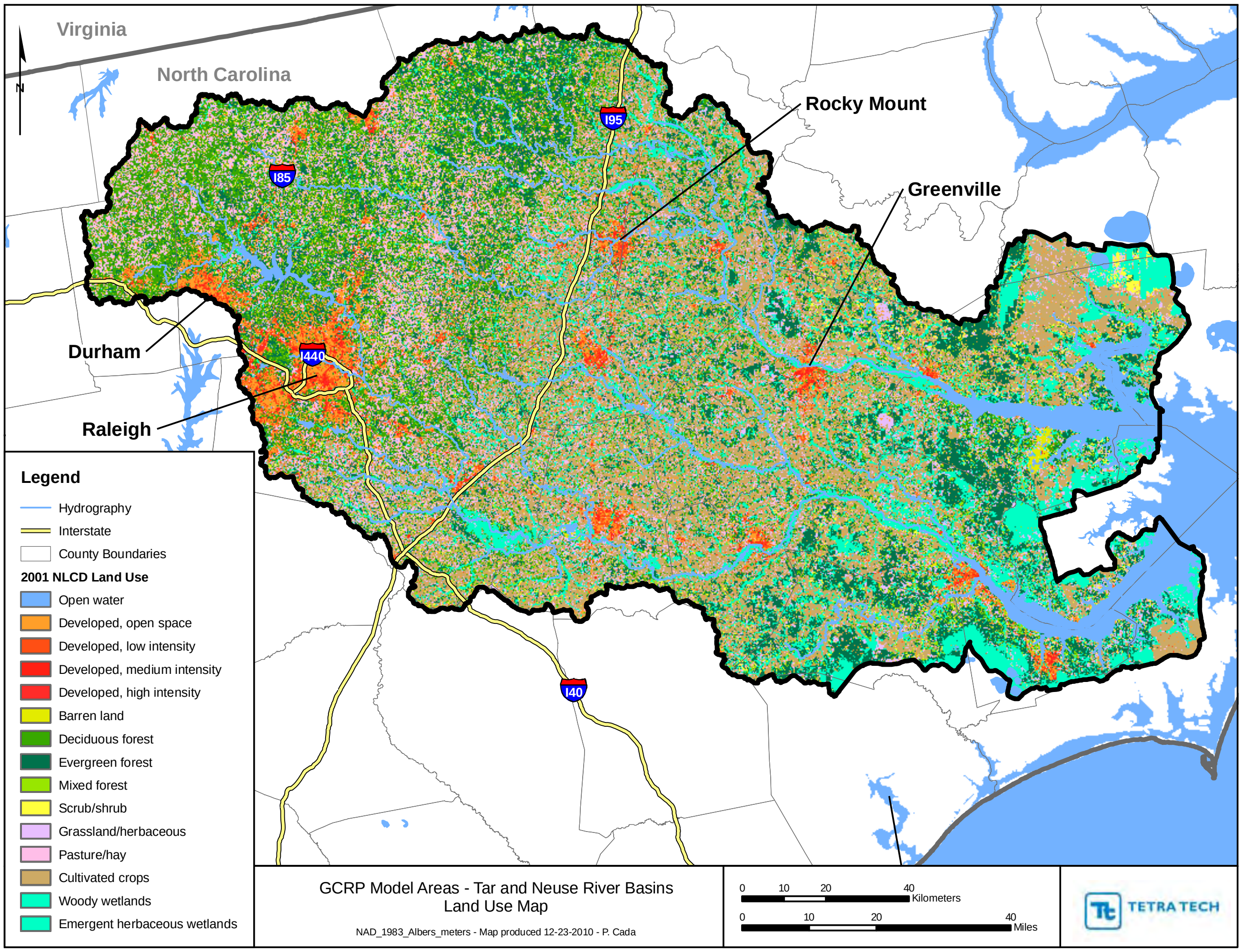

Figure 2. Land use in the Tar and Neuse River basin.

Table 1. Aggregation of NLCD land cover classes

NLCD class	Comments	SWAT class
11 Water	Water surface area usually accounted for as reach area	WATR
12 Perennial ice/snow		WATR
21 Developed open space		URLD
22 Dev. Low Intensity		URMD
23 Dev. Med. Intensity		URHD
24 Dev. High Intensity		UIDU
31 Barren Land		SWRN
41 Forest	Deciduous	FRSD
42 Forest	Evergreen	FRSE
43 Forest	Mixed	FRST
51-52 Shrubland		RNGB

NLCD class	Comments	SWAT class
71-74 Herbaceous Upland		RNGE
81 Pasture/Hay		HAY
82 Cultivated		AGRR
91-97 Wetland	Emergent & woody wetlands	WETF, WETL, WETN
98-99 Wetland	Aquatic bed wetlands (not emergent)	WATR

Table 2. Land use distribution for the Albemarle-Pamlico basin (2001 NLCD) (mi^2)

HUC 8 watershed	Open water	Developed[a] Open space	Low density	Medium density	High density	Barren land	Forest	Shrubland	Pasture/Hay	Cultivated	Wetland	Total
Upper Tar 03020101	11.6	84.5	22.8	7.9	2.8	2.5	599.6	115.3	212.9	157.1	87.7	1,304.8
Fishing 03020102	2.7	42.1	4.6	0.6	0.1	1.8	448.3	76.1	75.7	153.7	88.4	894.0
Lower Tar 03020103	6.5	53.0	17.3	6.4	2.0	0.4	257.4	125.6	27.0	330.5	134.1	960.2
Pamlico 03020104	184.5	37.9	6.3	1.3	0.2	9.7	259.5	129.0	6.6	262.4	277.7	1,175.2
Upper Neuse 03020201	40.1	244.9	96.2	37.0	9.4	4.4	908.0	200.2	288.6	287.0	156.4	2,272.1
Middle Neuse 03020202	10.2	59.7	19.0	6.5	2.2	0.8	276.7	126.9	28.6	332.0	202.9	1,065.4
Contentnea 03020203	10.2	69.8	21.8	6.8	1.9	1.0	274.6	105.5	82.3	412.1	156.6	1,142.6
Lower Neuse 03020204	182.6	47.5	14.0	4.3	1.5	0.4	312.6	114.0	4.9	170.7	305.6	1,158.1
Total	448.3	639.4	201.9	70.7	20.3	21.0	3,336.6	992.6	726.4	2,105.4	1,409.6	9,972.4

[a]The percent imperviousness applied to each of the developed land uses is as follows: open space (7.17%), low density (30.90%), medium density (61.05%), and high density (87.31%).

Point Sources

There are numerous point source discharges in the watershed. Only the major dischargers, generally defined as those with a design flow greater than 1 MGD are included in the simulation (Table 3). The major dischargers are represented at long-term average flows, without accounting for changes over time or seasonal variations.

Table 3. Major point source discharges in the Tar and Neuse River basin

NPDES ID	Name	Design flow (MGD)	Observed flow (MGD) (1991-2006 average)
NC0001881	PHILLIPS PLATING COMPANY INC	0.10	0.02
NC0003191	WEYERHAEUSER N R CO NEW BERN C	32.00	19.74
NC0003255	PCS PHOSPHATE CO INC AURORA MI	NA	62.83
NC0003417	CP&L CO DBA PROG ENRG CAROLINA	1.40	2.38
NC0003760	E I DUPONT DE NEMOURS E I DUPO	3.60	1.58
NC0003816	US MCAS CHERRY PT MCALF ATLANT	3.50	1.99
NC0020231	LOUISBURG WWTP	1.37	0.79
NC0020389	BENSON WWTP	1.50	1.50
NC0020605	TARBORO WWTP	5.00	2.10
NC0020648	WASHINGTON WWTP	3.65	1.76
NC0020834	WARRENTON WWTP	2.00	0.36
NC0023841	DURHAM NORTH DURHAM WRF	20.00	5.90
NC0023906	WILSON WWTP	14.00	10.52
NC0023931	GREENVILLE UTIL COMMISSION GUC	17.50	9.08
NC0024236	KINSTON REG WTR RECLAMATION FA	11.85	1.73
NC0025054	OXFORD WWTP	3.50	1.30
NC0025348	NEW BERN WWTP	7.00	3.26
NC0025453	CLAYTON LITTLE CREEK WWTP	2.50	1.10
NC0026042	ROBERSONVILLE WWTP	1.80	1.22
NC0026433	HILLSBOROUGH WWTP	3.00	1.15
NC0029033	RALEIGH NEUSE RIVER WWTP	75.00	47.24
NC0029572	FARMVILLE WWTP	3.50	2.05
NC0030317	ROCKY MOUNT TAR RIVER REG WWTP	21.00	11.76
NC0030716	JOHNSTON CO DEPARTMENT OF PUBL	7.00	4.15
NC0030759	RALEIGH SMITH CREEK WWTP	2.40	0.87
NC0032077	CONTENTNEA METRO SWRG DIS CONT	2.85	1.49
NC0048879	CARY NORTH CARY WRF	12.00	2.45

NPDES ID	Name	Design flow (MGD)	Observed flow (MGD) (1991-2006 average)
NC0064050	APEX WATER RECLAMATION FAC	3.60	4.58
NC0065102	CARY SOUTH CARY WRF	12.80	7.69
NC0066516	FUQUAY VARINA TERRIBLE CRK WWT	1.00	0.18
NC0069311	FRANKLIN CO PUBLIC UTIL FRANKL	1.00	0.41

Most of these point sources have reasonably complete monitoring for total phosphorus and total suspended solids (TSS). Many dischargers in the Tar and Neuse River basin also report total nitrogen (unlike other study areas) because of concerns over nitrogen impacts on the coastal estuaries. The point sources were initially represented in the model with the median of reported values for total phosphorus, TSS and total nitrogen.

Meteorological Data

The required meteorological time series for the 20 Watershed SWAT simulations are precipitation and air temperature. The 20 Watershed simulations do not include water temperature and uses a degree-day method for snowmelt. SWAT estimates Penmann-Monteith potential evapotranspiration using a statistical weather generator for inputs other than temperature and precipitation. These meteorological time series are drawn from the BASINS4 Meteorological Database (USEPA 2008), which provides a consistent, quality-assured set of nationwide data with gaps filled and records disaggregated. Scenario application requires simulation over 30 years, so the available stations are those with a common 30-year period of record (or one that can be filled from an approximately co-located station) that covers the year 2001. A total of 40 precipitation stations were identified for use in the Tar and Neuse River watershed model with a common period of record of 10/1/1973-9/30/2004 (Table 4). Temperature records are sparser; where these are absent temperature is taken from nearby stations with an elevation correction.

Table 4. Precipitation stations for the Tar and Neuse River watershed model

COOP ID	Latitude	Longitude	Temperature	Elevation (m)
NC310241	36.2912	-77.9822	x	101
NC310576	35.1500	-76.7167	x	3
NC310674	35.4993	-76.6864		2
NC311241	36.1279	-79.4068		195
NC311285	36.1414	-78.7736		108
NC311606	34.9833	-76.2999	x	2
NC311677	35.9086	-79.0794	x	152
NC311820	35.6408	-78.4633	x	91
NC311881	35.0248	-78.2758	x	48
NC312500	35.3247	-78.6881	x	61
NC312515	36.0425	-78.9625		122
NC312827	36.1686	-77.6749		34
NC313232	36.1050	-78.4591		114
NC313510	35.3445	-77.9646	x	33
NC313555	36.0504	-79.3727		201
NC313638	35.6401	-77.3983	x	10
NC313969	36.3482	-78.4119	x	146
NC314684	35.1967	-77.5433	x	7
NC314689	35.2975	-77.5721	x	18
NC314962	36.1326	-77.1707	x	15
NC315123	36.1029	-78.3038	x	79
NC315830	34.7337	-76.7357	x	3
NC316108	35.0667	-77.0499	x	5
NC316135	35.4486	-76.2108	x	1
NC316853	35.8722	-76.6591	x	6
NC317069	35.8707	-78.7864	x	127
NC317074	35.7283	-78.6843	x	128
NC317079	35.7945	-78.6988	x	122
NC317319	36.4783	-77.6717	x	64
NC317395	35.9100	-77.8892		40
NC317400	35.8936	-77.6805		34
NC317499	36.2119	-78.8568		165
NC317516	36.3469	-78.8858	x	216
NC317994	35.5164	-78.3457	x	46
NC318500	35.8848	-77.5386	x	11
NC318706	35.0667	-77.3499		9
NC319100	35.5554	-77.0721		3
NC319440	35.8529	-77.0306	x	6
NC319476	35.6939	-77.9455	x	34
VA444414	36.6003	-78.3011	x	76

Watershed Segmentation

The Tar and Neuse River basin was divided into 71 subwatersheds for the purposes of modeling (Figure 3). The initial calibration watershed (Contentnea Creek) is highlighted. The model encompasses the complete watershed and does not require specification of any upstream boundary conditions for application.

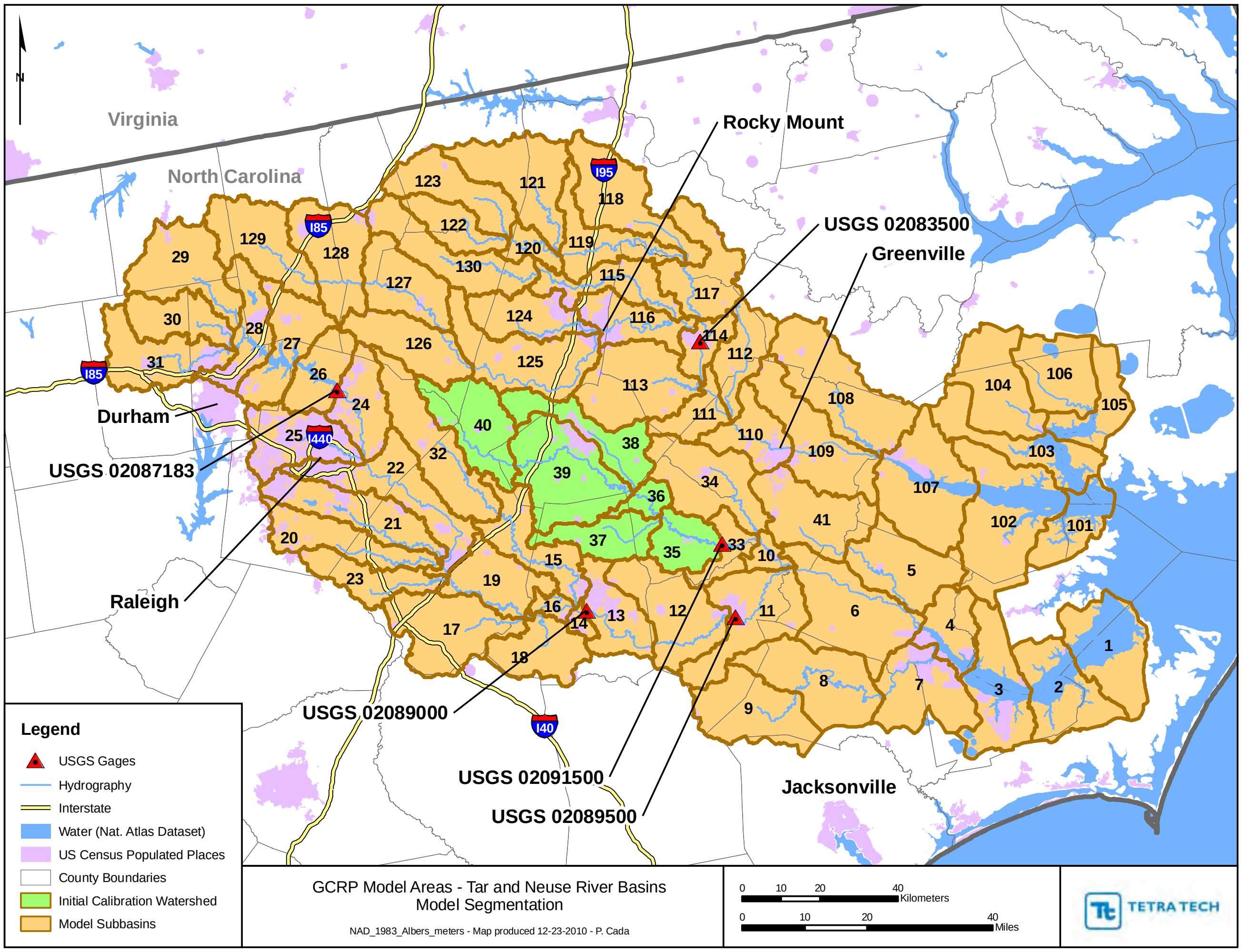

Figure 3. Model segmentation and USGS stations utilized for the Tar and Neuse River basin.

Calibration Data and Locations

The specific site chosen for initial calibration was the Contentnea Creek near Hookerton (USGS 02091500), a flow and water quality monitoring location that approximately coincides with the mouth of an 8-digit HUC at its outflow to the Neuse River. The Contentnea Creek watershed was selected because there is a good set of flow and water quality data available and the watershed lacks major point sources and impoundments. Additional calibration and validation was pursued at multiple locations (Table 5). Parameters derived on the Contentnea Creek were not fully transferable to other portions of the Tar and Neuse River basin, and additional calibration was conducted at multiple gage locations.

Table 5. Calibration and validation locations in the Tar and Neuse River basin

Station name	USGS ID	Drainage area (mi^2)	Hydrology calibration	Water quality calibration
Contentnea Creek near Hookerton, NC	02091500	733	X	X
Neuse River near Falls, NC	02087183	771	X	
Neuse River near Goldsboro, NC	02089000	2399	X	
Neuse River at Kinston, NC	02089500	2692	X	X
Tar River at Tarboro, NC	02083500	2183	X	X

The model hydrology calibration period was set to Water Years 1993-2003 (within the 32-year period of record for modeling). Hydrologic validation was then performed on Water Years 1983-1993. Water quality calibration used calendar years 1993-2003, while validation used 1983-1993.

SWAT Modeling

Assumptions

Falls Lake reservoir is the major impoundment in the Tar and Neuse River study area that was sufficiently large enough to represent in the model. It is located on the Neuse River. Pertinent reservoir information including surface area and storage at principal (normal) and emergency spillway levels for the reservoir was obtained from the US Army Corps of Engineers. The SWAT model provides four options to simulate reservoir outflow: measured daily outflow, measured monthly outflow, average annual release rate for uncontrolled reservoir, and controlled outflow with target release. Keeping in view the 20 Watershed climate change impact evaluation application to future climate scenarios, it was assumed that the best representation of the reservoir was to simulate it without supplying time series of outflow records. Therefore, the target release approach was used in the GCRP-SWAT model.

Hydrology Calibration

A spatial calibration approach was adopted for GCRP-SWAT modeling for the Tar and Neuse River basin. A systematic adjustment of parameters has been adopted and some adjustments are applied throughout the basin. Most of the calibration efforts were geared towards getting a closer match between simulated and observed flows at the outlet of calibration focus area.

Land Use / Soil / Slope Definition

A 5/10/5 percent threshold was used for land use/soil/slope in the SWAT model while defining the HRUs. Urban land use classes were exempted from the HRU overlay thresholds.

The calibration focus area (Contentnea Creek) includes five subwatersheds and is generally representative of the general land use characteristics of the overall watershed with the exception of a higher percentage of cultivated lands. The parameters were adjusted within the practical range to obtain reasonable fit between the simulated and measured flows in terms of Nash-Sutcliffe modeling efficiency and the high flow and low flow components as well as the seasonal flows.

The water balance of the whole Tar and Neuse River basin predicted by the SWAT model over the 32-year simulation period is as follows:

```
PRECIP =   1234.6 MM
SNOW FALL =   40.57 MM
SNOW MELT =    40.17 MM
SUBLIMATION =     0.39 MM
SURFACE RUNOFF Q =   170.61 MM
LATERAL SOIL Q =   18.20 MM
TILE Q =     0.00 MM
GROUNDWATER (SHAL AQ) Q =   223.76 MM
REVAP (SHAL AQ => SOIL/PLANTS) =   40.29 MM
DEEP AQ RECHARGE =    13.90 MM
TOTAL AQ RECHARGE = 277.94 MM
TOTAL WATER YLD =   410.46 MM
PERCOLATION OUT OF SOIL = 276.02 MM
ET =    763.0 MM
PET =   1433.2MM
TRANSMISSION LOSSES =     2.10 MM
```

Hydrologic calibration adjustments focused on the following parameters:

- CN2 (initial SCS runoff curve number for moisture condition II)
- ESCO (soil evaporation compensation factor)
- SURLAG (surface runoff lag coefficient)
- SOL_AWC (available water capacity of the soil layer, mm water/mm of soil)
- ALPHA_BF (baseflow alpha factor, days)
- GW_DELAY (groundwater delay time, days)
- GWQMIN (threshold depth of water in the shallow aquifer required for return flow to occur, mm)
- GW_REVAP (groundwater "revap" coefficient)
- CH_N2 (Manning's "n" value for main channels)

Calibration results for the Contentnea Creek are summarized in Figure 4, Figure 5, Figure 6, Figure 7 and Table 6.

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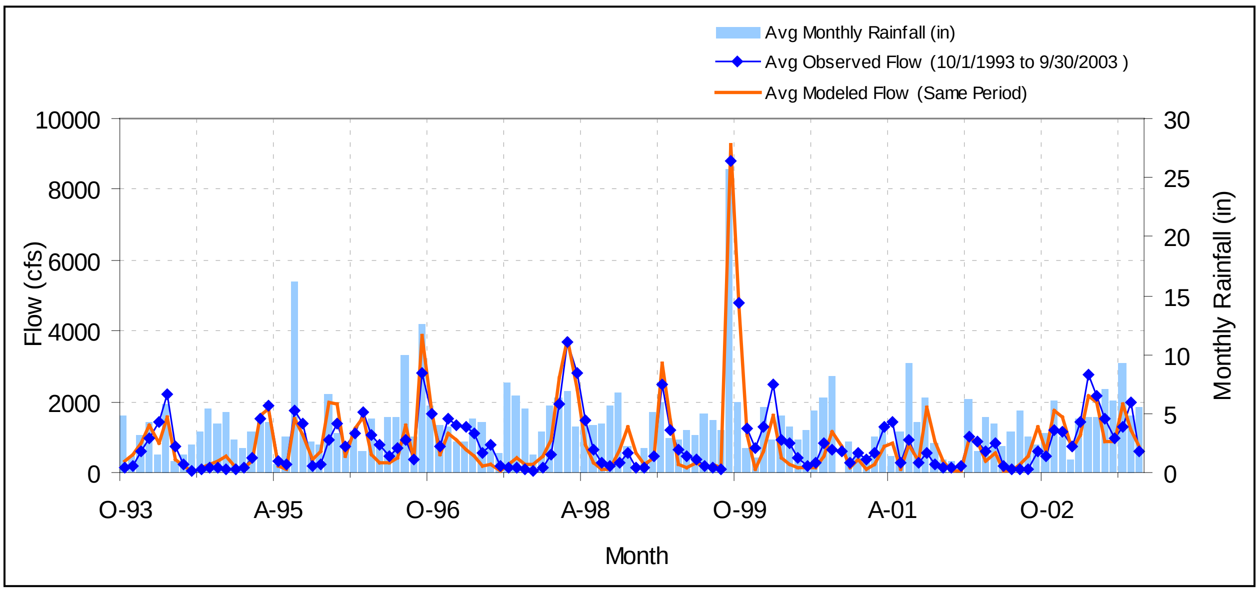

Figure 4. Mean monthly flow at USGS 02091500 Contentnea Creek near Hookerton, NC – calibration period.

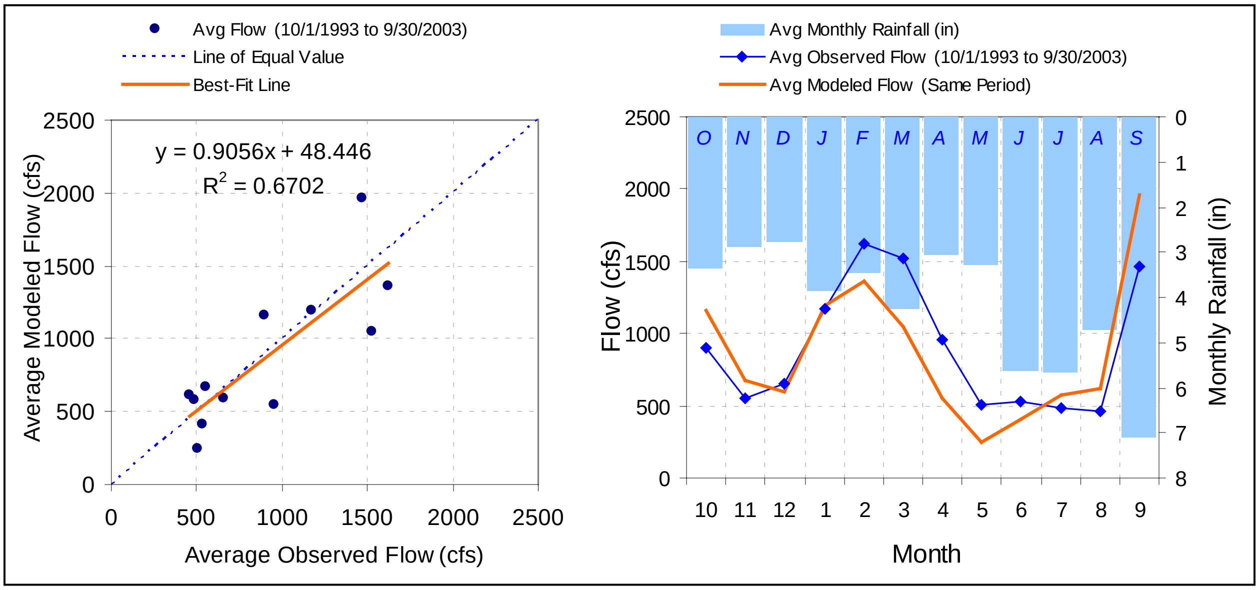

Figure 5. Seasonal regression and temporal aggregate at USGS 02091500 Contentnea Creek near Hookerton, NC – calibration period.

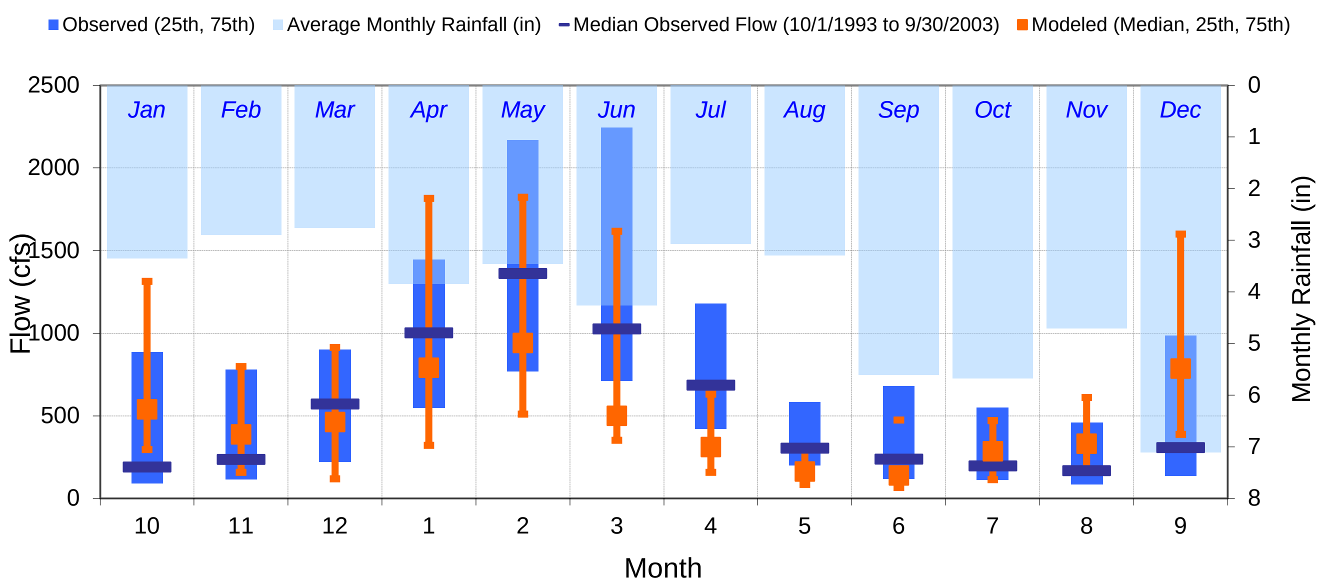

Figure 6. Seasonal medians and ranges at USGS 02091500 Contentnea Creek near Hookerton, NC – calibration period.

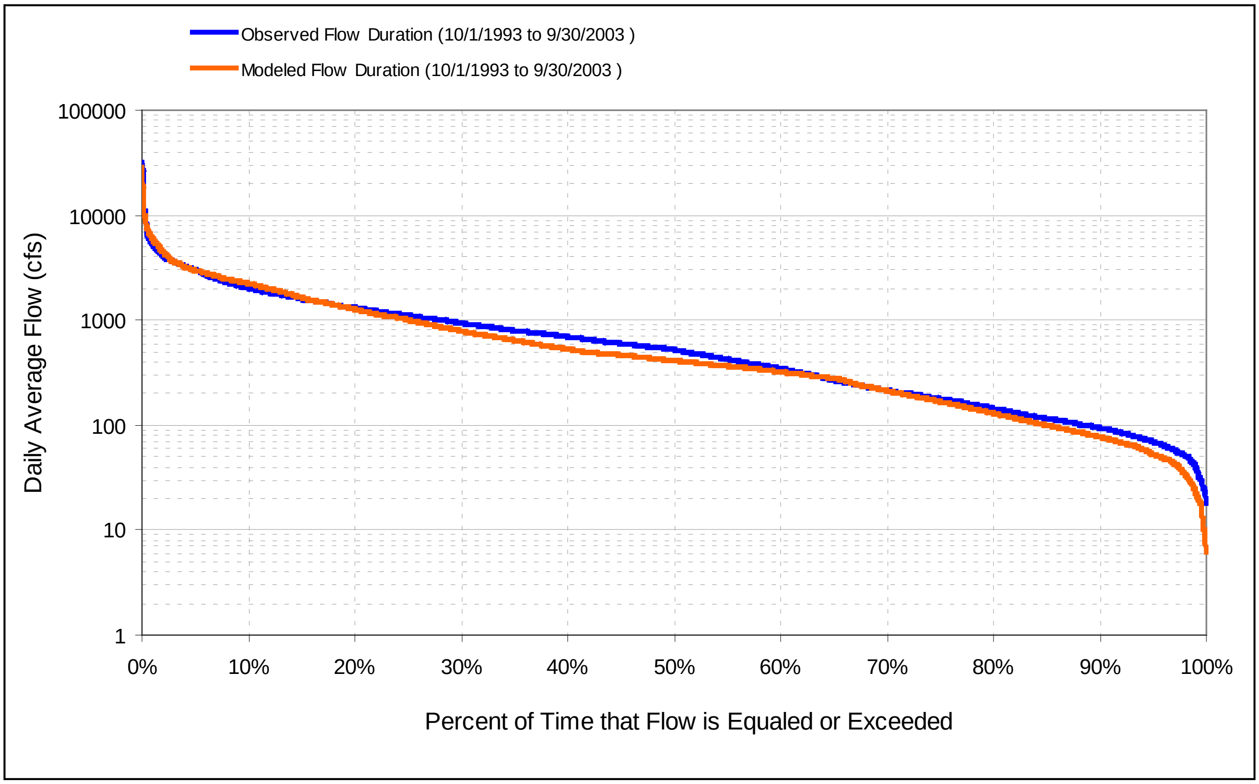

Figure 7. Flow exceedance at USGS 02091500 Contentnea Creek near Hookerton, NC – calibration period.

Table 6. Summary statistics at USGS 02091500 Contentnea Creek near Hookerton, NC – calibration period

SWAT Simulated Flow		Observed Flow Gage		
REACH OUTFLOW FROM OUTLET 35		USGS 02091500 CONTENTNEA CREEK AT HOOKERTON, NC		
10-Year Analysis Period: 10/1/1993 - 9/30/2003 Flow volumes are (inches/year) for upstream drainage area		Hydrologic Unit Code: 3020203 Latitude: 35.42888889 Longitude: -77.5825 Drainage Area (sq-mi): 733		
Total Simulated In-stream Flow:	**15.98**	Total Observed In-stream Flow:		**16.64**
Total of simulated highest 10% flows:	**7.16**	Total of Observed highest 10% flows:		**7.01**
Total of Simulated lowest 50% flows:	**1.78**	Total of Observed Lowest 50% flows:		**1.97**
Simulated Summer Flow Volume (months 7-9):	**4.86**	Observed Summer Flow Volume (7-9):		**3.72**
Simulated Fall Flow Volume (months 10-12):	**3.79**	Observed Fall Flow Volume (10-12):		**3.29**
Simulated Winter Flow Volume (months 1-3):	**5.48**	Observed Winter Flow Volume (1-3):		**6.56**
Simulated Spring Flow Volume (months 4-6):	**1.85**	Observed Spring Flow Volume (4-6):		**3.06**
Total Simulated Storm Volume:	**3.81**	Total Observed Storm Volume:		**4.35**
Simulated Summer Storm Volume (7-9):	**1.51**	Observed Summer Storm Volume (7-9):		**1.48**
Errors (Simulated-Observed)	*Error Statistics*	*Recommended Criteria*		
Error in total volume:	-3.98	10		
Error in 50% lowest flows:	-9.98	10		
Error in 10% highest flows:	2.15	15		
Seasonal volume error - Summer:	**30.50**	**30**		
Seasonal volume error - Fall:	15.05	>> 30		Clear
Seasonal volume error - Winter:	-16.48	30		
Seasonal volume error - Spring:	**-39.56**	**30**		
Error in storm volumes:	-12.39	20		
Error in summer storm volumes:	2.17	50		
Nash-Sutcliffe Coefficient of Efficiency, E:	0.678	Model accuracy increases		
Baseline adjusted coefficient (Garrick), E':	0.459	as E or E' approaches 1.0		
Monthly NSE	0.859			

Hydrology Validation

Hydrology validation for Contentnea Creek was performed for the period 10/1/1983 through 9/30/1993. Results are presented in Figures 8 through 11 and Table 7. The validation achieves a moderately high coefficient of model fit efficiency, but is over on 10 percent highest flow volume, and summer and fall seasonal volumes (Figure 8, Figure 9, Figure 10, Figure 11 and Table 7).

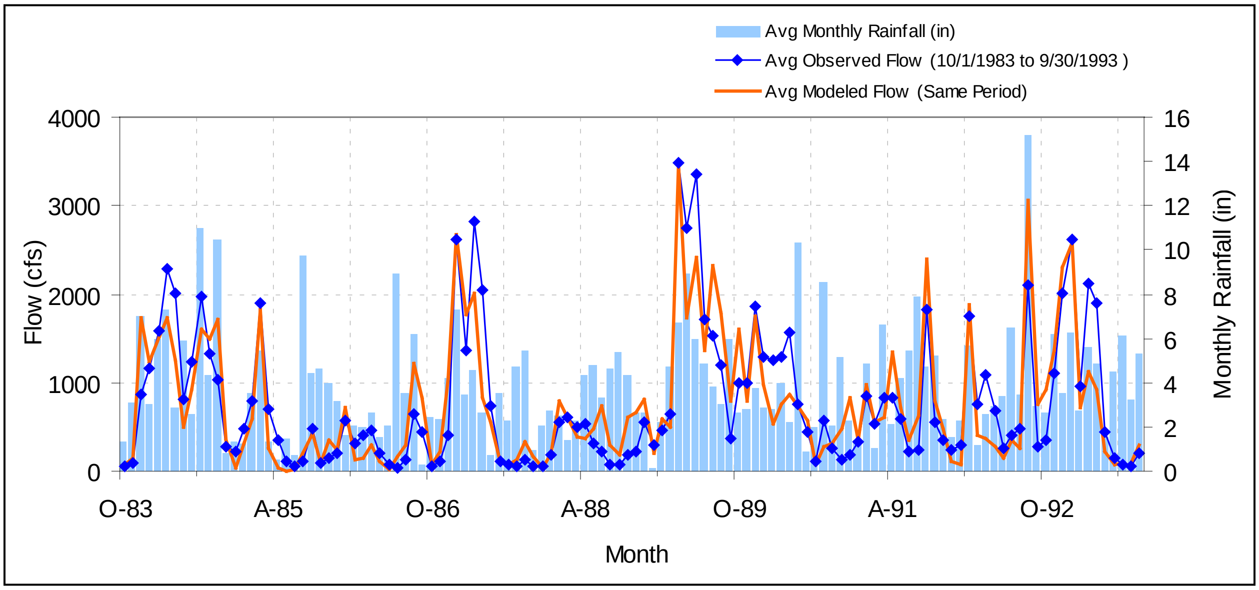

Figure 8. **Mean monthly flow at USGS 02091500 Contentnea Creek near Hookerton, NC – validation period.**

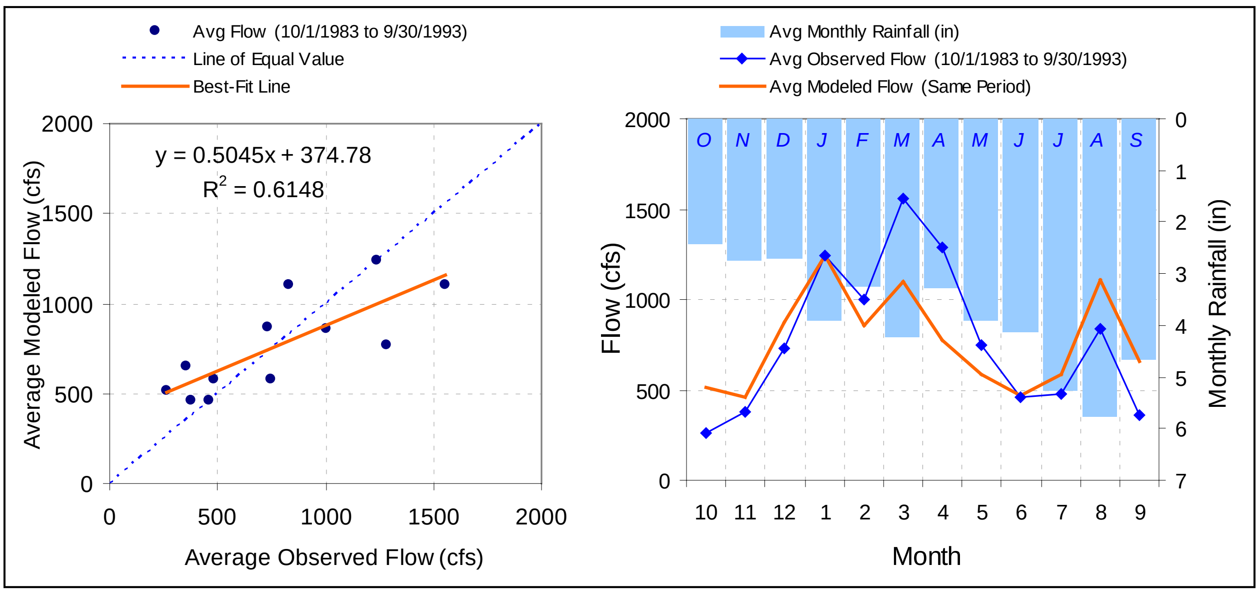

Figure 9. **Seasonal regression and temporal aggregate at USGS 02091500 Contentnea Creek near Hookerton, NC – validation period.**

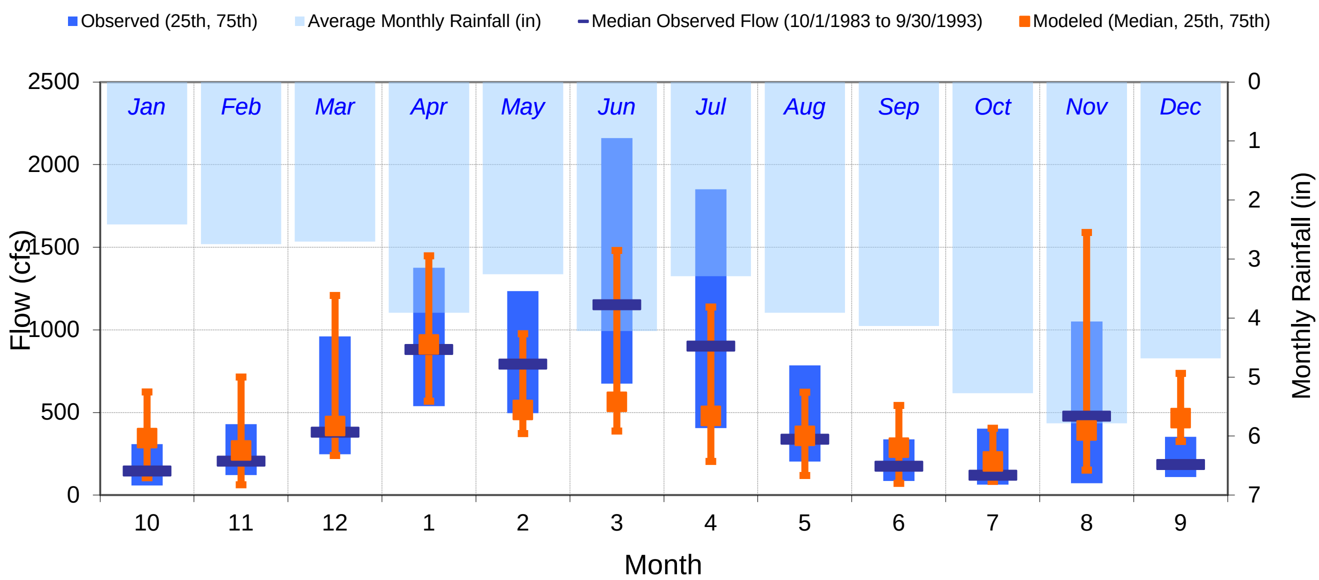

Figure 10. Seasonal medians and ranges at USGS 02091500 Contentnea Creek near Hookerton, NC – validation period.

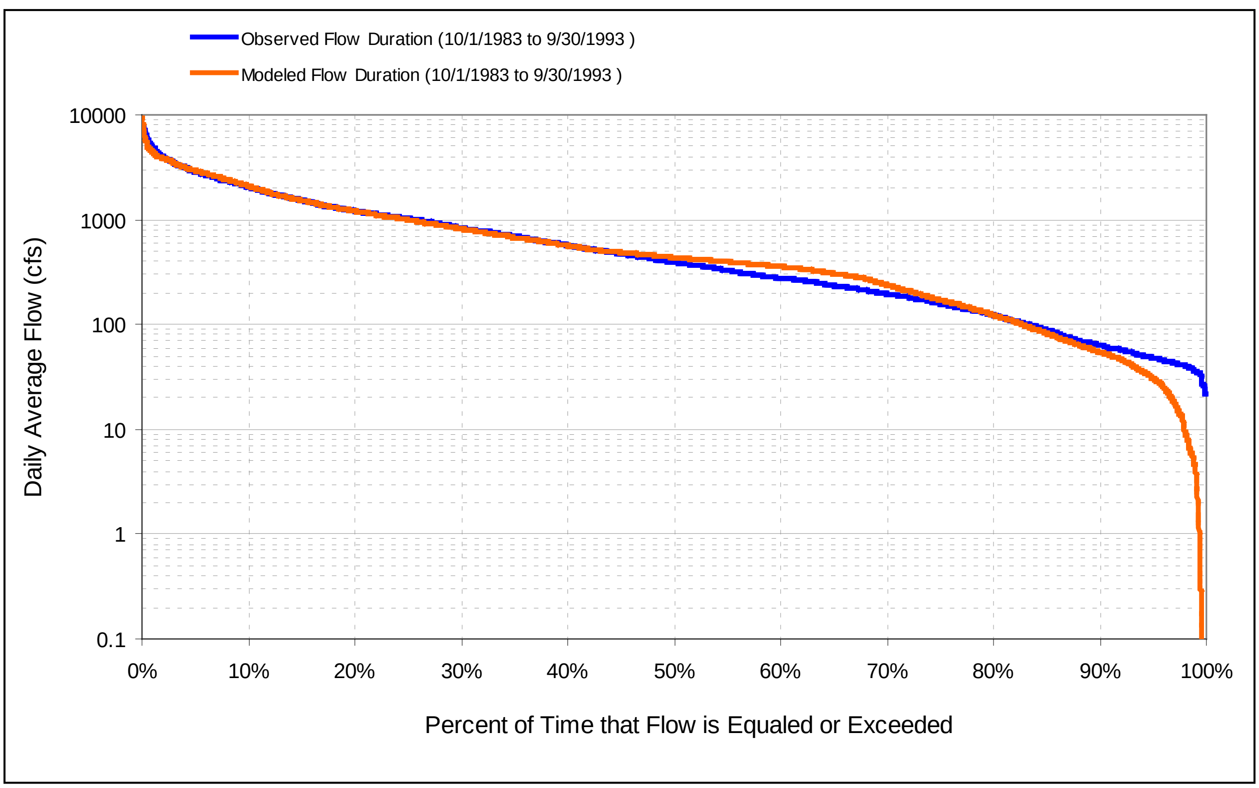

Figure 11. Flow exceedance at USGS 02091500 Contentnea Creek near Hookerton, NC – validation period.

Table 7. Summary statistics at USGS 02091500 Contentnea Creek near Hookerton, NC – validation period

SWAT Simulated Flow		Observed Flow Gage		
REACH OUTFLOW FROM OUTLET 35 10-Year Analysis Period: 10/1/1983 - 9/30/1993 Flow volumes are (inches/year) for upstream drainage area		USGS 02091500 CONTENTNEA CREEK AT HOOKERTON, NC Hydrologic Unit Code: 3020203 Latitude: 35.42888889 Longitude: -77.5825 Drainage Area (sq-mi): 733		
Total Simulated In-stream Flow:	**14.24**	Total Observed In-stream Flow:		**14.41**
Total of simulated highest 10% flows:	**5.76**	Total of Observed highest 10% flows:		**5.97**
Total of Simulated lowest 50% flows:	**1.79**	Total of Observed Lowest 50% flows:		**1.59**
Simulated Summer Flow Volume (months 7-9):	**3.65**	Observed Summer Flow Volume (7-9):		**2.61**
Simulated Fall Flow Volume (months 10-12):	**2.88**	Observed Fall Flow Volume (10-12):		**2.13**
Simulated Winter Flow Volume (months 1-3):	**4.91**	Observed Winter Flow Volume (1-3):		**5.84**
Simulated Spring Flow Volume (months 4-6):	**2.80**	Observed Spring Flow Volume (4-6):		**3.83**
Total Simulated Storm Volume:	**3.19**	Total Observed Storm Volume:		**3.66**
Simulated Summer Storm Volume (7-9):	**0.99**	Observed Summer Storm Volume (7-9):		**0.96**
Errors (Simulated-Observed)	*Error Statistics*	*Recommended Criteria*		
Error in total volume:	-1.18	10		
Error in 50% lowest flows:	**12.17**	**10**		
Error in 10% highest flows:	-3.49	15		
Seasonal volume error - Summer:	**39.76**	**30**		
Seasonal volume error - Fall:	**35.01** >>	**30**	Clear	
Seasonal volume error - Winter:	-15.83	30		
Seasonal volume error - Spring:	-26.94	30		
Error in storm volumes:	-13.04	20		
Error in summer storm volumes:	2.93	50		
Nash-Sutcliffe Coefficient of Efficiency, E:	0.635	Model accuracy increases		
Baseline adjusted coefficient (Garrick), E':	0.479	as E or E' approaches 1.0		
Monthly NSE	0.742			

Hydrology Results for Larger Watershed

As described above, parameters determined for the gage at Contentnea Creek were initially transferred to other gages in the watershed. However, changes to subbasin level parameter were required to fit the model to the observed flows. In all, calibration and validation was pursued at a total of five gages throughout the watershed, including one gage at the outlet of an 8-digit HUC, one gage at the outfall of the Falls Lake reservoir and three gages on the mainstem. Results of the calibration and validation exercise are summarized in Table 8 and Table 9, respectively. Calibration and validation results were acceptable at most gages.

Table 8. Summary statistics (percent error): all stations - calibration period

Station	02091500 Contentnea Creek near Hookerton, NC	02087183 Neuse River near Falls Lake, NC	02089000 Neuse River near Goldsboro, NC	02089500 Neuse River at Kinston, NC	02083500 Tar River at Tarboro, NC
Error in total volume:	-3.98	5.36	-3.95	-3.00	0.23
Error in 50% lowest flows:	-9.98	-11.43	-2.44	-0.14	0.92
Error in 10% highest flows:	2.15	-11.68	-1.26	1.23	-6.55
Seasonal volume error - Summer:	30.50	30.71	20.87	22.20	18.69
Seasonal volume error - Fall:	15.05	21.62	7.54	8.74	29.36
Seasonal volume error - Winter:	-16.48	3.54	-11.38	-9.95	-11.81
Seasonal volume error - Spring:	-39.56	-20.48	-26.07	-26.52	-21.93
Error in storm volumes:	-12.39	-61.90	-14.75	-10.38	-33.68
Error in summer storm volumes:	2.17	-29.11	3.89	2.19	-15.34
Daily Nash-Sutcliffe Coefficient of Efficiency, E:	0.678	0.417	0.736	0.732	0.754
Monthly Nash-Sutcliffe Coefficient	0.859	0.719	0.864	0.859	0.894

Table 9. Summary Statistics (percent error): All Stations - Validation Period

Station	02091500 Contentnea Creek near Hookerton, NC	02087183 Neuse River near Falls Lake, NC	02089000 Neuse River near Goldsboro, NC	02089500 Neuse River at Kinston, NC	02083500 Tar River at Tarboro, NC
Error in total volume:	-1.18	-1.02	-7.60	-8.55	-4.88
Error in 50% lowest flows:	12.17	-29.70	0.60	-2.55	-9.07
Error in 10% highest flows:	-3.49	-26.58	-20.17	-20.42	-20.23
Seasonal volume error - Summer:	39.76	5.54	14.56	14.73	39.72
Seasonal volume error - Fall:	35.01	29.41	16.15	12.09	26.83
Seasonal volume error - Winter:	-15.83	-7.93	-14.24	-14.46	-16.29
Seasonal volume error - Spring:	-26.94	-7.10	-22.37	-24.12	-22.16
Error in storm volumes:	-13.04	-63.68	-28.64	-27.30	-37.61
Error in summer storm volumes:	2.93	-46.92	-22.43	-20.82	-7.61
Daily Nash-Sutcliffe Coefficient of Efficiency, E:	0.635	0.620	0.775	0.767	0.688
Monthly Nash-Sutcliffe Coefficient	0.742	0.845	0.849	0.832	0.808

Water Quality Calibration and Validation

Initial calibration and validation of water quality was done on the Contentnea Creek (USGS 02091500), using 1993-2003 for calibration and 1983-1993 for validation. As with hydrology, water quality calibration was performed on the later period as this better reflects the land use included in the model.

Calibration adjustments for sediment focused on the following parameters:

- SPCON (linear parameter for estimating maximum amount of sediment that can be re-entrained during channel sediment routing)
- SPEXP (exponential parameter for estimating maximum amount of sediment that can be re-entrained during channel sediment routing)
- CH_COV (channel cover factor)
- CH_EROD (channel erodibility factor)
- USLE_P (USLE support practice factor)

Simulated and estimated sediment loads at the Contentnea Creek station for both the calibration and validation periods are shown in Figure 12 and statistics for the two periods are provided separately in Table 10. The key statistic in Table 10 is the relative percent error, which shows the error in the prediction of monthly load normalized to the estimated load. Table 10 also shows the relative average absolute error, which is the average of the relative magnitude of errors in individual monthly load predictions. This number is inflated by outlier months in which the simulated and estimated loads differ by large amounts (which may be as easily due to uncertainty in the estimated load due to limited data as to problems with the model) and the third statistic, the relative median absolute error, is likely more relevant and shows better agreement.

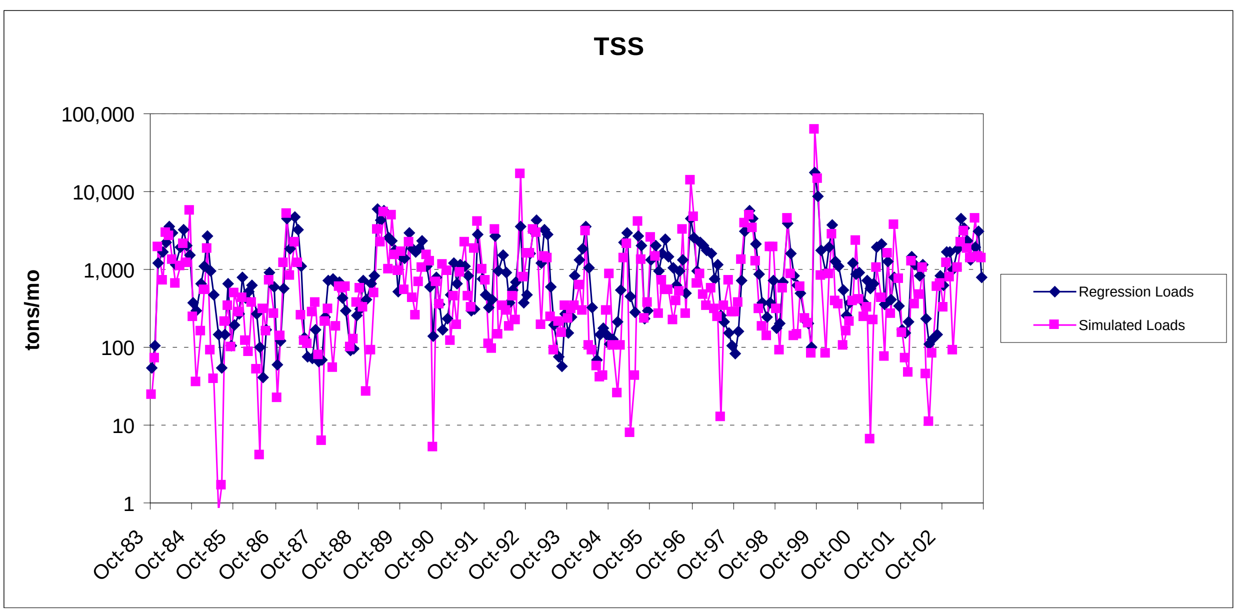

Figure 12. Fit for monthly load of TSS at USGS 02091500 Contentnea Creek near Hookerton, NC.

Table 10. Model fit statistics (observed minus predicted) for monthly sediment loads using stratified regression at USGS 02091500 Contentnea Creek near Hookerton, NC

Statistic	Calibration period (1993-2003)	Validation period (1983-1993)
Relative Percent Error	-19.9%	9.9%
Relative Average Absolute Error	81%	61%
Relative Median Absolute Error	34.7%	33.1%

Calibration adjustments for total phosphorus and total nitrogen focused on the following parameters:

- RHOQ (algal respiration rate at 20^{O} C)
- PHOSKD (phosphorus soil partitioning coefficient)
- PSP (phosphorus availability index)
- RS2 (benthic source rate for dissolved P in the reach at 20^{O} C)
- RS5 (organic P settling rate in the reach at 20^{O} C)
- BC4 (rate constant for mineralization of organic P to dissolved P in the reach at 20^{O} C)
- RS4 (rate coefficient for organic N settling in the reach at 20^{O} C)

Results for the phosphorus simulation are shown in Figure 13 and Table 11. Results for the nitrogen simulation are shown in Figure 14 and Table 12. The model fit is generally acceptable.

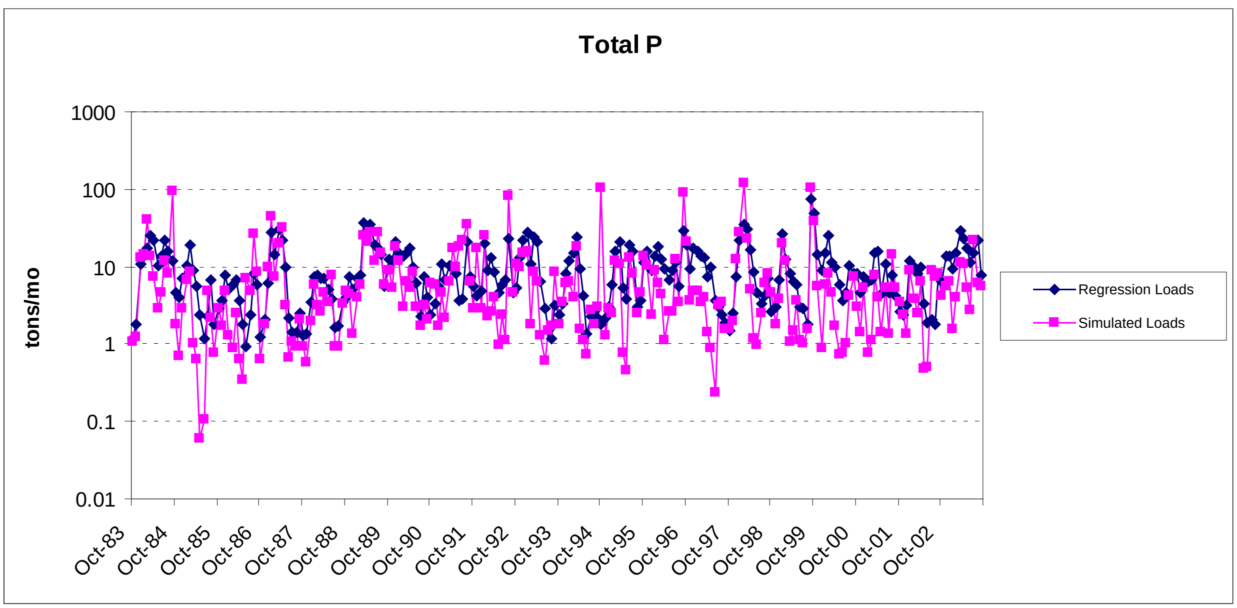

Figure 13. Fit for monthly load of total phosphorus at USGS 02091500 Contentnea Creek near Hookerton, NC.

Table 11. Model fit statistics (observed minus predicted) for monthly phosphorus loads using stratified regression at USGS 02091500 Contentnea Creek near Hookerton, NC

Statistic	Calibration period (1993-2003)	Validation period (1983-1993)
Relative Percent Error	15.9%	5.3%
Average Absolute Error	69%	66%
Median Absolute Error	49.3%	39.3%

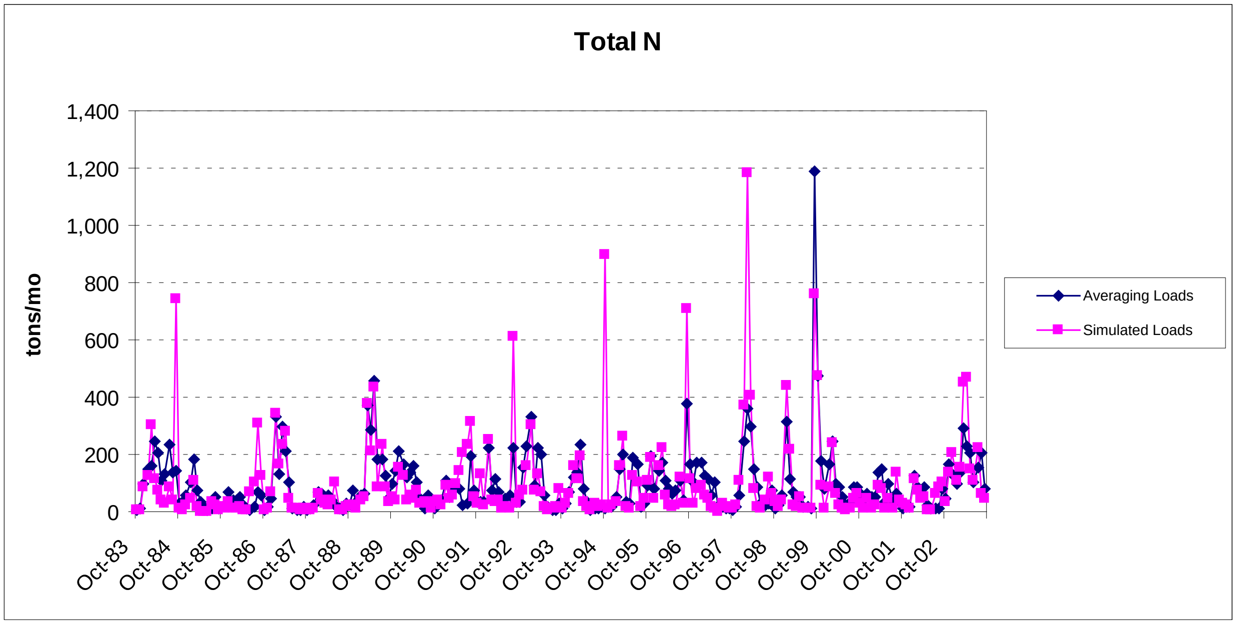

Figure 14. Fit for monthly load of total nitrogen at USGS 02091500 Contentnea Creek near Hookerton, NC.

Table 12. Model fit statistics (observed minus predicted) for monthly total nitrogen loads using averaging estimator at USGS 02091500 Contentnea Creek near Hookerton, NC

Statistic	Calibration period (1993-2003)	Validation period (1983-1993)
Relative Percent Error	-5.6%	5.3%
Average Absolute Error	56%	57%
Median Absolute Error	24.3%	31.6%

Water Quality Results for Larger Watershed

As with hydrology, a spatial calibration approach was adopted. Contentnea Creek watershed SWAT model parameters for water quality were transferred to other portions of the watershed with necessary changes to subwatershed level parameters. Summary statistics for the SWAT water quality calibration and validation at other stations in the watershed are provided in Table 13 and Table 14.

Table 13. Summary statistics for water quality at all stations – calibration period 1993-2003

Station	02091500 Contentnea Creek near Hookerton, NC	02089500 Neuse River at Kinston, NC	02083500 Tar River at Tarboro, NC
Relative Percent Error TSS Load	-19.9%	-6.7%	-5.1%
Relative Percent Error TP Load	15.9%	-10.5%	-0.4%
Relative Percent Error TN Load	-5.6%	-15%	-33.8%

Table 14. Summary statistics for water quality at all stations – validation period 1983-1993

Station	02091500 Contentnea Creek near Hookerton, NC	02089500 Neuse River at Kinston, NC	02083500 Tar River at Tarboro, NC
Relative Percent Error TSS Load	9.9%	17.3%	22.9%
Relative Percent Error TP Load	5.3%	2.5%	13.1%
Relative Percent Error TN Load	5.3%	6.7%	13.5%

References

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USEPA. 2008. Using the BASINS Meteorological Database (Version 2006). BASINS Technical Note 10. Office of Water, U.S. Environmental Protection Agency, Washington, DC. http://water.epa.gov/scitech/datait/models/basins/upload/2009_04_13_BASINSs_tecnote10.pdf (Accessed June, 2009).

Appendix K
Model Configuration, Calibration and Validation

Basin: Nebraska: Loup and Elkhorn Rivers (Neb)

Contents

Tables

Figures

Watershed Background

The Loup and Elkhorn River basins within the Central Nebraska NAWQA study area were selected as one of the 15 non-pilot application watersheds for the 20 Watershed study. Watershed modeling for the non-pilot areas is accomplished using the SWAT model only, and model calibration and validation results are presented in abbreviated form.

Water Body Characteristics

The Loup and Elkhorn River basins are tributary to the Platte River (Huntzinger and Ellis, 1993). Together they include 14 HUC8s within HUC 1021 and 1022 and cover approximately 22,100 mi^2 (Figure 1). The Loup River basin includes the North Loup, Middle Loup, and South Loup Rivers, as well as Calamus River, Cedar River, Dismal River, and Mud Creek. Major tributaries of the Elkhorn River include the North Fork Elkhorn River and Logan Creek.

The watersheds are located in the Central Plains ecoregion (Huntzinger and Ellis, 1993). The Loup River and its major tributaries originate in the Nebraska Sandhills, a region of steep grass-covered dunes, and then flow through dissected plains with broad valleys. Permeable soils and subsurface materials in the Loup River basin provide flows sustained by shallow groundwater and little if any runoff. The Elkhorn River, in the eastern and northeastern part of the watershed, flows through rolling hills and well-defined valleys of stable glacial material in the Western Corn Belt Plains except where it originates in the Sandhills. Runoff in the Elkhorn basin is the largest in the watershed because of the steeper slopes and fine-grained soils. The city of Omaha lies just outside the watershed. The portion of the watershed along the eastern boundary is influenced by the Omaha suburban area and is located near the mouth of the Platte River. Most of the water in the watershed is consumed by irrigation or used for power generation and returned to the stream for reuse. The water used for irrigation is primarily from groundwater. The few urban areas within the watershed use groundwater as a municipal water supply. The city of Omaha obtains part of its water supply from wells in the Elkhorn and Platte River Valleys.

The watersheds are dominated by rural areas. The land use is predominantly pasture and rangeland (66 percent) and croplands of row-cropped feed grains (27 percent). Groundwater development for irrigation has increased the productivity of agriculture in the valleys and uplands. Large areas have soils well suited to cultivated crops whereas other large areas are not suited to crops but to productive grasslands. Counties that are primarily cropland agriculture without urban areas have population densities of 50 persons per square mile or less. Areas in the west that are primarily rangeland have population densities of less than five persons per square mile.

The central Nebraska climate ranges from semiarid in the northwest to subhumid in the east. Hot summers, cold winters, and large daily and annual variations in temperature are typical. Precipitation is greatest in May and June. Mean annual precipitation varies from about 18 inches in the western part of the watershed to about 30 inches in the eastern part. Most of the study unit has at least 20 inches of annual precipitation, and more than one-half occurs during the growing season, April through September. Snowfall is a dominant climatic characteristic of central Nebraska. Mean annual snowfall ranges from about 25 inches in the southeast to about 35 inches in the northwest.

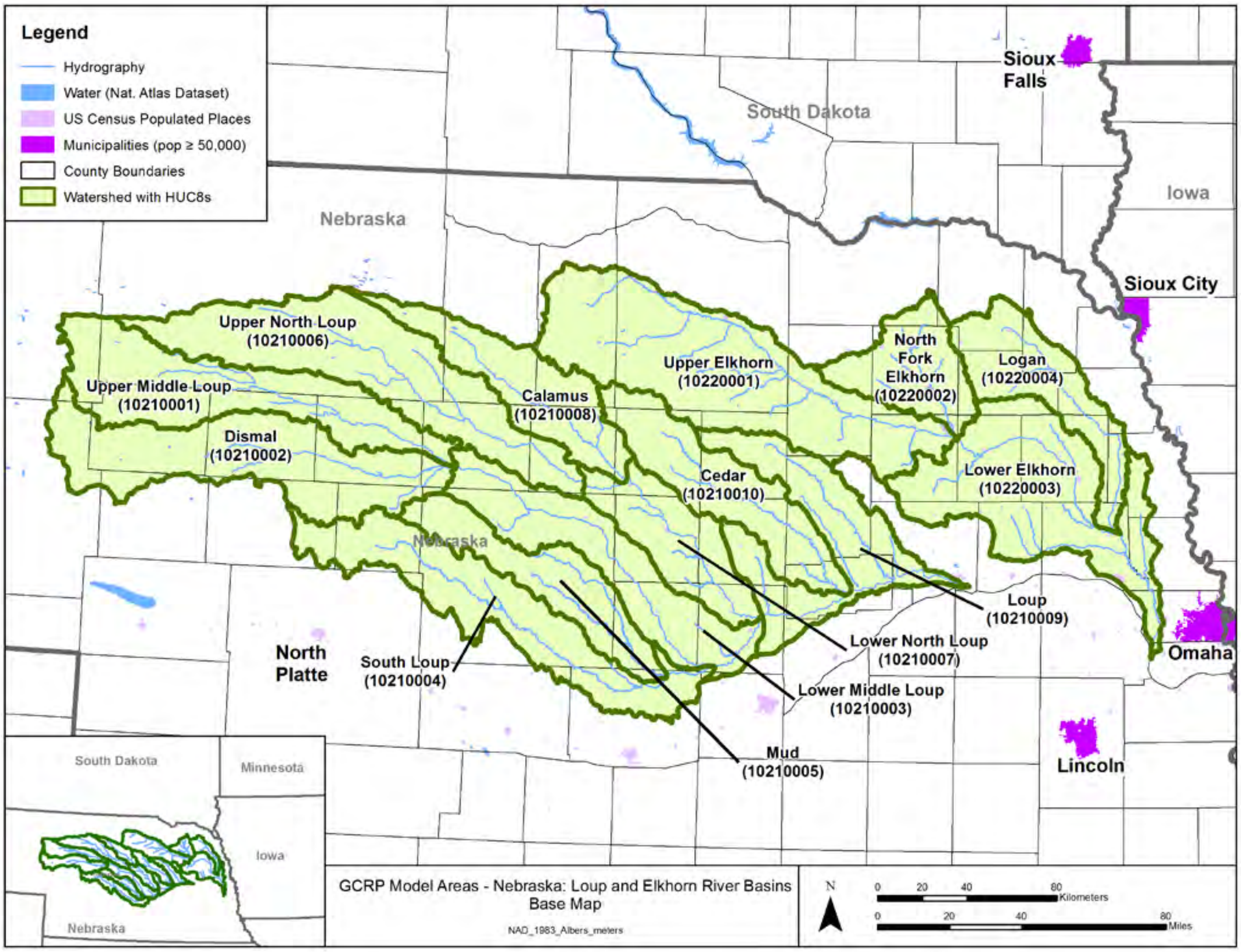

Figure 1. Location of the Loup and Elkhorn River basins

Soil Characteristics

Soils in the watershed, as described in STATSGO soil surveys, fall primarily into hydrologic soil groups (HSGs) A (high infiltration capacity) and B (moderately high infiltration capacity). SWAT uses information drawn directly from the soils data layer to populate the model.

Land Use Representation

Land use/cover in the watershed is based on the 2001 National Land Cover Database (NLCD) coverage and is predominantly rangeland in the northwest and row crop agriculture in the south and east (Figure 2). NLCD land cover classes were aggregated according to the scheme shown in Table 1 for representation in the 20 Watershed model. SWAT uses the built-in hydrologic response unit (HRU) overlay mechanism in the ArcSWAT interface. SWAT HRUs are formed from an intersection of land use and SSURGO major soils. The distribution of land use in the watershed is summarized in Table 2.

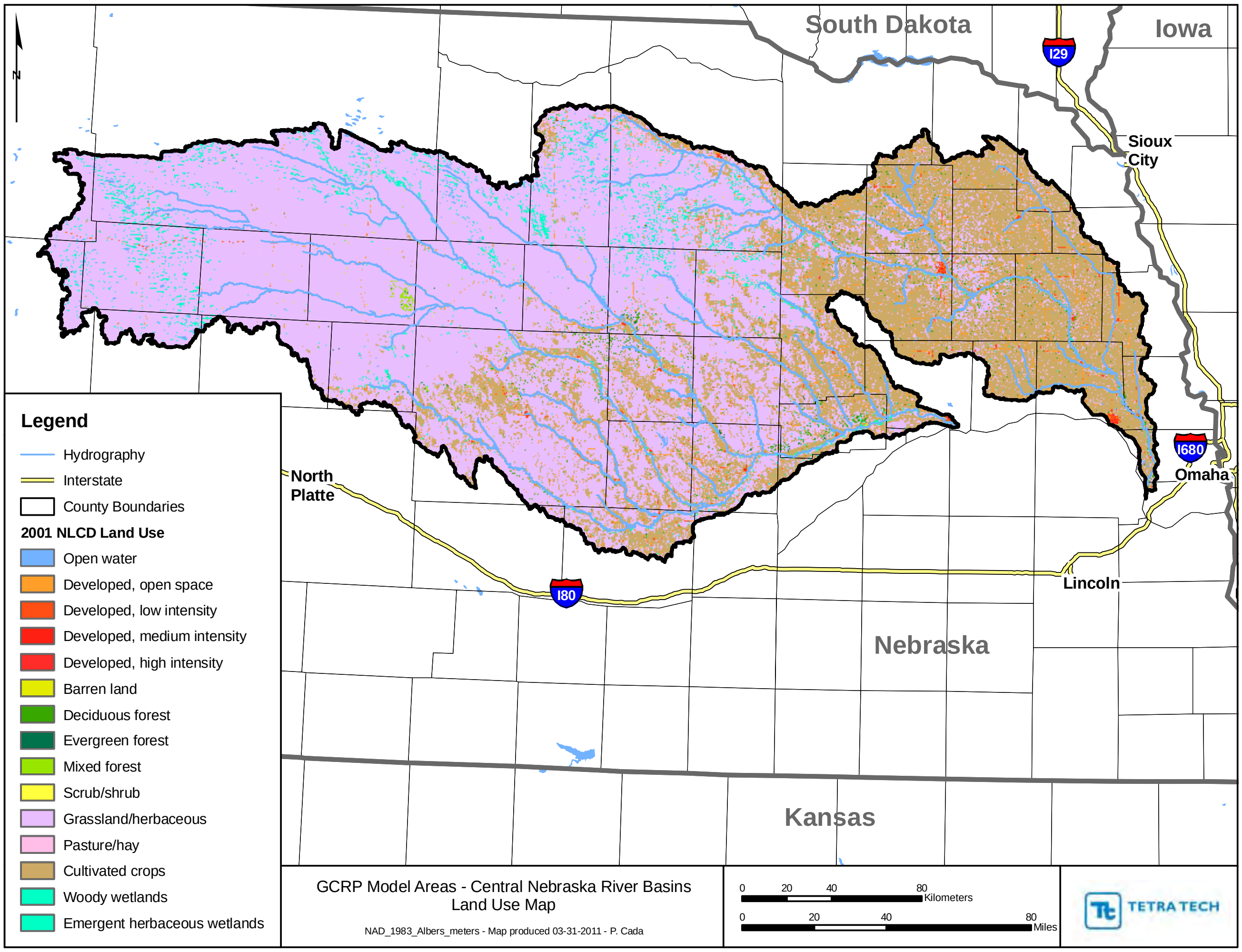

Figure 2. Land use in the Loup and Elkhorn River basins.

Table 1. Aggregation of NLCD land cover classes

NLCD Class	Comments	SWAT class
11 Water	Water surface area usually accounted for as reach area	WATR
12 Perennial ice/snow		WATR
21 Developed open space		URLD
22 Dev. Low Intensity		URMD
23 Dev. Med. Intensity		URHD
24 Dev. High Intensity		UIDU
31 Barren Land		SWRN
41 Forest	Deciduous	FRSD
42 Forest	Evergreen	FRSE
43 Forest	Mixed	FRST
51-52 Shrubland		RNGB
71-74 Herbaceous Upland		RNGE
81 Pasture/Hay		HAY
82 Cultivated		AGRR
91-97 Wetland	Emergent & woody wetlands	WETF, WETL, WETN
98-99 Wetland	Aquatic bed wetlands (not emergent)	WATR

Table 2. Land use distribution for the Loup and Elkhorn River basins (2001 NLCD) (mi^2)

HUC 8 watershed	Open water	Developed[a]				Barren land	Forest	Shrubland/ Grassland	Pasture/Hay	Cultivated	Wetland	Total
		Open space	Low density	Medium density	High density							
Upper Elkhorn **10220001**	25.2	71.8	10.9	2.1	1.1	2.6	22.5	1,724.7	129.4	719.9	182.6	**2,892.8**
North Fork Elkhorn **10220002**	2.9	34.6	7.6	1.5	0.8	0.1	17.0	198.0	1.2	580.8	4.2	**848.6**
Lower Elkhorn **10220003**	17.6	86.9	22.2	4.4	1.6	0.2	45.2	311.1	20.4	1,667.5	29.4	**2,206.6**
Logan **10220004**	2.7	40.5	10.1	0.9	0.4	0.0	7.1	111.2	10.9	866.1	3.1	**1,053.1**
Upper Middle Loup **10210001**	25.9	9.0	3.4	0.3	0.1	0.7	4.7	1,955.0	3.3	2.5	85.7	**2,090.6**
Dismal **10210002**	8.8	2.8	0.3	0.0	0.0	1.6	14.8	1,711.6	4.0	6.2	40.3	**1,790.5**
Lower Middle Loup **10210003**	19.6	48.7	9.4	1.1	0.2	1.0	21.7	1,310.2	10.9	347.9	38.7	**1,809.5**
South Loup **10210004**	4.1	42.3	5.5	0.3	0.1	0.8	14.8	1,133.3	10.5	335.1	34.0	**1,580.8**
Mud **10210005**	0.3	26.4	8.1	1.3	0.3	0.3	9.4	488.8	7.0	195.0	3.9	**740.8**
Upper North Loup **10210006**	25.7	10.5	0.9	0.0	0.0	0.9	3.1	2,181.3	3.3	20.4	103.4	**2,349.4**
Lower North Loup **10210007**	9.8	32.1	6.1	0.7	0.2	0.4	31.4	643.8	10.6	224.2	18.5	**977.9**
Calamus **10210008**	22.3	2.7	0.1	0.0	0.0	1.0	1.3	904.9	1.1	7.1	50.7	**991.3**
Loup **10210009**	12.4	51.1	9.9	1.3	0.6	1.6	26.0	678.1	28.6	663.5	60.5	**1,533.7**
Cedar **10210010**	6.5	28.5	3.1	0.2	0.1	1.2	14.7	897.7	9.2	226.2	42.6	**1,229.9**
Total	**183.8**	**488.0**	**97.4**	**14.3**	**5.5**	**12.5**	**233.8**	**14,249.7**	**250.4**	**5,862.5**	**697.4**	**22,095.4**

[a]The percent imperviousness applied to each of the developed land uses is as follows: open space (8.34%), low density (29.68%), medium density (60.14%), and high density (86.59%).

Point Sources

There are several point source discharges in the watershed. Only the major dischargers, primarily those with a design flow greater than 1 MGD, are included in the simulation (Table 3). The major dischargers are represented at long-term average flows, without accounting for changes over time or seasonal variations.

Table 3. Major point source discharges in the Loup and Elkhorn River basins

NPDES ID	Name	Design flow (MGD)	Observed flow (MGD) (1991-2006 average)
NE0000761	TYSON FRESH MEATS INC W POINT	1.3	0.79
NE0001392	TYSON FRESH MEATS, INC.	3.6	3.36
NE0028363	TYSON FRESH MEAT INC. MADISON	1.2	0.56
NE 0031381	FREMONT WWTF	10.5	4.05
NE0033421	NORFOLK WWTF	3.47	3.75
NE0035025	COLUMBUS WWTF	2.6	4.31
NE0111287	NUCOR STEEL NORFOLK	0.118	0.46

Most of these point sources have reasonably good monitoring data available for total suspended solids (TSS), but not for nutrients. The point sources were thus represented in the model with the median of reported values for TSS and nutrient concentrations set to representative values by SIC code (Tetra Tech 1999).

Meteorological Data

The required meteorological time series for the 20 Watershed SWAT simulations are precipitation and air temperature. The 20 Watershed simulations do not include water temperature simulation and use a degree-day method for snowmelt. SWAT estimates Penman-Monteith potential evapotranspiration using a statistical weather generator for inputs other than temperature and precipitation. These meteorological time series are drawn from the BASINS4 Meteorological Database (USEPA 2008), which provides a consistent, quality-assured set of nationwide data with gaps filled and records disaggregated. Scenario application requires simulation over 30 years, so the available stations are those with a common 30-year period of record (or one that can be filled from an approximately co-located station) that includes the year 2001, if possible. A total of 57 precipitation stations were identified for use in the Loup and Elkhorn River basins model with a common period of record of 10/1/1968-12/31/1999 (Table 4). Due to the discontinuance of many stations a simulation period ending slightly prior to 2001 was chosen. Temperature records are sparser; where these are absent temperature is taken from nearby stations with an elevation correction.

Table 4. Precipitation stations for the Loup and Elkhorn River basins model

COOP ID	Name	Latitude	Longitude	Temperature	Elevation (ft)
NE250070	ALBION	41.6842	-98.0033	X	546
NE250180	AMELIA 2W	42.2347	-98.9506	X	668
NE250245	ANSELMO 2 SE	41.5975	-99.8258	X	794
NE250320	ARCADIA	41.4244	-99.1231		658
NE250355	ARNOLD	41.4242	-100.193		838

COOP ID	Name	Latitude	Longitude	Temperature	Elevation (ft)
NE250365	ARTHUR	41.5697	-101.691	X	1067
NE250385	ASHTON	41.2481	-98.7989		620
NE250420	ATKINSON	42.5342	-98.9783	X	643
NE250525	BARTLETT 4S	41.8278	-98.5494		652
NE250680	BEEMER	41.9325	-96.8108		415
NE251130	BREWSTER	41.9375	-99.8628	X	760
NE251200	BROKEN BOW 2 W	41.4083	-99.675	X	762
NE251345	BURWELL	41.7769	-99.1433	X	663
NE251590	CHAMBERS	42.2031	-98.7467	X	649
NE251660	CLARKSON	41.7239	-97.1256	X	472
NE251776	COLERIDGE	42.5056	-97.2086		488
NE251835	COMSTOCK	41.5569	-99.2372		687
NE252380	DODGE	41.7233	-96.8828		427
NE252595	ELGIN	41.9872	-98.0747		590
NE252645	ELLSWORTH	42.0631	-102.283		1190
NE252647	ELLSWORTH 15 NNE	42.2647	-102.214	X	1210
NE252770	ERICSON 6 WNW	41.7986	-98.7842		642
NE252805	EWING	42.2611	-98.3417	X	564
NE253050	FREMONT	41.43	-96.4669	X	360
NE253075	FULLERTON	41.3594	-97.9761		503
NE253185	GENOA 2 W	41.4514	-97.7644	X	485
NE253425	GREELEY	41.5461	-98.5336	X	616
NE253630	HARTINGTON	42.6167	-97.2608	X	418
NE254986	LOUP CITY 6 NNE	41.3611	-98.9222		677
NE255050	LYONS	41.9378	-96.4789		390
NE255080	MADISON 2W	41.8306	-97.49	X	511
NE255250	MASON CITY	41.2231	-99.3008		689
NE255370	MEADOW GROVE	42.0292	-97.7386		497
NE255525	MILLER	40.9283	-99.3886		704
NE255702	MULLEN 21 NW	42.2506	-101.336	X	1055
NE255830	NELIGH	42.1303	-98.0275		536

COOP ID	Name	Latitude	Longitude	Temperature	Elevation (ft)
NE255925	NEWPORT	42.6008	-99.3333	X	680
NE256040	NORTH LOUP	41.4933	-98.7747	X	597
NE256135	OAKDALE	42.0678	-97.9675	X	521
NE256167	OCONTO	41.1439	-99.7633	X	786
NE256290	O NEILL	42.4594	-98.6564	X	607
NE256386	OSHKOSH 10 NE	41.5	-102.183	X	327
NE256395	OSMOND	42.3569	-97.5969	X	503
NE256630	PENDER	42.1153	-96.7058		408
NE256720	PIERCE	42.1958	-97.5206		485
NE256735	PILGER	42.0067	-97.0561		429
NE256970	PURDUM	42.065	-100.247	X	820
NE257040	RAVENNA	41.0333	-98.9142	X	625
NE257515	SAINT PAUL 4 N	41.2686	-98.4697	X	541
NE257685	SCRIBNER	41.6678	-96.6689		382
NE258025	SPALDING	41.6031	-98.3483		578
NE258110	STANTON	41.9564	-97.2222	X	469
NE258455	TAYLOR	41.7708	-99.3814		692
NE258480	TEKAMAH	41.7861	-96.2264	X	338
NE259050	WAYNE 4 NW	42.295	-97.0569		457
NE259200	WEST POINT	41.845	-96.7142	X	399
NE259262	WHITMAN 4 E	42.0828	-101.431		1093

Watershed Segmentation

The Loup and Elkhorn River basins was divided into 114 subwatersheds for the purposes of modeling (Figure 3). The initial calibration watershed was selected as Elkhorn River at Waterloo (USGS 06800500). The area modeled encompasses complete watersheds and does not require specification of any upstream boundary conditions for application.

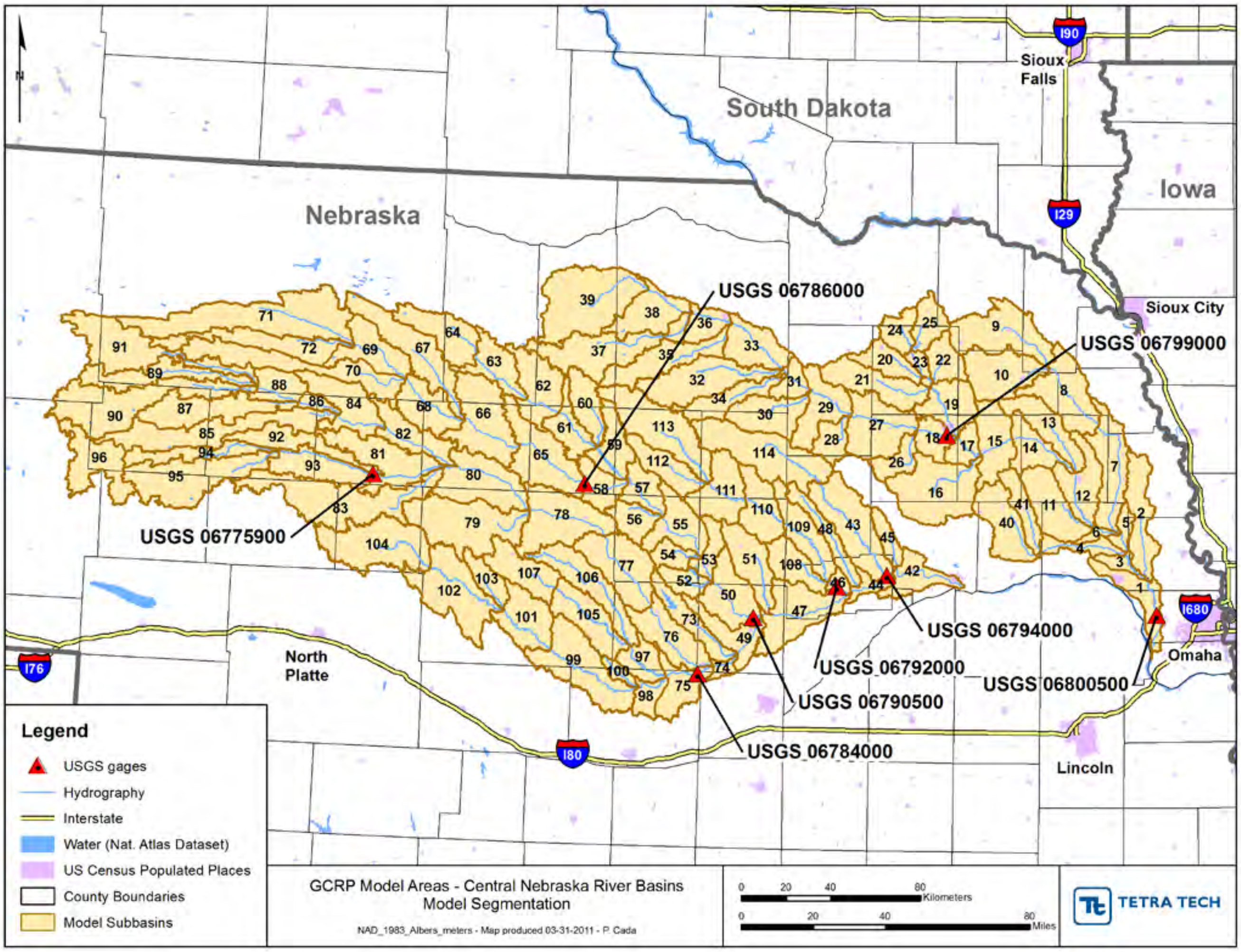

Figure 3. Model segmentation and USGS stations utilized for the Loup and Elkhorn River basins

Calibration Data and Locations

The specific site chosen for initial calibration was the Elkhorn River at Waterloo, NE, a flow and water quality monitoring location at the Elkhorn River outflow to the Platte River. The drainage area for this gage is somewhat larger than those selected for most other 20 Watershed study areas, but is the only station on the Elkhorn that provides both flow and TSS monitoring over long periods of time. The Elkhorn River watershed was selected for calibration focus because of the difficulties in obtaining model fit to the Sandhills area – both in this project and in the earlier USGS modeling effort (Strauch and Linard 2009). Calibration and validation were then pursued at multiple locations (Table 5), including multiple stations such as Dismal River that are entirely within the Sandhills. Parameters derived on the Elkhorn River were not fully transferable to other portions of the watershed; therefore, additional calibration was conducted at multiple gage locations.

Table 5. Calibration and validation locations in the Loup and Elkhorn River basins

Station name	USGS ID	Drainage area (mi^2)	Hydrology calibration	Water quality calibration
Dismal River near Thedford, NE	06775900	966	X	
South Loup River at Saint Michael, NE	06784000	2,320	X	
Middle Loup River at Saint Paul, NE	06785000	8,075	X	
North Loup River at Taylor, NE	06786000	2,350	X	
North Loup River near Saint Paul, NE	06790500	4,302	X	
Cedar River near Fullerton, NE	06792000	1,220	X	
Beaver Creek at Genoa, NE	06794000	677	X	X
Elkhorn River at Norfolk, NE	06799000	2,790	X	X
Elkhorn River at Waterloo, NE	06800500	6,900	X	X

The model hydrology calibration period was set to Water Years 1989-1999 (within the 30-year period of record for modeling). Hydrologic validation was then performed on Water Years 1978-1988. Water quality data availability is somewhat low for the watershed, and water quality calibration used calendar years 1990-1995, while validation used 1986-1989.

SWAT Modeling

Assumptions

The Sandhills present a major challenge for hydrologic simulation. Previous attempts by USGS (Strauch and Linard, 2009) found that it was very difficult to achieve a good fit to observed flows in the Sandhills region using the SWAT model. Flow in this region of highly permeable soils tends to maintain steady rates driven by groundwater discharge and much of the effort of calibration was focused on obtaining a reasonable representation of this behavior.

There is one major reservoir in the Loup River basin – the Calamus Reservoir, which was included in the model. Two smaller reservoirs (less than 100,000 AF storage) - Sherman Reservoir and Davis Creek Reservoir – were not explicitly modeled. Pertinent information on Calamus Reservoir including surface area and storage at principal (normal) and emergency spillway levels for the reservoirs modeled were obtained from the United Sates Bureau of Reclamation website. The SWAT model provides four options to simulate reservoir outflow: measured daily outflow, measured monthly outflow, average annual release rate for uncontrolled reservoir, and controlled outflow with target release. Keeping in view the 20 Watershed climate change impact evaluation application, it was assumed that the best representation of the reservoirs was to simulate them without supplying time series of outflow records. Therefore, target release approach was used in the GCRP-SWAT model.

The Loup River system has a major water withdrawal (Loup River Power Canal) just before the point of entry into the North Platte River. This withdrawal is represented in the model by monthly average rates and results in substantially lower flows in the Loup River at the mouth than upstream.

Hydrology Calibration

A spatial calibration approach was adopted for GCRP-SWAT modeling for the Loup and Elkhorn River basins. In particular, a distinctly different set of parameters was needed to simulate hydrology in the Sandhills area.

The initial calibration focus area (Elkhorn River) includes 39 subwatersheds, of which about half (the western portion) are in the Sandhills with the remainder more representative of typical plains land use. The Loup River basin also originates in the Sandhills and has similar downstream soils and land uses. The model parameters were adjusted to obtain reasonable fit between the simulated and measured flows in terms of Nash-Sutcliffe modeling efficiency and the high flow and low flow components as well as the seasonal flows.

The water balance was evaluated separately for the Elkhorn and Loup River watersheds. For the Elkhorn, the water balance predicted by the SWAT model over the 32-year simulation period is as follows:

```
PRECIP =    675.6 MM
SNOW FALL =   80.60 MM
SNOW MELT =    79.20 MM
SUBLIMATION =     1.40 MM
SURFACE RUNOFF Q =     0.48 MM
LATERAL SOIL Q =   57.86 MM
TILE Q =     0.00 MM
GROUNDWATER (SHAL AQ) Q =    26.08 MM
REVAP (SHAL AQ => SOIL/PLANTS) =   30.22 MM
DEEP AQ RECHARGE =     8.24 MM
TOTAL AQ RECHARGE =   82.42 MM
TOTAL WATER YLD =    84.42 MM
```

```
PERCOLATION OUT OF SOIL =   84.99 MM
ET =    530.1 MM
PET =   1750.5MM
TRANSMISSION LOSSES =     0.00 MM
```

The water balance for the Loup watershed is summarized as follows:

```
PRECIP =    579.4 MM
SNOW FALL =   77.00 MM
SNOW MELT =    76.25 MM
SUBLIMATION =     0.76 MM
SURFACE RUNOFF Q =     1.15 MM
LATERAL SOIL Q =   10.02 MM
TILE Q =     0.00 MM
GROUNDWATER (SHAL AQ) Q =    45.46 MM
REVAP (SHAL AQ => SOIL/PLANTS) =   25.69 MM
DEEP AQ RECHARGE =    66.73 MM
TOTAL AQ RECHARGE =  156.04 MM
TOTAL WATER YLD =    56.63 MM
PERCOLATION OUT OF SOIL =  158.39 MM
ET =    408.0 MM
PET =   1489.7MM
TRANSMISSION LOSSES =     0.00 MM
```

Hydrologic calibration adjustments focused on the following parameters:

- CN2 (initial SCS runoff curve number for moisture condition II)
- ESCO (soil evaporation compensation factor)
- SURLAG (surface runoff lag coefficient)
- SOL_AWC (available water capacity of the soil layer, mm water/mm of soil)
- ALPHA_BF (baseflow alpha factor, days)
- GW_DELAY (groundwater delay time, days)
- GWQMIN (threshold depth of water in the shallow aquifer required for return flow to occur, mm)
- GW_REVAP (groundwater "revap" coefficient)
- CH_N1 (Manning's "n" value for tributary channels)
- CH_N2 (Manning's "n" value for main channels)
- CH_K1 (Effective hydraulic conductivity in tributary channel alluvium)
- CH_K2 (Effective hydraulic conductivity in main channel alluvium)
- SFTMP (Snowfall temperature)
- SMTMP (Snowmelt base temperature)
- SMFMX (Maximum melt rate for snow during the year)
- SMFMN (Minimum melt rate for snow during the year)
- SOL_CRK (Crack volume potential of soil)

Calibration was performed for water years 1990-1999. Results for the Elkhorn River are summarized in Figure 4, Figure 5, Figure 6, Figure 7, and Table 6. The quality of fit is generally adequate, except that late winter/early spring high flow events tend to be underpredicted.

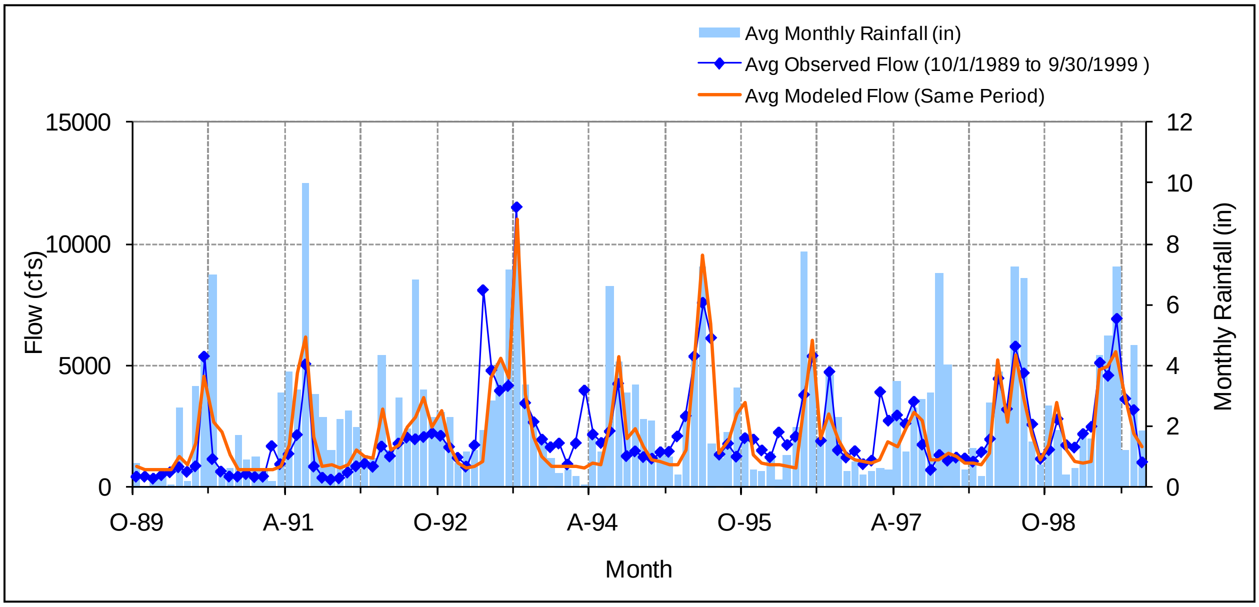

Figure 4. Mean monthly flow at USGS 06800500 Elkhorn River at Waterloo, NE – calibration period

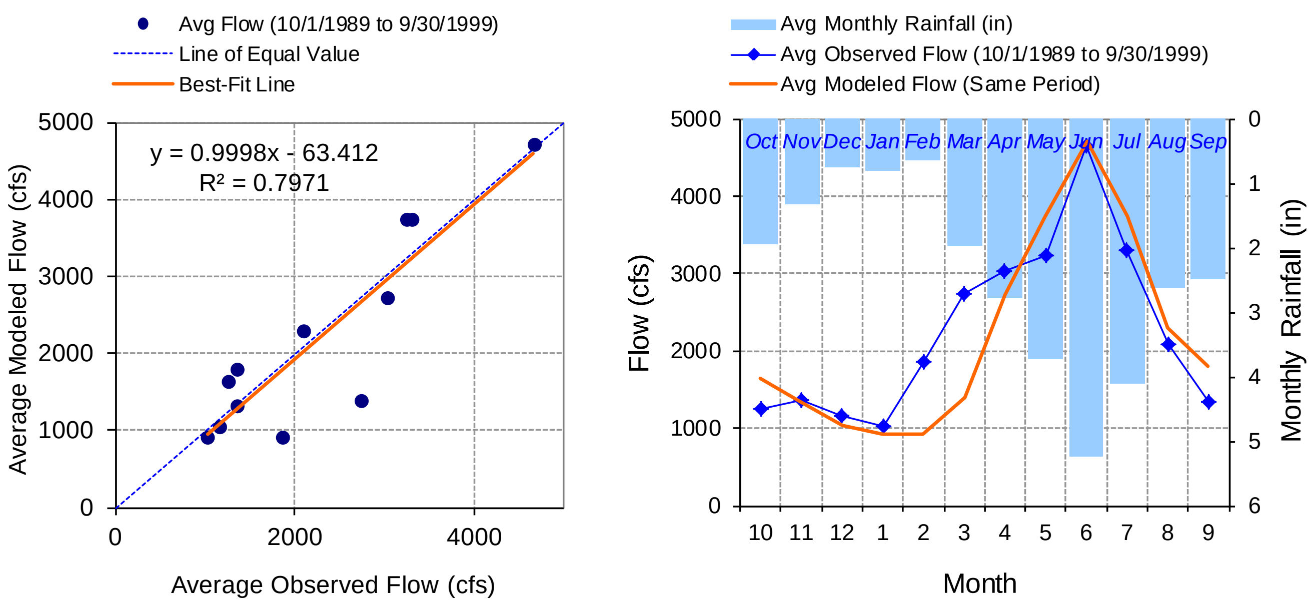

Figure 5. Seasonal regression and temporal aggregate at USGS 06800500 Elkhorn River at Waterloo, NE - calibration period

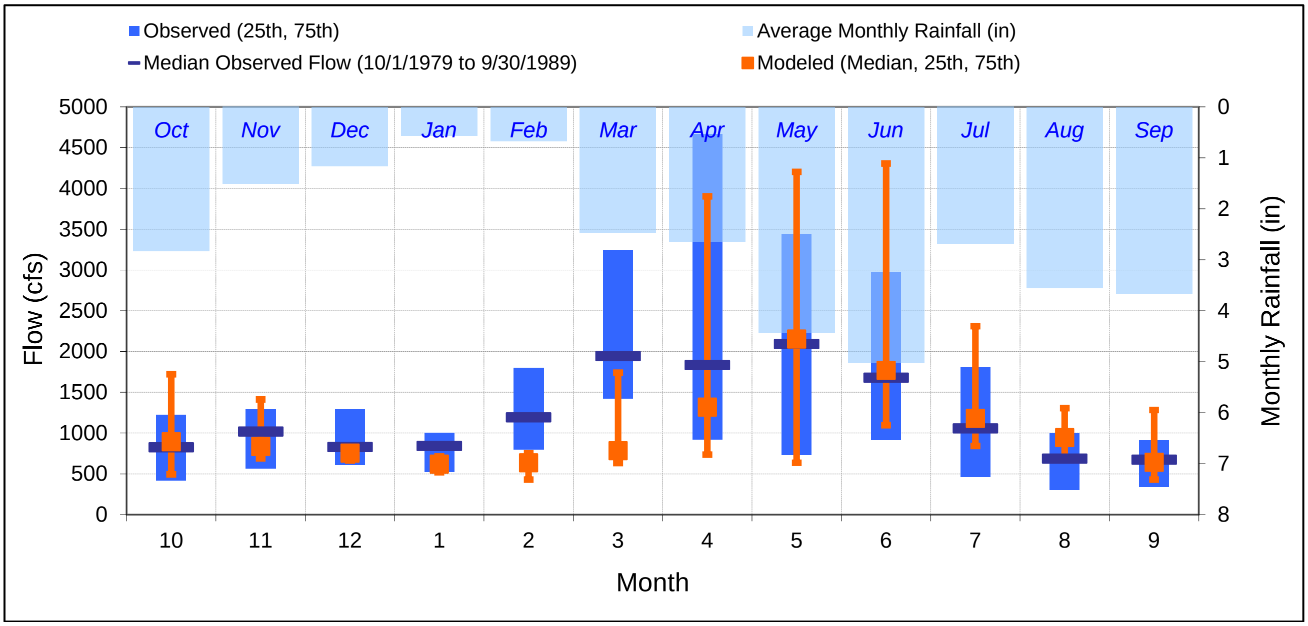

Figure 6. **Seasonal medians and ranges at USGS 06800500 Elkhorn River at Waterloo, NE – calibration period**

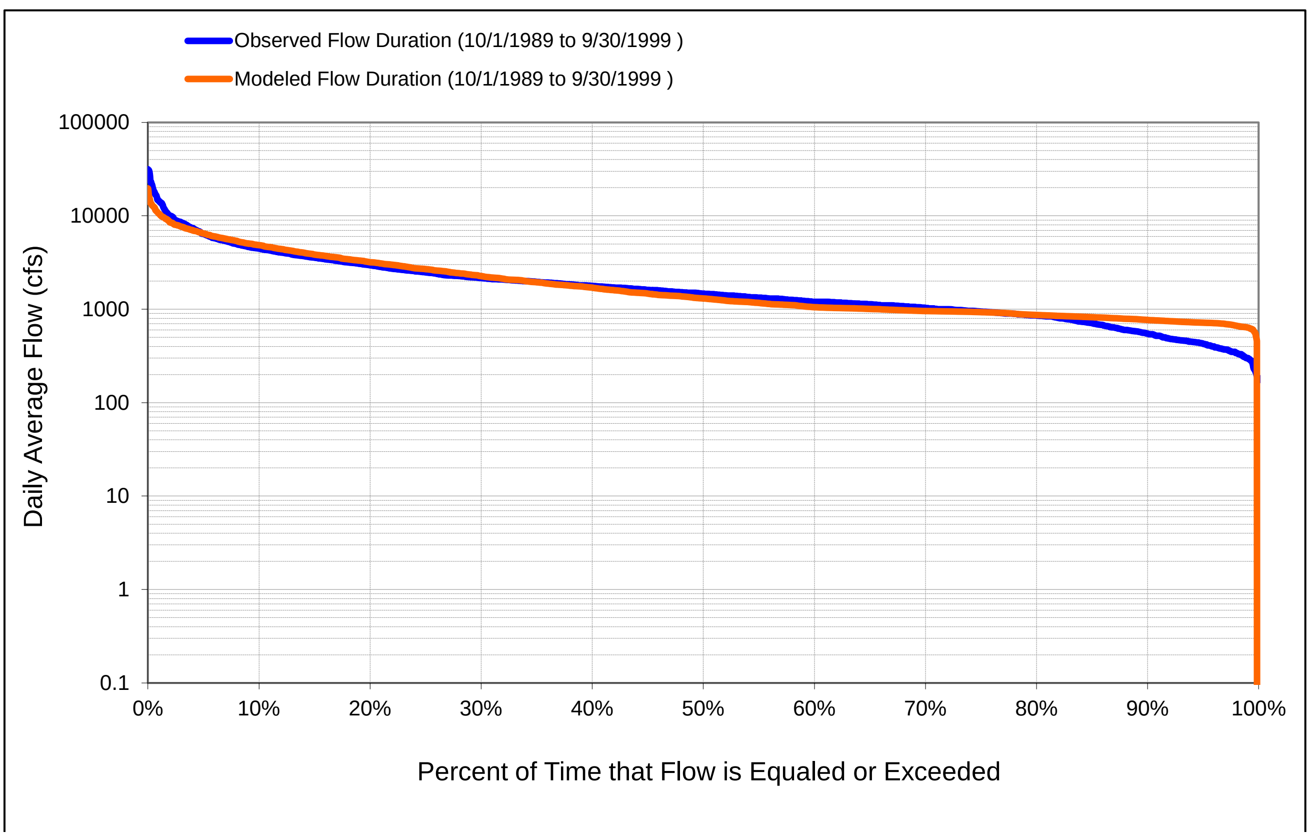

Figure 7. **Flow exceedance at USGS 06800500 Elkhorn River at Waterloo, NE - calibration period**

Table 6. Summary statistics at USGS 06800500 Elkhorn River at Waterloo, NE - calibration period

SWAT Simulated Flow		Observed Flow Gage	
REACH OUTFLOW FROM OUTLET 1 10-Year Analysis Period: 10/1/1989 - 9/30/1999 Flow volumes are (inches/year) for upstream drainage area		USGS 06800500 Elkhorn River at Waterloo, Nebr. Hydrologic Unit Code: 10220003 Latitude: 41.2933333 Longitude: -96.2838889 Drainage Area (sq-mi): 6900	
Total Simulated In-stream Flow:	**4.32**	Total Observed In-stream Flow:	**4.43**
Total of simulated highest 10% flows:	**1.43**	Total of Observed highest 10% flows:	**1.64**
Total of Simulated lowest 50% flows:	**0.91**	Total of Observed Lowest 50% flows:	**0.89**
Simulated Summer Flow Volume (months 7-9):	**1.30**	Observed Summer Flow Volume (7-9):	**1.12**
Simulated Fall Flow Volume (months 10-12):	**0.66**	Observed Fall Flow Volume (10-12):	**0.62**
Simulated Winter Flow Volume (months 1-3):	**0.52**	Observed Winter Flow Volume (1-3):	**0.91**
Simulated Spring Flow Volume (months 4-6):	**1.83**	Observed Spring Flow Volume (4-6):	**1.78**
Total Simulated Storm Volume:	**0.97**	Total Observed Storm Volume:	**1.50**
Simulated Summer Storm Volume (7-9):	**0.31**	Observed Summer Storm Volume (7-9):	**0.44**

Errors (Simulated-Observed)	*Error Statistics*	*Recommended Criteria*
Error in total volume:	-2.59	10
Error in 50% lowest flows:	2.09	10
Error in 10% highest flows:	-12.56	15
Seasonal volume error - Summer:	16.30	30
Seasonal volume error - Fall:	6.89	30
Seasonal volume error - Winter:	**-42.36**	**30**
Seasonal volume error - Spring:	2.58	30
Error in storm volumes:	**-35.47**	**20**
Error in summer storm volumes:	-30.24	50
Nash-Sutcliffe Coefficient of Efficiency, E:	0.416	Model accuracy increases
Baseline adjusted coefficient (Garrick), E':	0.337	as E or E' approaches 1.0
Monthly NSE	0.642	

>> Clear

Hydrology Validation

Hydrology validation for the Elkhorn River was performed for the period water years 1980-1989. The validation achieves a reasonable coefficient of model fit efficiency, but again appears to underpredict winter/spring storm events (Figure 8, Figure 9, Figure 10, Figure 11, and Table 7).

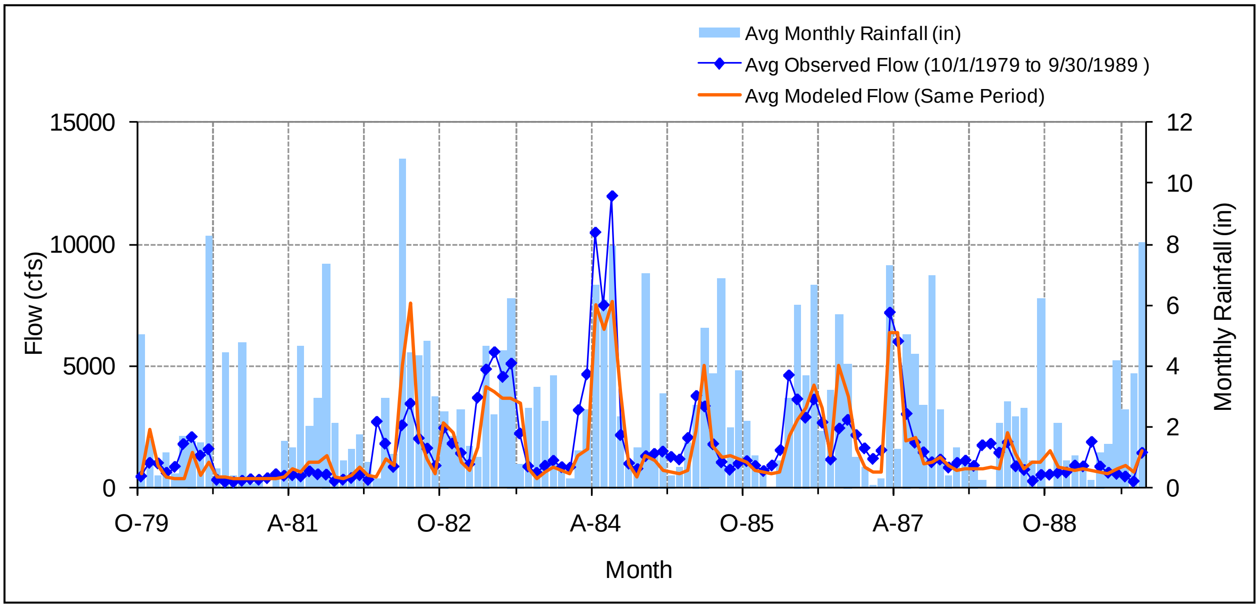

Figure 8. Mean monthly flow at USGS 06800500 Elkhorn River at Waterloo, NE – validation period

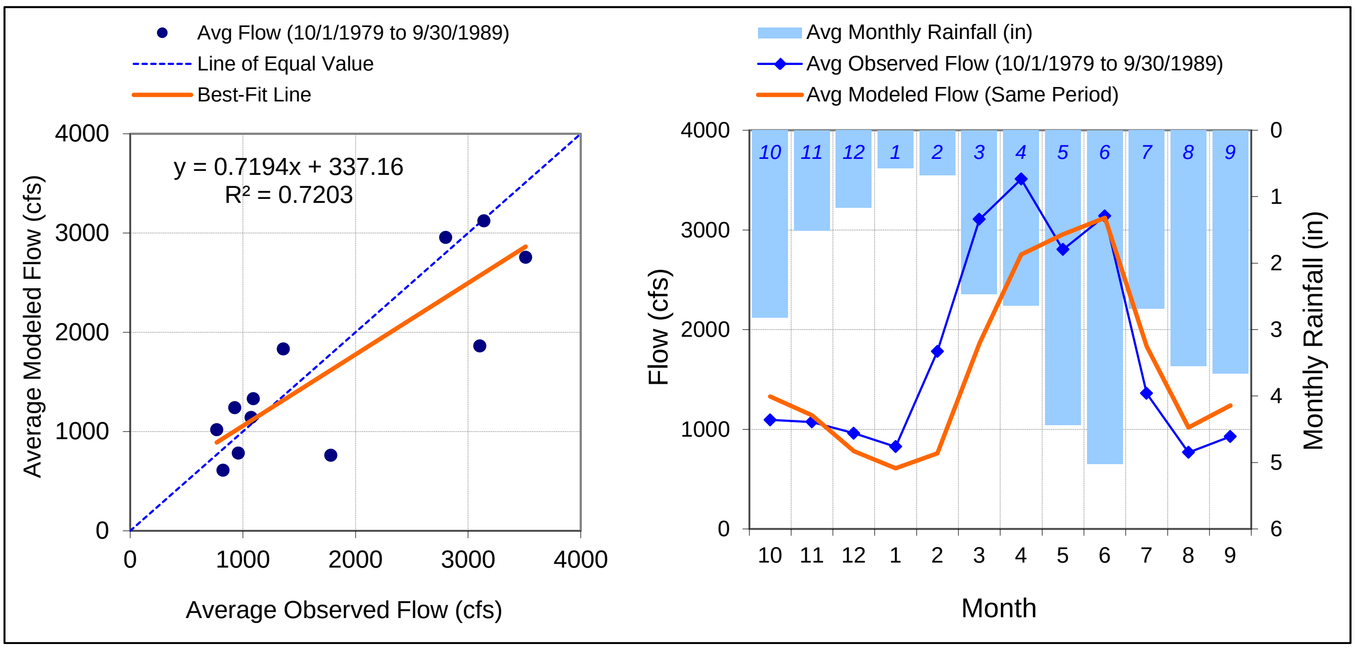

Figure 9. Seasonal regression and temporal aggregate at USGS 06800500 Elkhorn River at Waterloo, NE - validation period

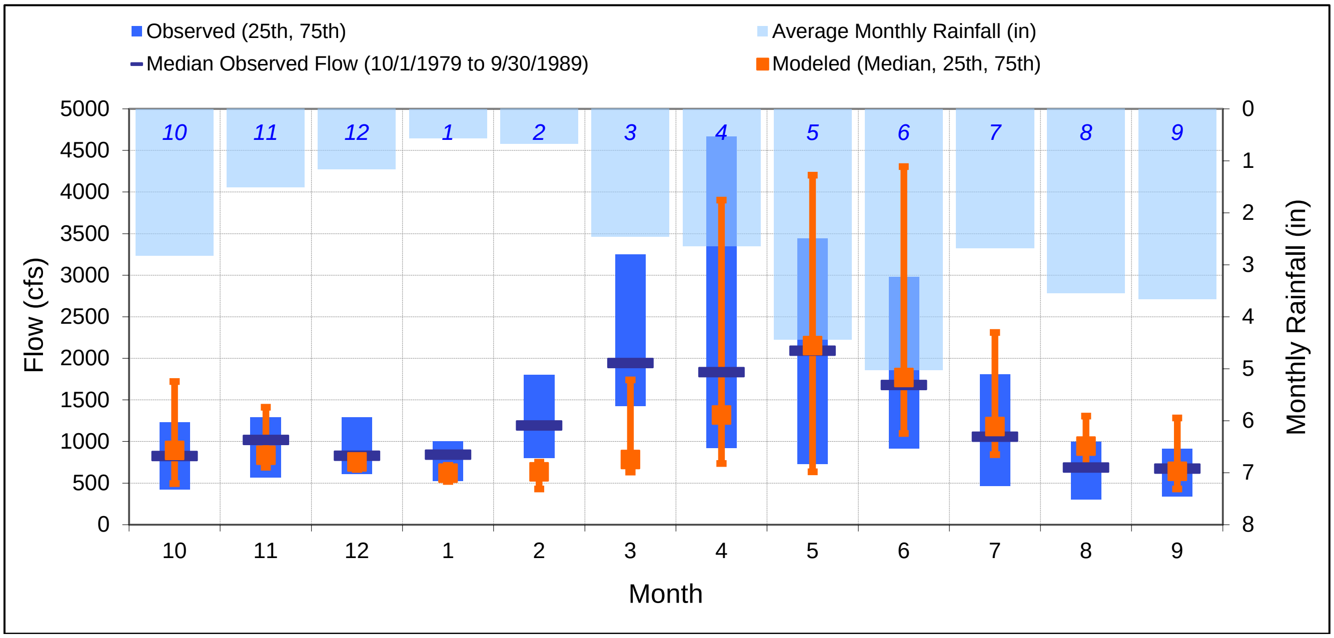

Figure 10. Seasonal medians and ranges at USGS 06800500 Elkhorn River at Waterloo, NE – validation period

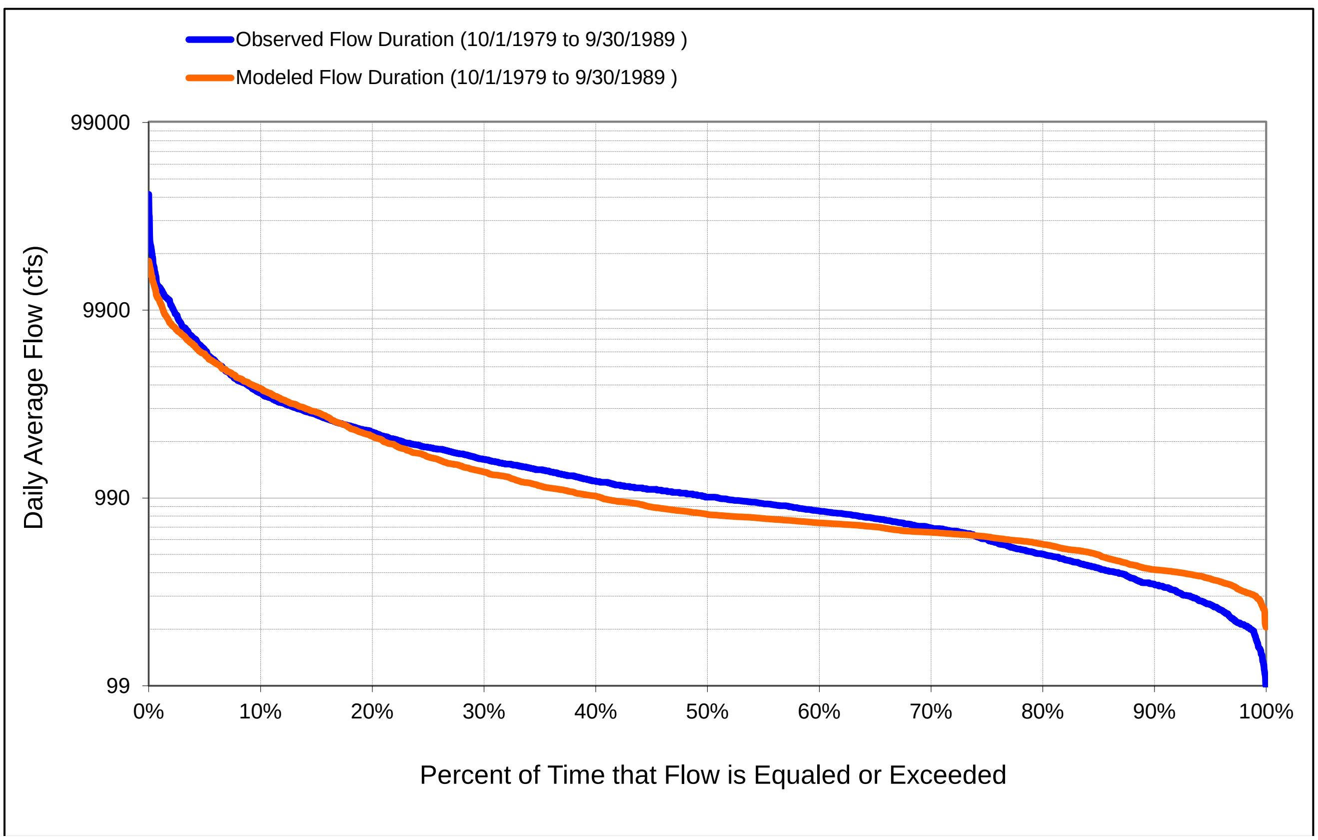

Figure 11. Flow exceedance at USGS 06800500 Elkhorn River at Waterloo, NE - validation period

Table 7. Summary statistics at USGS 06800500 Elkhorn River at Waterloo, NE - validation period

SWAT Simulated Flow		Observed Flow Gage	
REACH OUTFLOW FROM OUTLET 1 10-Year Analysis Period: 10/1/1979 - 9/30/1989 Flow volumes are (inches/year) for upstream drainage area		USGS 06800500 Elkhorn River at Waterloo, Nebr. Hydrologic Unit Code: 10220003 Latitude: 41.2933333 Longitude: -96.2838889 Drainage Area (sq-mi): 6900	
Total Simulated In-stream Flow:	**3.19**	Total Observed In-stream Flow:	**3.49**
Total of simulated highest 10% flows:	**1.32**	Total of Observed highest 10% flows:	**1.50**
Total of Simulated lowest 50% flows:	**0.57**	Total of Observed Lowest 50% flows:	**0.58**
Simulated Summer Flow Volume (months 7-9):	**0.68**	Observed Summer Flow Volume (7-9):	**0.51**
Simulated Fall Flow Volume (months 10-12):	**0.54**	Observed Fall Flow Volume (10-12):	**0.52**
Simulated Winter Flow Volume (months 1-3):	**0.53**	Observed Winter Flow Volume (1-3):	**0.93**
Simulated Spring Flow Volume (months 4-6):	**1.44**	Observed Spring Flow Volume (4-6):	**1.54**
Total Simulated Storm Volume:	**0.76**	Total Observed Storm Volume:	**1.23**
Simulated Summer Storm Volume (7-9):	**0.18**	Observed Summer Storm Volume (7-9):	**0.17**

Errors (Simulated-Observed)	*Error Statistics*	*Recommended Criteria*
Error in total volume:	-8.81	10
Error in 50% lowest flows:	-1.66	10
Error in 10% highest flows:	-12.33	15
Seasonal volume error - Summer:	**33.85**	**30**
Seasonal volume error - Fall:	3.94	30
Seasonal volume error - Winter:	**-43.05**	**30**
Seasonal volume error - Spring:	-6.46	30
Error in storm volumes:	**-38.41**	**20**
Error in summer storm volumes:	3.39	50
Nash-Sutcliffe Coefficient of Efficiency, E:	0.518	Model accuracy increases
Baseline adjusted coefficient (Garrick), E':	0.405	as E or E' approaches 1.0
Monthly NSE	0.701	

Hydrology Results for Larger Watershed

As described above, parameters determined for the Elkhorn gage were not fully transferable to other gages in the watershed, particularly in the Sandhills area. Calibration and validation was pursued at a total of ten gages throughout the watershed. Calibration results are summarized in Table 8. Those watersheds that are dominantly in the Sandhills area tend to show very low Nash-Sutcliffe coefficients of model fit efficiency for daily flows, but high values for monthly flow volumes, reflecting the complex, groundwater-dominated nature of flow in this area. The quality of fit is comparable to that obtained by Strauch and Linard (2009).

Results of the validation exercise are summarized in Table 9. Results are very similar to those obtained during the calibration period, although total volume is underpredicted at several stations.

Table 8. Summary statistics (percent error): all stations - calibration period

Station	06800500 Elkhorn River at Waterloo	067995000 Elkhorn River at Norfolk	06775900 Dismal River nr Thedford, NE	06784000 South Loup River at St. Michael	06785000 Middle Loup River at St. Paul	06786000 North Loup River at Taylor	06790500 North Loup River nr St. Paul	06792000 Cedar River nr Fullerton	06794000 Beaver Creek at Genoa
Error in total volume:	-2.59	8.47	-4.65	2.43	-3.78	-3.45	-2.07	5.07	-3.41
Error in 50% lowest flows:	2.09	28.72	-8.78	17.14	28.06	-4.99	-5.43	22.91	36.21
Error in 10% highest flows:	-12.56	6.49	1.51	-12.61	-28.75	6.93	-11.58	-12.09	-22.87
Seasonal volume error - Summer:	16.30	46.11	-4.90	26.54	43.95	34.75	0.36	26.71	20.98
Seasonal volume error - Fall:	6.89	20.94	-2.06	19.97	-12.90	-8.31	-6.61	15.37	30.25
Seasonal volume error - Winter:	-42.36	-24.17	-6.22	-13.83	-24.49	-21.70	-19.54	-16.91	-18.95
Seasonal volume error - Spring:	2.58	2.54	-5.45	-10.55	-0.68	-6.25	17.45	-0.34	-23.38
Error in storm volumes:	-35.47	-1.22	-37.60	-48.32	-51.06	-35.46	-44.46	-29.99	-18.33
Error in summer storm volumes:	-30.24	41.15	4.52	-23.62	-21.44	-8.13	-24.44	-22.99	1.85
Daily Nash-Sutcliffe Coefficient of Efficiency, E:	0.416	0.441	-1.595	0.239	0.206	-0.214	-0.025	0.140	0.032
Monthly Nash-Sutcliffe Coefficient	0.642	0.664	-2.111	0.451	0.252	-0.345	-0.412	0.383	0.356

Table 9. Summary statistics (percent error): all stations - validation period

Station	06800500 Elkhorn River at Waterloo	067995000 Elkhorn River at Norfolk	06775900 Dismal River nr Thedford, NE	06784000 South Loup River at St. Michael	06785000 Middle Loup River at St. Paul	06786000 North Loup River at Taylor	06790500 North Loup River nr St. Paul	06792000 Cedar River nr Fullerton	06794000 Beaver Creek at Genoa
Error in total volume:	-8.81	-15.83	2.93	-27.91	-21.34	-4.72	-5.74	-10.92	-20.87
Error in 50% lowest flows:	-1.66	-7.47	2.36	-29.93	3.64	-0.85	0.74	-17.86	-4.78
Error in 10% highest flows:	-12.33	-8.08	3.36	-28.29	-40.03	-0.84	-15.43	5.04	-28.94
Seasonal volume error - Summer:	33.85	55.96	4.73	-12.53	28.95	35.58	17.91	24.55	1.07
Seasonal volume error - Fall:	3.94	-2.64	1.79	-20.98	-28.56	-15.38	-8.56	-8.54	-2.33
Seasonal volume error - Winter:	-43.05	-40.10	-0.34	-37.75	-40.63	-23.08	-22.61	-27.14	-36.39
Seasonal volume error - Spring:	-6.46	-25.65	5.58	-32.18	-17.24	-0.91	-2.78	-20.96	-30.28
Error in storm volumes:	-38.41	-11.57	-43.85	-51.73	-53.82	-41.29	-39.38	-9.49	-6.55
Error in summer storm volumes:	3.39	125.83	-26.84	-46.64	-25.11	-16.61	-14.87	28.81	-9.23
Daily Nash-Sutcliffe Coefficient of Efficiency, E:	0.518	0.368	-0.779	0.217	0.105	-0.148	0.031	0.071	-0.051
Monthly Nash-Sutcliffe Coefficient	0.701	0.472	-1.232	0.169	0.022	-0.218	-0.210	0.086	0.149

Water Quality Calibration and Validation

Initial calibration and validation of water quality was done on the Elkhorn River at Waterloo (USGS 06800500), using 1990-1995 for calibration and 1979-1989 for validation. As with hydrology, calibration was performed on the later period as this better reflects the land use included in the model. The start of the validation period is constrained by data availability.

Calibration adjustments for sediment focused on the following parameters:

- SPCON (linear parameter for estimating maximum amount of sediment that can be re-entrained during channel sediment routing)
- SPEXP (exponential parameter for estimating maximum amount of sediment that can be re-entrained during channel sediment routing)
- CH_COV (channel cover factor)
- CH_EROD (channel erodibility factor)
- USLE_P (USLE support practice factor)

Simulated and estimated sediment loads at the Elkhorn River station for both the calibration and validation periods are shown in Figure 12 and statistics for the two periods are provided separately in Table 10. The key statistic in the Table 10 is the relative percent error, which shows the error in the prediction of monthly load normalized to the estimated load. Table 10 also shows the relative average absolute error, which is the average of the relative magnitude of errors in individual monthly load predictions. This number is inflated by outlier months in which the simulated and estimated loads differ by large amounts (which may be as easily due to uncertainty in the estimated load due to limited data as to problems with the model) and the third statistic, the relative median absolute error, is likely more relevant and shows better agreement. Overall, TSS loads seem to be somewhat underpredicted due to the representation of scattered spring high flow events. This likely reflects the underprediction of winter/spring storm flow peaks as noted under the hydrology calibration. Elevated TSS loads during these events is likely attributable to primarily channel scour.

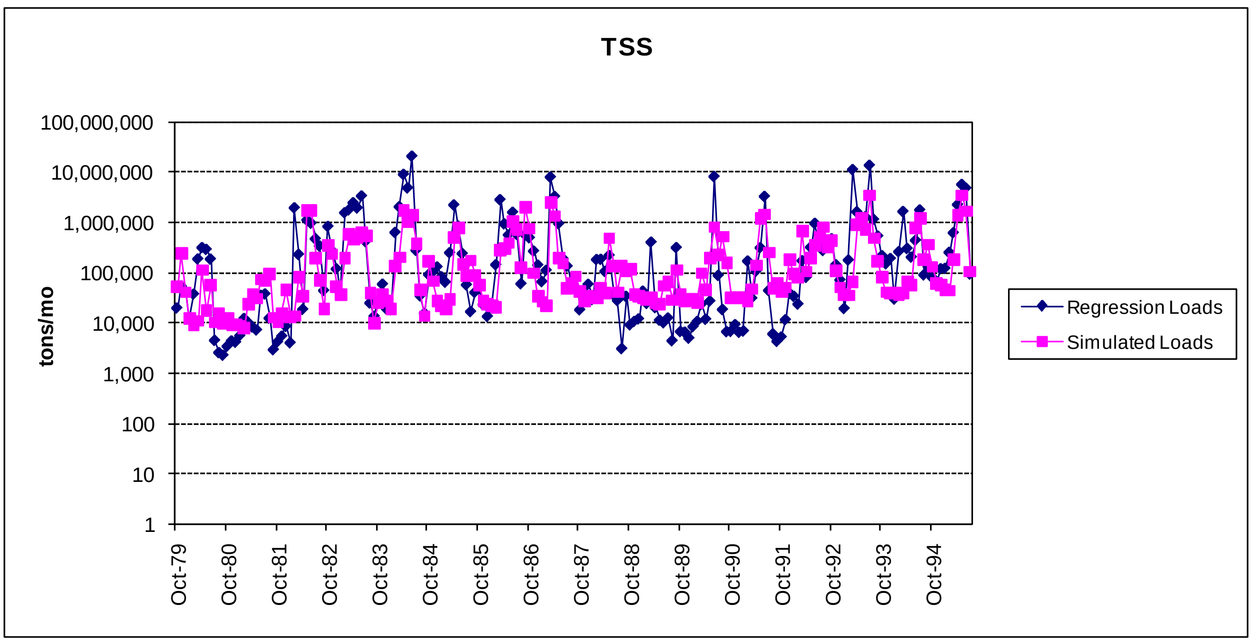

Figure 12. Fit for monthly load of TSS at USGS 06800500 Elkhorn River at Waterloo, NE

Table 10. Model fit statistics (observed minus predicted) for monthly sediment loads using stratified regression at USGS 06800500 Elkhorn River at Waterloo, NE

Statistic	Calibration period (1990-1995)	Validation period (1979-1989)
Relative Percent Error	59.6%	66.8%
Relative Average Absolute Error	73.9%	79.5%
Relative Median Absolute Error	14.3%	7.2%

Calibration adjustments for total phosphorus and total nitrogen focused on the following parameters:

- PHOSKD (phosphorus soil partitioning coefficient)
- PSP (phosphorus availability index)
- RS2 (benthic source rate for dissolved P in the reach at 20^{o} C)
- RS3 (Benthic source rate for NH_4-N in the reach at 20^{o} C)
- RS5 (organic P settling rate in the reach at 20^{o} C)
- BC4 (rate constant for mineralization of organic P to dissolved P in the reach at 20^{o} C)
- RS4 (rate coefficient for organic N settling in the reach at 20^{o} C)
- CH_ONCO (Channel organic nitrogen concentration)
- CH_OPCO (Channel organic phosphorus concentration)

Results for the phosphorus simulation are shown in Figure 13 and Table 11. Results for the nitrogen simulation are shown in Figure 14 and Table 12. The model fit reproduces observed seasonal trends, but appears to underpredict total load, reflecting the underprediction of TSS load.

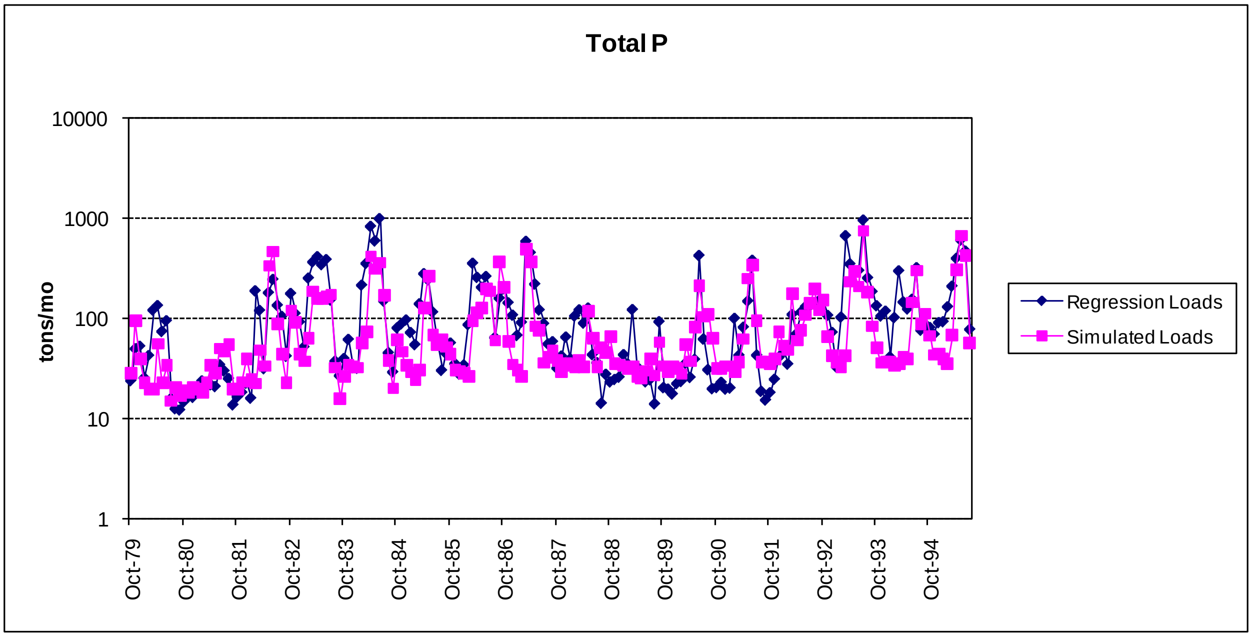

Figure 13. Fit for monthly load of total phosphorus at USGS 06800500 Elkhorn River at Waterloo, NE

Table 11. Model fit statistics (observed minus predicted) for monthly phosphorus loads using stratified regression at USGS 06800500 Elkhorn River at Waterloo, NE

Statistic	Calibration period (1993-2002)	Validation period (1986-1992)
Relative Percent Error	24.2%	34.9%
Average Absolute Error	39.8%	49.7%
Median Absolute Error	26.5%	15.6%

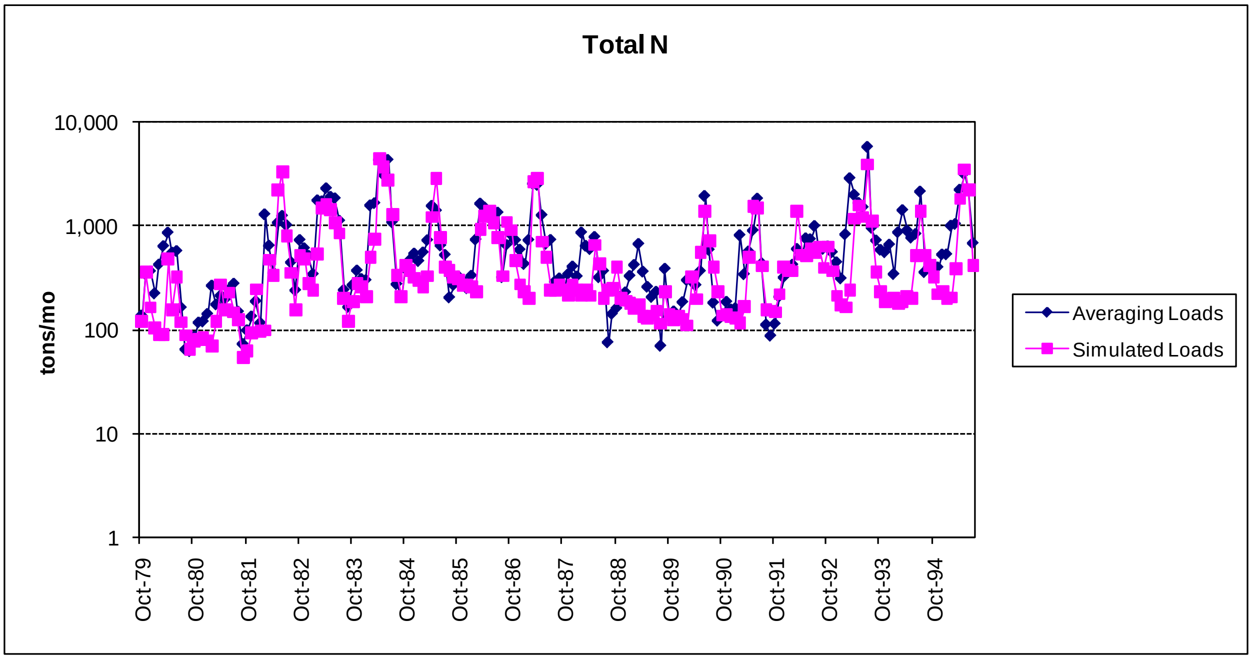

Figure 14. Fit for monthly load of total nitrogen at USGS 06800500 Elkhorn River at Waterloo, NE

Table 12. Model fit statistics (observed minus predicted) for monthly total nitrogen loads using averaging estimator at USGS 06800500 Elkhorn River at Waterloo, NE

Statistic	Calibration period (1993-2002)	Validation period (1986-1992)
Relative Percent Error	28.1%	18.1%
Average Absolute Error	39%	38%
Median Absolute Error	22.3%	19.2%

Water Quality Results for Larger Watershed

The Elkhorn River watershed SWAT model parameters for water quality were directly transferred to other portions of the watershed. Only very limited amounts of water quality data are readily available for the remainder of the watershed. Comparison to the data that are available suggests the model may underpredict loads associated with large flow events at other stations as well. Summary statistics for the SWAT water quality calibration other stations in the watershed are provided in Table 13. Insufficient monitoring data were readily available to provide additional validation tests.

Table 13. Summary statistics for water quality at all stations – calibration period 1993-2002

Station	06800500 Elkhorn River at Waterloo	06799000 Elkhorn River at Norfolk	06794000 Beaver Creek at Genoa
Relative Percent Error TSS Load	59.6%	ND	ND
Relative Percent Error TP Load	24.2%	35.8%	54.4%
Relative Percent Error TN Load	28.1%	35.5%	25.3%

References

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Appendix L
Model Configuration, Calibration and Validation

Basin: Cook Inlet (Cook)

Contents

Tables

Figures

Watershed Background

The Cook Inlet watershed was selected as one of the 15 non-pilot application watersheds for the 20 Watershed study. Watershed modeling for the non-pilot areas was accomplished using the SWAT model only and model calibration and validation results are presented in abbreviated form.

Water Body Characteristics

The Cook Inlet stretches 180 miles (290 km) from the Gulf of Alaska to Anchorage in south-central Alaska. The watershed draining to Cook Inlet covers 47,000 square miles east of the Aleutian Range and south of the Alaska Range including the drainage area of Mount McKinley (Figure 1). The model area includes seven HUC8s within HUC 1902, encompassing about 22,200 mi^2 of the Cook Inlet watershed. The Cook Inlet watershed receives water from its tributaries the Kenai, the Susitna and Matanuska rivers from the melting snow and ice from Mount McKinley, the Chugach Mountains, and the Aleutian Range. Cook Inlet branches into the Knik Arm and Turnagain Arm at its northern end, almost surrounding Anchorage.

The watershed is dominated by igneous rocks in the mountains and by continental shelf and alluvial deposits in the lowlands. Glaciation has dramatically altered the landscape and glaciers are extensive on the southeastern and northwestern boundaries of the watershed. Five physiographic regions – grading from plains and lowlands to extremely high rugged mountains – are represented in the watershed. Altitude ranges from sea level to 20,320 ft at the highest point in North America, Mount McKinley. Rugged mountains surround Cook Inlet and include four active volcanoes on the western side of the inlet. Precipitation is closely associated with altitude and ranges from about 15 to more than 200 inches annually (USGS, 2008b).

Numerous river systems drain the watershed, including the Susitna, Matanuska, and Kenai Rivers. The largest river, the Susitna, drains about half of the watershed. Most rivers have relatively small drainages but yield large quantities of water because of substantial snowfall in the mountains. Many streams are fed by glaciers and have different physical characteristics than streams that do not have glacial contributions. Glacier-fed streams have periods of sustained high flow during summers and are more turbid than streams lacking glacial contributions. Numerous wetlands and lakes also influence the physical and chemical characteristics of streams by moderating peak flows and trapping sediment and nutrients.

Land cover in the model area is dominated by forests (24 percent), shrubland (38 percent), and barren land (19 percent). Glaciers cover 8 percent of the area, and lakes and wetlands cover another 10 percent. Less than 1 percent of the basin is used for agricultural purposes. The Municipality of Anchorage dominates the urban and residential features of the basin; however, the total urban and residential land cover is less than 1 percent of the basin. More than half of the state's population lives in the metropolitan Anchorage area. Expansion of suburban areas continues to the north of Anchorage and residential density is increasing throughout the municipality. The remainder of the basin is largely unpopulated; however, native villages exist at a number of locations.

Watersheds of the Cook Inlet basin are largely undeveloped and contain parts of four national parks totaling about 6,300 mi^2. Nearly 1,800 mi^2 of the Chugach National Forest and the 3,000 mi^2 Kenai National Wildlife Refuge also are within the boundaries of the watershed.

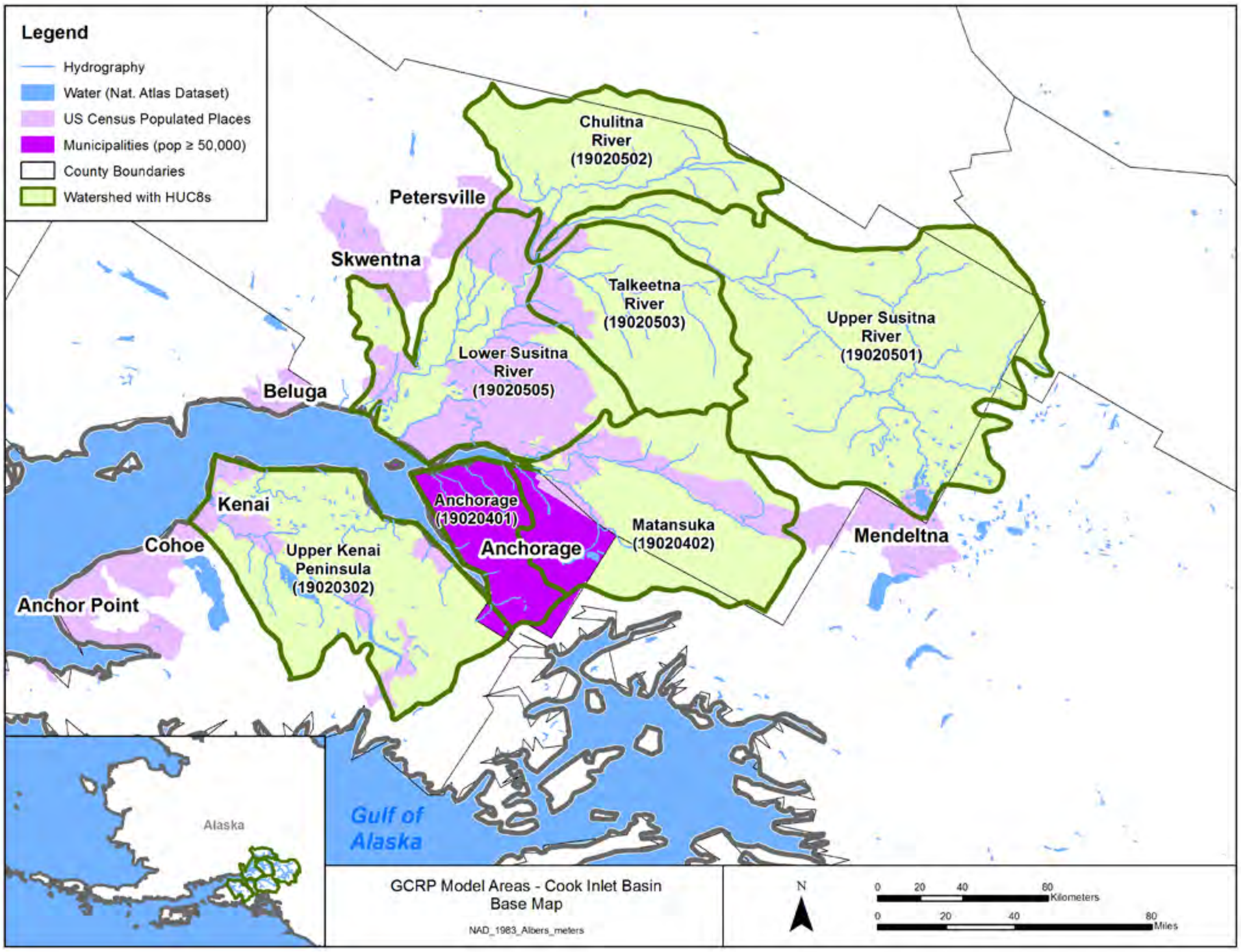

Figure 1. Location of the Cook Inlet watershed.

Soil Characteristics

Soils in the watershed, as described in STATSGO soil surveys, fall primarily into hydrologic soil groups (HSGs) B (moderately high infiltration capacity) and D (low infiltration capacity). SWAT uses information drawn directly from the soils data layer to populate the model.

Land Use Representation

Land use/cover in the watershed is based on the 2001 National Land Cover Database (NLCD) coverage and is predominantly rangeland (Figure 2). NLCD land cover classes were aggregated according to the scheme shown in Table 1 for representation in the 20 Watershed model. SWAT uses the built-in hydrologic response unit (HRU) overlay mechanism in the ArcSWAT interface. SWAT HRUs are formed from an intersection of land use and SSURGO major soils. The distribution of land use in the watershed is summarized in Table 2.

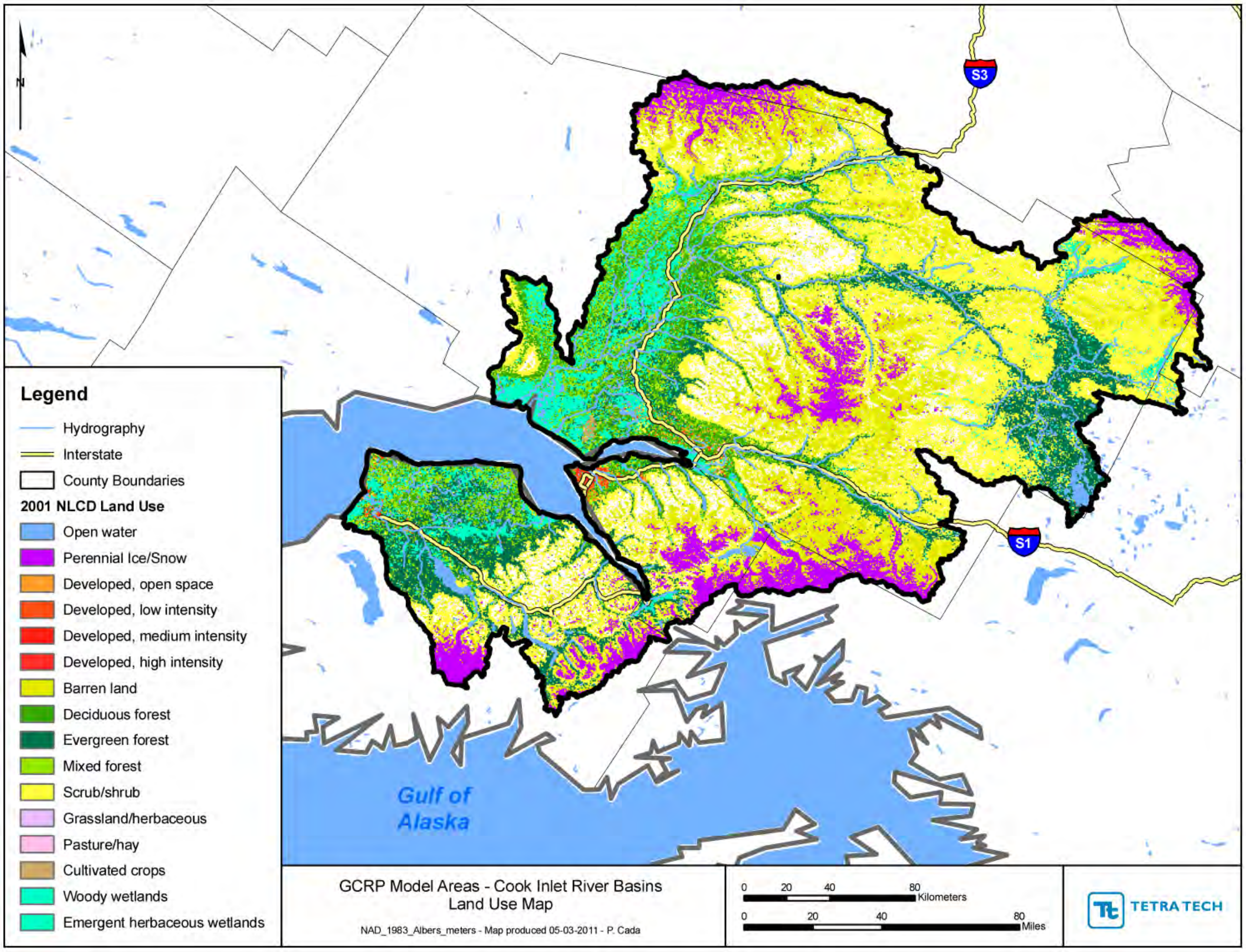

Figure 2. Land use in the Cook Inlet watershed.

Table 1. Aggregation of NLCD land cover classes

NLCD Class	Comments	SWAT class
11 Water	Water surface area usually accounted for as reach area	WATR
12 Perennial ice/snow		WATR
21 Developed open space		URLD
22 Dev. Low Intensity		URMD
23 Dev. Med. Intensity		URHD
24 Dev. High Intensity		UIDU
31 Barren Land		SWRN
41 Forest	Deciduous	FRSD
42 Forest	Evergreen	FRSE
43 Forest	Mixed	FRST
51-52 Shrubland		RNGB
71-74 Herbaceous Upland		RNGE
81 Pasture/Hay		HAY
82 Cultivated		AGRR
91-97 Wetland	Emergent & woody wetlands	WETF, WETL, WETN
98-99 Wetland	Aquatic bed wetlands (not emergent)	WATR

Table 2. Land use distribution for the Cook Inlet watershed (2001 NLCD) (mi^2)

HUC 8 watershed	Open water	Snow/Ice	Developed[a] Open space	Developed[a] Low density	Developed[a] Medium density	Developed[a] High density	Barren land	Forest	Shrubland/ Herbaceous	Pasture/Hay	Cultivated	Wetland	Total
Upper Kenai Peninsula **19020302**	173.02	267.71	12.15	19.40	3.51	1.45	323.25	1,439.93	1,049.19	0.77	2.20	353.91	**3,646.48**
Anchorage **19020401**	8.44	115.51	20.60	35.73	15.43	6.13	161.42	202.26	430.64	0.67	0.67	32.80	**1,030.29**
Matansuka **19020402**	46.94	622.93	6.85	8.65	1.07	0.17	1,323.82	384.32	1,018.62	5.36	1.57	65.32	**3,485.63**
Upper Susitna River **19020501**	174.21	171.92	0.82	1.57	0.01	0.00	951.59	1,119.99	3,399.62	0.01	0.00	244.20	**6,063.93**
Chulitna River **19020502**	37.54	258.50	0.56	1.17	0.06	0.01	780.26	330.32	862.14	0.00	0.00	72.82	**2,343.37**
Talkeetna River **19020503**	16.67	258.25	0.76	0.21	0.03	0.01	492.99	384.80	1,141.99	0.80	0.43	28.20	**2,325.13**
Lower Susitna River **19020505**	110.38	17.59	21.47	22.71	2.17	0.36	186.08	1,499.68	555.86	2.69	19.16	890.55	**3,328.70**
Total	**567.20**	**1,712.40**	**63.21**	**89.44**	**22.26**	**8.13**	**4,219.40**	**5,361.30**	**8,458.06**	**10.30**	**24.02**	**1,687.80**	**22,223.53**

[a]The percent imperviousness applied to each of the developed land uses is as follows: open space (10.11%), low density (29.79%), medium density (61.48%), and high density (87.17%).

Point Sources

There are only two point source discharges in the watershed. Only the major dischargers, with a design flow greater than 1 MGD are included in the simulation (Table 3). The major dischargers are represented at long-term average flows, without accounting for changes over time or seasonal variations.

Table 3. Major point source discharges in the Cook Inlet watershed

NPID	NAME	Design Flow (MGD)	Observed Flow (MGD)
AK0022543	ANCHORAGE, MUNICIPALITY OF	2.5	1.843066667
AK0047856	ANCHORAGE, MUNICIPALITY OF	0.6	0.3767

The point sources were initially represented in the model with the median of reported values for TSS and an assumed total nitrogen concentration of 11.2 mg/L and assumed total phosphorus concentration of 7.0 mg/L for secondary treatment facilities (Tetra Tech 1999).

Meteorological Data

The required meteorological time series needed for the 20 Watershed SWAT simulations are precipitation and air temperature. The 20 Watershed simulations do not include water temperature simulation and use a degree-day method for snowmelt. SWAT estimates Penman-Monteith potential evapotranspiration using a statistical weather generator for inputs other than temperature and precipitation. These meteorological time series are drawn from the BASINS4 Meteorological Database (USEPA 2008), which provides a consistent, quality-assured set of nationwide data with gaps filled and records disaggregated. Scenario application requires simulation over 30 years, so the available stations are those with a common 30-year period of record (or one that can be filled from an approximately co-located station) that covers the year 2001. A total of 14 precipitation stations were identified for use in the Cook Inlet model with a common period of record of 10/1/1972-9/30/2002 (Table 4). Temperature records are sparser; where these are absent temperature was taken from nearby stations with an elevation correction.

Table 4. Precipitation stations for the Cook Inlet watershed model

ID	Name	Latitude	Longitude	Elevation	Temperature
500243	AK500243	60.9584	-149.1100	83	Yes
500280	AK500280	61.1954	-150.0030	40	Yes
500302	AK500302	61.6245	-149.3390	140	Yes
500707	AK500707	61.5678	-149.1380	46	Yes
501926	AK501926	62.8293	-149.8960	433	Yes
502144	AK502144	60.3925	-149.6660	154	Yes
503299	AK503299	61.1001	-149.6930	689	Yes
504546	AK504546	60.5798	-151.2390	28	Yes
505733	AK505733	61.5665	-149.2540	52	Yes
506870	AK506870	61.4222	-149.0990	67	Yes
508371	AK508371	60.1040	-149.4430	34	Yes
508594	AK508594	62.0303	-146.6920	701	Yes
508976	AK508976	62.3201	-150.0940	107	Yes
509790	AK509790	61.7067	-149.9970	82	Yes

Watershed Segmentation

The Cook Inlet watershed was divided into 116 subwatersheds for the purposes of modeling (Figure 3). The model encompasses the complete watershed and does not require specification of any upstream boundary conditions for application.

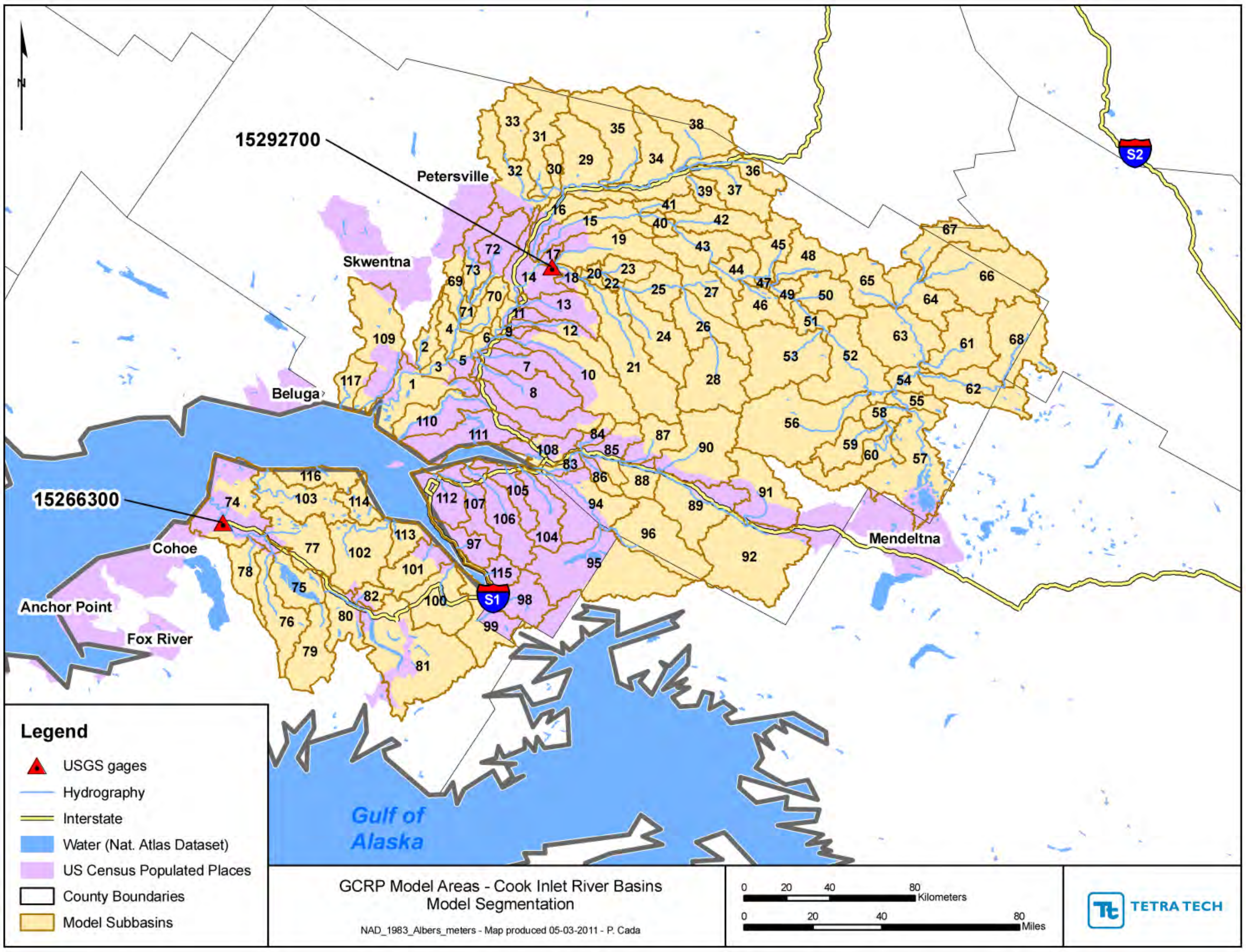

Figure 3. Model segmentation and USGS stations utilized for the Cook Inlet watershed.

Calibration Data and Locations

The specific site chosen for initial calibration was at the USGS station at the Kenai River at Soldotna, AK. Calibration and validation were pursued at two locations (Table 5).

Table 5. Calibration and validation locations in the Cook Inlet watershed

Station name	USGS ID	Drainage area (mi^2)	Hydrology calibration	Water quality calibration
Kenai River at Soldotna	15266300	1951	X	X
Talkeetna River near Talkeetna	15292700	1996	X	X

The model hydrology calibration period was set to Water Years 1992-2001 (within the 30-year period of record for modeling). Hydrologic validation was then performed on Water Years 1982-1991. Water quality calibration used calendar years 1985-2001, while validation used 1972-1984. However, there was some variation to this time period across the monitoring stations depending on the availability of monitored data.

SWAT Modeling

Assumptions

Two major reservoirs occur in the Cook Inlet watershed. Pertinent reservoir information including surface area and storage at principal (normal) and emergency spillway levels for the reservoirs modeled were obtained from the National Inventory of Dams (NID) database. The SWAT model provides four options to simulate reservoir outflow: measured daily outflow, measured monthly outflow, average annual release rate for uncontrolled reservoir, and controlled outflow with target release. Keeping in view the 20 Watershed climate change impact evaluation application, it was assumed that the best representation of the reservoirs was to simulate them without supplying time series of outflow records. Therefore, the target release approach was used in the GCRP-SWAT model.

Elevation bands were also created in the subwatersheds where elevation was above 500 m to account for the impact of higher elevation. Additionally, regions of permafrost were identified within the watershed and were accounted for by adding initial snow water content in the elevation bands.

Hydrology Calibration

A spatial calibration approach was adopted for GCRP-SWAT modeling for the Cook Inlet watershed; however, adjustments to specific subwatersheds were kept as minimal as possible. Moreover, a systematic adjustment of parameters was adopted and some adjustments were applied throughout the watershed. Most of the calibration efforts were geared toward getting a closer match between simulated and observed flows at one of the USGS gaging stations in the watershed.

Land Use / Soil / Slope Definition

A 5/10/5 percent threshold was used for land use/soil/slope in the SWAT model while defining the HRUs. Urban land use classes were exempted from the HRU overlay thresholds.

The parameters were adjusted within the practical range at the calibration focus area to obtain reasonable fit between the simulated and measured flows in terms of Nash-Sutcliffe modeling efficiency and the high flow and low flow components as well as the seasonal flows.

The water balance of the whole Cook Inlet watershed predicted by the SWAT model over the 30-year simulation period is as follows:

```
PRECIP =    653.3 MM
SNOW FALL =  351.55 MM
SNOW MELT =   544.51 MM
SUBLIMATION =    54.10 MM
SURFACE RUNOFF Q =    99.35 MM
LATERAL SOIL Q =  310.36 MM
TILE Q =     0.00 MM
GROUNDWATER (SHAL AQ) Q =   225.36 MM
REVAP (SHAL AQ => SOIL/PLANTS) =    6.71 MM
DEEP AQ RECHARGE =    26.93 MM
TOTAL AQ RECHARGE =  269.25 MM
TOTAL WATER YLD =   634.47 MM
```

```
PERCOLATION OUT OF SOIL =  269.04 MM
ET =    187.1 MM
PET =    405.8MM
TRANSMISSION LOSSES =     0.60 MM
```

Hydrologic calibration adjustments focused on the following parameters:

- Snow parameters SMTMP, SMFMX, SMFMN, TIMP
- Sol_AWC (available water capacity of the soil layer, mm water/mm of soil)
- Baseflow factor
- GW_DELAY (groundwater delay time)
- GWQMN (threshold depth of water in the shallow aquifer required for return flow to occur)
- SHALLST (Initial depth of water in the shallow aquifer)
- RevapMN (threshold depth of water in the shallow aquifer required for "revap" or percolation to the deep aquifer to occur
- Rchrg_DP
- CH_K2 (channel hydraulic conductivity)
- NDTarg
- Curve Number
- Temperature Lapse Rate
- Precipitation Lapse Rate

Calibration results for the Cook Inlet at Kenai River near Soldotna are summarized in the following Figures 4 through 7 and Table 6. In general, the model captured the timing of the peaks well but tends to underestimate both the high flows and the base flows resulting in overall underestimation of total volume by 18 percent (Figure 4, and Table 6).

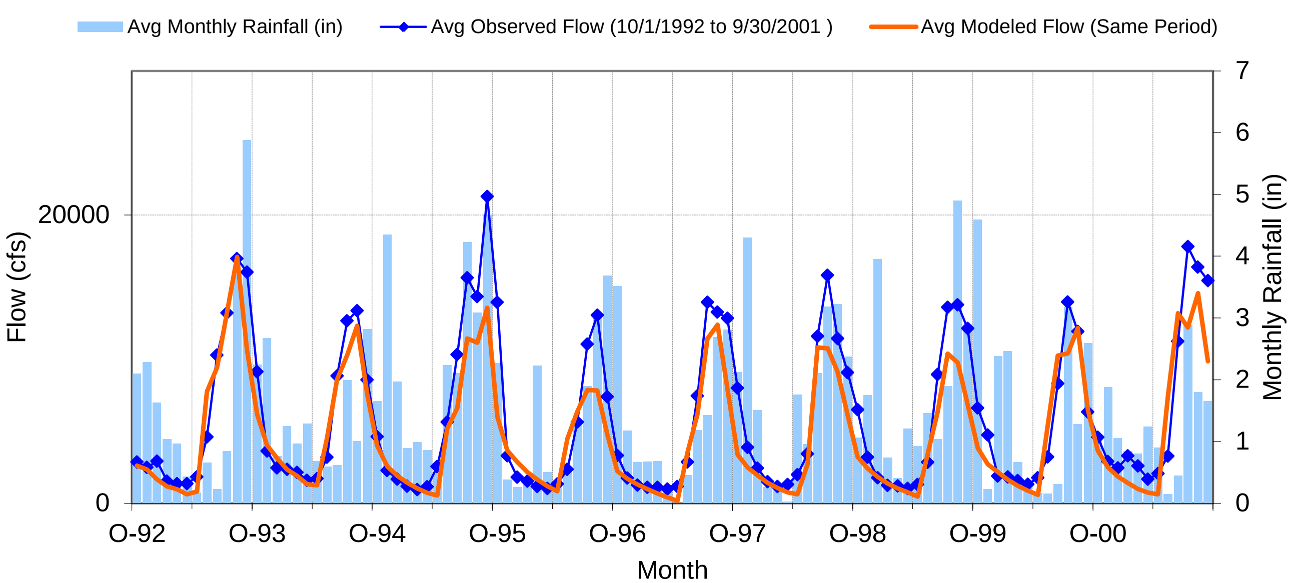

Figure 4. Mean monthly flow at USGS 15266300 Kenai River at Soldotna, AK - calibration period.

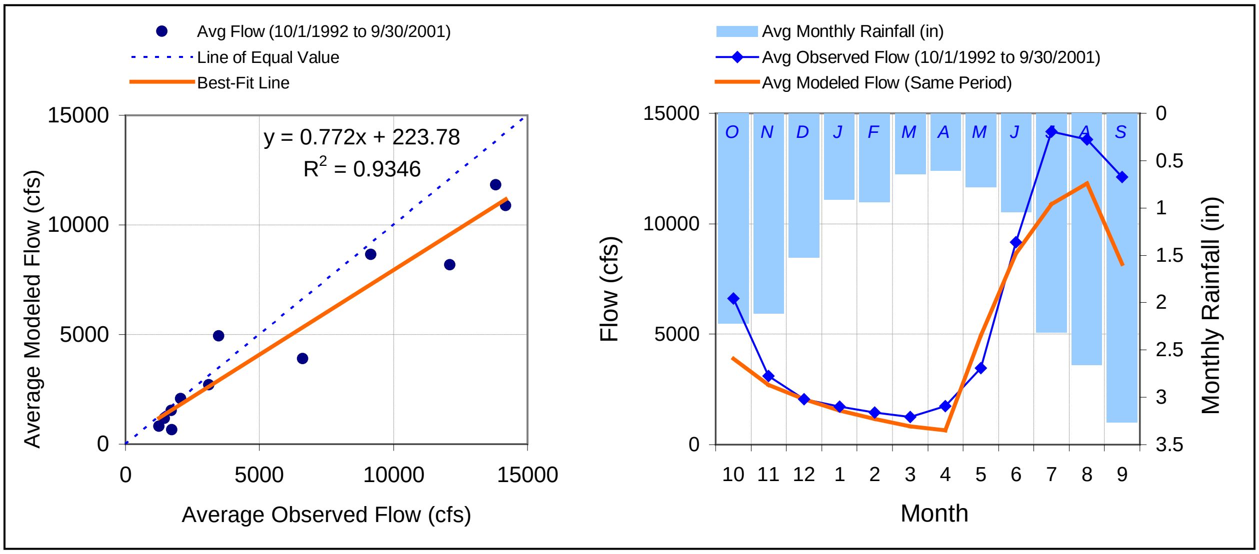

Figure 5. **Seasonal regression and temporal aggregate at USGS 15266300 Kenai River at Soldotna, AK - calibration period.**

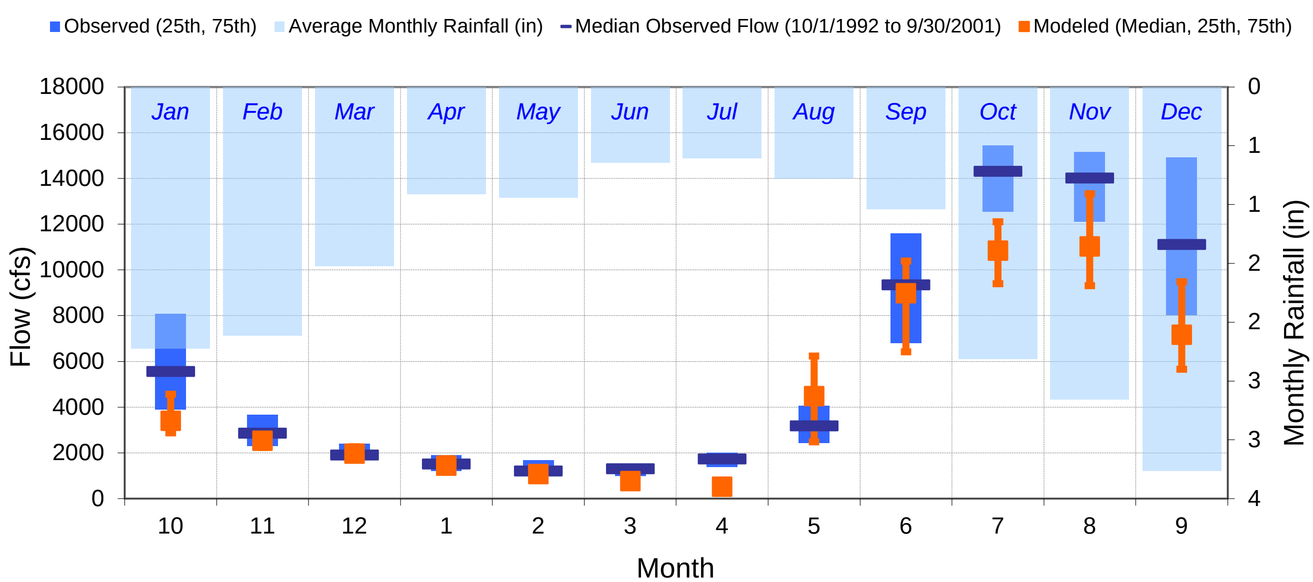

Figure 6. **Seasonal medians and ranges at USGS 15266300 Kenai River at Soldotna, AK - calibration period.**

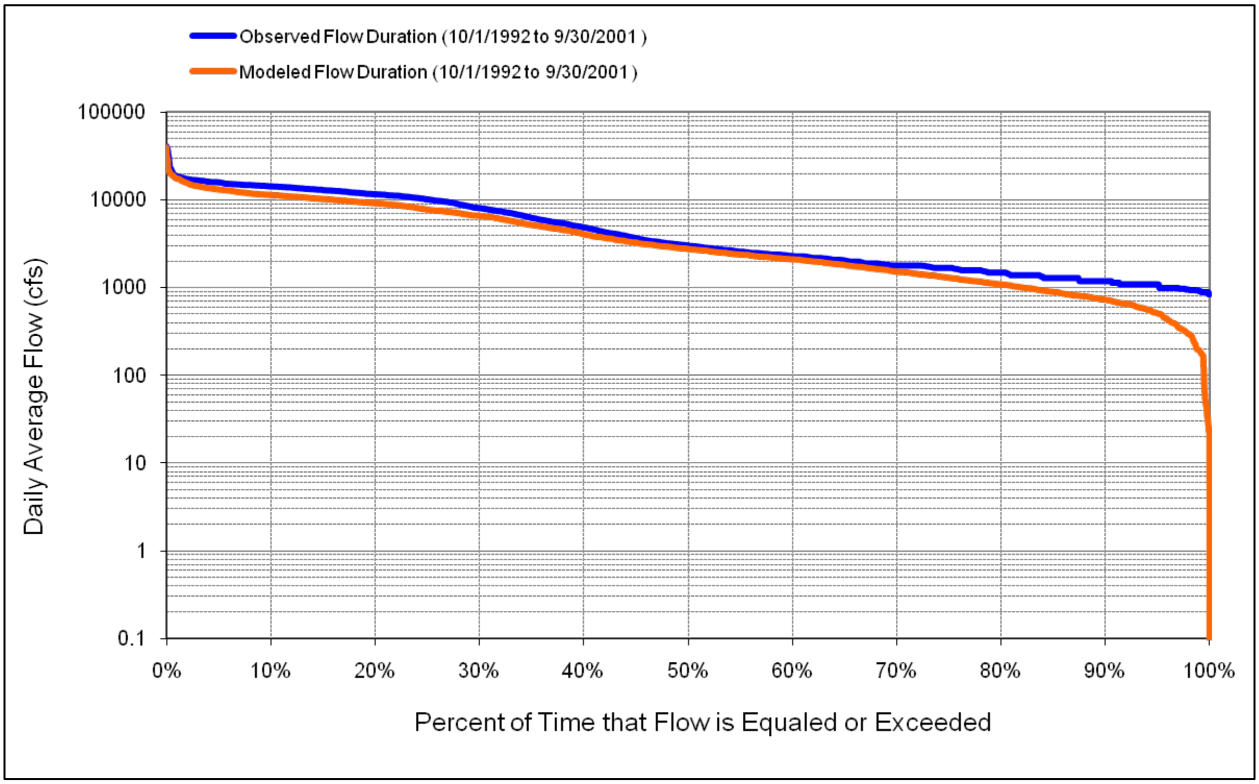

Figure 4. Flow exceedance at USGS 15266300 Kenai River at Soldotna, AK - calibration period.

Table 6. Summary statistics at USGS 15266300 Kenai River at Soldotna, AK - calibration period

SWAT Simulated Flow		Observed Flow Gage	
REACH OUTFLOW FROM OUTLET 74 9-Year Analysis Period: 10/1/1992 - 9/30/2001 Flow volumes are (inches/year) for upstream drainage area		USGS 15266300 Kenai R at Soldotna, AK Hydrologic Unit Code:19020302 Latitude: 60.4775 Longitude: -151.0738 Drainage Area (sq-mi): 1951	
Total Simulated In-stream Flow:	**21.27**	Total Observed In-stream Flow:	**26.24**
Total of simulated highest 10% flows:	**6.31**	Total of Observed highest 10% flows:	**7.52**
Total of Simulated lowest 50% flows:	**3.07**	Total of Observed Lowest 50% flows:	**3.87**
Simulated Summer Flow Volume (months 7-9):	**11.52**	Observed Summer Flow Volume (7-9):	**14.95**
Simulated Fall Flow Volume (months 10-12):	**3.22**	Observed Fall Flow Volume (10-12):	**4.40**
Simulated Winter Flow Volume (months 1-3):	**1.29**	Observed Winter Flow Volume (1-3):	**1.62**
Simulated Spring Flow Volume (months 4-6):	**5.24**	Observed Spring Flow Volume (4-6):	**5.28**
Total Simulated Storm Volume:	**3.41**	Total Observed Storm Volume:	**2.29**
Simulated Summer Storm Volume (7-9):	**1.85**	Observed Summer Storm Volume (7-9):	**1.22**

Errors (Simulated-Observed)	*Error Statistics*	*Recommended Criteria*		
Error in total volume:	**-18.96**	**10**		
Error in 50% lowest flows:	**-20.69**	**10**		
Error in 10% highest flows:	**-16.10**	**15**		
Seasonal volume error - Summer:	-22.93	30		
Seasonal volume error - Fall:	-26.68 >>	30	Clear	
Seasonal volume error - Winter:	-20.76	30		
Seasonal volume error - Spring:	-0.72	30		
Error in storm volumes:	**48.87**	**20**		
Error in summer storm volumes:	**51.66**	**50**		
Nash-Sutcliffe Coefficient of Efficiency, E:	0.684	Model accuracy increases		
Baseline adjusted coefficient (Garrick), E':	0.592	as E or E' approaches 1.0		
Monthly NSE	0.800			

Hydrology Validation

Hydrology validation for the Cook Inlet was performed for the period 10/1/1983 through 9/30/1992. Results are presented in Figures 8 through 11 and Table 7. The validation achieves a high coefficient of model fit efficiency, but is over predicted on 50 percent low volume, fall and winter volume and thereby the total flow is also overpredicted (Figure 5, Table 7).

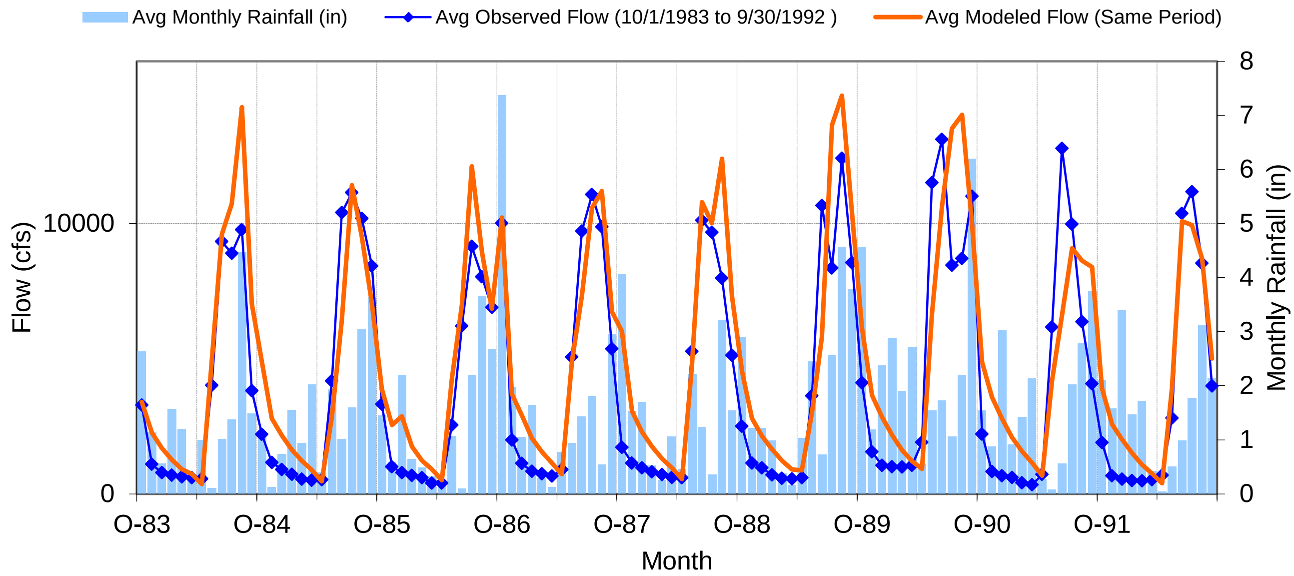

Figure 8. Mean monthly flow at USGS 15266300 Kenai River at Soldotna, AK - validation period.

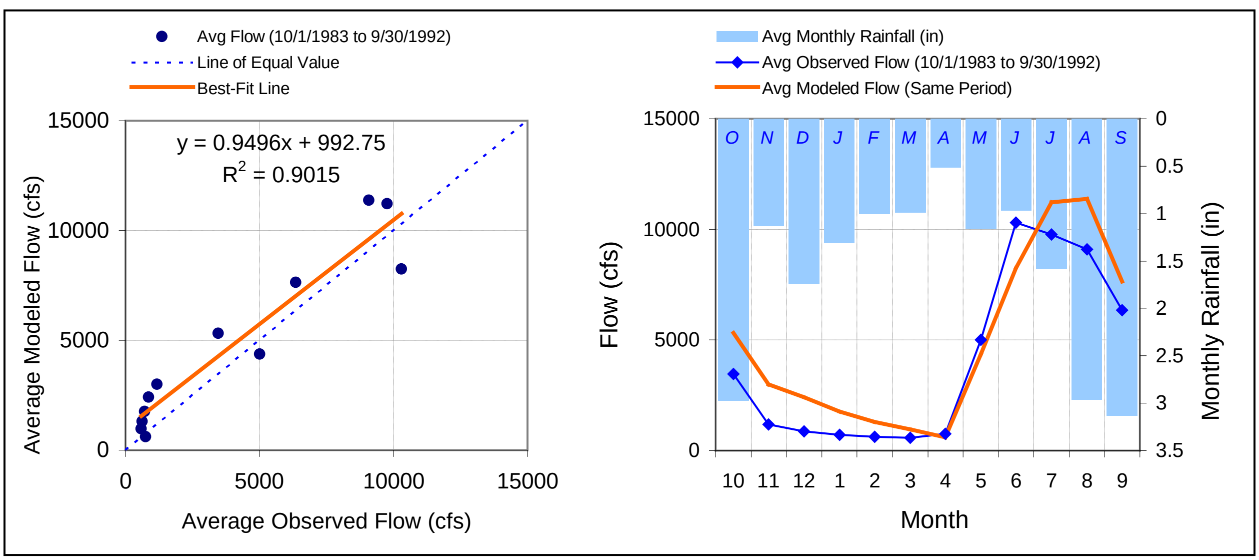

Figure 9. Seasonal regression and temporal aggregate at USGS 15266300 Kenai River At Soldotna, AK - validation period.

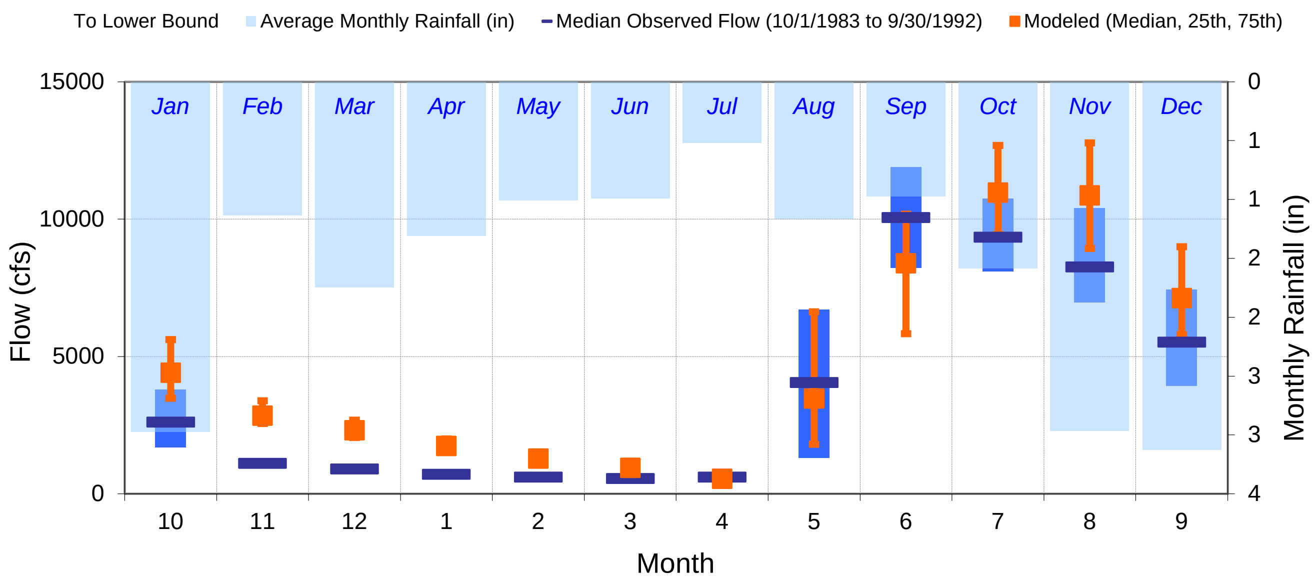

Figure 10. Seasonal medians and ranges at USGS 15266300 Kenai River at Soldotna, AK - validation period.

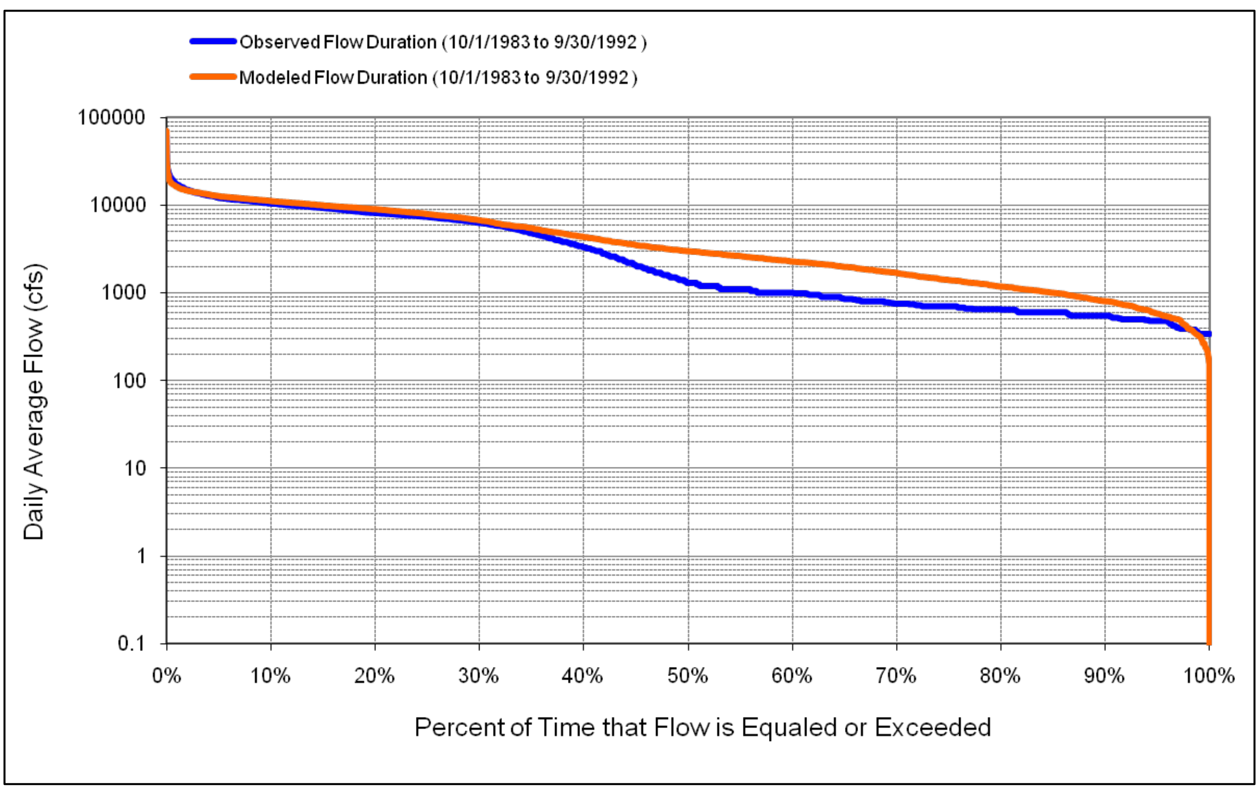

Figure 5. Flow exceedance at USGS 15266300 Kenai River at Soldotna, AK - validation period.

Table 7. Summary statistics at USGS 15266300 Kenai River at Soldotna, AK - validation period

SWAT Simulated Flow		Observed Flow Gage	
REACH OUTFLOW FROM OUTLET 74 9-Year Analysis Period: 10/1/1983 - 9/30/1992 Flow volumes are (inches/year) for upstream drainage area		USGS 15266300 Kenai R at Soldotna, AK Hydrologic Unit Code:19020302 Latitude: 60.4775 Longitude: -151.0738 Drainage Area (sq-mi): 1951	
Total Simulated In-stream Flow:	**21.61**	Total Observed In-stream Flow:	**18.08**
Total of simulated highest 10% flows:	**6.15**	Total of Observed highest 10% flows:	**6.01**
Total of Simulated lowest 50% flows:	**3.40**	Total of Observed Lowest 50% flows:	**1.64**
Simulated Summer Flow Volume (months 7-9):	**11.28**	Observed Summer Flow Volume (7-9):	**9.41**
Simulated Fall Flow Volume (months 10-12):	**3.99**	Observed Fall Flow Volume (10-12):	**2.06**
Simulated Winter Flow Volume (months 1-3):	**1.47**	Observed Winter Flow Volume (1-3):	**0.71**
Simulated Spring Flow Volume (months 4-6):	**4.87**	Observed Spring Flow Volume (4-6):	**5.91**
Total Simulated Storm Volume:	**3.57**	Total Observed Storm Volume:	**3.37**
Simulated Summer Storm Volume (7-9):	**1.81**	Observed Summer Storm Volume (7-9):	**1.77**

Errors (Simulated-Observed)	*Error Statistics*		*Recommended Criteria*		
Error in total volume:	**19.49**		**10**		
Error in 50% lowest flows:	**106.86**		**10**		
Error in 10% highest flows:	2.31		15		
Seasonal volume error - Summer:	19.94		30		
Seasonal volume error - Fall:	**94.13**	>>	**30**	Clear	
Seasonal volume error - Winter:	**107.45**		**30**		
Seasonal volume error - Spring:	-17.71		30		
Error in storm volumes:	6.05		20		
Error in summer storm volumes:	2.50		50		
Nash-Sutcliffe Coefficient of Efficiency, E:	0.554		Model accuracy increases		
Baseline adjusted coefficient (Garrick), E':	0.487		as E or E' approaches 1.0		
Monthly NSE	0.749				

Hydrology Results for Larger Watershed

As described above, parameters determined for the Soldotna gage were fully transferable to other gages in the watershed. In addition, calibration and validation was pursued at 2 gages in the watershed. Calibration results were acceptable at both gages (Table 8). Results of the validation exercise are summarized in Table 9.

Table 8. Summary statistics (percent error): all stations - calibration period

Station	USGS 15266300 Kenai R at Soldotna, AK	USGS 152927000 Talkeetna R nr Talkeetna, AK
Error in total volume:	-18.96	-18.84
Error in 50% lowest flows:	-20.69	-38.31
Error in 10% highest flows:	-16.10	16.27
Seasonal volume error - Summer:	-22.93	-25.08
Seasonal volume error - Fall:	-26.68	-54.40
Seasonal volume error - Winter:	-20.76	-31.58
Seasonal volume error - Spring:	-0.72	1.23
Error in storm volumes:	48.87	146.88
Error in summer storm volumes:	51.66	125.74
Daily Nash-Sutcliffe Coefficient of Efficiency, E:	0.684	0.240
Baseline adjusted coefficient (Garrick), E':	0.592	0.427
Monthly Nash-Sutcliffe Coefficient of Efficiency, E:	0.800	0.762

Table 9. Summary statistics: all stations - validation period

Station	USGS 15266300 Kenai R at Soldotna, AK	USGS 152927000 Talkeetna R nr Talkeetna, AK
Error in total volume:	19.49	2.40
Error in 50% lowest flows:	106.86	-9.55
Error in 10% highest flows:	2.31	35.16
Seasonal volume error - Summer:	19.94	2.03
Seasonal volume error - Fall:	94.13	-39.48
Seasonal volume error - Winter:	107.45	-9.75
Seasonal volume error - Spring:	-17.71	25.47
Error in storm volumes:	6.05	143.61
Error in summer storm volumes:	2.50	137.59
Daily Nash-Sutcliffe Coefficient of Efficiency, E:	0.554	0.174
Baseline adjusted coefficient (Garrick), E':	0.487	0.431
Monthly Nash-Sutcliffe Coefficient of Efficiency, E:	0.749	0.739

Water Quality Calibration and Validation

Initial calibration and validation of water quality was done on Cook Inlet at USGS 152927000 Talkeetna River near Talkeetna, AK, using 1985-2001 for calibration and 1972-1984 for validation. As with hydrology, calibration was performed on the later period as this better reflects the land use included in the model. The start of the validation period is constrained by data availability.

Calibration adjustments for sediment focused on the following parameters:

- SPCON (Linear parameters for estimating maximum amount of sediment that can be re-entrained during channel sediment routing)
- CH_COV (Channel cover factor)
- CH_EROD (Channel erodibility factor)

Simulated and estimated sediment loads at the USGS 152927000 Talkeetna River station for both the calibration and validation periods are shown in Figure 6 and statistics for the two periods are provided separately in Table 10. The key statistic in Table 10 is the relative percent error, which shows the error in the prediction of monthly load normalized to the estimated load. Table 10 also shows the relative average absolute error, which is the average of the relative magnitude of errors in individual monthly load predictions. This number is inflated by outlier months in which the simulated and estimated loads differ by large amounts (which may be as easily due to uncertainty in the estimated load due to limited data as to problems with the model) and the third statistic, the relative median absolute error, is likely more relevant and shows better agreement.

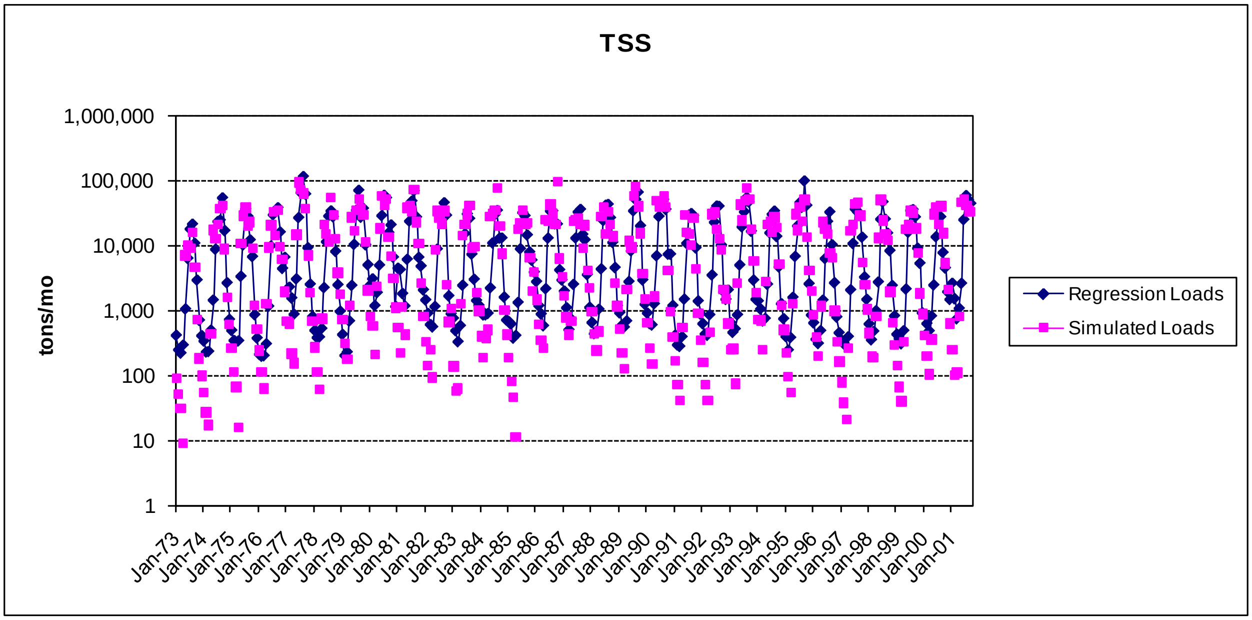

Figure 6. Fit for monthly load of TSS at USGS 152927000 Talkeetna River near Talkeetna, AK.

Table 10. Model fit statistics (observed minus predicted) for monthly sediment loads using stratified regression at USGS 152927000 Talkeetna River near Talkeetna, AK

Statistic	Calibration period (1985-2001)	Validation period (1972-1984)
Relative Percent Error	66.4%	64.1%
Relative Average Absolute Error	69%	68%
Relative Median Absolute Error	3.4%	3.1%

Calibration adjustments for total phosphorus and total nitrogen focused on the following parameters:

- PHOSKD (phosphorus soil partitioning coefficient)
- RS2
- RS3
- RS4
- RS5
- BC1, BC2 and BC4
- MUMAX

Results for the phosphorus simulation are shown in Figure 7 and Table 11. Results for the nitrogen simulation are shown in Figure 8 and Table 12. The model fit is generally acceptable.

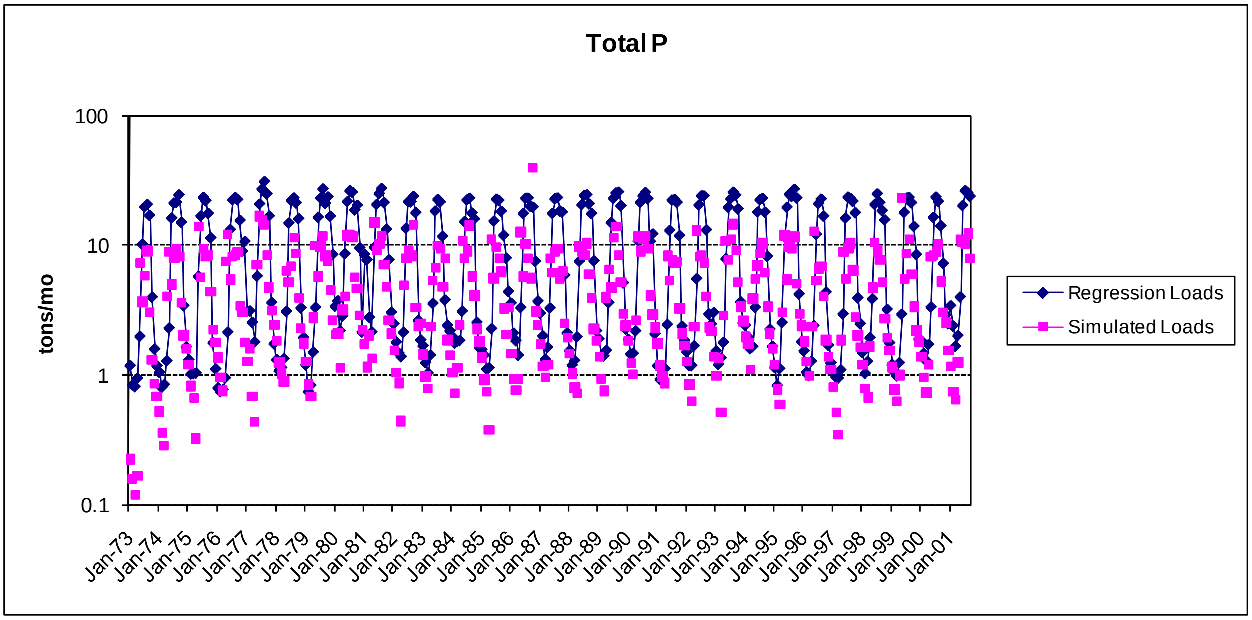

Figure 7. Fit for monthly load of total phosphorus at USGS 152927000 Talkeetna River near Talkeetna, AK.

Table 11. Model fit statistics (observed minus predicted) for monthly phosphorus loads using stratified regression at USGS 152927000 Talkeetna River near Talkeetna, AK

Statistic	Calibration period (1985-2001)	Validation period (1972-1984)
Relative Percent Error	83.2%	82.18%
Average Absolute Error	86%	88%
Median Absolute Error	8%	8.2%

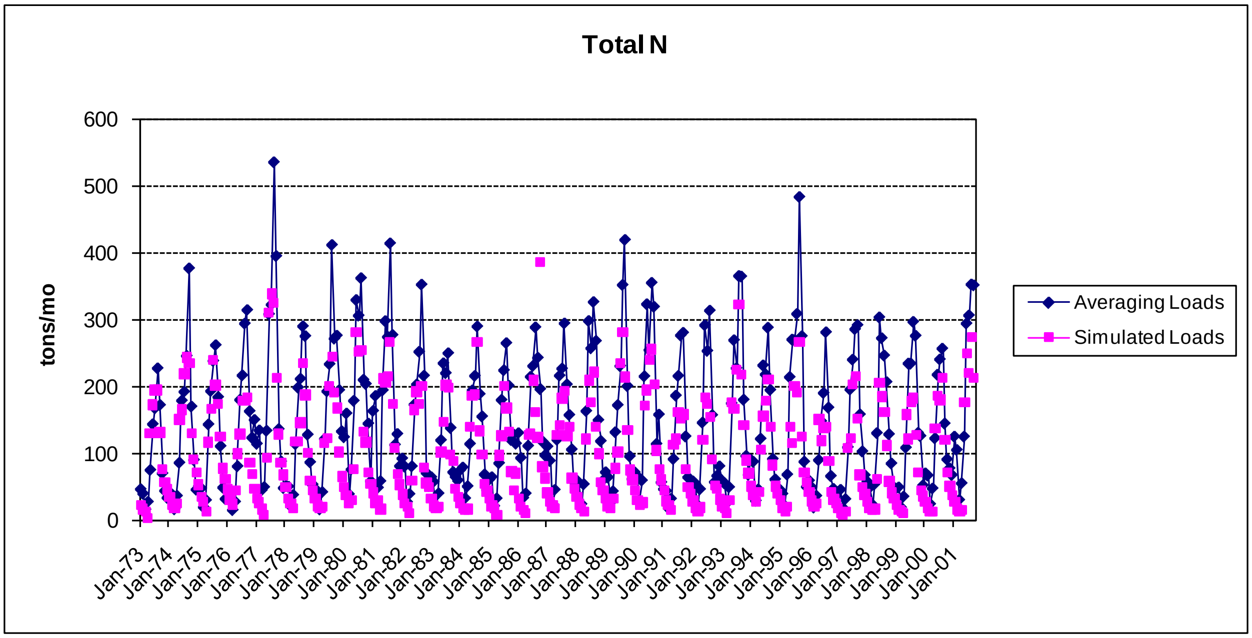

Figure 8. Fit for monthly load of total nitrogen at USGS 152927000 Talkeetna River near Talkeetna, AK.

Table 12. Model fit statistics (observed minus predicted) for monthly total nitrogen loads using averaging estimator at USGS 152927000 Talkeetna River near Talkeetna, AK

Statistic	Calibration period (1985-2001)	Validation period (1972-1984)
Relative Percent Error	57.3%	50.4%
Average Absolute Error	59%	51%
Median Absolute Error	22.1%	18.7%

Water Quality Results for Larger Watershed

As with hydrology, the SWAT model parameters used to calibrate at the Talkeetna River (USGS 152927000) station for water quality were directly transferred to other portions of the watershed. Application of the SWAT model without spatial adjustments resulted in relatively large errors in predicting loads and concentrations at some stations. Summary statistics for the SWAT water quality calibration and validation at other stations in the watershed are provided in Table 13 and Table 14.

Table 13. Summary statistics for water quality at all stations – calibration period 1985-2001

Station	USGS 15266300 Kenai R at Soldotna, AK	USGS 152927000 Talkeetna R nr Talkeetna, AK
Relative Percent Error TSS Load	-14.3%	66.4%
Relative Percent Error TP Load	49.8%	83.2%
Relative Percent Error TN Load	34.4%	57.3%

Table 14. Summary statistics for water quality at all stations – validation period 1971-1984

Station	USGS 15266300 Kenai R at Soldotna, AK	USGS 152927000 Talkeetna R nr Talkeetna, AK
Relative Percent Error TSS Load	-14.7%	64.1%
Relative Percent Error TP Load	50.24%	82.18%
Relative Percent Error TN Load	28.9%	50.4%

References

Tetra Tech. 1999. Improving Point Source Loadings Data for Reporting National Water Quality Indicators. Final Technical Report prepared for U.S. Environmental Protection Agency, Office of Wastewater Management, Washington, DC, by Tetra Tech, Inc., Fairfax, VA.

USEPA (United States Environmental Protection Agency). 2008. Using the BASINS Meteorological Database (Version 2006). BASINS Technical Note 10. Office of Water, U.S. Environmental Protection Agency, Washington, DC. http://water.epa.gov/scitech/datait/models/basins/upload/2009_04_13_BASINSs_tecnote10.pdf (Accessed June, 2009).

Appendix M
Model Configuration, Calibration and Validation

Basin: Georgia-Florida Coastal Plain (GaFl)

Contents

Tables

Figures

Watershed Background

The Georgia-Florida Coastal Plain drainages weres selected as one of the 15 non-pilot application watersheds for the 20 Watershed study. Watershed modeling for the non-pilot areas is accomplished using the SWAT model only, and model calibration and validation results are presented in abbreviated form.

Water Body Characteristics

The Georgia-Florida Coastal Plain model covers an area of about 17.500 mi^2 in portions of Georgia and Florida. The modeled area includes 15 HUC8s in two groups, one group draining to Tampa Bay (HUC 0310) and the remainder in southern Georgia and northwest Florida (in HUC 0311 and 0312; Figure 1). The watershed contains an EPA ORD Ecosystems Research Area (in the Tampa Bay drainage) and Tampa Bay is part of EPA's National Estuary Program.

Climate in the watershed is humid subtropical and influenced by air masses from the Gulf of Mexico. Average annual rainfall is around 45 to 53 inches per year, while the average annual temperatures is around 70 – 72 °F. The majority of precipitation is associated with summer convective storms, and tropical storms cross the area frequently. The study area has a climatic range from temperate in the north to subtropical in the south and along the Gulf Coast.

The major land uses in the watershed include forest, agriculture (citrus and row crops), wetlands, urban, and rangeland. Forested areas cover approximately 34 percent of the watershed. Much of the forest lands are softwood pines used to manufacture paper products (facial tissue, toilet paper, hand towels, bags, and boxes). Wetlands occupy about 26 percent of the watershed. Cultivated land covers approximately 11 percent, while developed land occupies over 10 percent of the area.

The populations of cities in the watershed increased from 10 to 30 percent between 1990 and 1999. The largest city in the watershed is Tampa, FL. Most water used in the watershed is derived from groundwater, primarily from the highly productive Floridan aquifer system.

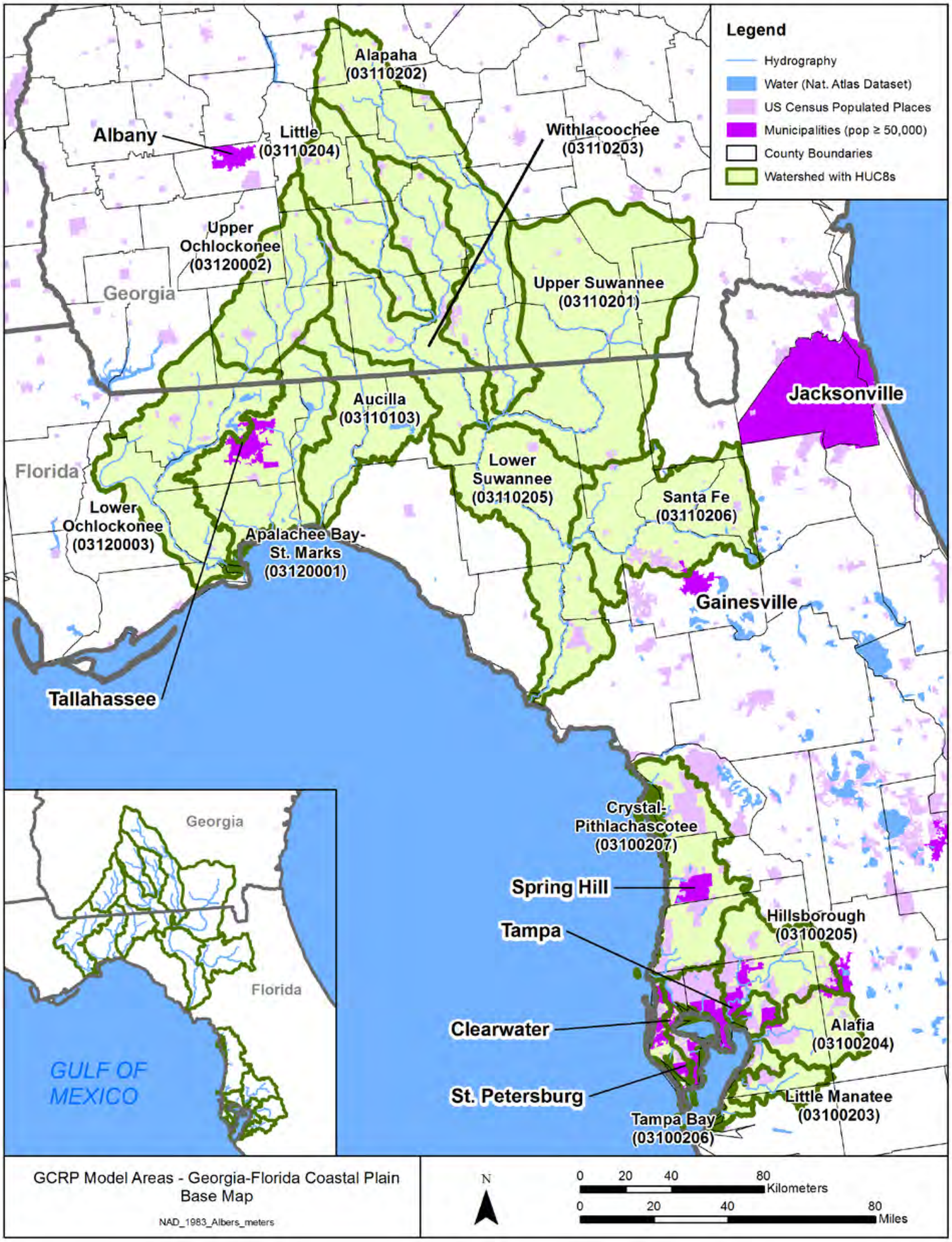

Figure 1. Location of the Georgia-Florida Coastal Plain model.

Soil Characteristics

Soils in the watershed are described in STATSGO soil surveys. SWAT uses information drawn directly from the soils data layer to populate the model.

Land Use Representation

Land use/cover in the watershed is based on the 2001 National Land Cover Database (NLCD) coverage (Figure 2). NLCD land cover classes were aggregated according to the scheme shown in Table 1 for representation in the 20 Watershed model. SWAT uses the built-in hydrologic response unit (HRU) overlay mechanism in the ArcSWAT interface. SWAT HRUs are formed from an intersection of land use and STATSGO major soils. The distribution of land use in the watershed is summarized in Table 2.

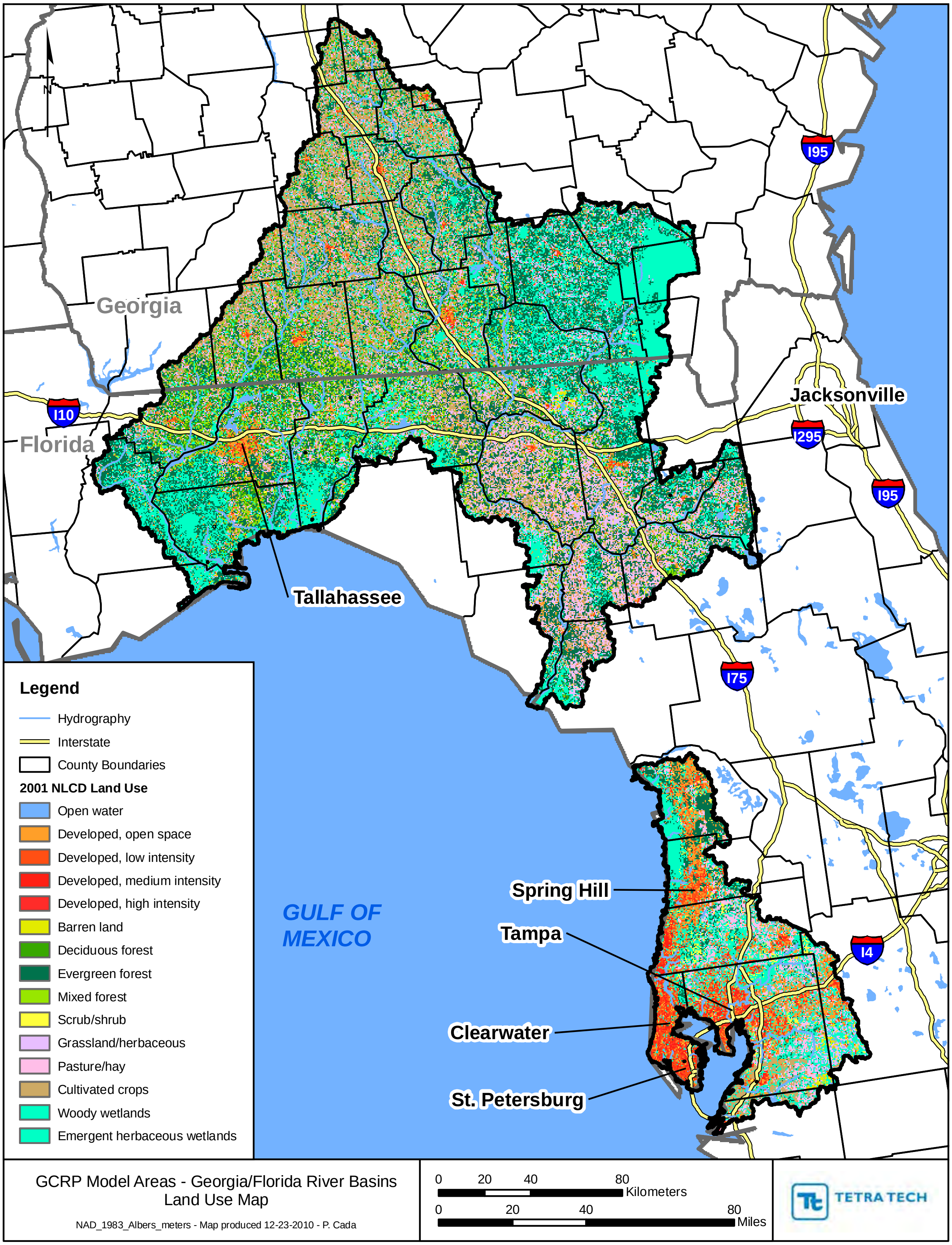

Figure 2. Land use in the Georgia-Florida Coastal Plain model.

Table 1. Aggregation of NLCD land cover classes

NLCD Class	Comments	SWAT class
11 Water	Water surface area usually accounted for as reach area	WATR
12 Perennial ice/snow		WATR
21 Developed open space		URLD
22 Dev. Low Intensity		URMD
23 Dev. Med. Intensity		URHD
24 Dev. High Intensity		UIDU
31 Barren Land		SWRN
41 Forest	Deciduous	FRSD
42 Forest	Evergreen	FRSE
43 Forest	Mixed	FRST
51-52 Shrubland		RNGB
71-74 Herbaceous Upland		RNGE
81 Pasture/Hay		HAY
82 Cultivated		AGRR
91-97 Wetland	Emergent & woody wetlands	WETF, WETL, WETN
98-99 Wetland	Aquatic bed wetlands (not emergent)	WATR

Table 2. Land use distribution for the Georgia-Florida Coastal Plain (2001 NLCD) (mi^2)

HUC 8 watershed	Open water	Developed[a] Open space	Low density	Medium density	High density	Barren land	Forest	Shrub and Grassland	Pasture/Hay	Cultivated	Wetland	Total
Little Manatee 03100203	3.28	12.89	5.92	3.77	0.41	11.02	8.32	9.61	35.45	51.00	64.58	206.25
Alafia 03100204	14.54	57.09	20.05	8.94	1.69	18.31	16.32	63.67	42.11	19.43	154.34	416.49
Hillsborough 03100205	6.95	109.61	52.21	30.46	9.82	1.53	36.32	30.35	115.04	15.32	238.80	646.41
Tampa Bay 03100206	14.74	85.28	97.65	66.80	23.62	0.60	16.16	17.35	22.23	30.04	115.03	489.49
Crystal-Pithlachascotee 03100207	13.46	171.27	155.40	66.08	14.78	2.96	193.61	49.35	78.46	2.07	304.20	1,051.64
Aucilla 03110103	2.56	37.36	4.58	0.88	0.40	0.87	407.91	80.61	48.99	79.08	301.57	964.81
Upper Suwannee 03110201	8.51	92.49	21.25	2.83	1.05	9.98	930.65	304.63	51.51	40.42	1,144.83	2,608.16
Alapaha 03110202	11.15	83.39	22.97	5.34	3.31	1.38	648.83	141.50	110.92	390.06	364.90	1,783.76
Withlacoochee 03110203	7.96	82.00	22.55	6.45	3.29	0.95	565.93	133.57	115.66	362.75	209.62	1,510.74
Little 03110204	6.22	38.31	13.15	2.53	1.09	0.88	263.72	57.54	83.81	282.16	126.03	875.42
Lower Suwannee 03110205	8.63	85.64	16.23	1.66	0.35	2.02	536.15	295.65	204.14	158.13	193.62	1,502.22
Santa Fe 03110206	19.51	70.92	15.33	3.41	0.97	4.47	534.92	268.37	166.54	68.38	202.26	1,355.07
Apalachee Bay-St. Marks 03120001	4.47	91.70	19.32	7.09	2.23	2.36	560.43	90.09	33.53	33.62	295.04	1,139.88
Upper Ochlockonee 03120002	5.53	42.28	13.04	2.11	1.11	1.11	328.10	67.64	62.55	264.89	113.10	901.45
Lower Ochlockonee 03120003	18.55	70.17	12.40	2.08	0.69	3.27	679.84	91.14	37.14	76.99	490.00	1,482.26
Total	121.29	950.82	413.86	167.24	52.89	30.87	5,666.23	1,597.45	1,015.47	1,788.59	3,860.20	15,664.90

[a]The percent imperviousness applied to each of the developed land uses is as follows: open space (7.20%), low density (31.87%), medium density (60.14%), and high density (87.47%).

Point Sources

There are numerous point source discharges in the watershed. Only the major dischargers, generally defined as those with a design flow greater than 1 MGD are included in the simulation (Table 3). The major dischargers are represented at long-term average flows, without accounting for changes over time or seasonal variations.

Table 3. Major point source discharges in the Georgia-Florida Coastal Plain model

NPDES ID	Name	Design flow (MGD)	Observed flow (MGD) (1991-2006 average)
FL0029033	CITY OF QUINCY WWTP	1.5	1.0
FL0025518	ARVAH B. HOPKINS GENERATING	1.9	0.3
GA0001279	AFFINITY FOODS OF GA		0.5
GA0024082	THOMASVILLE WPCP	6.5	3.7
GA0001678	ENGELHARD CORPORATION		1.1
FL0001465	GOLDKIST INC - LIVE OAK PROCES	1.5	1.3
GA0024911	ADEL WPCP	2.5	1.3
GA0000124	TIFTON ALUMUNUM CO		0.3
FL0027880	JASPER-WWTP	1.2	0.7
GA0020222	VALDOSTA (MUD CREEK WPCP)	3.2	2.1
GA0025852	ASHBURN (WPCP)	1.2	0.9
FL0028126	STARKE-MUNICIPAL STP	1.7	1.7
FL0002518	ST. MARKS POWDER, INC.	0.8	21.4
FL0025526	SAM O. PURDOM GEN STATION		21.0
FL0027839	MONTICELLO-STP	1.0	10.7
FL0026557	PLANT CITY STP	8.0	3.6
FL0040983	HILLSBOROUGH CTY VALRICO WWTP	6.0	5.2
FL0029653	AOC, LLC		0.1
FL0000523	CF INDUSTRIES - BARTOW PHOS.		4.0
FL0001589	MOSAIC FERTILIZER, LLC - BARTO		1.7
FL0034657	CORONET INDUSTRIES INC		62.7
FL0043869	TAMPA ELEC-POLK POWER STATION		2.7
FL0028061	HILLSBOROUGH CO-SOUTHWEST WTP	4.0	1.6
FL0030406	TARPON SPRINGS STP	4.0	3.2
FL0021326	DUNEDIN-MAINLAND STP	6.0	5.8
FL0021857	CLEARWATER-MARSHALL ST STP	10.0	6.7
FL0034789	MID-COUNTY SERVICES, INC	0.9	1.1
FL0000159	PROGRESS ENERGY CRYSTAL RIVER	0.7	0.0

NPDES ID	Name	Design flow (MGD)	Observed flow (MGD) (1991-2006 average)
FL0036366	PROGRESS ENERGY CRYSTAL R 4&5	99.0	4.0
FL0027821	RIVER OAKS AWWTP	10.0	8.0
FL0021865	CLEARWATER-EAST WWTF	4.3	10.2
FL0026603	LARGO, CITY OF	15.0	9.1
FL0000264	IMC-AGRICO CO - PORT SUTTON	0.5	3.1
FL0000809	TAMPA ELEC COMPANY-FJ GANNON		0.2
FL0020940	HOWARD F CURREN AWTP	96.0	148.8
FL0040614	HILLSBORO CO - FALKENBURG RD A	6.0	9.3
FL0027651	CITY OF OLDSMAR	2.3	1.2
FL0041670	NORTHWEST REGIONAL WRF	5.0	3.5

Most of these point sources have reasonably complete monitoring for total phosphorus and total suspended solids (TSS). In the Georgia-Florida Coastal basin more dischargers also report total nitrogen (unlike other study areas) due to concerns over nitrogen impacts on the coastal estuaries. The point sources were initially represented in the model with the median of reported values for total phosphorus, total suspended solids and total nitrogen.

Meteorological Data

The required meteorological time series for the 20 Watershed SWAT simulations are precipitation and air temperature. The 20 Watershed simulations do not include water temperature and uses a degree-day method for snowmelt. SWAT estimates Penman-Monteith potential evapotranspiration using a statistical weather generator for inputs other than temperature and precipitation. These meteorological time series are drawn from the BASINS4 Meteorological Database (USEPA 2008), which provides a consistent, quality-assured set of nationwide data with gaps filled and records disaggregated. Scenario application requires simulation over 30 years, so the available stations are those with a common 30-year period of record (or one that can be filled from an approximately co-located station) that covers the year 2002. A total of 51 precipitation stations were identified for use in the Georgia-Florida Coastal watershed model with a common period of record of 10/1/1971-9/30/2002 (Table 4). Temperature records are sparser; where these are absent temperature is taken from nearby stations with an elevation correction.

Table 4. Precipitation stations for the Georgia-Florida Coastal Plain model

COOP ID	Name	Latitude	Longitude	Temperature	Elevation (m)
097276	QUITMAN 2 NW	30.7836	-83.5691	x	56
098666	THOMASVILLE 3 NE	30.8673	-83.9318	x	79
090140	ALBANY 3 SE	31.5339	-84.1488	x	55
098703	TIFTON	31.4462	-83.4766	x	116
096087	MOULTRIE 2 ESE	31.1769	-83.7492	x	104
080478	BARTOW	27.8986	-81.8432	x	38
081046	BROOKSVILLE CHIN HILL	28.6164	-82.3657	x	73
084731	LAKE CITY 2 E	30.1854	-82.5942	x	59

COOP ID	Name	Latitude	Longitude	Temperature	Elevation (m)
085275	MADISON	30.4517	-83.4119	x	37
087205	PLANT CITY	28.0236	-82.1422	x	37
087851	SAINT LEO	28.3379	-82.2600	x	58
099186	WAYCROSS 4 NE	31.2515	-82.3127	x	44
084273	INGLIS 3 E	29.0254	-82.6157		9
084797	LAKELAND	28.0207	-81.9218		44
080975	BRANFORD	29.9625	-82.9107		9
082391	DOWLING PARK 1 W	30.2498	-83.2593		16
088758	TALLAHASSEE WSO AP	30.3932	-84.3533	x	17
088788	TAMPA WSCMO AP	27.9615	-82.5403	x	6
090586	BAINBRIDGE INTL PAPER C	30.8229	-84.6175		58
093312	FARGO	30.6908	-82.5632		35
096879	PEARSON	31.2928	-82.8422		62
082008	CROSS CITY 2 WNW	29.6497	-83.1663	x	13
083956	HIGH SPRINGS	29.8287	-82.5972	x	20
084289	INVERNESS 3 SE	28.8032	-82.3124	x	12
085879	MONTICELLO WTP	30.4923	-83.7832	x	30
087025	PERRY	30.0987	-83.5742	x	14
087886	ST PETERSBURG	27.7632	-82.6272	x	2
088824	TARPON SPRINGS SWG PLNT	28.1500	-82.7500	x	2
090010	ABBEVILLE 4 S	31.9381	-83.3078		73
091500	CAMILLA 3 SE	31.1904	-84.2035	x	53
092266	CORDELE	31.9848	-83.7758	x	94
092783	DOUGLAS	31.4890	-82.8205	x	71
093386	FITZGERALD	31.7108	-83.2516	x	113
093460	FOLKSTON 3 SW	30.7987	-82.0181		9
083986	HILLSBOROUGH RVR ST PK	28.1429	-82.2269		16
086880	PARRISH	27.6089	-82.3478	x	18
093465	FOLKSTON 9 SW	30.7400	-82.1277	x	37
087440	RAIFORD STATE PRISON	30.0678	-82.1928	x	37
085539	MAYO	30.0565	-83.1818	x	20
085099	LIVE OAK	30.2890	-82.9650	x	37
084394	JASPER	30.5229	-82.9446	x	45
098974	VALDOSTA 2 S	30.8056	-83.2736		81

COOP ID	Name	Latitude	Longitude	Temperature	Elevation (m)
083153	FORT GREEN 12 WSW	27.5706	-82.1377		34
089795	WOODRUFF DAM	30.7220	-84.8742		33
089120	USHER TOWER	29.4084	-82.8186	x	10
094429	HOMERVILLE 5 N	31.0767	-82.8002	x	57
090406	ASHBURN 3 ENE	31.7003	-83.6230	x	133
080945	BRADENTON 5 ESE	27.4467	-82.5014	x	6
087429	QUINCY 3 SSW	30.6001	-84.5499	x	75
089430	WEEKI WACHEE	28.5175	-82.5755	x	6

Watershed Segmentation

The Georgia-Florida Coastal basin was divided into 108 subwatersheds for the purposes of modeling (Figure 3). Ochlockonee River at USGS 02329000 was chosen for initial calibration. The model encompasses the complete watershed and does not require specification of any upstream boundary conditions for application.

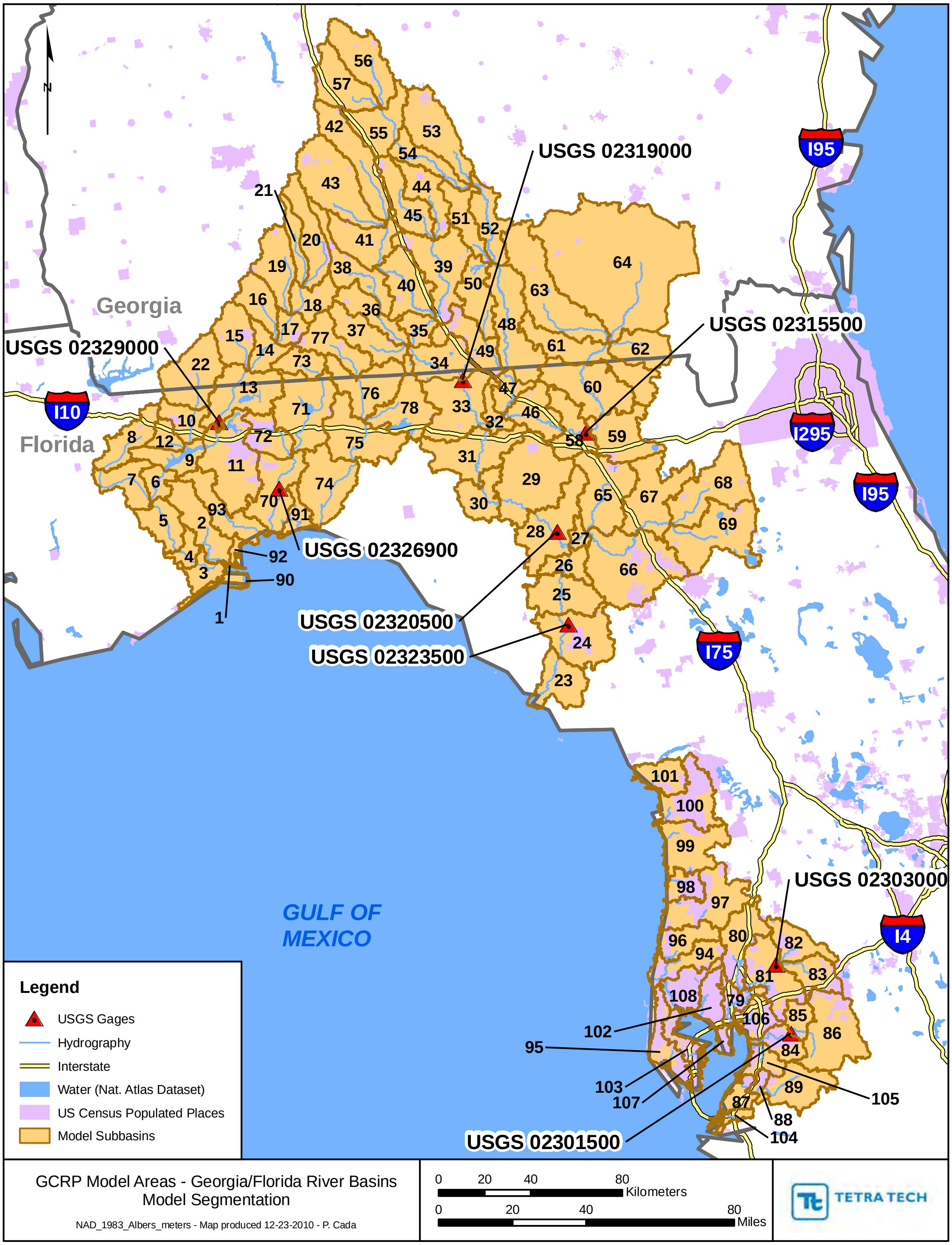

Figure 3. Model segmentation and USGS stations utilized for the Georgia-Florida Coastal Plain.

Calibration Data and Locations

The specific site chosen for initial calibration was the Ochlockonee River at Havana, FL, a flow and water quality monitoring location that approximately coincides with the mouth of an 8-digit HUC at its outflow to the Ochlockonee River. The Ochlockonee River watershed was selected because there is a good set of flow and water quality data available and the watershed lacks major point sources and impoundments. Additional calibration and validation was pursued at multiple locations (Table 5). Parameters derived on the Ochlockonee River were not fully transferable to other portions of the Georgia-Florida Coastal basin, and additional calibration was conducted at multiple gage locations.

Table 5. Calibration and validation locations in the Georgia-Florida Coastal Plain

Station name	USGS ID	Drainage area (mi^2)	Hydrology calibration	Water quality calibration
Alafia River at Lithia, FL	02301500	335	x	x
Hillsborough River near Zephyrhills, FL	02303000	220	x	x
Suwanee River at White Springs, FL	02315500	2430	x	
Withlacoochee River near Pinetta, FL	02319000	2120	x	
Suwanee River near Branford, FL	02320500	7880	x	x
Suwanee River near Wilcox, FL	02323500	9640	x	
St. Marks River near Newport, FL	02326900	535	x	
Ochlockonee River at Havana, FL	02329000	1140	x	x

The model hydrology calibration period was set to Water Years 1992-2002 (within the 32-year period of record for modeling). Hydrologic validation was then performed on Water Years 1982-1992. Water quality calibration used calendar years 1992-2002, while validation used 1982-1992.

SWAT Modeling

Assumptions

Hydrology Calibration

A spatial calibration approach was adopted for GCRP-SWAT modeling for the Georgia-Florida Coastal basin. A systematic adjustment of parameters was adopted and some adjustments were applied throughout the basin. Most of the calibration efforts were geared towards getting a closer match between simulated and observed flows at the outlet of calibration focus area.

Land Use / Soil / Slope Definition

A 5/10/5 percent threshold was used for land use/soil/slope in the SWAT model while defining the HRUs. Urban land use classes were exempted from the HRU overlay thresholds.

The calibration focus area (Ochlockonee River) includes nine subwatersheds and is generally representative of the general land use characteristics of the overall watershed. The parameters were adjusted within the practical range to obtain reasonable fit between the simulated and measured flows in terms of Nash-Sutcliffe modeling efficiency and the high flow and low flow components as well as the seasonal flows.

The water balance of the upper portion of the Georgia-Florida Coastal basin predicted by the SWAT model over the 32-year simulation period is as follows:

```
PRECIP =   1323.6 MM
SNOW FALL =    1.53 MM
SNOW MELT =     1.52 MM
SUBLIMATION =     0.01 MM
SURFACE RUNOFF Q =   167.16 MM
LATERAL SOIL Q =   18.39 MM
TILE Q =     0.00 MM
GROUNDWATER (SHAL AQ) Q =   223.44 MM
REVAP (SHAL AQ => SOIL/PLANTS) =  104.93 MM
DEEP AQ RECHARGE =    44.75 MM
TOTAL AQ RECHARGE =  374.05 MM
TOTAL WATER YLD =   397.68 MM
PERCOLATION OUT OF SOIL =  369.14 MM
ET =    766.5 MM
PET =   1576.8MM
TRANSMISSION LOSSES =    11.31 MM
```

The water balance of the lower portion of the Georgia-Florida Coastal basin predicted by the SWAT model over the 32-year simulation period is as follows:

```
PRECIP =   1314.8 MM
SNOW FALL =    0.10 MM
SNOW MELT =     0.10 MM
SUBLIMATION =     0.00 MM
SURFACE RUNOFF Q =   169.83 MM
```

```
LATERAL SOIL Q =   31.62 MM
TILE Q =      0.00 MM
GROUNDWATER (SHAL AQ) Q =   143.04 MM
REVAP (SHAL AQ => SOIL/PLANTS) =  100.62 MM
DEEP AQ RECHARGE =   162.45 MM
TOTAL AQ RECHARGE =  406.12 MM
TOTAL WATER YLD =   344.49 MM
PERCOLATION OUT OF SOIL =  409.81 MM
ET =     701.1 MM
PET =   1678.8MM
TRANSMISSION LOSSES =     0.00 MM
```

Hydrologic calibration adjustments focused on the following parameters:

- CN2 (initial SCS runoff curve number for moisture condition II)
- ESCO (soil evaporation compensation factor)
- SURLAG (surface runoff lag coefficient)
- SOL_AWC (available water capacity of the soil layer, mm water/mm of soil)
- ALPHA_BF (baseflow alpha factor, days)
- GW_DELAY (groundwater delay time, days)
- GWQMIN (threshold depth of water in the shallow aquifer required for return flow to occur, mm)
- GW_REVAP (groundwater "revap" coefficient)
- CH_N1 (Manning's "n" value for tributary channels)
- CH_N2 (Manning's "n" value for main channels)

Calibration results for the Ochlockonee River are summarized in Figure 4, Figure 5, Figure 6, Figure 7 and Table 6.

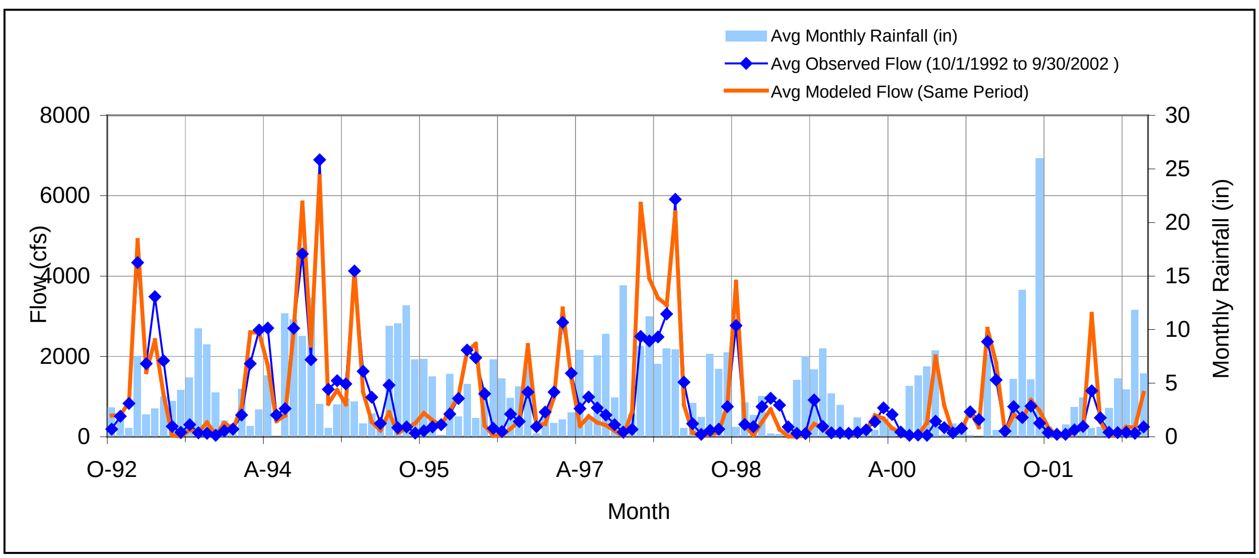

Figure 4. Mean monthly flow at USGS 02329000 Ochlockonee River at Havana, FL – calibration period.

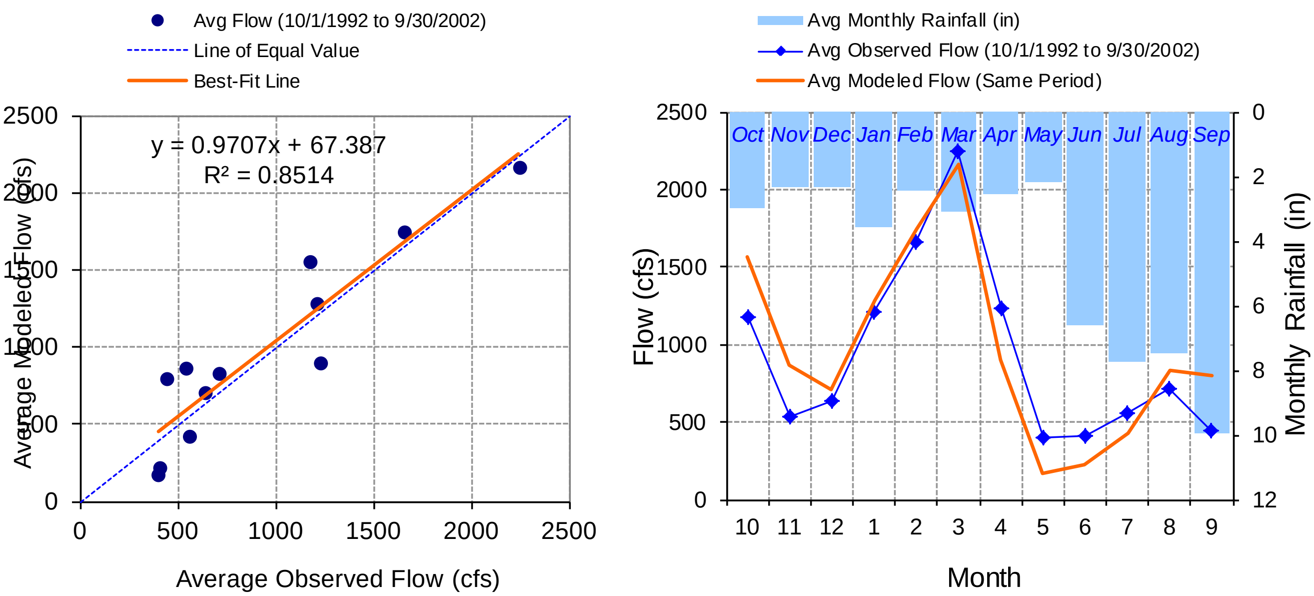

Figure 5. Seasonal regression and temporal aggregate at USGS 02329000 Ochlockonee River at Havana, FL – calibration period.

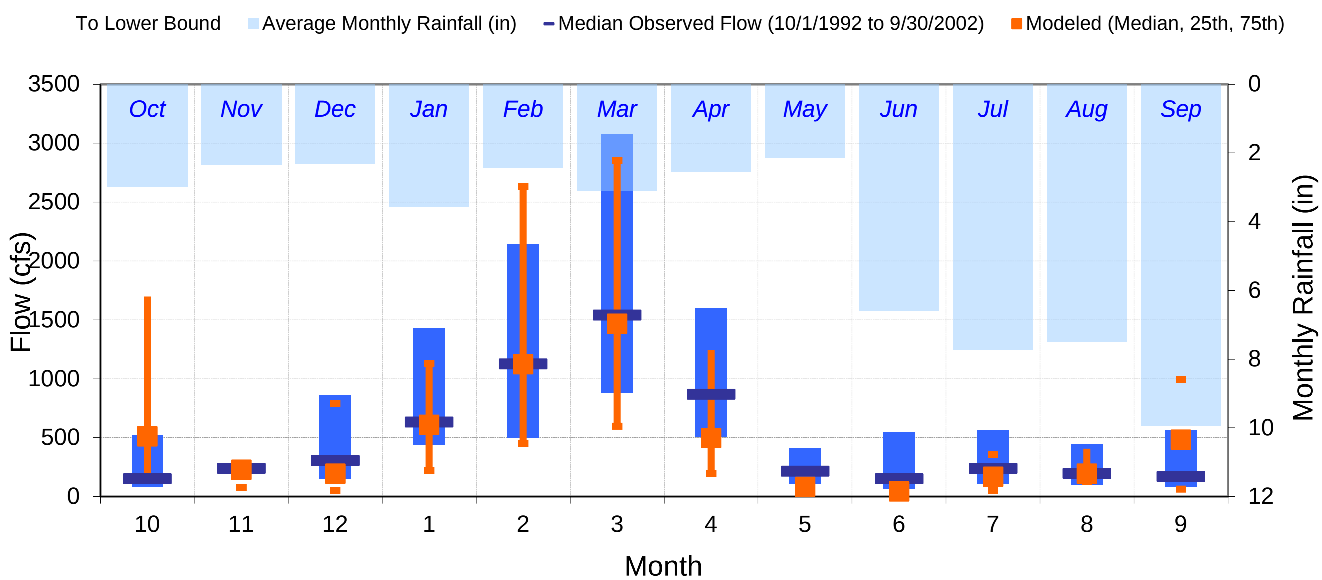

Figure 6. Seasonal medians and ranges at USGS 02329000 Ochlockonee River at Havana, FL – calibration period.

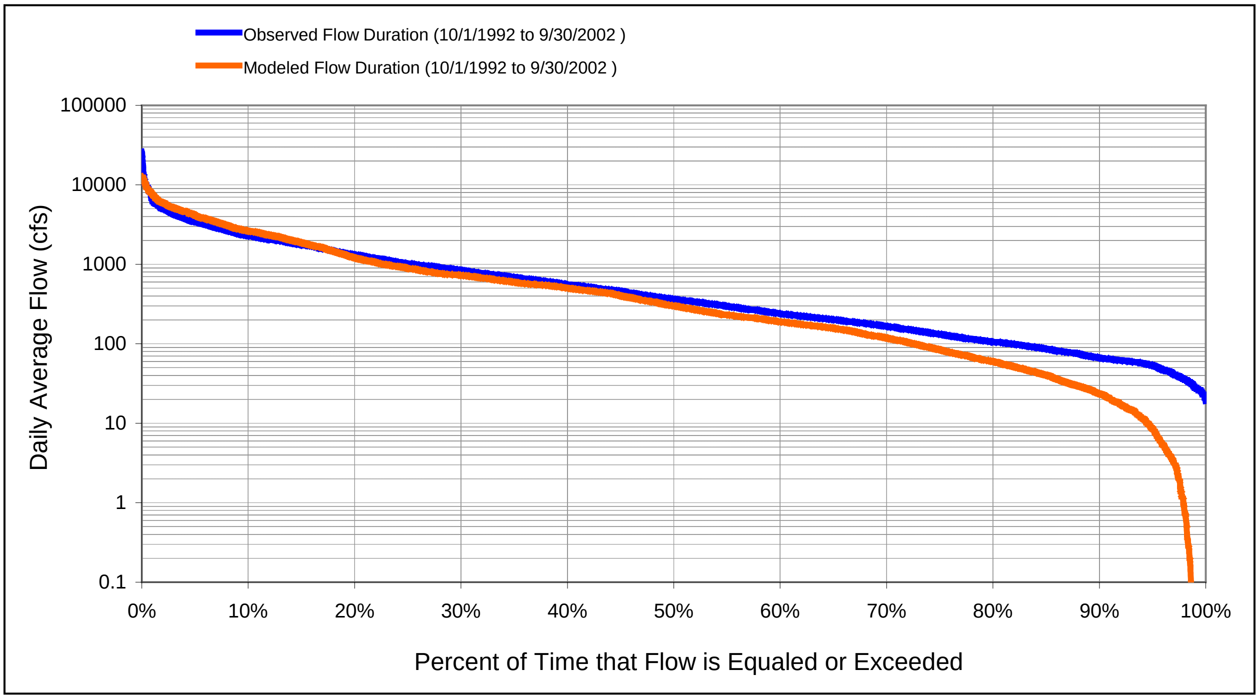

Figure 7. Flow exceedance at USGS 02329000 Ochlockonee River at Havana, FL – calibration period.

Table 6. Summary statistics at USGS 02329000 Ochlockonee River at Havana, FL – calibration period

SWAT Simulated Flow		Observed Flow Gage		
REACH OUTFLOW FROM OUTLET 13 10-Year Analysis Period: 10/1/1992 - 9/30/2002 Flow volumes are (inches/year) for upstream drainage area		USGS 02329000 OCHLOCKONEE RIVER NR HAVANA, FLA. Hydrologic Unit Code: 3120003 Latitude: 30.55408644 Longitude: -84.3840715 Drainage Area (sq-mi): 1140		
Total Simulated In-stream Flow:	**11.57**	Total Observed In-stream Flow:		**11.10**
Total of simulated highest 10% flows:	**6.08**	Total of Observed highest 10% flows:		**5.32**
Total of Simulated lowest 50% flows:	**0.66**	Total of Observed Lowest 50% flows:		**0.93**
Simulated Summer Flow Volume (months 7-9):	**2.06**	Observed Summer Flow Volume (7-9):		**1.72**
Simulated Fall Flow Volume (months 10-12):	**3.14**	Observed Fall Flow Volume (10-12):		**2.36**
Simulated Winter Flow Volume (months 1-3):	**5.10**	Observed Winter Flow Volume (1-3):		**5.01**
Simulated Spring Flow Volume (months 4-6):	**1.27**	Observed Spring Flow Volume (4-6):		**2.00**
Total Simulated Storm Volume:	**3.36**	Total Observed Storm Volume:		**3.51**
Simulated Summer Storm Volume (7-9):	**0.58**	Observed Summer Storm Volume (7-9):		**0.53**
Errors (Simulated-Observed)	*Error Statistics*	*Recommended Criteria*		
Error in total volume:	4.25	10		
Error in 50% lowest flows:	**-28.91**	**10**		
Error in 10% highest flows:	14.27	15		
Seasonal volume error - Summer:	19.83	30		
Seasonal volume error - Fall:	**33.10** >>	**30**	Clear	
Seasonal volume error - Winter:	1.60	30		
Seasonal volume error - Spring:	**-36.43**	**30**		
Error in storm volumes:	-4.28	20		
Error in summer storm volumes:	10.50	50		
Nash-Sutcliffe Coefficient of Efficiency, E:	0.711	Model accuracy increases		
Baseline adjusted coefficient (Garrick), E':	0.539	as E or E' approaches 1.0		
Monthly NSE	0.793			

Hydrology Validation

Hydrology validation for Ochlockonee River was performed for the period 10/1/1982 through 9/30/1992. The validation achieves a moderately high coefficient of model fit efficiency, but is over on 10 percent highest flow volume, and summer and fall seasonal volumes (Figure 8, Figure 9, Figure 10, Figure 11 and Table 7).

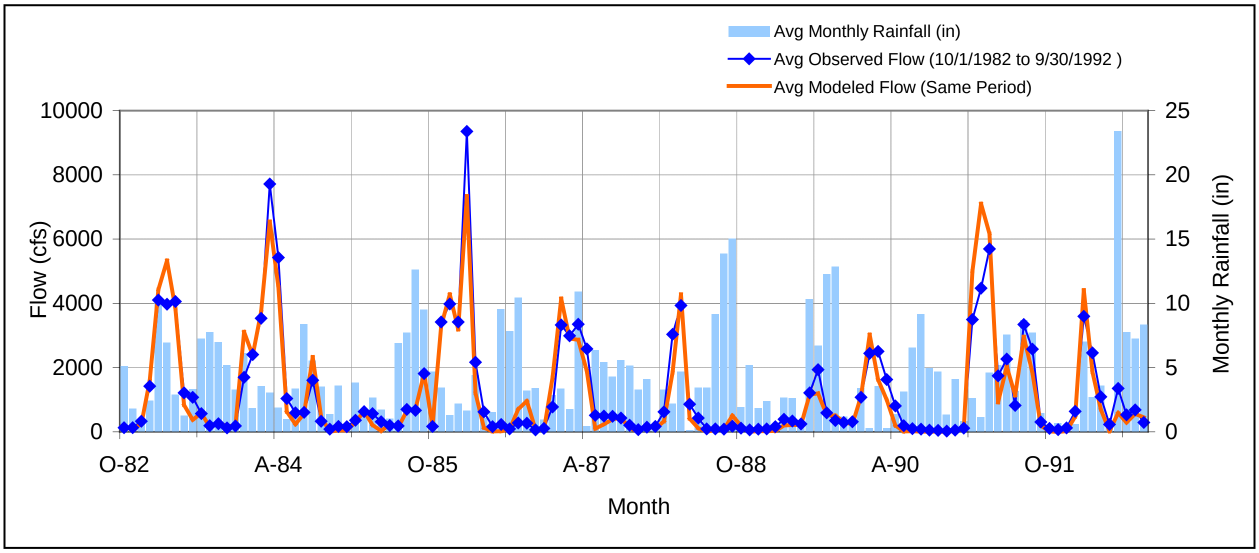

Figure 8. **Mean monthly flow at USGS 02329000 Ochlockonee River at Havana, FL – validation period.**

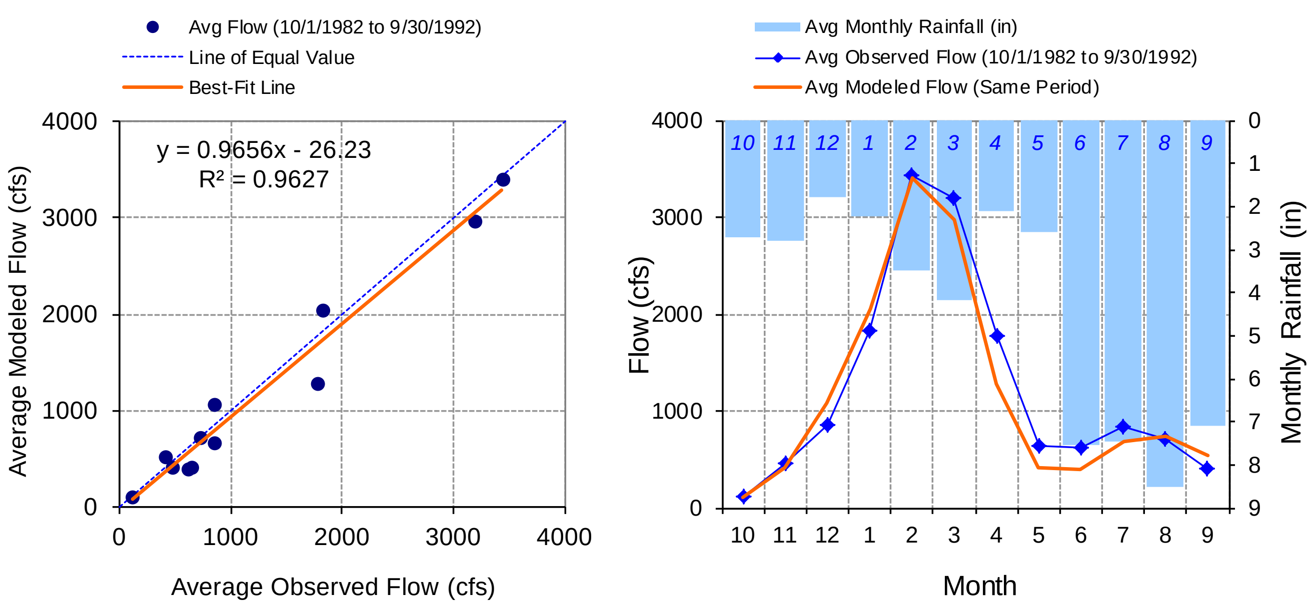

Figure 9. **Seasonal regression and temporal aggregate at USGS 02329000 Ochlockonee River at Havana, FL – validation period.**

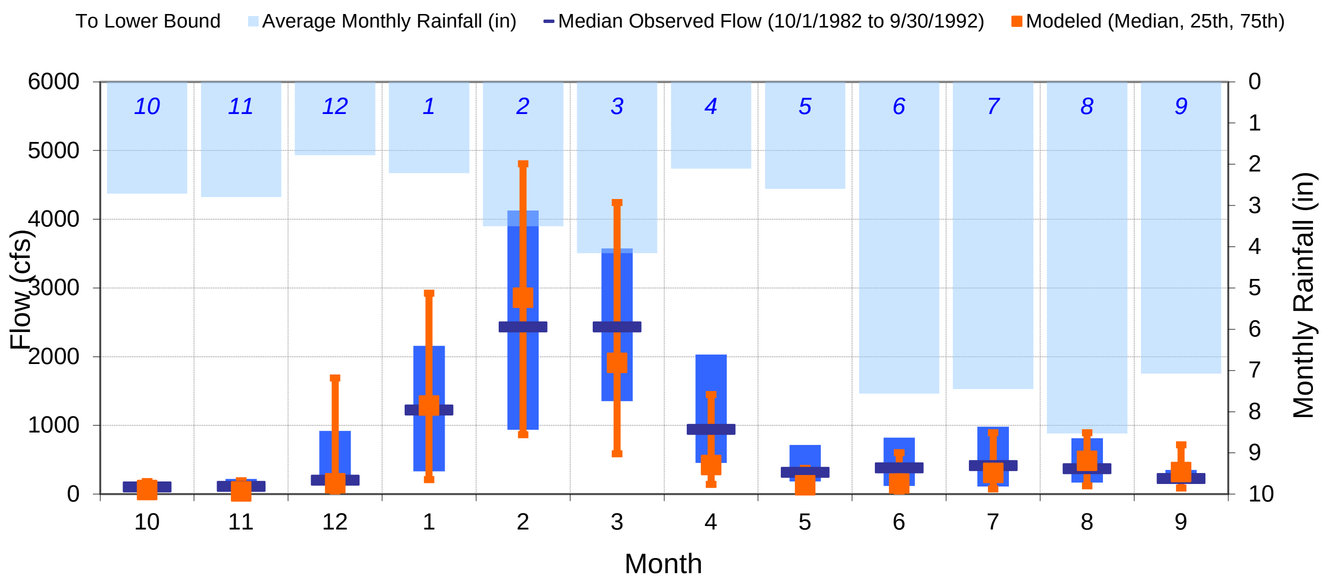

Figure 10. Seasonal medians and ranges at USGS 02329000 Ochlockonee River at Havana, FL – validation period.

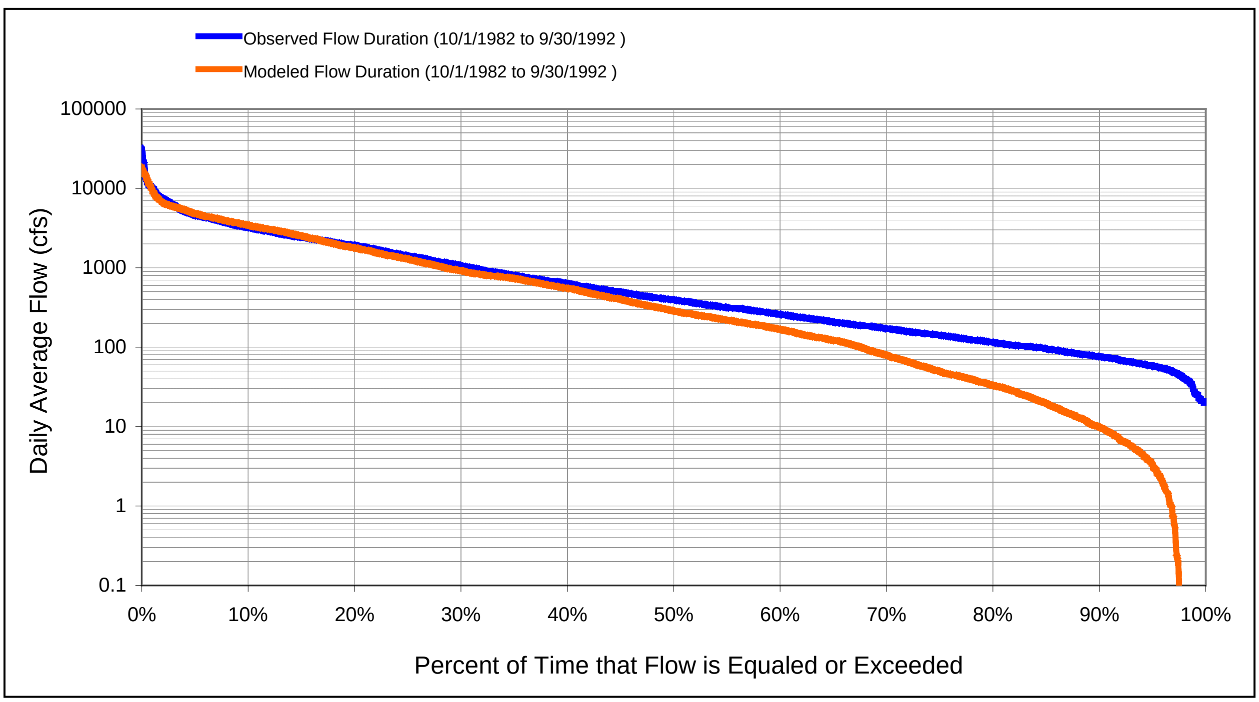

Figure 11. Flow exceedance at USGS 02329000 Ochlockonee River at Havana, FL – validation period.

Table 7. Summary statistics at USGS 02329000 Ochlockonee River at Havana, FL – validation period

SWAT Simulated Flow		Observed Flow Gage		
REACH OUTFLOW FROM OUTLET 13 10-Year Analysis Period: 10/1/1982 - 9/30/1992 Flow volumes are (inches/year) for upstream drainage area		USGS 02329000 OCHLOCKONEE RIVER NR HAVANA, FLA. Hydrologic Unit Code: 3120003 Latitude: 30.55408644 Longitude: -84.3840715 Drainage Area (sq-mi): 1140		
Total Simulated In-stream Flow:	**13.85**	Total Observed In-stream Flow:		**14.66**
Total of simulated highest 10% flows:	**7.22**	Total of Observed highest 10% flows:		**7.36**
Total of Simulated lowest 50% flows:	**0.51**	Total of Observed Lowest 50% flows:		**0.99**
Simulated Summer Flow Volume (months 7-9):	**1.95**	Observed Summer Flow Volume (7-9):		**1.97**
Simulated Fall Flow Volume (months 10-12):	**1.60**	Observed Fall Flow Volume (10-12):		**1.44**
Simulated Winter Flow Volume (months 1-3):	**8.22**	Observed Winter Flow Volume (1-3):		**8.24**
Simulated Spring Flow Volume (months 4-6):	**2.07**	Observed Spring Flow Volume (4-6):		**3.00**
Total Simulated Storm Volume:	**4.01**	Total Observed Storm Volume:		**4.94**
Simulated Summer Storm Volume (7-9):	**0.53**	Observed Summer Storm Volume (7-9):		**0.61**
Errors (Simulated-Observed)	*Error Statistics*	*Recommended Criteria*		
Error in total volume:	-5.54	10		
Error in 50% lowest flows:	**-48.00**	**10**		
Error in 10% highest flows:	-1.84	15		
Seasonal volume error - Summer:	-1.04	30		
Seasonal volume error - Fall:	11.57 >>	30	Clear	
Seasonal volume error - Winter:	-0.26	30		
Seasonal volume error - Spring:	**-31.19**	**30**		
Error in storm volumes:	-18.85	20		
Error in summer storm volumes:	-12.44	50		
Nash-Sutcliffe Coefficient of Efficiency, E:	0.799	Model accuracy increases		
Baseline adjusted coefficient (Garrick), E':	0.649	as E or E' approaches 1.0		
Monthly NSE	0.895			

Hydrology Results for Larger Watershed

As described above, parameters determined for the gage at Ochlockonee River were initially transferred to other gages in the watershed. However, changes to subwatershed level parameters were required to fit the model to the observed flows. In all, calibration and validation was pursued at a total of eight gages throughout the watershed. Results of the calibration and validation exercise are summarized in Table 8 and Table 9, respectively. Calibration and validation results were acceptable at most gages.

Table 8. Summary statistics (percent error): all stations - calibration period

Station	02301500	02303000	02315500	02319000	02320500	02323500	02326900	02329000
Error in total volume:	-4.77	-0.21	-8.07	-1.91	2.22	3.45	4.32	4.25
Error in 50% lowest flows:	32.79	8.10	55.83	9.25	14.34	11.46	15.97	-28.91
Error in 10% highest flows:	-10.46	-12.69	-14.74	-9.20	-3.57	1.83	0.32	14.27
Seasonal volume error - Summer:	5.48	8.36	28.40	41.01	10.89	20.53	-6.54	19.83
Seasonal volume error - Fall:	0.84	-2.28	14.11	23.55	19.48	18.31	22.26	33.10
Seasonal volume error - Winter:	-26.89	-17.54	-21.36	-15.83	-7.80	-7.73	1.85	1.60
Seasonal volume error - Spring:	-5.58	13.71	-21.16	-19.73	-2.98	-6.27	3.42	-36.43
Error in storm volumes:	-28.50	-9.30	-12.16	-34.73	19.91	-17.80	18.67	-4.28
Error in summer storm volumes:	-18.37	0.77	0.31	-10.47	48.43	-12.89	-12.42	10.50
Daily Nash-Sutcliffe Coefficient of Efficiency, E:	0.727	0.675	0.823	0.756	0.821	0.802	0.623	0.711
Monthly Nash-Sutcliffe Efficiency:	0.789	0.736	0.858	0.851	0.865	0.838	0.654	0.793

Table 9. Summary statistics (percent error): all stations - validation period

Station	02301500	02303000	02315500	02319000	02320500	02323500	02326900	02329000
Error in total volume:	1.39	3.17	-7.80	-2.51	-11.68	-17.18	-2.87	-5.54
Error in 50% lowest flows:	8.63	-3.25	42.55	-36.60	-22.56	-32.66	-4.93	-48.00
Error in 10% highest flows:	-3.36	-4.80	-19.13	-0.51	-6.19	-4.00	2.96	-1.84
Seasonal volume error - Summer:	3.79	9.87	6.07	-14.33	-20.22	-19.58	-12.90	-1.04
Seasonal volume error - Fall:	54.39	7.84	97.49	29.83	-3.66	-17.71	-3.76	11.57
Seasonal volume error - Winter:	-35.46	-14.76	-13.63	1.90	-6.19	-10.92	1.01	-0.26
Seasonal volume error - Spring:	-7.98	6.66	-30.57	-21.71	-17.18	-22.74	3.05	-31.19
Error in storm volumes:	-19.86	3.38	-7.60	-35.83	26.96	-6.77	11.11	-18.85
Error in summer storm volumes:	-22.13	-3.79	-12.02	-36.70	-0.67	-23.61	-19.59	-12.44
Daily Nash-Sutcliffe Coefficient of Efficiency, E:	0.416	0.720	0.722	0.801	0.850	0.788	0.584	0.799
Monthly Nash-Sutcliffe Efficiency:	0.393	0.760	0.755	0.903	0.893	0.820	0.624	0.895

Water Quality Calibration and Validation

Initial calibration and validation of water quality was done on the Ochlockonee River (USGS 02329000), using 1992-2002 for calibration and 1982-1992 for validation. As with hydrology, water quality calibration was performed on the later period as this better reflects the land use included in the model.

Calibration adjustments for sediment focused on the following parameters:

- SPCON (linear parameter for estimating maximum amount of sediment that can be re-entrained during channel sediment routing)
- SPEXP (exponential parameter for estimating maximum amount of sediment that can be re-entrained during channel sediment routing)
- CH_COV (channel cover factor)
- CH_EROD (channel erodibility factor)
- USLE_P (USLE support practice factor)

Simulated and estimated sediment loads at the Ochlockonee River station for both the calibration and validation periods are shown in Figure 12 and statistics for the two periods are provided separately in .
Table 10. The key statistic in Table 10 is the relative percent error, which shows the error in the prediction of monthly load normalized to the estimated load. Table 10 also shows the relative average absolute error, which is the average of the relative magnitude of errors in individual monthly load predictions. This number is inflated by outlier months in which the simulated and estimated loads differ by large amounts (which may be as easily due to

uncertainty in the estimated load due to limited data as to problems with the model) and the third statistic, the relative median absolute error, is likely more relevant and shows better agreement.

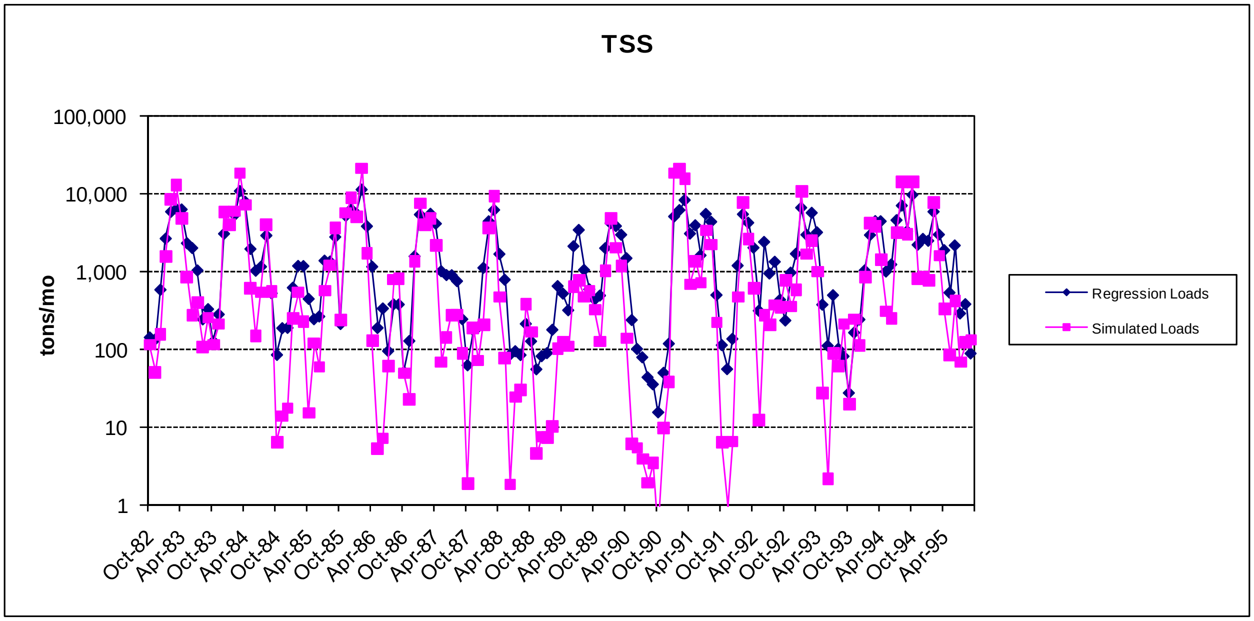

Figure 12. Fit for monthly load of TSS at USGS 02329000 Ochlockonee River at Havana, FL.

Table 10. Model fit statistics (observed minus predicted) for monthly sediment loads using stratified regression at USGS 02329000 Ochlockonee River at Havana, FL

Statistic	Calibration period (1992-1995)	Validation period (1982-1992)
Relative Percent Error	9.5%	-6.6%
Relative Average Absolute Error	55.5%	59.4%
Relative Median Absolute Error	36.7%	24.4%

Calibration adjustments for total phosphorus and total nitrogen focused on the following parameters:

- RHOQ (algal respiration rate at 20^{O} C)
- PHOSKD (phosphorus soil partitioning coefficient)
- PSP (phosphorus availability index)
- RS2 (benthic source rate for dissolved P in the reach at 20^{O} C)
- RS5 (organic P settling rate in the reach at 20^{O} C)
- BC4 (rate constant for mineralization of organic P to dissolved P in the reach at 20^{O} C)
- RS4 (rate coefficient for organic N settling in the reach at 20^{O} C)

Results for the phosphorus simulation are shown in Figure 13 and .
Table 11. Results for the nitrogen simulation are shown in Figure 14 and Table 12. The model fit is generally acceptable.

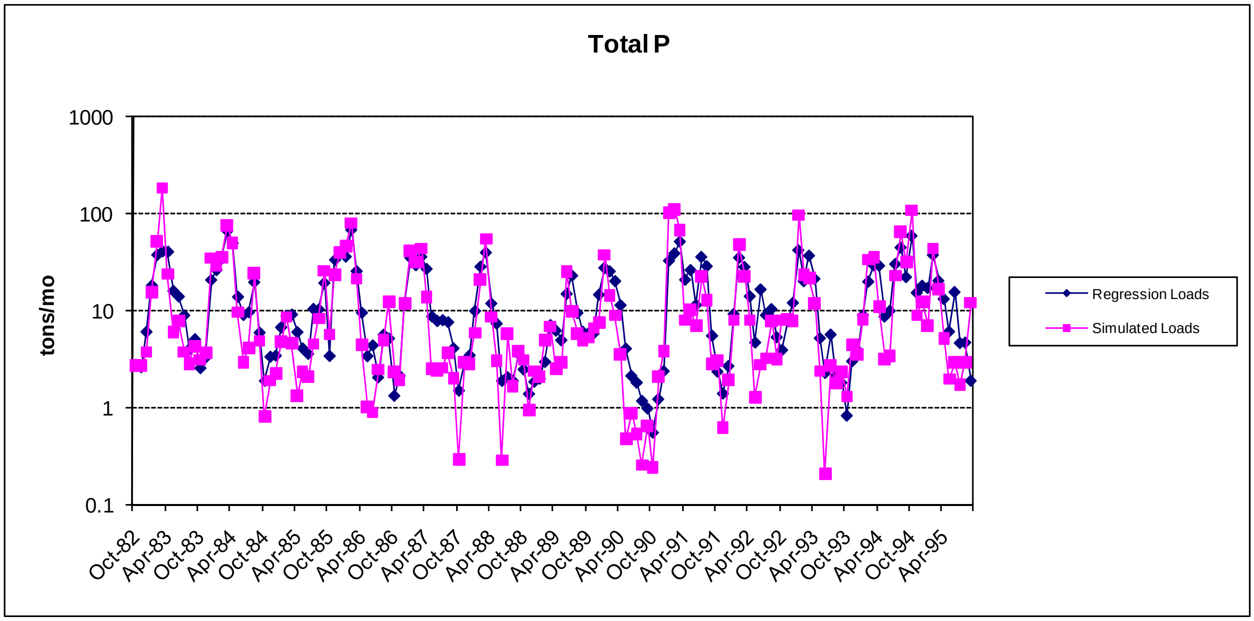

Figure 13. Fit for monthly load of total phosphorus at USGS 02329000 Ochlockonee River at Havana, FL.

Table 11. Model fit statistics (observed minus predicted) for monthly phosphorus loads using stratified regression at USGS 02329000 Ochlockonee River at Havana, FL

Statistic	Calibration period (1992-1995)	Validation period (1982-1992)
Relative Percent Error	-7.4%	-5.8%
Average Absolute Error	48.3%	52.4%
Median Absolute Error	22.8%	34.2%

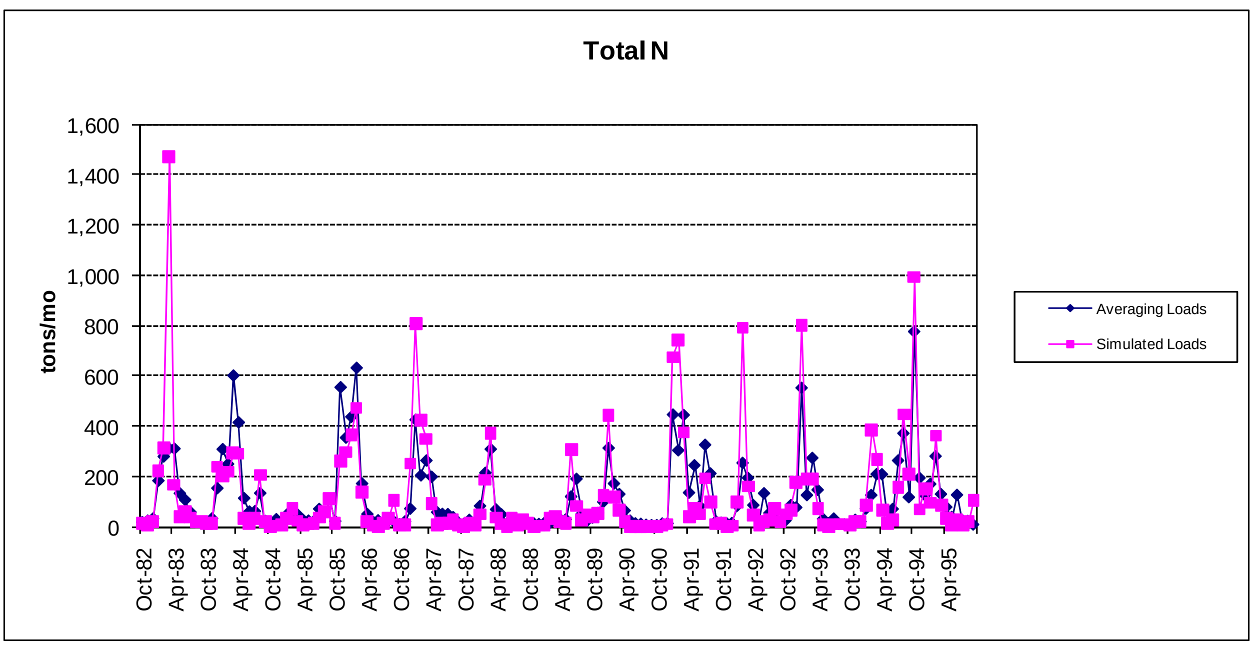

Figure 14. Fit for monthly load of total nitrogen at USGS 02329000 Ochlockonee River at Havana, FL.

Table 12. Model fit statistics (observed minus predicted) for monthly total nitrogen loads using averaging estimator at USGS 02329000 Ochlockonee River at Havana, FL

Statistic	Calibration period (1992-1995)	Validation period (1982-1992)
Relative Percent Error	-8.0%	-5.0%
Average Absolute Error	49.2%	58.6%
Median Absolute Error	32.9%	21.0%

Water Quality Results for Larger Watershed

As with hydrology, a spatial calibration approach was adopted. Ochlockonee River watershed SWAT model parameters for water quality were transferred to other portions of the watershed with necessary changes to subbasin level parameters. Summary statistics for the SWAT water quality calibration and validation at other stations in the watershed are provided in Table 13 and Table 14.

Table 13. Summary statistics for water quality at all stations – calibration period 1992-2002

Station	02301500	02303000	02320500	02329000
Relative Percent Error TSS Load	21.4%	10.0%	-12.5%	9.5%
Relative Percent Error TP Load	16.5%	27.1%	6.6%	-7.4%
Relative Percent Error TN Load	24.1%	-4.8%	9.2%	-8.0%

Table 14. Summary statistics for water quality at all stations – validation period 1982-1992

Station	02301500	02303000	02320500	02329000
Relative Percent Error TSS Load	-11.1%	-7.8%	18.1%	-6.6%
Relative Percent Error TP Load	-1.9%	4.2%	10.9%	-5.8%
Relative Percent Error TN Load	-26.1%	-20.2%	15.5%	-5.0%

References

USEPA. 2008. Using the BASINS Meteorological Database (Version 2006). BASINS Technical Note 10. Office of Water, U.S. Environmental Protection Agency, Washington, DC. http://water.epa.gov/scitech/datait/models/basins/upload/2009_04_13_BASINSs_tecnote10.pdf (Accessed June, 2009).

Appendix N
Model Configuration, Calibration and Validation

Basin: Illinois River (Illin)

Contents

Tables

Figures

Watershed Background

The Illinois River basin study area was selected as one of the 15 non-pilot application watersheds for the 20 Watershed study. Watershed modeling for the non-pilot areas is accomplished using the SWAT model only, and model calibration and validation results are presented in abbreviated form. The majority of the Illinois River basin lies in the state of Illinois except small portions extending into Wisconsin and Indiana. The Illinois River basin is comprised of 12 HUC8 cataloging units.

Water Body Characteristics

The Illinois River is approximately 273 miles in length and is one of the major tributaries to the Mississippi River. The Illinois River joins the Mississippi River near Grafton, IL, about 20 miles upstream from the confluence of the Missouri and the Mississippi rivers. This study addresses the upper portion of the basin (Figure 1), which has a drainage area of 17,004 mi^2 (44,040 km^2) and includes eleven HUC8s within HUC 0712 and HUC 0713 (Figure 1).

Within the upper portion of the basin (HUC 0712), over 80 percent of the land area is classified as part of the Central Corn Belt Plains ecoregion. With the exception of the Chicago metropolitan area, land use in the Central Corn Belt Plains is mostly corn and soybean cultivation for livestock feed crops and some livestock production. The flat topography of the lower portion of the basin (HUC 0713) is in the Till Plains Section of the Central Lowland physiographic province. The altitude of the land surface ranges from 600 to 800 ft above sea level. The area of greatest topographic relief is along the river valley, where topographic relief can range from 200 to 400 ft. The majority of the basin is extremely flat with less than 20 ft of relief.

Agriculture accounts for about 66 percent of the land use in the study area. Most of the recent urbanization is the result of development of new suburban and residential areas. Urban areas account for about 18 percent of the land use in the basin and are mainly concentrated in the metropolitan areas in and around Chicago. Forests cover about 10 percent of the study area and are concentrated along large-stream riparian areas.

Wetlands now make up a relatively small amount (1 percent) of land cover, but were once a major feature of the basin. The majority of wetlands in the basin were drained prior to the 1850's for the development of farmland. Remaining wetlands in the basin are mainly in riparian areas.

The climate of the Illinois River basin is classified as humid continental because of the cool, dry winters and warm, humid summers. The average annual temperature for the Illinois River basin ranges from 46° F in the north of the basin to 55° F in the south of the study area. Lake Michigan has a moderating effect on temperature near the shoreline. Average annual precipitation, including snowfall, ranges from less than 32 inches in the northern Wisconsin part of the basin to more than 38 inches near the southern and eastern Lake Michigan shoreline in the Indiana part of the basin.

Streamflow in the study area consists of overland flow, groundwater discharge, agricultural drainage, and point-source return flow. Local flooding generally is caused by isolated thunderstorms, whereas widespread flooding is caused by more extensive thunderstorms that cover a wide area, by rapid snowmelt in the spring, or by a combination of these factors. Flooding is common in the basin, in some years resulting in significant loss of life and property.

The Illinois River connects Great Lakes at Chicago to the Mississippi River via the Illinois Waterway System. It is also an important part of the Great Loop (the circumnavigation of Eastern North America by water). Originally the Illinois and Michigan canal, opened in 1849, connected the Illinois River to the Chicago River. Later, the Sanitary District of Chicago replaced the canal with the Chicago Sanitary and Shipping Canal and also reversed the flow of the Chicago River, originally flowing into Lake Michigan. Now, the Chicago Sanitary and Shipping Canal is part of the Illinois Waterway. The Illinois Waterway System is a system of rivers, lakes, and canals that provides shipping connection from the Great Lakes to the Gulf of Mexico via the Mississippi River. It consists of 336 miles (541 km) of water from the mouth of the Calumet River to the mouth of the Illinois River at Grafton, IL. River traffic and flood control is managed by eight locks and dams operated by the Army Corps of Engineers. The upper lock, T.J. O'Brien, is 7 miles from Lake Michigan on the Calumet River and the last lock is 90 miles (140 km) upstream of the Mississippi River at the LaGrange lock and dam.

The watershed does not contain major reservoirs. However, there are a number of smaller lakes and reservoirs that influence flow in this low gradient terrain. The river system in the Illinois River basin is highly manipulated by human intervention including the reversal of the Chicago River and the massive Illinois Waterway. The river flow and barge traffic is controlled by a series of lock and dams. Additional flow from Lake Michigan was not considered in the model. Irrigation and groundwater pumping in the watershed are generally small and, therefore, not included for the purposes of the 20 Watershed model.

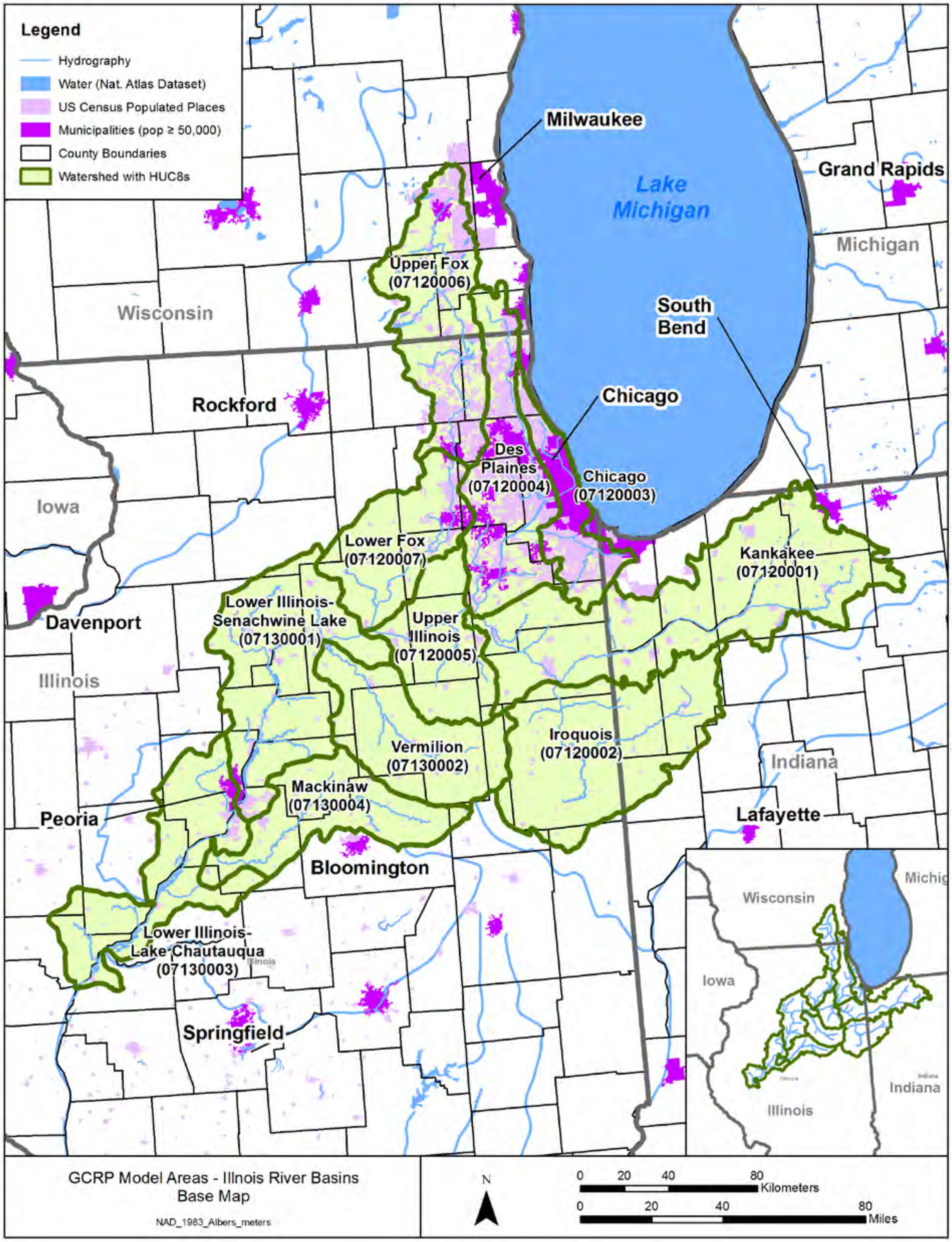

Figure 1. Location of the Illinois River basin.

Soil Characteristics

Soils in the watershed, as described in STATSGO soil surveys, fall primarily into hydrologic soil groups (HSGs) B (moderately high infiltration capacity) and C (moderately high runoff potential). SWAT uses information drawn directly from the soils data layer to populate the model.

Land Use Representation

Land use/cover in the watershed is based on the 2001 National Land Cover Database (NLCD) coverage and is predominantly row crop agriculture (Figure 2). NLCD land cover classes were aggregated according to the scheme shown in Table 1 for representation in the 20 Watershed model. SWAT uses the built-in hydrologic response unit (HRU) overlay mechanism in the ArcSWAT interface. SWAT HRUs are formed from an intersection of land use and STATSGO soils. The distribution of land use in the watershed is summarized in Table 2.

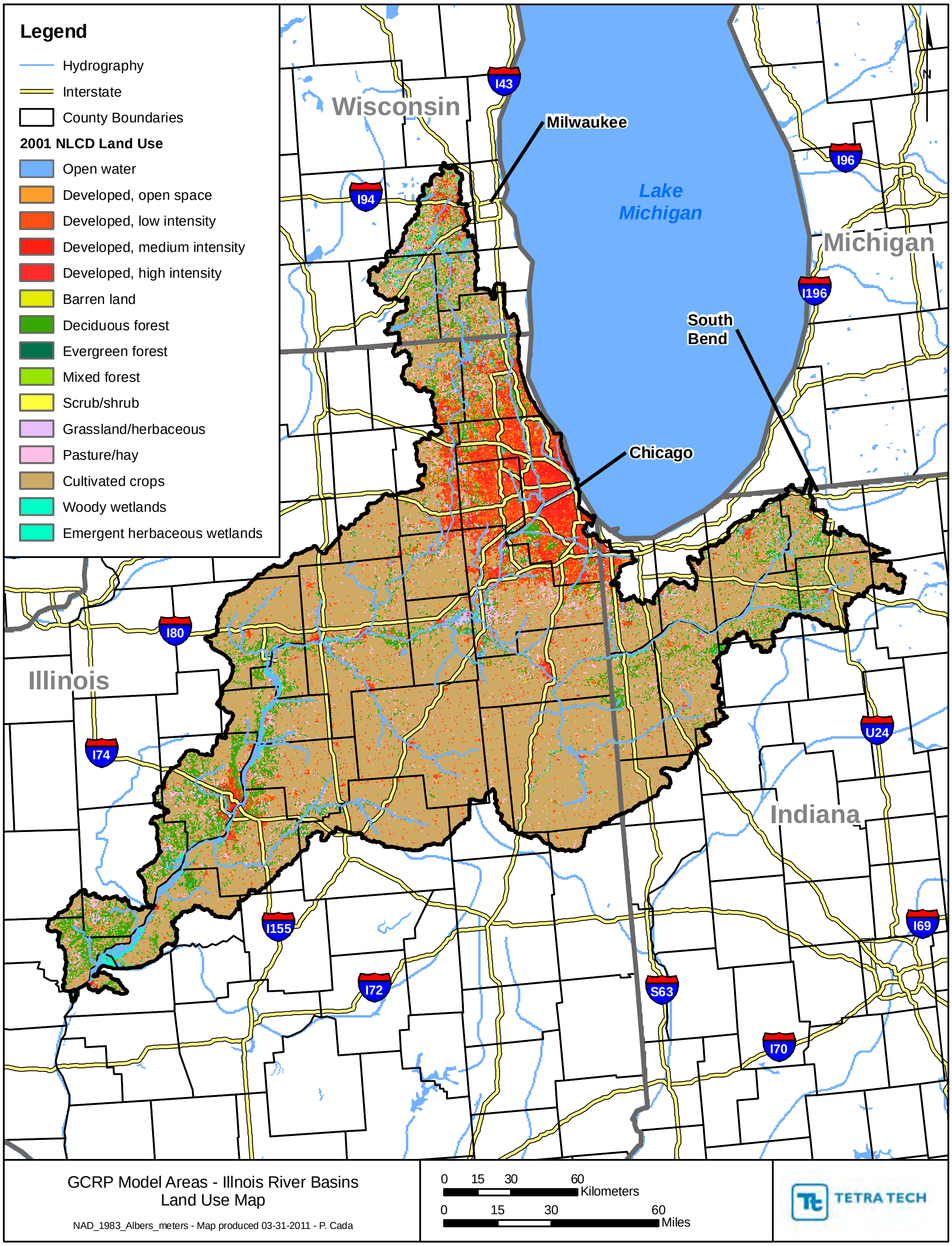

Figure 2. Land use in the Illinois River basin.

Table 1. Aggregation of NLCD land cover classes

NLCD Class	Comments	SWAT class
11 Water	Water surface area usually accounted for as reach area	WATR
12 Perennial ice/snow		WATR
21 Developed open space		URLD
22 Dev. Low Intensity		URMD
23 Dev. Med. Intensity		URHD
24 Dev. High Intensity		UIDU
31 Barren Land		SWRN
41 Forest	Deciduous	FRSD
42 Forest	Evergreen	FRSE
43 Forest	Mixed	FRST
51-52 Shrubland		RNGB
71-74 Herbaceous Upland		RNGE
81 Pasture/Hay		HAY
82 Cultivated		AGRR
91-97 Wetland	Emergent & woody wetlands	WETF, WETL, WETN
98-99 Wetland	Aquatic bed wetlands (not emergent)	WATR

Table 2. Land use distribution for the Illinois River basin (2001 NLCD) (mi^2)

HUC 8 watershed	Open water	Developed[a]				Barren land	Forest	Shrubland/ Grassland	Pasture/ Hay	Cultivated	Wetland	Total
		Open space	Low density	Medium density	High density							
Kankakee **07120001**	28.6	114.1	133.0	21.7	7.7	1.1	329.9	95.8	108.3	2,013.6	46.6	**2,900.4**
Iroquois **07120002**	6.7	76.2	60.1	4.9	1.4	0.8	86.9	7.8	42.6	1,837.2	12.4	**2,136.9**
Chicago **07120003**	8.7	67.7	238.1	175.2	87.3	1.2	60.9	29.4	4.1	32.2	0.9	**705.9**
Des Plaines **07120004**	27.1	166.8	414.4	174.0	81.2	2.0	145.2	76.4	26.0	258.3	9.9	**1,381.3**
Upper Illinois **07120005**	23.7	43.8	42.5	6.7	2.5	1.1	66.3	27.6	14.2	900.3	6.0	**1,134.8**
Upper Fox **07120006**	73.3	150.2	187.8	49.1	14.9	4.3	285.5	63.9	135.4	536.0	43.7	**1,544.1**
Lower Fox **07120007**	9.7	70.3	103.9	30.2	8.9	1.7	69.9	30.2	38.5	739.1	0.8	**1,103.1**
Lower Illinois-Senachwine Lake **07130001**	65.9	84.1	76.3	20.8	7.9	2.4	228.2	15.5	70.3	1,353.6	41.0	**1,966.0**
Vermilion **07130002**	4.4	42.8	47.9	6.2	1.5	1.6	29.5	6.6	20.4	1,171.0	1.3	**1,333.1**
Lower Illinois-Lake Chautauqua **07130003**	64.3	63.4	70.9	21.5	4.5	0.7	376.2	4.7	97.8	866.0	79.4	**1,649.4**
Mackinaw **07130004**	4.6	44.7	41.5	7.5	1.8	0.2	66.4	2.2	47.7	929.5	3.0	**1,149.1**
Total	**317.0**	**924.1**	**1,416.3**	**517.9**	**219.5**	**17.1**	**1,745.1**	**360.1**	**605.2**	**10,636.9**	**245.0**	**17,004.1**

[a]The percent imperviousness applied to each of the developed land uses is as follows: open space (8.83%), low density (32.36%), medium density (61.24%), and high density (88.70%).

Point Sources

There are numerous point source discharges in the watershed. Only the major dischargers, with a design flow greater than 1 MGD, are included in the simulation (Table 3). The major dischargers are represented at long-term average flows, without accounting for changes over time or seasonal variations.

Table 3. Major point source discharges in the Illinois River basin

NPDES ID	Name	Design flow (MGD)	Observed flow (MGD) (1991-2006 average)
IL0025135	BEARDSTOWN SD STP	1.13	1.31
IL0001830	CATERPILLAR INC.-MAPLETON	14.15	0.89
IL0027839	CANTON WEST STP	3.43	2.5284
IL0001953	AVENTINE RENEWABLE ENERGY	34.09	0.54
IL0001970	AMEREN ENERGY RESOURCES-EDWARD	357.90	5.06
IL0002232	MIDWEST GENERATION-POWERTON	530.10	11.13
IL0002526	KEYSTONE STEEL AND WIRE	10.12	5.06
IL0034495	PEKIN STP #1	4.50	3.43
IL0001414	CATERPILLAR INC-MOSSVILLE	1.44	0.86
IL0002291	CATERPILLAR INC.-EAST PEORIA	3.10	2.18
IL0021288	PEORIA SD STP	37.00	22.97
IL0028576	EAST PEORIA STP #1	4.22	3.85
IL0042412	WASHINGTON STP #2	1.50	2.02
IL0046213	EAST PEORIA STP #3	1.20	0.18
IL0001392	EMERALD PERFORMANCE MATERIALS	0.95	0.78
IL0002631	ARCELORMITTAL HENNEPIN INC	7.25	3.05
IL0029424	LASALLE STP	3.33	1.40
IL0030660	PERU STP #1	3.00	5.68
IL0031216	SPRING VALLEY STP	1.10	0.86
IL0030384	OTTAWA STP	4.00	2.84
IL0023221	MENDOTA STP	2.40	0.98
IL0022004	STREATOR STP	3.30	3.44
IL0030457	PONTIAC STP	3.50	2.97
IL0021059	MARSEILLES WWTP	1.23	1.04
IL0048151	EXELON GENERATION CO, LLC	35.02	0.04
IL0048321	EXELON GENERATION-BRAIDWOOD	22.85	0.15
IL0002917	EQUISTAR CHEMICALS, LP	6.47	2.38
IL0021113	MORRIS STP	2.50	2.13
IL0002224	EXELON GENERATION CO.,LLC	481.10	0.15
IL0021130	BLOOMINGDALE-REEVES WRF	3.45	2.20
IL0021547	GLENBARD WASTEWATER AUTH-MAIN	16.02	14.16
IL0023469	WEST CHICAGO REGIONAL STP	7.64	4.55
IL0026352	CAROL STREAM WRC	6.50	4.61

NPDES ID	Name	Design flow (MGD)	Observed flow (MGD) (1991-2006 average)
IL0027618	BARTLETT WWTP	3.68	2.30
IL0028967	GLENDALE HEIGHTS STP	5.26	3.31
IL0031739	WHEATON SD WWTF	8.90	5.99
IL0032735	BOLINGBROOK WRF #2	3.00	2.85
IL0034061	NAPERVILLE SPRINGBROOK WRC	26.25	16.03
IL0034479	HANOVER PARK STP #1	2.42	1.15
IL0036137	MWRDGC HANOVER PARK WRP	12.00	9.22
IL0048721	ROSELLE-J BOTTERMAN STP	1.22	0.78
IL0055913	MINOOKA STP	1.09	0.42
IL0074373	PLAINFIELD NORTH STP	3.50	2.28
IL0001619	INEOS NOVA LLC	0.12	0.08
IL0001643	BP AMOCO CHEMICAL-JOLIET	2.32	1.15
IL0001732	CATERPILLAR, INC.-JOLIET	2.12	0.36
IL0002216	MIDWEST GENERATION,LLC-JOLIET9	398.70	8.55
IL0002453	STEPAN COMPANY-ELWOOD	0.88	0.67
IL0002861	EXXONMOBIL OIL-JOLIET REFINERY	15.50	2.84
IL0033553	JOLIET WEST STP	14.00	10.91
IL0020532	FRANKFORT WEST WWTP	1.30	1.04
IL0020559	NEW LENOX STP #1	2.52	1.70
IL0024201	MOKENA STP	2.50	1.47
IL0045403	FRANKFORT NORTH STP	1.35	0.92
IL0001589	CITGO PETROLEUM CORPORATION	5.82	4.18
IL0022519	JOLIET EAST STP	18.20	18.02
IL0022586	FLAGG CREEK WRD MCELWAIN STP	12.00	12.11
IL0029611	LOCKPORT STP	3.40	3.64
IL0032760	IL AMERICAN WATER-SANTA FE	1.00	0.32
IL0025089	MANTENO WPCC	1.15	1.37
IL0021784	KANKAKEE RIVER METRO AGENCY	25.00	12.50
IL0022179	MOMENCE STP	1.60	1.04
IL0022161	WATSEKA STP	1.60	0.84
IN0023621	LOWELL MUNICIPAL STP	4.00	259.50
IN0037176	TWIN LAKES UTILITIES, INC WWTP	1.10	0.86
IN0030651	SOUTH HAVEN SEWER WORKS, INC.	2.00	1.03
IN0020991	PLYMOUTH MUNICIPAL STP	3.50	2.15
IN0025577	LAPORTE MUNICIPAL STP	7.00	5.40
IN0038172	ROLL COATER, INC.	0.14	0.07
IN0024520	SOUTH BEND MUNICIPAL STP	37.70	40.13
IN0020427	BREMEN MUNICIPAL WWTP	1.30	0.91
IN0021466	NAPPANEE MUNICIPAL STP	1.9	1.55

NPDES ID	Name	Design flow (MGD)	Observed flow (MGD) (1991-2006 average)
IL0030970	SANDWICH STP	1.50	0.64
IL0036412	YORKVILLE-BRISTOL SD STP	3.62	1.26
IL0062260	ELBURN STP	1.27	0.55
IL0020087	GENEVA STP	5.00	3.18
IL0022543	BATAVIA STP	4.20	2.98
IL0022705	ST. CHARLES EASTSIDE STP	9.00	4.41
IL0035891	FOX RIVER WRD WEST STP	5.00	1.20
IL0020583	FOX RIVER GROVE STP	1.25	0.80
IL0021733	LAKE IN THE HILLS SD STP	4.20	2.21
IL0023329	ALGONQUIN STP	3.00	2.31
IL0027944	CARPENTERSVILLE STP	4.50	2.50
IL0028282	CRYSTAL LAKE STP #2	5.80	4.01
IL0028541	EAST DUNDEE WWTP	2.30	0.37
IL0028657	FOX RIVER WRD SOUTH STP	25.00	15.62
IL0028665	FOX RIVER WRD NORTH STP	7.75	5.10
IL0001716	ROHM & HAAS CHEMICAL LLC	2.00	1.62
IL0020109	WAUCONDA STP	1.40	1.48
IL0020516	CARY STP	2.80	1.58
IL0021067	MCHENRY CENTRAL STP	3.00	2.06
IL0031933	NORTHERN MORAINE WW REC DIST	2.00	0.93
IL0053457	CRYSTAL LAKE STP #3	1.70	0.56
IL0066257	MCHENRY SOUTH WWTP	1.50	0.65
IL0031861	WOODSTOCK NORTH STP	3.50	2.20
IL0034282	WOODSTOCK SOUTH STP	1.75	1.02
IL0020354	ANTIOCH STP	1.60	1.46
IL0020958	FOX LAKE NW REGIONAL WRF	9.00	6.32
WI0022926	BURLINGTON WATER POLLUTION CON	2.50	3.01
WI0031496	SALEM UTILITY DISTRICT NO 2	1.57	0.89
WI0028291	UNION GROVE VILLAGE	1.00	0.91
WI0028754	WESTERN RACINE COUNTY SEWERAGE	0.92	0.95
WI0038938	TRENT TUBE DIV OF CRUCIBLE PLA	0.00	0.20
WI0020559	SUSSEX WASTEWATER TREATMENT FA	1.00	1.42
WI0023469	BROOKFIELD, CITY OF	10.00	7.52
WI0029971	WAUKESHA CITY	16.00	6.49
IL0020575	PRINCETON STP	2.15	1.82
IL0020061	WOOD DALE NORTH STP	1.97	1.83
IL0026280	ITASCA STP	2.60	2.01
IL0027367	ADDISON SOUTH-A.J. LAROCCA STP	3.20	1.95
IL0030953	SALT CREEK SD STP	3.30	3.01

NPDES ID	Name	Design flow (MGD)	Observed flow (MGD) (1991-2006 average)
IL0033812	ADDISON NORTH STP	5.30	3.58
IL0034274	WOOD DALE SOUTH STP	1.13	0.68
IL0036340	MWRDGC EGAN WRP	30.00	24.76
IL0022055	LCDPW-DES PLAINES STP	16.00	10.32
IL0022071	LCDPW-NEW CENTURY TOWN STP	6.00	2.48
IL0022501	MUNDELEIN STP	4.95	4.26
IL0020796	LINDENHURST SD STP	2.00	1.11
IL0035092	NSSD GURNEE STP	23.60	15.32
IL0071366	LAKE COUNTY DPW-MILL CREEK WRF	1.00	0.59
IL0002178	MIDWEST GENERATION,LLC-FISK	241.20	0.75
IL0002186	MIDWEST GENERATION,LLC-CRAWFRD	356.80	1.07
IL0002208	MIDWEST GENERATION,LLC-WILL CO	715.70	0.93
IL0028347	DEERFIELD WRF	3.50	3.02
IL0030171	NSSD CLAVEY ROAD STP	17.80	14.11
IL0028088	MWRDGC NORTHSIDE WRP	333.00	262.75
IL0028061	MWRDGC CALUMET WRP	354.00	266.94
IN0023060	HAMMOND MUNICIPAL STP	37.80	39.92
IN0024457	SCHERERVILLE MUNICIPAL STP	8.75	4.57
IN0039331	DYER MUNICIPAL WWTP	2.60	1.36
IL0024473	AQUA ILLINOIS-UNIV PARK	2.17	2.05
IL0027723	THORN CREEK BASIN SD STP	15.94	15.83

Most of these point sources have reasonably good monitoring for total phosphorus and total suspended solids (TSS), but not for total nitrogen. In many cases, only ammonia nitrogen is monitored. The point sources were initially represented in the model with the median of reported values for the constituents (total phosphorus, total nitrogen, and TSS) and an assumed total nitrogen concentration of 11.2 mg/L and assumed total phosphorus concentration of 7.0 mg/L for secondary treatment facilities (Tetra Tech 1999). However, in cases where point source contribution was deemed unusually high, average concentration of the available data was assumed for the missing ones.

Meteorological Data

The required meteorological time series for the 20 Watershed SWAT simulations are precipitation and air temperature. The 20 Watershed simulations do not include water temperature simulation and use a degree-day method for snowmelt. SWAT estimates Penman-Monteith potential evapotranspiration using a statistical weather generator for inputs other than temperature and precipitation. These meteorological time series are drawn from the BASINS4 Meteorological Database (USEPA 2008), which provides a consistent, quality-assured set of nationwide data with gaps filled and records disaggregated. Scenario application requires simulation over 30 years, so the available stations are those with a common 30-year period of record (or one that can be filled from an approximately co-located station) that covers the year 2001. A total of 72 precipitation stations were identified for use in the Illinois River basin model with a common period of record of 10/1/1971-9/30/2001 (Table 4). Temperature records are sparser; where these are absent temperature is taken from nearby stations with an elevation correction.

Table 4. Precipitation stations for the Illinois River basin model

COOP ID	Name	Latitude	Longitude	Temperature	Elevation (ft)
471205	WI471205	42.6508	-88.2544	X	751
473058	WI473058	43.2390	-88.1222	X	850
474174	WI474174	42.5609	-87.8156	X	600
474457	WI474457	42.5937	-88.4347	X	846
475474	WI475474	43.0719	-88.0293	X	725
475479	WI475479	42.9550	-87.9043	X	669
478723	WI478723	42.6904	-88.0336		732
478937	WI478937	43.0064	-88.2492	X	830
479190	WI479190	42.8508	-88.7246	X	876
110203	IL110203	42.4811	-88.0994	X	751
110338	IL110338	41.7806	-88.3092	X	659
110442	IL110442	42.1153	-88.1638		876
110492	IL110492	40.0179	-90.4381		449
110583	IL110583	42.2551	-88.8644		738
110761	IL110761	40.4957	-89.0006		774
111250	IL111250	40.5447	-90.0211		650
111420	IL111420	41.3978	-88.2818		505
111475	IL111475	40.7407	-88.7128	X	709
111549	IL111549	41.9950	-87.9335	X	659
111577	IL111577	41.7373	-87.7775	X	620
111627	IL111627	40.9156	-89.5031		535
112011	IL112011	41.4492	-87.6222		663
112223	IL112223	41.9342	-88.7755	X	873
112736	IL112736	42.0629	-88.2861		764
112923	IL112923	40.7512	-88.4983		689
113413	IL113413	40.4732	-88.3653		751
113940	IL113940	40.3431	-90.0164	X	459
114013	IL114013	41.3017	-89.3157	X	459
114198	IL114198	40.4745	-87.6557	X	709
114530	IL114530	41.5034	-88.1028		545
114603	IL114603	41.1382	-87.8855		640
114710	IL114710	41.2484	-89.8991	X	781
114805	IL114805	41.0415	-89.4060	X	459
115272	IL115272	40.5526	-89.3336		709
115326	IL115326	42.2928	-88.6469	X	814
115334	IL115334	40.5019	-90.3892		640
115372	IL115372	41.3287	-88.7532		489
115413	IL115413	40.2018	-89.6949	X	574
115493	IL115493	42.3103	-88.2524		741
115712	IL115712	40.9126	-89.0339	X	751

COOP ID	Name	Latitude	Longitude	Temperature	Elevation (ft)
116526	IL116526	41.3283	-88.9106	X	525
116616	IL116616	41.4933	-87.6800	X	709
116661	IL116661	41.7123	-88.9989	X	951
116711	IL116711	40.6675	-89.6838	X	650
116725	IL116725	41.3270	-87.7857		719
116753	IL116753	41.3503	-89.1072	X	620
116819	IL116819	40.7570	-88.1828	X	669
116910	IL116910	40.8854	-88.6389	X	650
117004	IL117004	40.9314	-89.7800	X	100000
117150	IL117150	40.3131	-88.1594	X	741
117551	IL117551	40.1159	-90.5608	X	659
118353	IL118353	41.0909	-88.8157		610
118756	IL118756	41.3242	-88.9857		459
118870	IL118870	39.9451	-90.2099		620
118916	IL118916	41.5520	-89.5989	X	689
119021	IL119021	40.7928	-87.7556	X	620
119029	IL119029	42.3493	-87.8828	X	699
119221	IL119221	41.8129	-88.0728	X	679
119816	IL119816	40.7765	-90.0203		676
123418	IN123418	41.5575	-85.8824	X	876
124527	IN124527	40.7592	-87.4352	X	696
124782	IN124782	41.5269	-86.2691		840
125174	IN125174	41.2647	-87.4177	X	666
125535	IN125535	41.1590	-86.9013		696
127298	IN127298	40.9357	-87.1564	X	650
127482	IN127482	41.0659	-86.2094	X	771
128187	IN128187	41.7073	-86.3331	X	774
128999	IN128999	41.5115	-87.0378	X	801
129222	IN129222	41.4437	-86.9300	X	735
129240	IN129240	41.2390	-85.8700	X	810
129511	IN129511	41.1947	-87.0578	X	666
129670	IN129670	41.0265	-86.5871	X	689

Watershed Segmentation

The Illinois River basin was divided into 100 subwatersheds for the purposes of modeling (Figure 3). The model encompasses the complete watershed without any external area draining into it and, therefore, does not require specification of any upstream boundary conditions for application. It should be noted, however, the Calumet River (subbasin 98) discharging to the Chicago Sanitary and Shipping Canal (CSSC) and the CSSC itself (subbasin 95) were disconnected from contributing to the downstream flow and the flow from CSSC was simulated as a point source.

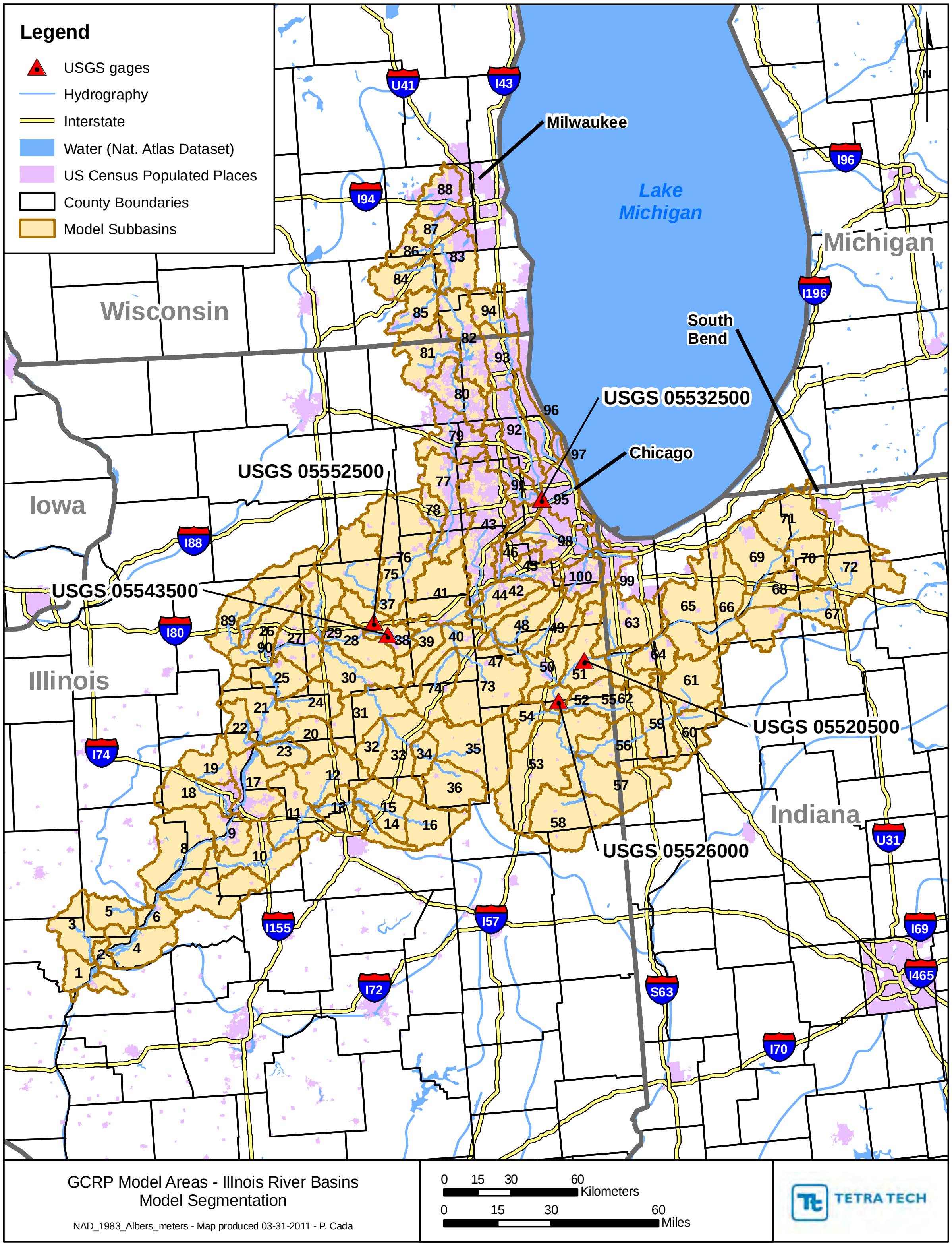

Figure 3. Model segmentation and USGS stations utilized for the Illinois River basin.

Calibration Data and Locations

The specific site chosen for initial calibration was the Iroquois River (HUC8: 07120002) near Chebanse, IL, a flow and water quality monitoring location that approximately coincides with the mouth of an 8-digit HUC just before Iroquois River joins Kankakee River. The Iroquois watershed was selected because there is a good set of flow and water quality data available and the watershed has no major point sources or impoundments. Parameters derived on the Iroquois River were not fully transferable to other portions of the Illinois River watershed and additional calibration and validation was conducted at multiple gage locations (Table 5).

Table 5. Calibration and validation locations in the Illinois River basin

Station name	USGS ID	Drainage area (mi^2)	Hydrology calibration	Water quality calibration
Iroquois River at Chebanse, IL	05526000	2,091	X	X
Kankakee River at Momence, IL	05520500	2,294	X	X
Des Plaines River at Riverside, IL	05532500	630	X	X
Fox River at Dayton, IL	05552500	2,642	X	X
Illinois river at Marseilles, IL	05543500	8,259	X	X

The model hydrology calibration period was set to Water Years 1992-2001 (within the 30-year period of record for modeling). Hydrologic validation was then performed on Water Years 1982-1992. Water quality calibration used calendar years 1985-2001, while validation used 1978-1984. However, there was some variation to this time period across the monitoring stations depending on the availability of monitored data.

SWAT Modeling

Assumptions

McHenry Lock and Dam on the Fox River and Peoria Lock and Dam on the Illinois River were represented as reservoirs in the model. Pertinent reservoir information including surface area and storage at principal (normal) and emergency spillway levels for the reservoirs modeled were obtained from the National Inventory of Dams (NID) database. The SWAT model provides four options to simulate reservoir outflow: measured daily outflow, measured monthly outflow, average annual release rate for uncontrolled reservoir, and controlled outflow with target release. Keeping in view the 20 Watershed climate change impact evaluation application, it was assumed that the best representation of the reservoirs was to simulate them without supplying time series of outflow records. Therefore, the target release approach was used in the GCRP-SWAT model.

Another important characteristic of the watershed is the widespread presence of subsurface tile drainage. Installation of tile drainage has converted what were predominantly glacial plain outwash depressional wetlands into productive farmland. The presence of tile drains, which include both surface and subsurface inlets, has radically altered the natural hydrology of the area. Surface inlet tile drains, in particular, may also play a significant role in the transport of sediment and pollutants from agricultural land to the river. It is not feasible to simulate individual tile drain systems at the large watershed scale. Further, neither the location nor the total density of tile drainage is known throughout the watershed. In most areas, only the public tile drains and ditches are documented in spatial coverage, and the extent of private tile drains is known only for limited areas. The SWAT model allows for some representation of tile drains in the form of three parameters: depth to the tile drains, time to drain soil to field capacity, and tile drain lag time. Tile drains were applied on poorly drained soils (identified from STATSGO data) under cultivation with slopes less than one percent.

Hydrology Calibration

Although, a spatial calibration approach was adopted for GCRP-SWAT modeling for the Illinois River basin, adjustments to specific subwatesheds were kept as minimal as possible. However, a systematic adjustment of parameters was been adopted and some adjustments were applied throughout the watershed. Most of the calibration efforts were geared toward getting a closer match between simulated and observed flows at the outlet of the calibration focus area.

Land Use / Soil / Slope Definition

A 5/10/5 percent threshold was used for land use/soil/slope in the SWAT model while defining the HRUs. The cropland HRUs were split into corn and soybean in the ratio 1:1. Urban land use classes were exempted from the HRU overlay thresholds.

The calibration focus area (Iroquois River) includes 10 subwatersheds and is representative of the general land use characteristics of the overall Illinois River basin. The parameters were adjusted within the practical range to obtain reasonable fit between the simulated and measured flows in terms of Nash-Sutcliffe modeling efficiency and the high flow and low flow components as well as the seasonal flows.

The overall water balance of the whole Illinois River basin predicted by the SWAT 20 Watershed model over the 30-year simulation period is as follows:

```
PRECIP =    958.1 MM
SNOW FALL =  127.74 MM
```

```
SNOW MELT =   122.18 MM
SUBLIMATION =     6.13 MM
SURFACE RUNOFF Q =   264.25 MM
LATERAL SOIL Q =    2.29 MM
TILE Q =    21.22 MM
GROUNDWATER (SHAL AQ) Q =    33.99 MM
REVAP (SHAL AQ => SOIL/PLANTS) =   78.22 MM
DEEP AQ RECHARGE =     4.71 MM
TOTAL AQ RECHARGE =   94.18 MM
TOTAL WATER YLD =   319.41 MM
PERCOLATION OUT OF SOIL =   91.80 MM
ET =    579.0 MM
PET =   1106.2MM
TRANSMISSION LOSSES =     2.35 MM
```

Hydrologic calibration adjustments focused on the following parameters:

- Curve numbers (all landuse except forest)
- CN (curve number) coefficient
- FFCB (fraction of field capacity)
- SURLAG (surface runoff lag coefficient)
- Baseflow factor
- GW_DELAY (groundwater delay time)
- GWQMN (threshold depth of water in the shallow aquifer required for return flow to occur)
- SHALLST (Initial depth of water in the shallow aquifer)
- CANMAX (maximum canopy storage)
- RevapMN (threshold depth of water in the shallow aquifer required for “revap” or percolation to the deep aquifer to occur
- CH_K2 (channel hydraulic conductivity)
- CH_N2 (channel Mannings’ coefficient)
- Sol_AWC (available water capacity of the soil layer, mm water/mm of soil)
- Depth to impervious surface
- Snow parameters SMTMP, SMFMX, SMFMN, TIMP
- Tile drain parameters (DDRAIN, TDRAIN and GDRAIN)
- Average wind speed in the weather database

Calibration results for the Iroquois River are summarized in Figures 4 through 7 and Table 6. In general, the model captured the timing of the peaks well but tends to underestimate the high flows resulting in overall underestimation by 17%.

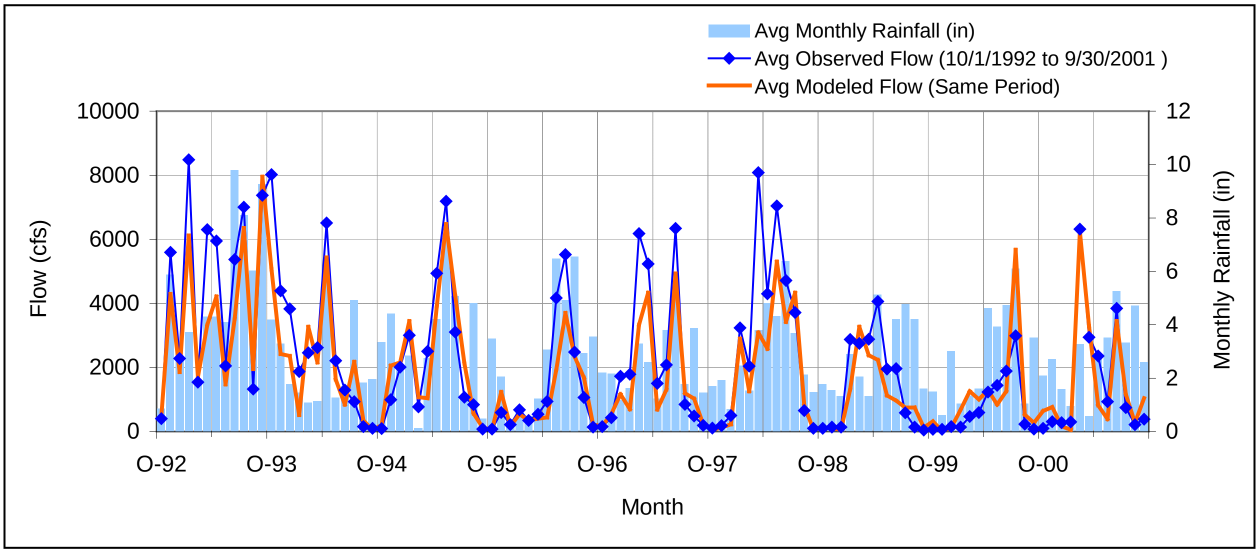

Figure 4. Mean monthly flow at USGS 05526000 Iroquois River near Chebanse, IL– calibration period.

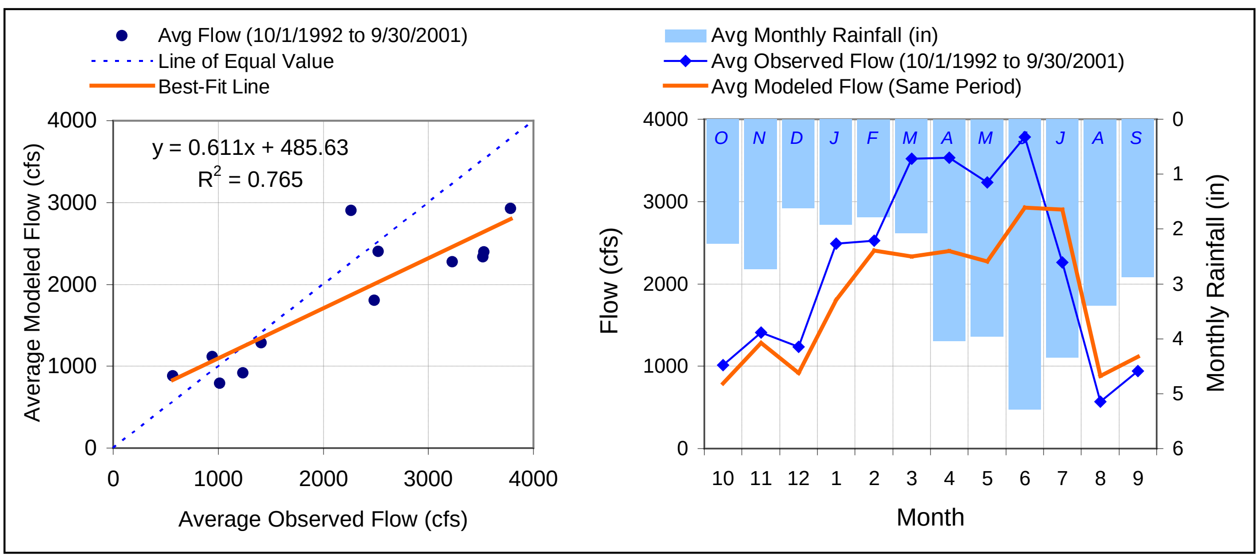

Figure 5. Seasonal regression and temporal aggregate at USGS 05526000 Iroquois River near Chebanse, IL - calibration period.

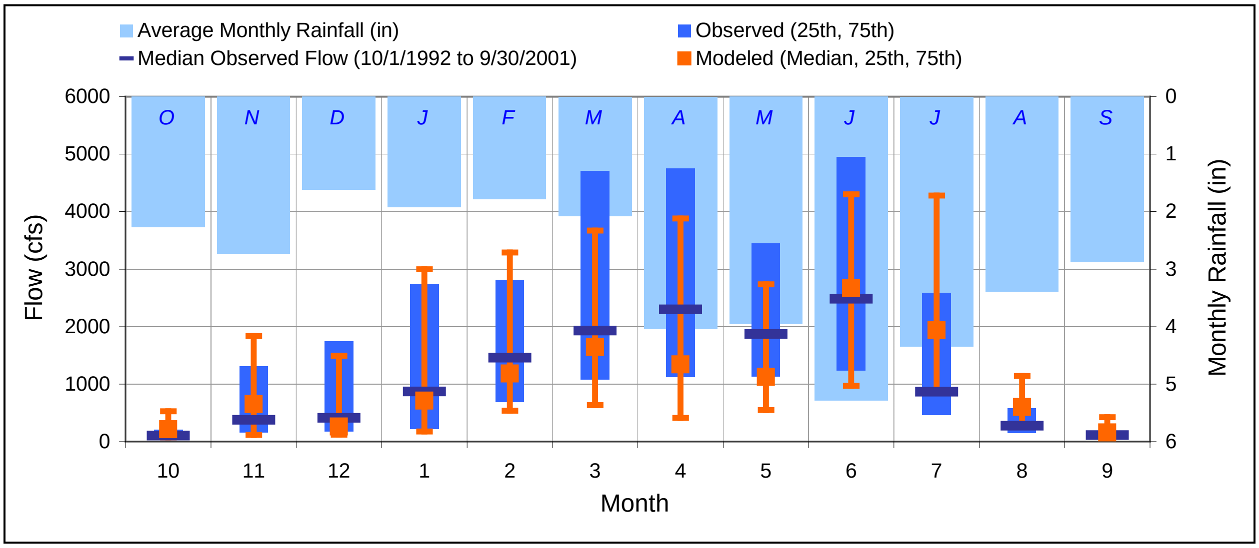

Figure 6. Seasonal medians and ranges at USGS 05526000 Iroquois River near Chebanse, IL – calibration period.

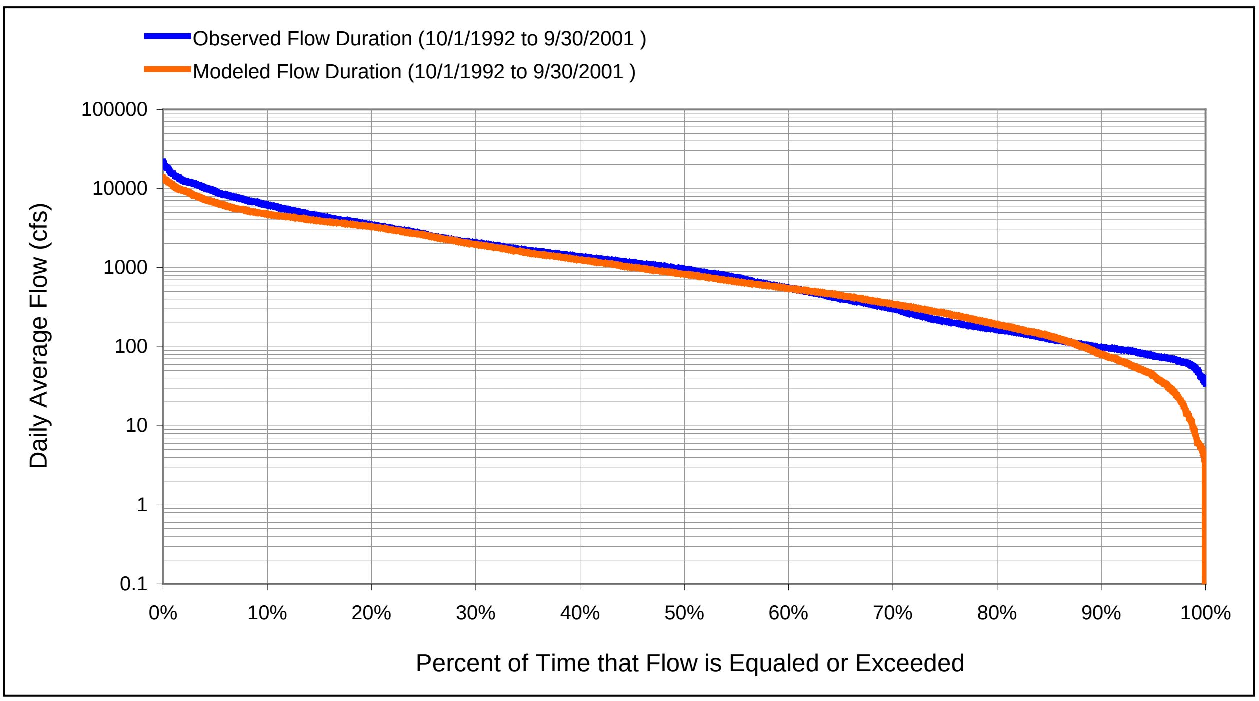

Figure 7. Flow exceedance at USGS 05526000 Iroquois River near Chebanse - calibration period.

Table 6. Summary statistics at USGS 05526000 Iroquois River near Chebanse, IL - calibration period

SWAT Simulated Flow		Observed Flow Gage	
REACH OUTFLOW FROM OUTLET 52 9-Year Analysis Period: 10/1/1992 - 9/30/2001 Flow volumes are (inches/year) for upstream drainage area		USGS 05526000 IROQUOIS RIVER NEAR CHEBANSE, IL Hydrologic Unit Code: 7120002 Latitude: 41.0089215 Longitude: -87.8233719 Drainage Area (sq-mi): 2091	
Total Simulated In-stream Flow:	**11.89**	Total Observed In-stream Flow:	**14.32**
Total of simulated highest 10% flows:	**4.85**	Total of Observed highest 10% flows:	**6.67**
Total of Simulated lowest 50% flows:	**1.03**	Total of Observed Lowest 50% flows:	**1.03**
Simulated Summer Flow Volume (months 7-9):	**2.68**	Observed Summer Flow Volume (7-9):	**2.07**
Simulated Fall Flow Volume (months 10-12):	**1.63**	Observed Fall Flow Volume (10-12):	**1.99**
Simulated Winter Flow Volume (months 1-3):	**3.49**	Observed Winter Flow Volume (1-3):	**4.58**
Simulated Spring Flow Volume (months 4-6):	**4.09**	Observed Spring Flow Volume (4-6):	**5.68**
Total Simulated Storm Volume:	**4.06**	Total Observed Storm Volume:	**6.30**
Simulated Summer Storm Volume (7-9):	**0.85**	Observed Summer Storm Volume (7-9):	**1.00**

Errors (Simulated-Observed)	*Error Statistics*	*Recommended Criteria*
Error in total volume:	**-16.99**	**10**
Error in 50% lowest flows:	-0.58	10
Error in 10% highest flows:	**-27.20**	**15**
Seasonal volume error - Summer:	29.82	30
Seasonal volume error - Fall:	-18.41	30
Seasonal volume error - Winter:	-23.84	30
Seasonal volume error - Spring:	-27.98	30
Error in storm volumes:	**-35.59**	**20**
Error in summer storm volumes:	-14.89	50
Nash-Sutcliffe Coefficient of Efficiency, E:	0.699	Model accuracy increases
Baseline adjusted coefficient (Garrick), E':	0.563	as E or E' approaches 1.0
Monthly NSE	0.768	

Hydrology Validation

Hydrology validation for the Iroquois River was performed for the period 10/1/1982 through 9/30/1992. Results are presented in Figures 8 through 11 and Table 7. The validation achieved a high Nash-Sutcliffe model efficiency, but is under on 50 percent low volume and over on summer volume (Figure 8, Figure 9, Figure 10, Figure 11, and Table 7). Although, the validation period is from 1982 to 1992 and the landuse data used in the model was obtained from 2001 NLCD, the model performance was very much comparable for both calibration and validation periods. This could be due to no major changes in the landuse/land management in the watershed and a somewhat consistent weather pattern.

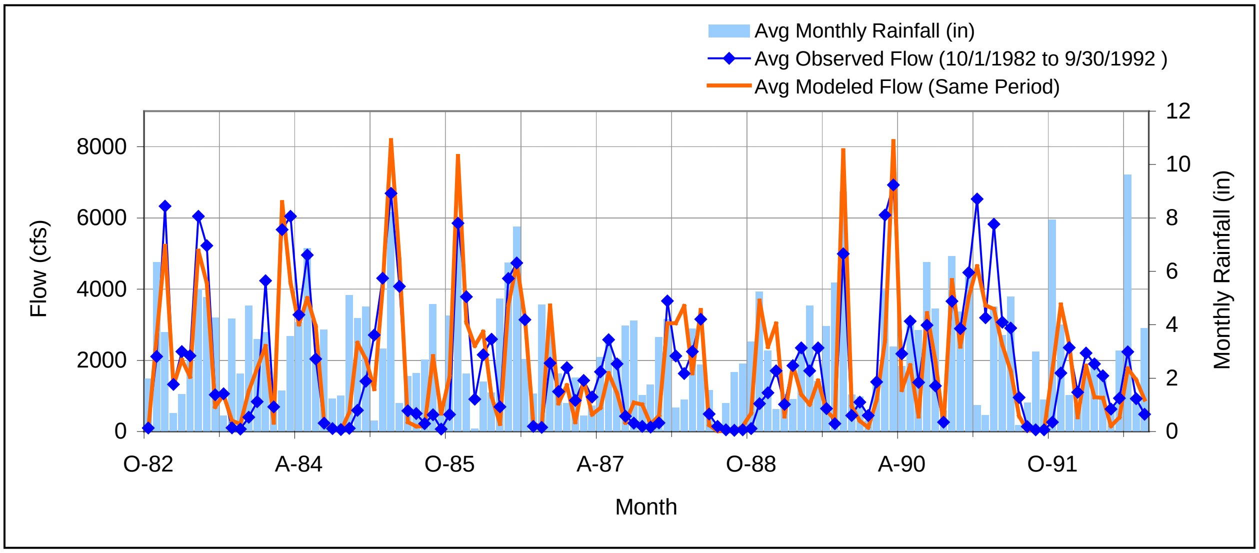

Figure 8. **Mean monthly flow at USGS 05526000 Iroquois River near Chebanse, IL – validation period.**

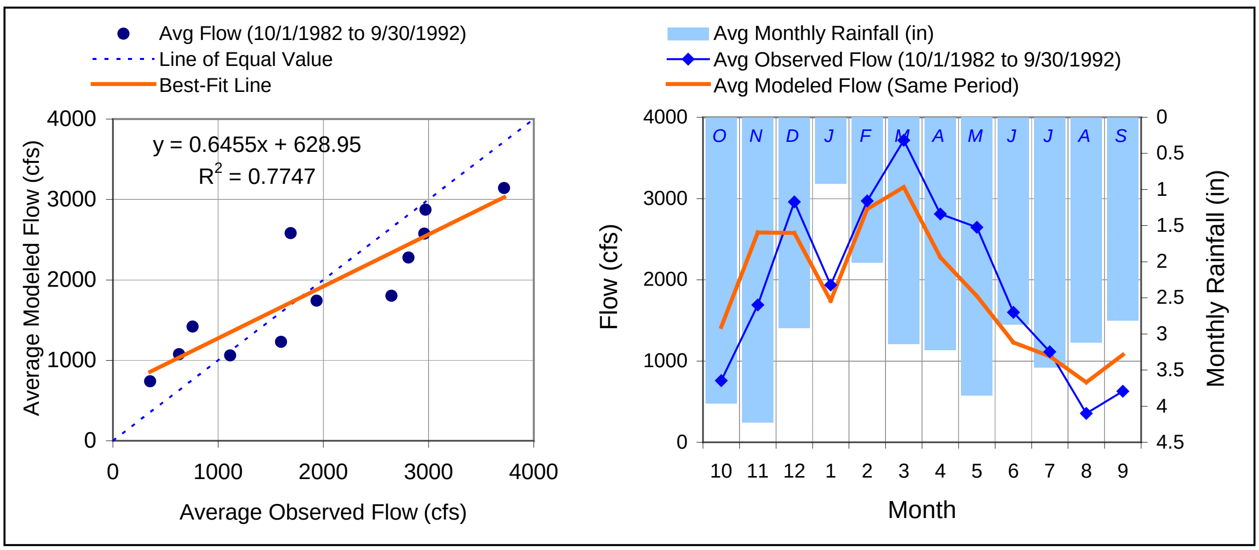

Figure 9. **Seasonal regression and temporal aggregate at USGS 05526000 Iroquois River near Chebanse, IL - validation period.**

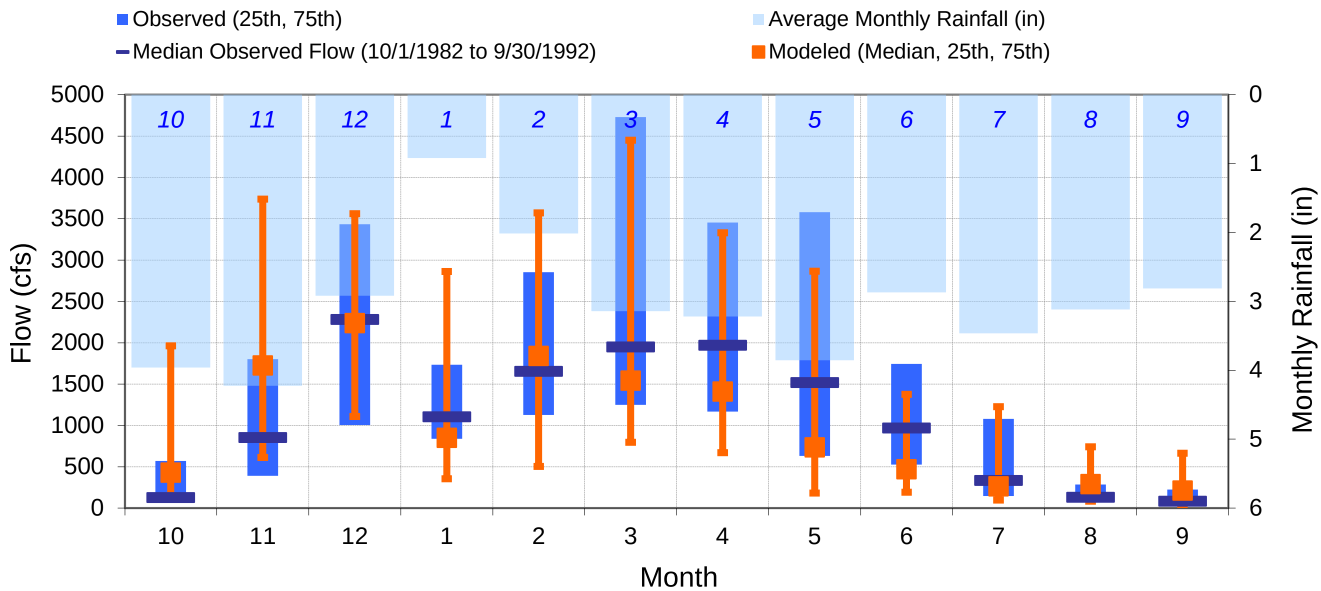

Figure 10. Seasonal medians and ranges at USGS 05526000 Iroquois River near Chebanse, IL – validation period.

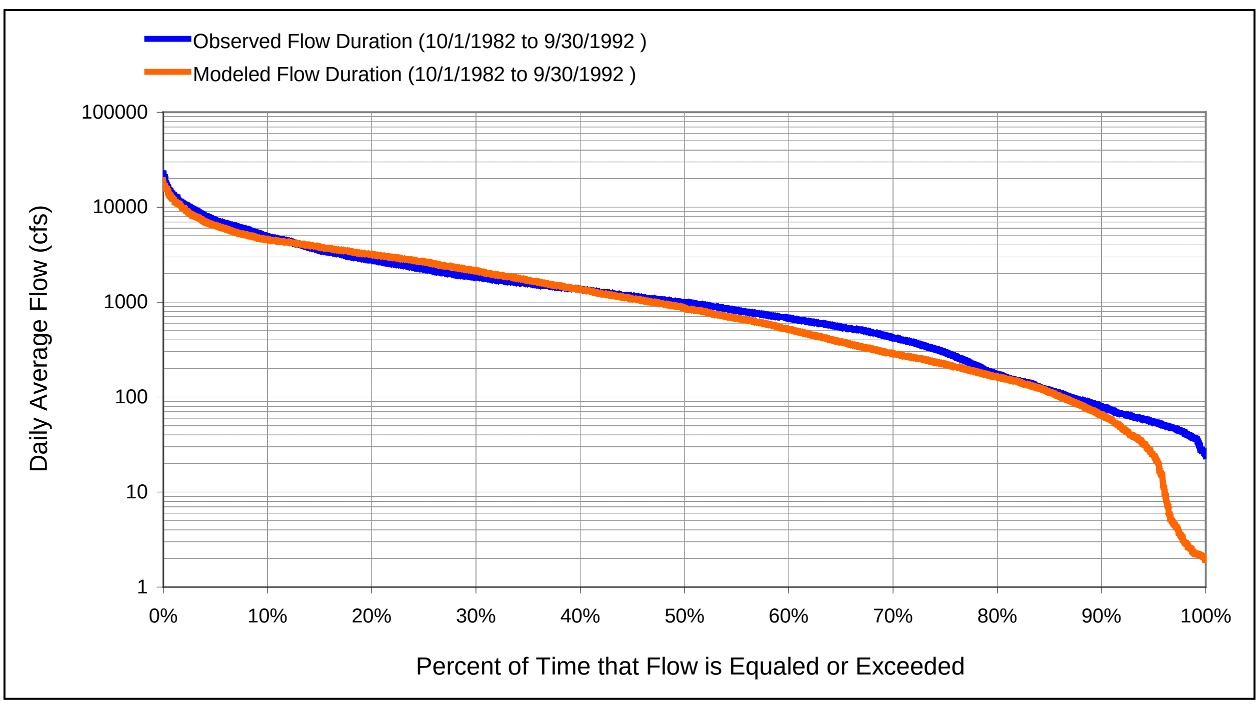

Figure 11. Flow exceedance at USGS 05526000 Iroquois River near Chebanse, IL - validation period.

Table 7. Summary statistics at USGS 05526000 Iroquois River near Chebanse, IL - validation period.

SWAT Simulated Flow		Observed Flow Gage	
REACH OUTFLOW FROM OUTLET 52		USGS 05526000 IROQUOIS RIVER NEAR CHEBANSE, IL	
10-Year Analysis Period: 10/1/1982 - 9/30/1992 Flow volumes are (inches/year) for upstream drainage area		Hydrologic Unit Code: 7120002 Latitude: 41.0089215 Longitude: -87.8233719 Drainage Area (sq-mi): 2091	
Total Simulated In-stream Flow:	**12.15**	Total Observed In-stream Flow:	**12.52**
Total of simulated highest 10% flows:	**5.02**	Total of Observed highest 10% flows:	**5.64**
Total of Simulated lowest 50% flows:	**0.95**	Total of Observed Lowest 50% flows:	**1.21**
Simulated Summer Flow Volume (months 7-9):	**1.57**	Observed Summer Flow Volume (7-9):	**1.15**
Simulated Fall Flow Volume (months 10-12):	**3.58**	Observed Fall Flow Volume (10-12):	**2.95**
Simulated Winter Flow Volume (months 1-3):	**4.14**	Observed Winter Flow Volume (1-3):	**4.61**
Simulated Spring Flow Volume (months 4-6):	**2.86**	Observed Spring Flow Volume (4-6):	**3.81**
Total Simulated Storm Volume:	**4.28**	Total Observed Storm Volume:	**5.19**
Simulated Summer Storm Volume (7-9):	**0.54**	Observed Summer Storm Volume (7-9):	**0.57**

Errors (Simulated-Observed)	*Error Statistics*	*Recommended Criteria*
Error in total volume:	-2.98	10
Error in 50% lowest flows:	**-21.27**	**10**
Error in 10% highest flows:	-11.00	15
Seasonal volume error - Summer:	**36.69**	**30**
Seasonal volume error - Fall:	21.34	30
Seasonal volume error - Winter:	-10.30	30
Seasonal volume error - Spring:	-24.88	30
Error in storm volumes:	-17.48	20
Error in summer storm volumes:	-4.76	50
Nash-Sutcliffe Coefficient of Efficiency, E:	0.674	Model accuracy increases
Baseline adjusted coefficient (Garrick), E':	0.457	as E or E' approaches 1.0
Monthly NSE	0.712	

>> Clear

Hydrology Results for Larger Watershed

Parameters determined for the Iroquois River monitoring station were not fully transferable to all other areas in the watershed, especially the Kankakee and Fox gages. Kankakee River originally drained one of the largest wetlands in North America and has since been significantly altered. The river now flows through primarily rural lands of reclaimed croplands. During the calibration, Channel Mannings' N had to be reduced for the Kankakee drainage area to reduce the peak flow rates in the channel. Higher upland erosion rates simulated by SWAT were controlled by reducing the P-factor for cropland HRUs for both Kankakee and Fox drainage areas. In general, calibration results were acceptable at most gages, as summarized in Table 8. Model performance was relatively poor at the Kankakee and Fox stations.

Results of the validation exercise are summarized in Table 9. Summer season flows were overestimated both during the calibration and validation periods at all stations except Kankakee. Unlike the calibration period, fall season flows were overestimated during the validation period. Overall, hydrology was simulated well at all gages, except the Kankakee station where low flows were underpredicted and high flows were over predicted, resulting in an overprediction of total storm volumes.

Table 8. Summary statistics (percent error): all stations - calibration period

Station	05526000 Iroquois River at Chebanse, IL	05520500 Kankakee River at Momence, IL	05532500 Des Plaines River at Riverside, IL	05552500 Fox River at Dayton, IL	05543500 Illinois River at Marseilles, IL
Error in total volume:	-16.99	-16.74	-7.97	-2.94	-6.75
Error in 50% lowest flows:	-0.58	-37.19	-6.98	-5.58	-8.18
Error in 10% highest flows:	-27.20	32.90	-14.69	1.14	-5.35
Seasonal volume error - Summer:	29.82	-5.31	29.05	47.39	11.96
Seasonal volume error - Fall:	-18.41	-24.23	-7.60	-8.61	-4.52
Seasonal volume error - Winter:	-23.84	-15.45	-18.09	-24.48	-12.03
Seasonal volume error - Spring:	-27.98	-20.05	-16.18	-6.00	-14.21
Error in storm volumes:	-35.59	44.06	-32.00	16.17	-5.03
Error in summer storm volumes:	-14.89	5.27	-21.41	57.63	3.30
Daily Nash-Sutcliffe Coefficient of Efficiency, E:	0.699	0.241	0.561	0.367	0.787
Monthly Nash-Sutcliffe Coefficient of Efficiency, E:	0.768	0.540	0.622	0.530	0.883

Table 9. Summary statistics: all stations - validation period

Station	05526000 Iroquois River at Chebanse, IL	05520500 Kankakee River at Momence, IL	05532500 Des Plaines River at Riverside, IL	05552500 Fox River at Dayton, IL	05543500 Illinois River at Marseilles, IL
Error in total volume:	-2.98	-9.24	12.69	9.52	5.78
Error in 50% lowest flows:	-21.27	-33.25	13.77	9.19	-3.45
Error in 10% highest flows:	-11.00	37.98	12.33	23.25	17.49
Seasonal volume error - Summer:	36.69	-5.79	42.17	52.54	18.46
Seasonal volume error - Fall:	21.34	9.77	12.41	2.17	21.78
Seasonal volume error - Winter:	-10.30	-11.44	1.08	-5.13	-2.24
Seasonal volume error - Spring:	-24.88	-23.42	4.55	10.02	-9.45
Error in storm volumes:	-17.48	68.38	-13.72	37.25	19.98
Error in summer storm volumes:	-4.76	13.56	-12.01	67.69	21.93
Daily Nash-Sutcliffe Coefficient of Efficiency, E:	0.674	0.036	0.586	0.418	0.571
Monthly Nash-Sutcliffe Coefficient of Efficiency, E:	0.712	0.473	0.635	0.702	0.635

Water Quality Calibration and Validation

Initial calibration and validation of water quality was done on the Iroquois River (USGS 05526000), using time period 1985-2001 for calibration and 1978-1984 for validation. As with hydrology, calibration was performed on the later period as this better reflects the land use included in the model. The validation period at stations is constrained by data availability.

Calibration adjustments for sediment focused on the following parameters:

- SPCON (Linear parameters for estimating maximum amount of sediment that can be re-entrained during channel sediment routing)
- PRF (Peak rate adjustment factor for sediment routing in the main channel)
- USLE-K (USLE erodibility factor)
- CH_COV (Channel cover factor)
- CH_EROD (Channel erodibility factor)
- USLE-P (USLE support practice factor)
- DIRTMX and curb length density in urban database

Simulated and estimated sediment loads at the Iroquois River station for both the calibration and validation periods are shown in Figure 12 and statistics for the two periods are provided separately in Table 10. The key statistic in Table 10 is the relative percent error, which shows the error in the prediction of monthly load normalized to the estimated load. Table 10 also shows the relative average absolute error, which is the average of the relative magnitude of errors in individual monthly load predictions. This number is inflated by outlier months in which the simulated and estimated loads differ by large amounts (which may be as easily due to uncertainty in the estimated load due to limited data as to problems with the model) and the third statistic, the relative median absolute error, is likely more relevant and shows better agreement.

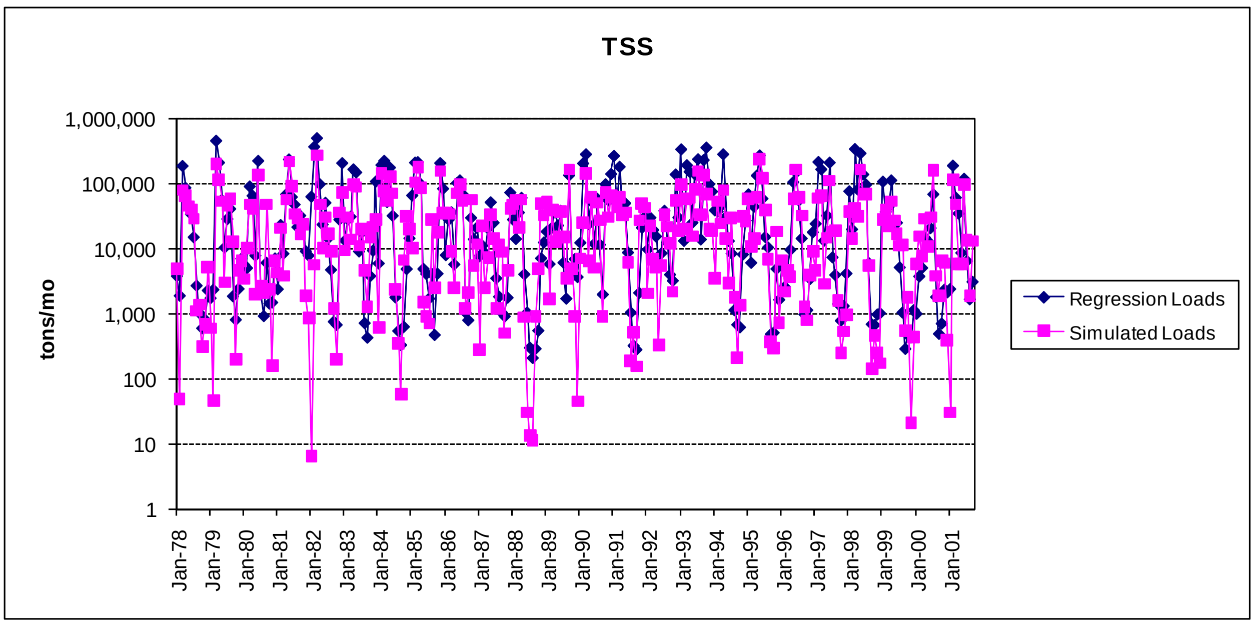

Figure 12. Fit for monthly load of TSS at USGS 05526000 Iroquois River near Chebanse, IL.

Table 10. Model fit statistics (observed minus predicted) for monthly sediment loads using stratified regression at USGS 05526000 Iroquois River near Chebanse, IL

Statistic	Calibration period (1985-2001)	Validation period (1978-1984)
Relative Percent Error	38%	39%
Relative Average Absolute Error	56%	51%
Relative Median Absolute Error	19.8%	9.9%

Calibration adjustments for total phosphorus and total nitrogen focused on the following parameters:

- Initial soil organic N and P
- PPERCO (phosphorus percolation coefficient)
- NPERCO (nitrogen percolation coefficient)
- PHOSKD (phosphorus soil partitioning coefficient)
- SOL_CBN1 (Organic carbon in the first soil layer)
- MUMAX
- QUAL2E parameters such as algal, organic nitrogen, and organic phosphorus settling rate in the reach, benthic source rate for dissolved phosphorus and NH4-N in the reach, fraction of algal biomass that is nitrogen and phosphorus, Michaelis-Menton half-saturation constant for nitrogen and phosphorus

Results for the phosphorus simulation are shown in Figure 13 and Table 11. Results for the nitrogen simulation are shown in Figure 14 and Table 12. The model fit is good for phosphorus and nitrogen was underpredicted.

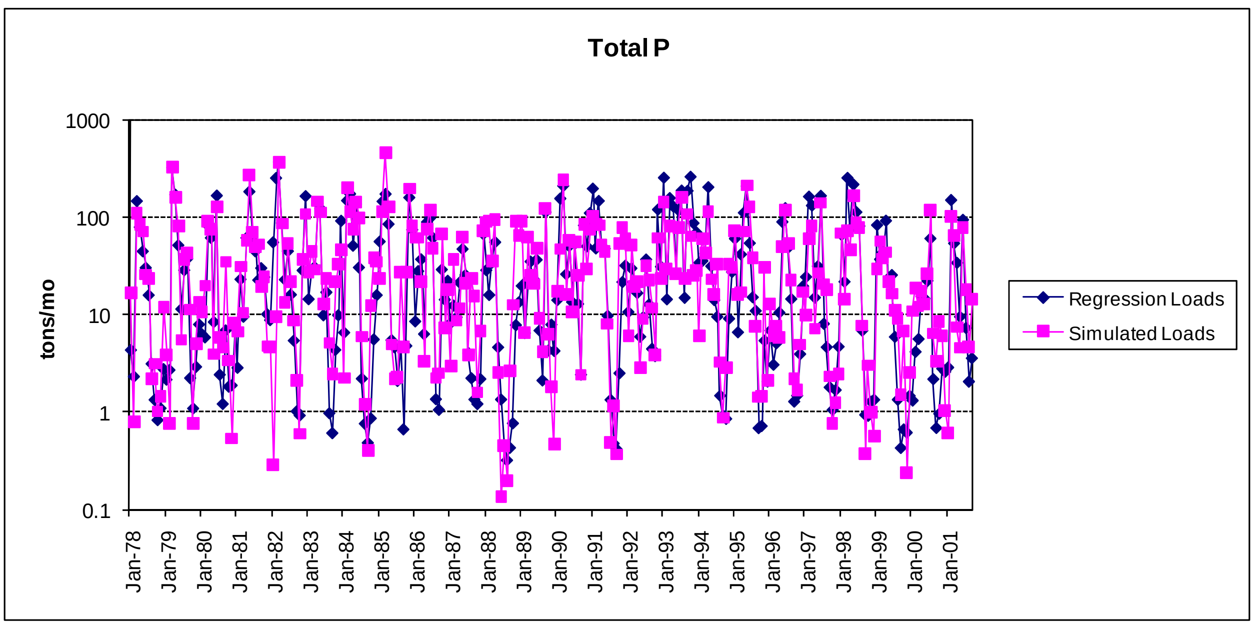

Figure 13. Fit for monthly load of total phosphorus at USGS 05526000 Iroquois River near Chebanse, IL.

Table 11. Model fit statistics (observed minus predicted) for monthly phosphorus loads using stratified regression at USGS 05526000 Iroquois River near Chebanse, IL

Statistic	Calibration period (1985-2001)	Validation period (1978-1984)
Relative Percent Error	5%	-1
Average Absolute Error	49%	33%
Median Absolute Error	16.9%	11.9%

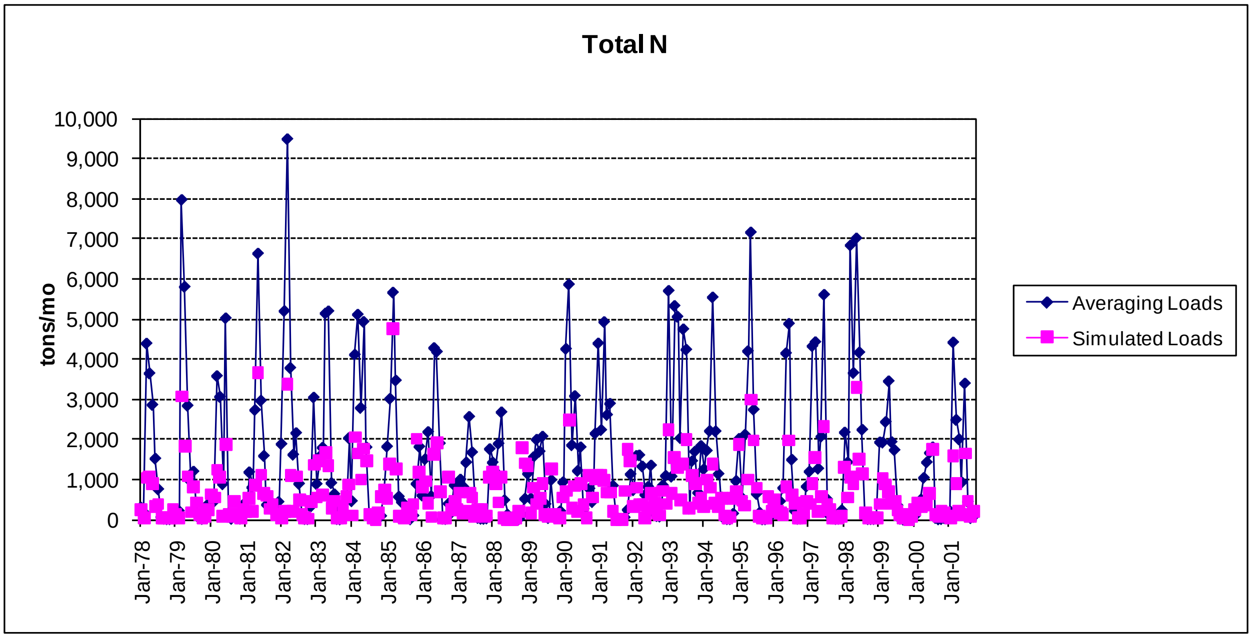

Figure 14. Fit for monthly load of total nitrogen at USGS 05526000 Iroquois River near Chebanse, IL.

Table 12. Model fit statistics (observed minus predicted) for monthly total nitrogen loads using averaging estimator at USGS 05526000 Iroquois River near Chebanse, IL

Statistic	Calibration period (1985-2001)	Validation period (1978-1984)
Relative Percent Error	56%	60%
Average Absolute Error	64%	64%
Median Absolute Error	29.8%	20.5%

Water Quality Results for Larger Watershed

Only the USLE P-factor was spatially adjusted to account for high upland erosion for the Kankakee and Fox watersheds. Summary statistics for the SWAT water quality calibration and validation at other stations in the watershed are provided in Table 13 and Table 14. There were unexplained high simulated sediment loads at the Fox stations that were not reflected in the measured sediment data at this station.

Table 13. Summary statistics for water quality at all stations – calibration period 1985-2001 (unless otherwise noted)

Station	05526000 Iroquois River at Chebanse, IL	05520500 Kankakee River at Momence, IL	05532500 Des Plaines River at Riverside, IL	05552500 Fox River at Dayton, IL (1990-2001)	05543500 Illinois River at Marseilles, IL
Relative Percent Error TSS Load	38	-7	-3	-234	-97
Relative Percent Error TP Load	5	-71	-54	-51	14
Relative Percent Error TN Load	56	-5	-46	-3	26

Table 14. Summary statistics for water quality at all stations – validation period 1978-1984 (unless otherwise noted)

Station	05526000 Iroquois River at Chebanse, IL	05520500 Kankakee River at Momence, IL	05532500 Des Plaines River at Riverside, IL	05552500 Fox River at Dayton, IL (1978-1989)	05543500 Illinois River at Marseilles, IL (1974-1984)
Relative Percent Error TSS Load	39	-1	-23	-267	-107
Relative Percent Error TP Load	-1	-100	-68	-71	9
Relative Percent Error TN Load	60	-13	-58	-14	24

References

Tetra Tech. 1999. Improving Point Source Loadings Data for Reporting National Water Quality Indicators. Final Technical Report prepared for U.S. Environmental Protection Agency, Office of Wastewater Management, Washington, DC, by Tetra Tech, Inc., Fairfax, VA.

USGS (United States Geological Survey). 1994. NAWQA Fact Sheet. Available at: http://il.water.usgs.gov/proj/lirb/pubs/pdfs/fctsheet.pdf

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Appendix O
Model Configuration, Calibration and Validation

Basin: Lake Erie Drainages (Erie)

Contents

Tables

Figures

Watershed Background

The Lake Erie drainages were selected as one of the 15 non-pilot application watersheds for the 20 Watershed study. Watershed modeling for the non-pilot areas is accomplished using the SWAT model only, and model calibration and validation results are presented in abbreviated form.

Water Body Characteristics

Lake Erie is the eleventh largest freshwater lake in the world. About two-thirds of the contributing watershed is in the United States, and includes portions of Michigan, Indiana, Ohio, Pennsylvania, and New York. The model study area focuses on drainages to the southwestern portion of Lake Erie and encompasses nearly 11,700 mi² in 12 HUC8s within HUC 0410 and HUC 0411 (Figure 1).

Situated in two major physiographic provinces, the Appalachian Plateaus and the Central Lowland, the watershed includes varied topographic and geomorphic features that affect the hydrology. The watershed consists of multiple independent drainages. The principal river in the study unit, the Maumee River, drains an area of 6,644 mi², or roughly one-third of the model study area. Other principal streams and their drainage areas in Ohio are the Sandusky River (1,420 mi², the Cuyahoga River (809 mi²), and the Grand River (705 mi²). The land surface is gently rolling to nearly flat (Myers et al., 2000).

The majority of the land use in the model area is agriculture (67 percent). The remaining land uses are urban land (15 percent), forest (13 percent), and open water or wetlands (4 percent). Corn, soybeans, and wheat are the typical parts in the western part of the basin. Other agricultural land uses include pasture and forage crops, grown predominantly in the eastern part of the basin. Forest and wetlands have been greatly reduced in the watershed since the mid-1800s. Major urban areas in the model area include Cleveland, Toledo, and Akron, Ohio, along with Fort Wayne, Indiana. These cities are important industrial and manufacturing centers. Major urban centers rely on abundant supplies of water for shipping, electric power generation, industry, domestic consumption, and waste assimilation.

Average annual precipitation across the model study area ranges from about 30 to 45 inches. Precipitation is highest to the northeast because of lake effect. The lowest amounts of precipitation are in the northwestern part of the basin near the Michigan border. The highest streamflows are typically in February, March, and April, as a result of increased precipitation, cold temperatures and little vegetative growth. The lowest streamflows are in August, September, and October. During low streamflow, groundwater typically contributes most of the flow.

Cooling during power generation accounts for 71 percent of the water use in the watershed. Public and domestic supply account for 17 percent, and industry and mining account for 10 percent of the total water use. Normal precipitation is generally adequate for agriculture, so irrigation accounts for less than 1 percent of water use. Most of the major cities are near Lake Erie and derive their water from the lake.

Population density and growth in the Lake Erie basin are among the highest in the Great Lakes basin. About 40 percent of the total population of the Great Lakes basin lives in the Lake Erie basin in 17 urban areas having populations of 50,000 or more. Water resources in the study unit are central to the economy and culture of the region. The surficial deposits of this area consist primarily of ground moraine and end moraine of glacial origin; valleys are filled with glacial outwash. The area is characterized by broad, low ridges with smooth, gentle slopes separated by flat, gently undulating plains. The Eastern Lake Section and the Till Plains Section within the province consist of wide expanses of flat land underlain by clayey till or lake deposits; this flat land is interspersed with sandy ridges that are remnants of glacial-lake beaches. Because soils are fertile and the climate is temperate, the primary land use in this part of the study unit is agricultural, ranging from orchards and vineyards near the Lake Erie shoreline to cropland in corn and soybeans further inland.

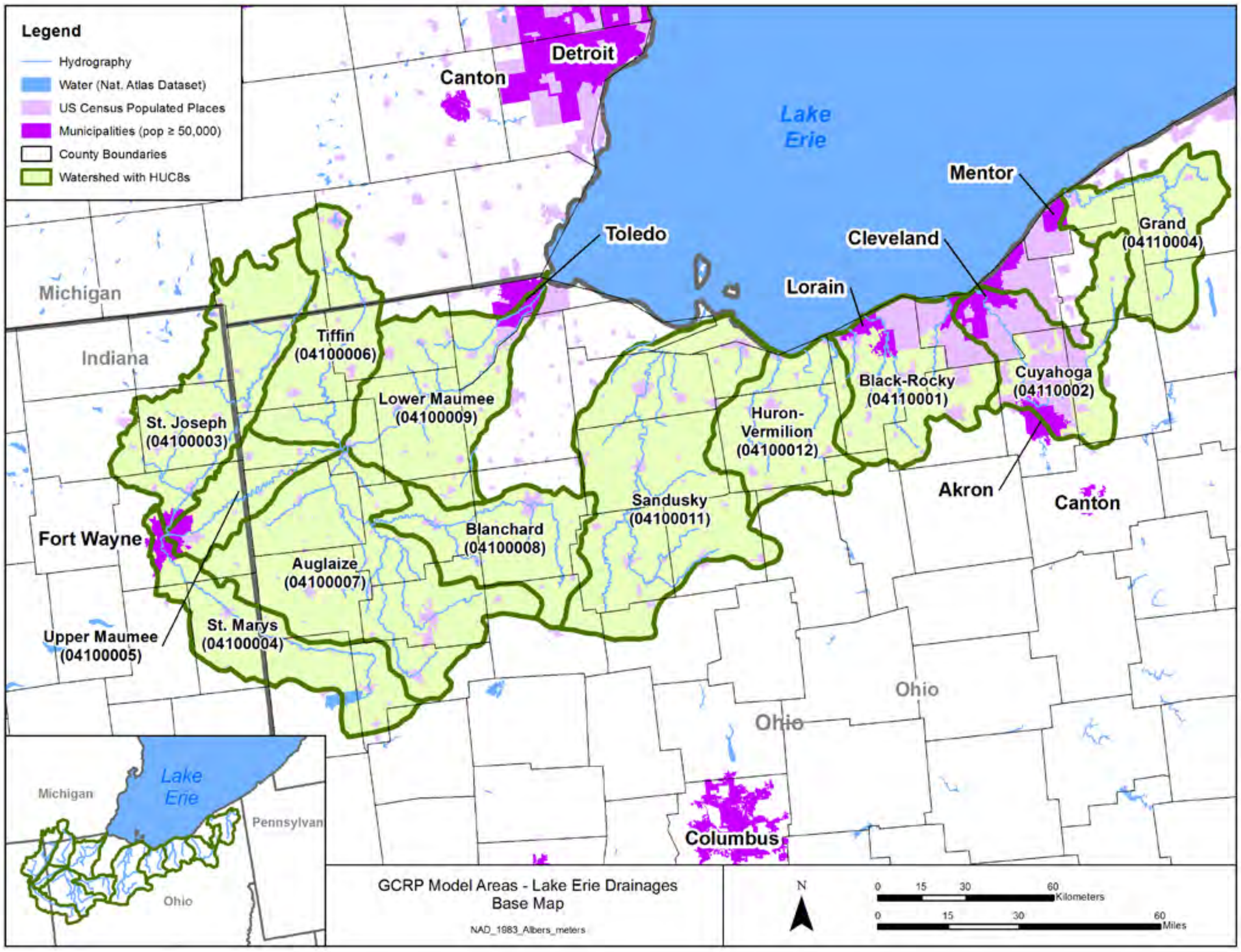


Figure 1. Location of the Lake Erie drainages.

Soil Characteristics

Soils in the watershed are described in STATSGO soil surveys. SWAT uses information drawn directly from the soils data layer to populate the model.

Land Use Representation

Land use/cover in the watershed is based on the 2001 National Land Cover Database (NLCD) coverage (Figure 2). NLCD land cover classes were aggregated according to the scheme shown in Table 1 for representation in the 20 Watershed model. SWAT uses the built-in hydrologic response unit (HRU) overlay mechanism in the ArcSWAT interface. SWAT HRUs are formed from an intersection of land use and SSURGO major soils. The distribution of land use in the watershed is summarized in Table 2.

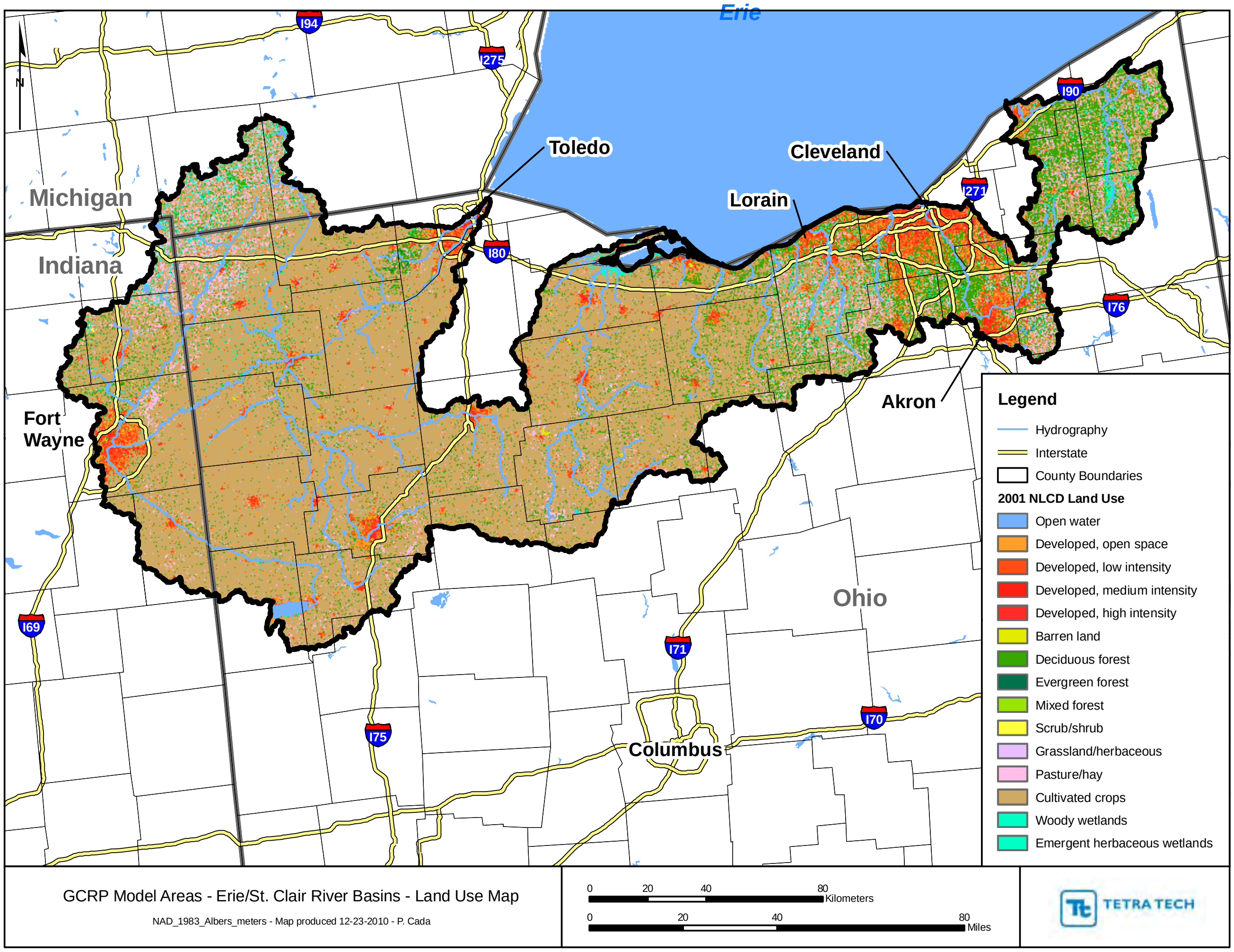


Figure 2. Land use in the Lake Erie drainages.

Table 1. Aggregation of NLCD land cover classes

NLCD Class	Comments	SWAT class
11 Water	Water surface area usually accounted for as reach area	WATR
12 Perennial ice/snow		WATR
21 Developed open space		URLD
22 Dev. Low Intensity		URMD
23 Dev. Med. Intensity		URHD
24 Dev. High Intensity		UIDU
31 Barren Land		SWRN
41 Forest	Deciduous	FRSD
42 Forest	Evergreen	FRSE
43 Forest	Mixed	FRST
51-52 Shrubland		RNGB
71-74 Herbaceous Upland		RNGE
81 Pasture/Hay		HAY
82 Cultivated		AGRR
91-97 Wetland	Emergent & woody wetlands	WETF, WETL, WETN
98-99 Wetland	Aquatic bed wetlands (not emergent)	WATR

Table 2. Land use distribution for the Lake Erie drainages (2001 NLCD) (mi^2)

HUC 8 watershed	Open water	Developed[a]				Barren land	Forest	Shrubland/ Grassland	Pasture/ Hay	Cultivated	Wetland	Total
		Open space	Low density	Medium density	High density							
St Joseph **04100003**	13.1	62.6	33.2	7.2	3.3	0.6	120.3	13.3	185.2	572.6	82.2	**1,093.6**
St Marys **04100004**	22.0	65.0	30.7	10.7	4.8	0.0	46.4	12.5	18.4	650.1	5.4	**866.1**
Upper Maumee **04100005**	4.4	28.4	18.9	4.4	2.5	0.1	19.4	2.6	16.0	286.2	4.4	**387.4**
Tiffin **04100006**	5.4	42.2	15.6	3.3	1.9	0.7	55.4	3.6	81.0	522.8	45.6	**777.6**
Auglaize **04100007**	8.9	118.0	43.2	9.2	5.6	1.6	87.8	20.0	30.5	1,336.3	5.3	**1,666.5**
Blanchard **04100008**	3.6	51.3	19.4	5.1	2.4	0.4	43.0	12.6	7.9	623.8	2.6	**772.0**
Lower Maumee **04100009**	14.8	82.3	47.8	17.1	8.0	1.1	72.2	10.7	14.4	806.8	5.5	**1,080.5**
Sandusky **04100011**	15.2	118.2	50.0	14.9	7.1	5.9	148.7	21.3	44.7	1,401.0	32.9	**1,859.8**
Huron-Vermilion **04100012**	6.1	45.3	18.9	4.3	2.0	0.1	147.3	2.4	38.6	490.0	9.3	**764.4**
Black-Rocky **04110001**	6.7	127.6	111.4	28.8	6.4	0.9	224.9	8.2	109.6	218.0	55.0	**897.6**
Cuyahoga **04110002**	19.2	141.7	144.4	56.7	20.6	0.6	251.3	27.9	61.5	65.4	22.1	**811.4**
Grand **04110004**	8.9	42.9	26.5	2.9	0.7	0.1	300.0	40.9	64.2	173.2	45.3	**705.6**
Total	**128.3**	**925.5**	**560.0**	**164.6**	**65.4**	**12.1**	**1,516.8**	**176.1**	**672.0**	**7,146.2**	**315.5**	**11,682.5**

[a]The percent imperviousness applied to each of the developed land uses is as follows: open space (7.30%), low density (32.53%), medium density (60.72%), and high density (86.75%).

Point Sources

There are numerous point source discharges in the watershed. Only the major dischargers, generally defined as those with a design flow greater than 1 MGD are included in the simulation (Table 3). The major dischargers are represented at long-term average flows, without accounting for changes over time or seasonal variations.

Table 3. Major point source discharges in the Lake Erie drainages

NPDES ID	Name	Design flow (MGD)	Observed flow (MGD)
OH0034223	LUCAS CO COMMISSIONERS	15.00	15.21
OH0002666	GENERAL MOTORS CORPORATION		1.90
OH0003298	CAMPBELL SOUP COMPANY		5.11
OH0020893	CITY OF NAPOLEON	2.50	2.92
OH0024899	CITY OF DEFIANCE	4.00	3.30
OH0025771	VILLAGE OF HICKSVILLE		0.75
OH0027910	CITY OF VAN WERT	2.78	3.39
OH0026921	VILLAGE OF OTTAWA		1.54
OH0027952	CITY OF WAPAKONETA	4.00	2.60
OH0023841	ALLEN COUNTY COMMISSIONERS		1.44
OH0037338	ALLEN CO. COMMISSIONERS		3.17
OH0002615	PCS NITROGEN OHIO, LP		3.50
OH0002623	LIMA REFINING COMPANY		17.70
OH0026069	CITY OF LIMA	18.50	26.33
OH0020851	VILLAGE OF BLUFFTON		2.28
OH0025135	CITY OF FINDLAY	9.00	10.18
OH0020532	CITY OF BRYAN	3.14	2.35
OH0020796	VILLAGE OF ARCHBOLD	1.75	1.36
IN0032191	FORT WAYNE MUNICIPAL WWTP	60.00	88.87
IN0000388	DANA SPICER MANUFACTURING INC.	1.36	0.98
IN0022462	BUTLER MUNICIPAL WWTP	2.00	0.67
IN0020672	AUBURN MUNICIPAL WPCP	4.50	2.70
OH0025291	CITY OF FREMONT	11.00	17.30
OH0052949	CITY OF TIFFIN	6.00	3.27
OH0020001	CITY OF UPPER SANDUSKY	1.50	1.47
OH0020664	CITY OF CRESTLINE		0.95
OH0022659	VILLAGE OF CHARDON		2.35
OH0026948	CITY OF PAINESVILLE	6.00	2.93
OH0000957	ISG CLEVELAND		3.69

NPDES ID	Name	Design flow (MGD)	Observed flow (MGD)
OH0024651	NEORSD - SOUTHERLY WWTP	175.00	115.67
OH0024040	CITY OF BEDFORD	3.20	2.38
OH0024058	CITY OF BEDFORD HEIGHTS	7.50	2.49
OH0027430	SOLON CITY CENTRAL	3.60	4.00
OH0027863	CITY OF TWINSBURG	3.40	2.92
OH0098043	EARTH TECH	1.40	2.72
OH0025917	CITY OF KENT	5.00	2.59
OH0064009	SUMMIT COUNTY - FISHCREEK #25	4.00	3.92
OH0023221	CITY OF RAVENNA	2.80	2.20
OH0001562	REPUBLIC ENGINEERED PRODUCTS		87.30
OH0023981	AVON LAKE WASTEWATER PLANT	6.50	9.67
OH0026093	CITY OF LORAIN	15.00	13.09
OH0020427	OBERLIN WATER ENV. PROTECTION	1.50	1.27
OH0025372	VILLAGE OF GRAFTON	1.00	3.74
OH0024660	NEORSD - WESTERLY WWTP	50.00	28.50
OH0026794	CITY OF NORTH ROYALTON	1.50	1.55
OH0030503	CITY OF ROCKY RIVER	22.00	11.13
OH0045748	MEDINA COUNTY COMM SD 300	2.00	1.66
OH0043567	MEDINA COUNTY COMM SD 500	10.00	9.04
OH0020125	HURON BASIN STP		0.87
OH0028118	CITY OF WILLARD	1.36	1.80
OH0021628	CITY OF AMHERST	2.00	1.88
OH0020672	CITY OF BELLEVUE	1.20	1.09
OH0024686	CITY OF CLYDE	1.90	1.95

Most of these point sources have reasonably complete monitoring for total suspended solids (TSS). Long term average values of total phosphorus and total nitrogen were assumed based upon the type of point source discharger. The point sources were initially represented in the model with the median of reported values for total phosphorus, total suspended solids and total nitrogen.

Meteorological Data

The required meteorological time series for the 20 Watershed SWAT simulations are precipitation and air temperature. The 20 Watershed simulations do not include water temperature and uses a degree-day method for snowmelt. SWAT estimates Penmann-Monteith potential evapotranspiration using a statistical weather generator for inputs other than temperature and precipitation. These meteorological time series are drawn from the BASINS4 Meteorological Database (USEPA 2008), which provides a consistent, quality-assured set of nationwide data with gaps filled and records disaggregated. Scenario application requires simulation over 30 years, so the available stations are those with a common 30-year period of record (or one that can be filled from an approximately co-located station) that covers the year 2000. A total of 57 precipitation stations were identified for use in the Lake Erie drainages watershed model with a common period of record of 10/1/1969-9/30/2000 (Table 4). Temperature records are sparser; where these are absent temperature is taken from nearby stations with an elevation correction.

Table 4. Precipitation stations for the Lake Erie drainages watershed model

COOP ID	Name	Latitude	Longitude	Temperature	Elevation (m)
IN120200	ANGOLA	41.6397	-84.9899	x	308
IN120676	BERNE	40.6684	-84.9305	x	265
IN122096	DECATUR 1 N	40.8482	-84.9294		250
IN123037	FORT WAYNE WSO AP	41.0062	-85.2056	x	252
IN123206	GARRETT	41.3330	-85.1329		82
IN124497	KENDALLVILLE	41.4428	-85.2613		297
MI200032	ADRIAN 2 NNE	41.9165	-84.0157	x	232
MI203823	HILLSDALE	41.9353	-84.6410	x	329
OH330058	AKRON CANTON WSO AP	40.9167	-81.4333	x	368
OH330059	AKRON WPCS	41.1500	-81.5669		70
OH330061	AKRON	41.0804	-81.5169	x	329
OH330107	ALLIANCE 3 NNW	40.9550	-81.1169		322
OH330256	ASHLAND 2 SW	40.8334	-82.3499	x	386
OH330862	BOWLING GREEN WWTP	41.3831	-83.6110	x	206
OH331042	BRYAN 2 SE	41.4670	-84.5330		68
OH331072	BUCYRUS	40.8129	-82.9693	x	291
OH331390	CELINA 3 NE	40.5695	-84.5364	x	262
OH331458	CHARDON	41.5834	-81.1833	x	344
OH331541	CHIPPEWA LAKE	41.0517	-81.9360	x	360
OH331657	CLEVELAND WSFO AP	41.4051	-81.8528	x	235
OH332098	DEFIANCE	41.2778	-84.3853	x	213
OH332251	DORSET	41.6834	-80.6667	x	299
OH332599	ELYRIA 3 E	41.3833	-82.0499	x	223
OH332786	FINDLAY FAA AIRPORT	41.0136	-83.6685	x	244
OH332791	FINDLAY WPCC	41.0462	-83.6621	x	234
OH332974	FREMONT	41.3334	-83.1166	x	183
OH333021	GALION WATER WORKS	40.7236	-82.7999		357
OH333421	GROVER HILL	41.0184	-84.4724		223
OH333780	HIRAM	41.3000	-81.1500	x	375
OH333874	HOYTVILLE 2 NE	41.2168	-83.7667	x	213

COOP ID	Name	Latitude	Longitude	Temperature	Elevation (m)
OH333915	HUNTSVILLE 3 N	40.4803	-83.8131		314
OH334189	KENTON	40.6489	-83.6060	x	303
OH334551	LIMA WWTP	40.7247	-84.1294	x	259
OH334865	MANSFIELD WSO AP	40.8204	-82.5177	x	395
OH334874	MANSFIELD 5 W	40.7668	-82.6166	x	411
OH334942	MARION 2 N	40.6168	-83.1333	x	294
OH335438	MONTPELIER	41.5804	-84.6077	x	262
OH335505	MOSQUITO CREEK LAKE	41.3000	-80.7667		277
OH335669	NAPOLEON	41.3940	-84.1144	x	208
OH336118	NORWALK WWTP	41.2668	-82.6166	x	204
OH336196	OBERLIN	41.2668	-82.2167	x	249
OH336342	OTTAWA	41.0318	-84.0528		223
OH336389	PAINESVILLE 4 NW	41.7500	-81.2999	x	183
OH336405	PANDORA	40.9543	-83.9616	x	235
OH336465	PAULDING	41.1245	-84.5922	x	221
OH336949	RAVENNA 2 S	41.1333	-81.2832		337
OH337383	ST MARYS 3 W	40.5447	-84.4374		267
OH337447	SANDUSKY	41.4501	-82.7167	x	178
OH337698	SIDNEY HIGHWAY DEPT	40.2983	-84.1633		314
OH338110	STRYKER	41.5057	-84.4300		213
OH338313	TIFFIN	41.1168	-83.1667	x	226
OH338357	TOLEDO EXPRESS WSO AP	41.5886	-83.8014	x	204
OH338534	UPPER SANDUSKY	40.8334	-83.2832	x	260
OH338539	UPPER SANDUSKY WATER WK	40.8167	-83.2832		250
OH338609	VAN WERT 1 S	40.8495	-84.5807	x	241
OH338769	WARREN 3 S	41.2001	-80.8166	x	274
OH338822	WAUSEON WATER PLANT	41.5184	-84.1453	x	229

Watershed Segmentation

The Lake Erie drainages were divided into 100 subwatersheds for the purposes of modeling (Figure 3). The model encompasses the complete watershed and does not require specification of any upstream boundary conditions for application.

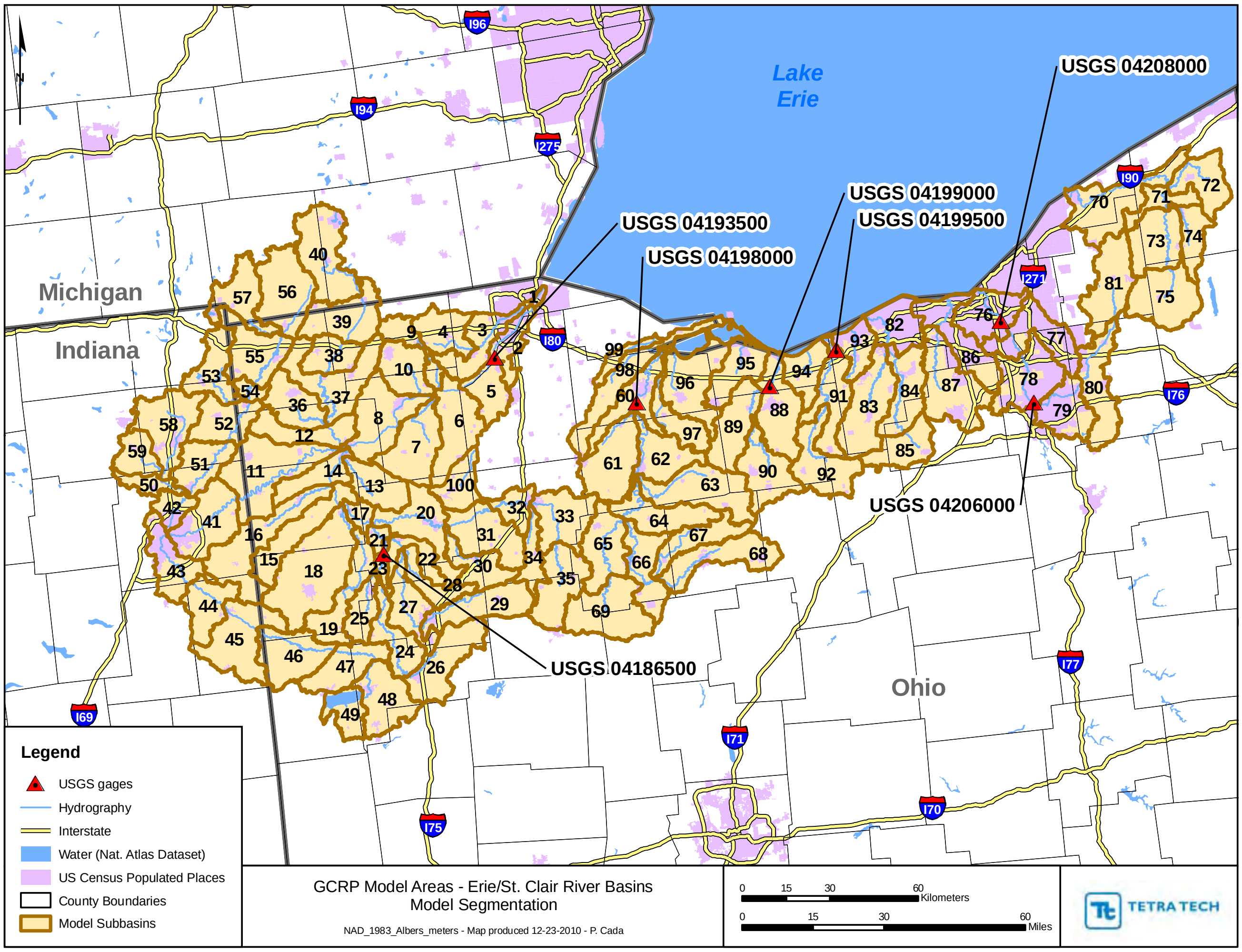


Figure 3. Model segmentation and USGS stations utilized for the Lake Erie drainages

Calibration Data and Locations

The specific site chosen for initial calibration was the Cuyahoga River at Independence (USGS 04208000), a flow and water quality monitoring location that approximately coincides with the mouth of an 8-digit HUC. The Cuyahoga River watershed was selected because there is a good set of flow and water quality data available and the watershed lacks major point sources and impoundments. Additional calibration and validation was pursued at multiple locations (Table 5). Parameters derived on the Cuyahoga River were not fully transferable to other portions of the Lake Erie drainages, and additional calibration was conducted at multiple gage locations.

Table 5. Calibration and validation locations in the Lake Erie drainages

Station name	USGS ID	Drainage area (mi^2)	Hydrology calibration	Water quality calibration
Auglaize River near Fort Jennings OH	04186500	332	x	
Maumee River at Waterville OH	04193500	6,330	x	x
Sandusky River near Fremont OH	04198000	1,251	x	x
Huron River at Milan OH	04199000	371	x	
Black River at Elyria OH	04200500	396	x	
Cuyahoga River at Old Portage OH	04206000	404	x	
Cuyahoga River at Independence OH	04208000	707	x	x

The model hydrology calibration period was set to Water Years 1990-2000 (within the 32-year period of record for modeling). Hydrologic validation was then performed on Water Years 1980-1990. Water quality calibration used calendar years 1990-2000, while validation used 1980-1990.

SWAT Modeling

Assumptions

There were no significant impoundments and/or diversions that needed representation in the watershed model for the Lake Erie drainages.

Hydrology Calibration

A spatial calibration approach was adopted for GCRP-SWAT modeling for the Lake Erie drainages. A systematic adjustment of parameters has been adopted and some adjustments are applied throughout the basin. Most of the calibration efforts were geared towards getting a closer match between simulated and observed flows at the outlet of calibration focus area.

Land Use / Soil / Slope Definition

A 5/10/5 percent threshold was used for land use/soil/slope in the SWAT model while defining the HRUs. Urban land use classes were exempted from the HRU overlay thresholds.

The calibration focus area (Cuyahoga River) includes six subwatersheds and is generally representative of the general land use characteristics of the overall watershed with the exception of a higher percentage of cultivated lands. The parameters were adjusted within the practical range to obtain reasonable fit between the simulated and measured flows in terms of Nash-Sutcliffe modeling efficiency and the high flow and low flow components as well as the seasonal flows.

The water balance of the whole Lake Erie drainages predicted by the SWAT model over the 32-year simulation period is as follows:

```
PRECIP =    934.7 MM
SNOW FALL = 125.69 MM
SNOW MELT =   122.44 MM
SUBLIMATION =     1.95 MM
SURFACE RUNOFF Q =   233.68 MM
LATERAL SOIL Q =    1.40 MM
TILE Q =     0.00 MM
GROUNDWATER (SHAL AQ) Q =    92.63 MM
REVAP (SHAL AQ => SOIL/PLANTS) =    4.67 MM
DEEP AQ RECHARGE =    13.62 MM
TOTAL AQ RECHARGE = 110.90 MM
TOTAL WATER YLD =   327.70 MM
PERCOLATION OUT OF SOIL = 110.91 MM
ET =    583.7 MM
PET =   1152.4MM
TRANSMISSION LOSSES =     0.00 MM
```

Hydrologic calibration adjustments focused on the following parameters:

- CN2 (initial SCS runoff curve number for moisture condition II)
- ESCO (soil evaporation compensation factor)
- SURLAG (surface runoff lag coefficient)
- SOL_AWC (available water capacity of the soil layer, mm water/mm of soil)

- ALPHA_BF (baseflow alpha factor, days)
- GW_DELAY (groundwater delay time, days)
- GWQMIN (threshold depth of water in the shallow aquifer required for return flow to occur, mm)
- GW_REVAP (groundwater "revap" coefficient)
- CH_N1 (Manning's "n" value for tributary channels)
- CH_N2 (Manning's "n" value for main channels)
- CH_K1 (Effective hydraulic conductivity in tributary channel alluvium)
- CH_K2 (Effective hydraulic conductivity in main channel alluvium)
- SFTMP (Snowfall temperature)
- SMTMP (Snowmelt base temperature)
- SMFMX (Maximum melt rate for snow during the year)
- SMFMN (Minimum melt rate for snow during the year)

The calibration achieves a moderately high coefficient of model fit efficiency, but is below on 50 percent lowest flow volume. Calibration results for the Cuyahoga River are summarized in Figure 4, Figure 5, Figure 6, Figure 7 and Table 6.

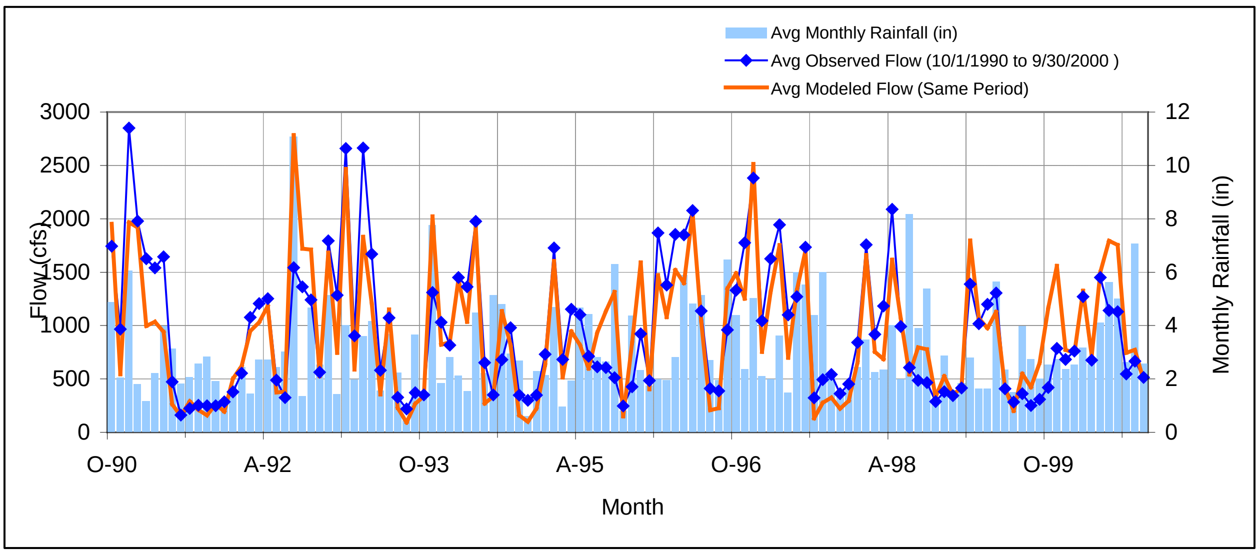


Figure 4. Mean monthly flow at USGS 04208000 Cuyahoga River at Independence, OH – calibration period.

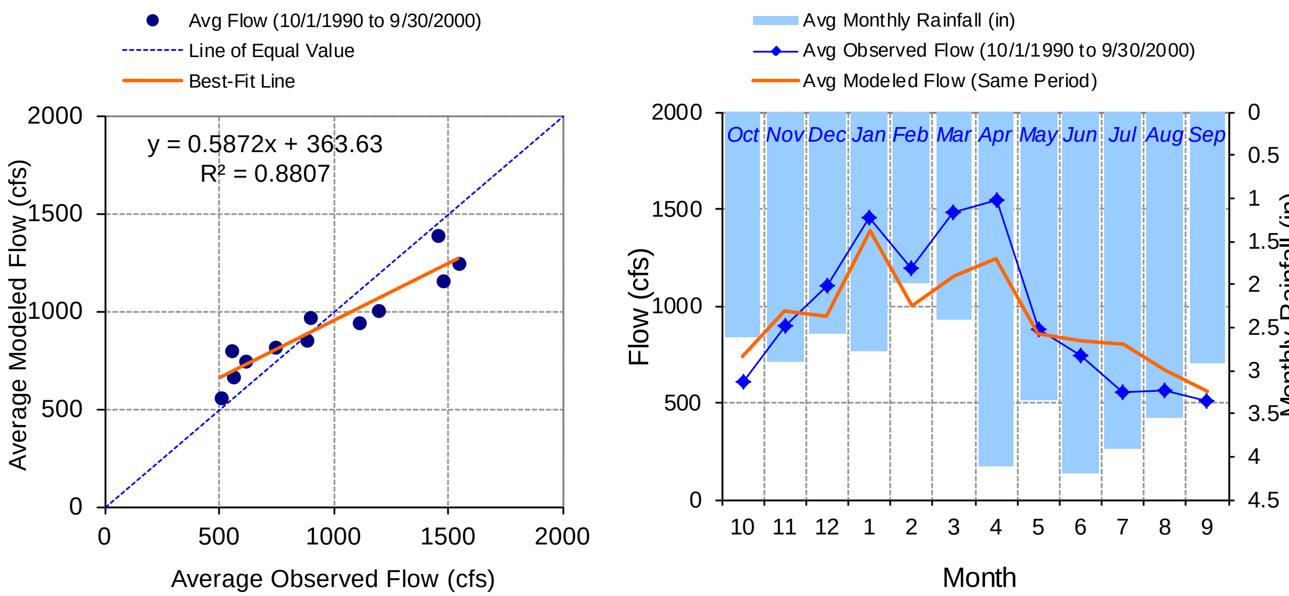


Figure 5. Seasonal regression and temporal aggregate at USGS 04208000 Cuyahoga River at Independence, OH – calibration period.

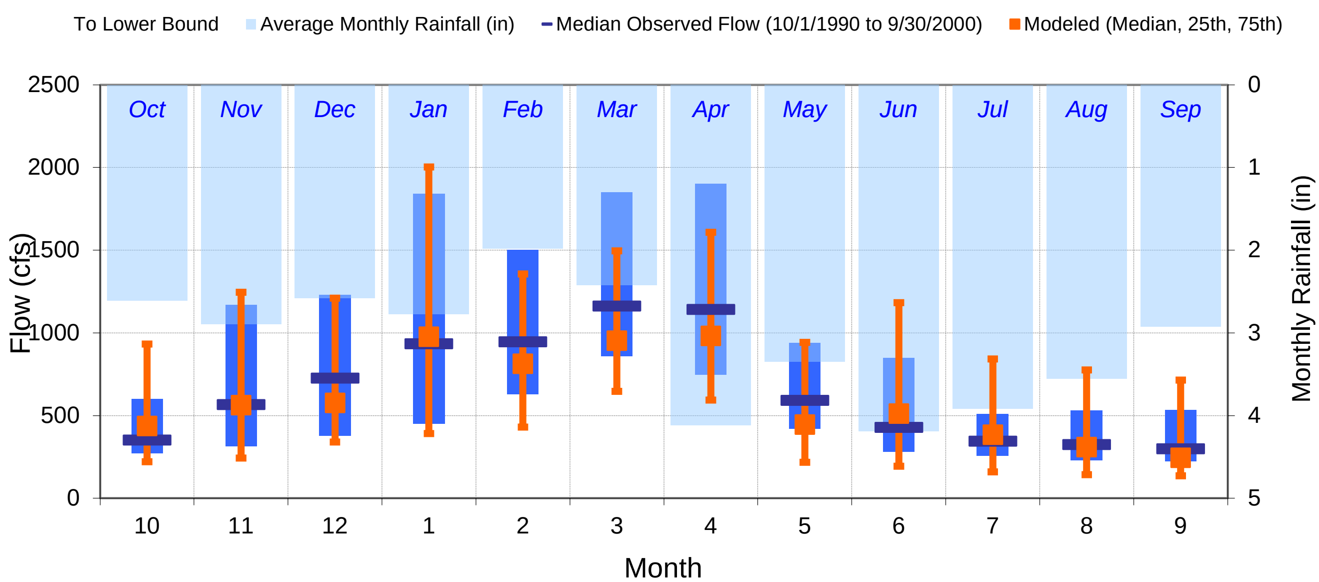


Figure 6. Seasonal medians and ranges at USGS 04208000 Cuyahoga River at Independence, OH – calibration period.

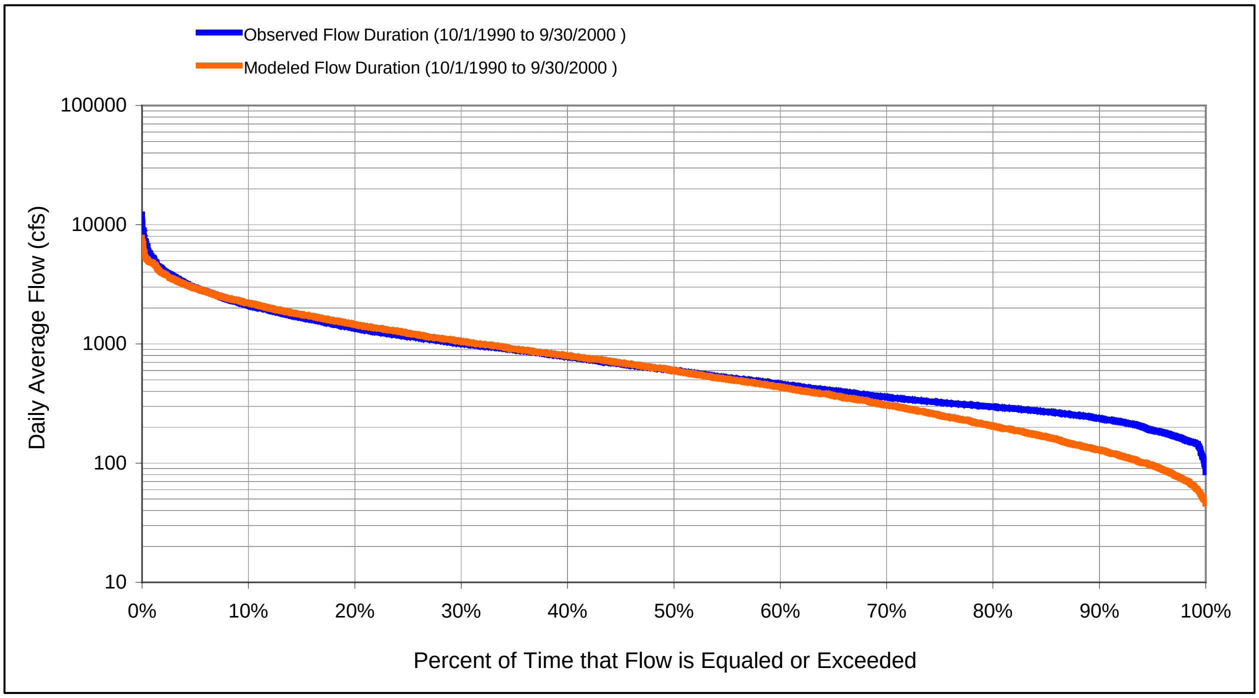


Figure 7. Flow exceedance at USGS 04208000 Cuyahoga River at Independence, OH – calibration period.

Table 6. Summary statistics at USGS 04208000 Cuyahoga River at Independence, OH – calibration period

SWAT Simulated Flow		Observed Flow Gage	
REACH OUTFLOW FROM OUTLET 77 10-Year Analysis Period: 10/1/1990 - 9/30/2000 Flow volumes are (inches/year) for upstream drainage area		USGS 04208000 Cuyahoga River at Independence OH Hydrologic Unit Code: 4110002 Latitude: 41.39533087 Longitude: -81.6298478 Drainage Area (sq-mi): 707	
Total Simulated In-stream Flow:	**17.82**	Total Observed In-stream Flow:	**18.43**
Total of simulated highest 10% flows:	**6.24**	Total of Observed highest 10% flows:	**6.64**
Total of Simulated lowest 50% flows:	**2.68**	Total of Observed Lowest 50% flows:	**3.29**
Simulated Summer Flow Volume (months 7-9):	**3.27**	Observed Summer Flow Volume (7-9):	**2.61**
Simulated Fall Flow Volume (months 10-12):	**4.28**	Observed Fall Flow Volume (10-12):	**4.22**
Simulated Winter Flow Volume (months 1-3):	**5.64**	Observed Winter Flow Volume (1-3):	**6.56**
Simulated Spring Flow Volume (months 4-6):	**4.64**	Observed Spring Flow Volume (4-6):	**5.04**
Total Simulated Storm Volume:	**6.32**	Total Observed Storm Volume:	**7.04**
Simulated Summer Storm Volume (7-9):	**1.40**	Observed Summer Storm Volume (7-9):	**1.09**

Errors (Simulated-Observed)	*Error Statistics*	*Recommended Criteria*		
Error in total volume:	-3.32	10		
Error in 50% lowest flows:	**-18.67**	**10**		
Error in 10% highest flows:	-6.08	15		
Seasonal volume error - Summer:	25.11	30		
Seasonal volume error - Fall:	1.39	30		
Seasonal volume error - Winter:	-14.11	30		
Seasonal volume error - Spring:	-7.94	30		
Error in storm volumes:	-10.20	20		
Error in summer storm volumes:	28.01	50		
Nash-Sutcliffe Coefficient of Efficiency, E:	0.610	Model accuracy increases		
Baseline adjusted coefficient (Garrick), E':	0.442	as E or E' approaches 1.0		
Monthly NSE	0.700			

>> Clear

Hydrology Validation

Hydrology validation for Cuyahoga River at Independence was performed for the period 10/1/1980 through 9/30/1990. The validation achieves a moderately high coefficient of model fit efficiency, but is below on total flow, 50 percent lowest flow and 10 percent highest flow volumes. Validation results for the Cuyahoga River are summarized in Figure 8, Figure 9, Figure 10, Figure 11 and Table 7.

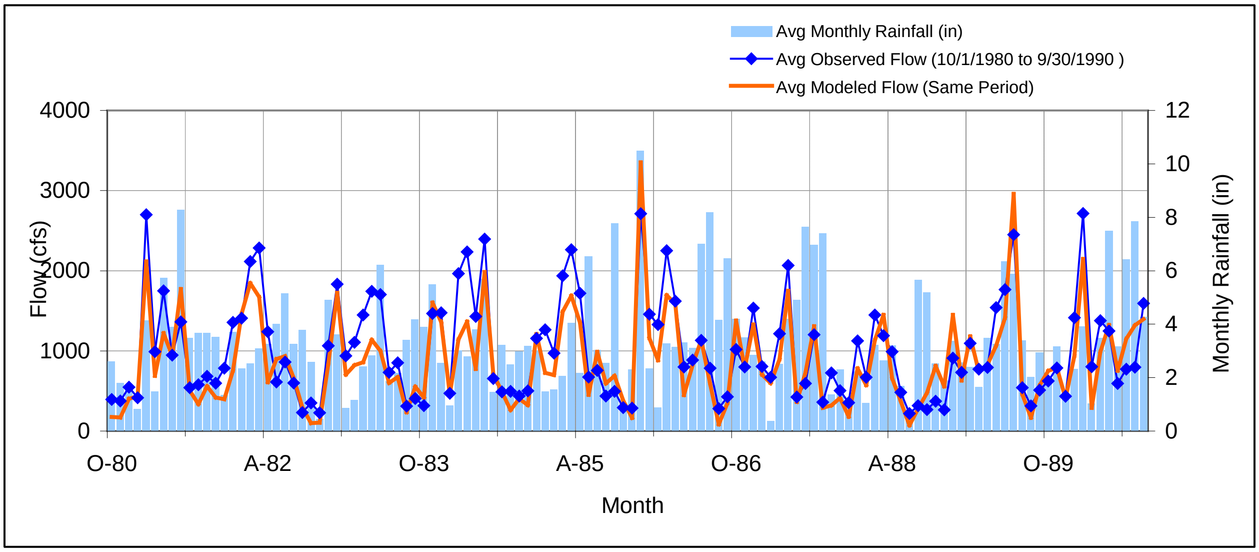


Figure 8. Mean monthly flow at USGS 04208000 Cuyahoga River at Independence, OH – validation period.

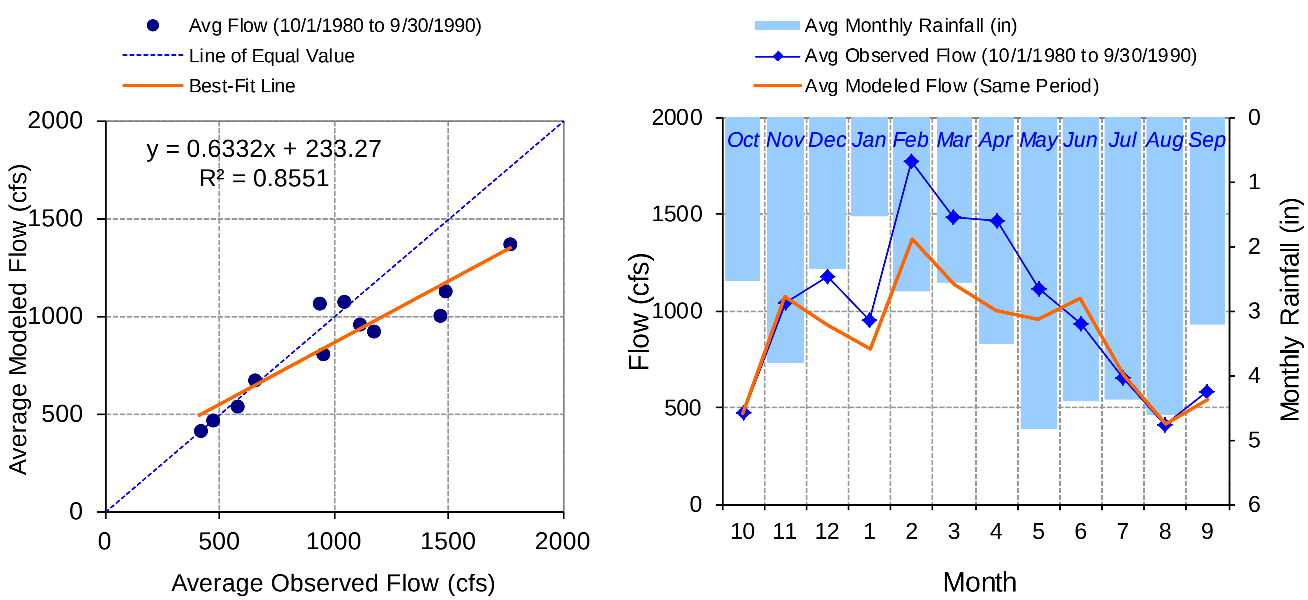


Figure 9. Seasonal regression and temporal aggregate at USGS 04208000 Cuyahoga River at Independence, OH – validation period.

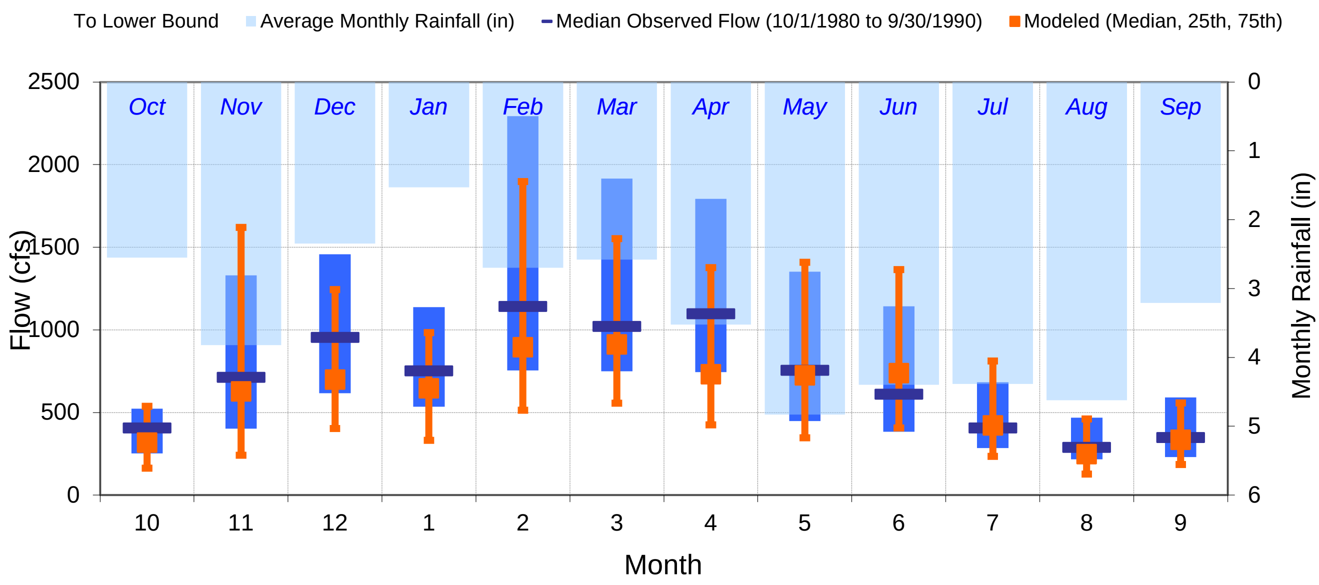


Figure 10. Seasonal medians and ranges at USGS 04208000 Cuyahoga River at Independence, OH – validation period.

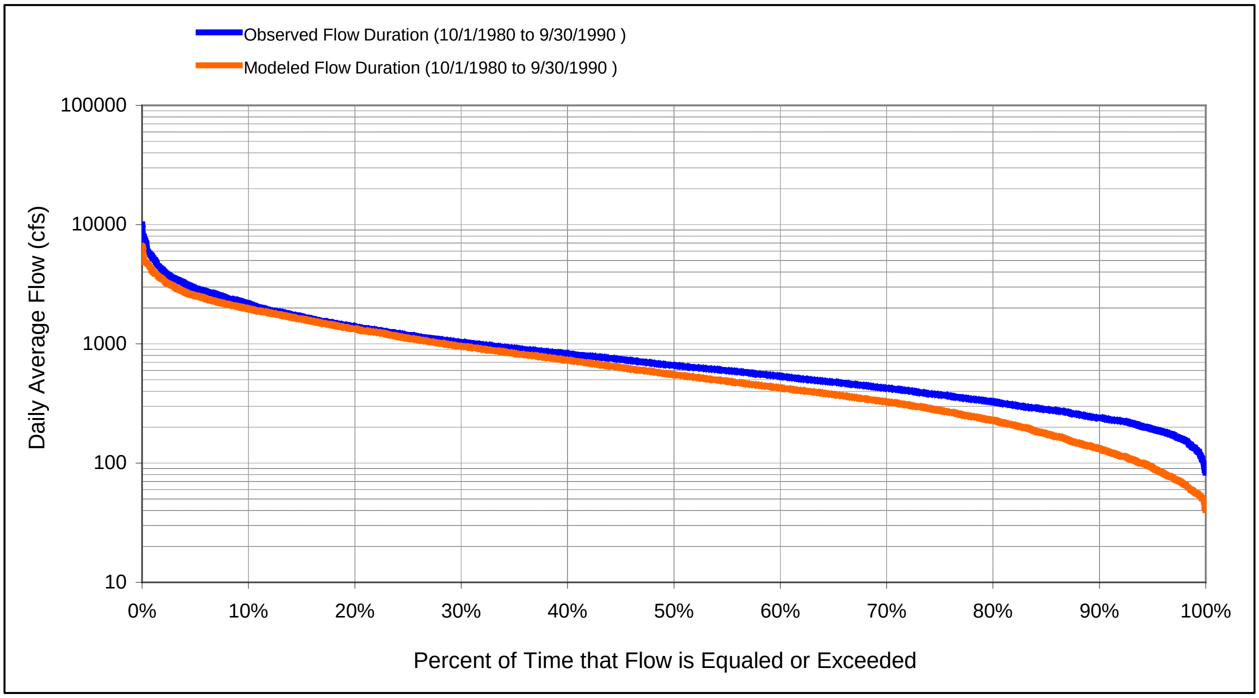


Figure 11. Flow exceedance at USGS 04208000 Cuyahoga River at Independence, OH – validation period.

Table 7. Summary statistics at USGS 04208000 Cuyahoga River at Independence, OH – validation period

SWAT Simulated Flow	Observed Flow Gage
REACH OUTFLOW FROM OUTLET 77 10-Year Analysis Period: 10/1/1980 - 9/30/1990 Flow volumes are (inches/year) for upstream drainage area	USGS 04208000 Cuyahoga River at Independence OH Hydrologic Unit Code: 4110002 Latitude: 41.39533087 Longitude: -81.6298478 Drainage Area (sq-mi): 707

Total Simulated In-stream Flow:	**16.61**	Total Observed In-stream Flow:	**19.18**
Total of simulated highest 10% flows:	**5.59**	Total of Observed highest 10% flows:	**6.65**
Total of Simulated lowest 50% flows:	**2.75**	Total of Observed Lowest 50% flows:	**3.70**
Simulated Summer Flow Volume (months 7-9):	**2.63**	Observed Summer Flow Volume (7-9):	**2.65**
Simulated Fall Flow Volume (months 10-12):	**3.98**	Observed Fall Flow Volume (10-12):	**4.33**
Simulated Winter Flow Volume (months 1-3):	**5.19**	Observed Winter Flow Volume (1-3):	**6.59**
Simulated Spring Flow Volume (months 4-6):	**4.82**	Observed Spring Flow Volume (4-6):	**5.60**
Total Simulated Storm Volume:	**5.64**	Total Observed Storm Volume:	**6.90**
Simulated Summer Storm Volume (7-9):	**1.08**	Observed Summer Storm Volume (7-9):	**1.11**

Errors (Simulated-Observed)	*Error Statistics*	*Recommended Criteria*		
Error in total volume:	**-13.38**	**10**		
Error in 50% lowest flows:	**-25.70**	**10**		
Error in 10% highest flows:	**-15.93**	**15**		
Seasonal volume error - Summer:	-0.83	30		
Seasonal volume error - Fall:	-8.18	>> 30		Clear
Seasonal volume error - Winter:	-21.31	30		
Seasonal volume error - Spring:	-14.01	30		
Error in storm volumes:	-18.14	20		
Error in summer storm volumes:	-2.36	50		
Nash-Sutcliffe Coefficient of Efficiency, E:	0.622	Model accuracy increases		
Baseline adjusted coefficient (Garrick), E':	0.441	as E or E' approaches 1.0		
Monthly NSE	0.732			

Hydrology Results for Larger Watershed

As described above, parameters determined for the gage at Cuyahoga River at Independence were initially transferred to other gages in the watershed. However, changes to subbasin level parameter were required to fit the model to the observed flows. In all, calibration and validation was pursued at a total of seven gages throughout the watershed. Results of the calibration and validation exercise are summarized in Table 8 and Table 9, respectively. Calibration and validation results were acceptable at most gages.

Table 8. Summary statistics (percent error): all stations - calibration period

Station	USGS 04186500	USGS 04193500	USGS 04198000	USGS 04199000	USGS 04200500	USGS 04206000
Error in total volume:	5.12	2.84	-4.64	-0.99	4.21	3.58
Error in 50% lowest flows:	6.38	56.11	-22.60	0.52	-1.16	6.29
Error in 10% highest flows:	-13.25	-17.02	-15.38	-14.74	-13.91	0.47
Seasonal volume error - Summer:	1.15	32.48	7.14	47.98	61.88	34.36
Seasonal volume error - Fall:	2.86	11.98	-4.26	-27.69	-9.71	10.28
Seasonal volume error - Winter:	0.49	-5.40	-10.53	-12.37	2.40	-8.25
Seasonal volume error - Spring:	14.92	-3.26	-1.41	11.29	-2.52	-0.57
Error in storm volumes:	-14.61	-13.55	-9.60	-14.98	-9.93	4.12
Error in summer storm volumes:	-22.24	7.55	2.62	27.73	47.01	30.36
Daily Nash-Sutcliffe Coefficient of Efficiency, E:	0.44	0.65	0.51	0.29	0.35	0.69
Monthly Nash-Sutcliffe Efficiency:	0.832	0.900	0.882	0.597	0.786	0.744

Table 9. Summary statistics (percent error): all stations - validation period

Station	USGS 04186500	USGS 04193500	USGS 04198000	USGS 04199000*	USGS 04200500	USGS 04206000
Error in total volume:	-1.78	1.97	1.22	ND	-2.34	6.41
Error in 50% lowest flows:	-35.07	26.39	-28.85	ND	-26.57	4.79
Error in 10% highest flows:	-11.70	-11.39	-11.72	ND	-17.25	0.84
Seasonal volume error - Summer:	-1.85	41.13	23.91	ND	59.12	33.99
Seasonal volume error - Fall:	5.85	1.71	10.39	ND	-2.63	12.35
Seasonal volume error - Winter:	-10.23	-7.70	-18.67	ND	-13.18	-2.88
Seasonal volume error - Spring:	3.98	3.07	13.05	ND	-1.16	1.39
Error in storm volumes:	-18.28	-8.68	-3.71	ND	-12.42	10.14
Error in summer storm volumes:	-14.19	19.02	21.09	ND	43.95	37.97
Daily Nash-Sutcliffe Coefficient of Efficiency, E:	0.30	0.71	0.43	ND	0.42	0.60
Monthly Nash-Sutcliffe Efficiency:	0.633	0.903	0.764	ND	0.798	0.715

*No data (ND) were available for the validation period at USGS station 04199000.

Water Quality Calibration and Validation

Initial calibration and validation of water quality was done on the Cuyahoga River at Independence (USGS 04208000), using 1990-2000 for calibration and 1980-1990 for validation. As with hydrology, water quality calibration was performed on the later period as this better reflects the land use included in the model.

Calibration adjustments for sediment focused on the following parameters:

- SPCON (linear parameter for estimating maximum amount of sediment that can be re-entrained during channel sediment routing)
- SPEXP (exponential parameter for estimating maximum amount of sediment that can be re-entrained during channel sediment routing)
- CH_COV (channel cover factor)
- CH_EROD (channel erodibility factor)
- USLE_P (USLE support practice factor)

Simulated and estimated sediment loads at the Cuyahoga River station for both the calibration and validation periods are shown in Figure 12 and statistics for the two periods are provided separately in Table 10. The key statistic in Table 10 is the relative percent error, which shows the error in the prediction of monthly load normalized to the estimated load. Table 10 also shows the relative average absolute error, which is the average of the relative magnitude of errors in individual monthly load predictions. This number is inflated by outlier months in which the simulated and estimated loads differ by large amounts (which may be as easily due to uncertainty in the estimated load due to limited data as to problems with the model) and the third statistic, the relative median absolute error, is likely more relevant and shows better agreement.

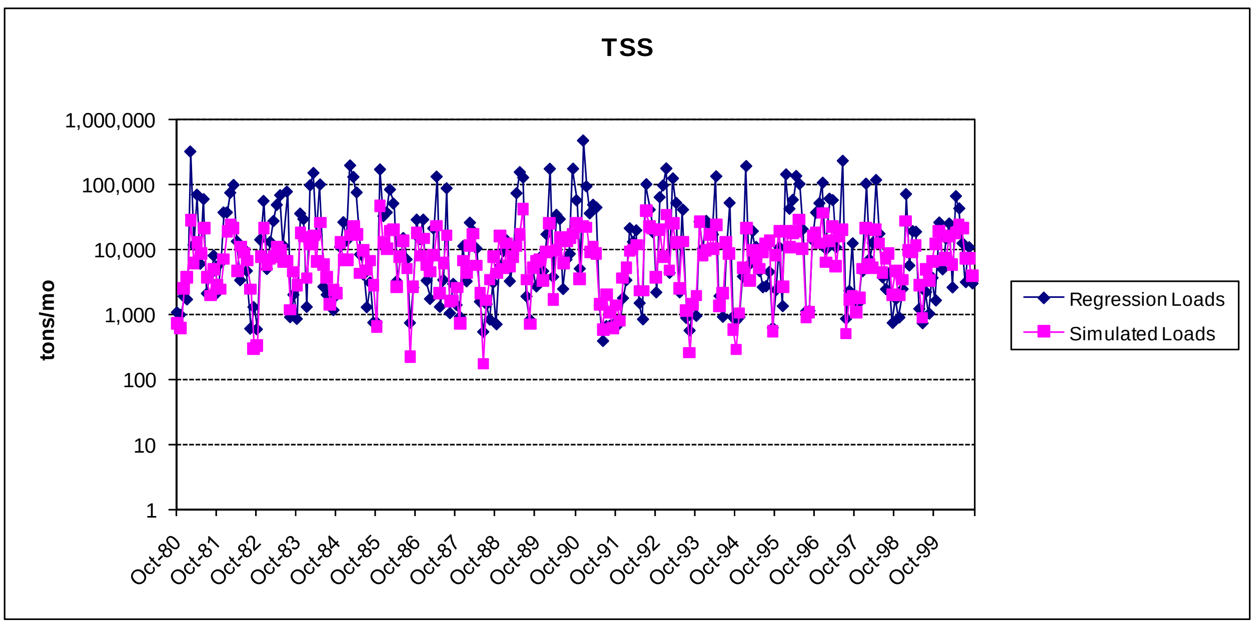


Figure 12. Fit for monthly Load of TSS at USGS 04208000 Cuyahoga River at Independence, OH.

Table 10. Model fit statistics (observed minus predicted) for monthly sediment loads using stratified regression at USGS 04208000 Cuyahoga River at Independence, OH

Statistic	Calibration period (1990-2000)	Validation period (1980-1990)
Relative Percent Error	67.9.9%	69.8%
Relative Average Absolute Error	74.5%	75.8%
Relative Median Absolute Error	11.9%	12.2%

Calibration adjustments for total phosphorus and total nitrogen focused on the following parameters:

- RHOQ (algal respiration rate at 20^{O} C)
- PHOSKD (phosphorus soil partitioning coefficient)

- PSP (phosphorus availability index)
- RS1 (Local algal settlement rate in the reach at 20^{o} C)
- AL1 (Fraction of algal biomass that is nitrogen)
- AL2 (Fraction of algal biomass that is phosphorus)
- MUMAX (Rate of oxygen uptake per unit NO_2-N oxidation at 20^{o} C)
- RHOQ (Algal respiration rate at 20^{o} C)
- RS2 (benthic source rate for dissolved P in the reach at 20^{o} C)
- RS3 (Benthic source rate for NH_4-N in the reach at 20^{o} C)
- RS5 (organic P settling rate in the reach at 20^{o} C)
- BC4 (rate constant for mineralization of organic P to dissolved P in the reach at 20^{o} C)
- RS4 (rate coefficient for organic N settling in the reach at 20^{o} C)
- CH_ONCO (Channel organic nitrogen concentration)
- CH_OPCO (Channel organic phosphorus concentration)
- SDNCO (Denitrification threshold water content)
- CDN (Denitrification exponential rate constant)

Results for the phosphorus simulation are shown in Figure 13 and Table 11.. Results for the nitrogen simulation are shown in Figure 14 and Table 12. The model fit is generally acceptable.

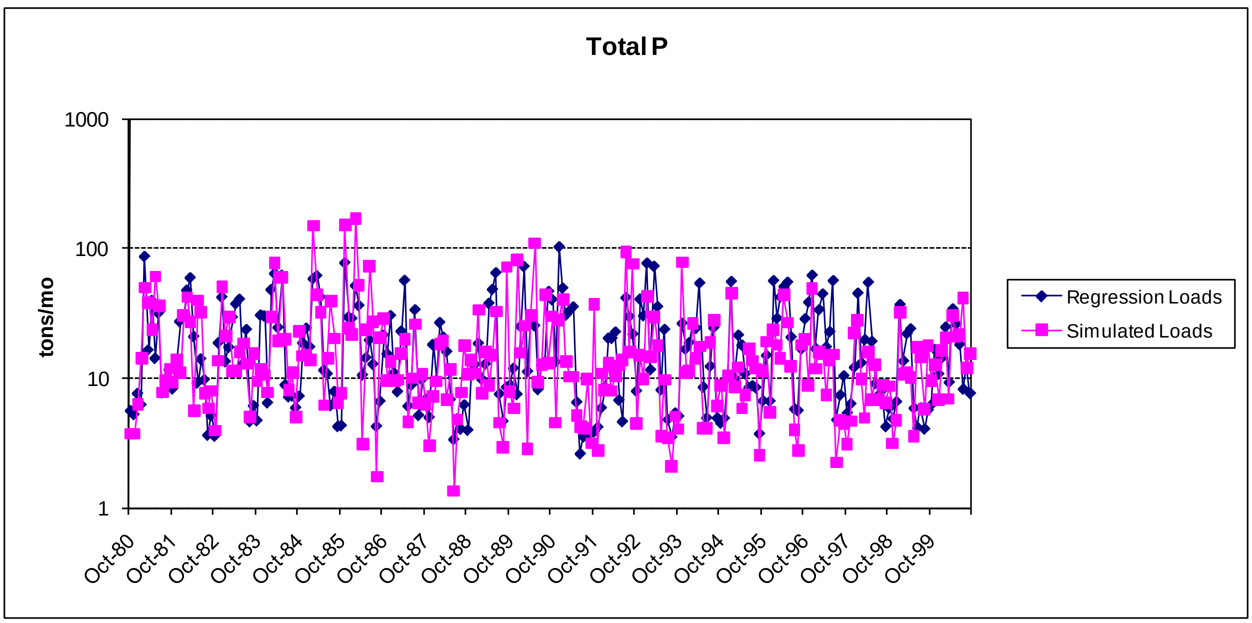


Figure 13. Fit for monthly load of total phosphorus at USGS 04208000 Cuyahoga River at Independence, OH.

Table 11. Model fit statistics (observed minus predicted) for monthly phosphorus loads using stratified regression at USGS 04208000 Cuyahoga River at Independence, OH

Statistic	Calibration period (1990-2000)	Validation period (1980-1990)
Relative Percent Error	23.9%	-12.5%
Average Absolute Error	54.2%	66.9%
Median Absolute Error	27.4%	33.2%

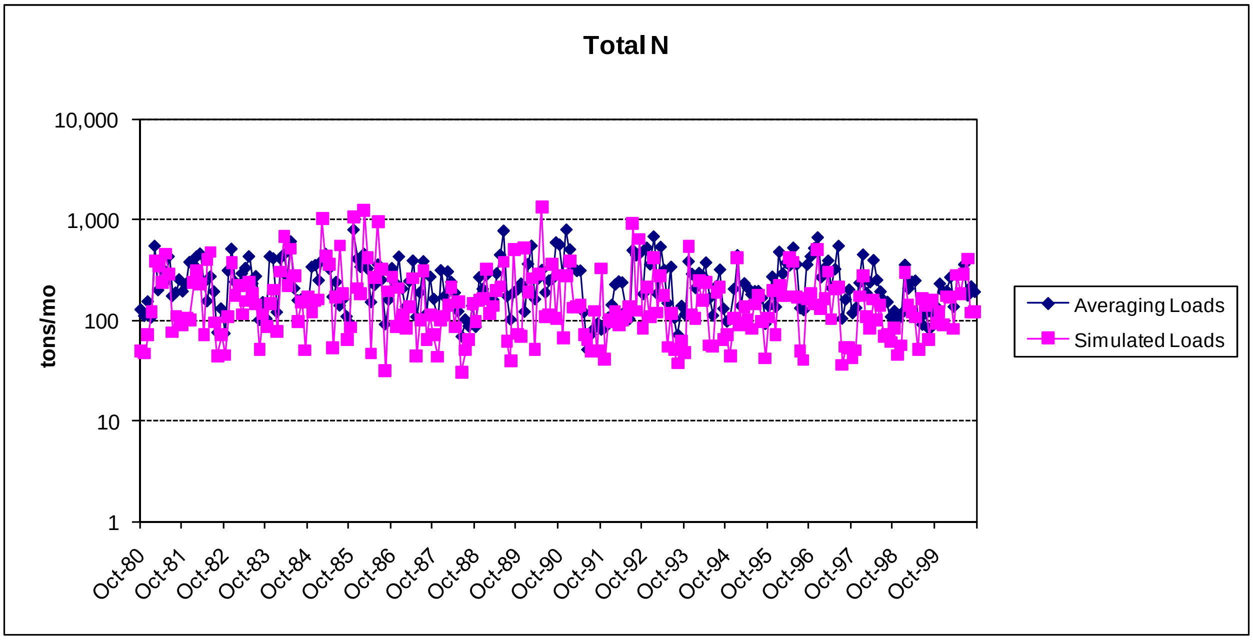


Figure 14. Fit for monthly load of total nitrogen at USGS 04208000 Cuyahoga River at Independence, OH.

Table 12. Model fit statistics (observed minus predicted) for monthly total nitrogen loads using averaging estimator at USGS 04208000 Cuyahoga River at Independence, OH

Statistic	Calibration period (1990-2000)	Validation period (1980-1990)
Relative Percent Error	35.8%	13.7%
Average Absolute Error	46.4%	53.6%
Median Absolute Error	37.4%	37.5%

Water Quality Results for Larger Watershed

As with hydrology, a spatial calibration approach was adopted. Cuyahoga River watershed SWAT model parameters for water quality were transferred to other portions of the watershed with necessary changes to subbasin level parameters. Summary statistics for the SWAT water quality calibration and validation at other stations in the watershed are provided in Table 13 and Table 14.

Table 13. Summary statistics for water quality at all stations – calibration period 1990-2000

Station	USGS 04193500	USGS 04198000
Relative Percent Error TSS Load	9.9%	17.0%
Relative Percent Error TP Load	33.5%	10.9%
Relative Percent Error TN Load	12.1%	16.8%

Table 14. Summary statistics for water quality at all stations – validation period 1980-1990

Station	USGS 04193500	USGS 04198000
Relative Percent Error TSS Load	11.2%	8.1%
Relative Percent Error TP Load	15.4%	-24.4%
Relative Percent Error TN Load	-5.0%	-19.6%

References

USEPA. 2008. Using the BASINS Meteorological Database (Version 2006). BASINS Technical Note 10. Office of Water, U.S. Environmental Protection Agency, Washington, DC. http://water.epa.gov/scitech/datait/models/basins/upload/2009_04_13_BASINSs_tecnote10.pdf (Accessed June, 2009).

Appendix P
Model Configuration, Calibration and Validation

Basin: New England Coastal (NewEng)

Contents

Tables

Figures

Watershed Background

The New England Coastal basin was selected as one of the 15 non-pilot application watersheds for the 20 Watershed study. Watershed modeling for the non-pilot areas is accomplished using the SWAT model only, and model calibration and validation results are presented in abbreviated form.

Water Body Characteristics

The New England Coastal basins study area encompasses 11 HUC8s and 10,359 mi^2 in Massachusetts, Maine, and New Hampshire (Figure 1). The study area includes one of EPA's National Estuary Program sites (Massachusetts Bays), which is also one of EPA's Climate Ready Estuaries sites. The entire model area is in the New England Physiographic Province. Elevations in the watershed range from sea level along the coast to greater than 6,000 ft in the White Mountains of New Hampshire.

Average annual precipitation in the watershed ranges from 40 to 50 inches, with higher amounts in the mountainous regions – up to 100 inches per year at the summit of Mount Washington. About one-half of this precipitation becomes surface runoff. Average annual air temperature varies from about 43° F in the north to about 50° F in the south.

Most of the rivers in this watershed originate in mountainous forested areas with headwaters defined by fast-flowing water with cobble and boulder-bottom streams. Flow in these rivers is generally regulated by upstream lakes, reservoirs, flood-control dams, and power plants. The watershed also contains a large number of natural lakes, many of which are enlarged and controlled by dams.

The land uses in the watershed are approximately 64 percent forested; 16 percent residential, commercial, and industrial; and 6 percent agricultural. Cities include Boston, MA, Portland, ME, Worcester, MA, and a variety of smaller cities near the Boston area. Major industries include light manufacturing, pulp and paper production, silviculture, hydroelectric-power generation, tourism, and seasonal recreation.

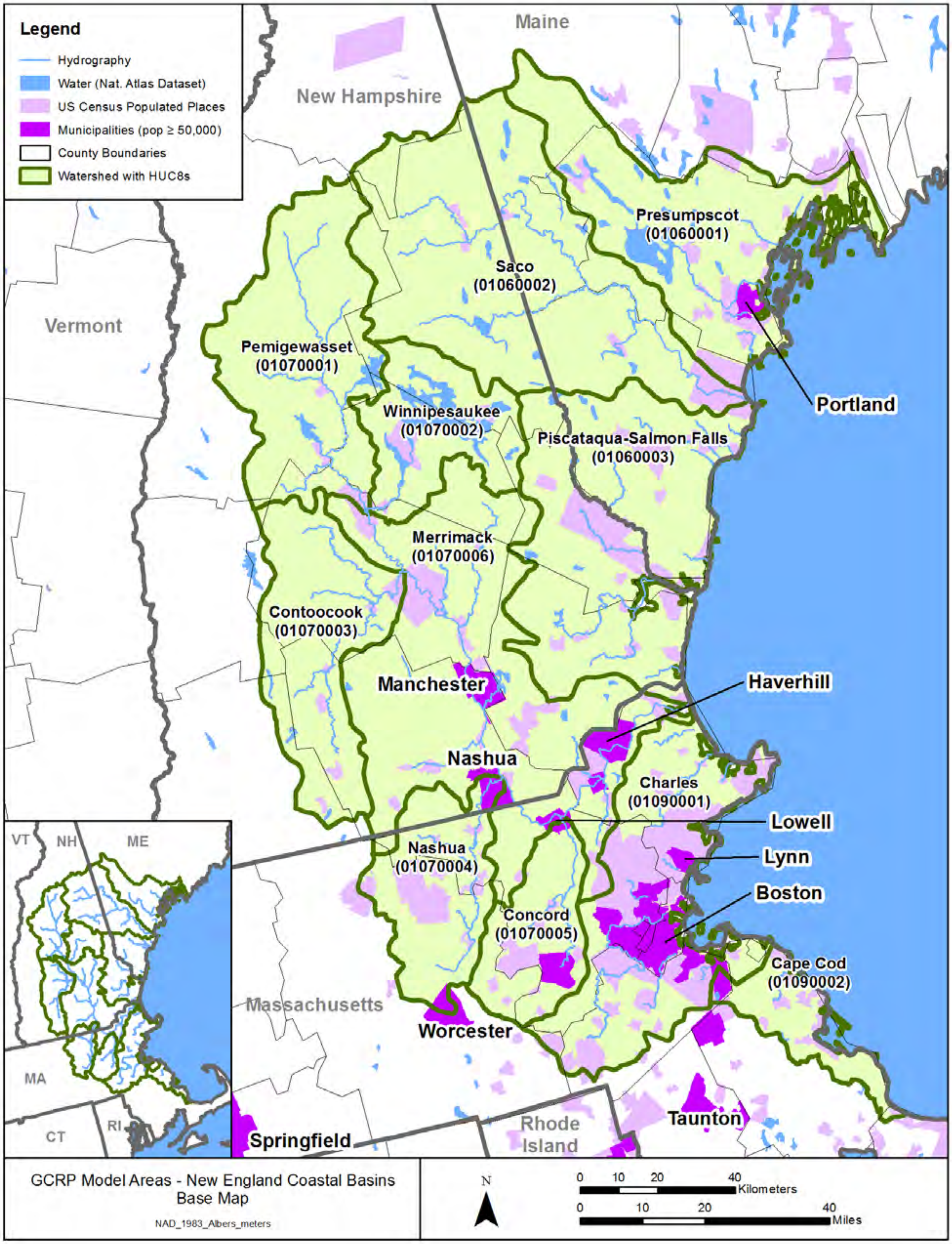


Figure 1. Location of the New England Coastal basin.

Soil Characteristics

Soils in the watershed, as described in STATSGO soil surveys, fall primarily into hydrologic soil groups (HSGs) B (moderately high infiltration capacity) and C (moderate infiltration capacity). SWAT uses information drawn directly from the soils data layer to populate the model.

Land Use Representation

Land use/cover in the watershed is based on the 2001 National Land Cover Database (NLCD) coverage (Figure 2). NLCD land cover classes were aggregated according to the scheme shown in Table 1 for representation in the 20 Watershed model. SWAT uses the built-in hydrologic response unit (HRU) overlay mechanism in the ArcSWAT interface. SWAT HRUs are formed from an intersection of land use and STATSGO major soils. The distribution of land use in the watershed is summarized in Table 2.

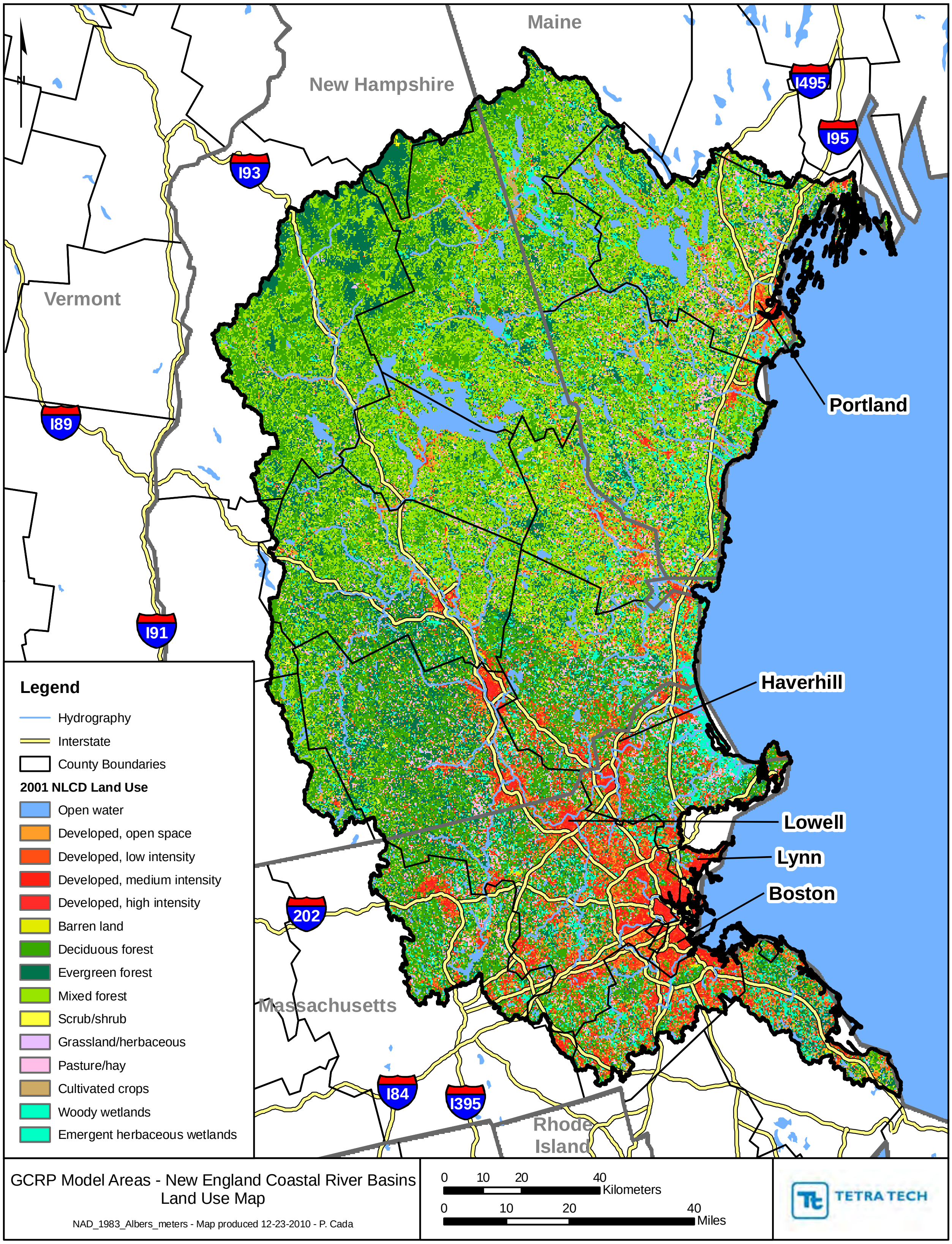


Figure 2. Land use in the New England Coastal basin.

Table 1. Aggregation of NLCD land cover classes

NLCD Class	Comments	SWAT class
11 Water	Water surface area usually accounted for as reach area	WATR
12 Perennial ice/snow		WATR
21 Developed open space		URLD
22 Dev. Low Intensity		URMD
23 Dev. Med. Intensity		URHD
24 Dev. High Intensity		UIDU
31 Barren Land		SWRN
41 Forest	Deciduous	FRSD
42 Forest	Evergreen	FRSE
43 Forest	Mixed	FRST
51-52 Shrubland		RNGB
71-74 Herbaceous Upland		RNGE
81 Pasture/Hay		HAY
82 Cultivated		AGRR
91-97 Wetland	Emergent & woody wetlands	WETF, WETL, WETN
98-99 Wetland	Aquatic bed wetlands (not emergent)	WATR

Table 2. Land use distribution for the New England Coastal basin (2001 NLCD) (mi^2)

HUC 8 watershed	Open water	Developed[a] Open space	Low density	Medium density	High density	Barren land	Forest	Shrubland/ Grassland	Pasture/Hay	Cultivated	Wetland	Total
Presumpscot **01060001**	84.7	76.8	44.5	15.3	7.5	4.1	631.1	28.0	65.7	14.6	77.9	**1,050.2**
Saco **01060002**	50.4	62.0	23.5	5.5	1.5	7.1	1,334.1	52.5	37.5	22.0	104.8	**1,700.8**
Piscataqua-Salmon Falls **01060003**	43.3	103.4	63.4	24.2	8.6	9.9	852.0	50.3	91.5	15.8	150.2	**1,412.6**
Pemigewasset **01070001**	26.1	21.8	9.3	2.8	0.4	1.9	905.7	16.6	10.6	11.7	15.8	**1,022.7**
Merrimack **01070002**	92.0	25.3	8.7	3.6	1.3	1.2	306.5	12.1	11.4	4.4	19.1	**485.8**
Contoocook **01070003**	18.9	29.4	11.3	3.1	0.4	1.4	613.1	11.1	29.2	5.1	40.9	**764.1**
Nashua **01070004**	17.5	30.3	33.1	23.1	6.9	1.9	323.1	7.8	42.0	5.3	43.2	**534.2**
Concord **01070005**	12.5	43.0	48.1	41.8	8.9	1.1	165.1	4.5	25.9	3.8	45.4	**400.3**
Winnipesaukee **01070006**	52.4	119.5	139.0	106.5	24.0	9.9	1,068.3	29.1	108.4	21.3	120.1	**1,798.6**
Charles **01090001**	29.3	100.0	134.2	160.5	58.7	5.9	292.0	8.6	38.7	3.5	130.8	**962.2**
Cape Cod **01090002**	8.3	28.0	27.5	12.5	2.6	3.9	93.3	2.8	5.3	5.3	38.0	**227.4**
Total	**435.5**	**639.5**	**542.7**	**398.9**	**120.7**	**48.5**	**6,584.3**	**223.5**	**466.2**	**112.9**	**786.2**	**10,358.9**

[a]The percent imperviousness applied to each of the developed land uses is as follows: open space (8.22%), low density (32.81%), medium density (60.90%), and high density (87.25%).

Point Sources

There are numerous point source discharges in the watershed. Only the major dischargers, generally defined as those with a design flow greater than 1 MGD are included in the simulation (Table 3). The major dischargers are represented at long-term average flows, without accounting for changes over time or seasonal variations.

Table 3. Major point source discharges in the New England Coastal basin

NPDES ID	Name	Design flow (MGD)	Observed flow (MGD) (1991-2006 average)
ME0101117	SACO WASTEWATER TREATMENT FACI	4.2	2.0
ME0100048	BIDDEFORD CITY OF	2.6	4.9
NH0100668	ROCHESTER WWTF	5.0	2.8
NH0100277	SOMERSWORTH WPCF	2.4	1.5
NH0100871	EXETER WWTF	3.0	2.7
MA0101745	AMESBURY WWTP	1.9	1.8
MA0101427	NEWBURYPORT WW P	3.4	2.6
MA0101621	HAVERHILL WPAF	18.0	10.7
MA0100447	GREATER LAWRENCE SD	52.0	34.2
MA0100633	LOWELL REGIONAL WW UTILITY	32.0	30.1
MA0100668	CONCORD WWTF	1.2	1.4
MA0101711	BILLERICA WWTP	5.5	2.9
NH0100056	DERRY WWTP	4.0	1.8
NH0100170	NASHUA WWTF	16.0	12.1
NH0100161	MERRIMACK WWTF	5.0	70.0
MA0100013	AYER WWTP	1.8	1.2
MA0004561	HOLLINGSWORTH & VOSE CO		2.4
MA0100986	EAST FITCHBURG WWTF	12.3	8.0
MA0100404	MWRA - CLINTON STP	3.0	2.6
MA0100579	MILFORD WWTF	4.3	3.6
NH0100471	MILFORD WWTF	2.2	1.4
NH0100447	MANCHESTER WWTF	34.0	43.3
NH0100901	CONCORD-HALL STREET WWTF	10.1	4.2
NH0100960	WINNIPESAUKEE RIVER BASIN	11.5	5.9
NH0100005	ASHLAND WWTF	1.6	1.0
NH0100706	LINCOLN WWTP	1.5	7.9
NH0000230	MONADNOCK PAPER MILLS, INC.	1.3	1.2
MA0100498	MARLBOROUGH EASTERLY WWTP	5.5	3.4

NPDES ID	Name	Design flow (MGD)	Observed flow (MGD) (1991-2006 average)
MA0101001	MAYNARD WWTF	1.5	1.0
MA0101788	HUDSON WWTF	2.7	2.9
MA0100480	MARLBOROUGH WESTERLY WWTP	2.9	3.6
MA0100412	WESTBOROUGH WWTP	7.7	5.2
ME0002321	S D WARREN COMPANY		17.4
MA0100978	MEDFIELD WWTP	1.5	1.3
MA0102598	CHARLES RIVER PCD	4.5	3.5
ME0100633	SOUTH PORTLAND CITY OF	9.3	5.0
ME0100617	SANFORD SEWER DISTRICT	4.4	2.8
NH0100625	HAMPTON WWTP	4.7	2.2
NH0100234	PORTSMOUTH-PIERCE ISLAND WWTP	4.8	47.9
MA0102695	SCITUATE_WWTP	1.6	1.3
MA0100587	PLYMOUTH WWTP	1.8	1.7
ME0100102	BRUNSWICK SEWER DISTRICT	3.9	2.7

Most of these point sources have reasonably complete monitoring for total suspended solids (TSS). Assumptions were made for total nitrogen and total phosphorus depending upon the type of facility. The point sources were initially represented in the model with the median of reported values for total phosphorus, TSS and total nitrogen.

Meteorological Data

The required meteorological time series for the 20 Watershed SWAT simulations are precipitation and air temperature. The 20 Watershed simulations do not include water temperature and uses a degree-day method for snowmelt. SWAT estimates Penmann-Monteith potential evapotranspiration using a statistical weather generator for inputs other than temperature and precipitation. These meteorological time series are drawn from the BASINS4 Meteorological Database (USEPA 2008), which provides a consistent, quality-assured set of nationwide data with gaps filled and records disaggregated. Scenario application requires simulation over 30 years, so the available stations are those with a common 30-year period of record (or one that can be filled from an approximately co-located station) that covers the year 2003. A total of 52 precipitation stations were identified for use in the New England Coastal watershed model with a common period of record of 10/1/1972-9/30/2003 (Table 4). Temperature records are sparser; where these are absent temperature is taken from nearby stations with an elevation correction.

Table 4. Precipitation stations for the New England Coastal watershed model

COOP ID	Name	Latitude	Longitude	Temperature	Elevation (m)
274732	LINCOLN	44.0500	-71.6667	x	267
273530	GRAFTON	43.5667	-71.9500	x	253
170934	BRUNSWICK	43.9000	-69.9333	x	21
199316	WEST MEDWAY	42.1333	-71.4333	x	64

COOP ID	Name	Latitude	Longitude	Temperature	Elevation (m)
278972	WEARE	43.0847	-71.7382	x	219
270998	BRISTOL	43.6001	-71.7167	x	143
273182	FRANKLIN FALLS DAM	43.4668	-71.6500	x	131
275780	NEW DURHAM 3 NNW	43.4833	-71.1833	x	195
278885	WARREN	43.9098	-71.8877	x	216
275013	MACDOWELL DAM	42.9000	-71.9832		293
276550	OTTER BROOK LAKE	42.9501	-72.2332	x	207
274218	FORT SCOTT	43.1830	-71.7500		41
275150	MARLOW	43.1168	-72.2000	x	357
174566	LEWISTON	44.1001	-70.2167		55
190408	BARRE FALLS DAM	42.4334	-72.0332		277
194105	LAWRENCE	42.7001	-71.1667		18
176905	PORTLAND WSFO AP	43.6423	-70.3044		14
190736	BLUE HILL	42.2123	-71.1146		192
190770	BOSTON WSFO AP	42.3606	-71.0105	x	6
272174	DURHAM	43.1500	-70.9500	x	24
271683	CONCORD WSO AIRPORT	43.1954	-71.5010	x	105
192451	EAST WAREHAM	41.7656	-70.6693	x	6
190190	ASHBURNHAM	42.6168	-71.8833	x	335
190860	BROCKTON	42.0500	-71.0000	x	24
192997	FRANKLIN	42.0834	-71.4167	x	73
193505	HAVERHILL	42.7592	-71.0608	x	5
193876	IPSWICH	42.6667	-70.8666	x	24
194313	LOWELL	42.6500	-71.3666		34
194744	MIDDLETON	42.6001	-71.0167	x	27
194760	MILFORD	42.1667	-71.5167		85
195285	NEWBURYPORT 3 WNW	42.8334	-70.9333	x	5
196486	PLYMOUTH-KINGSTON	41.9833	-70.7000		14
199923	WORCESTER WSO AP	42.2673	-71.8760		301
273024	FITZWILLIAM 2 W	42.7833	-72.1833	x	354
274480	LAKEPORT 2	43.5500	-71.4667		152
275211	MASSABESIC LAKE	42.9833	-71.4000		76
275639	MOUNT WASHINGTON	44.2668	-71.2999	x	1909
275712	NASHUA 2 NNW	42.7833	-71.4832	x	40

COOP ID	Name	Latitude	Longitude	Temperature	Elevation (m)
276818	PINKHAM NOTCH	44.2668	-71.2500		612
276945	PLYMOUTH	43.7833	-71.6500		201
177479	SANFORD 2 NNW	43.4668	-70.7832	x	85
179314	WEST BUXTON 2 NNW	43.7001	-70.6166	x	46
170844	BRIDGTON 3 NW	44.0834	-70.7332	x	171
190535	BEDFORD	42.4833	-71.2832	x	49
275629	MOUNT SUNAPEE	43.3334	-72.0832	x	387
196783	READING	42.5168	-71.1333	x	27
193624	HINGHAM	42.2333	-70.9167	x	9
272800	EPPING	43.0333	-71.0832	x	49
270681	BENTON 5 SW	44.0333	-71.9333	x	366
172238	EAST HIRAM	43.8833	-70.7500	x	161
198757	WALPOLE 2	42.1667	-71.2500	x	50

Watershed Segmentation

The New England Coastal basin was divided into 90 subwatersheds for the purposes of modeling (Figure 3). Saco River at USGS 01066000 was chosen for initial calibration. The model encompasses the complete watershed and does not require specification of any upstream boundary conditions for application.

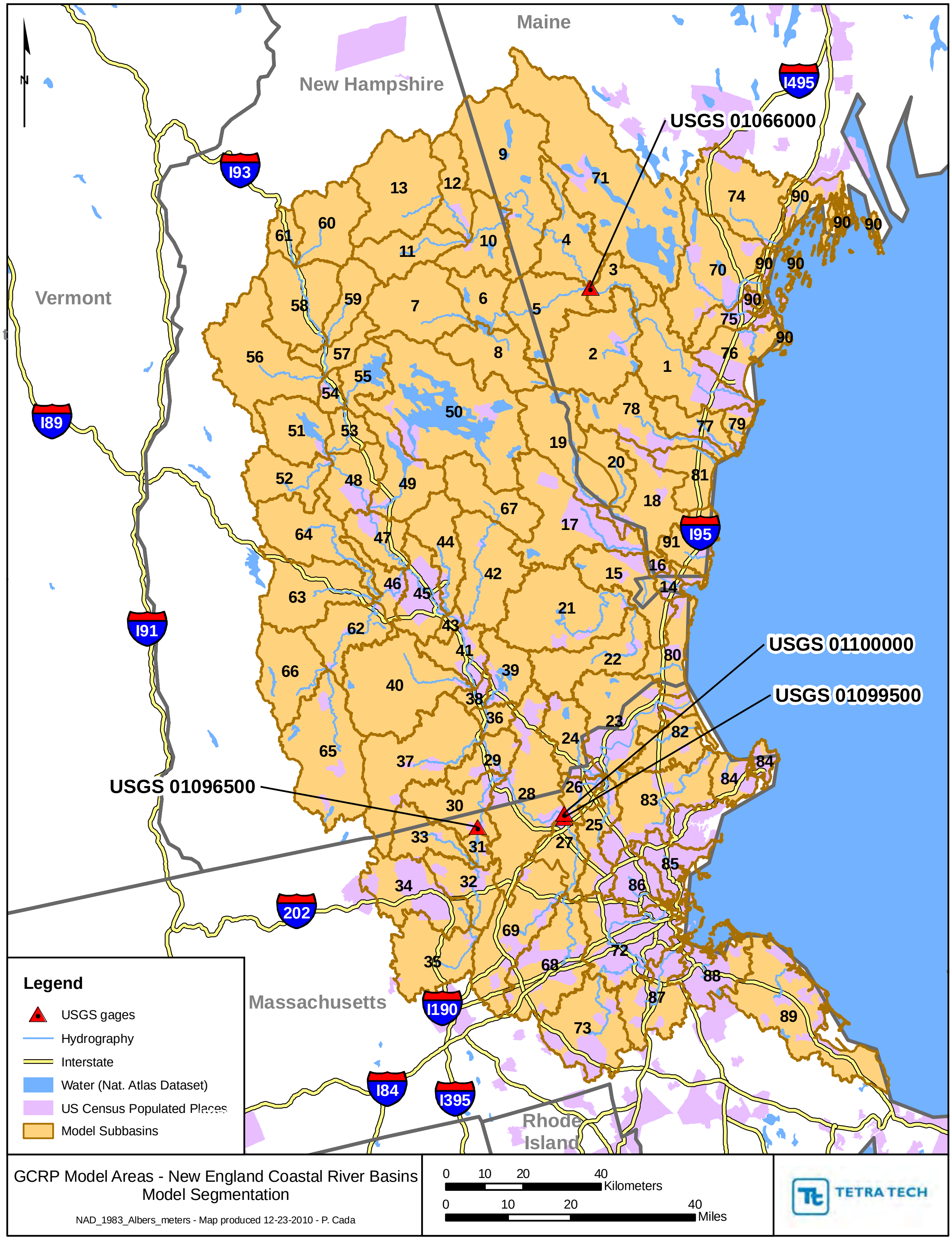


Figure 3. Model segmentation and USGS stations utilized for the New England Coastal basin.

Calibration Data and Locations

The specific site chosen for initial calibration was the Saco River at Cornish, Maine a flow and water quality monitoring location that approximately coincides with the mouth of an 8-digit HUC at its outflow to the Saco River. The Saco River watershed was selected because there is a good set of flow and water quality data available and the watershed lacks major point sources and impoundments. Additional calibration and validation was pursued at multiple locations (Table 5). Parameters derived on the Saco River were not fully transferable to other portions of the New England Coastal basin, and additional calibration was conducted at multiple gage locations.

Table 5. Calibration and validation locations in the New England Coastal basin

Station name	USGS ID	Drainage area (mi^2)	Hydrology calibration	Water quality calibration
Saco River at Cornish, Maine	01066000	1293	x	x
Nashua River at Eat Pepperel, MA	01096500	435	x	
Concord River at River Meadow Brook at Lowell, MA	01099500	400	x	
Merrimack River below Concord River at Lowell, MA	01100000	4635	x	x

The model hydrology calibration period was set to Water Years 1993-2003 (within the 32-year period of record for modeling). Hydrologic validation was then performed on Water Years 1983-1993. Water quality calibration used calendar years 1993-2003, while validation used 1983-1993.

SWAT Modeling

Hydrology Calibration

A spatial calibration approach was adopted for GCRP-SWAT modeling for the New England Coastal basin. A systematic adjustment of parameters has been adopted and some adjustments are applied throughout the basin. Most of the calibration efforts were geared toward getting a closer match between simulated and observed flows at the outlet of calibration focus area.

Land Use / Soil / Slope Definition

A 5/10/5 percent threshold was used for land use/soil/slope in the SWAT model while defining the HRUs. Urban land use classes were exempted from the HRU overlay thresholds.

The calibration focus area (Saco River) includes nine subwatersheds and is generally representative of the general land use characteristics of the overall watershed. The parameters were adjusted within the practical range to obtain reasonable fit between the simulated and measured flows in terms of Nash-Sutcliffe modeling efficiency and the high flow and low flow components as well as the seasonal flows.

The water balance of whole New England Coastal basin predicted by the SWAT model over the 32-year simulation period is as follows:

```
PRECIP =   1188.0 MM
SNOW FALL =  250.83 MM
SNOW MELT =   232.97 MM
SUBLIMATION =    16.71 MM
SURFACE RUNOFF Q =   236.32 MM
LATERAL SOIL Q =  144.44 MM
TILE Q =     0.00 MM
GROUNDWATER (SHAL AQ) Q =   214.89 MM
REVAP (SHAL AQ => SOIL/PLANTS) =   20.61 MM
DEEP AQ RECHARGE =    29.40 MM
TOTAL AQ RECHARGE =  265.08 MM
TOTAL WATER YLD =   571.26 MM
PERCOLATION OUT OF SOIL =  241.22 MM
ET =    555.8 MM
PET =   1041.6MM
TRANSMISSION LOSSES =    24.39 MM
```

Hydrologic calibration adjustments focused on the following parameters:

- CN2 (initial SCS runoff curve number for moisture condition II)
- ESCO (soil evaporation compensation factor)
- SURLAG (surface runoff lag coefficient)
- SOL_AWC (available water capacity of the soil layer, mm water/mm of soil)
- ALPHA_BF (baseflow alpha factor, days)
- GW_DELAY (groundwater delay time, days)
- GWQMIN (threshold depth of water in the shallow aquifer required for return flow to occur, mm)
- GW_REVAP (groundwater “revap” coefficient)
- CH_N1 (Manning’s “n” value for tributary channels)
- CH_N2 (Manning’s “n” value for main channels)

Calibration results for the Saco River are summarized in Figure 4, Figure 5, Figure 6, Figure 7 and Table 6.

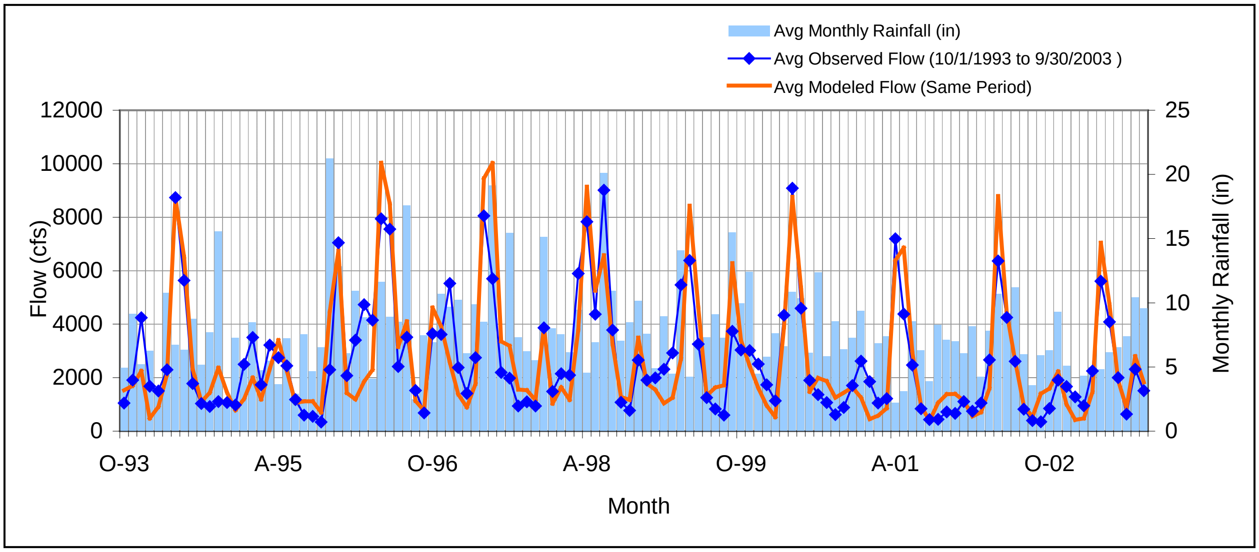


Figure 4. Mean monthly flow at USGS 01066000 Saco River at Cornish, Maine – calibration period.

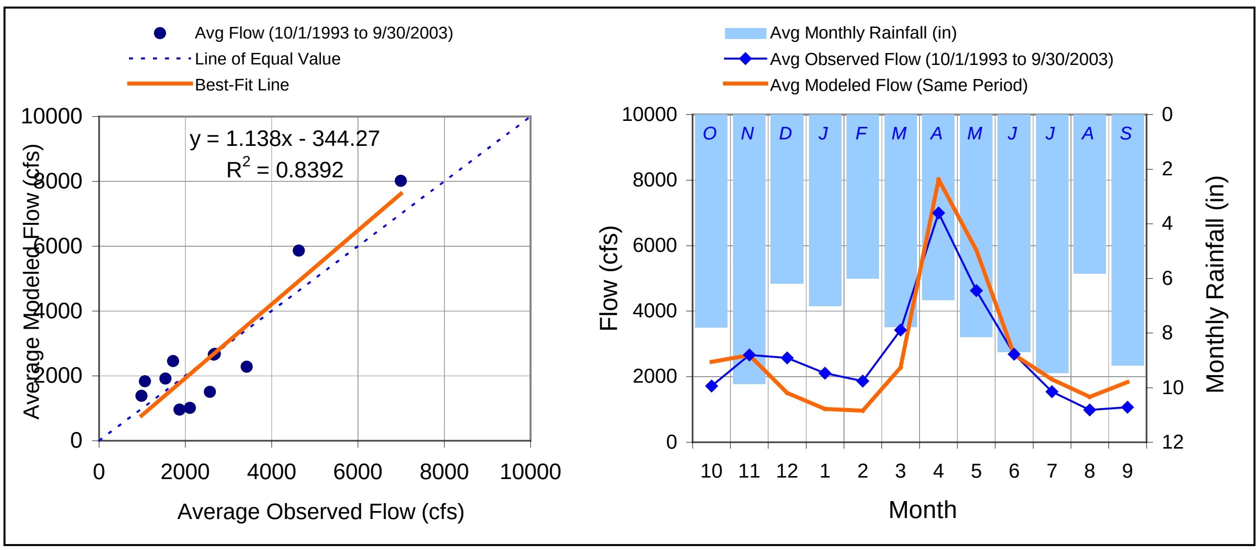


Figure 5. Seasonal regression and temporal aggregate at USGS 01066000 Saco River at Cornish, Maine – calibration period.

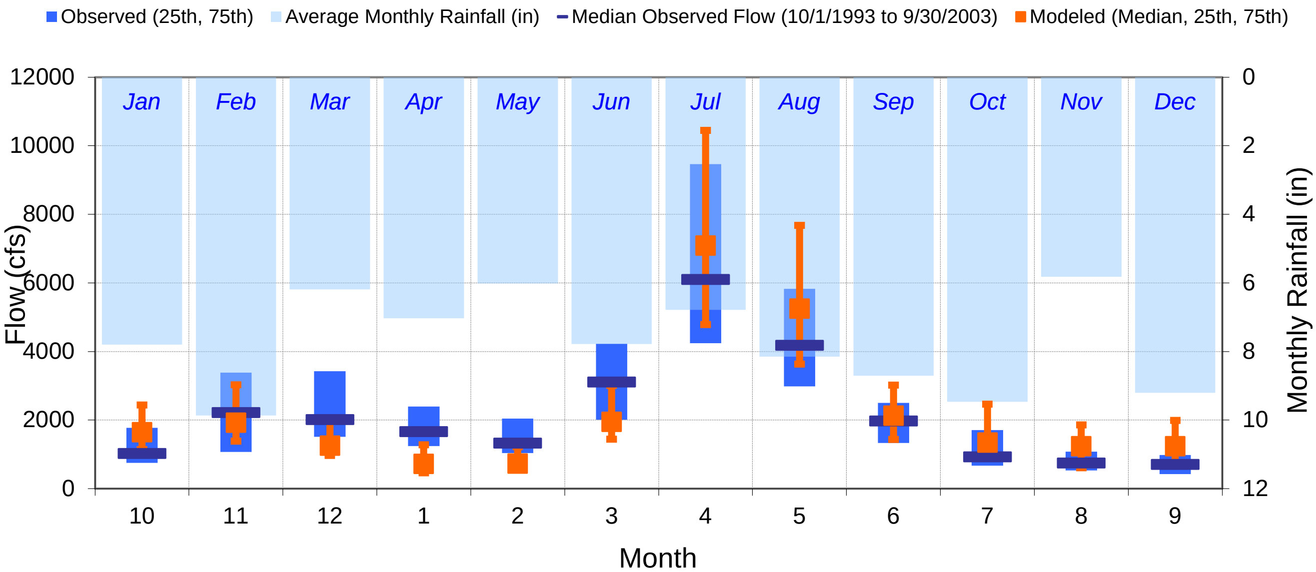


Figure 6. Seasonal medians and ranges at USGS 01066000 Saco River at Cornish, Maine – calibration period.

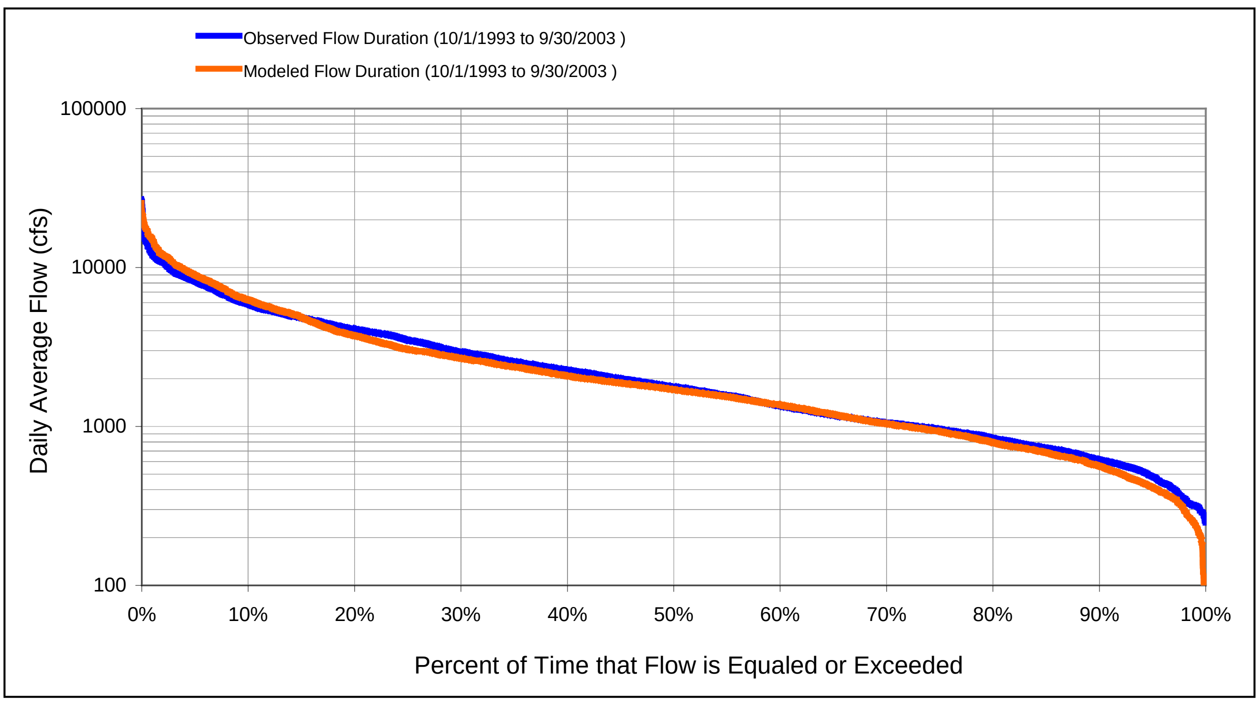


Figure 7. Flow exceedance at USGS 01066000 Saco River at Cornish, Maine – calibration period.

Table 6. Summary statistics at USGS 01066000 Saco River at Cornish, Maine – calibration period

SWAT Simulated Flow		Observed Flow Gage	
REACH OUTFLOW FROM OUTLET(S) 4, 5 10-Year Analysis Period: 10/1/1993 - 9/30/2003 Flow volumes are (inches/year) for upstream drainage area		USGS 01066000 Saco River at Cornish, Maine Hydrologic Unit Code: 1060002 Latitude: 43.80805556 Longitude: -70.7816667 Drainage Area (sq-mi): 1293	
Total Simulated In-stream Flow:	**28.52**	Total Observed In-stream Flow:	**28.21**
Total of simulated highest 10% flows:	**10.55**	Total of Observed highest 10% flows:	**9.38**
Total of Simulated lowest 50% flows:	**5.01**	Total of Observed Lowest 50% flows:	**5.17**
Simulated Summer Flow Volume (months 7-9):	**4.53**	Observed Summer Flow Volume (7-9):	**3.17**
Simulated Fall Flow Volume (months 10-12):	**5.82**	Observed Fall Flow Volume (10-12):	**6.12**
Simulated Winter Flow Volume (months 1-3):	**3.71**	Observed Winter Flow Volume (1-3):	**6.44**
Simulated Spring Flow Volume (months 4-6):	**14.45**	Observed Spring Flow Volume (4-6):	**12.48**
Total Simulated Storm Volume:	**6.37**	Total Observed Storm Volume:	**6.11**
Simulated Summer Storm Volume (7-9):	**1.17**	Observed Summer Storm Volume (7-9):	**0.83**

Errors (Simulated-Observed)	*Error Statistics*	*Recommended Criteria*		
Error in total volume:	1.08	10		
Error in 50% lowest flows:	-3.20	10		
Error in 10% highest flows:	12.54	15		
Seasonal volume error - Summer:	**42.85**	**30**		
Seasonal volume error - Fall:	-4.86	>> 30	Clear	
Seasonal volume error - Winter:	**-42.36**	**30**		
Seasonal volume error - Spring:	15.83	30		
Error in storm volumes:	4.18	20		
Error in summer storm volumes:	39.96	50		
Nash-Sutcliffe Coefficient of Efficiency, E:	0.611	Model accuracy increases		
Baseline adjusted coefficient (Garrick), E':	0.471	as E or E' approaches 1.0		
Monthly NSE	0.713			

Hydrology Validation

Hydrology validation for Saco River was performed for the period 10/1/1983 through 9/30/1993. Results are presented in below. The validation achieves a moderately high coefficient of model fit efficiency, but is over on summer flow volumes (Figure 8, Figure 9, Figure 10, Figure 11 and Table 7).

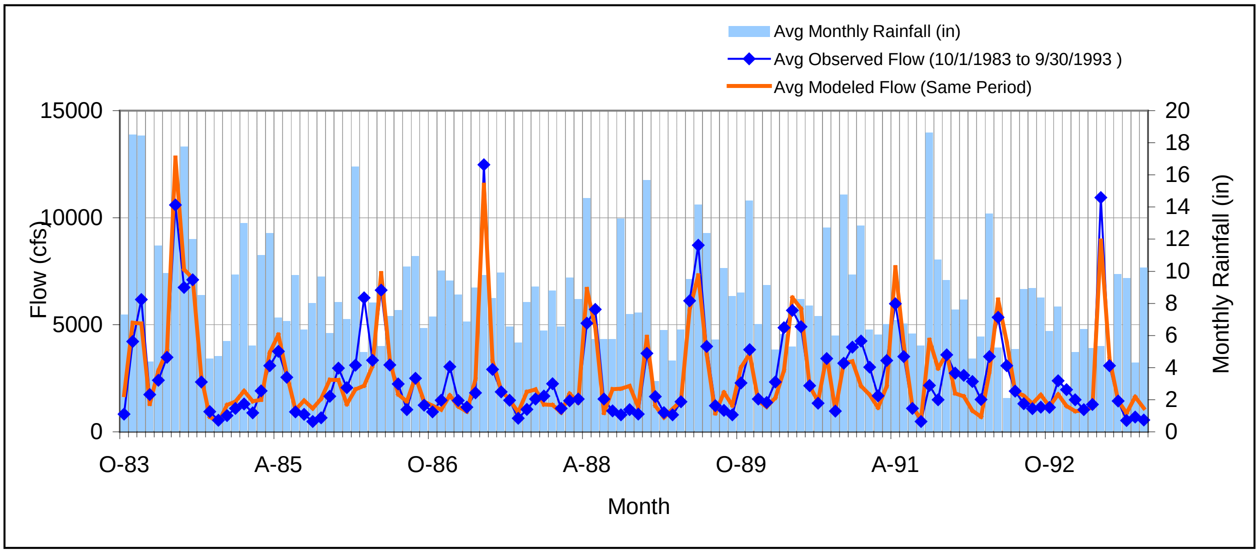


Figure 8. Mean monthly flow at USGS 01066000 Saco River at Cornish, Maine – validation period.

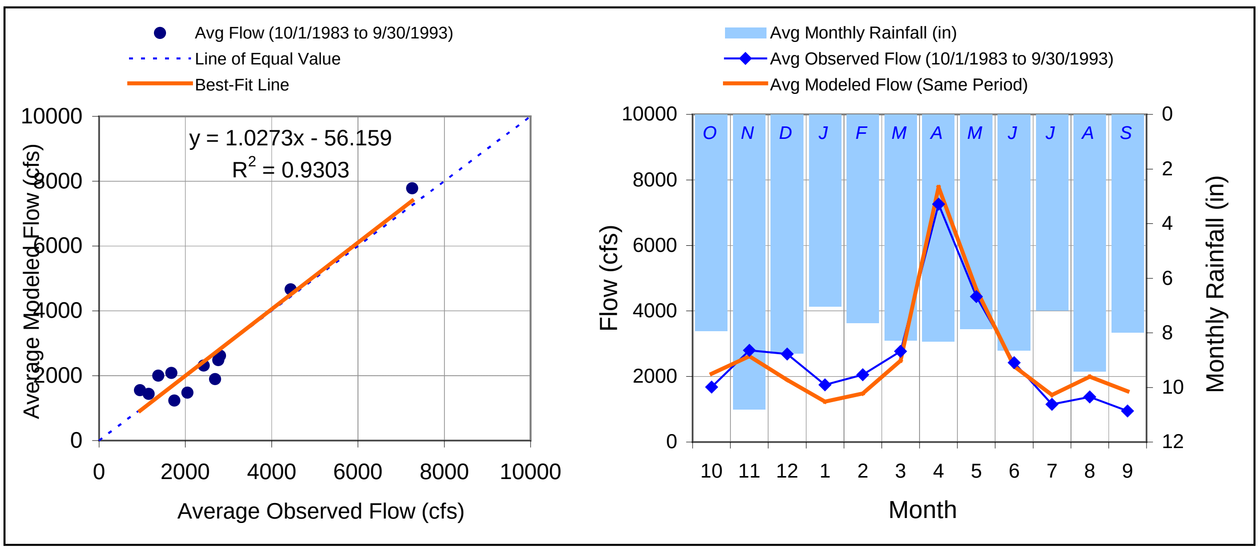


Figure 9. Seasonal regression and temporal aggregate at USGS 01066000 Saco River at Cornish, Maine – validation period.

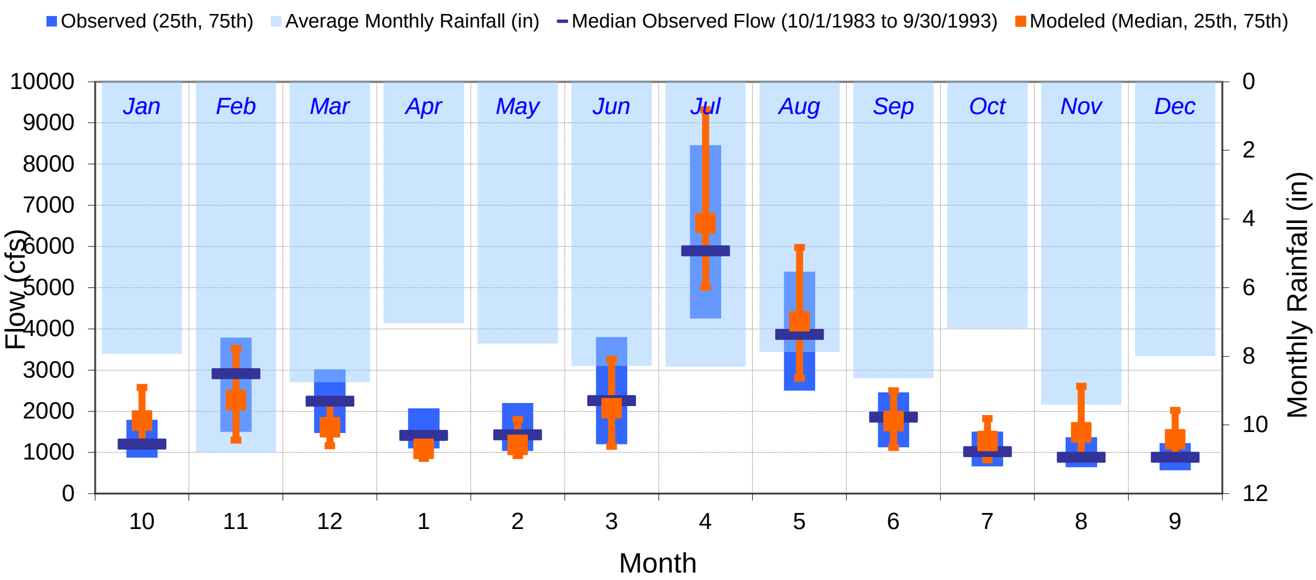


Figure 10. Seasonal medians and ranges at USGS 01066000 Saco River at Cornish, Maine – validation period.

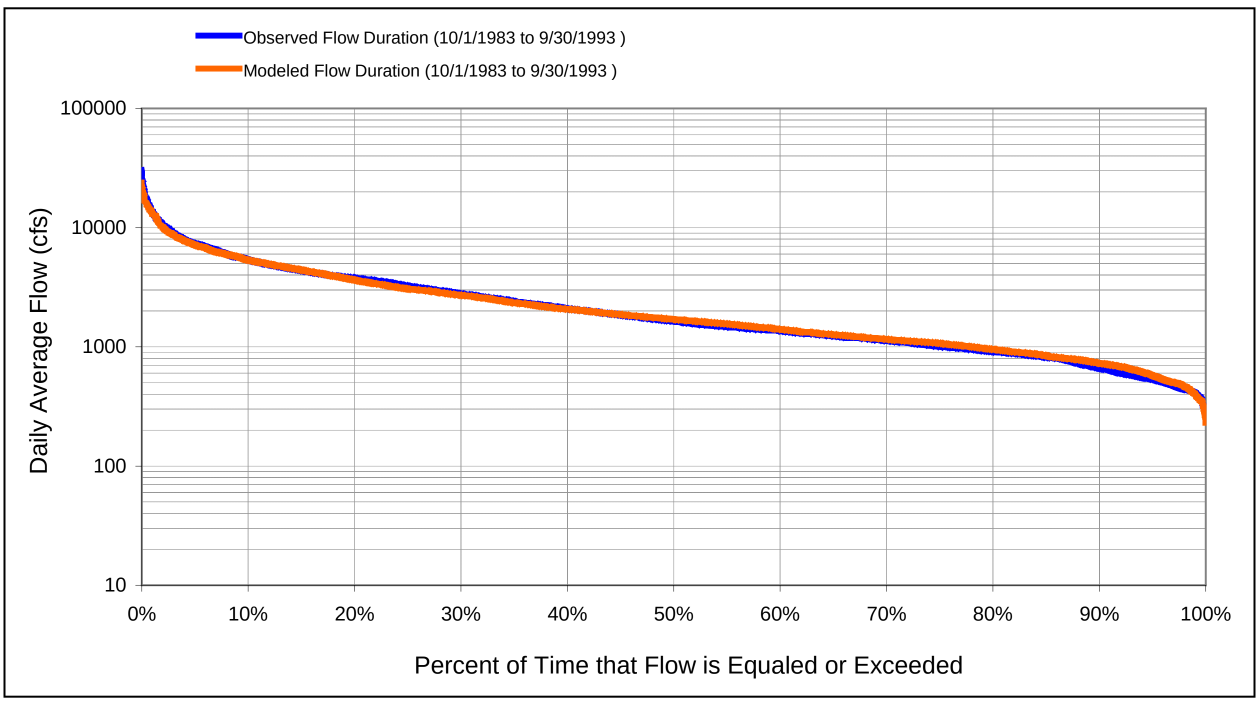


Figure 11. Flow exceedance at USGS 01066000 Saco River at Cornish, Maine – validation period.

Table 7. Summary statistics at USGS 01066000 Saco River at Cornish, Maine – validation period

SWAT Simulated Flow		Observed Flow Gage			
REACH OUTFLOW FROM OUTLET(S) 4, 5 10-Year Analysis Period: 10/1/1983 - 9/30/1993 Flow volumes are (inches/year) for upstream drainage area		USGS 01066000 Saco River at Cornish, Maine Hydrologic Unit Code: 1060002 Latitude: 43.80805556 Longitude: -70.7816667 Drainage Area (sq-mi): 1293			
Total Simulated In-stream Flow:	**27.57**	Total Observed In-stream Flow:			**27.39**
Total of simulated highest 10% flows:	**9.12**	Total of Observed highest 10% flows:			**9.32**
Total of Simulated lowest 50% flows:	**5.69**	Total of Observed Lowest 50% flows:			**5.35**
Simulated Summer Flow Volume (months 7-9):	**4.40**	Observed Summer Flow Volume (7-9):			**3.07**
Simulated Fall Flow Volume (months 10-12):	**5.81**	Observed Fall Flow Volume (10-12):			**6.31**
Simulated Winter Flow Volume (months 1-3):	**4.51**	Observed Winter Flow Volume (1-3):			**5.69**
Simulated Spring Flow Volume (months 4-6):	**12.86**	Observed Spring Flow Volume (4-6):			**12.31**
Total Simulated Storm Volume:	**5.75**	Total Observed Storm Volume:			**6.39**
Simulated Summer Storm Volume (7-9):	**1.04**	Observed Summer Storm Volume (7-9):			**0.79**
Errors (Simulated-Observed)	*Error Statistics*	*Recommended Criteria*			
Error in total volume:	0.67	10			
Error in 50% lowest flows:	6.45	10			
Error in 10% highest flows:	-2.12	15			
Seasonal volume error - Summer:	**43.06**	**30**			
Seasonal volume error - Fall:	-7.98	30		Clear	
Seasonal volume error - Winter:	-20.75	30			
Seasonal volume error - Spring:	4.43	30			
Error in storm volumes:	-9.91	20			
Error in summer storm volumes:	31.54	50			
Nash-Sutcliffe Coefficient of Efficiency, E:	0.764	Model accuracy increases			
Baseline adjusted coefficient (Garrick), E':	0.555	as E or E' approaches 1.0			
Monthly NSE	0.844				

Hydrology Results for Larger Watershed

As described above, parameters determined for the gage at Saco River were initially transferred to other gages in the watershed. However, changes to subbasin level parameter were required to fit the model to the observed flows. In all, calibration and validation was pursued at a total of eight gages throughout the watershed. Results of the calibration and validation exercise are summarized in Table 8 and Table 9, respectively. Calibration and validation results were acceptable at most gages.

Table 8. Summary statistics (percent error): all Stations - calibration period

Station	01066000	01096500	01099500	01100000
Error in total volume:	1.08	-7.58	-4.83	1.83
Error in 50% lowest flows:	-3.20	-26.88	7.26	4.19
Error in 10% highest flows:	12.54	-2.19	-6.16	-1.16
Seasonal volume error - Summer:	42.85	14.23	58.91	63.71
Seasonal volume error - Fall:	-4.86	2.20	25.28	19.04
Seasonal volume error - Winter:	-42.36	-20.66	-21.25	-22.06
Seasonal volume error - Spring:	15.83	-5.49	-19.03	-3.67
Error in storm volumes:	4.18	-18.32	2.38	-1.23
Error in summer storm volumes:	39.96	6.63	44.46	48.94
Daily Nash-Sutcliffe Coefficient of Efficiency, E:	0.611	0.627	0.715	0.714
Monthly Daily Nash-Sutcliffe Coefficient of Efficiency, E:	0.713	0.760	0.741	0.806

Table 9. Summary statistics (percent error): all stations - validation period

Station	01066000	01096500	01099500	01100000
Error in total volume:	0.67	-6.51	-9.06	-8.01
Error in 50% lowest flows:	6.45	-17.04	-8.56	-2.95
Error in 10% highest flows:	-2.12	-7.27	-1.91	-15.94
Seasonal volume error - Summer:	43.06	29.39	52.96	63.08
Seasonal volume error - Fall:	-7.98	0.24	8.74	3.27
Seasonal volume error - Winter:	-20.75	-16.04	-28.69	-30.46
Seasonal volume error - Spring:	4.43	-13.04	-21.37	-20.07
Error in storm volumes:	-9.91	-25.22	0.61	-17.38
Error in summer storm volumes:	31.54	-0.50	38.02	32.46
Daily Nash-Sutcliffe Coefficient of Efficiency, E:	0.764	0.700	0.759	0.719
Monthly Daily Nash-Sutcliffe Coefficient of Efficiency, E:	0.844	0.856	0.797	0.751

Water Quality Calibration and Validation

Initial calibration and validation of water quality was done on the Saco River (USGS 01066000), using 1993-2003 for calibration and 1983-1993 for validation. As with hydrology, calibration was performed on the later period as this better reflects the land use included in the model.

Calibration adjustments for sediment focused on the following parameters:

- SPCON (linear parameter for estimating maximum amount of sediment that can be re-entrained during channel sediment routing)

- SPEXP (exponential parameter for estimating maximum amount of sediment that can be re-entrained during channel sediment routing)
- CH_COV (channel cover factor)
- CH_EROD (channel erodibility factor)
- USLE_P (USLE support practice factor)

Simulated and estimated sediment loads at the Saco River station for both the calibration and validation periods are shown in Figure 12 and statistics for the two periods are provided separately in Table 10. The key statistic in Table 10 is the relative percent error, which shows the error in the prediction of monthly load normalized to the estimated load. Table 10 also shows the relative average absolute error, which is the average of the relative magnitude of errors in individual monthly load predictions. This number is inflated by outlier months in which the simulated and estimated loads differ by large amounts (which may be as easily due to uncertainty in the estimated load due to limited data as to problems with the model) and the third statistic, the relative median absolute error, is likely more relevant and shows better agreement.

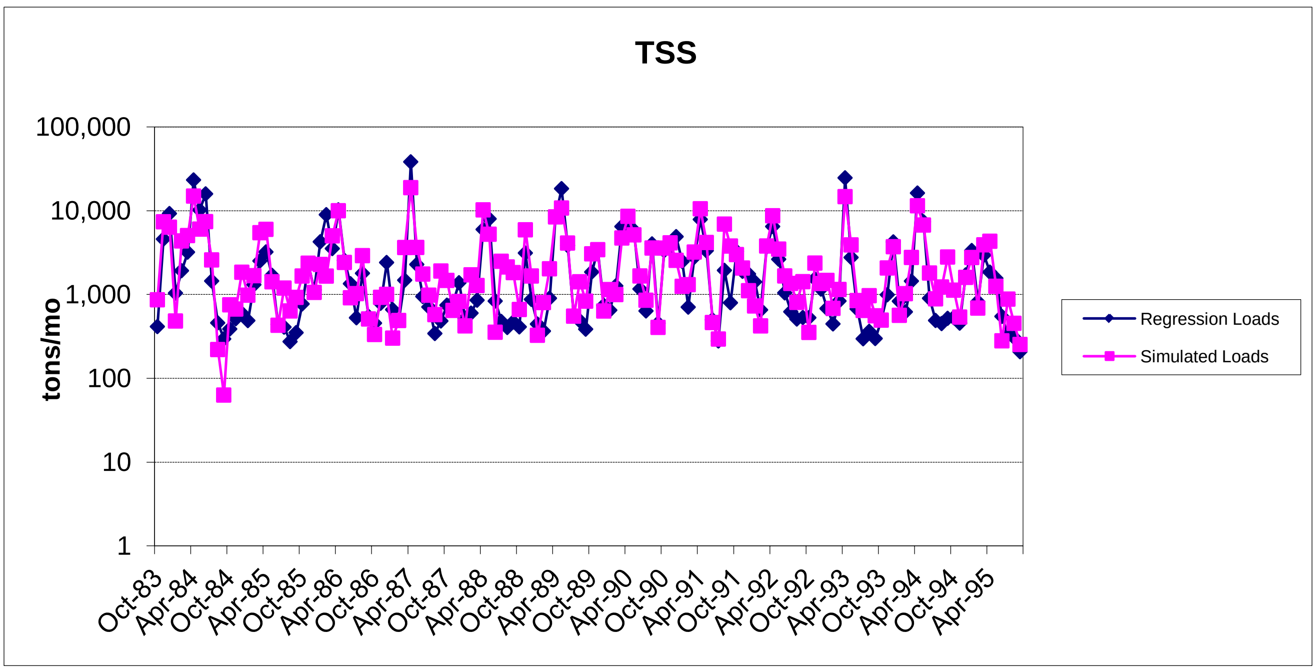


Figure 12. Fit for monthly load of TSS at USGS 01066000 Saco River at Cornish, Maine.

Table 10. Model fit statistics (observed minus predicted) for monthly sediment loads using stratified regression at USGS 01066000 Saco River at Cornish, Maine

Statistic	Calibration period (1993-1995)	Validation period (1983-1993)
Relative Percent Error	-9.0%	3.2%
Relative Average Absolute Error	39.9%	45.9%
Relative Median Absolute Error	26.2%	18.8%

Calibration adjustments for total phosphorus and total nitrogen focused on the following parameters:

- RHOQ (algal respiration rate at 20° C)
- PHOSKD (phosphorus soil partitioning coefficient)
- PSP (phosphorus availability index)
- RS2 (benthic source rate for dissolved P in the reach at 20° C)
- RS5 (organic P settling rate in the reach at 20° C)
- BC4 (rate constant for mineralization of organic P to dissolved P in the reach at 20° C)
- RS4 (rate coefficient for organic N settling in the reach at 20° C)

Results for the phosphorus simulation are shown in Figure 13 and Table 11. Results for the nitrogen simulation are shown in Figure 14 and Table 12. The model fit is generally acceptable.

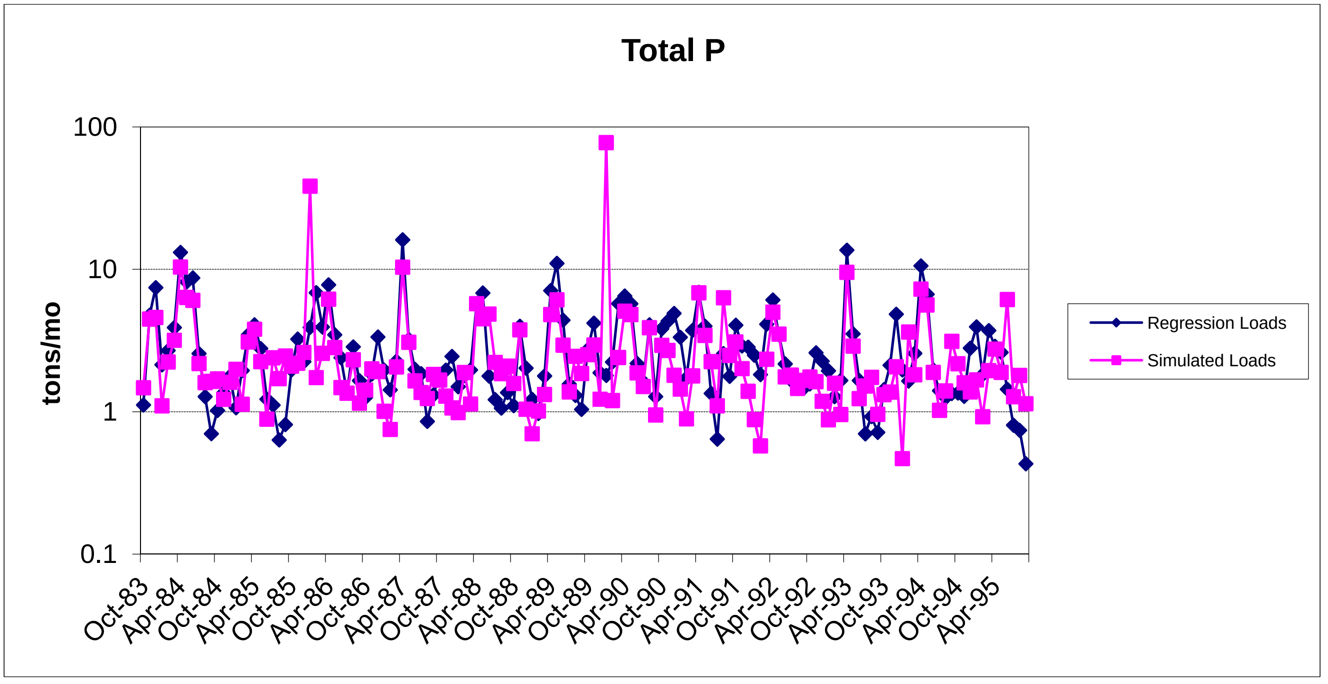


Figure 13. Fit for monthly load of total phosphorus at USGS 01066000 Saco River at Cornish, Maine.

Table 11. Model fit statistics (observed minus predicted) for monthly phosphorus loads using stratified regression at USGS 01066000 Saco River at Cornish, Maine

Statistic	Calibration period (1993-1995)	Validation period (1983-1993)
Relative Percent Error	9.6%	-11.5%
Average Absolute Error	48.5%	33.5%
Median Absolute Error	62.0%	23.6%

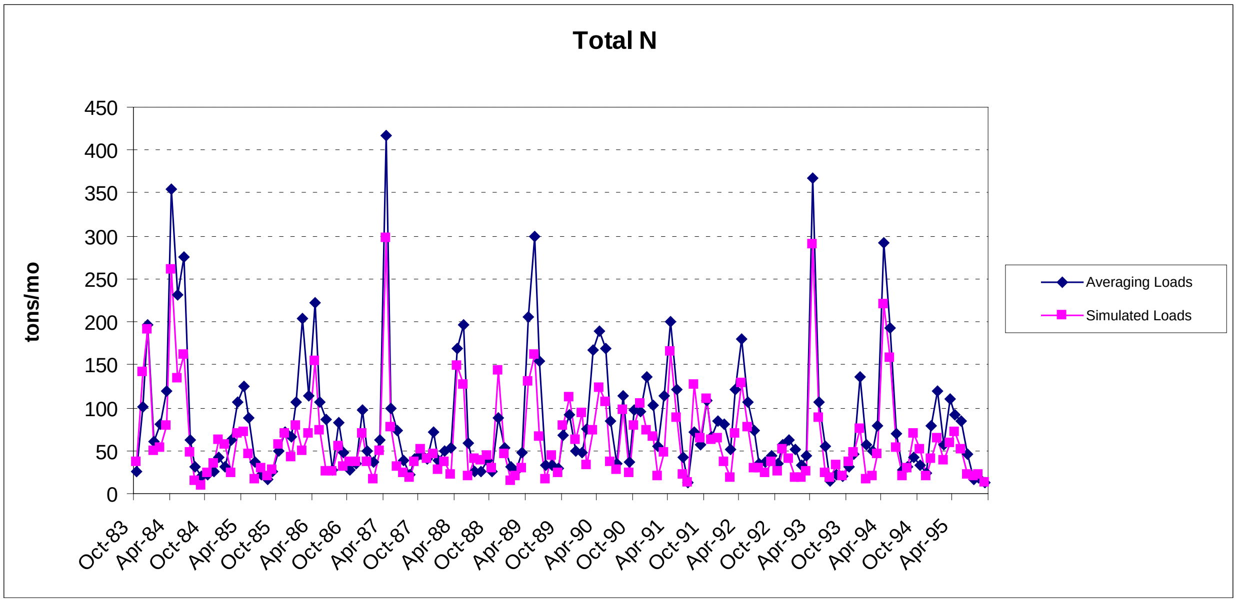


Figure 14. Fit for monthly load of total nitrogen at USGS 01066000 Saco River at Cornish, Maine.

Table 12. Model fit statistics (observed minus predicted) for monthly total nitrogen loads using averaging estimator at USGS 01066000 Saco River at Cornish, Maine

Statistic	Calibration period (1993-1995)	Validation period (1983-1993)
Relative Percent Error	27.5%	26.3%
Average Absolute Error	34.4%	29.9%
Median Absolute Error	34.6%	22.9%

Water Quality Results for Larger Watershed

As with hydrology, a spatial calibration approach was adopted. Saco River watershed SWAT model parameters for water quality were transferred to other portions of the watershed with necessary changes to subbasin level parameters. Summary statistics for the SWAT water quality calibration and validation at other stations in the watershed are provided in Table 13 and Table 14.

Table 13. Summary statistics for water quality at all stations – calibration period 1993-2003

Station	01066000	01100000
Relative Percent Error TSS Load	-9.0%	19.9%
Relative Percent Error TP Load	9.6%	-16.2%
Relative Percent Error TN Load	27.5%	-23.7%

Table 14. Summary statistics for water quality at all stations – validation period 1983-1993

Station	01066000	01100000
Relative Percent Error TSS Load	3.2%	-
Relative Percent Error TP Load	-11.5%	-
Relative Percent Error TN Load	26.3%	-

References

USEPA. 2008. Using the BASINS Meteorological Database (Version 2006). BASINS Technical Note 10. Office of Water, U.S. Environmental Protection Agency, Washington, DC. http://water.epa.gov/scitech/datait/models/basins/upload/2009_04_13_BASINSs_tecnote10.pdf (Accessed June, 2009).

Appendix Q
Model Configuration, Calibration and Validation

Basin: Rio Grande Valley (RioGra)

Contents

Tables

Figures

Watershed Background

The Rio Grande Valley was selected as one of the 15 non-pilot application watersheds for the 20 Watershed study. Watershed modeling for the non-pilot areas is accomplished using the SWAT model only, and model calibration and validation results are presented in abbreviated form.

Water Body Characteristics

The Rio Grande flows from southwestern Colorado to the Gulf of Mexico. The model study area is the upstream portion of the Rio Grande Valley, spanning parts of Colorado and New Mexico (Figure 1). This includes an area of about 19,000 mi^2 in ten HUC8s within HUCs 1301 and 1302.

The watershed is located in three physiographic provinces: Southern Rocky Mountains; Basin and Range Provinces; and Colorado Plateaus Provinces. Extreme contrasts in precipitation, runoff, and temperature characteristics exist between the Southern Rocky Mountains and the Basin and Range Provinces. These characteristics strongly affect land and water use in the watershed (Levings et al., 1998; USGS, 2009a).

The headwaters of the Rio Grande originate in the mountains of southern Colorado at an altitude of over 13,000 ft. At the lower end of the watershed, just downstream of Albuquerque, NM, the altitude is approximately 3,700 ft. The climate in the high mountain headwater areas of the Rio Grande and its northern tributaries is alpine tundra where average annual precipitation can exceed 50 inches, most in the form of snow. In contrast, near the lower boundary of the model area, the Rio Grande flows through desert where average annual precipitation is less than 9 inches, most in the form of summer thunderstorms.

Rangeland is dominant in the Basin and Range Province, and forest is dominant in the Southern Rocky Mountains and Colorado Plateaus Provinces; they occupy 54 percent and 35 percent of the model study area respectively. The cities of Taos, Santa Fe, Albuquerque, and Las Cruces, NM are located in the watershed but developed land constitutes less than 3 percent of the land area. Agricultural land use (5 percent) is limited primarily to areas where surface water or shallow groundwater is available for irrigation. Almost all public and domestic water supplies rely on groundwater, primarily from deeper aquifers. Surface water availability typically is necessary for agriculture with the exception of a few areas where groundwater is available in sufficient quantities.

Historically, streamflow in the Rio Grande was caused by spring snowmelt and summer monsoon thunderstorms. This natural streamflow pattern has been altered and regulated by the construction of reservoirs on the main stem and tributaries that impound and store water for later use, primarily irrigation. Complex interactions occur between groundwater and surface water in the Rio Grande flood plain. A system of canals distributes surface water for agricultural irrigation and a system of drains intercepts shallow groundwater and returns it to the Rio Grande. Surface water leaks from the Rio Grande and canals to recharge the shallow groundwater system. In places, deeper groundwater flows upward to recharge the shallow groundwater system and/or to contribute flow to the Rio Grande. In addition, excess applied irrigation water infiltrates and recharges the shallow groundwater system.

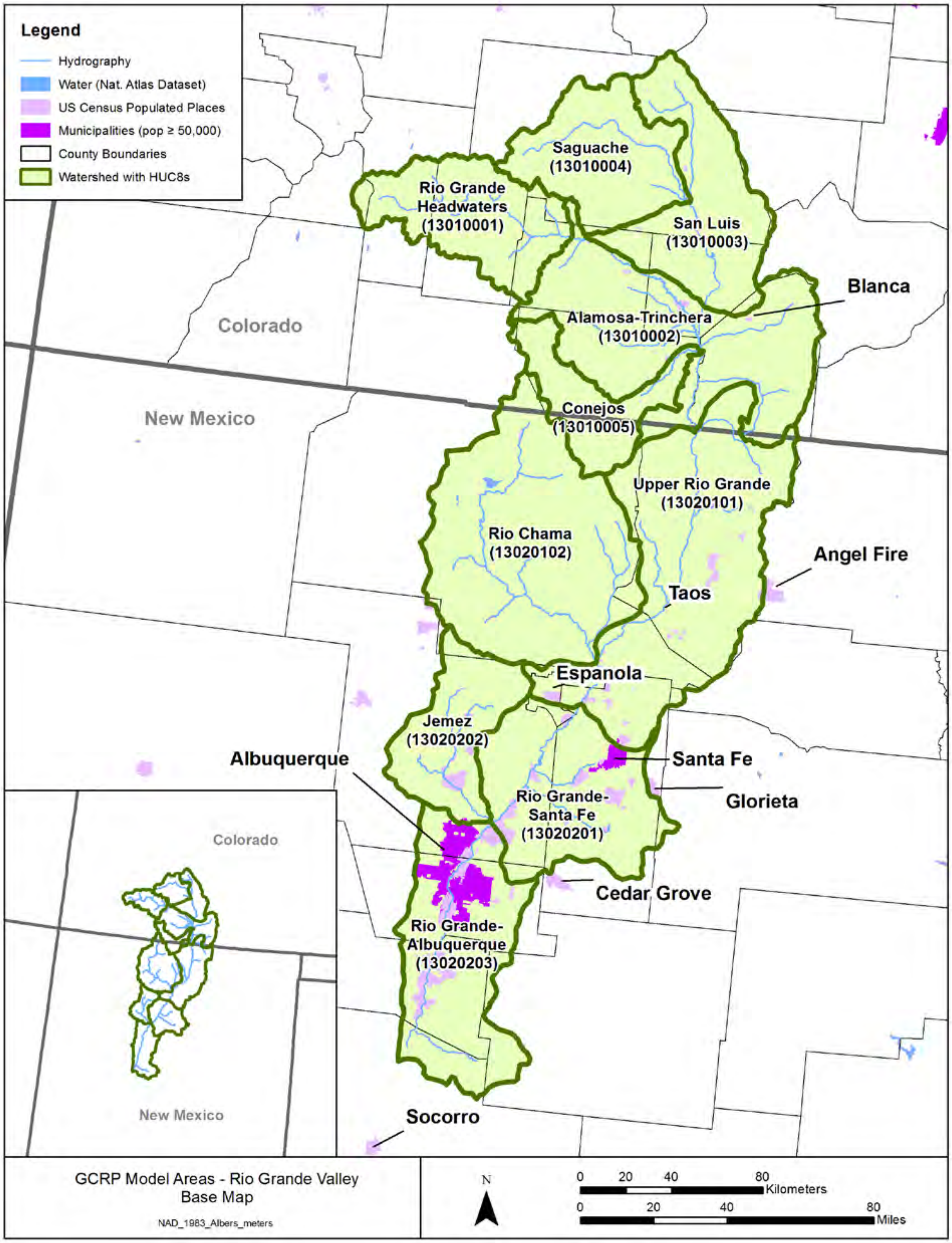


Figure 1. Location of the Rio Grande Valley.

Soil Characteristics

Soils in the watershed, as described in STATSGO soil surveys, fall primarily into hydrologic soil groups (HSGs) B (moderately high infiltration capacity) and D (low infiltration capacity). SWAT uses information drawn directly from the soils data layer to populate the model.

Land Use Representation

Land use/cover in the watershed is based on the 2001 National Land Cover Database (NLCD) coverage and is predominantly rangeland in the south, and forest in the Southern Rocky Mountains and Colorado Plateaus Provinces in the north (Figure 2). NLCD land cover classes were aggregated according to the scheme shown in Table 1 for representation in the 20 Watershed model. SWAT uses the built-in hydrologic response unit (HRU) overlay mechanism in the ArcSWAT interface. SWAT HRUs are formed from an intersection of land use and SSURGO major soils. The distribution of land use in the watershed is summarized in Table 2.

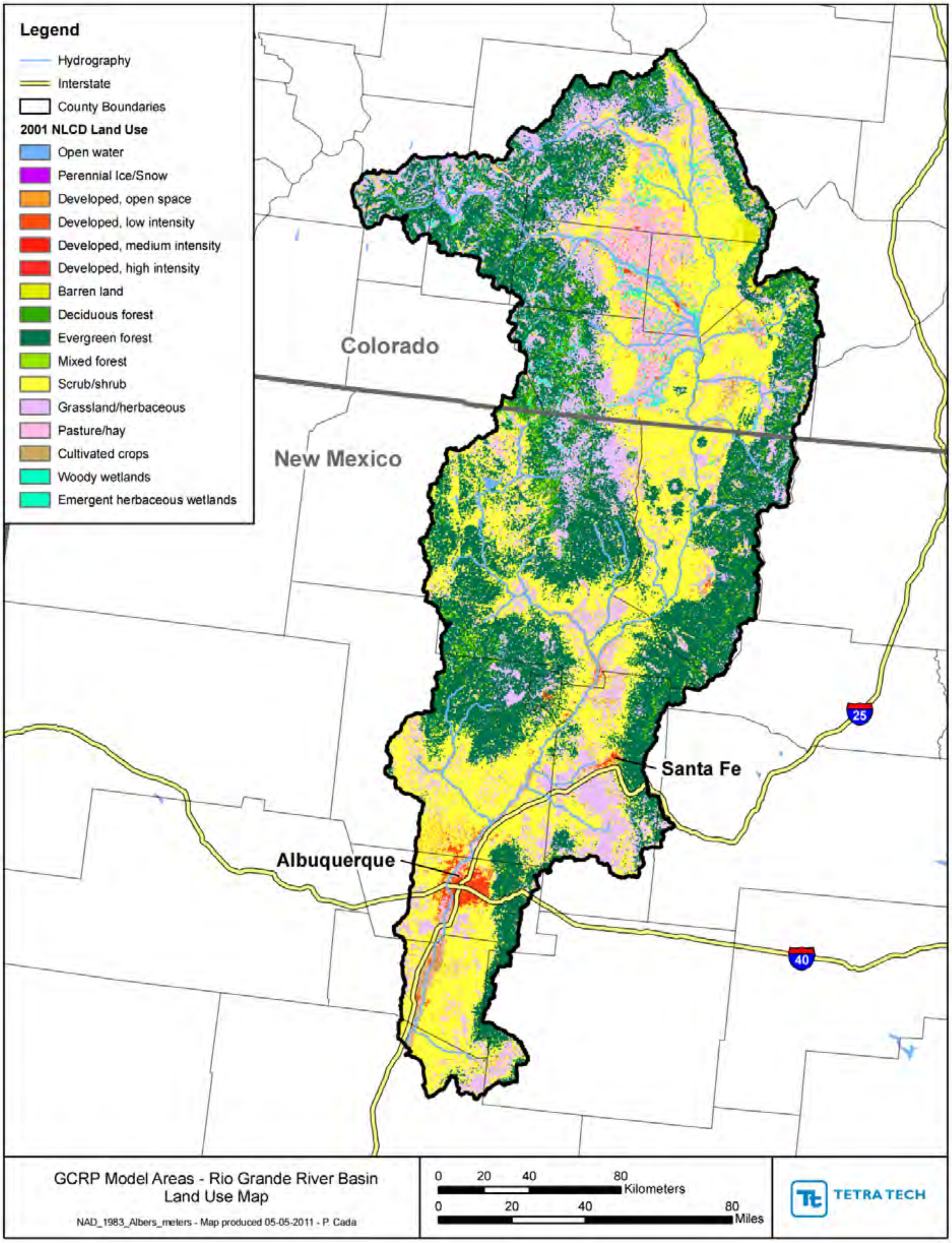


Figure 2. Land use in the Rio Grande Valley basin.

Table 1. Aggregation of NLCD land cover classes

NLCD Class	Comments	SWAT class
11 Water	Water surface area usually accounted for as reach area	WATR
12 Perennial ice/snow		WATR
21 Developed open space		URLD
22 Dev. Low Intensity		URMD
23 Dev. Med. Intensity		URHD
24 Dev. High Intensity		UIDU
31 Barren Land		SWRN
41 Forest	Deciduous	FRSD
42 Forest	Evergreen	FRSE
43 Forest	Mixed	FRST
51-52 Shrubland		RNGB
71-74 Herbaceous Upland		RNGE
81 Pasture/Hay		HAY
82 Cultivated		AGRR
91-97 Wetland	Emergent & woody wetlands	WETF, WETL, WETN
98-99 Wetland	Aquatic bed wetlands (not emergent)	WATR

Table 2. Land use distribution for the Rio Grande Valley basin (2001 NLCD; mi^2)

HUC 8 watershed	Open water	Developed[a]				Barren land	Forest	Shrub and Grassland	Pasture/ Hay	Cultivated	Wetland	Total
		Open space	Low density	Medium density	High density							
13010001	4.8	4.7	1.4	0.1	0.0	48.4	770.8	481.6	8.8	0.7	59.0	1,380.6
13010002	7.1	27.0	17.1	3.3	0.2	21.8	639.1	1,307.0	272.5	11.8	119.4	2,426.6
13010003	4.0	9.6	14.2	1.2	0.0	71.8	301.9	985.4	256.6	4.3	43.5	1,692.7
13010004	0.8	8.6	7.0	0.2	0.0	10.3	464.5	712.8	89.7	0.3	48.7	1,343.0
13010005	1.5	6.5	1.9	0.3	0.0	5.1	300.2	359.2	42.1	0.4	51.9	769.2
13020101	3.7	29.9	13.1	1.4	0.2	20.3	1,457.6	1,660.1	20.8	33.5	13.5	3,254.2
13020102	22.7	18.0	2.1	0.1	0.0	5.1	1,546.6	1,487.4	22.8	12.0	41.2	3,158.0
13020201	4.3	26.6	12.9	2.6	0.3	0.3	470.7	1,337.7	1.2	13.1	2.2	1,871.6
13020202	1.9	5.0	1.0	0.0	0.0	2.9	464.2	549.6	3.7	4.4	6.2	1,039.0
13020203	8.2	81.9	94.4	33.6	5.6	10.8	273.7	1,400.8	56.3	46.6	12.1	2,024.1
Total	59.0	217.8	165.1	42.8	6.4	196.9	6,689.3	10,281.6	774.6	127.0	397.9	18,959.0

[a]The percent imperviousness applied to each of the developed land uses is as follows: open space (8.76%), low density (32.36%), medium density (60.49%), and high density (84.32%).

Point Sources

There are several point source discharges in the watershed. Only the major dischargers, with a design flow greater than 1 MGD are included in the simulation (Table 3). The major dischargers are represented at long-term average flows, without accounting for changes over time or seasonal variations.

Table 3. Major point source discharges in the Rio Grande Valley basin

ID	Name	Design glow (mgd)	Observed flow (mgd)
NM0020150	Belen, City of	1.2	0.79
NM0022250	Albuquerque, City of (WWTP#2)	60	58.57
NM0027987	Rancho, City of	2.4	3.02
NM0022292	Santa Fe, City of (Airport Rd)	6.5	5.79
NM0028355	Los Alamos National Laboratory		0.62
NM0029351	Espanola, City of	1.01	0.91
NM0024066	Taos, Town of	1.25	0.98
NM0022101	Village of Taos Ski Valley	0.13	0.04
NM0022306	Molycorp Inc - Questa		0.49
NM0024899	Red River AWWT, Town of	2.5	0.47
NM0020141	Los Alamos County (Bayo Canyon)	1.37	12.22
CO0044458	Alamosa, City of	2.6	1.53

The point sources were initially represented in the model with the median of reported values for TSS and an assumed total nitrogen concentration of 11.2 mg/L and assumed total phosphorus concentration of 7.0 mg/L for secondary treatment facilities (Tetra Tech 1999).

Meteorological Data

The required meteorological time series data for the 20 Watershed SWAT simulations are precipitation and air temperature. The 20 Watershed simulations do not include water temperature simulation and use a degree-day method for snowmelt. SWAT estimates Penman-Monteith potential evapotranspiration using a statistical weather generator for inputs other than temperature and precipitation. These meteorological time series are drawn from the BASINS4 Meteorological Database (USEPA 2008), which provides a consistent, quality-assured set of nationwide data with gaps filled and records disaggregated. Scenario application requires simulation over 30 years, so the available stations are those with a common 30-year period of record (or one that can be filled from an approximately co-located station) that covers the year 2001. A total of 54 precipitation stations were identified for use in the Rio Grande model with a common period of record of 10/1/1972-9/30/2002 (Table 4). Temperature records are sparser; where these are absent temperature is taken from nearby stations with an elevation correction.

Table 4. Precipitation stations for the Rio Grande Valley watershed model

ID	Name	Latitude	Longitude	Elevation	Temperature
50130	CO050130	37.4389	-105.8610	2296	Yes
50776	CO050776	37.4723	-105.5040	2390	Yes
51458	CO051458	37.7067	-106.1440	2339	Yes
51713	CO051713	38.4462	-106.7610	2438	Yes
52184	CO052184	37.6742	-106.3240	2397	Yes
53541	CO053541	37.7333	-105.5110	2494	Yes

ID	Name	Latitude	Longitude	Elevation	Temperature
53951	CO053951	37.7718	-107.1090	2758	Yes
54734	CO054734	38.0248	-107.3140	2643	Yes
55322	CO055322	37.1742	-105.9390	2344	Yes
55706	CO055706	37.5811	-106.1870	2345	Yes
56203	CO056203	38.0207	-107.6680	2390	Yes
57337	CO057337	38.0858	-106.1440	2347	Yes
57428	CO057428	37.1954	-107.6650	2421	No
57460	CO057460	38.4040	-105.4660	2579	No
57656	CO057656	37.8193	-106.4270	2828	Yes
58220	CO058220	37.0708	-106.6210	2521	No
58931	CO058931	38.1312	-106.0560	2396	Yes
290041	NM290041	36.2403	-106.8320	1945	Yes
290234	NM290234	35.0357	-105.5950	1618	Yes
290245	NM290245	36.0909	-106.5780	1731	Yes
290915	NM290915	34.4220	-106.9680	1443	Yes
291000	NM291000	36.3120	-107.0000	2635	No
291180	NM291180	36.7444	-105.2620	2440	No
291389	NM291389	36.4820	-106.7300	2386	No
291630	NM291630	36.7409	-106.0810	2332	yes
291664	NM291664	36.9178	-106.0340	2393	yes
291982	NM291982	35.6414	-105.4480	1695	No
292241	NM292241	36.0106	-106.6870	2147	yes
292608	NM292608	36.9359	-107.0540	2071	yes
292700	NM292700	36.5575	-106.3210	2524	yes
292837	NM292837	36.5928	-106.7610	2054	yes
293031	NM293031	35.9882	-106.2600	1702	yes
293060	NM293060	34.8242	-105.6880	1871	yes
293488	NM293488	35.8918	-105.4030	2515	yes
293511	NM293511	36.3336	-106.3650	1981	No
293586	NM293586	35.5817	-105.9750	2292	No
293592	NM293592	35.2656	-105.9430	2042	No
294366	NM294366	35.3886	-105.5860	1642	No
294369	NM294369	35.7784	-106.5530	1909	Yes
294960	NM294960	36.3043	-107.1810	2201	Yes
295084	NM295084	35.8645	-106.7460	2263	Yes
295150	NM295150	34.7675	-105.8610	1475	Yes
295965	NM295965	34.5209	-105.5040	1987	Yes
296676	NM296676	35.5490	-106.1440	2096	Yes
297323	NM297323	36.7059	-106.7610	2644	Yes
298015	NM298015	35.2106	-106.3240	2143	Yes

ID	Name	Latitude	Longitude	Elevation	Temperature
298085	NM298085	35.6194	-105.5110	2059	Yes
298518	NM298518	35.1767	-107.1090	1943	Yes
298668	NM298668	36.3906	-107.3140	2123	Yes
298845	NM298845	36.7664	-105.9390	2275	Yes
299031	NM299031	35.7992	-106.1870	2042	Yes
299085	NM299085	36.6511	-107.6680	2481	No
299820	NM299820	35.9479	-106.1440	2505	Yes

Watershed Segmentation

The Rio Grande basin was divided into 74 subwatersheds for the purposes of modeling (Figure 3). The model encompasses the complete watershed and does not require specification of any upstream boundary conditions for application.

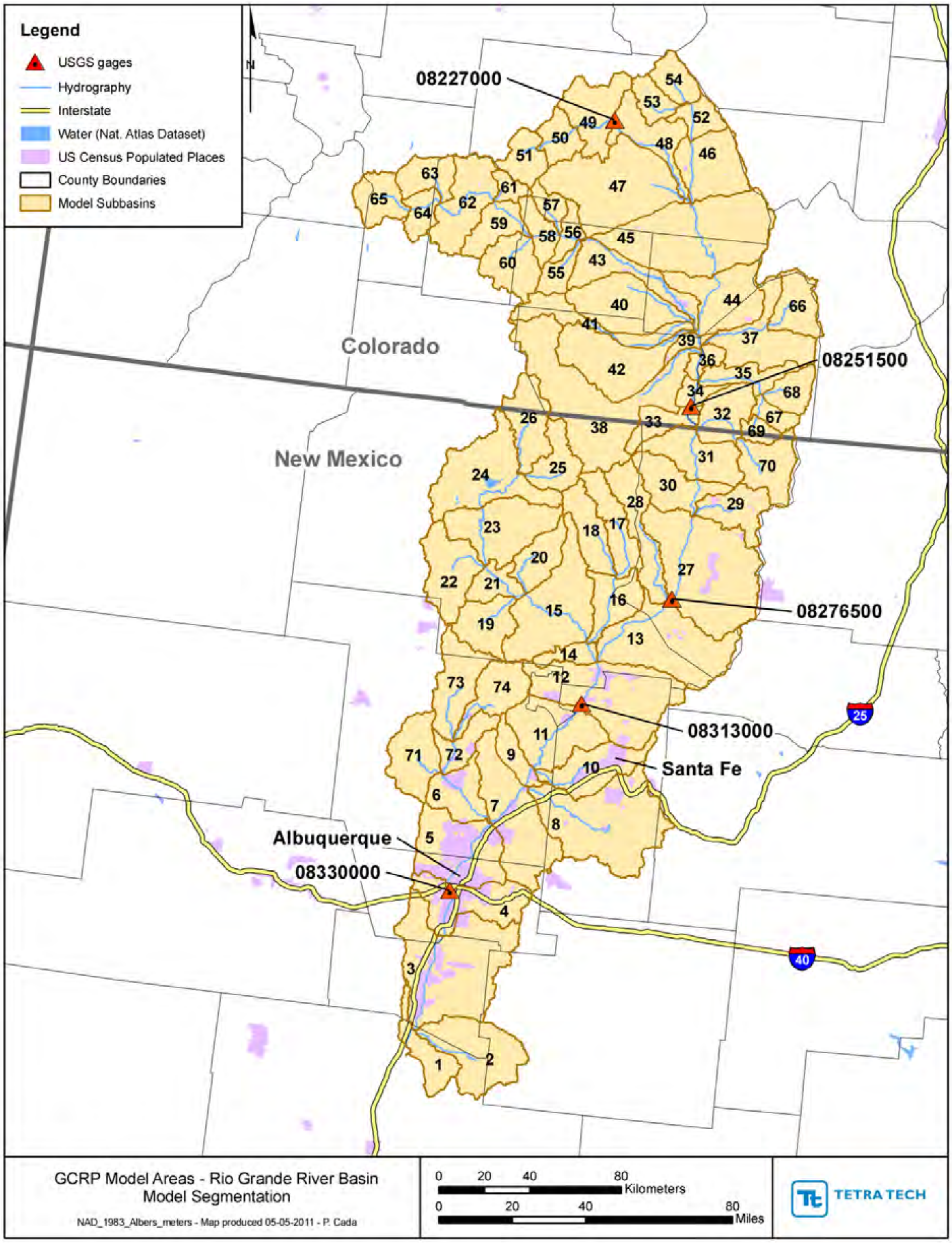


Figure 3. **Model segmentation and USGS stations utilized for the Rio Grande Valley basin.**

Calibration Data and Locations

The specific site chosen for initial calibration was Saguache Creek near Saguache, CO (USGS 08227000), which is the only gaging station in the basin without any reservoirs. Calibration and validation were pursued at multiple locations (Table 5). Parameters derived at the Saguache Creek station were transferred to other portions of the Rio Grande basin.

Table 5. Calibration and validation locations in the Rio Grande Valley basin

Station Name	USGS ID	Drainage area (mi^2)	Hydrology calibration	Water quality calibration
Saguache Creek near Saguache, CO	08227000	595	X	X
Rio Grande near Lobatos, NM	08251500	7700	X	X
RioGrande near Taos, NM	08276500	9730	X	X
RioGrande at Otowi Bridge, NM	08313000	14300	X	X
RioGrande at Albuquerque	08330000	17440	X	X

The model hydrology calibration period was set to Water Years 1992-2001 (within the 30-year period of record for modeling). Hydrologic validation was then performed on Water Years 1982-1991. Water quality calibration used calendar years 1985-2003, while validation used 1973-1984. However, there was some variation to this time period across the monitoring stations depending on the availability of monitored data.

SWAT Modeling

Assumptions

Ten major reservoirs occur in the Rio Grande basin. Pertinent reservoir information including surface area and storage at principal (normal) and emergency spillway levels for the reservoirs modeled were obtained from the National Inventory of Dams (NID) database. The SWAT model provides four options to simulate reservoir outflow: measured daily outflow, measured monthly outflow, average annual release rate for uncontrolled reservoir, and controlled outflow with target release. Keeping in view the 20 Watershed climate change impact evaluation application, it was assumed that the best representation of the reservoirs was to simulate them without supplying time series of outflow records. Therefore, the target release approach was used in the GCRP-SWAT model.

Elevation bands were also created in the subwatersheds where elevation was above 3,000 m to account for the impact of higher elevation. Moreover, since the northern and southern part of the Rio Grande basin are geographically different, certain parameters have different values for the Colorado part of Rio Grande and for the New Mexico part of the Rio Grande basin, respectively.

Hydrology Calibration

A spatial calibration approach was not adopted for GCRP-SWAT modeling for the Rio Grande basin; however, a systematic adjustment of parameters was adopted and some adjustments were applied throughout the basin. Most of the calibration efforts were geared toward getting a closer match between simulated and observed flows at one of the USGS gaging stations in the basin.

Land Use / Soil / Slope Definition

A 5/10/5 percent threshold was used for land use/soil/slope in the SWAT model while defining the HRUs. Urban land use classes were exempted from the HRU overlay thresholds.

The parameters were adjusted within the practical range at the calibration focus area to obtain reasonable fit between the simulated and measured flows in terms of Nash-Sutcliffe modeling efficiency and the high flow and low flow components as well as the seasonal flows.

The water balance of the whole Rio Grande basin predicted by the SWAT model over the 30-year simulation period is as follows:

```
PRECIP =    307.4 MM
SNOW FALL =   38.57 MM
SNOW MELT =    34.39 MM
SUBLIMATION =     4.58 MM
SURFACE RUNOFF Q =     5.73 MM
LATERAL SOIL Q =   15.40 MM
TILE Q =     0.00 MM
GROUNDWATER (SHAL AQ) Q =     6.51 MM
REVAP (SHAL AQ => SOIL/PLANTS) =    7.47 MM
DEEP AQ RECHARGE =     1.22 MM
TOTAL AQ RECHARGE =   15.21 MM
TOTAL WATER YLD =    24.24 MM
PERCOLATION OUT OF SOIL =   12.18 MM
ET =    274.8 MM
```

```
PET =   1946.4MM
TRANSMISSION LOSSES =     3.41 MM
```

Hydrologic calibration adjustments focused on the following parameters:

- Snow parameters SMTMP, SMFMX, SMFMN, TIMP
- Baseflow factor
- GW_DELAY (groundwater delay time)
- GWQMN (threshold depth of water in the shallow aquifer required for return flow to occur)
- Rchrg_DP
- CH_K2 (channel hydraulic conductivity)
- NDTarg
- Curve Number
- Temperature Lapse Rate
- SURLAG (surface runoff lag time [days])
- ESCO (soil evaporation compensation factor)
- FFCB (fraction of field capacity)

Calibration results for the Rio Grande basin at Saguache Creek near Saguache, CO are summarized in Figures 4 through 7 and Table 6. In general, the model represents the observed flow adequately, both in terms of volume and timing of the peaks (Figure 7 and Table 6).

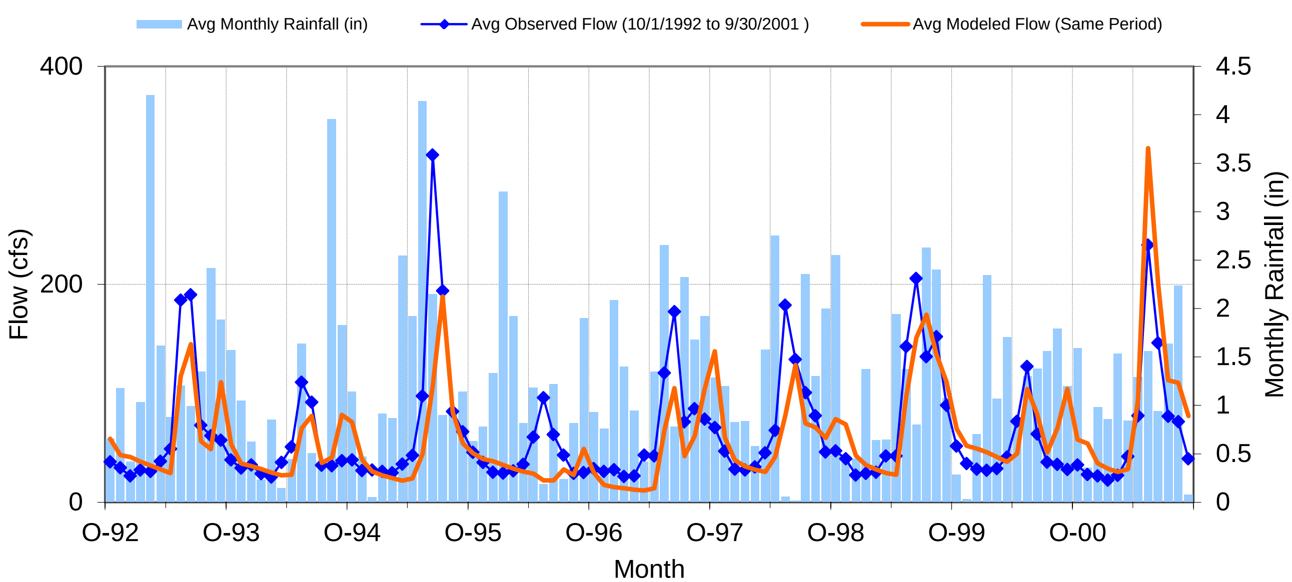


Figure 4. Mean monthly flow at USGS 08227000 Saguache Creek near Saguache, CO - calibration period.

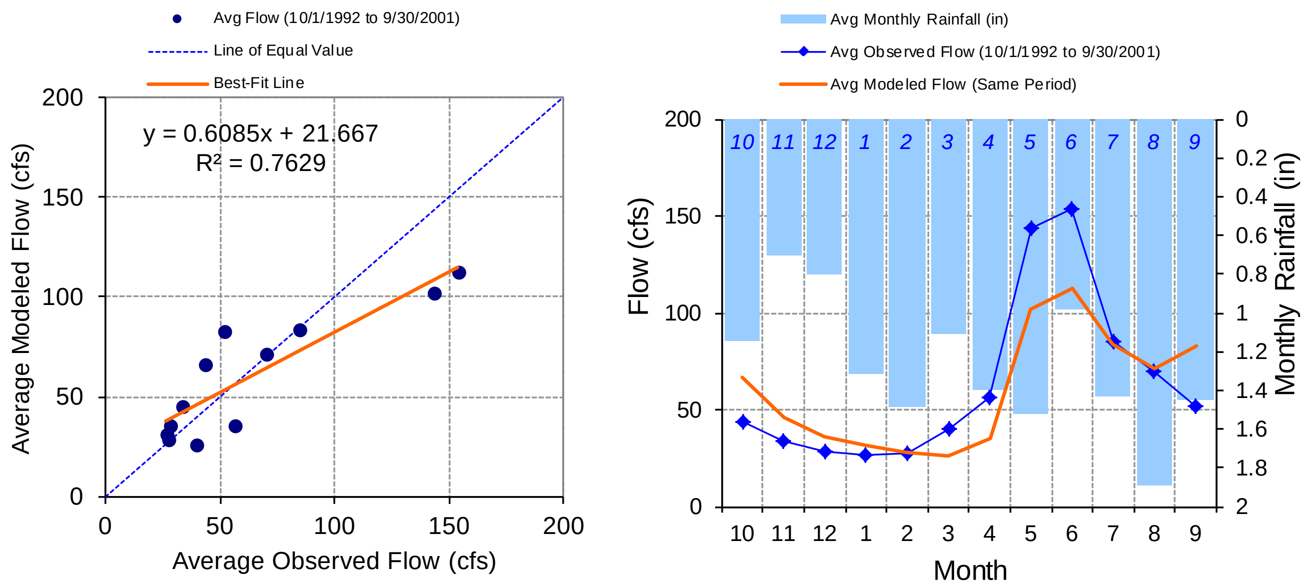


Figure 5. Seasonal regression and temporal aggregate at USGS 08227000 Saguache Creek near Saguache, CO - calibration period

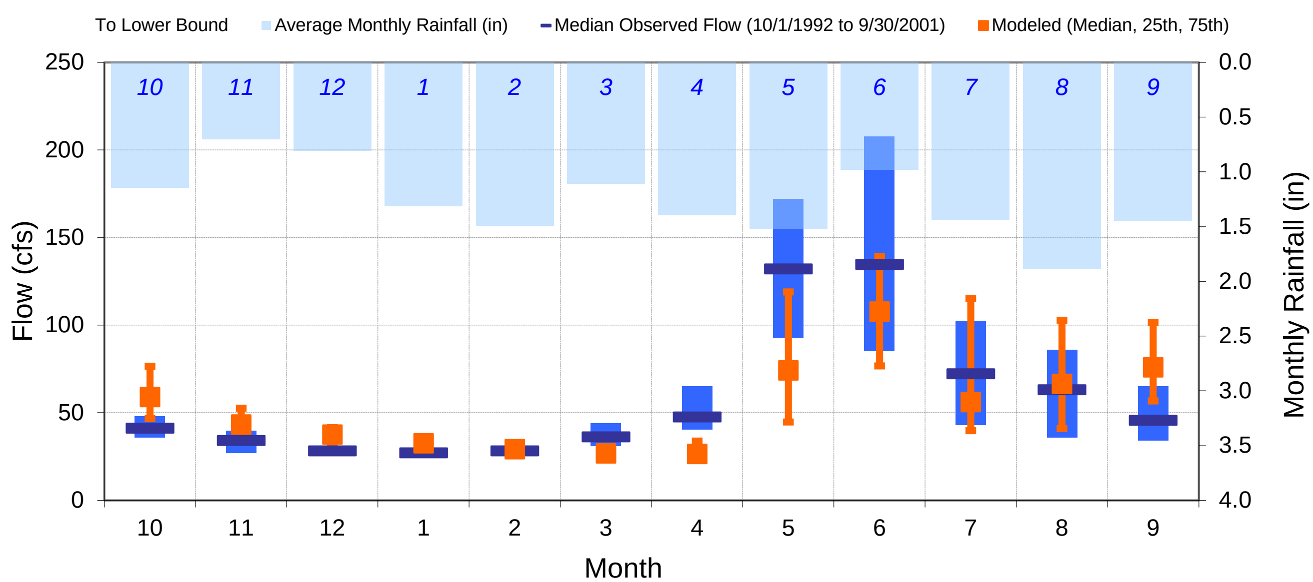


Figure 6. Seasonal medians and ranges at USGS 08227000 Saguache Creek near Saguache, CO - calibration period

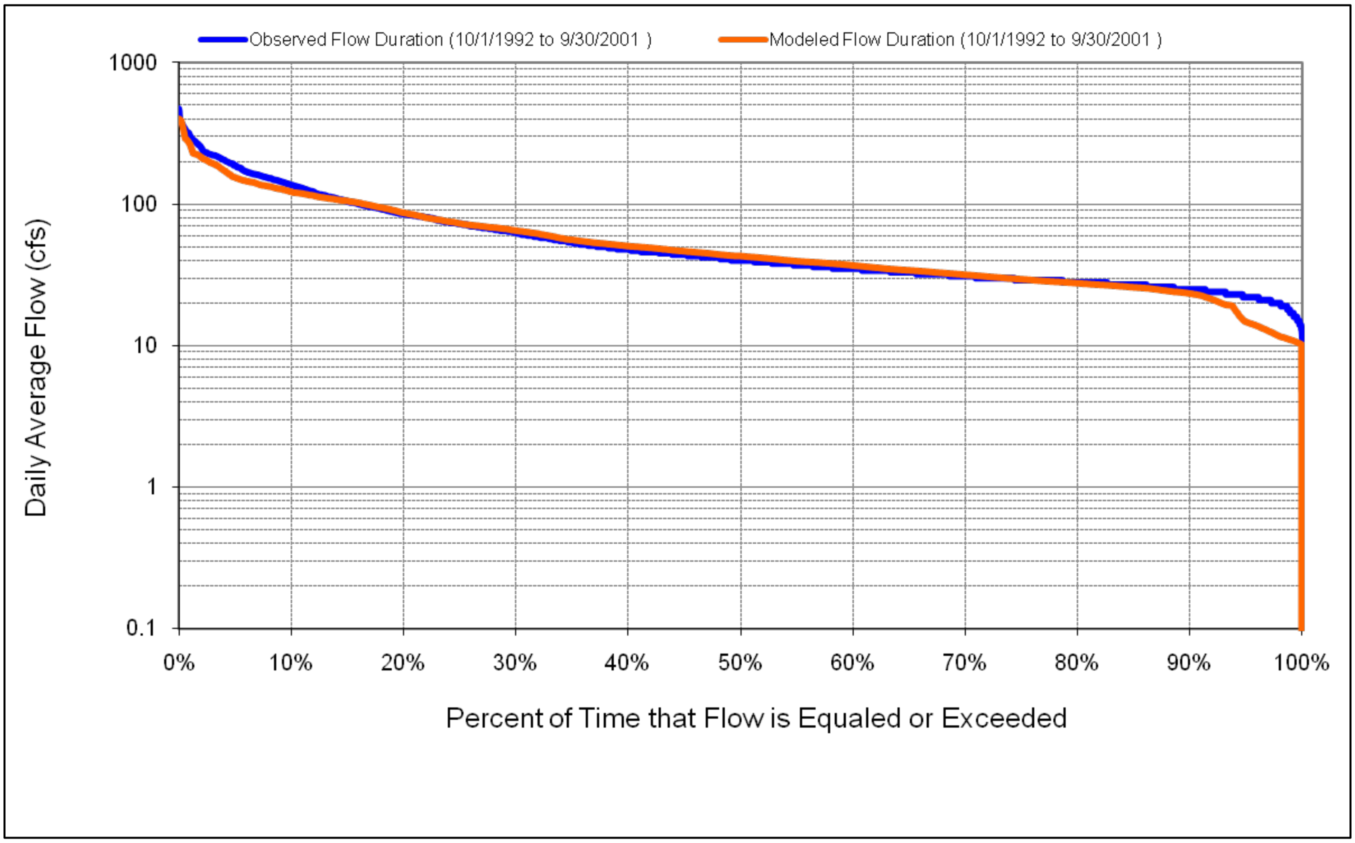


Figure 7. Flow exceedance at USGS 08227000 Saguache Creek near Saguache, CO - calibration period.

Table 6. Summary statistics USGS 08227000 Saguache Creek near Saguache, CO - calibration period

SWAT Simulated Flow		Observed Flow Gage	
REACH OUTFLOW FROM OUTLET 49 9-Year Analysis Period: 10/1/1992 - 9/30/2001 Flow volumes are (inches/year) for upstream drainage area		USGS 08227000 SAGUACHE CREEK NEAR SAGUACHE, CO Hydrologic Unit Code: 13010004 Latitude: 38.16333294 Longitude: -106.2838 Drainage Area (sq-mi): 595	
Total Simulated In-stream Flow:	**1.38**	Total Observed In-stream Flow:	**1.45**
Total of simulated highest 10% flows:	**0.41**	Total of Observed highest 10% flows:	**0.48**
Total of Simulated lowest 50% flows:	**0.33**	Total of Observed Lowest 50% flows:	**0.34**
Simulated Summer Flow Volume (months 7-9):	**0.46**	Observed Summer Flow Volume (7-9):	**0.40**
Simulated Fall Flow Volume (months 10-12):	**0.28**	Observed Fall Flow Volume (10-12):	**0.20**
Simulated Winter Flow Volume (months 1-3):	**0.16**	Observed Winter Flow Volume (1-3):	**0.18**
Simulated Spring Flow Volume (months 4-6):	**0.48**	Observed Spring Flow Volume (4-6):	**0.67**
Total Simulated Storm Volume:	**0.08**	Total Observed Storm Volume:	**0.20**
Simulated Summer Storm Volume (7-9):	**0.03**	Observed Summer Storm Volume (7-9):	**0.06**

Errors (Simulated-Observed)	*Error Statistics*	*Recommended Criteria*		
Error in total volume:	-4.92	10		
Error in 50% lowest flows:	-2.42	10		
Error in 10% highest flows:	-14.20	15		
Seasonal volume error - Summer:	14.91	30		
Seasonal volume error - Fall:	**39.93**	>> **30**		Clear
Seasonal volume error - Winter:	-8.39	30		
Seasonal volume error - Spring:	-29.24	30		
Error in storm volumes:	**-60.14**	**20**		
Error in summer storm volumes:	-47.15	50		
Nash-Sutcliffe Coefficient of Efficiency, E:	0.467	Model accuracy increases		
Baseline adjusted coefficient (Garrick), E':	0.336	as E or E' approaches 1.0		
Monthly NSE	0.526			

Hydrology Validation

Hydrology validation for the Rio Grande basin was performed for the period 10/1/1973 through 9/30/1982 at the Saguache Creek USGS station due to unavailability of data for 1983-1992. The validation period for the other stations was 1983-1992. Results are presented in Figure 8 through Figure 11 and Table 7.

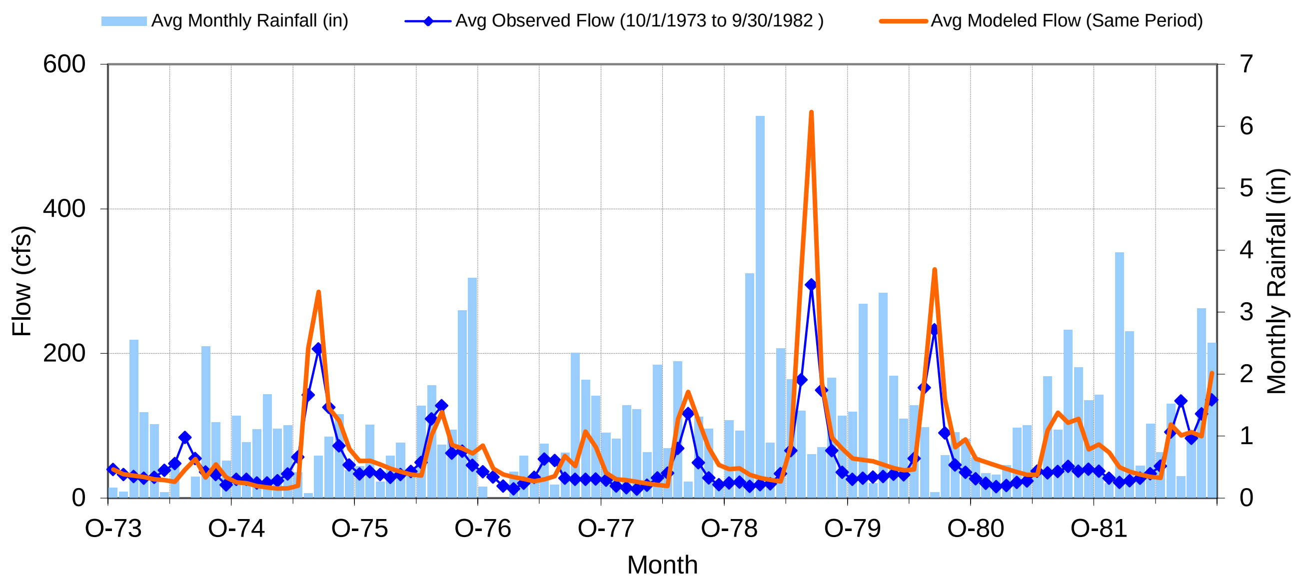


Figure 8. Mean monthly flow at USGS 08227000 Saguache Creek near Saguache, CO - validation period.

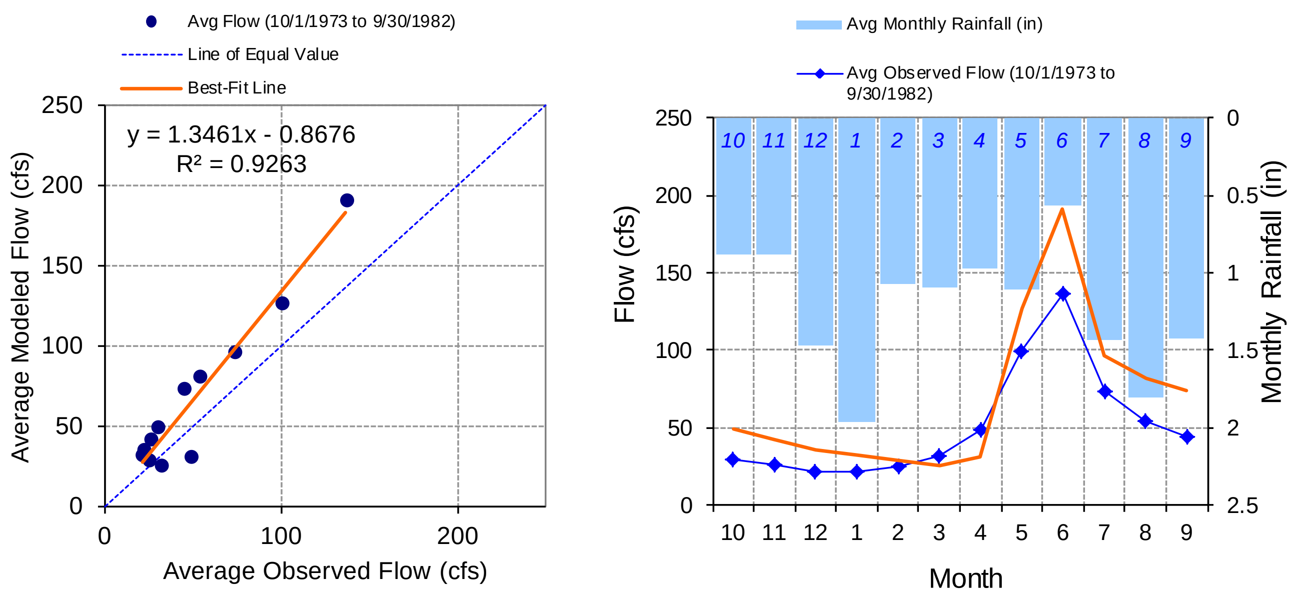


Figure 9. Seasonal regression and temporal aggregate at USGS 08227000 Saguache Creek near Saguache, CO - validation period.

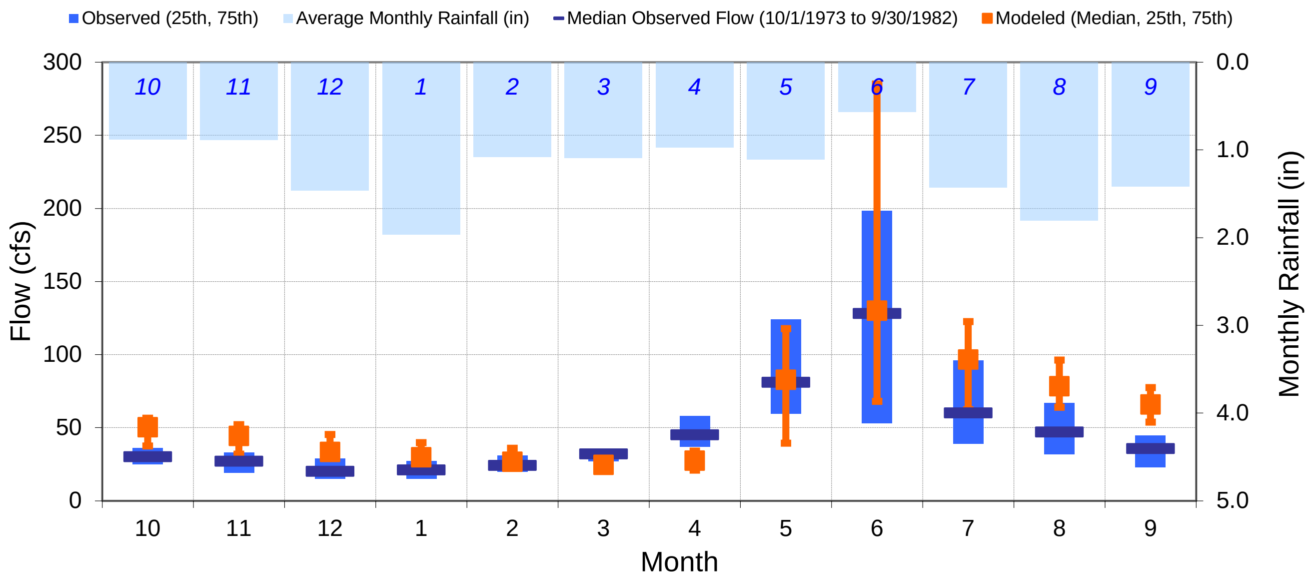


Figure 10. Seasonal medians and ranges at USGS 08227000 Saguache Creek near Saguache, CO - validation period.

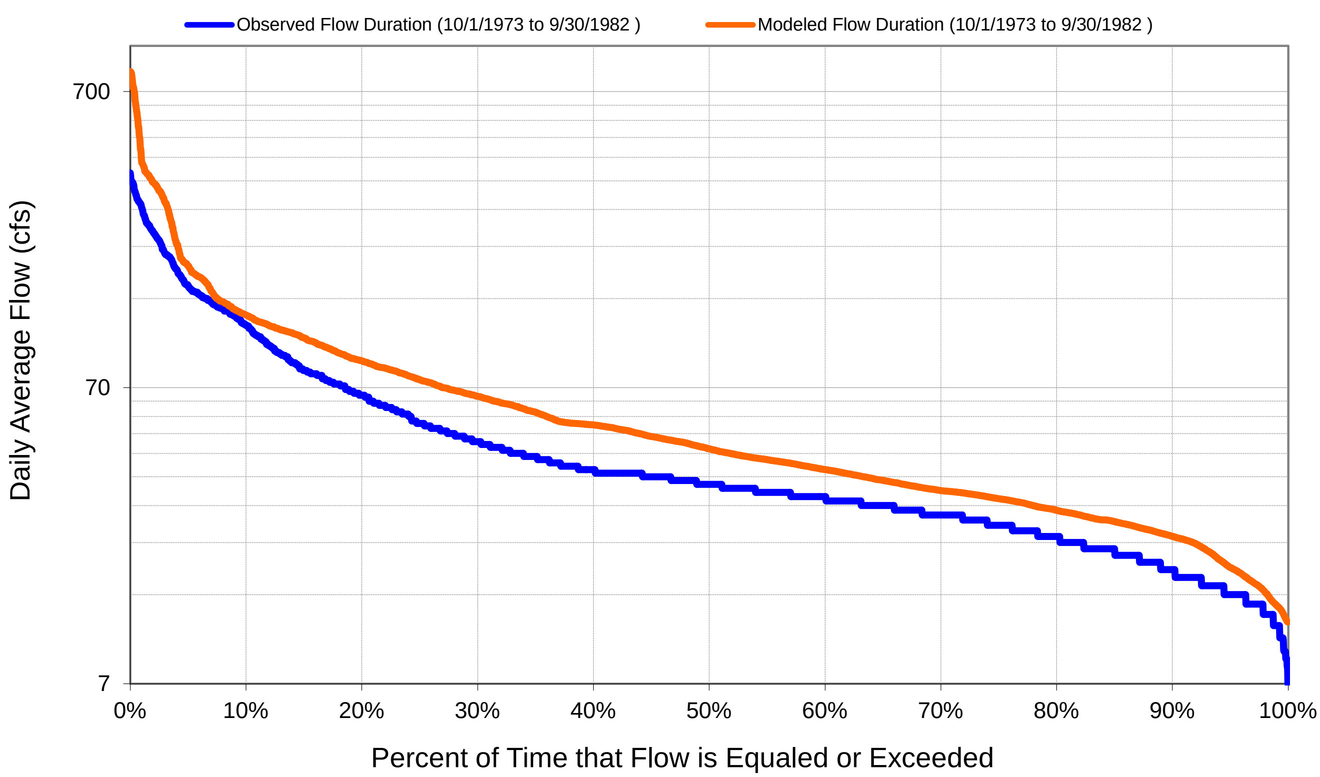


Figure 11. Flow exceedance at USGS 08227000 Saguache Creek near Saguache, CO - validation period.

Table 7. Summary statistics at USGS 08227000 Saguache Creek near Saguache, CO – validation period (percent error)

SWAT Simulated Flow		Observed Flow Gage	
REACH OUTFLOW FROM OUTLET 49 9-Year Analysis Period: 10/1/1973 - 9/30/1982 Flow volumes are (inches/year) for upstream drainage area		USGS 08227000 SAGUACHE CREEK NEAR SAGUACHE, CO Hydrologic Unit Code: 13010004 Latitude: 38.16333294 Longitude: -106.2838 Drainage Area (sq-mi): 595	
Total Simulated In-stream Flow:	**1.55**	Total Observed In-stream Flow:	**1.17**
Total of simulated highest 10% flows:	**0.57**	Total of Observed highest 10% flows:	**0.41**
Total of Simulated lowest 50% flows:	**0.33**	Total of Observed Lowest 50% flows:	**0.27**
Simulated Summer Flow Volume (months 7-9):	**0.48**	Observed Summer Flow Volume (7-9):	**0.33**
Simulated Fall Flow Volume (months 10-12):	**0.24**	Observed Fall Flow Volume (10-12):	**0.15**
Simulated Winter Flow Volume (months 1-3):	**0.16**	Observed Winter Flow Volume (1-3):	**0.15**
Simulated Spring Flow Volume (months 4-6):	**0.66**	Observed Spring Flow Volume (4-6):	**0.54**
Total Simulated Storm Volume:	**0.10**	Total Observed Storm Volume:	**0.15**
Simulated Summer Storm Volume (7-9):	**0.03**	Observed Summer Storm Volume (7-9):	**0.05**

Errors (Simulated-Observed)	*Error Statistics*	*Recommended Criteria*		
Error in total volume:	**32.99**	**10**		
Error in 50% lowest flows:	**25.16**	**10**		
Error in 10% highest flows:	**38.45**	**15**		
Seasonal volume error - Summer:	**46.11**	**30**		
Seasonal volume error - Fall:	**63.28**	>> **30**	Clear	
Seasonal volume error - Winter:	11.01	30		
Seasonal volume error - Spring:	22.61	30		
Error in storm volumes:	**-34.14**	**20**		
Error in summer storm volumes:	-46.45	50		
Nash-Sutcliffe Coefficient of Efficiency, E:	0.071	Model accuracy increases		
Baseline adjusted coefficient (Garrick), E':	0.159	as E or E' approaches 1.0		
Monthly NSE	0.313			

Hydrology Results for Larger Watershed

As described above, parameters determined for the Saguache Creek gage were assumed transferable to other areas of the watershed. In addition, calibration and validation was pursued at a total of 5 gages throughout the watershed. Calibration results are fair to poor at most gages (Table 8). The flow statistics at most gages was affected by the presence of major reservoirs on the main stem and also due to the complex interaction between surface water and groundwater in this region. Results of the validation exercise are summarized in Table 9.

Table 8. Summary statistics (percent error): all stations - calibration period

Station	Saguache Creek near Saguache CO 08227000	Rio Grande near Lobatos, NM 08251500	Rio Grande near Taos, NM 08276500	Rio Grande at Otowi Bridge, NM 08313000	Rio Grande at Albuquerque 08330000
Error in total volume:	-4.92	26.41	0.58	-32.08	-6.06
Error in 50% lowest flows:	-2.42	121.00	36.50	-12.26	38.00
Error in 10% highest flows:	-14.20	-27.38	-44.58	-61.45	-55.65
Seasonal volume error - Summer:	14.91	140.32	59.47	-12.41	40.71
Seasonal volume error - Fall:	39.93	137.69	91.40	56.44	89.73
Seasonal volume error - Winter:	-8.39	-20.45	-20.57	-18.20	9.78
Seasonal volume error - Spring:	-29.24	-41.03	-50.51	-74.12	-62.19
Error in storm volumes:	-60.14	-76.95	-80.60	-85.08	-73.33
Error in summer storm volumes:	-47.15	-60.47	-73.62	-81.09	-60.36
Daily Nash-Sutcliffe Coefficient of Efficiency, E:	0.47	-0.29	-0.08	-0.29	-0.11
Baseline adjusted coefficient (Garrick), E':	0.34	-0.26	-0.09	-0.04	-0.07
Monthly Nash-Sutcliffe Coefficient of Efficiency, E:	0.53	-0.34	-0.12	-0.34	-0.10

Table 9. Summary statistics: all stations - validation period

Station	Saguache Creek near Saguache, CO 08227000	Rio Grande near Lobatos, NM 08251500	Rio Grande near Taos, NM 08276500	Rio Grande at Otowi Bridge, NM 08313000	Rio Grande at Albuquerque 08330000
Error in total volume:	32.99	20.30	1.51	-30.04	-2.77
Error in 50% lowest flows:	25.16	160.26	62.77	7.42	93.64
Error in 10% highest flows:	38.45	-53.82	-57.80	-64.33	-47.39
Seasonal volume error - Summer:	46.11	354.31	140.26	29.36	50.54
Seasonal volume error - Fall:	63.28	150.71	112.77	69.62	132.95
Seasonal volume error - Winter:	11.01	-11.36	-13.42	-27.66	-7.73
Seasonal volume error - Spring:	22.61	-57.22	-58.06	-75.28	-61.01
Error in storm volumes:	-34.14	-80.42	-80.47	-85.28	-76.43
Error in summer storm volumes:	-46.45	-69.42	-73.25	-85.39	-76.27
Daily Nash-Sutcliffe Coefficient of Efficiency, E:	0.07	-0.17	-0.12	-0.29	-0.23
Baseline adjusted coefficient (Garrick), E':	0.16	-0.25	-0.13	0.00	-0.09
Monthly Nash-Sutcliffe Coefficient of Efficiency, E:	0.31	-0.18	-0.13	-0.33	-0.26

Water Quality Calibration and Validation

Initial calibration and validation of water quality was done at the Rio Grande near Taos, NM (USGS 08276500) using 1985-2003 for calibration and 1973-1984 for validation. As with hydrology, calibration was performed on the later period as this better reflects the land use included in the model. The start of the validation period is constrained by data availability.

Calibration adjustments for sediment focused on the following parameters:

- SPCON (Linear parameters for estimating maximum amount of sediment that can be re-entrained during channel sediment routing)
- CH_COV (Channel cover factor)
- CH_EROD (Channel erodibility factor)
- SPEXP (exponent parameter for calculating sediment re-entrained during channel sediment routing)

Simulated and estimated sediment loads at the Rio Grande near Taos (USGS 08276500) station for both the calibration and validation periods are shown in Figure 12 and statistics for the two periods are provided separately in Table 10. The key statistic in the table is the relative percent error, which shows the error in the prediction of monthly load normalized to the estimated load. The table also shows the relative average absolute error, which is the average of the relative magnitude of errors in individual monthly load predictions. This number is inflated by outlier months in which the simulated and estimated loads differ by large amounts (which may be as easily due to uncertainty in the estimated load due to limited data as to problems with the model) and the third statistic, the relative median absolute error, is likely more relevant and shows better agreement.

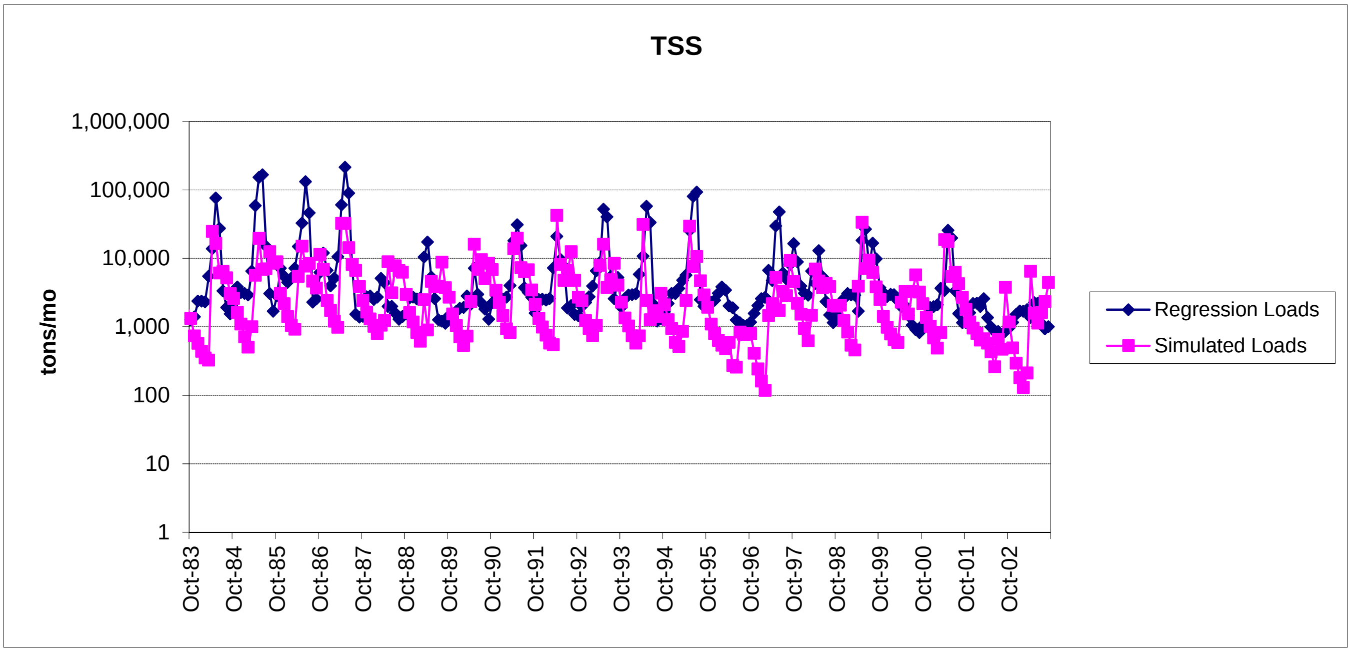


Figure 12. Fit for monthly load of TSS at USGS 08276500 Rio Grande near Taos, NM.

Table 10. Model fit statistics (observed minus predicted) for monthly sediment loads using stratified regression at USGS 08276500 Rio Grande near Taos, NM

Statistic	Calibration period (1985-2001)	Validation period (1972-1984)
Relative Percent Error	57.3%	41%
Relative Average Absolute Error	82%	69%
Relative Median Absolute Error	22.1%	19.7%

Calibration adjustments for total phosphorus and total nitrogen focused on the following parameters:

- PHOSKD (Phosphorus soil partitioning coefficient)
- RS2 (benthic source rate for dissolved phosphorus in the reach [mg P/m2*day])
- RS3 (benthic source rate for NH4-N in the reach [mg N/m2*day])
- RS4 (rate coefficient for organic N settling in the reach [day-1])
- RS5 (organic phosphorus settling rate in the reach [day-1])
- BC1 (rate constant for biological oxidation of NH4 to NO2 in the reach [day-1])
- BC2 (rate constant for biological oxidation of NO2 to NO3 in the reach [day-1])
- BC4 (rate constant for mineralization of organic P to dissolved P in the reach [day-1])
- MUMAX (maximum specific algal growth rate [day-1])

Results for the phosphorus simulation are shown in Figure 13 and Table 11. Results for the nitrogen simulation are shown in Figure 14 and Table 12. The model fit is generally weak due to problems in simulating the details of the hydrograph.

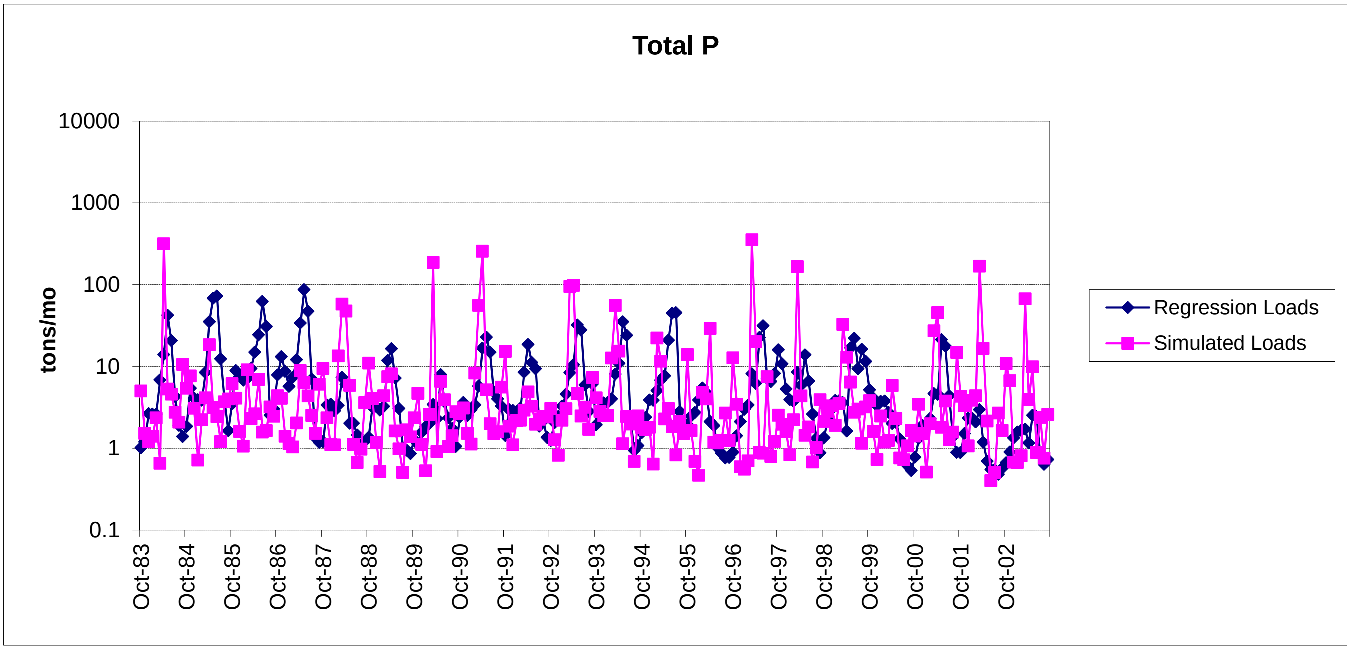


Figure 13. Fit for monthly load of total phosphorus at USGS 08276500 Rio Grande near Taos, NM.

Table 11. Model fit statistics (observed minus predicted) for monthly phosphorus loads using stratified regression at USGS 08276500 Rio Grande near Taos, NM

Statistic	Calibration period (1985-2003)	Validation period (1973-1984)
Relative Percent Error	-46.9%	-653.98%
Average Absolute Error	180%	773%
Median Absolute Error	32.1%	45%

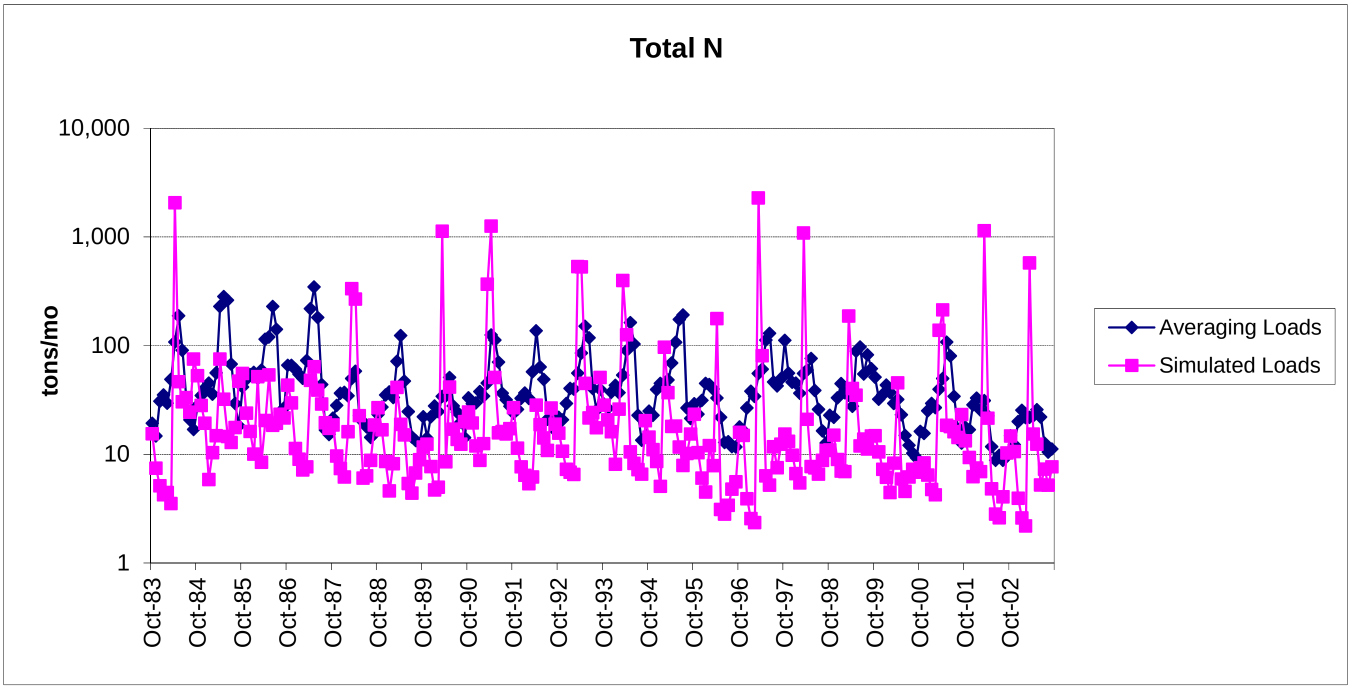


Figure 14. Fit for monthly load of total nitrogen at USGS 08276500 Rio Grande near Taos, NM.

Table 12. Model fit statistics (observed minus predicted) for monthly total nitrogen loads using averaging estimator at USGS 08276500 Rio Grande near Taos, NM

Statistic	Calibration period (1985-2003)	Validation period (1973-1984)
Relative Percent Error	-28.3%	-909.1%
Average Absolute Error	155%	996%
Median Absolute Error	46.6%	58.5%

Water Quality Results for Larger Watershed

As with hydrology, the SWAT model parameters used to calibrate at the USGS 08276500 Rio Grande near Taos, NM for water quality were directly transferred to other portions of the watershed. Application of the SWAT model without spatial adjustments resulted in relatively large errors in predicting loads and concentrations at some stations. Summary statistics for the SWAT water quality calibration and validation at other stations in the watershed are provided in Table 13 and Table 14.

Table 13. Summary statistics for water quality at all stations – calibration period 1985-2003

Station	Saguache Creek near Saguache, CO 08227000	Rio Grande near Lobatos, NM 08251500	Rio Grande near Taos, NM 08276500	Rio Grande at Otowi Bridge, NM 08313000	Rio Grande at Albuquerque 08330000
Relative Percent Error TSS Load	20.2%	55.0%	57.3%	98.1%	95.6%
Relative Percent Error TP Load	93.0%	-198.0%	-46.9%	42.2%	-85.1%
Relative Percent Error TN Load	77.8%	-193.6%	-28.3%	30.4%	-41.3%

Table 14. Summary statistics for water quality at all stations – validation period 1973-1984

Station	Saguache Creek near Saguache, CO 08227000	RioGrande near Lobatos, NM 08251500	RioGrande near Taos, NM 08276500	RioGrande at Otowi Bridge, NM 08313000	RioGrande at Albuquerque 08330000
Relative Percent Error TSS Load	-63.9%	55.6%	41.0%	97.6%	94.1%
Relative Percent Error TP Load	86.80%	-708.19%	-653.98%	-151.77%	9.41%
Relative Percent Error TN Load	44.1%	-1093.7%	-909.1%	-411.8%	-26.7%

References

Tetra Tech. 1999. Improving Point Source Loadings Data for Reporting National Water Quality Indicators. Final Technical Report prepared for U.S. Environmental Protection Agency, Office of Wastewater Management, Washington, DC, by Tetra Tech, Inc., Fairfax, VA.

USEPA (United States Environmental Protection Agency). 2008. Using the BASINS Meteorological Database (Version 2006). BASINS Technical Note 10. Office of Water, U.S. Environmental Protection Agency, Washington, DC. http://water.epa.gov/scitech/datait/models/basins/upload/2009_04_13_BASINSs_tecnote10.pdf (Accessed June, 2009).

Appendix R
Model Configuration, Calibration and Validation

Basin: Sacramento River (Sac)

Contents

Tables

Figures

Watershed Background

The Sacramento River basin was selected as one of the 15 non-pilot application watersheds for the 20 Watershed study. Watershed modeling for the non-pilot areas is accomplished using the SWAT model only, and model calibration and validation results are presented in abbreviated form.

Water Body Characteristics

The Sacramento River is the largest river in California, originating from eastern slopes of the Klamath Mountains and emptying into Suisun Bay (an arm of the San Francisco Bay) and eventually into the Pacific Ocean.

The Sacramento River in northern California is vital to the state's economy and for providing freshwater flow to the San Francisco Bay. Lake Shasta impounds the mainstem and is subject to complex operational rules. This study considers only the portion of the Sacramento River basin from Lake Shasta to just before the confluence with the Feather River (Figure 1). Information was not available for this study to represent changes in reservoir operations in response to climate change. Lake Shasta outflow time series were thus considered a fixed upstream boundary condition. The resulting model area contains over 8,300 mi^2 in 11 HUC8s, all within HUC 1802.

The average annual precipitation in the entire watershed ranges from 18 in/yr near Sacramento to about 75 in/yr at the highest elevations, mostly occurring from November through March. Snow melt is the major source of flow for the rivers of the watershed.

The Sacramento River is a major source of drinking water for residents of northern and southern California, and is a principal source of irrigation water for Sacramento and San Joaquin Valley farmers. The land uses in the valley portion of the Sacramento River basin model area are dominated by agriculture, which makes up 22 percent of the model area. The Sacramento Valley supports a diverse agricultural economy, much of which depends on the availability of irrigation water. Dairy products and crops including rice, fruits and nuts, tomatoes, sugar beets, corn, alfalfa, and wheat are important agricultural commodities. The larger cities in the watershed, located in the Sacramento Valley, include Chico and Redding, with developed land occupying a little over 4 percent of the watershed. The remaining areas are primarily forest and range.

Agriculture is the largest consumer of water in the basin. Up to about 6 million acre-feet per year of water also is exported from the basin, principally to areas in southern California. Part of the runoff from winter rains and spring snowmelt is stored in reservoirs and released during the normally dry summer months. Most of the water supplies are derived from these reservoirs. The water is mainly used to provide irrigation water to the Sacramento and San Joaquin Valley agricultural communities, and to provide drinking water to Central Valley residents and residents of southern California, and to protect water quality of the delta of the Sacramento and San Joaquin Rivers.

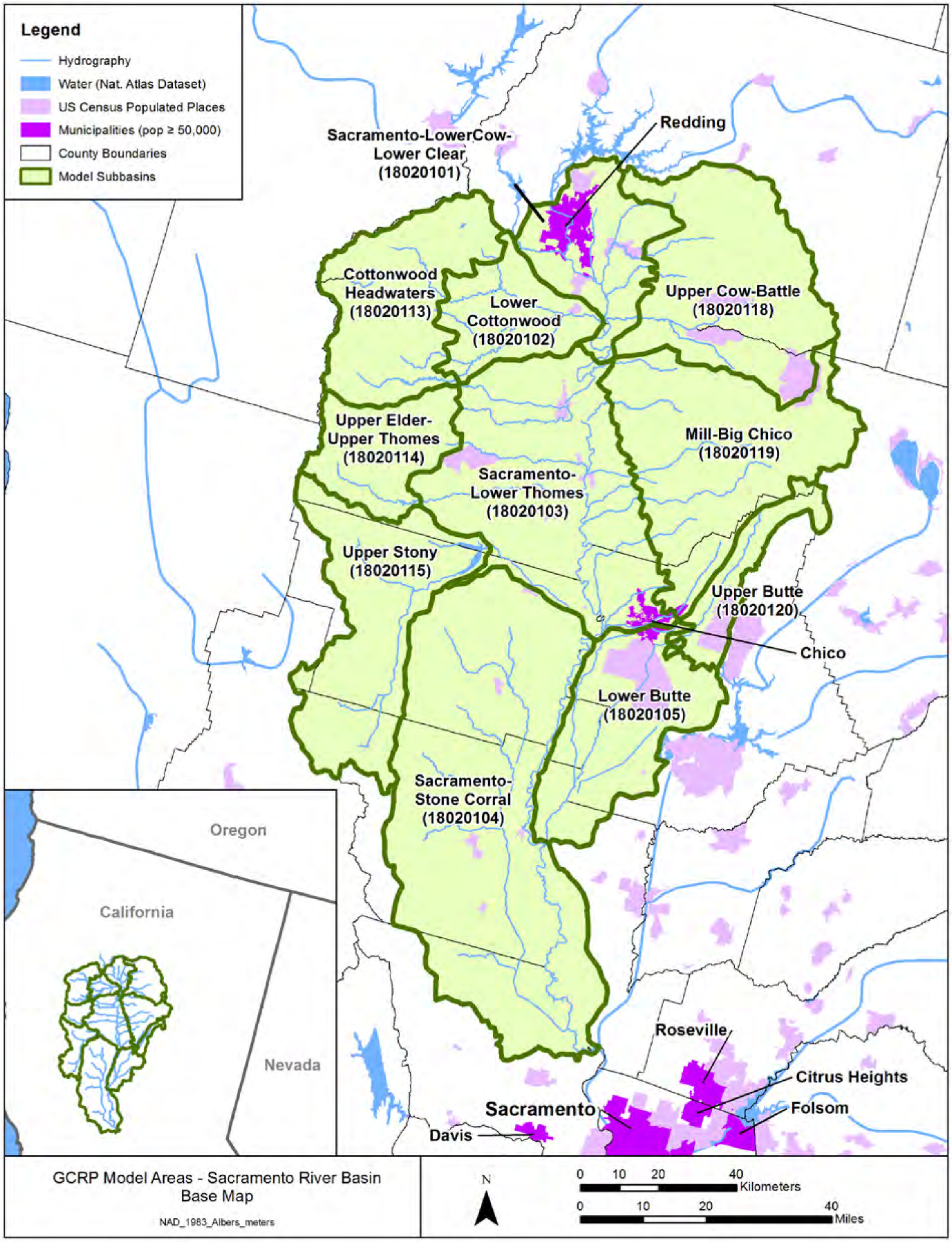


Figure 1. Location of the Sacramento River watershed.

Soil Characteristics

Soils in the watershed, as described in STATSGO soil surveys, fall primarily into hydrologic soil groups (HSGs) D (low infiltration capacity and high runoff potential) and B (moderately high infiltration capacity; correspondingly, moderately low runoff potential). SWAT uses information drawn directly from the soils data layer to populate the model.

Land Use Representation

Land use/cover in the watershed is based on the 2001 National Land Cover Database (NLCD) coverage and is predominantly range grass and shrubland, which together occupy 48 percent of the area. The other dominate uses are forested land and agriculture, each of which covers about 22 percent of the watershed (Figure 2). NLCD land cover classes were aggregated according to the scheme shown in Table 1 for representation in the 20 Watershed model. SWAT uses the built-in hydrologic response unit (HRU) overlay mechanism in the ArcSWAT interface. SWAT HRUs are formed from an intersection of land use and SSURGO major soils. The distribution of land use in the watershed is summarized in Table 2.

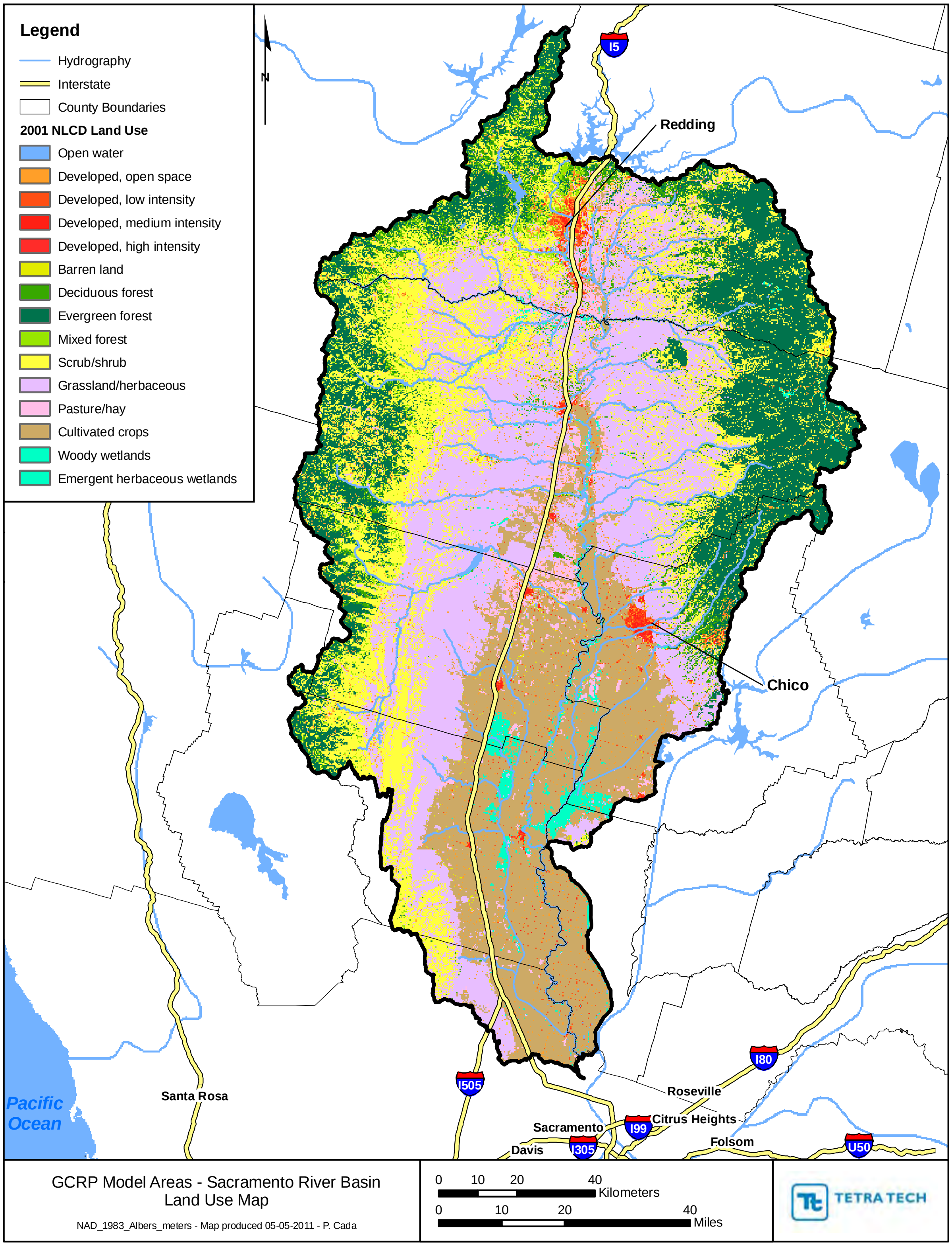


Figure 2. Land use in the Sacramento River watershed.

Table 1. Aggregation of NLCD land cover classes

NLCD Class	Comments	SWAT class
11 Water	Water surface area usually accounted for as reach area	WATR
12 Perennial ice/snow		WATR
21 Developed open space		URLD
22 Dev. Low Intensity		URMD
23 Dev. Med. Intensity		URHD
24 Dev. High Intensity		UIDU
31 Barren Land		SWRN
41 Forest	Deciduous	FRSD
42 Forest	Evergreen	FRSE
43 Forest	Mixed	FRST
51-52 Shrubland		RNGB
71-74 Herbaceous Upland		RNGE
81 Pasture/Hay		HAY
82 Cultivated		AGRR
91-97 Wetland	Emergent & woody wetlands	WETF, WETL, WETN
98-99 Wetland	Aquatic bed wetlands (not emergent)	WATR

Table 2. Land use distribution for the Sacramento River watershed (2001 NLCD) (mi^2)

HUC 8 watershed	Open water	Developed[a]				Barren land	Forest	Shrubland/ Grassland	Pasture/ Hay	Cultivated	Wetland	Total
		Open space	Low density	Medium density	High density							
Sacramento-Stone Corral **18020104**	11.9	54.2	19.1	7.7	1.4	11.9	3.1	653.8	43.8	1,018.1	67.0	**1,891.8**
Upper Stony **18020115**	10.0	22.3	0.8	0.3	0.1	7.2	203.0	518.5	5.5	4.2	3.3	**775.5**
Clear Creek-Sacramento River **18020151**	0.5	10.1	1.1	0.2	0.0	0.6	188.6	204.0	19.2	4.4	0.9	**429.5**
Cow Creek 18020152	0.8	24.5	1.4	0.5	0.1	2.2	251.3	636.7	12.7	0.4	12.4	**943.1**
Cottonwood Creek **18020153**	0.4	4.1	0.2	0.0	0.0	1.7	223.3	134.0	1.7	0.9	2.9	**369.2**
Battle Creek-Sacramento River **18020154**	8.9	42.7	16.9	9.6	2.2	1.4	301.4	262.8	22.7	9.5	4.6	**682.7**
Paynes Creek-Sacramento River **18020155**	2.8	13.7	2.6	2.2	0.6	1.2	35.1	356.1	3.6	2.2	3.6	**423.6**
Thomes Creek-Sacramento River **18020156**	2.8	26.0	3.3	1.0	0.3	7.4	257.2	625.7	30.6	48.5	5.9	**1,008.7**
Big Chico Creek-Sacramento River 18020157	2.9	23.6	10.9	8.5	1.5	4.3	236.2	469.7	37.4	136.1	11.1	**942.4**
Butte Creek **18020158**	1.6	27.2	10.4	5.2	1.4	2.4	162.2	158.9	12.5	385.2	52.3	**819.4**
Cache Slough-Sacramento River **18020163**	0.8	1.1	0.2	0.2	0.0	0.1	0.0	0.1	0.5	25.4	1.2	**29.6**
Total	**43.6**	**249.6**	**66.8**	**35.2**	**7.7**	**40.3**	**1,861.5**	**4,020.2**	**190.3**	**1,635.0**	**165.2**	**8,315.5**

[a]The percent imperviousness applied to each of the developed land uses is as follows: open space (5.95%), low density (30.02%), medium density (55.41%), and high density (81.20%).

Point Sources

There are numerous point source discharges in the watershed (Table 3). These are represented at long-term average flows, without accounting for changes over time or seasonal variations.

Table 3. Major point source discharges in the Sacramento River watershed

NPDES ID	Name	Design flow (MGD)	Observed flow (MGD) (1991-2006 average)
CA0079081	CHICO, CITY OF	9.00	4.17
CA0004821	PACTIV CORP	2.70	1.97
CA0077704	ANDERSON, CITY OF	2.00	1.42
CA0079731	REDDING, CITY OF	8.80	8.01
CA0078034	WILLOWS, CITY OF	1.12	0.91

Most of these point sources have reasonably good monitoring for total suspended solids (TSS), but not for total phosphorus and total nitrogen. The point sources were initially represented in the model with the median of reported values for the constituents (total phosphorus, total nitrogen, and TSS) and an assumed total nitrogen concentration of 11.2 mg/L and assumed total phosphorus concentration of 7.0 mg/L for secondary treatment facilities (Tetra Tech 1999). However, in cases where point source contribution was deemed unusually high, assumed values were substituted with the average concentration of the reported data.

Meteorological Data

The required meteorological time series for the 20 Watershed SWAT simulations are precipitation and air temperature. The 20 Watershed simulations do not include water temperature simulation and use a degree-day method for snowmelt. SWAT estimates Penman-Monteith potential evapotranspiration using a statistical weather generator for inputs other than temperature and precipitation. These meteorological time series are drawn from the BASINS4 Meteorological Database (USEPA 2008), which provides a consistent, quality-assured set of nationwide data with gaps filled and records disaggregated. Scenario application requires simulation over 30 years, so the available stations are those with a common 30-year period of record (or one that can be filled from an approximately co-located station) that covers the year 2001. A total of 28 precipitation stations were identified for use in the Sacramento River watershed model with a common period of record of 10/1/1971-9/30/2001 (Table 4). Temperature records are sparser; where these are absent temperature is taken from nearby stations with an elevation correction.

Table 4. Precipitation stations for the Sacramento River watershed model

COOP ID	Name	Latitude	Longitude	Temperature	Elevation (ft)
40546	CA040546	40.4000	-122.1500	No	128
41159	CA041159	39.9372	-121.3140	No	1890
41700	CA041700	40.3034	-121.2420	Yes	4531
41715	CA041715	39.6911	-121.8210	Yes	184
41806	CA041806	38.9240	-122.5670	Yes	1348
41907	CA041907	40.4000	-122.1430	No	420
41948	CA041948	39.1806	-122.0290	Yes	49
42084	CA042084	39.8261	-123.0840	No	1512
42402	CA042402	39.8739	-121.6170	Yes	2710
42640	CA042640	39.3593	-122.5170	Yes	1204
43791	CA043791	40.3636	-122.9650	No	2749
45311	CA045311	40.5419	-121.5760	Yes	5751
45385	CA045385	39.1459	-121.5850	Yes	56
45679	CA045679	40.3458	-121.6090	Yes	4875
46194	CA046194	38.9261	-121.5440	No	43
46506	CA046506	39.7459	-122.1990	Yes	253
46521	CA046521	39.5179	-121.5530	Yes	171
46685	CA046685	39.7540	-121.6240	Yes	1749
46726	CA046726	39.8876	-122.5530	No	755
47292	CA047292	40.1519	-122.2530	Yes	354
47581	CA047581	40.7957	-121.9350	No	2100
48135	CA048135	40.7142	-122.4160	Yes	1076
48580	CA048580	39.3754	-122.5460	No	1171
48587	CA048587	39.5862	-122.5340	Yes	801
49390	CA049390	40.4569	-121.8650	No	2221
49621	CA049621	40.6117	-122.5280	Yes	1296
49699	CA049699	39.5231	-122.3050	Yes	233
49781	CA049781	38.6829	-121.7940	Yes	69

Watershed Segmentation

The Sacramento River basin was divided into 71 subwatersheds for the purposes of modeling (Figure 3). The model doesn't encompass the complete watershed. The Upper Sacramento and Pit Rivers join in Lake Shasta, a huge reservoir formed by Shasta Dam. The watershed area considered for this 20 Watershed study is the drainage between downstream of Shasta to the confluence of Feather River and Sacramento River. The outflow from Lake Shasta was considered as a boundary condition. No specific site was considered as a calibration focus area.

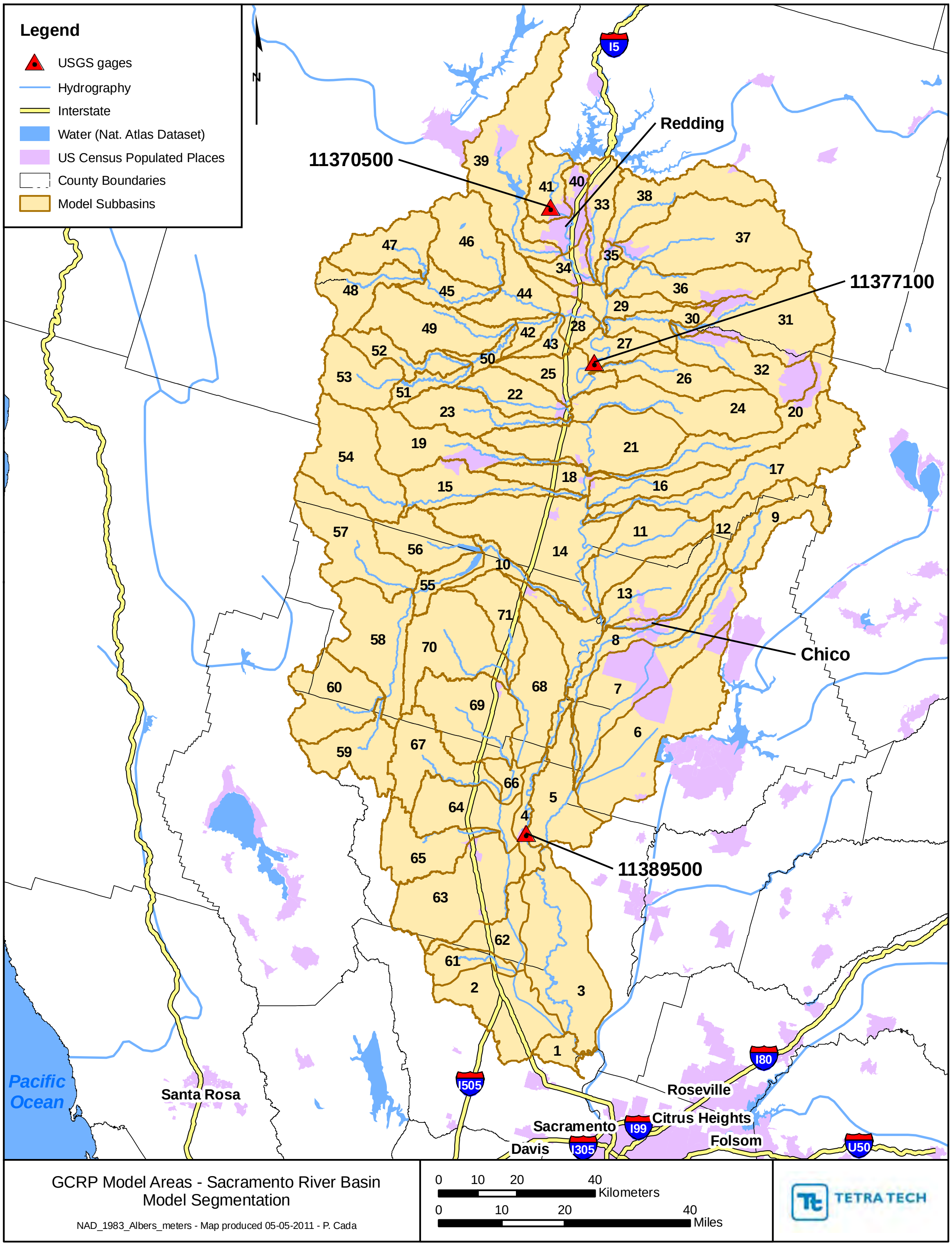


Figure 3. Model segmentation and USGS stations utilized for the Sacramento River watershed.

Calibration Data and Locations

There are three gages at which long term streamflow data were available (Table 5). All the three gages are on the main stem of Sacramento River. As mentioned earlier, the watershed area considered for this study is the drainage between downstream of Shasta to the confluence of Feather River and Sacramento River. Therefore, no specific site was chosen for initial calibration. The results at the gaging site on Sacramento River above Bend Bridge near Red Bluff are presented in detail.

Table 5. Calibration and validation locations in the Sacramento River watershed

Station name	USGS ID	Drainage area (mi^2)	Hydrology calibration	Water quality calibration
Sacramento River above Bend Bridge near Red Bluff, CA	11377100	8,900	X	X
Sacramento River at Colusa, CA	11389500	12,090	X	
Sacramento River at Keswick, CA	11370500	6,468	X	

The model hydrology calibration period was set to Water Years 1992-2001 (within the 30-year period of record for modeling). Hydrologic validation was then performed on Water Years 1983-1992. Unfortunately, the Sacramento River watershed had no good water quality data. Water quality data available at the Keswick station were used as a point source in the simulation because of the lack of these data from Shasta Dam, unlike the outflow data availability. Due to very limited data at Colusa station, only Bend Bridge station was used for water quality calibration. Although sediment data were available for a longer period, the nutrient data were again limited. A period from 1997-2001 was used for calibration and 1973-1996 was used for validation.

SWAT Modeling

Assumptions

The reservoirs simulated in this study include Black Butte, East Park, Stony Gorge, and Whiskeytown dams. Pertinent reservoir information including surface area and storage at principal (normal) and emergency spillway levels for the reservoirs modeled were obtained from the National Inventory of Dams (NID) database. The SWAT model provides four options to simulate reservoir outflow: measured daily outflow, measured monthly outflow, average annual release rate for uncontrolled reservoir, and controlled outflow with target release. Keeping in view the 20 Watershed climate change impact evaluation application, it was assumed that the best representation of the reservoirs was to simulate them without supplying time series of outflow records. Therefore, the target release approach was used in the GCRP-SWAT model.

The monthly reservoir target storage was calculated based on daily reservoir storage data obtained from Department of Water Resources-California Data Exchange Center (http://cdec.water.ca.gov/selectQuery.html) and input in the reservoir input files in the model. A diversion was simulated for subwatershed 25 to represent removal of water for irrigation from the Sacramento River near Red Bluff. Elevation bands were input for selected subwatersheds to account for high altitudes.

Hydrology Calibration

A spatial calibration approach was not adopted for GCRP-SWAT modeling for the Sacramento River watershed. As no specific calibration focus area was considered, simulated results were compared with the observed flow at all three gaging stations, simultaneously.

Land Use / Soil / Slope Definition

A 5/10/5 percent threshold was used for land use/soil/slope in the SWAT model while defining the HRUs. Urban land use classes were exempted from the HRU overlay thresholds.

The parameters were adjusted within the practical range to obtain reasonable fit between the simulated and measured flows in terms of Nash-Sutcliffe modeling efficiency and the high flow and low flow components as well as the seasonal flows.

The water balance of the whole Sacramento GRCP model predicted by the SWAT model over the 30-year simulation period is as follows:

```
PRECIP =    864.7 MM
SNOW FALL =  152.06 MM
SNOW MELT =   132.35 MM
SUBLIMATION =    20.93 MM
SURFACE RUNOFF Q =   138.52 MM
LATERAL SOIL Q =  200.95 MM
TILE Q =     0.00 MM
GROUNDWATER (SHAL AQ) Q =    24.57 MM
REVAP (SHAL AQ => SOIL/PLANTS) =   74.30 MM
DEEP AQ RECHARGE =   100.46 MM
TOTAL AQ RECHARGE =  200.92 MM
TOTAL WATER YLD =   360.76 MM
PERCOLATION OUT OF SOIL =  198.01 MM
ET =    353.1 MM
PET =   1590.3MM
TRANSMISSION LOSSES =     2.50 MM
```

Hydrologic calibration adjustments focused on the following parameters:

- Curve Number
- FFCB (initial soil water storage)
- SURLAG (surface runoff lag coefficient)
- CNCOEFF (plant ET curve number coefficient)
- Baseflow factor
- GW_DELAY (groundwater delay time)
- GWQMN (threshold depth of water in the shallow aquifer for return flow to occur [mmH2O])
- RevapMN (threshold depth of water in the shallow aquifer required for "revap" or percolation to the deep aquifer to occur
- RCHRG_DP (deep aquifer percolation fraction)
- Sol_AWC (available water capacity of the soil layer, mm water/mm of soil)
- Snow parameters SFTMP, SMTMP, SMFMX and SMFMN, TIMP
- ESCO (soil evaporation compensation factor)
- CH_K2 (channel hydraulic conductivity)
- Elevation bands
- TLAPS (temperature lapse rate)

Calibration results for the Sacramento River above Bend Bridge near Red Bluff, CA (USGS 11377100) are summarized in Figures 4 through 7 and Table 6. In general, model simulated streamflows, both in magnitude and timing, compared very well with observed except some overestimation of total storm volumes, especially the summer storm volumes (Figure 4, Figure 5, Figure 6, Figure 7, and Table 6).

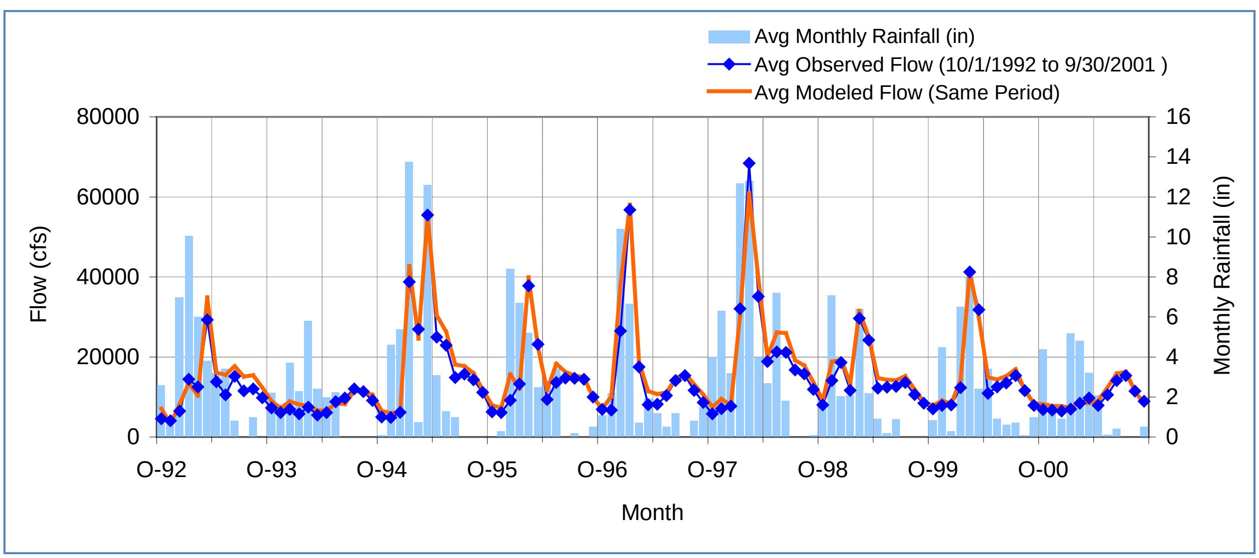


Figure 4. Mean monthly flow at USGS 11377100 Sacramento River at Bend Bridge near Red Bluff, CA – calibration period.

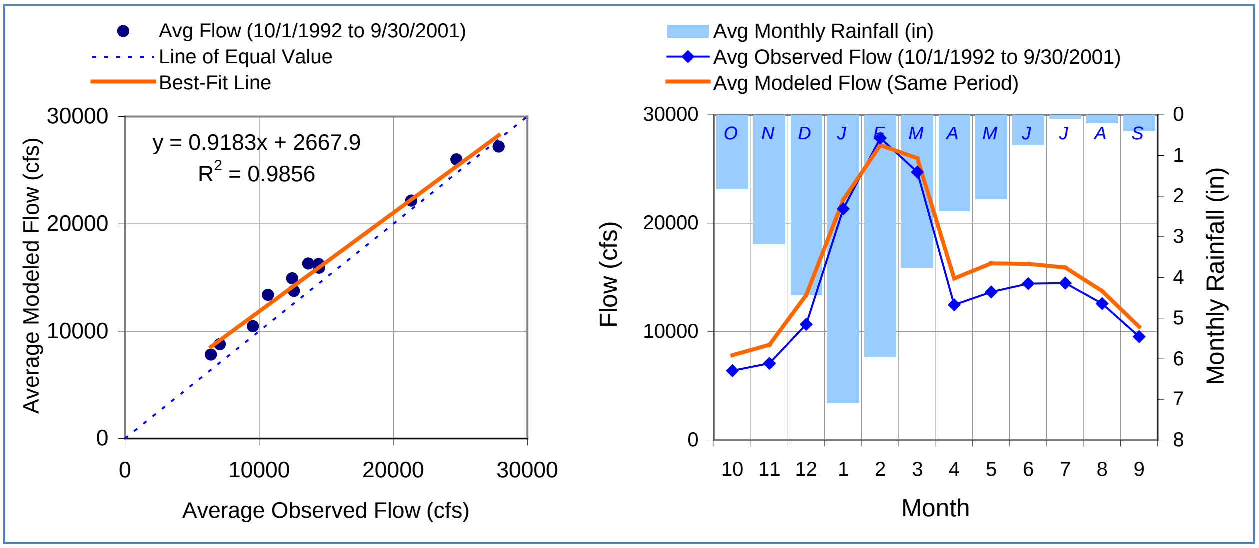


Figure 5. Seasonal regression and temporal aggregate at USGS 11377100 Sacramento River at Bend Bridge near Red Bluff, CA - calibration period.

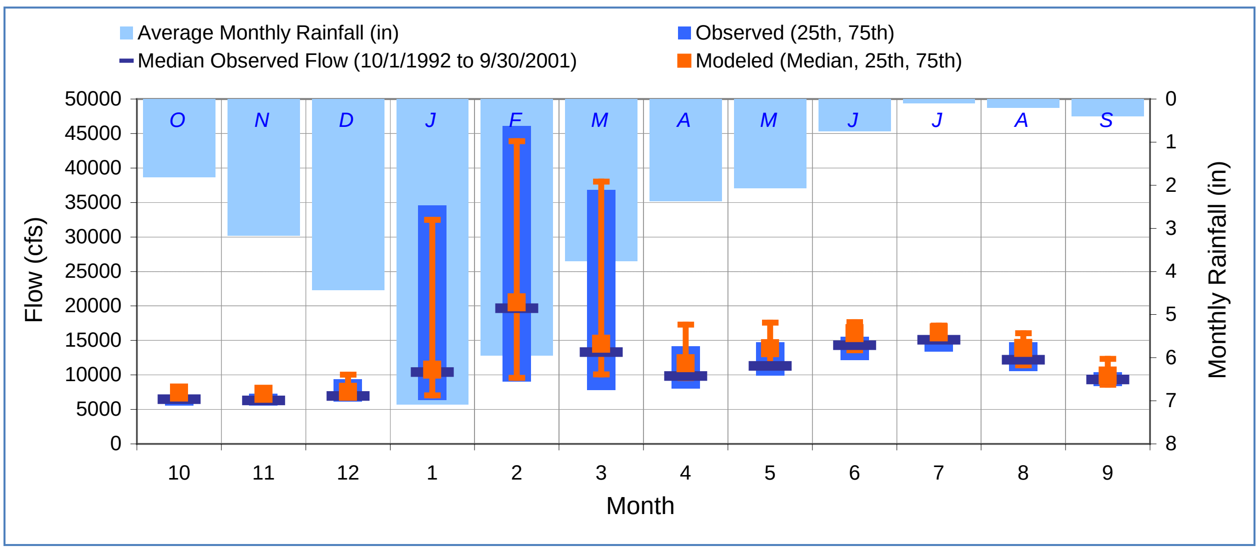


Figure 6. Seasonal medians and ranges at USGS 05317000 USGS 11377100 Sacramento River at Bend Bridge near Red Bluff, CA – calibration period.

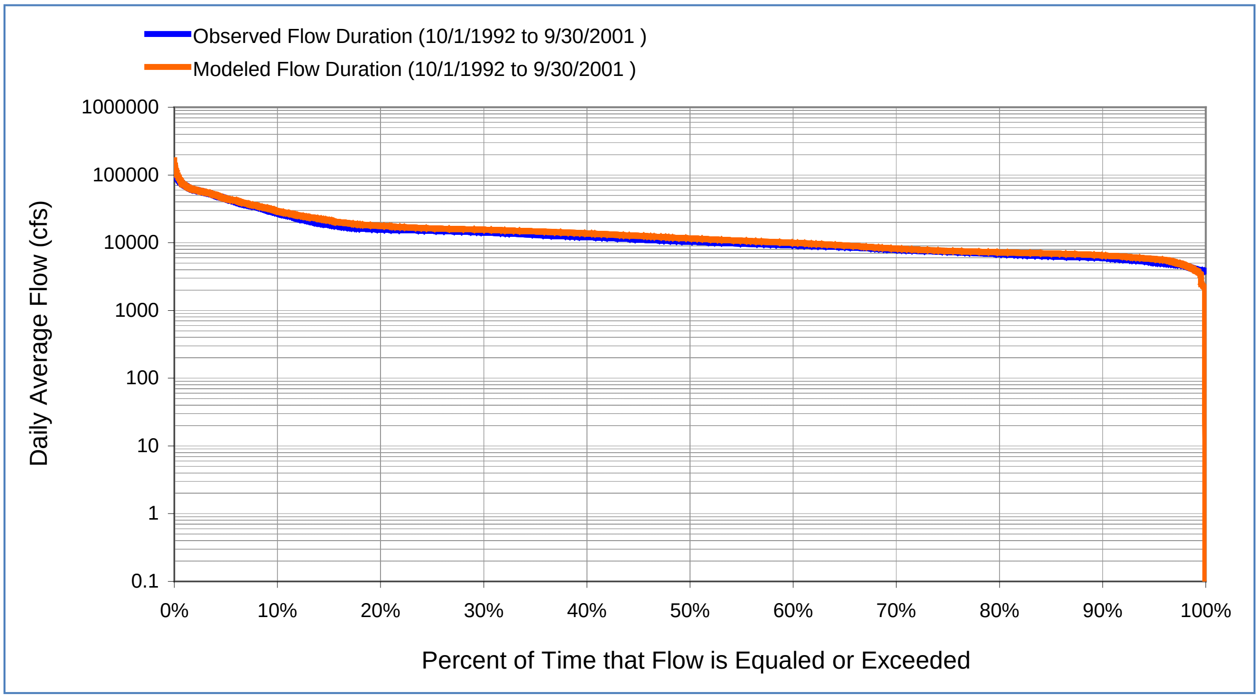


Figure 7. Flow exceedance at USGS 11377100 Sacramento River at Bend Bridge near Red Bluff, CA - calibration period.

Table 6. Summary statistics at USGS 11377100 Sacramento River at Bend Bridge near Red Bluff, CA - calibration period

SWAT Simulated Flow		Observed Flow Gage	
REACH OUTFLOW FROM OUTLET 27 9-Year Analysis Period: 10/1/1992 - 9/30/2001 Flow volumes are (inches/year) for upstream drainage area		USGS 11377100 SACRAMENTO R AB BEND BRIDGE NR RED BLUFF CA Hydrologic Unit Code: 18020103 Latitude: 40.28848836 Longitude: -122.1866645 Drainage Area (sq-mi): 8900	
Total Simulated In-stream Flow:	**24.47**	Total Observed In-stream Flow:	**22.20**
Total of simulated highest 10% flows:	**7.94**	Total of Observed highest 10% flows:	**7.47**
Total of Simulated lowest 50% flows:	**6.21**	Total of Observed Lowest 50% flows:	**5.68**
Simulated Summer Flow Volume (months 7-9):	**5.15**	Observed Summer Flow Volume (7-9):	**4.70**
Simulated Fall Flow Volume (months 10-12):	**3.85**	Observed Fall Flow Volume (10-12):	**3.10**
Simulated Winter Flow Volume (months 1-3):	**9.45**	Observed Winter Flow Volume (1-3):	**9.25**
Simulated Spring Flow Volume (months 4-6):	**6.02**	Observed Spring Flow Volume (4-6):	**5.14**
Total Simulated Storm Volume:	**6.33**	Total Observed Storm Volume:	**4.39**
Simulated Summer Storm Volume (7-9):	**0.47**	Observed Summer Storm Volume (7-9):	**0.26**

Errors (Simulated-Observed)	*Error Statistics*	*Recommended Criteria*		
Error in total volume:	**10.23**	**10**		
Error in 50% lowest flows:	9.28	10		
Error in 10% highest flows:	6.22	15		
Seasonal volume error - Summer:	9.59	30		
Seasonal volume error - Fall:	24.24 >>	30	Clear	
Seasonal volume error - Winter:	2.11	30		
Seasonal volume error - Spring:	16.99	30		
Error in storm volumes:	**43.97**	**20**		
Error in summer storm volumes:	**78.74**	**50**		
Nash-Sutcliffe Coefficient of Efficiency, E:	0.746	Model accuracy increases		
Baseline adjusted coefficient (Garrick), E':	0.625	as E or E' approaches 1.0		
Monthly NSE	0.944			

Hydrology Validation

Hydrology validation results for the station on the Sacramento River above Bend Bridge near Red Bluff, CA (USGS 11377100), performed for the period 10/1/1982 through 9/30/1992 are presented in Figures 8 throiugh 11 and Table 7. Based on the model performance statistics, it can be noted that the timing and magnitude of simulated flows, overall as well as seasonal flows were consistent with the pattern observed during the calibration period (Figure 8, Figure 9, Figure 10, Figure 11, and Table 7).

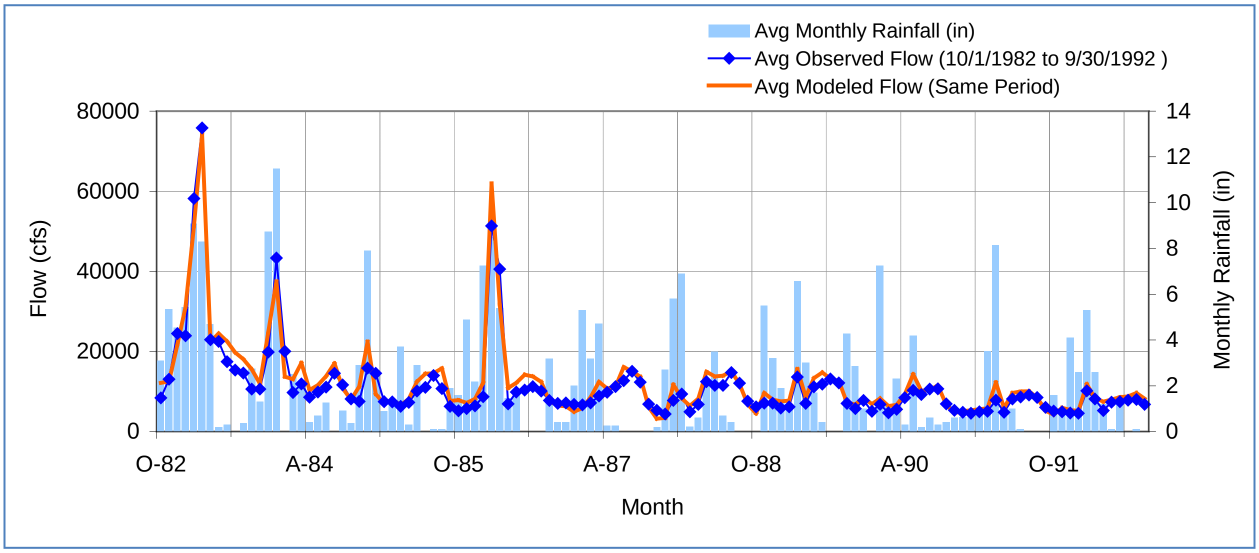


Figure 8. Mean monthly flow at USGS 11377100 Sacramento River at Bend Bridge near Red Bluff, CA – validation period.

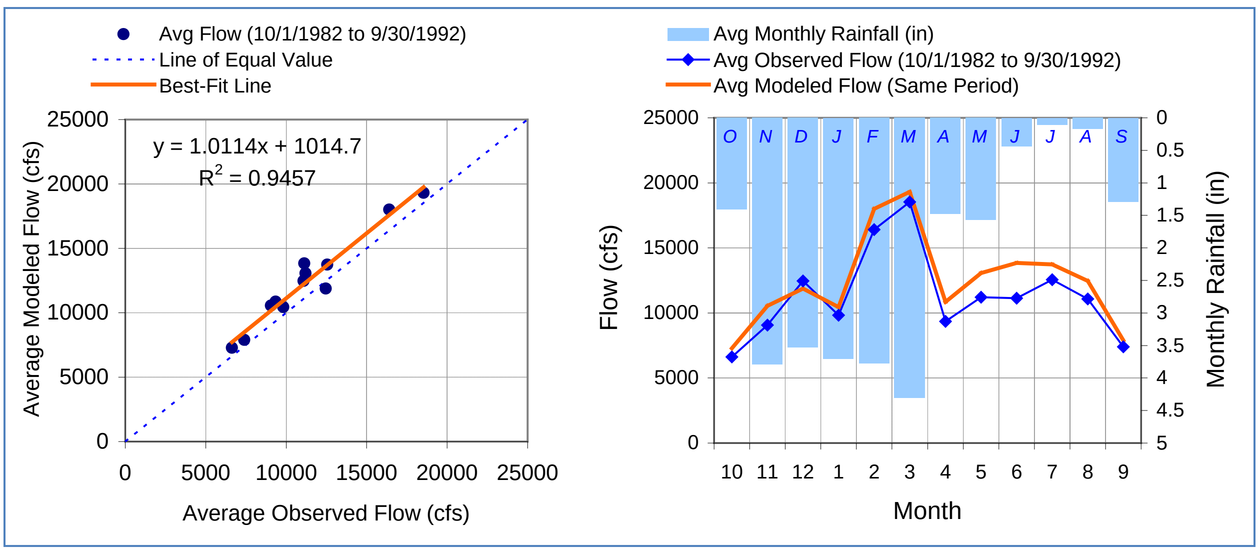


Figure 9. Seasonal regression and temporal aggregate at USGS 11377100 Sacramento River at Bend Bridge near Red Bluff, CA – validation period.

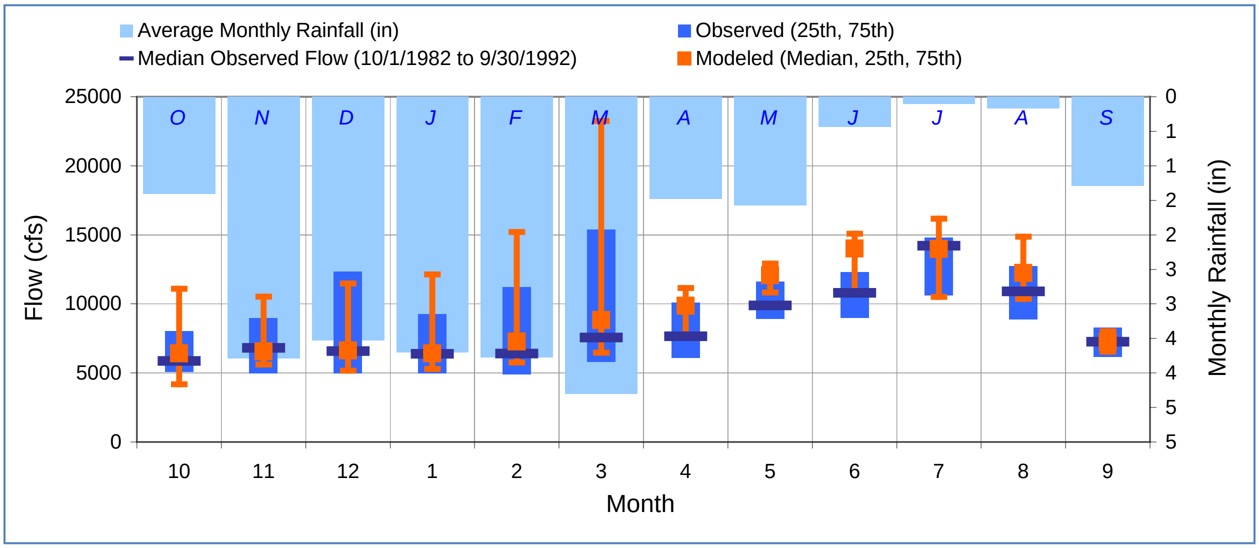


Figure 10. Seasonal medians and ranges at USGS 11377100 Sacramento River at Bend Bridge near Red Bluff, CA – validation period.

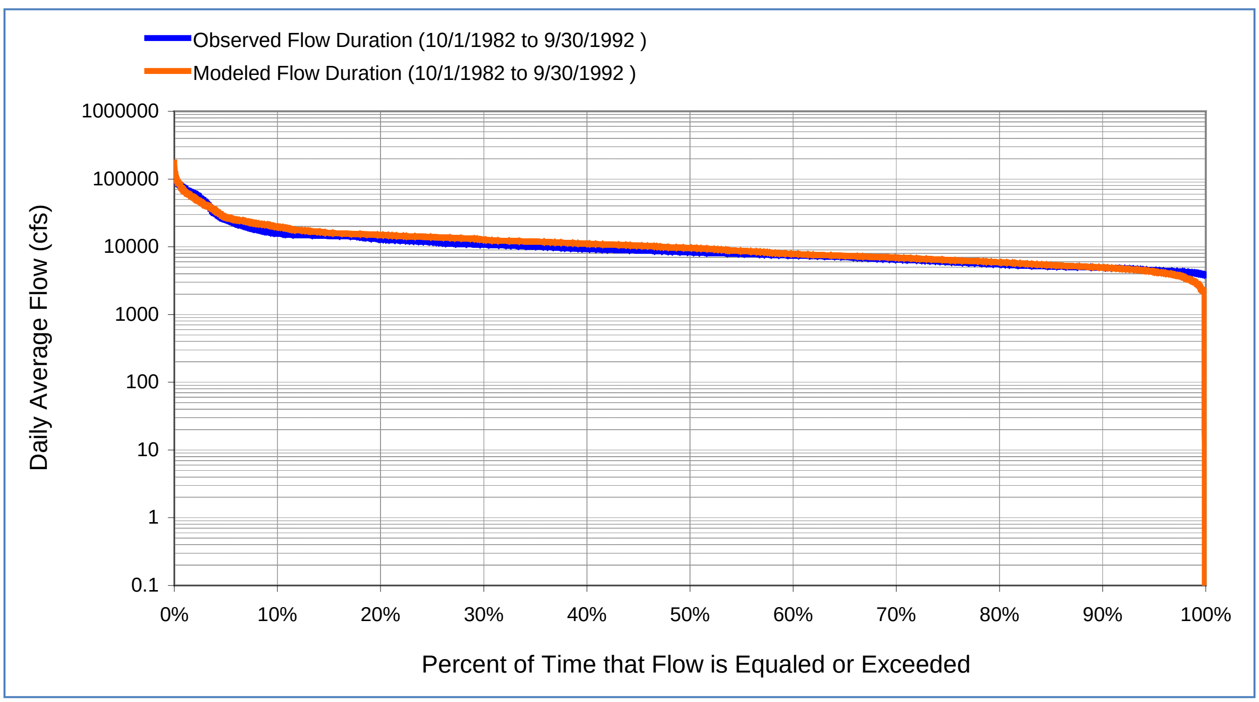


Figure 11. Flow exceedance at USGS 11377100 Sacramento River at Bend Bridge near Red Bluff, CA – validation period.

Table 7. Summary statistics at USGS 11377100 Sacramento River Bend Bridge near Red Bluff, CA – validation period

SWAT Simulated Flow		Observed Flow Gage	
REACH OUTFLOW FROM OUTLET 27 10-Year Analysis Period: 10/1/1982 - 9/30/1992 Flow volumes are (inches/year) for upstream drainage area		USGS 11377100 SACRAMENTO R AB BEND BRIDGE NR RED BLUFF CA Hydrologic Unit Code: 18020103 Latitude: 40.28848836 Longitude: -122.1866645 Drainage Area (sq-mi): 8900	
Total Simulated In-stream Flow:	**18.96**	Total Observed In-stream Flow:	**17.23**
Total of simulated highest 10% flows:	**5.87**	Total of Observed highest 10% flows:	**5.65**
Total of Simulated lowest 50% flows:	**4.93**	Total of Observed Lowest 50% flows:	**4.67**
Simulated Summer Flow Volume (months 7-9):	**4.38**	Observed Summer Flow Volume (7-9):	**3.99**
Simulated Fall Flow Volume (months 10-12):	**3.80**	Observed Fall Flow Volume (10-12):	**3.61**
Simulated Winter Flow Volume (months 1-3):	**5.98**	Observed Winter Flow Volume (1-3):	**5.61**
Simulated Spring Flow Volume (months 4-6):	**4.79**	Observed Spring Flow Volume (4-6):	**4.02**
Total Simulated Storm Volume:	**3.91**	Total Observed Storm Volume:	**3.10**
Simulated Summer Storm Volume (7-9):	**0.42**	Observed Summer Storm Volume (7-9):	**0.23**

Errors (Simulated-Observed)	*Error Statistics*	*Recommended Criteria*
Error in total volume:	**10.06**	**10**
Error in 50% lowest flows:	5.52	10
Error in 10% highest flows:	3.98	15
Seasonal volume error - Summer:	9.90	30
Seasonal volume error - Fall:	5.42	30
Seasonal volume error - Winter:	6.62	30
Seasonal volume error - Spring:	19.20	30
Error in storm volumes:	**26.05**	**20**
Error in summer storm volumes:	**81.28**	**50**
Nash-Sutcliffe Coefficient of Efficiency, E:	0.571	Model accuracy increases
Baseline adjusted coefficient (Garrick), E':	0.403	as E or E' approaches 1.0
Monthly NSE	0.923	

>> Clear

Hydrology Results for Larger Watershed

As mentioned above, no specific site was chosen for initial calibration and no spatial calibration was carried out except some adjustments made to the diversion introduced in one subwatershed. Along with the Bend Bridge site, two other sites on the main stem of the Sacramento River were chosen to compare model simulated streamflows with observed flow. The calibration results for all three sites are summarized in Table 8. The Keswick site is right downstream of Shasta Dam and the measured outflow from Shasta was used as a boundary condition. Lack of accurate representation of the amounts and timings of withdrawal from diversions above the Colusa site, most likely, resulted in poor Nash-Sutcliffe modeling efficiency at this site. Results of the validation exercise summarized in Table 9 reflect the same successes and problems experienced during the calibration period.

Table 8. Summary statistics (percent error): all stations - calibration period

Station	11377100 Sacramento River above Bend Bridge near Red Bluff, CA	11389500 Sacramento River at Colusa, CA	11370500 Sacramento River at Keswick, CA
Error in total volume:	10.23	-0.13	-1.31
Error in 50% lowest flows:	9.28	-8.68	-3.21
Error in 10% highest flows:	6.22	26.63	5.35
Seasonal volume error - Summer:	9.59	15.44	-6.04
Seasonal volume error - Fall:	24.24	9.62	5.14
Seasonal volume error - Winter:	2.11	-13.18	2.18
Seasonal volume error - Spring:	16.99	5.10	-4.76
Error in storm volumes:	43.97	55.14	36.67
Error in summer storm volumes:	78.74	-45.91	69.25
Daily Nash-Sutcliffe Coefficient of Efficiency, E:	0.746	-0.484	0.952
Monthly Nash-Sutcliffe Coefficient of Efficiency, E:	0.944	0.632	0.979

Table 9. Summary statistics: all stations - validation period

Station	11377100 Sacramento River above Bend Bridge near Red Bluff, CA	11389500 Sacramento River at Colusa, CA	11370500 Sacramento River at Keswick, CA
Error in total volume:	10.06	-8.63	-5.38
Error in 50% lowest flows:	5.52	-27.84	-11.24
Error in 10% highest flows:	3.98	10.85	-8.59
Seasonal volume error - Summer:	9.90	15.74	-6.58
Seasonal volume error - Fall:	5.42	-13.05	-10.64
Seasonal volume error - Winter:	6.62	-17.70	-2.81
Seasonal volume error - Spring:	19.20	-9.92	-2.38
Error in storm volumes:	26.05	15.20	-24.11
Error in summer storm volumes:	81.28	-41.12	69.72
Daily Nash-Sutcliffe Coefficient of Efficiency, E:	0.571	-0.469	0.617
Monthly Nash-Sutcliffe Coefficient of Efficiency, E:	0.923	0.546	0.902

Water Quality Calibration and Validation

The model calibration and validation relied on the data from only one station (11377100; Sacramento River above Bend Bridge near Red Bluff, CA) in the entire modeled watershed. A period from 1997-2001 was used for calibration and 1973-1996 was used for validation.

Calibration adjustments for sediment focused on the following parameters:

- SPCON (Linear parameters for estimating maximum amount of sediment that can be re-entrained during channel sediment routing)
- PRF (Peak rate adjustment factor for sediment routing in the main channel)
- USLE-P (USLE support practice factor)
- USLE-K (USLE erodibility factor)
- SLSUBBSN (average slope length)
- RSDCO (Residue decomposition coefficient)

Simulated and estimated sediment loads at the Bend Bridge station for both the calibration and validation periods are shown in Figure 12 and statistics for the two periods are provided separately in Table 10. The key statistic in

Table 10 is the relative percent error, which shows the error in the prediction of monthly load normalized to the estimated load. Table 10 also shows the relative average absolute error, which is the average of the relative magnitude of errors in individual monthly load predictions. This number is inflated by outlier months in which the simulated and estimated loads differ by large amounts (which may be as easily due to uncertainty in the estimated load due to limited data as to problems with the model) and the third statistic, the relative median absolute error, is likely more relevant and shows better agreement.

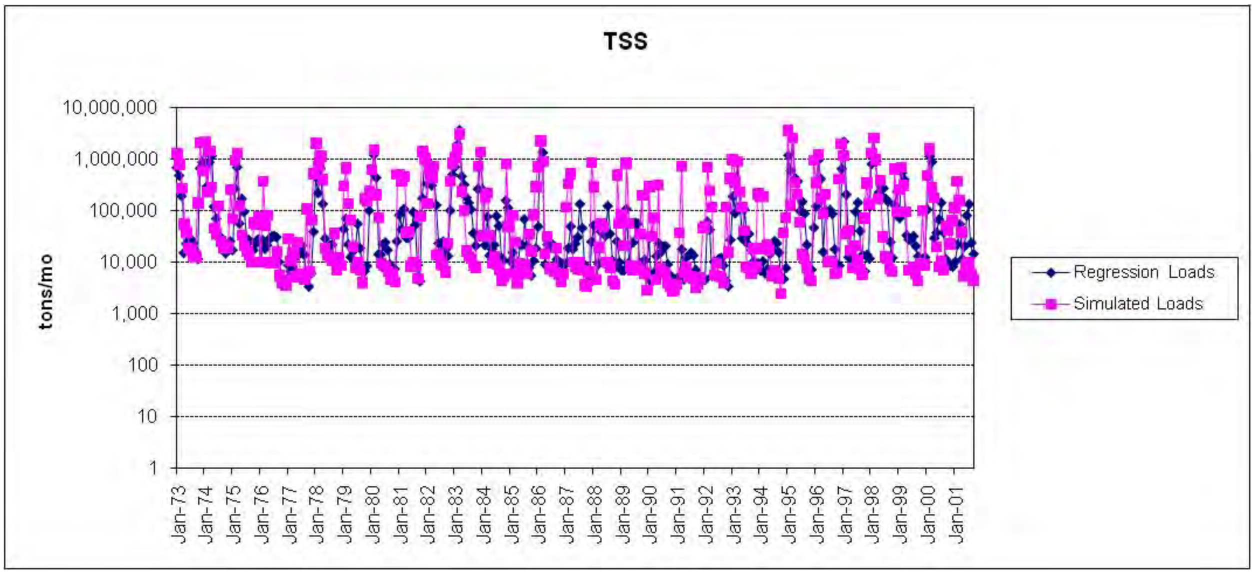


Figure 12. Fit for monthly load of TSS at USGS 11377100 Sacramento River at Bend Bridge near Red Bluff, CA.

Table 10. Model fit statistics (observed minus predicted) for monthly sediment loads using stratified regression at USGS 11377100 Sacramento River at Bend Bridge near Red Bluff, CA

Statistic	Calibration period (1997-2001)	Validation period (1973-1996)
Relative Percent Error	-2%	-55%
Relative Average Absolute Error	59%	92%
Relative Median Absolute Error	28.4%	18.2%

Calibration adjustments for total phosphorus and total nitrogen focused on the following parameters:

- CMN (rate factor of humus mineralization of active organic nutrients)
- NPERCO (nitrogen percolation coefficient)
- PHOSKD (phosphorus soil partitioning coefficient)
- SOL_CBN1 (organic carbon in the first soil layer)
- QUAL2E parameters such as organic nitrogen settling rate in the reach, fraction of algal biomass that is nitrogen, benthic source rate for ammonia in the reach, rate coefficient for organic N settling in the reach, rate constant for biological oxidation of nitrite to nitrate in the reach, rate constant for hydrolysis of organic N to ammonia, Michaelis-Menton half-saturation constant for nitrogen, Maximum specific algal growth rate

Results for the phosphorus simulation are shown in Figure 13 and Table 11. Results for the nitrogen simulation are shown in Figure 14 and Table 12. The model fit is generally good for phosphorus. However, the model overestimates nitrogen loads. The calibration efforts were limited because of the lack of long term monitored nutrient data. Moreover, only one station had monitored data that were used in model calibration.

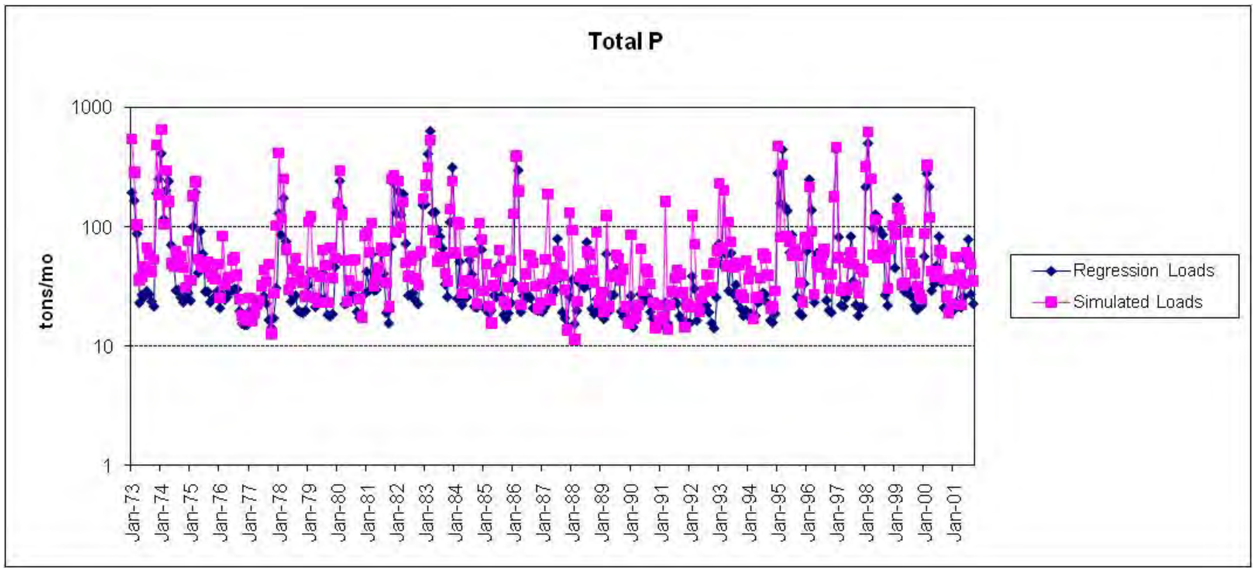


Figure 13. Fit for monthly load of total phosphorus at USGS 11377100 Sacramento River at Bend Bridge near Red Bluff, CA.

Table 11. Model fit statistics (observed minus predicted) for monthly phosphorus loads using stratified regression at USGS 11377100 Sacramento River at Bend Bridge near Red Bluff, CA

Statistic	Calibration period (1997-2001)	Validation period (1973-1996)
Relative Percent Error	-8%	-33
Average Absolute Error	29%	52%
Median Absolute Error	20.3%	27.8%

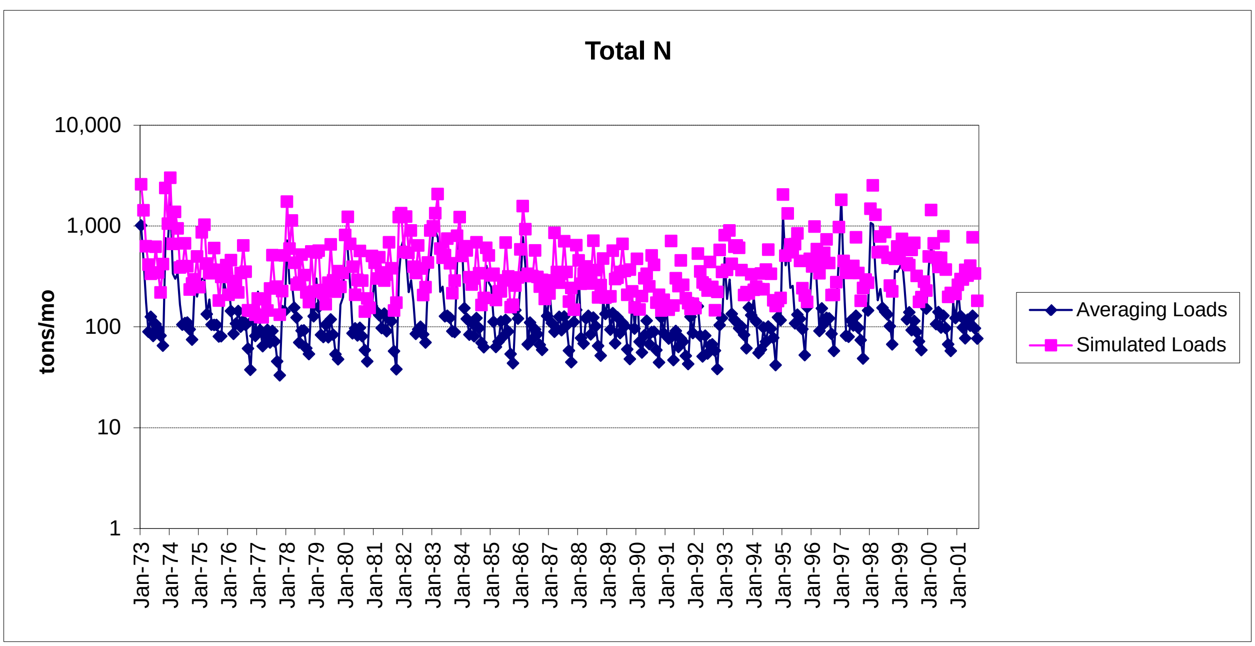


Figure 14. Fit for monthly load of total nitrogen at USGS 11377100 Sacramento River at Bend Bridge near Red Bluff, CA.

Table 12. Model fit statistics (observed minus predicted) for monthly total nitrogen loads using averaging estimator at USGS 11377100 Sacramento River at Bend Bridge near Red Bluff, CA

Statistic	Calibration period (1997-2001)	Validation period (1973-1996)
Relative Percent Error	-135%	-156%
Average Absolute Error	136%	159%
Median Absolute Error	111.5%	124.5%

References

Tetra Tech. 1999. Improving Point Source Loadings Data for Reporting National Water QualityIndicators. Final Technical Report prepared for U.S. Environmental Protection Agency, Office of Wastewater Management, Washington, DC, by Tetra Tech, Inc., Fairfax, VA.

USEPA. 2008. Using the BASINS Meteorological Database (Version 2006). BASINS Technical Note 10. Office of Water, U.S. Environmental Protection Agency, Washington, DC. http://water.epa.gov/scitech/datait/models/basins/upload/2009_04_13_BASINSs_tecnote10.pdf (Accessed June, 2009).

Appendix S
Model Configuration, Calibration and Validation

Basin: Southern California Coastal (SoCal)

Contents

Tables

Figures

Watershed Background

The Southern California Coastal basin was selected as one of the 15 non-pilot application watersheds for the 20 Watershed study. Watershed modeling for the non-pilot areas is accomplished using the SWAT model only, and model calibration and validation results are presented in abbreviated form.

Water Body Characteristics

Coastal Southern California basins

The Coastal Southern California basins encompass a land area of over 11,000 mi2 located along the southern coast of California. The modeled area includes 12 HUC8s within HUC 1807. Major subbasins included in this study are the Santa Clara River, Los Angeles River, San Gabriel River, Santa Ana River, San Juan River, and Santa Margarita River (Figure 1). The Coastal Southern California watersheds are characterized by a mild semi-arid climate with an average rainfall of 15 inches per year. The region is highly urbanized, with substantial amounts of residential, commercial, and industrial developed land (36 percent) on flatter terrain at lower elevations; the rugged mountains in the watershed are primarily in forest and rangeland, which together account for 58 percent of the area.

The Santa Clara River is the largest river system in southern California that remains in a relatively natural state. The watershed drains 1,634 mi^2 from its headwaters in the San Gabriel Mountains to its mouth at the Pacific Ocean. Ninety percent of the watershed consists of rugged mountains, ranging up to 8,800 feet high; the reminder consists of valley floor and coastal plain. The climate in the watershed varies from moist, Mediterranean in Ventura County near the Pacific coast to near desert at the extreme eastern boundary in Los Angeles County.

The Los Angeles and San Gabriel River watersheds are highly urbanized watersheds that encompass 835 mi^2 and 640 mi^2, respectively. The Los Angeles and San Gabriel Rivers both originate in mountainous areas including a large portion of the Angeles National Forest. They flow from the mountains into the San Fernando and San Gabriel Valleys. The rivers then continue on over the coastal plain of Los Angeles and eventually into the Pacific Ocean. Both rivers have been highly modified with dams (51 in the Los Angeles River watershed and 26 in San Gabriel River watershed). Virtually the entire Los Angeles River has been channelized and paved. The San Gabriel River is also channelized and developed for much of its length. These modifications have resulted in a loss of habitat and human access to the rivers. Diversion of water for use in groundwater recharge, significant discharges of sewage treatment plant reclaimed waters, and urban runoff have dramatically changed the natural hydrology of the rivers.

The Santa Ana River is the largest stream system in southern California and encompasses an area of about 2,700 mi^2 in parts of Orange, San Bernardino, Riverside, and Los Angeles Counties. The headwaters are in the San Bernardino Mountains, which reach altitudes over 10,000 feet. The river flows more than 100 miles to the Pacific Ocean. The population of over 4 million people relies on water resources that originate within the watershed as well as water imported from northern California and the Colorado River. The Santa Ana watershed is highly urbanized with about 32 percent of the land use residential, commercial, or industrial. Agricultural land use accounts for about 10 percent of the watershed. Under natural conditions, the Santa Ana River would be intermittent with little or no flow in the summer months. Groundwater is the main source of water supply in the watershed, providing about 66 percent of the consumptive water demand. Imported water from northern California and the Colorado River account for 27 percent of the consumptive demand. Other sources of supply include surface water derived from precipitation within the watershed (4 percent) and recycled water (3 percent).

The San Juan River watershed encompasses about 500 mi^2. Watershed concerns include channelization, poor surface water quality from discharge of nonpoint sources, loss of habitat in the floodplain, loss of riparian habitat, paving of the flood plain, decline of water supply and flows, biodiversity loss, invasive species, surface erosion, and over use of existing resources. The majority of the watershed is urbanized.

The Santa Margarita River watershed encompasses 750 mi^2. The headwaters are on Palomar Mountain and there are 27 miles of free-flowing river. It is the least disturbed river system south of the Santa Ynez River in Santa Barbara County. Unlike most of the rivers of the southern coast of California, the riparian habitat is of particularly high quality, and is essential for the protection of waterfowl and a number of endangered plants and animals.

Groundwater is the main source of water supply in the watershed, providing about 66 percent of the consumptive water demand. Imported water from northern California and the Colorado River is also an important source of water supply, accounting for 27 percent of the consumptive demand. Other sources of supply include surface water derived from precipitation within the basin (4 percent) and recycled water (3 percent).

Enhanced recharge of groundwater is an important component of the hydrologic cycle in the Santa Ana watershed. The volume of water recharged is 37 percent of the volume pumped, with most of the enhanced recharge consisting of surface water derived from precipitation within the basin. Discharge from wastewater treatment facilities is also an important component of the hydrologic cycle, providing base flow in many parts of the drainage network. These activities are among the many factors affecting water quality in the watershed.

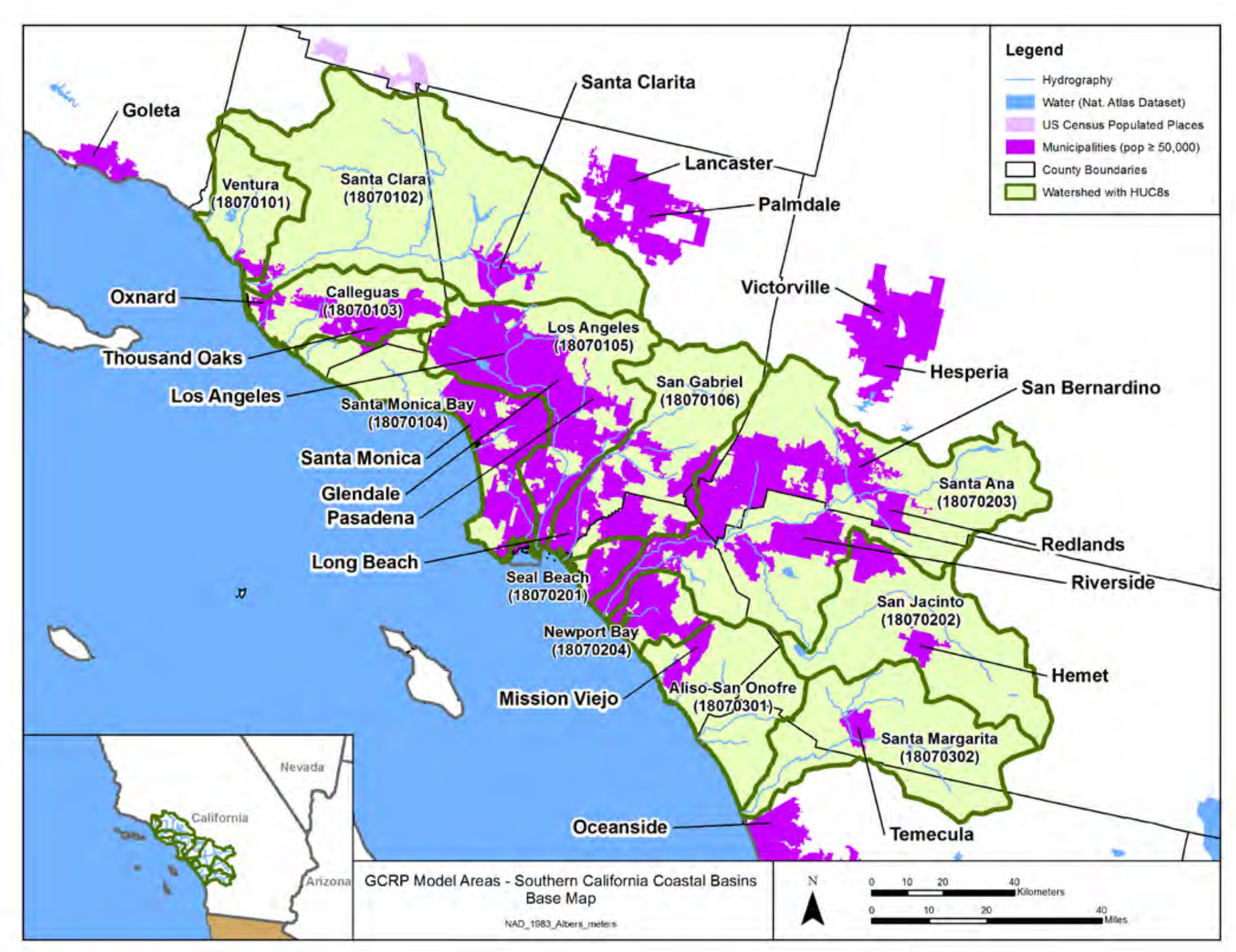


Figure 1. Location of the Coastal Southern California basin.

Soil Characteristics

Soils in the watershed are described in STATSGO soil surveys. SWAT uses information drawn directly from the soils data layer to populate the model.

Land Use Representation

Land use/cover in the watershed is based on the 2001 National Land Cover Database (NLCD) coverage (Figure 2). NLCD land cover classes were aggregated according to the scheme shown in Table 1 for representation in the 20 Watershed model. SWAT uses the built-in hydrologic response unit (HRU) overlay mechanism in the ArcSWAT interface. SWAT HRUs are formed from an intersection of land use and SSURGO major soils. The distribution of land use in the watershed is summarized in Table 2.

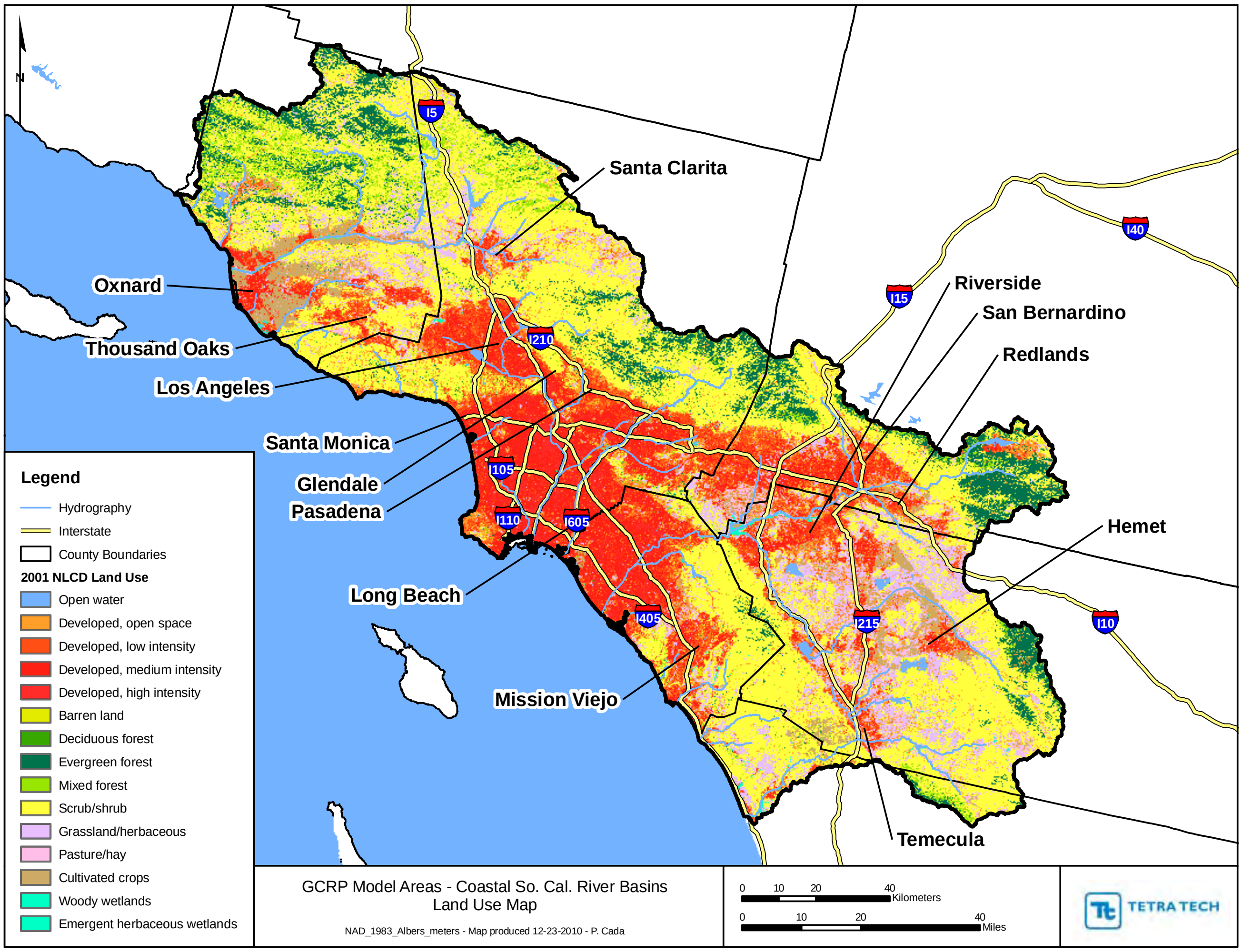


Figure 2. Land use in the Southern California Coastal basin.

Table 1. Aggregation of NLCD land cover classes

NLCD Class	Comments	SWAT class
11 Water	Water surface area usually accounted for as reach area	WATR
12 Perennial ice/snow		WATR
21 Developed open space		URLD
22 Dev. Low Intensity		URMD
23 Dev. Med. Intensity		URHD
24 Dev. High Intensity		UIDU
31 Barren Land		SWRN
41 Forest	Deciduous	FRSD
42 Forest	Evergreen	FRSE
43 Forest	Mixed	FRST
51-52 Shrubland		RNGB
71-74 Herbaceous Upland		RNGE
81 Pasture/Hay		HAY
82 Cultivated		AGRR
91-97 Wetland	Emergent & woody wetlands	WETF, WETL, WETN
98-99 Wetland	Aquatic bed wetlands (not emergent)	WATR

Table 2. Land use distribution for the Southern California Coastal basin (2001 NLCD) (mi^2)

HUC 8 watershed	Open water	Developed[a]				Barren land	Forest	Shrubland	Pasture/Hay	Cultivated	Wetland	Total
		Open space	Low density	Medium density	High density							
Ventura **18070101**	3.6	17.7	4.9	2.2	0.1	0.3	89.5	121.4	1.7	5.4	1.0	247.8
Santa Clara **18070102**	9.6	82.0	33.6	26.7	1.7	17.0	325.3	1,090.8	8.2	44.2	5.8	1,644.7
Calleguas **18070103**	1.2	41.9	47.8	42.8	1.9	1.7	4.0	155.6	5.1	70.8	2.2	374.9
Santa Monica Bay **18070104**	1.4	65.2	60.0	137.0	68.7	1.0	13.8	214.0	2.1	0.0	1.1	564.5
Los Angeles **18070105**	1.5	87.7	135.5	221.7	70.7	2.0	43.3	273.9	0.1	0.1	1.8	838.4
San Gabriel **18070106**	2.0	62.0	87.5	183.3	51.1	3.4	85.3	240.1	0.5	1.2	1.4	717.7
Seal Beach **18070201**	0.4	4.0	11.3	46.3	13.6	0.2	0.1	1.7	0.0	1.6	0.4	79.6
San Jacinto **18070202**	9.7	88.9	40.1	30.9	0.3	3.5	62.7	446.9	24.3	57.5	0.3	765.3
Santa Ana **18070203**	9.0	209.8	233.1	200.4	16.1	13.1	212.9	741.0	22.6	25.9	10.2	1,694.1
Newport Bay **18070204**	0.4	22.4	32.9	48.0	13.5	0.7	0.8	35.2	0.4	2.6	0.5	157.5
Aliso-San Onofre 18070301	0.5	40.8	40.0	35.5	3.9	2.2	10.7	356.7	0.4	2.1	3.7	496.5
Santa Margarita 18070302	9.2	62.2	21.6	16.3	1.0	1.9	31.5	556.7	13.7	20.8	6.2	741.1
Total	48.4	784.4	748.3	991.3	242.5	47.1	879.9	4,234.1	79.2	232.2	34.6	8,321.9

[a]The percent imperviousness applied to each of the developed land uses is as follows: open space (7.75%), low density (35.39%), medium density (61.31%), and high density (88.93%).

Point Sources

There are numerous point source discharges in the watershed. Only the major dischargers, generally defined as those with a design flow greater than 1 MGD are included in the simulation (Table 3). The major dischargers are represented at long-term average flows, without accounting for changes over time or seasonal variations.

Table 3. Major point source discharges in the Southern California Coastal basin

NPDES ID	Name	Design flow (MGD)	Observed flow (MGD) (1991-2006 average)
CA0053651	SAN BUENAVENTURA, CITY OF	14.000	7.499
CA0054224	SANTA PAULA, CITY OF	2.550	41.259
CA0054216	LA CO SANITATION DISTRICTS	21.600	12.377
CA0054313	LA CO SANITATION DISTRICTS	6.500	5.184
CA0053716	LA CO SANITATION DISTRICTS	15.000	27.341
CA0053953	LOS ANGELES, CITY OF	20.000	12.964
CA0055531	BURBANK, CITY OF	9.000	11.401
CA0001309	BOEING COMPANY	178.000	4.041
CA0056227	LOS ANGELES, CITY OF	80.000	52.668
CA0053911	LA CO SANITATION DISTRICTS	100.000	122.795
CA0054011	LA CO SANITATION DISTRICTS	37.500	31.785
CA0054119	LA CO SANITATION DISTRICTS	25.000	15.331
CA0053619	LA CO SANITATION DISTRICTS	15.000	7.553
CA8000383	CORONA, CITY OF	9.000	5.578
CA0105279	INLAND EMPIRE UTILITIES AGENCY	51.000	59.101
CA8000073	INLAND EMPIRE UTILITIES AGENCY	10.200	11.589
CA8000402	INLAND EMPIRE UTILITIES AGENCY	15.000	12.199
CA0105236	COLTON, CITY OF	8.400	5.309
CA0105295	RIALTO, CITY OF	11.700	6.212
CA0105350	RIVERSIDE, CITY	40.000	45.261
CA8000304	COLTON/SAN BERNARDINO RTT&WRA	40.000	57.208
CA0105376	BEAUMONT, CITY OF	4.000	2.035
CA0105619	YUCAIPA VALLEY WATER DISTRICT	4.500	2.598
CA0105392	SAN BERNARDINO, CITY OF	28.000	28.501
CA0053961	OJAI VALLEY SANITARY DISTRICT	3.000	1.935
CA0053597	CAMARILLO SANITARY DISTRICT	6.750	3.300
CA0055221	SIMI VALLEY, CITY OF	12.500	8.994

NPDES ID	Name	Design flow (MGD)	Observed flow (MGD) (1991-2006 average)
CA0056294	THOUSAND OAKS, CITY OF	10.800	8.652
CA0055387	EXXONMOBIL OIL CORP	1.430	2.824
CA8000326	IRVINE RANCH WATER DISTRICT	18.000	12.394

Most of these point sources have reasonably complete monitoring for total suspended solids (TSS). Long term average values of total phosphorus and total nitrogen were assumed based upon the type of point source discharger. The point sources were initially represented in the model with the median of reported values for total phosphorus, total suspended solids and total nitrogen.

Meteorological Data

The required meteorological time series for the 20 Watershed SWAT simulations are precipitation and air temperature. The 20 Watershed simulations do not include water temperature and uses a degree-day method for snowmelt. SWAT estimates Penmann-Monteith potential evapotranspiration using a statistical weather generator for inputs other than temperature and precipitation. These meteorological time series are drawn from the BASINS4 Meteorological Database (USEPA 2008), which provides a consistent, quality-assured set of nationwide data with gaps filled and records disaggregated. Scenario application requires simulation over 30 years, so the available stations are those with a common 30-year period of record (or one that can be filled from an approximately co-located station) that covers the year 2001. A total of 85 precipitation stations were identified for use in the Southern California Coastal watershed model with a common period of record of 10/1/1970-9/30/2001 (Table 4). Temperature records are sparser; where these are absent temperature is taken from nearby stations with an elevation correction.

Table 4. Precipitation stations for the Southern California Coastal watershed model

COOP ID	Name	Latitude	Longitude	Temperature	Elevation (m)
045218	LYTLE CREEK R S	34.2384	-117.4700		832
046162	NEWHALL S FC32CE	34.3869	-118.5340		379
046569	OXNARD	34.1981	-119.1750	X	15
049087	TUSTIN IRVINE RANCH	33.7026	-117.7530	X	72
047723	SAN BERNARDINO F S 226	34.1344	-117.2530	X	347
040235	ANZA	33.5558	-116.6730		1193
047953	SANTA MONICA PIER	34.0081	-118.4980	X	4
046940	PIRU 2 ESE	34.4062	-118.7550		223
047779	SAN GABRIEL DAM FC425B	34.2054	-117.8600		451
042198	CRYSTAL LAKE FC238C	34.3178	-117.8400		1637
042494	DOWNEY FIRE STN FC107C	33.9297	-118.1450		34
042805	ELSINORE	33.6692	-117.3310	X	392
045632	MILL CREEK INTAKE	34.0915	-116.9360		1507
041369	CAMP ANGELUS	34.1493	-116.9800		1759
047600	RUNNING SPRINGS 1 E	34.2067	-117.0860		1818
048992	TRABUCO CANYON	33.6583	-117.5890		296
046379	OCEANSIDE PUMPING PLT	33.2170	-117.3490		3
040606	BEAUMONT	33.9293	-116.9740		796
042164	CRESTLINE	34.2330	-117.2990		455
048844	TEMECULA	33.5000	-117.1500		95
041484	CANOGA PARK PIERCE COLL	34.1819	-118.5740	X	241
047306	REDLANDS	34.0528	-117.1890	X	402
047470	RIVERSIDE FIRE STA 3	33.9511	-117.3880	X	256
044647	LAGUNA BEACH	33.5472	-117.7800	X	11
046719	PASADENA	34.1483	-118.1440	X	263
046175	NEWPORT BEACH HARBOR	33.6025	-117.8800	X	3
042214	CULVER CITY	34.0051	-118.4120	X	17
047785	SAN GABRIEL FIRE DEPT	34.1061	-118.0990	X	137
041194	BURBANK VALLEY PUMP PLA	34.1868	-118.3480	X	200
045114	LOS ANGELES INTL AP	33.9381	-118.3880	X	30
047050	POMONA FAIRPLEX	34.0811	-117.7650	X	317
040014	ACTON ESCONDIDO FC261	34.4948	-118.2710		905
042941	FAIRMONT	34.7043	-118.4270	X	933

COOP ID	Name	Latitude	Longitude	Temperature	Elevation (m)
043896	HEMET	33.7459	-116.9400		504
044211	IDYLLWILD FIRE DEPT	33.7572	-116.7060	X	1640
044422	JUNCAL DAM	34.4909	-119.5060		679
044671	LAKE ARROWHEAD	34.2467	-117.1880	X	1586
044863	LEBEC	34.8328	-118.8640		1093
045115	LOS ANGELES DOWNTOWN	34.0511	-118.2350	X	70
046006	MT WILSON NO 2	34.2309	-118.0710	X	1740
046399	OJAI	34.4479	-119.2270	X	227
046657	PALOMAR MOUNTAIN OBSERV	33.3782	-116.8400	X	1692
047473	RIVERSIDE CITRUS EXP ST	33.9670	-117.3610	X	301
047735	SANDBERG	34.7437	-118.7240	X	1375
047776	SAN GABRIEL CANYON P H	34.1553	-117.9070		227
047888	SANTA ANA FIRE STATION	33.7442	-117.8660	X	41
047957	SANTA PAULA	34.3120	-119.1330	X	72
048014	SAUGUS POWER PLANT 1	34.5894	-118.4540		642
049152	U C L A	34.0697	-118.4420	X	131
049285	VENTURA	34.2825	-119.2910		32
044650	LAGUNA BEACH 2	33.5567	-117.8000		64
048230	SIGNAL HILL FC 415	33.7968	-118.1680		30
040144	ALTADENA	34.1819	-118.1380		344
040798	BIG TUJUNGA DAM FC46DE	34.2942	-118.1870		706
042090	COVINA CITY YRD FC387B	34.0920	-117.8800		178
043452	GLENDORA FC 287B	34.1464	-117.8470		280
044628	LA CRESCENTA FC 251C	34.2223	-118.2420		477
046602	PACOIMA DAM FC 33 A-E	34.3326	-118.3990		457
046663	PALOS VERDES EST FC43D	33.7998	-118.3910		66
047749	SAN DIMAS FIRE FC95	34.1072	-117.8050		291
048967	TOPANGA PATROL STN FC6	34.0843	-118.5980		227
048973	TORRANCE	33.8017	-118.3410	X	34
049660	WHITTIER CITY YD FC106C	33.9762	-118.0220		128
041272	CAJON WEST SUMMIT	34.3901	-117.5920		1457
047926	SANTA FE DAM	34.1119	-117.9700		130
047762	SAN FERNANDO PH 3	34.3133	-118.4920		381
041682	CHATSWORTH RESERVOIR	34.2264	-118.6160		277

COOP ID	Name	Latitude	Longitude	Temperature	Elevation (m)
048092	SEPULVEDA DAM	34.1662	-118.4730		207
040742	BIG BEAR LAKE DAM	34.2414	-116.9740		2077
041057	BREA DAM	33.8906	-117.9260		84
041754	CHUCHUPATE RANGER STN	34.8079	-119.0110		1603
043285	FULLERTON DAM	33.8964	-117.8880		104
046473	ORANGE COUNTY RESERVOIR	33.9379	-117.8850		201
047123	PRADO DAM	33.8904	-117.6450		171
047813	SAN JACINTO R S	33.7870	-116.9580		475
048243	SILVERADO RANGER STN	33.7425	-117.6590		334
046377	OCEANSIDE MARINA	33.2097	-117.3940	X	3
048436	SPADRA LANTERMAN HOSP	34.0419	-117.8090		206
049378	VISTA 2 NNE	33.2294	-117.2260	X	155
045085	LONG BEACH AP	33.8118	-118.1460	X	9
040741	BIG BEAR LAKE	34.2442	-116.9030	X	2060
044181	HURKEY CREEK PARK	33.6830	-116.6830		408
046910	PINE MOUNTAIN INN	34.6001	-119.3490		392
041540	CARPINTERIA RSVR	34.4000	-119.4830		36
045417	MATILIJA DAM	34.4830	-119.2990		98

Watershed Segmentation

The Southern California Coastal basin was divided into 65 subwatersheds for the purposes of modeling (Figure 3). The model encompasses the complete watershed and does not require specification of any upstream boundary conditions for application.

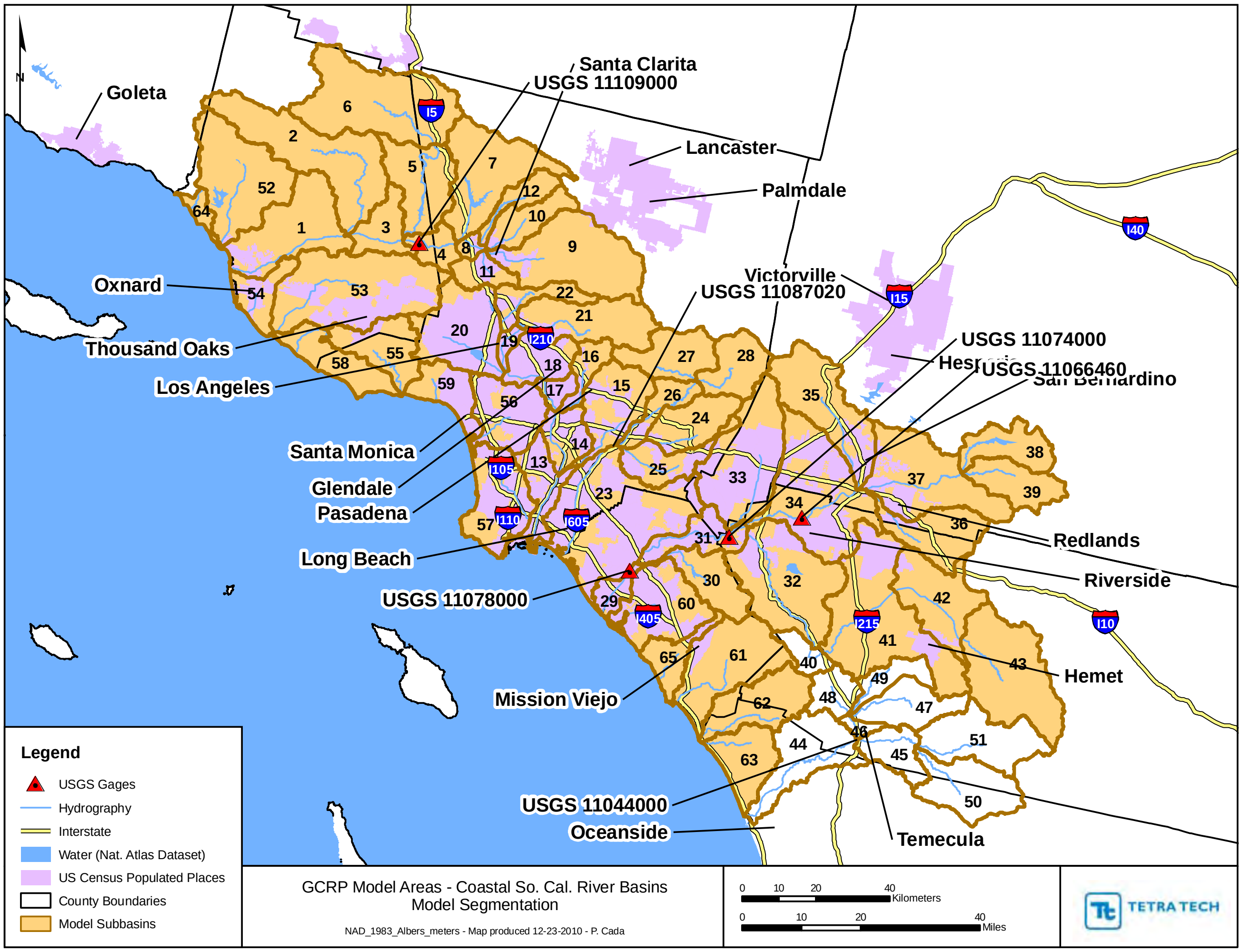


Figure 3. Model segmentation and USGS stations utilized for the Southern California Coastal basin.

Calibration Data and Locations

The specific site chosen for initial calibration was the Santa Ana River at MWD Crossing, a flow and water quality monitoring location that approximately coincides with the mouth of an 8-digit HUC. The Santa Ana River watershed was selected because there is a good set of flow and water quality data available and the watershed lacks major point sources and impoundments. Additional calibration and validation was pursued at multiple locations (Table 5). Parameters derived on the Santa Ana River were not fully transferable to other portions of the Southern California Coastal basin, and additional calibration was conducted at multiple gage locations.

Table 5. Calibration and validation locations in the Southern California Coastal basin

Station name	USGS ID	Drainage area (mi^2)	Hydrology calibration	Water quality calibration
Santa Ana River at MWD Crossing, CA	11066460	852	X	X
Santa Margarita River near Temecula, CA	11044000	588	X	X
Santa Ana river below Prado Dam, CA	11074000	2,258	X	
San Gabriel River above Whittier Narrows Dam, CA	11087020	2,692	X	
Santa Clara River near Piru, CA	11109000	2,183	X	

The model hydrology calibration period was set to Water Years 1991-2001 (within the 32-year period of record for modeling). Hydrologic validation was then performed on Water Years 1981-1991. Water quality calibration used calendar years 1991-2001, while validation used 1981-1991.

SWAT Modeling

Assumptions

There are numerous diversions and impoundments in the Southern California Coastal basin. Since the objective of the 20 Watershed modeling effort is to measure relative change, only major impoundments and/or diversions have been represented in the model. Vail Lake and Prado Dam were the two impoundments represented in the Southern California Coastal model. Vail Lake is located on the Temecula Creek, a tributary of Santa Margarita River. Prado Dam is located on the Santa Ana River. Pertinent reservoir information including surface area and storage at principal (normal) and emergency spillway levels for the reservoirs were obtained from the US Army Corps of Engineers. The SWAT model provides four options to simulate reservoir outflow: measured daily outflow, measured monthly outflow, average annual release rate for uncontrolled reservoir, and controlled outflow with target release. Keeping in view the 20 Watershed climate change impact evaluation application to future climate scenarios, it was assumed that the best representation of the reservoirs were to simulate them without supplying time series of outflow records. Therefore, target release approach was used in the GCRP-SWAT model.

Hydrology Calibration

A spatial calibration approach was adopted for GCRP-SWAT modeling for the Southern California Coastal basin. A systematic adjustment of parameters has been adopted and some adjustments are applied throughout the basin. Most of the calibration efforts were geared towards getting a closer match between simulated and observed flows at the outlet of calibration focus area.

Land Use / Soil / Slope Definition

A 5/10/5 percent threshold was used for land use/soil/slope in the SWAT model while defining the HRUs. Urban land use classes were exempted from the HRU overlay thresholds.

The calibration focus area (Santa Ana River at MWD Crossing) includes six subwatersheds and is generally representative of the general land use characteristics of the overall watershed with the exception of a higher percentage of cultivated lands. The parameters were adjusted within the practical range to obtain reasonable fit between the simulated and measured flows in terms of Nash-Sutcliffe modeling efficiency and the high flow and low flow components as well as the seasonal flows.

The water balance of the whole Southern California Coastal basin predicted by the SWAT model over the 32-year simulation period is as follows:

```
PRECIP =    494.8 MM
SNOW FALL =   24.25 MM
SNOW MELT =    23.76 MM
SUBLIMATION =     0.50 MM
SURFACE RUNOFF Q =   143.40 MM
LATERAL SOIL Q =   85.39 MM
TILE Q =     0.00 MM
GROUNDWATER (SHAL AQ) Q =    94.83 MM
REVAP (SHAL AQ => SOIL/PLANTS) =    1.99 MM
DEEP AQ RECHARGE =     9.06 MM
TOTAL AQ RECHARGE = 105.88 MM
TOTAL WATER YLD =   277.58 MM
```

```
PERCOLATION OUT OF SOIL =   61.28 MM
ET =     225.2 MM
PET =    1712.7MM
TRANSMISSION LOSSES =    46.04 MM
```

Hydrologic calibration adjustments focused on the following parameters:

- CN2 (initial SCS runoff curve number for moisture condition II)
- ESCO (soil evaporation compensation factor)
- SURLAG (surface runoff lag coefficient)
- SOL_AWC (available water capacity of the soil layer, mm water/mm of soil)
- ALPHA_BF (baseflow alpha factor, days)
- GW_DELAY (groundwater delay time, days)
- GWQMIN (threshold depth of water in the shallow aquifer required for return flow to occur, mm)
- GW_REVAP (groundwater "revap" coefficient)
- CH_N1 (Manning's "n" value for tributary channels)
- CH_N2 (Manning's "n" value for main channels)
- CH_K1 (Effective hydraulic conductivity in tributary channel alluvium)
- CH_K2 (Effective hydraulic conductivity in main channel alluvium)
- SFTMP (Snowfall temperature)
- SMTMP (Snowmelt base temperature)
- SMFMX (Maximum melt rate for snow during the year)
- SMFMN (Minimum melt rate for snow during the year)

The calibration achieves a moderately high coefficient of model fit efficiency. Calibration results for the Santa Ana River at MWD Crossing are summarized in Figure 4, Figure 5, Figure 6, Figure 7 and Table 6.

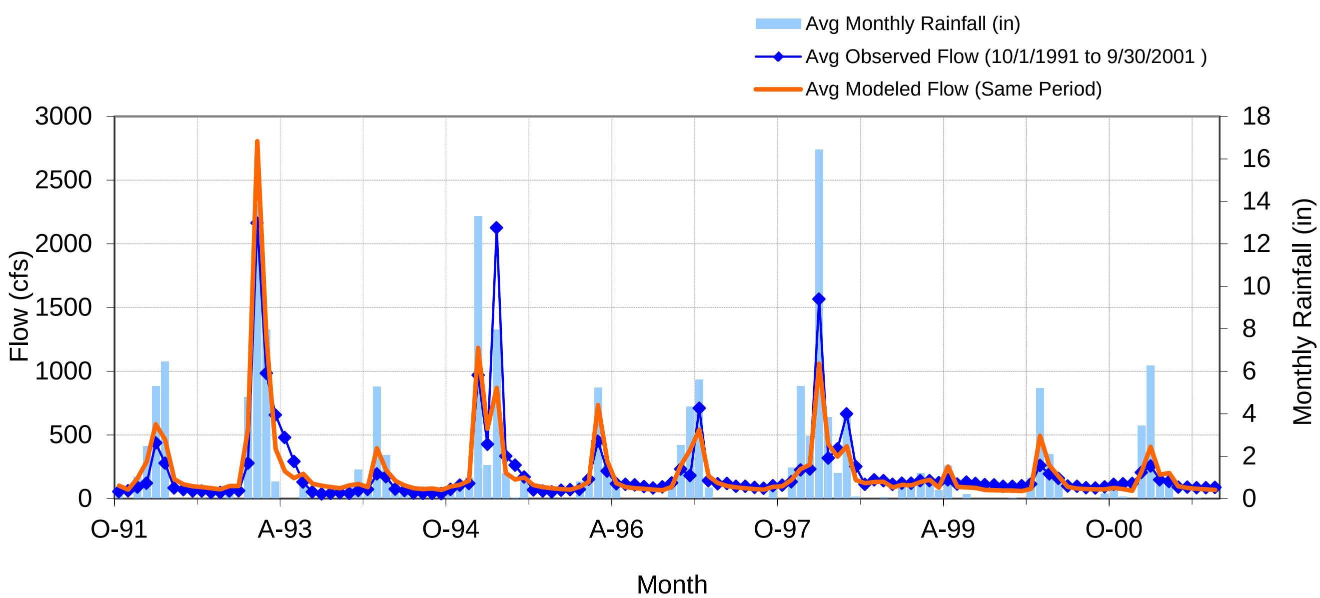


Figure 4. Mean monthly flow at USGS 11066460 Santa Ana River at MWD Crossing, CA – calibration period.

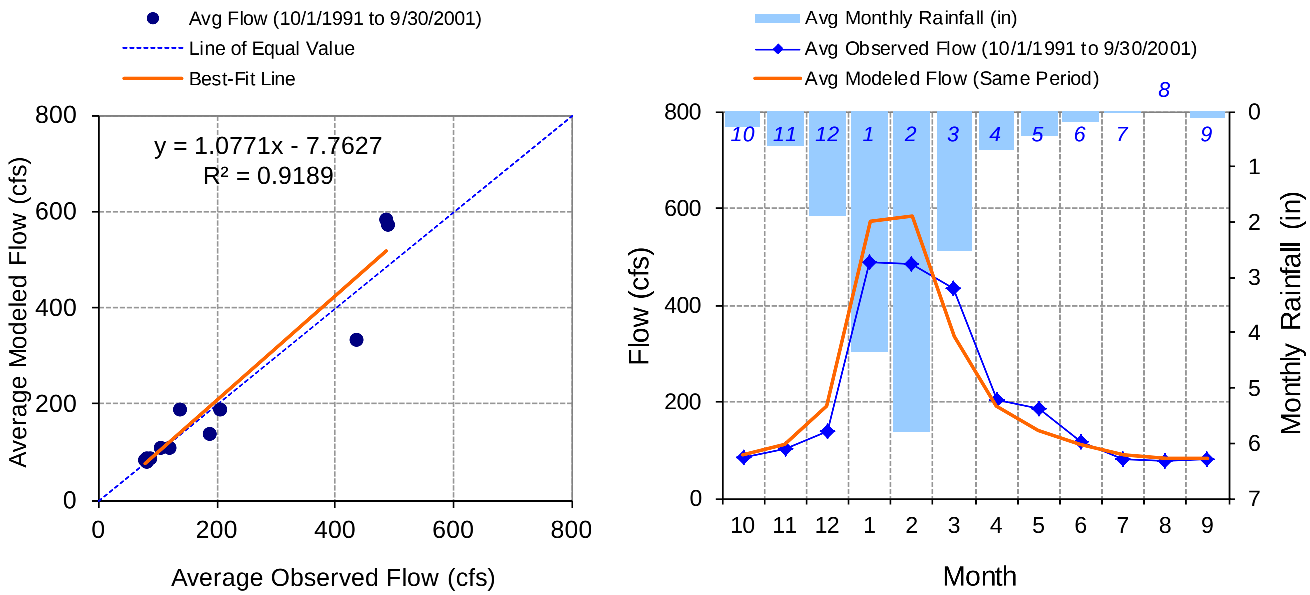


Figure 5. **Seasonal regression and temporal aggregate at USGS 11066460 Santa Ana River at MWD Crossing, CA – calibration period.**

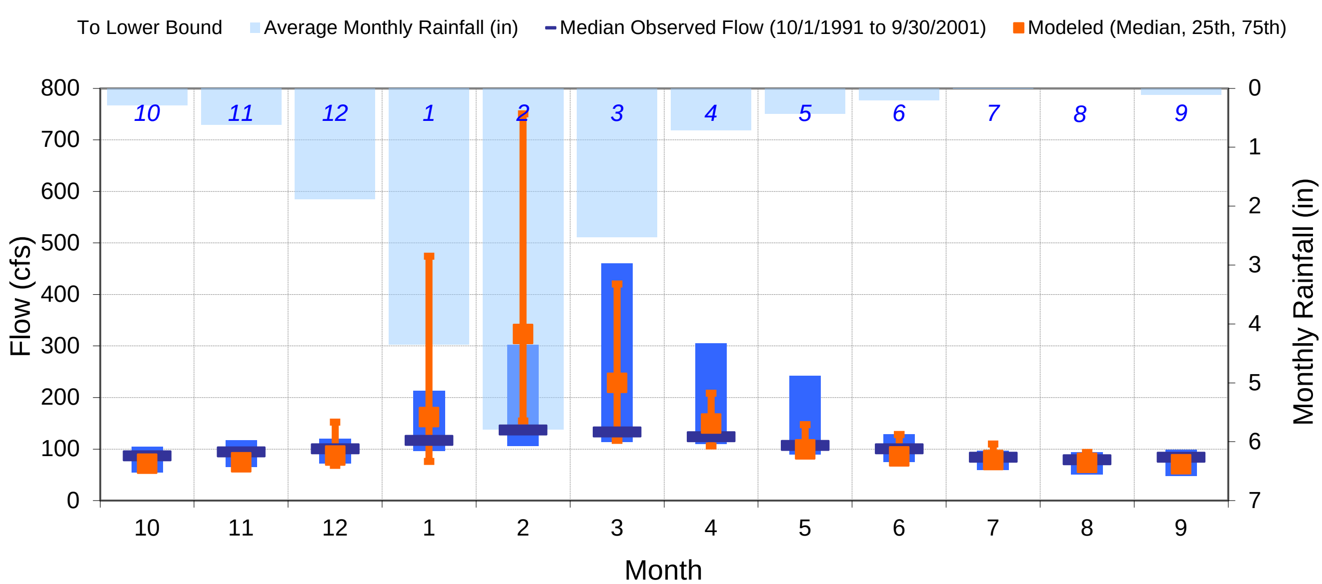


Figure 6. **Seasonal medians and ranges at USGS 11066460 Santa Ana River at MWD Crossing, CA – calibration period.**

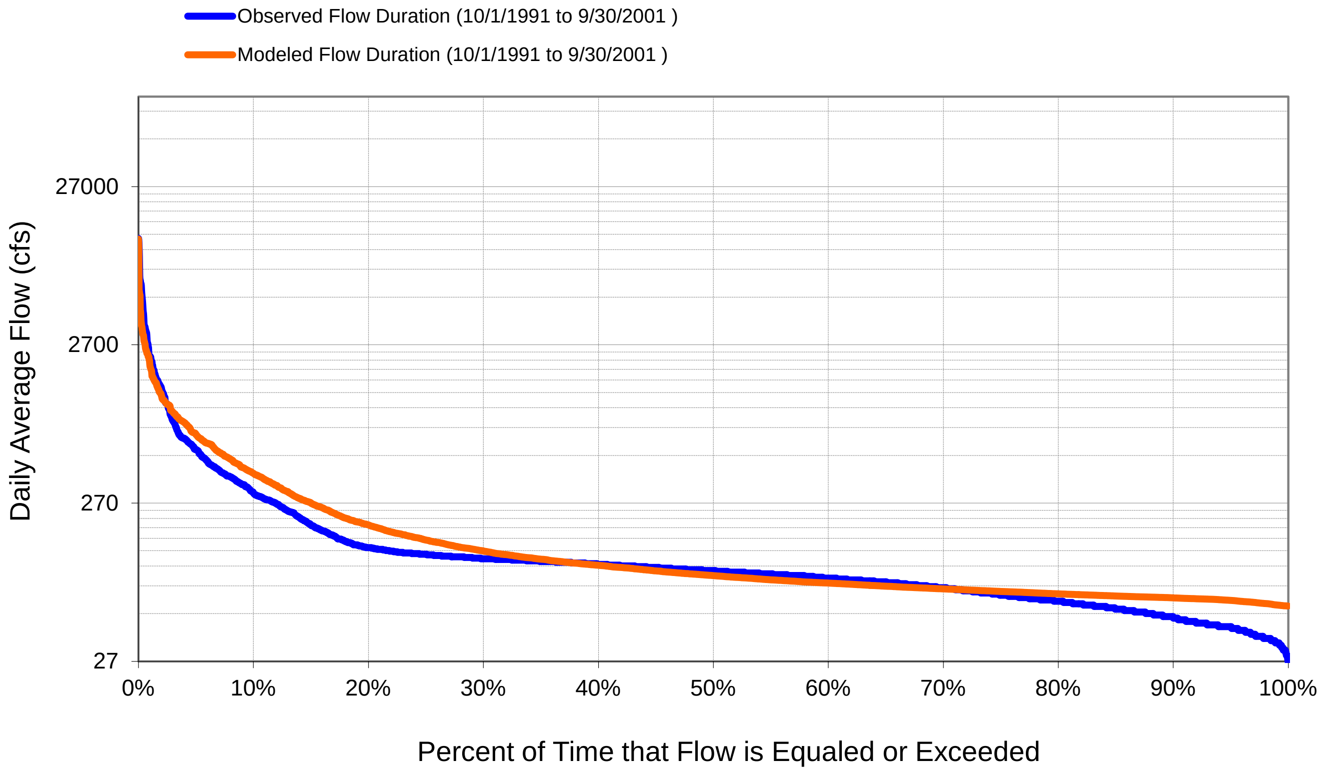


Figure 7. Flow exceedance at USGS 11066460 Santa Ana River at MWD Crossing, CA – calibration period.

Table 6. Summary statistics at USGS 11066460 Santa Ana River at MWD Crossing, CA – calibration period

SWAT Simulated Flow		Observed Flow Gage	
REACH OUTFLOW FROM OUTLET 34 10-Year Analysis Period: 10/1/1991 - 9/30/2001 Flow volumes are (inches/year) for upstream drainage area		USGS 11066460 SANTA ANA R A MWD CROSSING CA Hydrologic Unit Code: 18070203 Latitude: 33.96862566 Longitude: -117.4483806 Drainage Area (sq-mi): 852	
Total Simulated In-stream Flow:	**3.40**	Total Observed In-stream Flow:	**3.28**
Total of simulated highest 10% flows:	**1.74**	Total of Observed highest 10% flows:	**1.82**
Total of Simulated lowest 50% flows:	**0.60**	Total of Observed Lowest 50% flows:	**0.56**
Simulated Summer Flow Volume (months 7-9):	**0.34**	Observed Summer Flow Volume (7-9):	**0.32**
Simulated Fall Flow Volume (months 10-12):	**0.52**	Observed Fall Flow Volume (10-12):	**0.44**
Simulated Winter Flow Volume (months 1-3):	**1.95**	Observed Winter Flow Volume (1-3):	**1.85**
Simulated Spring Flow Volume (months 4-6):	**0.58**	Observed Spring Flow Volume (4-6):	**0.67**
Total Simulated Storm Volume:	**1.22**	Total Observed Storm Volume:	**1.38**
Simulated Summer Storm Volume (7-9):	**0.02**	Observed Summer Storm Volume (7-9):	**0.03**

Errors (Simulated-Observed)	*Error Statistics*	*Recommended Criteria*		
Error in total volume:	3.71	10		
Error in 50% lowest flows:	7.28	10		
Error in 10% highest flows:	-4.65	15		
Seasonal volume error - Summer:	7.40	30		
Seasonal volume error - Fall:	19.91	>> 30	Clear	
Seasonal volume error - Winter:	5.46	30		
Seasonal volume error - Spring:	-13.35	30		
Error in storm volumes:	-11.70	20		
Error in summer storm volumes:	-46.22	50		
Nash-Sutcliffe Coefficient of Efficiency, E:	0.625	Model accuracy increases		
Baseline adjusted coefficient (Garrick), E':	0.438	as E or E' approaches 1.0		
Monthly NSE	0.747			

Hydrology Validation

Hydrology validation for Santa Ana River at MWD Crossing was performed for the period 10/1/1981 through 9/30/1991. The validation achieves an acceptable coefficient of model fit efficiency (Figure 8, Figure 9, Figure 10, Figure 11 and Table 7).

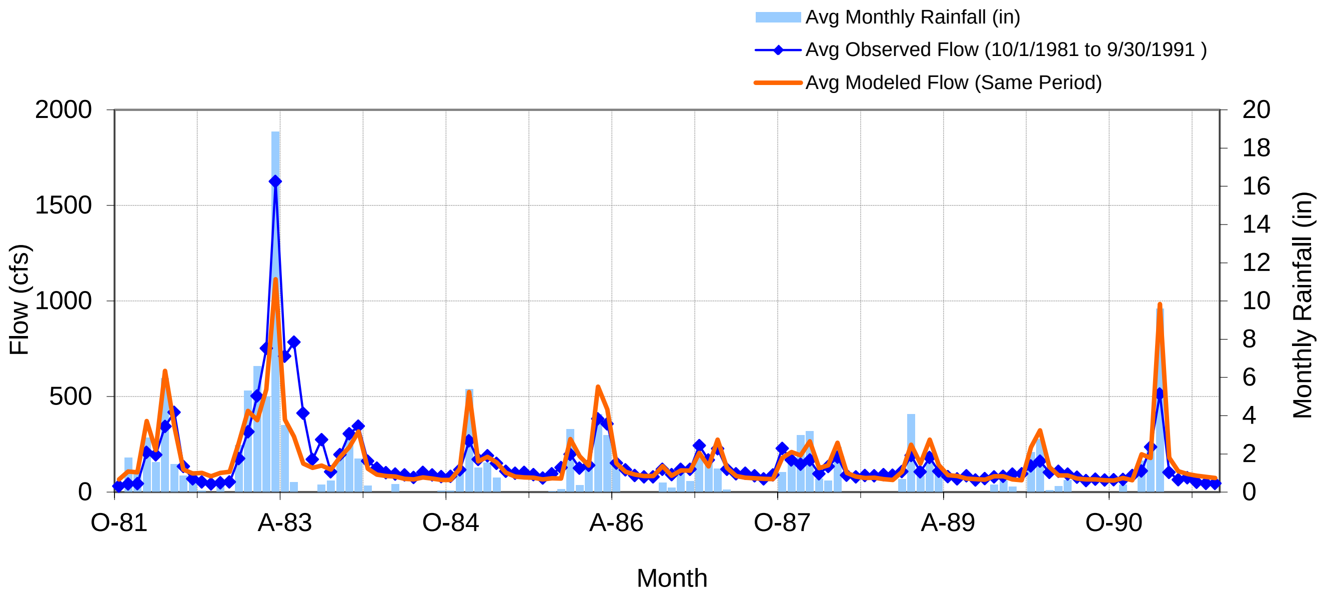


Figure 8. Mean Monthly Flow at USGS 11066460 Santa Ana River at MWD Crossing, CA – Validation Period

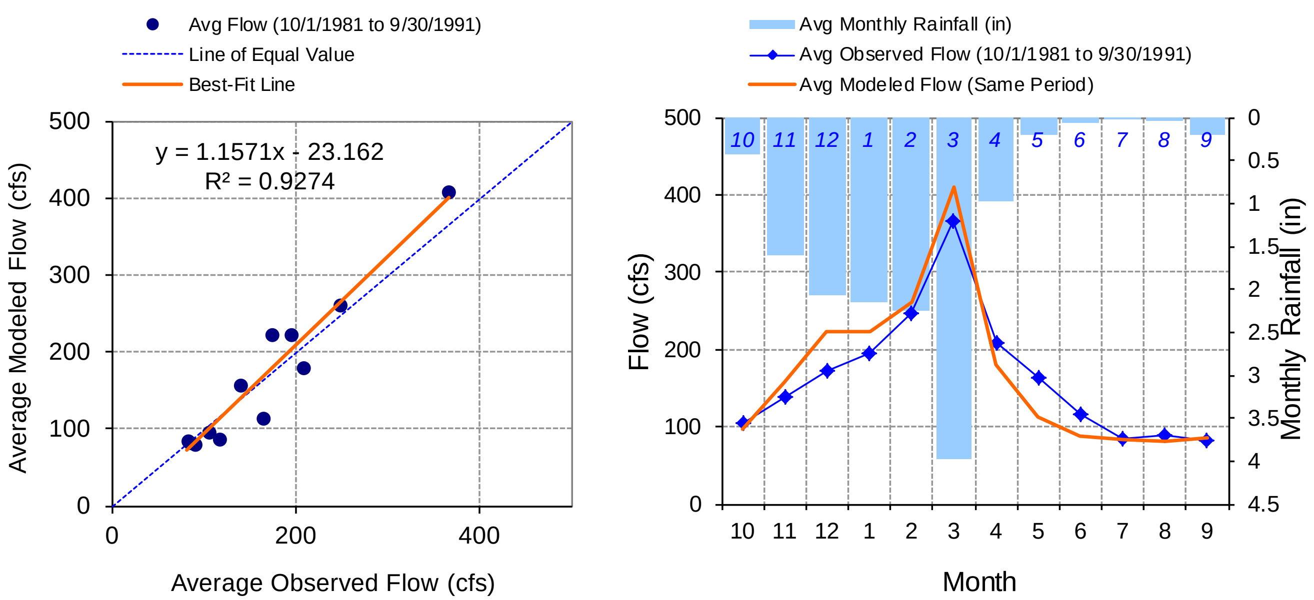


Figure 9. Seasonal regression and temporal aggregate at USGS 11066460 Santa Ana River at MWD Crossing, CA – validation period.

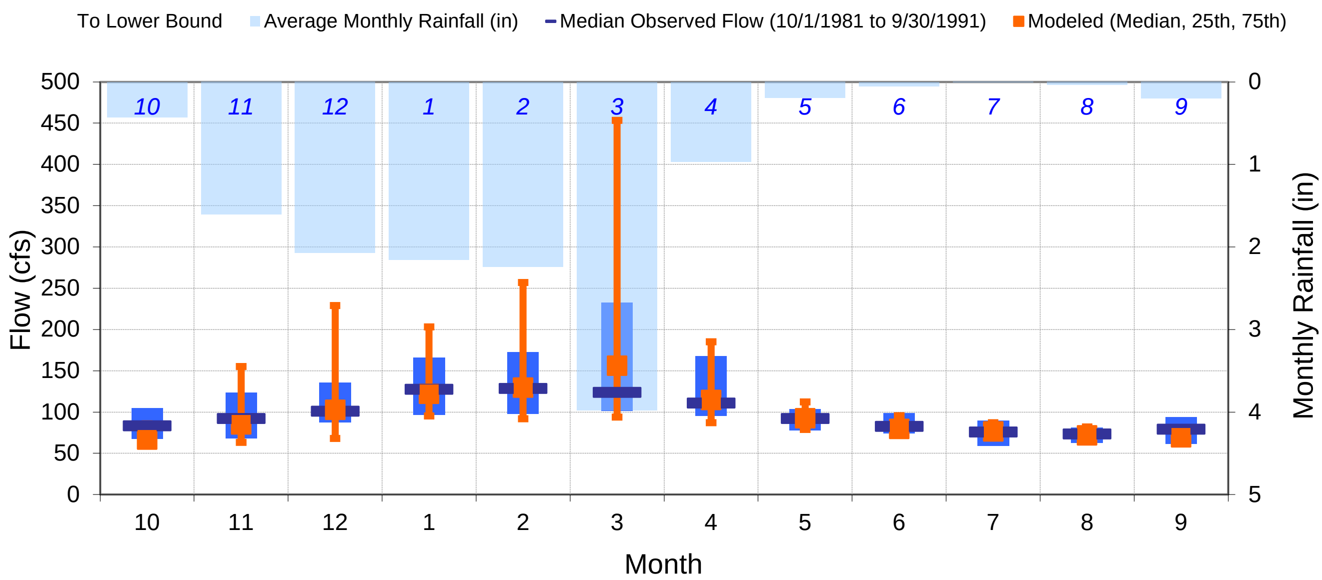


Figure 10. Seasonal medians and ranges at USGS 11066460 Santa Ana River at MWD Crossing, CA – validation period.

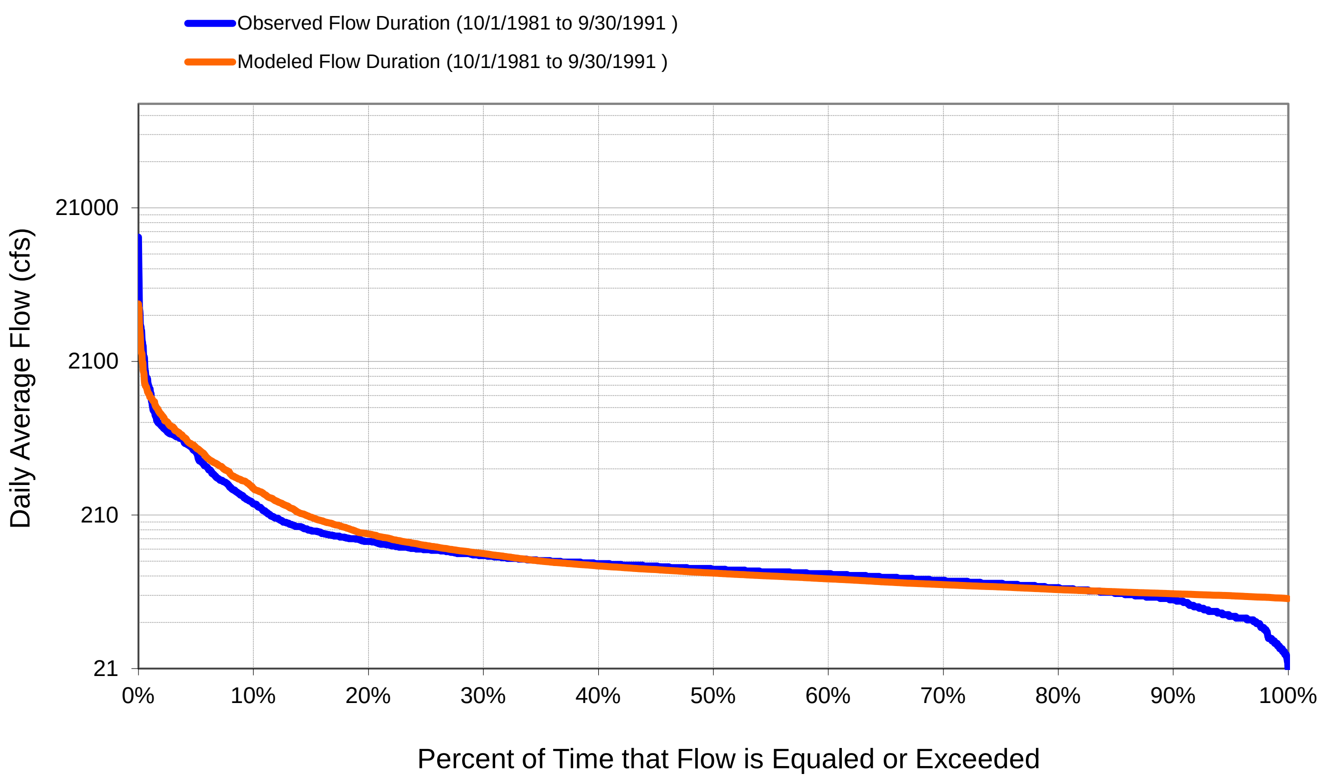


Figure 11. Flow exceedance at USGS 11066460 Santa Ana River at MWD Crossing, CA – validation period.

Table 7. Summary statistics at USGS 11066460 Santa Ana River at MWD Crossing, CA – validation period

SWAT Simulated Flow		Observed Flow Gage	
REACH OUTFLOW FROM OUTLET 34 10-Year Analysis Period: 10/1/1981 - 9/30/1991 Flow volumes are (inches/year) for upstream drainage area		USGS 11066460 SANTA ANA R A MWD CROSSING CA Hydrologic Unit Code: 18070203 Latitude: 33.96862566 Longitude: -117.4483806 Drainage Area (sq-mi): 852	
Total Simulated In-stream Flow:	**2.65**	Total Observed In-stream Flow:	**2.61**
Total of simulated highest 10% flows:	**1.20**	Total of Observed highest 10% flows:	**1.24**
Total of Simulated lowest 50% flows:	**0.58**	Total of Observed Lowest 50% flows:	**0.57**
Simulated Summer Flow Volume (months 7-9):	**0.33**	Observed Summer Flow Volume (7-9):	**0.34**
Simulated Fall Flow Volume (months 10-12):	**0.64**	Observed Fall Flow Volume (10-12):	**0.56**
Simulated Winter Flow Volume (months 1-3):	**1.18**	Observed Winter Flow Volume (1-3):	**1.06**
Simulated Spring Flow Volume (months 4-6):	**0.50**	Observed Spring Flow Volume (4-6):	**0.65**
Total Simulated Storm Volume:	**0.89**	Total Observed Storm Volume:	**0.85**
Simulated Summer Storm Volume (7-9):	**0.03**	Observed Summer Storm Volume (7-9):	**0.06**

Errors (Simulated-Observed)	*Error Statistics*	*Recommended Criteria*		
Error in total volume:	1.61	10		
Error in 50% lowest flows:	1.21	10		
Error in 10% highest flows:	-2.74	15		
Seasonal volume error - Summer:	-2.97	30		
Seasonal volume error - Fall:	14.41 >>	30		Clear
Seasonal volume error - Winter:	10.63	30		
Seasonal volume error - Spring:	-21.87	30		
Error in storm volumes:	4.72	20		
Error in summer storm volumes:	-49.23	50		
Nash-Sutcliffe Coefficient of Efficiency, E:	0.587	Model accuracy increases		
Baseline adjusted coefficient (Garrick), E':	0.368	as E or E' approaches 1.0		
Monthly NSE	0.678			

Hydrology Results for Larger Watershed

As described above, parameters determined for the gage at the Santa Ana River were initially transferred to other gages in the watershed. However, changes to subwatershed level parameters were required to fit the model to the observed flows. In all, calibration and validation was pursued at a total of five gages throughout the watershed. Results of the calibration and validation exercise are summarized in Table 8 and Table 9, respectively. Calibration and validation results were acceptable at most gages.

Table 8. Summary statistics (percent error): all stations - calibration period

Station	USGS 11044000	USGS 11074000	USGS 11087020	USGS 11109000 (1996 –2001)
Error in total volume:	-14.16	-0.63	-2.03	-27.78
Error in 50% lowest flows:	-34.24	-48.91	-9.33	-58.29
Error in 10% highest flows:	-24.17	17.53	-5.28	-6.60
Seasonal volume error - Summer:	63.03	-39.86	-10.77	-52.09
Seasonal volume error - Fall:	14.79	-33.47	-27.72	-13.02
Seasonal volume error - Winter:	-20.76	13.39	4.18	-12.67
Seasonal volume error - Spring:	20.89	14.16	-3.02	-61.49
Error in storm volumes:	-30.11	-33.40	-18.43	21.68
Error in summer storm volumes:	0.26	-41.45	-84.03	-74.54
Daily Nash-Sutcliffe Coefficient of Efficiency, E:	0.746	0.635	0.539	0.290
Monthly Nash-Sutcliffe Efficiency:	0.907	0.854	0.771	0.875

Table 9. Summary statistics (percent error): all stations - validation period

Station	USGS 11044000	USGS 11074000	USGS 11087020
Error in total volume:	29.64	9.60	-7.95
Error in 50% lowest flows:	-7.02	-37.19	37.06
Error in 10% highest flows:	7.39	30.78	-1.74
Seasonal volume error - Summer:	156.76	-22.67	-25.74
Seasonal volume error - Fall:	153.72	-9.62	-9.15
Seasonal volume error - Winter:	-4.59	32.70	-1.41
Seasonal volume error - Spring:	122.83	9.33	-14.90
Error in storm volumes:	2.38	-17.19	-29.85
Error in summer storm volumes:	339.73	-36.25	-65.40
Daily Nash-Sutcliffe Coefficient of Efficiency, E:	0.456	0.372	0.589
Monthly Nash-Sutcliffe Efficiency:	0.721	0.494	0.797

Water Quality Calibration and Validation

Initial calibration and validation of water quality was done on the Santa River at MWD Crossing (USGS 11066460), using 1998-2000 for calibration due to limited water quality data availability. No water quality data were available for the validation period. As with hydrology, calibration was performed on the later period as this better reflects the land use included in the model.

Calibration adjustments for sediment focused on the following parameters:

- SPCON (linear parameter for estimating maximum amount of sediment that can be re-entrained during channel sediment routing)
- SPEXP (exponential parameter for estimating maximum amount of sediment that can be re-entrained during channel sediment routing)
- CH_COV (channel cover factor)
- CH_EROD (channel erodibility factor)
- USLE_P (USLE support practice factor)

Simulated and estimated sediment loads at the Santa Ana River station for both the calibration and validation periods are shown in Figure 12 and statistics for the two periods are provided separately in Table 10. The key statistic in Table 10 is the relative percent error, which shows the error in the prediction of monthly load normalized to the estimated load. Table 10 also shows the relative average absolute error, which is the average of the relative magnitude of errors in individual monthly load predictions. This number is inflated by outlier months in which the simulated and estimated loads differ by large amounts (which may be as easily due to uncertainty in the estimated load due to limited data as to problems with the model) and the third statistic, the relative median absolute error, is likely more relevant and shows better agreement.

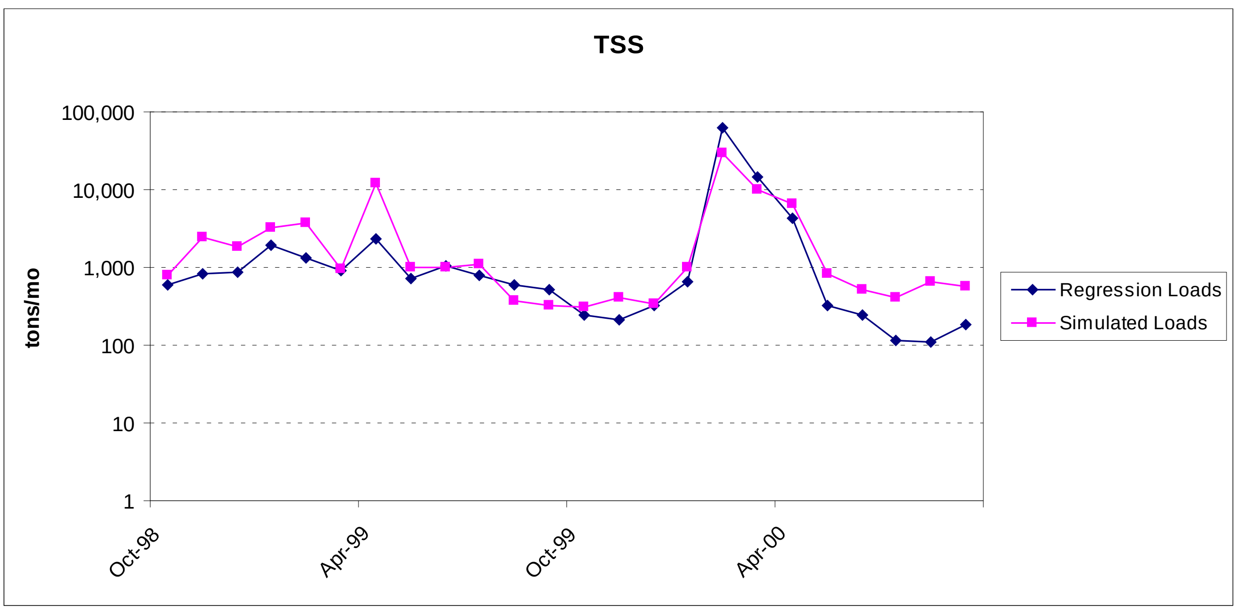


Figure 12. Fit for monthly load of TSS at USGS 11066460 Santa Ana River at MWD Crossing, CA.

Table 10. Model fit statistics (observed minus predicted) for monthly sediment loads using stratified regression at USGS 11066460 Santa Ana River at MWD Crossing, CA

Statistic	Calibration period (1998-2000)
Relative Percent Error	19.0%
Relative Average Absolute Error	62.5%
Relative Median Absolute Error	7.6%

Calibration adjustments for total phosphorus and total nitrogen focused on the following parameters:

- RHOQ (algal respiration rate at 20^{O} C)
- PHOSKD (phosphorus soil partitioning coefficient)
- PSP (phosphorus availability index)
- RS1 (Local algal settlement rate in the reach at 20^{O} C)
- AL1 (Fraction of algal biomass that is nitrogen)
- AL2 (Fraction of algal biomass that is phosphorus)
- MUMAX (Rate of oxygen uptake per unit NO_2-N oxidation at 20^{O} C)
- RHOQ (Algal respiration rate at 20^{O} C)
- RS2 (benthic source rate for dissolved P in the reach at 20^{O} C)
- RS3 (Benthic source rate for NH_4-N in the reach at 20^{O} C)
- RS5 (organic P settling rate in the reach at 20^{O} C)
- BC4 (rate constant for mineralization of organic P to dissolved P in the reach at 20^{O} C)
- RS4 (rate coefficient for organic N settling in the reach at 20^{O} C)
- CH_ONCO (Channel organic nitrogen concentration)
- CH_OPCO (Channel organic phosphorus concentration)
- SDNCO (Denitrification threshold water content)
- CDN (Denitrification exponential rate constant)

Results for the phosphorus simulation are shown in Figure 13 and Table 11. Results for the nitrogen simulation are shown in Figure 14 and Table 12. The model fit is generally acceptable.

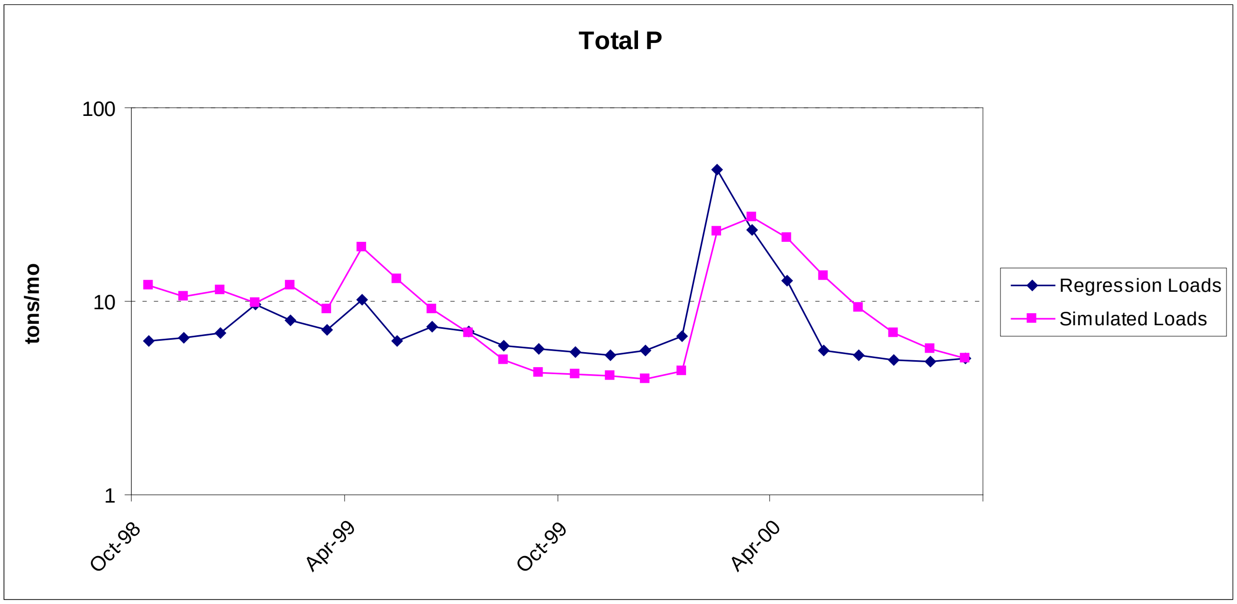


Figure 13. Fit for monthly load of total phosphorus at USGS 11066460 Santa Ana River at MWD Crossing, CA.

Table 11. Model fit statistics (observed minus predicted) for monthly phosphorus loads using stratified regression at USGS 11066460 Santa Ana River at MWD Crossing, CA

Statistic	Calibration period (1998-2000)
Relative Percent Error	-14.7%
Average Absolute Error	45.8%
Median Absolute Error	23.7%

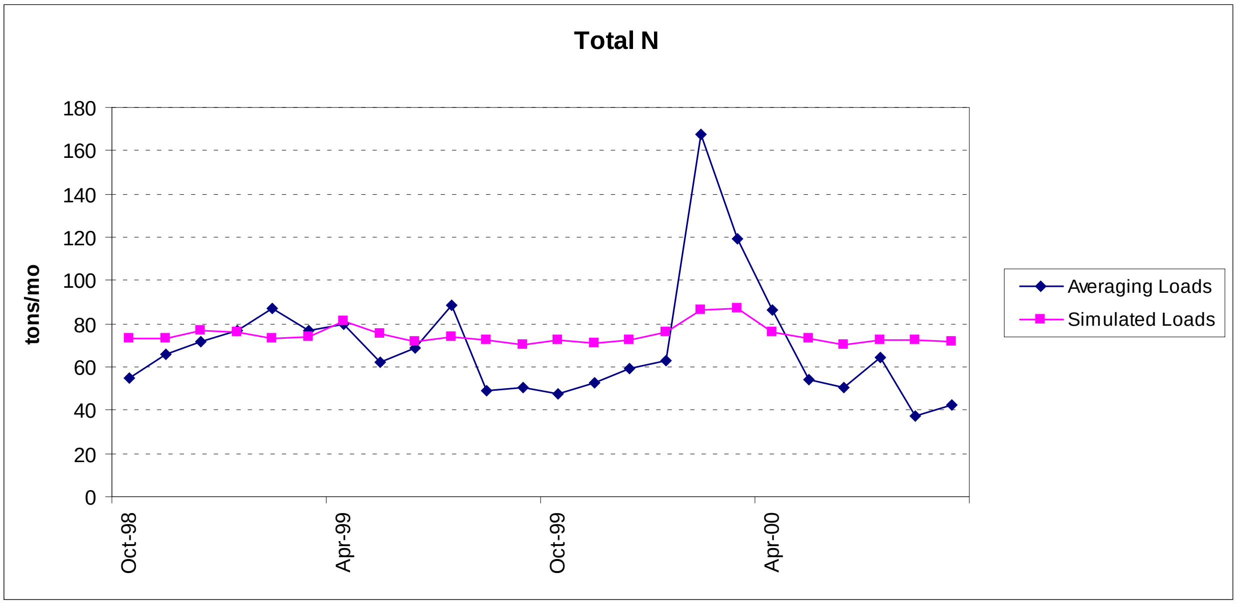


Figure 14. Fit for monthly load of total nitrogen at USGS 11066460 Santa Ana River at MWD Crossing, CA.

Table 12. Model fit statistics (observed minus predicted) for monthly total nitrogen loads using averaging estimator at USGS 11066460 Santa Ana River at MWD Crossing, CA

Statistic	Calibration period (1998-2000)
Relative Percent Error	-5.5%
Average Absolute Error	24.6%
Median Absolute Error	19.2%

Water Quality Results for Larger Watershed

As with hydrology, a spatial calibration approach was adopted. Santa Ana River watershed SWAT model parameters for water quality were transferred to other portions of the watershed with necessary changes to subbasin level parameters. Summary statistics for the SWAT water quality calibration and validation at other stations in the watershed are provided in Table 13 and Table 14.

Table 13. Summary statistics for water quality at all stations – calibration period 1991-2001

Station	USGS 11044000
Relative Percent Error TSS Load	98.0%
Relative Percent Error TP Load	-17.7%
Relative Percent Error TN Load	41.7%

Table 14. Summary statistics for water quality at all stations – validation period 1981-1991

Station	USGS 11044000 (1987 – 1991)
Relative Percent Error TSS Load	97.5%
Relative Percent Error TP Load	1.6%
Relative Percent Error TN Load	75.0%

References

USEPA (United States Environmental Protection Agency). 2008. Using the BASINS Meteorological Database (Version 2006). BASINS Technical Note 10. Office of Water, U.S. Environmental Protection Agency, Washington, DC. http://water.epa.gov/scitech/datait/models/basins/upload/2009_04_13_BASINSs_tecnote10.pdf (Accessed June, 2009).

Appendix T
Model Configuration, Calibration and Validation

Basin: South Platte (SoPlat)

Contents

Tables

Figures

Watershed Background

The South Platte River basin study area was selected as one of the 15 non-pilot application watersheds for the 20 Watershed study. Watershed modeling for the non-pilot areas is accomplished using the SWAT model only, and model calibration and validation results are presented in abbreviated form.

Water Body Characteristics

The South Platte River originates in the mountains of central Colorado at the Continental Divide and flows about 450 miles northeast across the Great Plains to its confluence with the North Platte River at North Platte, Nebraska. The model study area is almost 15,000 mi^2 in size and extends from the headwaters to the plains of central Colorado, consisting of 11 HUC8s within HUC 1019 (Figure 1). Elevation in the model study area ranges from 14,286 ft at Mt. Lincoln on the Continental Divide to about 4,400 ft at the downstream end of the model area. The basin includes two physiographic provinces, the Front Range Section of the Southern Rocky Mountain Province and the Colorado Piedmont Section of the Great Plains Province (Dennehy et al., 1993, 1998; USGS, 2008).

The basin has a continental-type climate modified by topography, in which there are large temperature ranges and irregular seasonal and annual precipitation. Mean temperatures increase from west to east and on the plains from north to south. Areas along the Continental Divide average 30 inches or more of precipitation annually, which includes snowfall in excess of 300 inches. In contrast, the annual precipitation on the plains east of Denver, Colorado, and in the South Park area in the southwest part of the basin, ranges from 7 to 15 inches. Most of the precipitation on the plains occurs as rain, which typically falls between April and September, while most of the precipitation in the mountains occurs as snow, which typically falls between October and March.

Land use and land cover in the South Platte River basin is divided into rangeland (46 percent), agricultural land (18 percent), forest land (24 percent), urban land (7 percent), and other land (5 percent). Rangeland is present across all areas of the basin except over the high mountain forests. Agricultural land is somewhat more restricted to the plains and the South Park area near Fairplay, Colorado. Forest land occurs in a north-south band in the mountains. Urban land is present primarily in the Front Range urban corridor. Irrigated agriculture comprises only 8 percent of the basin but accounts for 71 percent of the water use. Urban lands comprise only 7 percent of the basin but account for 12 percent of the water use (or 27 percent if power generation is considered an urban water use).

To augment water supplies in the basin there are significant diversions of water into the South Platte tributaries from tunnels that connect to the wetter, western side of the Continental Divide, most notably the Colorado-Big Thompson Project (Adams Tunnel) which transports about 285,000 acre-feet per year of Colorado River water through a 13-mile tunnel under the Continental Divide into the Big Thompson River. Overall there are 15 inter-basin transfers into the basin and almost 1,000 reservoirs. Only the three largest mainstem reservoirs are explicitly represented in the model. The limited data available on reservoirs and inter-basin transfers creates significant challenges for hydrologic simulation in this watershed.

The population of the South Platte River basin is about 2.8 million people, over 95 percent of them in Colorado. The basin contains the most concentrated population density in the Rocky Mountain region, located in the Denver metropolitan area and along the Front Range urban corridor in Colorado where the mountains meet the plains. Population densities outside the urban corridor are small and centered in small towns located along the principal streams. The principal economy in the mountainous headwaters is based on tourism and recreation; the economy in the urbanized south-central region mostly is related to manufacturing, service and trade industries, and government services; and the economy of the basin downstream from Denver is based on agriculture and livestock production.

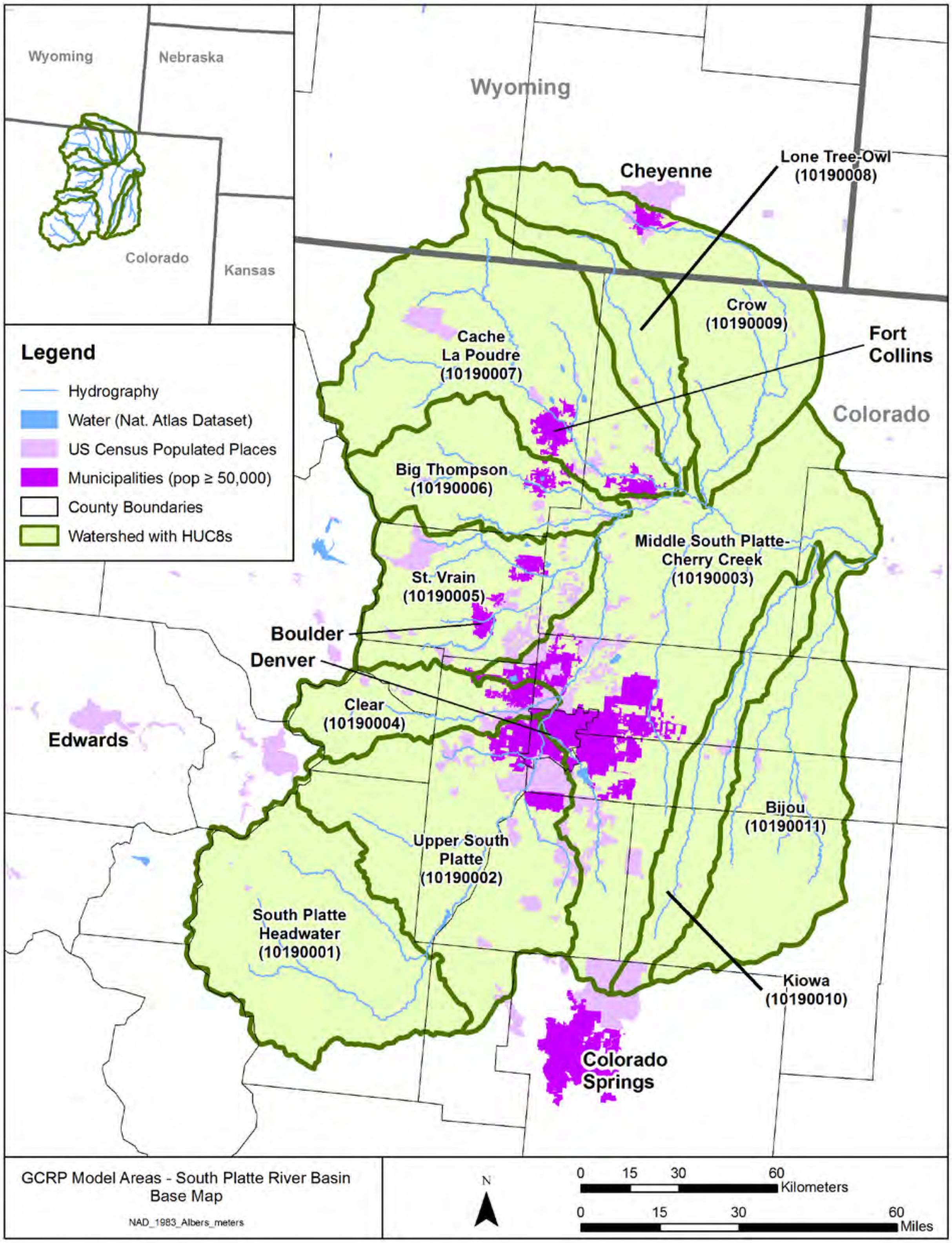


Figure 1. Location of the South Platte watershed.

Soil Characteristics

Soils in the watershed, as described in STATSGO soil surveys, fall primarily (56 percent) into hydrologic soil group (HSG) B (moderately high infiltration capacity). SWAT uses information drawn directly from the soils data layer to populate the model.

Land Use Representation

Land use/cover in the watershed is based on the 2001 National Land Cover Database (NLCD) coverage and is predominantly grassland in the high plains and forest in the mountains, with substantial urban development in the Denver area (Figure 2). NLCD land cover classes were aggregated according to the scheme shown in Table 1 for representation in the GCRP model. SWAT uses the built-in hydrologic response unit (HRU) overlay mechanism in the ArcSWAT interface. SWAT HRUs are formed from an intersection of land use and SSURGO major soils. The distribution of land use in the watershed is summarized in Table 2.

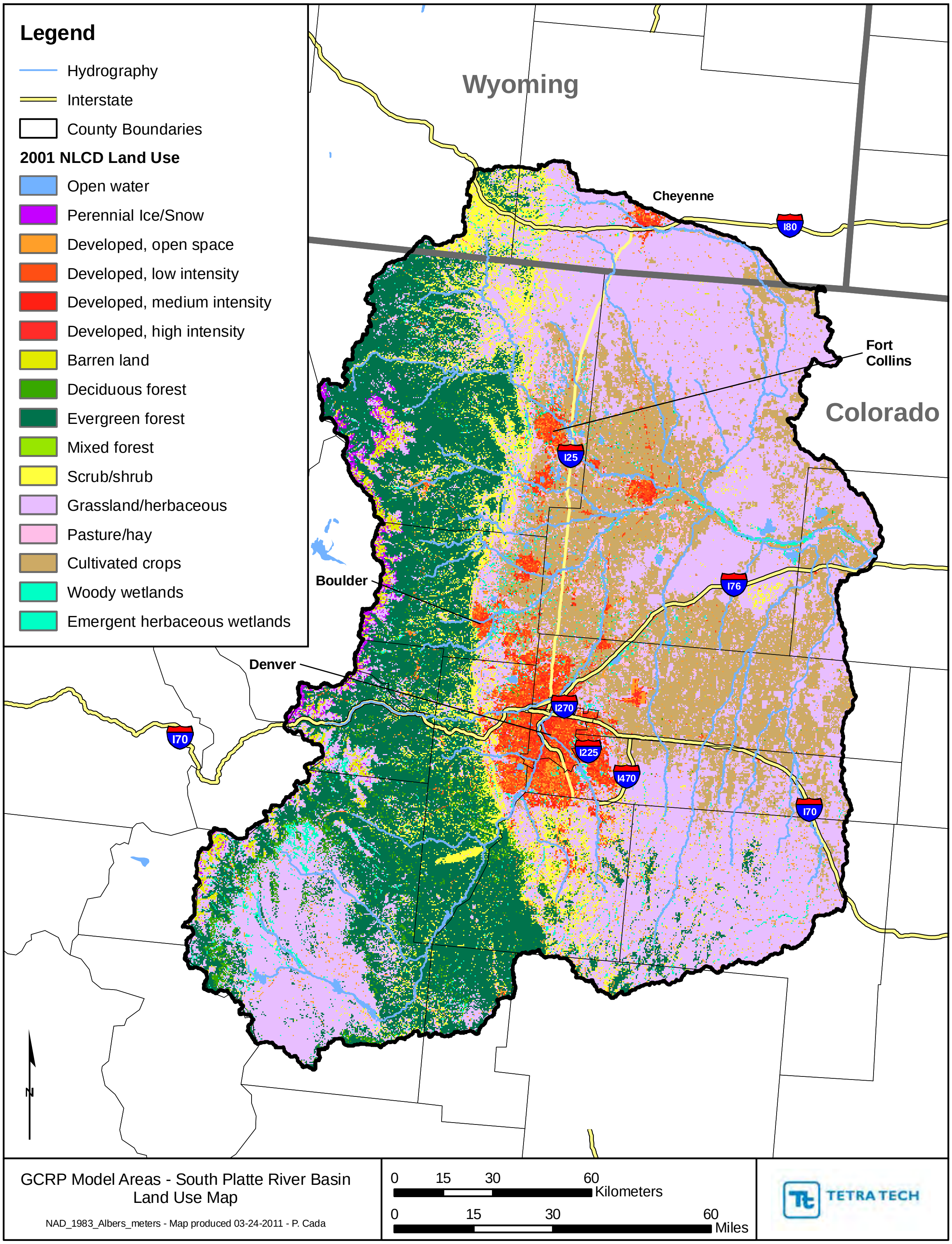


Figure 2. Land use in the South Platte watershed.

Table 1. Aggregation of NLCD land cover classes

NLCD Class	Comments	SWAT class
11 Water	Water surface area usually accounted for as reach area	WATR
12 Perennial ice/snow		WATR
21 Developed open space		URLD
22 Dev. Low Intensity		URMD
23 Dev. Med. Intensity		URHD
24 Dev. High Intensity		UIDU
31 Barren Land		SWRN
41 Forest	Deciduous	FRSD
42 Forest	Evergreen	FRSE
43 Forest	Mixed	FRST
51-52 Shrubland		RNGB
71-74 Herbaceous Upland		RNGE
81 Pasture/Hay		HAY
82 Cultivated		AGRR
91-97 Wetland	Emergent & woody wetlands	WETF, WETL, WETN
98-99 Wetland	Aquatic bed wetlands (not emergent)	WATR

Table 2. Land use distribution for the South Platte watershed (2001 NLCD) (mi^2)

HUC 8 watershed	Open water	Snow/Ice	Developed[a] Open space	Developed[a] Low density	Developed[a] Medium density	Developed[a] High density	Barren land	Forest	Shrubland	Pasture/Hay	Cultivated	Wetland	Total
South Platte Headwater. **10190001**	13.7	7.5	19.8	1.2	0.0	0.0	37.9	526.3	921.1	6.6	0.1	70.0	1,604.3
Upper Southe Platte **10190002**	9.5	3.2	68.3	94.6	34.3	11.5	16.7	1,125.5	440.9	3.2	2.5	39.7	1,849.7
Middle South Platte-Cherry Creek **10190003**	40.0	0.0	131.9	129.8	71.2	27.6	4.2	45.4	1,301.2	71.6	977.5	78.3	2,878.6
Clear **10190004**	3.3	19.8	18.7	40.7	13.0	3.9	21.2	280.9	153.1	1.5	0.6	9.2	565.8
St. Vrain, **10190005**	16.6	27.5	29.0	43.5	15.7	3.9	25.6	397.4	174.1	42.1	166.8	37.1	979.2
Big Thompson. **10190006**	13.1	13.4	17.1	17.7	5.9	1.0	21.6	379.8	196.6	17.1	131.2	17.4	832.0
Cache La Poudre. **10190007**	27.0	24.7	36.1	41.8	14.1	3.3	18.3	630.0	721.8	44.6	288.4	40.3	1,890.5
Lone Tree-Owl.. **10190008**	0.7	0.0	14.9	2.2	0.5	0.0	1.3	1.9	414.9	6.9	130.9	3.6	578.0
Crow. **10190009**	1.9	0.0	33.2	12.8	7.0	1.8	5.6	30.9	1,126.2	12.7	148.5	9.1	1,389.8
Kiowa. **10190010**	0.2	0.0	23.1	1.5	0.5	0.1	0.6	31.0	414.6	4.2	231.0	10.1	716.8
Bijou **10190011**	1.1	0.0	42.9	2.3	0.5	0.0	0.6	27.9	938.9	8.7	342.0	18.8	1,383.7
Total	127.2	96.1	434.8	388.1	162.7	53.2	153.5	3,477.0	6,803.3	219.2	2,419.4	333.8	14,668.3

[a]The percent imperviousness applied to each of the developed land uses is as follows: open space (6.41%), low density (33.46%), medium density (60.79%), and high density (86.76%).

Point Sources

There are numerous point source discharges in the watershed. Only the major dischargers, with a design flow greater than 1 MGD are included in the simulation (Table 3). The major dischargers are represented at long-term average flows, without accounting for changes over time or seasonal variations.

Table 3. Major point source discharges in the South Platte watershed

NPDES ID	Name	Design flow (MGD)	Observed flow (MGD) (1991-2006 average)
CO0001091	PUBLIC SERVICE CO. OF COLORADO		0.2798
CO0001104	PUBLIC SERVICE CO. OF COLO.		1.8487
CO0001139	PUBLIC SERVICE COMPANY OF COLO		0.0985
CO0001147	SUNCOR ENERGY (USA) INC.		1.7383
CO0001163	COORS BREWING COMPANY		11.436
CO0001511	LOCKHEED MARTIN SPACE SYSTEMS		0.3062
CO0020290	ESTES PARK SANITATION DISTRICT	1.5	0.5006
CO0020320	WINDSOR, TOWN OF	1.5	1.001
CO0020478	BOXELDER SANITATION DISTRICT	2.34	1.6335
CO0020508	EVANS, CITY OF	0.9	0.8319
CO0020737	SOUTH FORT COLLINS SAN DIST	3	1.0112
CO0021440	FORT LUPTON, CITY OF	2.75	1.0882
CO0021547	BRIGHTON, CITY OF	3	1.8255
CO0021580	ST. VRAIN SANITATION DISTRICT	1.5	0.5402
CO0023078	LOUISVILLE, CITY OF	3.4	1.8457
CO0023124	LAFAYETTE, CITY OF	4.4	1.6297
CO0024147	BOULDER, CITY OF	20.5	16.177
CO0024171	WESTMINSTER, CITY OF	9.2	6.3946
CO0026409	BROOMFIELD, CITY OF	3.2	3.7007
CO0026425	FORT COLLINS, CITY OF	7	16.261
CO0026611	AURORA, CITY OF	2.6	2.7601
CO0026638	METRO WASTEWATER RECLAM DIST	220	159.81
CO0026662	SOUTH ADAMS COUNTY W&S DIST	2.28	2.8959
CO0026671	LONGMONT, CITY OF	17	7.9692
CO0026701	LOVELAND, CITY OF	10	5.6427
CO0027707	SWIFT BEEF COMPANY	2.8	2.5889
CO0032999	LITTLETON/ENGLEWOOD, CITIES OF	28	24.182
CO0037966	CENTENNIAL WATER & SAN. DIST.	8.48	3.5751
CO0040258	GREELEY, CITY OF	14.7	8.0844
CO0040681	ARAPAHOE COUNTY W&WW AUTHORITY	2.4	0.842
CO0041700	ST. VRAIN SANITATION DISTRICT	3	1.0304
CO0043010	SUPERIOR METROPOLITAN DIST NO1		0.2913
WY0000442	Frontier Refining Inc	0	0.8737
WY0022381	Cheyenne BOPU	3.5	3.675

Most of these point sources have relatively sparse water quality monitoring for nutrients. The point sources were initially represented in the model with an assumed total phosphorus concentration of 7.2 mg/L and total nitrogen concentration of 11.2 mg/L for secondary treatment facilities (Tetra Tech 1999).

Meteorological Data

The required meteorological time series for the GCRP SWAT simulations are precipitation and air temperature. The GCRP simulations do not include water temperature simulation and use a degree-day method for snowmelt. SWAT estimates Penman-Monteith potential evapotranspiration using a statistical weather generator for inputs other than temperature and precipitation. These meteorological time series are drawn from the BASINS4 Meteorological Database (USEPA 2008), which provides a consistent, quality-assured set of nationwide data with gaps filled and records disaggregated. Scenario application requires simulation over 30 years, so the available stations are those with a common 30-year period of record (or one that can be filled from an approximately co-located station) that covers the year 2000. A total of 33precipitation stations were identified for use in the Minnesota River model with a common period of record of 10/1/1969-9/30/2000 (Table 4). Temperature records are sparser; where these are absent temperature is taken from nearby stations with an elevation correction.

Table 4. Precipitation stations for the South Platte watershed model

COOP ID	Name	Latitude	Longitude	Temperature	Elevation (m)
CO050183	ALLENSPARK 2SE	40.1881	-105.502	X	2504
CO050263	ANTERO RESERVOIR	38.9933	-105.892	X	2719
CO050454	BAILEY	39.4047	-105.477	X	2356
CO050843	BOULDER 2	40.0339	-105.281	X	1650
CO050848	BOULDER	39.9919	-105.267	X	1672
CO050945	BRIGGSDALE	40.635	-104.327	X	1473
CO051179	BYERS 5 ENE	39.7403	-104.128	X	1554
CO051186	CABIN CREEK	39.6553	-105.709	X	3054
CO051528	CHEESMAN	39.2203	-105.278	X	2097
CO051547	CHERRY CREEK DAM	39.6261	-104.832	X	1721
CO052162	DEER TRAIL 3 NW	39.6419	-104.078		1554
CO052220	DENVER STAPELTON	39.7633	-104.869	X	1611
CO052494	EASTONVILLE 2 NNW	39.1092	-104.6		2198
CO052790	EVERGREEN	39.6381	-105.315	X	2129
CO053005	FORT COLLINS	40.6147	-105.131	X	1525
CO053038	FORT MORGAN	40.2617	-103.804	X	1320
CO053530	GRANT	39.4608	-105.679	X	2644
CO053553	GREELEY UNC	40.4022	-104.699	X	1437
CO053584	GREENLAND 6 NE	39.2167	-104.738		2103
CO054155	HOYT	39.9875	-104.085		1460
CO054452	KASSLER	39.49	-105.095	X	1703
CO054762	LAKEWOOD	39.7489	-105.121	X	1719
CO055116	LONGMONT 2 ESE	40.1589	-105.074	X	1509
CO055121	LONGMONT 6 NW	40.2467	-105.146		1570
CO056023	NUNN	40.7064	-104.783	X	1584
CO057510	SEDALIA 4 SSE	39.4036	-104.952		1821
CO057664	SIMLA	39.1397	-104.088		1828
CO058839	WATERDALE	40.4256	-105.21	X	1594

COOP ID	Name	Latitude	Longitude	Temperature	Elevation (m)
CO059210	WOODLAND PARK 8 NNW	39.1006	-105.094		2365
WY481547	CARPENTER 3N	41.0844	-104.379	X	1657
WY481675	CHEYENNE WSFO AP	41.1578	-104.807	X	1864
WY484930	JELM 2S	41.06	-106.026		2310
WY485420	LARAMIE 2 WSW	41.3042	-105.641		2187

Watershed Segmentation

The South Platte River watershed was divided into 75 subwatersheds for the purposes of modeling (Figure 3). The initial calibration was done at gage 06714000, South Platte River at Denver. The model encompasses the complete watershed; however, there are significant inter-basin transfers across the Continental Divide into the headwaters of the system. These external sources are represented based on best available data and not changed for climate scenarios. The scenarios thus represent the changes due only to potential weather changes within the watershed.

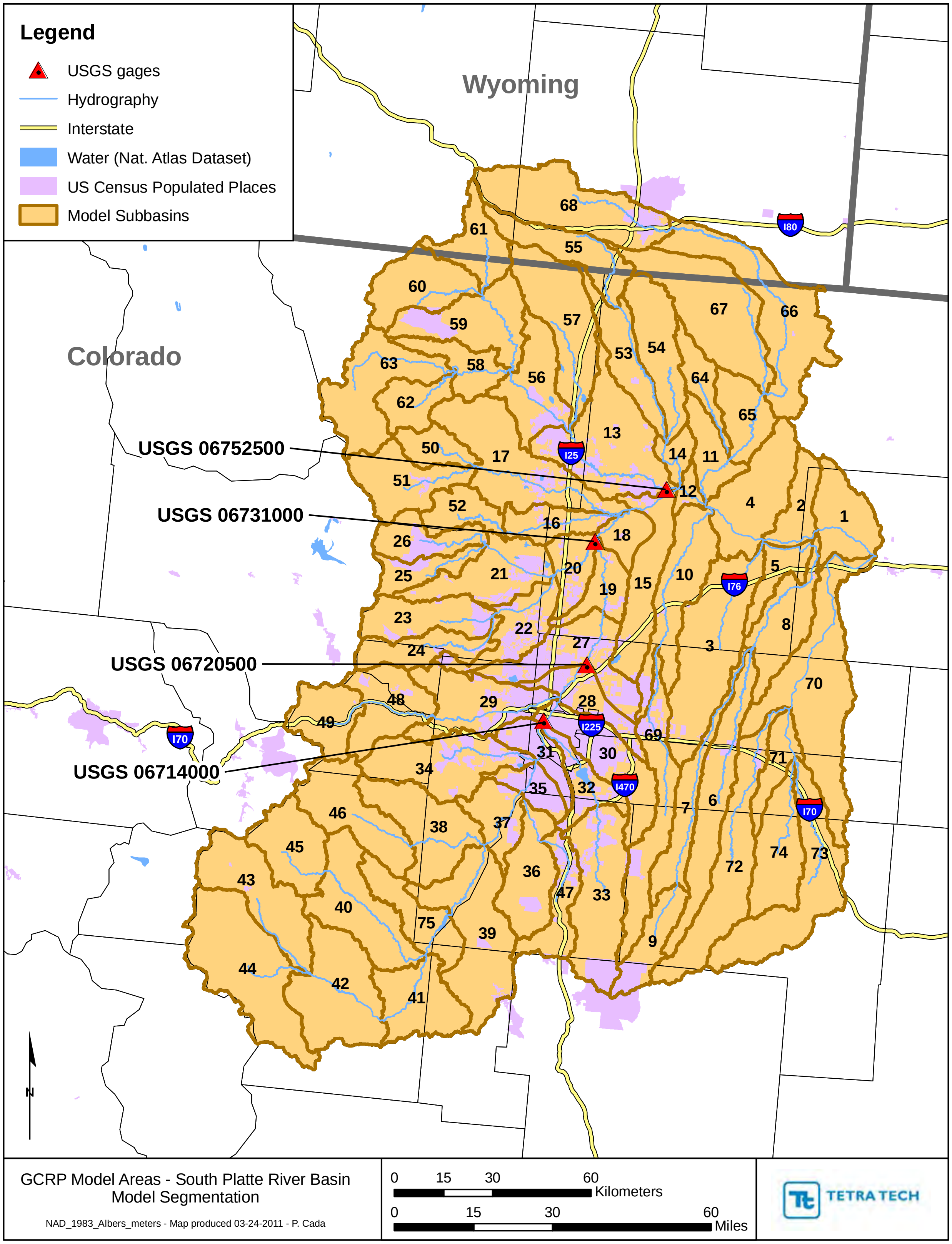


Figure 3. Model segmentation and USGS stations utilized for the South Platte River watershed.

Calibration Data and Locations

The specific site chosen for initial calibration was the South Platte River at Denver (USGS 06714000), a flow and water quality monitoring location that approximately coincides with the mouth of an 8-digit HUC covering the upstream portion of the watershed. This station was selected because there is a good set of flow and water quality data available and the watershed lacks major point sources and impoundments. Calibration and validation were pursued at multiple locations (Table 5). Parameters derived at the initial station were not fully transferable to other portions of the watershed, and additional calibration was conducted at multiple gage locations.

Table 5. Calibration and validation locations in the South Platte watershed

Station name	USGS ID	Drainage area (mi^2)	Hydrology calibration	Water quality calibration
South Platte River at Denver, CO	06714000	3,861	X	X
South Platte River at Henderson, CO	06720500	4,768	X	X
South Platte River near Kersey, CO	06754000	9,659	X	X
South Platte River near Weldona, CO	06758500	13,190	X	X

The model hydrology calibration period was set to Water Years 1991-2000 (within the 30-year period of record for modeling). Hydrologic validation was then performed on Water Years 1981-1990. Water quality calibration used calendar years 1993-2000, while validation used 1988-1990, as only limited data were available for earlier years.

SWAT Modeling

Assumptions

The South Platte River basin has primarily a semiarid climate and, as a result, a long history of water development beginning about 1870 with live stream diversions from the Cache la Poudre River. Water shortages in the 1930s prompted the creation of large scale inter-basin transports, most notably the Colorado-Big Thompson Project (Adams Tunnel) which transports about 285,000 acre-feet per year of Colorado River water through a 13-mile tunnel under the Continental Divide into the Big Thompson River. Overall there are 15 inter-basin transfers into the basin and almost 1,000 reservoirs (Dennehy et al. 1993). There are also multiple water diversions within the system.

Representing these managed features is a challenge for modeling. The three largest inter-basin transfers, each with a quantity of greater than 50,000 acre feet per year (Adams, Moffat, and Roberts, to the Big Thompson River, Boulder Creek, and Bear Creek respectively) were represented in the model based on a constant monthly pattern. These account for about 95 percent of the inter-basin transfers (383,000 acre feet per year). Only a few of the many reservoirs in the basin are modeled explicitly, with a focus on those that control flow in the mainstem rather than providing sidestream storage. Three reservoirs were represented in the South Platte watershed model, namely, Eleven Mile Canyon, Cheesman and Chatfield. The target storage method was adopted for these reservoirs, yielding an approximation of actual behavior. Pertinent reservoir information was collected from the Colorado Decision Support Systems.

Numerous other reservoirs and water transfers are not included in the model. This limits the ability of the simulation to mimic observed flows. Conclusions should thus be drawn on the relative change in flows predicted under future scenarios, rather than on quantitative estimates of flow.

Hydrology Calibration

A spatial calibration approach was adopted for GCRP-SWAT modeling for the South Platte basin. The initial calibration at the edge of the Rockies was extended downstream with adjustment of parameters for the high plains portion of the watershed. The calibration is strongly influenced by assumptions about water transfers, withdrawals, and discharges in the basin.

The initial calibration focus area (South Platte River at Denver) includes 15 subwatersheds and is representative the Rocky Mountain portion of the overall watershed. The parameters were adjusted within the practical range to obtain reasonable fit between the simulated and measured flows in terms of Nash-Sutcliffe modeling efficiency and the high flow and low flow components as well as the seasonal flows.

The water balance of the whole South Platte River basin predicted by the SWAT model over the 30-year simulation period is as follows:

```
PRECIP =    384.4 MM
SNOW FALL =  108.78 MM
SNOW MELT =    99.46 MM
SUBLIMATION =     9.04 MM
SURFACE RUNOFF Q =    41.26 MM
LATERAL SOIL Q =   26.55 MM
TILE Q =     0.00 MM
GROUNDWATER (SHAL AQ) Q =    32.28 MM
REVAP (SHAL AQ => SOIL/PLANTS) =    2.96 MM
```

```
DEEP AQ RECHARGE =     0.00 MM
TOTAL AQ RECHARGE =   35.25 MM
TOTAL WATER YLD =    79.88 MM
PERCOLATION OUT OF SOIL =   15.10 MM
ET =    346.2 MM
PET =   1383.3MM
TRANSMISSION LOSSES =    20.20 MM
```

Hydrologic calibration adjustments focused on the following parameters:

- CN2 (initial SCS runoff curve number for moisture condition II)
- ESCO (soil evaporation compensation factor)
- SURLAG (surface runoff lag coefficient)
- SOL_AWC (available water capacity of the soil layer, mm water/mm of soil)
- ALPHA_BF (baseflow alpha factor, days)
- GW_DELAY (groundwater delay time, days)
- GWQMIN (threshold depth of water in the shallow aquifer required for return flow to occur, mm)
- GW_REVAP (groundwater “revap” coefficient)
- CH_N1 (Manning’s “n” value for tributary channels)
- CH_N2 (Manning’s “n” value for main channels)
- CH_K1 (Effective hydraulic conductivity in tributary channel alluvium)
- CH_K2 (Effective hydraulic conductivity in main channel alluvium)
- SFTMP (Snowfall temperature)
- SMTMP (Snowmelt base temperature)
- SMFMX (Maximum melt rate for snow during the year)
- SMFMN (Minimum melt rate for snow during the year)

Calibration results for the South Platte River at Denver are summarized in Figure 4, Figure 5, Figure 6, Figure 7, and Table 6. The quality of the fit is fair, with a tendency to underpredict flows in the winter and overpredict flows in the summer and fall. Much of this discrepancy is believed to be due to the complex series of water imports, storage, and withdrawals in the watershed.

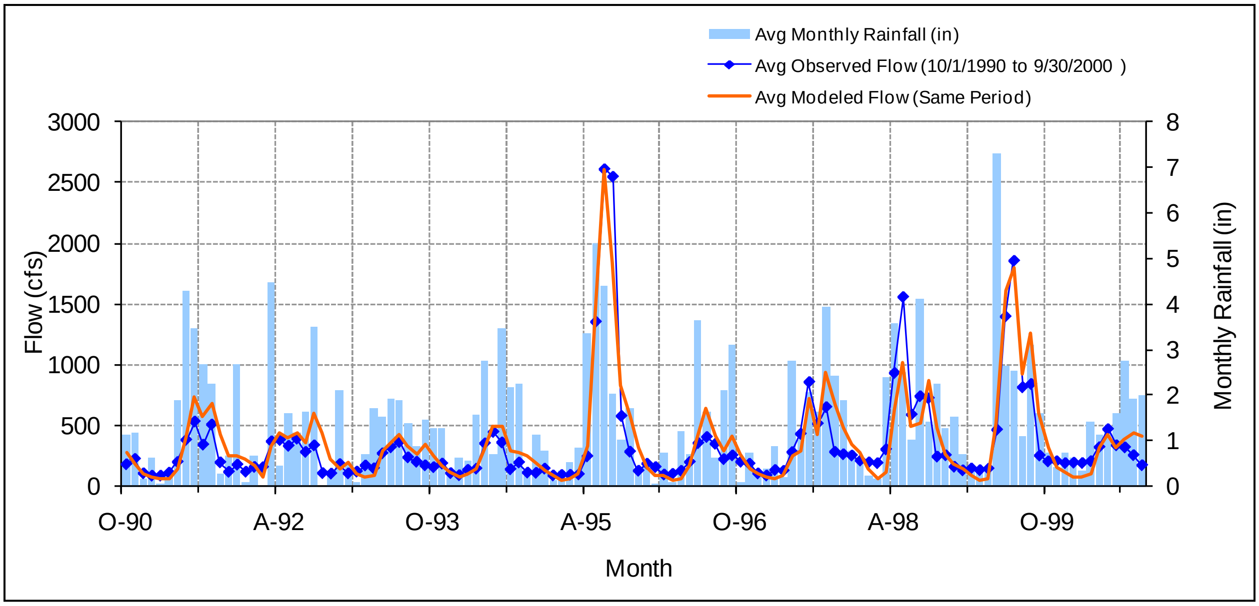


Figure 4. Mean monthly flow at USGS 06714000, South Platte River at Denver, CO – calibration period.

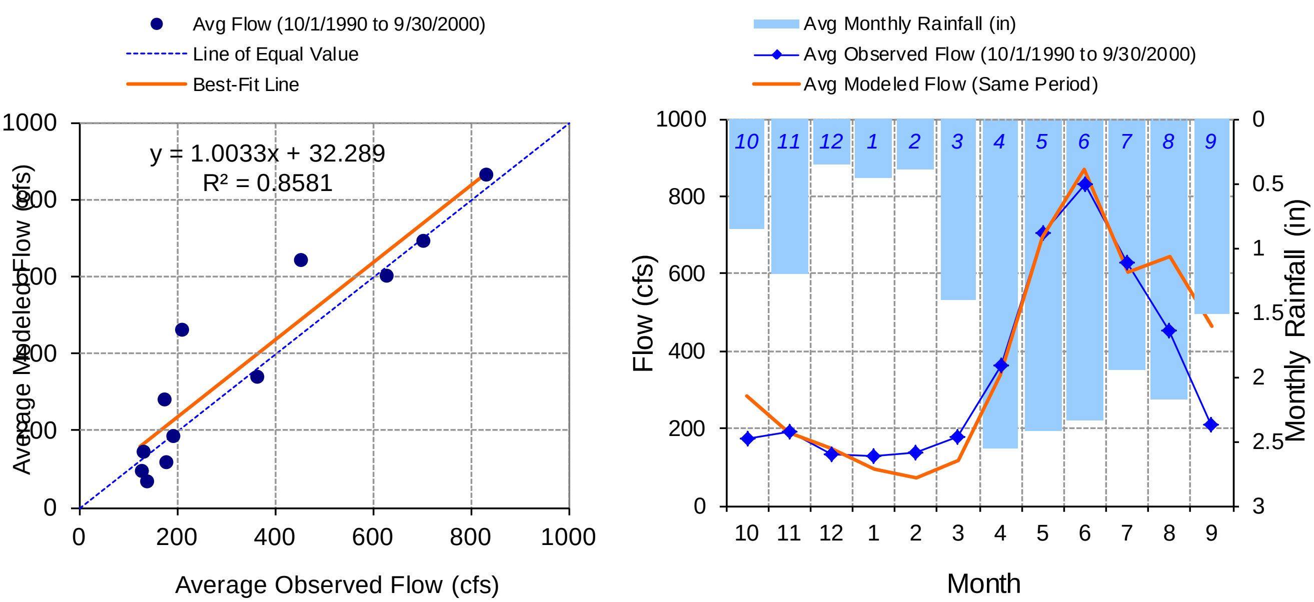


Figure 5. Seasonal regression and temporal aggregate at USGS 06714000, South Platte River at Denver, CO - calibration period.

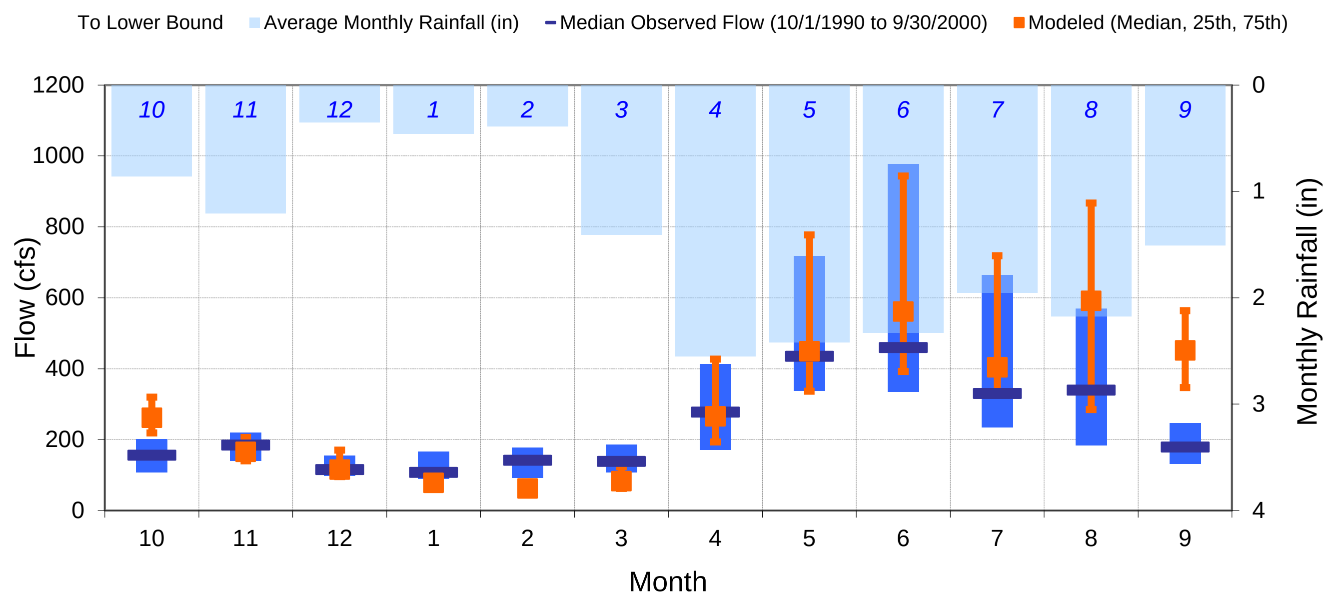


Figure 6. **Seasonal medians and ranges at USGS 06714000, South Platte River at Denver, CO – calibration period.**

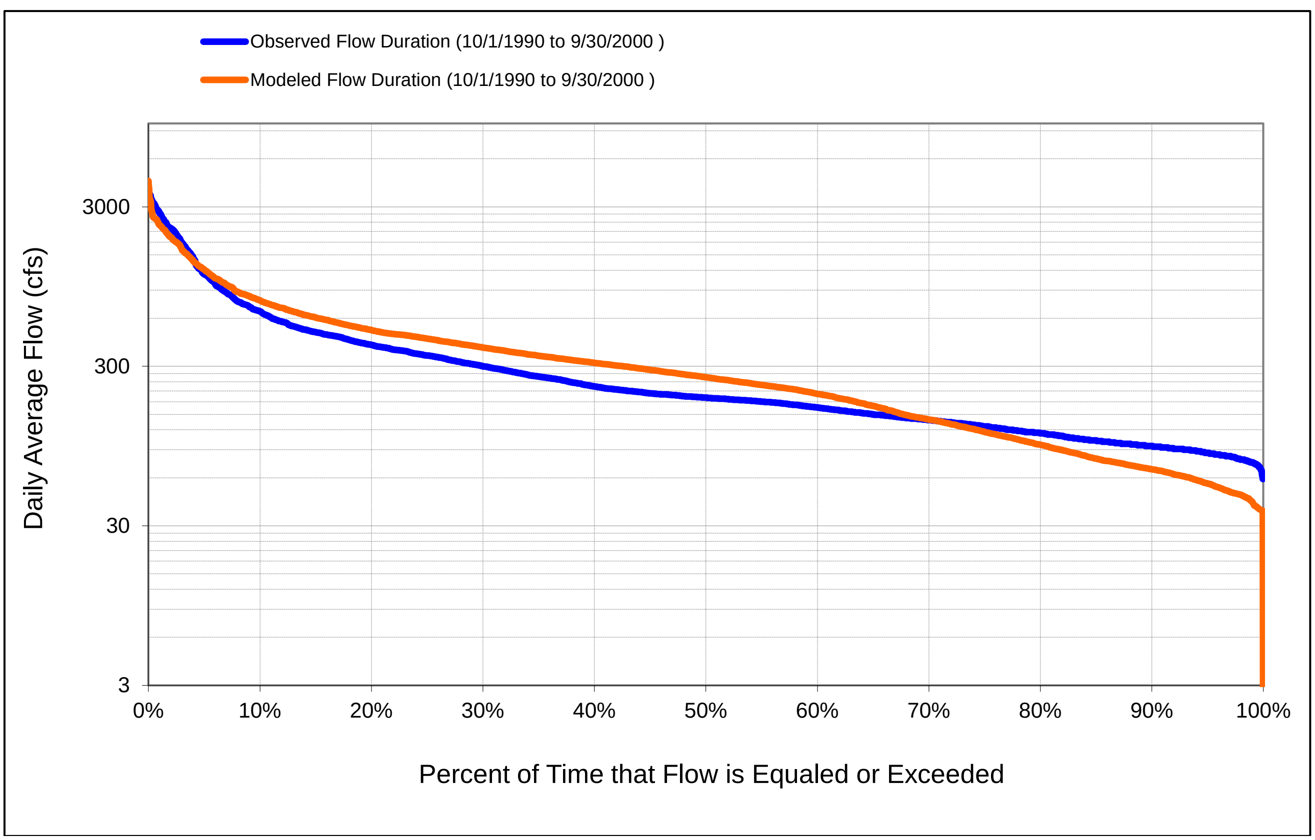


Figure 7. **Flow exceedance at USGS 06714000, South Platte River at Denver, CO - calibration period.**

Table 6. Summary statistics at USGS 06714000, South Platte River at Denver, CO – calibration period

SWAT Simulated Flow		Observed Flow Gage	
REACH OUTFLOW FROM OUTLET(S) 31, 32 10-Year Analysis Period: 10/1/1990 - 9/30/2000 Flow volumes are (inches/year) for upstream drainage area		USGS 06714000 SOUTH PLATTE RIVER AT DENVER, CO Hydrologic Unit Code: 10190003 Latitude: 39.759722222 Longitude: -105.166666666 Drainage Area (sq-mi): 3861	
Total Simulated In-stream Flow:	**1.05**	Total Observed In-stream Flow:	**0.95**
Total of simulated highest 10% flows:	**0.40**	Total of Observed highest 10% flows:	**0.41**
Total of Simulated lowest 50% flows:	**0.18**	Total of Observed Lowest 50% flows:	**0.18**
Simulated Summer Flow Volume (months 7-9):	**0.40**	Observed Summer Flow Volume (7-9):	**0.30**
Simulated Fall Flow Volume (months 10-12):	**0.14**	Observed Fall Flow Volume (10-12):	**0.11**
Simulated Winter Flow Volume (months 1-3):	**0.07**	Observed Winter Flow Volume (1-3):	**0.10**
Simulated Spring Flow Volume (months 4-6):	**0.44**	Observed Spring Flow Volume (4-6):	**0.44**
Total Simulated Storm Volume:	**0.20**	Total Observed Storm Volume:	**0.29**
Simulated Summer Storm Volume (7-9):	**0.07**	Observed Summer Storm Volume (7-9):	**0.10**

Errors (Simulated-Observed)	*Error Statistics*	*Recommended Criteria*		
Error in total volume:	9.82	10		
Error in 50% lowest flows:	1.05	10		
Error in 10% highest flows:	-3.29	15		
Seasonal volume error - Summer:	**32.89**	**30**		
Seasonal volume error - Fall:	26.06 >>	30	Clear	
Seasonal volume error - Winter:	**-35.47**	**30**		
Seasonal volume error - Spring:	0.17	30		
Error in storm volumes:	**-29.43**	**20**		
Error in summer storm volumes:	-35.56	50		
Nash-Sutcliffe Coefficient of Efficiency, E:	0.738	Model accuracy increases		
Baseline adjusted coefficient (Garrick), E':	0.439	as E or E' approaches 1.0		
Monthly NSE	0.857			

Hydrology Validation

Hydrology validation for the South Platte River at Denver was performed for the period 10/1/1980 through 9/30/1990. Like the calibration, the validation fails to achieve all desired seasonal criteria and attains only a mediocre value for model fit efficiency – likely due in large part to water imports and withdrawals. Results are summarized in Figure 8, Figure 9, Figure 10, Figure 11, and Table 7.

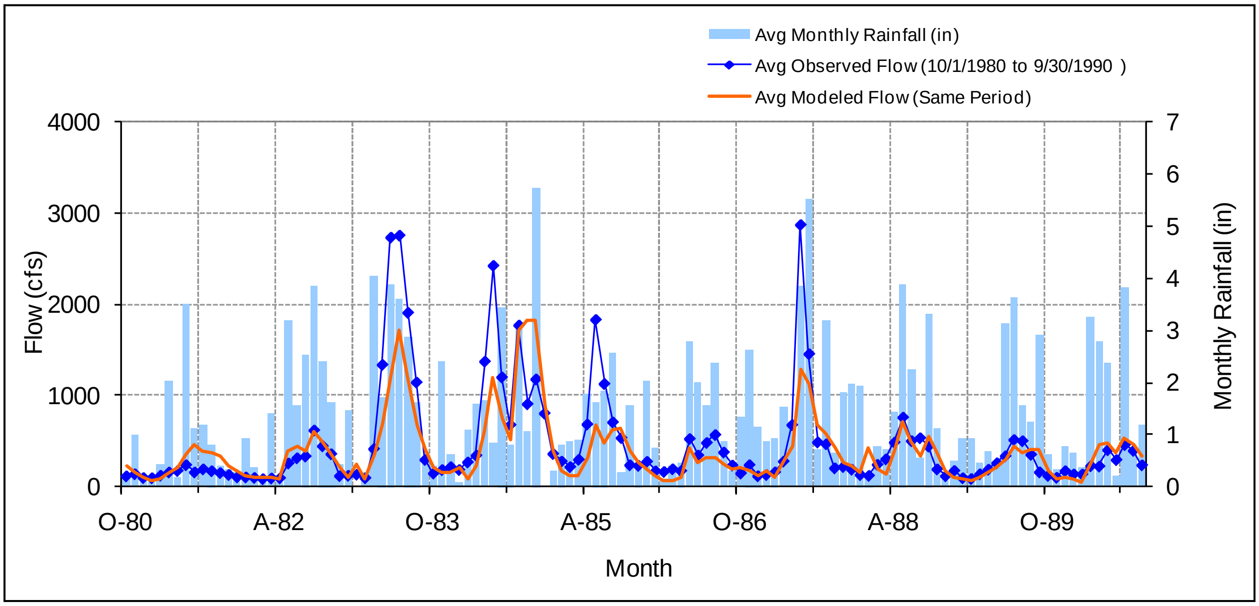
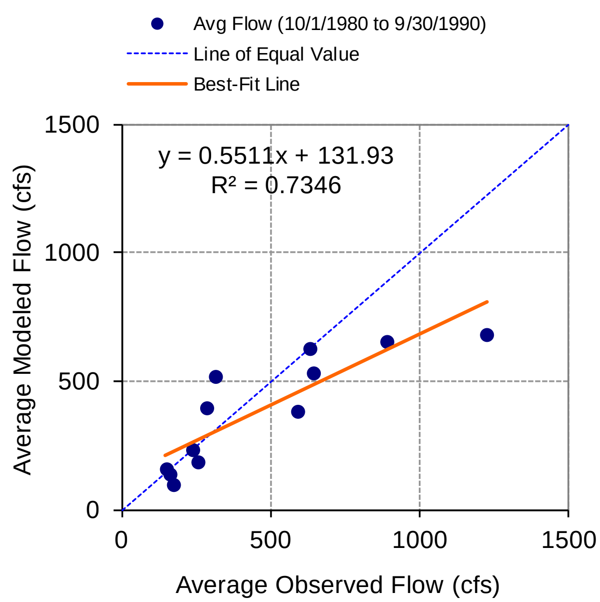


Figure 8. Mean monthly flow at USGS 06714000, South Platte River at Denver, CO – validation period.



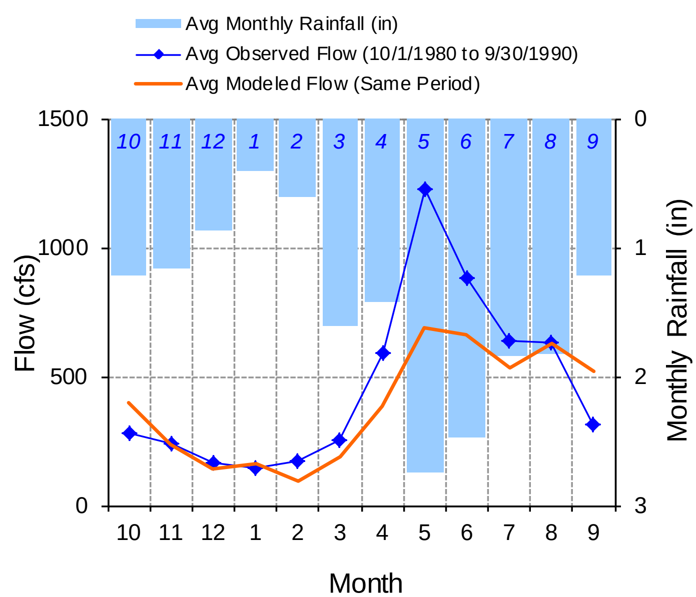


Figure 9. Seasonal regression and temporal aggregate at USGS 06714000, South Platte River at Denver, CO - validation period.

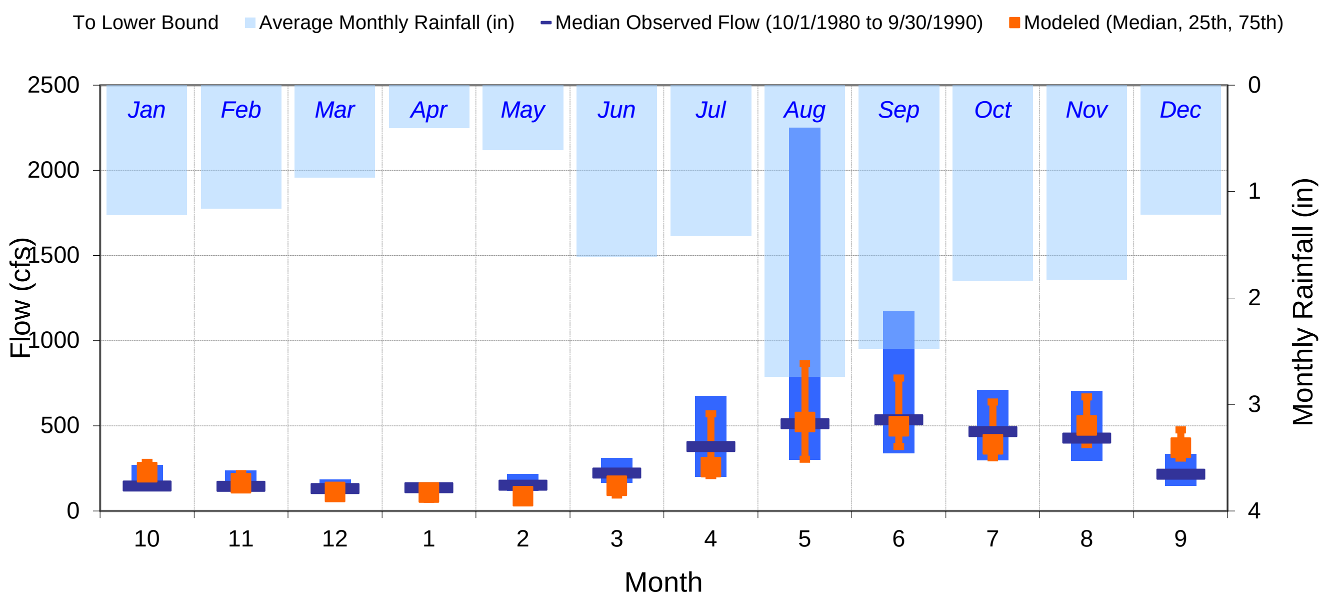


Figure 10. Seasonal medians and ranges at USGS 06714000, South Platte River at Denver, CO – validation period.

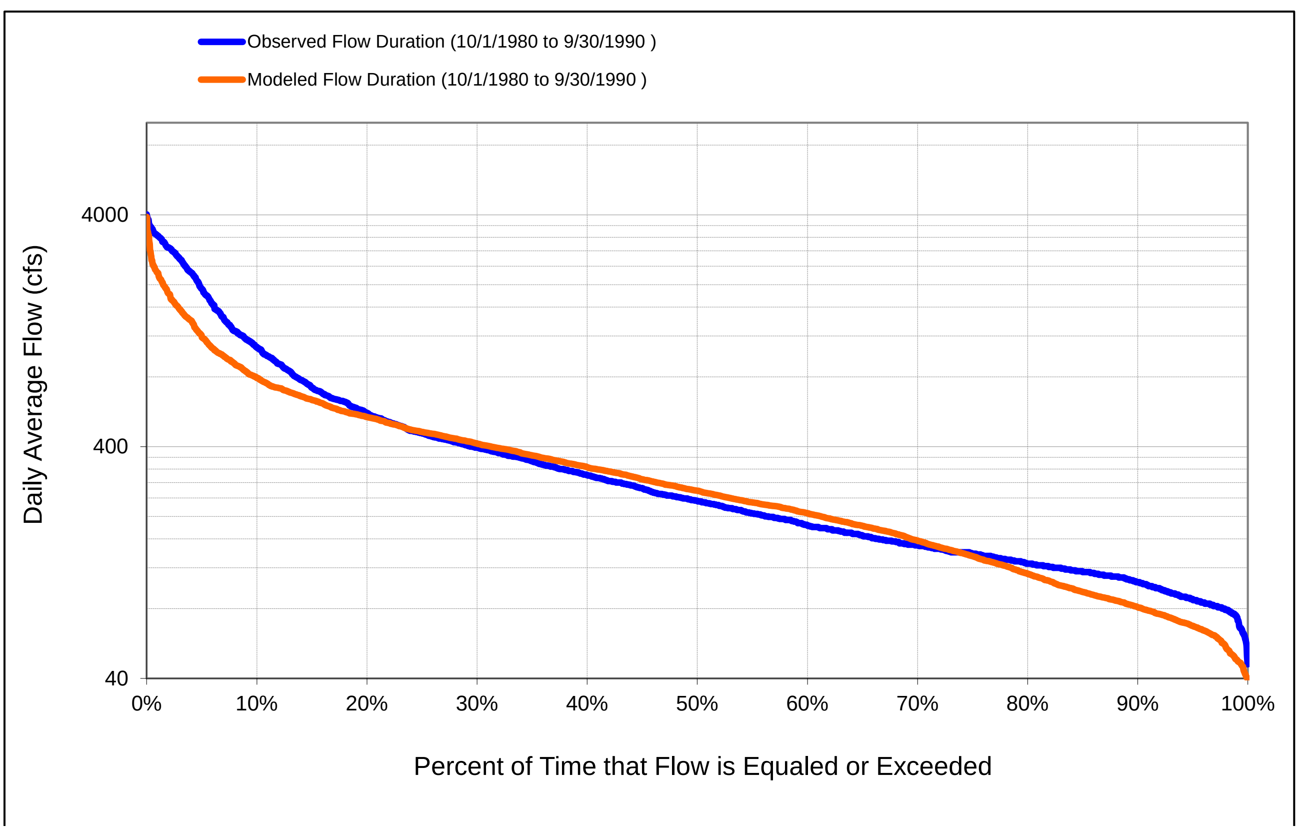


Figure 11. Flow exceedance at USGS 06714000, South Platte River at Denver, CO - validation period.

Table 7. Summary statistics at USGS 06714000, South Platte River at Denver, CO - validation period

SWAT Simulated Flow		Observed Flow Gage	
REACH OUTFLOW FROM OUTLET(S) 31, 32 10-Year Analysis Period: 10/1/1980 - 9/30/1990 Flow volumes are (inches/year) for upstream drainage area		USGS 06714000 SOUTH PLATTE RIVER AT DENVER, CO Hydrologic Unit Code: 10190003 Latitude: 39.759722222 Longitude: -105.166666666 Drainage Area (sq-mi): 3861	
Total Simulated In-stream Flow:	**1.07**	Total Observed In-stream Flow:	**1.28**
Total of simulated highest 10% flows:	**0.39**	Total of Observed highest 10% flows:	**0.58**
Total of Simulated lowest 50% flows:	**0.20**	Total of Observed Lowest 50% flows:	**0.20**
Simulated Summer Flow Volume (months 7-9):	**0.39**	Observed Summer Flow Volume (7-9):	**0.37**
Simulated Fall Flow Volume (months 10-12):	**0.18**	Observed Fall Flow Volume (10-12):	**0.16**
Simulated Winter Flow Volume (months 1-3):	**0.10**	Observed Winter Flow Volume (1-3):	**0.13**
Simulated Spring Flow Volume (months 4-6):	**0.40**	Observed Spring Flow Volume (4-6):	**0.62**
Total Simulated Storm Volume:	**0.25**	Total Observed Storm Volume:	**0.42**
Simulated Summer Storm Volume (7-9):	**0.08**	Observed Summer Storm Volume (7-9):	**0.14**
Errors (Simulated-Observed)	*Error Statistics*	*Recommended Criteria*	
Error in total volume:	**-16.28**	**10**	
Error in 50% lowest flows:	-0.62	10	
Error in 10% highest flows:	**-32.91**	**15**	
Seasonal volume error - Summer:	5.88	30	
Seasonal volume error - Fall:	13.67	>> 30	Clear
Seasonal volume error - Winter:	-21.65	30	
Seasonal volume error - Spring:	**-35.95**	**30**	
Error in storm volumes:	**-39.52**	**20**	
Error in summer storm volumes:	-39.71	50	
Nash-Sutcliffe Coefficient of Efficiency, E:	0.523	Model accuracy increases	
Baseline adjusted coefficient (Garrick), E':	0.423	as E or E' approaches 1.0	
Monthly NSE	0.627		

Hydrology Results for Larger Watershed

Minor adjustments were made to the parameters determined for the initial calibration gage to improve the fit downstream. Calibration and validation was pursued at a total of four gages in the watershed. Calibration results were fair at most gages, as summarized in Table 8, with significant seasonal volume errors. This is primarily the result of the simplified representation of inter-basin transfers and reservoir storage in the watershed, and so is deemed acceptable.

Results of the validation exercise are summarized in Table 9. Problems similar to those experienced in the calibration period were seen at all the gages and total flows tended to be underpredicted, likely due to an increase in storage and withdrawals since the 1980s.

Table 8. Summary statistics (percent error): all stations - calibration period

Station	06714000 South Platte River at Denver, CO	06720500 South Platte River at Henderson, CO	06754000 South Platte River near Kersey, CO	06758500 South Platte River near Weldona, CO
Error in total volume:	9.82	3.89	10.69	-0.38
Error in 50% lowest flows:	1.05	1.79	-1.85	-9.55
Error in 10% highest flows:	-3.29	-3.37	-1.04	8.26
Seasonal volume error - Summer:	32.89	14.68	54.26	33.55
Seasonal volume error - Fall:	26.06	-5.77	-25.53	-28.93
Seasonal volume error - Winter:	-35.47	-27.37	-23.18	-45.57
Seasonal volume error - Spring:	0.17	10.68	20.03	11.49
Error in storm volumes:	-29.43	-0.10	-32.95	-41.56
Error in summer storm volumes:	-35.56	-0.31	-24.85	-25.86
Daily Nash-Sutcliffe Coefficient of Efficiency, E:	0.738	0.610	0.597	0.628
Monthly Nash-Sutcliffe Coefficient:	0.857	0.811	0.689	0.734

Table 9. Summary statistics: all stations - validation period

Station	06714000 South Platte River at Denver, CO	06720500 South Platte River at Henderson, CO	06754000 South Platte River near Kersey, CO	06758500 South Platte River near Weldona, CO
Error in total volume:	-16.28	-15.23	-18.38	-34.38
Error in 50% lowest flows:	-0.62	-3.83	-3.73	-15.24
Error in 10% highest flows:	-32.91	-26.23	-36.86	-37.64
Seasonal volume error - Summer:	5.88	3.72	16.98	-3.46
Seasonal volume error - Fall:	13.67	-6.26	-32.91	-49.87
Seasonal volume error - Winter:	-21.65	-28.43	-39.92	-57.46
Seasonal volume error - Spring:	-35.95	-25.81	-18.82	-32.82
Error in storm volumes:	-39.52	-7.64	-42.20	-52.40
Error in summer storm volumes:	-39.71	6.38	-42.38	-37.33
Daily Nash-Sutcliffe Coefficient of Efficiency, E:	0.523	0.521	0.572	0.568
Monthly Nash-Sutcliffe Coefficient:	0.627	0.665	0.612	0.632

Water Quality Calibration and Validation

Initial calibration of water quality was done for the South Platte River at Denver (USGS 06714000), using available data for 1993-2000. Insufficient earlier data were available to allow a separate validation period at this station; however, validation for brief earlier periods was performed at downstream sites. As with hydrology, water quality calibration was performed on the later period as this better reflects the land use included in the model. The start of the validation period is constrained by data availability.

Calibration adjustments for sediment focused on the following parameters:

- SPCON (linear parameter for estimating maximum amount of sediment that can be re-entrained during channel sediment routing)
- SPEXP (exponential parameter for estimating maximum amount of sediment that can be re-entrained during channel sediment routing)
- CH_COV (channel cover factor)
- CH_EROD (channel erodibility factor)
- USLE_P (USLE support practice factor)

Simulated and estimated sediment loads for the South Platte River at Denver station are shown in Figure 12 and statistics are provided in Table 10. The key statistic in Table 10 is the relative percent error, which shows the error in the prediction of monthly load normalized to the estimated load. Several large loading events were underpredicted by the model, likely due to uncertainty in the simulation of reservoir trapping. Table 10 also shows the relative average absolute error, which is the average of the relative magnitude of errors in individual monthly load predictions. This number is inflated by outlier months in which the simulated and estimated loads differ by large amounts (which may be as easily due to uncertainty in the estimated load due to limited data as to problems with the model) and the third statistic, the relative median absolute error, is likely more relevant and shows better agreement.

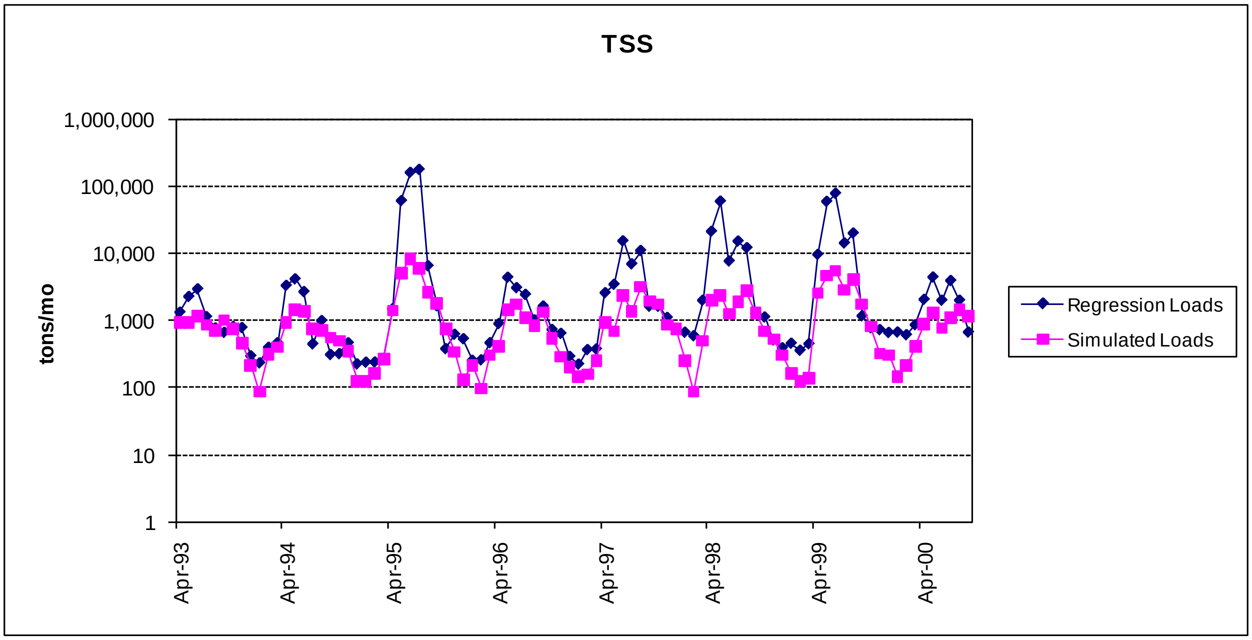


Figure 12. Fit for monthly load of TSS at USGS 06714000, South Platte River at Denver, CO.

Table 10. Model fit statistics (observed minus predicted) for monthly sediment loads using stratified regression at USGS 06714000, South Platte River at Denver, CO

Statistic	Calibration period (1993-2000)
Relative Percent Error	86.6%
Relative Average Absolute Error	77%
Relative Median Absolute Error	4.2%

Calibration adjustments for total phosphorus and total nitrogen focused on the following parameters:

- RHOQ (algal respiration rate at 20^{O} C)
- PHOSKD (phosphorus soil partitioning coefficient)
- PSP (phosphorus availability index)
- RS1 (Local algal settlement rate in the reach at 20^{O} C)
- AL1 (Fraction of algal biomass that is nitrogen)
- AL2 (Fraction of algal biomass that is phosphorus)
- MUMAX (Rate of oxygen uptake per unit NO_2-N oxidation at 20^{O} C)
- RHOQ (Algal respiration rate at 20^{O} C)

- RS2 (benthic source rate for dissolved P in the reach at 20^{o} C)
- RS3 (Benthic source rate for NH_4-N in the reach at 20^{o} C)
- RS5 (organic P settling rate in the reach at 20^{o} C)
- BC4 (rate constant for mineralization of organic P to dissolved P in the reach at 20^{o} C)
- RS4 (rate coefficient for organic N settling in the reach at 20^{o} C)
- CH_ONCO (Channel organic nitrogen concentration)
- CH_OPCO (Channel organic phosphorus concentration)
- SDNCO (Denitrification threshold water content)
- CDN (Denitrification exponential rate constant)

Results for the phosphorus simulation are shown in Figure 13 and Table 11. Results for the nitrogen simulation are shown in Figure 14 and Table 12. The model fit is generally good for the nutrients.

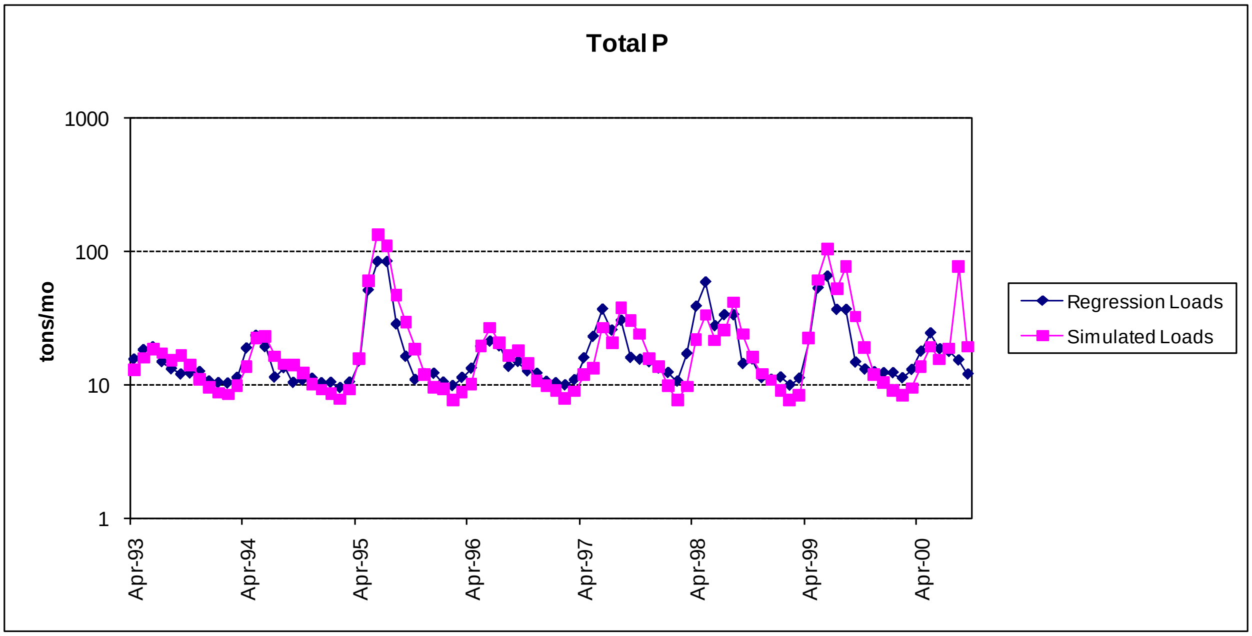


Figure 13. Fit for monthly load of total phosphorus at USGS 06714000, South Platte River at Denver, CO.

Table 11. Model fit statistics (observed minus predicted) for monthly phosphorus loads using stratified regression at USGS 06714000, South Platte River at Denver, CO

Statistic	Calibration period (1993-2000)
Relative Percent Error	-14.0%
Average Absolute Error	34%
Median Absolute Error	13.4%

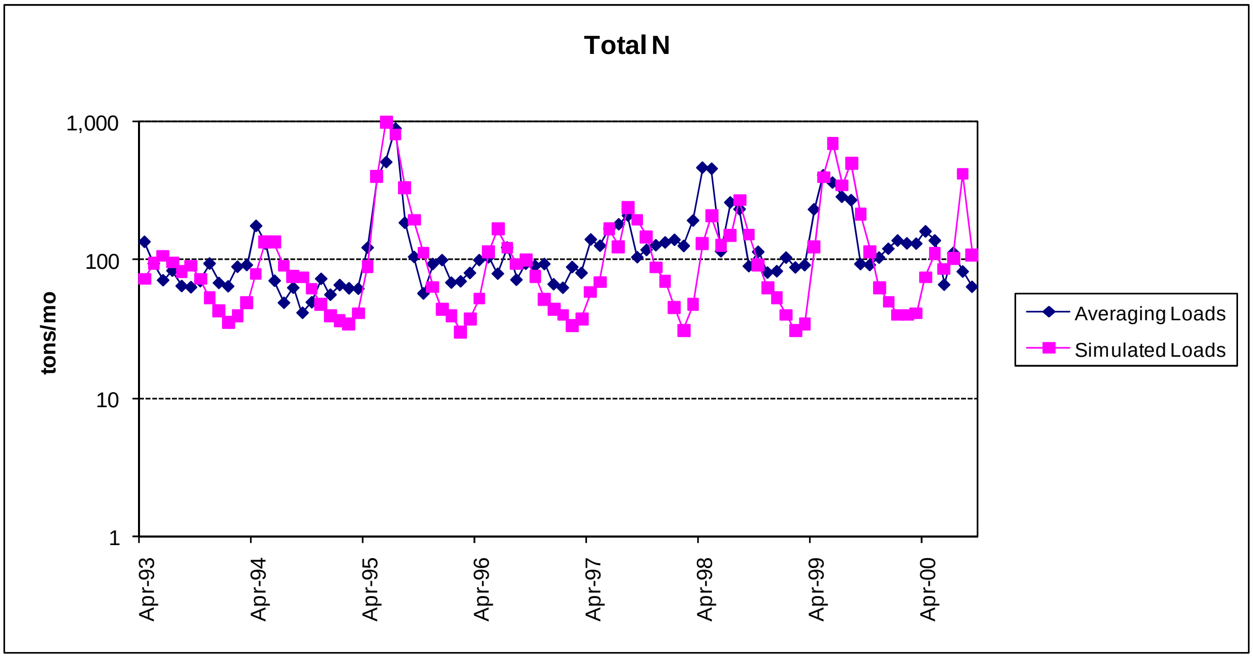


Figure 14. Fit for monthly load of total nitrogen at USGS 06714000, South Platte River at Denver, CO.

Table 12. Model fit statistics (observed minus predicted) for monthly total nitrogen loads using averaging estimator at USGS 06714000, South Platte River at Denver, CO

Statistic	Calibration period (1993-2000)
Relative Percent Error	6.1%
Average Absolute Error	46%
Median Absolute Error	29.4%

Water Quality Results for Larger Watershed

The SWAT model parameters for water quality determined for South Platte River at Denver were directly transferred to other portions of the watershed. Application of the SWAT model without spatial adjustments resulted in relatively large errors in predicting loads and concentrations at some stations. Sediment loads appear to be under-predicted throughout, reflecting the underprediction at the upstream station, but nutrients are fit fairly well. Summary statistics for the SWAT water quality calibration and validation at other stations in the watershed are provided in Table 13 and Table 14.

Table 13. Summary statistics for water quality at all stations – calibration period 1993-2002

Station	06714000 South Platte River at Denver, CO	06720500 South Platte River at Henderson, CO	06754000 South Platte River near Kersey, CO	06758500 South Platte River near Weldona, CO
Relative Percent Error TSS Load	86.6%	75.2%	73.3%	ND
Relative Percent Error TP Load	-14.0%	-6.8%	0.5%	36.9%
Relative Percent Error TN Load	6.1%	11.9%	9.1%	-36.0%

Table 14. Summary statistics for water quality at all stations – validation period 1986-1992

Station	06714000 South Platte River at Denver, CO	06720500 South Platte River at Henderson, CO	06754000 South Platte River near Kersey, CO	06758500 South Platte River near Weldona, CO
Relative Percent Error TSS Load	ND	14.7%	ND	ND
Relative Percent Error TP Load	ND	-0.8%	ND	5.0%
Relative Percent Error TN Load	ND	2.7%	ND	7.7%

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Appendix U
Model Configuration, Calibration and Validation

Basin: Trinity River (Trin)

Contents

Tables

Figures

Watershed Background

The Trinity River basin was selected as one of the 15 non-pilot application watersheds for the 20 Watershed study. Watershed modeling for the non-pilot areas is accomplished using the SWAT model only, and model calibration and validation results are presented in abbreviated form.

Water Body Characteristics

The Trinity River basin is located in east central Texas. It extends on a southeast diagonal, from immediately south of the Oklahoma-Texas border to the Trinity Bay at the Gulf of Mexico. The model study area encompasses almost 18,000 mi^2 in 12 HUC8s in HUC 1203 (Figure 1). The watershed is dissected by alternate bands of rolling, treeless prairies, smooth to slightly rolling prairies, rolling timbered hills, and a relatively flat coastal plain. The watershed slopes gradually from about 1,200 ft above sea level in the northwest, to about 600 ft mid-basin, and on to sea level in the southeastern section of the area, at Trinity Bay (Land et al., 1998; Ulery et al., 1993).

Past and current human activities, including construction of reservoirs, urbanization, farming, ranching, and oil and gas production, have greatly altered the natural environment in the Trinity River basin. Approximately 37 percent of the watershed is cropland or pasture. Major crops include corn, cotton, peanuts, sorghum, soybeans, rice, and wheat. Wheat and cotton are dry cropland crops, while rice is an irrigated crop. Forest and wetlands represent about 33 percent of the watershed and developed land makes up about 19 percent of the watershed. The population in the watershed is mainly clustered in the Dallas-Fort Worth metropolitan area, with a few secondary population clusters (Denton, McKinney, Corsicana, and Waxahachie).

The climate of the basin is described as modified-marine, subtropical-humid, having warm summers and a predominant onshore flow of tropical maritime air from the Gulf of Mexico. Precipitation varies considerably across the watershed. Average annual precipitation ranges from less than 27 inches in the northwest part of the watershed to greater than 52 inches in the southeast. On average, the watershed experiences a winter surplus and a summer deficiency of precipitation. Average annual temperature is fairly uniform throughout the basin, ranging from about 69° F in the southeastern area of the watershed to about 65° F in the northwest.

There are 22 large reservoirs in the Trinity River basin and hundreds of smaller reservoirs, mostly flood control structures. Reservoirs have been built to retain runoff on all major tributaries and the mainstem of the Trinity River. Diversions move water within the basin and to and from adjacent river basins. The largest interbasin diversion is out of the basin, from the Trinity River below Livingston Reservoir to the Houston metropolitan area. There are numerous other inter- and intrabasin diversions.

The largest consumptive use in the watershed is domestic with the majority being used in Dallas and Tarrant counties because of their large populations. Surface water, almost entirely from reservoirs, supplies more than 90 percent of the water used in the basin. Groundwater is used for municipal and domestic supply in some of the smaller towns and in rural areas. Transfers of water, from the adjoining basins and from reservoirs below Dallas and Fort Worth, are required to meet the needs of the Dallas-Fort Worth area. Relatively little water is used for irrigating crops.

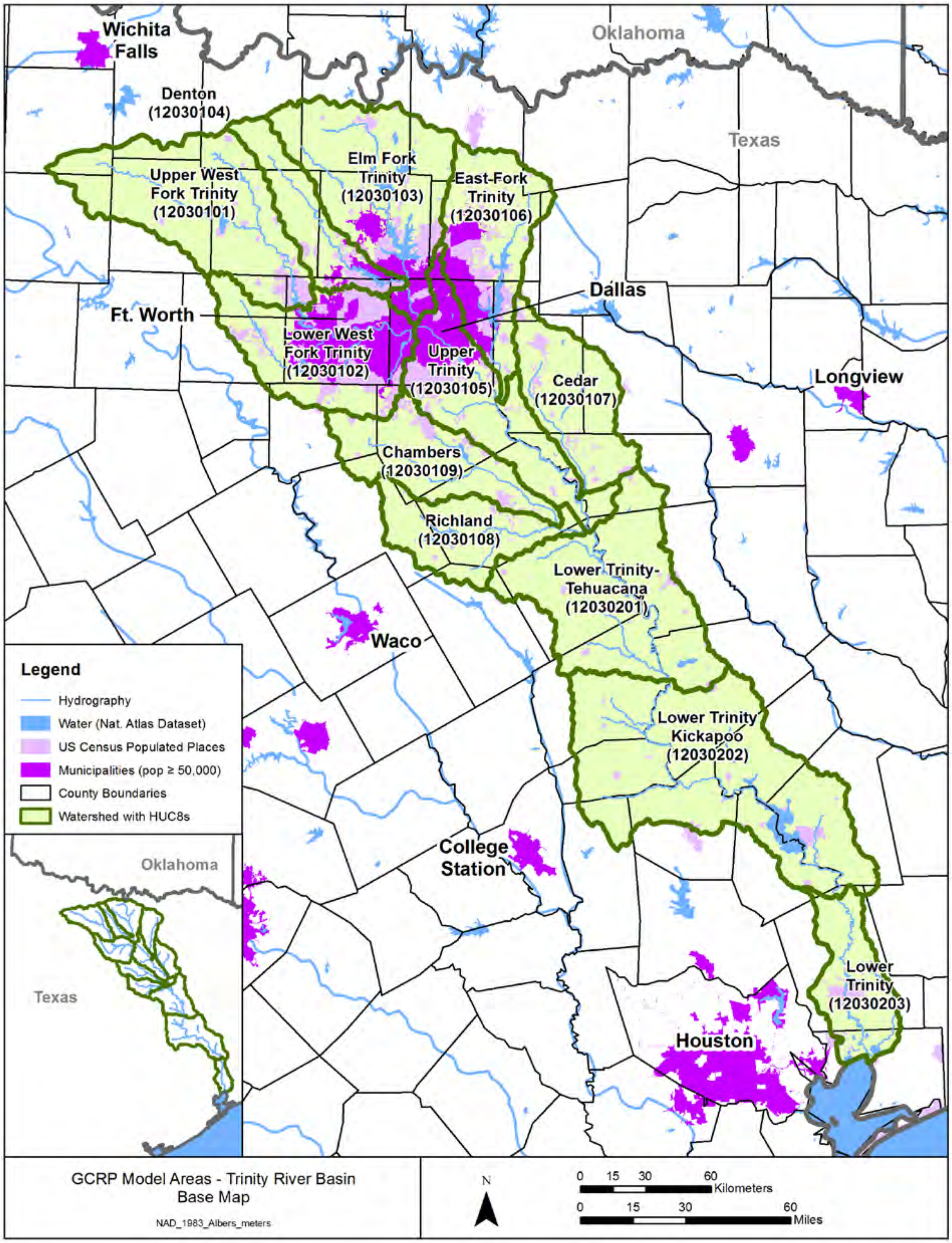


Figure 1. Location of the Trinity River basin.

Soil Characteristics

Soils in the watershed, as described in STATSGO soil surveys, fall primarily into hydrologic soil groups (HSGs) C (moderately low infiltration capacity) and D (low infiltration capacity). Soils range from course textured loamy sands to fine textured montmorillonitic clays. Soil depths vary from very shallow to deep. SWAT uses information drawn directly from the soils data layer to populate the model.

Land Use Representation

Land use/cover in the watershed is based on the 2001 National Land Cover Database (NLCD) coverage and is predominantly rangeland (Figure 2). NLCD land cover classes were aggregated according to the scheme shown in Table 1 for representation in the 20 Waterhsed model. SWAT uses the built-in hydrologic response unit (HRU) overlay mechanism in the ArcSWAT interface. SWAT HRUs are formed from an intersection of land use and SSURGO major soils. The distribution of land use in the watershed is summarized in Table 2.

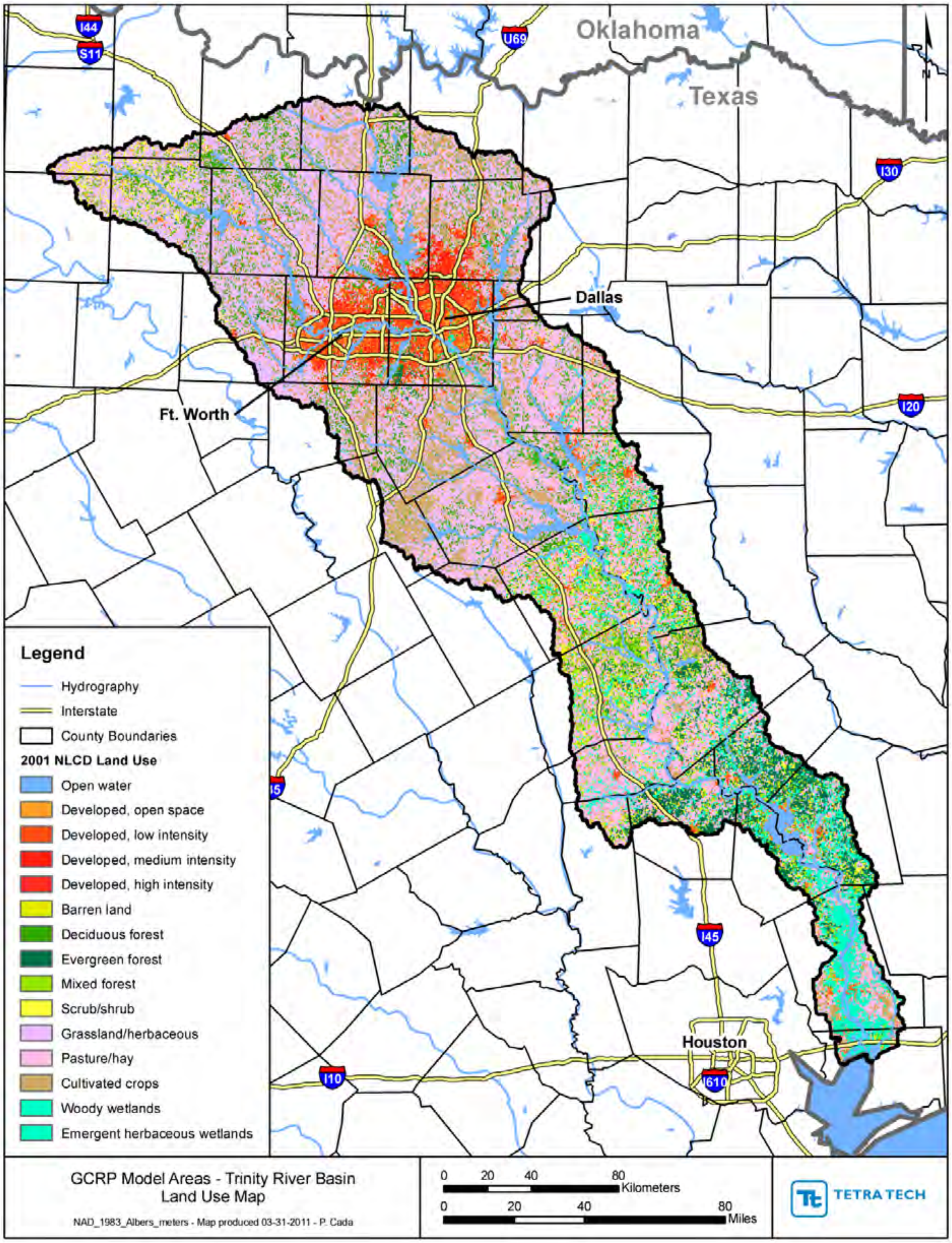


Figure 2. Land use in the Trinity River basin.

Table 1. Aggregation of NLCD land cover classes

NLCD Class	Comments	SWAT class
11 Water	Water surface area usually accounted for as reach area	WATR
12 Perennial ice/snow		WATR
21 Developed open space		URLD
22 Dev. Low Intensity		URMD
23 Dev. Med. Intensity		URHD
24 Dev. High Intensity		UIDU
31 Barren Land		SWRN
41 Forest	Deciduous	FRSD
42 Forest	Evergreen	FRSE
43 Forest	Mixed	FRST
51-52 Shrubland		RNGB
71-74 Herbaceous Upland		RNGE
81 Pasture/Hay		HAY
82 Cultivated		AGRR
91-97 Wetland	Emergent & woody wetlands	WETF, WETL, WETN
98-99 Wetland	Aquatic bed wetlands (not emergent)	WATR

Table 2. Land use distribution for the Trinity River basin (2001 NLCD) (mi^2)

HUC 8 watershed	Open water	Developed[a]				Barren land	Forest	Shrubland	Pasture/Hay	Cultivated	Wetland	Total
		Open space	Low density	Medium density	High density							
12030101	45.0	116.5	31.3	7.1	2.0	8.0	321.0	1,283.3	88.1	52.9	1.4	1,956.7
12030102	40.4	159.9	232.1	107.0	62.0	2.8	183.9	557.2	108.4	49.4	10.9	1,514.1
12030103	103.6	116.8	98.2	71.1	35.7	1.9	188.2	746.1	256.0	228.9	11.5	1,858.1
12030104	15.0	37.6	25.9	13.7	5.2	0.9	100.5	389.5	83.1	45.8	2.3	719.4
12030105	25.2	112.4	121.2	67.4	49.0	2.2	182.1	300.6	299.2	152.2	58.3	1,369.7
12030106	74.2	94.3	110.6	82.4	25.0	0.7	152.3	414.6	160.5	167.7	21.1	1,303.2
12030107	61.6	40.0	46.9	5.8	2.6	0.7	136.8	185.1	479.1	55.5	51.7	1,065.8
12030108	56.8	42.7	4.9	1.1	0.3	0.4	100.3	354.0	200.7	145.2	10.4	916.7
12030109	39.6	59.3	21.9	6.7	3.6	1.6	124.5	416.7	182.3	208.0	10.9	1,075.0
12030201	31.6	74.2	64.3	6.1	2.4	32.2	515.8	315.1	705.5	63.8	295.1	2,106.0
12030202	140.5	123.5	75.4	6.9	2.2	4.3	880.3	479.3	956.9	41.3	547.1	3,257.7
12030203	35.2	40.9	18.0	2.6	1.2	4.4	58.7	53.1	169.0	45.8	377.5	806.6
Total	668.6	1,018.2	850.6	378.1	191.2	59.9	2,944.2	5,494.6	3,688.9	1,256.5	1,398.2	17,949.1

[a]The percent imperviousness applied to each of the developed land uses is as follows: open space (7.74%), low density (31.65%), medium density (60.78%), and high density (89.15%).

Point Sources

There are numerous point source discharges in the watershed. Only the major dischargers, with a design flow greater than 1 MGD are included in the simulation (Table 3). The major dischargers are represented at long-term average flows, without accounting for changes over time or seasonal variations.

Table 3. Major point source discharges in the Trinity River basin

ID	Name	Design flow (MGD)	Observed flow (MGD)
TX0001007	EXTEX LAPORTE LIMITED PARTNERS	927	1.24
TX0001023	LUMINANT GENEATION COMPANY LLC	870	0.58
TX0001198	EXTEX LAPORTE LIMITED PARTNERS	1280	10.67
TX0020354	UPPER TRINITY REGIONAL WATER D	5	2.15
TX0020711	FLOWER MOUND, TOWN OF	10	3.49
TX0022241	NORTH TEXAS MWD	1.2	0.72
TX0022357	GAINESVILLE, CITY OF	4.14	1.74
TX0022527	TERRELL, CITY OF - KINGS CREEK	3	2.45
TX0022802	TRINITY RIVER AUTHORITY OF TEX	162	133.25
TX0023116	AZLE, CITY OF	0.941	0.69
TX0023931	NORTH TEXAS MWD	4.75	2.025
TX0024163	LIVINGSTON, CITY OF	2.25	1.029
TX0024678	GARLAND, CITY OF (DUCK CREEK)	30	21.15
TX0024686	GARLAND, CITY OF (ROWLETT CREE	24	14.67
TX0024911	DECATUR, CITY OF	1.2	0.92
TX0025011	TRINITY RIVER AUTHORITY OF TEX	0.9	11.54
TX0025364	ATHENS, CITY OF	1.367	0.81
TX0025372	ATHENS, CITY OF	1.027	54.76
TX0025453	PALESTINE CITY OF-TOWN CREEK	2.05	2.88
TX0025950	NORTH TEXAS MWD	2	3.00
TX0030180	BIG BROWN POWER COMPANY LLC	1015	1.15
TX0031577	TEXAS DEPARTMENT OF CRIMINAL J	2.85	1.77
TX0032018	GRAPEVINE, CITY OF	5.75	2.51
TX0047180	DENTON, CITY OF (PECAN CREEK)	12	10.28
TX0047261	ENNIS, CITY OF	3.1	1.64
TX0047295	FORT WORTH, CITY OF	166	106.75
TX0047431	NORTH TEXAS MWD	25	12.17
TX0047724	WEATHERFORD, CITY OF	4.5	2.046
TX0047830	DALLAS, CITY OF (CENTRAL)	150	130.29
TX0047848	DALLAS, CITY OF (SOUTHSIDE)	110	67.85
TX0047911	NORTH TEXAS MWD	16	18.08
TX0052892	LEWISVILLE, CITY OF	12	7.63
TX0052990	MEXIA, CITY OF	2	0.55
TX0053112	THE COLONY, CITY OF	3.39	1.68

ID	Name	Design flow (MGD)	Observed flow (MGD)
TX0055735	TROPHY CLUB MUD NO. 1	1.4	0.58
TX0056731	CORSICANA, CITY OF	4.95	3.05
TX0062189	BRAZOS ELECTRIC POWER COOPERAT	85	1.78
TX0070831	CROCKETT, CITY OF	2	0.68
TX0072974	HUNTSVILLE, CITY OF	4.15	2.97
TX0074284	LIBERTY,CITY OF	2.5	1.38
TX0075388	TEXAS DEPARTMENT OF CRIMINAL J	1.44	0.73
TX0078565	NORTH TEXAS MUNICIPAL WATER DI	2.25	0.90
TX0079391	KAUFMAN, CITY OF	1.2	0.57
TX0088633	NORTH TEXAS MWD	24	26.1
TX0092789	TEXAS DEPARTMENT OF CRIMINAL J	1.5	0.76
TX0100170	DAYTON, CITY OF	2	1.47
TX0103501	NORTH TEXAS MUNICIPAL WATER DI	5	3.98
TX0104345	TRINITY RIVER AUTHORITY OF TEX	3.5	1.95
TX0104957	TRINITY RIVER AUTHORITY OF TEX	5	1.31

Most of these point sources have reasonably good monitoring for total suspended solids (TSS), but not for total nitrogen and total phosphorus. The point sources were initially represented in the model with the median of reported values for TSS and an assumed total nitrogen concentration of 11.2 mg/L and assumed total phosphorus concentration of 7.0 mg/L for secondary treatment facilities (Tetra Tech 1999).

Meteorological Data

The required meteorological time series for the 20 Waterhsed SWAT simulations are precipitation and air temperature. The 20 Waterhsed simulations do not include water temperature simulation and use a degree-day method for snowmelt. SWAT estimates Penman-Monteith potential evapotranspiration using a statistical weather generator for inputs other than temperature and precipitation. These meteorological time series are drawn from the BASINS4 Meteorological Database (USEPA 2008), which provides a consistent, quality-assured set of nationwide data with gaps filled and records disaggregated. Scenario application requires simulation over 30 years, so the available stations are those with a common 30-year period of record (or one that can be filled from an approximately co-located station) that covers the year 2001. A total of 64 precipitation stations were identified for use in the Trinity River model with a common period of record of 10/1/1972-9/30/2002 (Table 4). Temperature records are sparser; where these are absent, temperature is taken from nearby stations with an elevation correction.

Table 4. Precipitation stations for the Trinity River watershed model

ID	Name	Latitude	Longitude	Elevation	Temperature
410129	TX410129	32.6444	-97.5617	241	No
410206	TX410206	33.3867	-97.7163	308	No
410235	TX410235	29.7879	-94.6342	7	Yes
410271	TX410271	33.4407	-98.3708	317	No
410337	TX410337	32.7395	-97.1277	200	No
410440	TX410440	32.2067	-96.7957	162	No
410518	TX410518	32.2636	-96.6375	141	Yes

ID	Name	Latitude	Longitude	Elevation	Temperature
410691	TX410691	32.6476	-97.4438	241	Yes
410984	TX410984	33.5511	-97.8472	329	Yes
411063	TX411063	33.2067	-97.7716	227	Yes
411596	TX411596	31.2581	-95.9744	98	Yes
411800	TX411800	32.3139	-97.4064	239	Yes
411810	TX411810	30.3637	-95.0838	60	Yes
411870	TX411870	30.5334	-95.1500	108	Yes
412019	TX412019	32.1078	-96.4746	126	Yes
412096	TX412096	32.5562	-97.6697	346	No
412114	TX412114	31.3073	-95.4508	106	No
412244	TX412244	32.8525	-96.8555	134	No
412404	TX412404	33.1990	-97.1050	192	Yes
412772	TX412772	32.3657	-95.6085	155	No
413047	TX413047	31.7322	-96.2078	132	Yes
413080	TX413080	33.1397	-96.3974	179	No
413133	TX413133	32.5340	-96.6607	143	Yes
413284	TX413284	32.8193	-97.3614	209	No
413285	TX413285	32.8339	-97.2974	196	No
413370	TX413370	33.1519	-96.8122	226	No
413415	TX413415	33.6359	-97.1444	238	No
413642	TX413642	33.7970	-96.8568	221	No
413668	TX413668	33.1025	-98.5849	320	Yes
413691	TX413691	32.9507	-97.0553	178	No
414182	TX414182	32.0162	-97.1093	168	Yes
414315	TX414315	29.7284	-95.1306	11	No
414382	TX414382	30.7064	-95.5421	151	Yes
414517	TX414517	33.2384	-98.1453	314	Yes
414679	TX414679	33.0798	-97.2967	195	No
414705	TX414705	32.5590	-96.2724	128	Yes
414972	TX414972	33.2251	-97.8316	265	No
415094	TX415094	33.0353	-96.4860	155	Yes
415192	TX415192	33.0689	-97.0100	169	No
415196	TX415196	30.0593	-94.7950	11	Yes
415271	TX415271	30.7394	-94.9256	54	Yes
415477	TX415477	30.9392	-95.9202	77	Yes
415766	TX415766	33.2365	-96.6419	190	Yes
415869	TX415869	31.6833	-96.4832	163	Yes
416130	TX416130	33.6536	-97.3752	306	No
416210	TX416210	31.9611	-96.6881	138	Yes
416331	TX416331	33.4561	-98.0253	323	No

ID	Name	Latitude	Longitude	Elevation	Temperature
416636	TX416636	33.3737	-98.7657	364	Yes
416641	TX416641	33.4372	-98.7806	361	No
416757	TX416757	31.7832	-95.6038	142	Yes
417028	TX417028	33.3659	-97.0122	210	Yes
417556	TX417556	32.9537	-97.5738	235	No
417586	TX417586	30.5382	-95.8457	96	No
417588	TX417588	32.9522	-96.7664	190	No
417659	TX417659	33.0068	-97.2246	190	No
417707	TX417707	32.9334	-96.4667	166	No
417773	TX417773	32.4612	-96.4493	111	No
418274	TX418274	33.7033	-96.6419	232	Yes
418929	TX418929	32.7668	-96.2831	157	No
419125	TX419125	33.4254	-96.3393	232	No
419286	TX419286	33.4869	-97.1572	221	No
419522	TX419522	32.4287	-96.8432	192	Yes
419532	TX419532	32.7484	-97.7699	291	Yes
419800	TX419800	32.7018	-96.0150	158	Yes

Watershed Segmentation

The Trinity River basin was divided into 73 subwatersheds for the purposes of modeling (Figure 3). The model encompasses the complete watershed and does not require specification of any upstream boundary conditions for application.

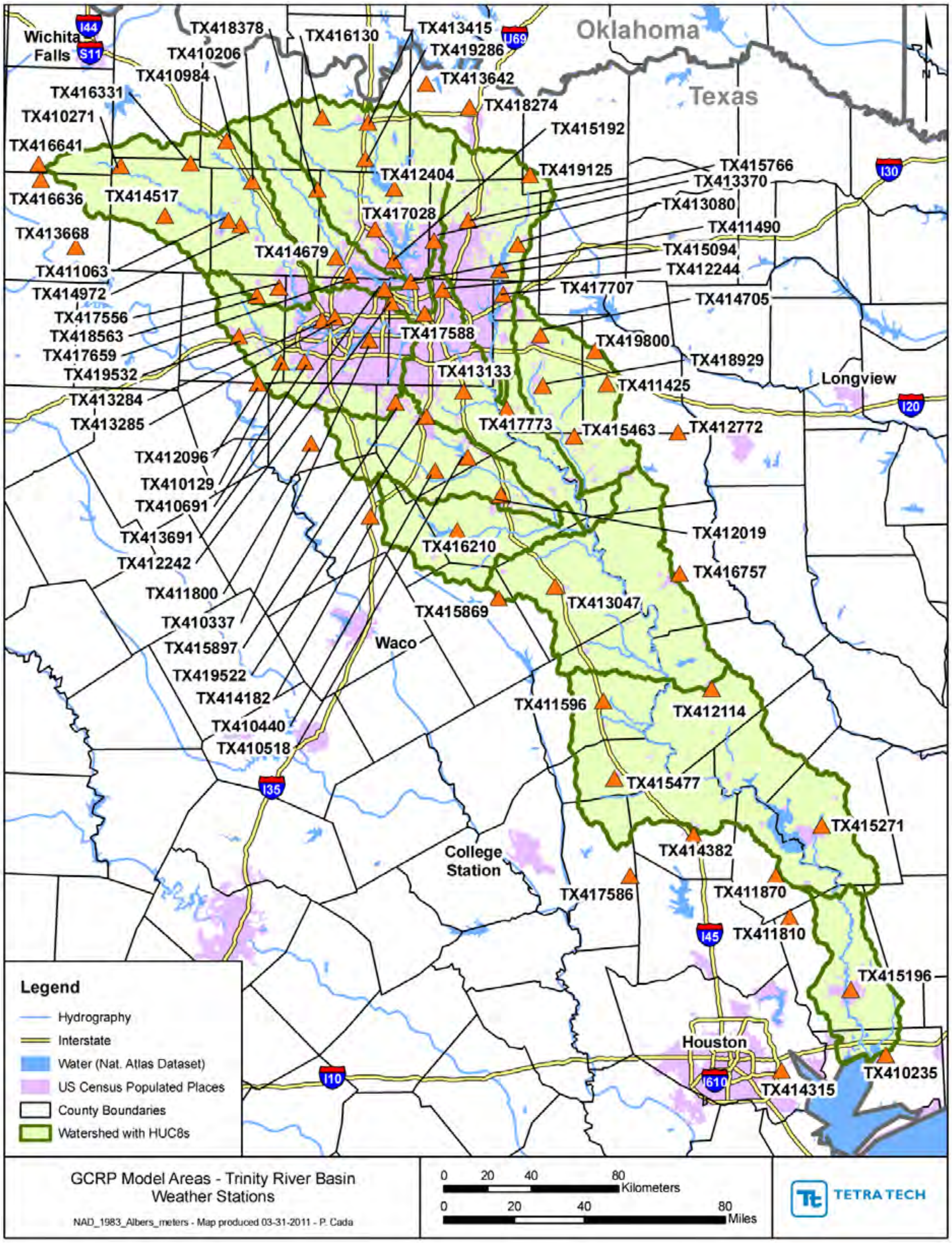


Figure 3. Model segmentation and USGS stations utilized for the trinity river watershed

Calibration Data and Locations

The specific site chosen for initial calibration was the Trinity River at Romayor, which is the most downstream gaging station in the basin. Calibration and validation were pursued at multiple locations (Table 5). Parameters derived on the Trinity River at Romayor were transferred to other portions of the Trinity River basin.

Table 5. Calibration and validation locations in the Trinity River basin

Station name	USGS ID	Drainage area (mi^2)	Hydrology calibration	Water quality calibration
East Fork Trinity River at Grand Prairie, TX	08062000	629	X	X
Clear Creek at Sanger, TX	08051500	1,300	X	X
East Fork Trinity near Crandall, TX	08062000	851	X	X
Trinity River at Rosser, TX	08062500	2,410	X	X
Trinity River at Trinidad, TX	08062700	1,110	X	X
Trinity River near Crockett, Tx	08065350	14,900	X	X
Trinity River at Romayor, Tx	08066500	16,200	X	X

The model hydrology calibration period was set to Water Years 1992-2001 (within the 30-year period of record for modeling). Hydrologic validation was then performed on Water Years 1982-1991. Water quality calibration used calendar years 1985-2001, while validation used 1972-1984. However, there was some variation to this time period across the monitoring stations depending on the availability of monitored data.

SWAT Modeling

Assumptions

Eighteen major reservoirs occur in the upper portion of the Trinity River basin. Pertinent reservoir information including surface area and storage at principal (normal) and emergency spillway levels for the reservoirs modeled were obtained from the National Inventory of Dams (NID) database. The SWAT model provides four options to simulate reservoir outflow: measured daily outflow, measured monthly outflow, average annual release rate for uncontrolled reservoir, and controlled outflow with target release. Keeping in view the 20 Waterhsed climate change impact evaluation application, it was assumed that the best representation of the reservoirs was to simulate them without supplying time series of outflow records. Therefore, the target release approach was used in the GCRP-SWAT model.

Hydrology Calibration

A spatial calibration approach was not adopted for GCRP-SWAT modeling for Trinity River basin; however, a systematic adjustment of parameters was adopted and some adjustments were applied throughout the basin. Most of the calibration efforts were geared toward getting a closer match between simulated and observed flows at the outlet closest to the most downstream USGS gaging station of the basin.

Land Use / Soil / Slope Definition

A 5/10/5 percent threshold was used for land use/soil/slope in the SWAT model while defining the HRUs. Urban land use classes were exempted from the HRU overlay thresholds.

The parameters were adjusted within the practical range at the calibration focus area to obtain reasonable fit between the simulated and measured flows in terms of Nash-Sutcliffe modeling efficiency and the high flow and low flow components as well as the seasonal flows.

The water balance of the whole Trinity River basin predicted by the SWAT model over the 30-year simulation period is as follows:

```
PRECIP =   1046.9 MM
SNOW FALL =   16.34 MM
SNOW MELT =    16.21 MM
SUBLIMATION =     0.13 MM
SURFACE RUNOFF Q =   167.49 MM
LATERAL SOIL Q =   10.66 MM
TILE Q =     0.00 MM
GROUNDWATER (SHAL AQ) Q =    16.31 MM
REVAP (SHAL AQ => SOIL/PLANTS) =  151.18 MM
DEEP AQ RECHARGE =     8.86 MM
TOTAL AQ RECHARGE =  177.28 MM
TOTAL WATER YLD =   192.80 MM
PERCOLATION OUT OF SOIL =  175.92 MM
ET =    703.4 MM
PET =   1937.8MM
TRANSMISSION LOSSES =     1.66 MM
```

Hydrologic calibration adjustments focused on the following parameters:

- SURLAG (surface runoff lag coefficient)
- CNCOEFF (plant ET curve number coefficient)
- Baseflow factor
- GWQMn (threshold depth of water in the shallow aquifer for return flow to occur [mmH2O])
- NDTarg (number of days needed to reach target storage from current pond storage)
- CN2 (initial SCS runoff curve number for moisture condition II)
- ESCO (soil evaporation compensation factor)
- Revap coeff

Calibration results for the Trinity River at Romayor are summarized in Figures 4 through 7 and Table 6. The calibration results show a good match (both in volume and timing) between the observed and the simulated flows (Figure 4, Figure 5, Figure 6, Figure 7, and Table 6).

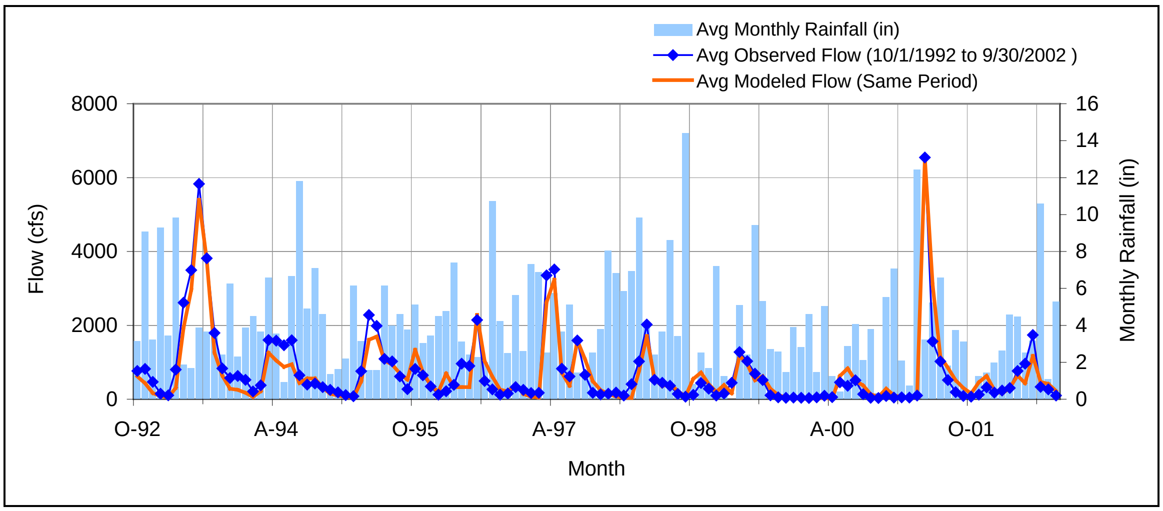
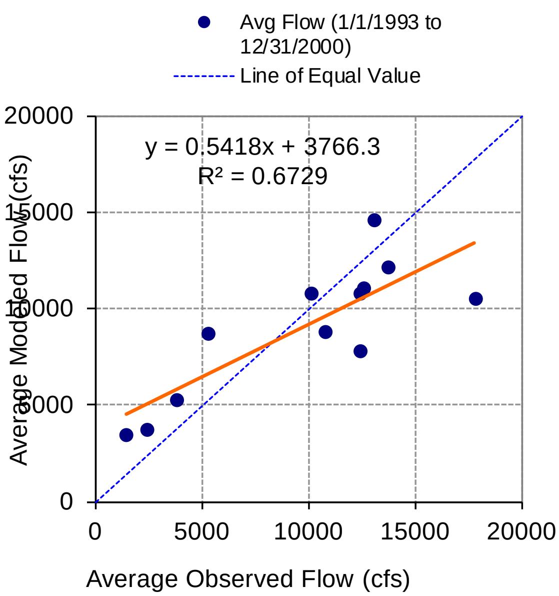


Figure 4. Mean monthly flow at USGS 08066500 Trinity River at Romayor, TX – calibration period.



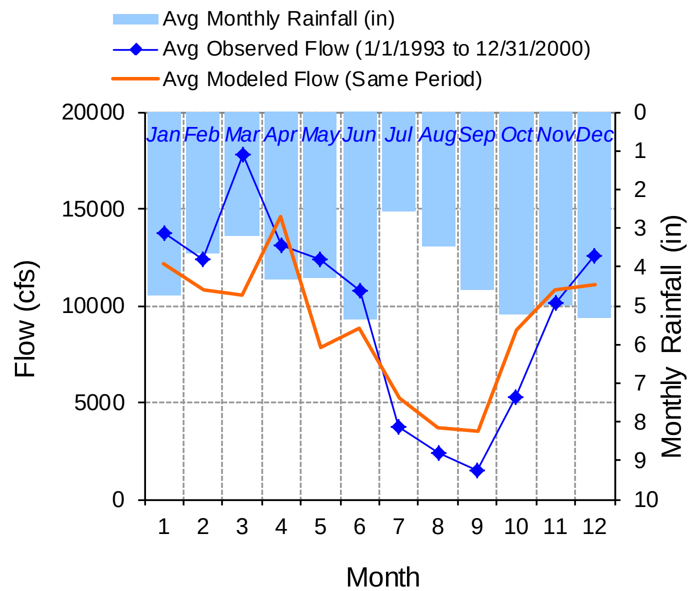


Figure 5. Seasonal regression and temporal aggregate at USGS 08066500 Trinity River at Romayor, TX - calibration period.

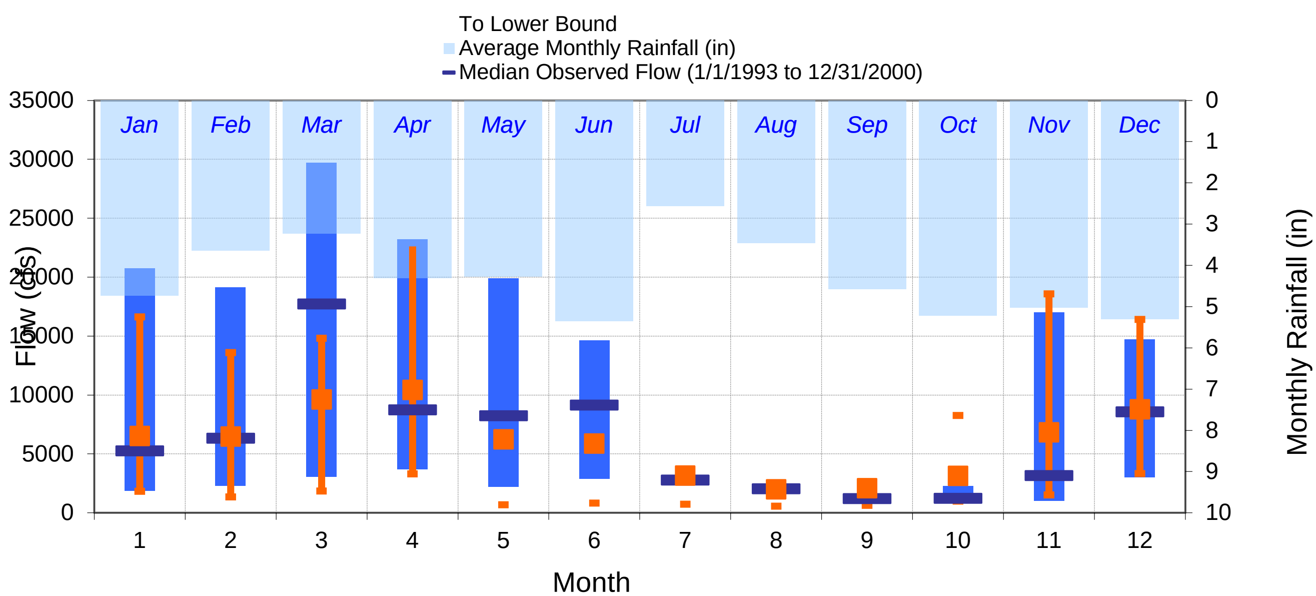


Figure 6. Seasonal medians and ranges at USGS 08066500 Trinity River at Romayor, TX – calibration period.

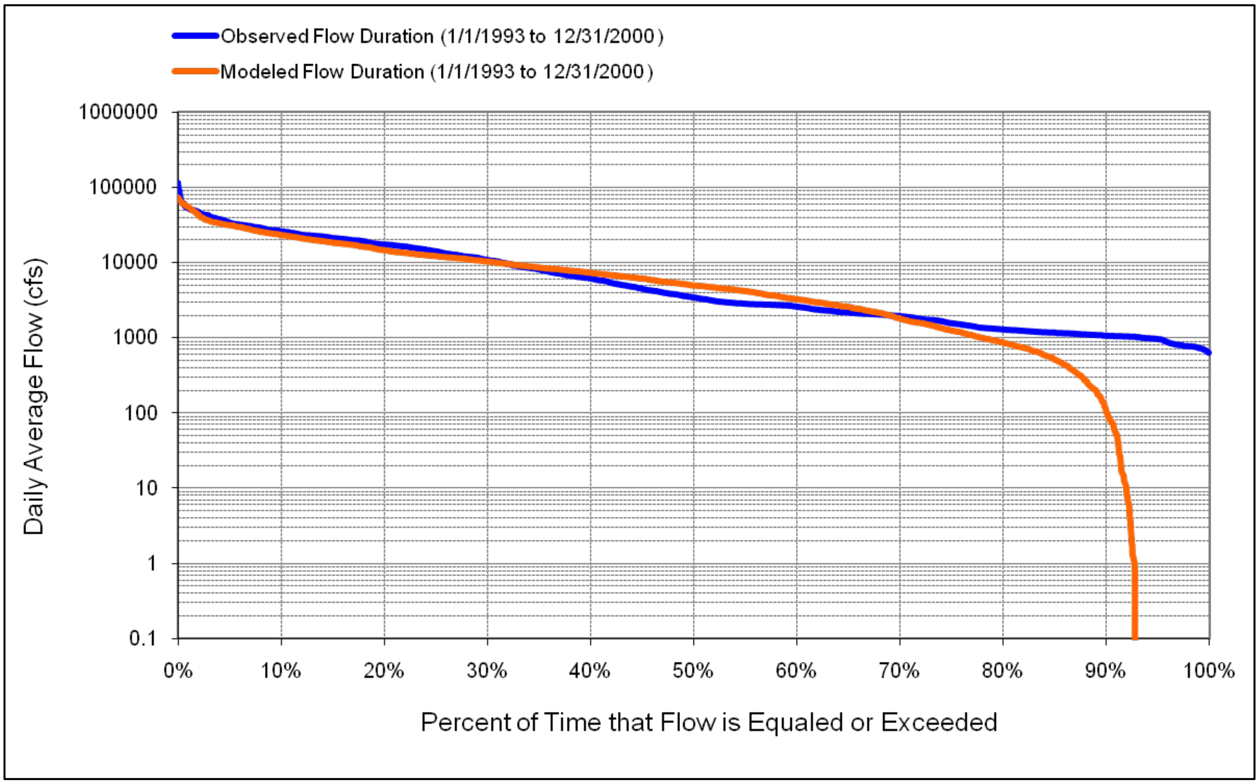


Figure 7. Flow exceedance at USGS 08066500 Trinity River at Romayor, TX - calibration period.

Table 6. Summary statistics at USGS 08066500 Trinity River at Romayor, TX - calibration period

SWAT Simulated Flow		**Observed Flow Gage**	
REACH OUTFLOW FROM OUTLET 3 8-Year Analysis Period: 1/1/1993 - 12/31/2000 Flow volumes are (inches/year) for upstream drainage area		USGS 08066500 Trinity Rv at Romayor, TX Hydrologic Unit Code: 12030202 Latitude: 30.4252067 Longitude: -94.8507622 Drainage Area (sq-mi): 17186	
Total Simulated In-stream Flow:	**7.10**	Total Observed In-stream Flow:	**7.62**
Total of simulated highest 10% flows:	**2.80**	Total of Observed highest 10% flows:	**3.09**
Total of Simulated lowest 50% flows:	**0.67**	Total of Observed Lowest 50% flows:	**0.69**
Simulated Summer Flow Volume (months 7-9):	**0.83**	Observed Summer Flow Volume (7-9):	**0.51**
Simulated Fall Flow Volume (months 10-12):	**2.04**	Observed Fall Flow Volume (10-12):	**1.85**
Simulated Winter Flow Volume (months 1-3):	**2.18**	Observed Winter Flow Volume (1-3):	**2.88**
Simulated Spring Flow Volume (months 4-6):	**2.04**	Observed Spring Flow Volume (4-6):	**2.38**
Total Simulated Storm Volume:	**2.85**	Total Observed Storm Volume:	**2.41**
Simulated Summer Storm Volume (7-9):	**0.39**	Observed Summer Storm Volume (7-9):	**0.13**

Errors (Simulated-Observed)	*Error Statistics*	*Recommended Criteria*		
Error in total volume:	-6.88	10		
Error in 50% lowest flows:	-2.33	10		
Error in 10% highest flows:	-9.48	15		
Seasonal volume error - Summer:	**63.58**	**30**		
Seasonal volume error - Fall:	9.93	>> 30		Clear
Seasonal volume error - Winter:	-24.04	30		
Seasonal volume error - Spring:	-14.28	30		
Error in storm volumes:	18.68	20		
Error in summer storm volumes:	**210.14**	**50**		
Nash-Sutcliffe Coefficient of Efficiency, E:	0.623	Model accuracy increases		
Baseline adjusted coefficient (Garrick), E':	0.482	as E or E' approaches 1.0		
Monthly NSE	0.740			

Hydrology Validation

Hydrology validation for the Trinity River was performed for the period 10/1/1983 through 9/30/1992. The results are presented in Figures 8 through 11 and Table 7. The validation achieves a reasonable coefficient of model fit efficiency, but is under on 50 percent low volume and over on seasonal volumes for summer and fall (Figure 8 through Figure 11 and Table 7).

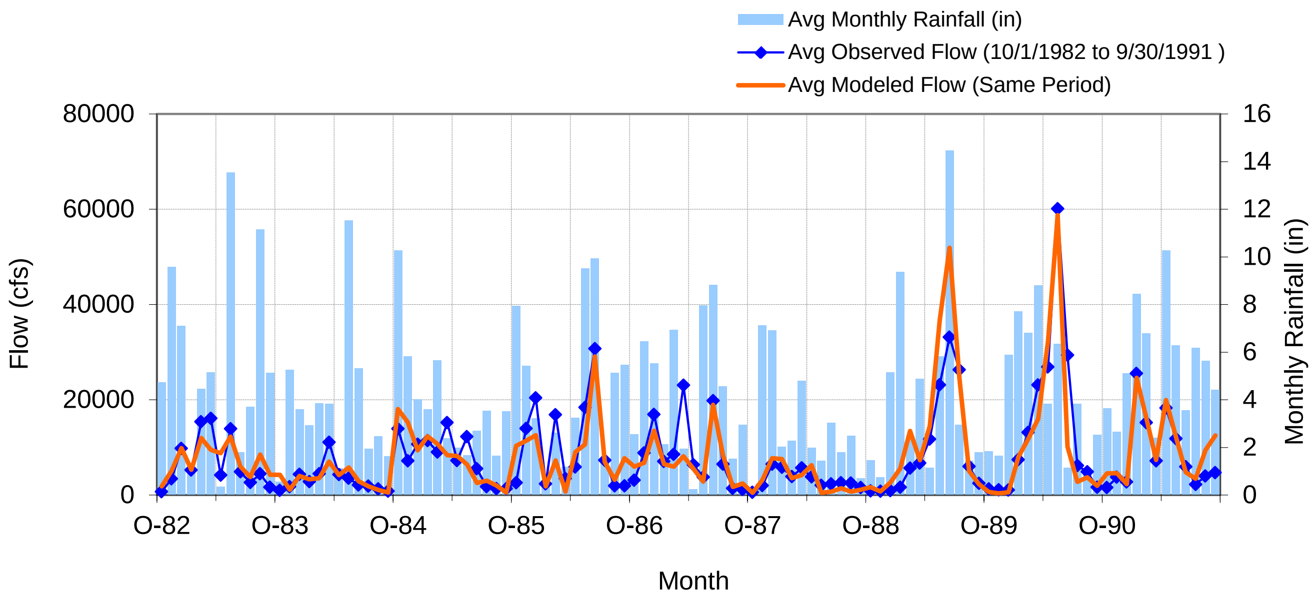
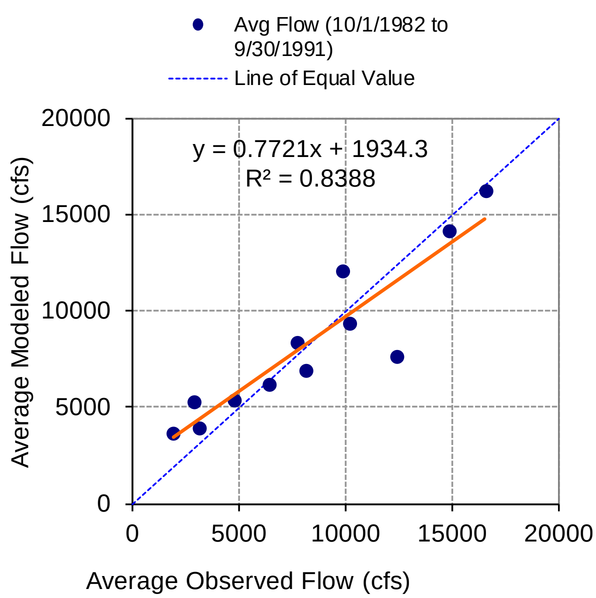


Figure 8. Mean monthly flow at USGS 08066500 Trinity River at Romayor, TX- validation period.



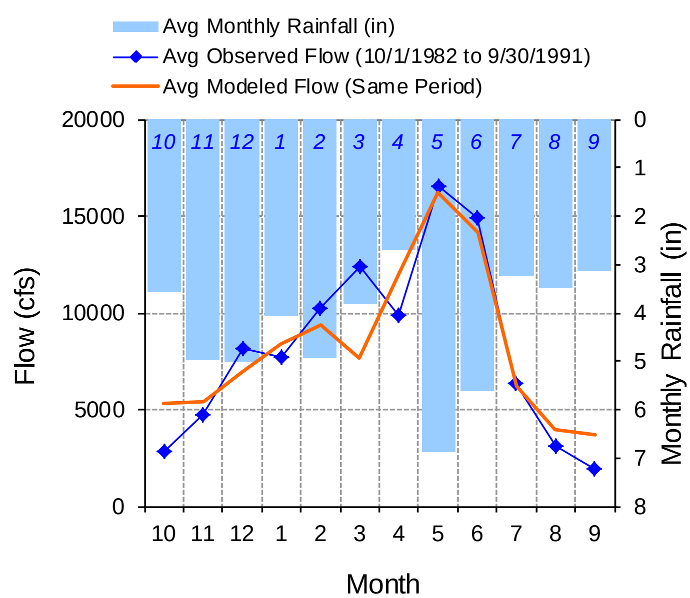


Figure 9. Seasonal regression and temporal aggregate at USGS 08066500 Trinity River at Romayor, TX – validation period.

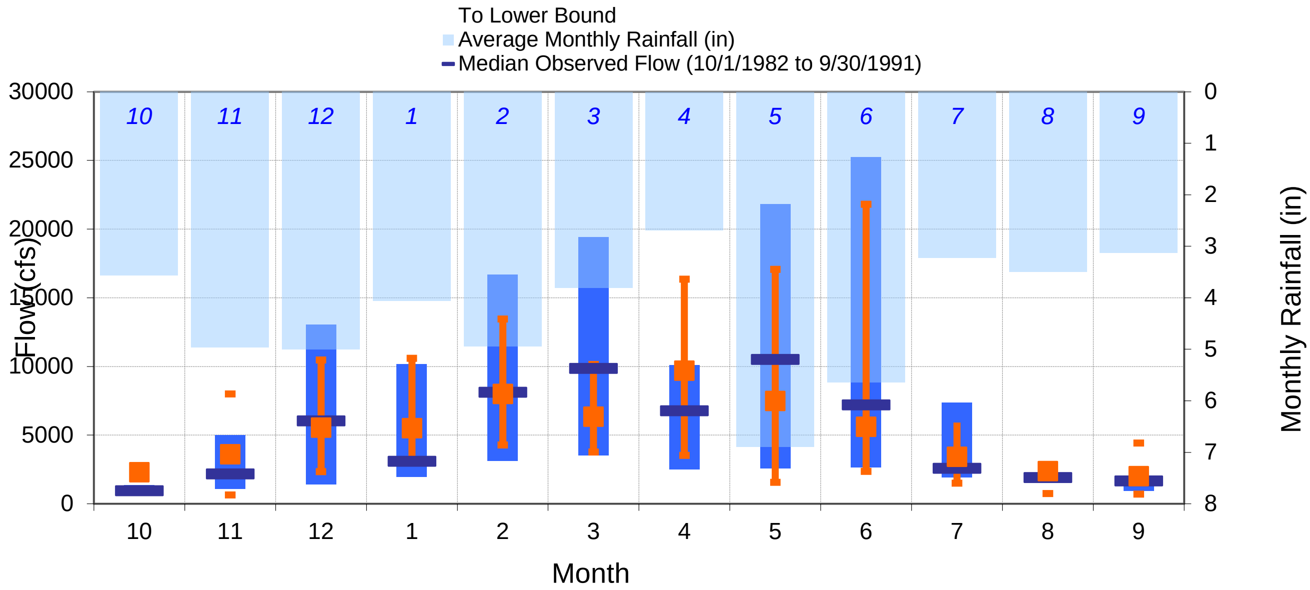


Figure 10. Seasonal medians and ranges at USGS 08066500 Trinity River at Romayor, TX – validation period.

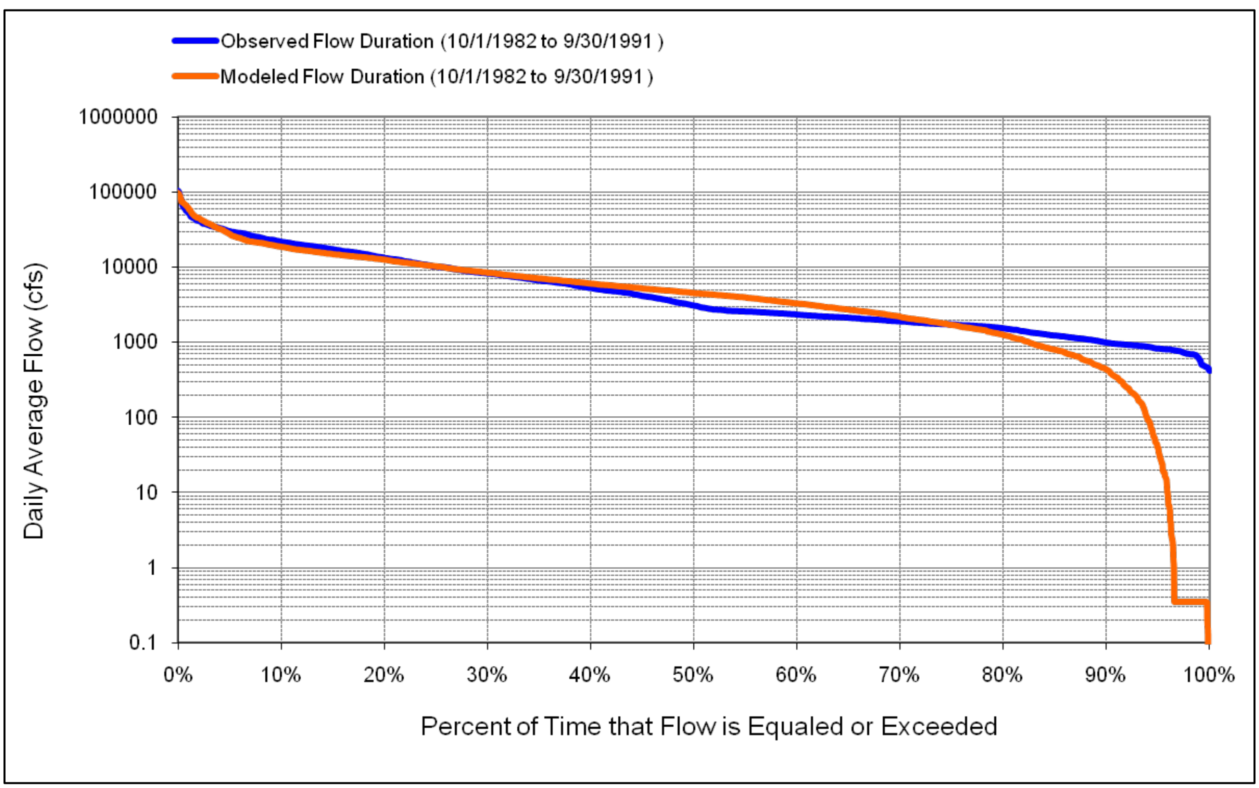


Figure 11. Flow exceedance at USGS 08066500 Trinity River at Romayor, TX - validation period.

Table 7. Summary statistics at USGS 08066500 Trinity River at Romayor, TX - validation period

SWAT Simulated Flow		Observed Flow Gage	
REACH OUTFLOW FROM OUTLET 3 9-Year Analysis Period: 10/1/1982 - 9/30/1991 Flow volumes are (inches/year) for upstream drainage area		USGS 08066500 Trinity Rv at Romayor, TX Hydrologic Unit Code: 12030202 Latitude: 30.4252067 Longitude: -94.8507622 Drainage Area (sq-mi): 17186	
Total Simulated In-stream Flow:	**6.54**	Total Observed In-stream Flow:	**6.49**
Total of simulated highest 10% flows:	**2.76**	Total of Observed highest 10% flows:	**2.78**
Total of Simulated lowest 50% flows:	**0.74**	Total of Observed Lowest 50% flows:	**0.67**
Simulated Summer Flow Volume (months 7-9):	**0.92**	Observed Summer Flow Volume (7-9):	**0.76**
Simulated Fall Flow Volume (months 10-12):	**1.18**	Observed Fall Flow Volume (10-12):	**1.05**
Simulated Winter Flow Volume (months 1-3):	**1.64**	Observed Winter Flow Volume (1-3):	**1.97**
Simulated Spring Flow Volume (months 4-6):	**2.79**	Observed Spring Flow Volume (4-6):	**2.71**
Total Simulated Storm Volume:	**2.48**	Total Observed Storm Volume:	**2.39**
Simulated Summer Storm Volume (7-9):	**0.41**	Observed Summer Storm Volume (7-9):	**0.23**

Errors (Simulated-Observed)	*Error Statistics*	*Recommended Criteria*
Error in total volume:	0.70	10
Error in 50% lowest flows:	**11.67**	**10**
Error in 10% highest flows:	-0.63	15
Seasonal volume error - Summer:	21.78	30
Seasonal volume error - Fall:	12.35	30
Seasonal volume error - Winter:	-16.62	30
Seasonal volume error - Spring:	2.88	30
Error in storm volumes:	3.66	20
Error in summer storm volumes:	**77.98**	**50**
Nash-Sutcliffe Coefficient of Efficiency, E:	0.471	Model accuracy increases
Baseline adjusted coefficient (Garrick), E':	0.431	as E or E' approaches 1.0
Monthly NSE	0.760	

>> Clear

Hydrology Results for Larger Watershed

As described above, parameters determined for the Romayor gage were fully transferable to other gages in the watershed. In addition, calibration and validation was pursued at a total of seven gages throughout the watershed. Calibration results were acceptable at most gages (Table 8).

Results of the validation exercise are summarized in Table 9**.** Problems similar to those experienced on the Romayor gage were seen at most of the tributary gages, with over-prediction of seasonal flows in summer and under-prediction in winter and spring. However, as noted above, this is likely due to the use of land use and model parameters that are more reflective of current conditions and is not believed to present a bar to application of the model.

Table 8. Summary statistics (percent error): all Stations - calibration period

Station	08049500 West Fork Trinity River at Grand Prairie	08051500 Clear Creek near Sanger	08062000 East Fork Trinity near Crandall	08062500 Trinity River near Rosser	08062700 Trinity River near Trinidad	08065350 Trinity River near Crockett	08066500 Trinity River at Romayor
Error in total volume:	-21.5	-1.45	-4.33	-36.72	-28.22	-13.76	-6.88
Error in 50% lowest flows:	-22.96	-68.43	-12.98	-22.65	-15.64	-20.30	-2.33
Error in 10% highest flows:	-22.09	4.2	-2.26	-30.65	-25.85	1.63	-9.48
Seasonal volume error - Summer:	27.87	169.54	110.48	44.47	58.55	47.56	63.58
Seasonal volume error - Fall:	-2.90	20.8	28.55	-22.01	-15.66	2.84	9.93
Seasonal volume error - Winter:	-28.82	-15.79	-30.22	-45.18	-38.74	-30.16	-24.04
Seasonal volume error - Spring:	-42.02	-16.05	-6.16	-61.25	-46.16	-17.33	-14.28
Error in storm volumes:	-32.74	3.55	-6.33	-27.19	-21.96	29.75	18.68
Error in summer storm volumes:	55.10	192.89	159.69	116.13	149.46	155.46	210.14
Daily Nash-Sutcliffe Coefficient of Efficiency, E:	0.556	0.3	0.258	0.388	0.496	0.265	0.623
Baseline adjusted coefficient (Garrick), E':	0.424	0.380	0.323	0.358	0.427	0.368	0.482
Monthly Nash-Sutcliffe Coefficient of Efficiency, E:	0.541	0.584	0.595	0.388	0.605	0.651	0.740

Table 9. Summary statistics: all stations - validation period

Station	08049500 West Fork Trinity River at Grand Prairie	08051500 Clear Creek near Sanger	08062000 East Fork Trinity near Crandall	08062500 Trinity River near Rosser	08062700 Trinity River near Trinidad	08065350 Trinity River near Crockett	08066500 Trinity River at Romayor
Error in total volume:	6.38	-2.4	12.95	-25.22	-12.94	-11.10	0.7
Error in 50% lowest flows:	10.4	-86.16	22.86	-8.38	1.87	-17.16	11.67
Error in 10% highest flows:	-4.43	1.86	13.16	-20.01	-9.75	4.38	-0.63
Seasonal volume error - Summer:	104.35	8.88	55.60	15.41	29.18	11.0	21.78
Seasonal volume error - Fall:	29.01	41.28	82.61	-11.38	-1.31	-1.24	12.35
Seasonal volume error - Winter:	-29.5	-35.41	-36.32	-47.22	-41.84	-41.97	-16.62
Seasonal volume error - Spring:	-2.74	5.30	15.48	-30.13	-12.50	0.66	2.88
Error in storm volumes:	-19.03	1.84	-2.03	-22.33	-11.06	18.61	3.66
Error in summer storm volumes:	97.08	42.3	160.45	103.72	142.79	59.70	81.05
Daily Nash-Sutcliffe Coefficient of Efficiency, E:	0.820	0.605	0.367	0.705	0.626	0.128	0.471
Baseline adjusted coefficient (Garrick), E':	0.550	0.540	0.268	0.462	0.455	0.32	0.431
Monthly Nash-Sutcliffe Coefficient of Efficiency, E:	0.932	0.864	0.732	0.807	0.833	0.730	0.760

Water Quality Calibration and Validation

Initial calibration and validation of water quality was done on Trinity River at Romayor (USGS 08066500), using 1985-2001 for calibration and 1972-1984 for validation. As with hydrology, water quality calibration was performed on the later period as this better reflects the land use included in the model. The start of the validation period is constrained by data availability.

Calibration adjustments for sediment focused on the following parameters:

- SPCON (linear parameters for estimating maximum amount of sediment that can be re-entrained during channel sediment routing)
- CH_COV (channel cover factor)
- CH_EROD (channel erodibility factor)

Simulated and estimated sediment loads at the Romayor station for both the calibration and validation periods are shown in Figure 12 and statistics for the two periods are provided separately in Table 10. The key statistic in Table 10 is the relative percent error, which shows the error in the prediction of monthly load normalized to the estimated load. Table 10 also shows the relative average absolute error, which is the average of the relative magnitude of errors in individual monthly load predictions. This number is inflated by outlier months in which the simulated and estimated loads differ by large amounts (which may be as easily due to uncertainty in the estimated load due to limited data as to problems with the model) and the third statistic, the relative median absolute error, is likely more relevant and shows better agreement.

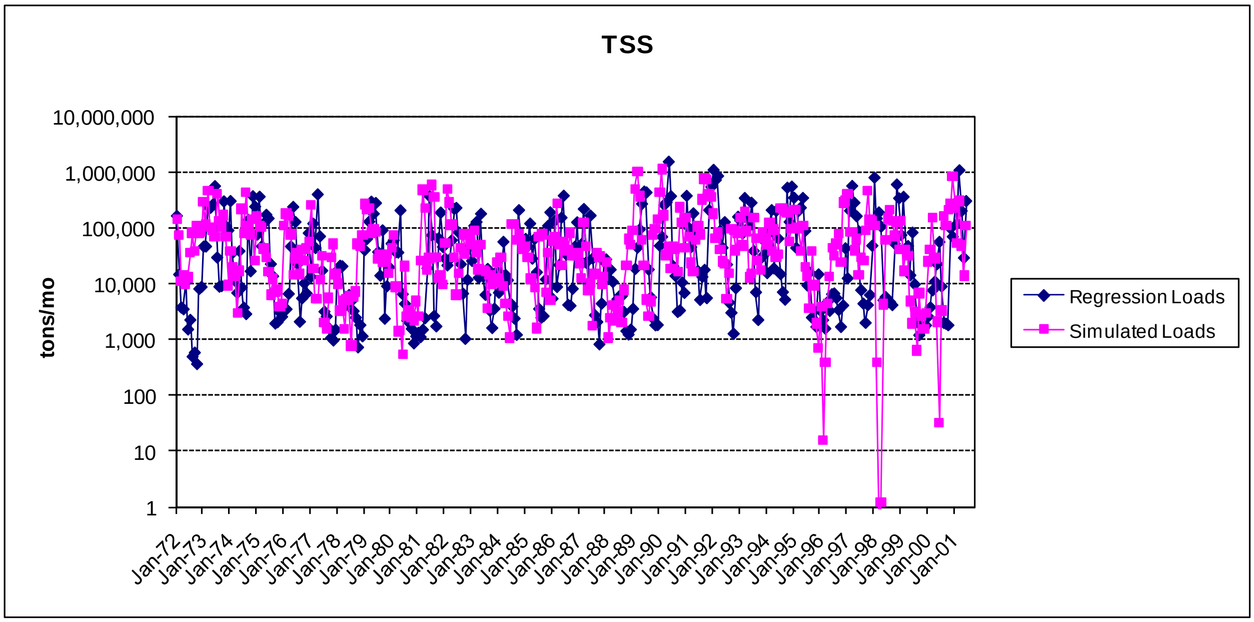


Figure 12. Fit for monthly load of TSS at USGS 08066500 Trinity River at Romayor, TX.

Table 10. Model fit statistics (observed minus predicted) for monthly sediment loads using stratified regression at USGS 08066500 Trinity River at Romayor, TX

Statistic	Calibration period (1985-2001)	Validation period (1972-1984)
Relative Percent Error	9.2%	-17.4%
Relative Average Absolute Error	129%	137%
Relative Median Absolute Error	58.8%	56.4%

Calibration adjustments for total phosphorus and total nitrogen focused on the following parameters:

- PHOSKD (Phosphorus soil partitioning coefficient)
- RS2(benthic source rate for dissolved phosphorus in the reach [mg P/m2*day])
- RS3 (benthic source rate for NH4-N in the reach [mg N/m2*day])
- RS4 (rate coefficient for organic N settling in the reach [day-1])

- RS5 (organic phosphorus settling rate in the reach [day-1])
- BC1 (rate constant for biological oxidation of NH4 to NO2 in the reach [day-1])
- BC2 (rate constant for biological oxidation of NO2 to NO3 in the reach [day-1])
- BC4 (rate constant for mineralization of organic P to dissolved P in the reach [day-1])
- MUMAX (maximum specific algal growth rate [day-1])

Results for the phosphorus simulation are shown in Figure 13 and Table 11. Results for the nitrogen simulation are shown in Figure 14 and Table 12. The model fit is generally good.

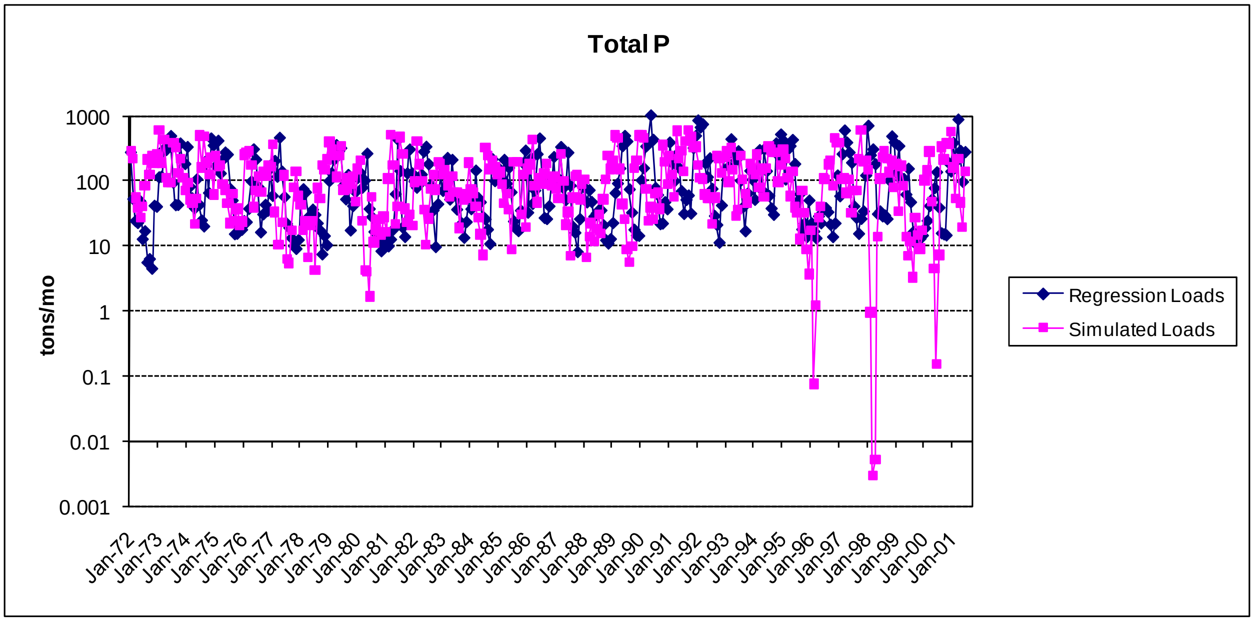


Figure 13. Fit for monthly load of total phosphorus at USGS 08066500 Trinity River at Romayor, TX.

Table 11. Model fit statistics (observed minus predicted) for monthly phosphorus loads using stratified regression at USGS 08066500 Trinity River at Romayor, TX

Statistic	Calibration period (1985-2001)	Validation period (1972-1984)
Relative Percent Error	3.0%	-21.58
Average Absolute Error	108%	110%
Median Absolute Error	75.7%	68.6%

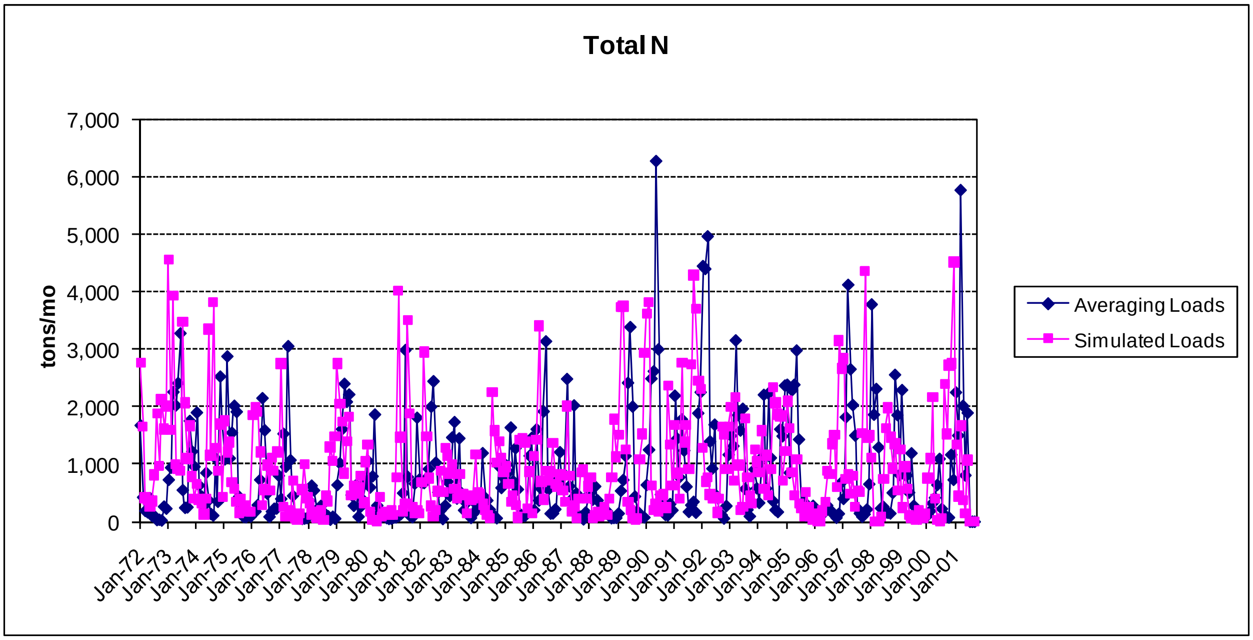


Figure 14. Fit for monthly load of total nitrogen at USGS 08066500 Trinity River at Romayor, TX.

Table 12. Model fit statistics (observed minus predicted) for monthly total nitrogen loads using averaging estimator at USGS 08066500 Trinity River at Romayor, TX

Statistic	Calibration period (1985-2001)	Validation period (1972-1984)
Relative Percent Error	-3.8%	-31.9%
Average Absolute Error	107%	113%
Median Absolute Error	78.4%	66.7%

Water Quality Results for Larger Watershed

As with hydrology, the SWAT model parameters used to calibrate at the USGS 08066500 Trinity River at Romayor, TX station for water quality were directly transferred to other portions of the watershed. Application of the SWAT model without spatial adjustments resulted in relatively large errors in predicting loads and concentrations at some stations. Summary statistics for the SWAT water quality calibration and validation at other stations in the watershed are provided in Table 13 and Table 14.

Table 13. Summary statistics for water quality at all stations – calibration period 1985-2001

Station	08049500 West Fork Trinity River at Grand Prairie	08051500 Clear Creek near Sanger	08062000 East Fork Trinity near Crandall	08062500 Trinity River near Rosser	08062700 Trinity River near Trinidad	08065350 Trinity River near Crockett	08066500 Trinity River at Romayor
Relative Percent Error TSS Load	62.9%	98.3%	-26.4%	44.9%	58.1%	53.4%	9.2%
Relative Percent Error TP Load	38.9%	77%	-186.9%	12.4%	9%	15.8%	3.0%
Relative Percent Error TN Load	77.3%	83.9%	41.2%	63.0%	60.7%	50.5%	-3.8%

Table 14. Summary statistics for water quality at all stations – validation period 1972-1984

Station	08049500 West Fork Trinity River at Grand Prairie	08051500 Clear Creek near Sanger	08062000 East Fork Trinity near Crandall	08062500 Trinity River near Rosser	08062700 Trinity River near Trinidad	08065350 Trinity River near Crockett	08066500 Trinity River at Romayor
Relative Percent Error TSS Load	58.1%	97.4%	-43.3%	36.4%	55.8%	54.0%	-17.4%
Relative Percent Error TP Load	36.58%	50.06%	-192.45%	14.42%	9.48%	17.04%	-21.58%
Relative Percent Error TN Load	60.0%	64.2%	18.8%	45.7%	42.4%	36.9%	-31.9%

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Appendix V
Model Configuration, Calibration and Validation

Basin: Upper Colorado River (UppCol)

Contents

Tables

Figures

Watershed Background

The Upper Colorado River basin was selected as one of the 15 non-pilot application watersheds for the 20 Watershed study. Watershed modeling for the non-pilot areas is accomplished using the SWAT model only, and model calibration and validation results are presented in abbreviated form.

Water Body Characteristics

The Upper Colorado River basin model area has a drainage area of about 17,800 mi² and contains 12 HUC8s within HUC 1401 and 1402. All except 100 mi² of this area is in Colorado (Figure 1).

The Colorado River and its tributaries originate in the mountains of central Colorado and flow about southwest into Utah. The Continental Divide marks the eastern and southern boundary of the basin, with altitudes over 14,000 ft. Topography in the western part of the basin generally consists of high plateaus bordered by steep cliffs along the valleys, and the lowest altitude (4,300 ft) is near the Colorado-Utah border. The basin is divided almost equally into two physiographic provinces: the Southern Rocky Mountains in the east and the Colorado Plateau in the west (USGS, 2006; Apodaca et al., 1996).

Because of large changes in altitude, the climate in the basin varies from alpine conditions in the east to semiarid in the west. Mean annual temperatures range from as low as 32.8° F in Gunnison County near the Continental Divide to as high as 54.1° F near Grand Junction, Colorado. Precipitation in the basin ranges from more than 40 inches per year in the eastern mountainous regions to less than 10 inches per year in the lower altitude western regions. Mountain areas receive most of their precipitation during the winter months when accumulation of snow can exceed an annual average of 100 inches.

The Upper Colorado River basin is largely rural. Rangeland and forest occupy about 88 percent of the basin. Livestock (sheep and cattle) use large areas of rangeland for foraging. Forest land that includes most of the mountain and plateau areas is used for some commercial lumber production. Large parts of the watershed are set aside for recreational use, including all or parts of 4 National Park Service areas, 5 National Forests and numerous wilderness areas, 11 state parks, numerous State Wildlife Management areas, and 17 ski areas. Mining activities are also an important land use and have included the extraction of metals and energy fuels.

Less than 2 percent of the land area is developed. The largest population center is Grand Junction (population less than 60,000 in 2010), which is located at the confluence of the Colorado and Gunnison Rivers. The larger cities in the basin are located predominantly near agricultural lands or in mountain recreational communities. Agricultural activities (about 4 percent of the area) include production of crops such as alfalfa, fruits, grains, hay, and vegetables. Little crop production is possible without irrigation because of the semiarid climate. Irrigated lands are predominantly in river valleys or low-altitude regions where the water is supplied by an extensive system of canals and ditches.

The natural hydrology of the Upper Colorado River basin has been considerably altered by water development, which includes numerous reservoirs and diversions. In the watershed, there are 9 major interbasin water transfers, 7 major water diversions, 9 major reservoirs, and 10 major municipal discharges. The interbasin water transfers provide supplementary irrigation and municipal water supplies to the South Platte, Arkansas, and Rio Grande drainages. About 25 percent of the interbasin water transfers are to the South Platte watershed for the municipal water supply for the Denver metropolitan area. Most of the water used in the watershed comes from surface water sources. Groundwater sources account for less than 1 percent of the water used. Irrigation accounts for about 97 percent of off-stream water use. Besides off-stream water uses, there are in-stream water uses such as hydroelectric power generation.

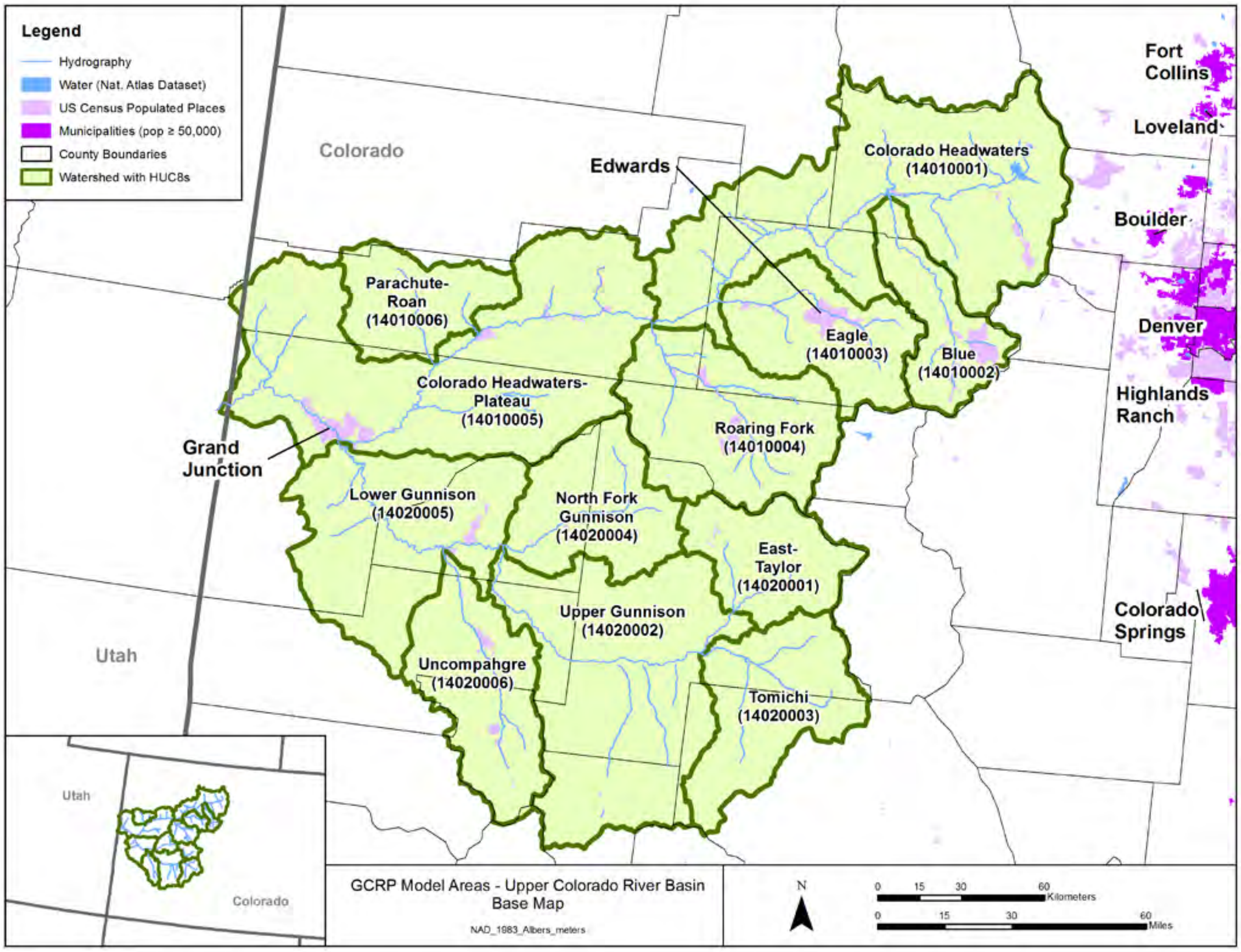

Figure 1. Location of the Upper Colorado River basin.

Soil Characteristics

Soils in the watershed, as described in STATSGO soil surveys, fall primarily into hydrologic soil groups (HSGs) B (moderately high infiltration capacity) and C (moderate infiltration capacity). SWAT uses information drawn directly from the soils data layer to populate the model.

Land Use Representation

Land use/cover in the watershed is based on the 2001 National Land Cover Database (NLCD) coverage (Figure 2). NLCD land cover classes were aggregated according to the scheme shown in Table 1 for representation in the GCRP model. SWAT uses the built-in hydrologic response unit (HRU) overlay mechanism in the ArcSWAT interface. SWAT HRUs are formed from an intersection of land use and STATSGO major soils. The distribution of land use in the watershed is summarized in Table 2.

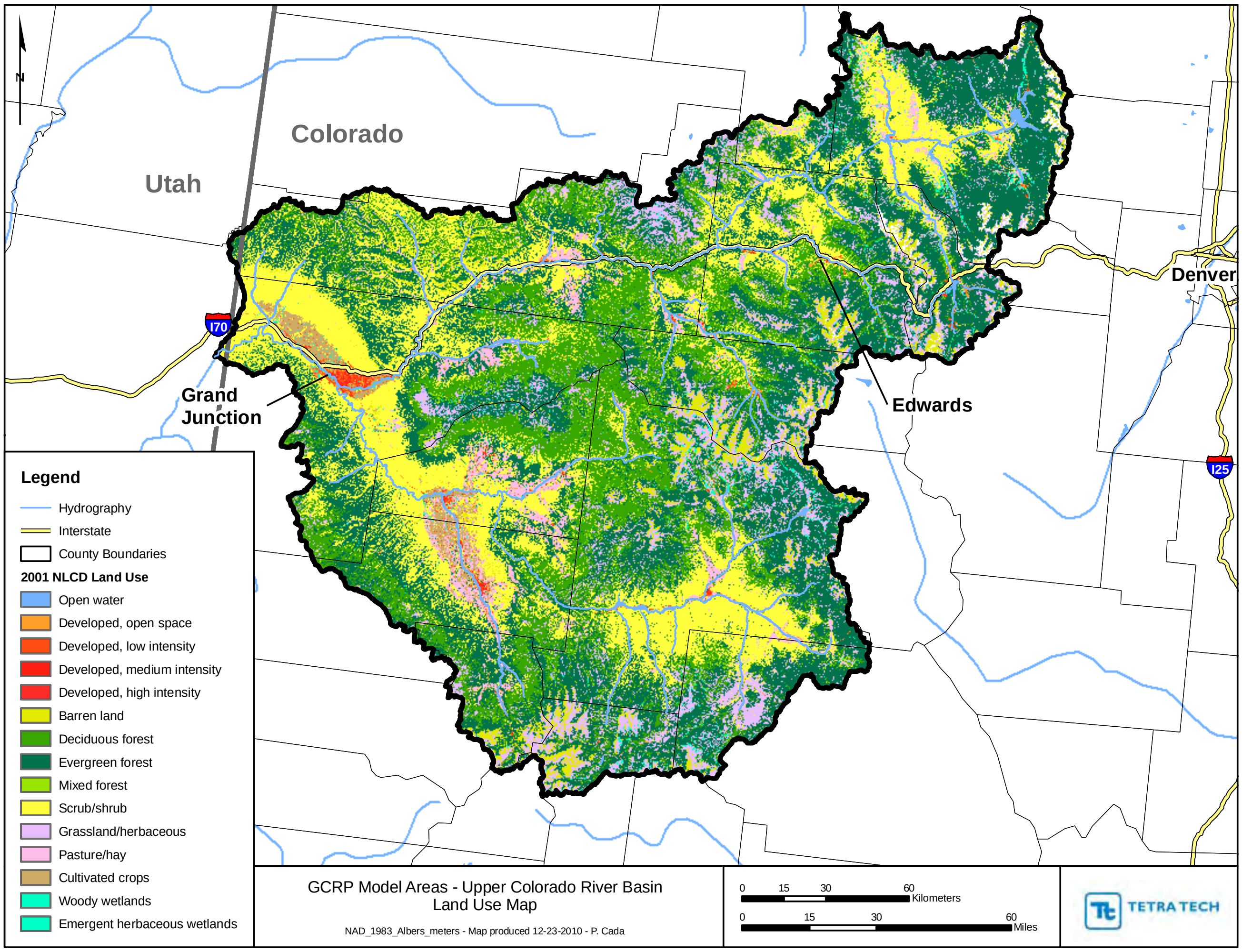

Figure 2. Land use in the Upper Colorado River basin.

Table 1. Aggregation of NLCD land cover classes

NLCD Class	Comments	SWAT class
11 Water	Water surface area usually accounted for as reach area	WATR
12 Perennial ice/snow		WATR
21 Developed open space		URLD
22 Dev. Low Intensity		URMD
23 Dev. Med. Intensity		URHD
24 Dev. High Intensity		UIDU
31 Barren Land		SWRN
41 Forest	Deciduous	FRSD
42 Forest	Evergreen	FRSE
43 Forest	Mixed	FRST
51-52 Shrubland		RNGB
71-74 Herbaceous Upland		RNGE
81 Pasture/Hay		HAY
82 Cultivated		AGRR
91-97 Wetland	Emergent & woody wetlands	WETF, WETL, WETN
98-99 Wetland	Aquatic bed wetlands (not emergent)	WATR

Table 2. Land use distribution for the Upper Colorado River basin (2001 NLCD) (mi^2)

HUC 8 watershed	Open water	Snow/Ice	Developed[a] Open space	Developed[a] Low density	Developed[a] Medium density	Developed[a] High density	Barren land	Forest	Shrubland	Pasture/Hay	Cultivated	Wetland	Total
Colorado Headwaters **14010001**	26.4	82.2	12.7	5.8	0.8	0.1	64.7	1,597.3	986.8	54.5	0.3	70.2	2,901.9
Blue **14010002**	10.0	26.5	8.1	6.2	2.2	0.2	66.7	334.9	205.7	5.1	0.2	17.2	683.1
Eagle **14010003**	1.7	6.2	8.3	8.5	2.6	0.2	48.8	563.4	306.6	10.2	0.3	15.6	972.5
Roaring Fork **14010004**	3.6	3.8	9.5	6.8	2.3	0.2	126.0	876.2	361.2	30.8	0.4	33.9	1,454.6
Colorado Headwaters-Plateau **14010005**	12.7	0.0	27.4	42.9	13.5	3.1	46.4	1,544.8	1,167.6	119.8	94.4	46.0	3,118.7
Parachute-Roan **14010006**	0.0	0.0	0.8	0.9	0.1	0.0	44.7	353.4	282.1	22.6	0.2	2.5	707.3
East-Taylor **14020001**	3.6	0.9	3.3	0.9	0.2	0.0	61.8	441.5	215.4	5.6	0.0	33.7	766.9
Upper Gunnison **14020002**	17.1	0.0	10.0	4.2	0.8	0.0	96.4	1,312.2	888.0	57.0	0.5	25.1	2,411.3
Tomichi **14020003**	0.5	0.1	5.4	1.2	0.4	0.1	17.4	544.5	488.5	30.8	0.0	13.9	1,102.7
North Fork Gunnison **14020004**	1.2	0.0	5.6	2.6	0.3	0.1	26.2	655.2	207.9	57.2	1.6	11.1	969.0
Lower Gunnison **14020005**	5.9	0.0	8.0	11.2	2.7	0.4	23.8	821.2	664.2	61.9	44.7	18.7	1,662.7
Uncompahgre **14020006**	2.3	0.0	12.0	13.2	4.1	1.0	52.9	576.8	282.4	109.1	54.5	6.3	1,114.6
Total	85.0	119.7	111.1	104.4	30.0	5.3	675.8	9,621.5	6,056.4	564.6	197.1	294.3	17,865.2

[a]The percent imperviousness applied to each of the developed land uses is as follows: open space (9.78%), low density (31.89%), medium density (60.48%), and high density (87.41%).

Point Sources

There are numerous point source discharges in the watershed. Only the major dischargers, generally defined as those with a design flow greater than 1 MGD are included in the simulation (Table 3). The major dischargers are represented at long-term average flows, without accounting for changes over time or seasonal variations.

Table 3. Major point source discharges in the Upper Colorado River basin

NPDES ID	Name	Design flow (MGD)	Observed flow (MGD) (1991-2006 average)
CO0040053	MESA CO./GRAND JUNCTION - CITY	12.500	7.484
CO0039641	DELTA, CITY OF	3.800	1.060
CO0039624	MONTROSE, CITY OF	3.200	1.709
CO0035394	U.S. MOLY CORP.	0.000	0.347
CO0020516	GLENWOOD SPRINGS, CITY OF	2.300	0.875
CO0023086	SNOWMASS WATER & SAN DISTRICT	1.600	0.792
CO0026387	ASPEN CONSOLIDATED SAN DISTRCT	1.870	1.683
CO0020451	FRISCO SANITATION DISTRICT	1.700	0.577
CO0029955	SUMMIT CO BOARD OF COMMISS	2.600	0.631
CO0045420	IOWA HILL WATER RECLAMATION	1.500	0.683
CO0000230	CLIMAX MOLYBDENUM COMPANY	0.000	1.385
CO0037681	THREE LAKES WATER & SAN DIST	2.000	0.419
CO0040142	FRASER SANITATION DISTRICT	2.000	0.729
CO0024431	EAGLE RIVER WATER & SAN. DIST.	4.300	2.195
CO0037311	EAGLE RIVER WATER & SAN. DIST.	12.500	7.484
CO0021369	EAGLE RIVER WATER & SAN. DIST.	3.800	1.060
CO0042480	CBS OPERATIONS, INC.	3.200	1.709

Most of these point sources have reasonably complete monitoring for total suspended solids (TSS). Assumptions were made for total nitrogen and total phosphorus depending upon the type of facility. The point sources were initially represented in the model with the median of reported values for total phosphorus, total suspended solids and total nitrogen.

Meteorological Data

The required meteorological time series data for the GCRP SWAT simulations are precipitation and air temperature. The GCRP simulations do not include water temperature and uses a degree-day method for snowmelt. SWAT estimates Penmann-Monteith potential evapotranspiration using a statistical weather generator for inputs other than temperature and precipitation. These meteorological time series are drawn from the BASINS4 Meteorological Database (USEPA 2008), which provides a consistent, quality-assured set of nationwide data with gaps filled and records disaggregated. Scenario application requires simulation over 30 years, so the available stations are those with a common 30-year period of record (or one that can be filled from an approximately co-located station) that covers the year 2002. A total of 47 precipitation stations were identified for use in the Upper Colorado River watershed model with a common period of record of 10/1/1972-9/30/2003

(Table 4). Temperature records are sparser; where these are absent temperature is taken from nearby stations with an elevation correction.

Table 4. Precipitation stations for the Upper Colorado River watershed model

COOP ID	Name	Latitude	Longitude	Temperature	Elevation (m)
050183	ALLENSPARK 2 NNW	40.1881	-105.5010		2504
050214	ALTENBERN	39.5008	-108.3790	x	1731
050797	BLUE MESA LAKE	38.4668	-107.1670		2316
050843	BOULDER 2	40.0340	-105.2810	x	1650
050909	BRECKENRIDGE	39.4862	-106.0430		2920
051071	BUENA VISTA 2 S	38.8247	-106.1270	x	2422
051186	CABIN CREEK	39.6553	-105.7080	x	3054
051609	CIMARRON	38.4443	-107.5590	x	2102
051660	CLIMAX	39.3672	-106.1890	x	3442
051713	COCHETOPA CREEK	38.4462	-106.7610	x	2438
051772	COLORADO NATL MONUMENT	39.1014	-108.7330	x	1762
051959	CRESTED BUTTE	38.8743	-106.9760	x	2698
052281	DILLON 1 E	39.6262	-106.0350	x	2763
053146	FRUITA 1 W	39.1645	-108.7340	x	1373
053246	GATEWAY	38.6825	-108.9720	x	1387
053359	GLENWOOD SPGS #2	39.5181	-107.3170	x	1792
053488	GRAND JUNCTION WALKER	39.1342	-108.5400	x	1481
053489	GRAND JUNCTION 6 ESE	39.0423	-108.4660	x	1451
053496	GRAND LAKE 1 NW	40.2669	-105.8320	x	2658
053500	GRAND LAKE 6 SSW	40.1851	-105.8660	x	2526
053530	GRANT	39.4608	-105.6780	x	2644
053592	GREEN MT DAM	39.8790	-106.3330	x	2359
053662	GUNNISON 3 SW	38.5250	-106.9680	x	2329
053951	HERMIT 7 ESE	37.7718	-107.1090	x	2758
054664	KREMMLING	40.0575	-106.3680		2274
054734	LAKE CITY	38.0248	-107.3140	x	2643
055507	MEREDITH	39.3619	-106.7420	x	2385
055722	MONTROSE NO 2	38.4858	-107.8790	x	1763
056012	NORWOOD	38.1318	-108.2860	x	2140
056203	OURAY	38.0207	-107.6680	x	2390
056266	PALISADE	39.1136	-108.3500	x	1466

COOP ID	Name	Latitude	Longitude	Temperature	Elevation (m)
056306	PAONIA 1 SW	38.8523	-107.6230	x	1701
056524	PLACERVILLE	37.9944	-108.0210		2301
057031	RIFLE	39.5329	-107.7920	x	1661
057337	SAGUACHE	38.0858	-106.1440	x	2347
057460	SARGENTS	38.4040	-106.4230		2579
057618	SHOSHONE	39.5717	-107.2260		1807
057656	SILVERTON	37.8193	-107.6650	x	2828
057848	SPICER	40.4725	-106.4470	x	2556
057936	STEAMBOAT SPRINGS	40.4884	-106.8230	x	2094
058064	SUGARLOAF RESERVOIR	39.2495	-106.3710	x	2968
058184	TAYLOR PARK	38.8184	-106.6080	x	2806
058204	TELLURIDE 4 WNW	37.9492	-107.8730	x	2643
058501	TWIN LAKES RES	39.0937	-106.3510	x	2806
058560	URAVAN	38.3762	-108.7420	x	1527
059175	WINTER PARK	39.8904	-105.7610		2775
059265	YAMPA	40.1562	-106.9090	x	2405

Watershed Segmentation

The Upper Colorado River basin was divided into 89 subwatersheds for the purposes of modeling (Figure 3). Colorado River near Dotsero at USGS 09070500 was chosen for initial calibration. The model encompasses the complete watershed and does not require specification of any upstream boundary conditions for application.

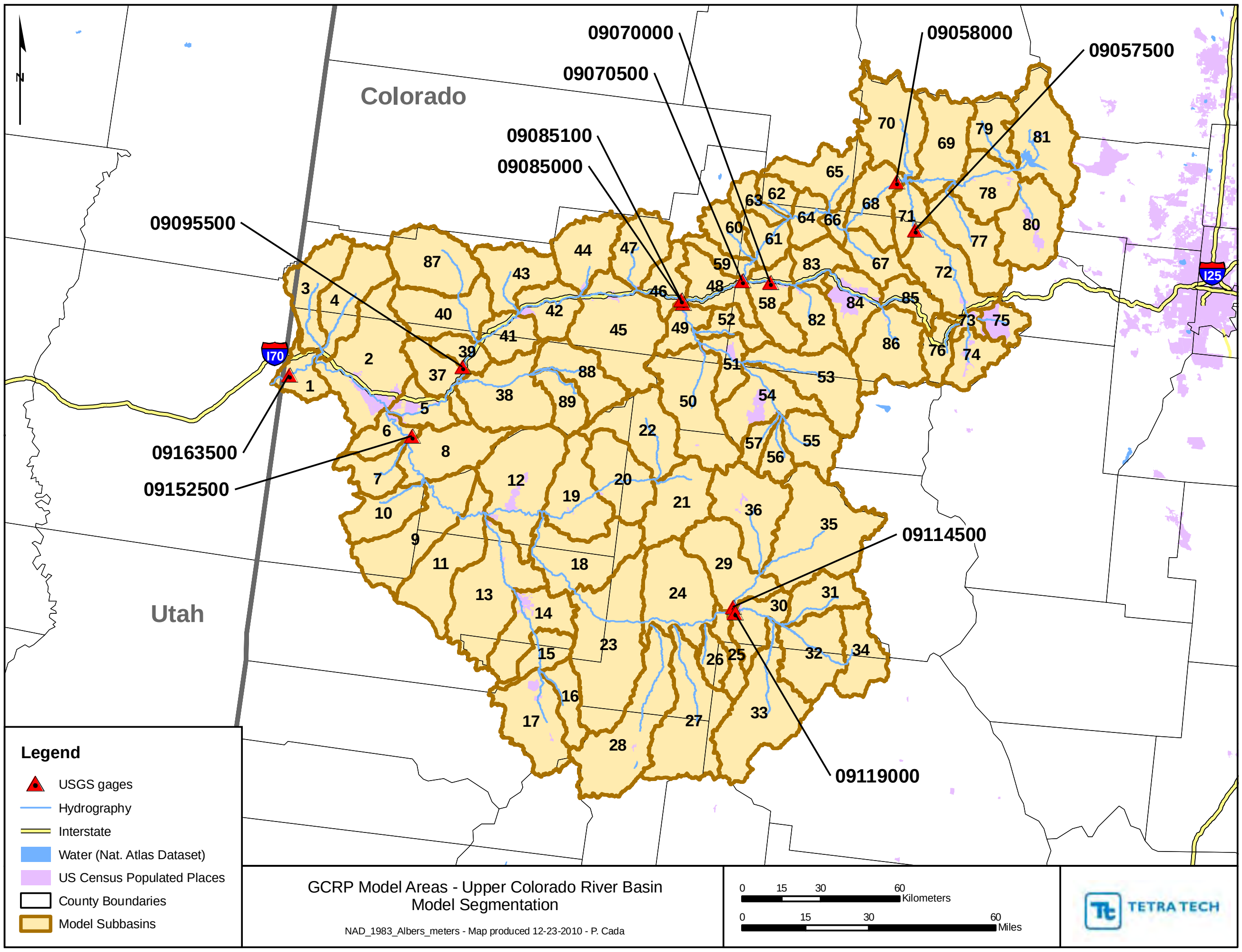

Figure 3. Model segmentation and USGS stations utilized for the Upper Colorado River basin.

Calibration Data and Locations

The specific site chosen for initial calibration was the Colorado River near Dotsero, CO (USGS 09070500) a flow and water quality monitoring location. The USGS gage located at Colorado River near Dotsero was selected because there is a good set of flow and water quality data available and the watershed lacks major point sources and impoundments. Additional calibration and validation was pursued at multiple locations (Table 5). Parameters derived from the initial calibration were not fully transferable to other portions of the Upper Colorado River basin, and additional calibration was conducted at multiple gage locations.

Table 5. Calibration and validation locations in the Upper Colorado River basin

Station name	USGS ID	Drainage area (mi^2)	Hydrology calibration	Water quality calibration
Colorado River near Kremmling, CO	09058000	2,379	x	x
Eagle River below Gypsum, CO	09070000	945	x	
Colorado River near Dotsero, CO	09070500	4,390	x	x
Colorado river below Glenwood Springs, CO	09085100	6,014	x	
Roaring fork River at Glenwood Springs, CO	09085000	1,451	x	x
Colorado River near Cameo, CO	09095500	7,986	x	x
Gunnison River near Gunnison, CO	09114500	1,011	x	x
Tomichi Creek at Gunnison, CO	09119000	1,061	x	x
Gunnison River near Grand Junction, CO	09152500	7,928	x	x
Colorado River near Utah State Line, CO	09163500	17, 843	x	x

The model hydrology calibration period was set to Water Years 1992-2002 (within the 32-year period of record for modeling). Hydrologic validation was then performed on Water Years 1982-1992. Water quality calibration used calendar years 1992-2002, while validation used 1982-1992.

SWAT Modeling

Assumptions

The Upper Colorado River basin is comprised of the areas drained by the Colorado River and Gunnison River. There are a number of reservoirs and diversion structures on Colorado and Gunnison rivers. Only major reservoirs in the basin, namely, Green Mountain, Blue Mesa and Morrow Point, were represented in the model. The Green Mountain reservoir is located on the Colorado River, while the Blue Mesa and Morrow Point reservoirs are located on the Gunnison River. Pertinent reservoir information including surface area and storage at principal (normal) and emergency spillway levels for the reservoir were obtained from the Colorado Bureau of Reclamation. The SWAT model provides four options to simulate reservoir outflow: measured daily outflow, measured monthly outflow, average annual release rate for uncontrolled reservoir, and controlled outflow with target release. Keeping in view, the GCRP climate change impact evaluation application to future climate scenarios, it was assumed that the best representation of the reservoir was to simulate it without supplying time series of outflow records. The target release approach was used for the Green Mountain reservoir. Due to lack of detailed data annual average release approach was used fort the Blue Mesa and Morrow Point reservoirs.

Hydrology Calibration

A spatial calibration approach was adopted for GCRP-SWAT modeling for the Upper Colorado River basin. A systematic adjustment of parameters has been adopted and some adjustments are applied throughout the basin. Most of the calibration efforts were geared towards getting a closer match between simulated and observed flows at the outlet of calibration focus area.

Land Use / Soil / Slope Definition

A 5/10/5 percent threshold was used for land use/soil/slope in the SWAT model while defining the HRUs. Urban land use classes were exempted from the HRU overlay thresholds.

The calibration focus area includes twenty-eight subwatersheds and is generally representative of the general land use characteristics of the overall watershed. The parameters were adjusted within the practical range to obtain reasonable fit between the simulated and measured flows in terms of Nash-Sutcliffe modeling efficiency and the high flow and low flow components as well as the seasonal flows.

The water balance of whole Upper Colorado River basin predicted by the SWAT model over the 32-year simulation period is as follows:

```
PRECIP =    418.2 MM
SNOW FALL = 177.21 MM
SNOW MELT =   136.22 MM
SUBLIMATION =    38.94 MM
SURFACE RUNOFF Q =    15.54 MM
LATERAL SOIL Q =   80.11 MM
TILE Q =     0.00 MM
GROUNDWATER (SHAL AQ) Q =    44.64 MM
REVAP (SHAL AQ => SOIL/PLANTS) =    0.00 MM
DEEP AQ RECHARGE =     5.87 MM
TOTAL AQ RECHARGE =   50.51 MM
TOTAL WATER YLD =   127.56 MM
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```
PERCOLATION OUT OF SOIL =   38.88 MM
ET =     332.7 MM
PET =    1075.9MM
TRANSMISSION LOSSES =    12.72 MM
```

Hydrologic calibration adjustments focused on the following parameters:

- CN2 (initial SCS runoff curve number for moisture condition II)
- ESCO (soil evaporation compensation factor)
- SURLAG (surface runoff lag coefficient)
- SOL_AWC (available water capacity of the soil layer, mm water/mm of soil)
- ALPHA_BF (baseflow alpha factor, days)
- GW_DELAY (groundwater delay time, days)
- GWQMIN (threshold depth of water in the shallow aquifer required for return flow to occur, mm)
- GW_REVAP (groundwater "revap" coefficient)
- CH_N1 (Manning's "n" value for tributary channels)
- CH_N2 (Manning's "n" value for main channels)
- CH_K1 (Effective hydraulic conductivity in tributary channel alluvium)
- CH_K2 (Effective hydraulic conductivity in main channel alluvium)
- SFTMP (Snowfall temperature)
- SMTMP (Snowmelt base temperature)
- SMFMX (Maximum melt rate for snow during the year)
- SMFMN (Minimum melt rate for snow during the year)

Calibration results for the Colorado River near Dotsero are summarized in Figure 4, Figure 5, Figure 6, Figure 7 and Table 6.

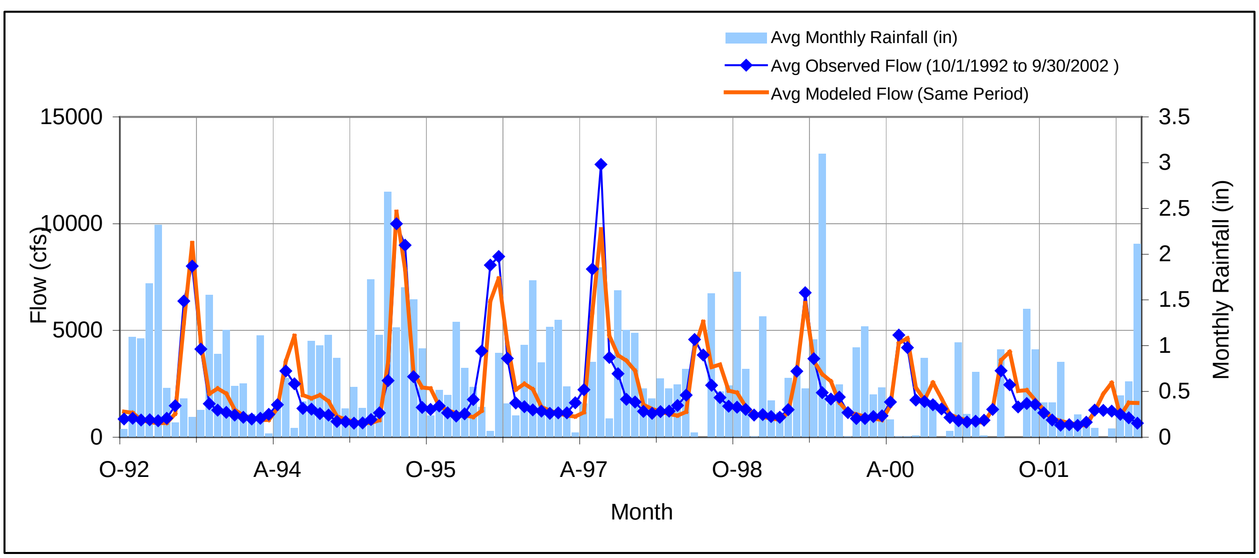

Figure 4. Mean monthly flow at USGS 09070500 Colorado River near Dotsero, Colorado – calibration period.

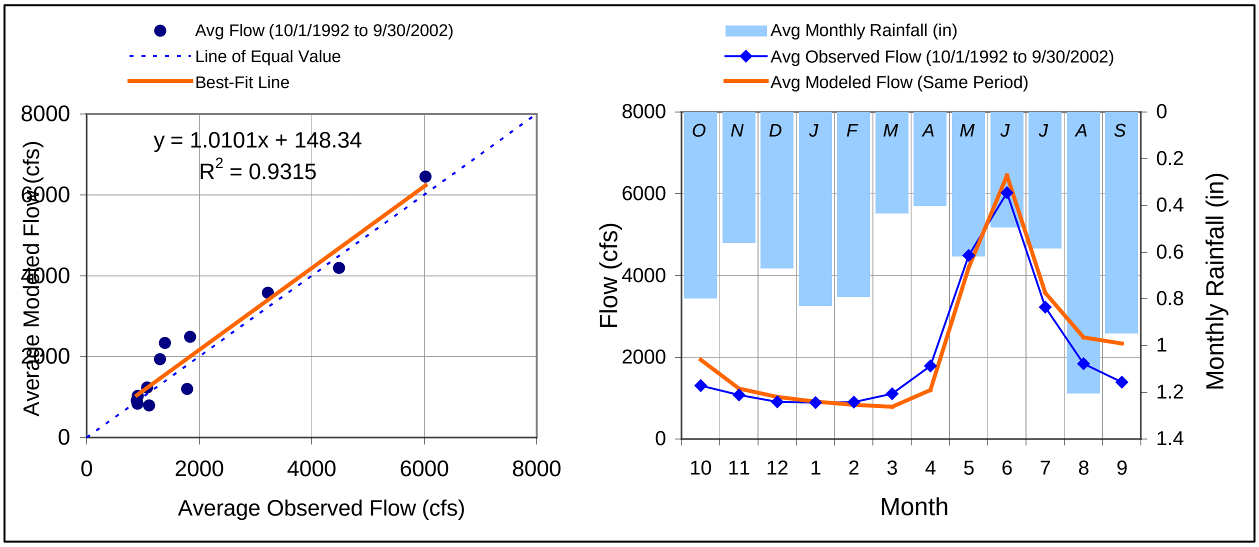

Figure 5. Seasonal regression and temporal aggregate at USGS 09070500 Colorado River near Dotsero, Colorado – calibration period.

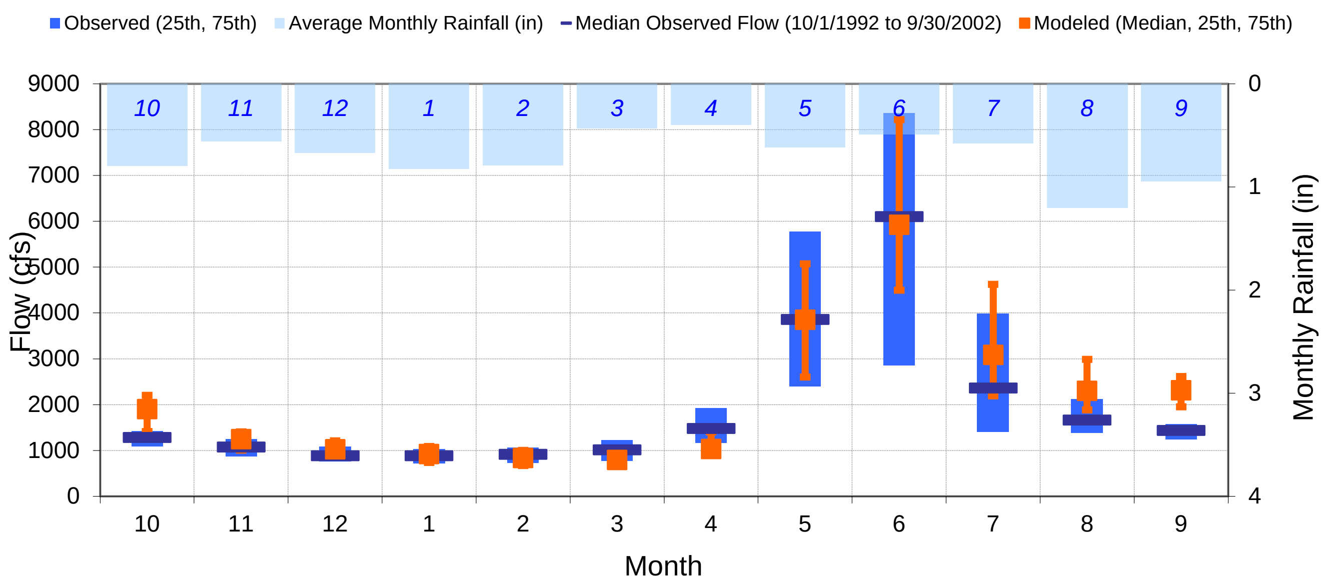

Figure 6. Seasonal medians and ranges at USGS 09070500 Colorado River near Dotsero, Colorado – calibration period.

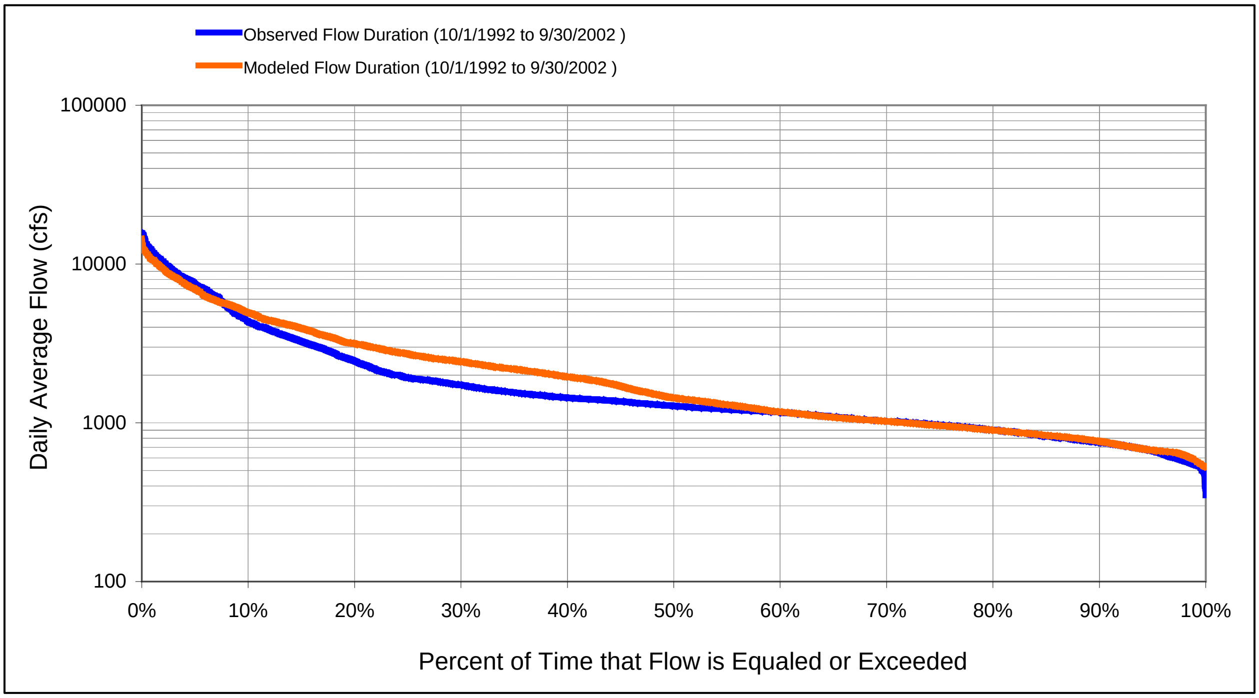

Figure 7. Flow exceedance at USGS 09070500 Colorado River near Dotsero, Colorado – calibration period.

Table 6. Summary statistics at USGS 09070500 Colorado River near Dotsero, Colorado – calibration period

SWAT Simulated Flow		Observed Flow Gage	
REACH OUTFLOW FROM OUTLET(S) 58, 59 10-Year Analysis Period: 10/1/1992 - 9/30/2002 Flow volumes are (inches/year) for upstream drainage area		USGS 09070500 COLORADO RIVER NEAR DOTSERO, CO Hydrologic Unit Code: 14010001 Latitude: 39.6446111 Longitude: -107.0780139 Drainage Area (sq-mi): 4394	
Total Simulated In-stream Flow:	**6.97**	Total Observed In-stream Flow:	**6.44**
Total of simulated highest 10% flows:	**2.27**	Total of Observed highest 10% flows:	**2.46**
Total of Simulated lowest 50% flows:	**1.49**	Total of Observed Lowest 50% flows:	**1.47**
Simulated Summer Flow Volume (months 7-9):	**2.18**	Observed Summer Flow Volume (7-9):	**1.68**
Simulated Fall Flow Volume (months 10-12):	**1.09**	Observed Fall Flow Volume (10-12):	**0.85**
Simulated Winter Flow Volume (months 1-3):	**0.65**	Observed Winter Flow Volume (1-3):	**0.74**
Simulated Spring Flow Volume (months 4-6):	**3.04**	Observed Spring Flow Volume (4-6):	**3.16**
Total Simulated Storm Volume:	**0.69**	Total Observed Storm Volume:	**0.98**
Simulated Summer Storm Volume (7-9):	**0.23**	Observed Summer Storm Volume (7-9):	**0.23**

Errors (Simulated-Observed)	*Error Statistics*	*Recommended Criteria*		
Error in total volume:	8.18	10		
Error in 50% lowest flows:	1.31	10		
Error in 10% highest flows:	-7.51	15		
Seasonal volume error - Summer:	29.83	30		
Seasonal volume error - Fall:	27.91 >>	30		Clear
Seasonal volume error - Winter:	-12.66	30		
Seasonal volume error - Spring:	-3.78	30		
Error in storm volumes:	**-29.75**	**20**		
Error in summer storm volumes:	0.27	50		
Nash-Sutcliffe Coefficient of Efficiency, E:	0.829	Model accuracy increases		
Baseline adjusted coefficient (Garrick), E':	0.580	as E or E' approaches 1.0		
Monthly NSE	0.864			

Hydrology Validation

Hydrology validation for Saco River was performed for the period 10/1/1982 through 9/30/1992. The validation achieves a moderately high coefficient of model fit efficiency, but is over on summer flow volumes (Table 8, Table 9, Table 10, Table 11and Table 7).

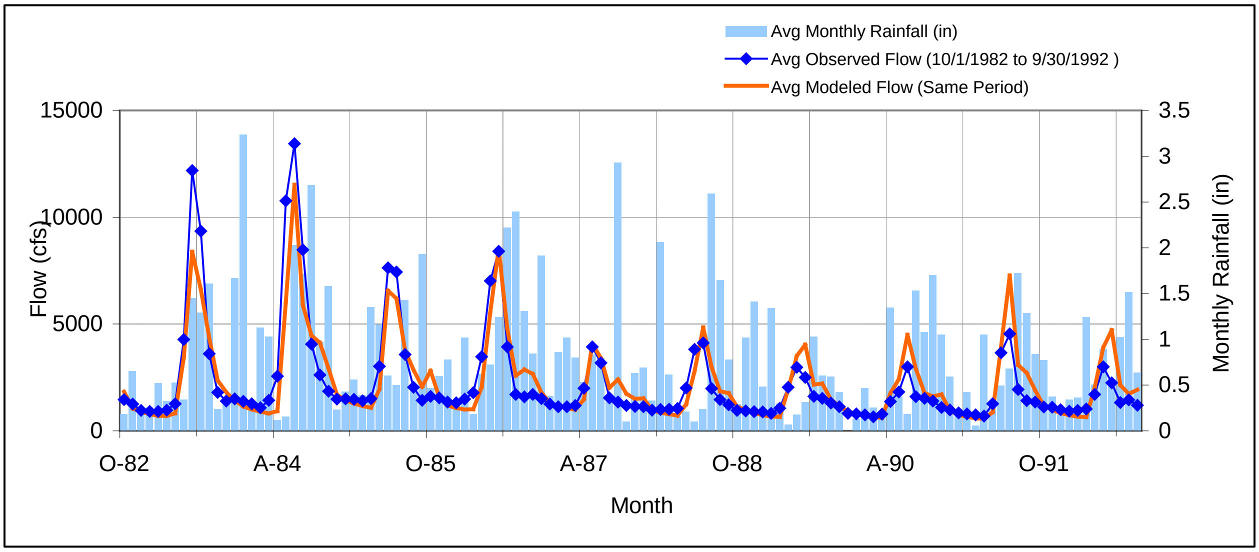

Figure 8. Mean monthly flow at USGS 09070500 Colorado River near Dotsero, Colorado – validation period.

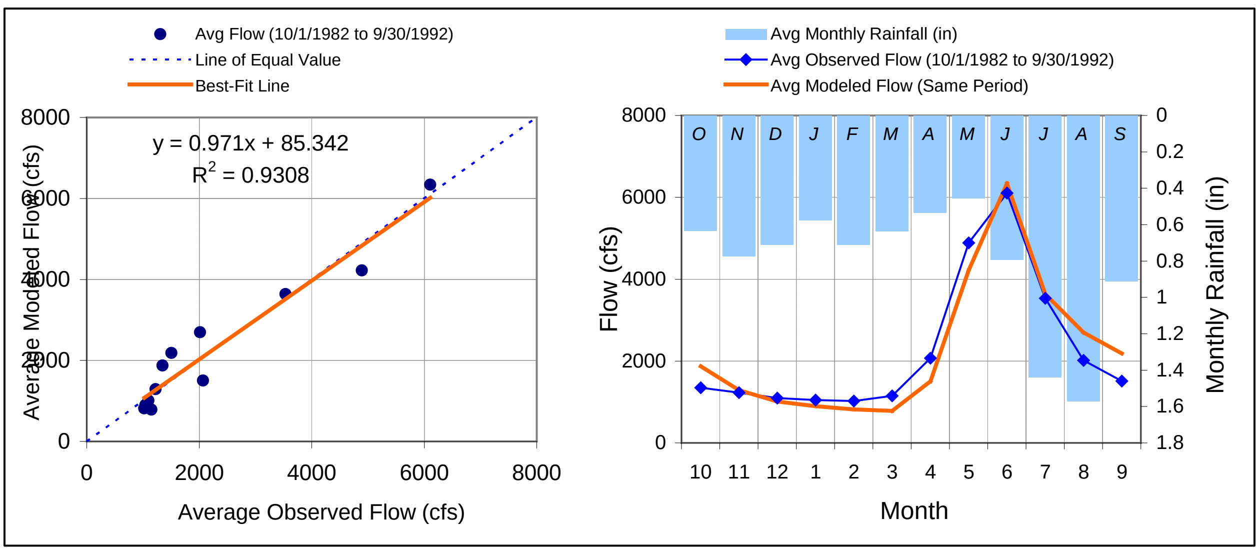

Figure 9. Seasonal regression and temporal aggregate at USGS 09070500 Colorado River near Dotsero, Colorado – validation period.

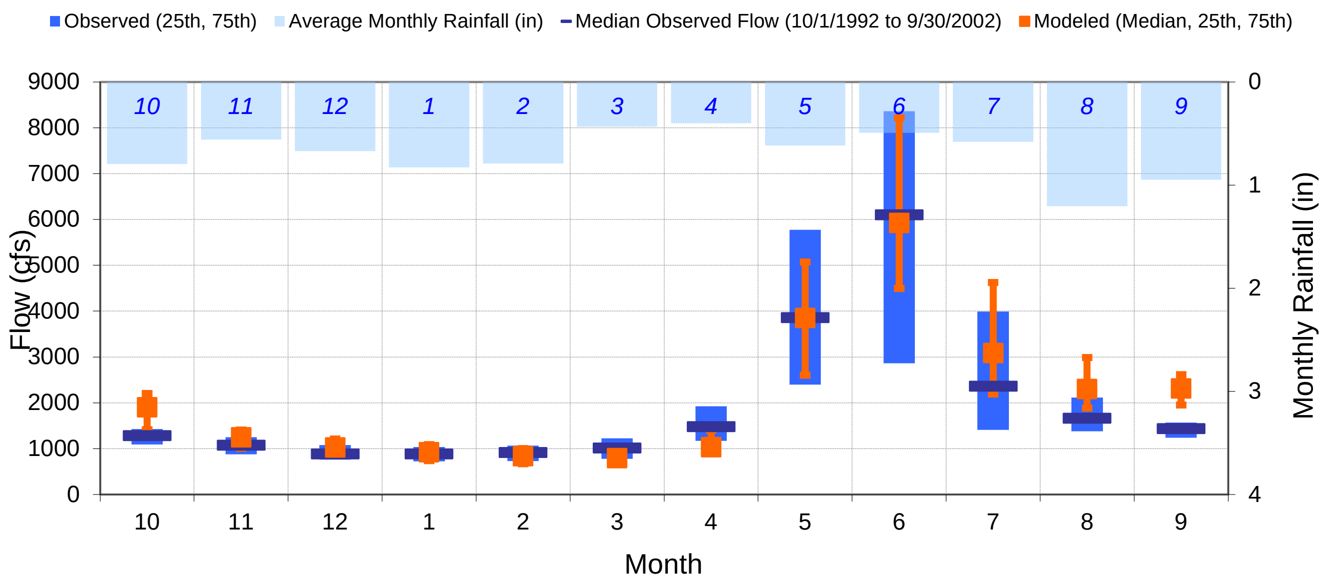

Figure 10. Seasonal medians and ranges at USGS 09070500 Colorado River near Dotsero, Colorado – validation period.

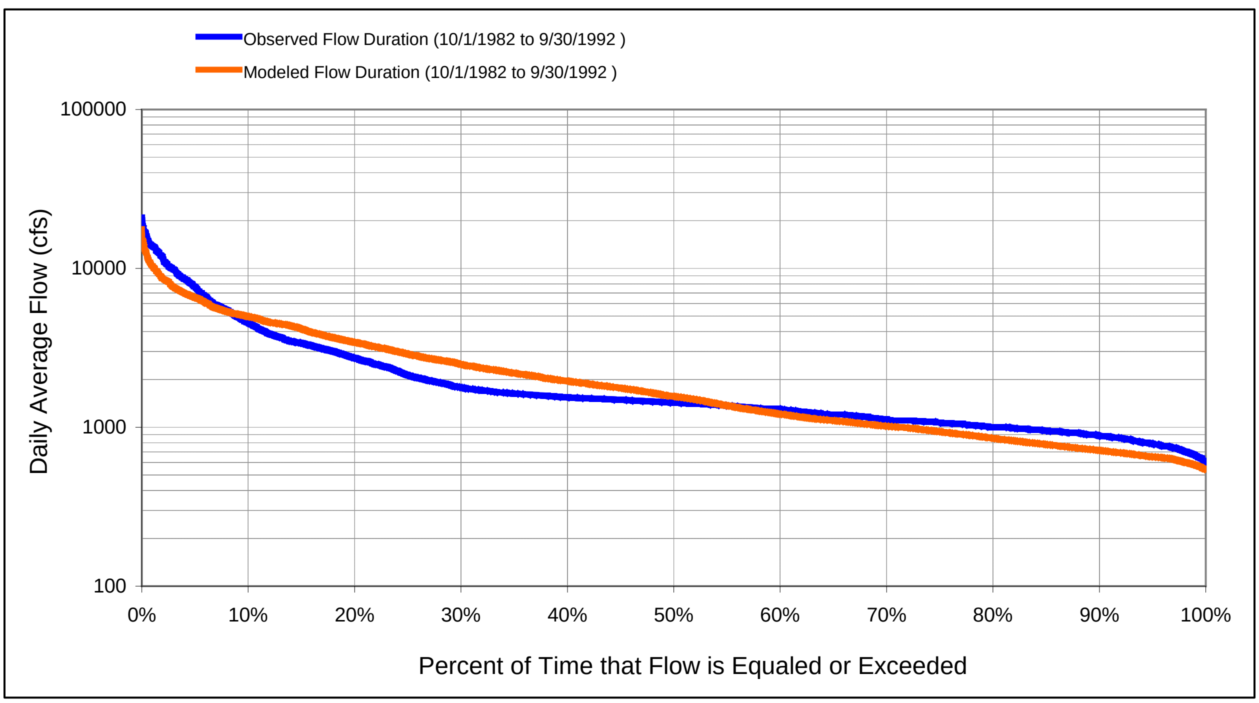

Figure 11. Flow exceedance at USGS 09070500 Colorado River near Dotsero, Colorado – validation period.

Table 7. Summary statistics at USGS 09070500 Colorado River near Dotsero, Colorado – validation period.

SWAT Simulated Flow		Observed Flow Gage	
REACH OUTFLOW FROM OUTLET(S) 58, 59 10-Year Analysis Period: 10/1/1982 - 9/30/1992 Flow volumes are (inches/year) for upstream drainage area		USGS 09070500 COLORADO RIVER NEAR DOTSERO, CO Hydrologic Unit Code: 14010001 Latitude: 39.6446111 Longitude: -107.0780139 Drainage Area (sq-mi): 4394	
Total Simulated In-stream Flow:	**7.03**	Total Observed In-stream Flow:	**6.97**
Total of simulated highest 10% flows:	**2.19**	Total of Observed highest 10% flows:	**2.63**
Total of Simulated lowest 50% flows:	**1.48**	Total of Observed Lowest 50% flows:	**1.66**
Simulated Summer Flow Volume (months 7-9):	**2.22**	Observed Summer Flow Volume (7-9):	**1.84**
Simulated Fall Flow Volume (months 10-12):	**1.08**	Observed Fall Flow Volume (10-12):	**0.95**
Simulated Winter Flow Volume (months 1-3):	**0.64**	Observed Winter Flow Volume (1-3):	**0.82**
Simulated Spring Flow Volume (months 4-6):	**3.10**	Observed Spring Flow Volume (4-6):	**3.36**
Total Simulated Storm Volume:	**0.69**	Total Observed Storm Volume:	**0.98**
Simulated Summer Storm Volume (7-9):	**0.20**	Observed Summer Storm Volume (7-9):	**0.24**

Errors (Simulated-Observed)	*Error Statistics*	*Recommended Criteria*
Error in total volume:	0.93	10
Error in 50% lowest flows:	**-10.42**	**10**
Error in 10% highest flows:	**-16.51**	**15**
Seasonal volume error - Summer:	20.53	30
Seasonal volume error - Fall:	13.79	30
Seasonal volume error - Winter:	-22.44	30
Seasonal volume error - Spring:	-7.74	30
Error in storm volumes:	**-29.14**	**20**
Error in summer storm volumes:	-16.53	50
Nash-Sutcliffe Coefficient of Efficiency, E:	0.780	Model accuracy increases
Baseline adjusted coefficient (Garrick), E':	0.545	as E or E' approaches 1.0
Monthly NSE	0.819	

>> Clear

Hydrology Results for Larger Watershed

As described above, parameters determined for the gage at Colorado River at Dotsero were initially transferred to other gages in the watershed. However, changes to subwatershed level parameters were required to fit the model to the observed flows. In all, calibration and validation was pursued at a total of ten gages throughout the watershed. Results of the calibration and validation exercise are summarized in Table 8 and Table 9, respectively. Calibration and validation results were acceptable at most gages.

Table 8. Summary statistics (percent error): all stations - calibration period

Station	09058000	09070000	09085100	09085000	09095500	09114500	09119000	09152500	09163500
Error in total volume:	1.25	8.77	-1.09	8.13	1.99	-0.20	3.22	3.82	4.43
Error in 50% lowest flows:	-10.98	-19.88	-9.84	-2.04	-3.28	6.02	-23.16	3.70	7.11
Error in 10% highest flows:	4.73	3.06	-6.45	-2.62	-14.74	3.27	13.39	-9.13	-13.89
Seasonal volume error - Summer:	2.01	33.81	15.28	29.89	28.02	8.52	34.72	30.15	39.13
Seasonal volume error - Fall:	8.41	13.61	-1.55	18.07	21.42	29.01	4.60	-2.68	13.70
Seasonal volume error - Winter:	-21.75	-28.40	-11.66	-12.04	-18.43	5.64	-48.21	-18.15	-19.72
Seasonal volume error - Spring:	5.65	2.88	-8.73	-2.31	-12.04	-12.12	2.18	1.02	-8.47
Error in storm volumes:	-7.91	-3.45	8.00	-18.68	-32.12	17.03	-27.67	6.01	-29.66
Error in summer storm volumes:	2.53	42.75	28.46	16.84	0.28	6.25	-11.96	43.58	-7.11
Daily Nash-Sutcliffe Coefficient of Efficiency, E:	0.484	0.812	0.847	0.877	0.858	0.638	0.678	0.629	0.817
Monthly Nash-Sutcliffe Coefficient of Efficiency, E:	0.636	0.904	0.912	0.922	0.892	0.790	0.762	0.694	0.843

Table 9. Summary statistics (percent error): all stations - validation period

Station	09058000	09070000	09085100	09085000	09095500	09114500	09119000	09152500	09163500
Error in total volume:	-6.24	1.02	-3.72	1.29	-3.41	-9.88	0.51	1.76	-3.29
Error in 50% lowest flows:	-20.25	-16.89	-10.53	-8.69	-3.35	-9.66	-15.95	9.77	4.74
Error in 10% highest flows:	-6.85	-4.81	-9.36	-12.98	-24.88	-5.91	-8.04	-19.66	-27.78
Seasonal volume error - Summer:	-4.31	9.24	8.19	20.69	20.15	2.80	35.99	39.80	30.79
Seasonal volume error - Fall:	0.85	1.21	-9.61	8.36	16.70	10.92	3.17	3.70	10.27
Seasonal volume error - Winter:	-27.64	-27.33	-13.61	-17.52	-19.76	-16.02	-29.15	-27.50	-25.03
Seasonal volume error - Spring:	-3.48	1.09	-6.83	-7.04	-16.89	-20.52	-8.20	-4.02	-16.84
Error in storm volumes:	-8.73	-7.96	2.88	-24.74	-35.18	-6.67	-37.92	1.83	-33.40
Error in summer storm volumes:	-11.69	5.33	17.51	-2.57	-20.98	-22.07	-25.04	41.16	-13.83
Daily Nash-Sutcliffe Coefficient of Efficiency, E:	0.504	0.795	0.847	0.853	0.796	0.440	0.480	0.554	0.701
Monthly Nash-Sutcliffe Coefficient of Efficiency, E:	0.586	0.882	0.887	0.914	0.834	0.639	0.525	0.618	0.739

Water Quality Calibration and Validation

Initial calibration and validation of water quality was done at USGS 09070500, Colorado River near Dotsero from water years 1995 to 2002, due to limited water quality data. Subject to the availability of water quality data for the other gages, 1992-2002 was adopted as the calibration period and 1982-1992 was adopted as the validation period. As with hydrology, calibration was performed on the later period as this better reflects the land use included in the model.

Calibration adjustments for sediment focused on the following parameters:

- SPCON (linear parameter for estimating maximum amount of sediment that can be re-entrained during channel sediment routing)
- SPEXP (exponential parameter for estimating maximum amount of sediment that can be re-entrained during channel sediment routing)
- CH_COV (channel cover factor)
- CH_EROD (channel erodibility factor)
- USLE_P (USLE support practice factor)

Simulated and estimated sediment loads at the Colorado River station near Dotsero for both the calibration and validation periods are shown in Figure 12 and statistics are provided separately in Table 10. The key statistic in Table 10 is the relative percent error, which shows the error in the prediction of monthly load normalized to the estimated load. Table 10 also shows the relative average absolute error, which is the average of the relative magnitude of errors in individual monthly load predictions. This number is inflated by outlier months in which the simulated and estimated loads differ by large amounts (which may be as easily due to uncertainty in the estimated load due to limited data as to problems with the model) and the third statistic, the relative median absolute error, is likely more relevant and shows better agreement.

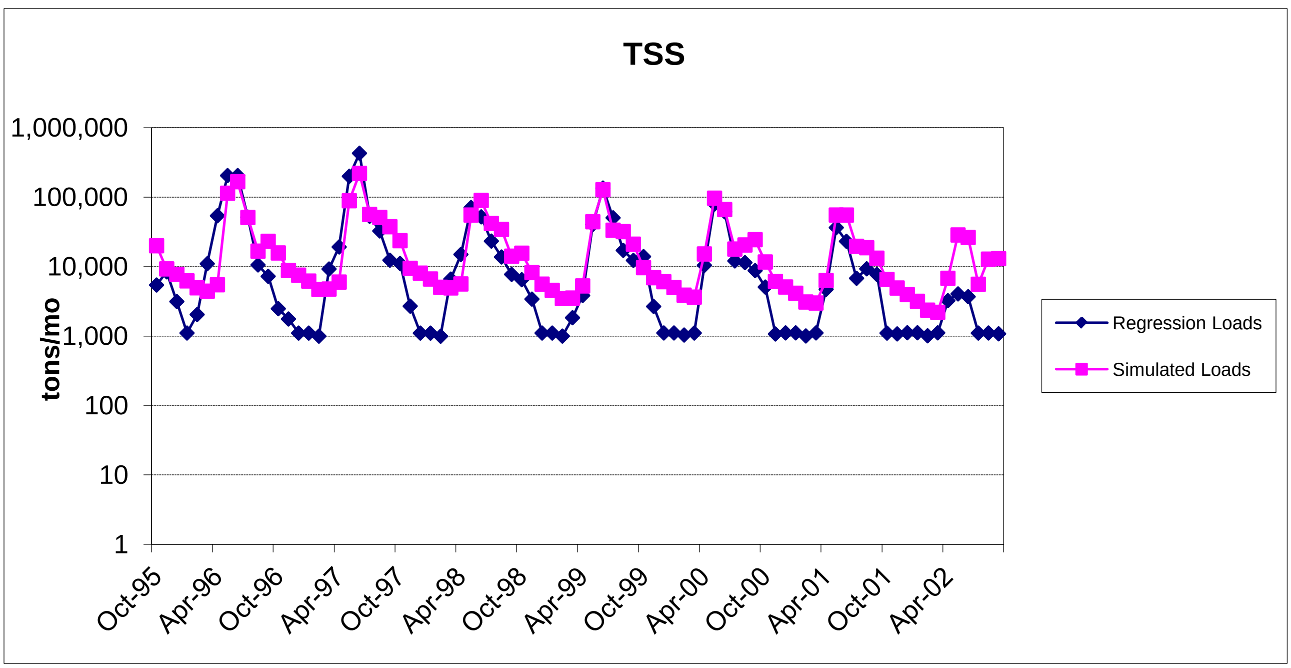

Figure 12. Fit for monthly load of TSS at USGS 09070500 Colorado River near Dotsero, Colorado.

Table 10. Model fit statistics (observed minus predicted) for monthly sediment loads using stratified regression at USGS 09070500 Colorado River near Dotsero, Colorado

Statistic	Calibration/validation period (1995-2002)
Relative Percent Error	0.4%
Relative Average Absolute Error	53.7%
Relative Median Absolute Error	21.6%

Calibration adjustments for total phosphorus and total nitrogen focused on the following parameters:

- RHOQ (algal respiration rate at 20^{O} C)
- PHOSKD (phosphorus soil partitioning coefficient)
- PSP (phosphorus availability index)
- RS1 (Local algal settlement rate in the reach at 20^{O} C)
- AL1 (Fraction of algal biomass that is nitrogen)
- AL2 (Fraction of algal biomass that is phosphorus)
- MUMAX (Rate of oxygen uptake per unit NO_2-N oxidation at 20^{O} C)
- RHOQ (Algal respiration rate at 20^{O} C)
- RS2 (benthic source rate for dissolved P in the reach at 20^{O} C)
- RS3 (Benthic source rate for NH_4-N in the reach at 20^{O} C)
- RS5 (organic P settling rate in the reach at 20^{O} C)
- BC4 (rate constant for mineralization of organic P to dissolved P in the reach at 20^{O} C)
- RS4 (rate coefficient for organic N settling in the reach at 20^{O} C)
- CH_ONCO (Channel organic nitrogen concentration)
- CH_OPCO (Channel organic phosphorus concentration)
- SDNCO (Denitrification threshold water content)
- CDN (Denitrification exponential rate constant)

Results for the phosphorus simulation are shown in Figure 13 and Table 11. Results for the nitrogen simulation are shown in Figure 14 and Table 12. The model fit is generally acceptable.

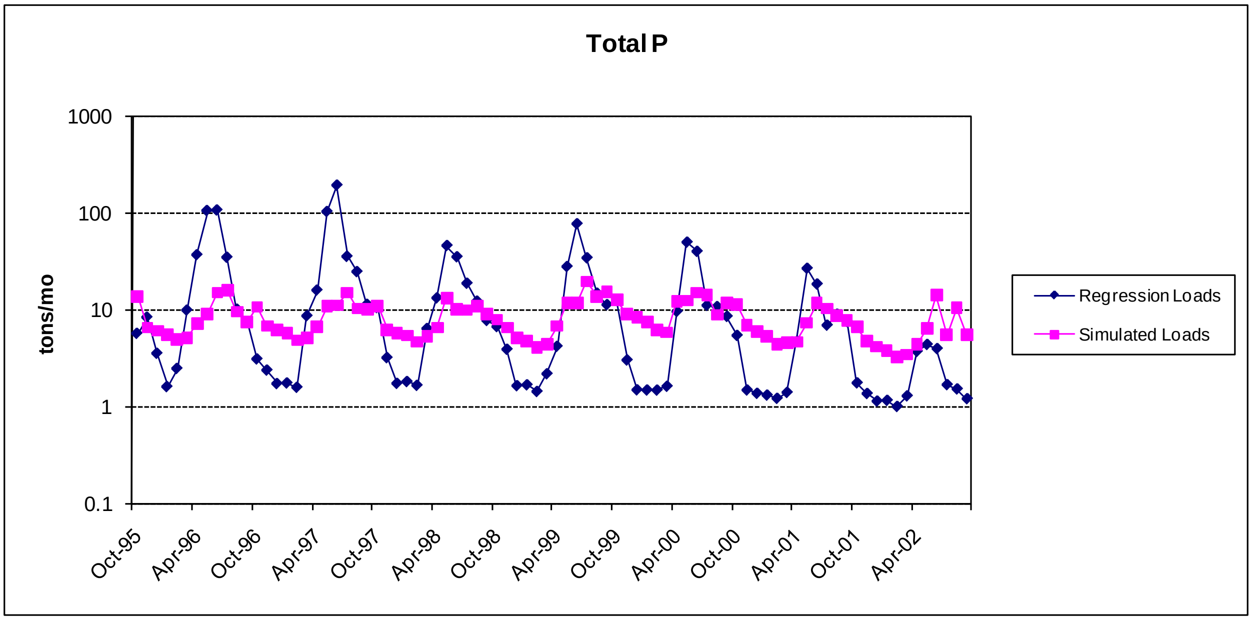

Figure 13. Fit for monthly load of total phosphorus at USGS 09070500 Colorado River near Dotsero, Colorado.

Table 11. Model fit statistics (observed minus predicted) for monthly phosphorus loads using stratified regression at USGS 09070500 Colorado River near Dotsero, Colorado

Statistic	Calibration/validation period (1995-2002)
Relative Percent Error	47.4%
Relative Average Absolute Error	75.9%
Relative Median Absolute Error	23.8%

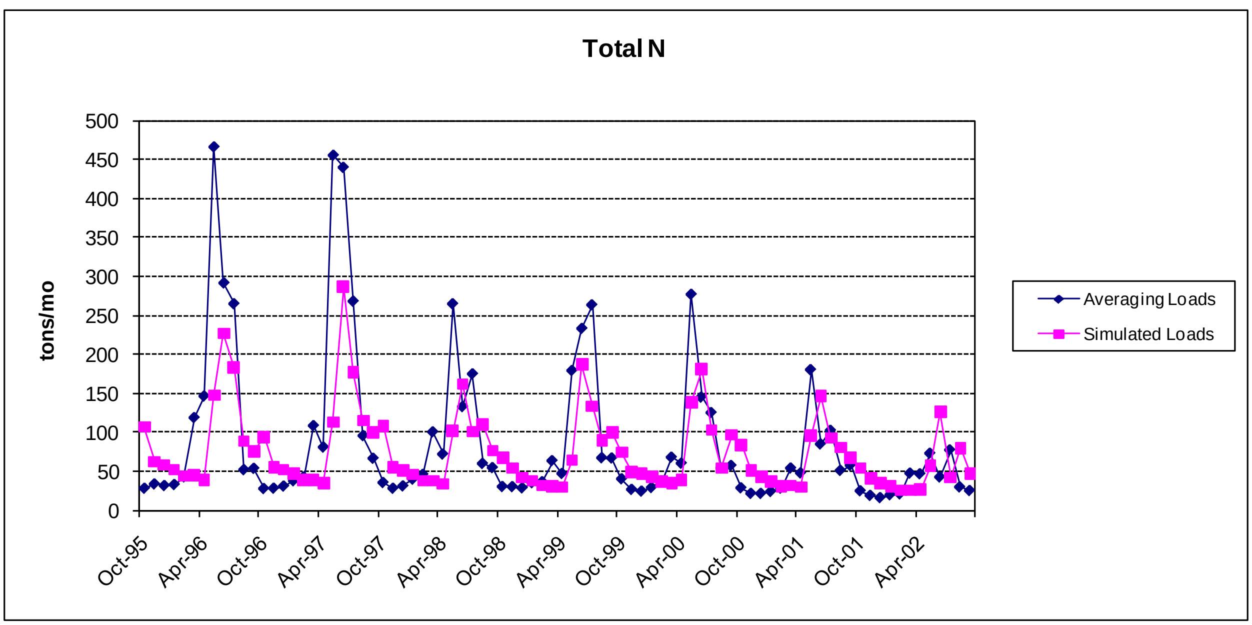

Figure 14. Fit for monthly load of total nitrogen at USGS 09070500 Colorado River near Dotsero, Colorado.

Table 12. Model fit statistics (observed minus predicted) for monthly total nitrogen loads using averaging estimator at USGS 09070500 Colorado River near Dotsero, Colorado

Statistic	Calibration/Validation period (1995-2002)
Relative Percent Error	15.1%
Relative Average Absolute Error	52.2%
Relative Median Absolute Error	32.4%

Water Quality Results for Larger Watershed

As with hydrology, a spatial calibration approach was adopted. SWAT model parameters for water quality derived from calibrations performed at the USGS gage at Colorado River near Dotsero were transferred to other portions of the watershed with necessary changes to subbasin level parameters. Summary statistics for the SWAT water quality calibration and validation at other stations in the watershed are provided in Table 13 and Table 14.

Table 13. Summary statistics for water quality at all stations – calibration period 1992-2002

Station	09058000	09085000 (1996-2002)	09095500	09114500 (1995-2002)	09119000 (1995-2002)	09152500	09163500
Relative Percent Error TSS Load			33.3	4.9	19.3	25.1	43.9
Relative Percent Error TP Load	14.1	13.1	80.1	-27.5	28.7	-9.7	60.6
Relative Percent Error TN Load	29.7	-25.9	-22.0	-37.4	17.9	-42.9	-60.9

Table 14. Summary statistics for water quality at all stations – validation period 1982-1992

Station	09058000 (1989-1992)	09085000	09095500	09114500	09119000	09152500	09163500
Relative Percent Error TSS Load			47.9			36.9	60.2
Relative Percent Error TP Load	-26.4		84.8			-1.2	66.8
Relative Percent Error TN Load	7.7		-11.5			-38.6	-48.9

References

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Appendix W
Model Configuration, Calibration and Validation

Basin: Powder and Tongue Rivers (PowTon)

Contents

Tables

Figures

Watershed Background

The Powder/Tongue River basin was selected as one of the 15 non-pilot application watersheds for the 20 Watershed study. This basin was selected as representative of conditions in the northern plains. Watershed modeling for the non-pilot areas is accomplished using the SWAT model only, and model calibration and validation results are presented in abbreviated form.

Water Body Characteristics

The Powder River and Tongue River are major tributaries to the Yellowstone River, which in turn is part of the Missouri River system on the east side of the Rocky Mountains. The model study area consists of almost 19,000 mi^2 in Montana and Wyoming and consists of 12 HUC8s in HUC 1009 (Figure 1).

The watershed lies in parts of the Great Plains, Middle Rocky Mountains, Wyoming Basin, and Northern Rocky Mountains physiographic provinces (Zelt et al., 1999). Elevation ranges from over 13,000 ft on the crest of the Big Horn Range to less than 3,000 ft at the confluence of the Powder and Yellowstone Rivers. This large elevation range has important impacts on climate in the watershed, which ranges from cold and moist in the mountainous areas to temperate and semiarid in the plains areas. Mean annual temperatures range from less than 32° F at the highest elevations to about 50° F along the river valleys in Montana. Annual temperature extremes range from about -40° F during the winter to hotter than 100° F during the summer. Mean annual precipitation ranges from about 12 inches in the plains to more than 35 inches at high elevations. Snowfall composes a substantial part of annual precipitation in most years.

Streams in the mountainous areas of the basin generally are perennial and derived primarily from snowmelt runoff. Most streams originating in the plains areas of the basin are ephemeral, flowing only as a result of local snowmelt or intense rainstorms (Peterson et al. 2004). In some subbasins, where irrigated agriculture is a major land use, most of the streamflow results from agricultural return flow and sustained base flows.

Rangeland is the dominant land cover (85 percent of the watershed). Cropland and pasture compose less than 2 percent of the watershed. Silviculture is another important land use activity and forests cover about 10 percent of the model study area. The watershed is sparsely populated and developed land accounts for only 0.5 percent of the watershed.

In addition to agriculture, silviculture, and urban uses, other important land uses in the watershed include metals and coal mining and hydrocarbon production. One of the nation’s largest natural gas fields lies in the watershed and production from the low-sulfur coal beds in the Powder River basin is increasing rapidly in response to the demand for low-sulfur steam coal by electric utility consumers. All of the active coal mines in the watershed are surface (strip) mines.

There are no major storage reservoirs in the watershed, although the Tongue River is impounded near the state line. However, hundreds of small impoundments for water supply, recreation, power, and flood control have been constructed in the watershed.

The plains streams tend to have relatively high concentrations of nitrogen, mostly as organic nitrogen and from natural sources. Phosphorus concentrations are also relatively high and due to natural sources in marine sedimentary rocks. The sparse vegetative cover and erodible soils in the plains areas contribute to large suspended sediment concentrations, and the Powder River is estimated to produce an annual suspended sediment yield of about 275 tons per square mile (Peterson et al. 2004).

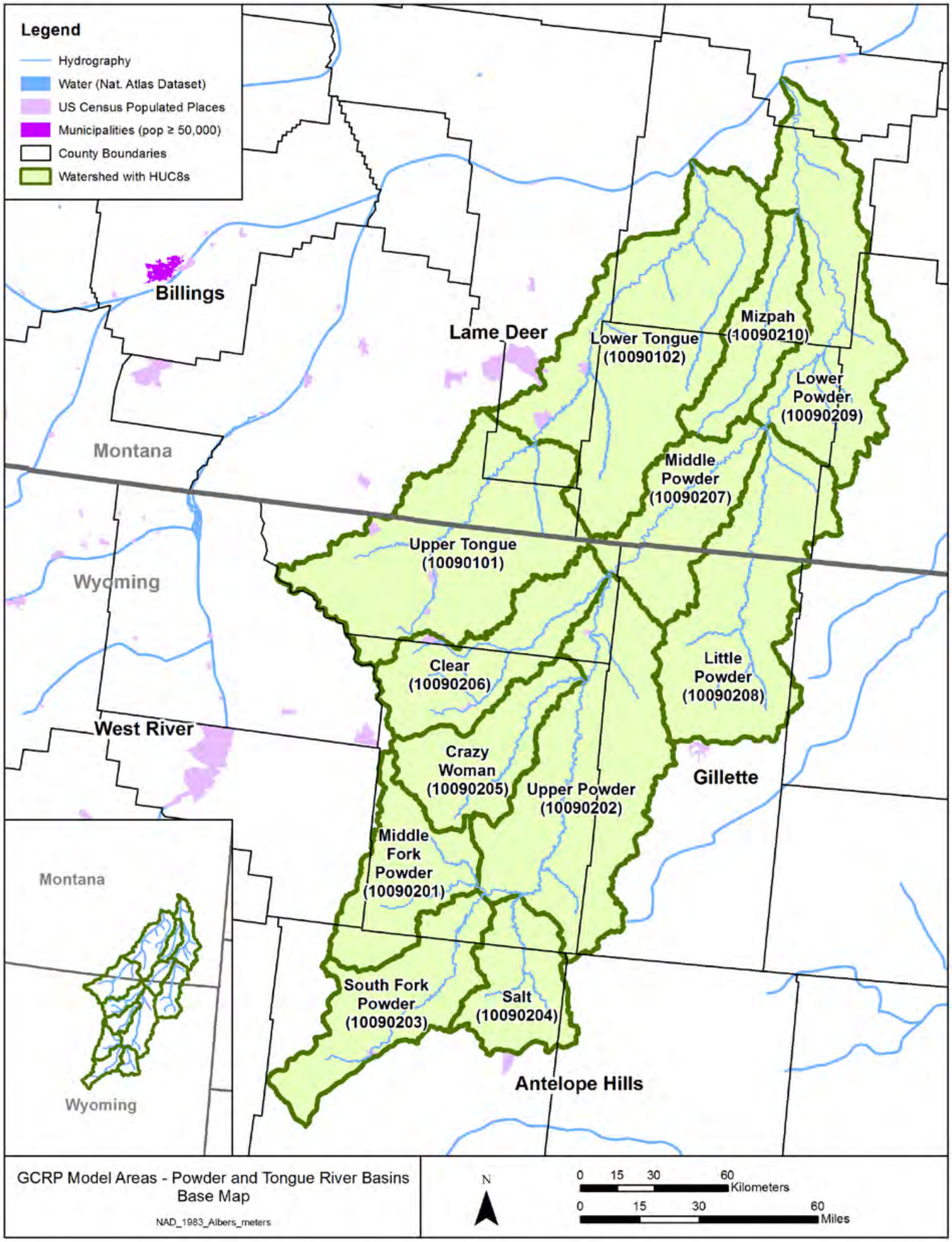


Figure 1. Location of the Powder and Tongue River basin.

Soil Characteristics

Soils in the watershed, as described in STATSGO soil surveys, fall primarily into hydrologic soil groups (HSGs) B (moderately high infiltration capacity) and C (moderate infiltration capacity). SWAT uses information drawn directly from the soils data layer to populate the model.

Land Use Representation

Land use/cover in the watershed is based on the 2001 National Land Cover Database (NLCD) coverage (Figure 2). NLCD land cover classes were aggregated according to the scheme shown in Table 1 for representation in the 20 Watershed model. SWAT uses the built-in hydrologic response unit (HRU) overlay mechanism in the ArcSWAT interface. SWAT HRUs are formed from an intersection of land use and STATSGO major soils. The distribution of land use in the watershed is summarized in Table 2.

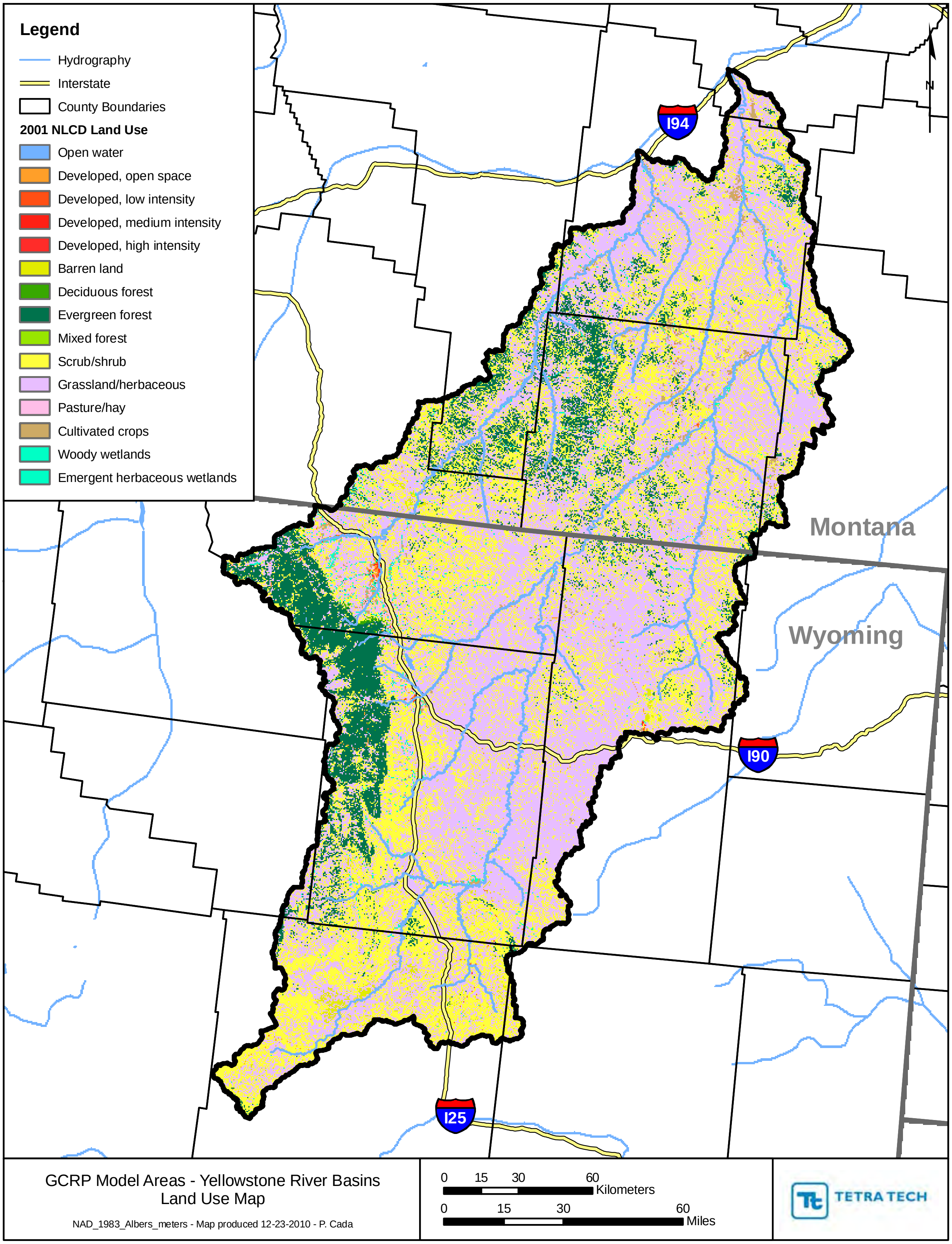


Figure 2. Land use in the Powder and Tongue River basin.

Table 1. Aggregation of NLCD land cover classes

NLCD Class	Comments	SWAT class
11 Water	Water surface area usually accounted for as reach area	WATR
12 Perennial ice/snow		WATR
21 Developed open space		URLD
22 Dev. Low Intensity		URMD
23 Dev. Med. Intensity		URHD
24 Dev. High Intensity		UIDU
31 Barren Land		SWRN
41 Forest	Deciduous	FRSD
42 Forest	Evergreen	FRSE
43 Forest	Mixed	FRST
51-52 Shrubland		RNGB
71-74 Herbaceous Upland		RNGE
81 Pasture/Hay		HAY
82 Cultivated		AGRR
91-97 Wetland	Emergent & woody wetlands	WETF, WETL, WETN
98-99 Wetland	Aquatic bed wetlands (not emergent)	WATR

Table 2. Land use distribution for the Powder and Tongue River basin (2001 NLCD) (mi^2)

HUC 8 watershed	Open water	Snow/Ice	Developed[a]				Barren land	Forest	Shrubland	Pasture/Hay	Cultivated	Wetland	Total
			Open space	Low density	Medium density	High density							
Lower Powder **10090209**	0.48	0.00	4.71	1.36	0.08	0.00	0.73	61.75	1,732.77	2.01	38.36	35.26	**1,877.51**
Lower Tongue **10090102**	0.96	0.00	9.19	1.91	0.54	0.06	2.85	525.93	2,209.00	12.89	31.45	62.91	**2,857.68**
Mizpah **10090210**	0.18	0.00	3.59	0.62	0.00	0.00	0.35	20.03	728.90	0.49	35.57	7.58	**797.31**
Upper Tongue **10090101**	3.35	0.00	16.81	5.92	2.03	0.51	13.14	493.15	1,838.36	52.52	23.30	79.80	**2,528.87**
Middle Powder **10090207**	1.04	0.00	2.22	0.68	0.11	0.01	3.85	111.08	913.59	3.36	10.16	16.88	**1,062.99**
Little Powder **10090208**	0.27	0.00	6.06	0.73	0.40	0.09	11.99	77.75	1,867.11	2.52	23.95	23.82	**2,014.69**
Clear **10090206**	6.95	0.36	7.31	2.34	0.73	0.10	1.32	229.32	848.49	17.76	10.55	24.20	**1,149.40**
Upper Powder **10090202**	0.15	0.00	5.10	1.02	0.01	0.00	9.19	18.02	2,449.96	2.77	7.98	29.52	**2,523.71**
Crazy Woman **10090205**	0.43	0.00	3.27	1.33	0.05	0.00	2.09	143.47	767.88	6.80	1.52	11.95	**938.79**
Middle Fork Powder **10090201**	0.10	0.00	1.52	0.59	0.04	0.00	8.34	170.87	781.65	4.96	0.18	19.42	**987.66**
South Fork Powder **10090203**	0.19	0.00	2.54	0.63	0.01	0.00	48.47	20.03	1,115.46	1.96	0.01	3.48	**1,192.80**
Salt **10090204**	0.08	0.00	2.26	2.44	0.21	0.00	22.02	8.40	759.54	0.02	0.00	2.49	**797.47**
Total	**14.19**	**0.36**	**64.58**	**19.57**	**4.21**	**0.77**	**124.32**	**1,879.79**	**16,012.71**	**108.05**	**183.04**	**317.31**	**18,728.90**

[a]The percent imperviousness applied to each of the developed land uses is as follows: open space (7.42%), low density (31.64%), medium density (59.16%), and high density (85.99%).

Point Sources

There are numerous point source discharges in the watershed. Only the major dischargers, generally defined as those with a design flow greater than 1 MGD are included in the simulation (Table 3). The major dischargers are represented at long-term average flows, without accounting for changes over time or seasonal variations.

Table 3. Major point source discharges in the Powder and Tongue River basin

NPDES ID	Name	Design flow (MGD)	Observed flow (MGD) (1991-2006 average)
MT0000892	DECKER COAL CO (WEST MINE)		0.861
MT0020001	MILES CITY- CITY OF	1.980	1.0638
MT0024210	DECKER COAL CO (EAST MINE)		0.884
WY0020010	SHERIDAN, CITY OF		2.489

Most of these point sources have reasonably complete monitoring for total suspended solids (TSS). Assumptions were made for total nitrogen and total phosphorus depending upon the type of facility. The point sources were initially represented in the model with the median of reported values for total phosphorus, total suspended solids and total nitrogen.

Meteorological Data

The required meteorological time series for the 20 Watershed SWAT simulations are precipitation and air temperature. The 20 Watershed simulations do not include water temperature and uses a degree-day method for snowmelt. SWAT estimates Penmann-Monteith potential evapotranspiration using a statistical weather generator for inputs other than temperature and precipitation. These meteorological time series are drawn from the BASINS4 Meteorological Database (USEPA 2008), which provides a consistent, quality-assured set of nationwide data with gaps filled and records disaggregated. Scenario application requires simulation over 30 years, so the available stations are those with a common 30-year period of record (or one that can be filled from an approximately co-located station) that covers the year 2003. A total of 37 precipitation stations were identified for use in the Powder and Tongue River watershed model with a common period of record of 10/1/1972-9/30/2003 (Table 4). Temperature records are sparser; where these are absent temperature is taken from nearby stations with an elevation correction.

Table 4. Precipitation stations for the Powder and Tongue River watershed model

COOP ID	Name	Latitude	Longitude	Temperature	Elevation (m)
241084	BRANDENBERG	45.8161	-106.2310	X	844
241127	BROADUS	45.4443	-105.4070	X	924
241297	BUSBY	45.5398	-106.9590	X	1045
241905	COLSTRIP	45.8944	-106.6330	X	981
242266	DECKER 4 NNE	45.0117	-106.8630		1073
242689	EKALAKA	45.8904	-104.5460	X	1044
244442	ISMAY	46.4997	-104.7990	X	762
245303	MAC KENZIE	46.1423	-104.7350		856
245690	MILES CITY AP	46.4267	-105.8820	X	800

COOP ID	Name	Latitude	Longitude	Temperature	Elevation (m)
245754	MIZPAH 4 NNW	46.2859	-105.2910	X	756
245870	MOORHEAD 9 NE	45.1759	-105.7510	X	981
246691	POWDERVILLE 8 NNE	45.8525	-105.0340	X	853
247034	RIDGEWAY 1 S	45.5023	-104.4470	X	1011
247740	SONNETTE 2 WNW	45.4184	-105.8680	X	1189
248165	TERRY	46.7940	-105.3020	X	685
248607	VOLBORG	45.8437	-105.6800		908
249175	WYOLA 1 SW	45.1217	-107.4060	X	1137
480740	BILLY CREEK	44.1243	-106.7310	X	1516
481165	BUFFALO	44.3450	-106.7200	X	1423
481220	BURGESS JUNCTION	44.7743	-107.5210	X	2457
481570	CASPER WSCMO	42.8976	-106.4630	X	1627
482881	ECHETA 2 NW	44.4828	-105.8990	X	1219
483801	GAS HILLS 4 E	42.8394	-107.5130		1972
483855	GILLETTE 6 SE	44.2645	-105.4910	X	1414
485055	KAYCEE	43.7144	-106.6370	X	1420
485506	LEITER 9 N	44.8501	-106.2880	X	1268
486195	MIDWEST	43.4132	-106.2770	X	1481
486395	MOORCROFT 3 S	44.2170	-104.9290	X	1318
487375	POWDER RIVER SCHOOL	43.0359	-106.9880		1736
487376	POWDER RIVER NO 2	43.0350	-106.9880	X	1737
487545	RECLUSE	44.7409	-105.7260		1265
488155	SHERIDAN AP	44.7694	-106.9680	X	1202
488160	SHERIDAN FIELD STN	44.8407	-106.8380	X	1143
488626	STORY	44.5772	-106.8960		1549
488852	TEN SLEEP 4 NE	44.0657	-107.3800	X	1469
488858	TEN SLEEP 16 SSE	43.8112	-107.3640	X	1426
489580	WESTON 1 E	44.6406	-105.3050	X	1074

Watershed Segmentation

The Powder and Tongue River basin was divided into 77 subwatersheds for the purposes of modeling (Figure 3). Tongue River at State Line near Decker at USGS 06306300 was chosen for initial calibration. The model encompasses the complete watershed and does not require specification of any upstream boundary conditions for application.

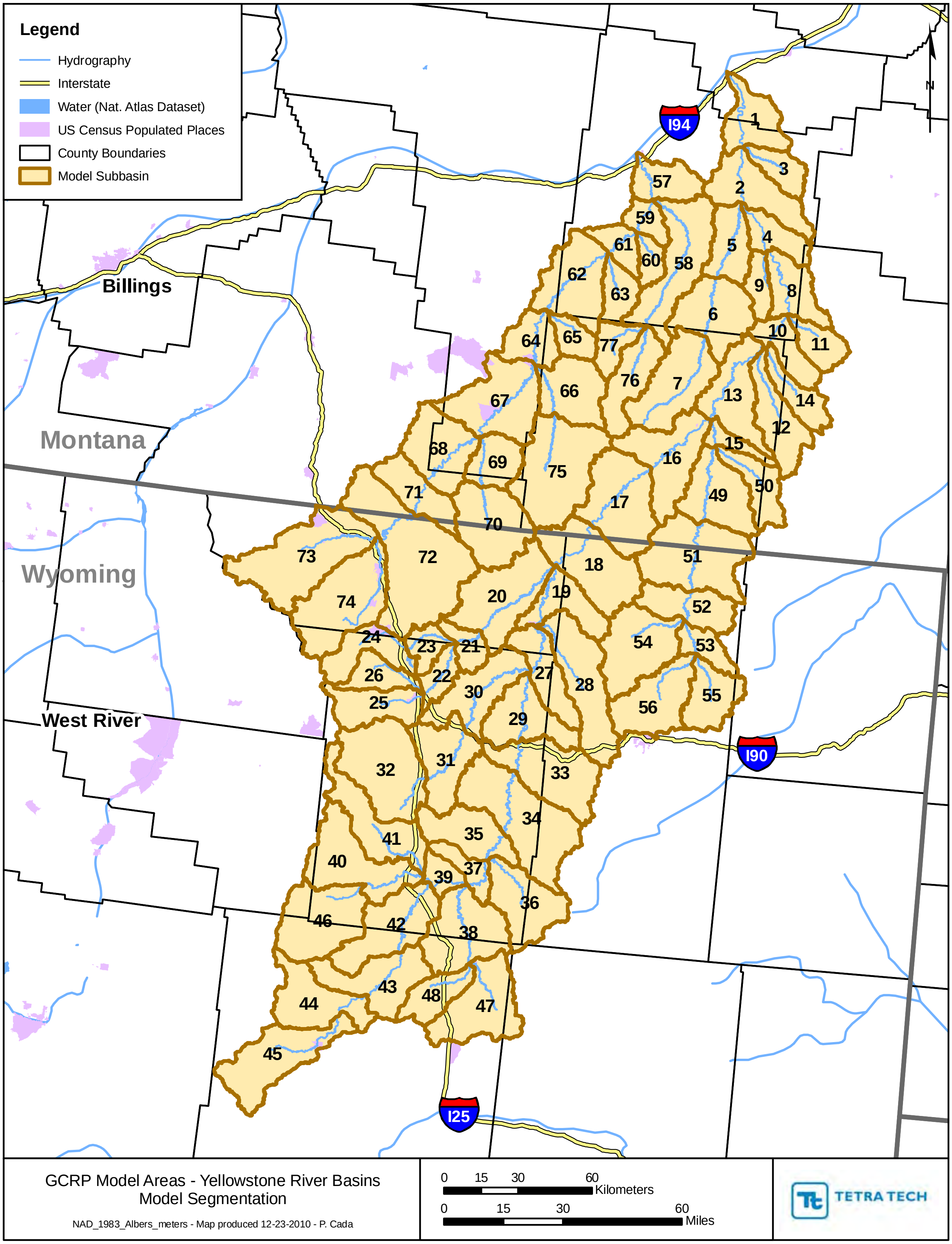


Figure 3. Model segmentation and USGS stations utilized for the Powder and Tongue River basin.

Calibration Data and Locations

The specific site chosen for initial calibration was the Tongue River at State Line near Decker, MT a flow and water quality monitoring location. The USGS gage located at Tongue River at State Line near Decker was selected because there is a good set of flow and water quality data available and the watershed lacks major point sources and impoundments. Additional calibration and validation was pursued at multiple locations (Table 5). Parameters derived from the initial calibration were not fully transferable to other portions of the Powder and Tongue River basin, and additional calibration was conducted at multiple gage locations.

Table 5. Calibration and validation locations in the Powder and Tongue River basin

Station name	USGS ID	Drainage area (mi^2)	Hydrology calibration	Water quality calibration
Tongue River at Tongue R Dam nr Decker MT	06307500	1,770	x	
Tongue River at State Line nr Decker MT	06306300	1,453	x	x
Tongue River at Birney Day School Br nr Birney MT	06307616	2,621	x	
Tongue River at Miles City MT	06308500	5,397	x	x
Powder River at Moorhead MT	06324500	8,086	x	
Powder River near Locate MT	06326500	13,068	x	

The model hydrology calibration period was set to Water Years 1993-2003 (within the 32-year period of record for modeling). Hydrologic validation was then performed on Water Years 1983-1993. Water quality calibration used calendar years 1993-2003, while validation used 1983-1993.

SWAT Modeling

Assumptions

The Powder and Tongue River basin is comprised of the areas drained by the Tongue River and Powder River. Tongue River reservoir is the only major impoundment that is represented in the model. Pertinent reservoir information including surface area and storage at principal (normal) and emergency spillway levels for the reservoir were obtained from the State Water Resources Bureau. The SWAT model provides four options to simulate reservoir outflow: measured daily outflow, measured monthly outflow, average annual release rate for uncontrolled reservoir, and controlled outflow with target release. Keeping in view the 20 Watershed climate change impact evaluation application to future climate scenarios, it was assumed that the best representation of the reservoir was to simulate it without supplying time series of outflow records. Hence, the target release approach was used for the Tongue River reservoir.

Hydrology Calibration

A spatial calibration approach was adopted for GCRP-SWAT modeling for the Powder and Tongue River basin. A systematic adjustment of parameters has been adopted and some adjustments are applied throughout the basin. Most of the calibration efforts were geared towards getting a closer match between simulated and observed flows at the outlet of calibration focus area.

Land Use / Soil / Slope Definition

A 5/10/5 percent threshold was used for land use/soil/slope in the SWAT model while defining the HRUs. Urban land use classes were exempted from the HRU overlay thresholds.

The calibration focus area includes three subwatersheds and is generally representative of the general land use characteristics of the overall watershed. The parameters were adjusted within the practical range to obtain reasonable fit between the simulated and measured flows in terms of Nash-Sutcliffe modeling efficiency and the high flow and low flow components as well as the seasonal flows.

The Tongue River and Powder River basins were modeled separately. The water balance of the Tongue River basin predicted by the SWAT model over the 32-year simulation period is as follows:

```
PRECIP =    374.4 MM
SNOW FALL = 116.02 MM
SNOW MELT =    98.58 MM
SUBLIMATION =    16.87 MM
SURFACE RUNOFF Q =    26.86 MM
LATERAL SOIL Q =   22.46 MM
TILE Q =     0.00 MM
GROUNDWATER (SHAL AQ) Q =    17.25 MM
REVAP (SHAL AQ => SOIL/PLANTS) =    0.09 MM
DEEP AQ RECHARGE =    10.78 MM
TOTAL AQ RECHARGE =   28.11 MM
TOTAL WATER YLD =    66.57 MM
PERCOLATION OUT OF SOIL =   28.46 MM
ET =    388.6 MM
PET =   1268.1MM
TRANSMISSION LOSSES =     0.00 MM
```

The water balance of the Powder River basin predicted by the SWAT model over the 32-year simulation period is as follows:

```
PRECIP =    363.5 MM
SNOW FALL = 106.55 MM
SNOW MELT =    91.10 MM
SUBLIMATION =    15.05 MM
SURFACE RUNOFF Q =    25.65 MM
LATERAL SOIL Q =   17.88 MM
TILE Q =     0.00 MM
GROUNDWATER (SHAL AQ) Q =    14.03 MM
REVAP (SHAL AQ => SOIL/PLANTS) =    0.04 MM
DEEP AQ RECHARGE =     0.00 MM
TOTAL AQ RECHARGE =   14.06 MM
TOTAL WATER YLD =    55.33 MM
PERCOLATION OUT OF SOIL =   12.00 MM
ET =    441.3 MM
PET =   1427.9MM
TRANSMISSION LOSSES =     2.23 MM
```

Hydrologic calibration adjustments focused on the following parameters:

- CN2 (initial SCS runoff curve number for moisture condition II)
- ESCO (soil evaporation compensation factor)
- SURLAG (surface runoff lag coefficient)
- SOL_AWC (available water capacity of the soil layer, mm water/mm of soil)
- ALPHA_BF (baseflow alpha factor, days)
- GW_DELAY (groundwater delay time, days)
- GWQMIN (threshold depth of water in the shallow aquifer required for return flow to occur, mm)
- GW_REVAP (groundwater “revap” coefficient)
- CH_N1 (Manning’s “n” value for tributary channels)
- CH_N2 (Manning’s “n” value for main channels)
- CH_K1 (Effective hydraulic conductivity in tributary channel alluvium)
- CH_K2 (Effective hydraulic conductivity in main channel alluvium)
- SFTMP (Snowfall temperature)
- SMTMP (Snowmelt base temperature)
- SMFMX (Maximum melt rate for snow during the year)
- SMFMN (Minimum melt rate for snow during the year)

The calibration achieves a moderately high coefficient of model fit efficiency, but is above on summer flow volumes. Calibration results for the Tongue River at State Line near Decker are summarized in Figure 4, Figure 5, Figure 6, Figure 7 and Table 6).

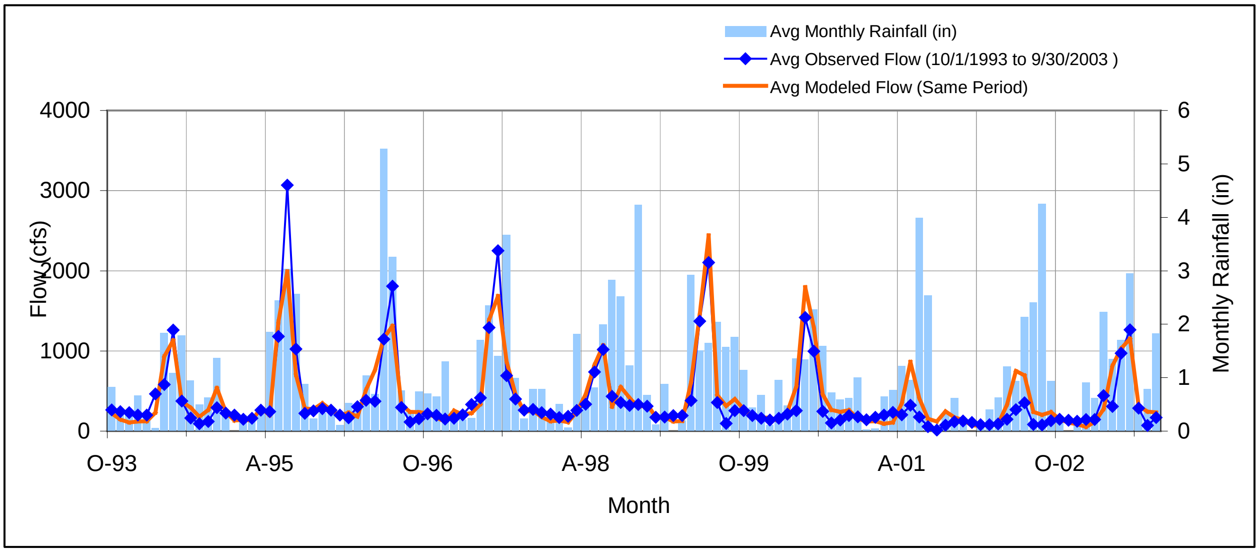


Figure 4. **Mean monthly flow at USGS 06306300 Tongue River at State Line near Decker, MT – calibration period.**

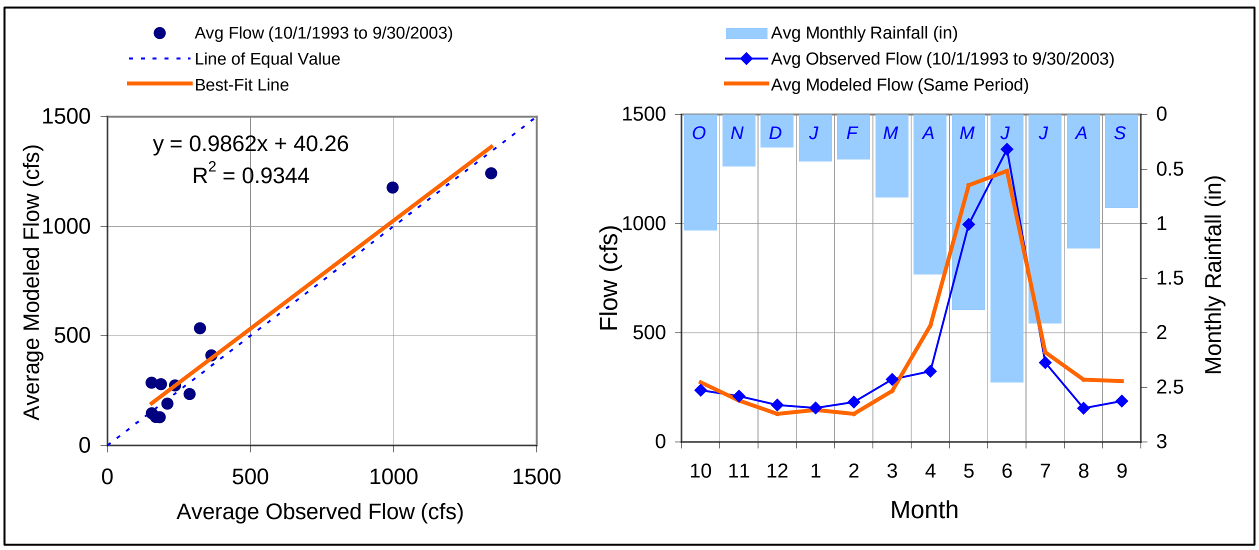


Figure 5. **Seasonal regression and temporal aggregate at USGS 06306300 Tongue River at State Line near Decker, MT – calibration period.**

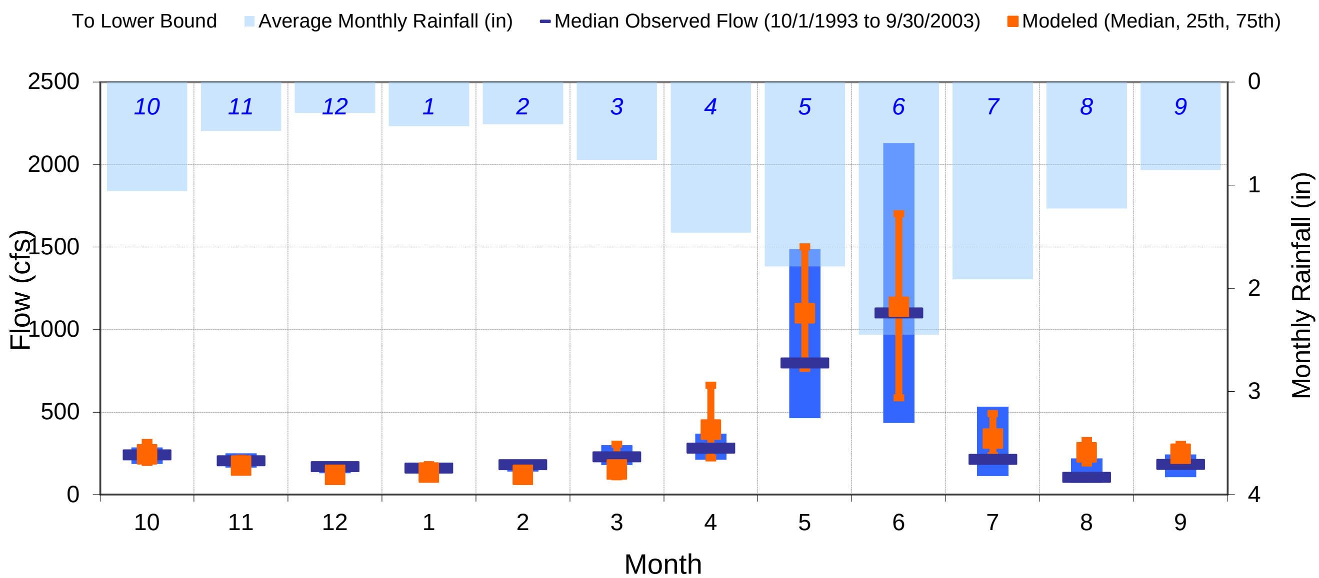


Figure 6. Seasonal medians and ranges at USGS 06306300 Tongue River at State Line near Decker, MT – calibration period.

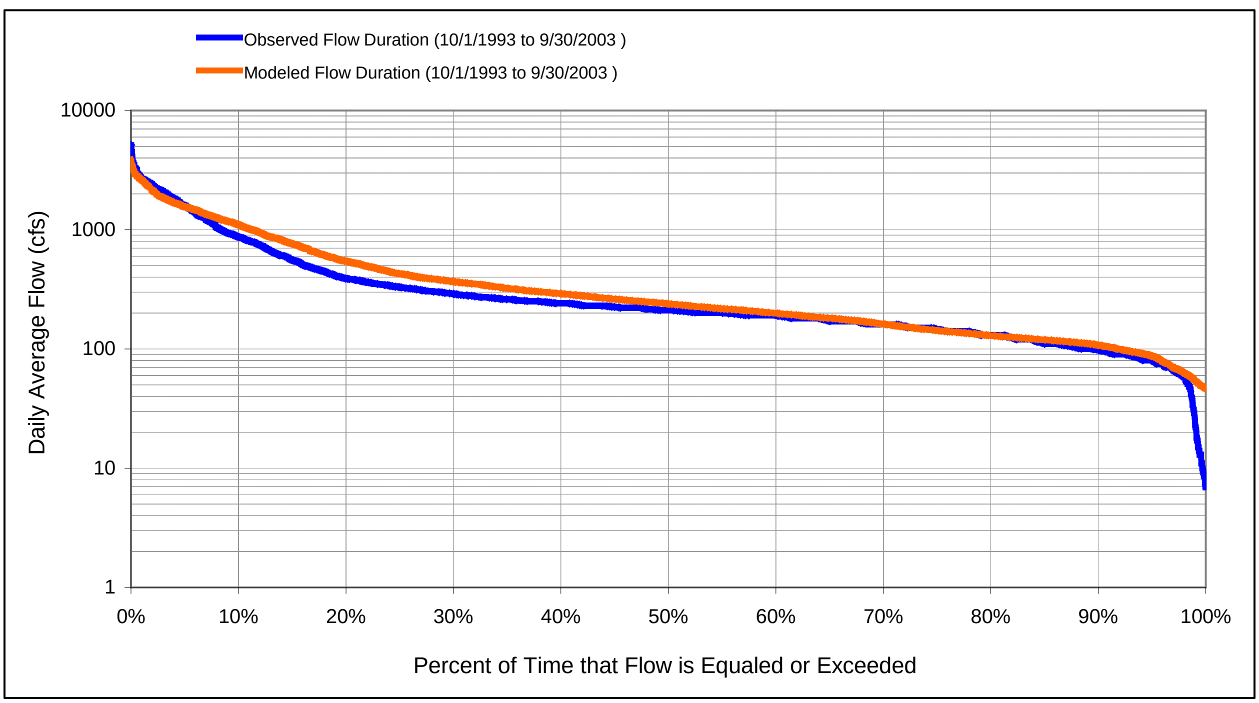


Figure 7. Flow exceedance at USGS 06306300 Tongue River at State Line near Decker, MT – calibration period.

Table 6. Summary statistics at USGS 06306300 Tongue River at State Line near Decker, MT – calibration period

SWAT Simulated Flow		Observed Flow Gage	
REACH OUTFLOW FROM OUTLET 16 10-Year Analysis Period: 10/1/1993 - 9/30/2003 Flow volumes are (inches/year) for upstream drainage area		USGS 06306300 Tongue River at State Line nr Decker MT Hydrologic Unit Code: 10090101 Latitude: 45.0088632 Longitude: -106.836178 Drainage Area (sq-mi): 1453	
Total Simulated In-stream Flow:	**3.92**	Total Observed In-stream Flow:	**3.59**
Total of simulated highest 10% flows:	**1.58**	Total of Observed highest 10% flows:	**1.63**
Total of Simulated lowest 50% flows:	**0.69**	Total of Observed Lowest 50% flows:	**0.66**
Simulated Summer Flow Volume (months 7-9):	**0.77**	Observed Summer Flow Volume (7-9):	**0.55**
Simulated Fall Flow Volume (months 10-12):	**0.47**	Observed Fall Flow Volume (10-12):	**0.48**
Simulated Winter Flow Volume (months 1-3):	**0.39**	Observed Winter Flow Volume (1-3):	**0.48**
Simulated Spring Flow Volume (months 4-6):	**2.30**	Observed Spring Flow Volume (4-6):	**2.07**
Total Simulated Storm Volume:	**0.83**	Total Observed Storm Volume:	**0.73**
Simulated Summer Storm Volume (7-9):	**0.13**	Observed Summer Storm Volume (7-9):	**0.10**

Errors (Simulated-Observed)	*Error Statistics*		*Recommended Criteria*		
Error in total volume:	9.26		10		
Error in 50% lowest flows:	4.58		10		
Error in 10% highest flows:	-2.92		15		
Seasonal volume error - Summer:	**38.16**		**30**		
Seasonal volume error - Fall:	-3.70	>>	30	Clear	
Seasonal volume error - Winter:	-18.41		30		
Seasonal volume error - Spring:	10.99		30		
Error in storm volumes:	13.40		20		
Error in summer storm volumes:	27.25		50		
Nash-Sutcliffe Coefficient of Efficiency, E:	0.719		Model accuracy increases		
Baseline adjusted coefficient (Garrick), E':	0.494		as E or E' approaches 1.0		
Monthly NSE	0.832				

Hydrology Validation

Hydrology validation for Tongue River was performed for the period 10/1/1983 through 9/30/1993. The validation achieves a moderately high coefficient of model fit efficiency, but is below on 50% low flow and winter flow volumes (Figure 8, Figure 9, Figure 10, Figure 11 and Table 7).

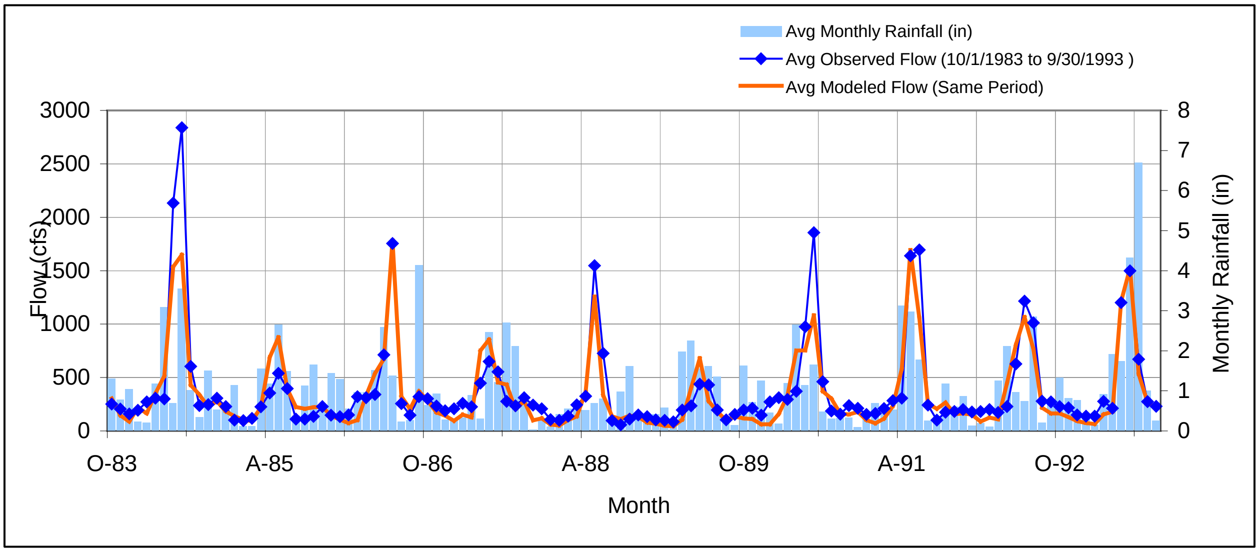


Figure 8. **Mean monthly flow at USGS 06306300 Tongue River at State Line near Decker, MT – validation period.**

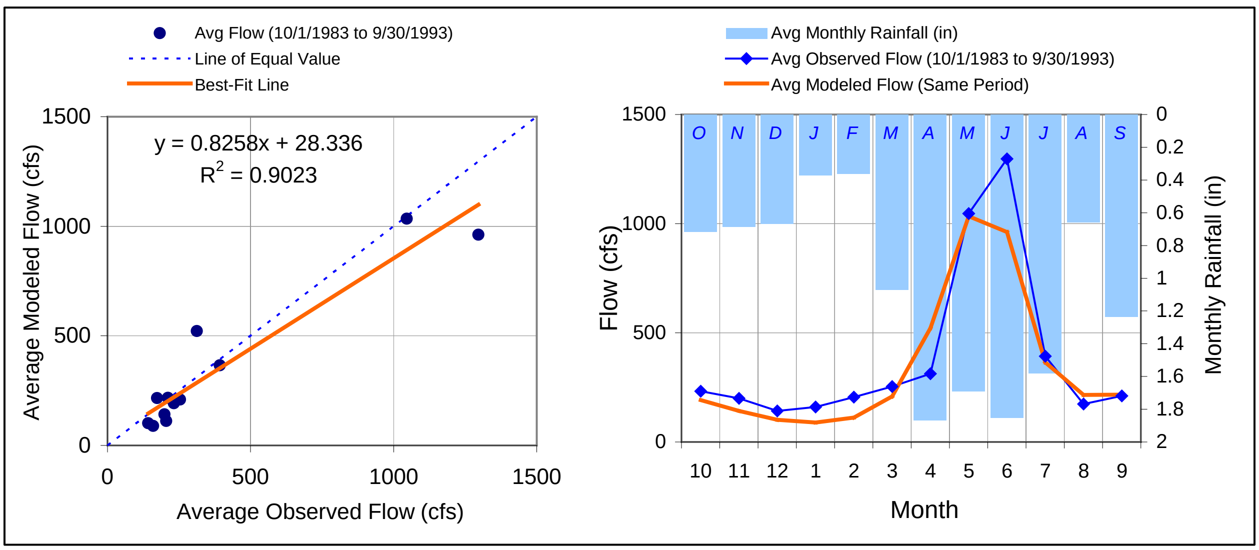


Figure 9. **Seasonal regression and temporal aggregate at USGS 06306300 Tongue River at State Line near Decker, MT – validation period.**

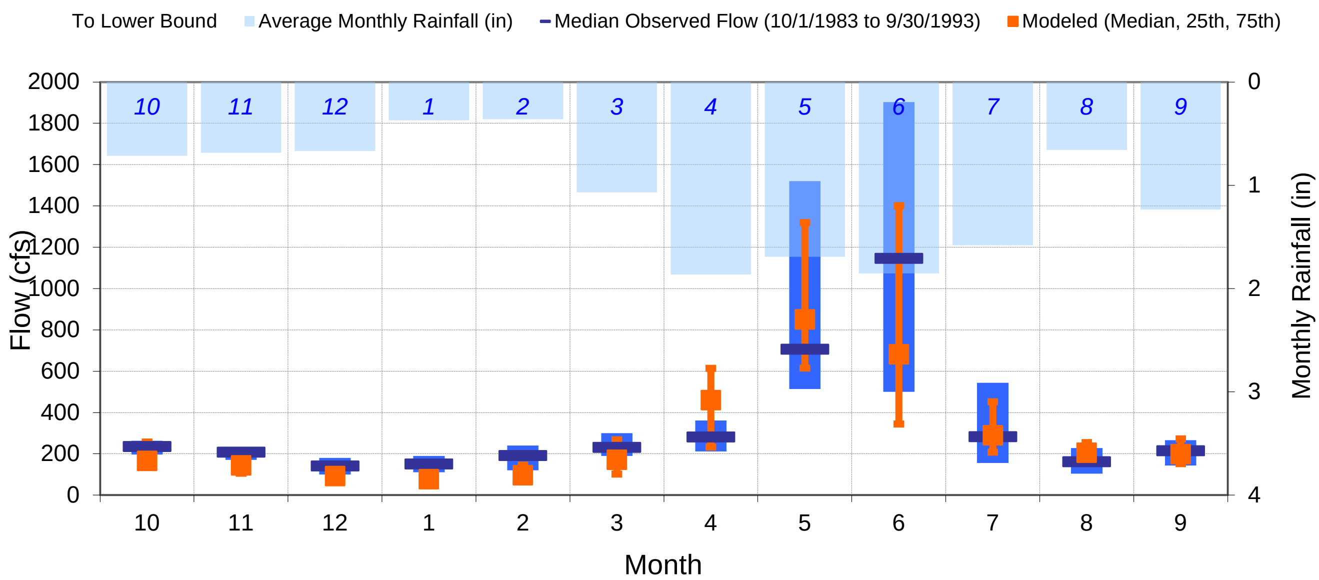


Figure 10. Seasonal medians and ranges at USGS 06306300 Tongue River at State Line near Decker, MT – validation period.

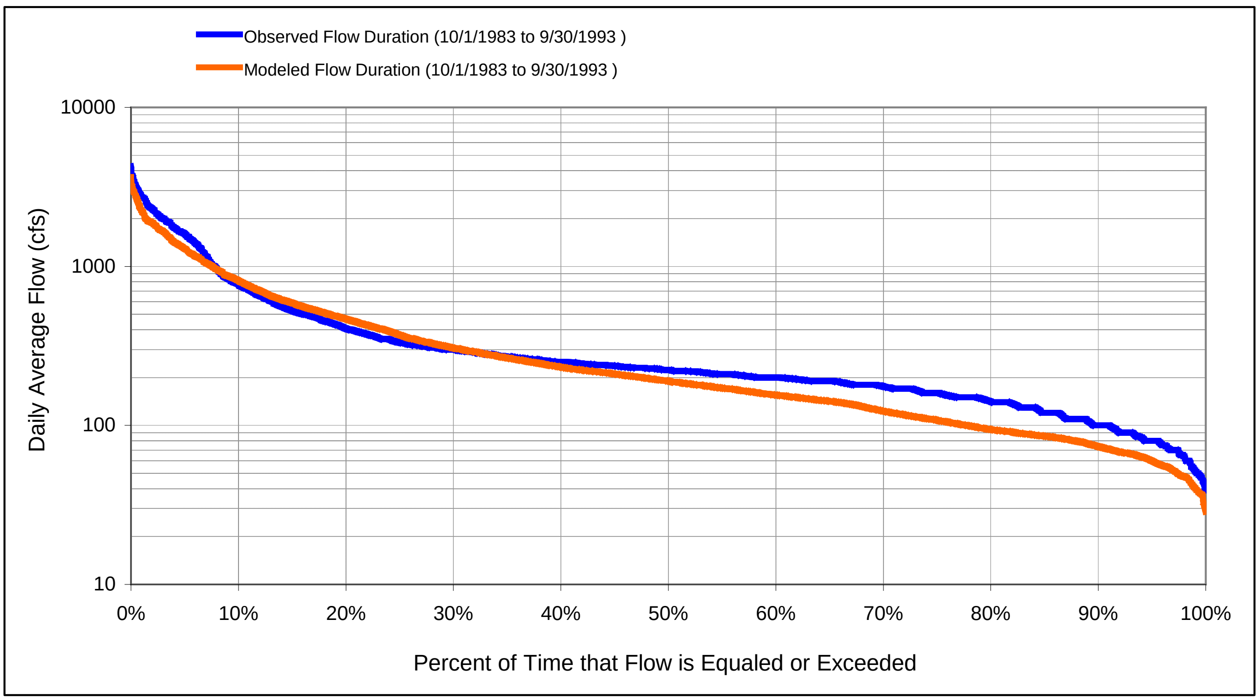


Figure 11. Flow exceedance at USGS 06306300 Tongue River at State Line near Decker, MT – validation period.

Table 7. Summary statistics at USGS 06306300 Tongue River at State Line near Decker, MT – validation period

SWAT Simulated Flow		Observed Flow Gage	
REACH OUTFLOW FROM OUTLET 16 10-Year Analysis Period: 10/1/1983 - 9/30/1993 Flow volumes are (inches/year) for upstream drainage area		USGS 06306300 Tongue River at State Line nr Decker MT Hydrologic Unit Code: 10090101 Latitude: 45.0088632 Longitude: -106.836178 Drainage Area (sq-mi): 1453	
Total Simulated In-stream Flow:	**3.25**	Total Observed In-stream Flow:	**3.60**
Total of simulated highest 10% flows:	**1.36**	Total of Observed highest 10% flows:	**1.59**
Total of Simulated lowest 50% flows:	**0.53**	Total of Observed Lowest 50% flows:	**0.71**
Simulated Summer Flow Volume (months 7-9):	**0.63**	Observed Summer Flow Volume (7-9):	**0.61**
Simulated Fall Flow Volume (months 10-12):	**0.34**	Observed Fall Flow Volume (10-12):	**0.45**
Simulated Winter Flow Volume (months 1-3):	**0.32**	Observed Winter Flow Volume (1-3):	**0.48**
Simulated Spring Flow Volume (months 4-6):	**1.96**	Observed Spring Flow Volume (4-6):	**2.07**
Total Simulated Storm Volume:	**0.73**	Total Observed Storm Volume:	**0.74**
Simulated Summer Storm Volume (7-9):	**0.10**	Observed Summer Storm Volume (7-9):	**0.11**

Errors (Simulated-Observed)	*Error Statistics*	*Recommended Criteria*		
Error in total volume:	-9.95	10		
Error in 50% lowest flows:	**-25.59**	**10**		
Error in 10% highest flows:	-14.65	15		
Seasonal volume error - Summer:	2.57	30		
Seasonal volume error - Fall:	-24.24	>> 30		Clear
Seasonal volume error - Winter:	**-33.45**	**30**		
Seasonal volume error - Spring:	-5.12	30		
Error in storm volumes:	-0.73	20		
Error in summer storm volumes:	-3.56	50		
Nash-Sutcliffe Coefficient of Efficiency, E:	0.703	Model accuracy increases		
Baseline adjusted coefficient (Garrick), E':	0.494	as E or E' approaches 1.0		
Monthly NSE	0.818			

Hydrology Results for Larger Watershed

As described above, parameters determined for the gage at Tongue River at State Line near Decker were initially transferred to other gages in the watershed. However, changes to subwatershed level parameters were required to fit the model to the observed flows. In all, calibration and validation was pursued at a total of six gages throughout the watershed. Results of the calibration and validation exercise are summarized in Table 8 and Table 9, respectively. Calibration and validation results were acceptable at most gages.

Table 8. Summary statistics (percent error): all stations - calibration period

Station	06307500	06306300	06307616	06308500	06324500	06326500
Error in total volume:	0.01	9.26	1.10	-5.78	7.55	-1.83
Error in 50% lowest flows:	1.04	4.58	-6.88	-18.16	17.10	16.25
Error in 10% highest flows:	-6.35	-2.92	-3.80	0.83	-7.16	3.35
Seasonal volume error - Summer:	-18.08	38.16	-21.91	28.90	35.93	10.13
Seasonal volume error - Fall:	2.93	-3.70	0.48	-33.44	16.00	54.07
Seasonal volume error - Winter:	-3.32	-18.41	16.34	-31.74	3.45	1.59
Seasonal volume error - Spring:	10.83	10.99	10.69	3.58	-0.63	-22.23
Error in storm volumes:	-18.89	13.40	-19.82	-40.42	13.11	-7.26
Error in summer storm volumes:	22.94	27.25	5.64	1.54	16.28	-24.77
Daily Nash-Sutcliffe Coefficient of Efficiency, E:	0.68	0.72	0.67	0.36	0.49	0.28
Monthly Nash-Sutcliffe Efficiency:	0.800	0.832	0.822	0.718	0.631	0.535

Table 9. Summary statistics (percent error): all stations - validation period

Station	06307500	06306300	06307616	06308500	06324500	06326500
Error in total volume:	-15.51	-9.95	-13.85	-0.30	-14.83	-10.20
Error in 50% lowest flows:	-11.29	-25.59	-29.38	-41.64	-21.34	-33.18
Error in 10% highest flows:	-13.96	-14.65	-8.00	35.98	-22.75	21.75
Seasonal volume error - Summer:	-30.86	2.57	-24.08	62.05	2.81	59.27
Seasonal volume error - Fall:	-14.00	-24.24	-18.99	-22.35	-29.02	-22.23
Seasonal volume error - Winter:	-17.72	-33.45	-5.64	-42.94	-7.25	-12.83
Seasonal volume error - Spring:	-5.72	-5.12	-8.23	-6.63	-19.24	-29.50
Error in storm volumes:	-10.41	-0.73	-7.07	-14.47	-0.77	-16.65
Error in summer storm volumes:	68.91	-3.56	76.33	38.90	-7.71	-2.84
Daily Nash-Sutcliffe Coefficient of Efficiency, E:	0.65	0.70	0.53	-0.55	0.47	-0.43
Monthly Nash-Sutcliffe Efficiency:	0.760	0.818	0.631	-0.532	0.727	-0.367

Water Quality Calibration and Validation

Initial calibration and validation of water quality was done at USGS 06306300, Tongue River at State Line near Decker from water years 1983 to 2003. Subject to the availability of water quality data for the other gages, 1993-2003 was adopted as the calibration period and 1982-1992 was adopted as the validation period. As with hydrology, calibration was performed on the later period as this better reflects the land use included in the model.

Calibration adjustments for sediment focused on the following parameters:

- SPCON (linear parameter for estimating maximum amount of sediment that can be re-entrained during channel sediment routing)
- SPEXP (exponential parameter for estimating maximum amount of sediment that can be re-entrained during channel sediment routing)
- CH_COV (channel cover factor)
- CH_EROD (channel erodibility factor)
- USLE_P (USLE support practice factor)

Simulated and estimated sediment loads at the Tongue River station at State Line near Decker for both the calibration and validation periods are shown in Figure 12 and statistics are provided separately in Table 10. The key statistic in Table 10 is the relative percent error, which shows the error in the prediction of monthly load normalized to the estimated load. Table 10 also shows the relative average absolute error, which is the average of the relative magnitude of errors in individual monthly load predictions. This number is inflated by outlier months in which the simulated and estimated loads differ by large amounts (which may be as easily due to uncertainty in the estimated load due to limited data as to problems with the model) and the third statistic, the relative median absolute error, is likely more relevant and shows better agreement.

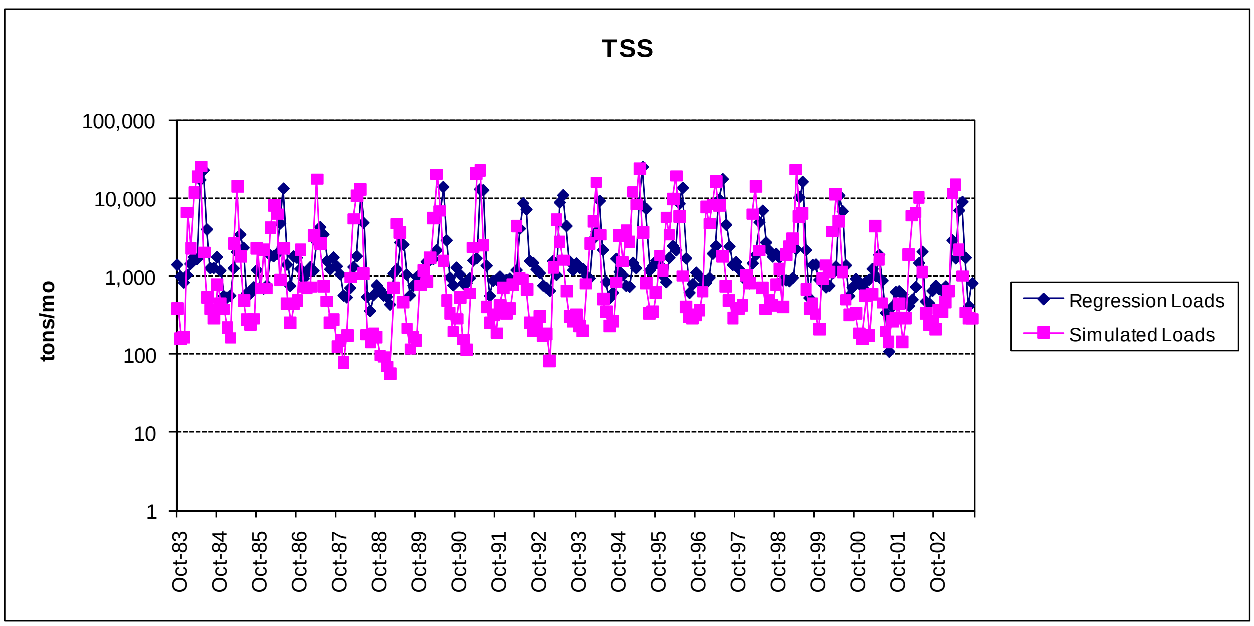


Figure 12. Fit for monthly load of TSS at USGS 06306300 Tongue River at State Line near Decker, MT.

Table 10. Model fit statistics (observed minus predicted) for monthly sediment loads using stratified regression at USGS 06306300 Tongue River at State Line near Decker, MT

Statistic	Calibration period	Validation period
Relative Percent Error	-21.8%	-3.4%
Relative Average Absolute Error	128.5%	109.7%
Relative Median Absolute Error	43.2%	38.2%

Calibration adjustments for total phosphorus and total nitrogen focused on the following parameters:

- RHOQ (algal respiration rate at 20^{O} C)
- PHOSKD (phosphorus soil partitioning coefficient)
- PSP (phosphorus availability index)
- RS1 (Local algal settlement rate in the reach at 20^{O} C)
- AL1 (Fraction of algal biomass that is nitrogen)
- AL2 (Fraction of algal biomass that is phosphorus)
- MUMAX (Rate of oxygen uptake per unit NO_2-N oxidation at 20^{O} C)
- RHOQ (Algal respiration rate at 20^{O} C)
- RS2 (benthic source rate for dissolved P in the reach at 20^{O} C)
- RS3 (Benthic source rate for NH_4-N in the reach at 20^{O} C)
- RS5 (organic P settling rate in the reach at 20^{O} C)
- BC4 (rate constant for mineralization of organic P to dissolved P in the reach at 20^{O} C)
- RS4 (rate coefficient for organic N settling in the reach at 20^{O} C)
- CH_ONCO (Channel organic nitrogen concentration)
- CH_OPCO (Channel organic phosphorus concentration)
- SDNCO (Denitrification threshold water content)
- CDN (Denitrification exponential rate constant)

Results for the phosphorus simulation are shown in Figure 13 and Table 11. Results for the nitrogen simulation are shown in Figure 14 and Table 12. The model fit is generally acceptable.

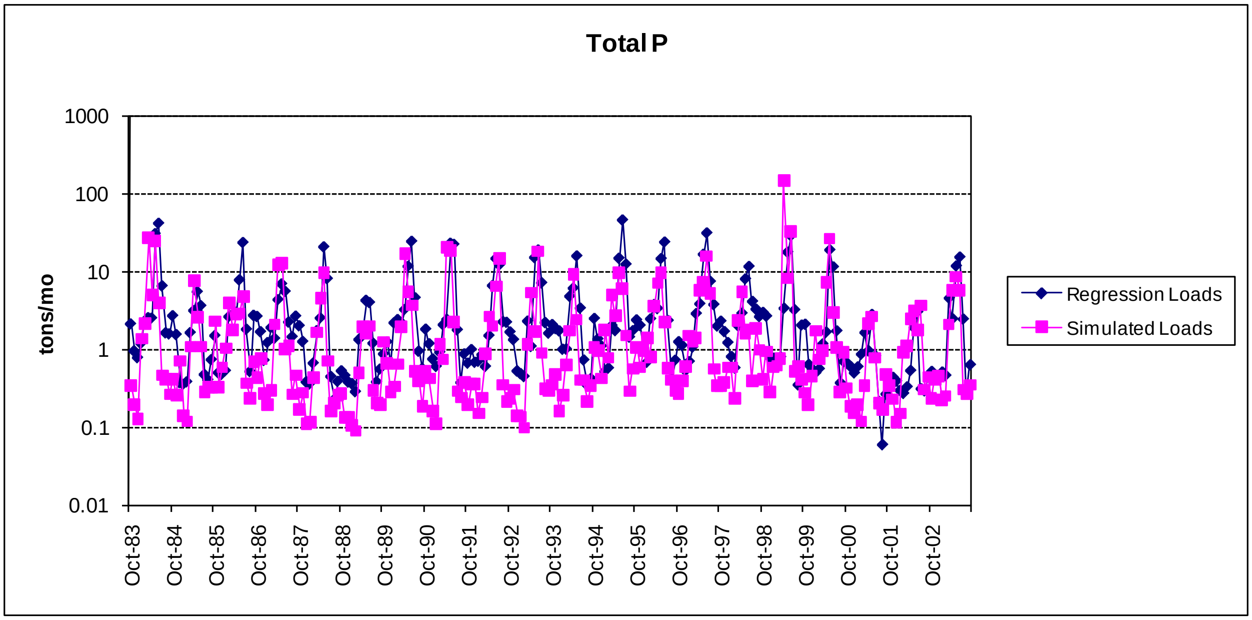


Figure 13. Fit for monthly load of total phosphorus at USGS 06306300 Tongue River at State Line near Decker, MT.

Table 11. Model fit statistics (observed minus predicted) for monthly phosphorus loads using stratified regression at USGS 06306300 Tongue River at State Line near Decker, MT

Statistic	Calibration period	Validation period
Relative Percent Error	8.8%	35.1%
Relative Average Absolute Error	94.1%	76.0%
Relative Median Absolute Error	27.6%	25.7%

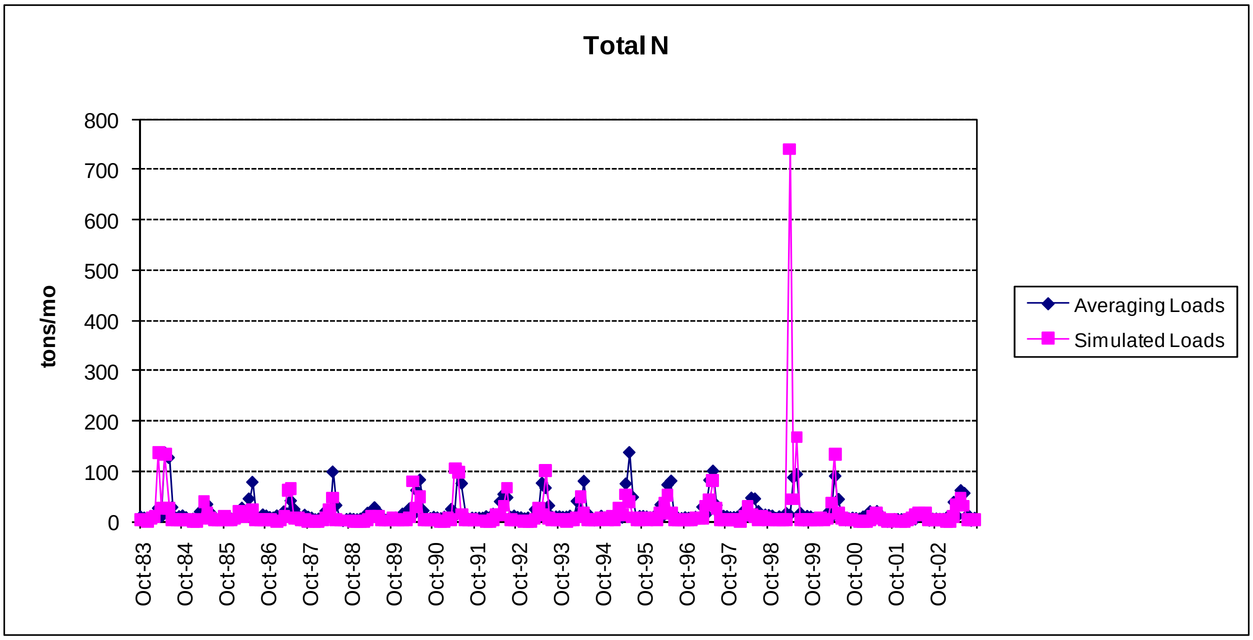


Figure 14. Fit for monthly load of total nitrogen at USGS 06306300 Tongue River at State Line near Decker, MT.

Table 12. Model fit statistics (observed minus predicted) for monthly total nitrogen loads using averaging estimator at USGS 06306300 Tongue River at State Line near Decker, MT

Statistic	Calibration period	Validation period
Relative Percent Error	3.9%	31.5%
Relative Average Absolute Error	93.3%	74.5%
Relative Median Absolute Error	33.6%	37.1%

Water Quality Results for Larger Watershed

As with hydrology, a spatial calibration approach was adopted. SWAT model parameters for water quality derived from calibrations performed at the USGS gage at Tongue River at State Line near Decker were transferred to other portions of the watershed with necessary changes to subbasin level parameters. Summary statistics for the SWAT water quality calibration and validation at other stations in the watershed are provided in Table 13 and Table 14.

Table 13. Summary statistics for water Quality at all stations – calibration period 1993-2003

Station	06308500
Relative Percent Error TSS Load	35.6
Relative Percent Error TP Load	12.5
Relative Percent Error TN Load	3.8

Table 14. Summary statistics for water quality at all stations – validation period 1983-1993

Station	06308500
Relative Percent Error TSS Load	-14.1
Relative Percent Error TP Load	-45.5
Relative Percent Error TN Load	-52.9

References

Peterson, D.A., K.A. Miller, T.T. Bartos, M.L. Clark, S.D. Porter, and T.L. Quinn. 2004. Water Quality in the Yellowstone River Basin, Wyoming, Montana, and North Dakota, 1999-2001. Circular 1234. U.S. Geological Survey, Reston, VA.

USEPA (United States Environmental Protection Agency). 2008. Using the BASINS Meteorological Database (Version 2006). BASINS Technical Note 10. Office of Water, U.S. Environmental Protection Agency, Washington, DC. http://water.epa.gov/scitech/datait/models/basins/upload/2009_04_13_BASINSs_tecnote10.pdf (Accessed June, 2009).

Zelt, R.B., G. Boughton, K.A. Miller, J.P. Mason, and L.M. Gianakos. 1999. Environmental Setting of the Yellowstone River Basin, Montana, North Dakota, and Wyoming Water-Resources Investigations Report 98-4269. Cheyenne, Wyoming.

Appendix X

Scenario Results for the Five Pilot Watersheds

Contents

Apalachicola-Chattahoochee-Flint Basin, HSPF Model Results at Downstream Stationk

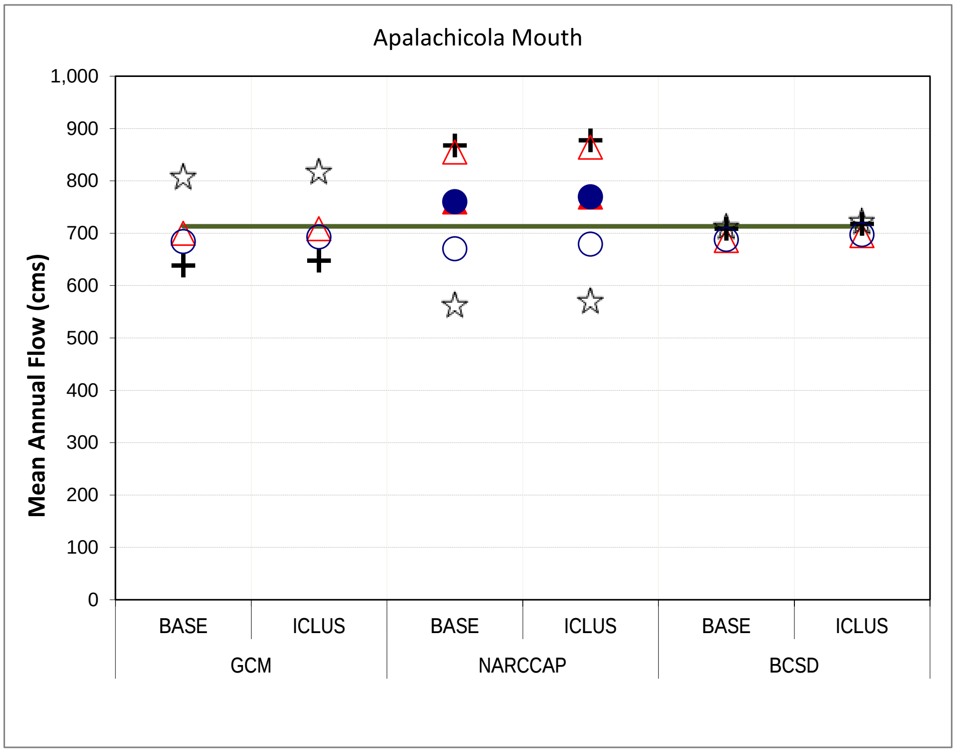


Figure 1. Mean Annual Flow (cms), Apalachicola River at Mouth (HSPF)

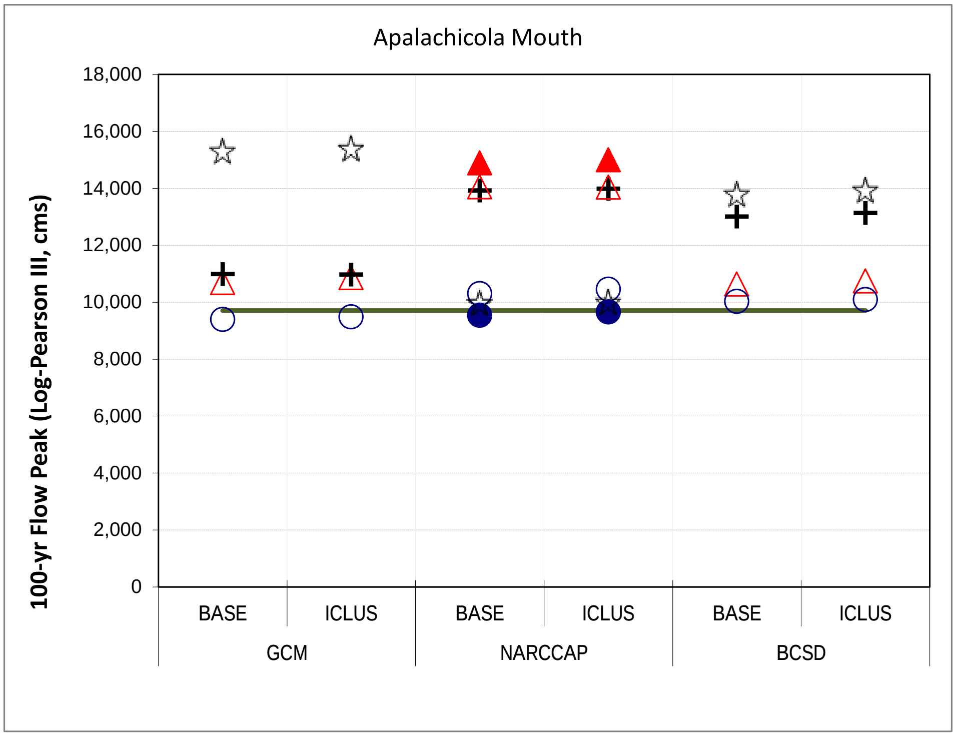


Figure 2. 100-yr Flow Peak (Log-Pearson III, cms), Apalachicola River at Mouth (HSPF)

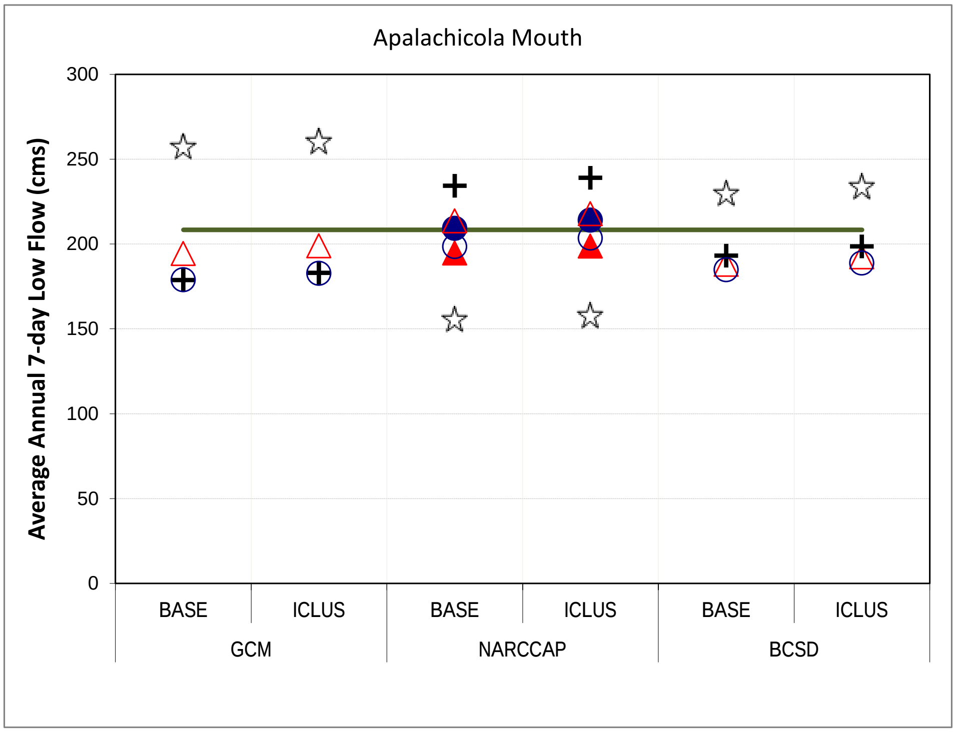


Figure 3. Average Annual 7-day Low Flow (cms), Apalachicola River at Mouth (HSPF)

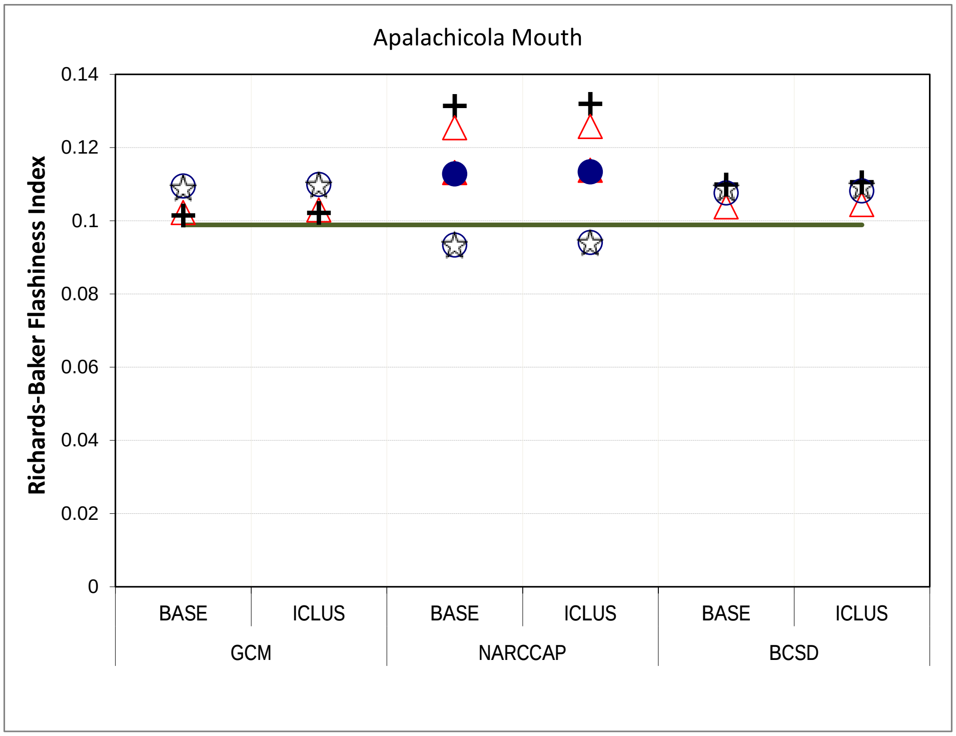


Figure 4. Richards-Baker Flashiness Index, Average Annual 7-day Low Flow (cms), Apalachicola River at Mouth (HSPF)

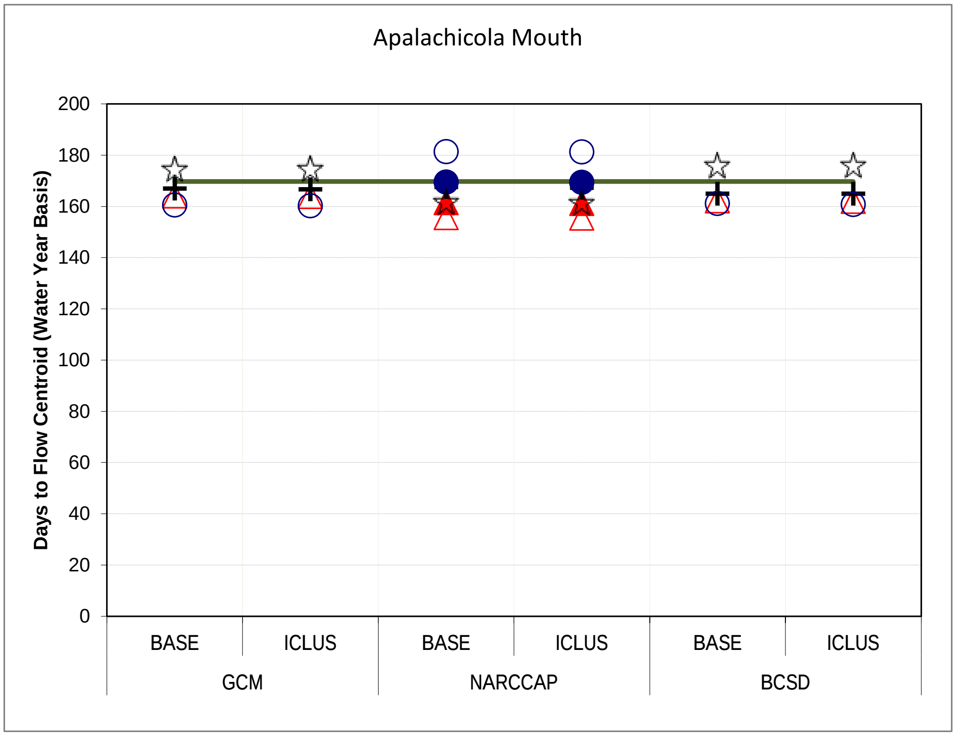


Figure 5. Days to Flow Centroid (Water Year Basis), Apalachicola River at Mouth (HSPF)

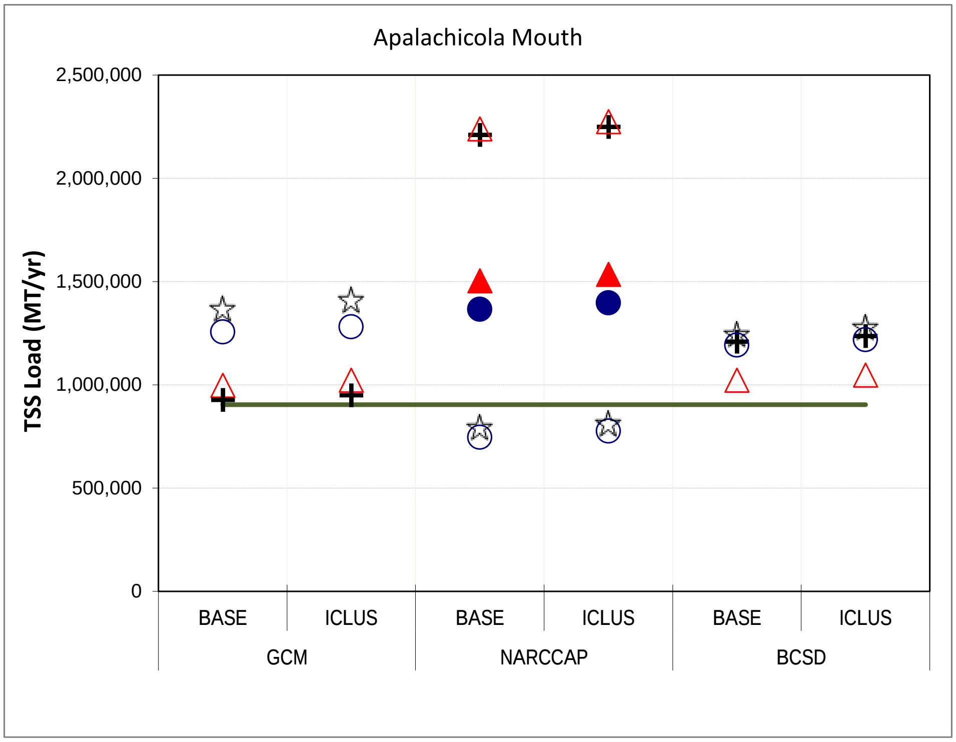


Figure 6. TSS Load (MT/yr), Apalachicola River at Mouth (HSPF)

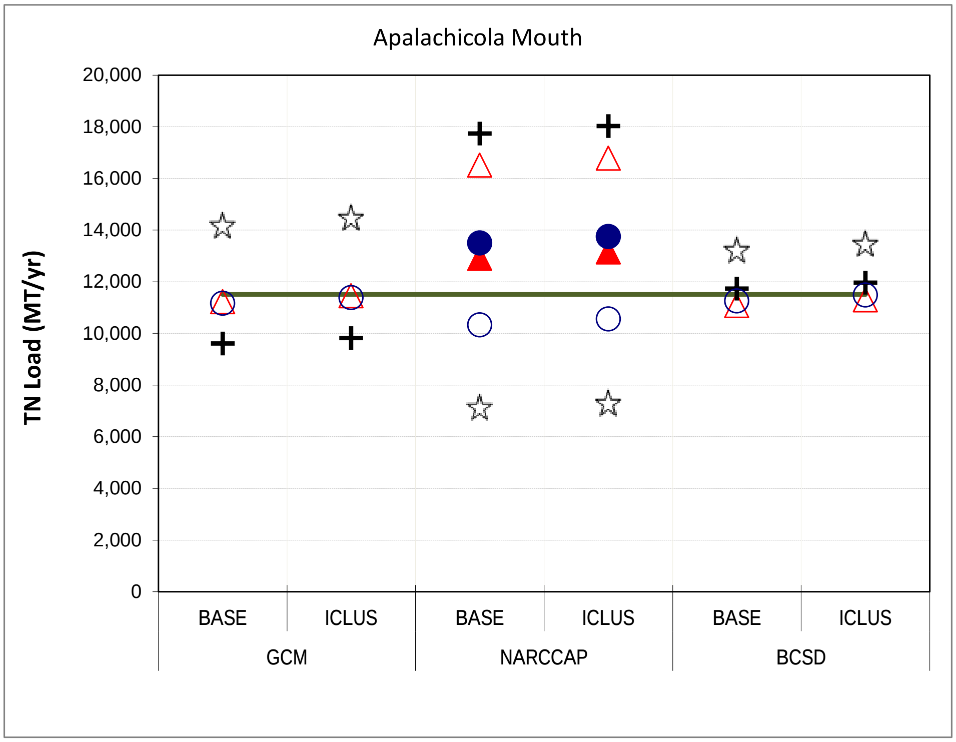


Figure 7. TN Load (MT/yr), Apalachicola River at Mouth (HSPF)

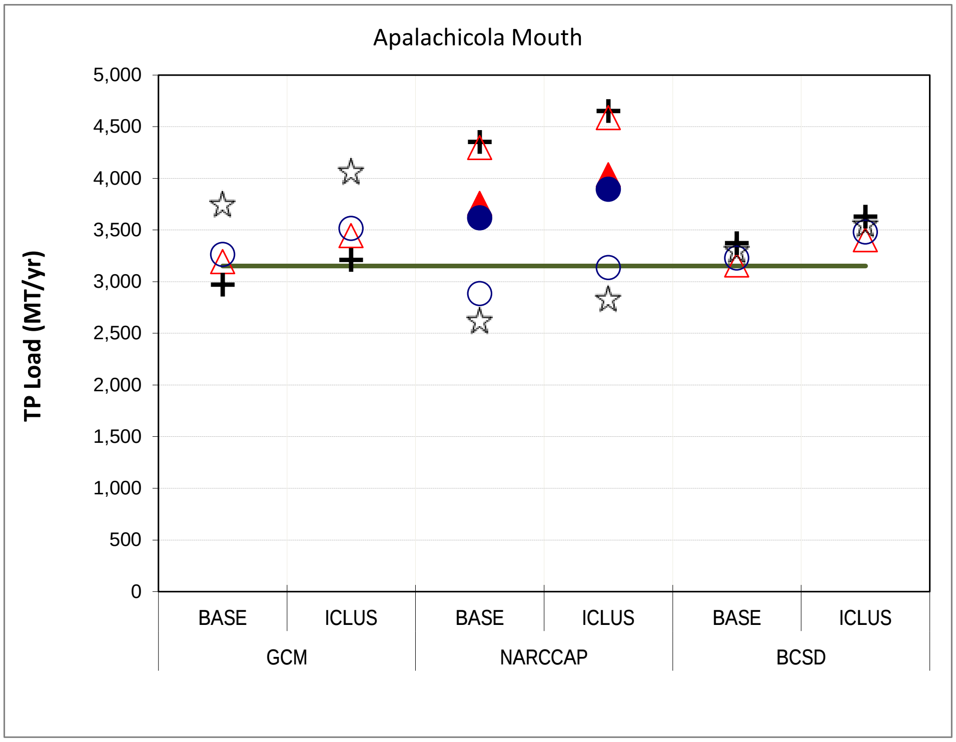


Figure 8. TP Load (MT/yr), Apalachicola River at Mouth (HSPF)

Results at Multiple Stations

Table 1. Summary of Range of Change Relative to Existing Conditions for NARCCAP Dynamically Downscaled Scenarios, Apalachicola-Chattahoochee-Flint Basin HSPF Model

	Results without LU Change				Results with LU Change			
	Min	Median	Mean	Max	Min	Median	Mean	Max
Flint River near Montezuma (gage 02349605)								
Flow	-18.62%	8.70%	6.49%	20.02%	-18.44%	8.67%	6.47%	19.92%
TSS	-13.15%	40.66%	41.77%	94.31%	-15.22%	32.89%	33.16%	76.35%
TN	-23.92%	17.08%	14.35%	36.43%	-23.37%	16.27%	13.57%	34.78%
TP	-15.02%	21.84%	18.58%	41.91%	-14.72%	19.58%	16.26%	37.40%
Chattahoochee River near Cornelia (gage 02331600)								
Flow	-5.84%	5.18%	4.56%	11.13%	-5.82%	5.19%	4.56%	11.11%
TSS	20.99%	51.30%	56.56%	99.56%	20.06%	47.02%	51.73%	90.90%
TN	-3.45%	11.31%	11.24%	21.95%	-3.52%	11.00%	10.91%	21.35%
TP	3.50%	19.70%	18.22%	32.21%	2.87%	18.66%	17.19%	30.49%
Peachtree Creek (gage 02336300)								
Flow	-11.06%	6.31%	5.58%	14.40%	-10.62%	6.32%	5.59%	14.24%
TSS	-6.08%	17.47%	14.88%	27.63%	-6.21%	16.92%	14.10%	25.95%
TN	-8.98%	6.82%	5.84%	13.47%	-8.76%	6.48%	5.39%	12.48%
TP	-9.95%	12.15%	9.31%	18.03%	-9.98%	11.86%	9.02%	17.51%
Chattahoochee at Atlanta (gage 02336000)								
Flow	-13.84%	0.51%	0.07%	8.41%	-13.36%	0.89%	0.41%	8.65%
TSS	-9.66%	22.22%	21.98%	47.03%	-10.37%	19.29%	17.43%	36.75%
TN	-8.27%	3.57%	3.35%	10.66%	-8.55%	3.37%	3.06%	9.91%
TP	-9.55%	10.03%	7.95%	19.82%	-10.73%	8.98%	6.77%	17.76%
Ichawaynochaway Creek (gage 02353500)								
Flow	-18.49%	9.21%	5.64%	23.80%	-18.48%	9.21%	5.64%	23.80%
TSS	-0.63%	138.28%	140.22%	282.06%	-0.64%	137.95%	139.86%	281.35%
TN	-25.45%	20.94%	14.52%	45.86%	-25.45%	20.93%	14.51%	45.85%
TP	-15.16%	38.74%	33.16%	77.57%	-15.16%	38.72%	33.14%	77.51%
Chattahoochee River at West Point (gage 02339500)								

	Results without LU Change				Results with LU Change			
	Min	Median	Mean	Max	Min	Median	Mean	Max
Flow	-14.64%	2.82%	1.71%	11.46%	-14.26%	3.00%	1.90%	11.54%
TSS	-11.13%	32.90%	31.91%	72.52%	-13.41%	26.00%	25.48%	58.86%
TN	-14.38%	6.47%	5.20%	18.35%	-14.34%	6.24%	4.96%	17.66%
TP	-10.14%	10.65%	8.03%	20.33%	-11.18%	10.21%	7.43%	19.53%
Chattahoochee River near Columbia (gage 02343801)								
Flow	-17.57%	5.35%	3.73%	16.78%	-17.30%	5.40%	3.79%	16.72%
TSS	-7.19%	55.37%	57.84%	127.37%	-6.08%	53.44%	55.81%	122.70%
TN	-25.53%	13.71%	11.00%	36.63%	-25.29%	13.47%	10.77%	35.95%
TP	-12.29%	11.02%	8.54%	23.25%	-12.62%	10.86%	8.29%	22.77%
Flint River at Newton (gage 02353000)								
Flow	-17.76%	9.62%	6.69%	21.63%	-17.66%	9.60%	6.68%	21.56%
TSS	-1.54%	61.44%	59.67%	131.16%	-3.84%	56.79%	54.98%	121.31%
TN	-22.22%	19.43%	15.16%	40.01%	-22.16%	19.16%	14.91%	39.49%
TP	-12.51%	24.78%	20.68%	46.91%	-12.75%	23.48%	19.40%	44.40%
Apalachicola River at Seminole (gage 02358000)								
Flow	-18.57%	7.23%	4.89%	19.75%	-18.38%	7.24%	4.91%	19.68%
TSS	-8.60%	68.64%	70.10%	150.58%	-7.25%	65.74%	67.07%	144.64%
TN	-26.90%	18.07%	14.00%	43.52%	-26.77%	17.86%	13.81%	43.01%
TP	-13.60%	16.94%	13.63%	34.81%	-13.77%	16.36%	13.03%	33.52%
Apalachicola Mouth								
Flow	-20.76%	6.58%	4.66%	21.68%	-20.57%	6.60%	4.68%	21.59%
TSS	-17.46%	58.76%	63.45%	147.71%	-16.56%	57.62%	62.15%	144.58%
TN	-37.64%	14.70%	13.18%	54.13%	-37.39%	14.64%	13.09%	53.65%
TP	-16.43%	16.96%	13.90%	38.06%	-16.39%	16.47%	13.37%	36.72%

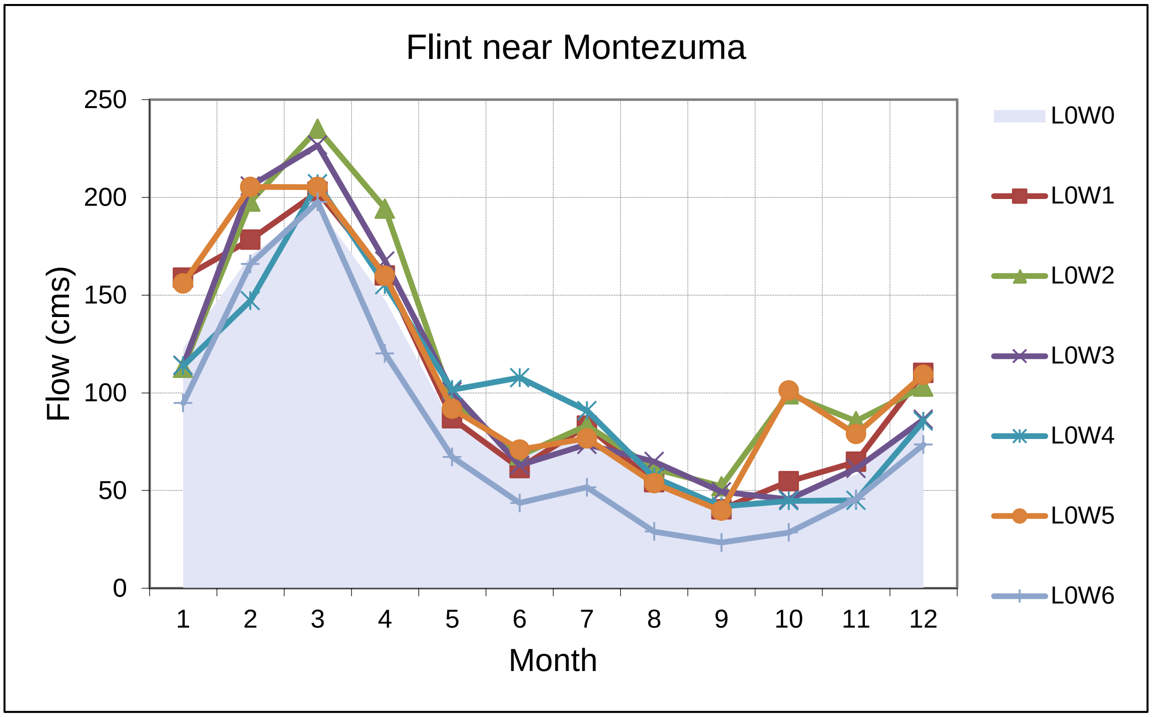


Figure 9. Monthly Average Flows, Flint River near Montezuma (HSPF)

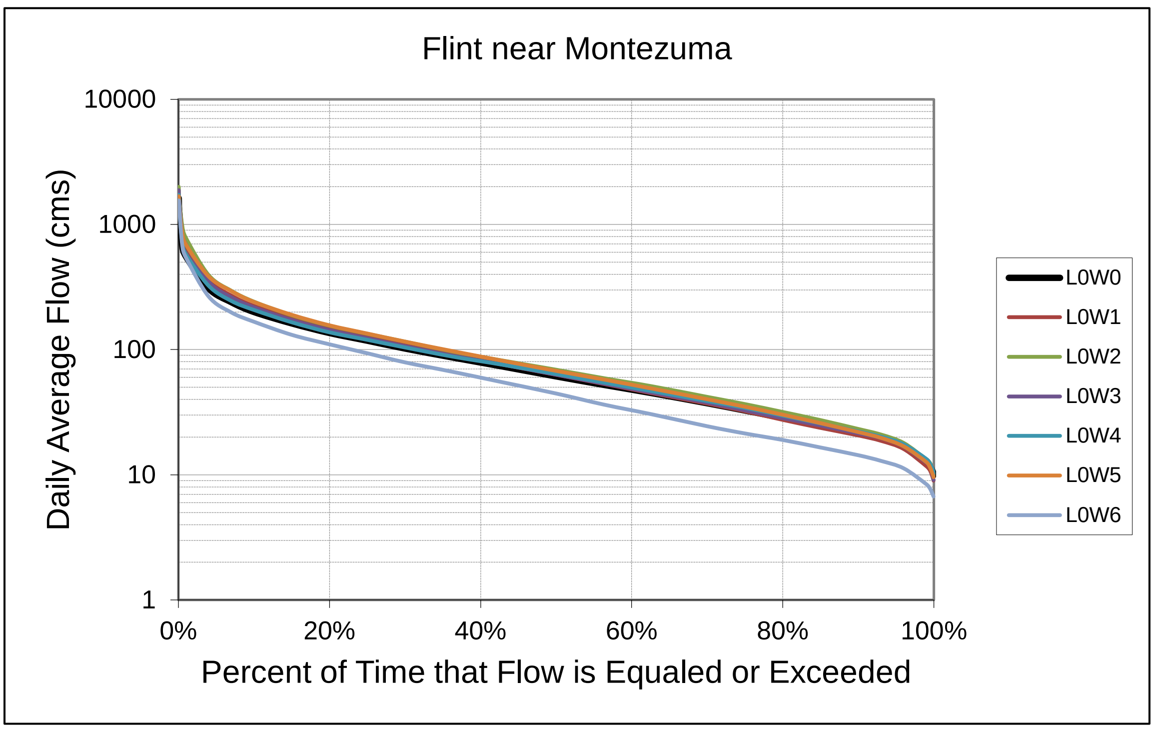


Figure 10. Flow Duration, Flint River near Montezuma (HSPF)

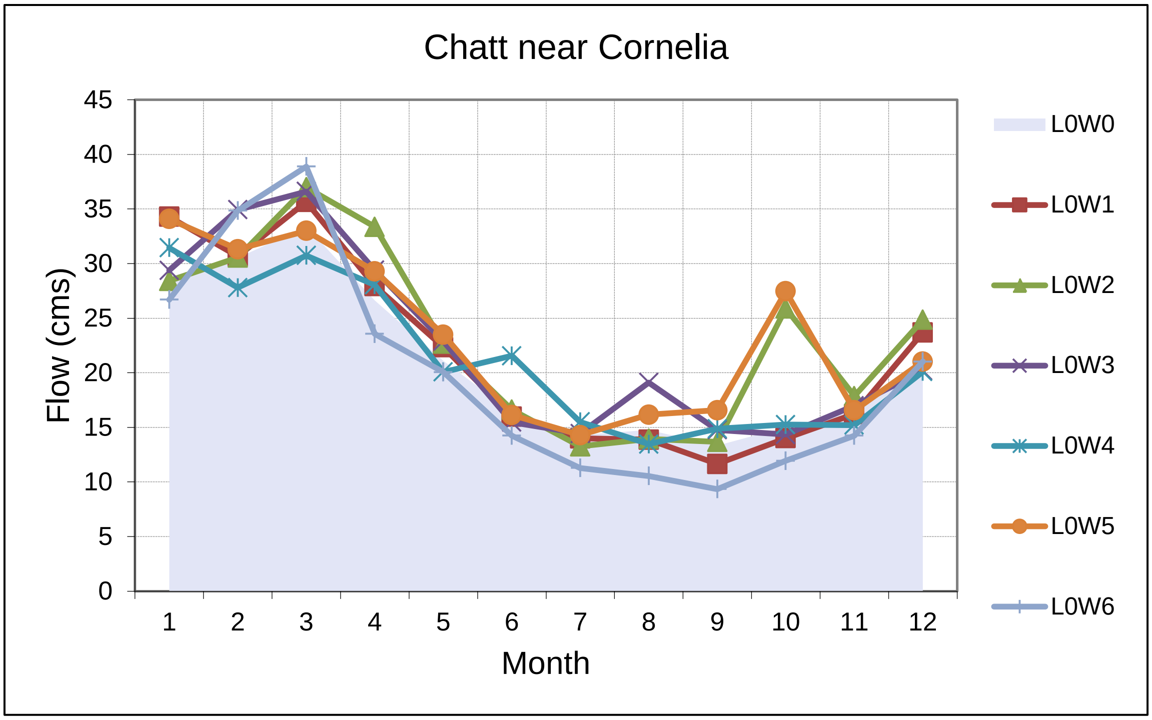


Figure 11. Monthly Average Flows, Chattahoochee River near Cornelia (HSPF)

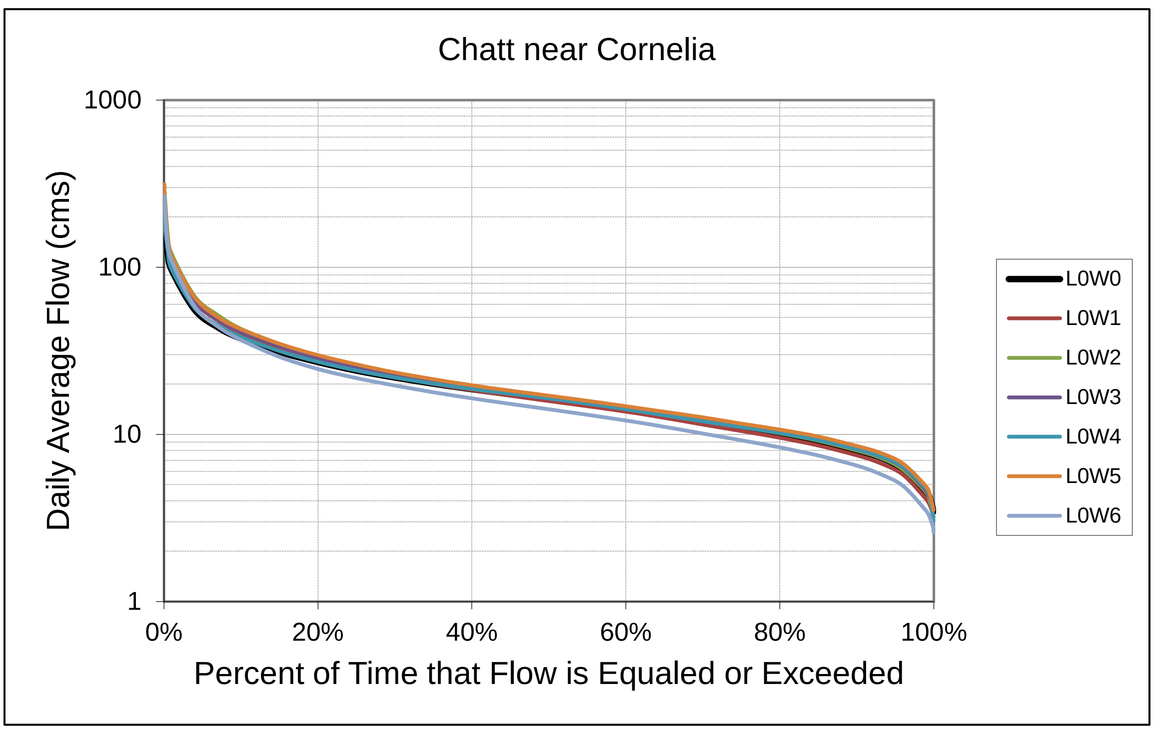


Figure 12. Flow Duration, Chattahoochee River near Cornelia (HSPF)

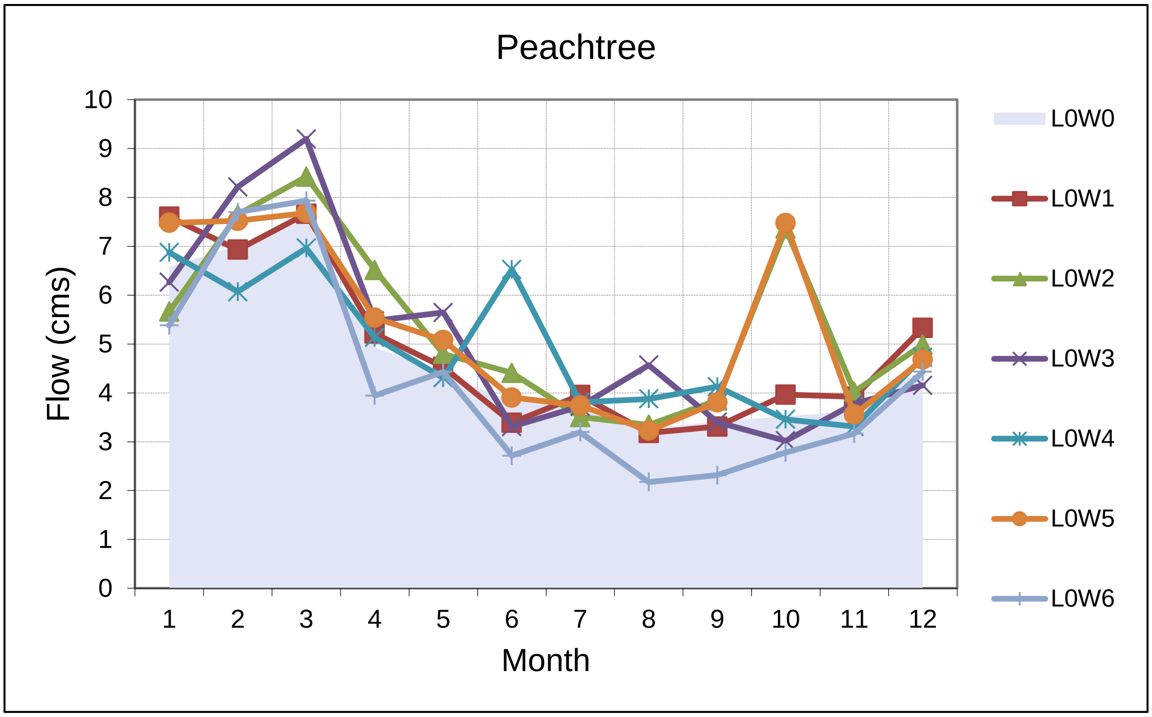


Figure 13. Monthly Average Flows, Peachtree Creek (HSPF)

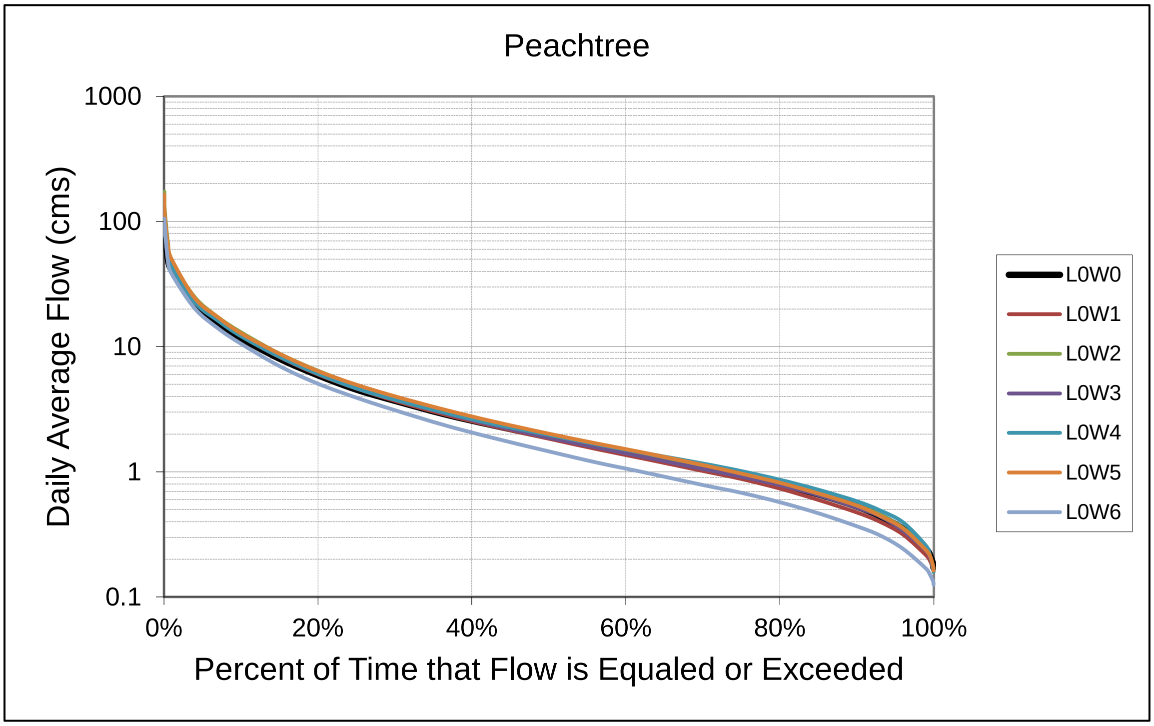


Figure 14. Flow Duration, Peachtree Creek (HSPF)

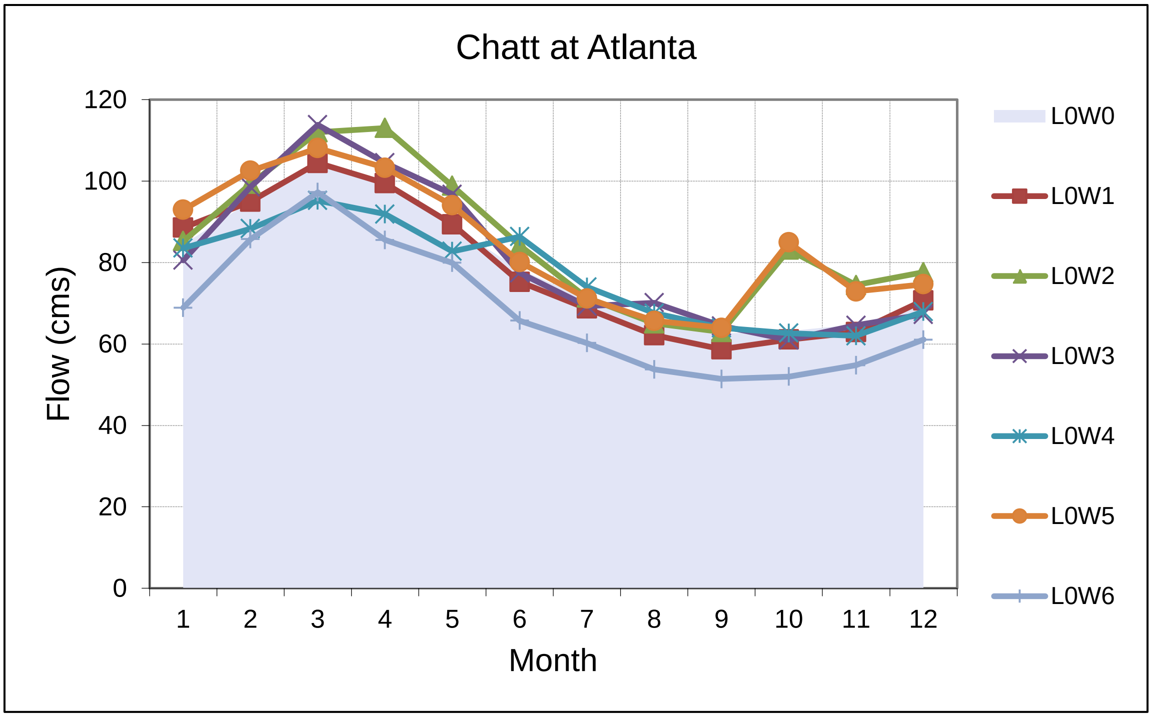


Figure 15. Monthly Average Flows, Chattahoochee River at Atlanta (HSPF)

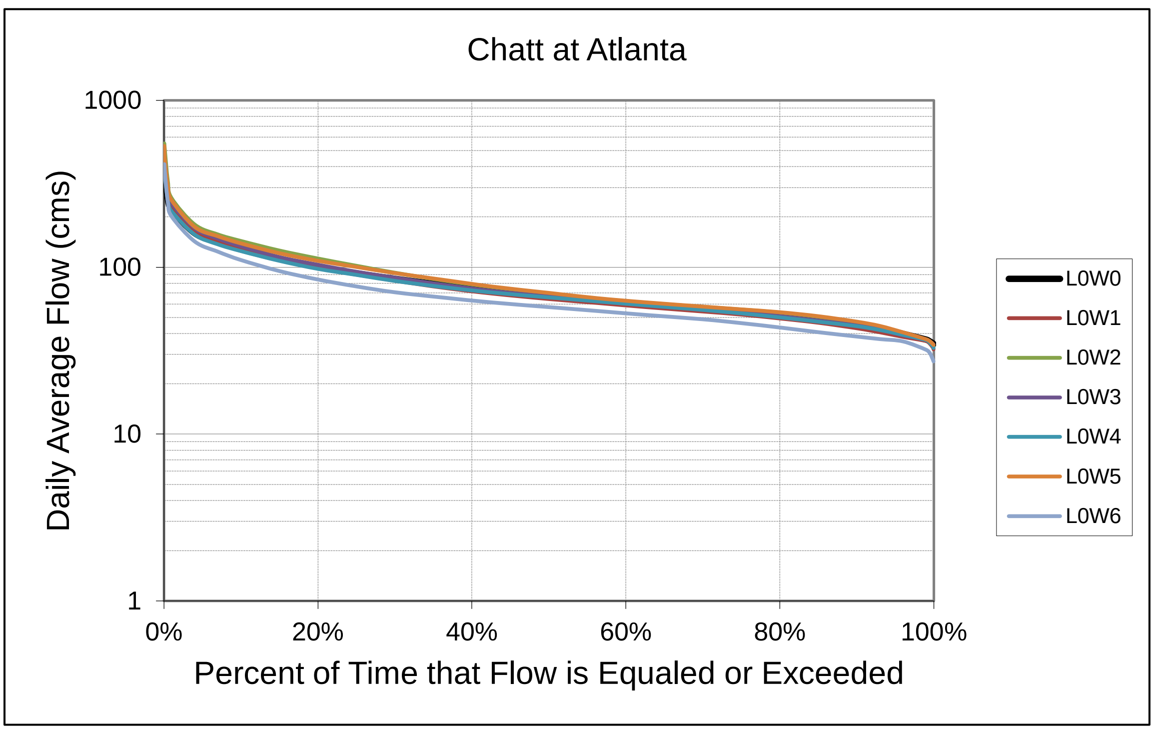


Figure 16. Flow Duration, Chattahoochee River at Atlanta (HSPF)

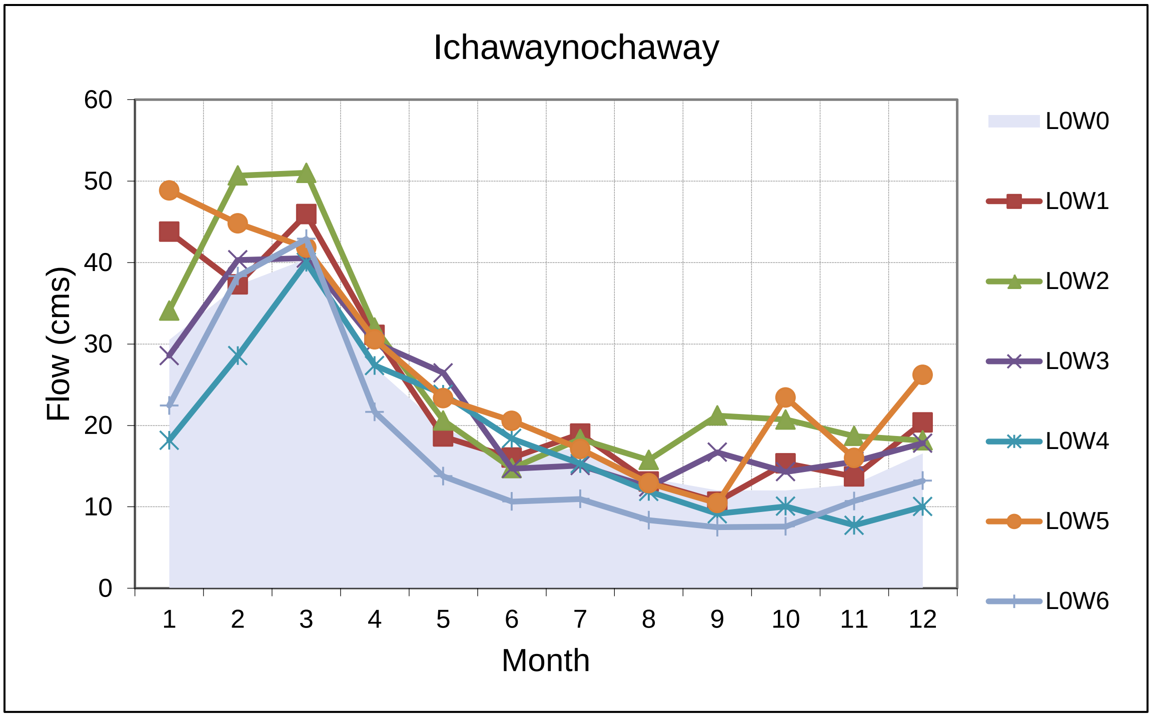


Figure 17. Monthly Average Flows, Ichawaynochaway Creek (HSPF)

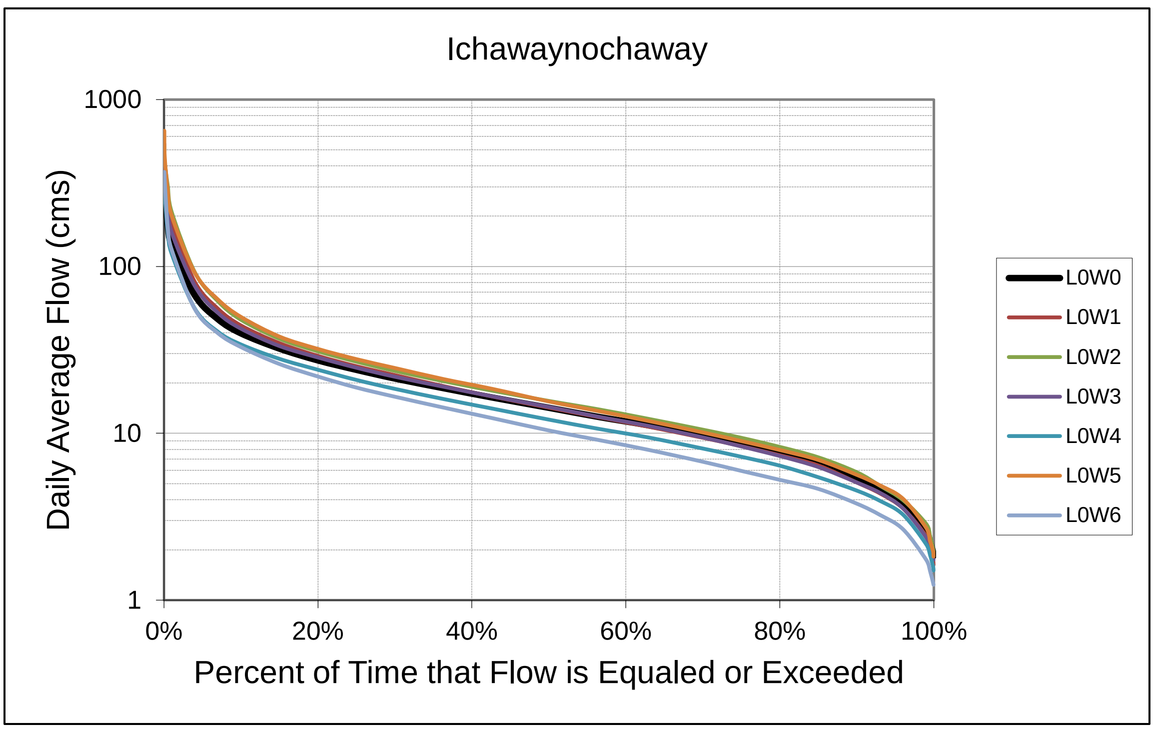


Figure 18. Flow Duration, Ichawaynochaway Creek (HSPF)

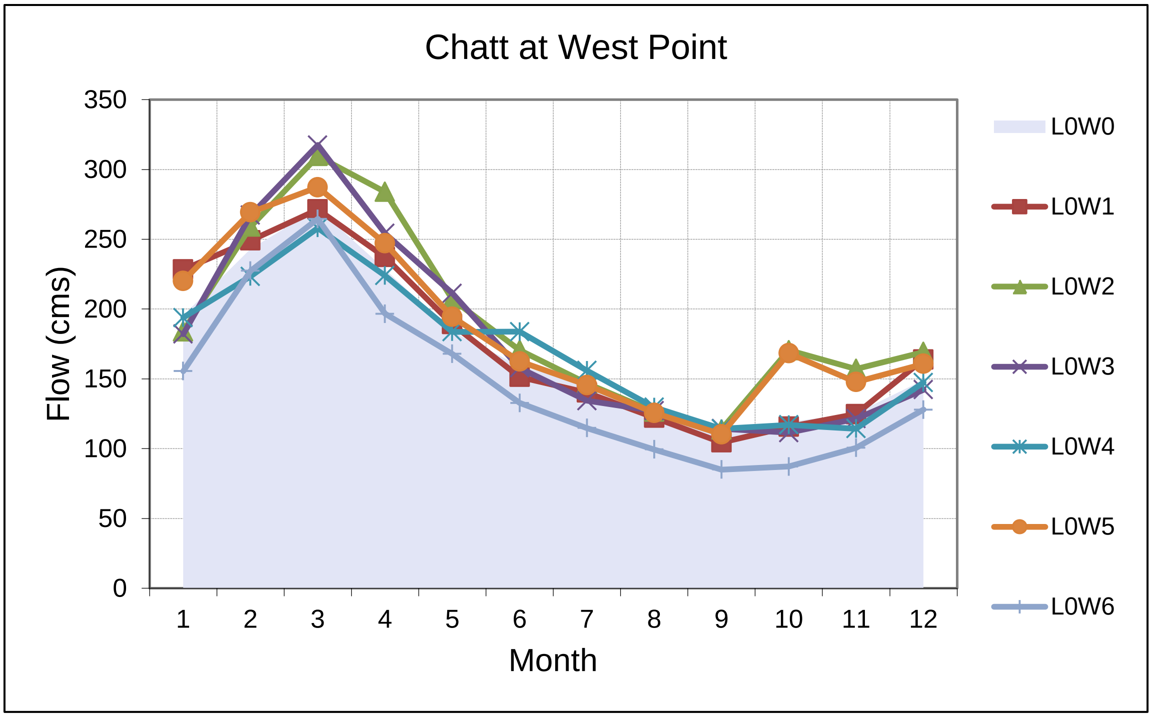


Figure 19. Monthly Average Flows, Chattahoochee River at West Point (HSPF)

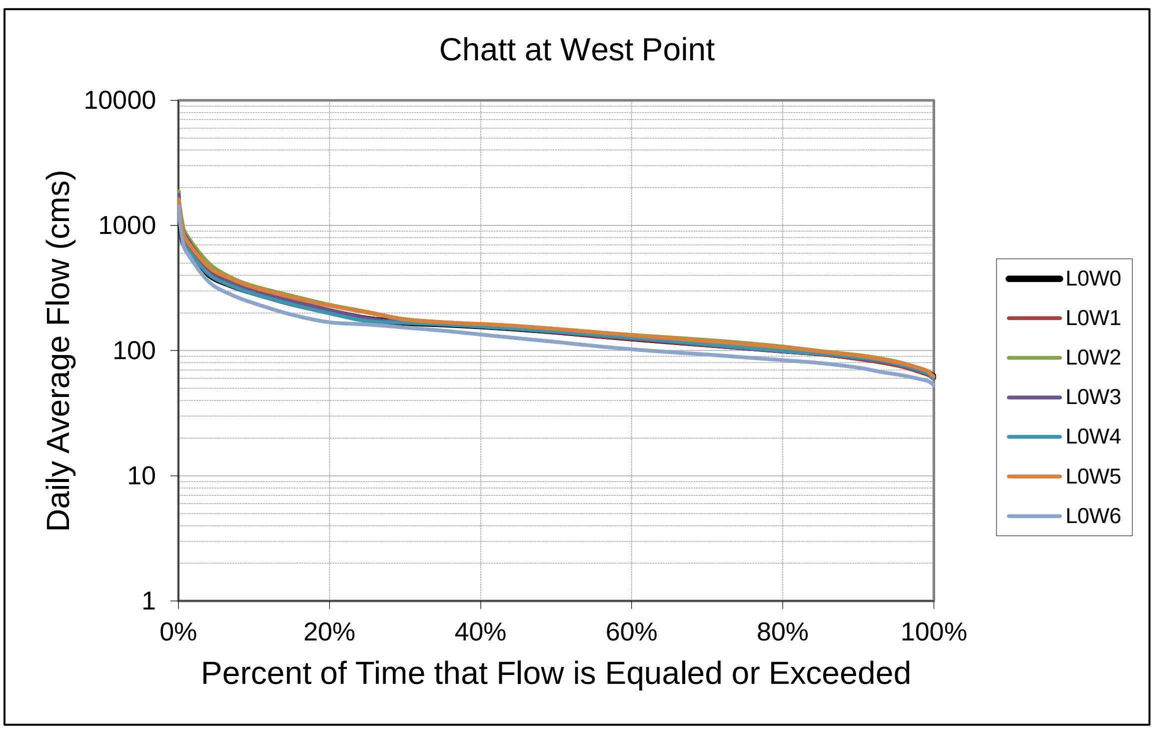


Figure 20. Flow Duration, Chattahoochee River at West Point (HSPF)

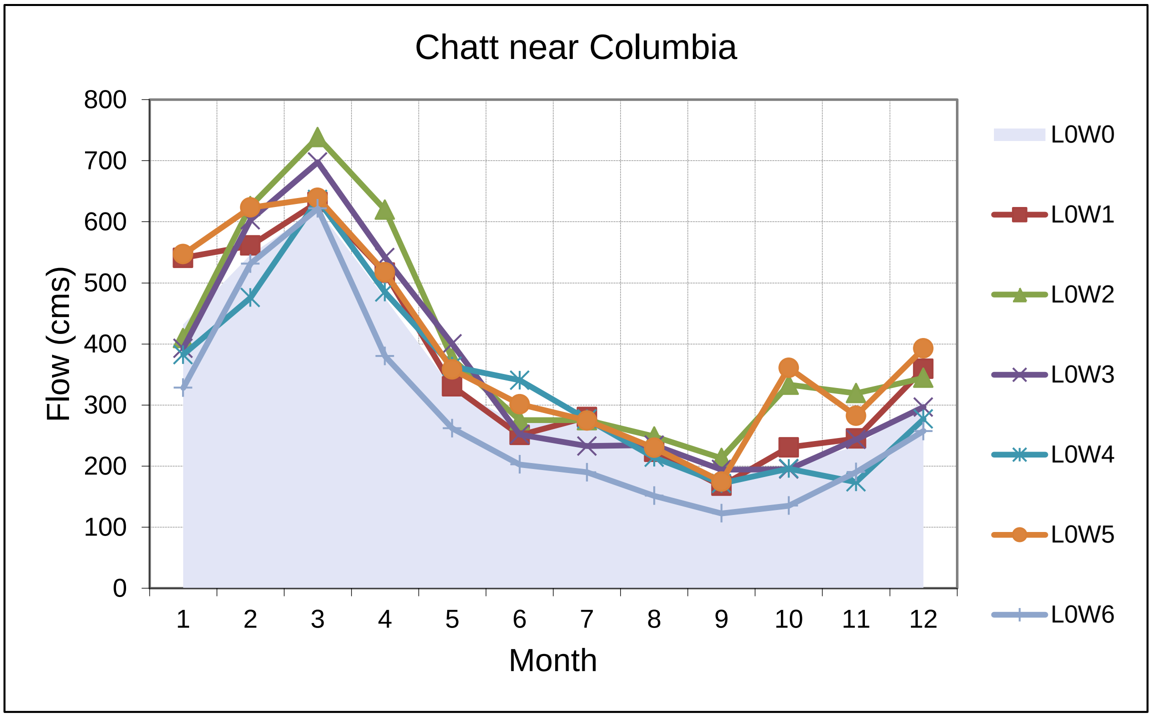


Figure 21. Monthly Average Flows, Chattahoochee River near Columbia (HSPF)

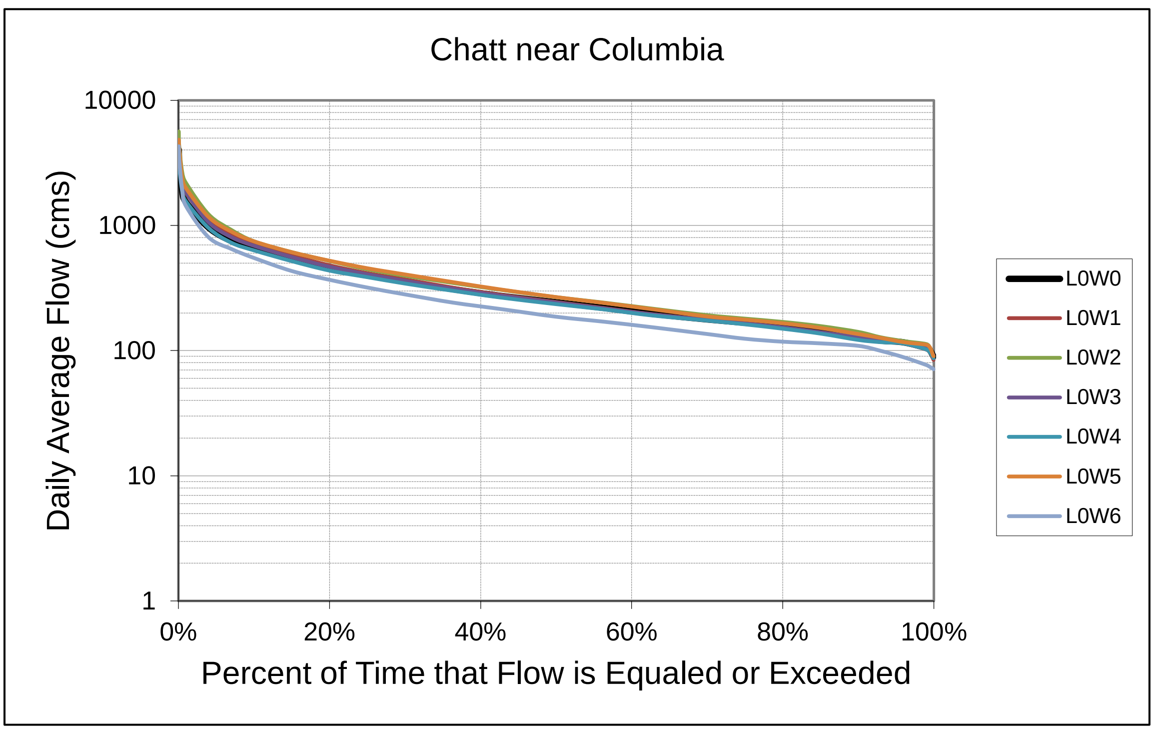


Figure 22. Flow Duration, Chattahoochee River near Columbia (HSPF)

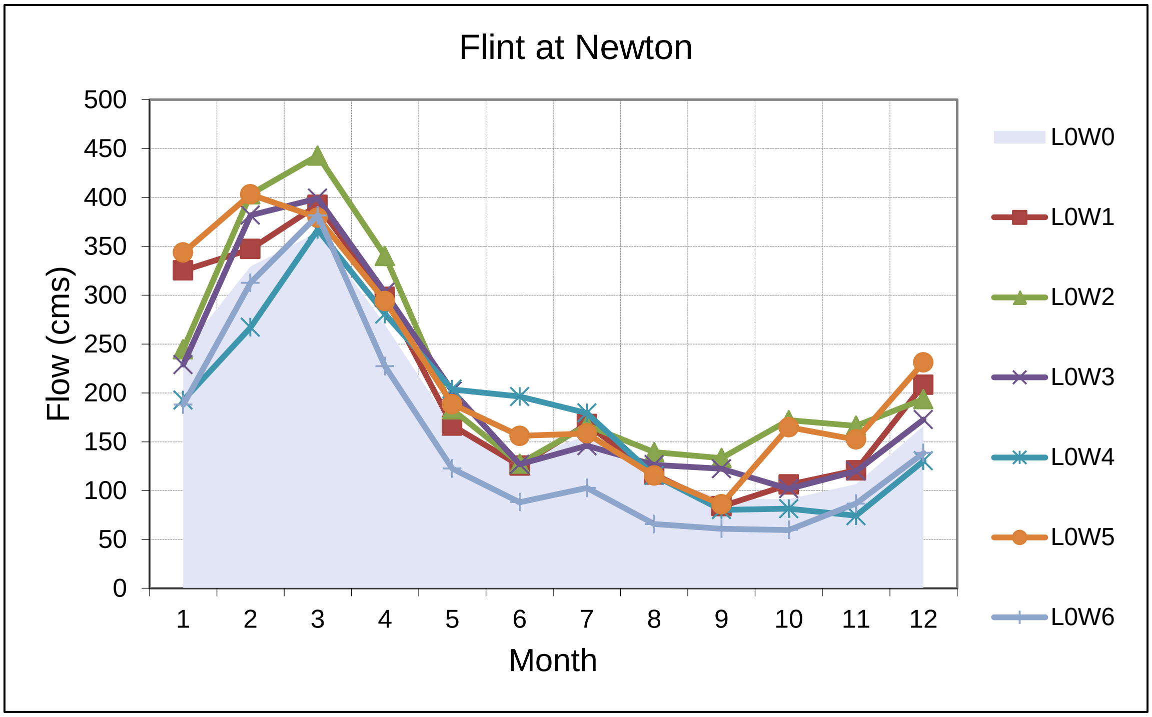


Figure 23. Monthly Average Flows, Flint River at Newton (HSPF)

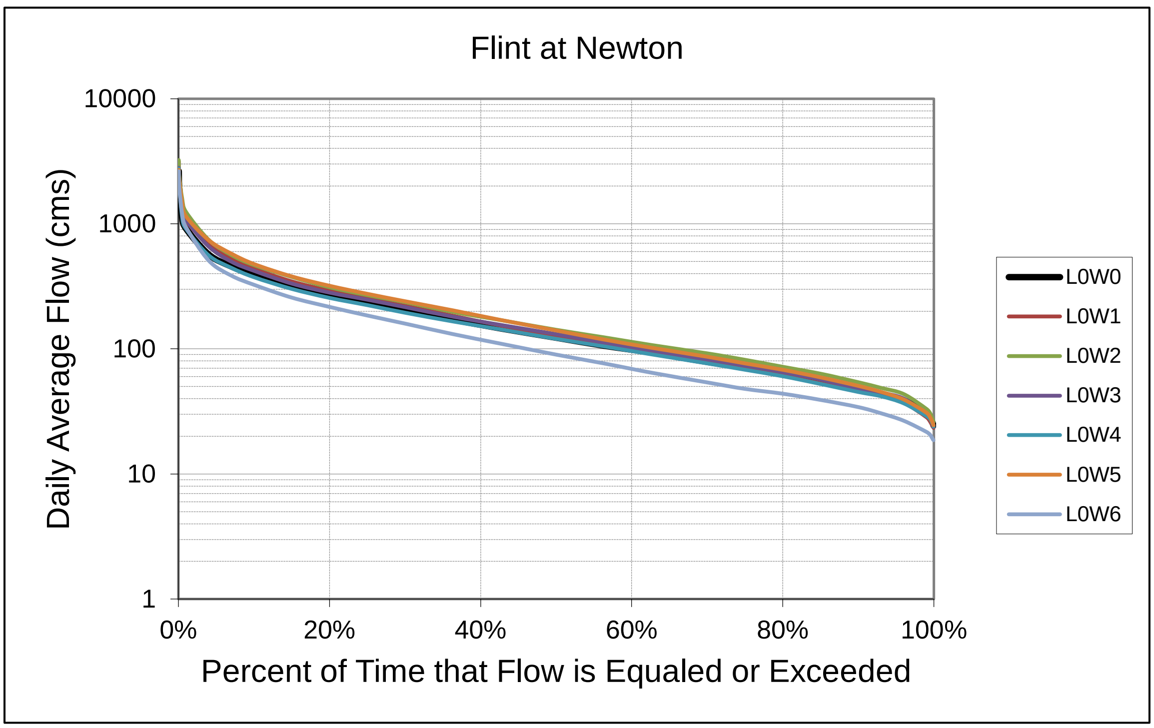


Figure 24. Flow Duration, Flint River at Newton (HSPF)

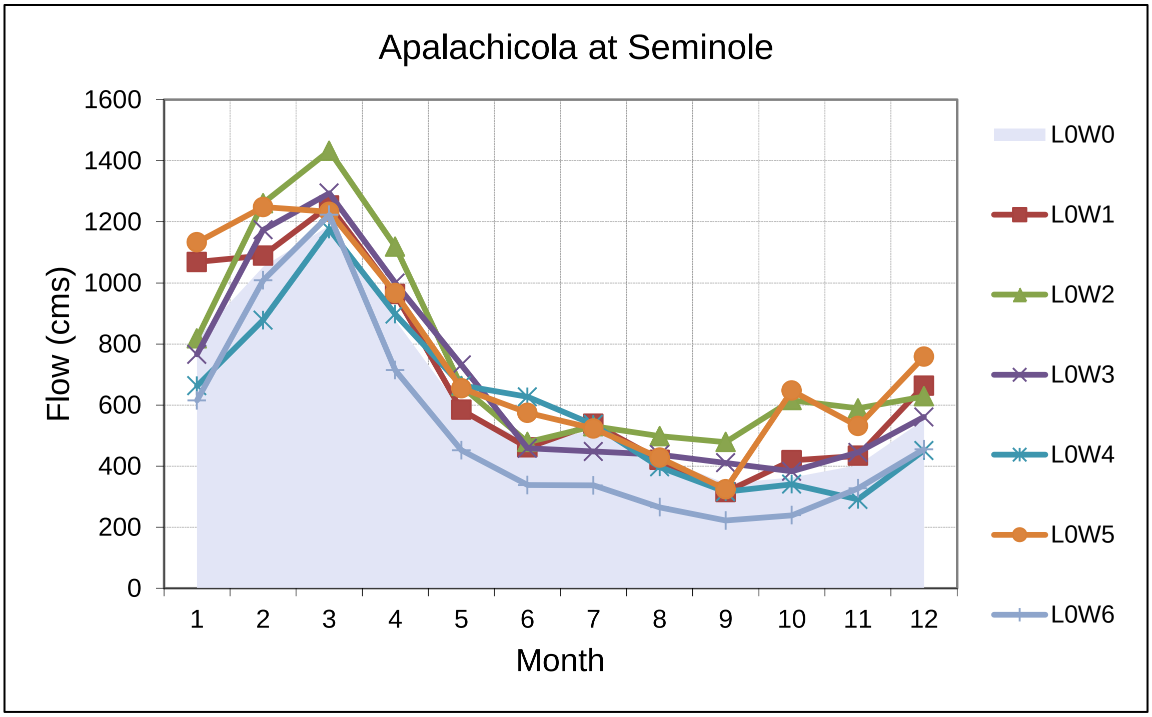


Figure 25. Monthly Average Flows, Apalachicola River at Seminole (HSPF)

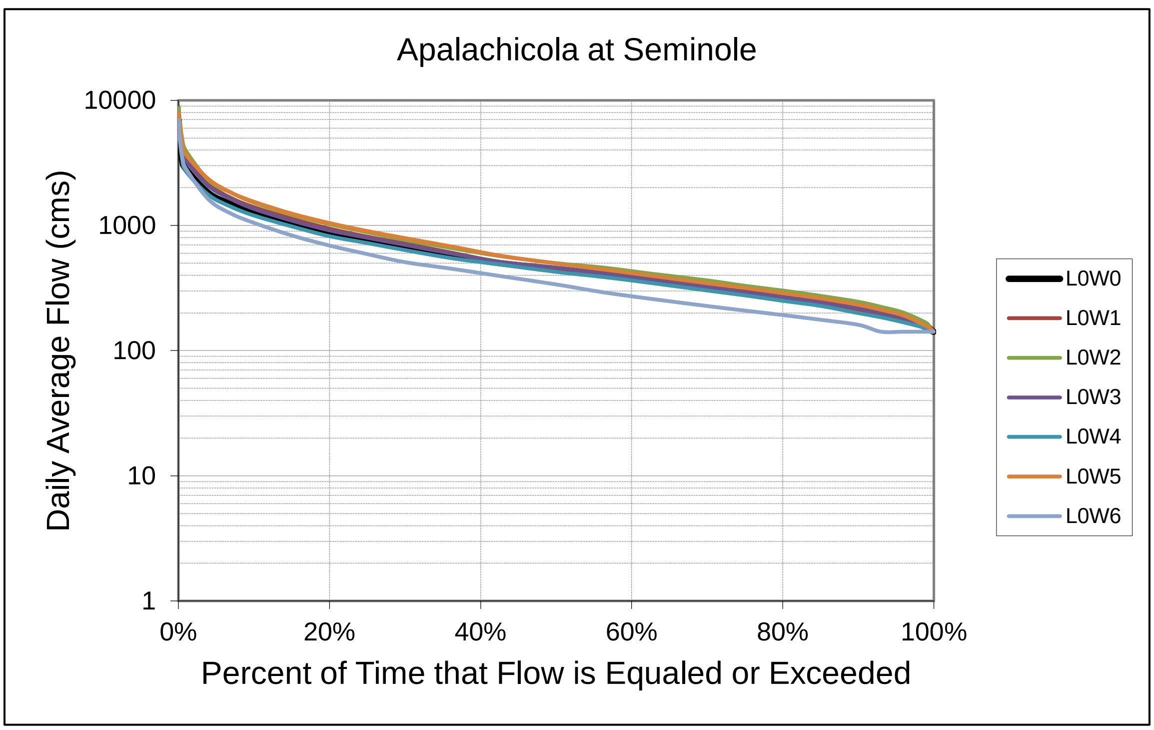


Figure 26. Flow Duration, Apalachicola River at Seminole (HSPF)

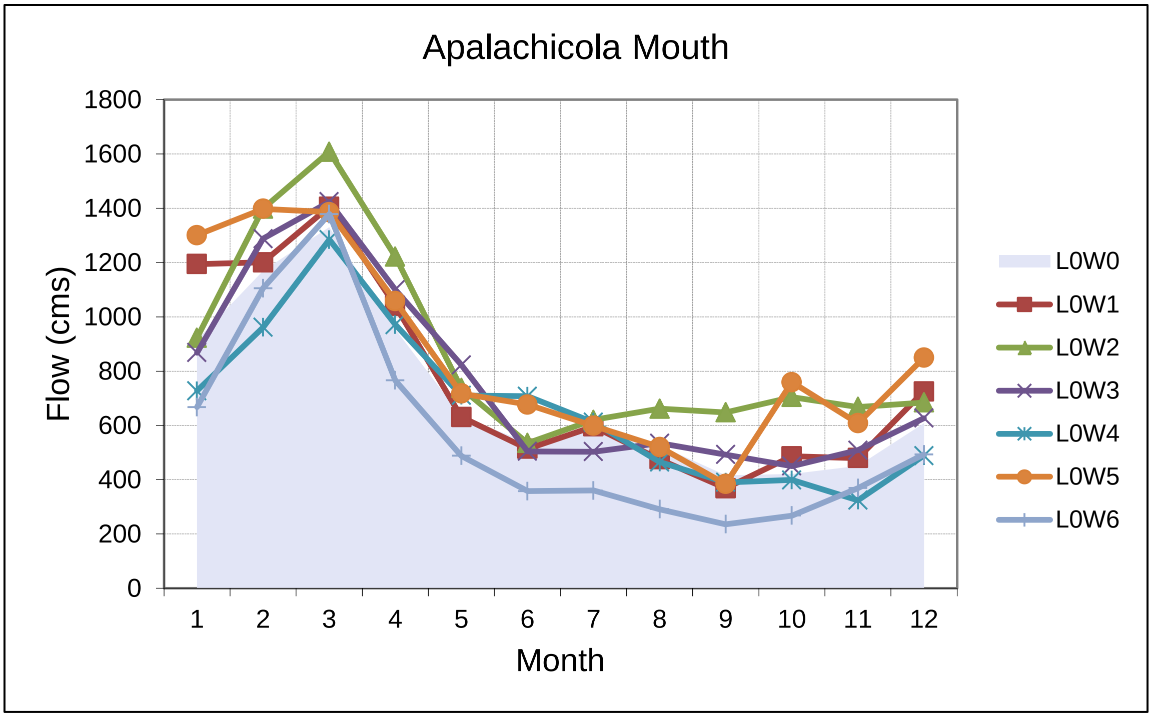


Figure 27. Monthly Average Flows, Apalachicola River at Mouth (HSPF)

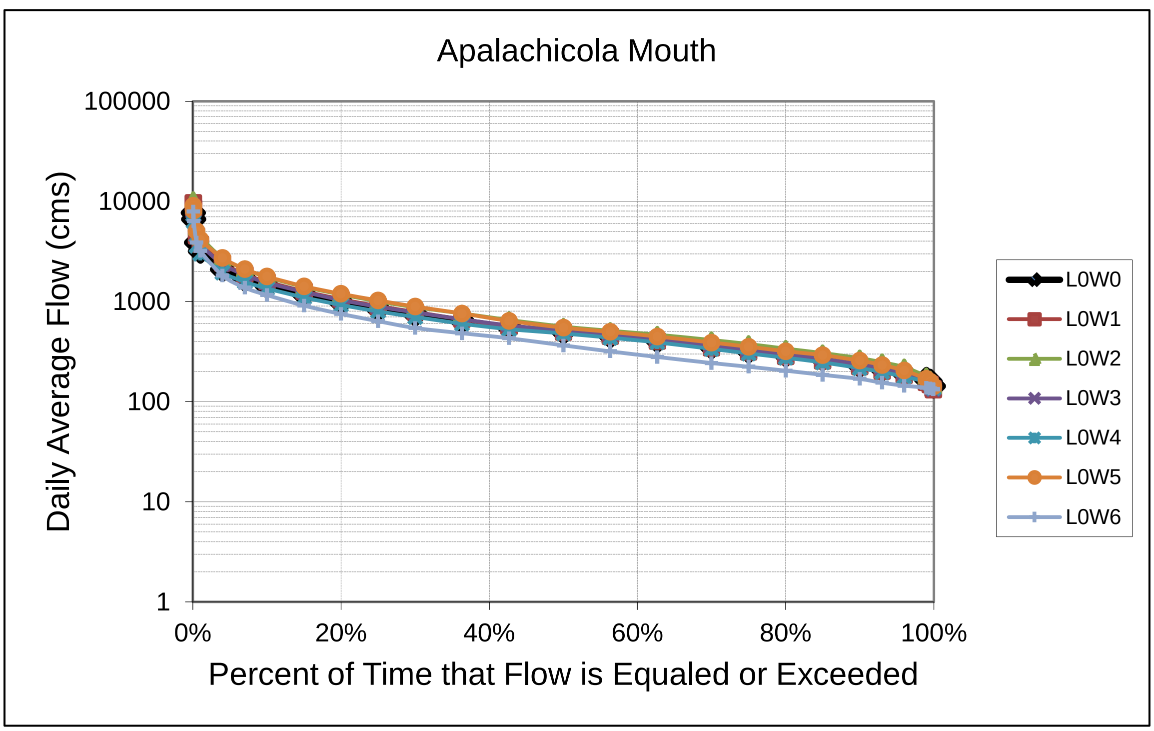


Figure 28. Flow Duration, Apalachicola River at Mouth (HSPF)

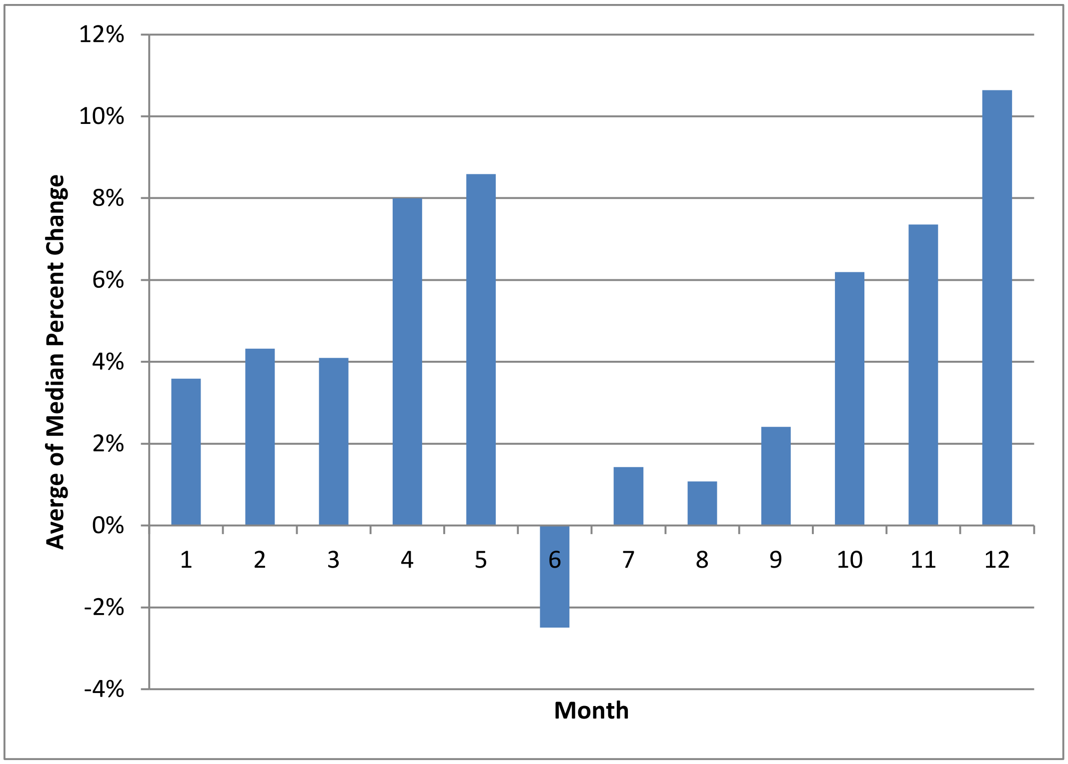


Figure 29. Average of Median Percent Change in Flow; NARCCAP Scenarios W1-W6 at all Stations, Apalachicola-Chattahoochee-Flint Basin (HSPF)

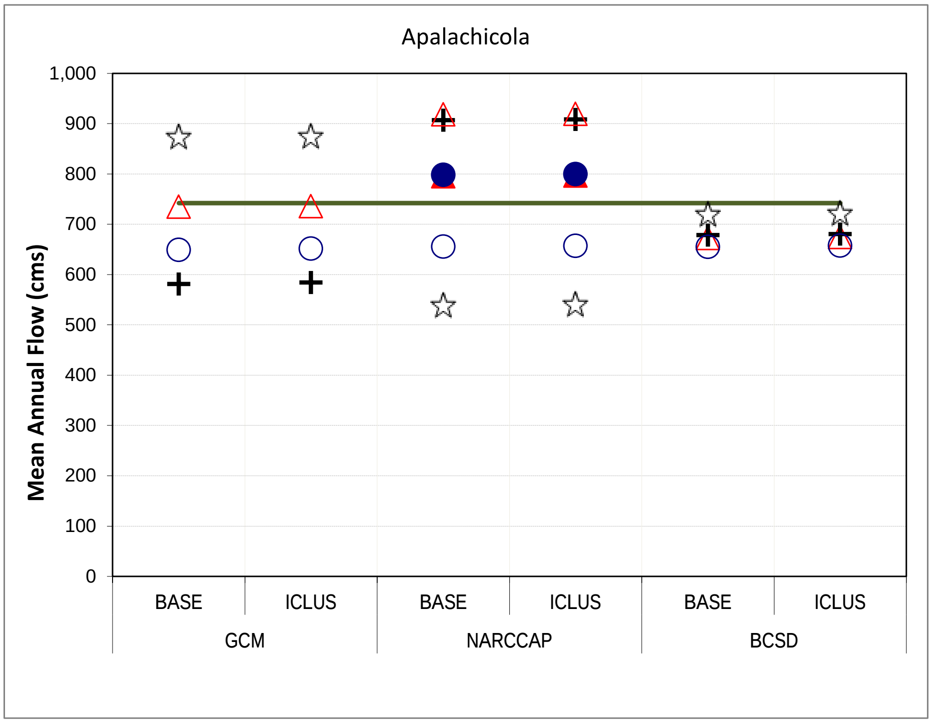


Figure 30. Mean Annual Flow, Apalachicola River at Mouth (SWAT)

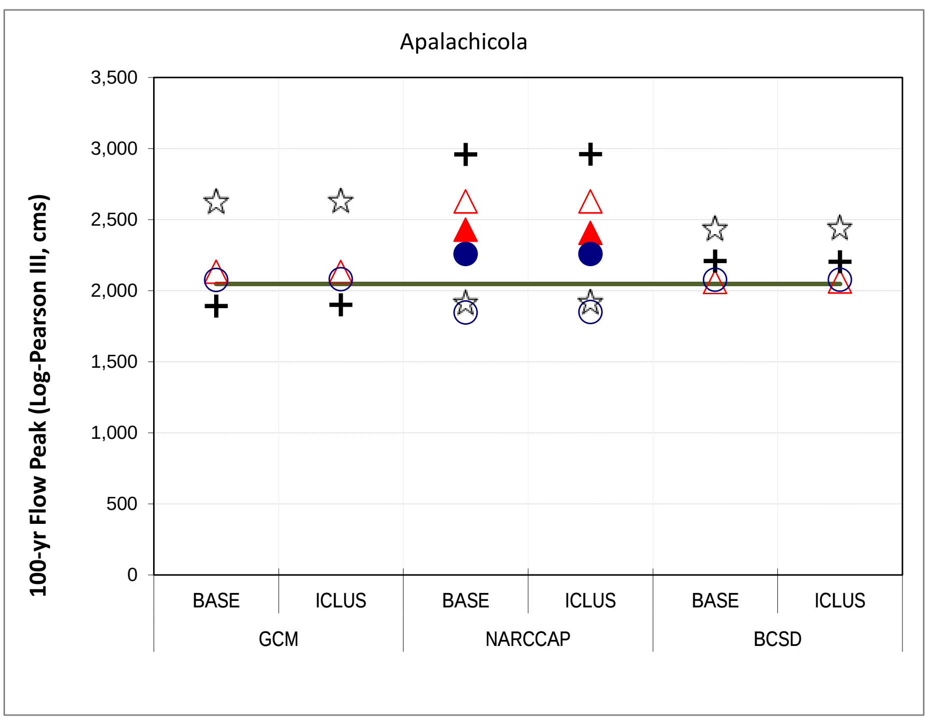


Figure 31. 100-yr flow Peak (Log-Pearson III), Apalachicola River at Mouth (SWAT)

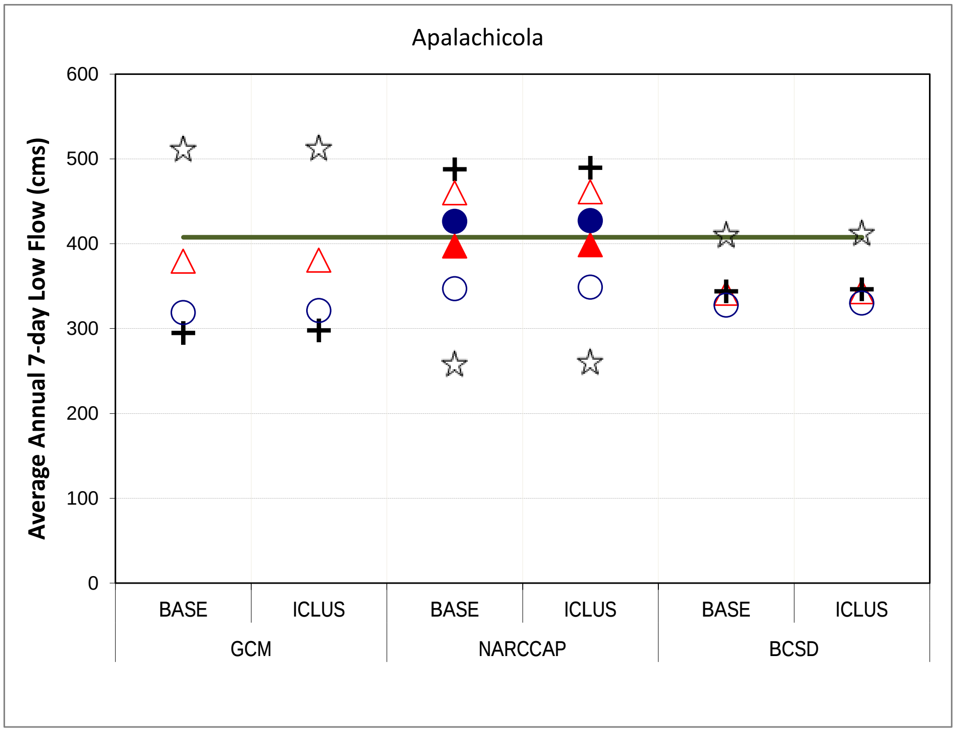


Figure 32. Average Annual 7-day Low Flow, Apalachicola River at Mouth (SWAT)

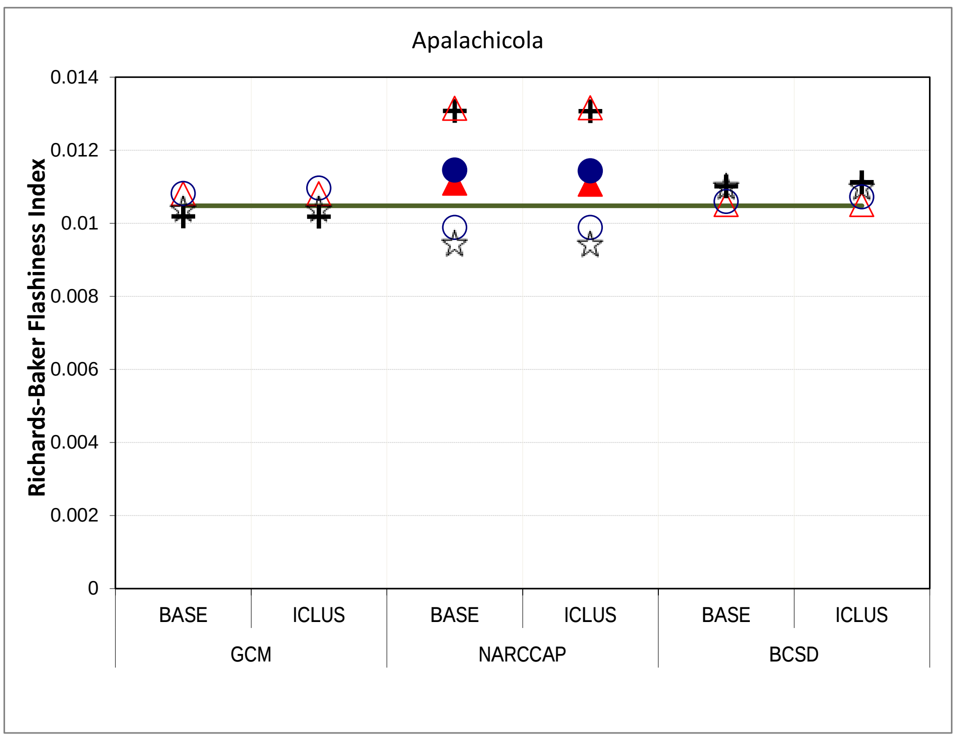


Figure 33. Richards-Baker Flashiness Index, Apalachicola River at Mouth (SWAT)

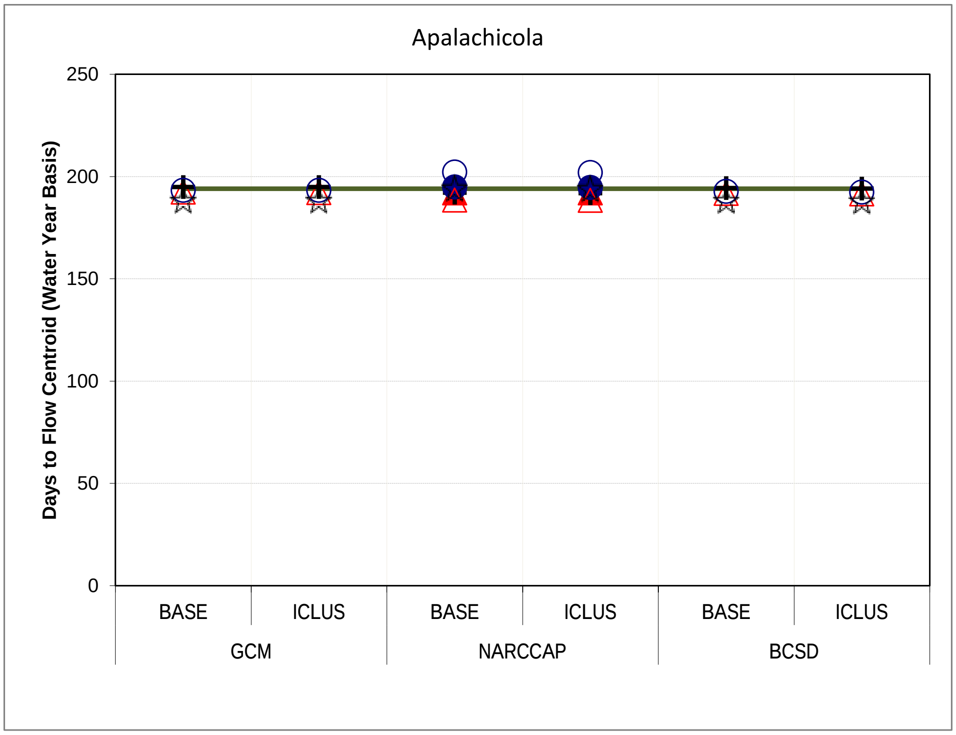


Figure 34. Days to Flow Centroid, Apalachicola River at Mouth (SWAT)

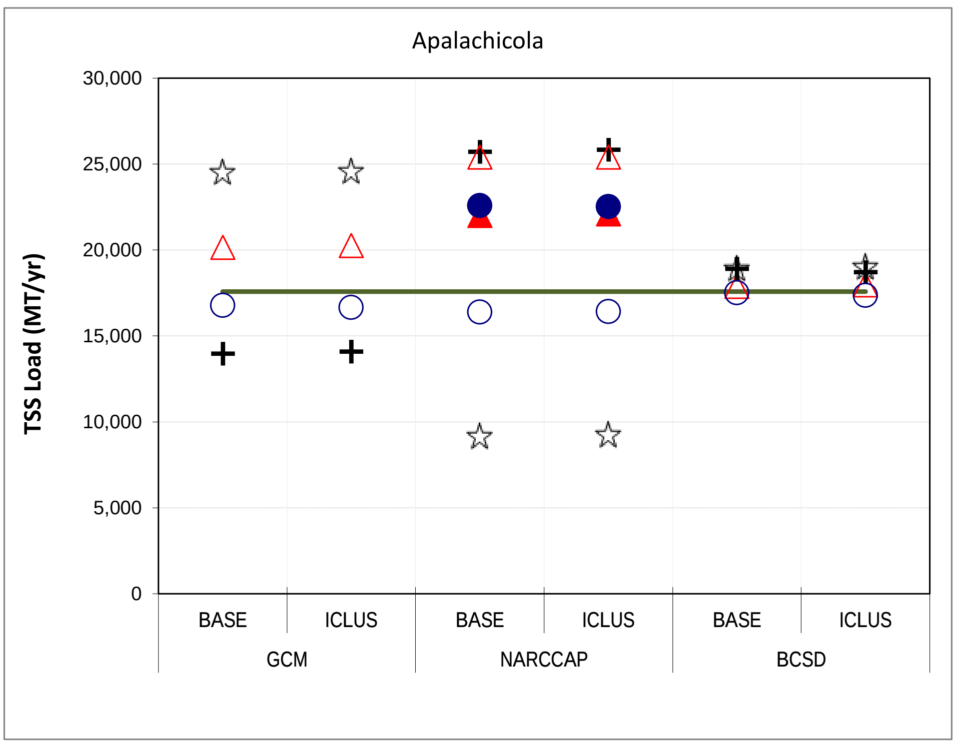


Figure 35. TSS Load, Apalachicola River at Mouth (SWAT)

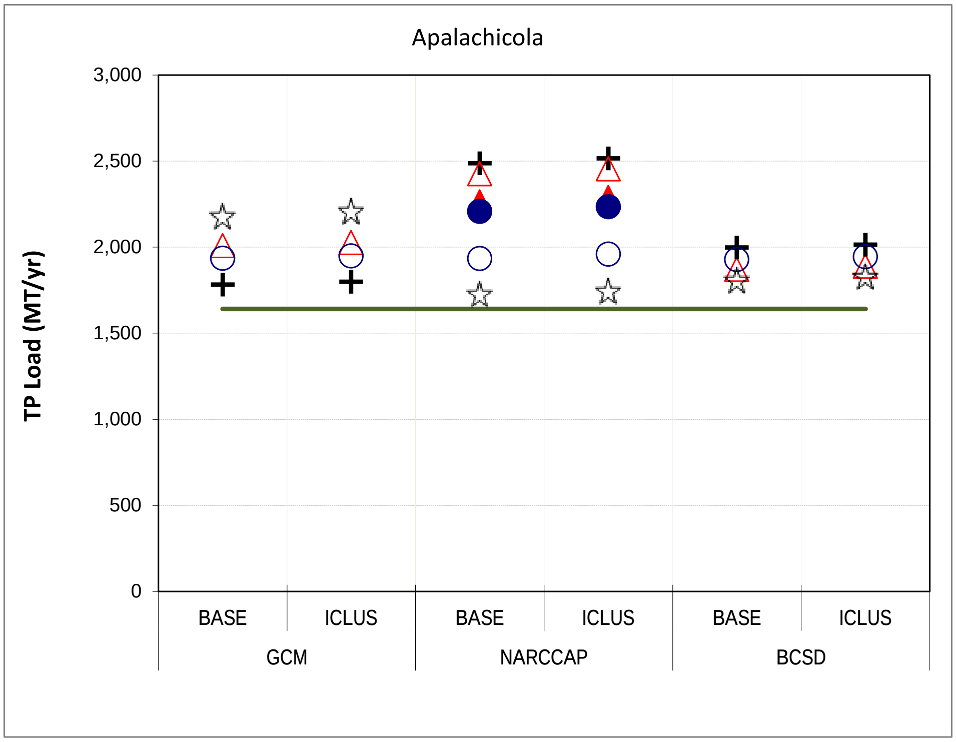


Figure 36. TP Load, Apalachicola River at Mouth (SWAT)

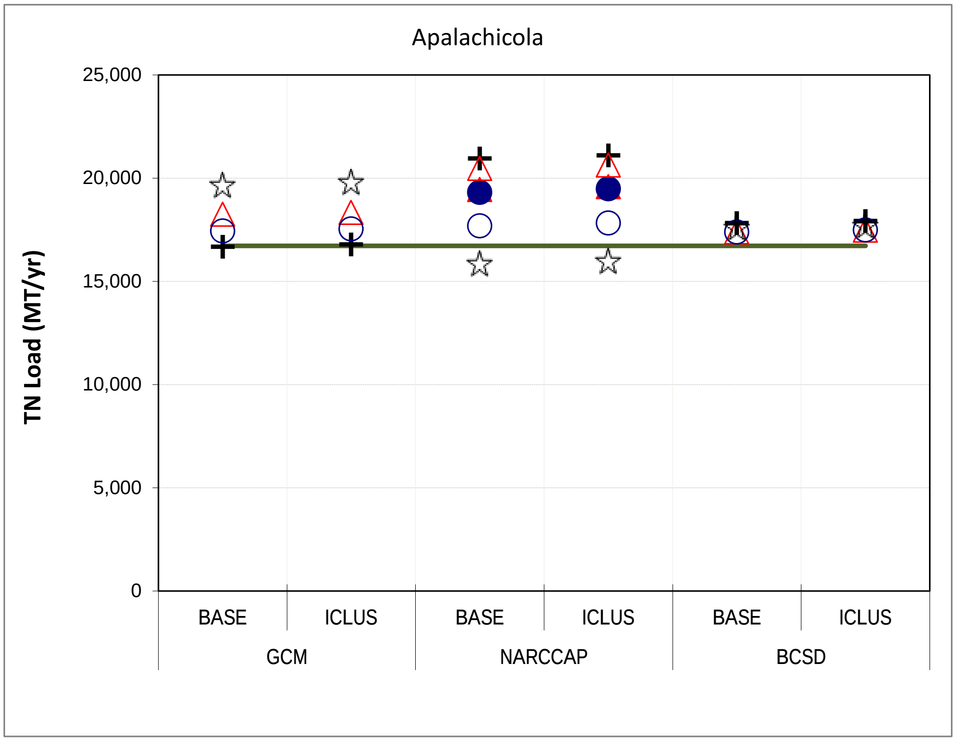


Figure 37. TN Load, Apalachicola River at Mouth (SWAT)

Results at Multiple Stations

Table 2. Summary of Range of Change Relative to Existing Conditions for NARCCAP Dynamically Downscaled Scenarios, Apalachicola-Chattahoochee-Flint Basin SWAT Model

	Results without LU Change				Results with LU Change			
	Min	**Median**	**Mean**	**Max**	**Min**	**Median**	**Mean**	**Max**
Chattahoochee at Atlanta HUC 03130001								
Flow	-4.97%	15.45%	14.11%	23.72%	-4.52%	15.17%	13.98%	23.28%
TSS	5.73%	40.72%	34.45%	49.87%	7.02%	35.31%	31.78%	46.32%
TN	3.07%	11.73%	10.27%	12.43%	5.05%	14.50%	13.06%	15.71%
TP	19.25%	35.55%	33.73%	38.87%	18.55%	37.32%	35.00%	41.04%
Middle Chattahoochee – Lake Harding HUC 03130002								
Flow	-14.55%	14.78%	11.98%	24.84%	-14.15%	14.49%	11.81%	24.58%
TSS	-16.80%	49.05%	44.01%	77.45%	-15.78%	48.57%	43.61%	76.55%
TN	-2.12%	5.91%	5.11%	7.86%	-1.84%	6.30%	5.49%	8.28%
TP	8.33%	26.99%	24.78%	31.90%	7.72%	27.42%	25.08%	32.49%
Middle Chattahoochee – WF George HUC 03130003								
Flow	-18.68%	12.52%	9.37%	24.24%	-18.37%	12.34%	9.28%	23.94%
TSS	-14.99%	59.60%	52.46%	92.84%	-14.31%	59.50%	52.32%	92.49%
TN	-1.24%	9.81%	8.61%	12.95%	-0.98%	10.20%	8.99%	13.35%
TP	8.01%	29.42%	26.82%	36.55%	7.66%	29.68%	27.02%	36.92%
Lower Chattahoochee HUC 03130004								
Flow	-19.63%	11.89%	8.52%	24.74%	-19.35%	11.74%	8.44%	24.48%
TSS	-30.48%	26.43%	21.16%	55.50%	-29.74%	27.07%	21.83%	56.08%
TN	-1.48%	10.33%	9.07%	14.40%	-1.22%	10.68%	9.41%	14.77%
TP	9.76%	29.85%	27.41%	37.97%	9.47%	30.05%	27.57%	38.25%
Peachtree Creek (gage 02336300)								
Flow	-7.54%	17.56%	16.16%	27.69%	-7.00%	16.48%	15.25%	26.39%
TSS	-5.41%	31.74%	27.21%	43.52%	-2.24%	30.58%	26.46%	41.69%
TN	20.49%	32.31%	33.30%	49.14%	25.31%	38.46%	40.42%	59.42%
TP	32.59%	45.86%	48.09%	64.21%	35.39%	51.13%	53.11%	72.85%

	Results without LU Change				Results with LU Change			
	Min	Median	Mean	Max	Min	Median	Mean	Max
Upper Flint HUC 03130005								
Flow	-21.50%	11.78%	8.12%	22.24%	-21.32%	11.44%	7.86%	21.87%
TSS	-20.29%	33.66%	27.97%	50.19%	-20.18%	33.00%	27.52%	49.49%
TN	8.28%	38.60%	32.62%	41.83%	8.72%	39.65%	33.73%	42.82%
TP	19.70%	62.54%	54.68%	66.95%	18.54%	61.28%	53.50%	66.48%
Middle Flint HUC 03130006								
Flow	-23.41%	11.34%	6.51%	23.31%	-23.28%	11.20%	6.41%	23.10%
TSS	-24.04%	29.06%	21.37%	50.70%	-23.84%	28.81%	21.26%	50.79%
TN	1.80%	39.97%	31.73%	45.52%	2.33%	41.64%	32.75%	46.13%
TP	8.52%	50.28%	42.57%	59.55%	8.42%	50.47%	42.62%	59.46%
Kinchafonee-Muckalee HUC 03130007								
Flow	-23.90%	10.90%	5.58%	24.80%	-23.75%	10.99%	5.69%	24.88%
TSS	-27.37%	16.78%	8.52%	29.04%	-27.09%	16.63%	8.42%	28.94%
TN	-2.98%	37.39%	31.24%	48.55%	-1.72%	40.15%	33.23%	50.51%
TP	0.10%	39.40%	34.00%	51.33%	0.79%	41.44%	35.46%	53.06%
Lower Flint HUC 03130008								
Flow	-25.22%	10.59%	4.96%	24.78%	-25.12%	10.50%	4.90%	24.64%
TSS	-26.70%	23.36%	15.83%	46.79%	-26.59%	23.20%	15.78%	46.57%
TN	-1.07%	35.94%	28.43%	45.00%	-0.82%	36.87%	28.99%	45.39%
TP	7.81%	44.98%	38.40%	56.09%	7.71%	45.09%	38.44%	56.16%
Ichawaynochaway HUC 03130009								
Flow	-30.02%	6.79%	0.18%	22.33%	-30.02%	6.79%	0.19%	22.33%
TSS	-28.90%	12.70%	5.06%	31.45%	-28.89%	12.70%	5.07%	31.51%
TN	-3.74%	31.14%	26.85%	52.16%	-3.86%	31.19%	26.84%	52.19%
TP	8.37%	39.07%	34.88%	55.22%	8.28%	39.13%	34.89%	55.27%
Spring HUC 03130010								
Flow	-31.06%	3.87%	-1.58%	22.04%	-31.05%	3.88%	-1.57%	22.05%

	Results without LU Change				Results with LU Change			
	Min	Median	Mean	Max	Min	Median	Mean	Max
TSS	-31.24%	8.99%	3.96%	33.14%	-31.26%	8.98%	3.95%	33.11%
TN	-11.68%	27.23%	19.99%	45.46%	-11.61%	27.33%	20.12%	45.70%
TP	2.54%	35.05%	29.00%	49.26%	2.56%	35.06%	29.07%	49.43%
Apalachicola HUC 03130011								
Flow	-27.10%	7.37%	3.66%	23.75%	-26.92%	7.28%	3.62%	23.58%
TSS	-47.39%	26.84%	15.07%	46.35%	-47.25%	26.16%	14.63%	46.09%
TN	-4.82%	15.84%	13.38%	25.28%	-4.56%	16.26%	13.74%	25.62%
TP	5.56%	36.17%	32.51%	51.52%	5.41%	36.25%	32.58%	51.62%
Chipola HUC 03130012								
Flow	-45.73%	-8.86%	-8.70%	22.72%	-45.71%	-8.84%	-8.69%	22.73%
TSS	-46.43%	1.58%	7.65%	62.14%	-46.52%	1.58%	7.63%	62.12%
TN	-20.99%	13.68%	16.33%	63.05%	-21.17%	13.55%	16.34%	63.38%
TP	-6.27%	28.47%	29.53%	72.78%	-6.62%	28.23%	29.46%	73.13%

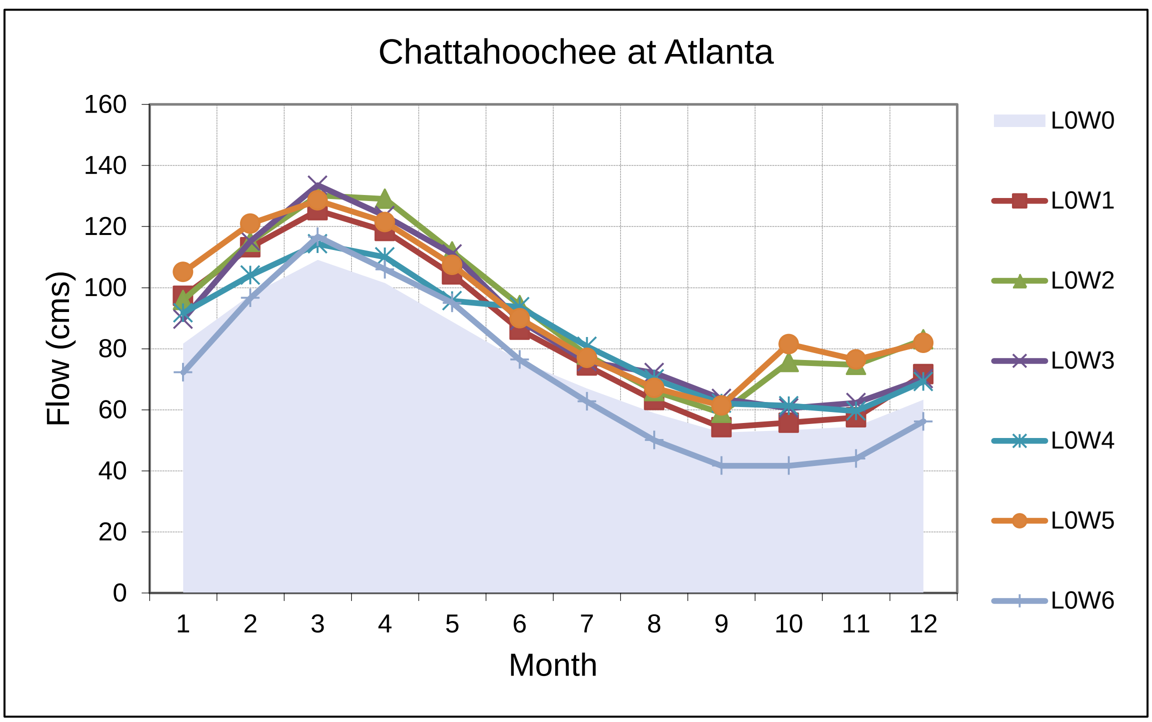


Figure 38. Monthly Average Flows, Chattahoochee River at Atlanta (SWAT)

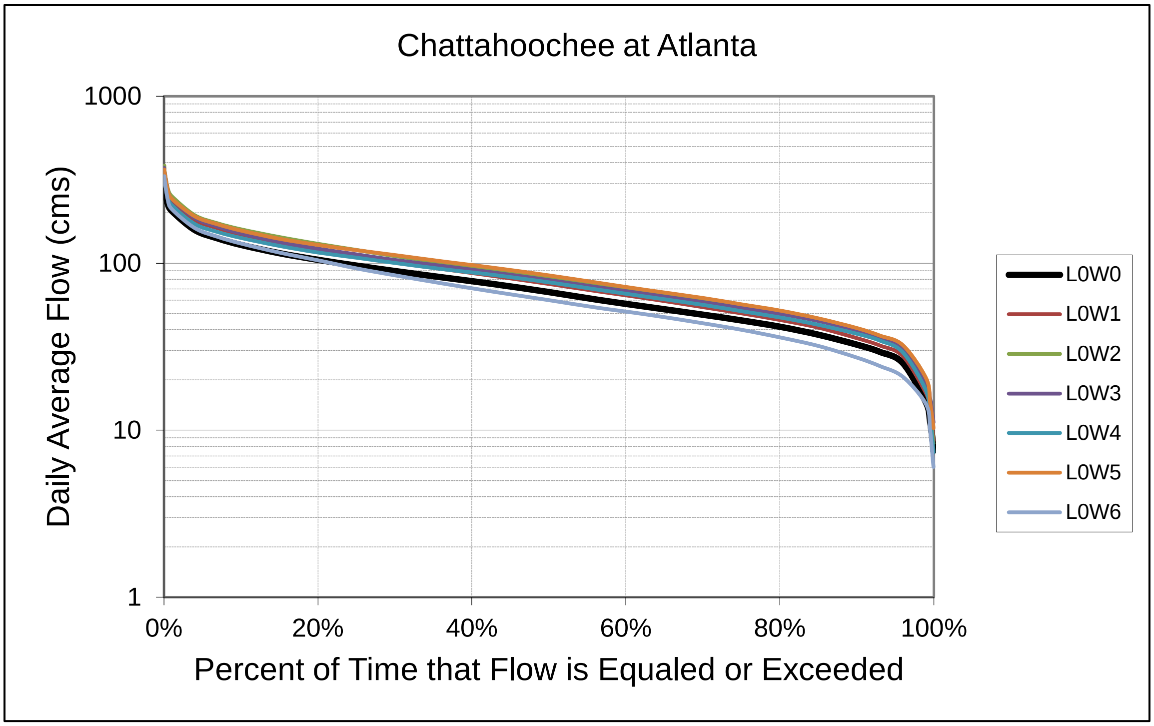


Figure 39. Flow Duration, Chattahoochee River at Atlanta (SWAT)

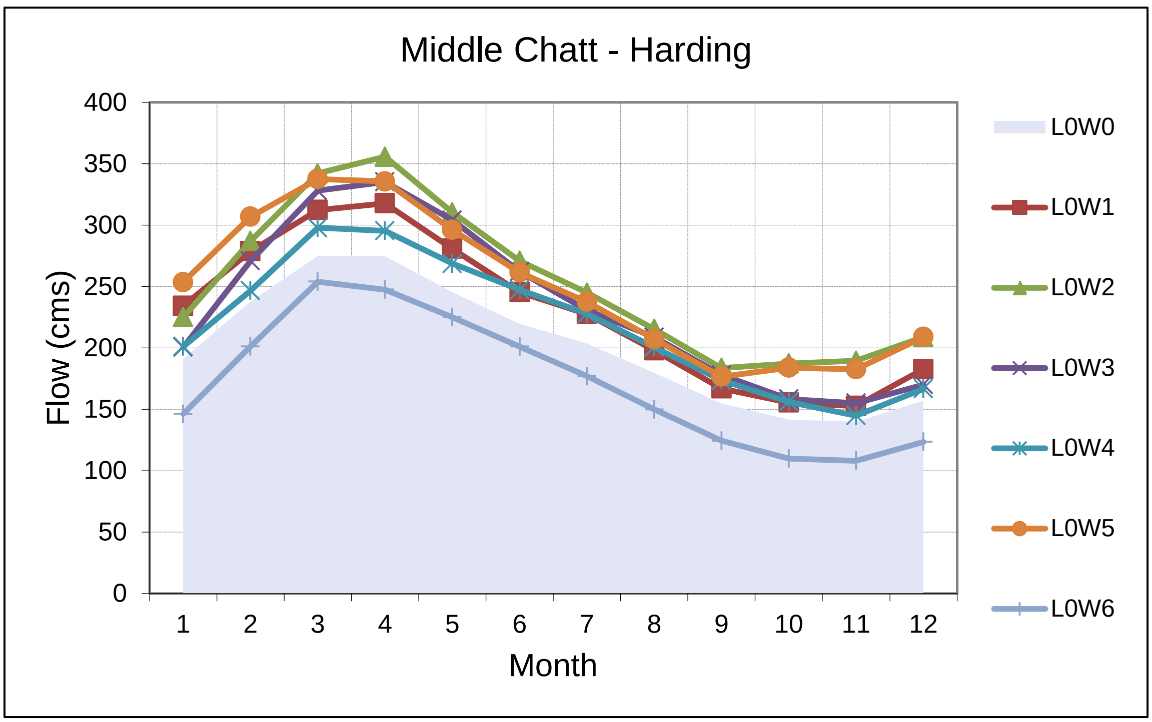


Figure 40. Monthly Average Flows, Middle Chattahoochee River at Harding (SWAT)

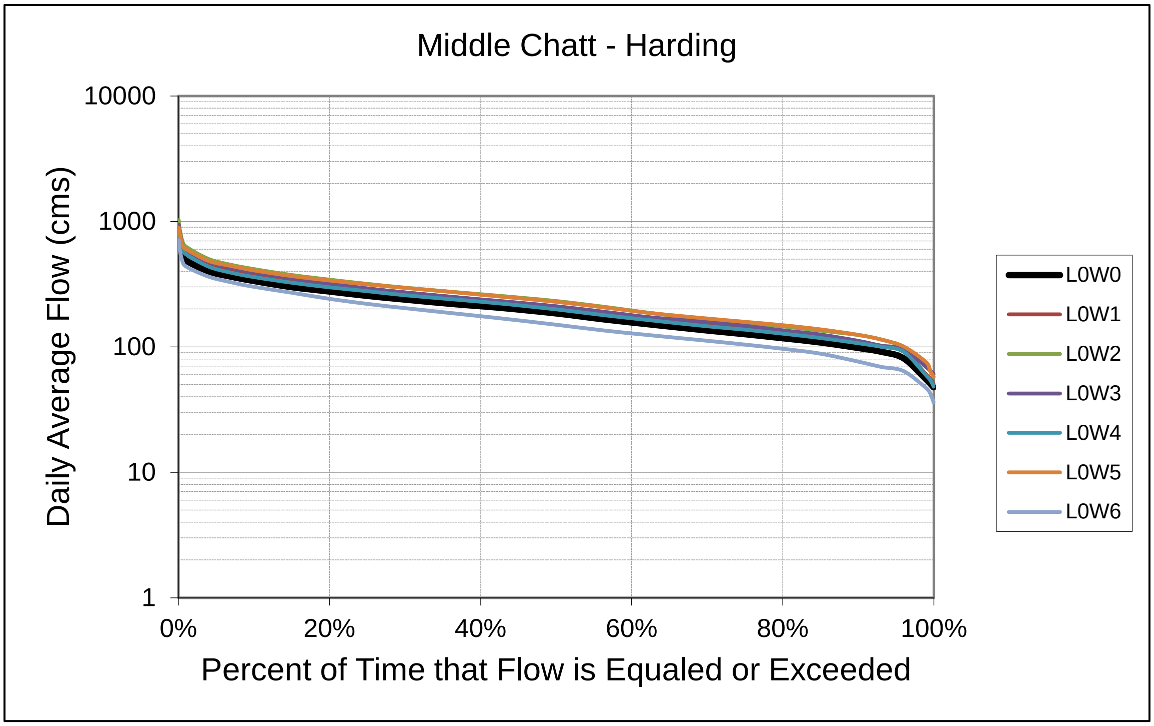


Figure 41. Flow Duration, Middle Chattahoochee River at Harding (SWAT)

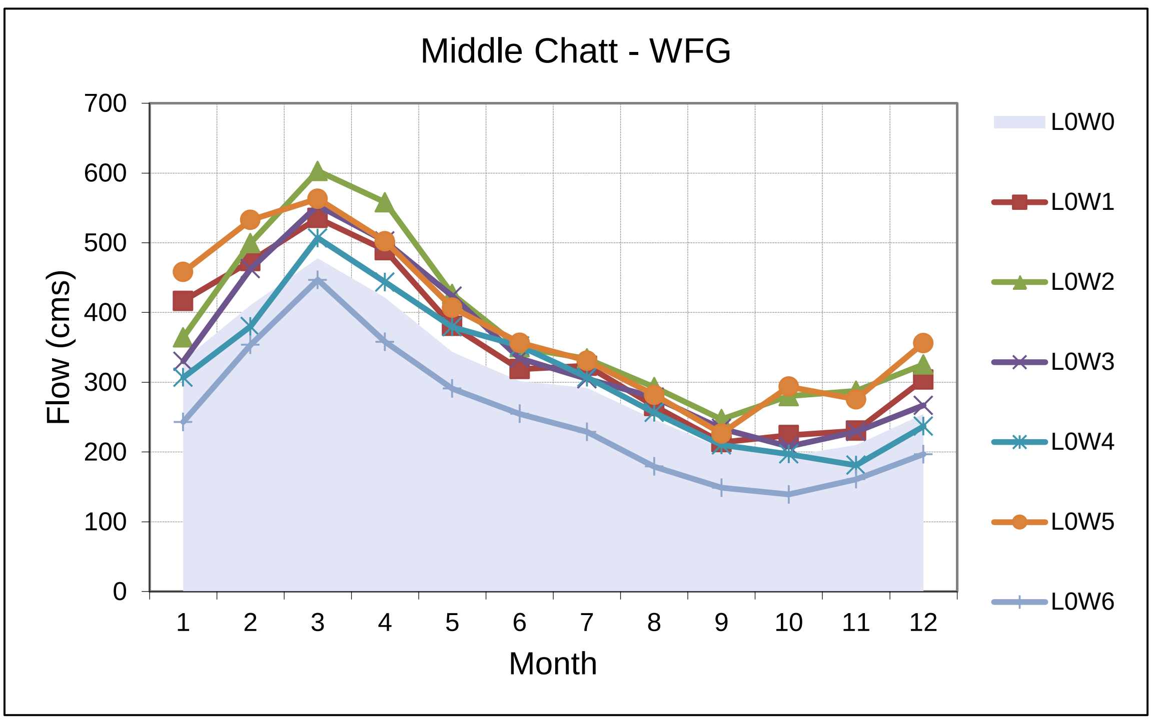


Figure 42. Monthly Average Flows, Middle Chattahoochee River at WF Geroge (SWAT)

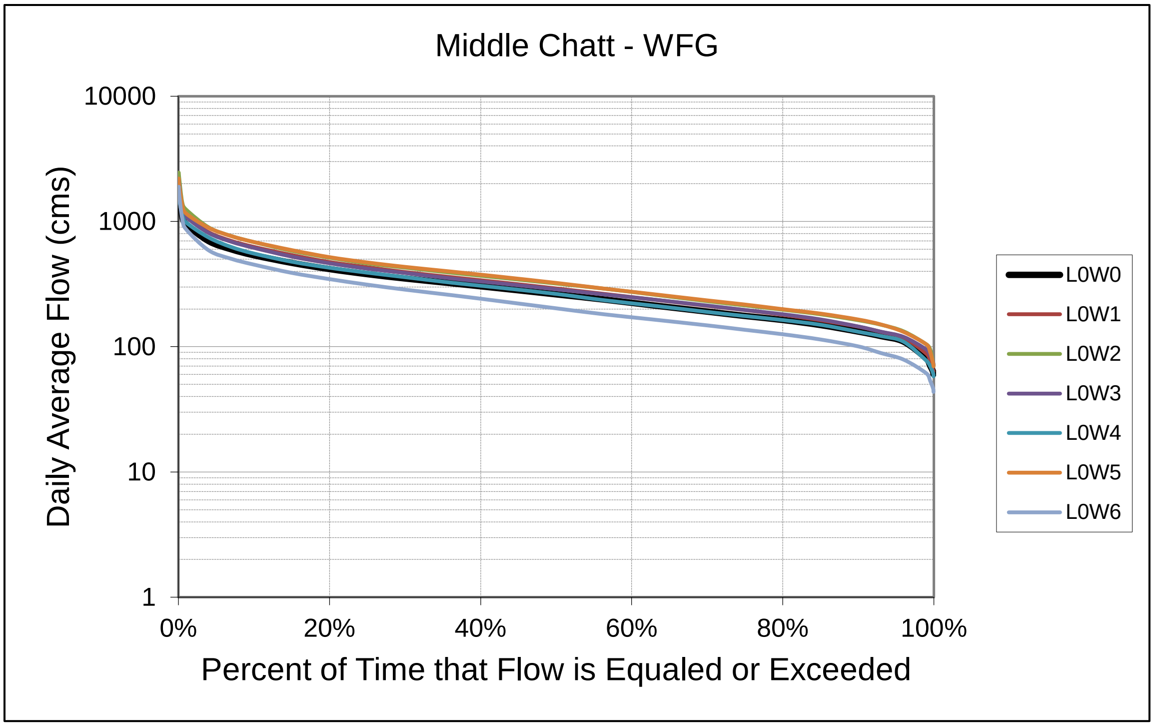


Figure 43. Flow Duration, Middle Chattahoochee River at WF George (SWAT)

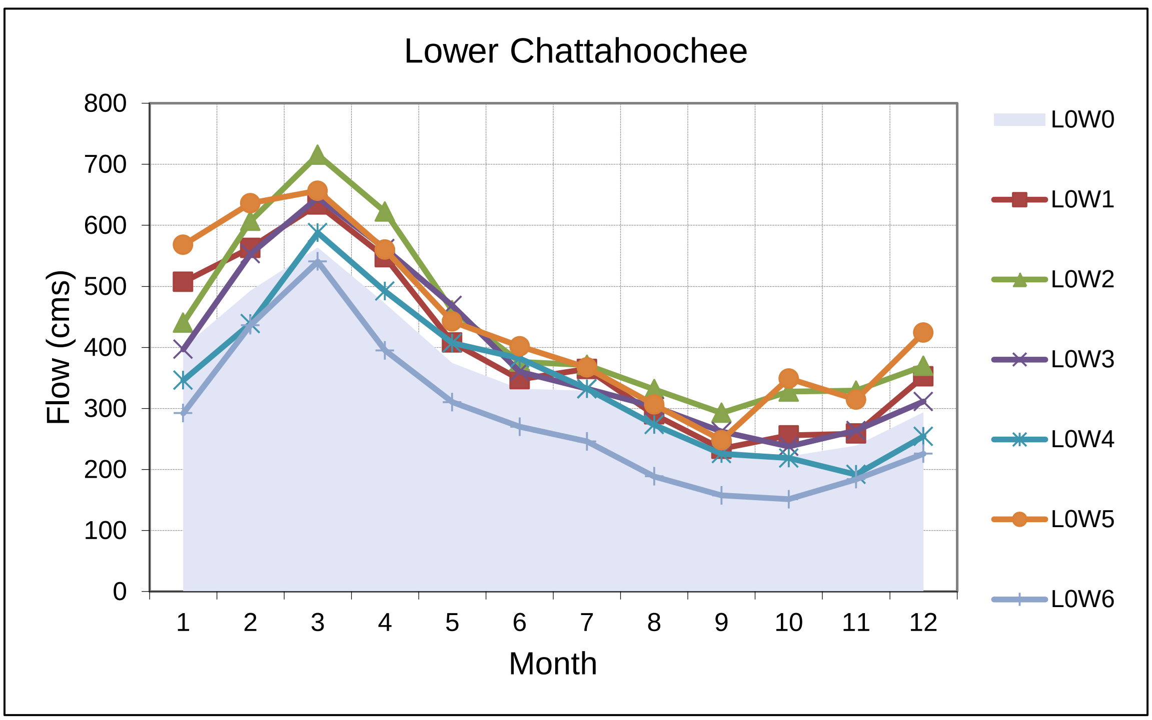


Figure 44. Monthly Average Flows, Lower Chattahoochee River (SWAT)

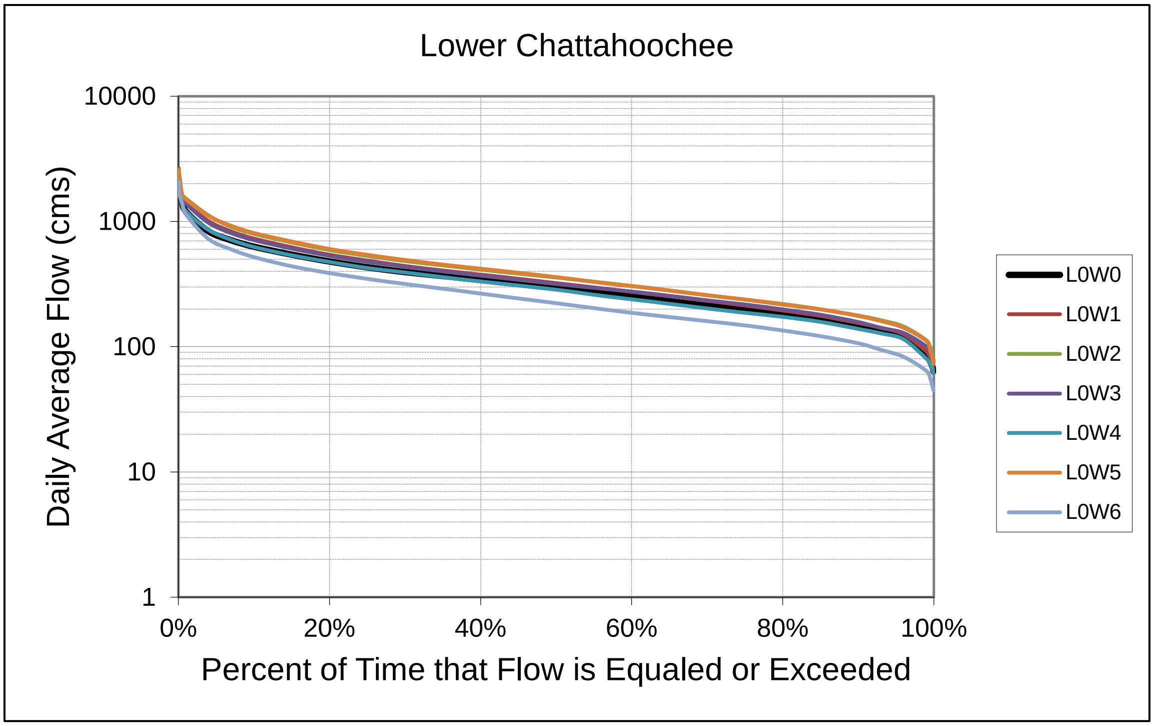


Figure 45. Flow Duration, Lower Chattahoochee River (SWAT)

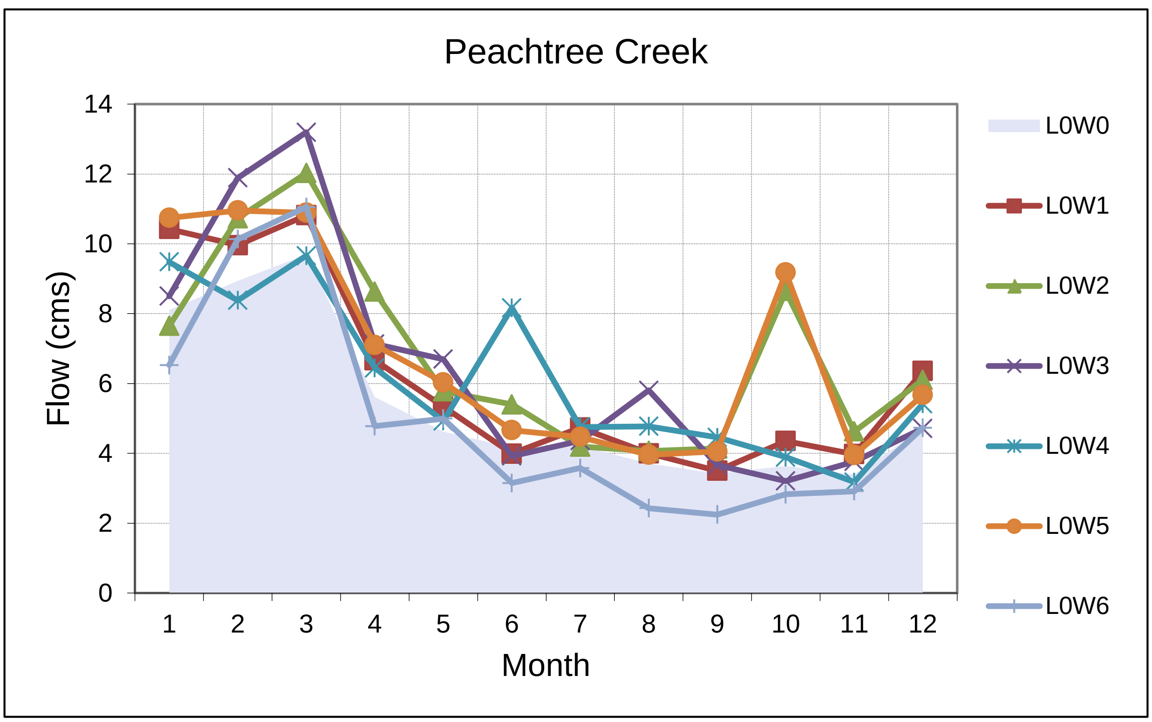


Figure 46. Monthly Average Flows, Peachtree Creek (SWAT)

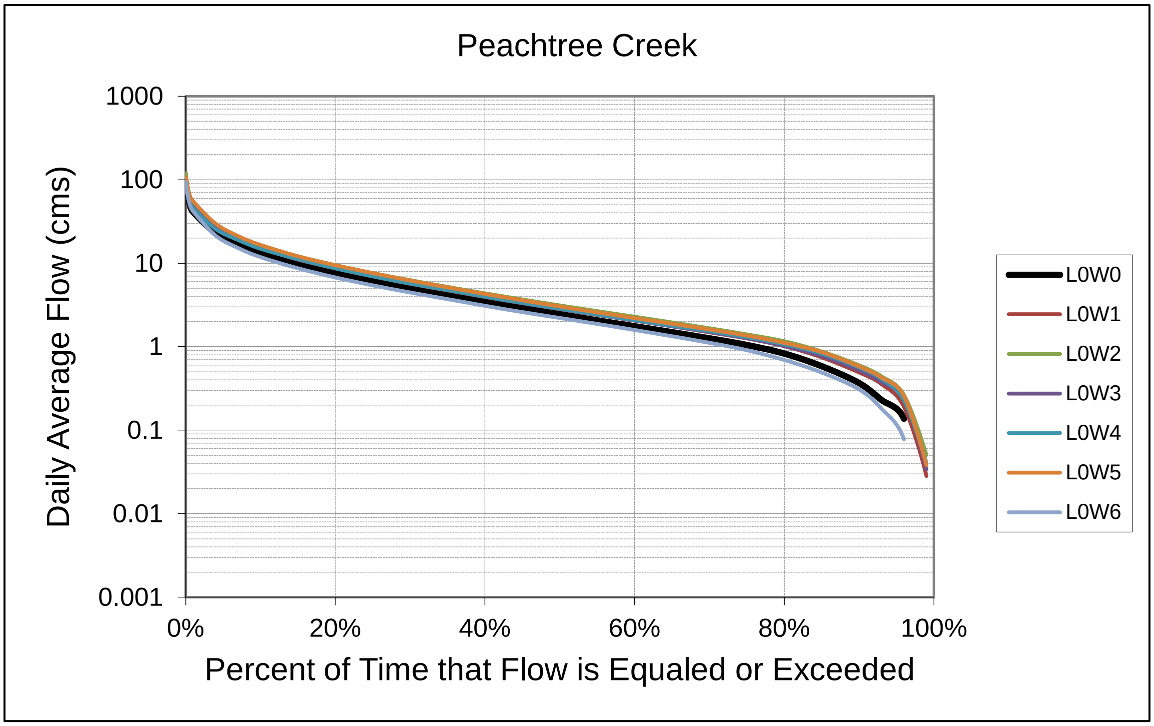


Figure 47. Flow Duration, Peachtree Creek (SWAT)

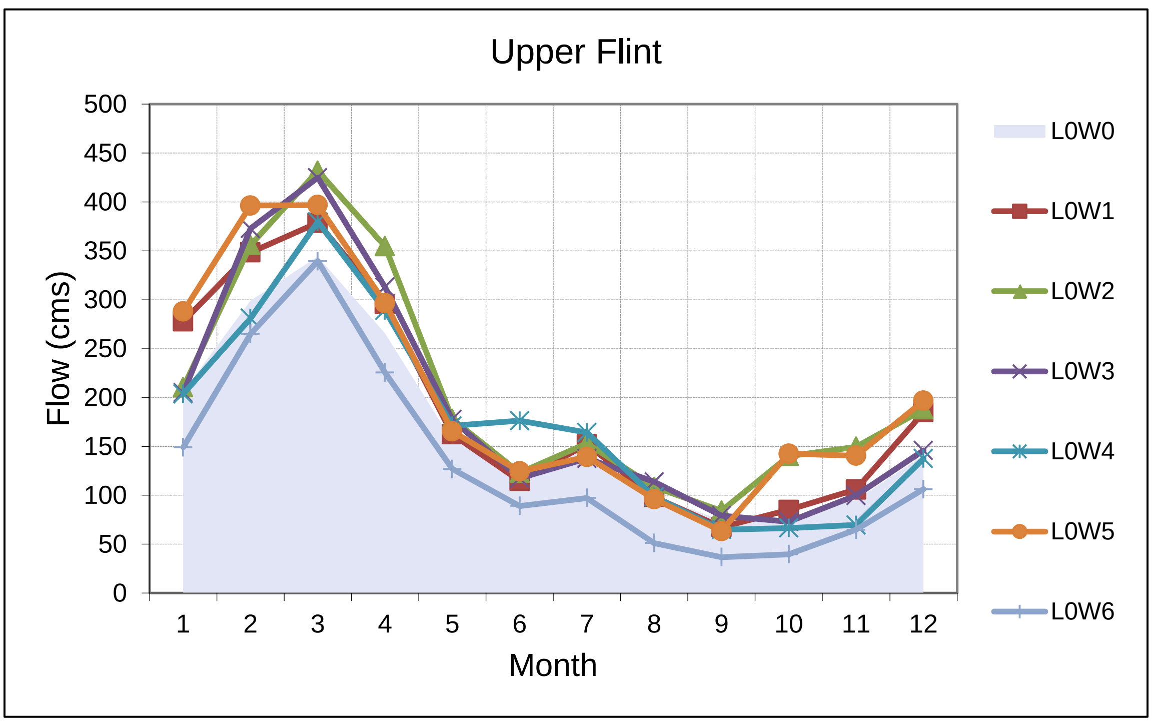


Figure 48. Monthly Average Flows, Upper Flint River (SWAT)

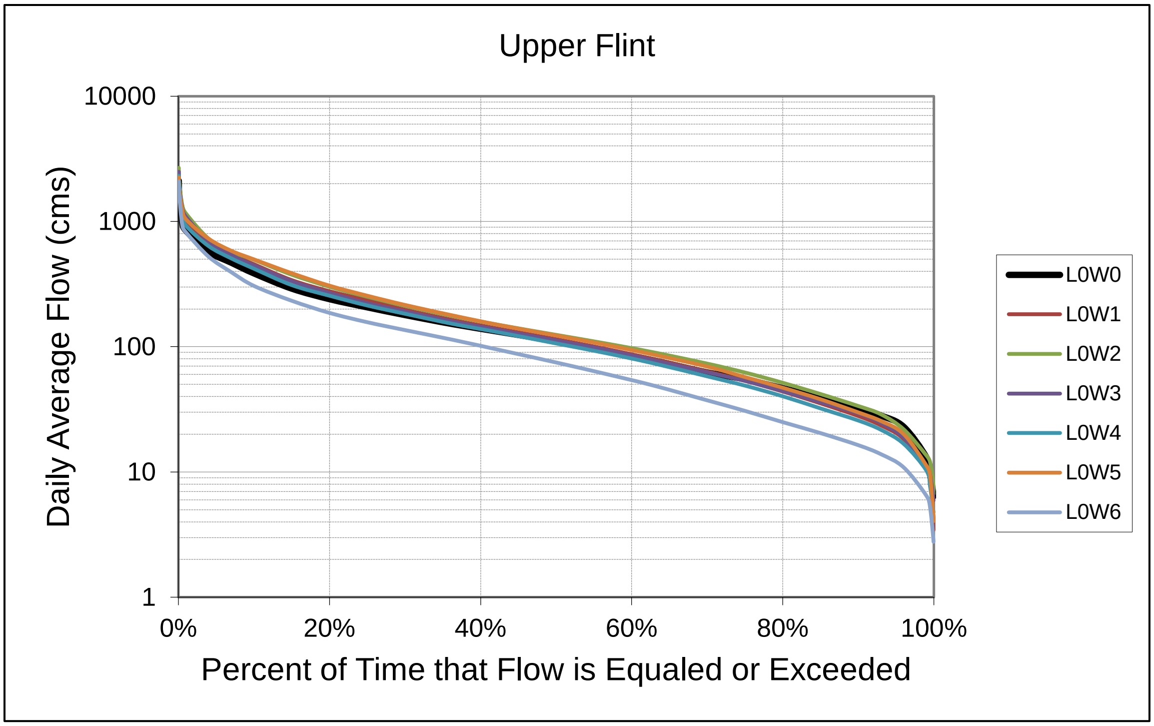


Figure 49. Flow Duration, Upper Flint River (SWAT)

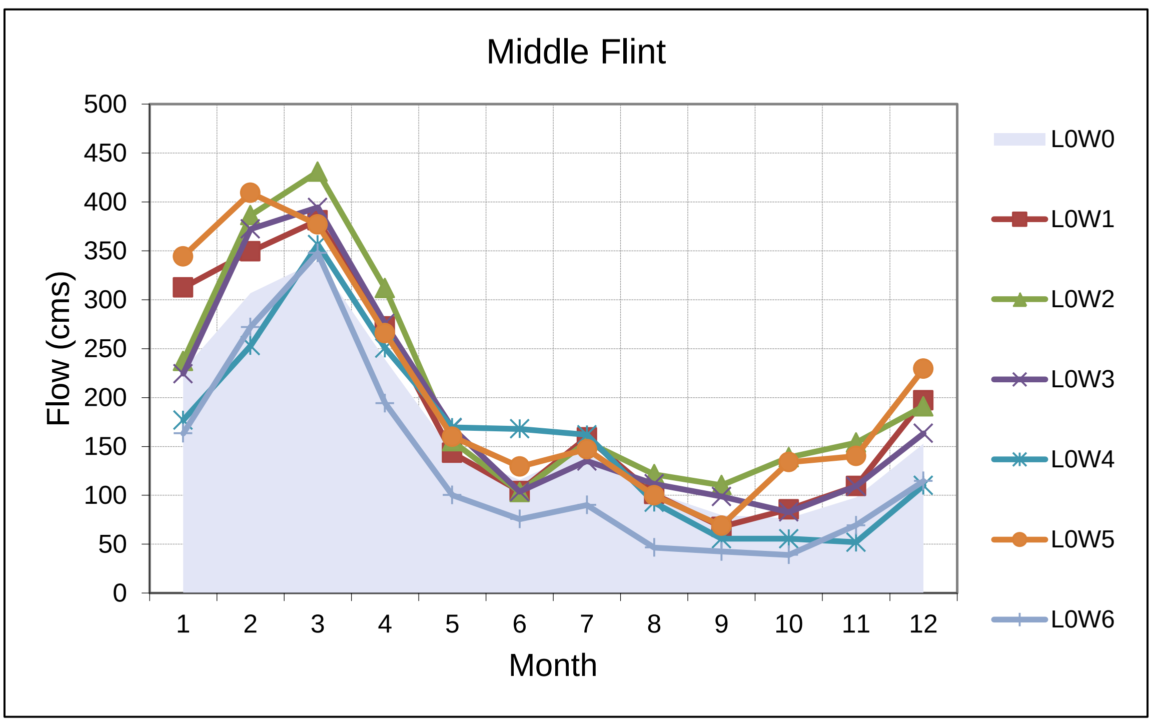


Figure 50. Monthly Average Flows, Middle Flint River (SWAT)

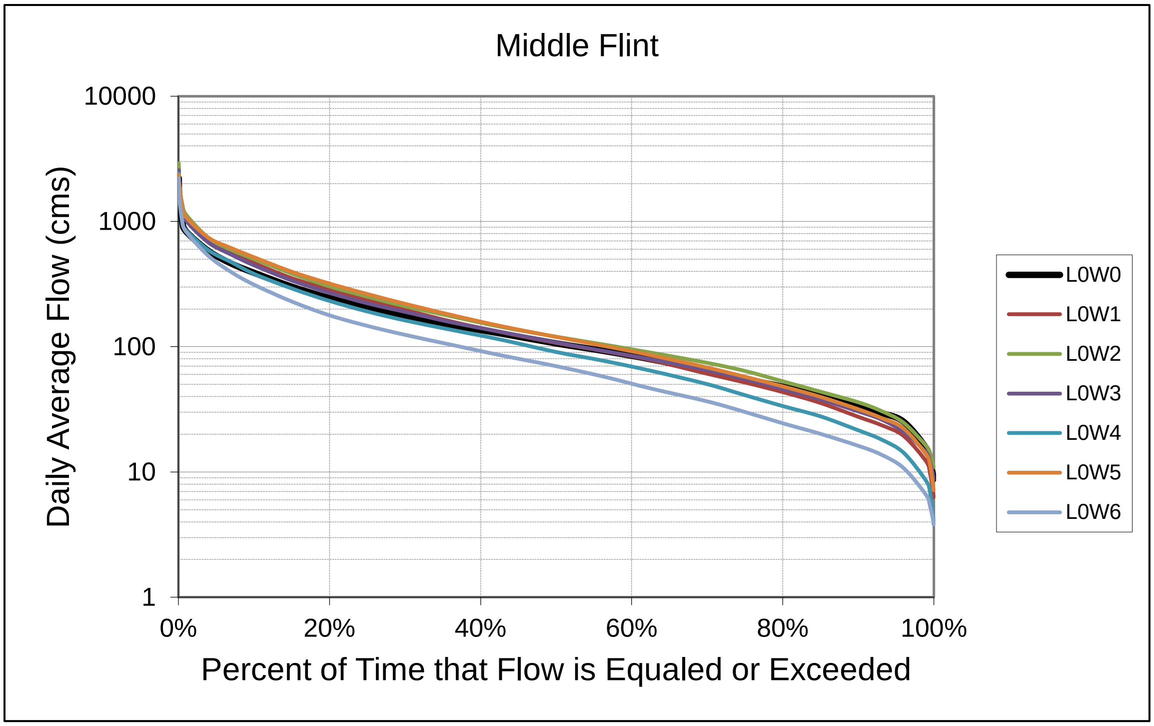


Figure 51. Flow Duration, Middle Flint River (SWAT)

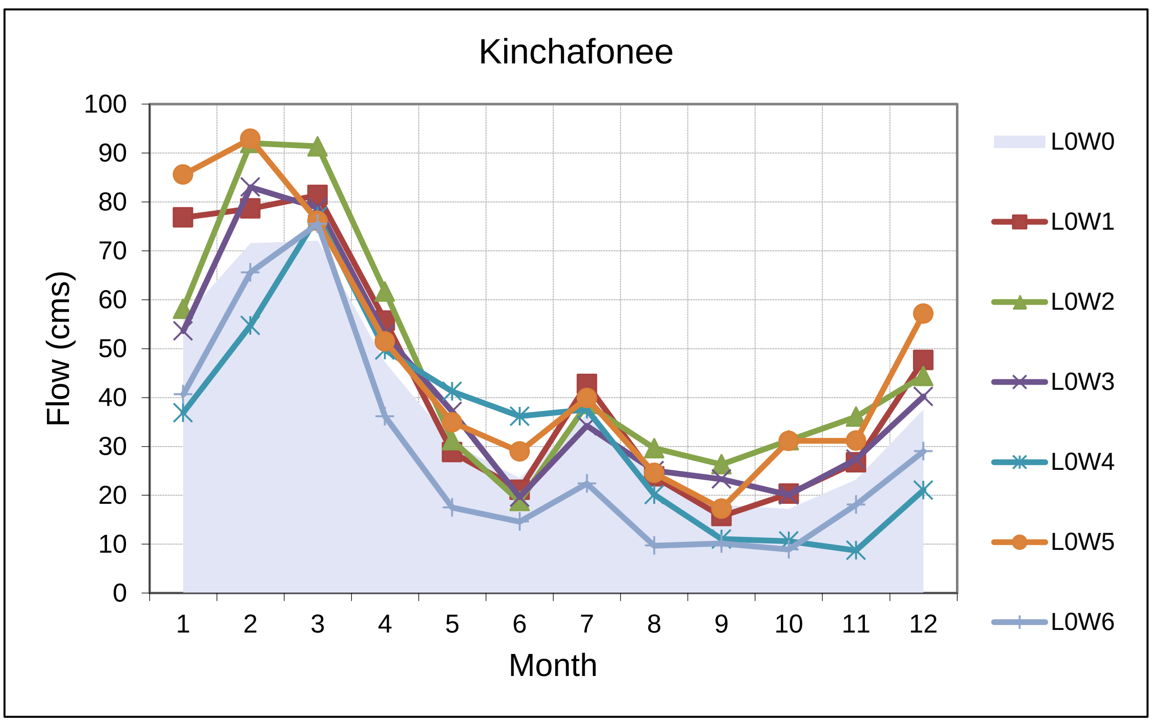


Figure 52. Monthly Average Flows, Kinchafonee River (SWAT)

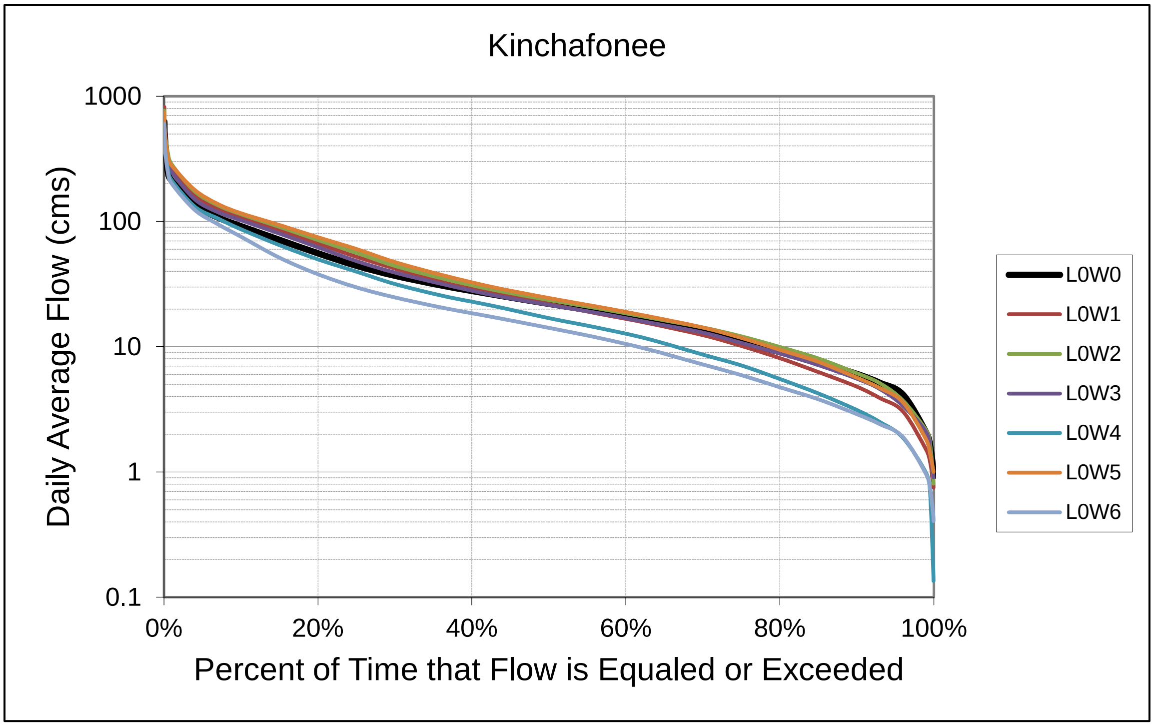


Figure 53. Flow Duration, Kinchafonee River (SWAT)

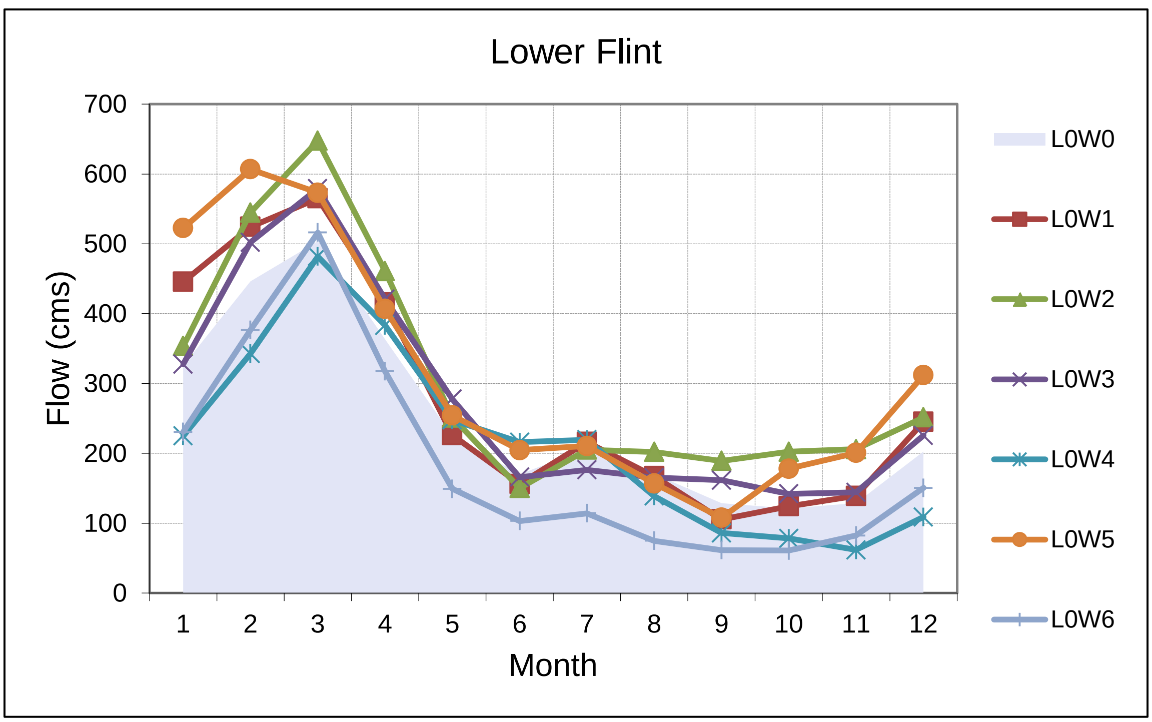


Figure 54. Monthly Average Flows, Lower Flint River (SWAT)

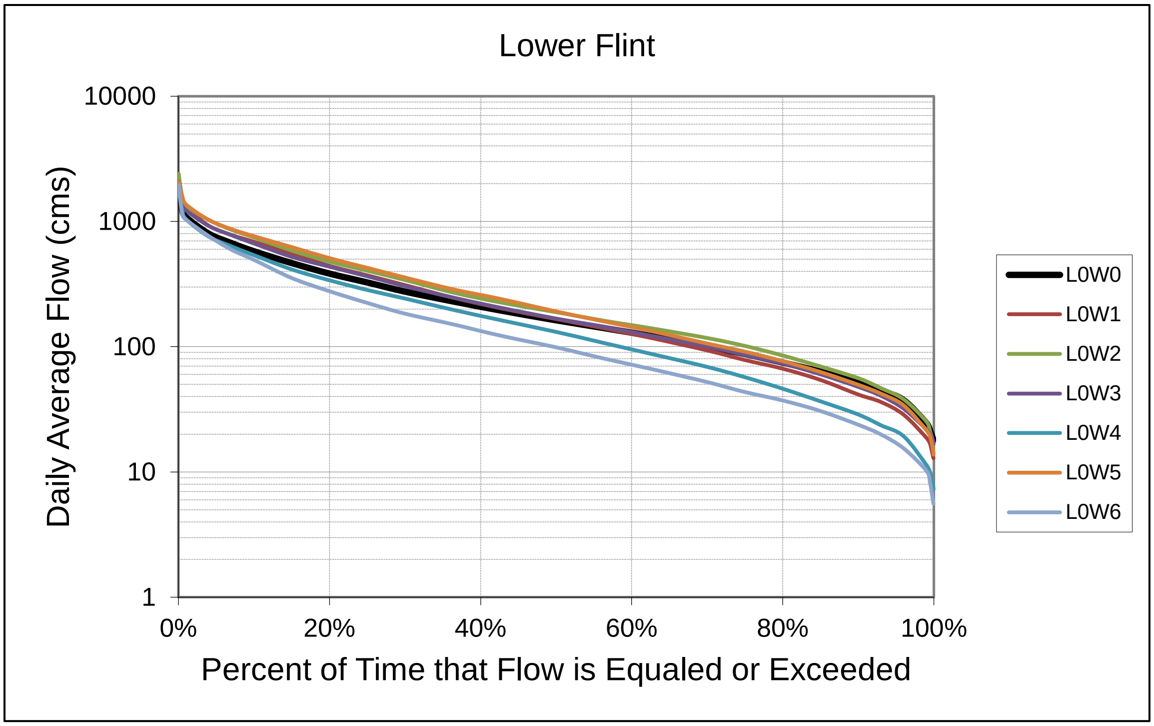


Figure 55. Flow Duration, Lower Flint River (SWAT)

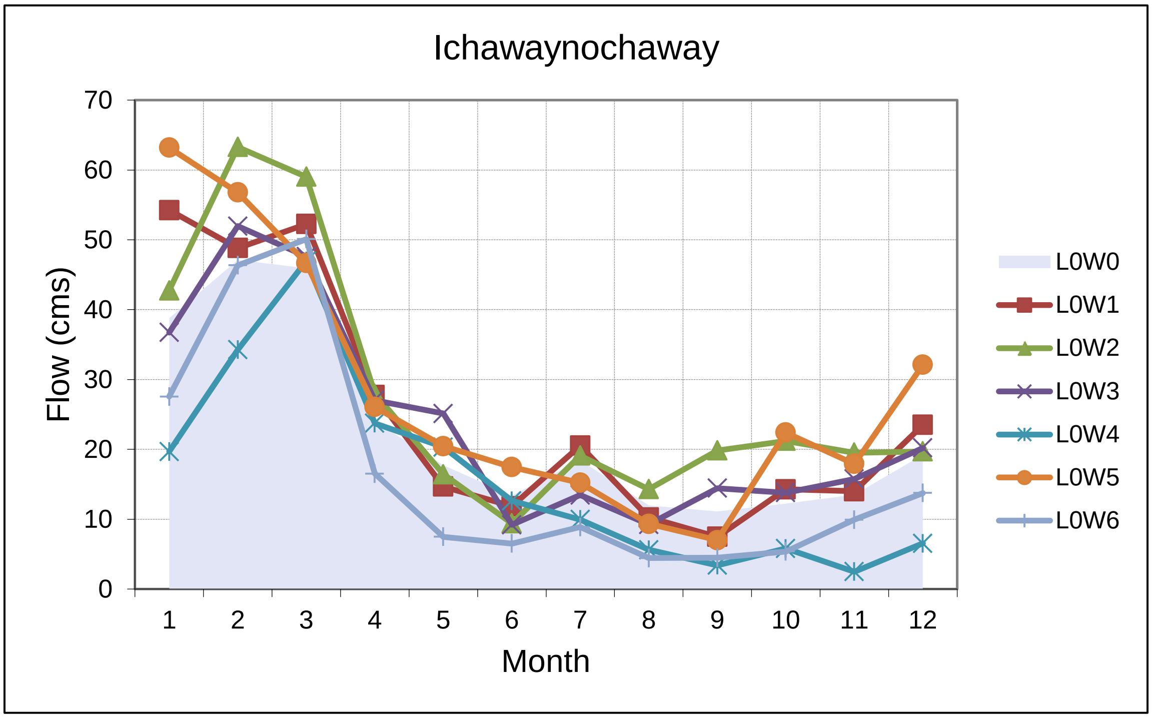


Figure 56. Monthly Average Flows, Ichawaynochaway Creek (SWAT)

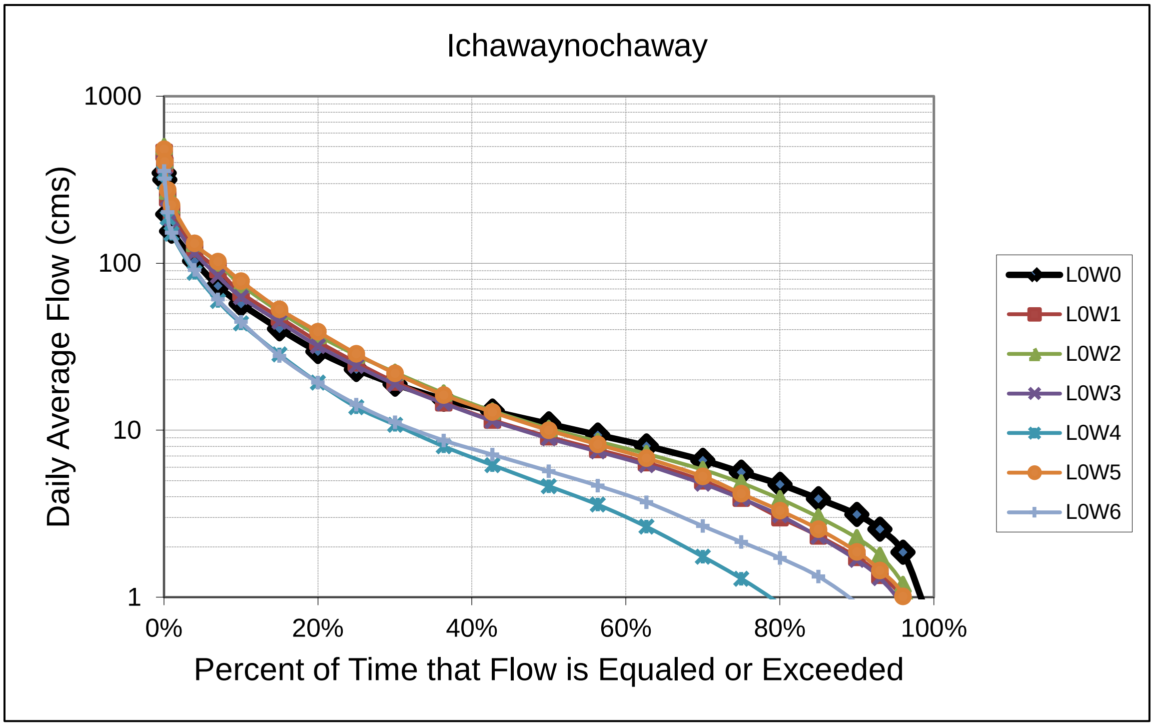


Figure 57. Flow Duration, Ichawaynochaway Creek (SWAT)

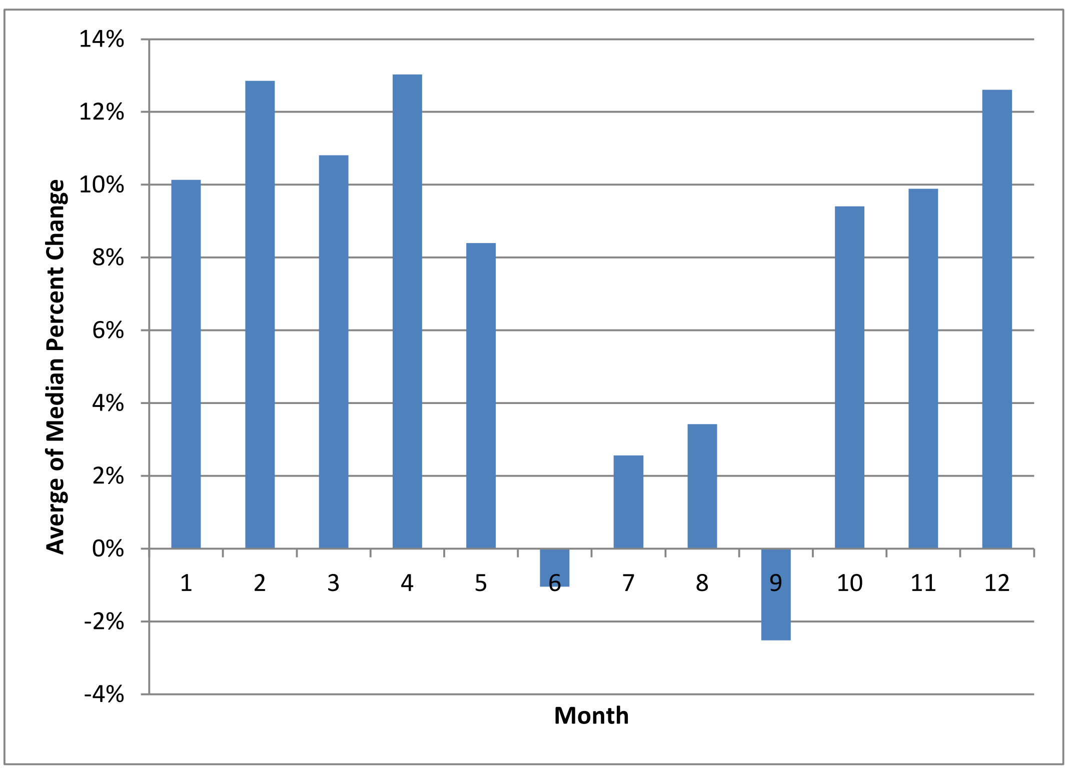


Figure 58. Average of Median Percent Change in Flow; NARCCAP Scenarios W1-W6 at all Stations, Apalachicola-Chattahoochee-Flint Basin (SWAT)

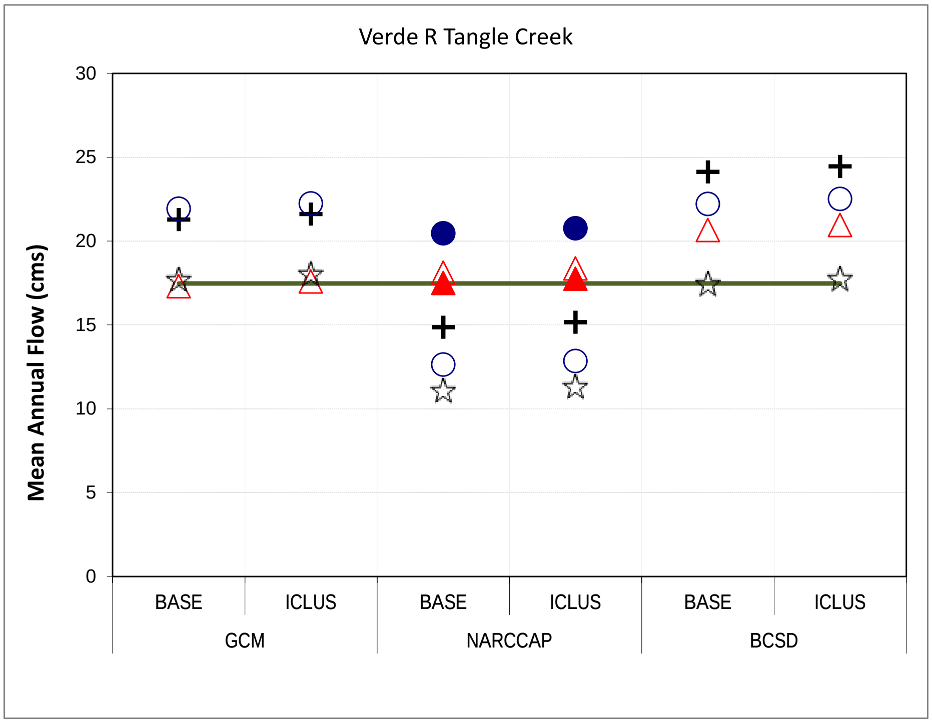


Figure 59. Mean Annual Flow, Verde River below Tangle Creek (HSPF)

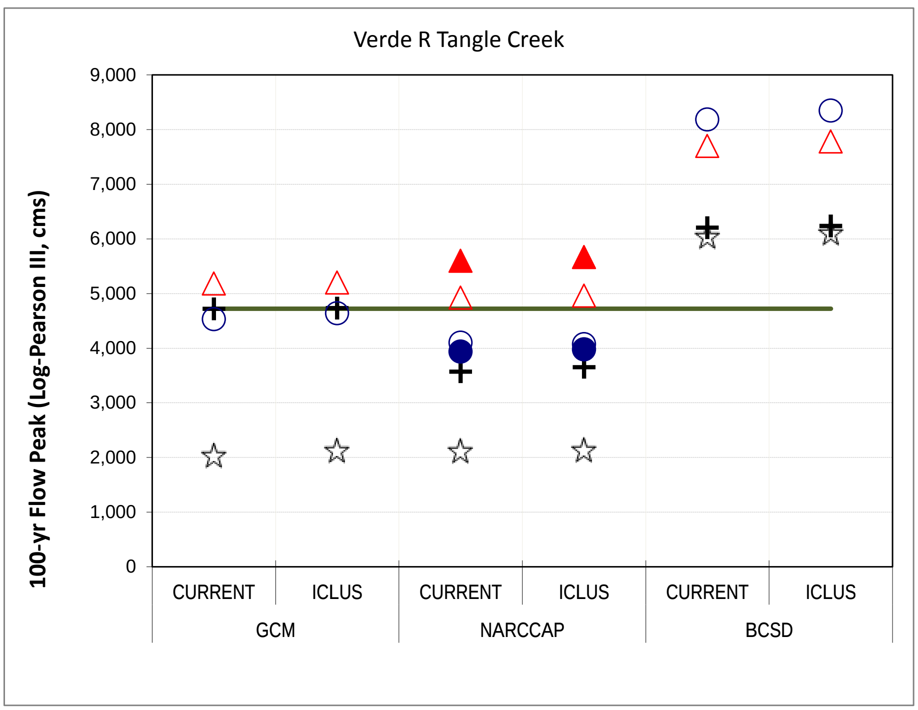


Figure 60. 100-yr Flow Peak, Verde River below Tangle Creek (HSPF)

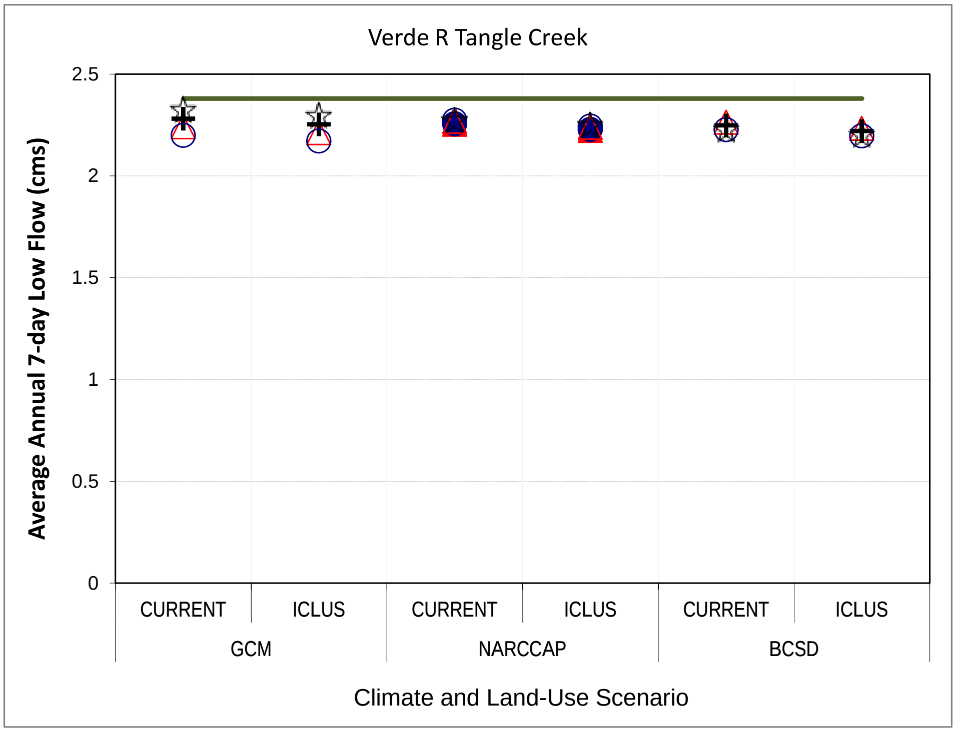


Figure 61. Average Annual 7-day Low Flow, Verde River below Tangle Creek (HSPF)

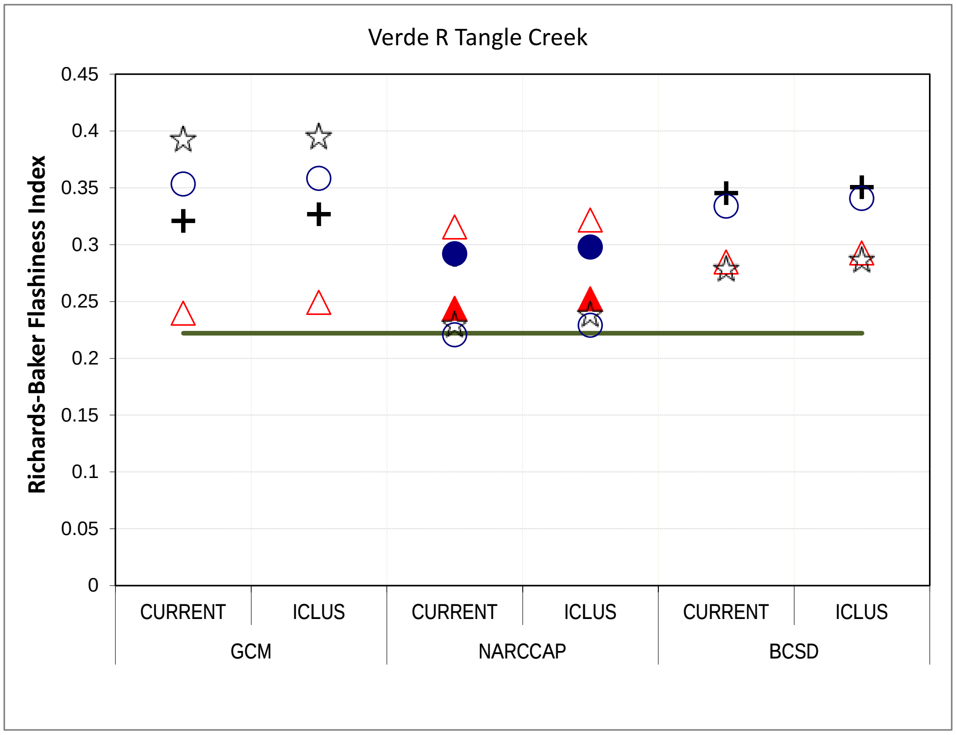


Figure 62. Richards-Baker Flashiness Index, Verde River below Tangle Creek (HSPF)

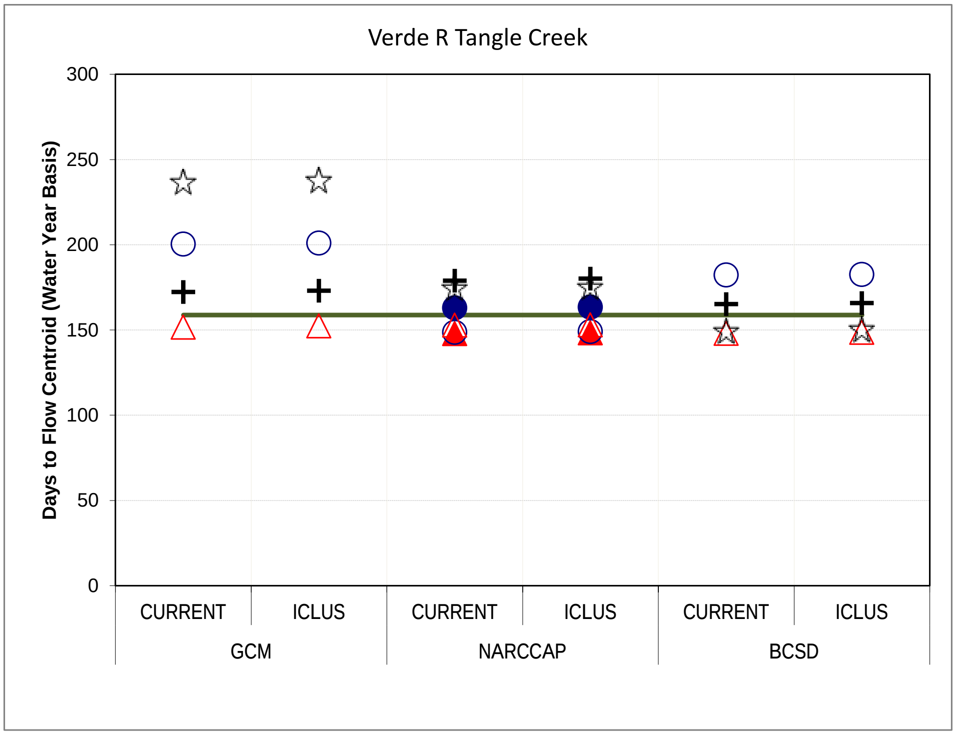


Figure 63. Days to flow Centroid, Verde River below Tangle Creek (HSPF)

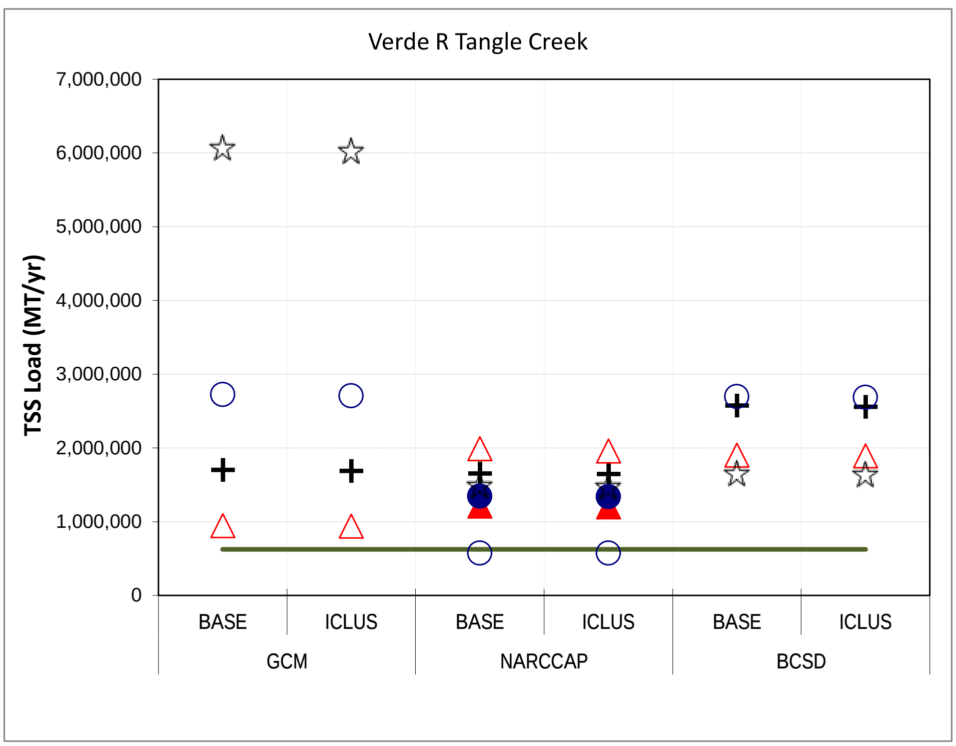


Figure 64. TSS Load, Verde River below Tangle Creek (HSPF)

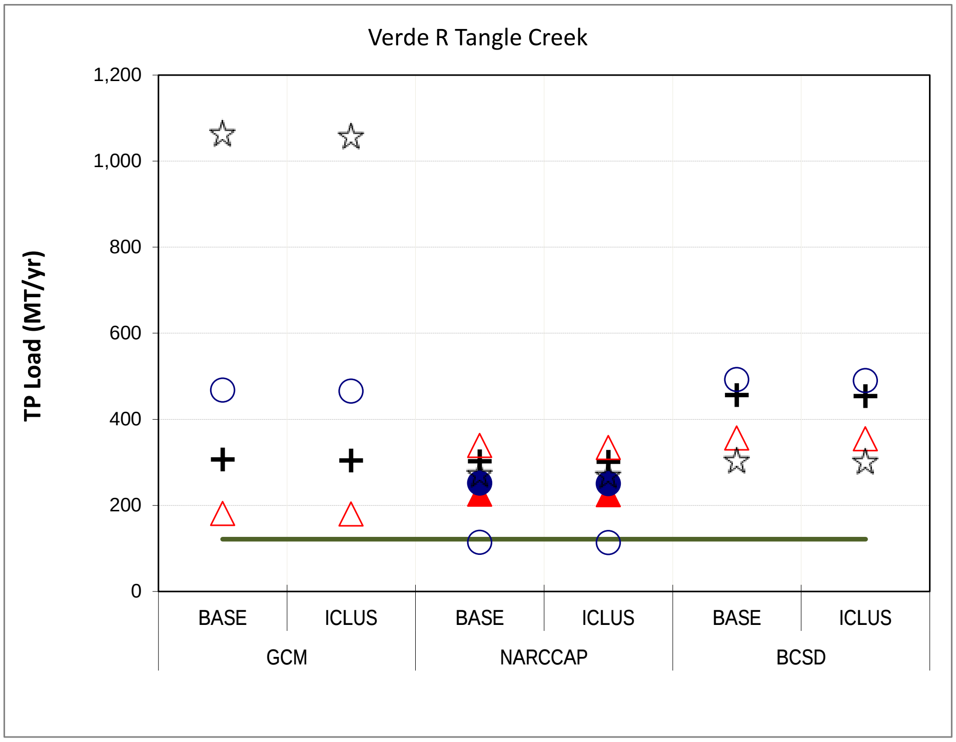


Figure 65. TP Load, Verde River below Tangle Creek (HSPF)

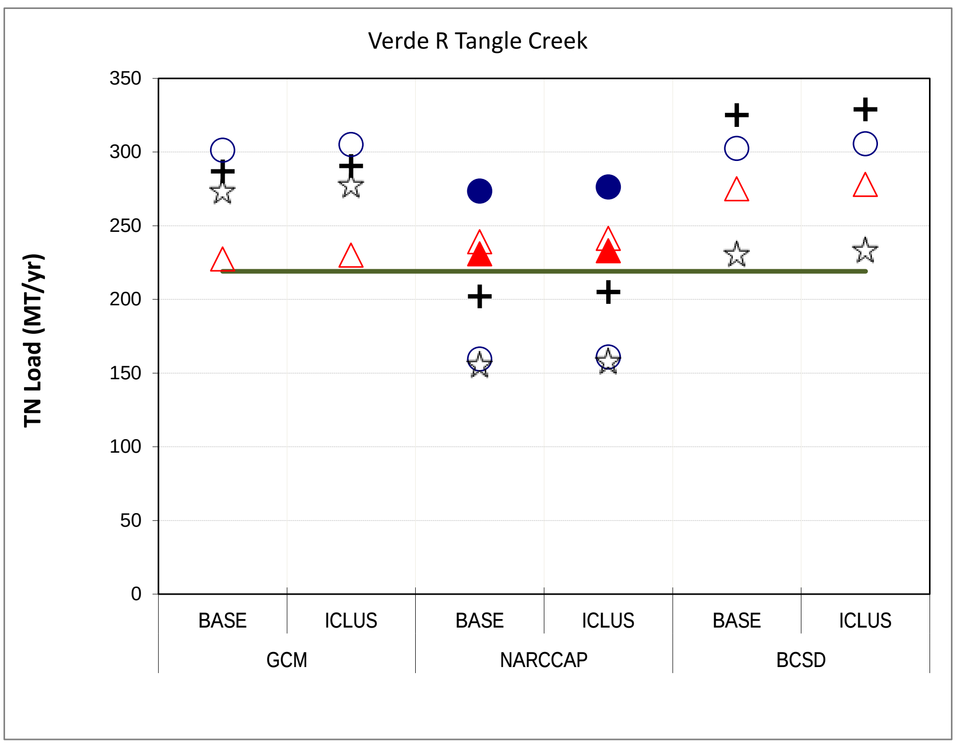


Figure 66. TN Load, Verde River below Tangle Creek (HSPF)

Results at Multiple Stations

Table 3. Summary of Range of Change Relative to Existing Conditions for NARCCAP Dynamically Downscaled Scenarios, Verde-Salt-San Pedro Basins (HSPF)

	Results without LU Change				Results with LU Change			
	Min	Median	Mean	Max	Min	Median	Mean	Max
Verde River nr Paulden (gage 09503700)								
Flow	-19.22%	13.20%	4.35%	21.91%	-19.77%	11.36%	2.87%	20.01%
TSS	-46.64%	279.87%	325.08%	921.15%	-46.06%	264.17%	308.86%	890.16%
TN	-24.46%	17.02%	6.57%	24.87%	-26.72%	15.54%	6.06%	23.92%
TP	-35.96%	215.57%	248.32%	702.29%	-35.51%	210.93%	244.42%	702.04%
Verde River nr Clarkdale (gage 09504000)								
Flow	-28.25%	-3.86%	-6.28%	16.58%	-28.44%	-3.93%	-6.39%	16.14%
TSS	-54.11%	117.39%	154.81%	443.83%	-53.86%	113.80%	152.75%	439.42%
TN	-31.46%	2.79%	-1.53%	26.70%	-32.01%	2.92%	-1.43%	26.45%
TP	-50.03%	82.97%	115.72%	349.54%	-49.86%	81.08%	115.16%	348.35%
Oak Creek at Sedona (gage 09504430)								
Flow	-38.15%	-19.65%	-18.62%	14.90%	-37.84%	-19.53%	-18.48%	14.93%
TSS	-61.24%	-22.59%	11.14%	164.74%	-61.06%	-21.83%	11.97%	167.07%
TN	-35.08%	-11.82%	-10.35%	33.10%	-35.14%	-11.77%	-10.23%	33.35%
TP	-56.30%	-21.87%	8.85%	146.41%	-56.16%	-21.22%	9.58%	148.54%
Oak Creek at Cornville (gage 09504500)								
Flow	-37.33%	-18.41%	-17.40%	15.51%	-36.86%	-18.22%	-17.19%	15.51%
TSS	-61.08%	-23.51%	11.98%	164.82%	-60.86%	-22.75%	12.66%	166.85%
TN	-28.75%	-9.49%	-8.30%	26.81%	-28.89%	-9.43%	-8.15%	27.18%
TP	-52.97%	-22.59%	7.87%	135.13%	-52.89%	-21.97%	8.55%	137.46%
West Clear Creek at Camp Verde (gage 09505800)								
Flow	-43.20%	-18.41%	-16.72%	10.66%	-43.12%	-18.37%	-16.70%	10.65%
TSS	-44.58%	73.76%	63.12%	161.47%	-44.63%	73.64%	62.98%	161.31%
TN	-43.49%	-16.25%	-13.93%	18.10%	-43.41%	-16.20%	-13.90%	18.13%
TP	-41.20%	58.84%	51.02%	135.70%	-41.22%	58.66%	50.85%	135.47%

	Results without LU Change				Results with LU Change			
	Min	Median	Mean	Max	Min	Median	Mean	Max
Verde River at Camp Verde (gage 09506000)								
Flow	-39.47%	-10.71%	-12.65%	17.18%	-38.81%	-10.51%	-12.50%	16.91%
TSS	-37.08%	97.58%	107.27%	280.92%	-36.84%	96.97%	105.74%	275.63%
TN	-33.23%	-3.95%	-6.35%	26.09%	-32.66%	-3.65%	-6.14%	26.13%
TP	-34.75%	79.98%	87.03%	222.59%	-34.52%	79.70%	86.04%	218.97%
East Verde River nr Childs (gage 09507980)								
Flow	-34.22%	-9.91%	-9.06%	11.98%	-34.20%	-9.91%	-9.06%	11.98%
TSS	60.12%	202.10%	219.40%	478.93%	60.11%	202.07%	219.38%	478.93%
TN	-19.93%	-7.00%	-5.28%	16.29%	-19.91%	-7.00%	-5.27%	16.29%
TP	54.92%	189.14%	205.77%	451.05%	54.92%	189.12%	205.75%	451.05%
Verde River below Tangle Creek (gage 09508500)								
Flow	-36.24%	-7.44%	-9.71%	17.07%	-35.83%	-7.36%	-9.65%	16.89%
TSS	-8.29%	127.73%	120.35%	217.62%	-8.01%	127.01%	119.53%	214.23%
TN	-28.54%	-1.20%	-4.04%	24.81%	-28.17%	-1.01%	-3.91%	24.85%
TP	-6.45%	116.26%	106.51%	178.54%	-6.17%	115.84%	106.05%	176.27%
Salt River nr Roosevelt (gage 09498500)								
Flow	-39.83%	-27.83%	-20.06%	25.58%	-39.80%	-27.83%	-20.06%	25.51%
TSS	-0.96%	142.09%	930.13%	4839.81 %	-1.01%	141.98%	929.57%	4836.98 %
TN	-33.90%	-20.75%	-10.78%	35.77%	-33.89%	-20.79%	-10.82%	35.70%
TP	4.11%	145.45%	962.01%	5023.14 %	4.05%	145.33%	961.41%	5020.12 %
Salt River Outlet								
Flow	-38.23%	-22.22%	-16.28%	24.37%	-38.21%	-22.23%	-16.29%	24.33%
TSS	14.29%	218.77%	865.40%	4239.97 %	14.27%	218.68%	865.08%	4238.43 %
TN	-34.80%	-18.63%	-10.07%	31.43%	-34.79%	-18.66%	-10.09%	31.39%
TP	15.63%	225.65%	899.44%	4422.64 %	15.61%	225.54%	899.09%	4420.97 %
San Pedro River nr Redington (gage 09472000)								

	Results without LU Change				Results with LU Change			
	Min	Median	Mean	Max	Min	Median	Mean	Max
Flow	-33.37%	-1.82%	19.76%	87.15%	-33.37%	-1.83%	19.76%	87.13%
TSS	-63.44%	447.10%	647.37%	1888.65 %	-63.43%	447.01%	647.19%	1888.12 %
TN	-53.16%	295.85%	429.27%	1268.83 %	-53.14%	295.76%	429.10%	1268.31 %
TP	-28.80%	-13.76%	5.12%	56.11%	-28.79%	-13.77%	5.12%	56.10%
Aravaipa Crk nr Mammoth (gage 09473000)								
Flow	-1.83%	5.17%	12.10%	36.57%	-1.99%	4.52%	11.57%	36.08%
TSS	-0.17%	6.59%	69.35%	338.59%	-0.22%	6.70%	69.41%	338.36%
TN	-0.15%	20.28%	171.24%	814.29%	-0.42%	20.85%	170.75%	809.21%
TP	-0.30%	-0.06%	0.87%	3.28%	-0.35%	-0.09%	0.84%	3.29%
San Pedro River Outlet								
Flow	-15.97%	2.69%	18.78%	70.25%	-16.15%	2.32%	18.36%	69.40%
TSS	-9.43%	72.40%	176.29%	672.54%	-9.46%	72.38%	176.10%	671.55%
TN	-19.88%	129.84%	312.06%	1179.94 %	-19.86%	129.61%	310.88%	1174.21 %
TP	-2.32%	-0.88%	1.66%	8.51%	-2.41%	-0.96%	1.62%	8.51%

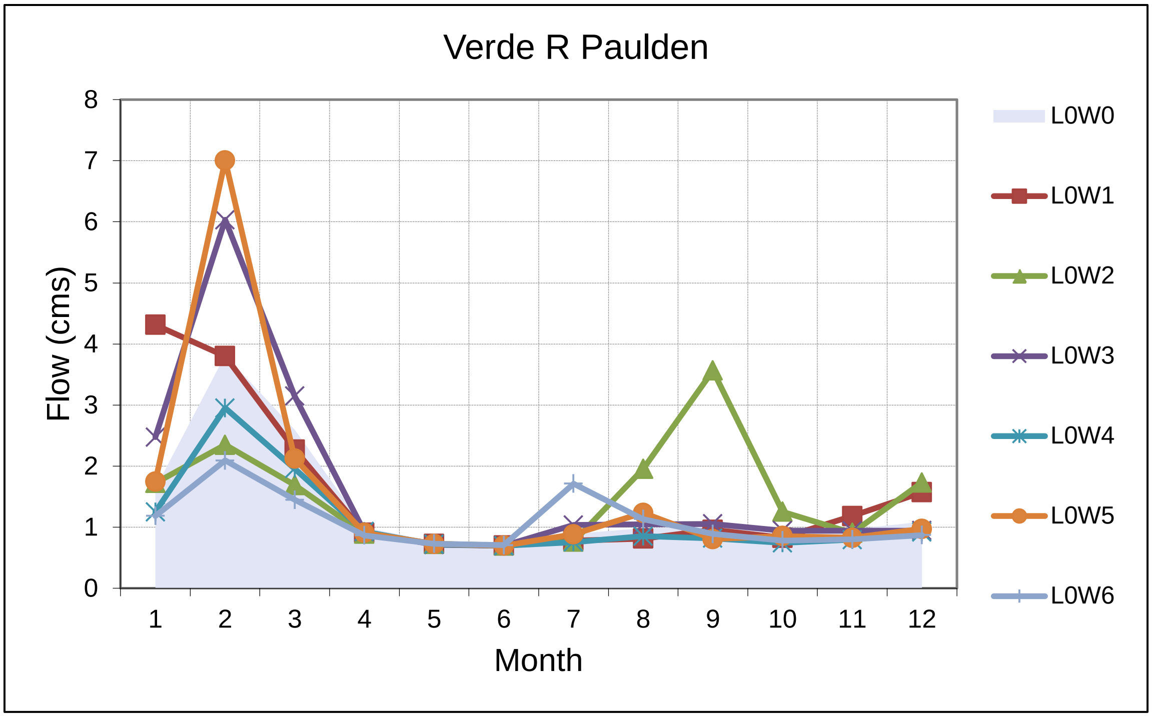


Figure 67. Monthly Average Flows, Verde River near Paulden (HSPF)

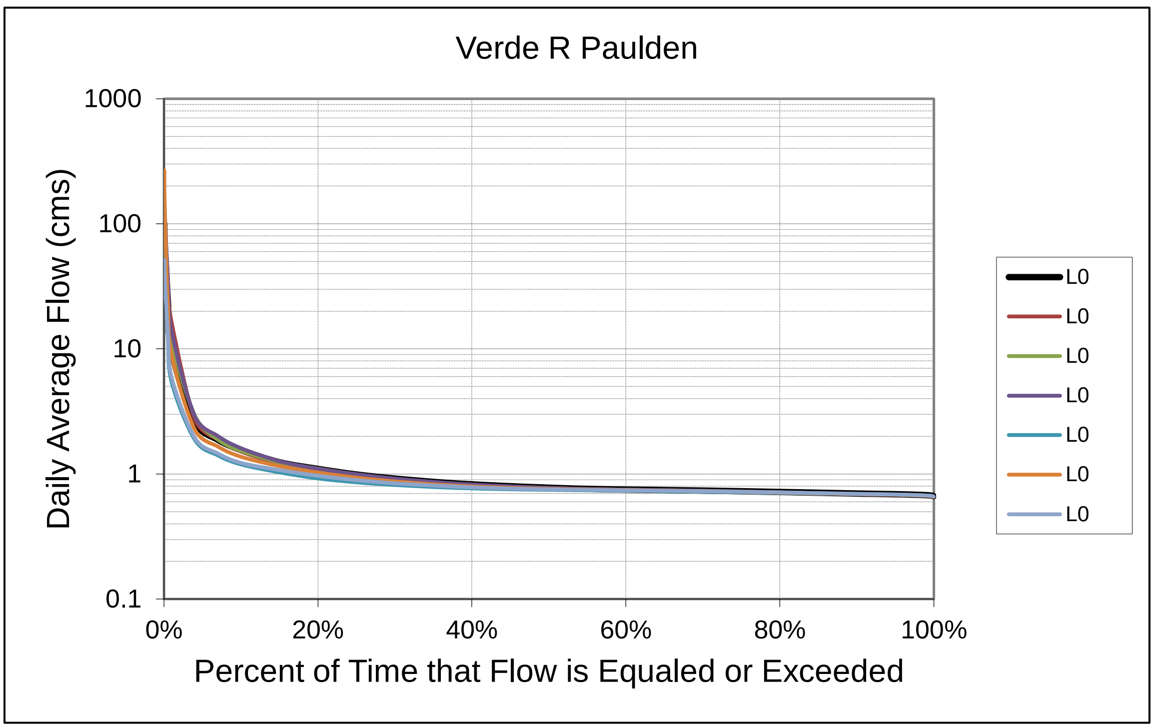


Figure 68. Flow Duration, Verde River near Paulden (HSPF)

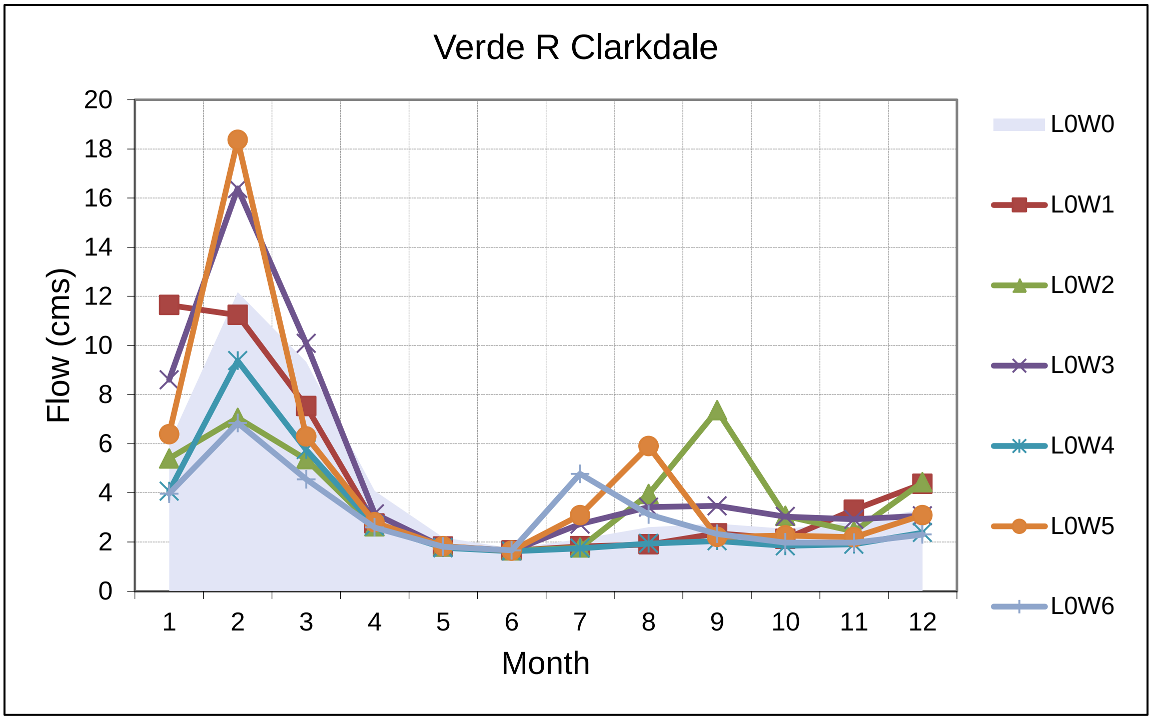


Figure 69. Monthly Average Flows, Verde River near Clarkdale (HSPF)

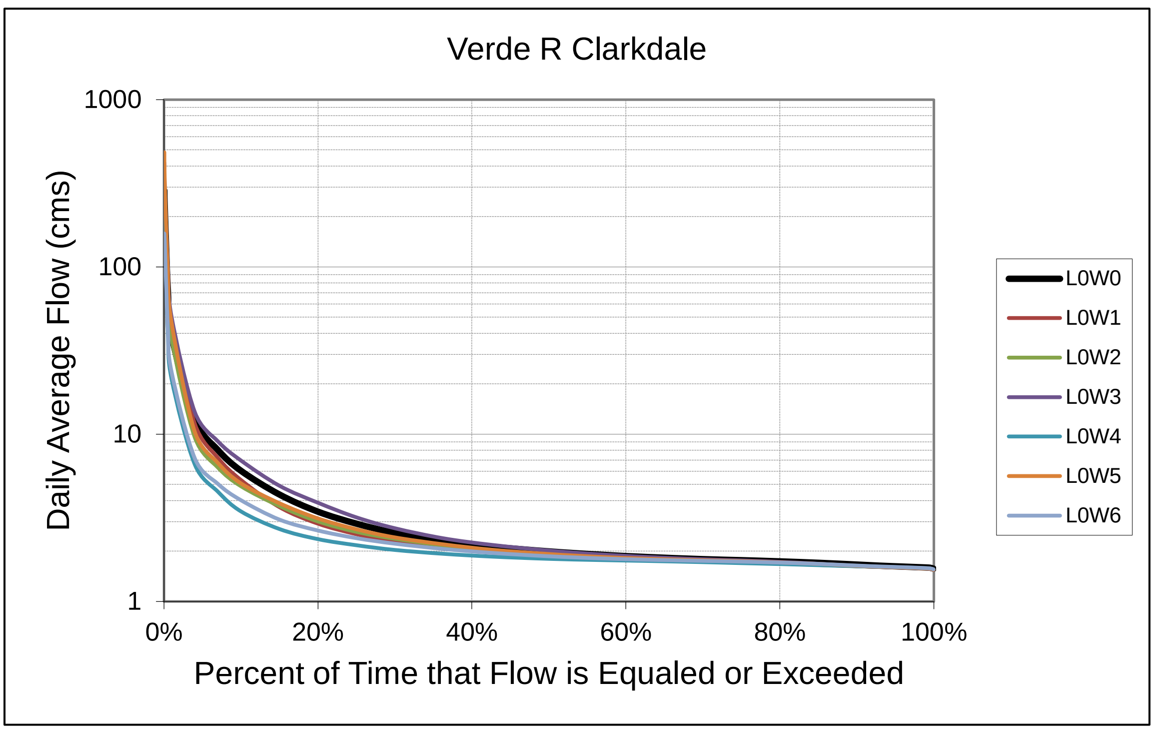


Figure 70. Flow Duration, Verde River near Clarkdale (HSPF)

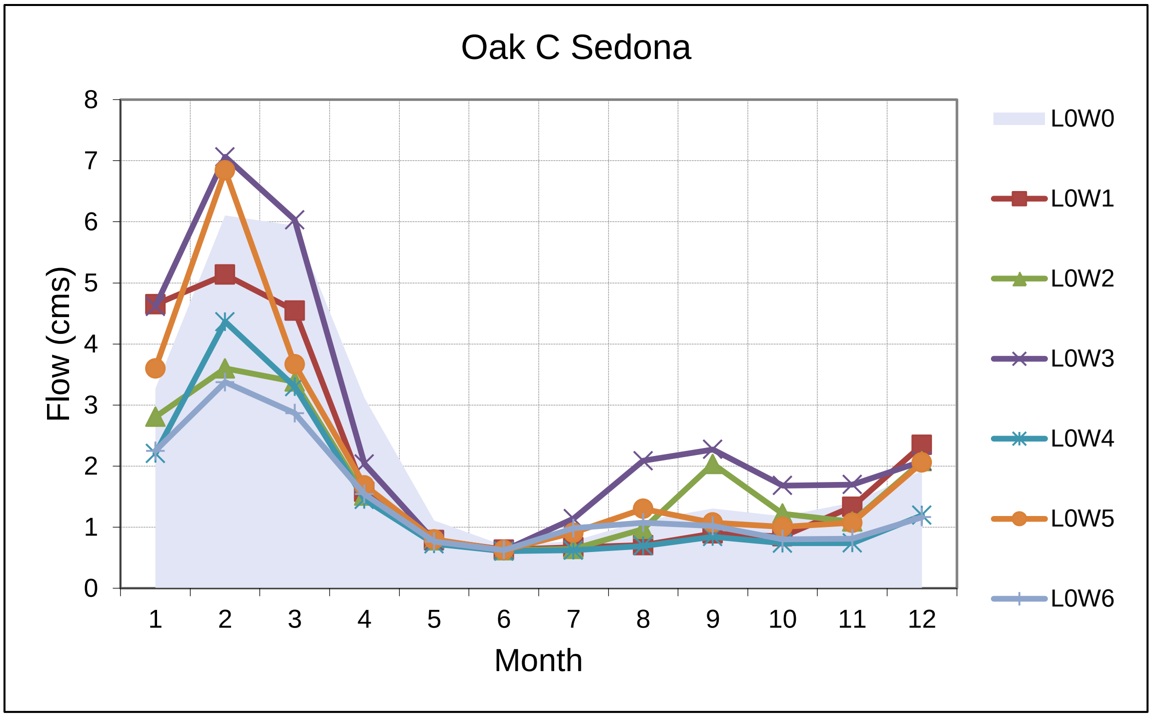


Figure 71. Monthly Average Flows, Oak Creek at Sedona (HSPF)

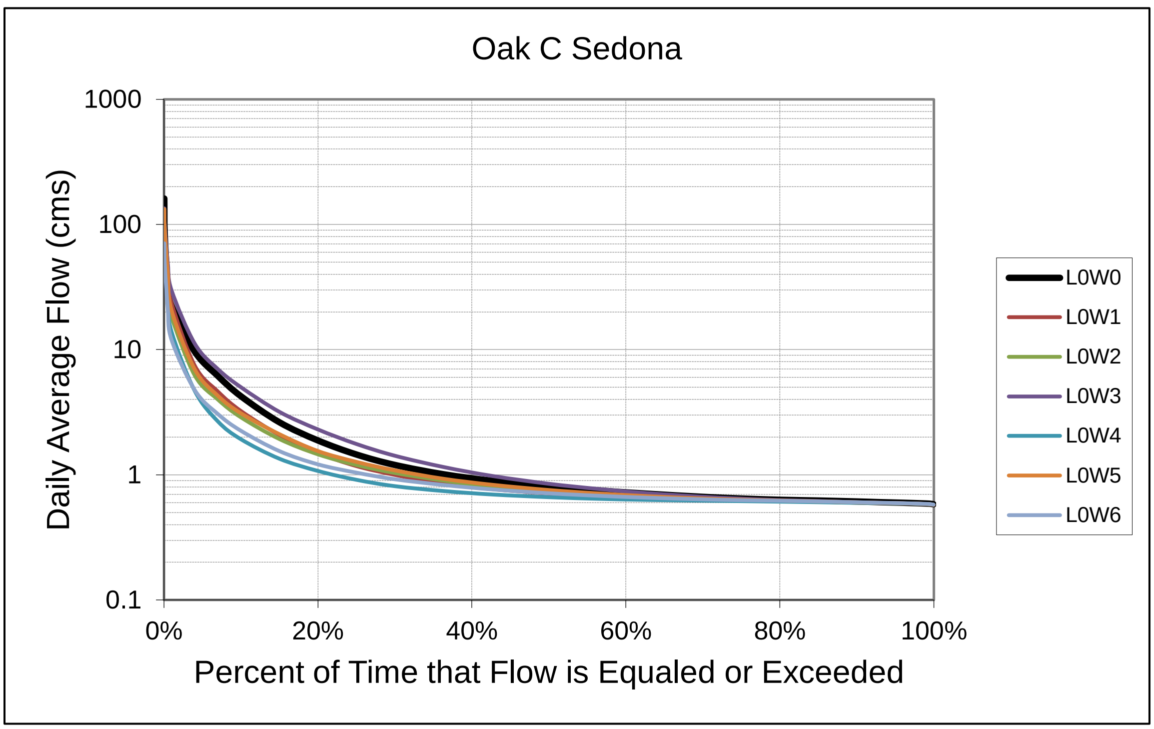


Figure 72. Flow Duration, Oak Creek at Sedona (HSPF)

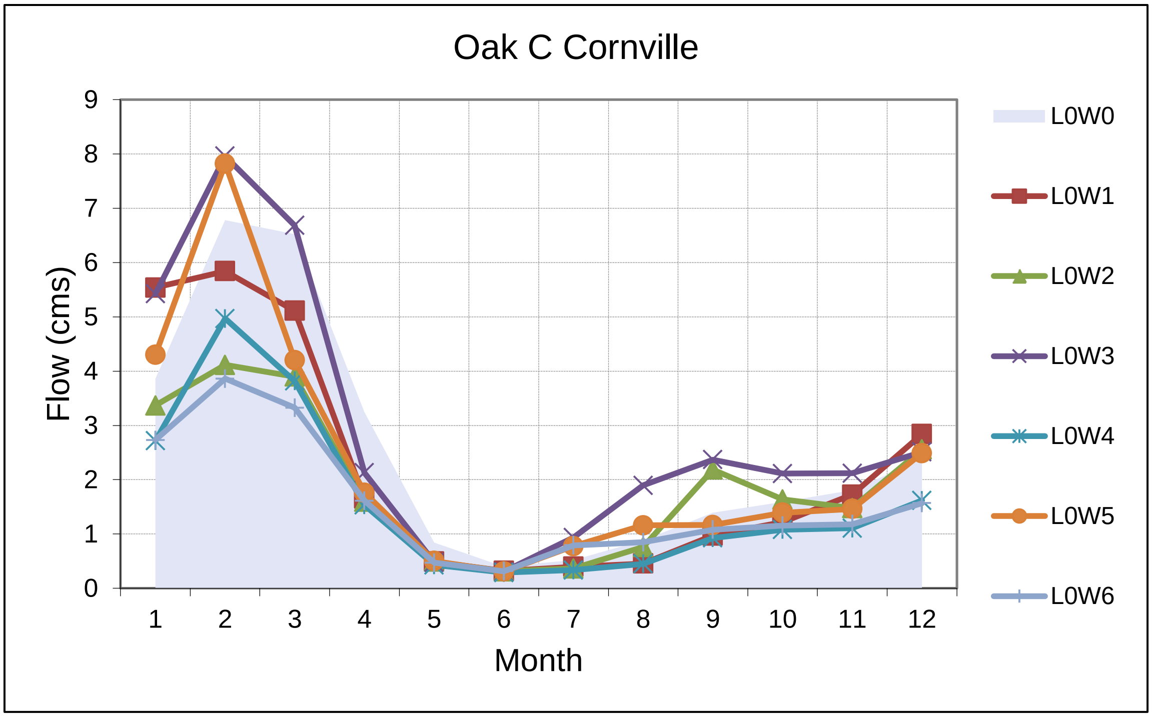


Figure 73. Monthly Average Flows, Oak Creek at Cornville (HSPF)

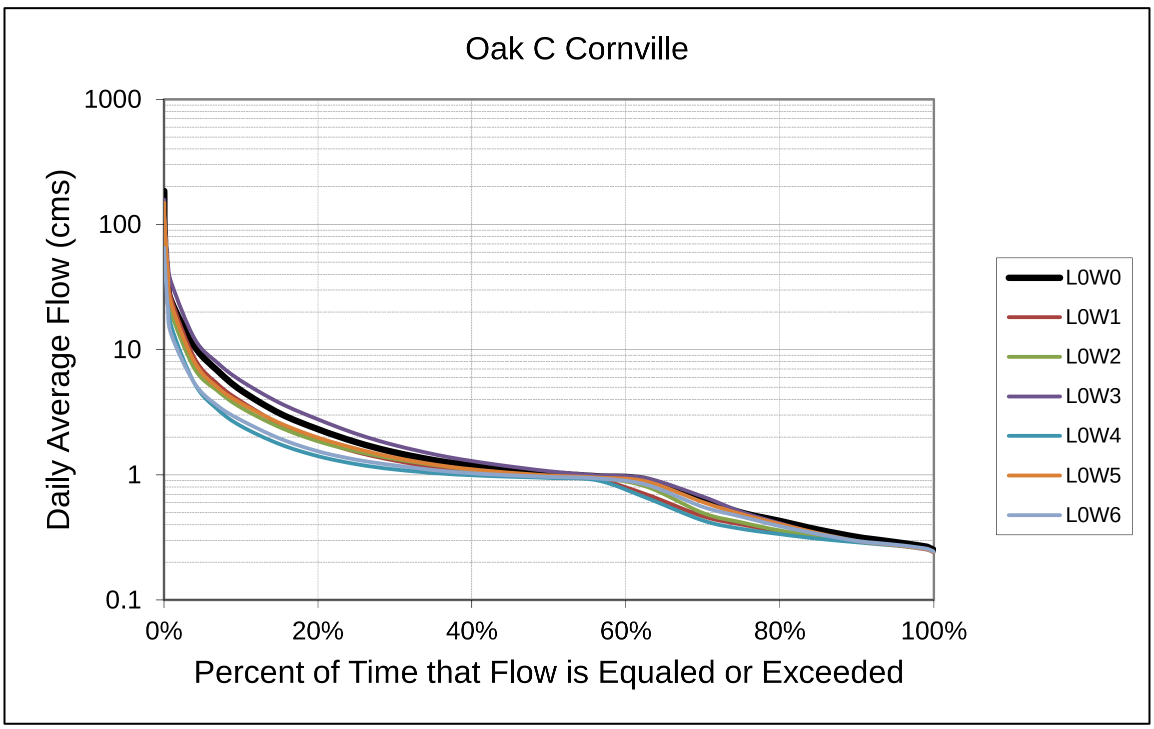


Figure 74. Flow Duration, Oak Creek at Cornville (HSPF)

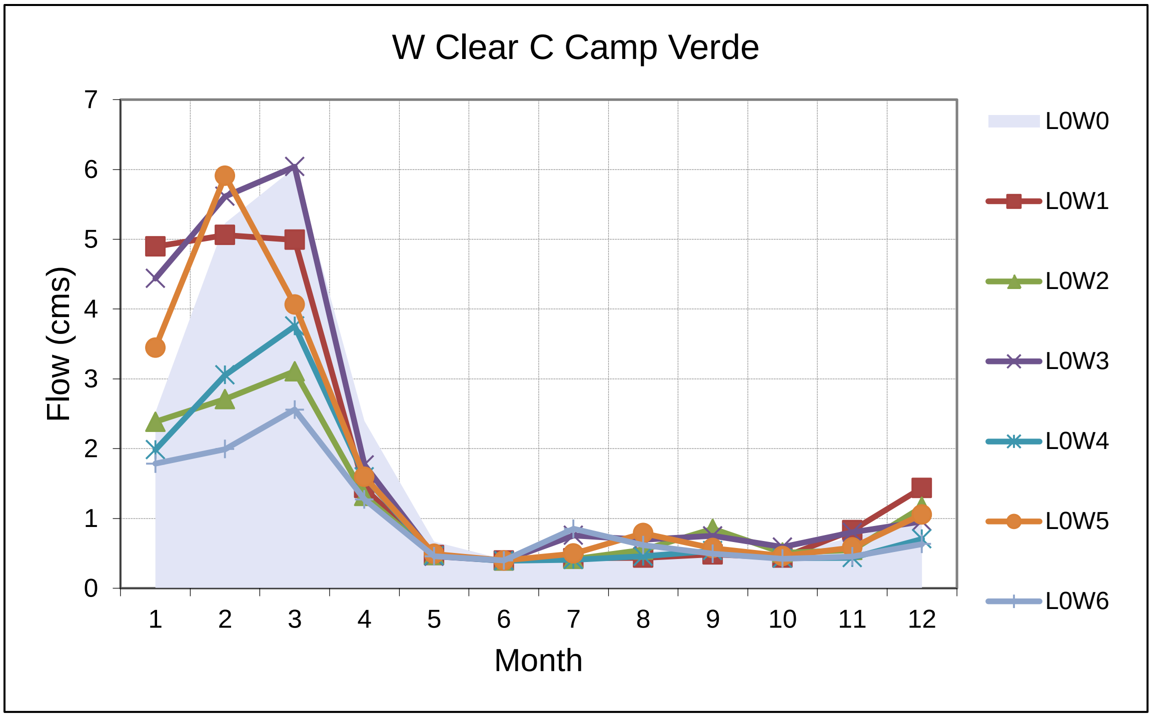


Figure 75. Monthly Average Flows, West Clear Creek at Camp Verde (HSPF)

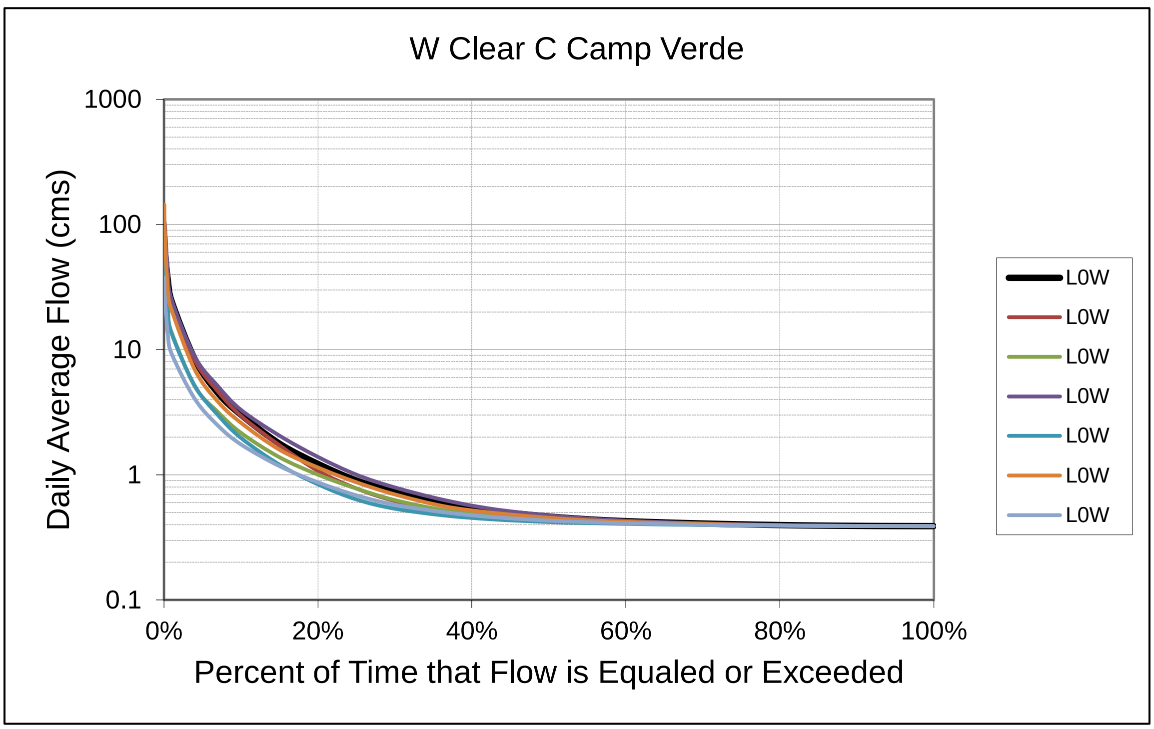


Figure 76. Flow Duration, West Clear Creek at Camp Verde (HSPF)

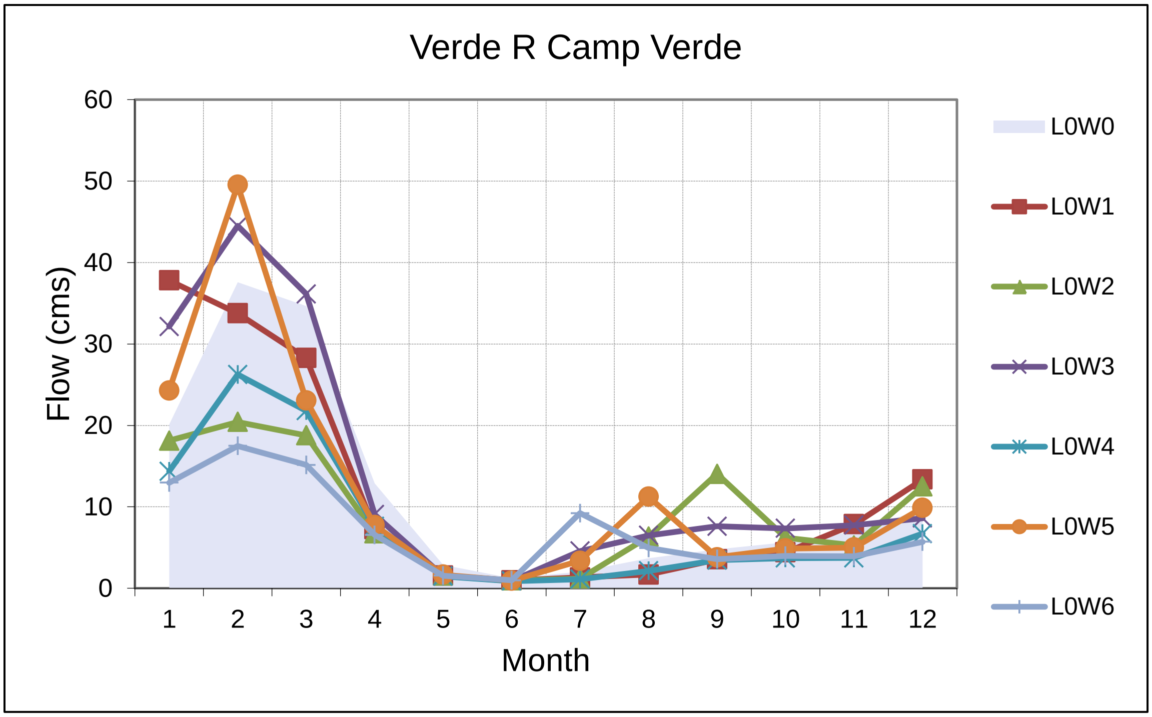


Figure 77. Monthly Average Flows, Verde River at Camp Verde (HSPF)

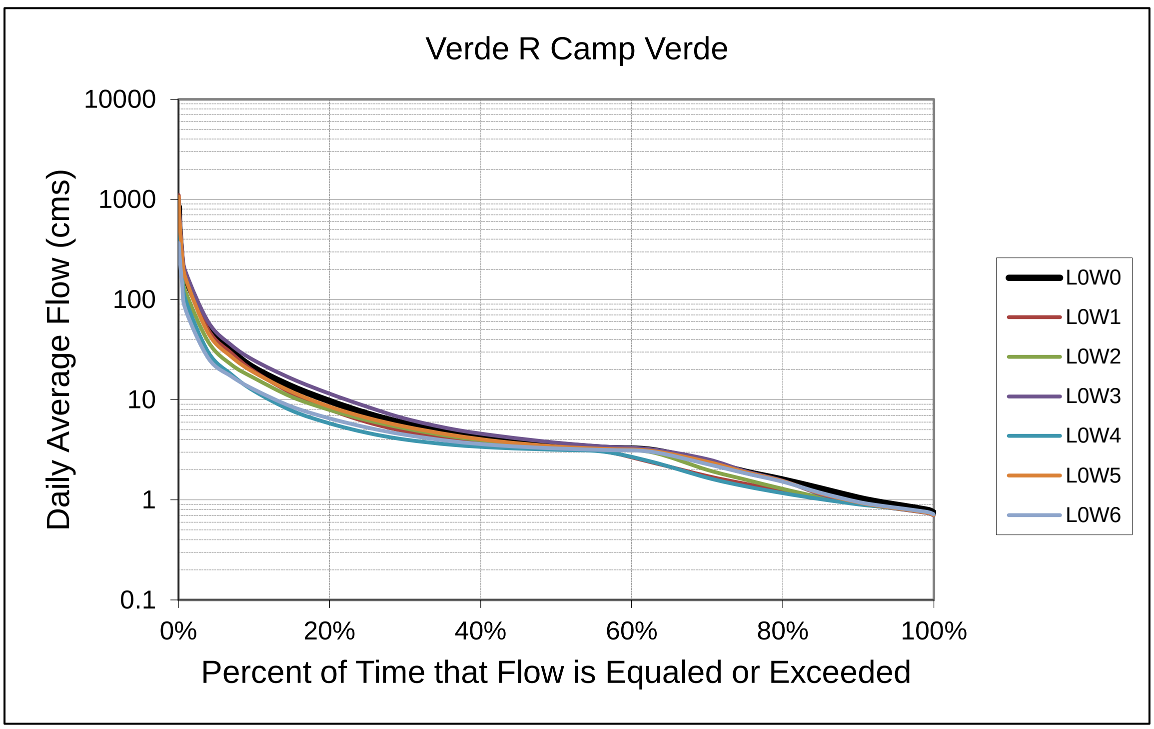


Figure 78. Flow Durations, Verde River at Camp Verde (HSPF)

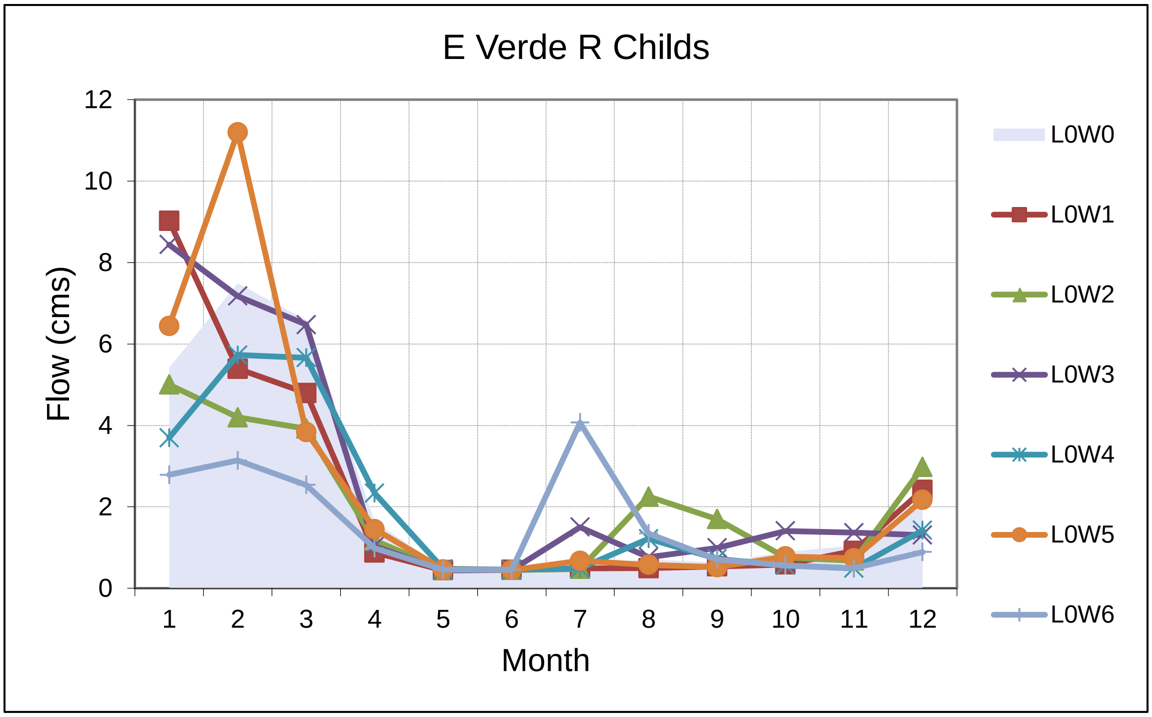


Figure 79. Monthly Average Flows, East Verde River at Childs (HSPF)

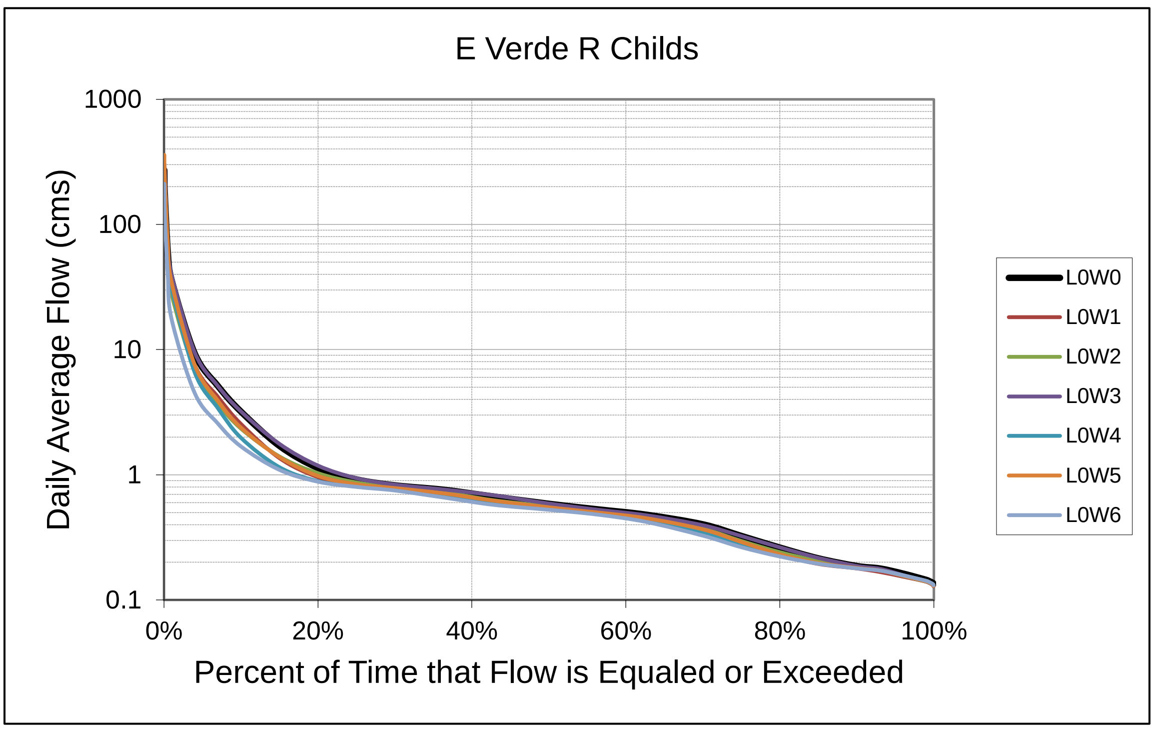


Figure 80. Flow Duration, East Verde River at Childs (HSPF)

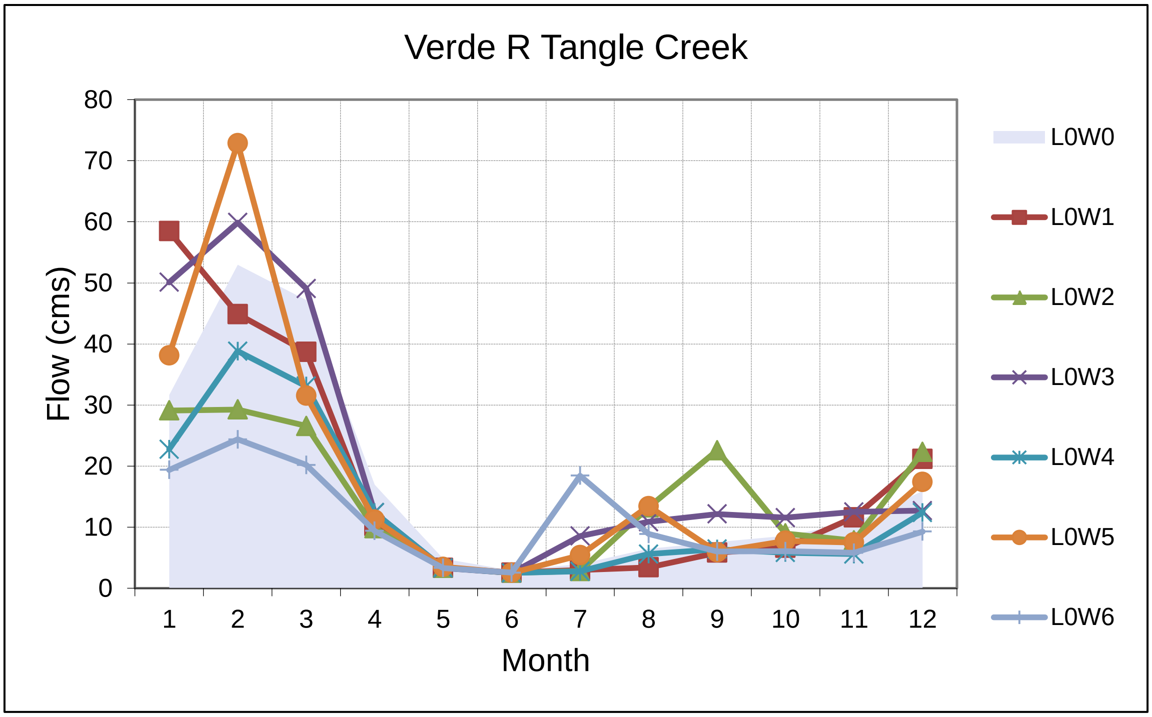


Figure 81. Monthly Average Flows, Verde River at Tangle Creek (HSPF)

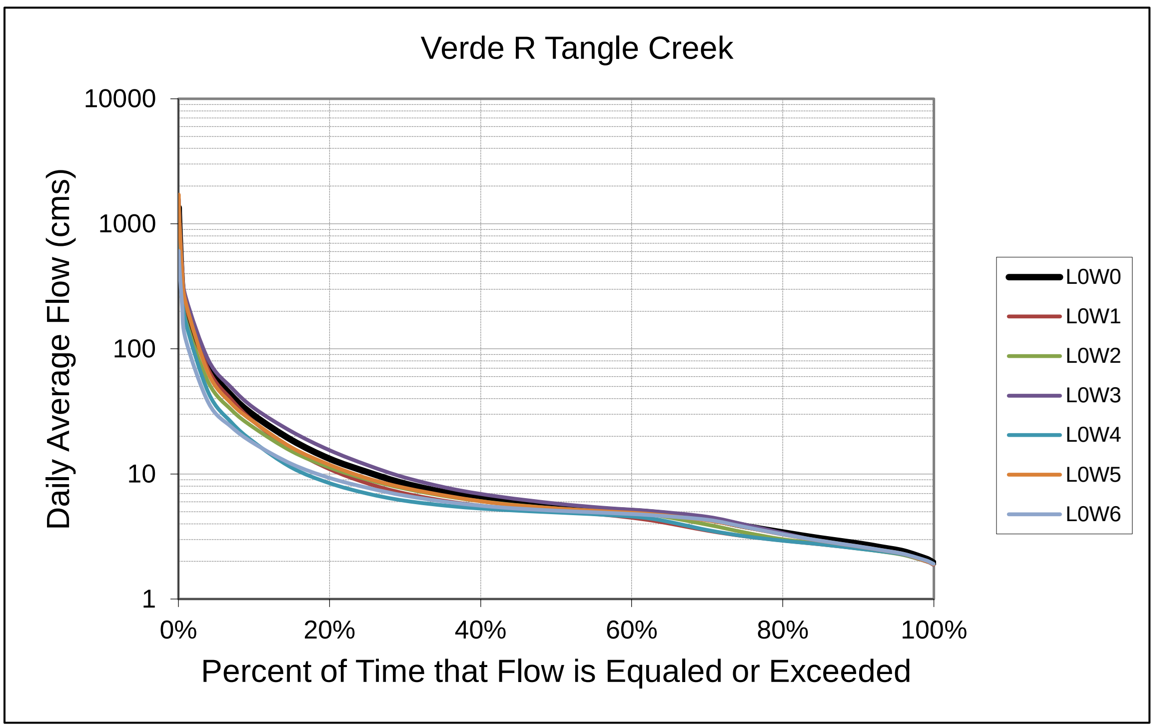


Figure 82. Flow Duration, Verde River at Tangle Creek (HSPF)

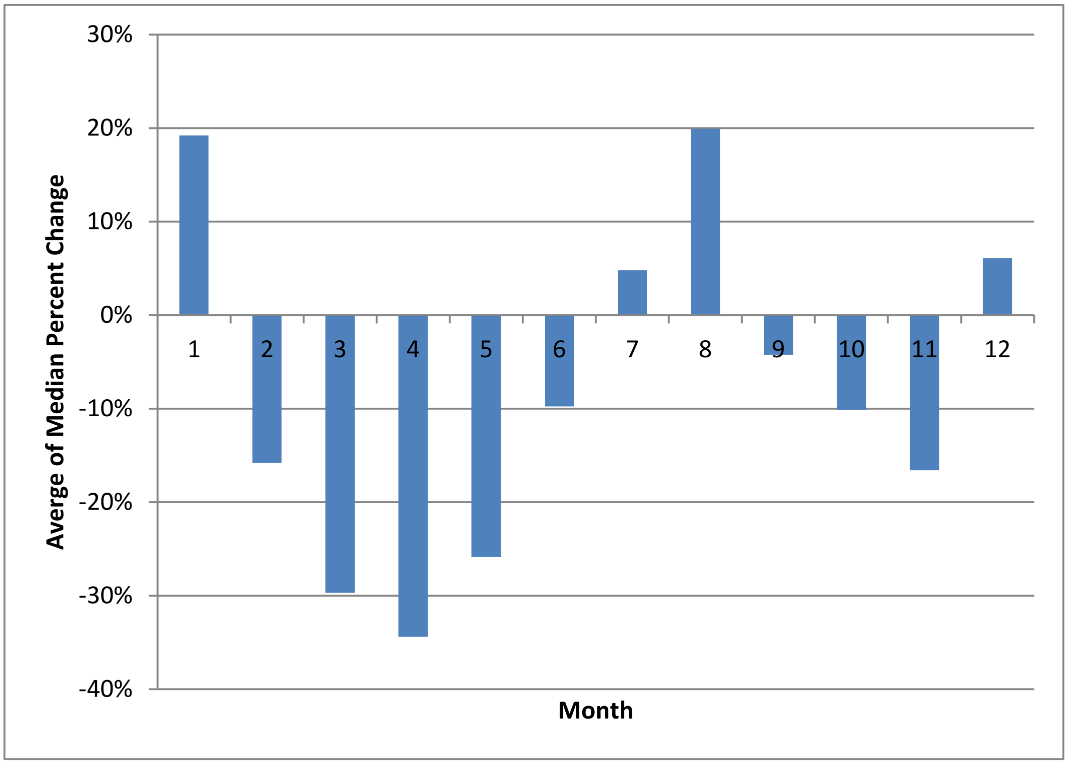


Figure 83. Average of Median Percent Change in Flow; NARCCAP Scenarios W1-W6 at all Stations, Verde-Basin (HSPF)

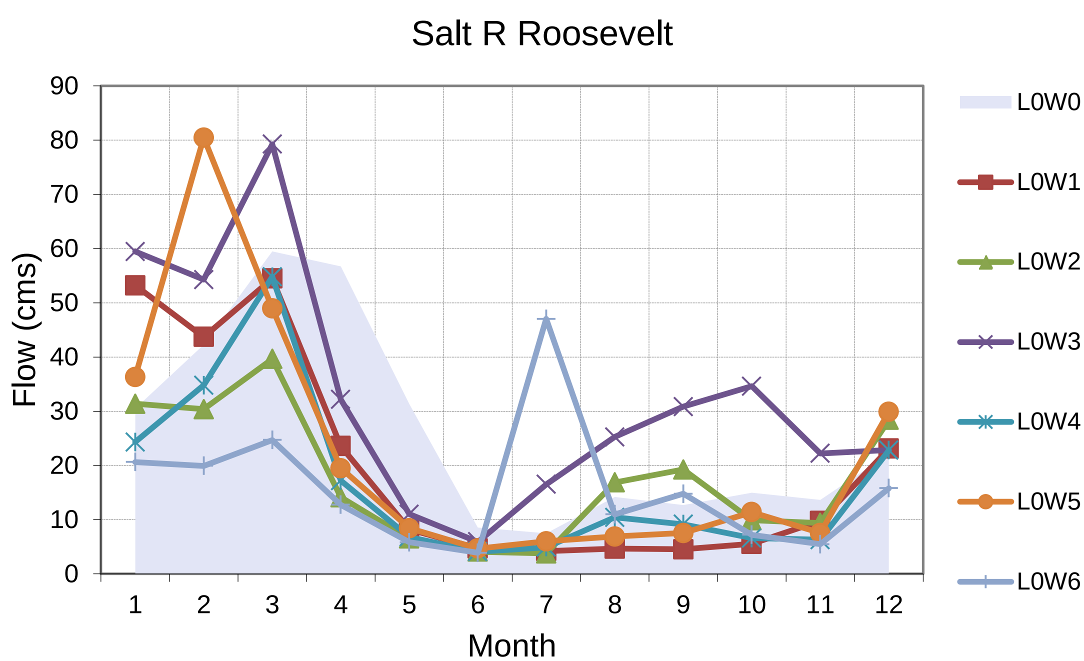


Figure 84. Monthly Average Flows, Salt River nr Roosevelt (HSPF)

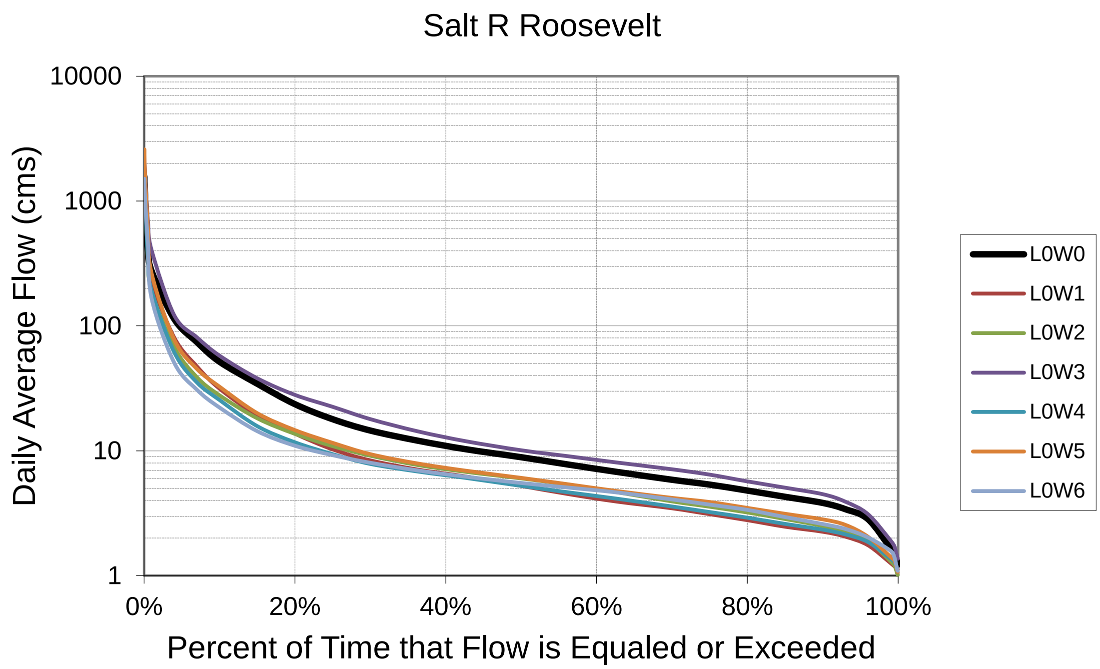


Figure 85. Flow Duration, Salt River nr Roosevelt (HSPF)

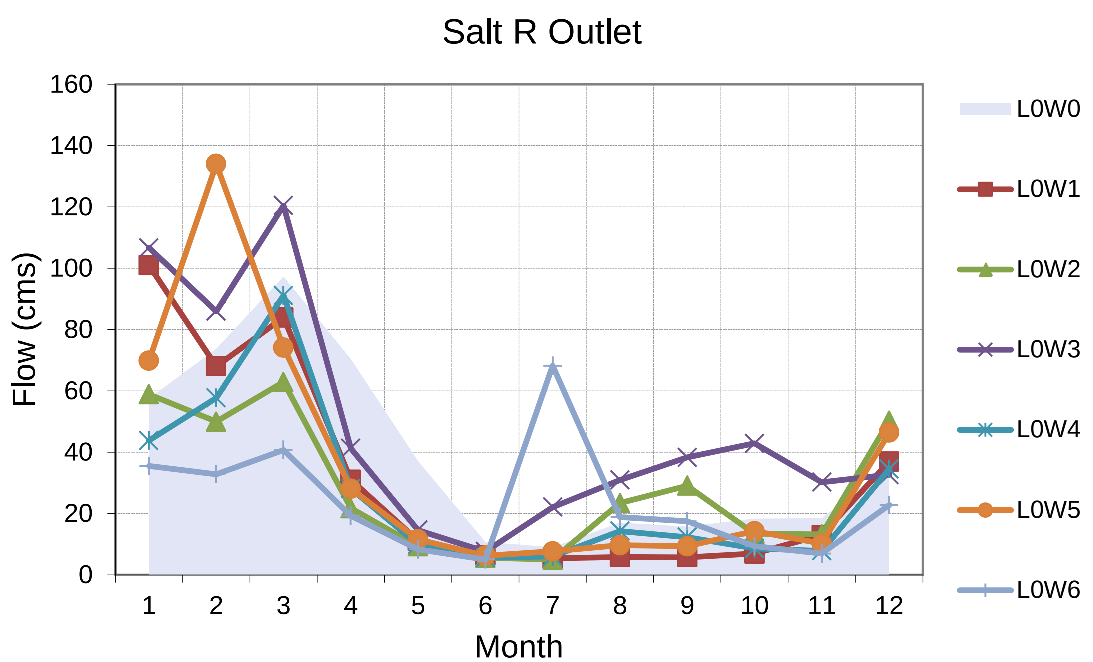


Figure 86. Monthly Average Flows, Salt River at Outlet (HSPF)

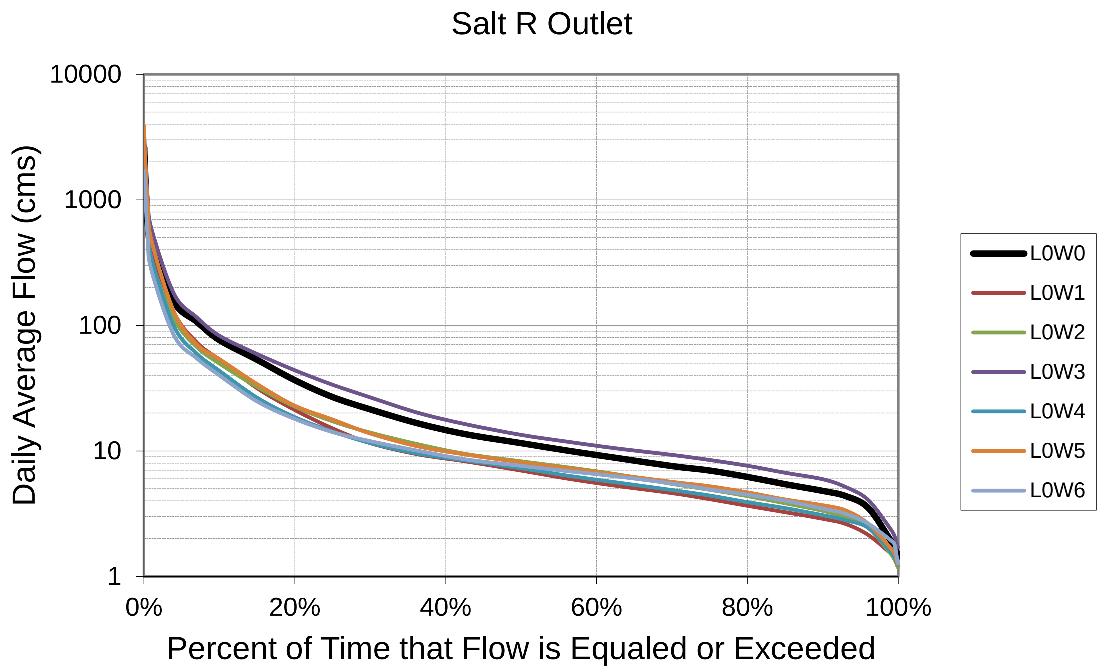


Figure 87. Flow Duration, Salt River at Outlet (HSPF)

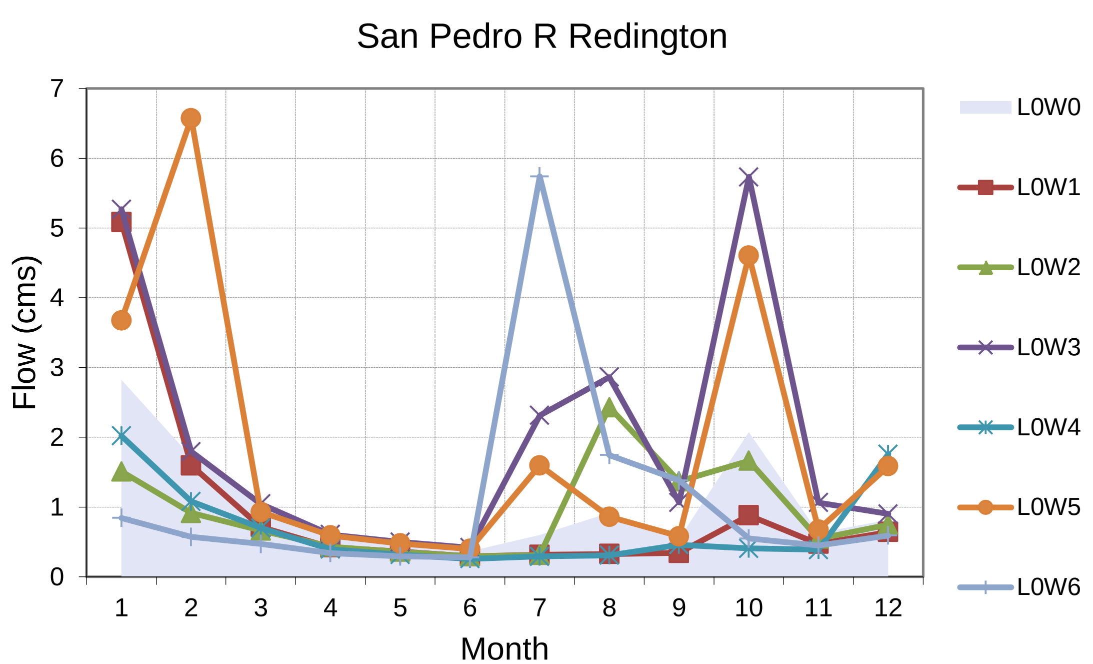


Figure 88. Monthly Average Flows, San Pedro River at Redington (HSPF)

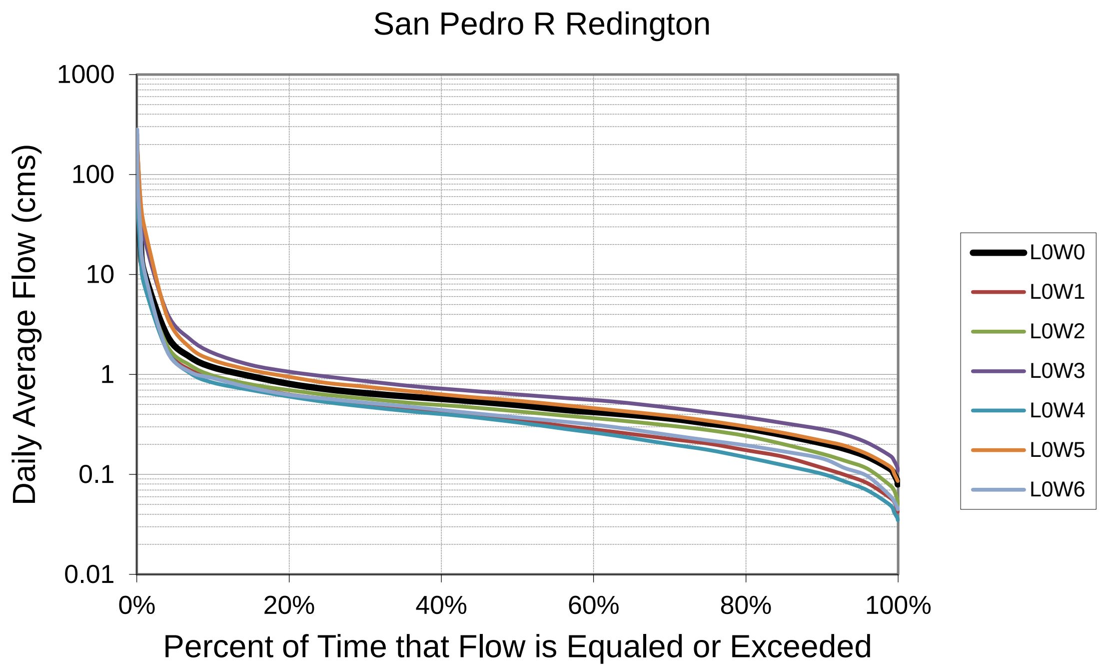


Figure 89. Flow Duration, San Pedro River at Redington (HSPF)

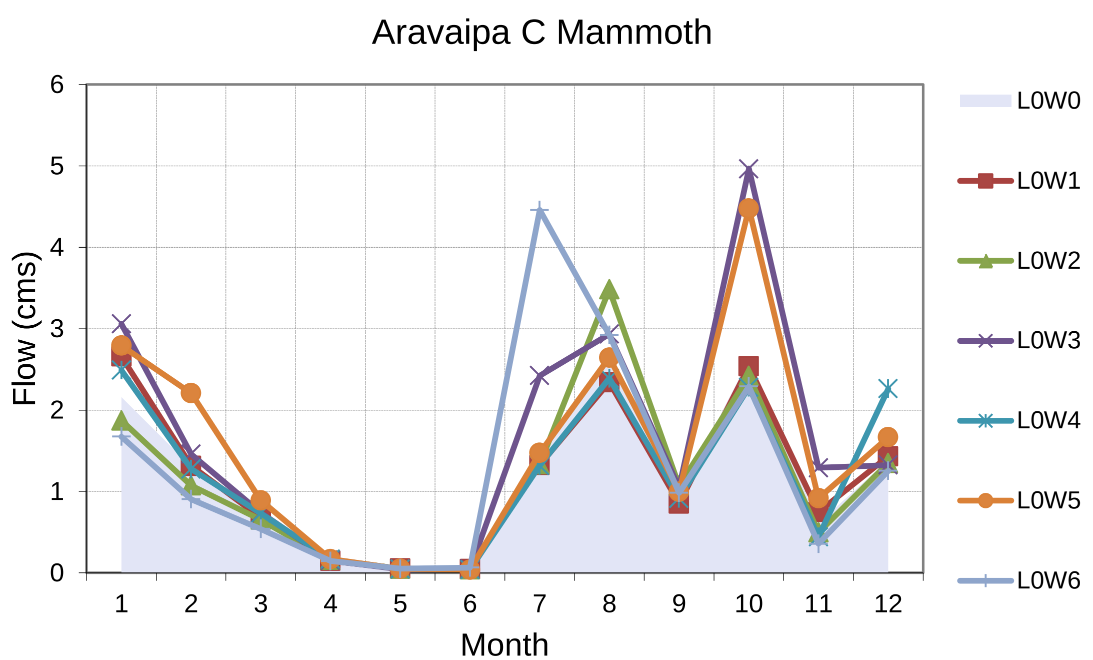


Figure 90. Monthly Average Flows, Aravaipa Creek at Mammoth (HSPF)

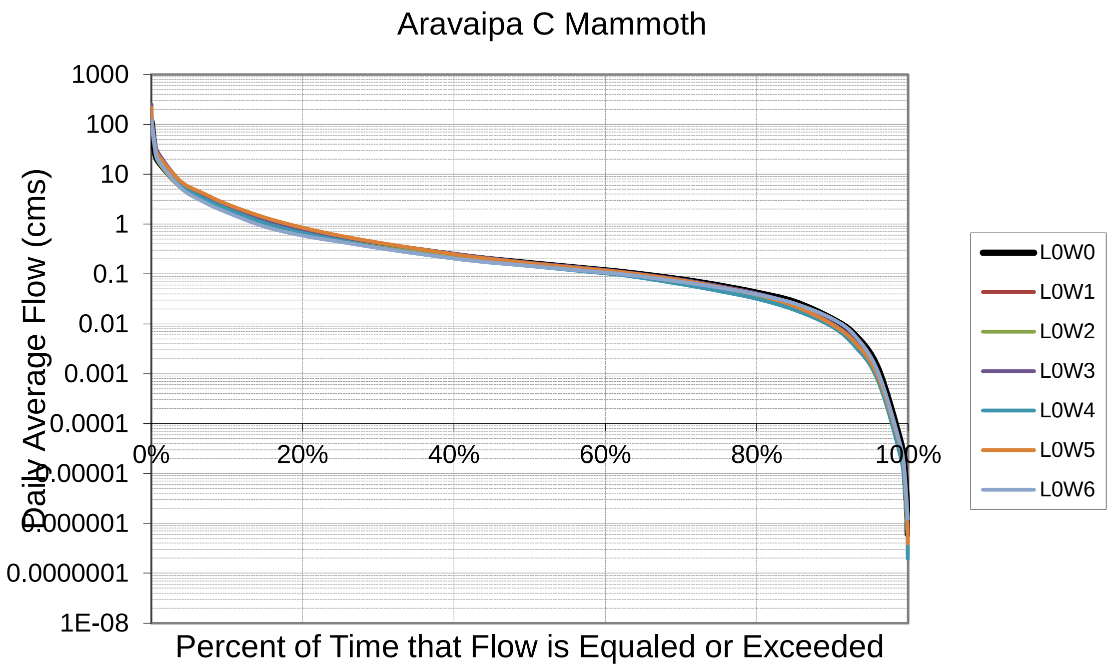


Figure 91. Flow Duration, Aravaipa Creek at Mammoth (HSPF)

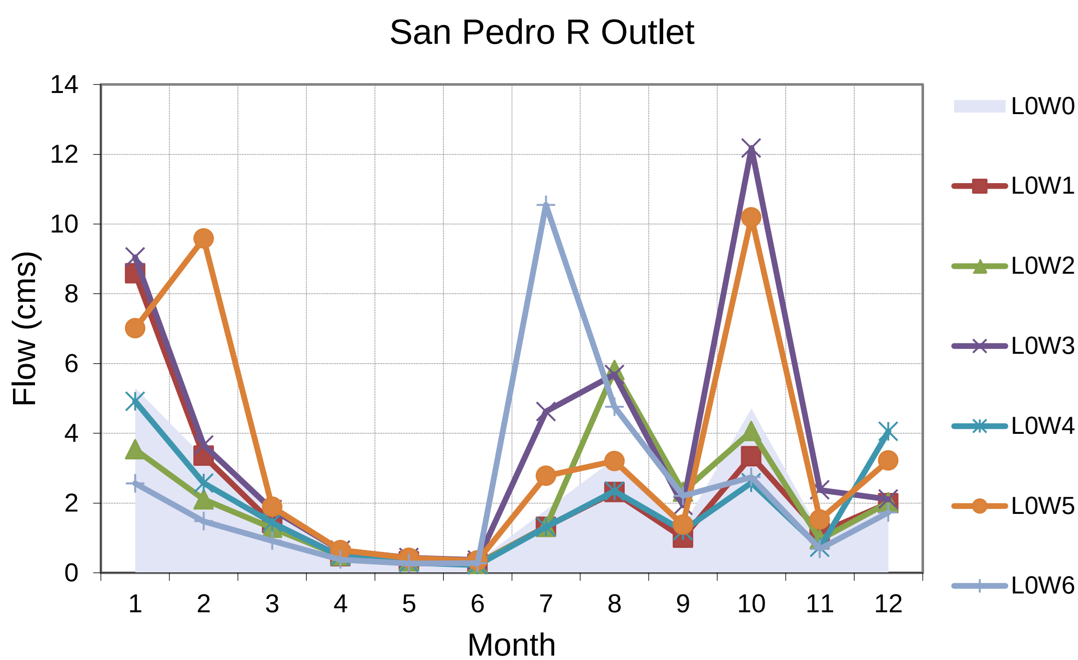


Figure 92. Monthly Average Flows, San Pedro River at Outlet (HSPF)

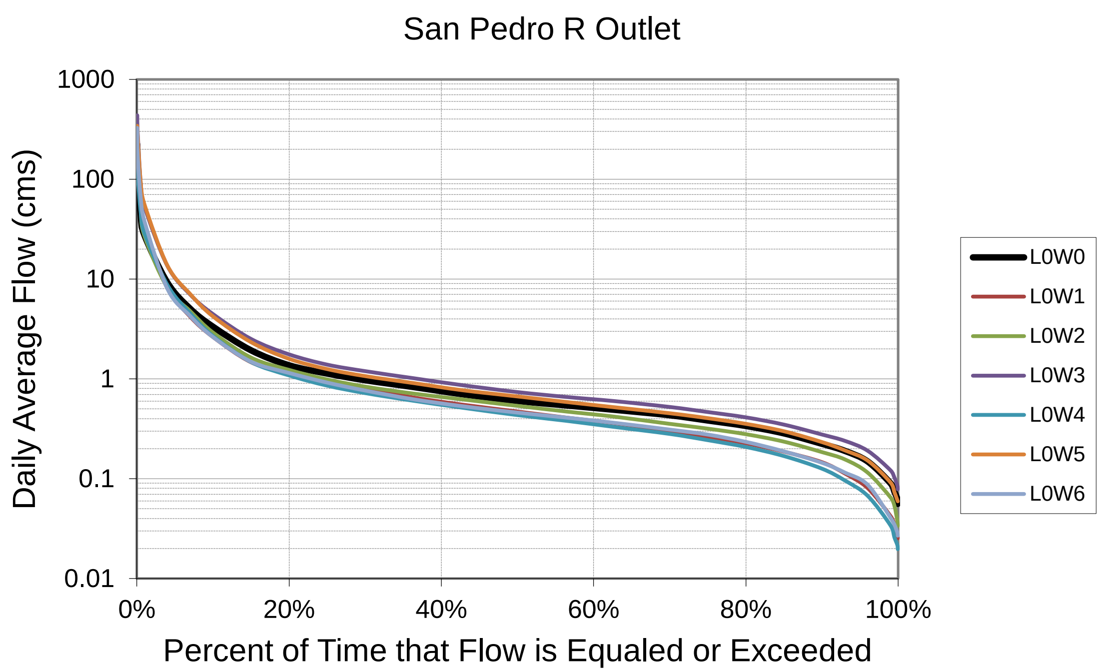


Figure 93. Flow Duration, San Pedro River at Outlet (HSPF)

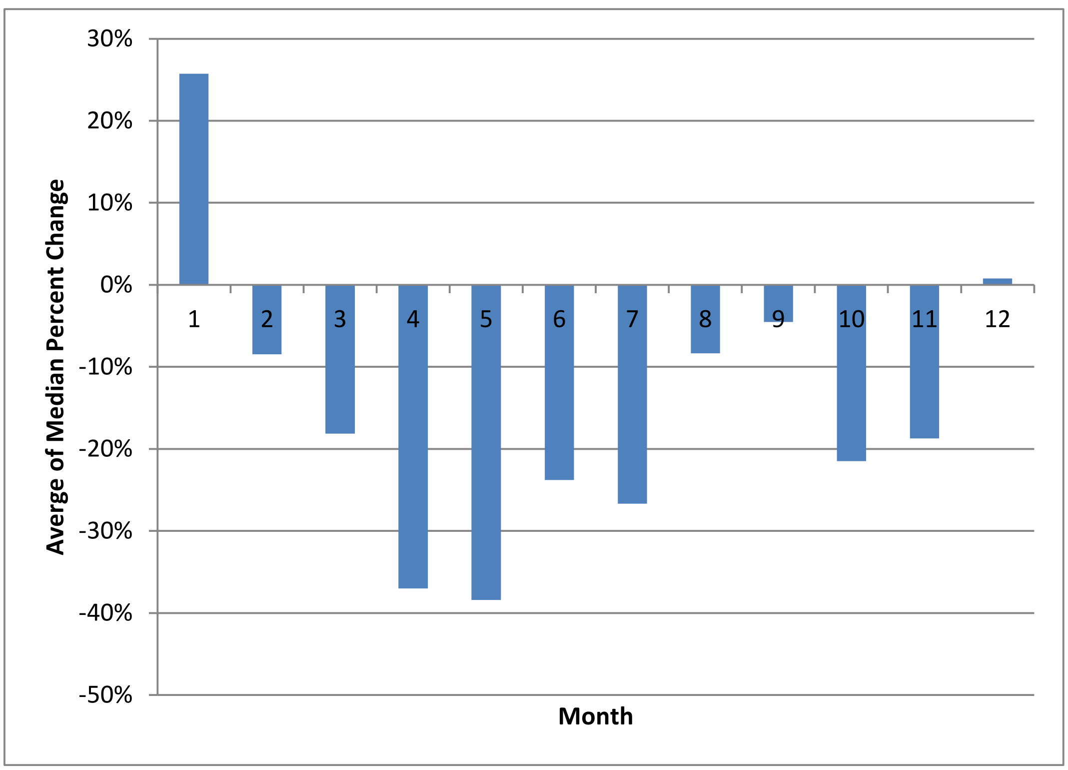


Figure 94. Average of Median Percent Change in Flow; NARCCAP Scenarios W1-W6 at all Stations, Salt and San Pedro Basins (HSPF)

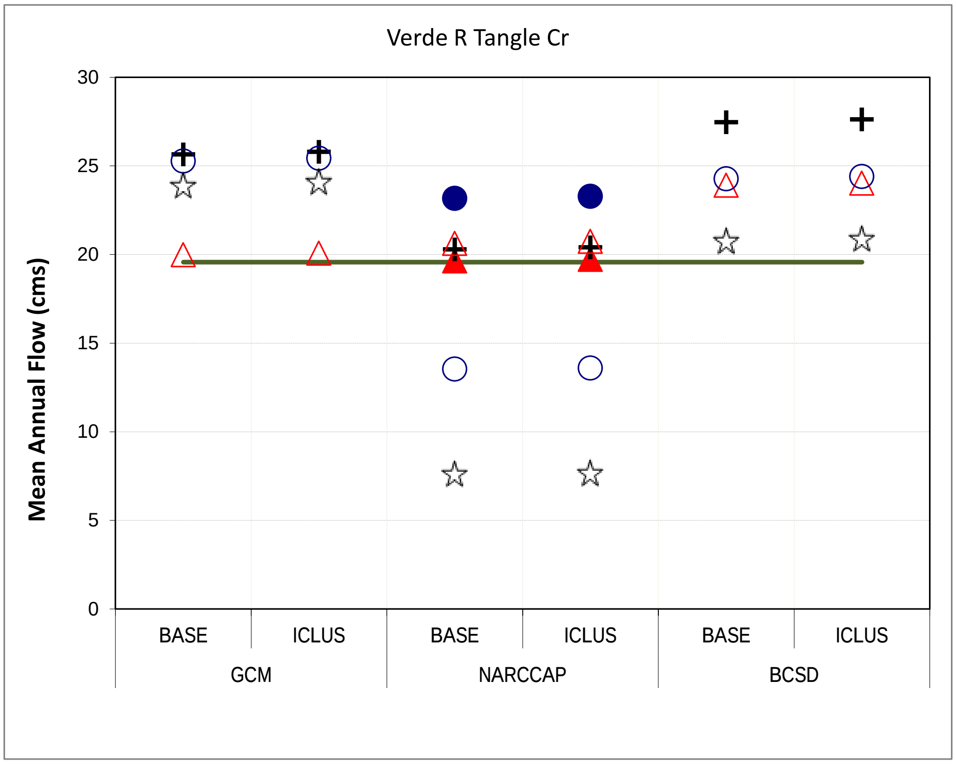


Figure 95. Mean Annual Flow, Verde River below Tangle Creek (SWAT)

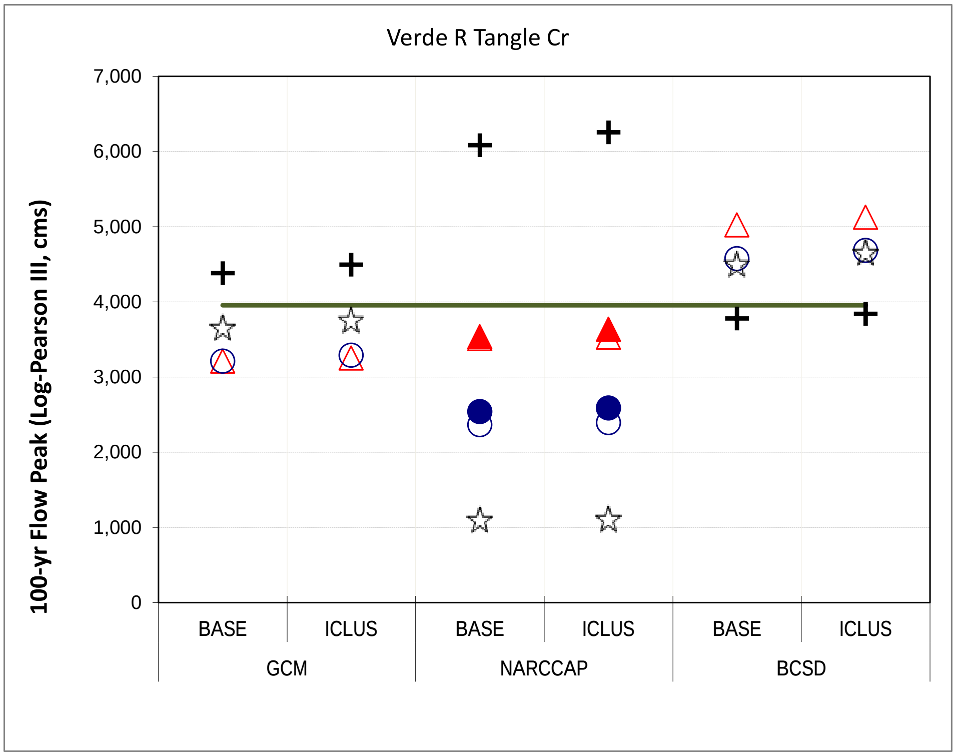


Figure 96. **100-yr Flow Peak, Verde River below Tangle Creek (SWAT)**

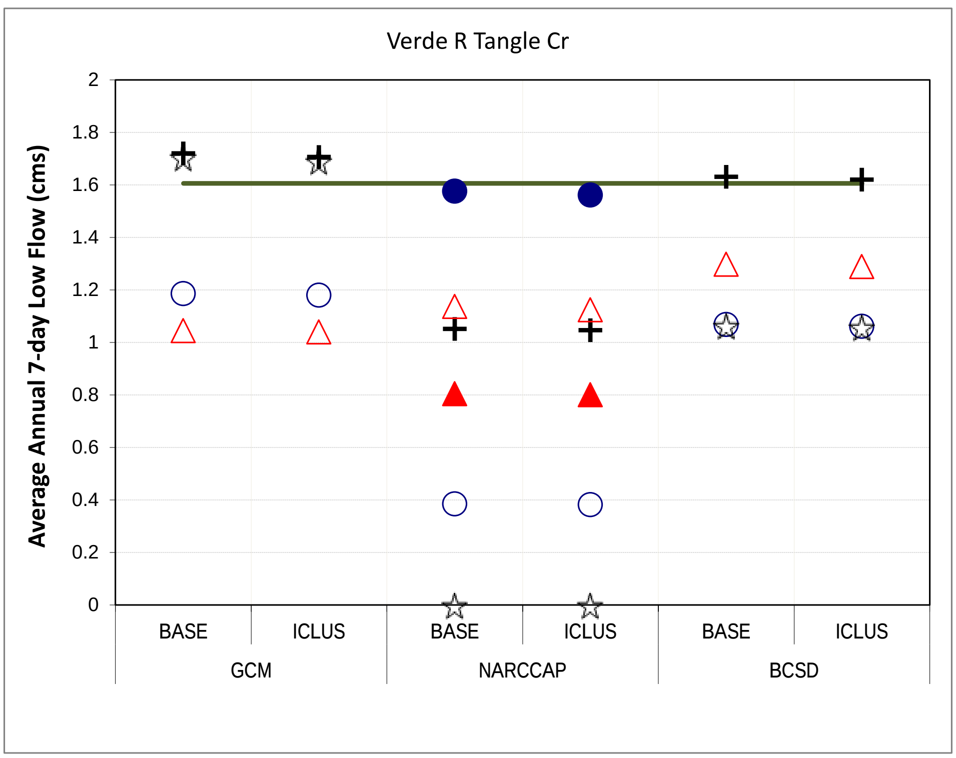


Figure 97. **Average Annual 7-day Low Flow, Verde River below Tangle Creek (SWAT)**

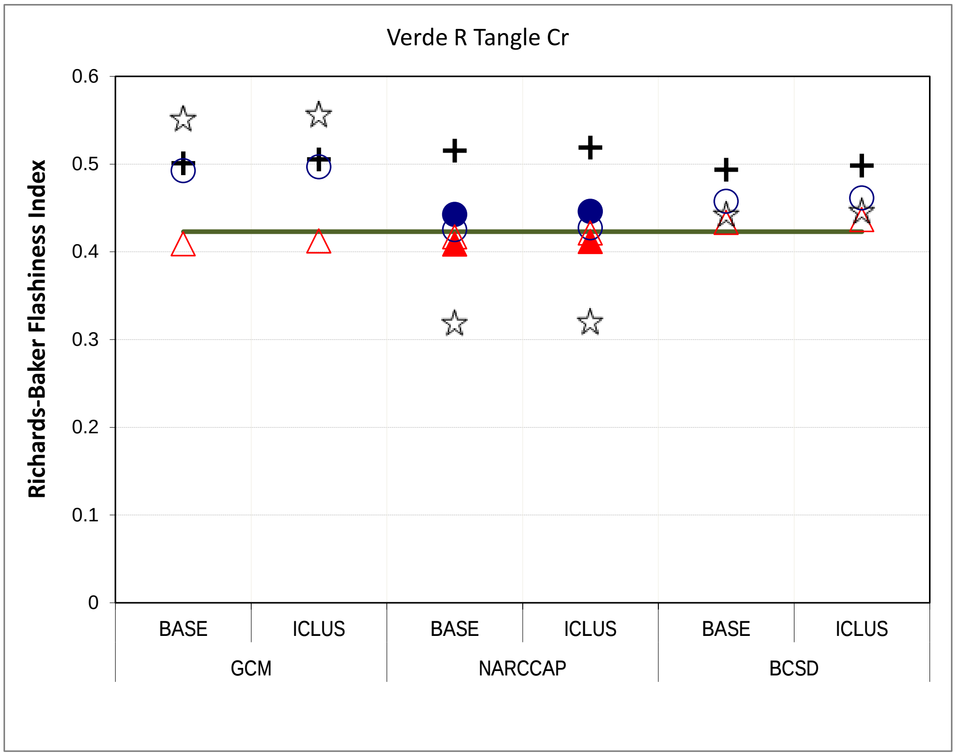


Figure 98. **Richards-Baker Flashiness Index, Verde River below Tangle Creek (SWAT)**

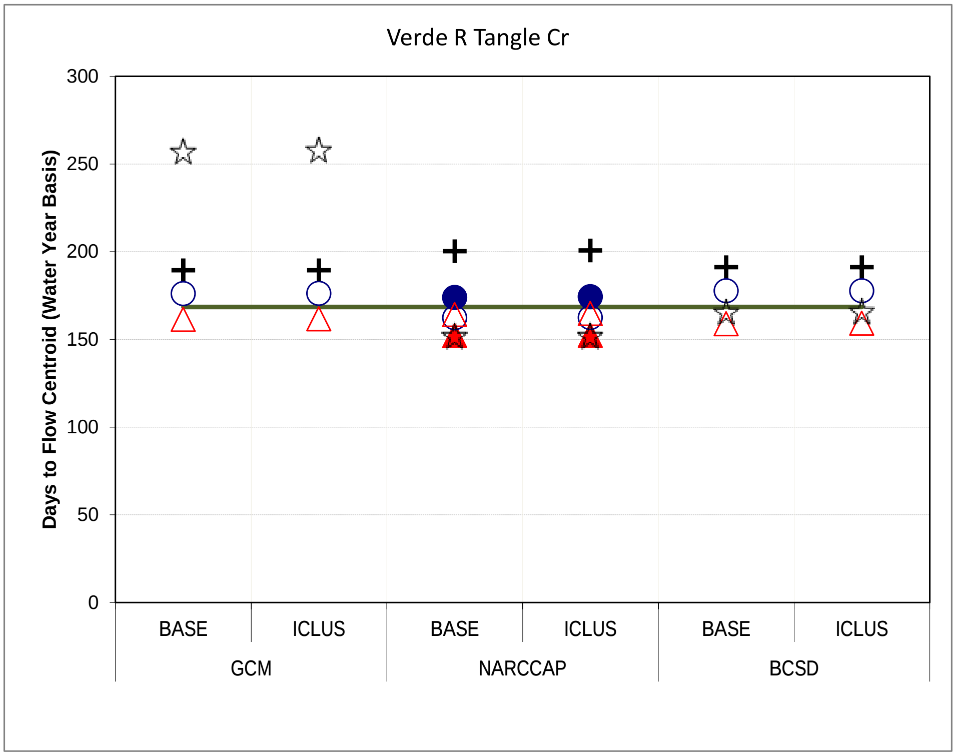


Figure 99. **Days to Flow Centroid, Verde River below Tangle Creek (SWAT)**

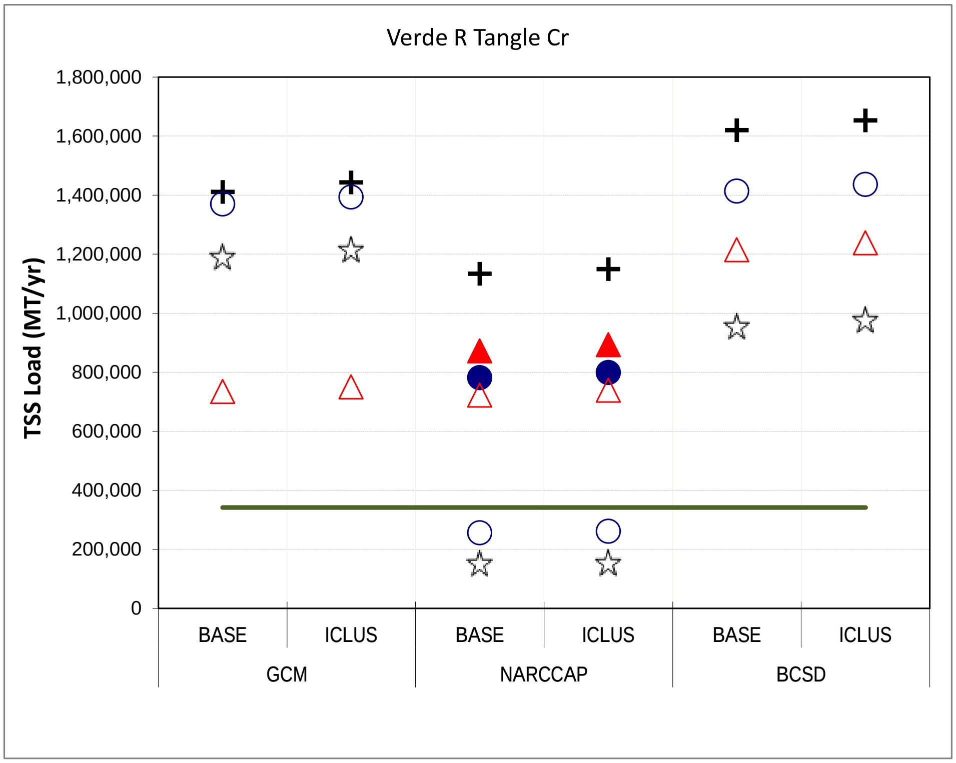


Figure 100. TSS Load, Verde River below Tangle Creek (SWAT)

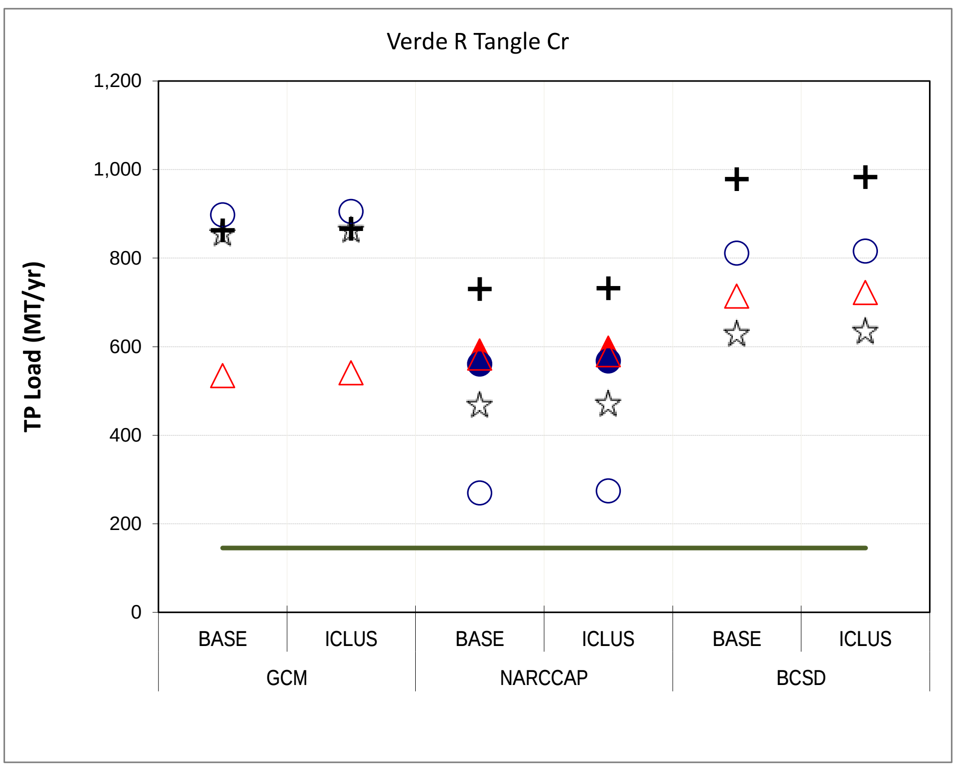


Figure 101. TP Load, Verde River below Tangle Creek (SWAT)

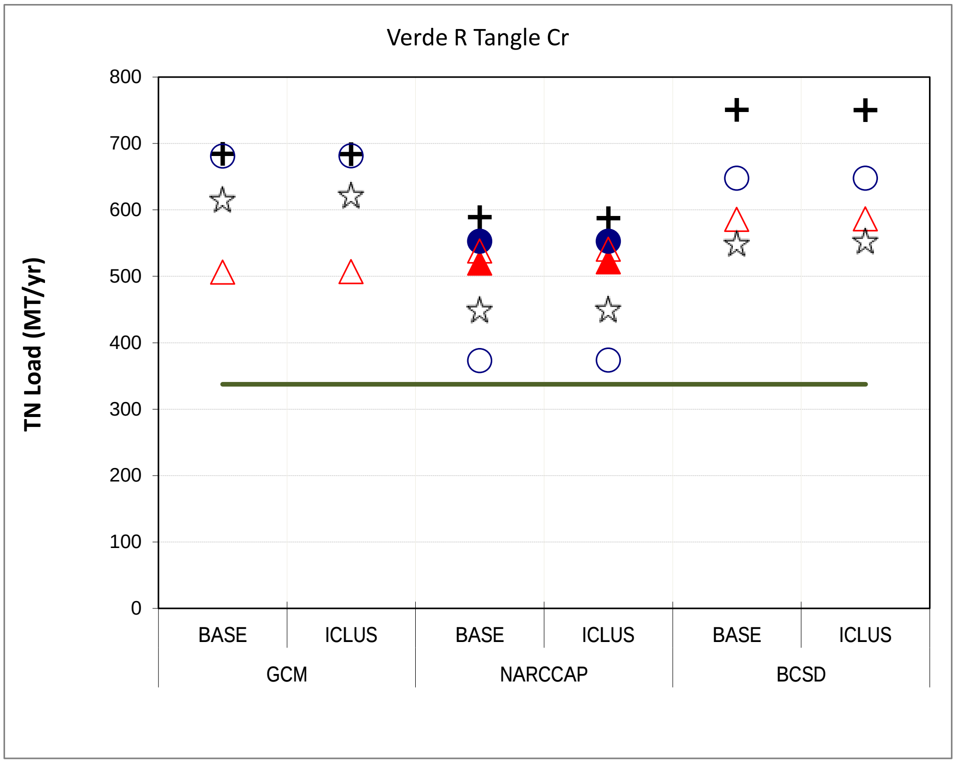


Figure 102. TN Load, Verde River below Tangle Creek (SWAT)

Results at Multiple Stations

Table 4. Summary of Range of Change Relative to Existing Conditions for NARCCAP Dynamically Downscaled Scenarios, Verde-Salt-San Pedro Basins, SWAT Model

	Results without LU Change				Results with LU Change			
	Min	Median	Mean	Max	Min	Median	Mean	Max
West Clear Creek (gage 09505800)								
Flow	-87.93%	-68.10%	-69.82%	-54.47%	-87.91%	-68.08%	-69.79%	-54.43%
TSS	543.91%	3311.03%	3021.91 %	5220.10 %	552.58%	3325.16 %	3034.34 %	5235.42 %
TN	21.54%	123.92%	115.04%	190.03%	21.12%	123.31%	114.49%	189.35%
TP	-15.30%	195.72%	169.16%	296.84%	-14.76%	196.78%	170.16%	298.27%
East Verde (gage 09507980)								
Flow	-66.54%	-16.20%	-21.46%	4.52%	-66.54%	-16.21%	-21.47%	4.51%
TSS	-78.88%	-11.01%	-18.43%	15.93%	-78.81%	-11.01%	-18.42%	15.89%

	Results without LU Change				Results with LU Change			
	Min	Median	Mean	Max	Min	Median	Mean	Max
TN	-29.56%	32.19%	24.06%	47.16%	-29.53%	32.12%	24.01%	47.03%
TP	-73.79%	-20.35%	-25.56%	0.91%	-73.77%	-20.22%	-25.48%	0.97%
Oak Creek at Sedona (gage 09504430)								
Flow	-26.58%	25.10%	23.80%	88.54%	-26.55%	24.98%	23.69%	88.29%
TSS	-12.39%	54.46%	54.84%	144.80%	-12.97%	52.63%	52.78%	140.72%
TN	-14.21%	-5.00%	-5.55%	1.10%	-14.16%	-4.96%	-5.46%	1.32%
TP	-10.82%	50.38%	51.52%	128.63%	-11.36%	49.10%	50.05%	125.88%
Verde R nr Camp Verde (gage 09506000)								
Flow	-60.26%	5.11%	-10.05%	18.48%	-60.38%	4.95%	-10.21%	18.22%
TSS	-46.00%	148.54%	108.65%	233.25%	-47.03%	145.93%	106.06%	227.65%
TN	10.21%	72.87%	64.09%	99.87%	11.36%	74.50%	65.57%	100.72%
TP	108.69%	357.05%	327.69%	495.44%	108.58%	354.07%	323.53%	485.56%
Verde R nr Clarkdale (gage 09504000)								
Flow	-41.14%	40.02%	19.88%	51.52%	-41.65%	39.32%	19.19%	50.94%
TSS	40.26%	323.83%	346.55%	855.28%	38.05%	318.14%	336.94%	824.50%
TN	25.20%	111.17%	109.75%	191.14%	27.62%	114.61%	111.88%	191.47%
TP	285.71%	780.15%	831.65%	1480.95 %	275.32%	749.04%	794.13%	1403.92 %
Verde R below Tangle Crk (gage 09508500)								
Flow	-60.72%	1.99%	-10.64%	18.41%	-60.81%	1.89%	-10.75%	18.22%
TSS	-54.22%	119.71%	91.02%	231.21%	-55.24%	117.36%	88.48%	225.00%
TN	10.57%	56.75%	49.38%	74.63%	11.33%	58.16%	50.29%	75.01%
TP	85.59%	290.98%	267.10%	403.13%	85.91%	289.64%	264.76%	396.67%
Salt River nr Roosevelt (gage 09498500)								
Flow	-57.18%	-10.92%	-3.41%	69.62%	-57.18%	-10.95%	-3.43%	69.56%
TSS	-72.06%	-14.60%	-4.17%	100.90%	-72.07%	-14.65%	-4.23%	100.71%
TN	-16.91%	9.14%	19.70%	77.68%	-16.91%	9.21%	19.77%	77.78%
TP	-10.18%	43.82%	59.75%	161.34%	-10.35%	43.58%	59.45%	160.79%
Aravaipa Cr nr Mammoth (gage 09473000)								

	Results without LU Change				Results with LU Change			
	Min	Median	Mean	Max	Min	Median	Mean	Max
Flow	-84.35%	-12.33%	1.99%	90.11%	-84.35%	-12.33%	1.99%	90.11%
TSS	-93.09%	9.80%	44.27%	220.47%	-93.09%	9.77%	44.24%	220.40%
TN	-0.71%	37.01%	44.84%	110.18%	-0.73%	36.82%	44.68%	109.88%
TP	-89.99%	18.57%	56.87%	252.59%	-89.94%	18.54%	56.66%	251.78%
San Pedro R nr Redington (gage 0947200)								
Flow	-70.72%	5.05%	18.43%	118.68%	-70.83%	5.05%	18.40%	118.56%
TSS	-65.76%	11.84%	47.17%	212.38%	-65.93%	11.39%	47.37%	213.42%
TN	-17.50%	68.76%	131.04%	355.31%	-17.86%	68.34%	129.83%	352.89%
TP	-84.13%	57.68%	73.97%	322.07%	-84.06%	57.10%	73.46%	320.27%

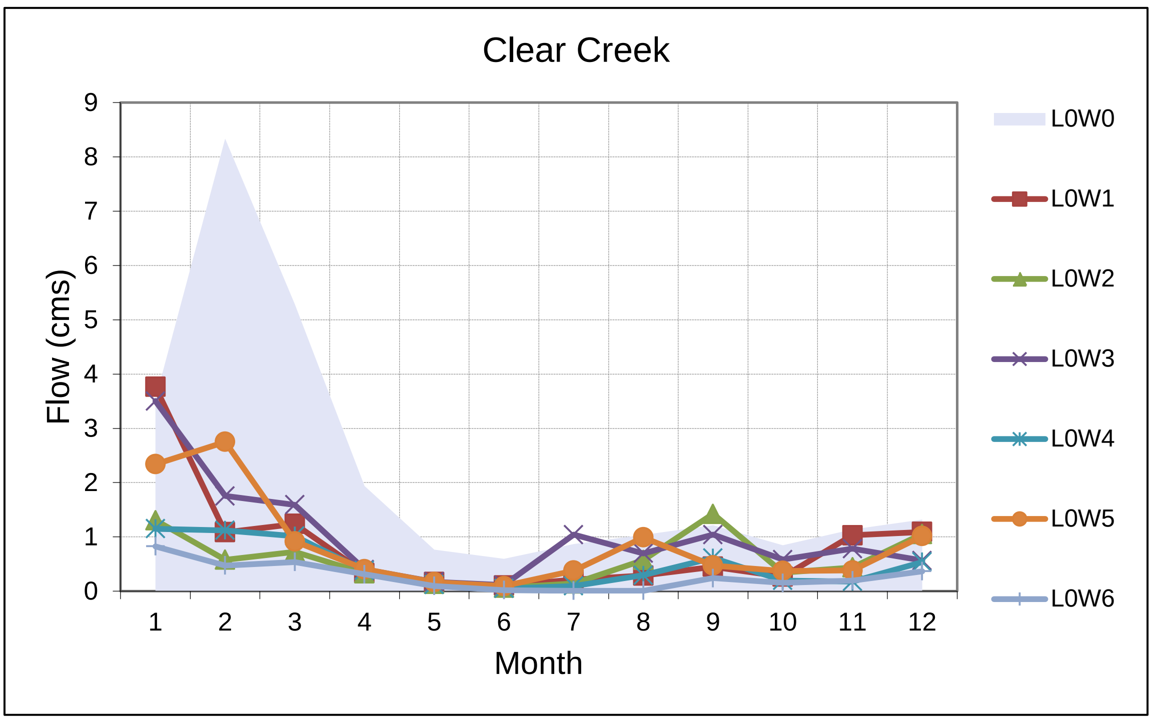


Figure 103. Monthly Average Flows, Clear Creek (SWAT)

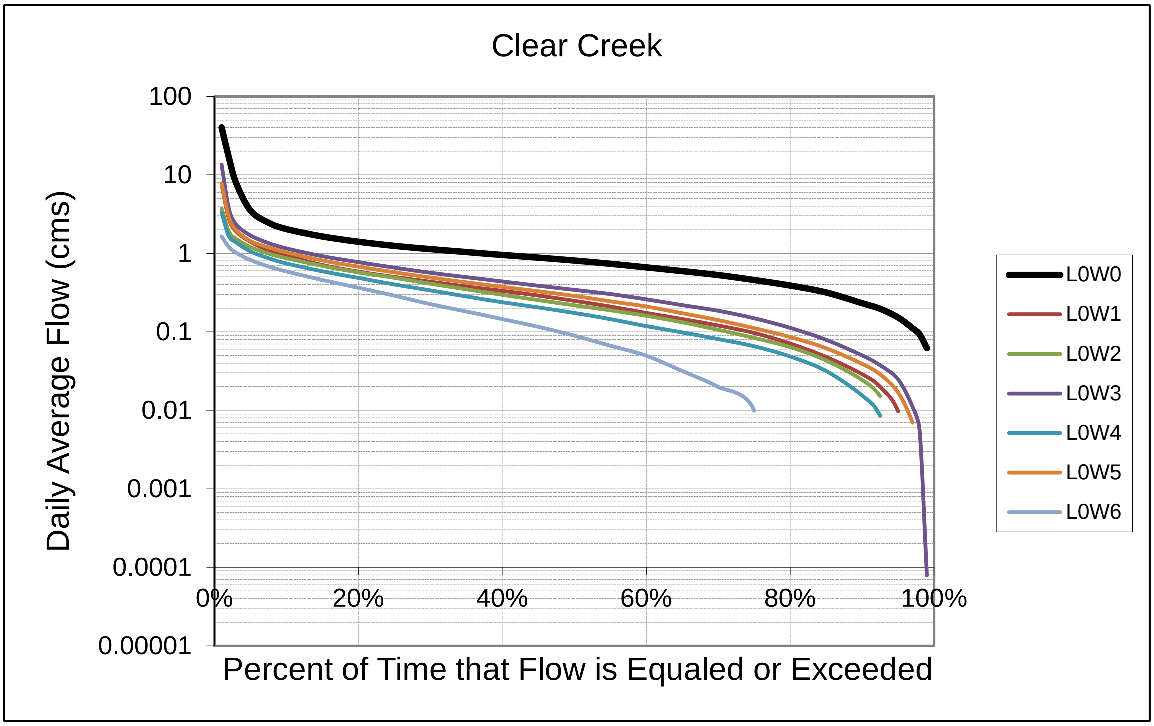


Figure 104. **Flow Duration, Clear Creek (SWAT)**

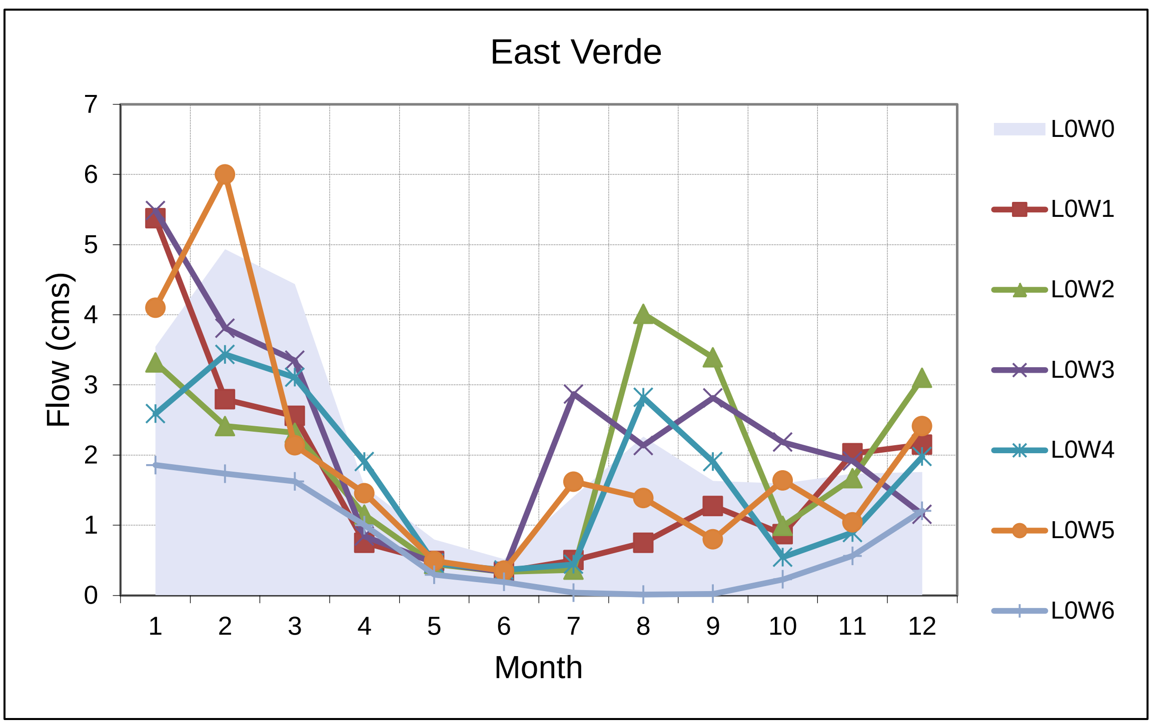


Figure 105. **Monthly Average Flows, East Verde River (SWAT)**

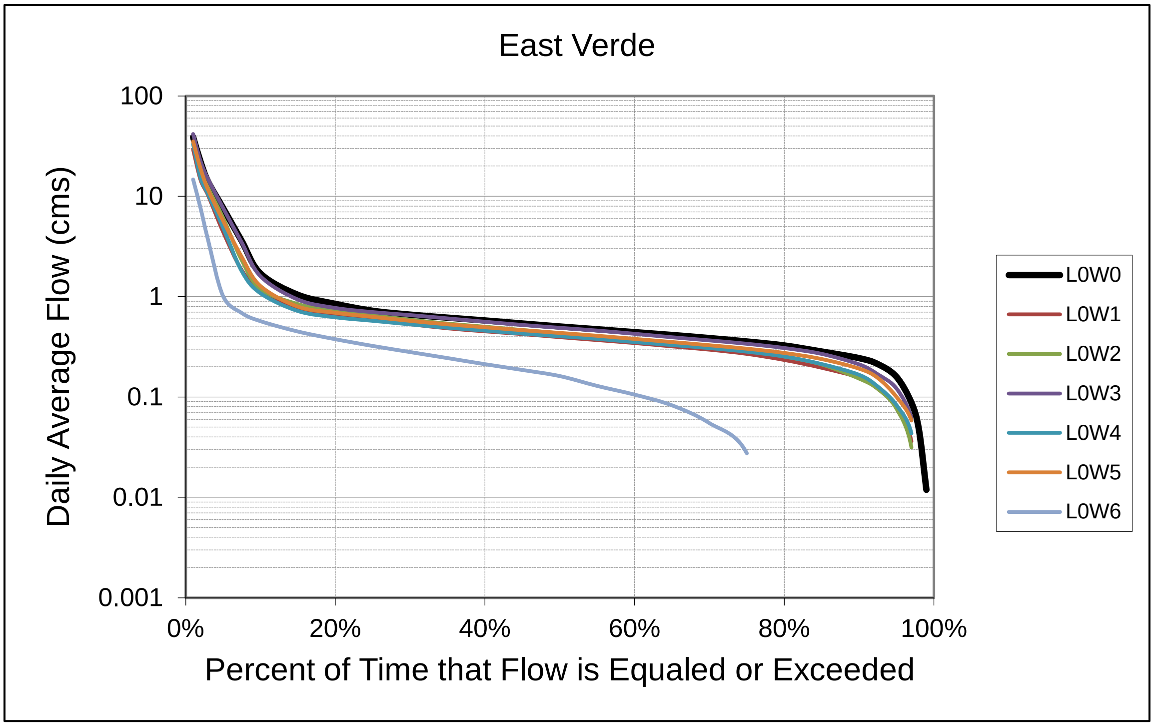


Figure 106. Flow Duration, East Verde River (SWAT)

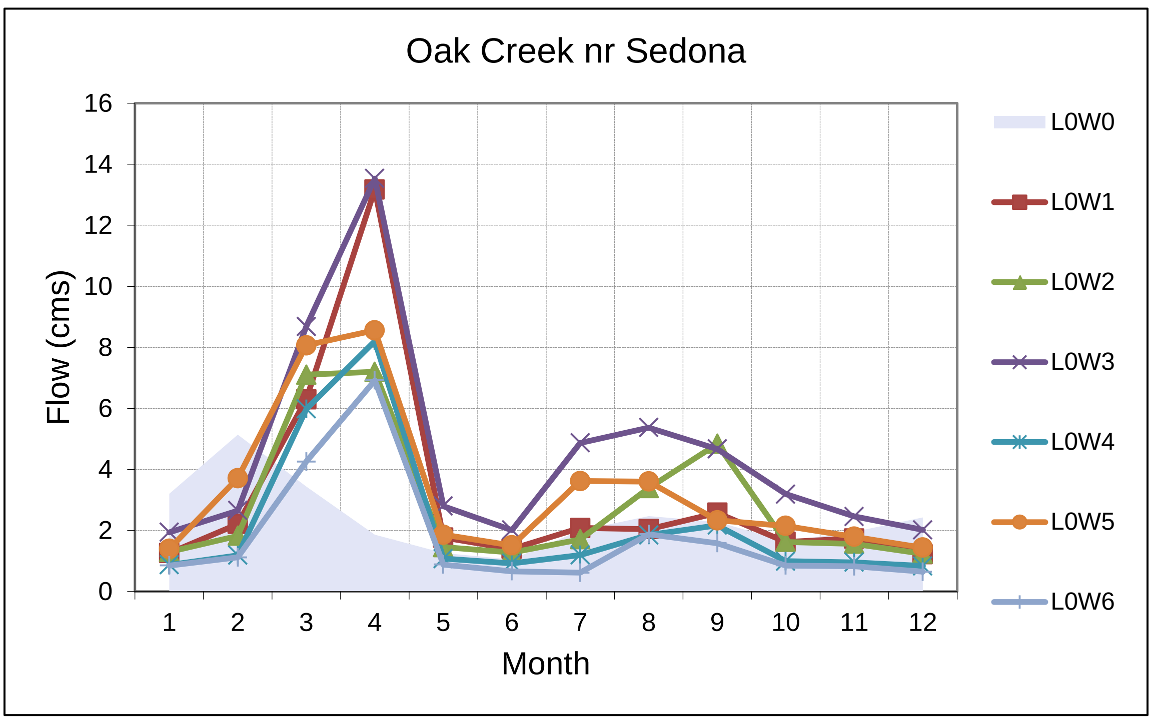


Figure 107. Monthly Average Flows, Oak Creek near Sedona (SWAT)

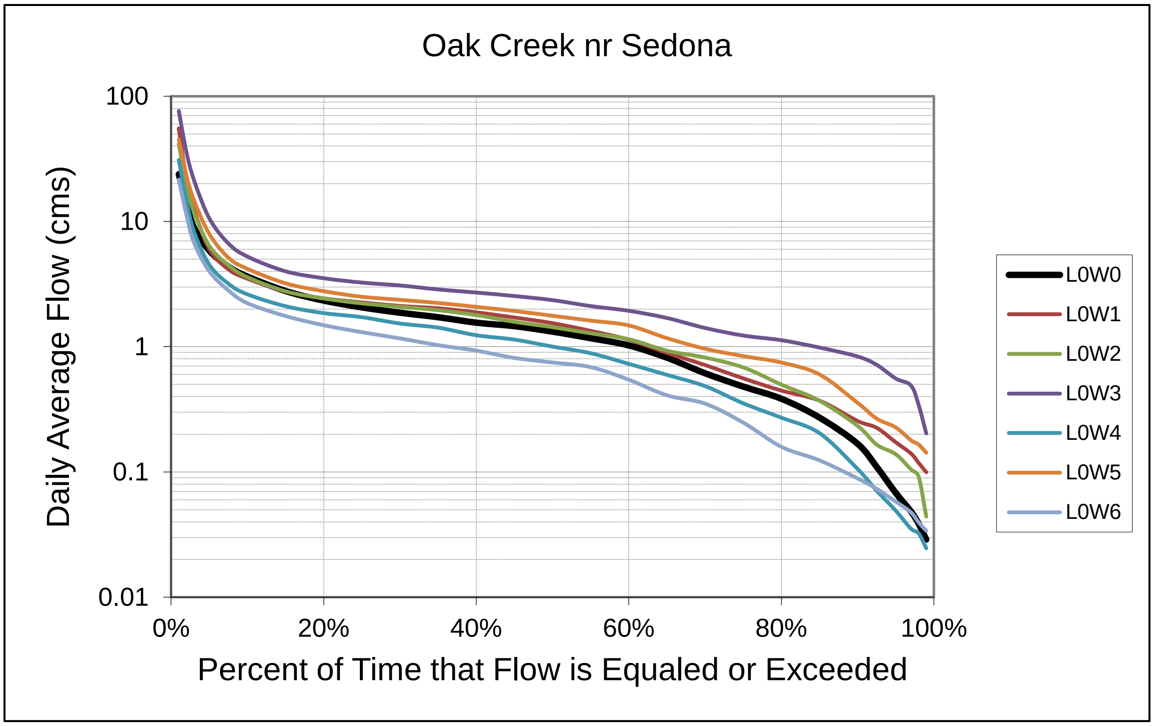


Figure 108. **Flow Duration, Oak Creek near Sedona (SWAT)**

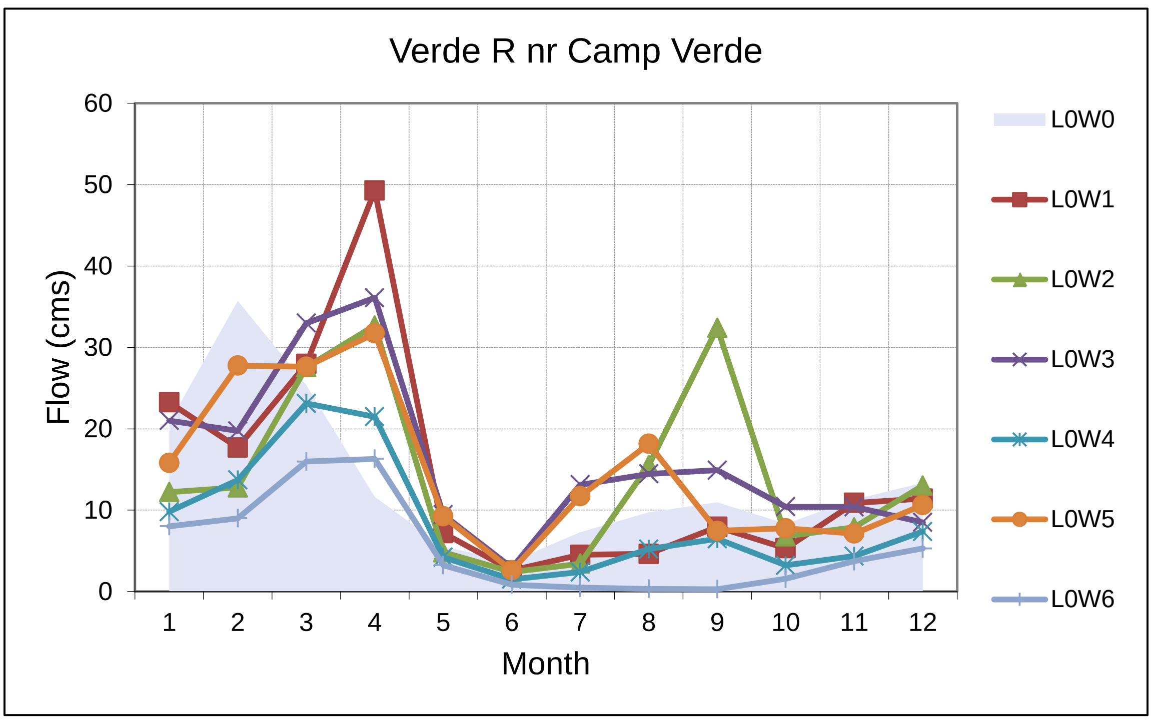


Figure 109. **Monthly Average Flows, Verde River near Camp Verde (SWAT)**

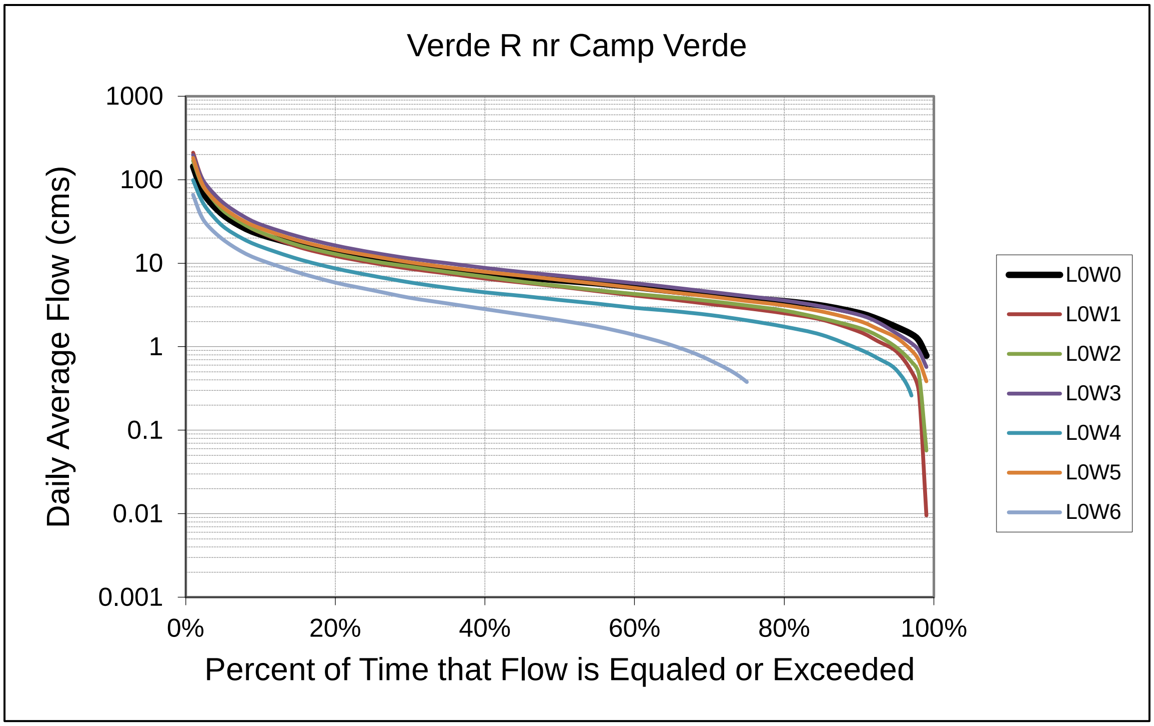


Figure 110. **Flow Duration, Verde River near Camp Verde (SWAT)**

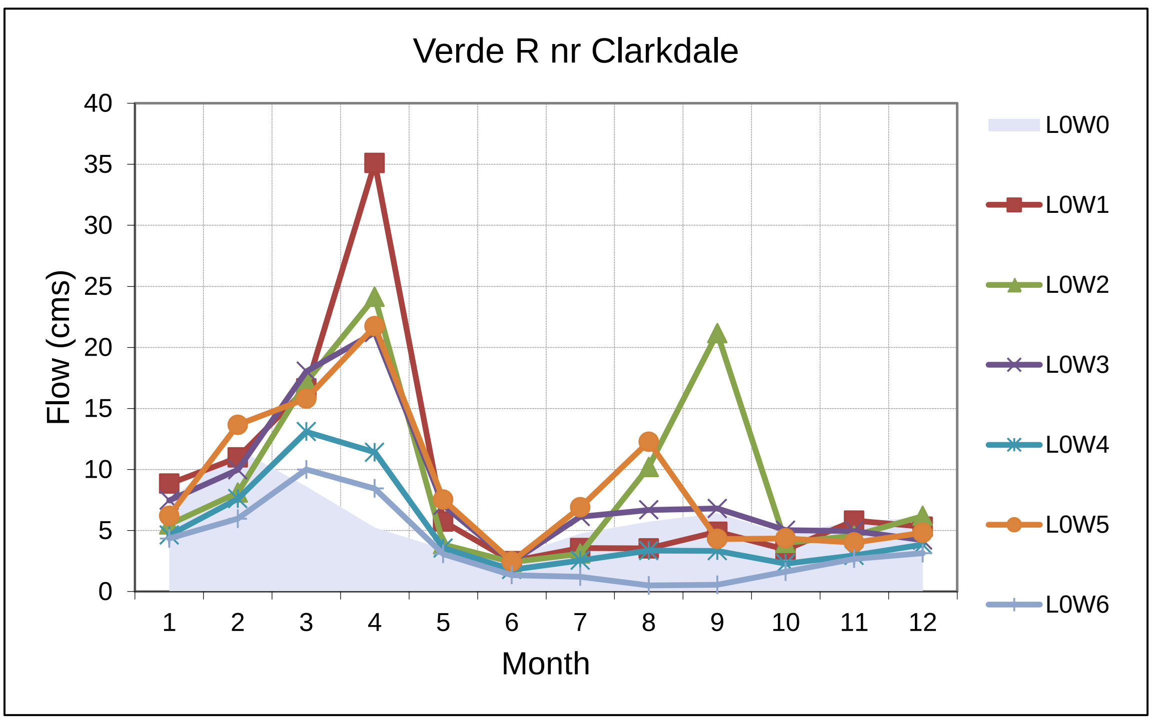


Figure 111. **Monthly Average Flows, Verde River near Clarkdale (SWAT)**

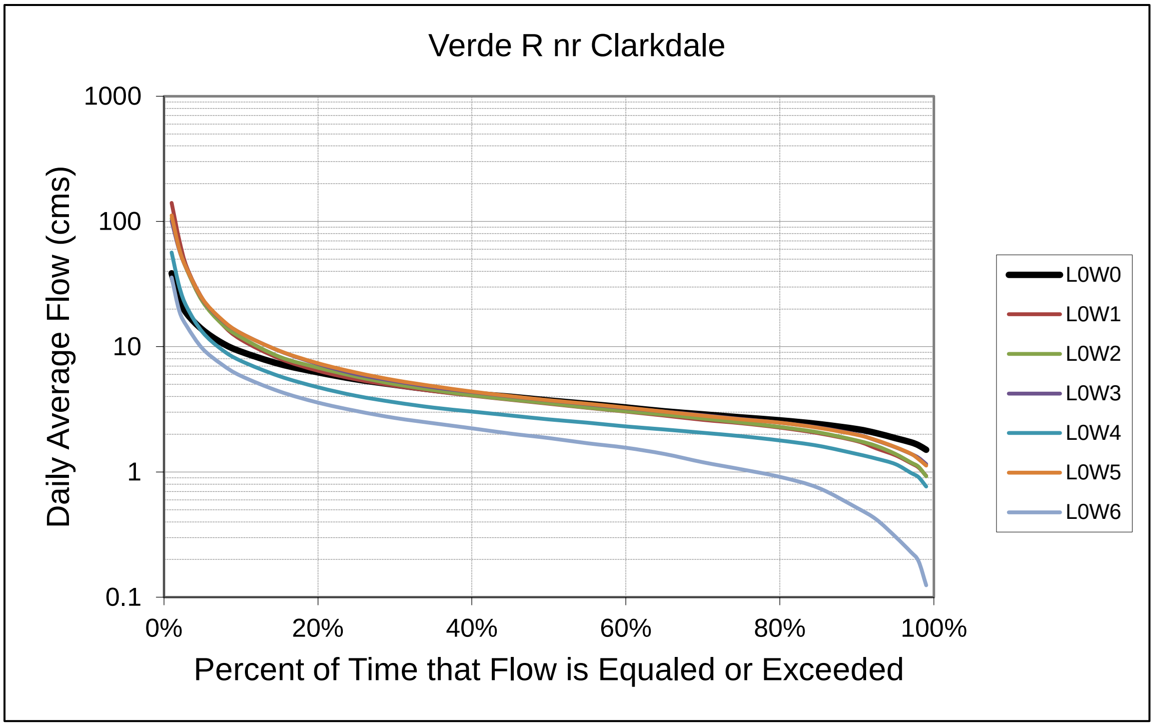


Figure 112. **Flow Duration, Verde River near Clarkdale (SWAT)**

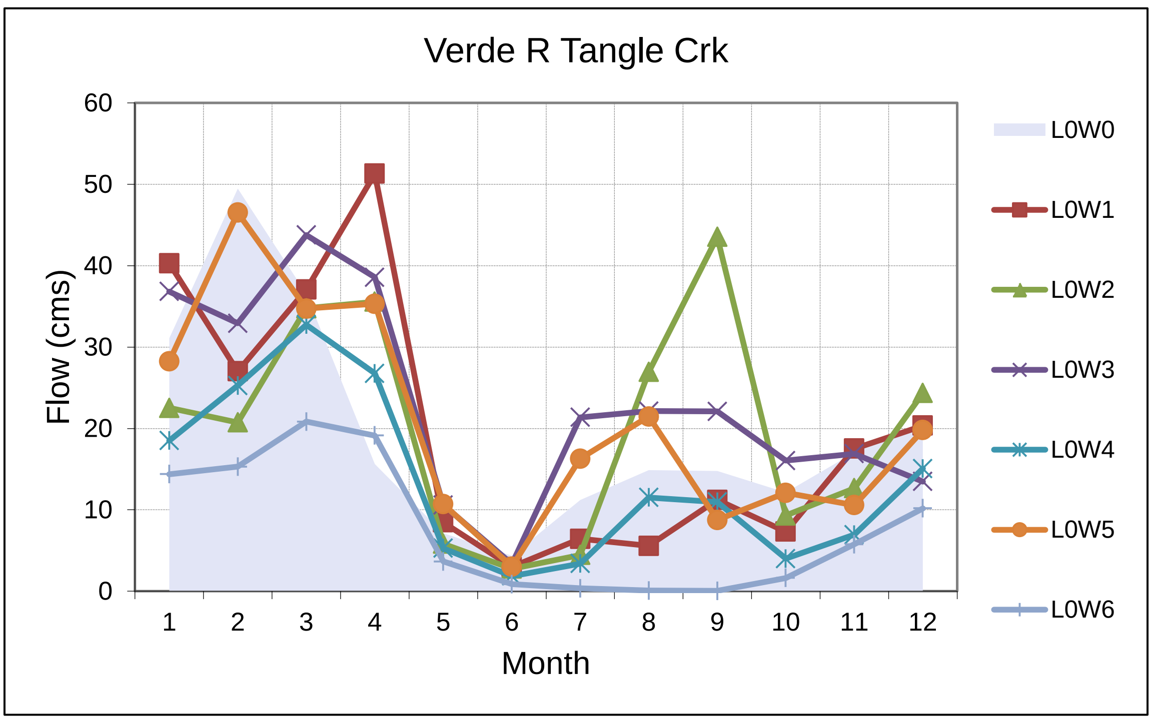


Figure 113. Monthly Average Flows, Verde River below Tangle Creek (SWAT)

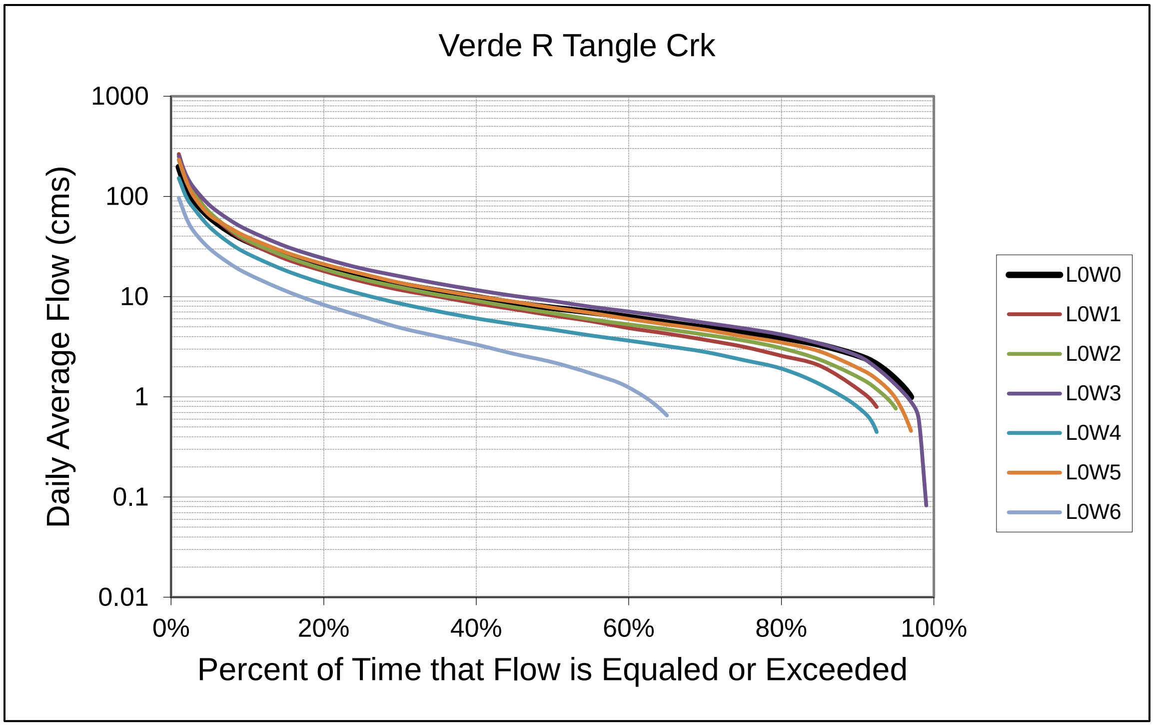


Figure 114. **Flow Duration, Verde River below Tangle Creek (SWAT)**

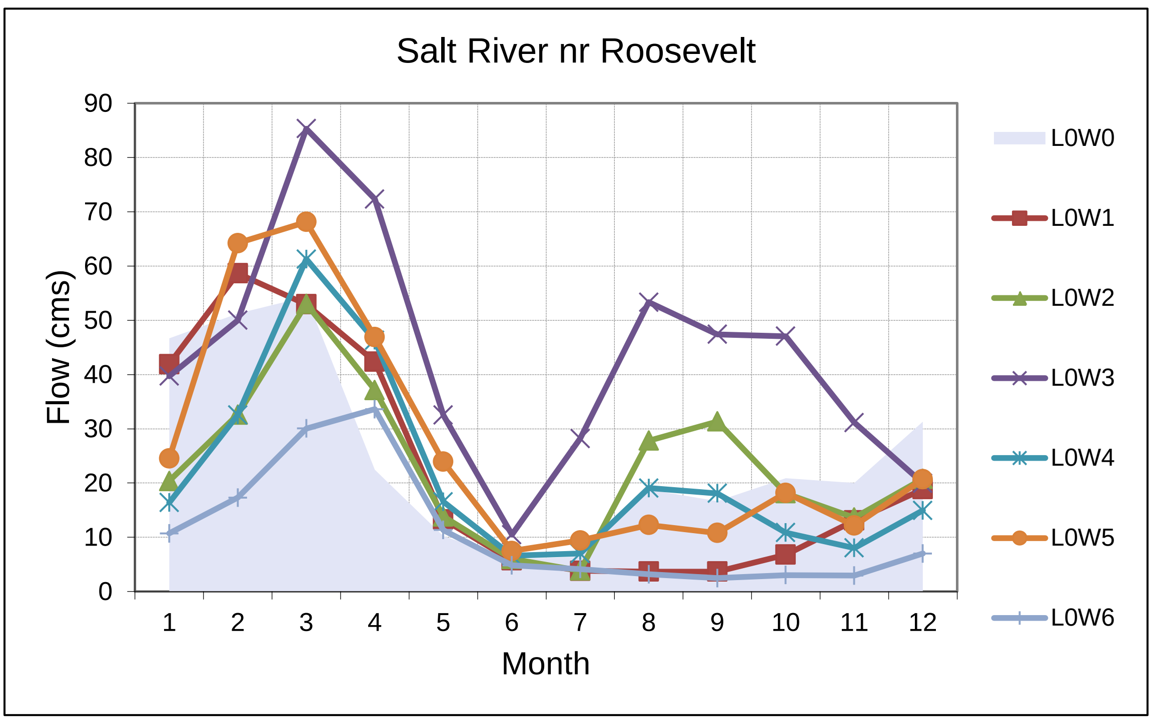


Figure 115. **Monthly Average Flows, Salt River near Roosevelt (SWAT)**

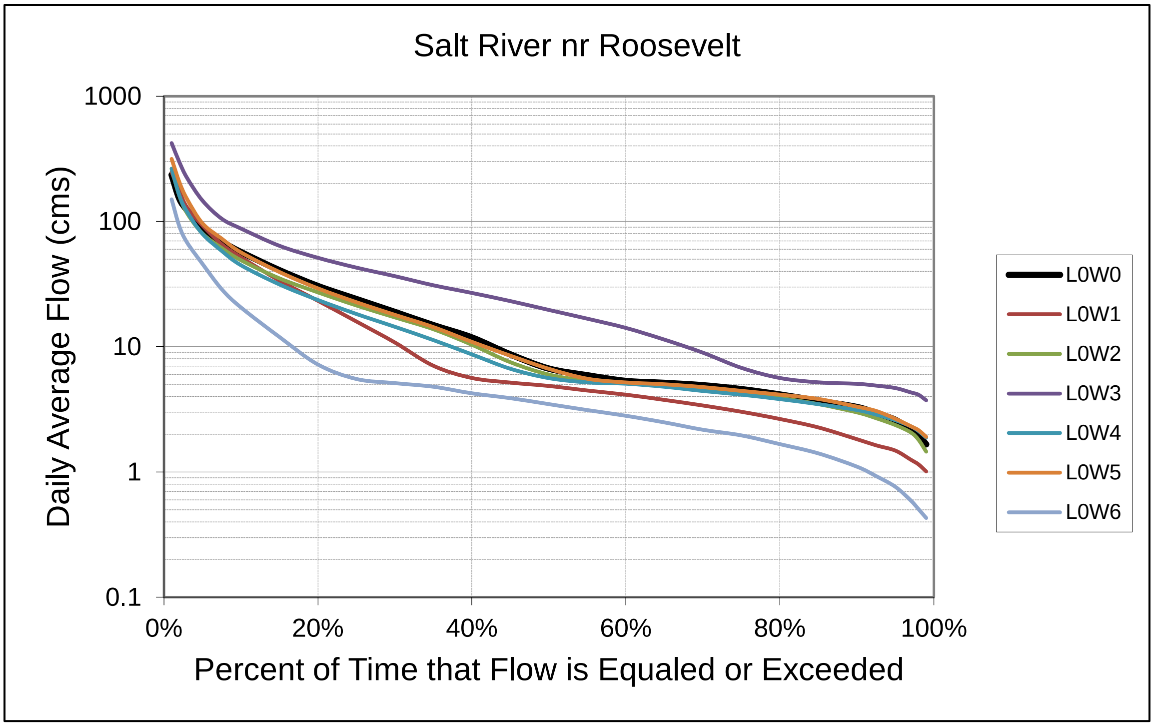


Figure 116. Flow Duration, Salt River near Roosevelt (SWAT)

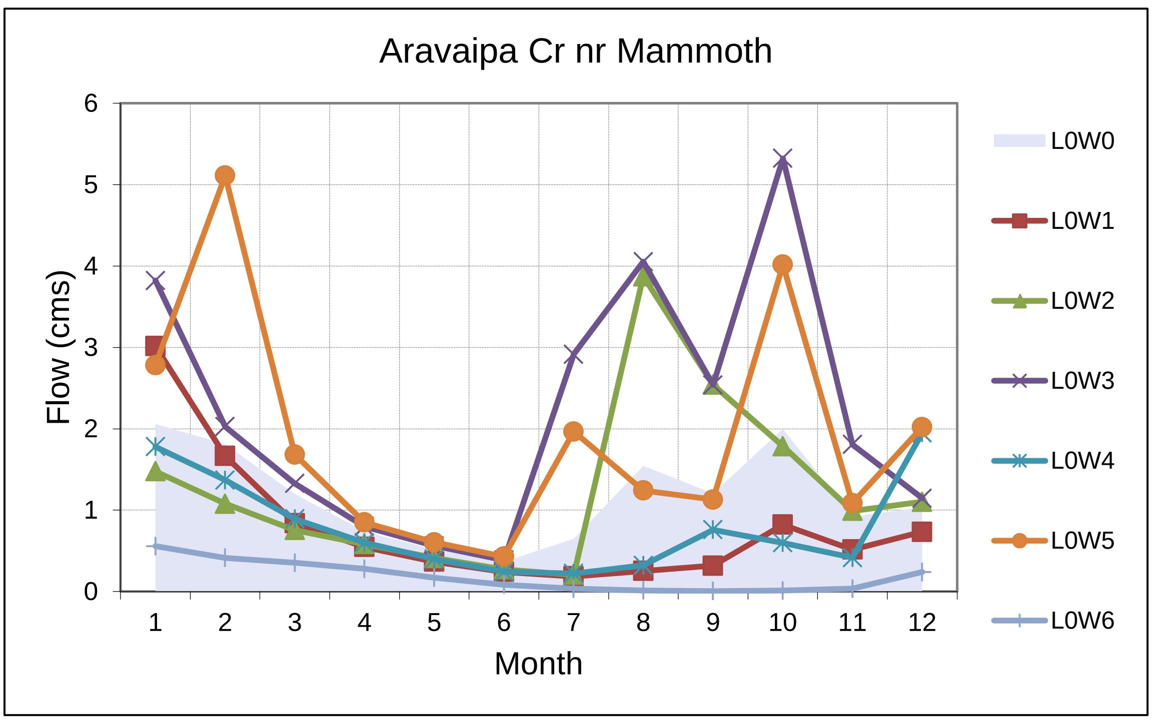


Figure 117. Monthly Average Flows, Aravaipa Creek near Mammoth (SWAT)

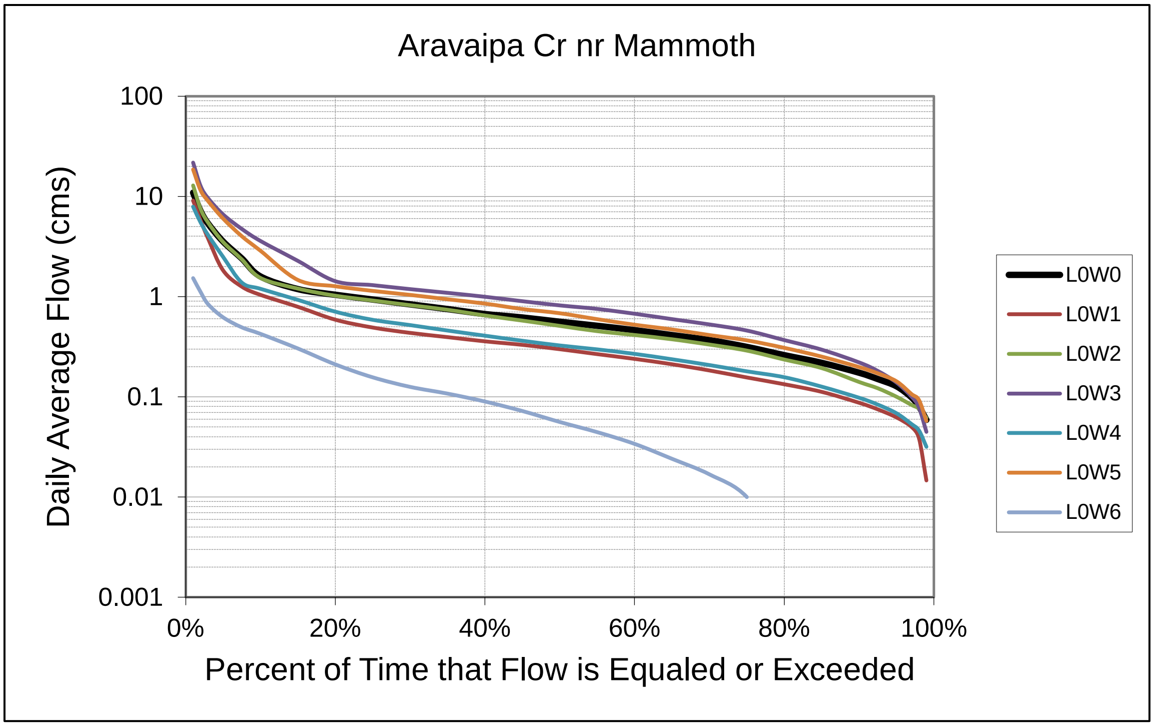


Figure 118. **Flow Duration, Aravaipa Creek near Mammoth (SWAT)**

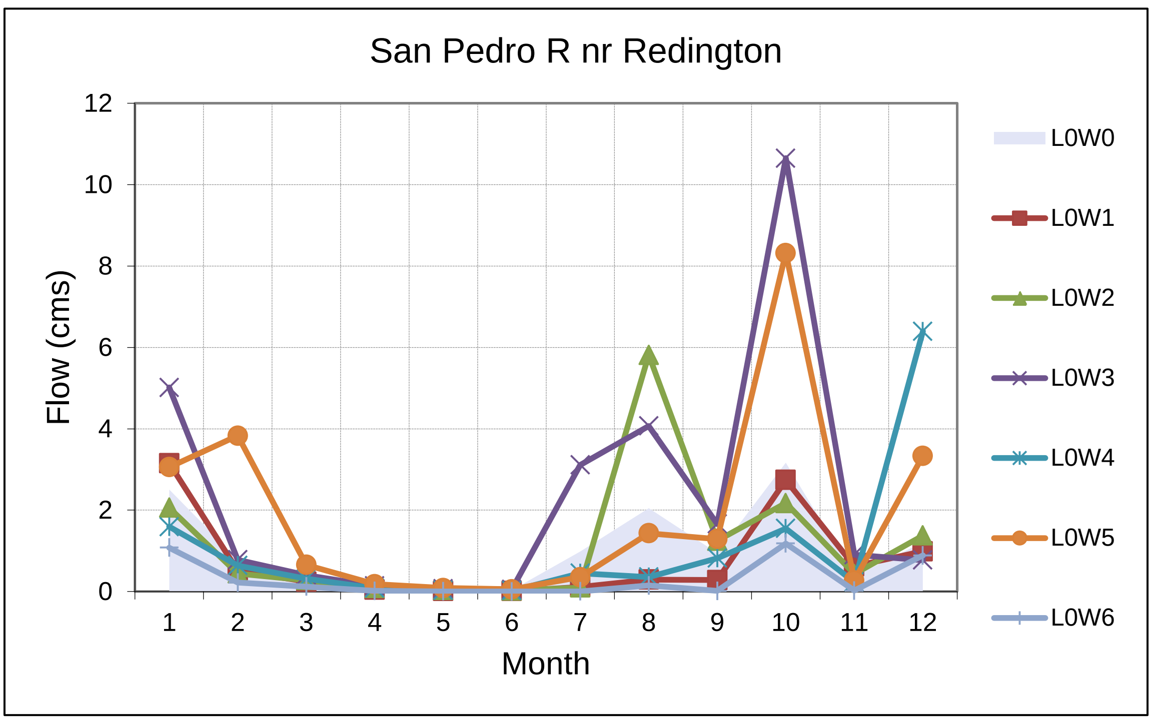


Figure 119. **Monthly Average Flows, San Pedro River near Redington (SWAT)**

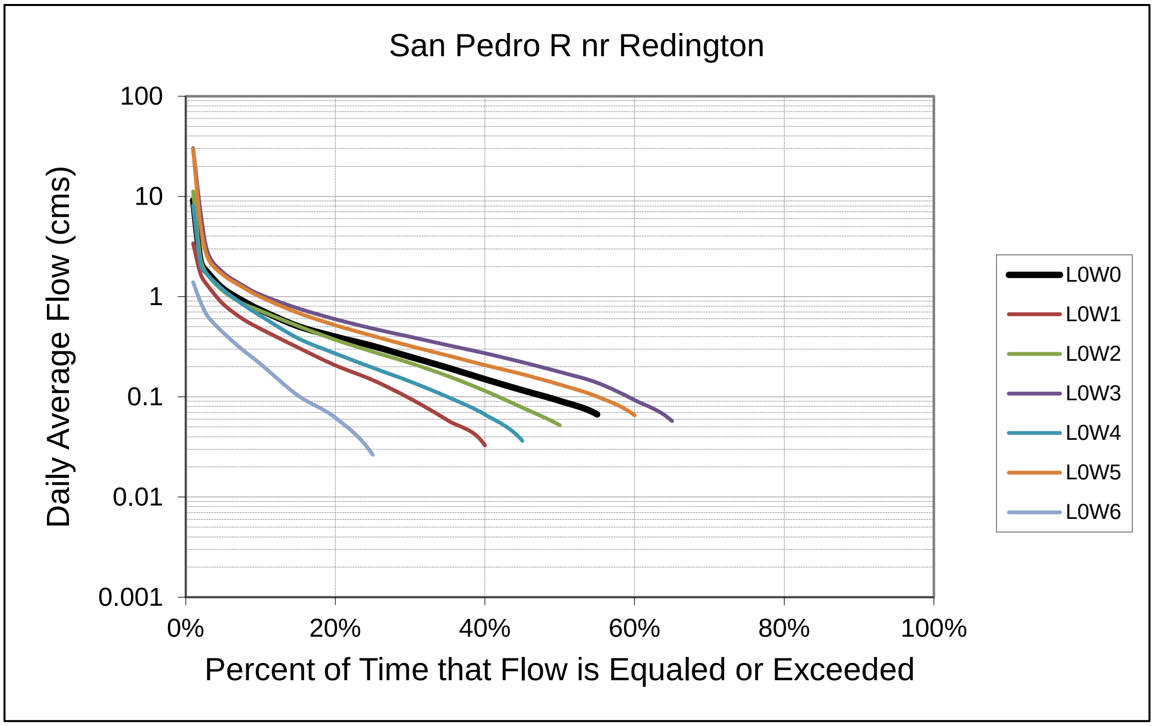


Figure 120. Flow Duration, San Pedro River near Redington (SWAT)

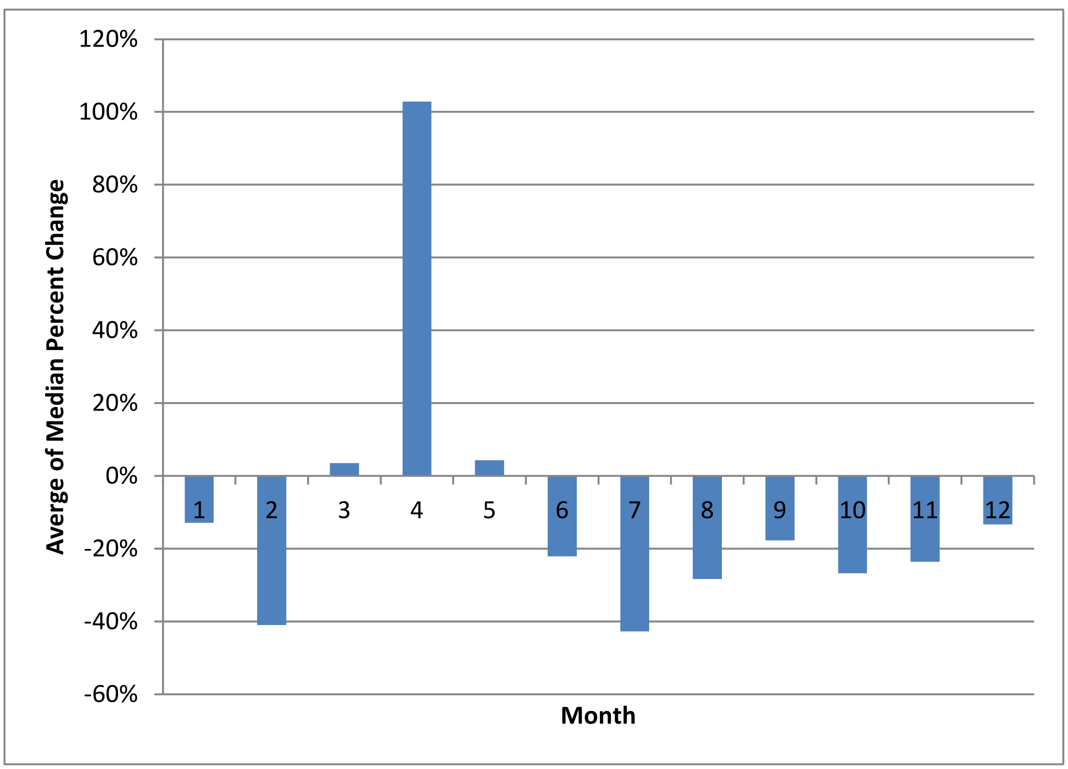


Figure 121. Average of Median Percent Change in Flow; NARCCAP Scenarios W1-W6 at all Stations, Verde-Salt-San Pedro Basins (SWAT)

Minnesota River (Upper Mississippi Basin), HSPF Model Results at Downstream Station

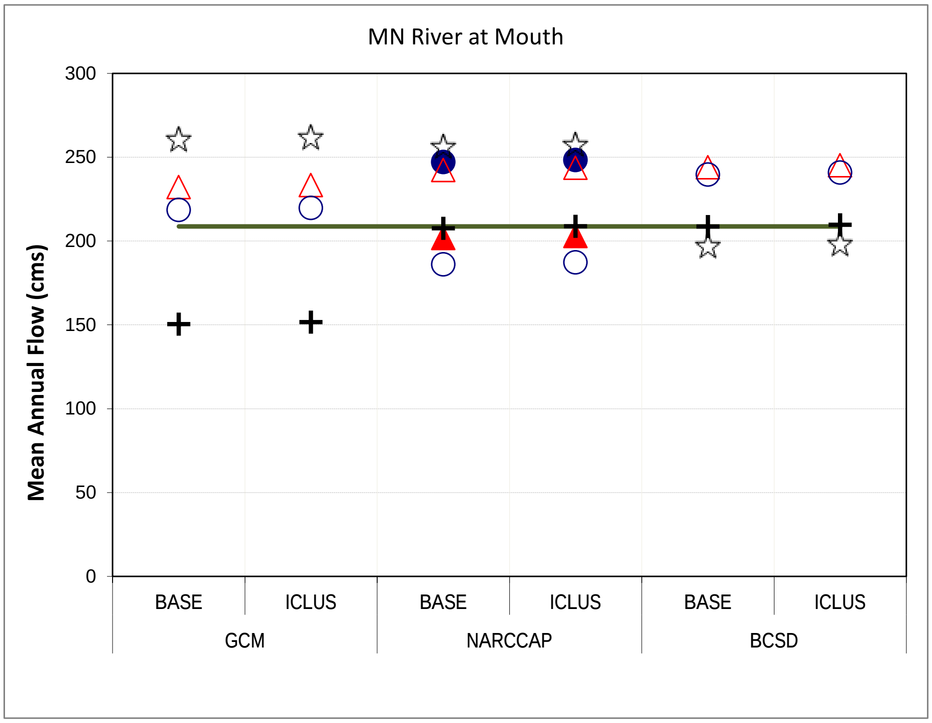


Figure 122. Mean Annual Flow, Minnesota River at Mouth (HSPF)

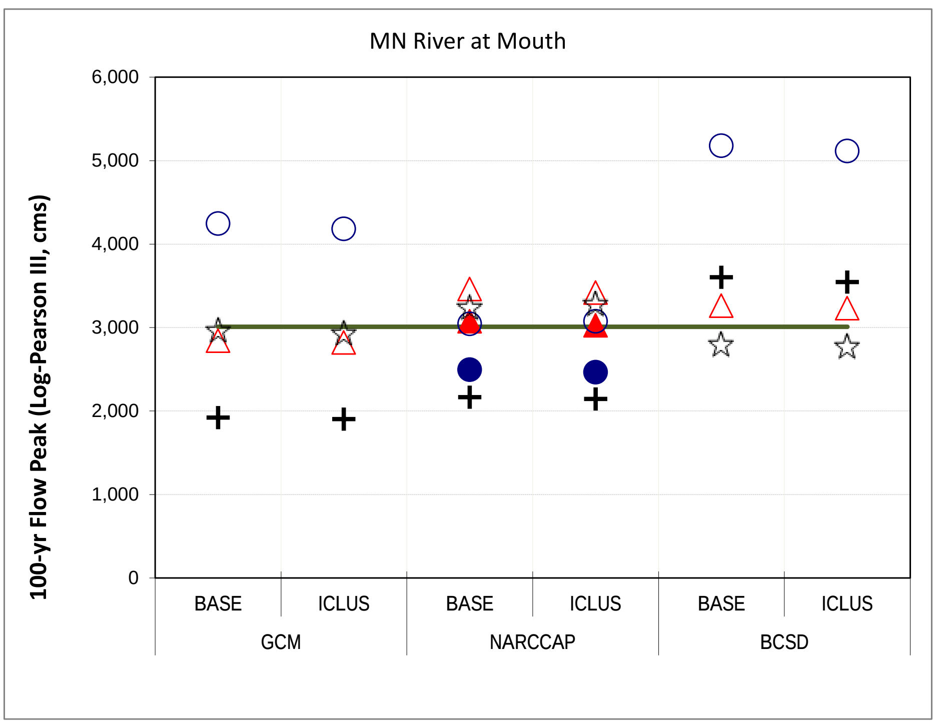


Figure 123. 100-yr Flow Peak, Minnesota River at Mouth (HSPF)

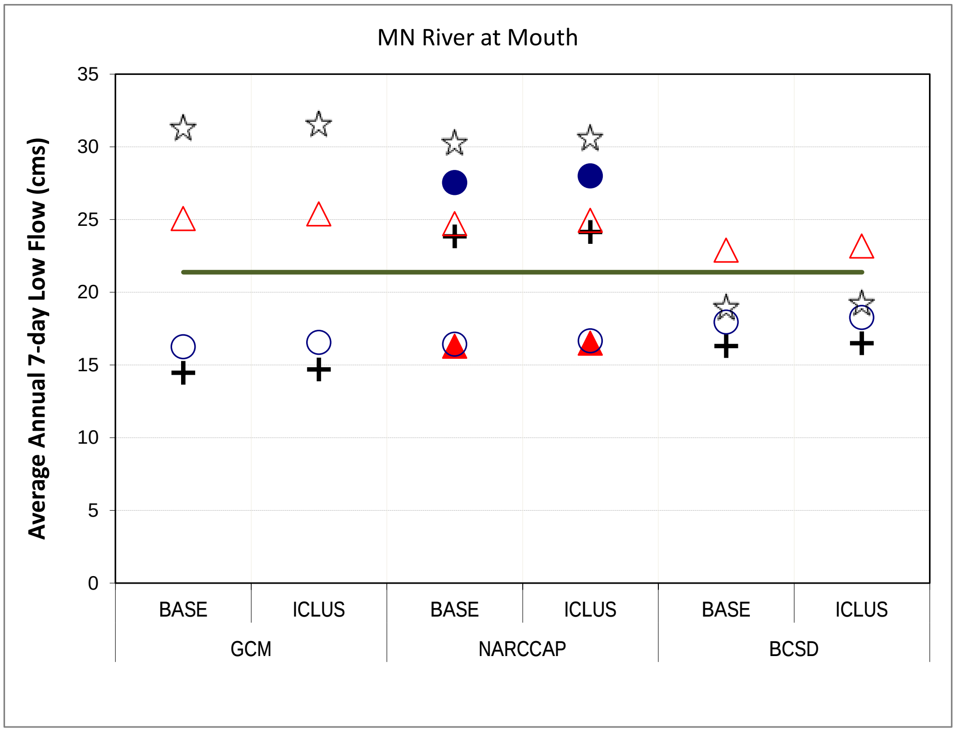


Figure 124. **Average Annual 7-day Low Flow, Minnesota River at Mouth (HSPF)**

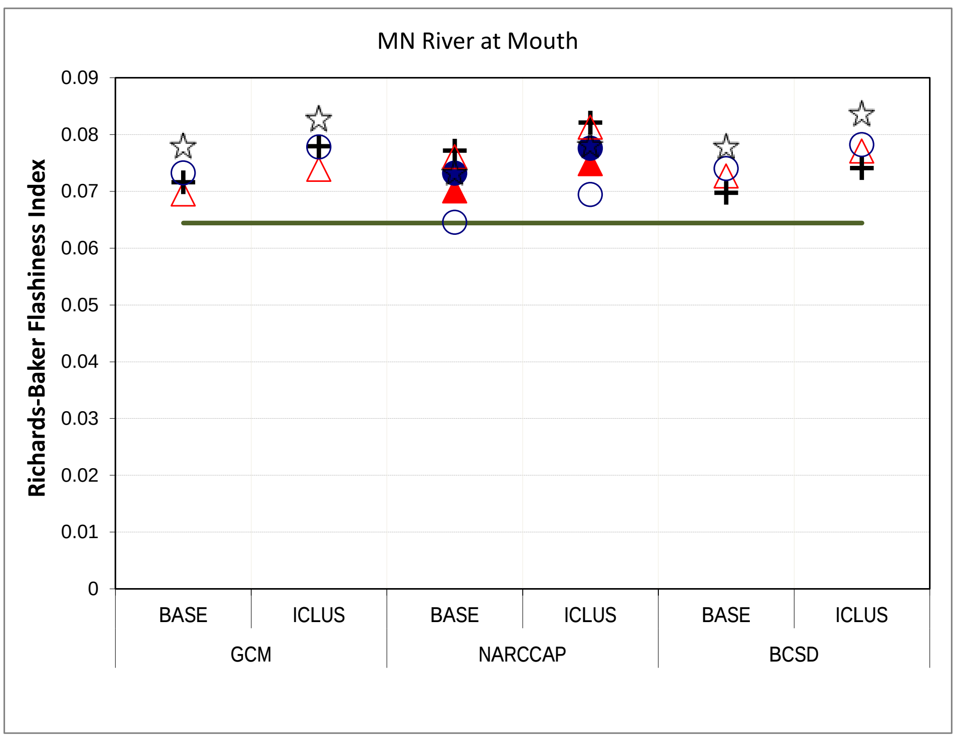


Figure 125. **Richards-Baker Flashiness Index, Minnesota River at Mouth (HSPF)**

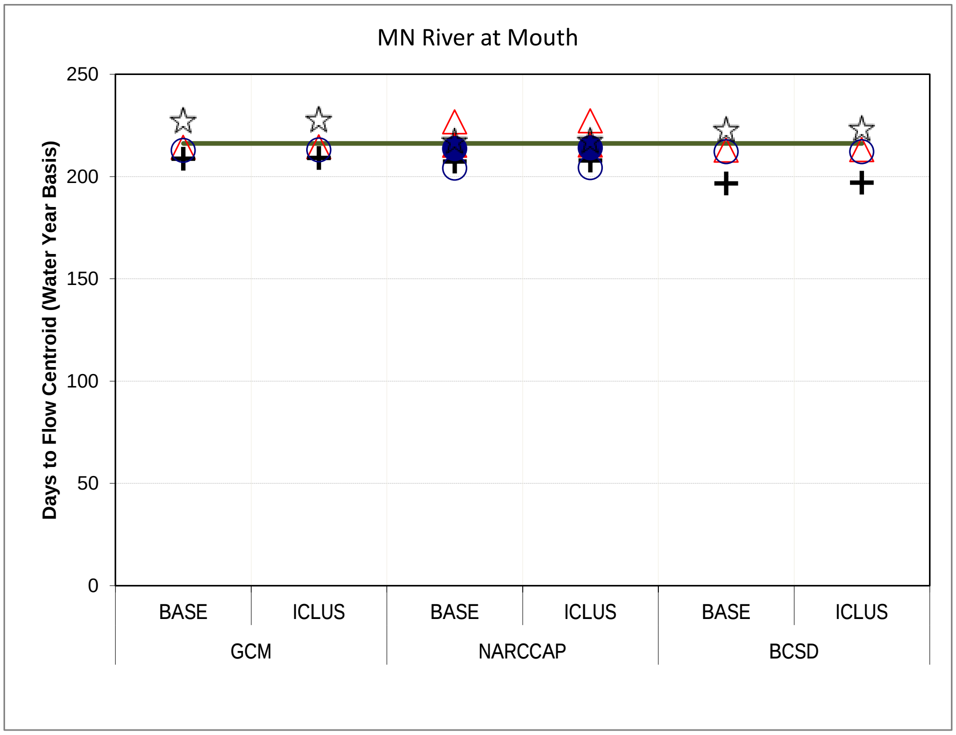


Figure 126. Days Flow to Centroid, Minnesota River at Mouth (HSPF)

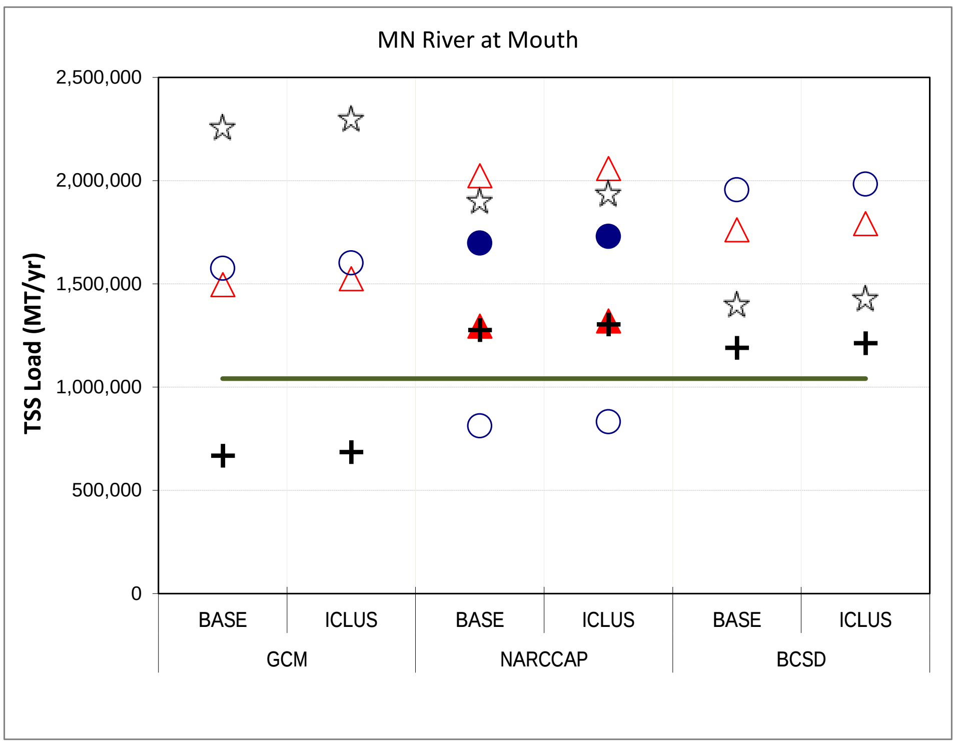


Figure 127. TSS Load, Minnesota River at Mouth (HSPF)

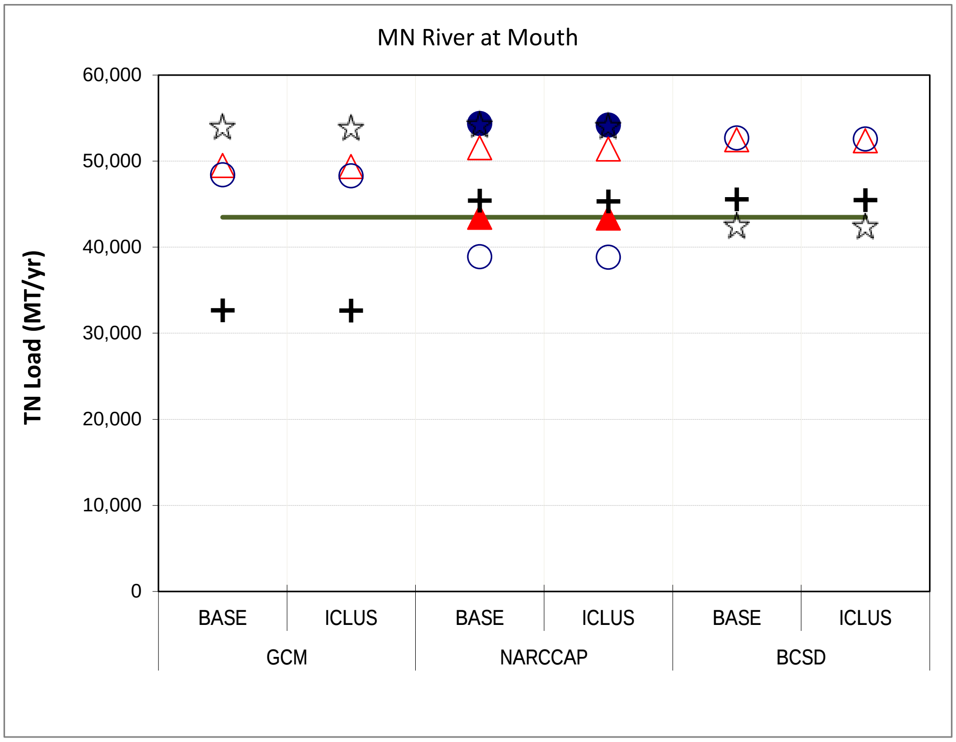


Figure 128. **TN Load, Minnesota River at Mouth (HSPF)**

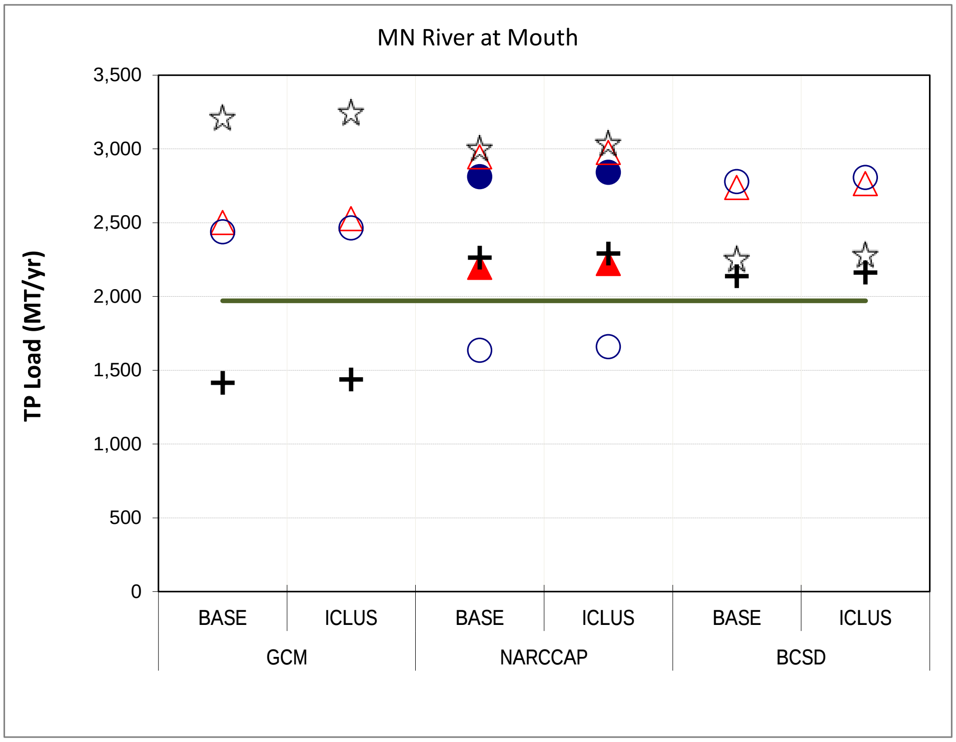


Figure 129. **TP Load, Minnesota River at Mouth (HSPF)**

Results at Multiple Stations

Table 5. Summary of Range of Change Relative to Existing Conditions for NARCCAP Dynamically Downscaled Scenarios, Minnesota River Basin (HSPF)

	Results without LU Change				Results with LU Change			
	Min	Median	Mean	Max	Min	Median	Mean	Max
Yellow Medicine River (gage 05313500)								
Flow	-10.06%	9.40%	7.36%	20.56%	-10.06%	9.40%	7.36%	20.56%
TSS	-3.34%	46.70%	35.03%	59.07%	-3.34%	46.70%	35.03%	59.07%
TN	-6.39%	11.21%	9.90%	25.60%	-6.39%	11.21%	9.90%	25.60%
TP	-1.76%	31.49%	24.62%	45.60%	-1.76%	31.49%	24.62%	45.60%
Redwood River (gage 05316500)								
Flow	-4.49%	6.06%	7.85%	19.63%	-4.49%	6.06%	7.85%	19.63%
TSS	16.60%	57.24%	46.60%	60.37%	16.60%	57.23%	46.60%	60.37%
TN	-5.15%	13.05%	11.20%	27.70%	-5.15%	13.05%	11.20%	27.70%
TP	4.81%	27.67%	25.86%	45.04%	4.81%	27.67%	25.86%	45.04%
Cottonwood River (gage 05317000)								
Flow	-6.44%	5.79%	7.01%	20.75%	-6.44%	5.79%	7.01%	20.75%
TSS	-10.25%	52.99%	45.40%	90.03%	-10.25%	52.99%	45.40%	90.03%
TN	-5.65%	11.50%	13.10%	31.28%	-5.65%	11.50%	13.10%	31.28%
TP	-9.23%	42.09%	36.16%	67.39%	-9.23%	42.09%	36.16%	67.39%
Watonwan River (gage 05319500)								
Flow	-14.52%	13.51%	7.94%	24.23%	-14.52%	13.51%	7.94%	24.23%
TSS	-51.07%	75.47%	52.86%	119.88 %	-51.07%	75.46%	52.86%	119.87 %
TN	-12.09%	22.67%	18.00%	39.28%	-12.09%	22.67%	18.00%	39.28%
TP	-30.36%	42.97%	28.82%	59.21%	-30.36%	42.97%	28.82%	59.21%
Blue Earth River (gage 05320000)								
Flow	-17.47%	11.89%	6.06%	19.42%	-17.46%	11.89%	6.06%	19.42%
TSS	-42.34%	70.22%	47.96%	93.08%	-42.34%	70.22%	47.96%	93.08%
TN	-14.64%	14.34%	10.30%	26.52%	-14.64%	14.34%	10.30%	26.52%

	Results without LU Change				Results with LU Change			
	Min	Median	Mean	Max	Min	Median	Mean	Max
TP	-26.44%	35.32%	22.11%	42.29%	-26.44%	35.32%	22.11%	42.29%
LeSueur River (gage 05320500)								
Flow	-16.91%	14.00%	7.53%	22.37%	-16.91%	14.00%	7.53%	22.36%
TSS	-36.35%	45.96%	29.11%	62.79%	-36.34%	45.95%	29.10%	62.78%
TN	-15.26%	10.17%	5.53%	19.82%	-15.26%	10.17%	5.53%	19.81%
TP	-21.68%	32.09%	20.28%	39.93%	-21.68%	32.09%	20.28%	39.93%
Minnesota River at Mankato (gage 05325000)								
Flow	-10.06%	7.15%	6.94%	21.84%	-10.06%	7.15%	6.94%	21.84%
TSS	-21.39%	43.35%	42.43%	86.59%	-21.39%	43.35%	42.43%	86.58%
TN	-10.65%	10.70%	9.44%	23.23%	-10.65%	10.70%	9.44%	23.23%
TP	-16.40%	28.88%	25.91%	50.99%	-16.40%	28.87%	25.91%	50.99%
Minnesota River nr Jordan (gage 05330000)								
Flow	-10.66%	7.67%	7.15%	22.77%	-10.65%	7.67%	7.15%	22.76%
TSS	-21.05%	46.52%	46.52%	97.42%	-21.04%	46.37%	46.37%	97.12%
TN	-10.80%	11.65%	10.45%	25.23%	-10.79%	11.64%	10.43%	25.19%
TP	-17.31%	29.59%	26.31%	53.21%	-17.29%	29.55%	26.28%	53.16%
Minnesota River at Mouth								
Flow	-10.83%	7.79%	7.16%	23.12%	-10.79%	7.80%	7.15%	23.05%
TSS	-22.00%	43.74%	44.32%	94.35%	-22.04%	42.85%	43.43%	92.79%
TN	-10.57%	11.48%	10.39%	25.07%	-10.54%	11.40%	10.31%	24.88%
TP	-17.10%	28.68%	25.64%	52.72%	-16.95%	28.44%	25.43%	52.40%

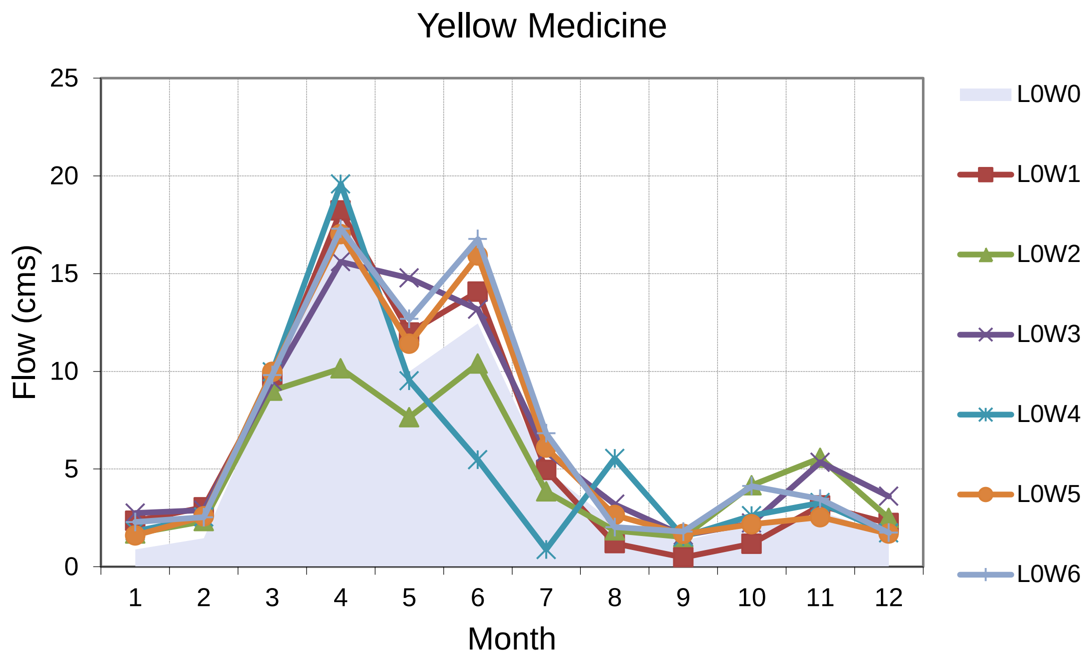


Figure 130. Monthly Average Flows, Yellow Medicine River (HSPF)

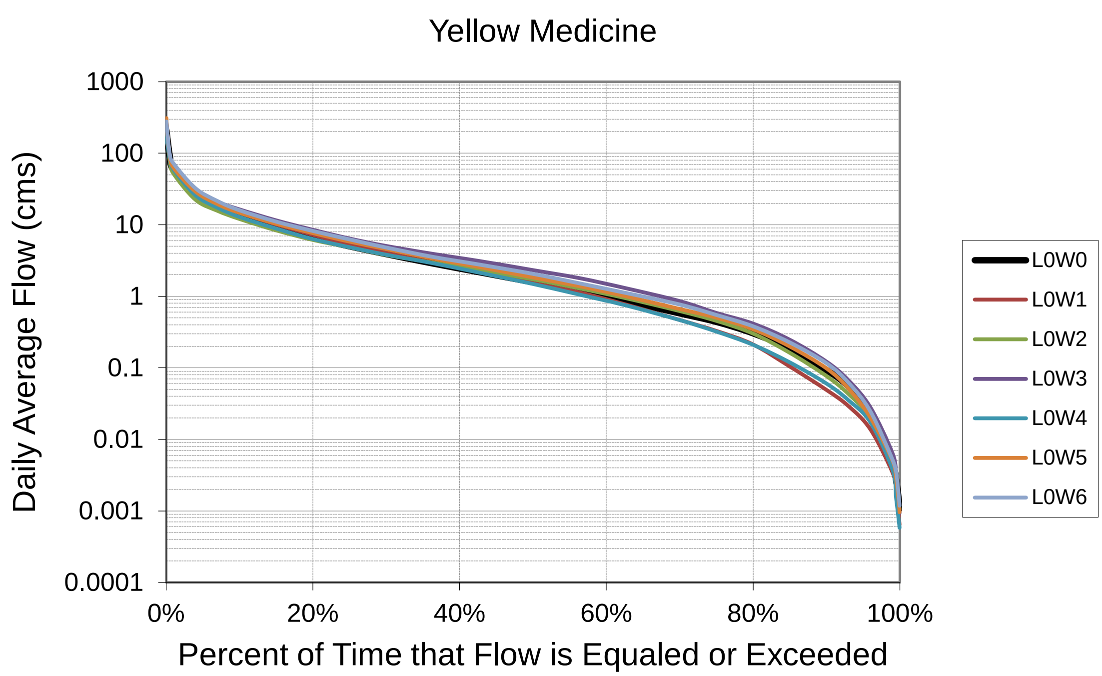


Figure 131. Flow Duration, Yellow Medicine River (HSPF)

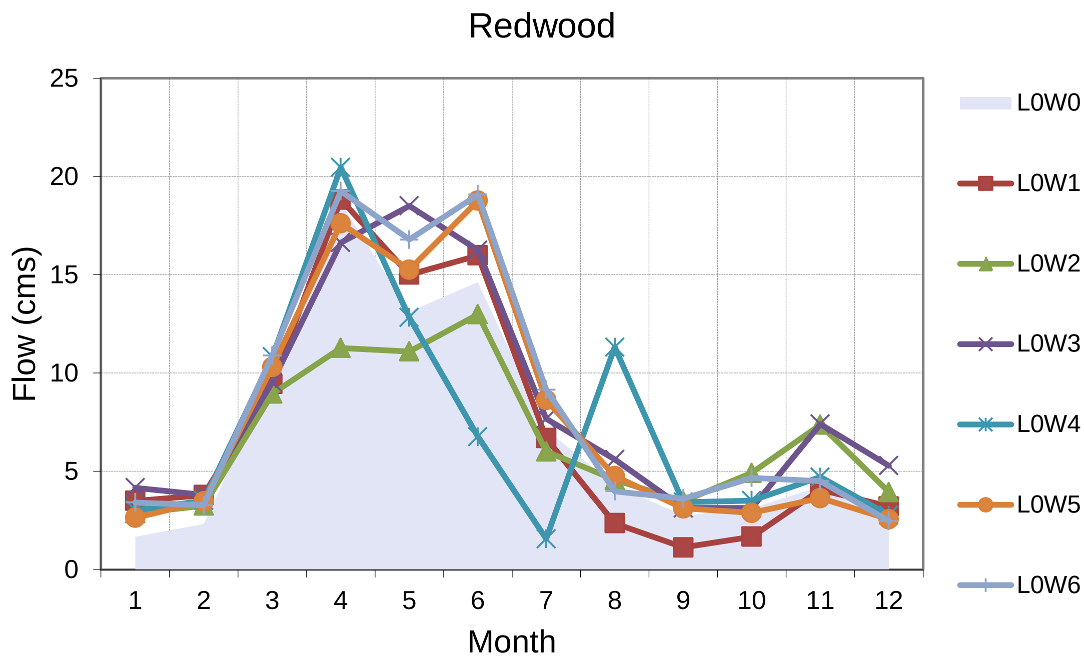


Figure 132. Monthly Average Flows, Redwood River (HSPF)

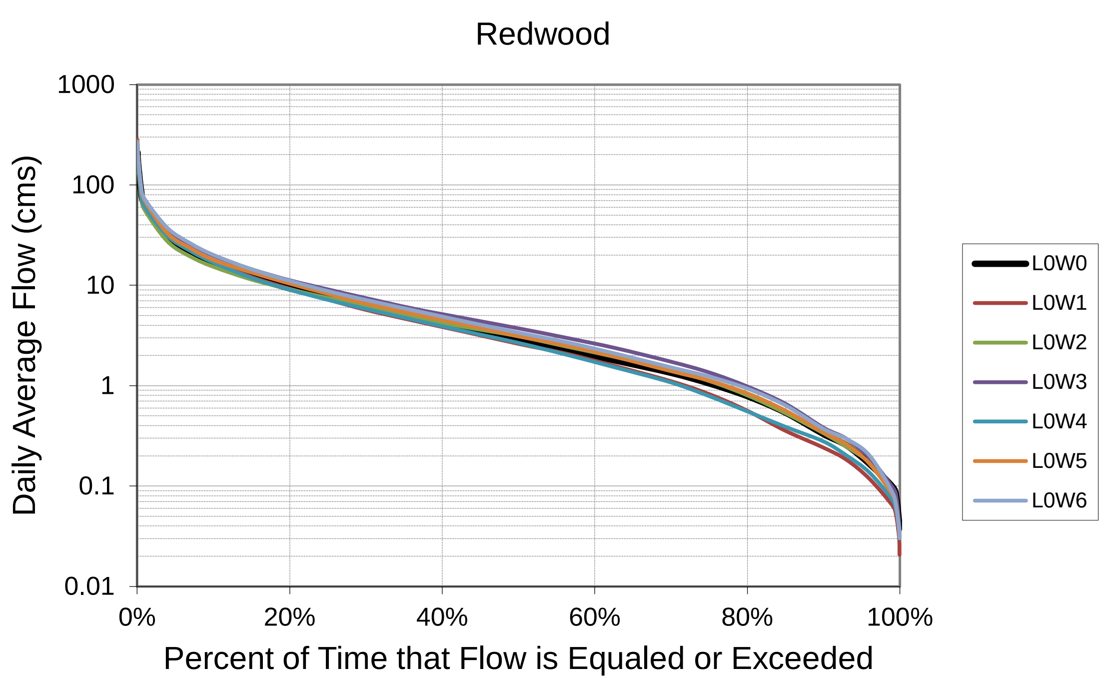


Figure 133. Flow Duration, Redwood River (HSPF)

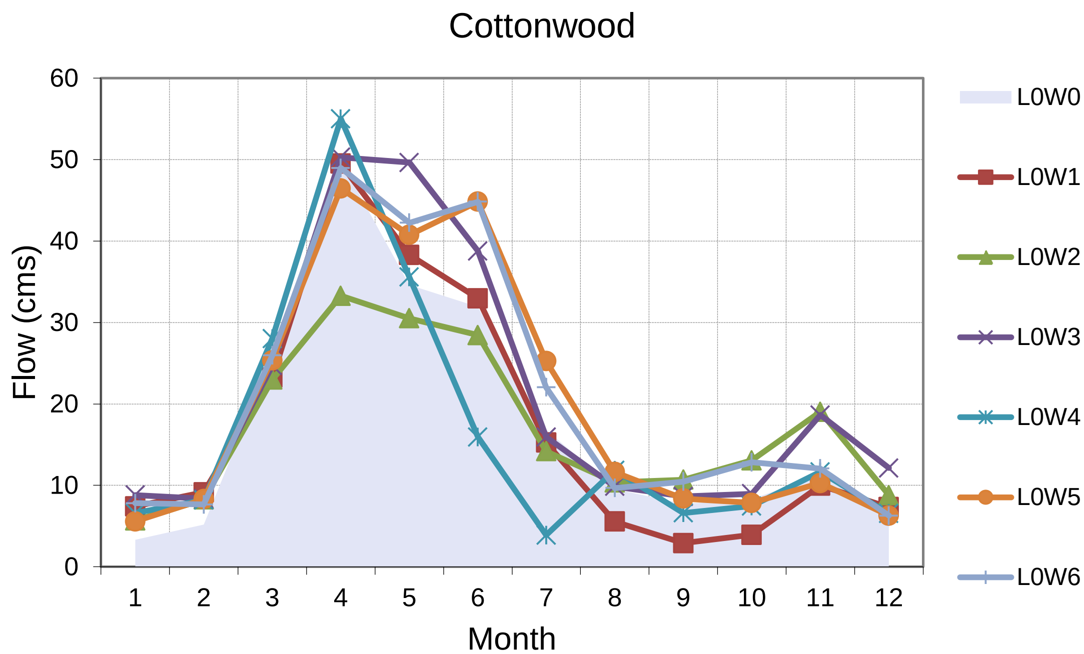


Figure 134. **Monthly Average Flows, Cottonwood River (HSPF)**

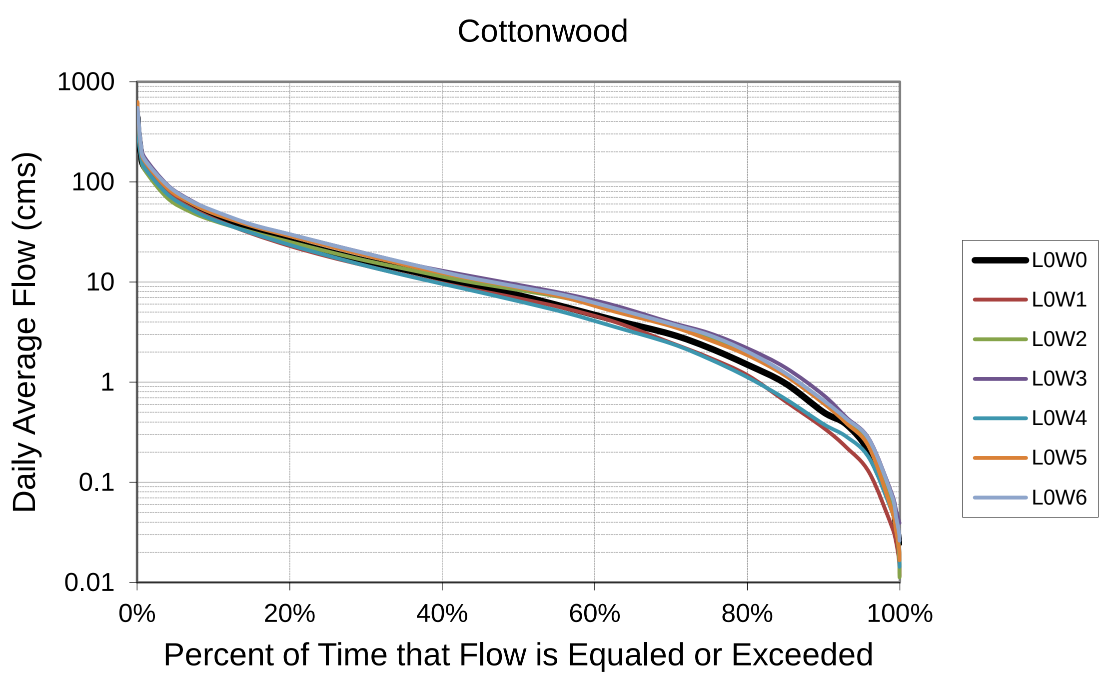


Figure 135. **Flow Duration, Cottonwood River (HSPF)**

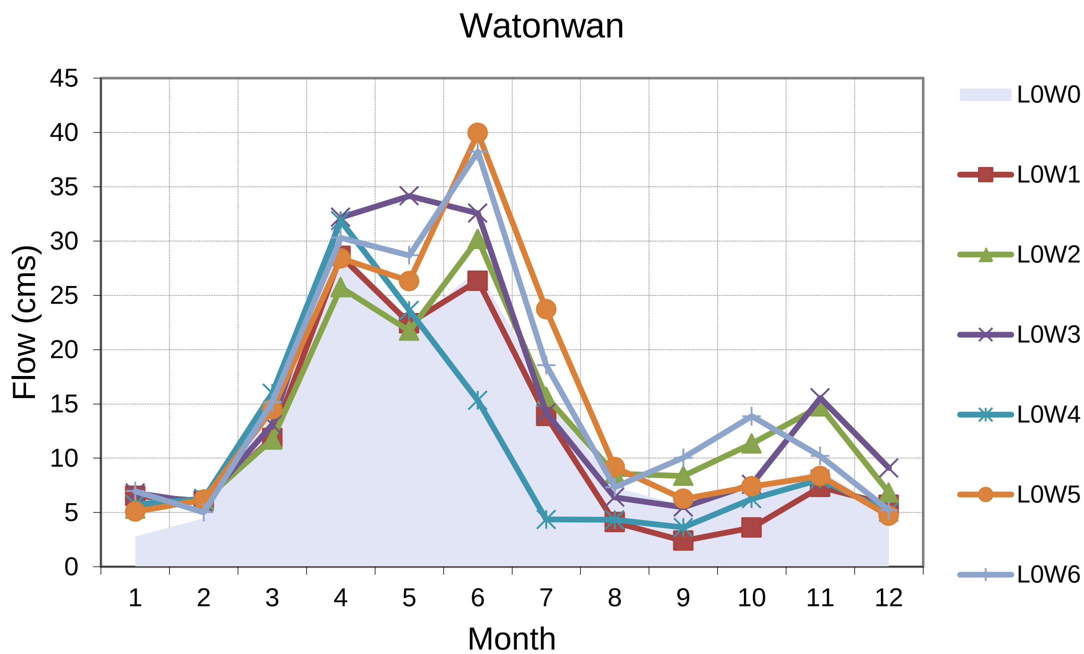


Figure 136. Monthly Average Flows, Watonwan River (HSPF)

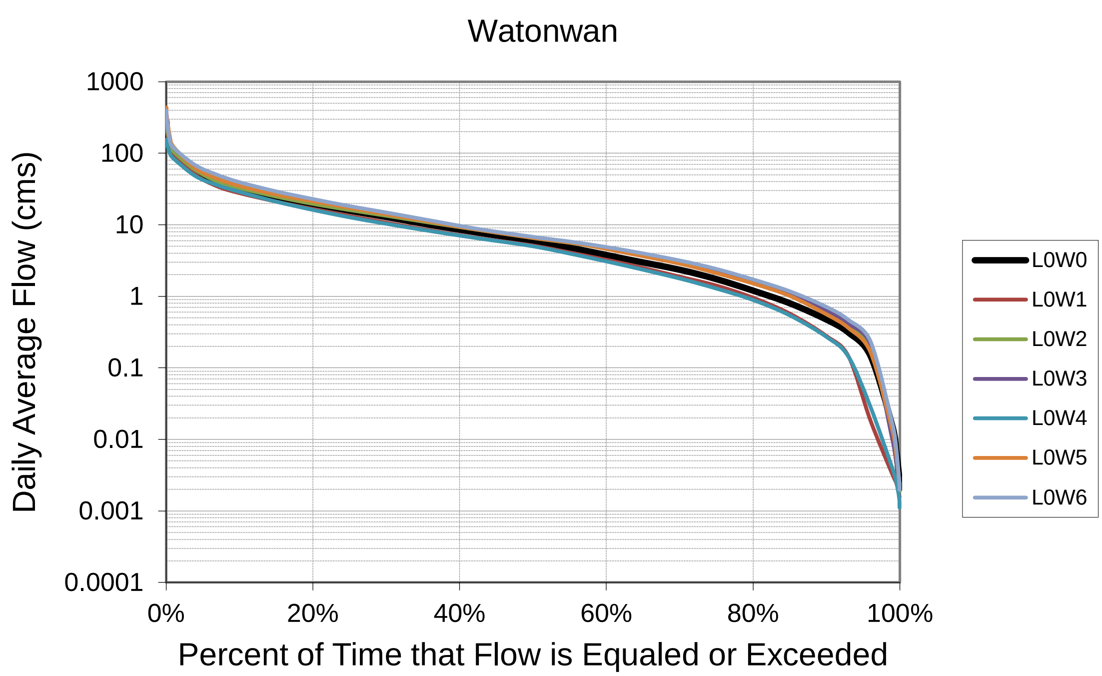


Figure 137. Flow Duration, Watonwan River (HSPF)

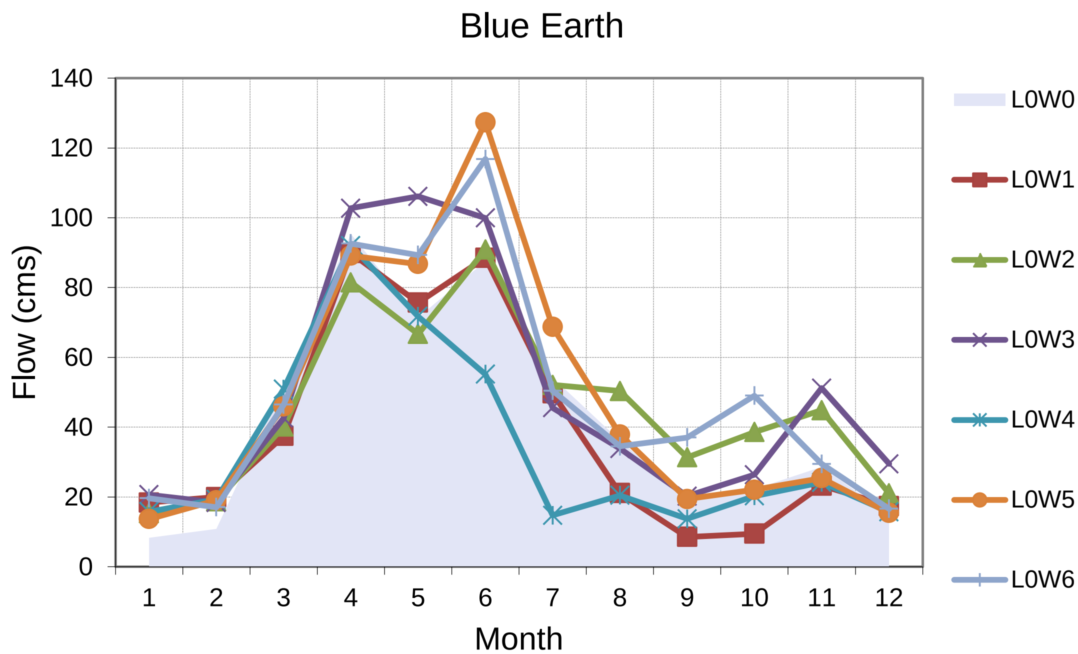


Figure 138. **Monthly Average Flows, Blue Earth River (HSPF)**

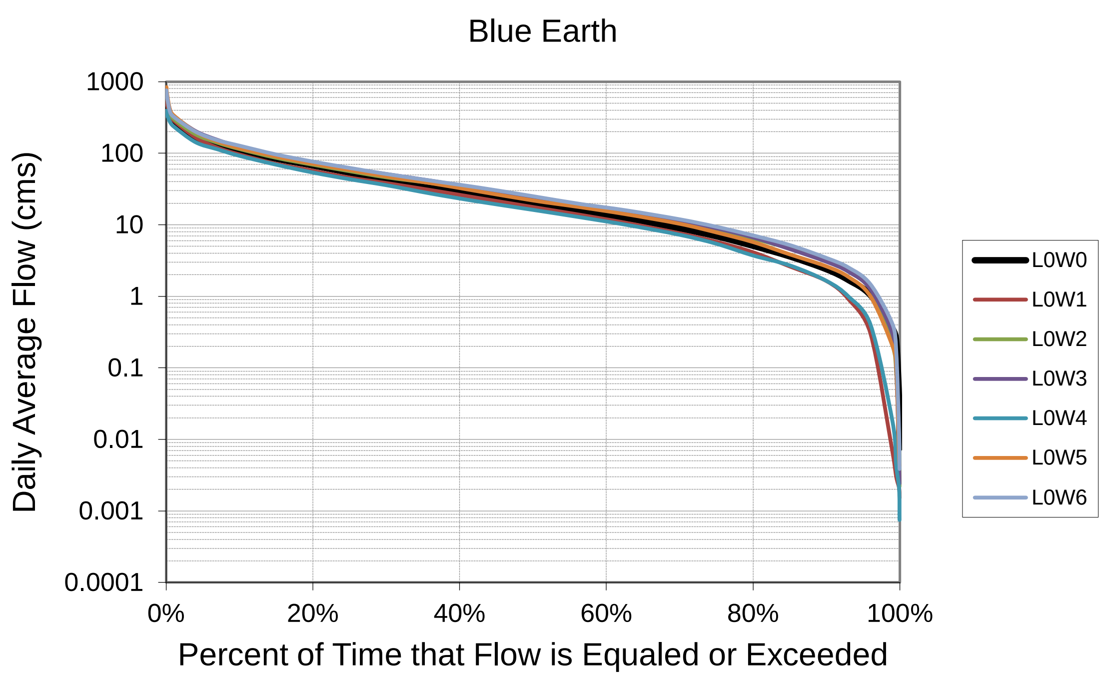


Figure 139. **Flow Duration, Blue Earth River (HSPF)**

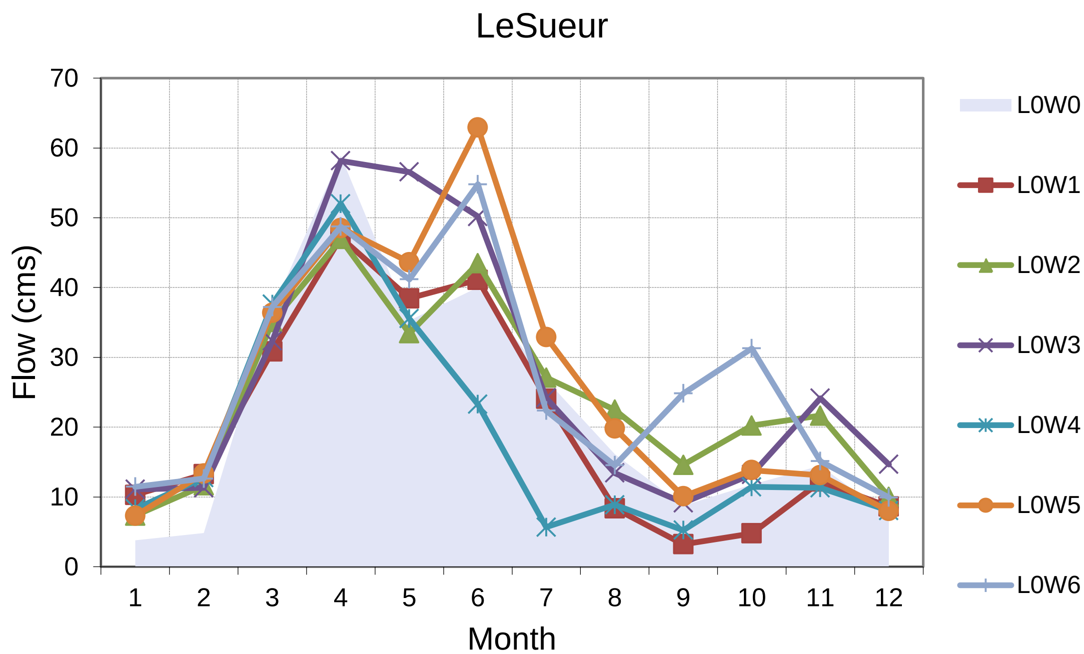


Figure 140. Monthly Average Flows, Le Sueur River (HSPF)

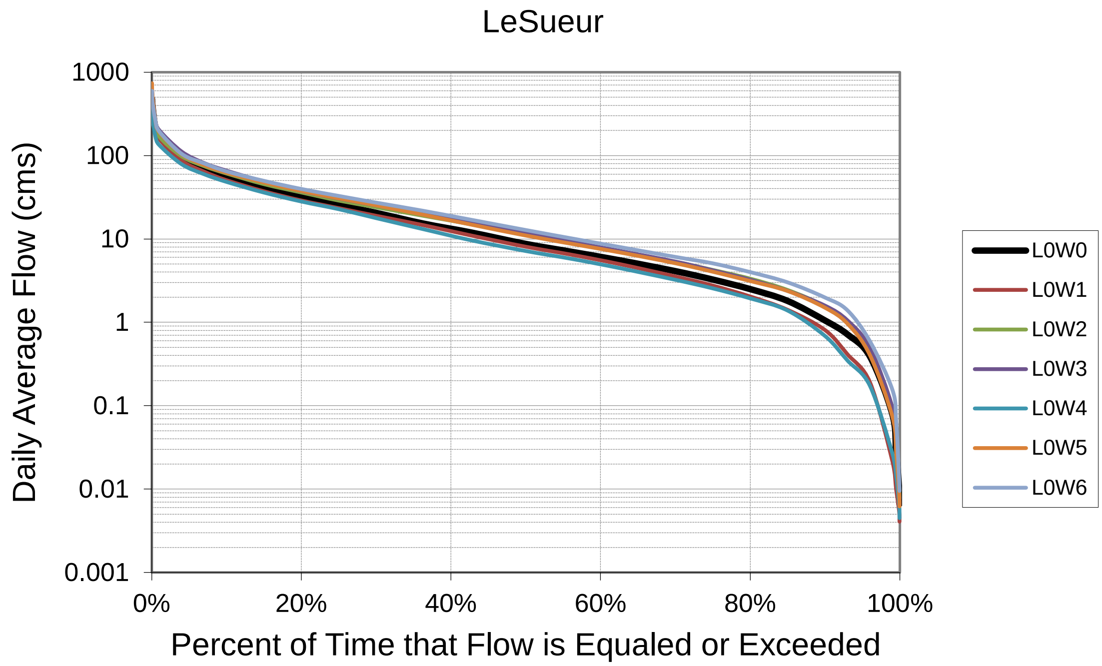


Figure 141. Flow Duration, Le Sueur River (HSPF)

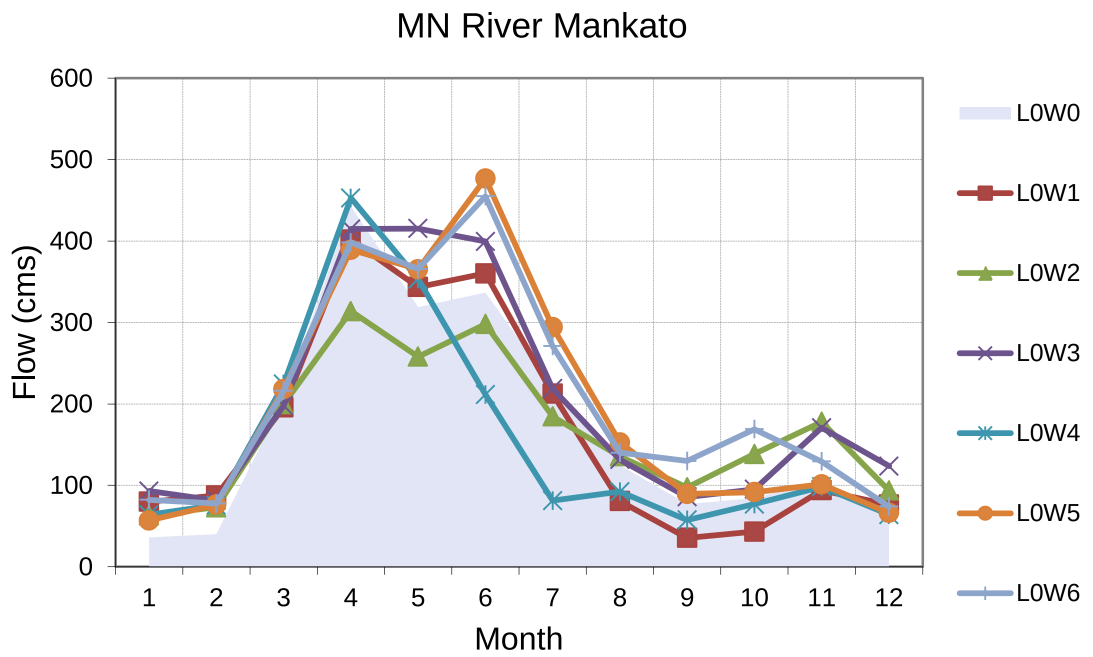


Figure 142. Monthly Average Flows, Minnesota River at Mankato (HSPF)

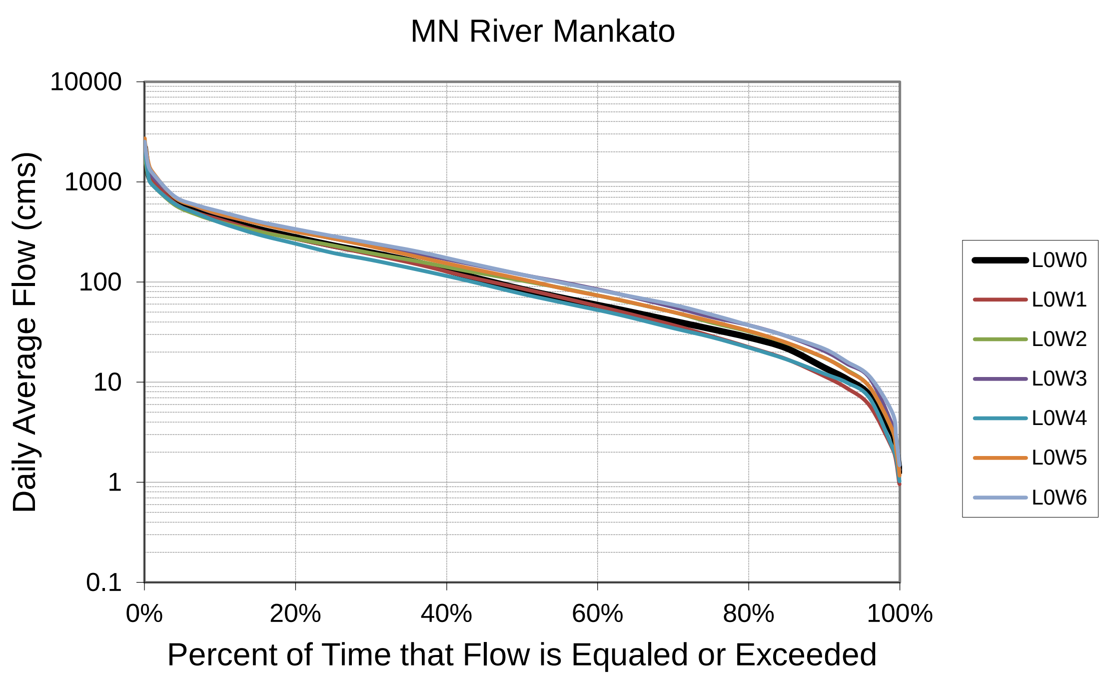


Figure 143. Flow Duration, Minnesota River at Mankato (HSPF)

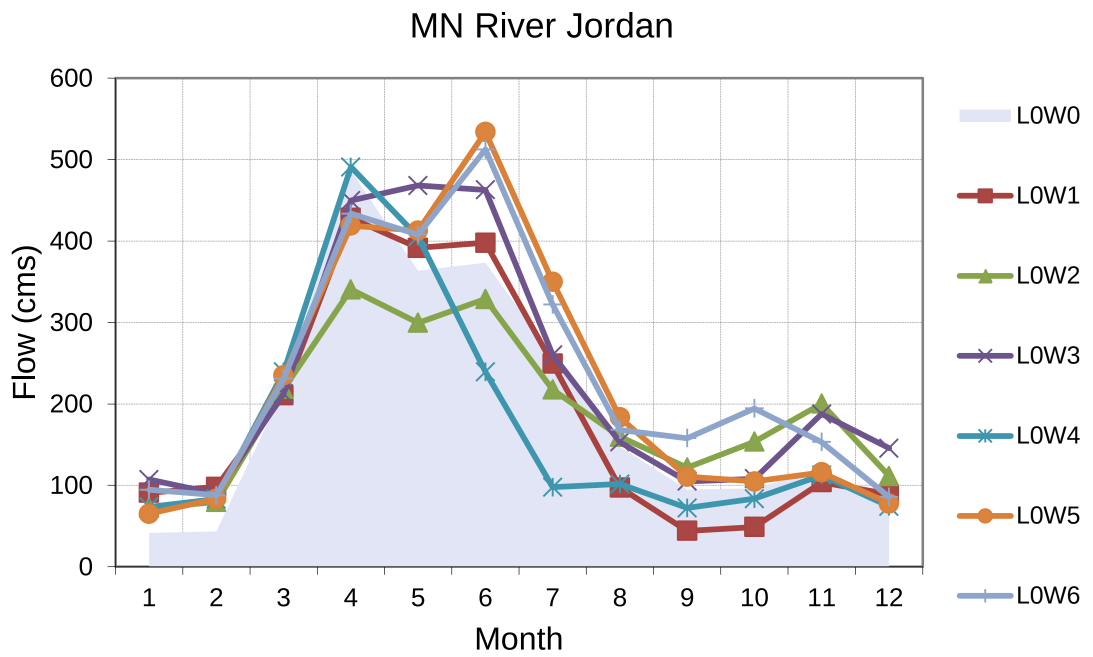


Figure 144. Monthly Average Flows, Minnesota River near Jordan (HSPF)

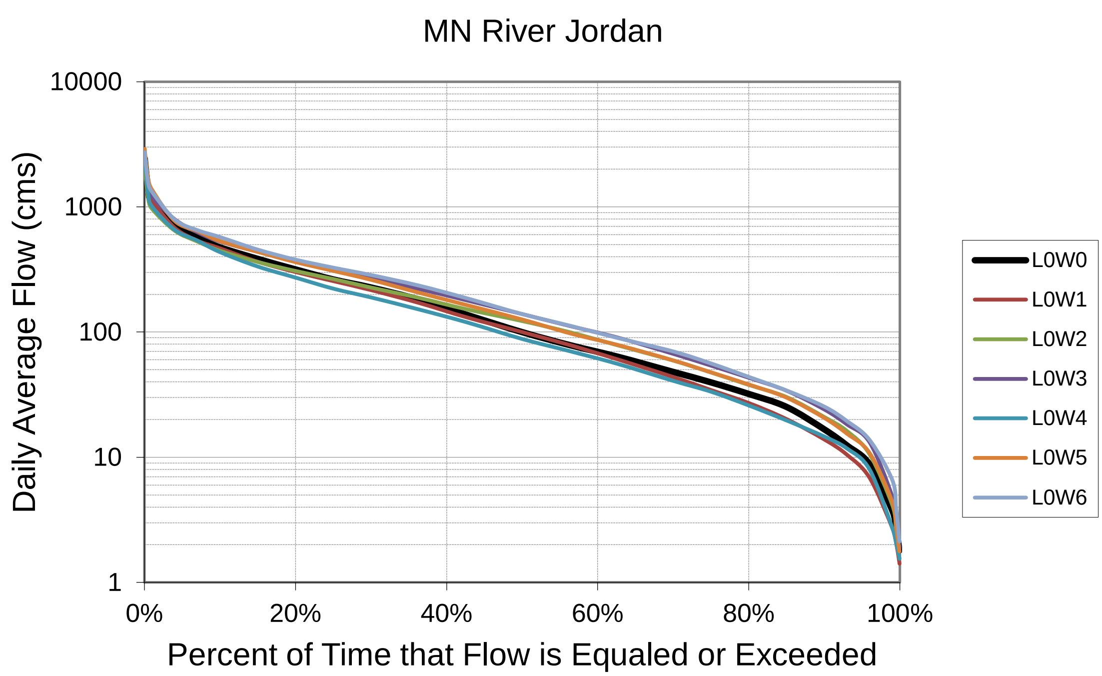


Figure 145. Flow Duration, Minnesota River near Jordan (HSPF)

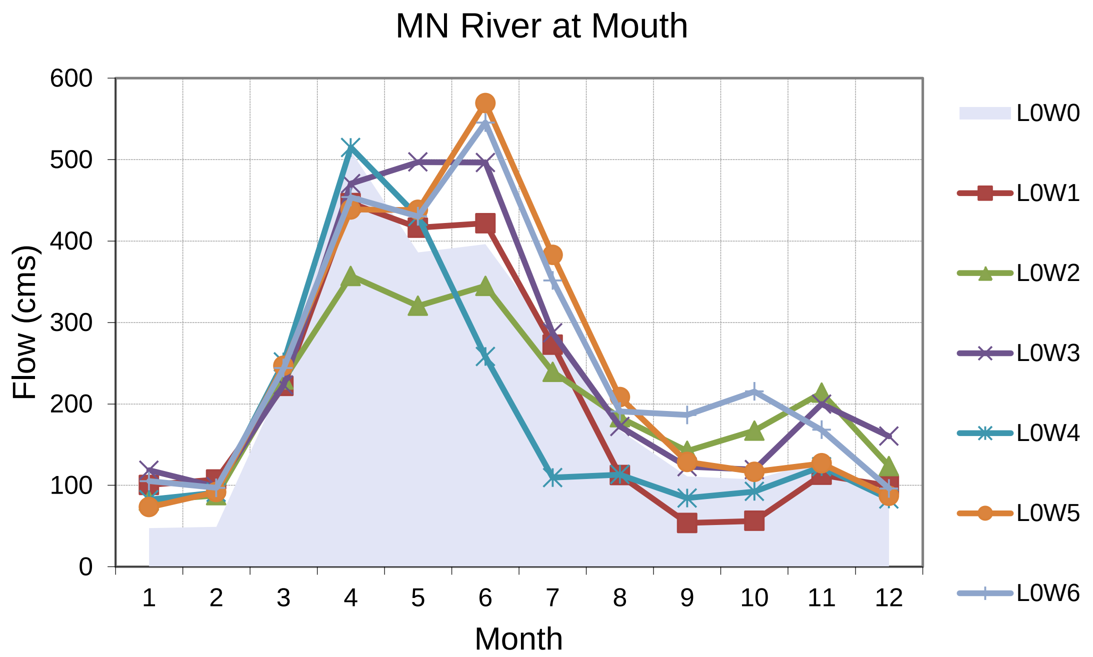


Figure 146. Monthly Average Flows, Minnesota River at Mouth (HSPF)

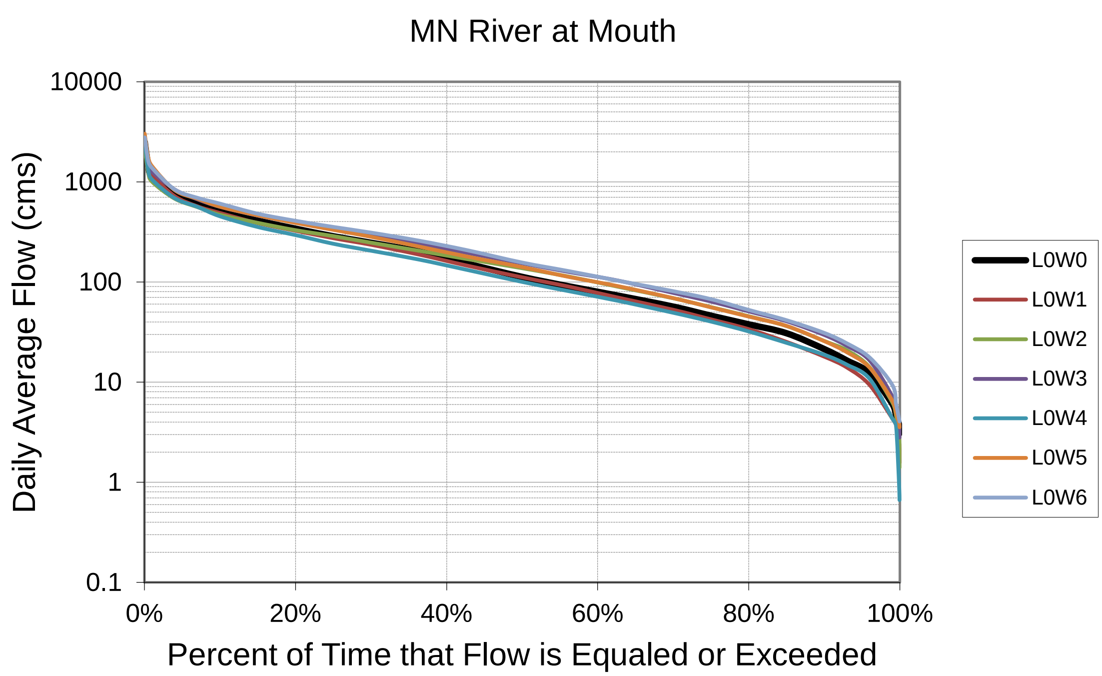


Figure 147. Flow Duration, Minnesota River at Mouth (HSPF)

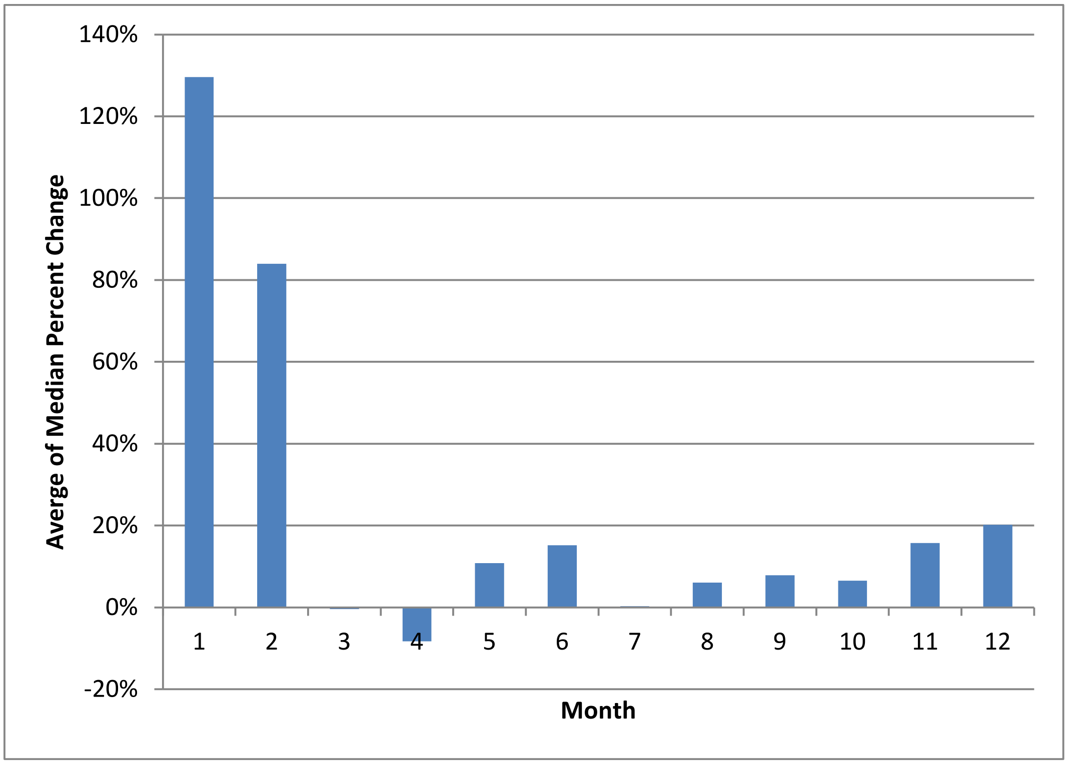


Figure 148. Average of Median Percent Change in Flow; NARCCAP Scenarios W1-W6 at all Stations, Minnesota River Basin (HSPF)

Minnesota River (Upper Mississippi Basin), SWAT Model Results at Downstream Station

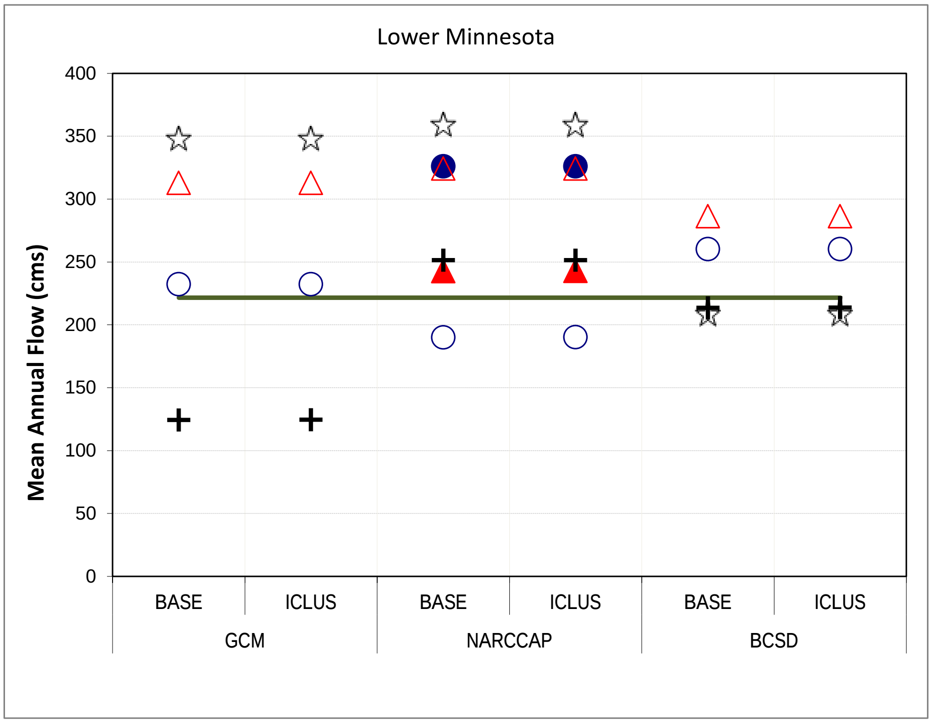


Figure 149. Mean Annual Flow, Lower Minnesota River (SWAT)

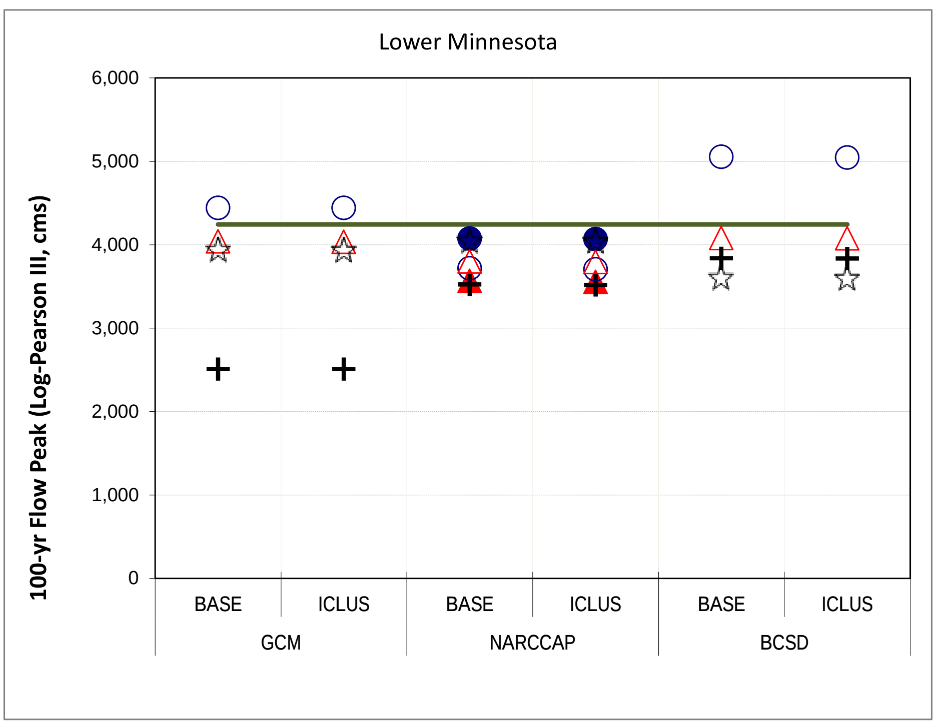


Figure 150. 100-yr Flow Peak, Lower Minnesota River (SWAT)

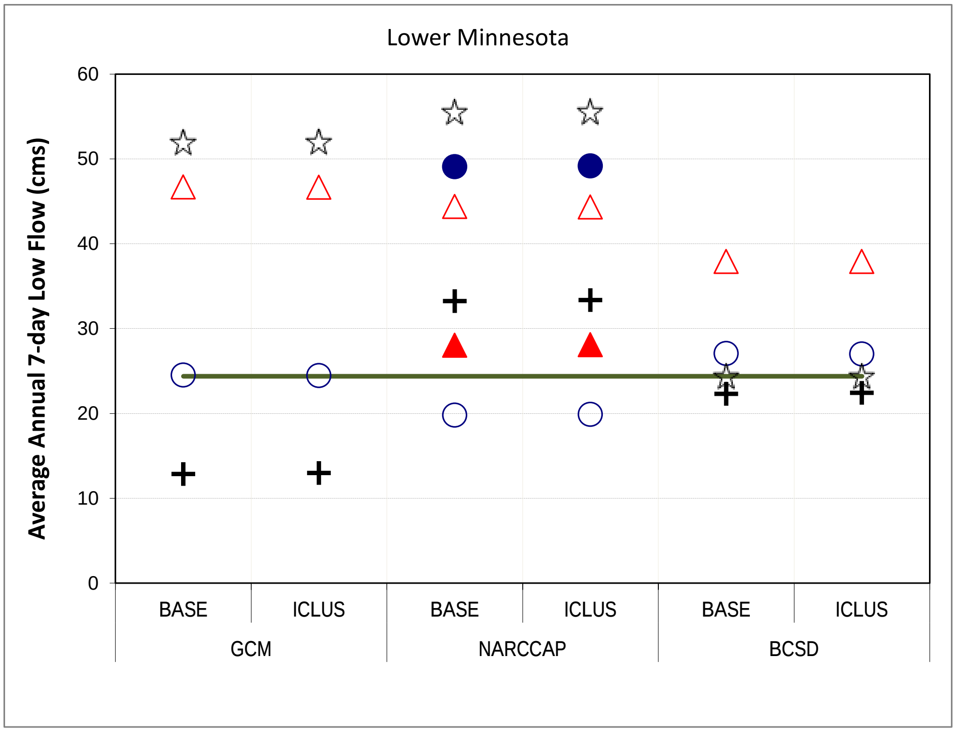


Figure 151. Average Annual 7-day Low Flow, Lower Minnesota River (SWAT)

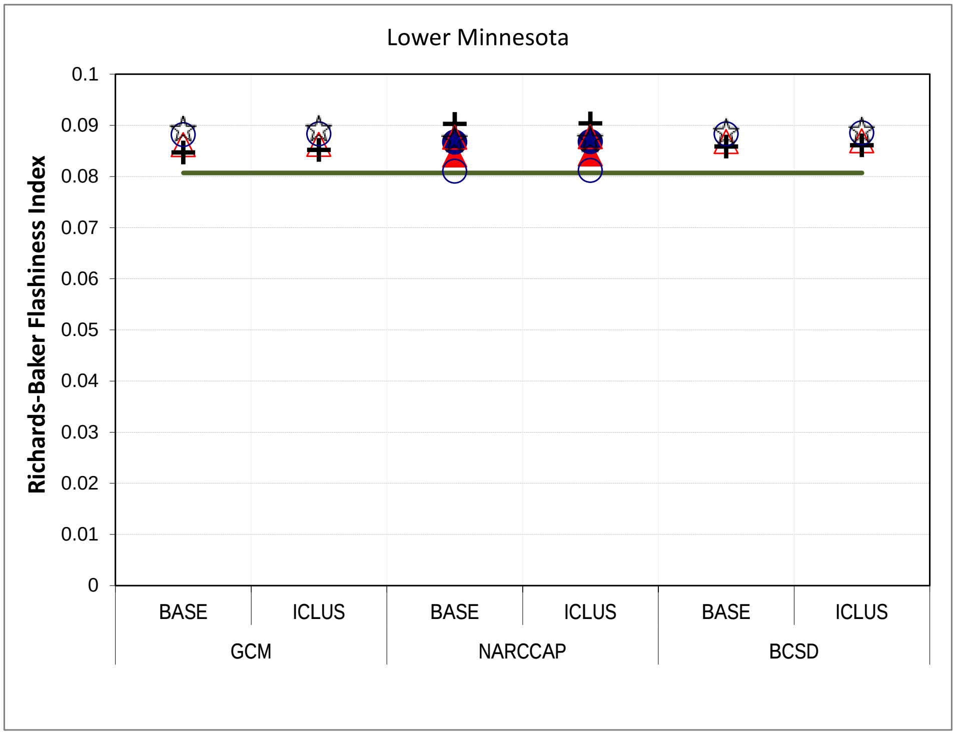


Figure 152. Richards-Baker Flashiness Index, Lower Minnesota River (SWAT)

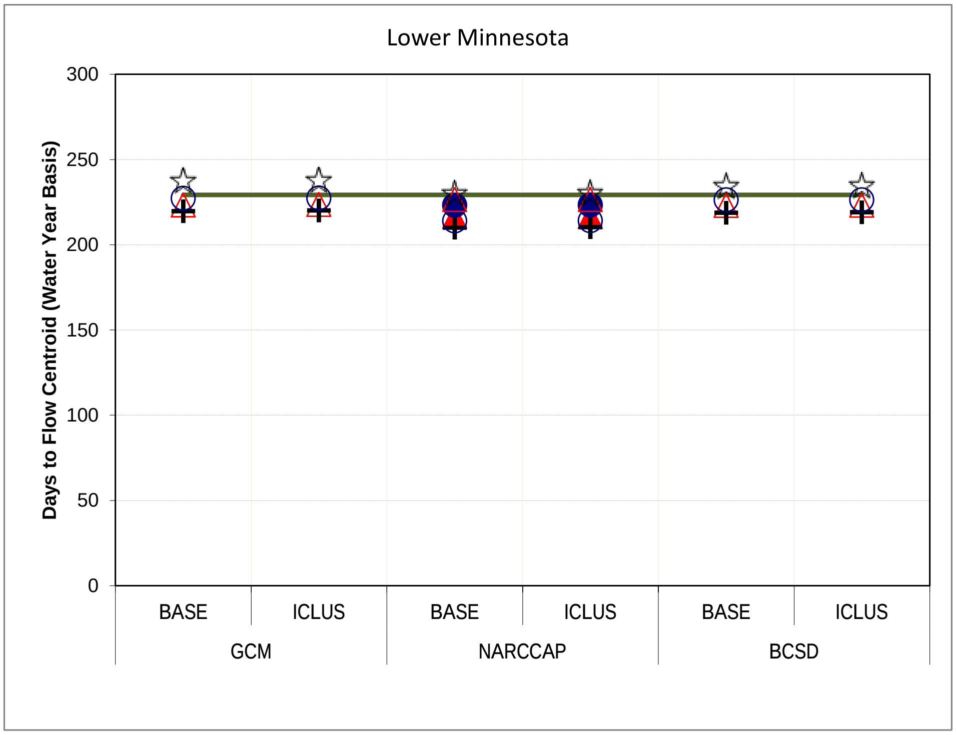


Figure 153. Days to Flow Centroid, Lower Minnesota River (SWAT)

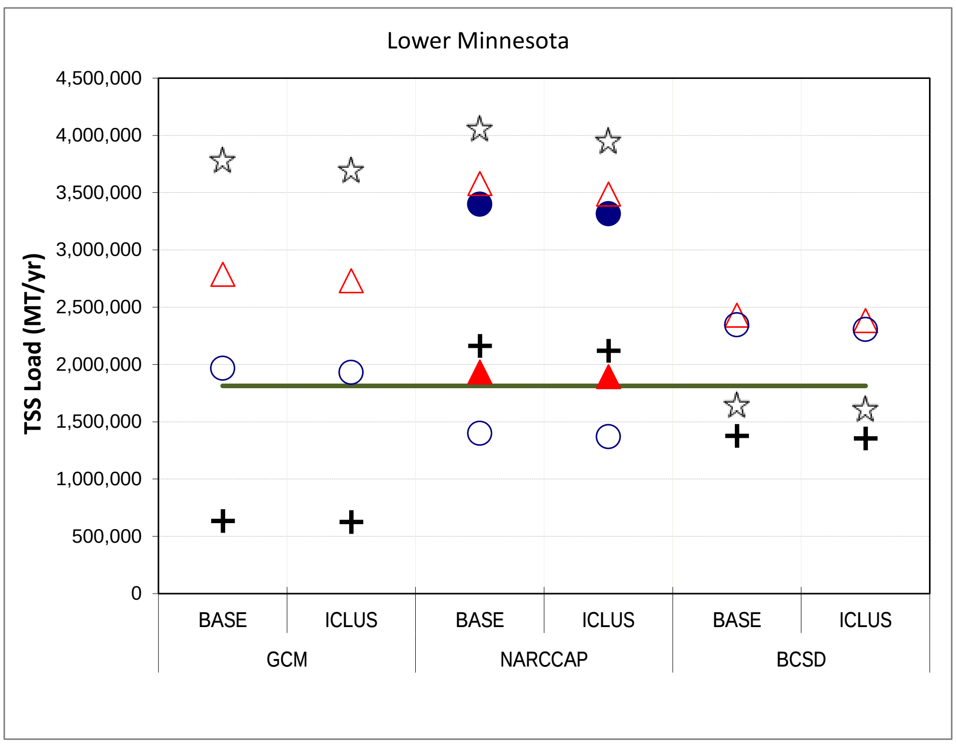


Figure 154. TSS Load, Lower Minnesota River (SWAT)

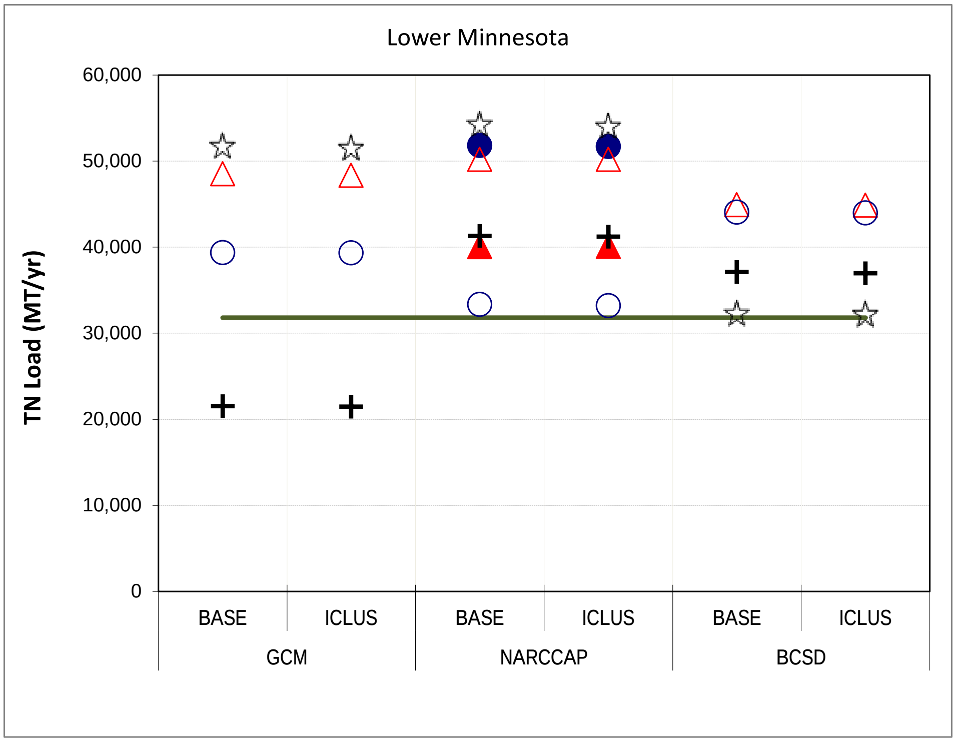


Figure 155. TN Load, Lower Minnesota River (SWAT)

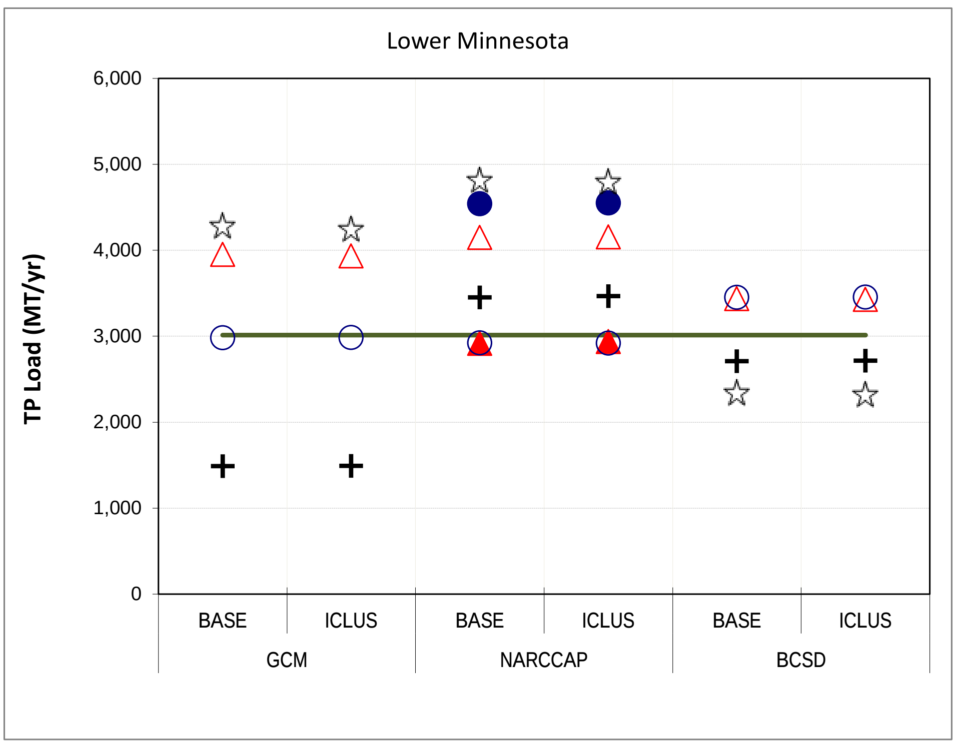


Figure 156. TP Load, Lower Minnesota River (SWAT)

Results at Multiple Stations

Table 6. Summary of Range of Change Relative to Existing Conditions for NARCCAP Dynamically Downscaled Scenarios, Minnesota River Basin SWAT Model

	Results without LU Change				Results with LU Change			
	Min	**Median**	**Mean**	**Max**	**Min**	**Median**	**Mean**	**Max**
Upper Minnesota HUC 07020001								
Flow	-3.95%	39.98%	36.17%	85.38%	-3.95%	39.98%	36.17%	85.38%
TSS	-17.42%	44.98%	47.84%	127.01%	-17.42%	44.98%	47.84%	127.01%
TN	19.73%	70.17%	67.01%	122.77%	19.73%	70.19%	67.03%	122.80%
TP	-12.85%	20.85%	25.01%	75.93%	-12.85%	20.87%	25.03%	75.97%
Pomme de Terre HUC 07020003								
Flow	-6.62%	33.48%	32.66%	77.84%	-6.62%	33.48%	32.66%	77.84%
TSS	-21.07%	30.07%	39.65%	115.54%	-21.07%	30.07%	39.65%	115.54%
TN	13.41%	53.98%	56.56%	107.51%	13.41%	53.99%	56.57%	107.53%
TP	-19.42%	16.76%	24.47%	83.00%	-19.42%	16.79%	24.50%	83.04%
Lac qui Parle HUC 07020002								
Flow	-7.31%	36.35%	32.40%	71.11%	-7.31%	36.35%	32.40%	71.11%
TSS	-17.12%	35.86%	33.84%	100.96%	-17.12%	35.86%	33.84%	100.96%
TN	9.56%	54.59%	48.18%	83.64%	9.56%	54.60%	48.18%	83.64%
TP	-13.85%	16.56%	18.02%	57.03%	-13.86%	16.57%	18.03%	57.05%
Yellow Medicine River HUC 07020004 (part)								
Flow	-7.92%	34.59%	31.53%	67.46%	-7.92%	34.59%	31.53%	67.46%
TSS	-16.42%	41.72%	36.16%	94.48%	-16.42%	41.72%	36.16%	94.48%
TN	0.03%	50.01%	43.94%	78.07%	0.12%	50.02%	43.97%	78.07%
TP	-20.52%	18.54%	18.61%	54.03%	-20.52%	18.55%	18.62%	54.05%
Chippewa River HUC 07020005								
Flow	-9.95%	25.69%	23.79%	65.55%	-9.95%	25.68%	23.79%	65.55%
TSS	-22.48%	32.97%	40.29%	126.59%	-22.48%	32.97%	40.29%	126.59%
TN	-0.76%	36.51%	36.79%	78.51%	-0.76%	36.53%	36.81%	78.50%
TP	-24.54%	10.93%	17.45%	70.94%	-24.56%	10.91%	17.46%	70.89%

	Results without LU Change				Results with LU Change			
	Min	Median	Mean	Max	Min	Median	Mean	Max
Redwood River HUC 07020006								
Flow	-3.78%	24.23%	25.92%	53.95%	-3.78%	24.23%	25.92%	53.94%
TSS	-6.11%	32.18%	36.06%	86.18%	-6.11%	32.18%	36.06%	86.18%
TN	-0.31%	36.42%	34.70%	64.01%	-0.31%	36.43%	34.70%	64.02%
TP	-5.61%	13.19%	16.08%	44.46%	-5.61%	13.20%	16.09%	44.46%
Middle Minnesota HUC 07020007								
Flow	-12.67%	29.75%	27.94%	62.35%	-12.67%	29.74%	27.94%	62.34%
TSS	-17.81%	52.83%	47.38%	101.14%	-17.81%	52.82%	47.38%	101.13%
TN	4.32%	43.11%	41.13%	70.64%	4.36%	43.18%	41.21%	70.72%
TP	-5.46%	25.85%	24.83%	59.67%	-5.39%	25.92%	24.88%	59.72%
Cottonwood HUC 07020008								
Flow	-10.24%	33.77%	31.00%	61.72%	-10.24%	33.77%	31.00%	61.72%
TSS	-5.91%	43.69%	48.11%	104.61%	-5.91%	43.69%	48.11%	104.61%
TN	4.22%	45.84%	44.97%	75.87%	4.22%	45.84%	44.97%	75.87%
TP	-5.03%	20.93%	25.34%	63.13%	-5.03%	20.93%	25.34%	63.13%
Blue Earth HUC 07020009								
Flow	-20.61%	33.56%	22.74%	49.17%	-20.61%	33.55%	22.74%	49.17%
TSS	-24.04%	57.91%	45.79%	98.51%	-24.04%	57.91%	45.78%	98.50%
TN	-11.15%	45.50%	35.07%	63.82%	-11.14%	45.55%	35.09%	63.86%
TP	-19.24%	39.82%	29.02%	67.12%	-19.24%	39.90%	29.07%	67.19%
Watonwan HUC 07020010								
Flow	-23.39%	40.81%	28.64%	65.41%	-23.39%	40.81%	28.64%	65.41%
TSS	-30.63%	62.21%	52.72%	124.99%	-30.63%	62.21%	52.72%	124.98%
TN	-23.34%	46.15%	38.06%	89.14%	-23.34%	46.15%	38.05%	89.14%
TP	-31.51%	38.20%	31.53%	92.71%	-31.52%	38.19%	31.51%	92.70%
Le Sueur HUC 07020011								
Flow	-13.79%	31.64%	21.83%	43.28%	-13.80%	31.63%	21.81%	43.26%
TSS	-5.12%	52.63%	41.27%	75.30%	-5.12%	52.63%	41.27%	75.29%
TN	-0.63%	41.60%	33.83%	56.00%	-0.23%	42.25%	34.33%	56.43%

	Results without LU Change				Results with LU Change			
	Min	Median	Mean	Max	Min	Median	Mean	Max
TP	-5.35%	35.45%	28.50%	57.54%	-4.78%	36.34%	29.17%	58.15%
Lower Minnesota HUC 07020012								
Flow	-14.28%	29.82%	27.39%	62.41%	-14.34%	29.59%	27.16%	62.09%
TSS	-22.81%	53.38%	52.06%	124.50%	-22.87%	52.90%	51.41%	122.93%
TN	4.88%	43.83%	42.08%	71.13%	4.88%	44.37%	42.44%	71.09%
TP	-3.26%	26.08%	26.14%	60.28%	-2.52%	27.28%	27.15%	60.74%
Minnesota River at Jordan (gage 05330000)								
Flow	-13.54%	30.38%	28.14%	63.25%	-13.58%	30.31%	28.07%	63.16%
TSS	-19.49%	53.66%	51.35%	115.45%	-19.48%	53.58%	51.27%	115.24%
TN	5.17%	42.75%	41.55%	70.98%	5.17%	42.84%	41.58%	70.91%
TP	-6.65%	23.91%	24.52%	59.80%	-6.28%	24.19%	24.68%	59.53%
Minnesota River at Mankato (gage 05325000)								
Flow	-13.01%	30.10%	28.11%	62.93%	-13.01%	30.09%	28.10%	62.93%
TSS	-17.21%	50.29%	46.00%	101.54%	-17.21%	50.28%	46.00%	101.52%
TN	4.83%	42.80%	41.32%	70.91%	4.85%	42.85%	41.38%	70.97%
TP	-5.52%	25.21%	24.99%	59.64%	-5.49%	25.27%	25.02%	59.65%

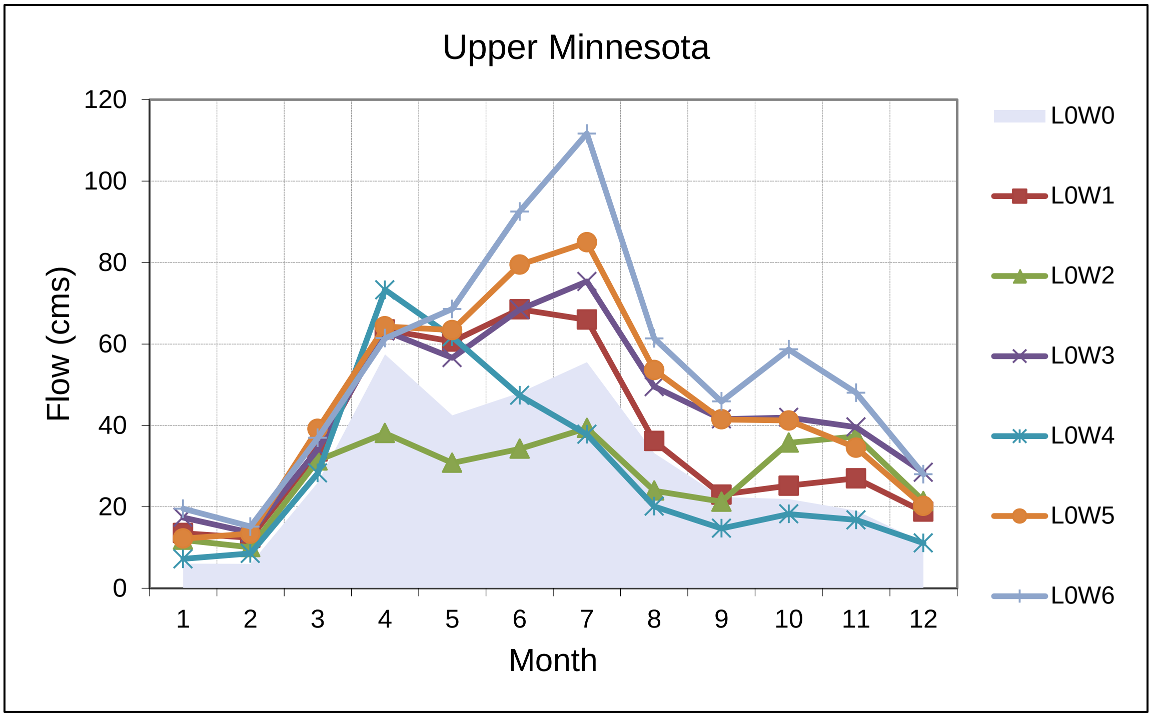


Figure 56. Monthly Average Flows, Upper Minnesota River (SWAT)

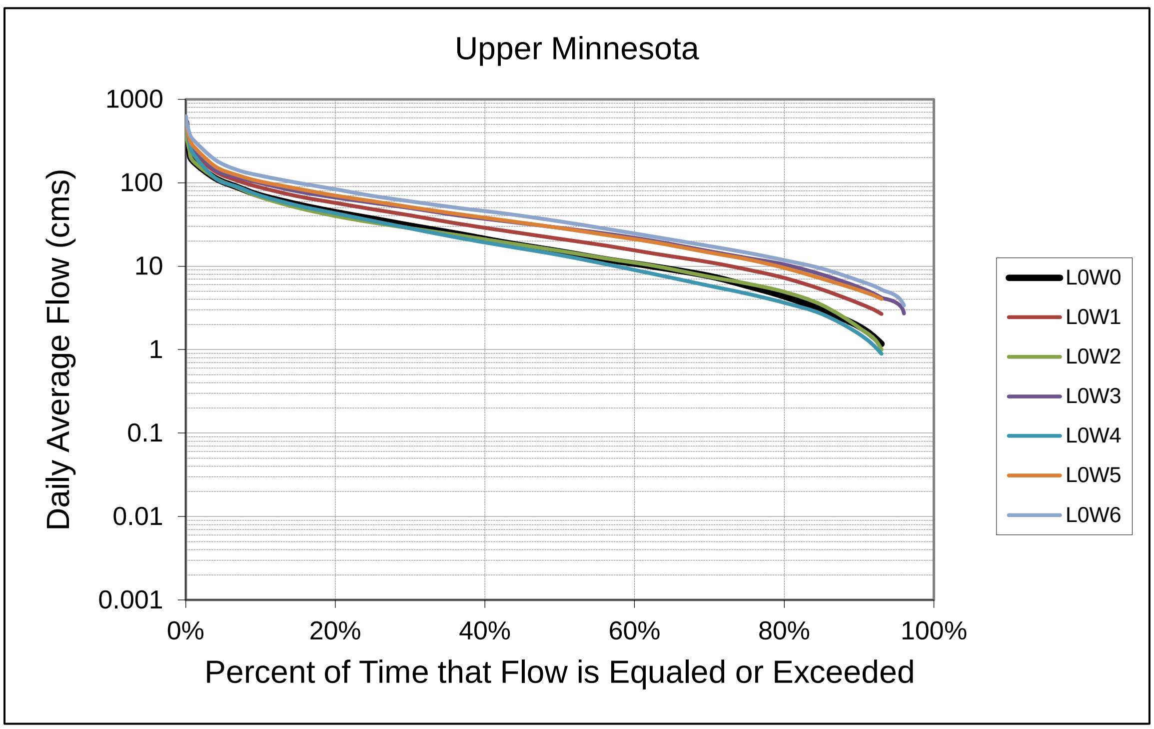


Figure 158. Flow Duration, Upper Minnesota River (SWAT)

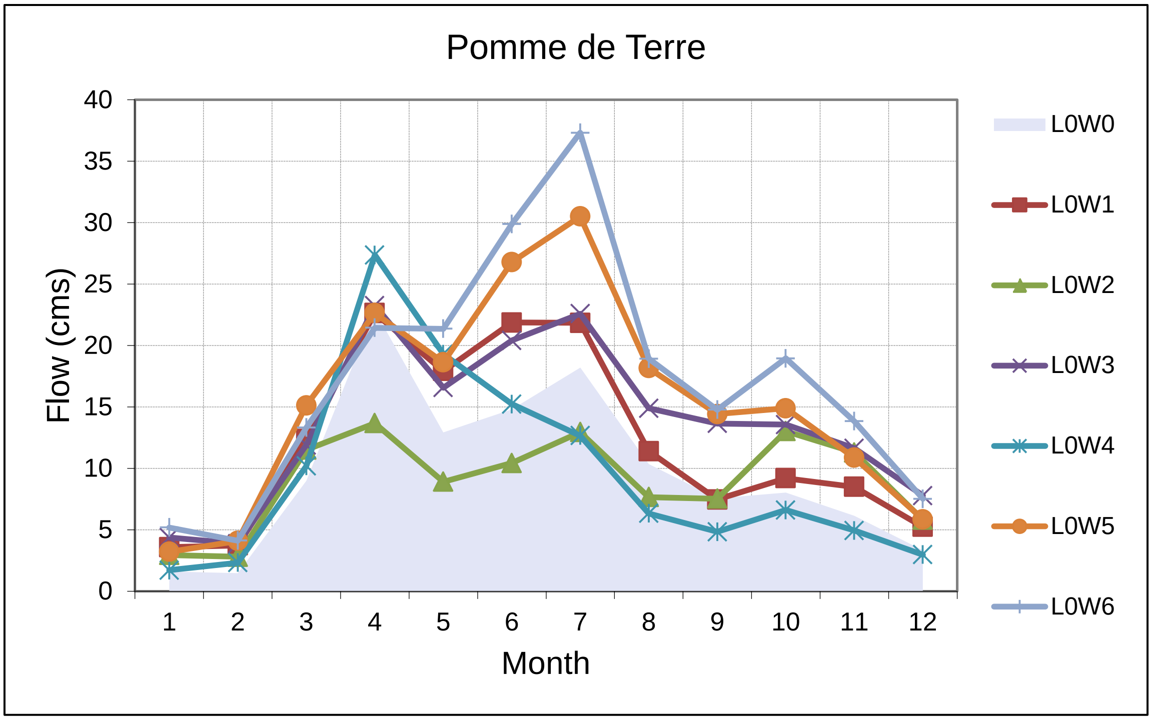


Figure 159. Monthly Average Flows, Pomme de Terre (SWAT)

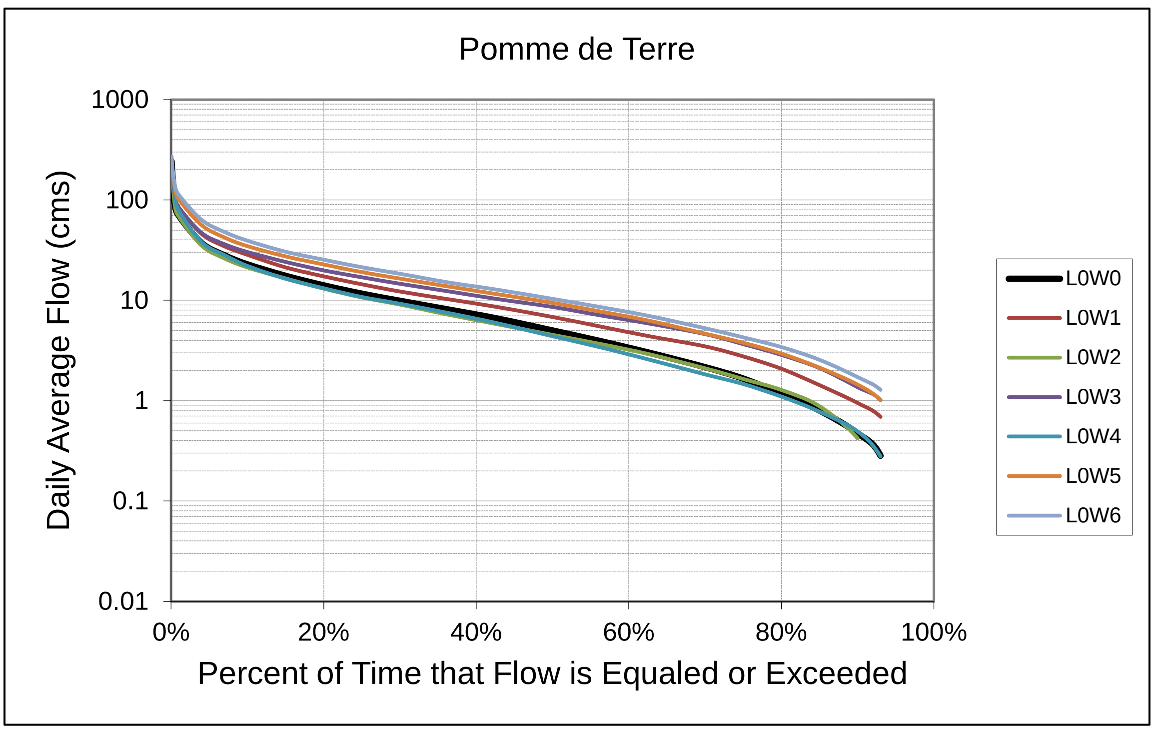


Figure 160. Flow Duration, Pomme de Terre (SWAT)

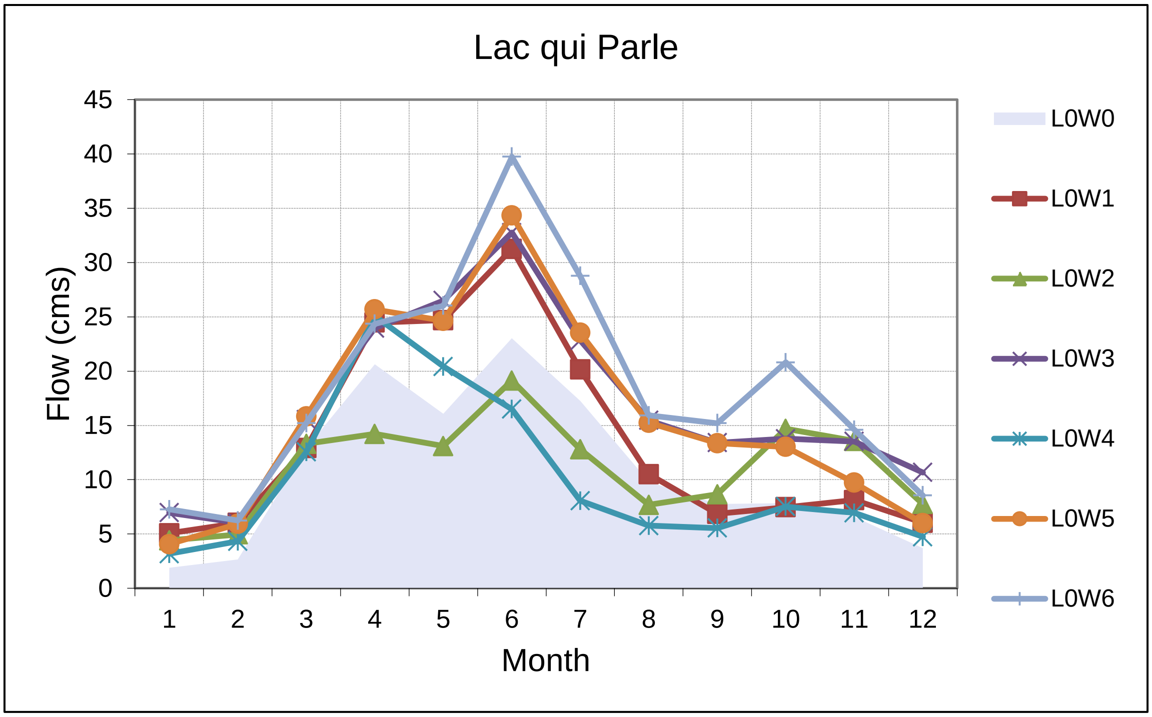


Figure 161. **Monthly Average Flows, Minnesota River at Lac qui Parle (SWAT)**

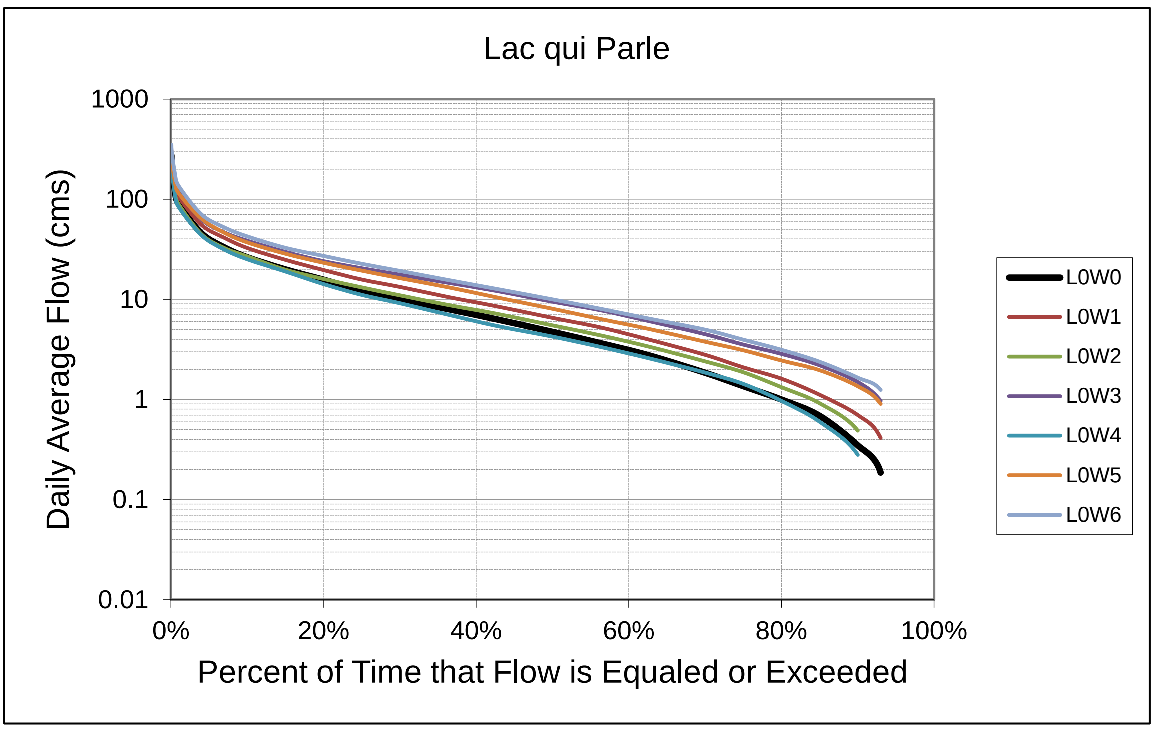


Figure 162. **Flow Duration, Minnesota River at Lac qui Parle (SWAT)**

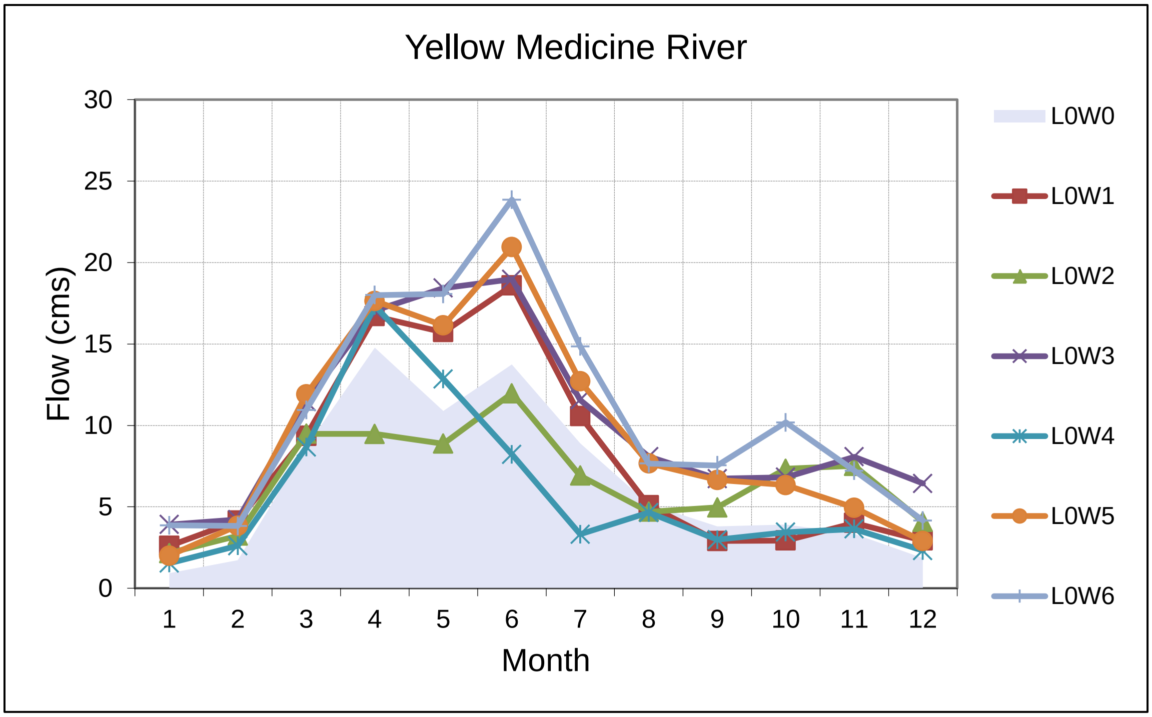


Figure 163. **Monthly Average Flows, Yellow Medicine River (SWAT)**

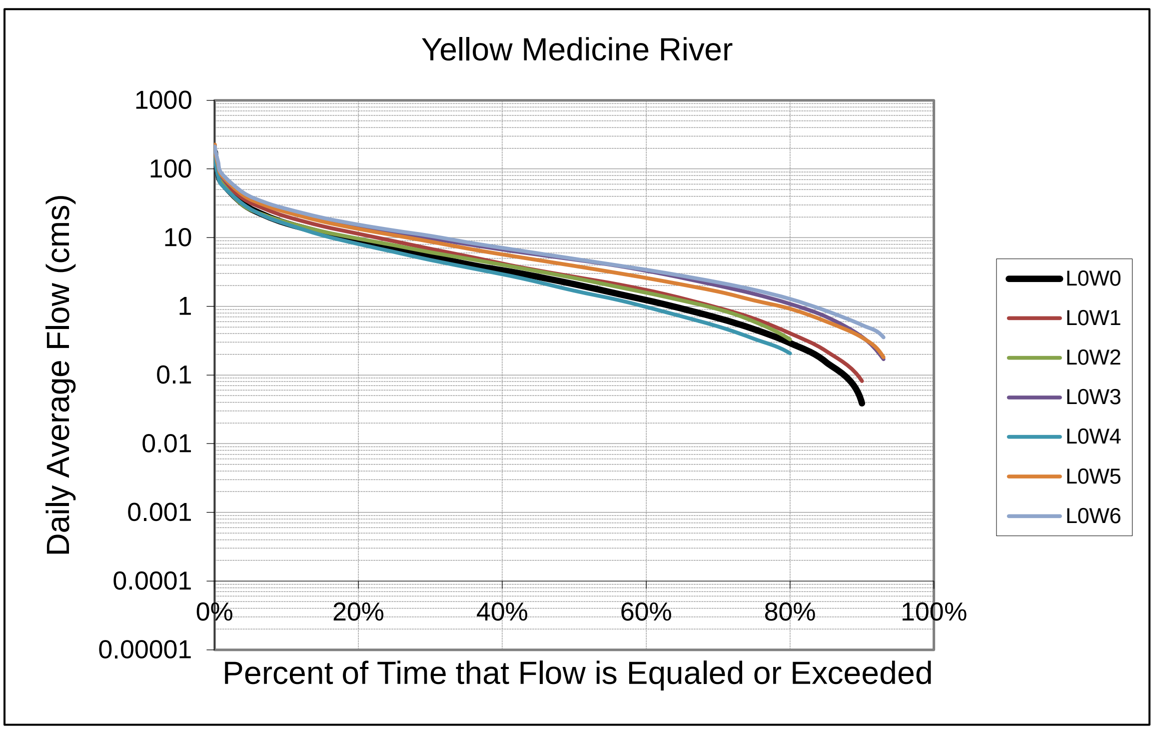


Figure 164. **Flow Duration, Yellow Medicine River (SWAT)**

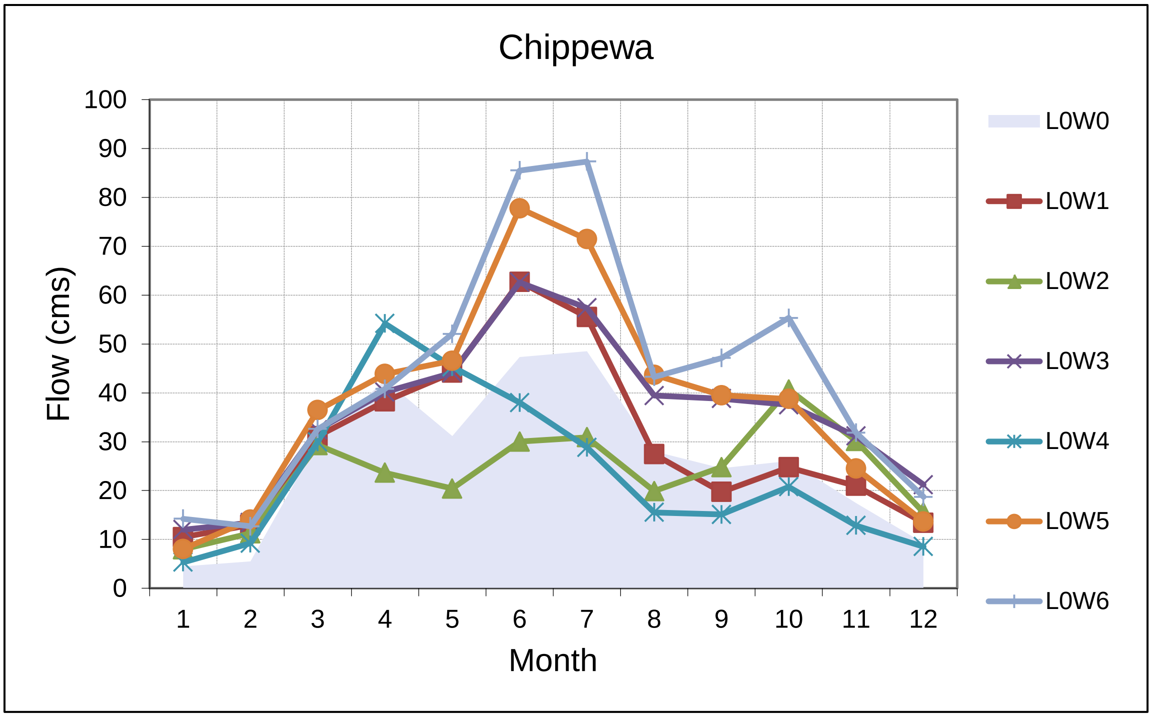


Figure 165. Monthly Average Flows, Chippewa River (SWAT)

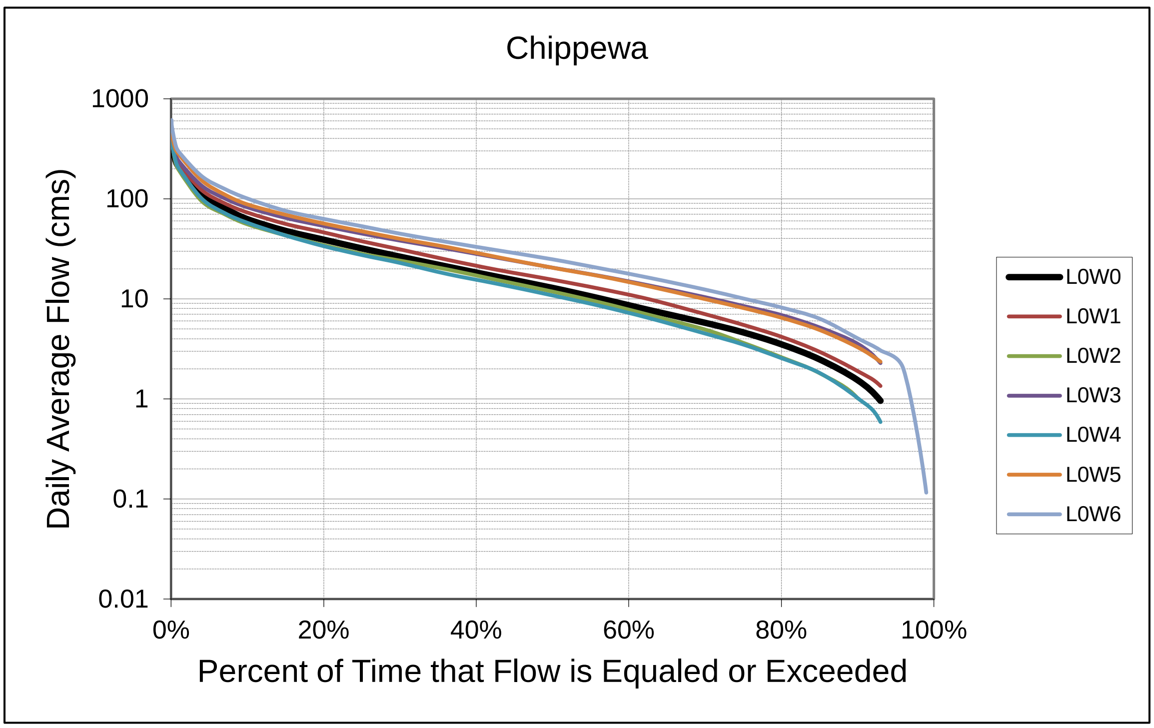


Figure 166. Flow Duration, Chippewa River (SWAT)

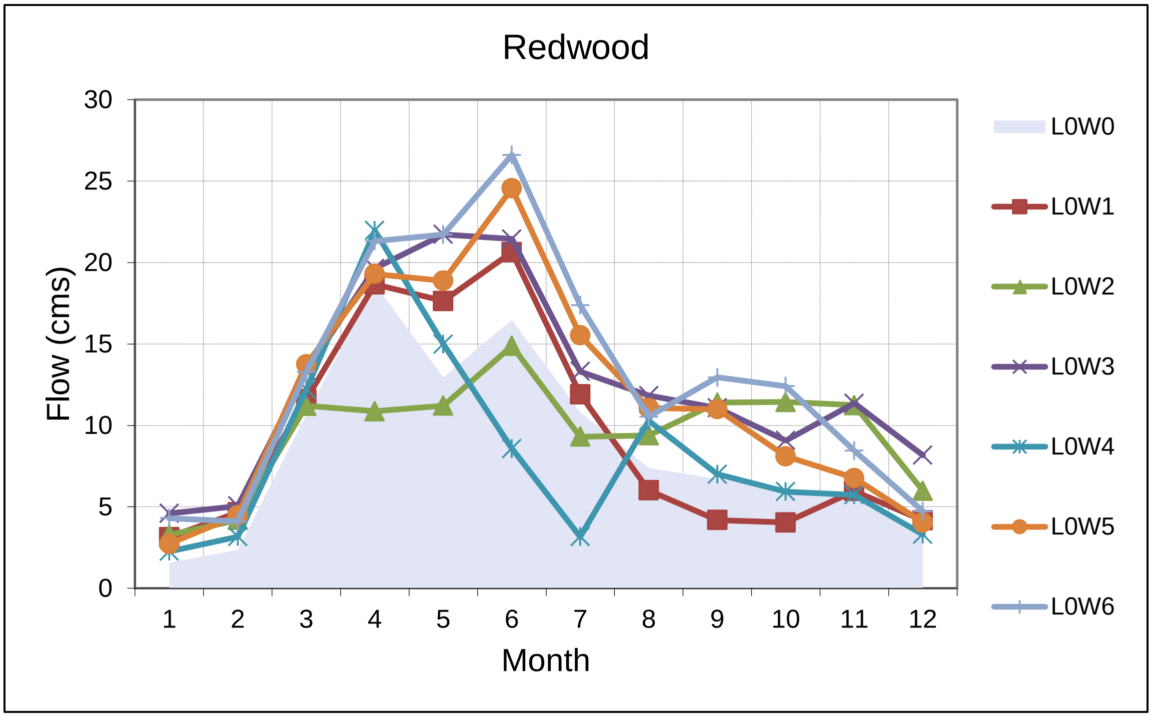


Figure 167. Monthly Average Flows, Redwood River (SWAT)

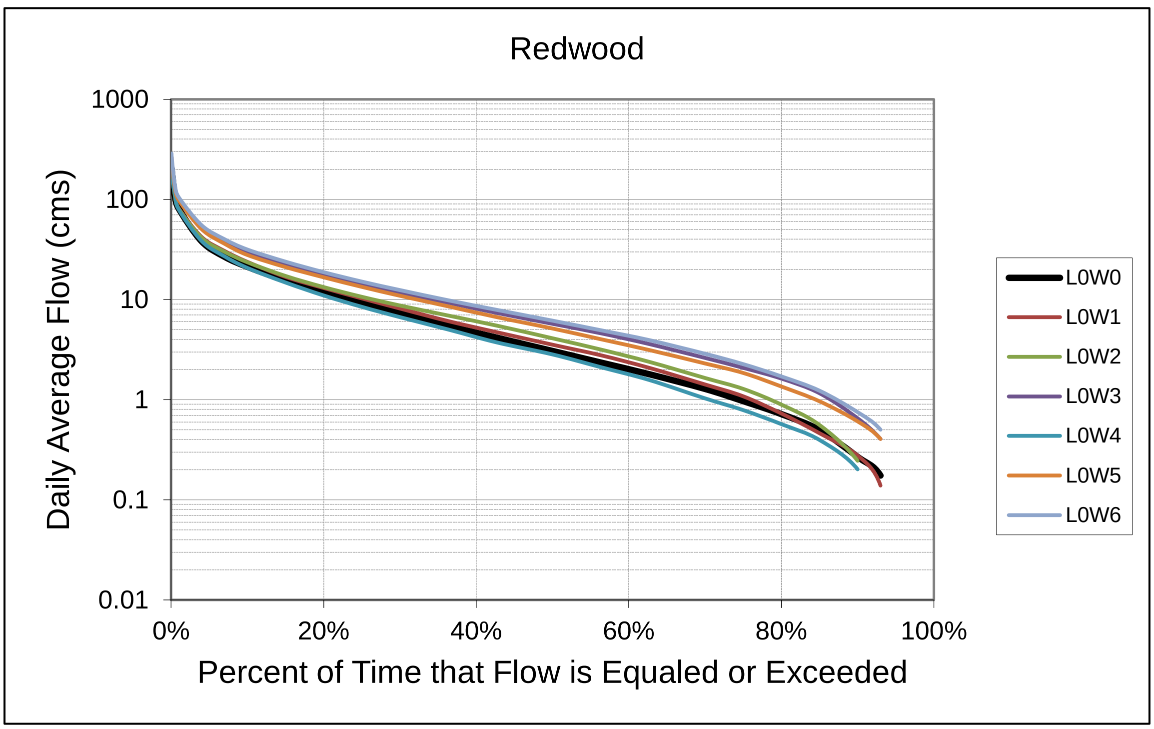


Figure 168. Flow Duration, Redwood River (SWAT)

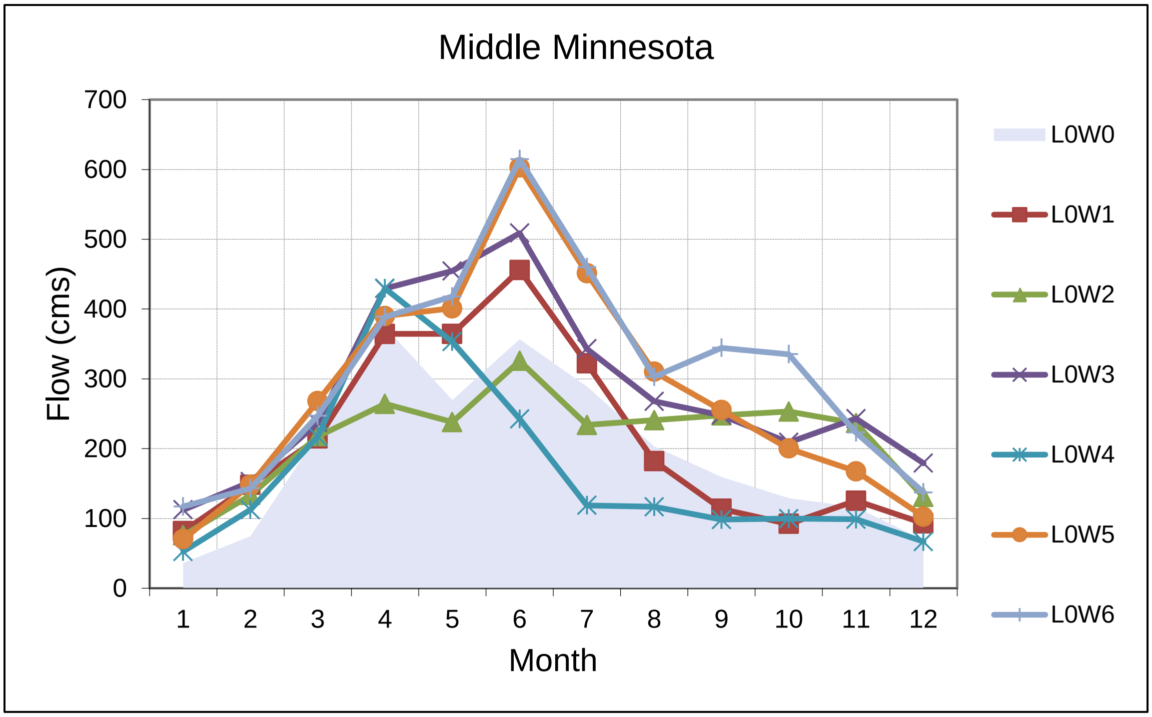


Figure 169. Monthly Average Flows, Middle Minnesota River (SWAT)

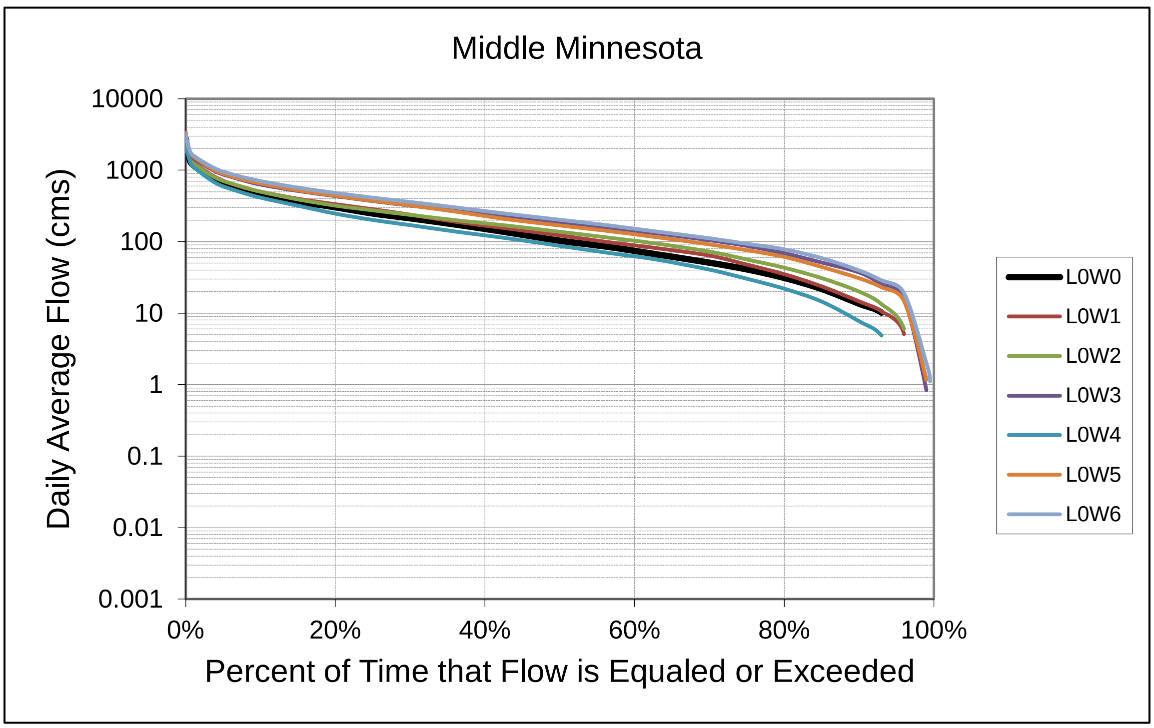


Figure 170. Flow Duration, Middle Minnesota River (SWAT)

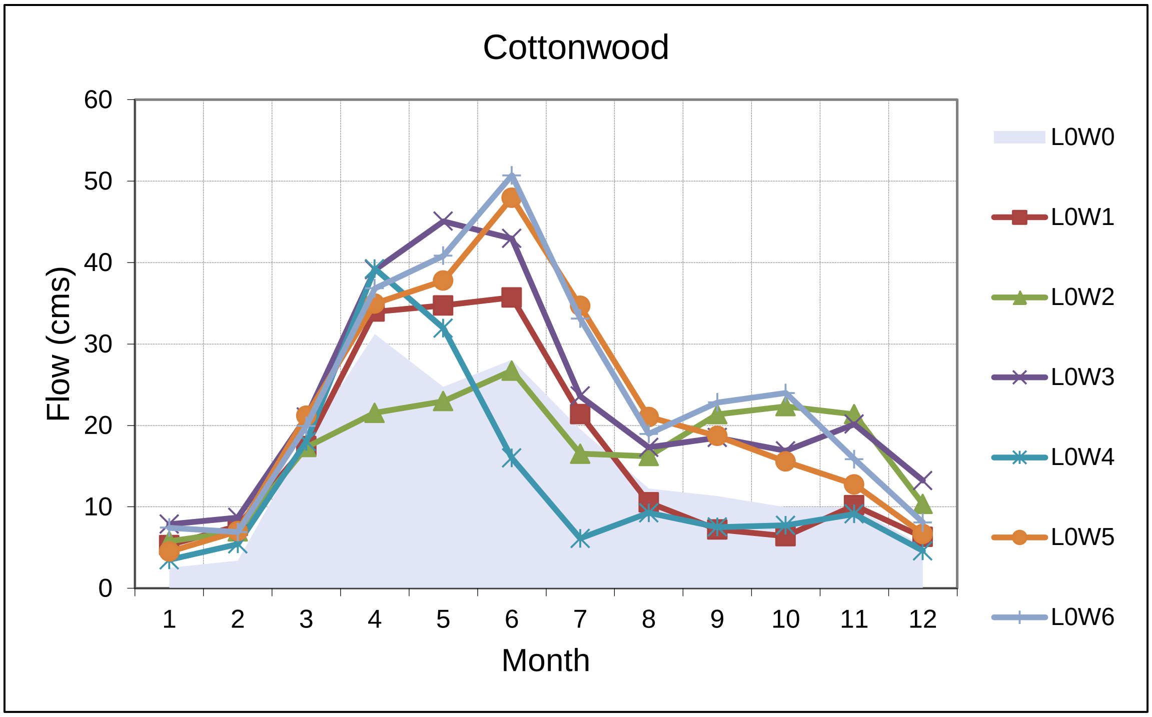


Figure 171. **Monthly Average Flows, Cottonwood River (SWAT)**

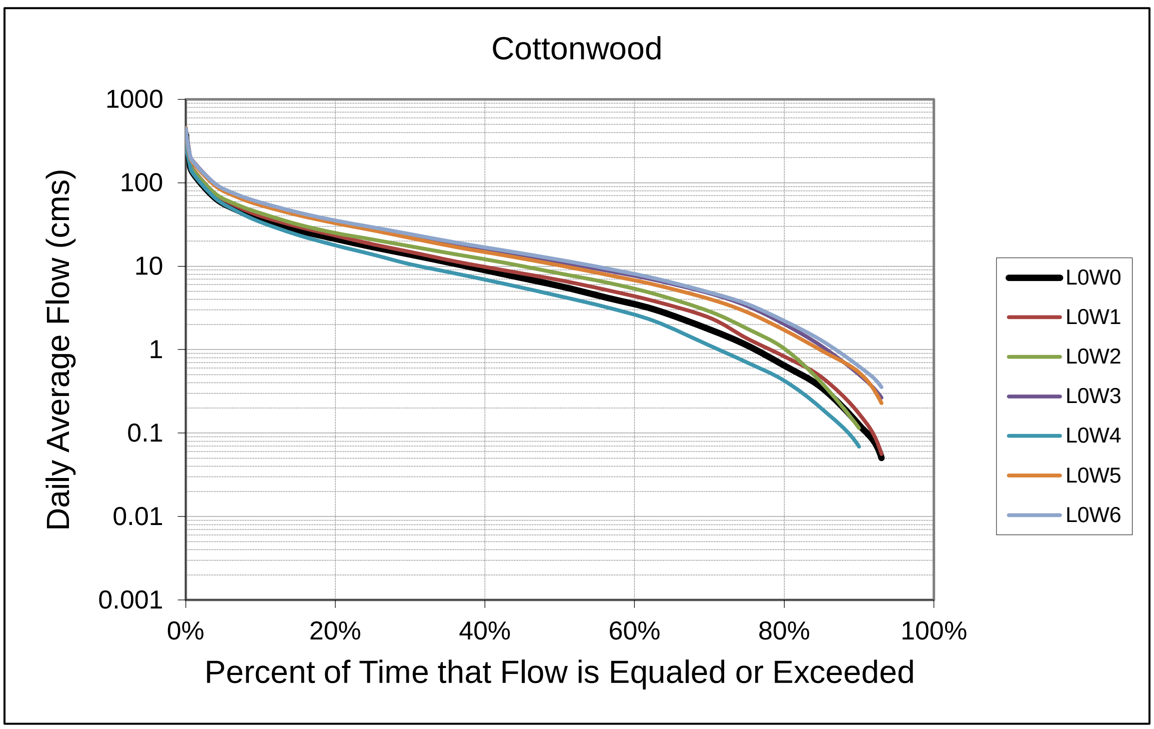


Figure 172. **Flow Duration, Cottonwood River (SWAT)**

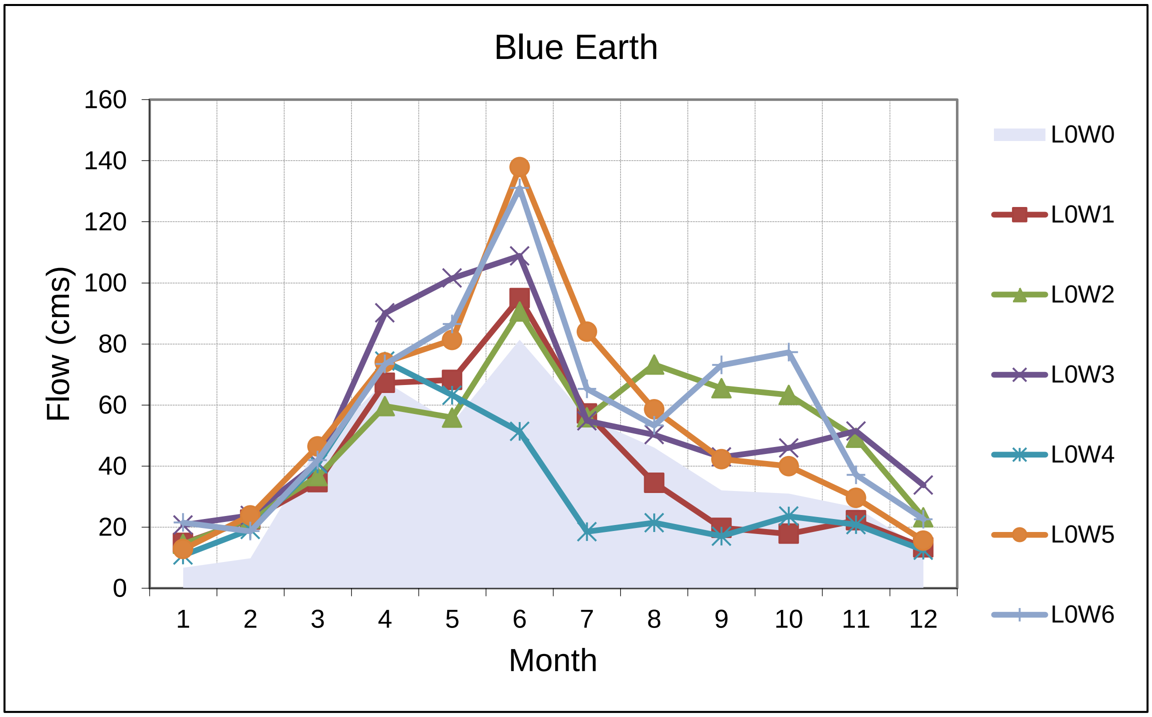


Figure 173. Monthly Average Flows, Blue Earth River (SWAT)

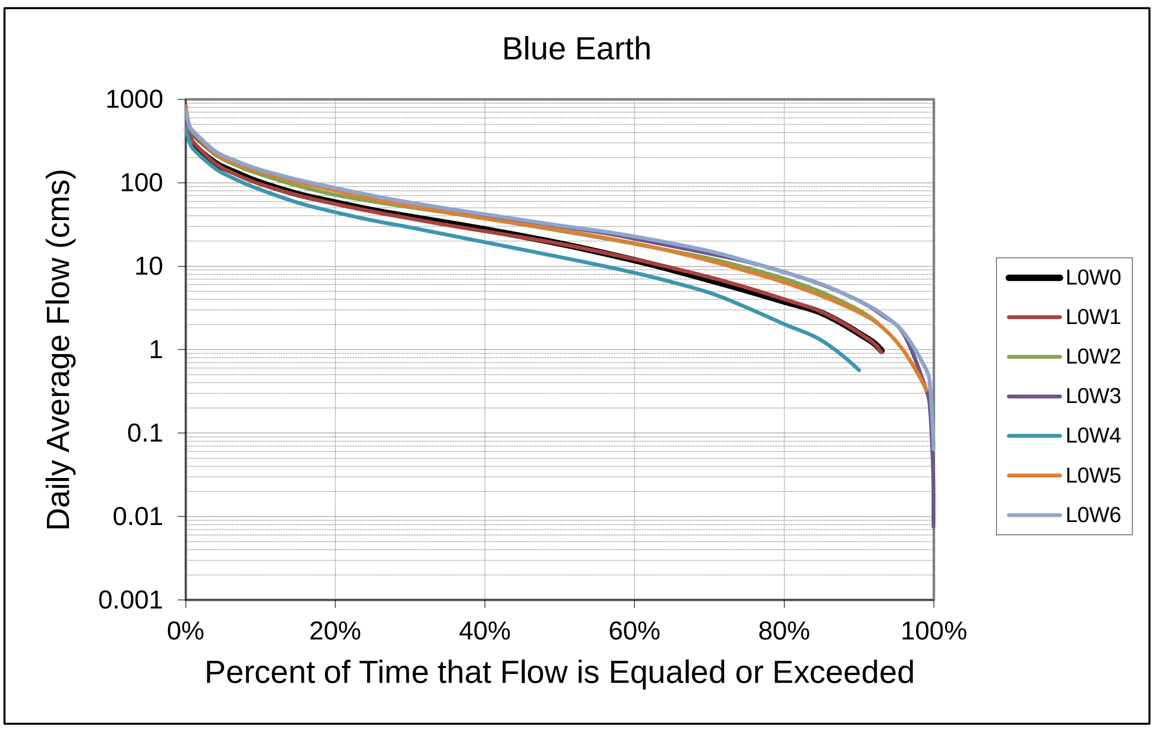


Figure 174. Flow Duration, Blue Earth River (SWAT)

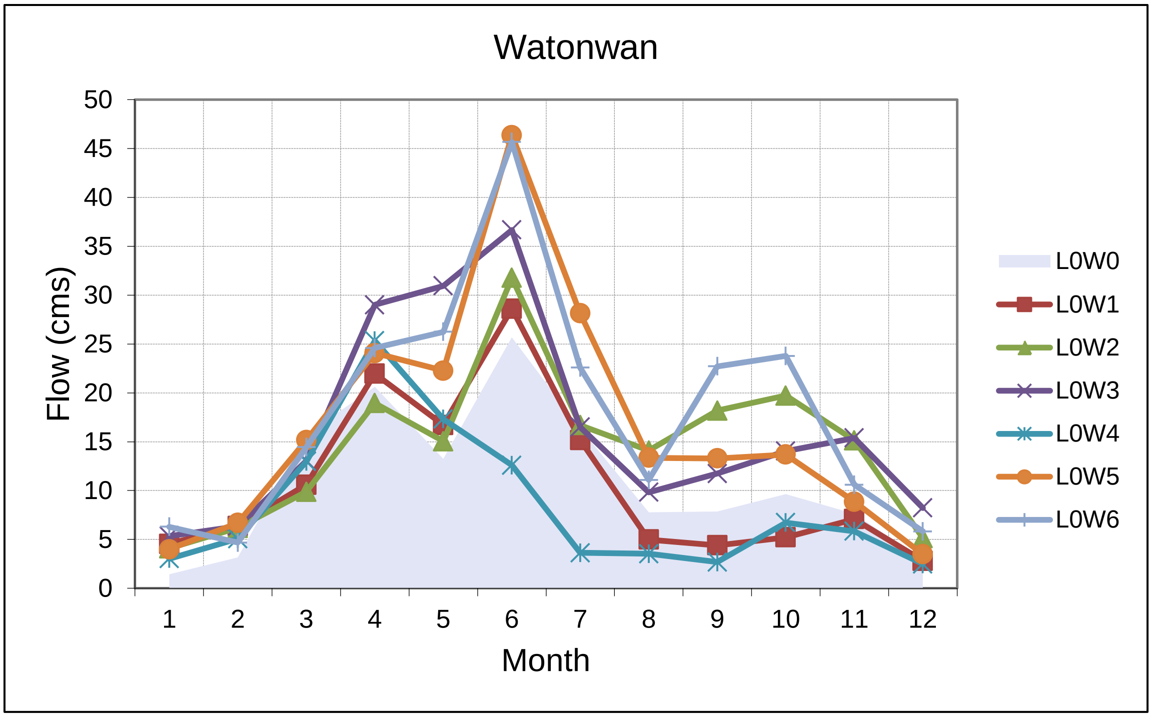


Figure 175. Monthly Average Flows, Watowan River (SWAT)

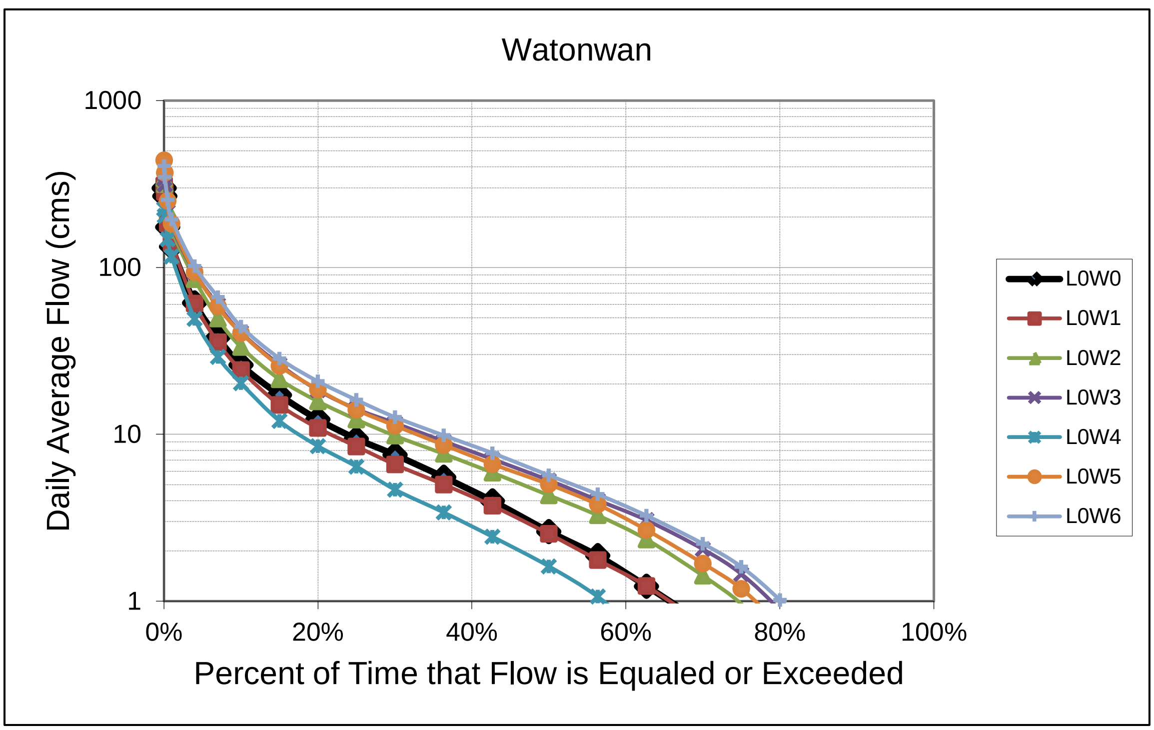


Figure 176. Flow Duration, Watowan River (SWAT)

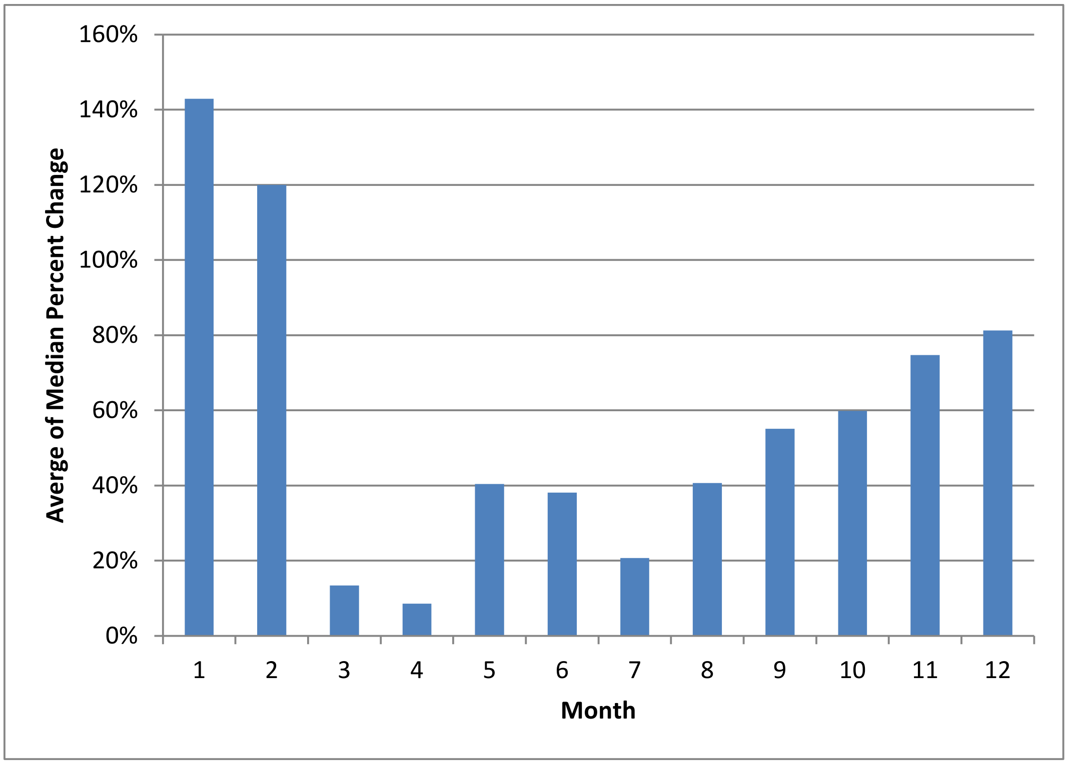


Figure 177. Average of Median Percent Change in Flow; NARCCAP Scenarios W1-W6 at all Stations, Minnesota River Basin (SWAT)

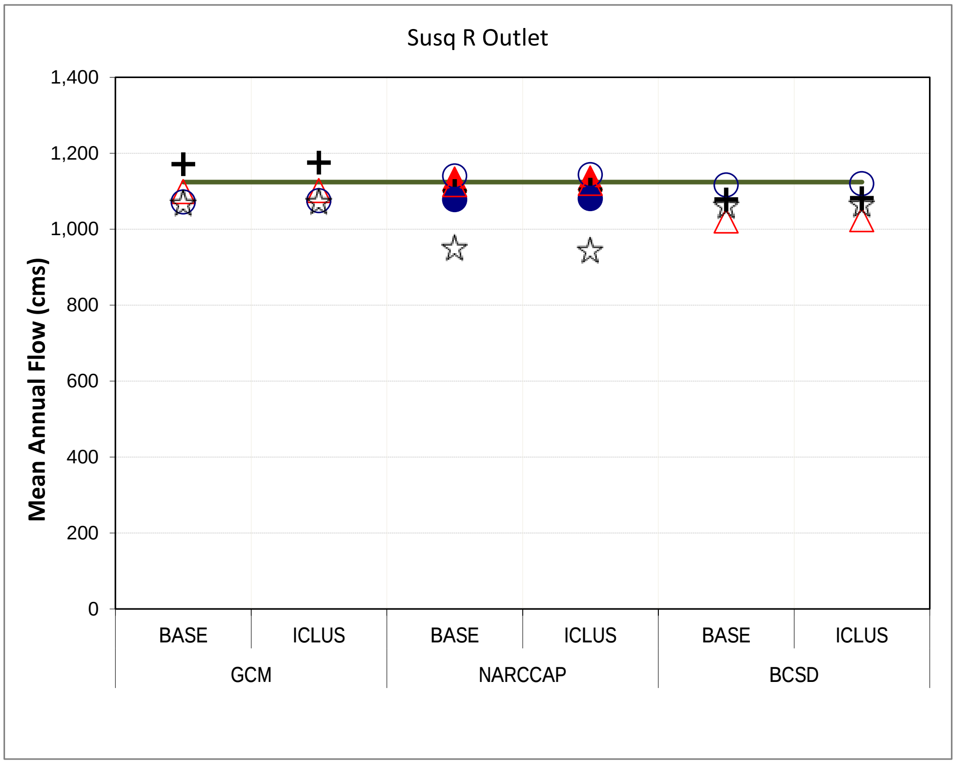


Figure 178. Mean Annual Flow, Susquehanna River Outlet (HSPF)

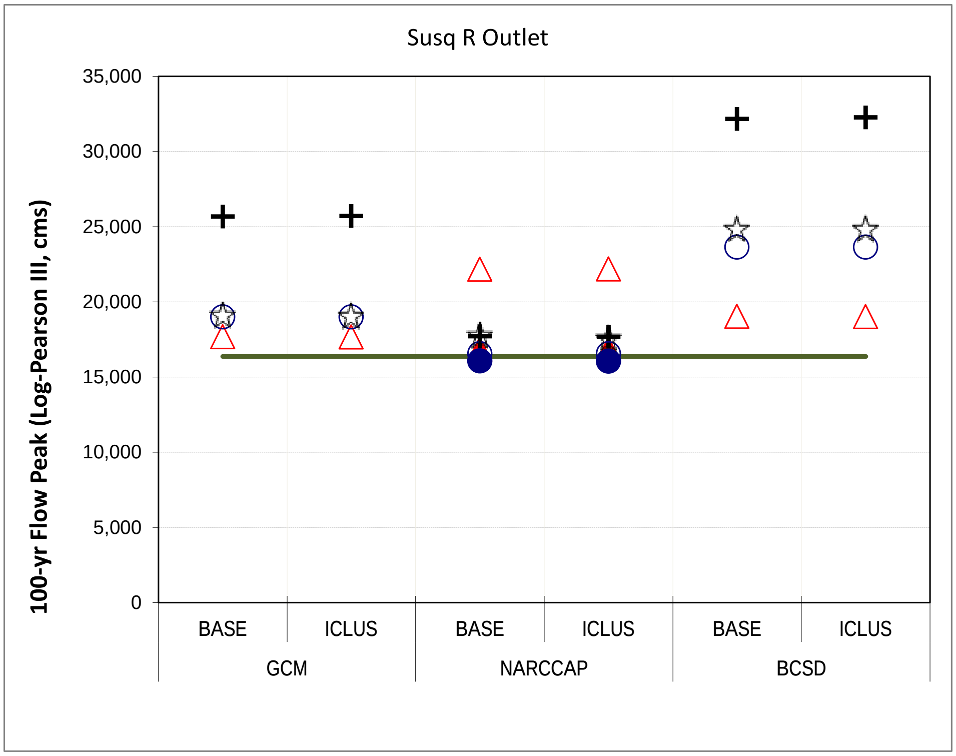


Figure 179. 100-yr Flow Peak, Susquehanna River Outlet (HSPF)

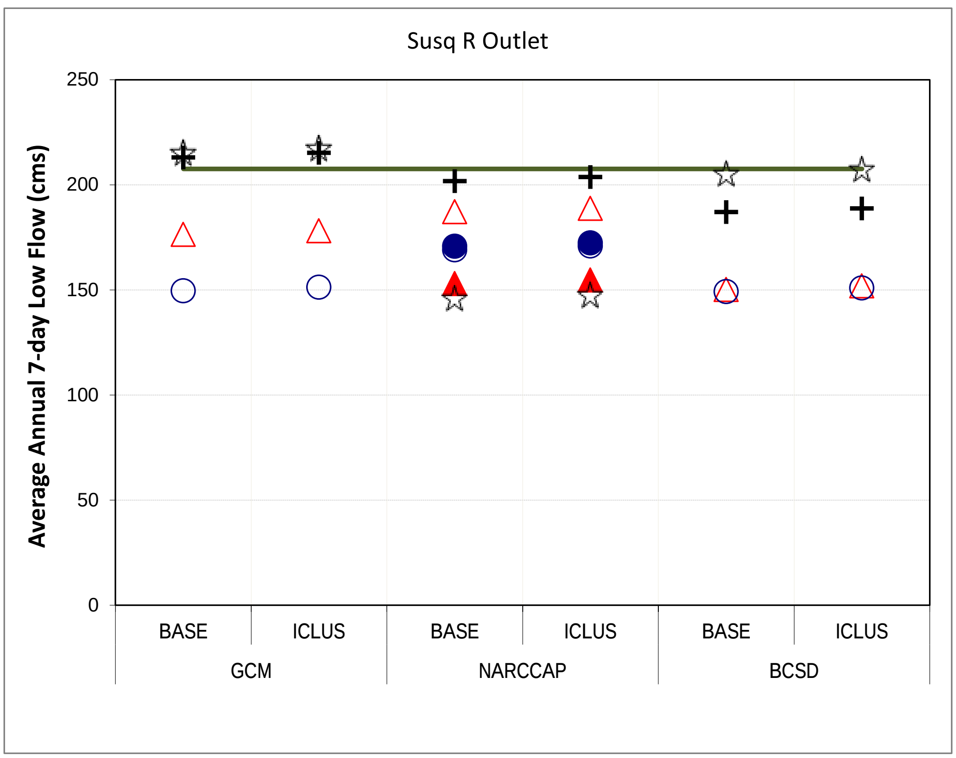


Figure 180. Average Annual 7-day Low Flow, Susquehanna River Outlet (HSPF)

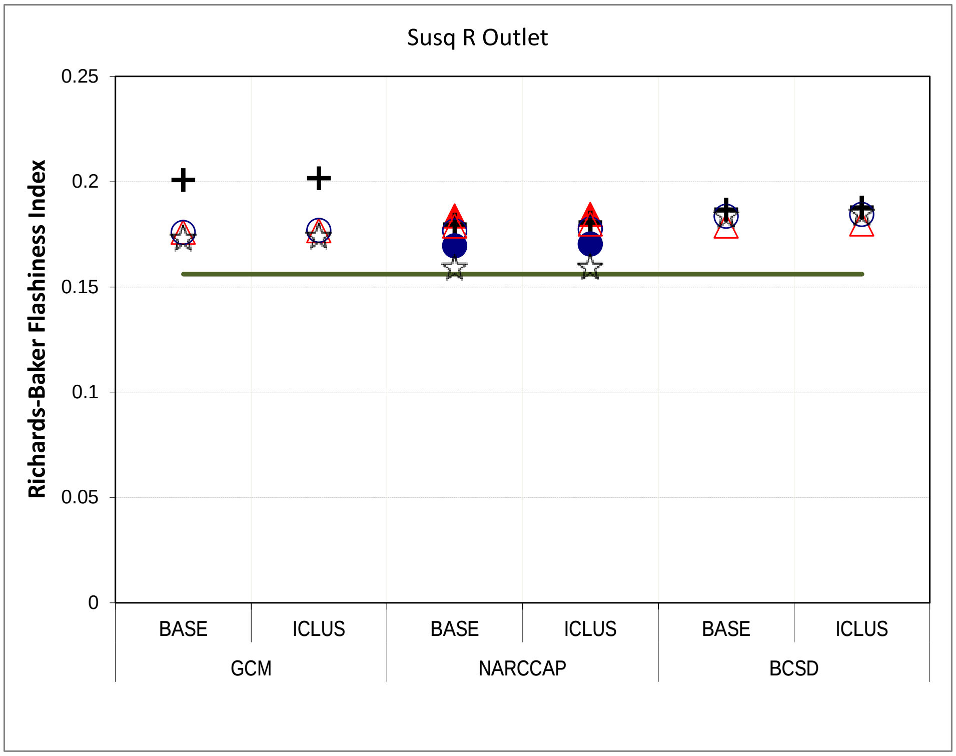


Figure 181. Richards-Baker Flashiness Index, Susquehanna River Outlet (HSPF)

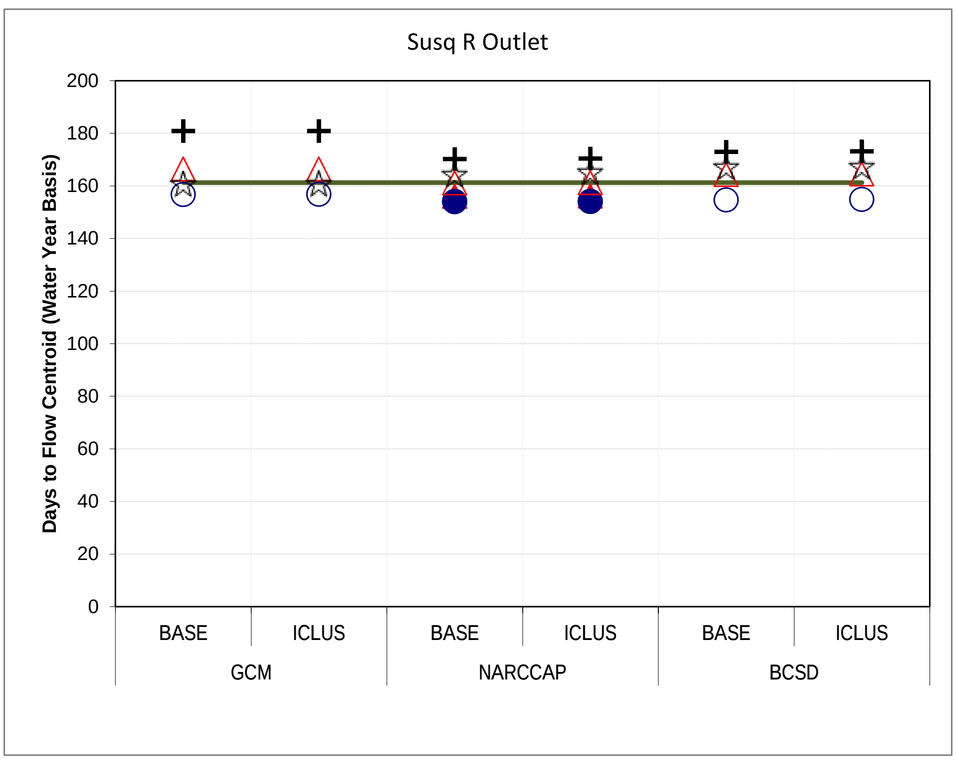


Figure 182. Days to Flow Centroid, Susquehanna River Outlet (HSPF)

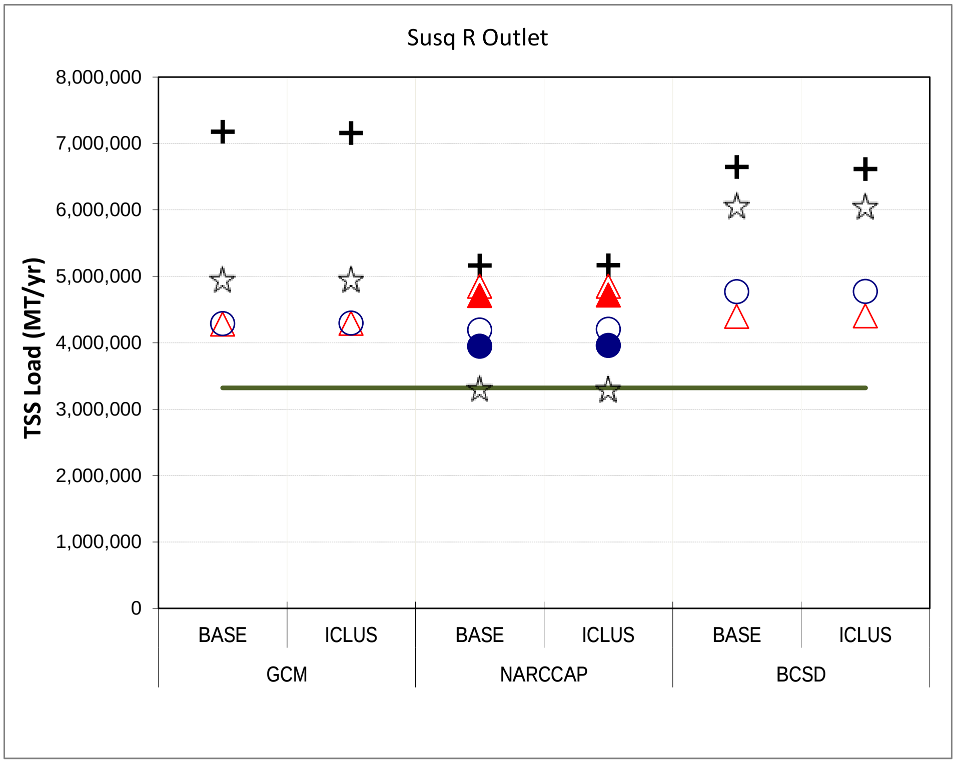


Figure 183. **TSS Load, Susquehanna River Outlet (HSPF)**

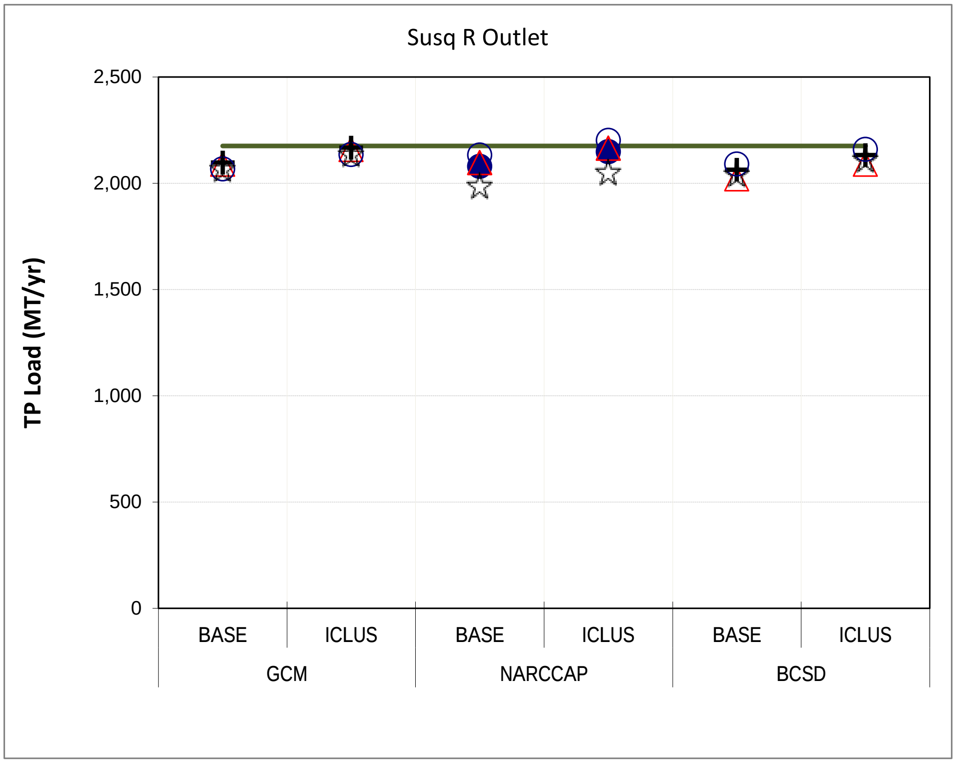


Figure 184. **TP Load, Susquehanna River Outlet (HSPF)**

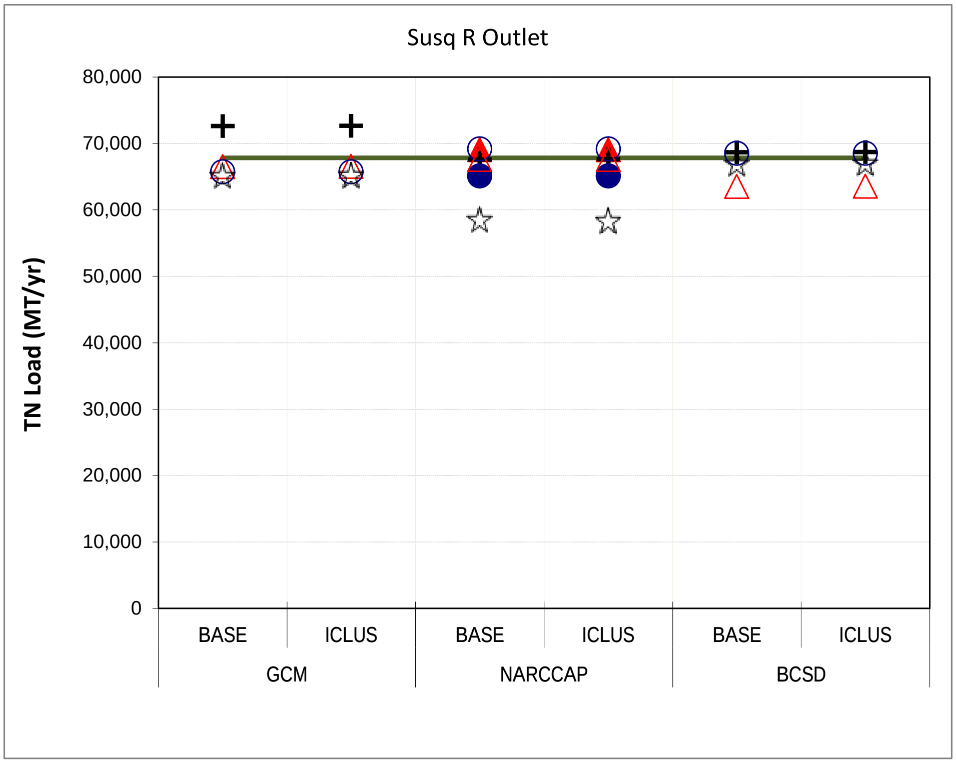


Figure 185. **TN Load, Susquehanna River Outlet (HSPF)**

Results at Multiple Stations

Table 7. Summary of Range of Change Relative to Existing Conditions for NARCCAP Dynamically Downscaled Scenarios, Susquehanna River Basin HSPF Model

	Results without LU Change				Results with LU Change			
	Min	Median	Mean	Max	Min	Median	Mean	Max
Raystown Branch Juniata River at Saxton (gage 01562000)								
Flow	-17.99%	-3.61%	-1.61%	14.36%	-17.99%	-3.61%	-1.61%	14.36%
TSS	-17.18%	42.95%	45.51%	115.70 %	-17.18%	42.95%	45.51%	115.70 %
TN	-17.45%	-2.53%	-0.70%	16.09%	-17.45%	-2.53%	-0.70%	16.09%
TP	-13.26%	-6.66%	-6.21%	2.03%	-13.26%	-6.66%	-6.21%	2.03%
WB Susquehanna River at Lewisberg								
Flow	-20.17%	-2.47%	-5.30%	0.18%	-20.14%	-2.45%	-5.29%	0.20%
TSS	-4.00%	28.43%	26.18%	44.79%	-4.02%	28.31%	26.08%	44.63%
TN	-15.17%	-0.43%	-3.23%	1.51%	-15.12%	-0.40%	-3.21%	1.51%
TP	-7.37%	-3.41%	-3.88%	-2.38%	-7.35%	-3.39%	-3.86%	-2.36%
Susquehanna River at Danville (gage 01540500)								
Flow	-14.40%	-1.67%	-3.58%	-0.50%	-14.40%	-1.67%	-3.58%	-0.50%
TSS	5.03%	30.55%	30.01%	57.81%	5.03%	30.55%	30.01%	57.81%
TN	-13.56%	-1.86%	-3.74%	-1.10%	-13.56%	-1.85%	-3.74%	-1.10%
TP	-7.90%	-4.19%	-4.77%	-3.53%	-7.90%	-4.19%	-4.77%	-3.53%
Susquehanna River at Marietta (gage 01576000)								
Flow	-15.39%	-1.56%	-3.51%	1.06%	-16.29%	-1.54%	-3.65%	1.06%
TSS	0.59%	33.94%	30.88%	53.97%	-0.32%	33.81%	30.60%	53.76%
TN	-13.82%	-0.79%	-2.74%	1.48%	-14.16%	-0.77%	-2.79%	1.47%
TP	-8.00%	-3.87%	-4.28%	-2.19%	-8.14%	-3.83%	-4.27%	-2.16%
Susquehanna River Outlet								
Flow	-15.14%	-1.35%	-3.33%	1.40%	-15.95%	-1.32%	-3.44%	1.41%
TSS	0.15%	33.95%	31.38%	55.42%	-0.62%	33.68%	30.94%	54.89%
TN	-13.43%	-0.36%	-2.39%	1.99%	-13.71%	-0.33%	-2.44%	1.96%
TP	-8.39%	-3.98%	-4.40%	-2.02%	-8.41%	-3.87%	-4.33%	-1.96%

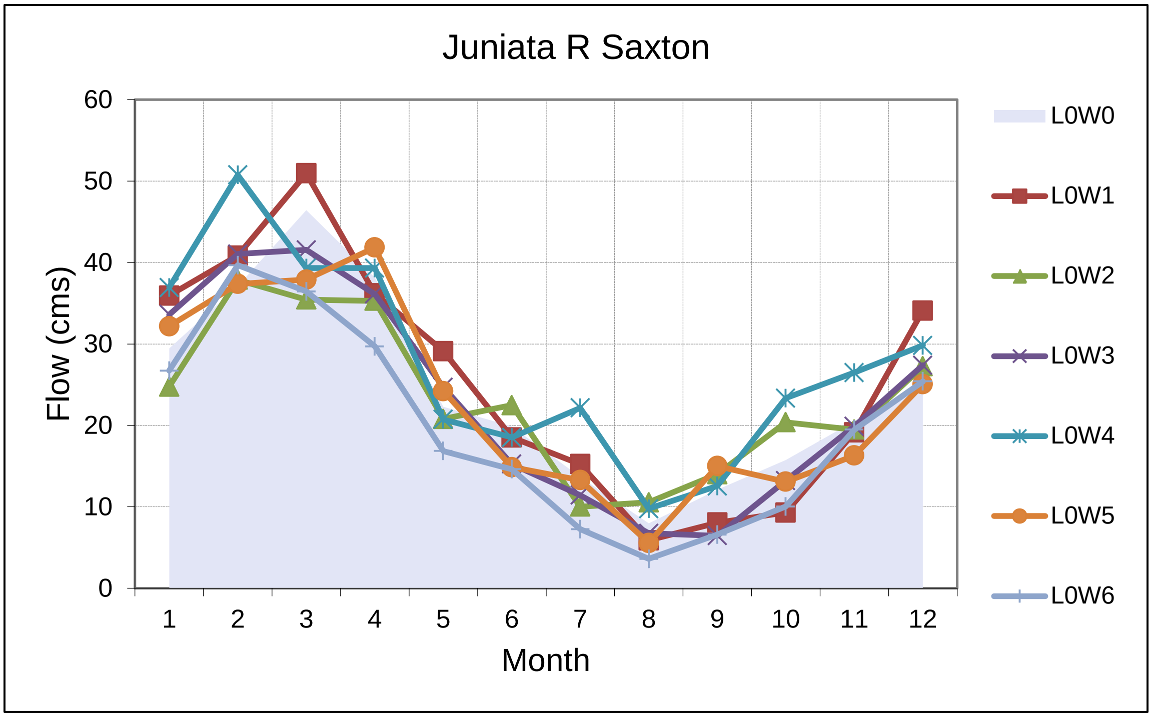


Figure 186. Monthly Average Flow, Raystown Branch Juniata River at Saxton (HSPF)

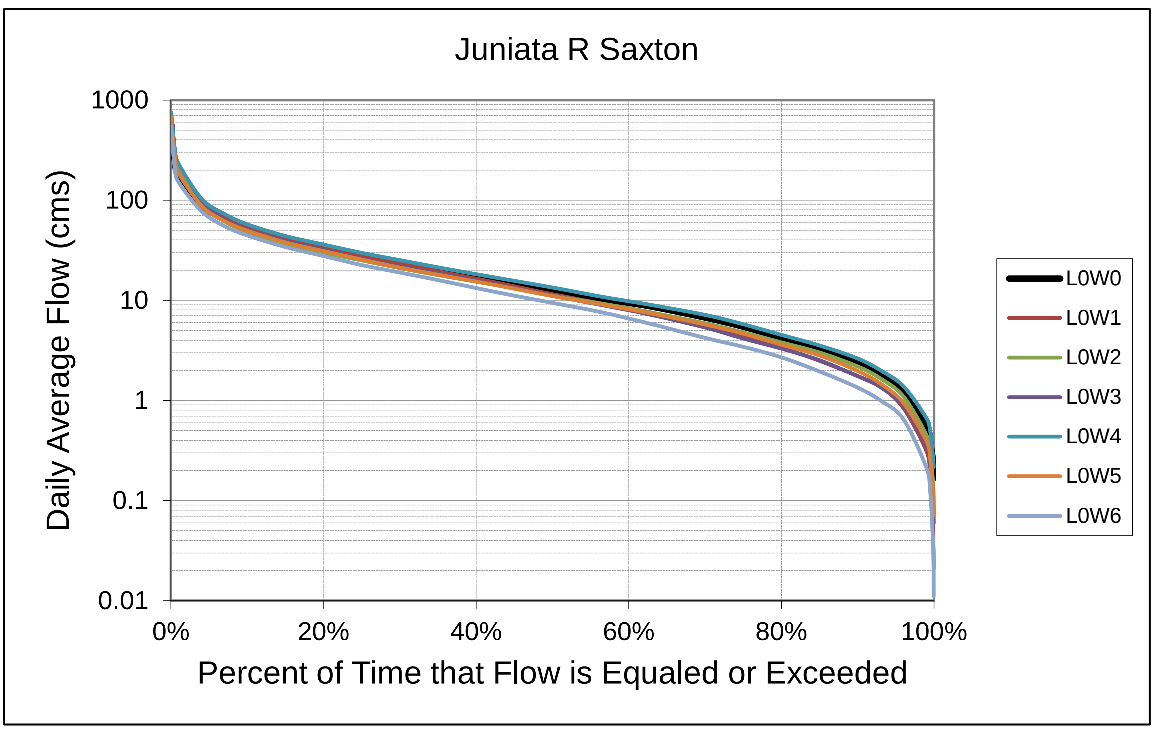


Figure 187. Flow Duration, Raystown Branch Juniata River at Saxton (HSPF)

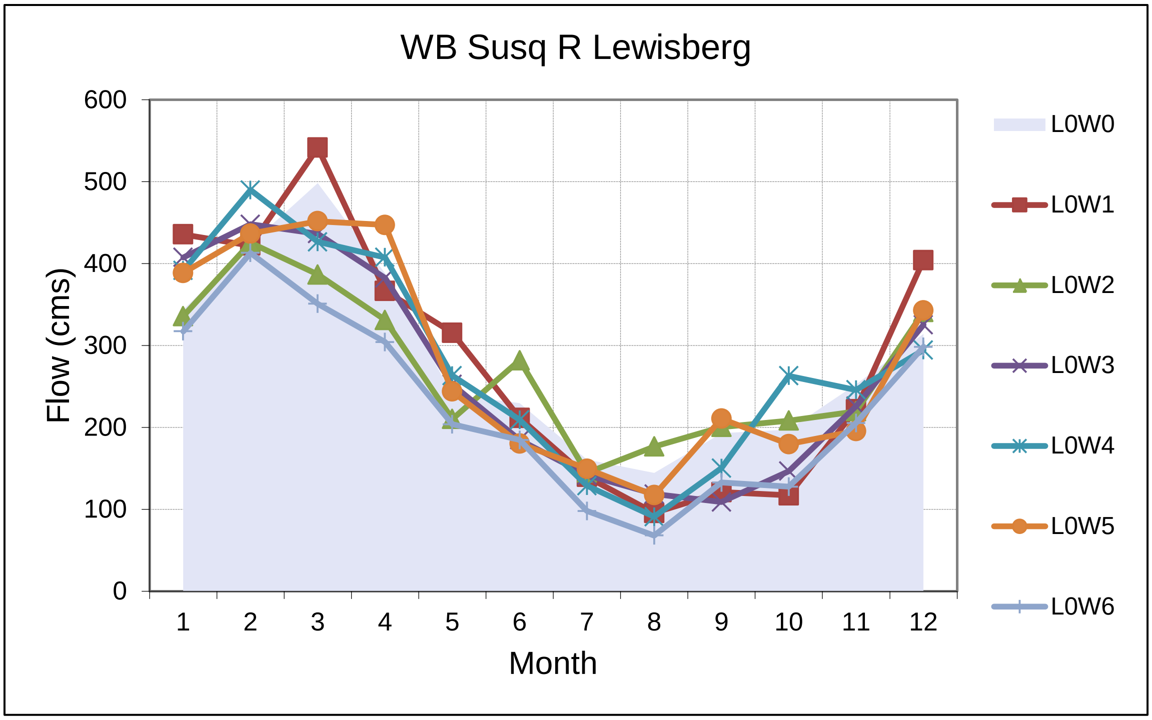


Figure 188. **Monthly Average Flow, West Branch Susquehanna River at Lewisberg (HSPF)**

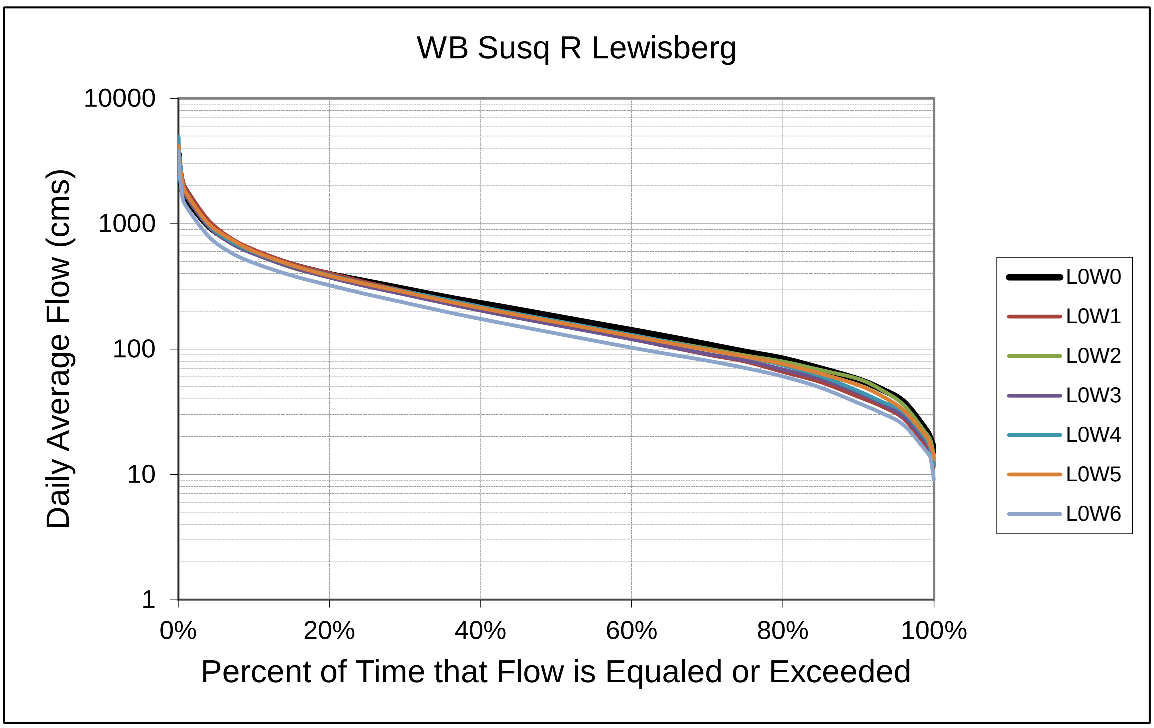


Figure 189. **Flow Duration, West Branch Susquehanna River at Lewisberg (HSPF)**

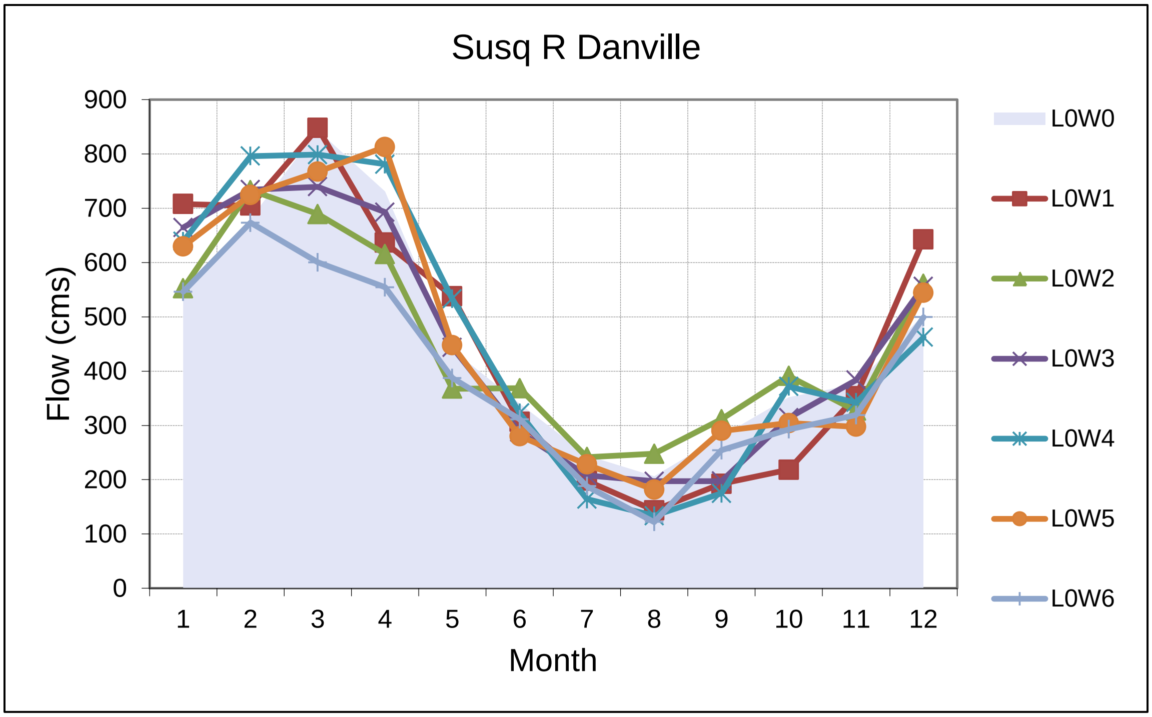


Figure 190. Monthly Average Flow, Susquehanna River at Danville (HSPF)

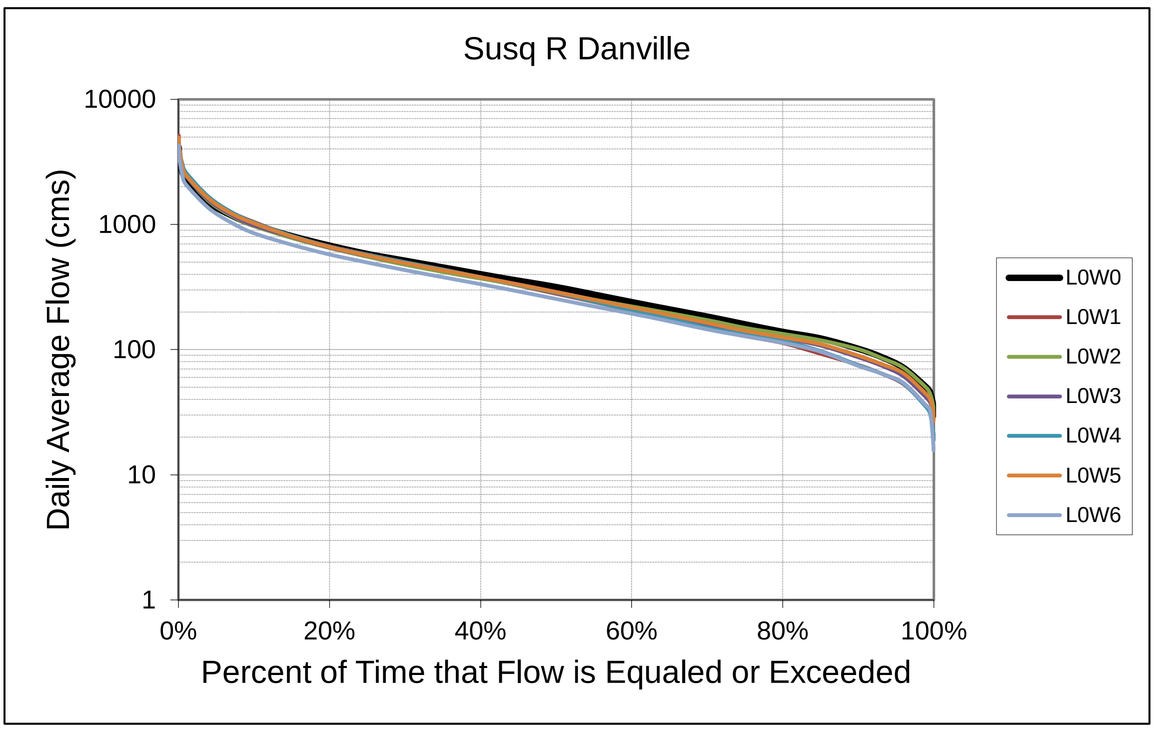


Figure 191. Flow Duration, Susquehanna River at Danville (HSPF)

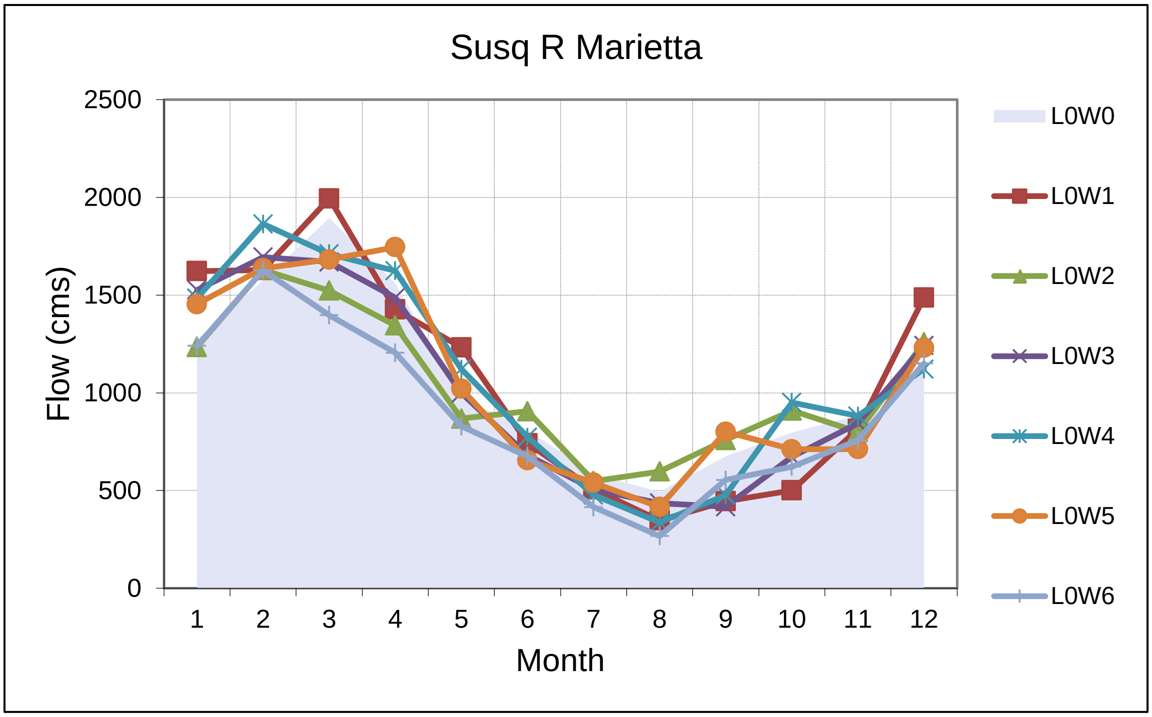


Figure 192. **Monthly Average Flow, Susquehanna River at Marietta (HSPF)**

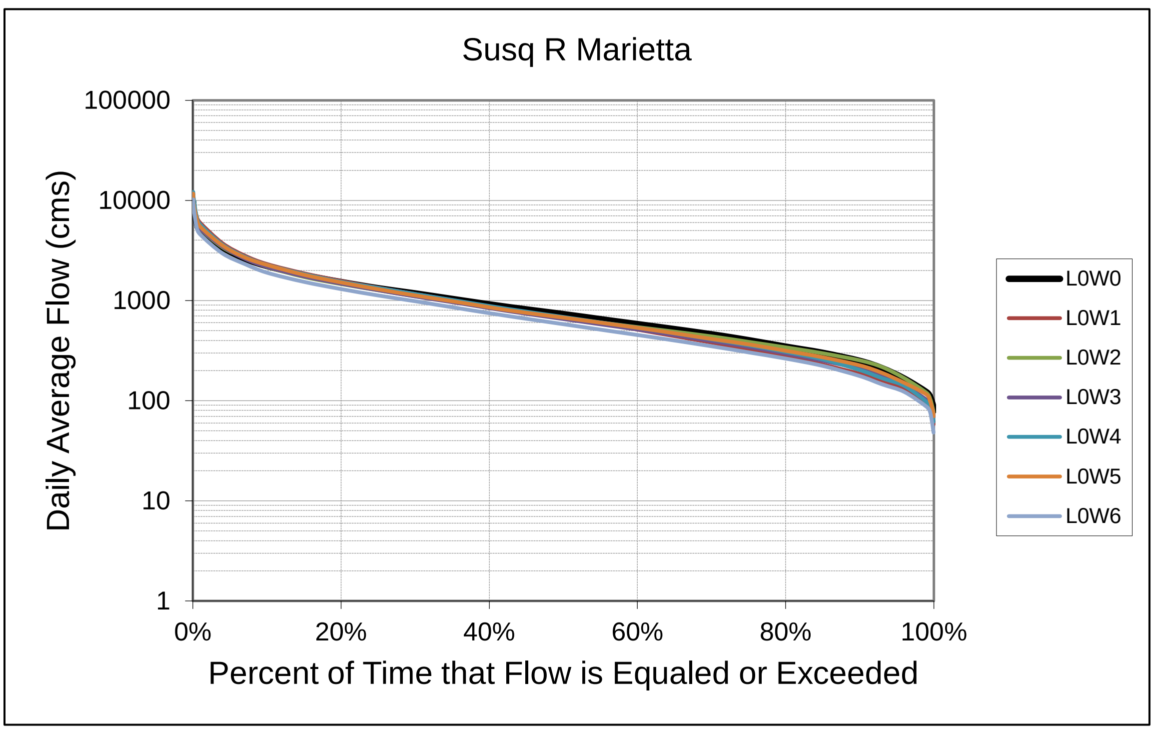


Figure 193. **Flow Duration, Susquehanna River at Marietta (HSPF)**

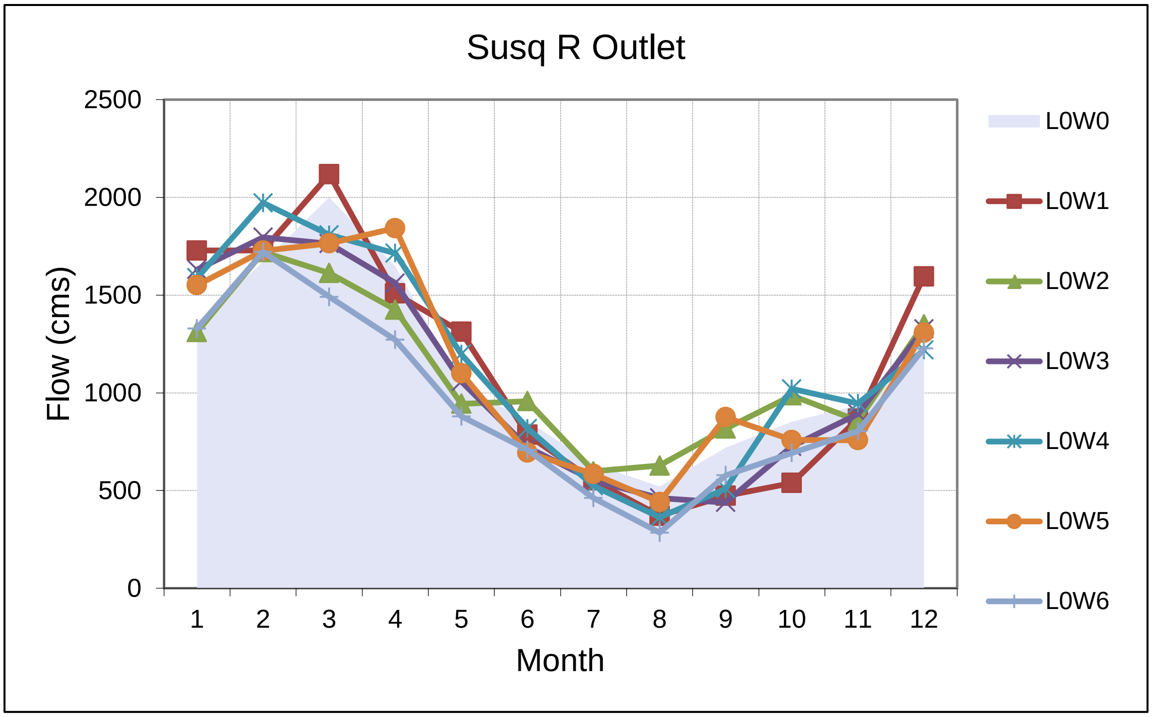


Figure 194. **Monthly Average Flow, Susquehanna River at Outlet (HSPF)**

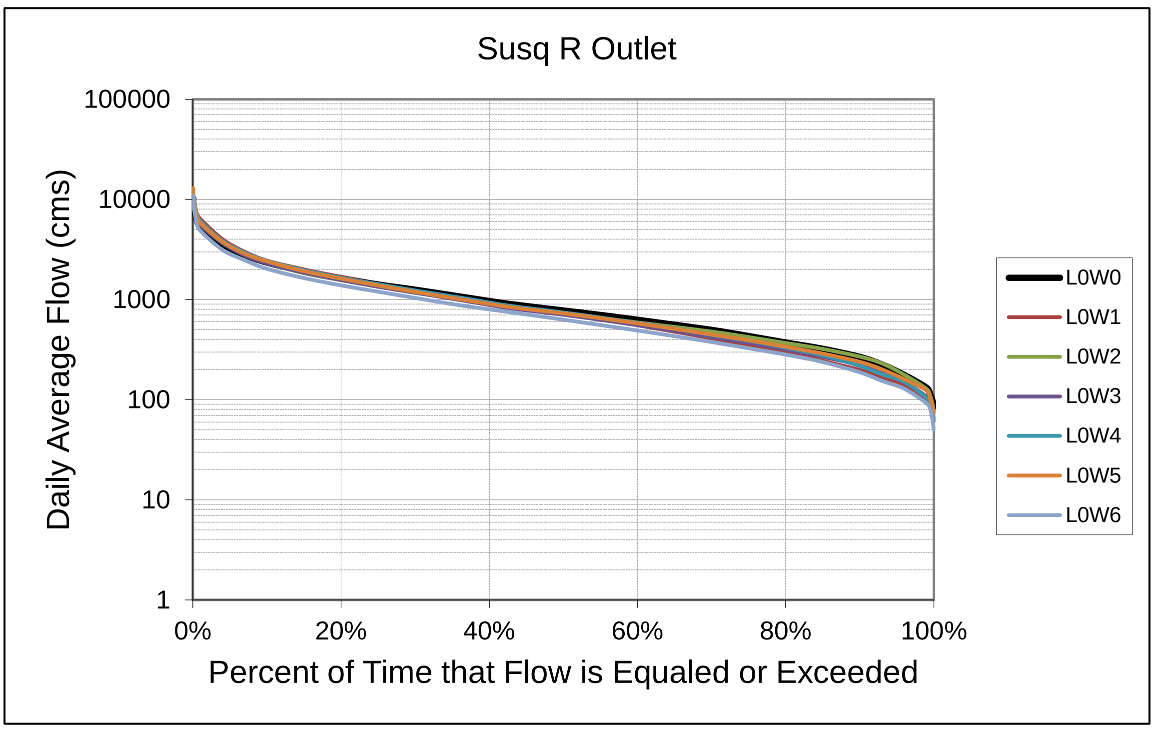


Figure 195. **Flow Duration, Susquehanna River at Outlet (HSPF)**

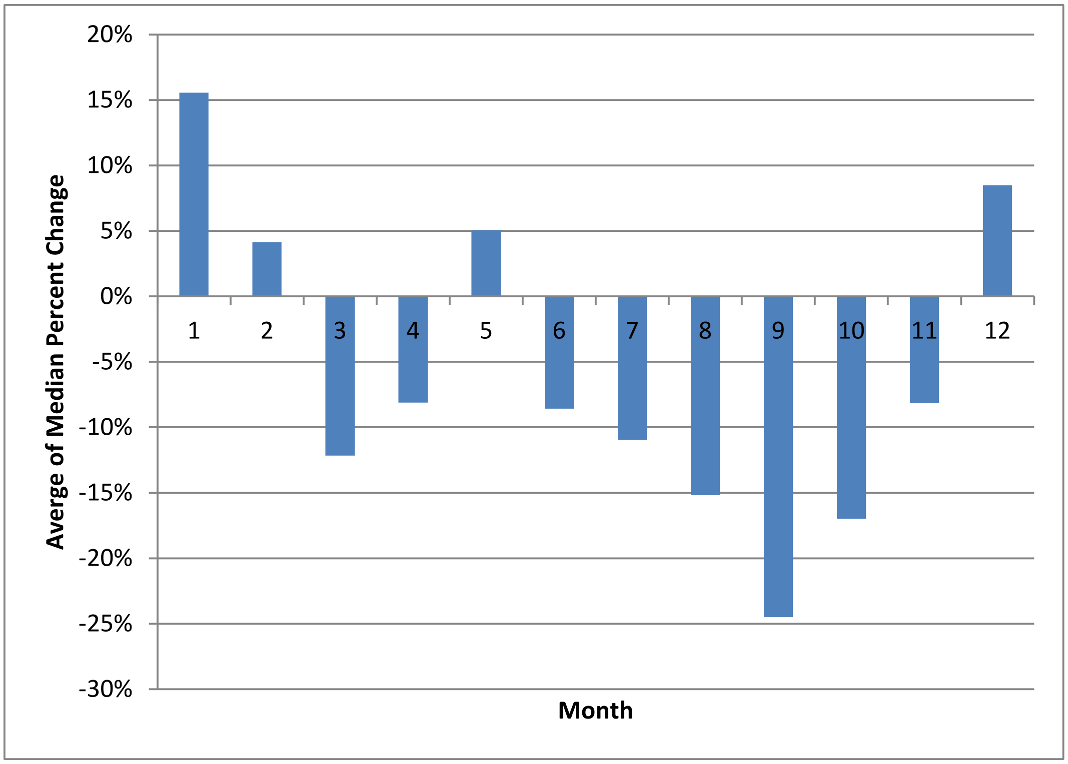


Figure 196. Average of Median Percent Change in Flow; NARCCAP Scenarios W1-W6 at all Stations, Susquehanna River Basin (HSPF)

Susquehanna River Basin, SWAT Model Results at Downstream Station

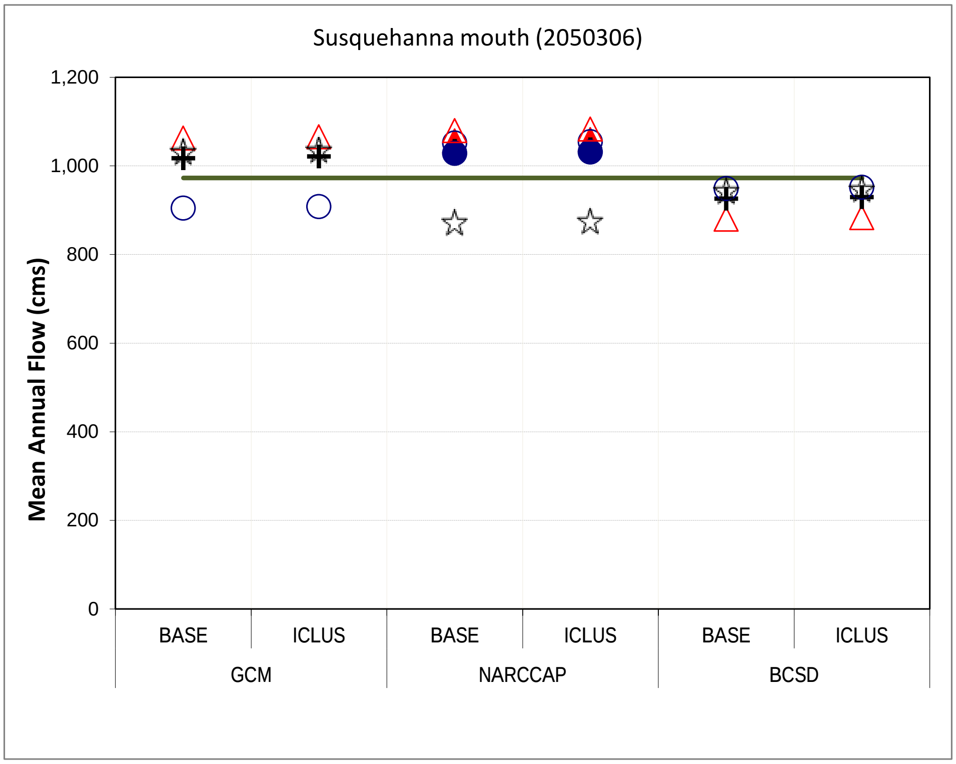


Figure 197. Mean Annual Flow, Susquehanna River Mouth (SWAT)

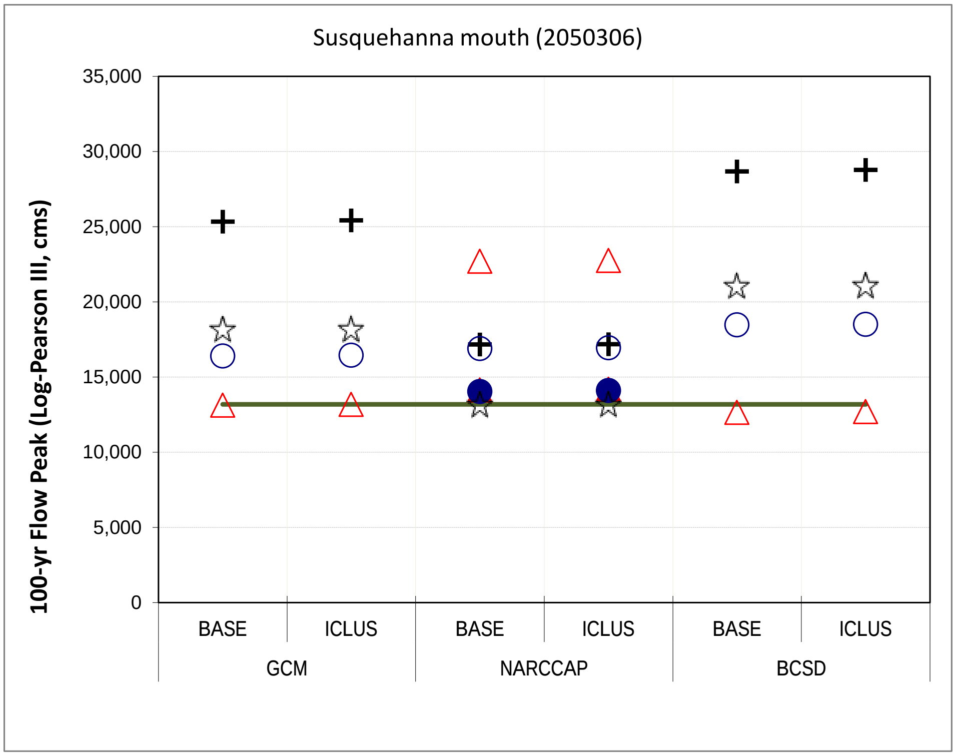


Figure 198. 100-yr Flow Peak, Susquehanna River Mouth (SWAT)

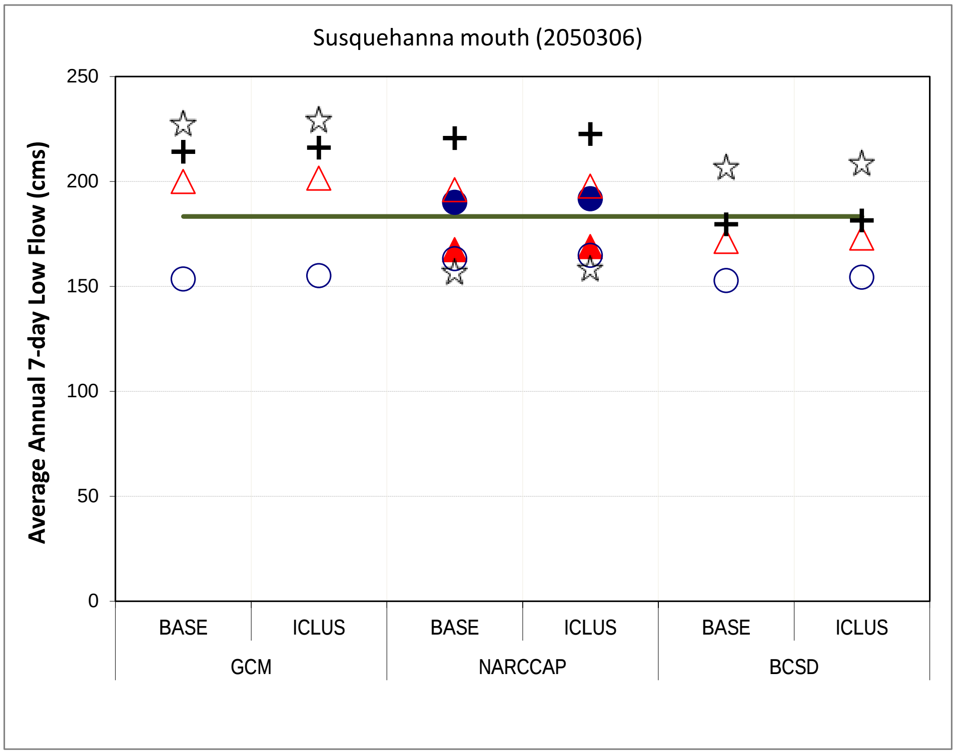


Figure 199. Average Annual 7-day Low Flow, Susquehanna River Mouth (SWAT)

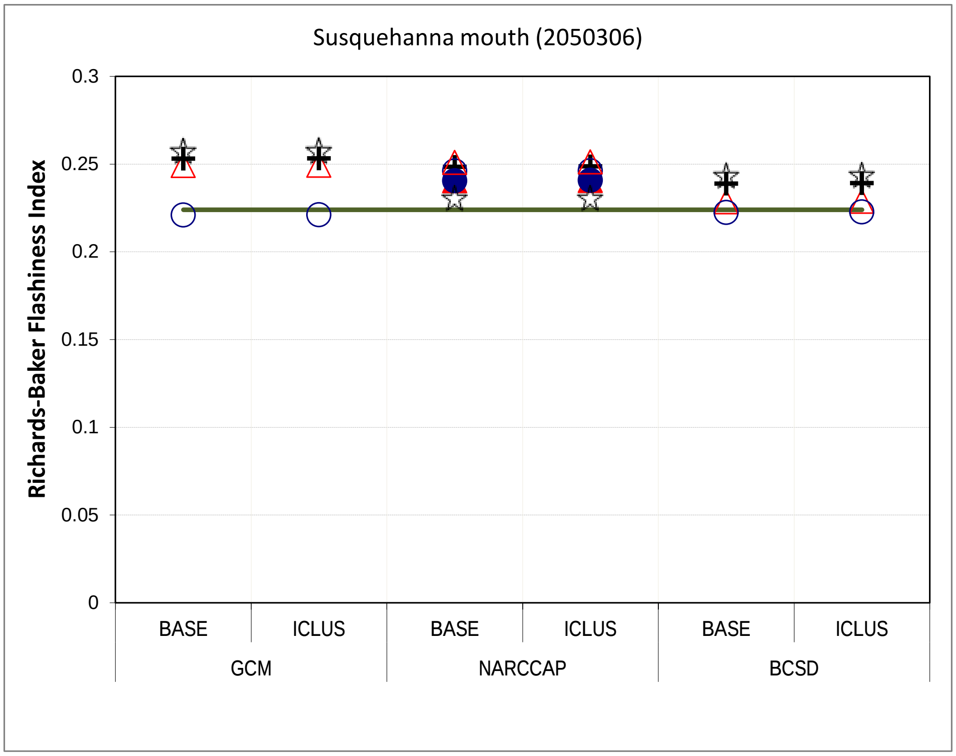


Figure 200. Richards-Baker Flashiness Index, Susquehanna River Mouth (SWAT)

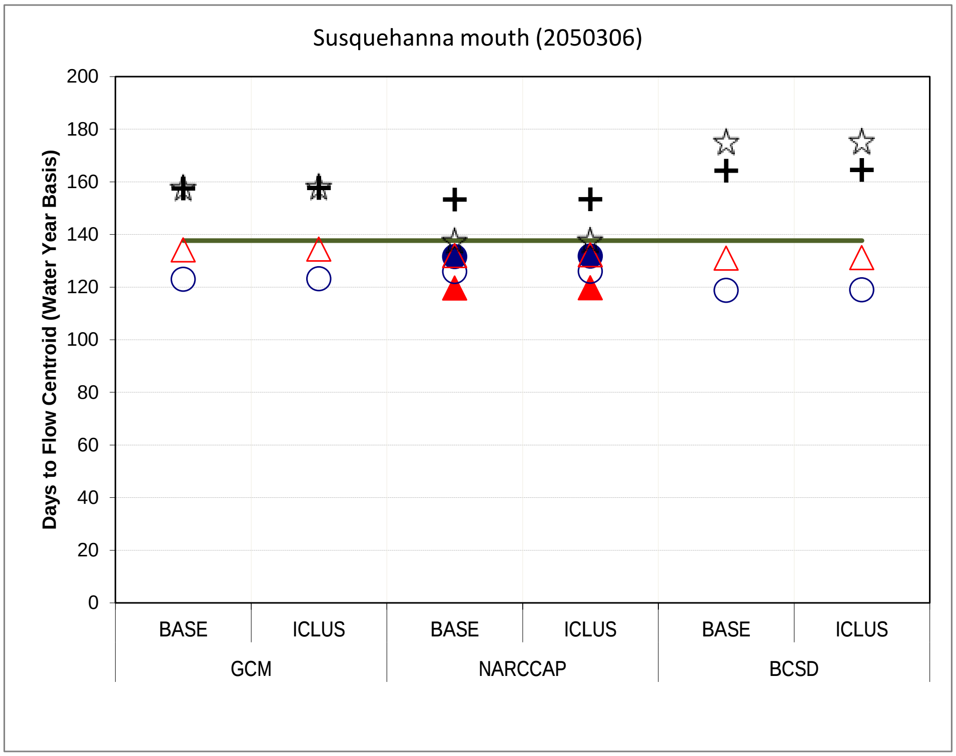


Figure 201. Days to Flow Centroid, Susquehanna River Mouth (SWAT)

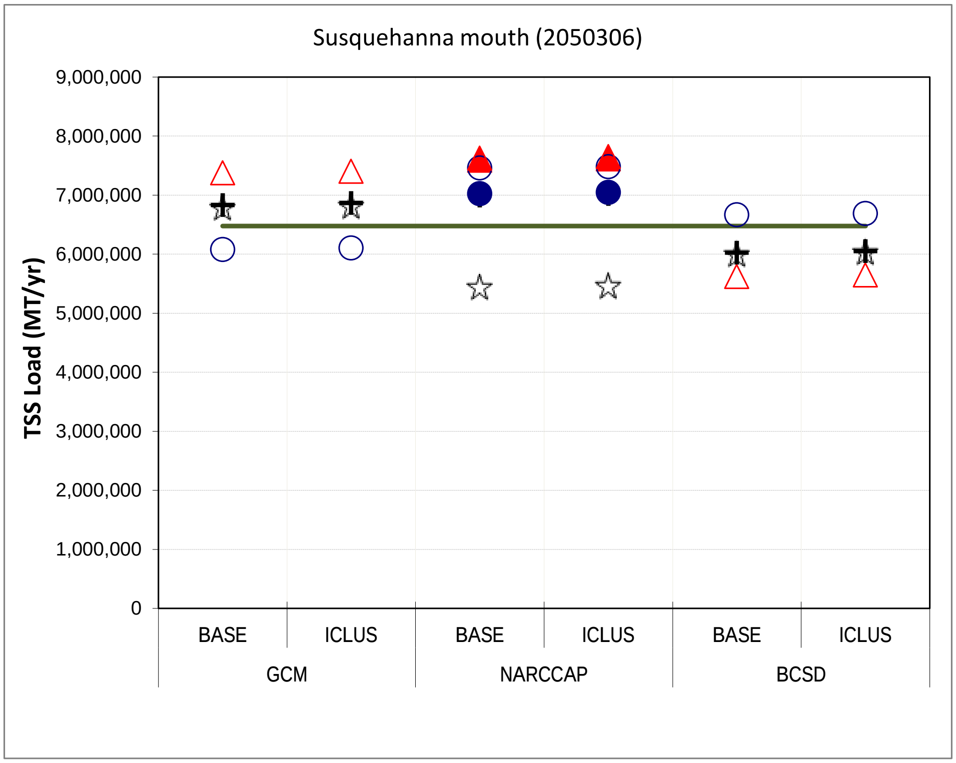


Figure 202. TSS Load, Susquehanna River Mouth (SWAT)

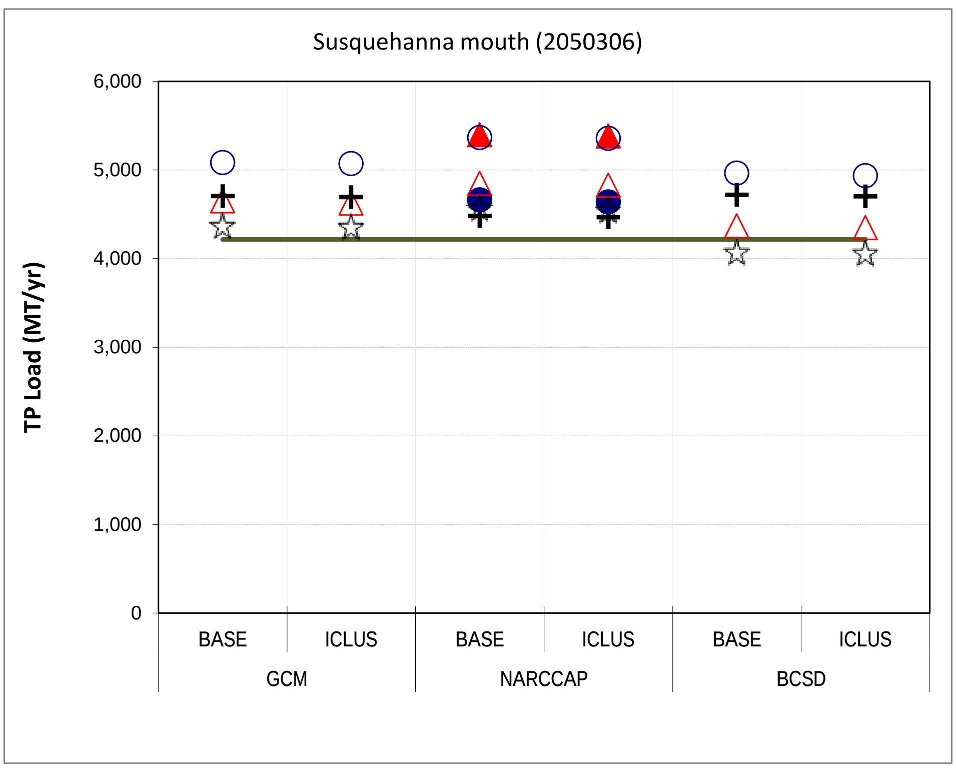


Figure 203. TP Load, Susquehanna River Mouth (SWAT)

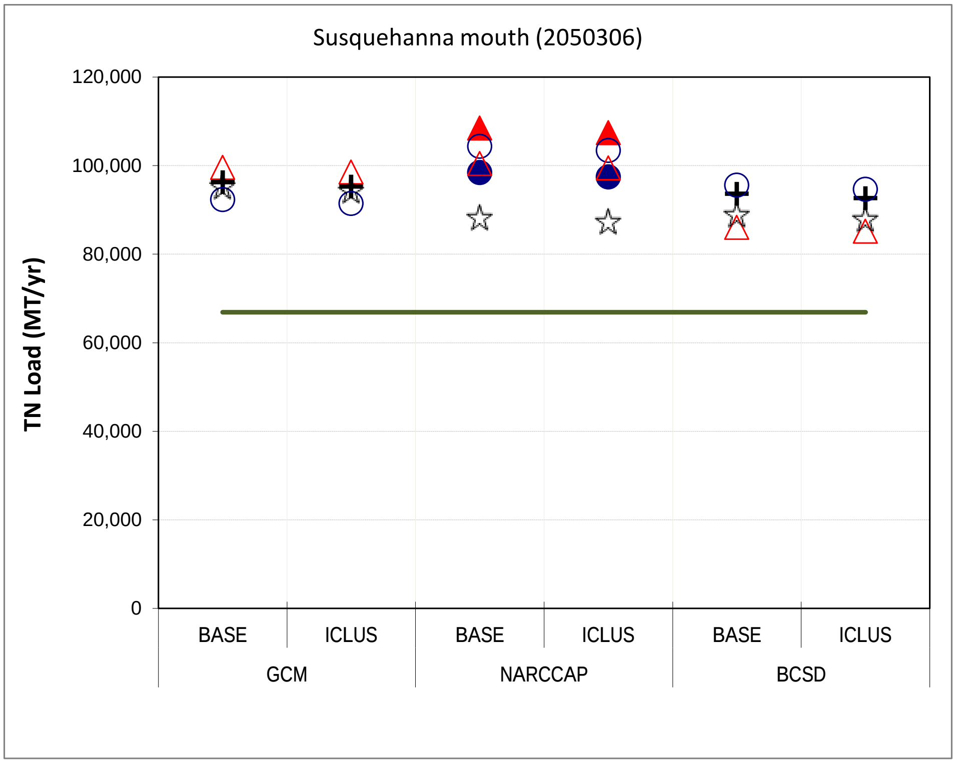


Figure 204. TN Load, Susquehanna River Mouth (SWAT)

Results at Multiple Stations

Table 8. Summary of Range of Change Relative to Existing Conditions for NARCCAP Dynamically Downscaled Scenarios, Susquehanna River Basin (SWAT)

	Results without LU Change				Results with LU Change			
	Min	Median	Mean	Max	Min	Median	Mean	Max
Upper Susquehanna HUC 02050101								
Flow	-2.93%	12.56%	10.45%	15.50%	-2.93%	12.56%	10.45%	15.50%
TSS	-5.62%	18.17%	14.02%	21.68%	-5.62%	18.17%	14.02%	21.67%
TN	45.88%	75.36%	76.83%	99.64%	45.88%	75.36%	76.83%	99.64%
TP	3.04%	27.68%	27.36%	59.62%	3.05%	27.69%	27.37%	59.64%
Chenango HUC 02050102								
Flow	-1.33%	13.06%	10.39%	16.13%	-1.32%	13.06%	10.39%	16.13%
TSS	-6.39%	15.86%	13.94%	24.18%	-6.42%	15.82%	13.90%	24.14%
TN	32.00%	48.75%	51.04%	68.74%	31.98%	48.73%	51.02%	68.71%
TP	6.83%	14.34%	12.96%	16.77%	6.78%	14.30%	12.92%	16.72%
Owego-Wappasening HUC 02050103								
Flow	-2.16%	12.58%	10.35%	16.13%	-2.16%	12.58%	10.35%	16.13%
TSS	-8.14%	17.35%	13.91%	25.19%	-8.13%	17.36%	13.91%	25.20%
TN	39.16%	61.49%	63.16%	82.59%	39.15%	61.46%	63.13%	82.56%
TP	1.55%	14.40%	13.10%	24.10%	1.53%	14.36%	13.07%	24.07%
Tioga HUC 02050104								
Flow	-5.57%	12.57%	10.25%	16.43%	-5.57%	12.57%	10.25%	16.43%
TSS	-9.02%	17.47%	14.23%	25.28%	-9.02%	17.48%	14.23%	25.28%
TN	21.38%	42.38%	39.90%	52.61%	21.37%	42.37%	39.90%	52.60%
TP	-6.17%	10.06%	7.86%	13.87%	-6.17%	10.05%	7.85%	13.87%
Chemung HUC 02050105								
Flow	-4.38%	12.63%	10.18%	19.43%	-4.38%	12.63%	10.18%	19.43%
TSS	-12.77%	19.73%	18.69%	44.35%	-12.77%	19.73%	18.69%	44.35%
TN	28.01%	49.52%	46.02%	57.58%	28.01%	49.52%	46.02%	57.58%
TP	-1.02%	13.10%	12.22%	20.53%	-1.02%	13.10%	12.22%	20.53%

	Results without LU Change				Results with LU Change			
	Min	Median	Mean	Max	Min	Median	Mean	Max
Upper Susquehanna - Lackawanna HUC 02050107								
Flow	-5.85%	8.79%	7.24%	14.08%	-5.85%	8.79%	7.24%	14.08%
TSS	-10.13%	17.56%	13.91%	24.94%	-10.13%	17.56%	13.91%	24.95%
TN	25.64%	44.63%	43.97%	58.47%	25.64%	44.62%	43.96%	58.46%
TP	3.34%	14.91%	13.94%	20.04%	3.33%	14.90%	13.93%	20.03%
Upper West Branch Susquehanna HUC 02050201								
Flow	-23.80%	-2.72%	-4.76%	2.53%	-23.81%	-2.73%	-4.77%	2.52%
TSS	4.05%	63.07%	57.82%	82.45%	4.02%	63.02%	57.77%	82.39%
TN	67.29%	94.34%	90.48%	99.00%	67.27%	94.17%	90.42%	99.04%
TP	33.51%	45.30%	44.90%	57.08%	33.74%	45.08%	44.99%	57.26%
Sinnemahoning HUC 02050202								
Flow	-14.29%	5.33%	3.08%	9.54%	-14.29%	5.33%	3.08%	9.54%
TSS	-14.32%	17.04%	14.25%	26.19%	-14.32%	17.04%	14.25%	26.19%
TN	36.24%	62.62%	62.69%	84.45%	36.15%	62.48%	62.56%	84.28%
TP	-4.98%	23.38%	22.14%	44.63%	-5.09%	23.17%	21.94%	44.37%
Pine HUC 02050205								
Flow	-8.36%	9.77%	6.66%	11.67%	-8.36%	9.77%	6.66%	11.67%
TSS	-10.51%	16.48%	12.22%	20.93%	-10.51%	16.48%	12.22%	20.93%
TN	-2.43%	23.34%	22.34%	37.97%	-2.43%	23.31%	22.32%	37.95%
TP	-24.19%	9.79%	5.12%	22.56%	-24.13%	9.77%	5.11%	22.53%
Lower West Branch Susquehanna HUC 02050206								
Flow	-14.99%	3.29%	0.92%	7.08%	-14.94%	3.32%	0.95%	7.11%
TSS	-20.99%	3.46%	0.98%	9.63%	-20.89%	3.57%	1.09%	9.73%

	Results without LU Change				Results with LU Change			
	Min	Median	Mean	Max	Min	Median	Mean	Max
TN	20.95%	38.10%	37.14%	48.13%	20.71%	37.79%	36.90%	47.89%
TP	5.23%	19.50%	25.19%	46.70%	4.95%	19.21%	25.15%	47.18%
Lower Susquehanna - Penns HUC 02050301								
Flow	-9.65%	6.11%	4.62%	11.36%	-9.64%	6.12%	4.63%	11.37%
TSS	-16.11%	11.76%	8.58%	19.88%	-16.10%	11.77%	8.58%	19.89%
TN	25.20%	42.75%	42.26%	55.42%	25.13%	42.68%	42.20%	55.35%
TP	7.40%	14.40%	18.75%	32.05%	7.24%	14.23%	18.66%	32.22%
Raystown HUC 02050303								
Flow	-14.94%	9.00%	7.75%	25.79%	-14.94%	9.00%	7.75%	25.79%
TSS	-16.49%	32.88%	34.95%	82.05%	-16.49%	32.88%	34.95%	82.05%
TN	57.89%	80.61%	84.77%	110.76%	57.90%	80.62%	84.78%	110.78%
TP	-1.88%	21.52%	25.52%	47.14%	-1.86%	21.55%	25.55%	47.19%
Lower Juniata HUC 02050304								
Flow	-10.44%	10.01%	7.44%	14.53%	-10.43%	10.02%	7.44%	14.53%
TSS	-11.79%	17.24%	13.86%	24.60%	-11.78%	17.29%	13.89%	24.64%
TN	41.30%	55.01%	57.70%	76.08%	41.29%	55.01%	57.69%	76.09%
TP	-2.88%	5.01%	5.03%	14.45%	-2.90%	5.02%	5.03%	14.45%
Susquehanna mouth HUC 02050306								
Flow	-10.08%	7.19%	4.92%	10.98%	-9.97%	7.27%	5.00%	11.04%
TSS	-15.67%	11.82%	8.49%	17.75%	-15.55%	11.90%	8.59%	17.84%
TN	32.30%	48.76%	49.18%	62.17%	32.07%	48.51%	48.96%	61.94%
TP	6.27%	12.74%	15.92%	27.94%	6.28%	12.63%	15.92%	28.09%
Susquehanna River at Marietta (gage 01576000)								
Flow	-9.97%	6.97%	4.96%	11.18%	-9.94%	6.99%	4.98%	11.19%

	Results without LU Change				Results with LU Change			
	Min	Median	Mean	Max	Min	Median	Mean	Max
TSS	-15.13%	12.16%	8.77%	18.47%	-15.12%	12.12%	8.74%	18.43%
TN	29.75%	46.51%	46.61%	59.51%	29.62%	46.37%	46.49%	59.40%
TP	6.04%	12.82%	16.08%	28.35%	5.91%	12.68%	16.02%	28.45%

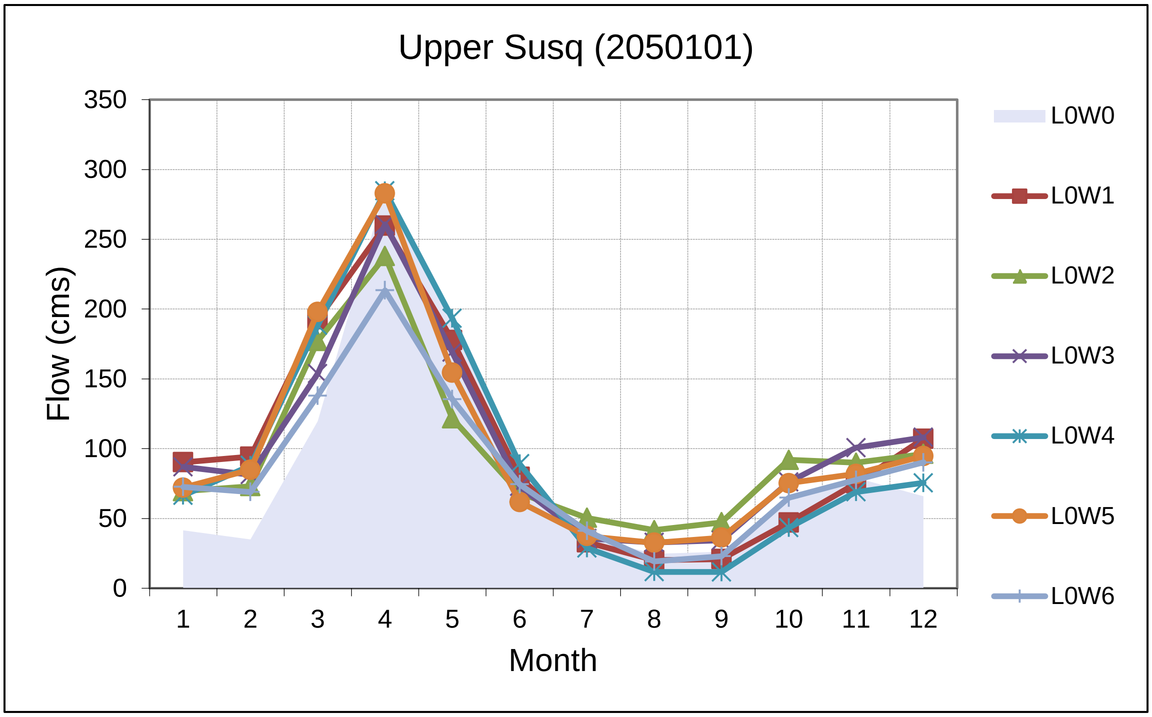


Figure 205. Monthly Average Flows, Upper Susquehanna River (SWAT)

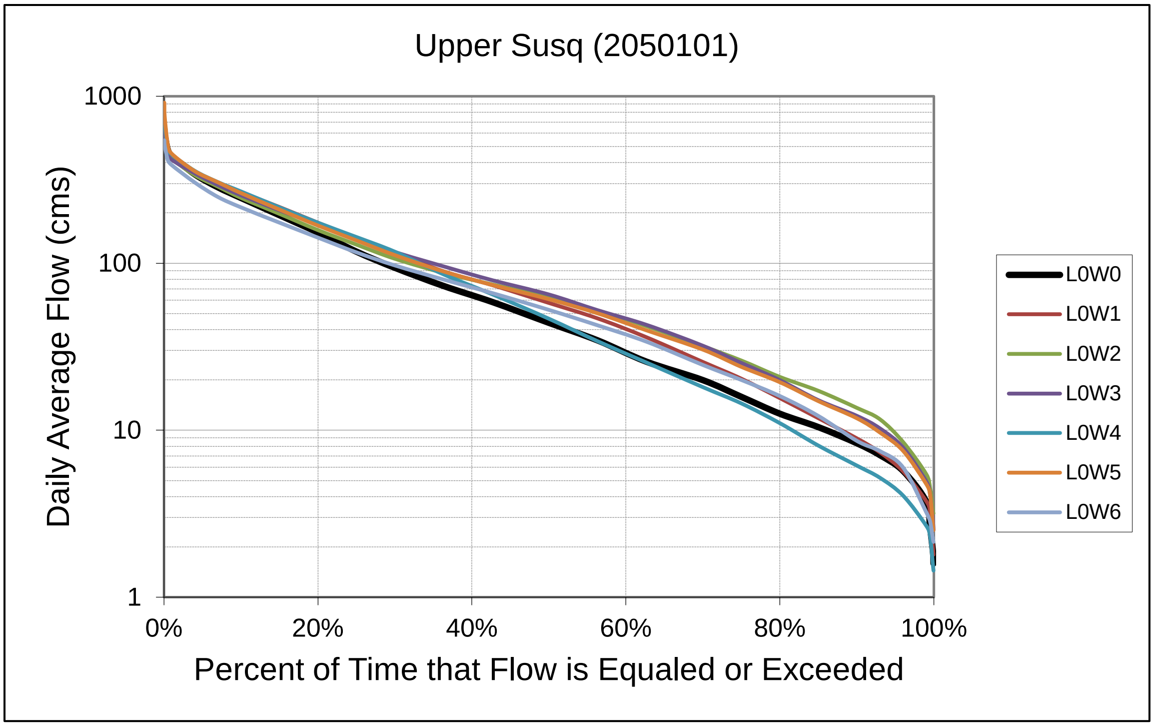


Figure 206. **Flow Duration, Upper Susquehanna River (SWAT)**

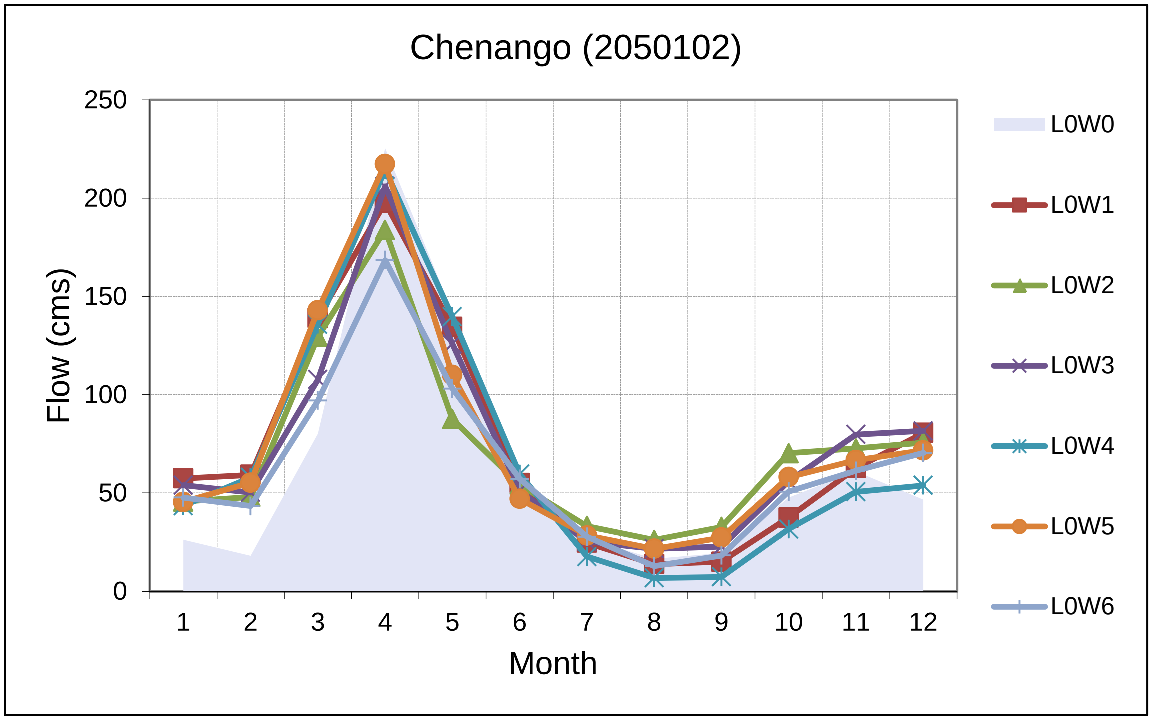


Figure 207. **Monthly Average Flows, Chenango (SWAT)**

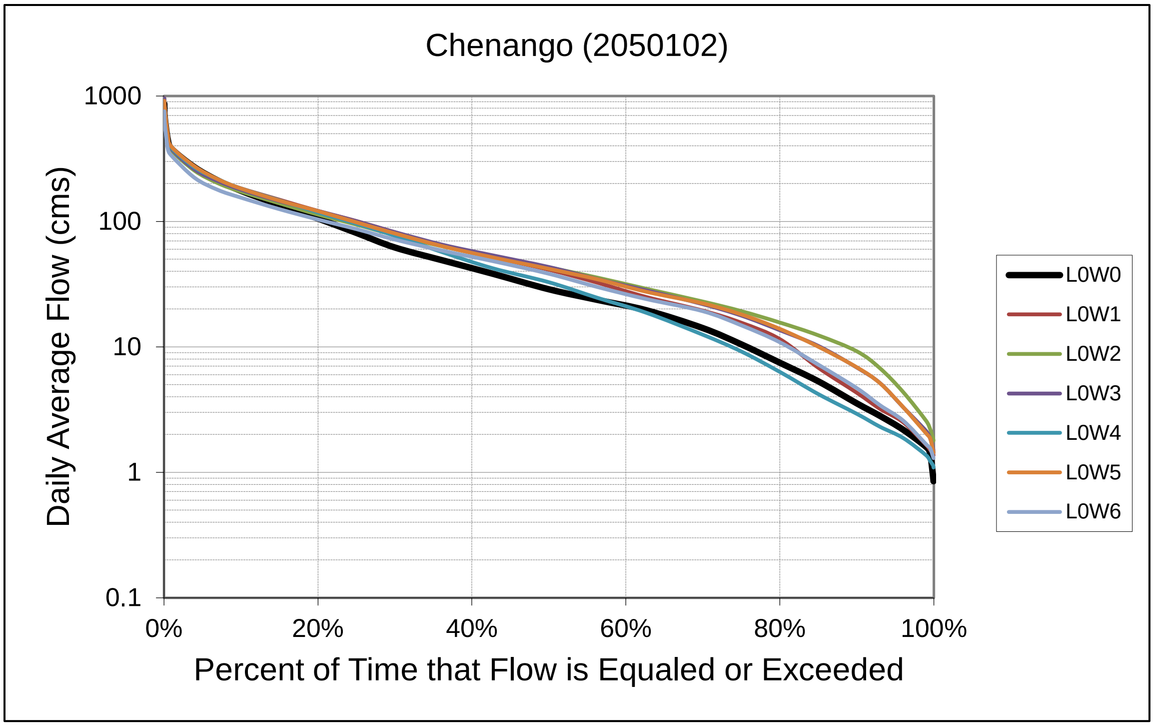


Figure 208. Flow Duration, Chenango (SWAT)

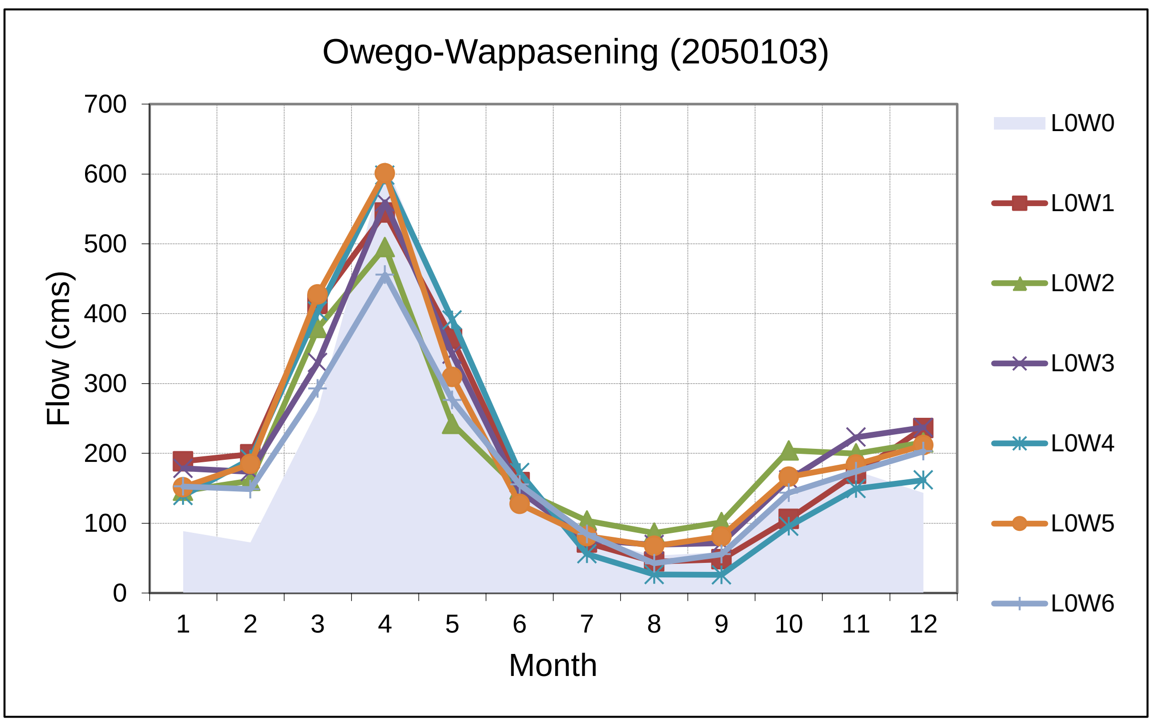


Figure 209. Monthly Average Flows, Owego-Wappasening (SWAT)

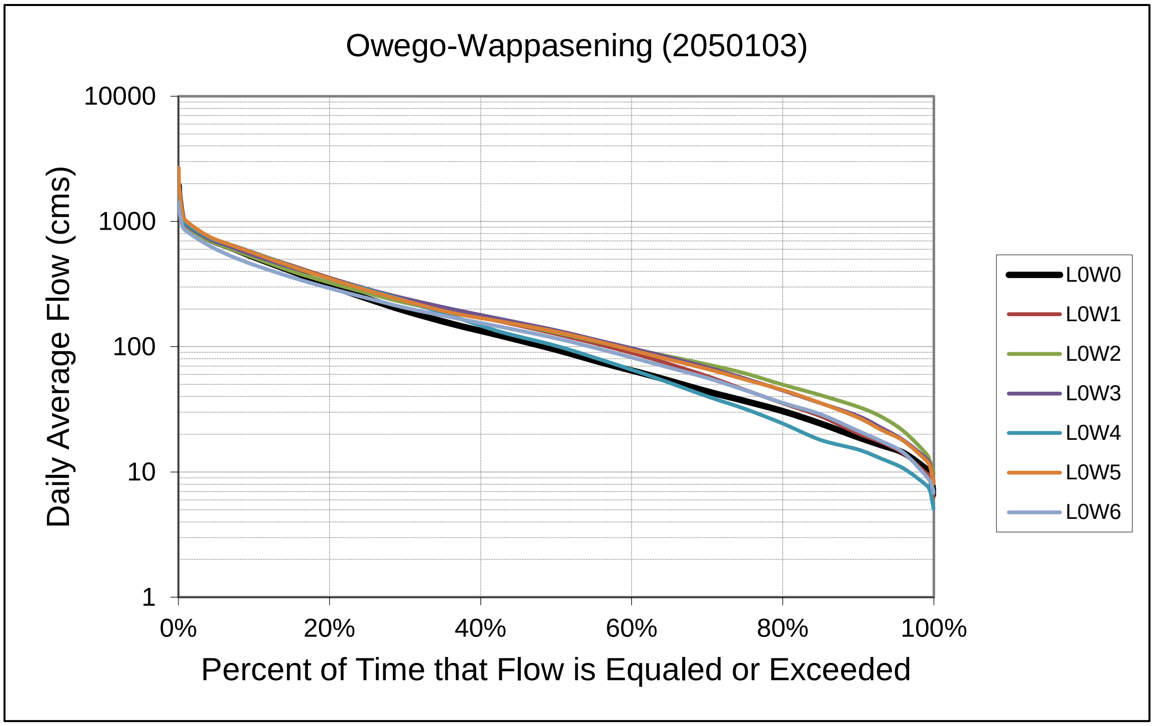


Figure 210. Flow Duration, Owego-Wappasening (SWAT)

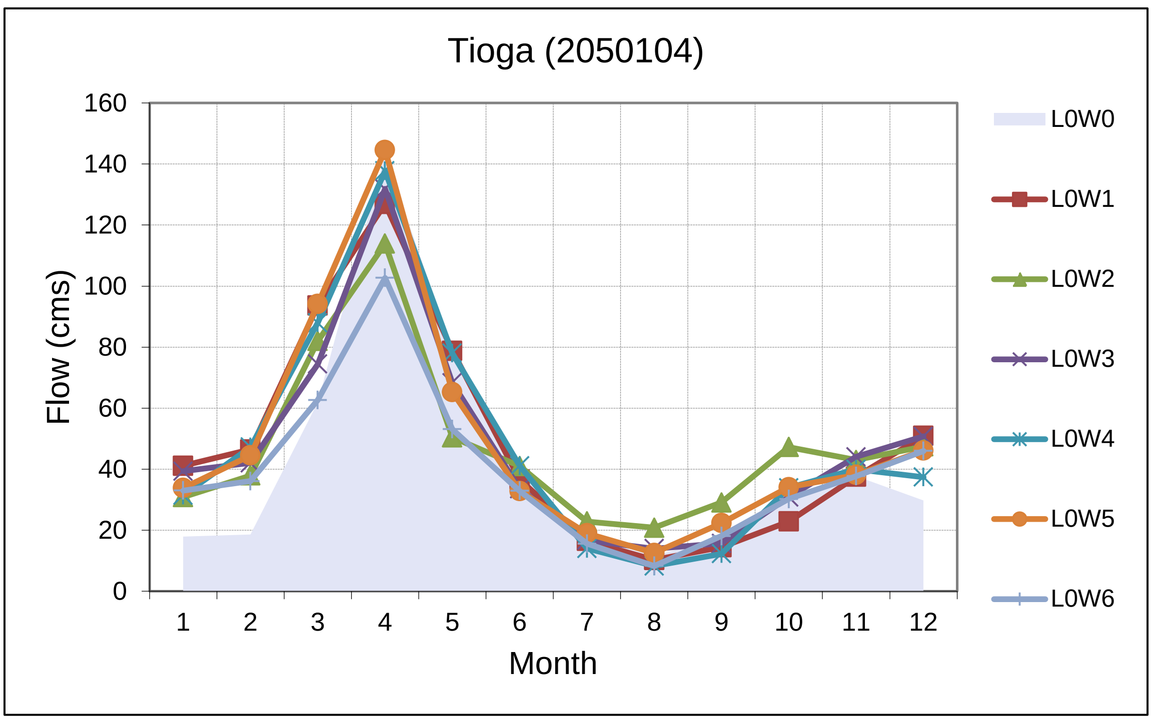


Figure 211. Monthly Average Flows, Tioga (SWAT)

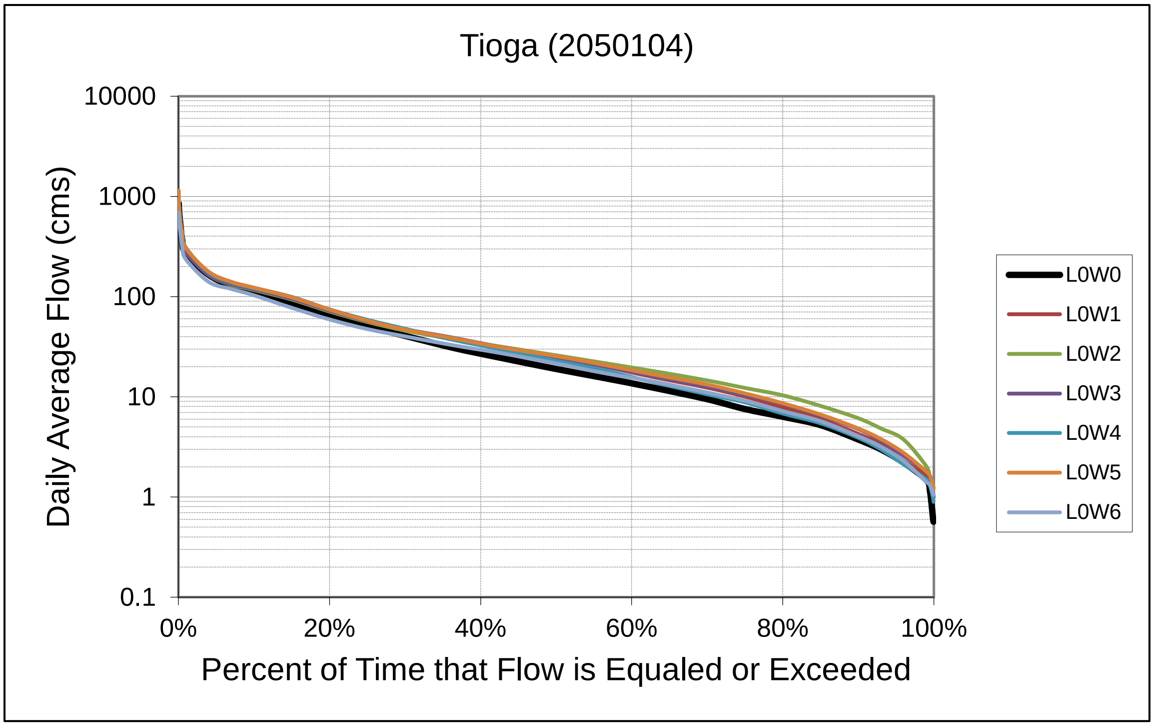


Figure 212. Flow Duration, Tioga (SWAT)

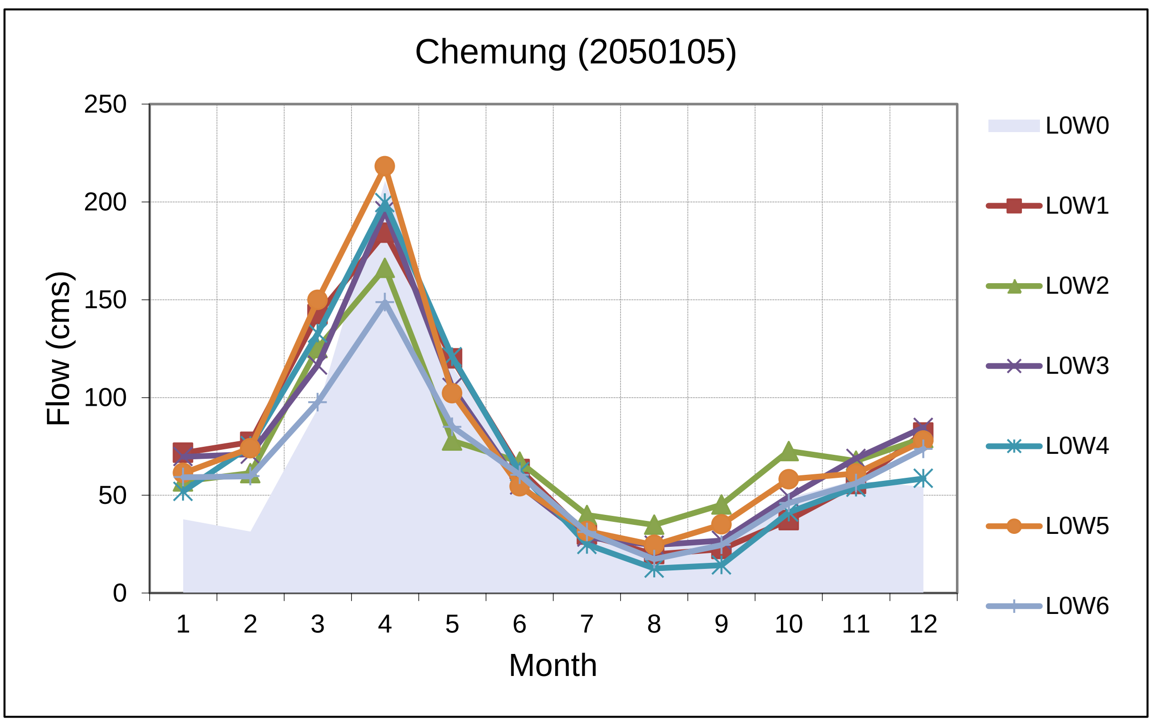


Figure 213. Monthly Average Flows, Chemung (SWAT)

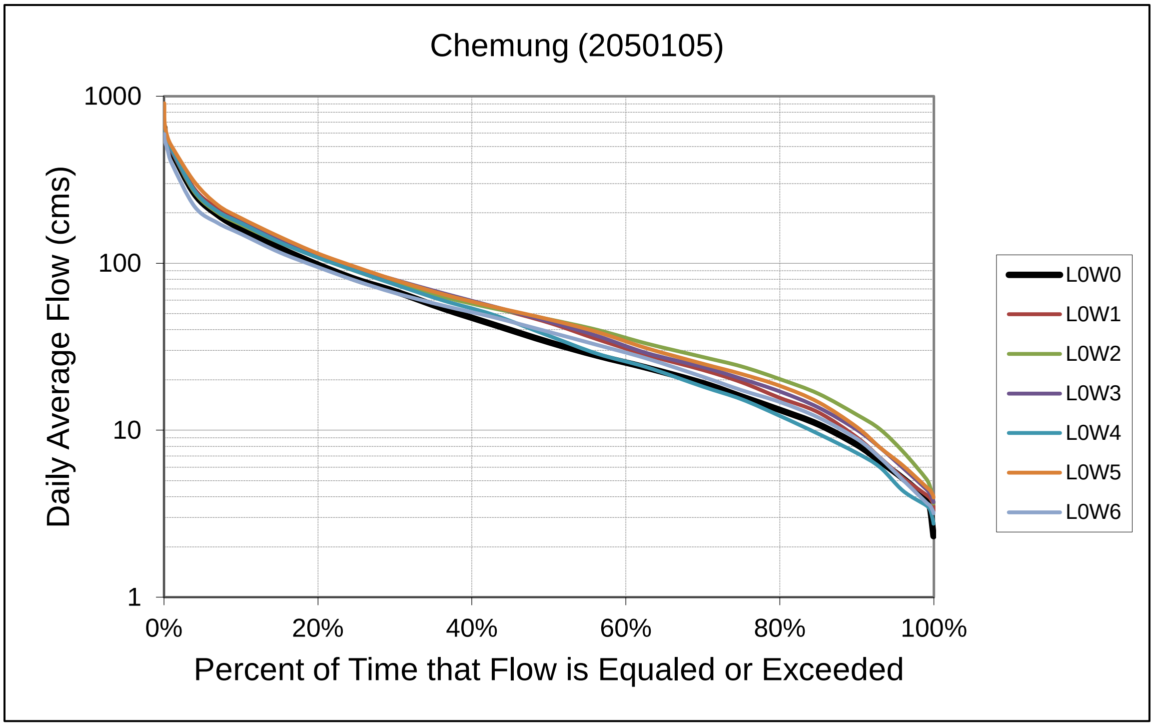


Figure 214. Flow Duration, Chemung (SWAT)

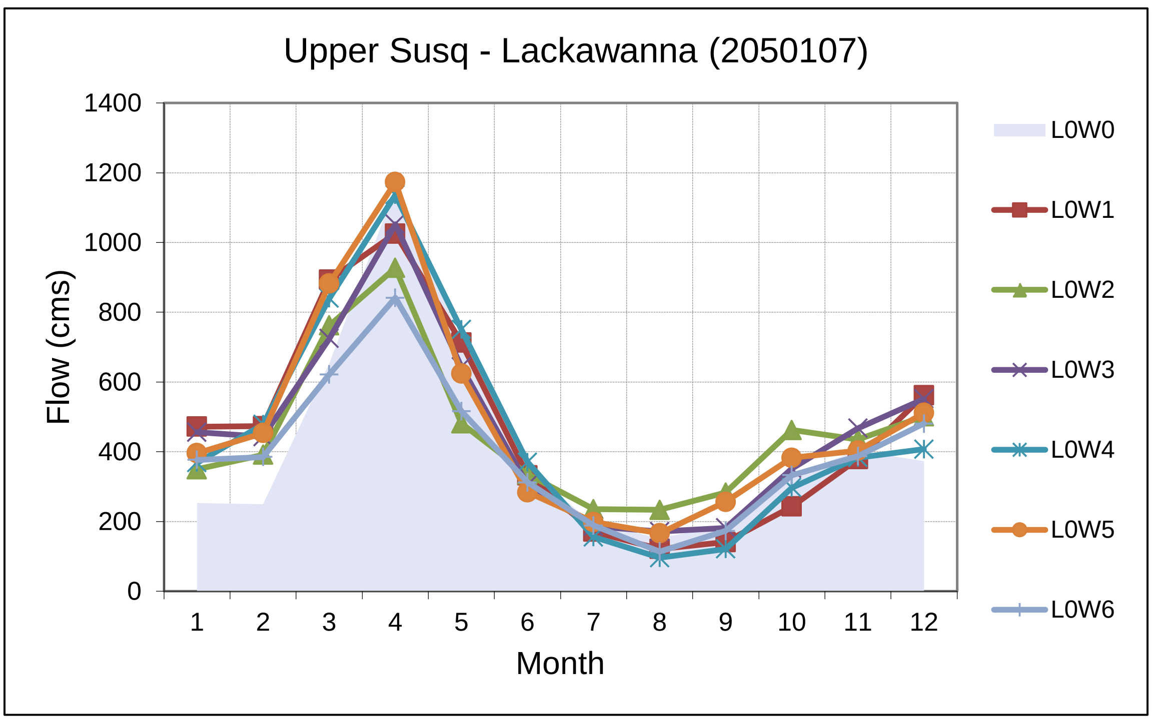


Figure 215. Monthly Average Flows, Upper Susquehanna River - Lackawanna (SWAT)

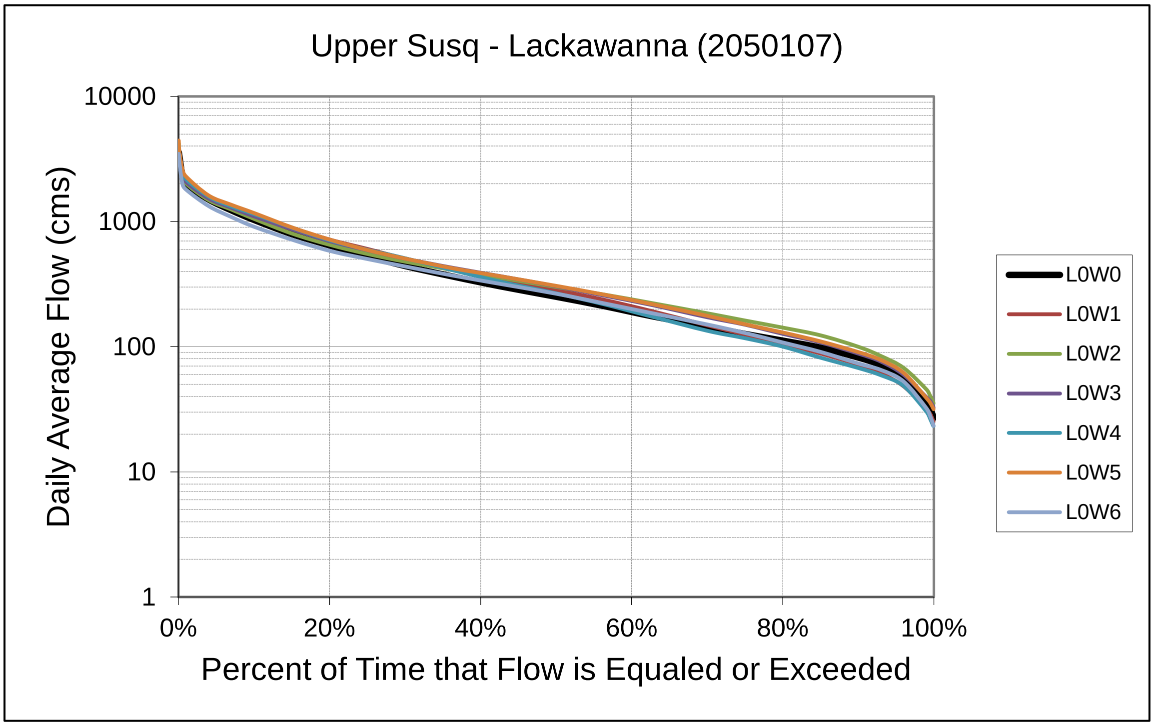


Figure 216. **Flow Duration, Upper Susquehanna River - Lackawanna (SWAT)**

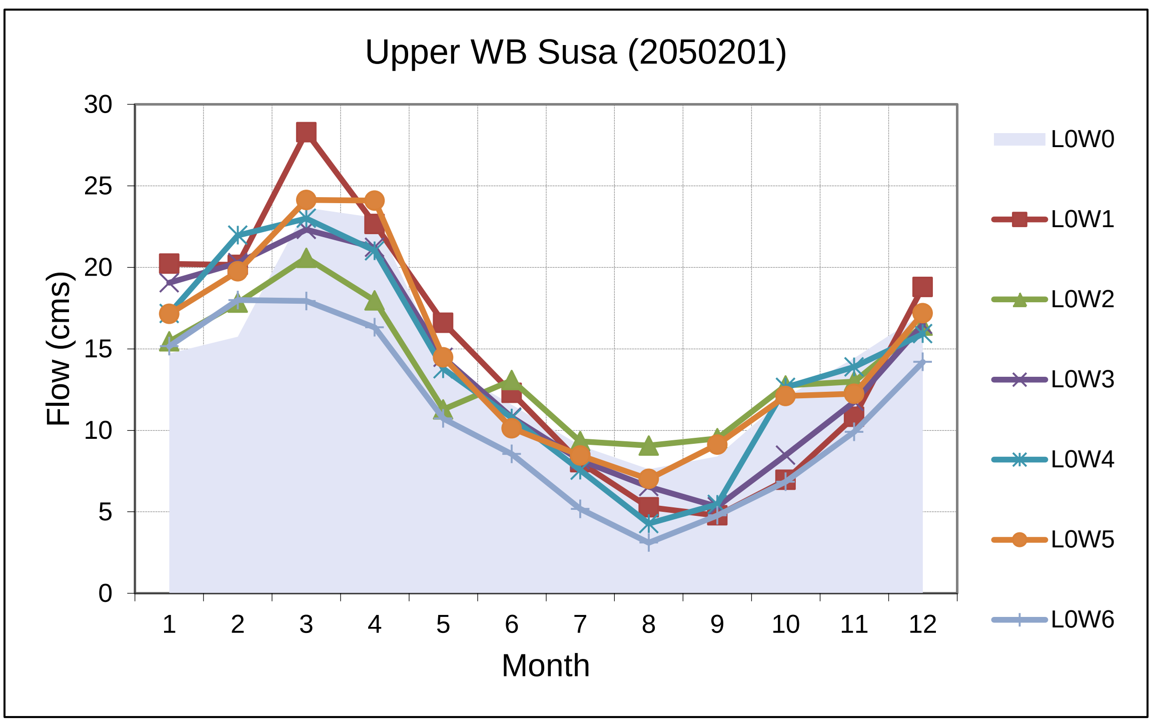


Figure 217. **Monthly Average Flows, Upper West Branch Susquehanna River (SWAT)**

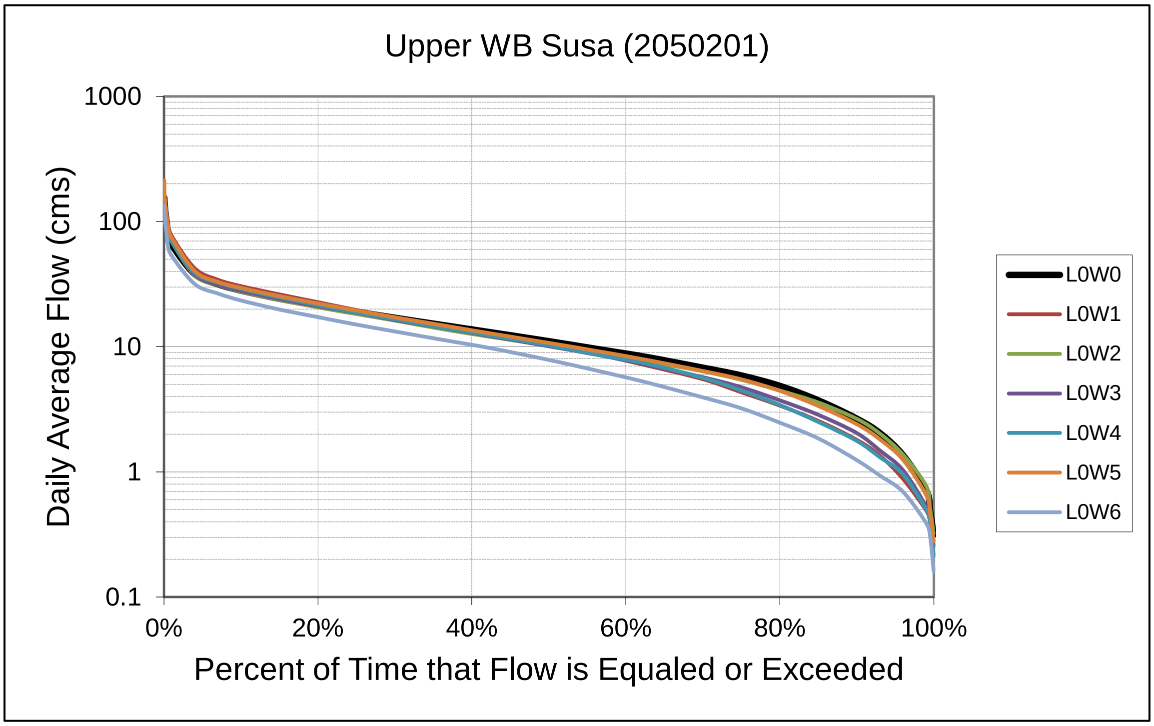


Figure 218. **Flow Duration, Upper West Branch Susquehanna River (SWAT)**

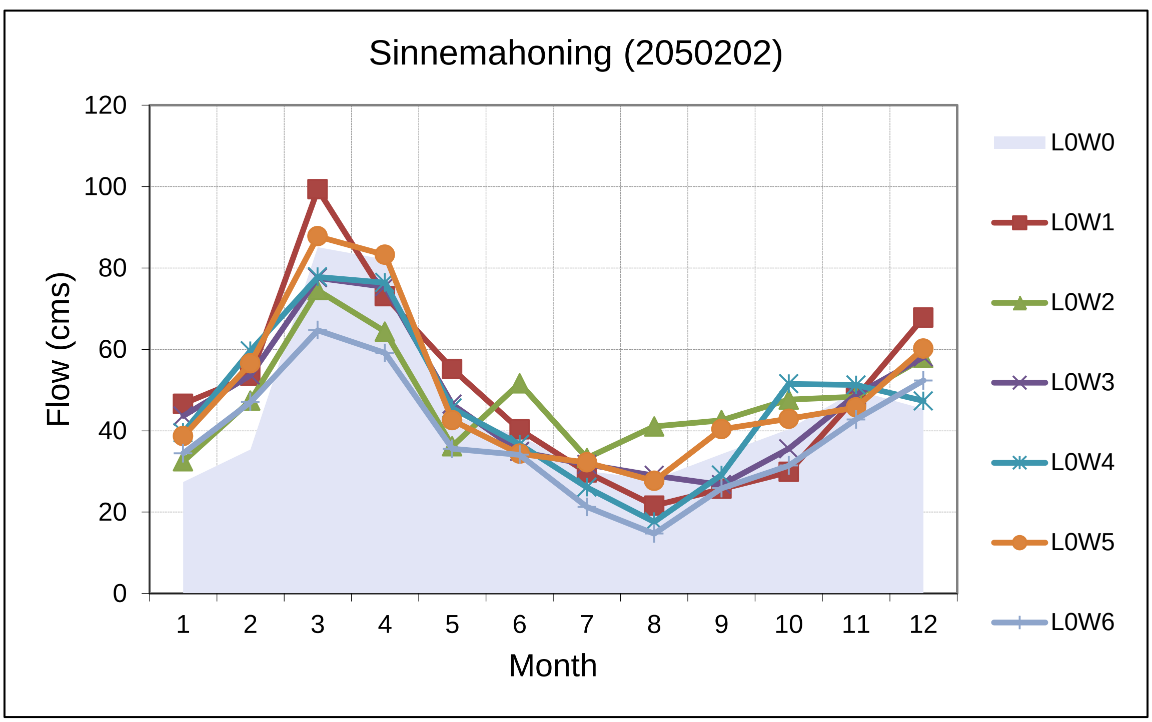


Figure 219. **Monthly Average Flows, Sinnemahoning (SWAT)**

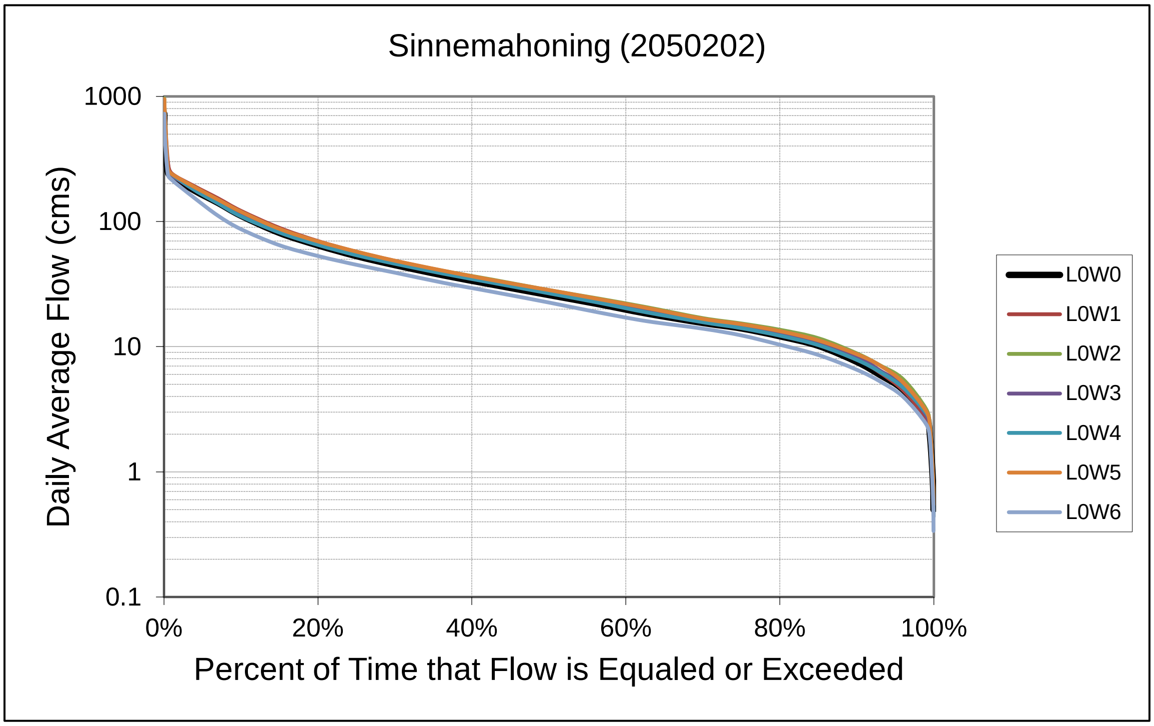


Figure 220. **Flow Duration, Sinnemahoning (SWAT)**

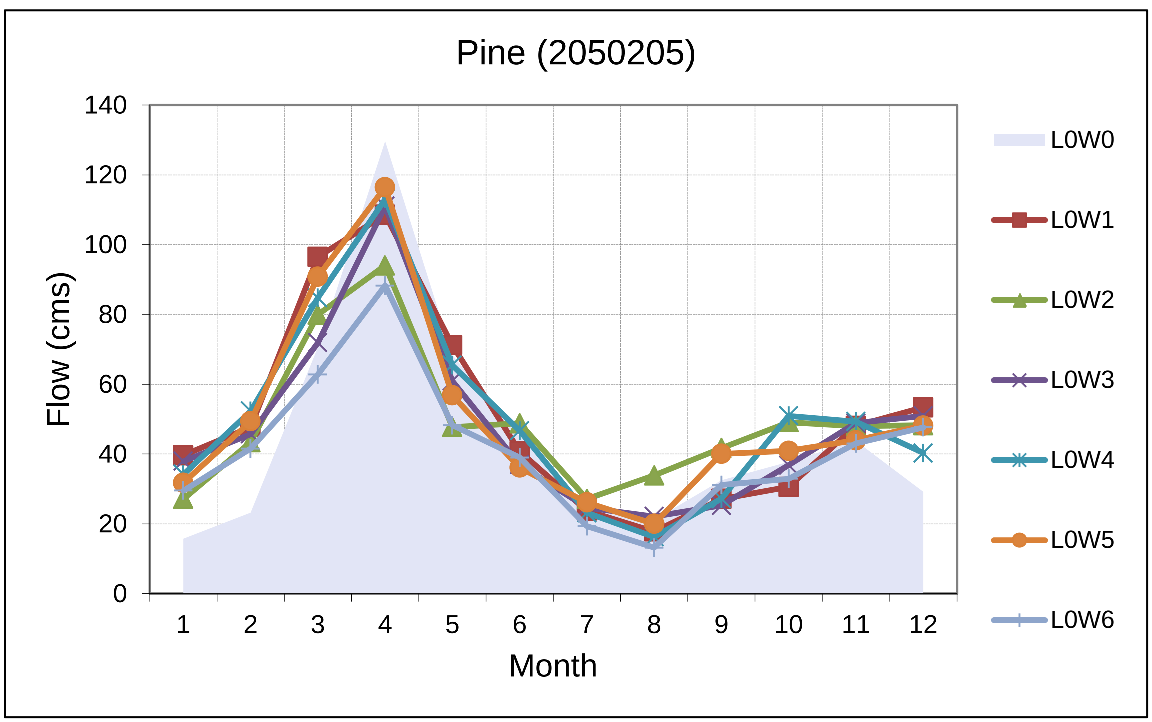


Figure 221. **Monthly Average Flows, Pine (SWAT)**

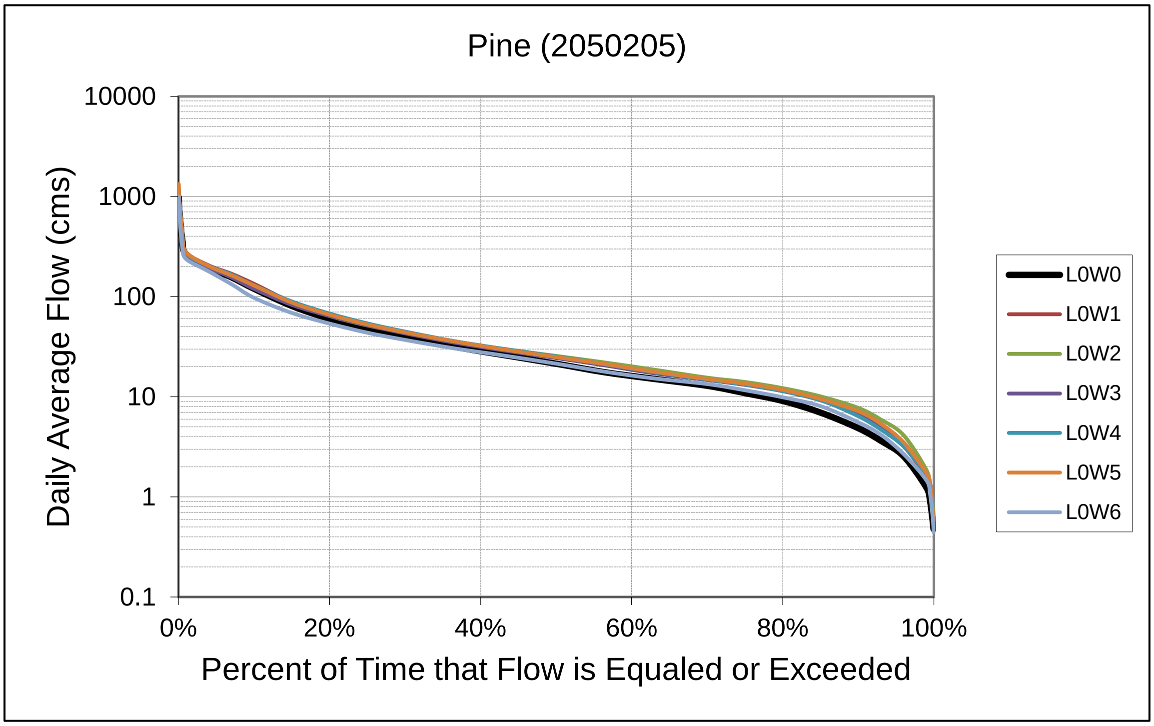


Figure 222. Flow Duration, Pine (SWAT)

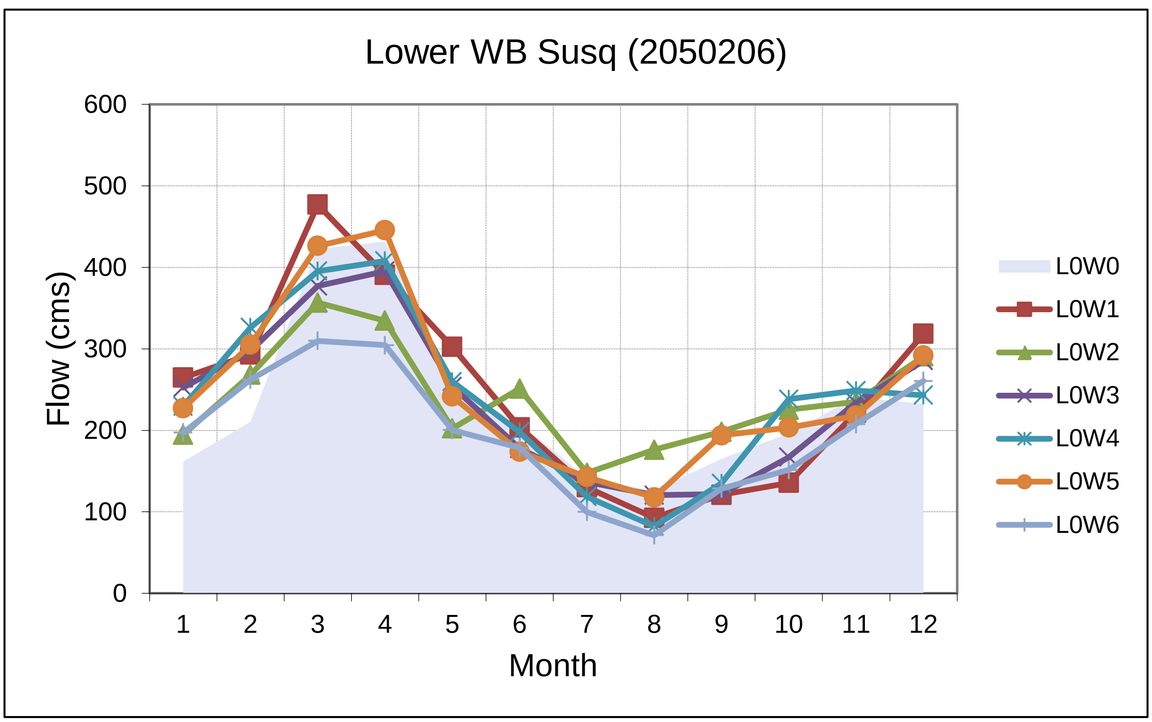


Figure 223. Monthly Average Flows, Lower West Branch Susquehanna River (SWAT)

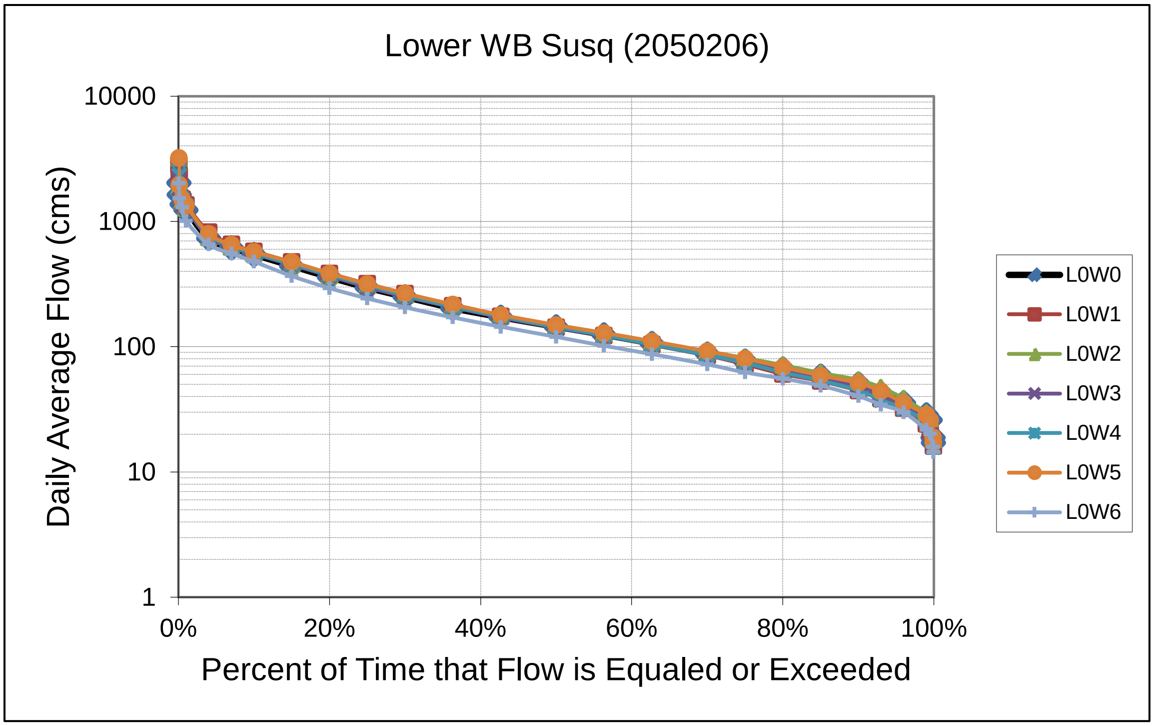


Figure 224. Flow Duration, Lower West Branch Susquehanna River (SWAT)

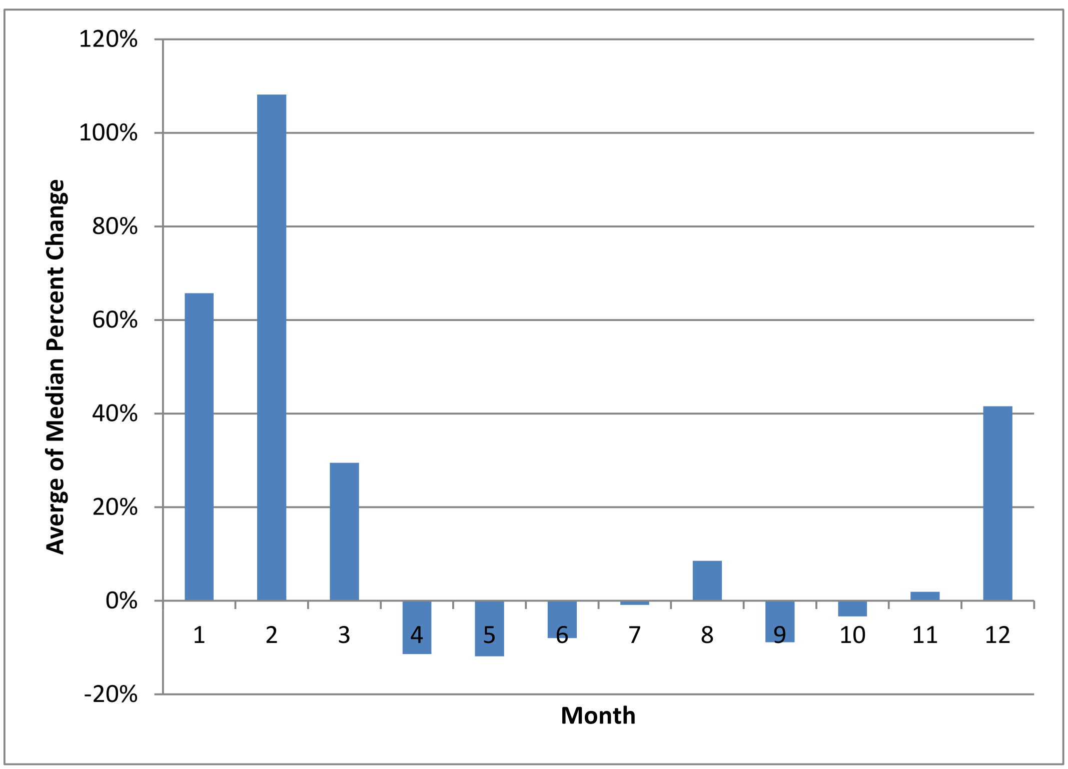


Figure 225. Average of Median Percent Change in Flow; NARCCAP Scenarios W1-W6 at all Stations, Susquehanna River Basin (SWAT)

Willamette River Basin, HSPF Model
Results at Downstream Station

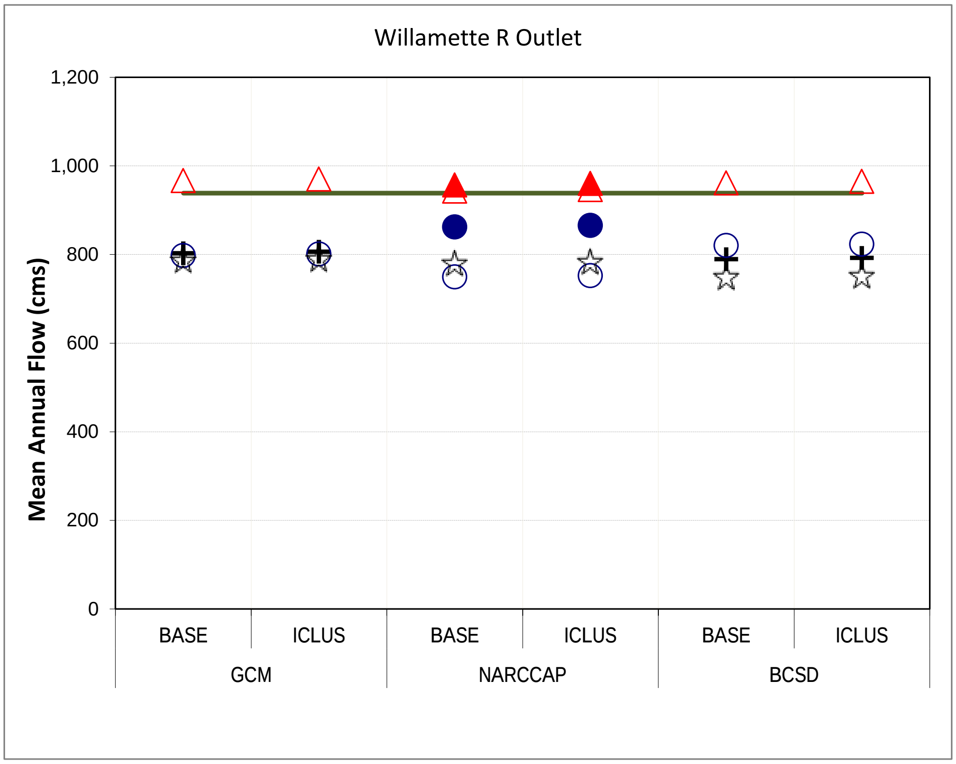


Figure 226. Mean Annual Flow, Willamette River Outlet (HSPF)

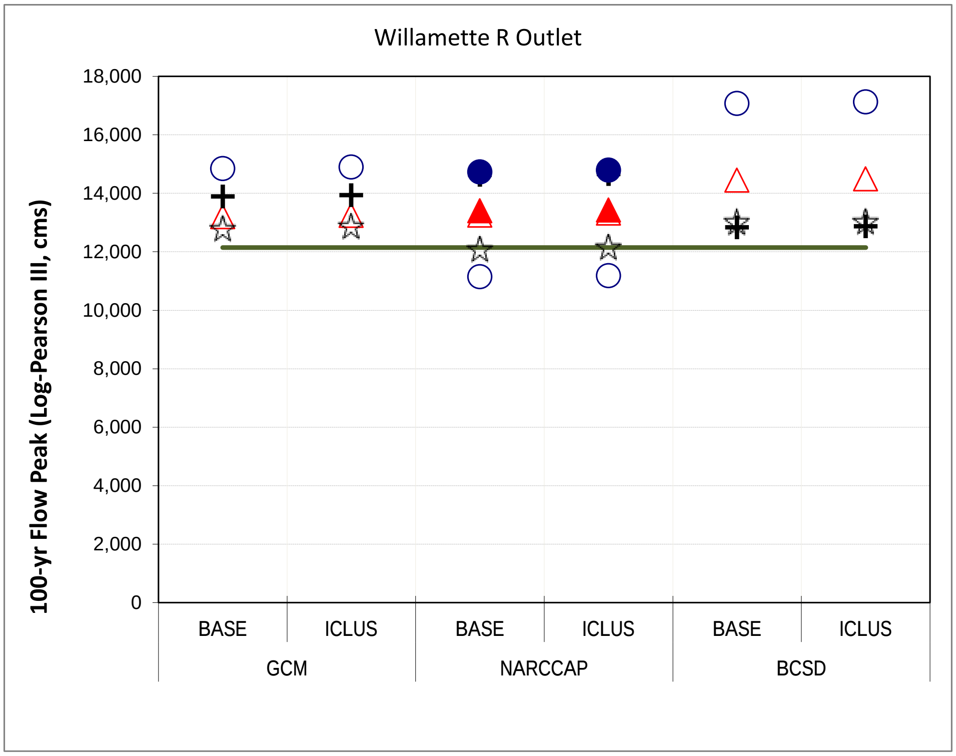


Figure 227. **100-yr Flow Peak, Willamette River Outlet (HSPF)**

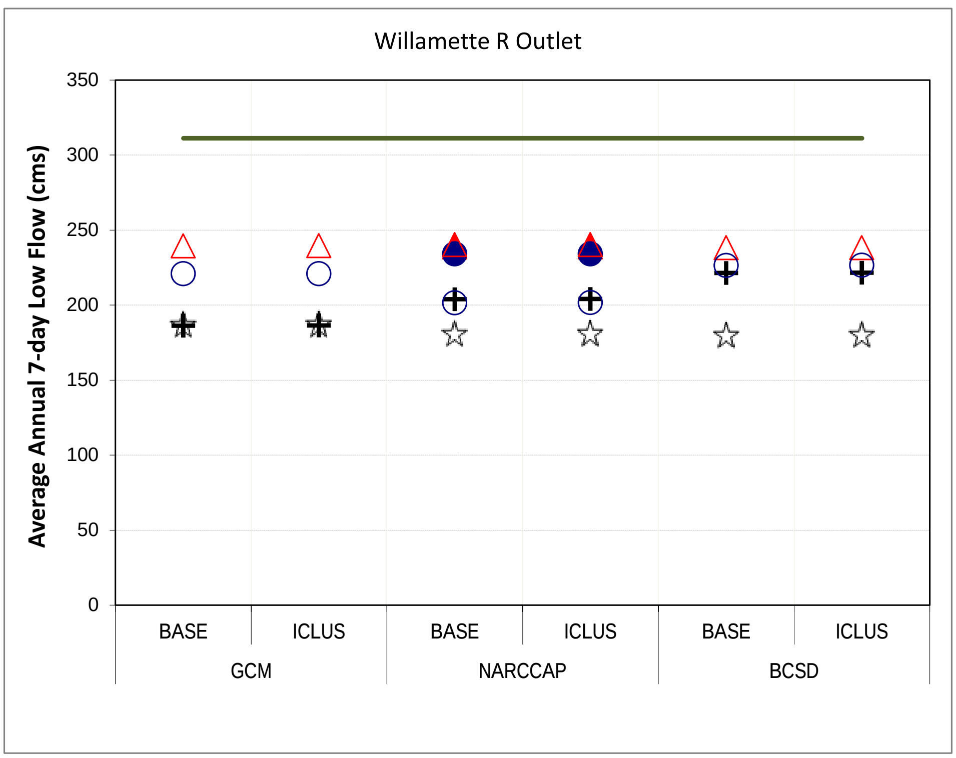


Figure 228. **Average Annual 7-day Low Flow, Willamette River Outlet (HSPF)**

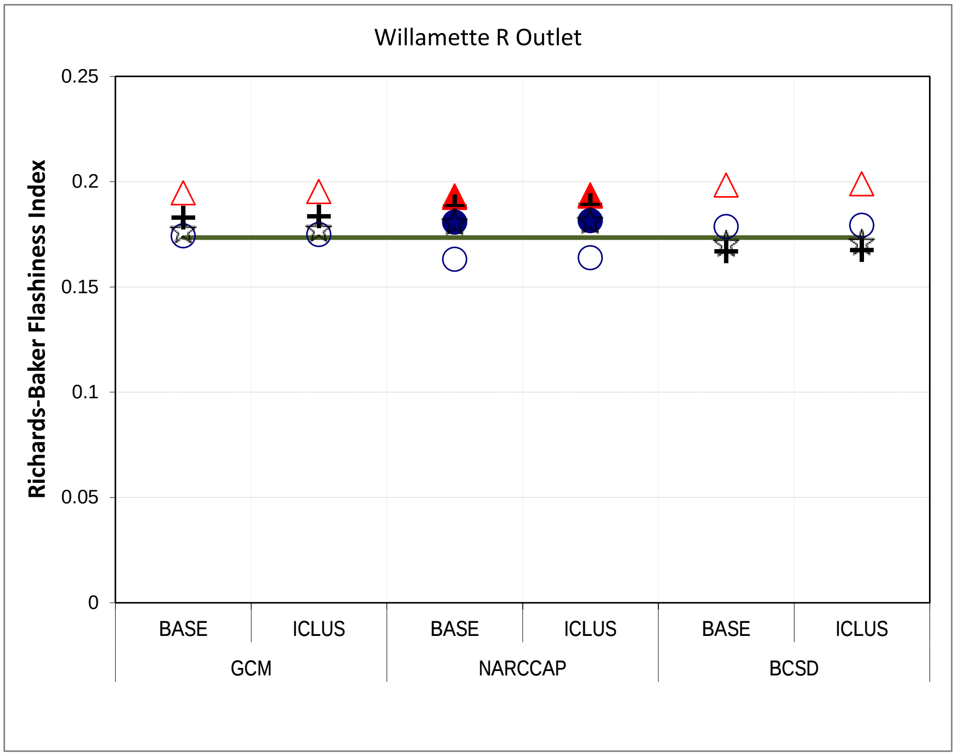


Figure 229. Richards-Baker Flashiness Index, Willamette River Outlet (HSPF)

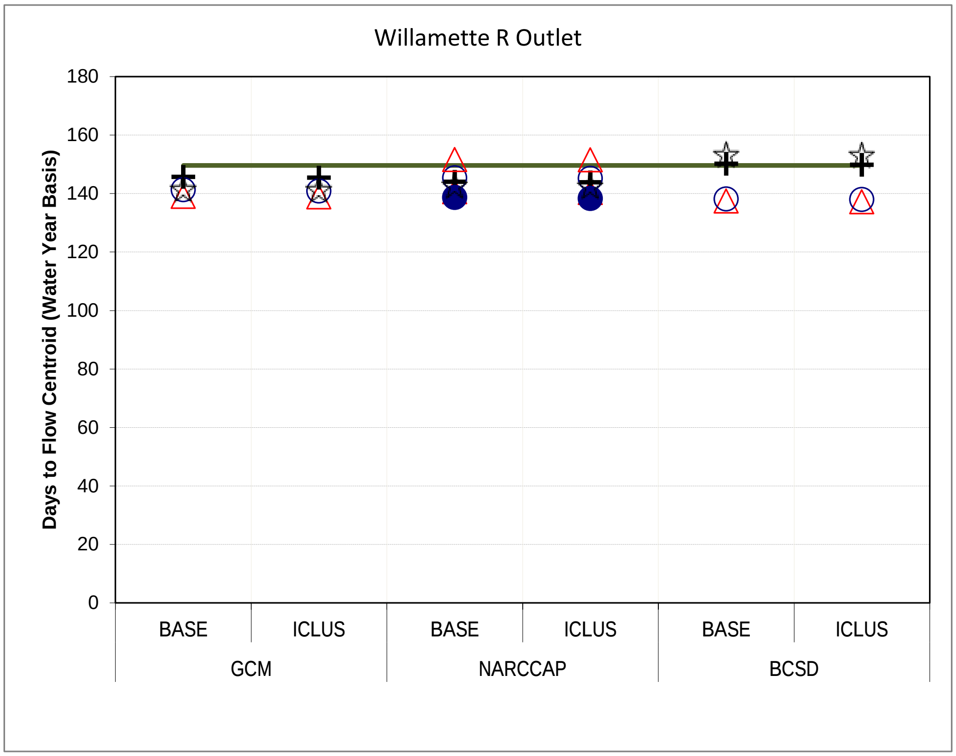


Figure 230. Days to Flow Centroid, Willamette River Outlet (HSPF)

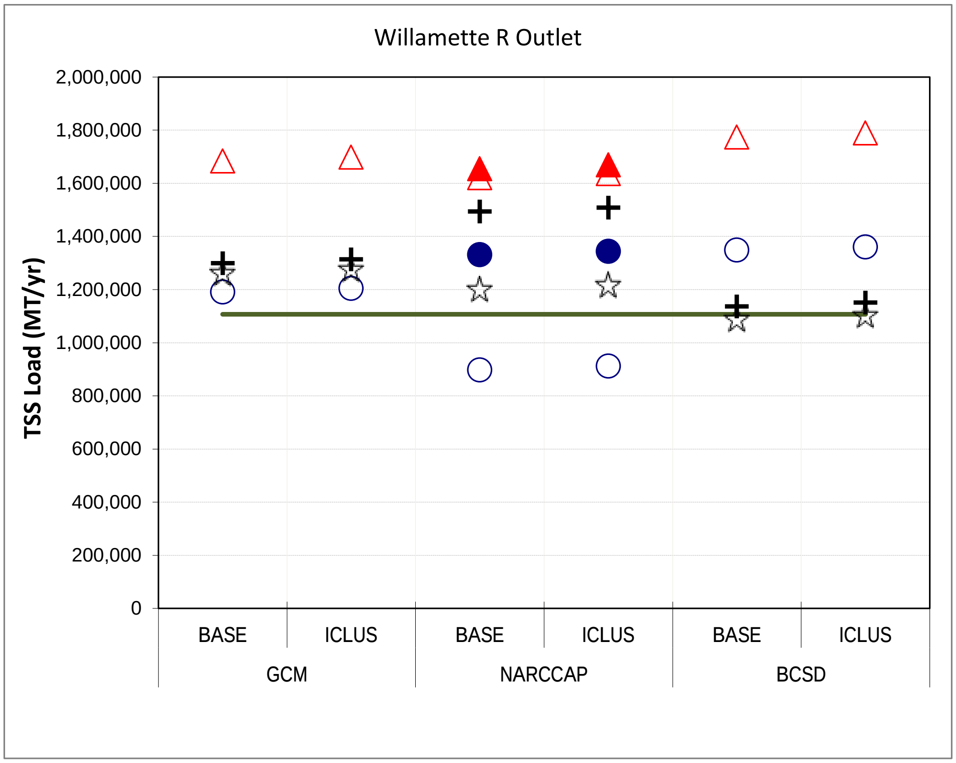


Figure231. TSS Load, Willamette River Outlet (HSPF)

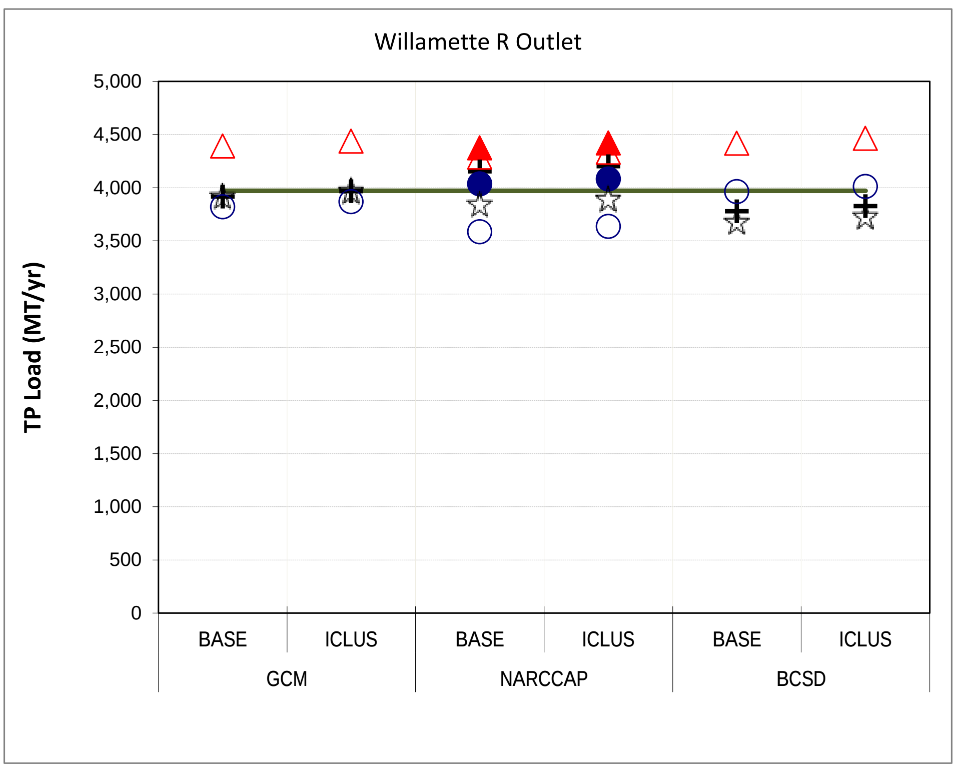


Figure 232. TP Load, Willamette River Outlet (HSPF)

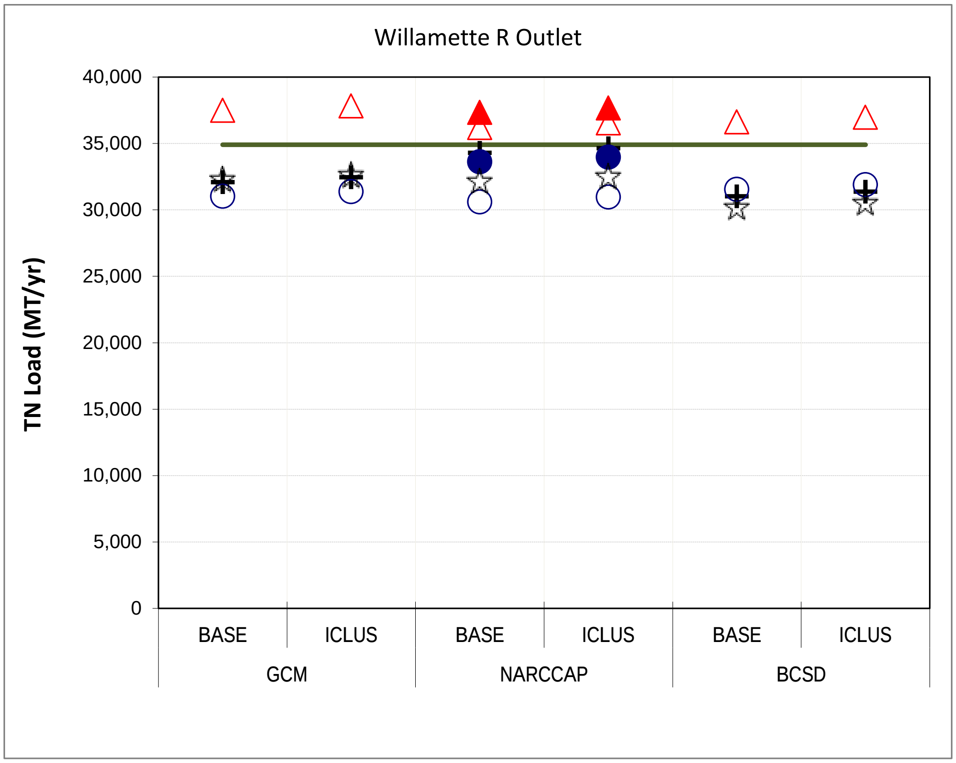


Figure 233. TN Load, Willamette River Outlet (HSPF)

Table 9. Summary of Range of Change Relative to Existing Conditions for NARCCAP Dynamically Downscale Scenarios, Willamette River Basin HSPF Model

	Results without LU Change				Results with LU Change			
	Min	Median	Mean	Max	Min	Median	Mean	Max
Tualatin River at West Linn (gage 14207500)								
Flow	-13.42%	-4.50%	-1.79%	12.35%	-13.02%	-4.18%	-1.62%	12.02%
TSS	-25.17%	10.27%	15.01%	48.58%	-23.87%	8.88%	13.31%	44.17%
TN	-10.72%	-3.96%	-2.59%	6.34%	-9.95%	-3.88%	-2.55%	5.71%
TP	-14.21%	0.17%	1.56%	15.23%	-12.79%	-0.07%	1.24%	13.34%
Pudding River at Aurora (gage 1402000)								
Flow	-16.00%	-2.54%	-2.68%	11.19%	-15.86%	-2.48%	-2.63%	11.10%
TSS	-30.22%	28.41%	16.43%	46.12%	-29.58%	27.24%	15.64%	44.45%
TN	-15.76%	-2.60%	-2.92%	10.07%	-15.31%	-2.64%	-2.90%	9.73%
TP	-19.31%	8.63%	3.67%	19.98%	-18.64%	8.16%	3.42%	19.06%
South Yamhill River at McMinnville (gage 14194150)								
Flow	-13.06%	-3.46%	-1.22%	11.94%	-13.05%	-3.45%	-1.22%	11.93%
TSS	-25.38%	15.18%	13.24%	44.55%	-25.29%	15.03%	13.12%	44.25%
TN	-13.03%	-2.56%	-1.42%	9.66%	-12.98%	-2.57%	-1.42%	9.62%
TP	-17.48%	4.54%	4.02%	21.59%	-17.38%	4.49%	3.99%	21.44%
Mohawk River nr Springfield (gage 14165000)								
Flow	-16.75%	-3.37%	-2.88%	10.17%	-16.74%	-3.37%	-2.88%	10.16%
TSS	-31.73%	16.15%	10.93%	36.72%	-	16.10%	10.90%	36.66%

	Results without LU Change				Results with LU Change			
	Min	Median	Mean	Max	Min	Median	Mean	Max
					31.69%			
TN	-18.86%	-2.17%	-3.61%	8.92%	- 18.81%	-2.18%	-3.60%	8.90%
TP	-26.14%	8.44%	3.67%	20.10%	- 26.05%	8.39%	3.64%	20.02%
Willamette River at Salem (gage 14191000)								
Flow	-21.09%	-8.49%	-8.99%	1.03%	- 21.07%	-8.48%	-8.98%	1.04%
TSS	-17.43%	30.36%	25.97%	50.61%	- 17.40%	30.24%	25.88%	50.47%
TN	-13.71%	-2.48%	-2.43%	7.65%	- 13.66%	-2.49%	-2.43%	7.61%
TP	-12.82%	6.46%	4.40%	15.17%	- 12.77%	6.41%	4.37%	15.09%
Willamette River Outlet								
Flow	-20.16%	-8.10%	-8.42%	1.96%	- 20.10%	-8.06%	-8.38%	1.98%
TSS	-18.90%	27.60%	23.54%	49.49%	- 18.75%	27.05%	23.10%	48.68%
TN	-12.36%	-2.72%	-2.46%	6.96%	- 12.19%	-2.73%	-2.45%	6.82%
TP	-9.71%	3.12%	1.96%	10.17%	-9.58%	3.03%	1.90%	9.95%

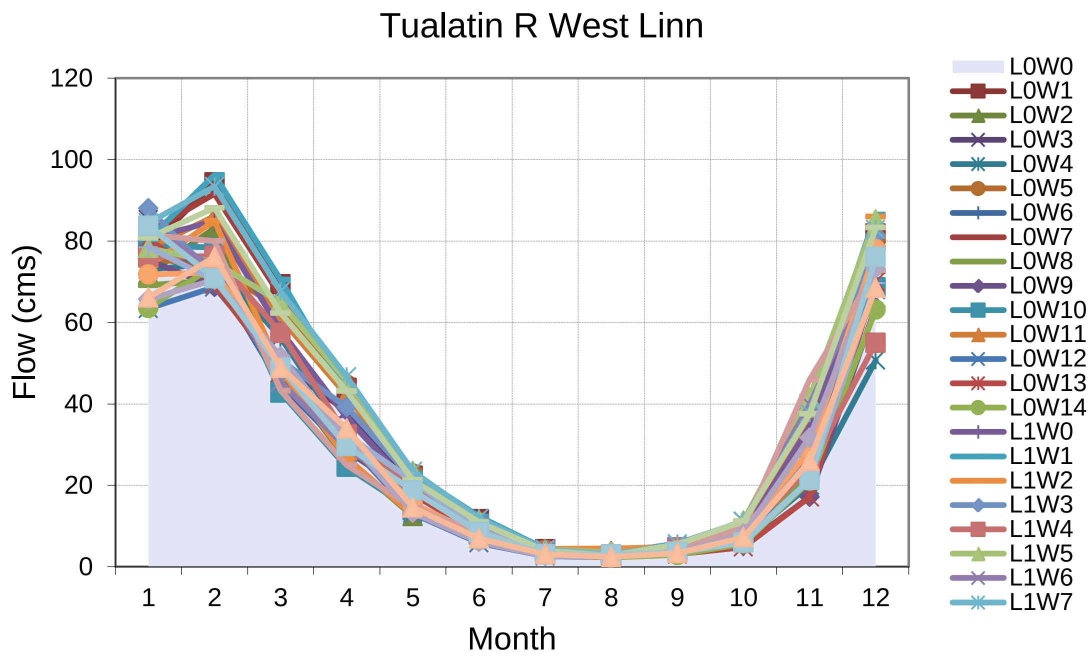


Figure 234. **Monthly Average Flows, Tualatin River at West Linn (HSPF)**

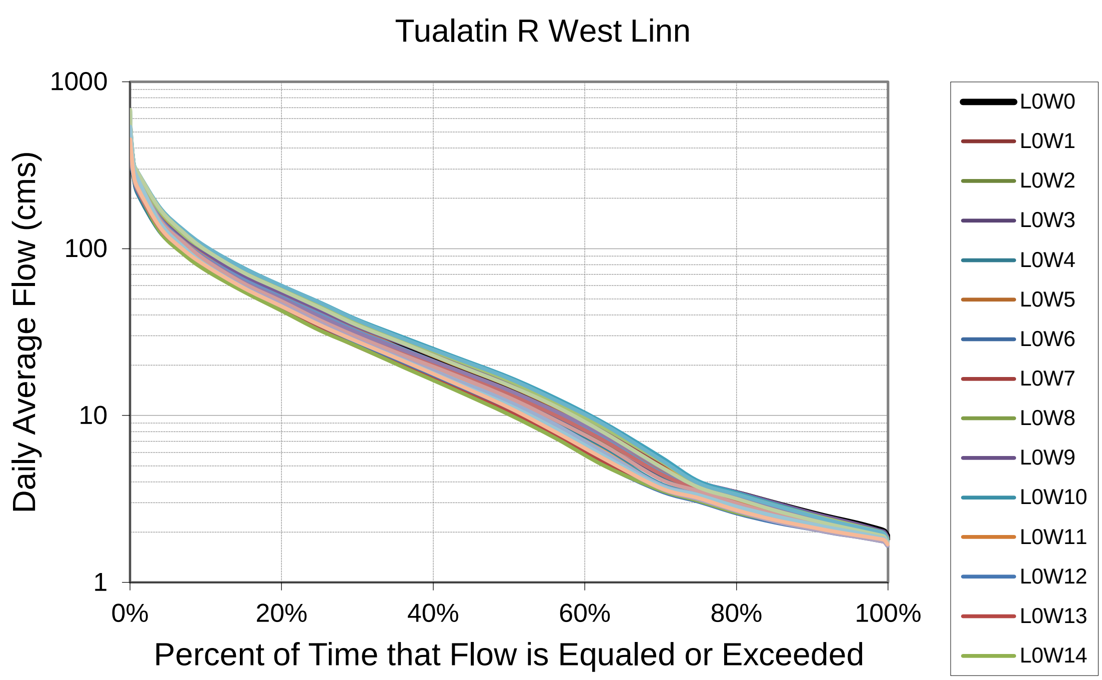


Figure 235. **Flow Duration, Tualatin River at West Linn (HSPF)**

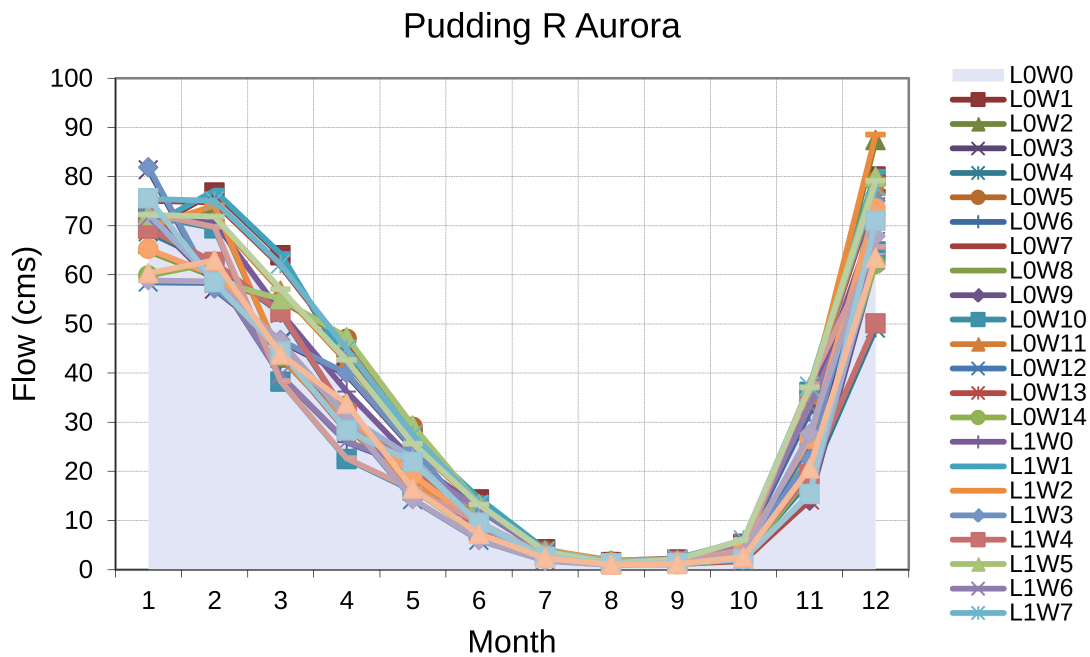


Figure 236. Monthly Average Flows, Pudding River at Aurora (HSPF)

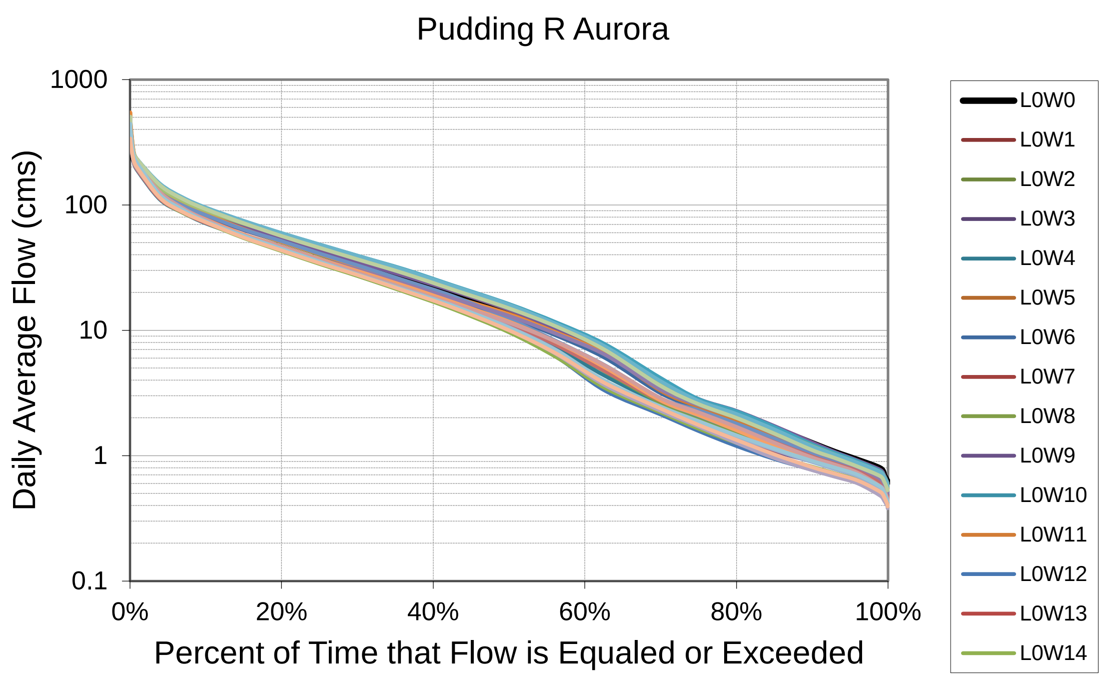


Figure 237. Flow Duration, Pudding River at Aurora (HSPF)

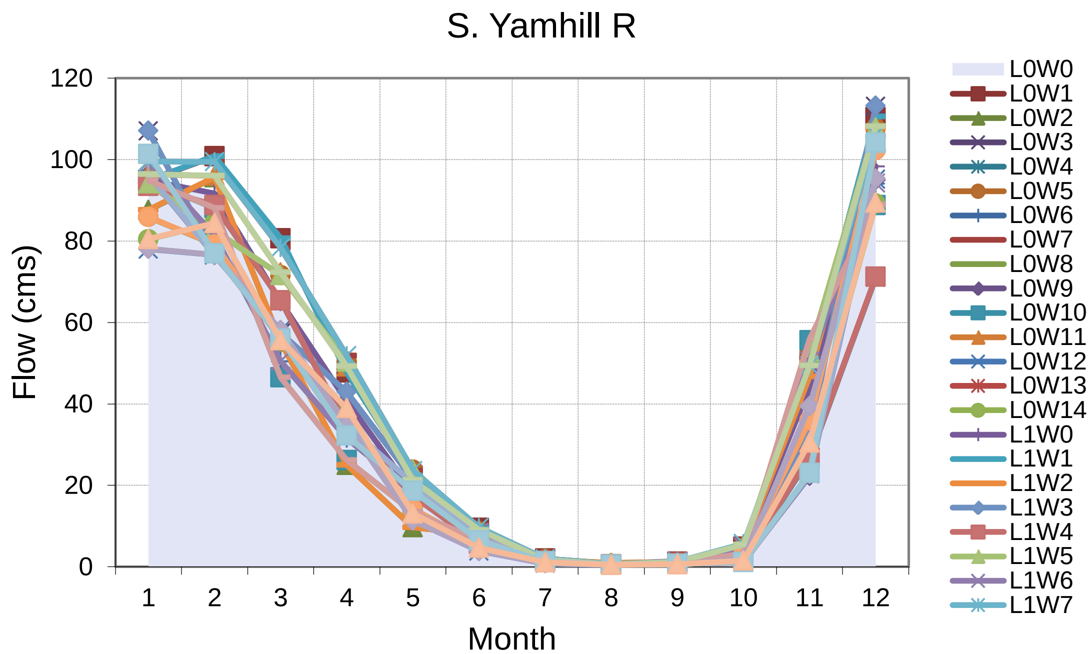


Figure 238. Monthly Average Flows, South Yamhill River (HSPF)

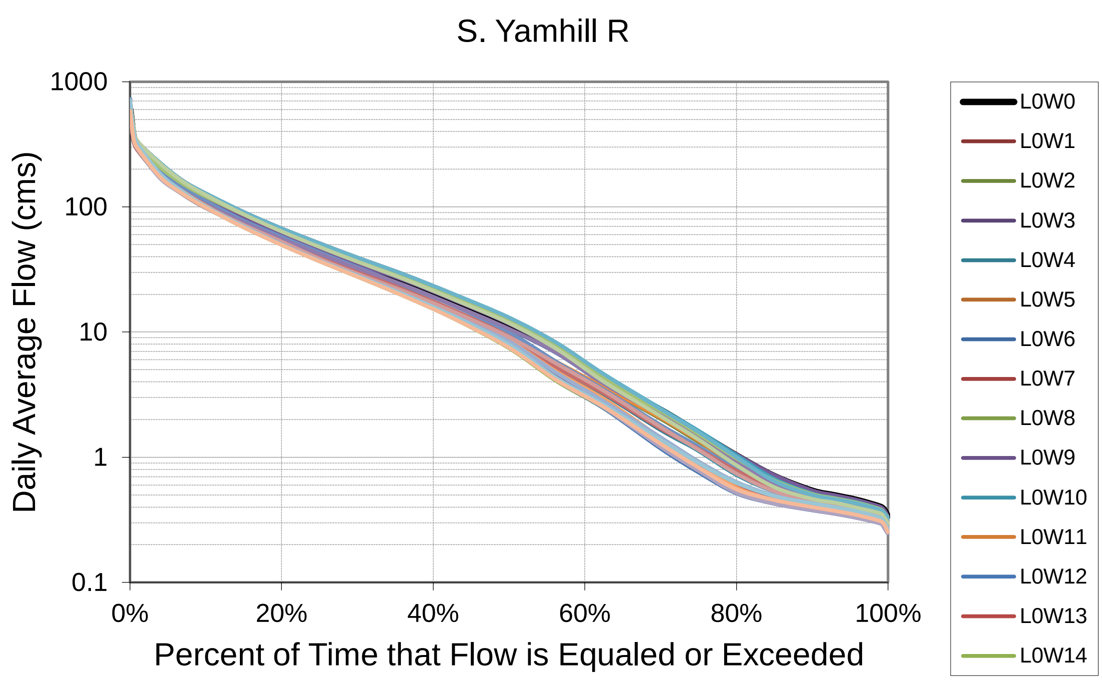


Figure 239. Flow Duration, South Yamhill River (HSPF)

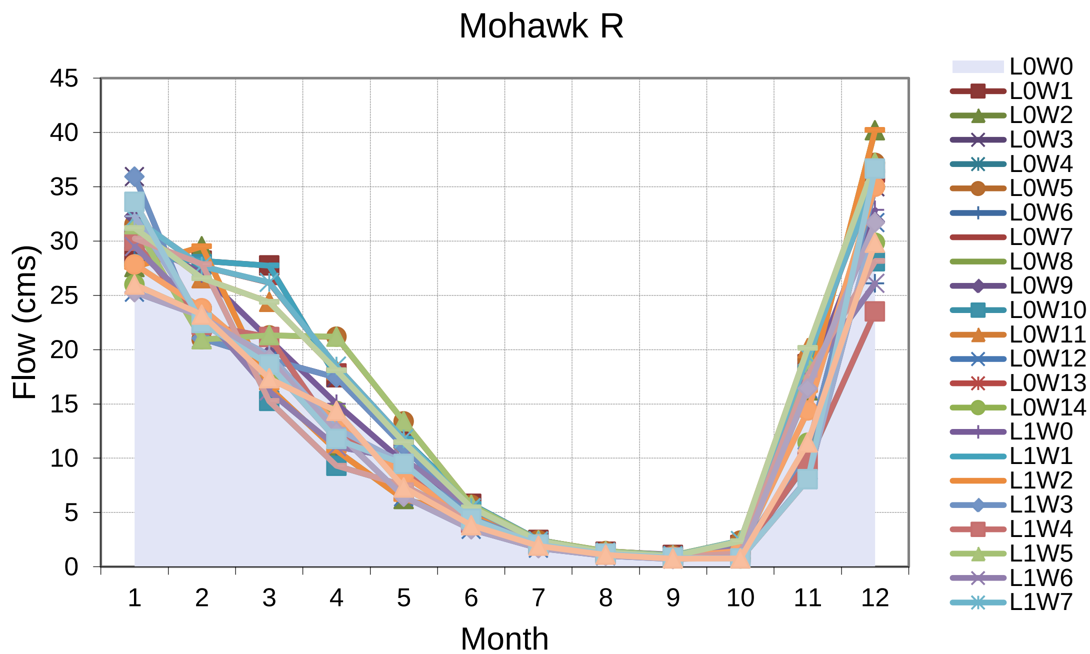


Figure 240. **Monthly Average Flows, Mohawk River (HSPF)**

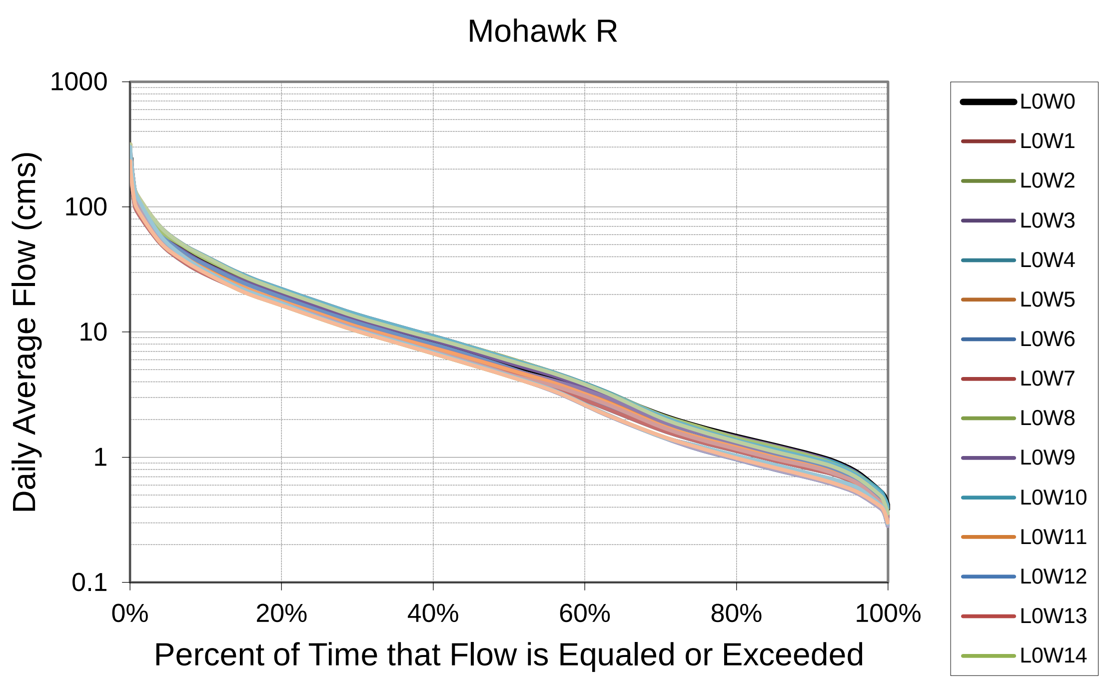


Figure 241. **Flow Duration, Mohawk River (HSPF)**

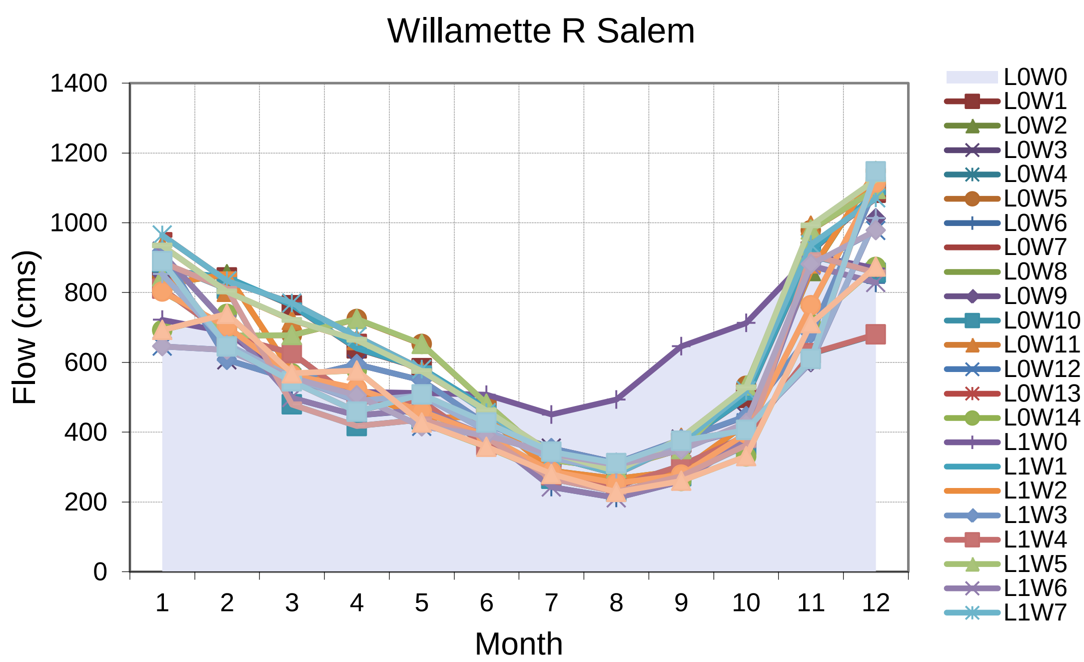


Figure 242. **Monthly Average Flows, Willamette River at Salem (HSPF)**

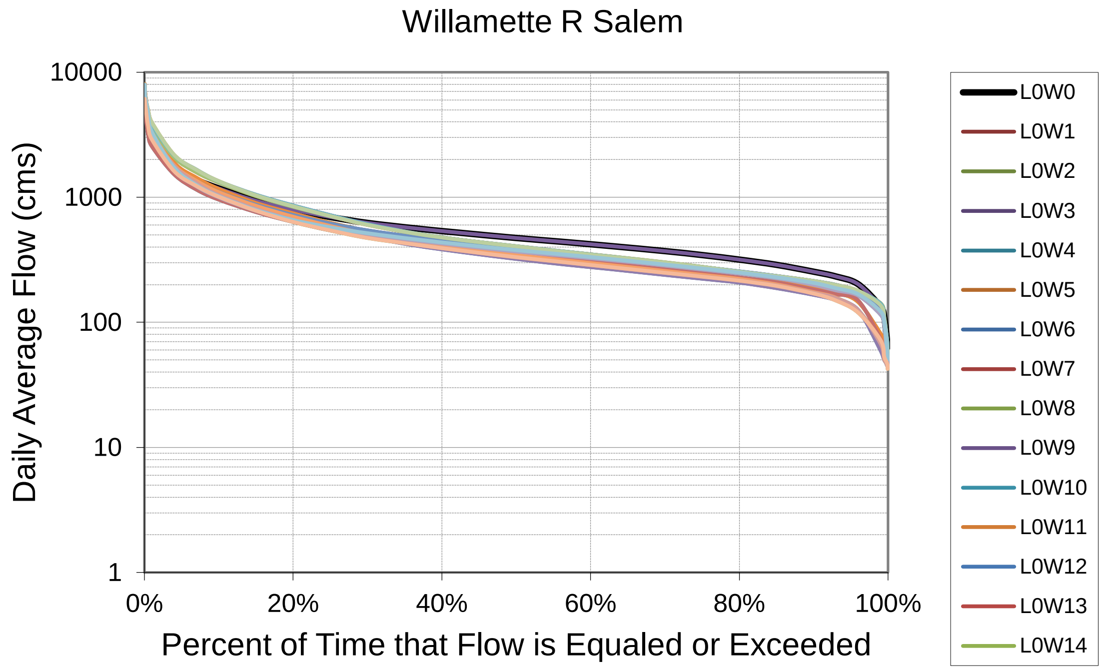


Figure 243. **Flow Duration, Willamette River at Salem (HSPF)**

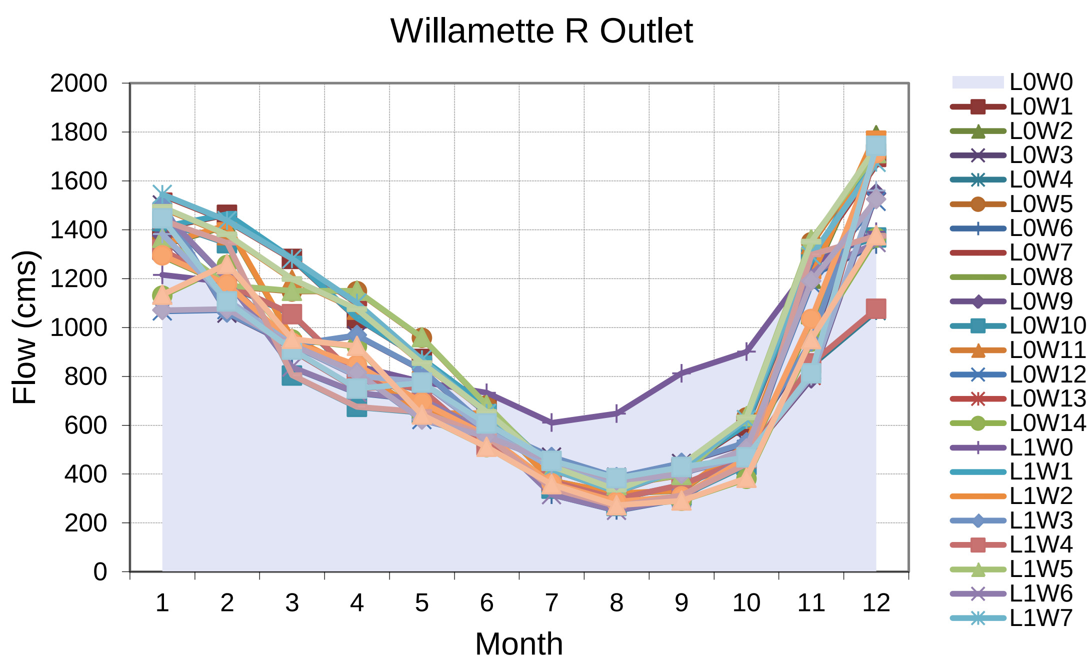


Figure 244. **Monthly Average Flows, Willamette River Outlet (HSPF)**

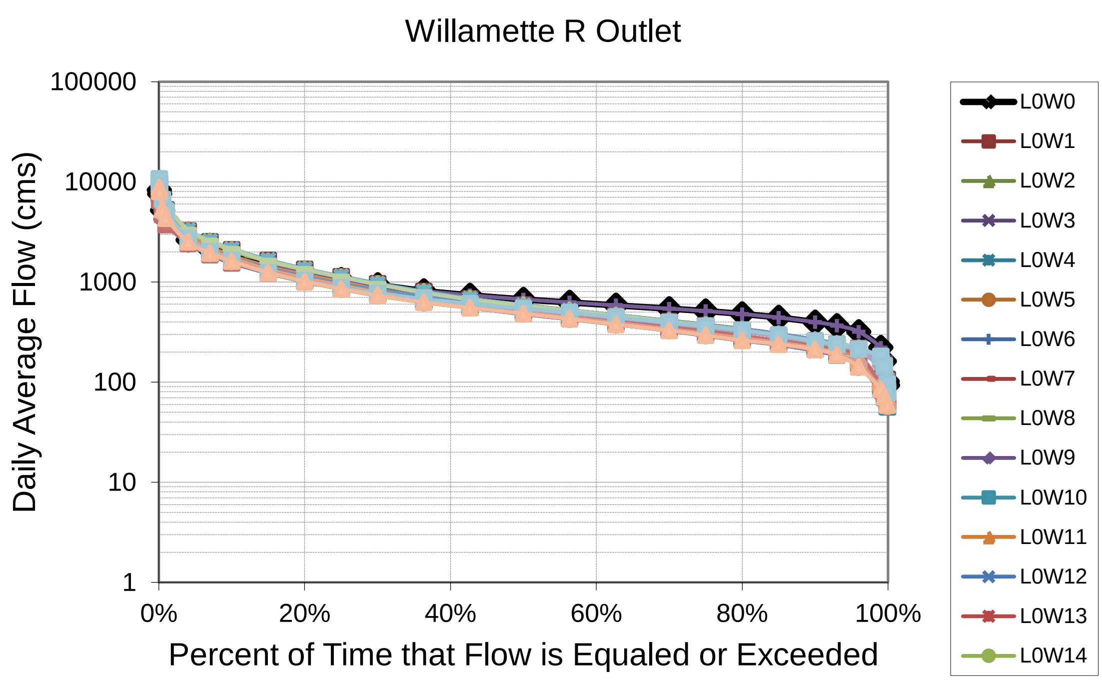


Figure 245. **Flow Duration, Willamette River Outlet (HSPF)**

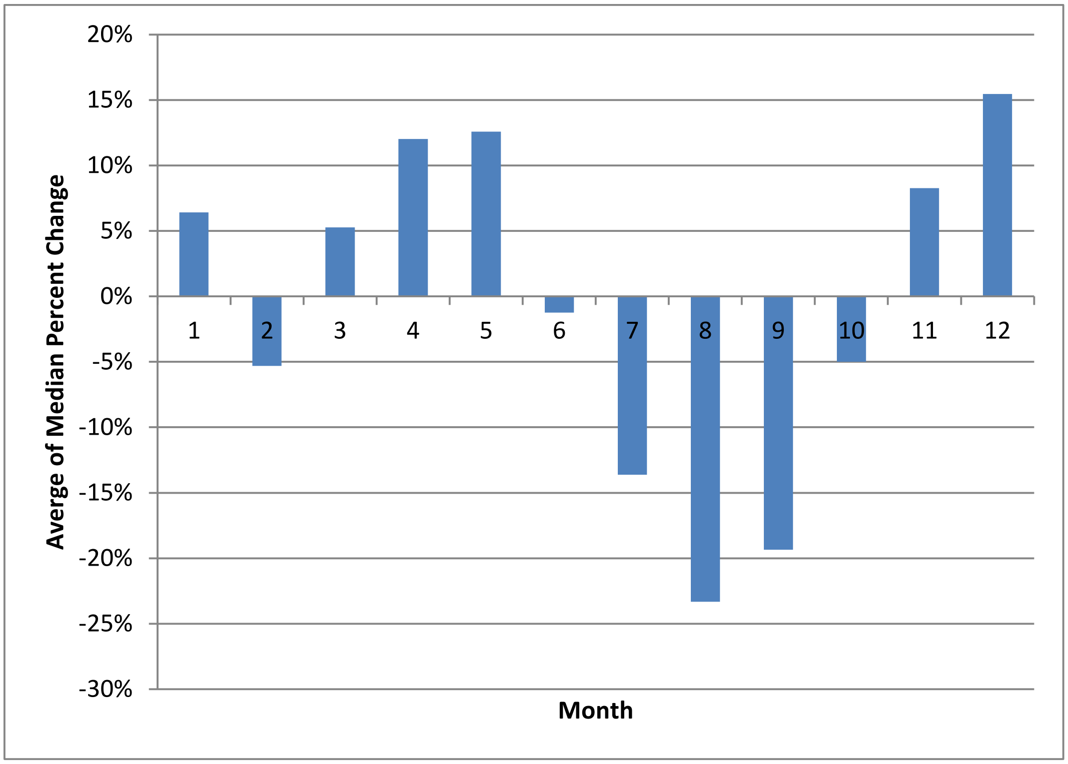


Figure 246. Average of Median Percent Change in Flow; NARCCAP Scenarios W1-W6 at all Stations, Willamette River Basin (HSPF)

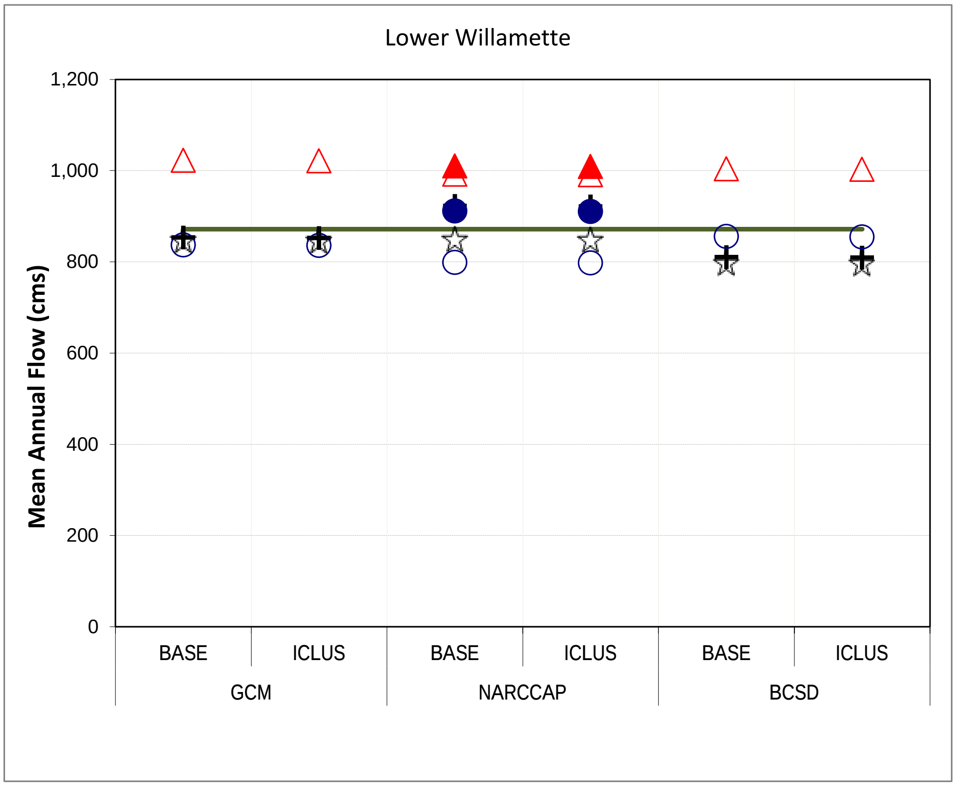


Figure 247. Mean Annual Flow, Lower Willamette River (SWAT)

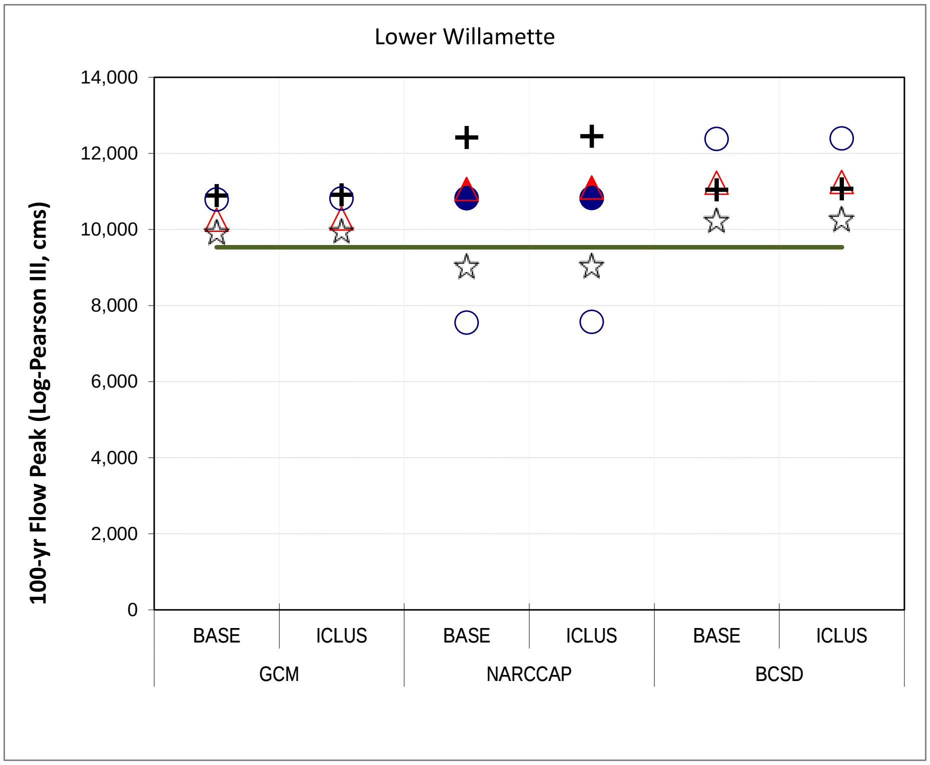


Figure 248. **100-yr Flow Peak, Lower Willamette River (SWAT)**

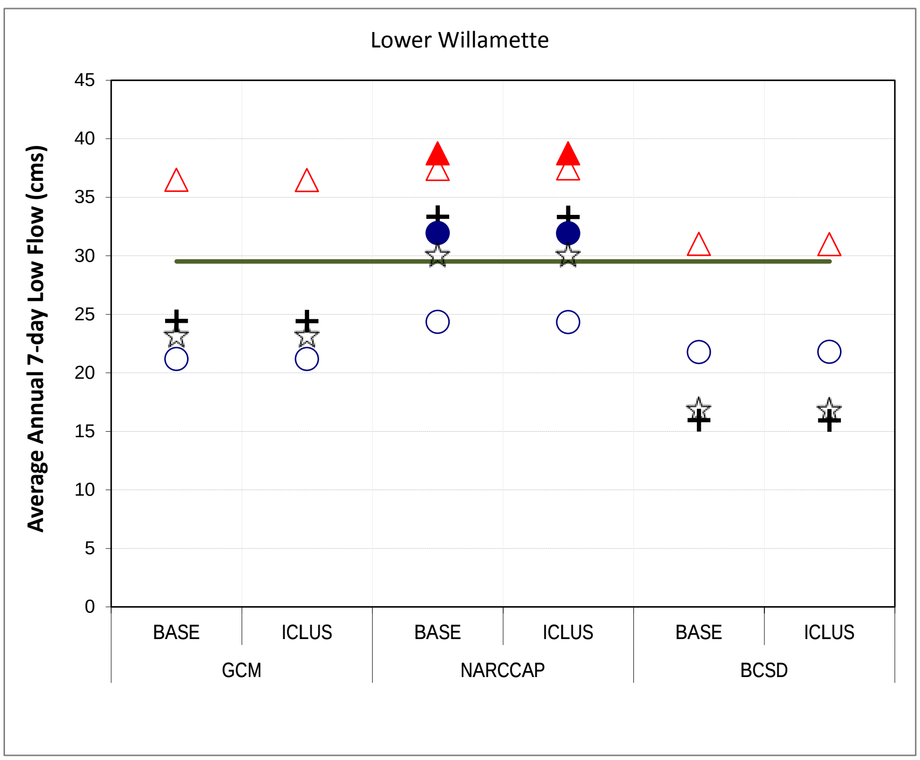


Figure 249. **Average Annual 7-day Low Flow, Lower Willamette River (SWAT)**

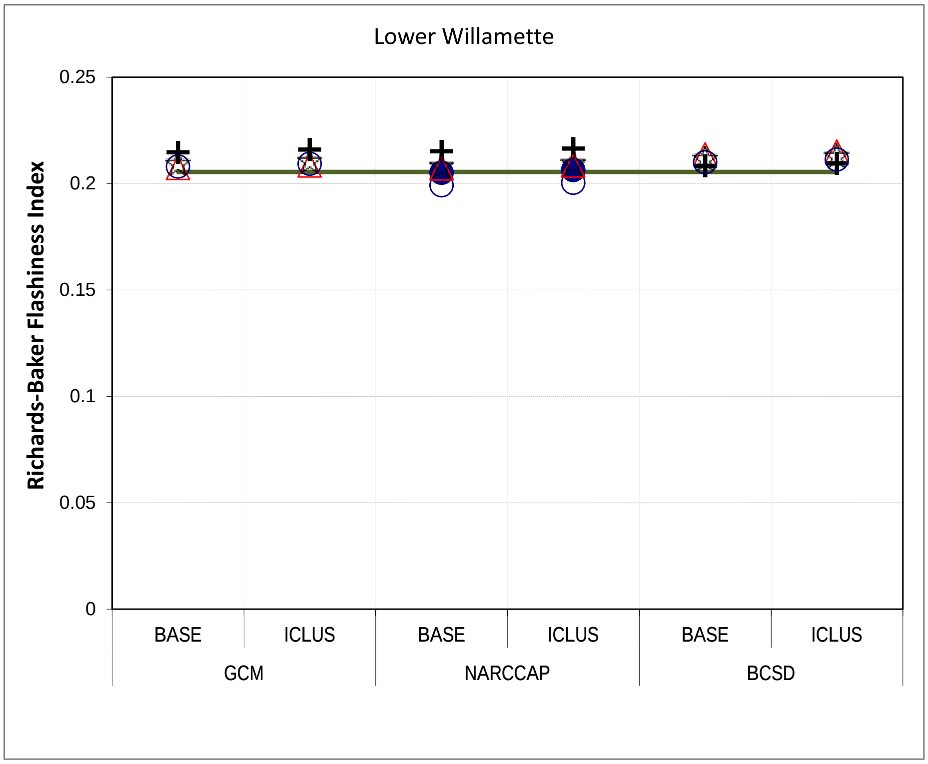


Figure 250. Richards-Baker Flashiness Index, Lower Willamette River (SWAT)

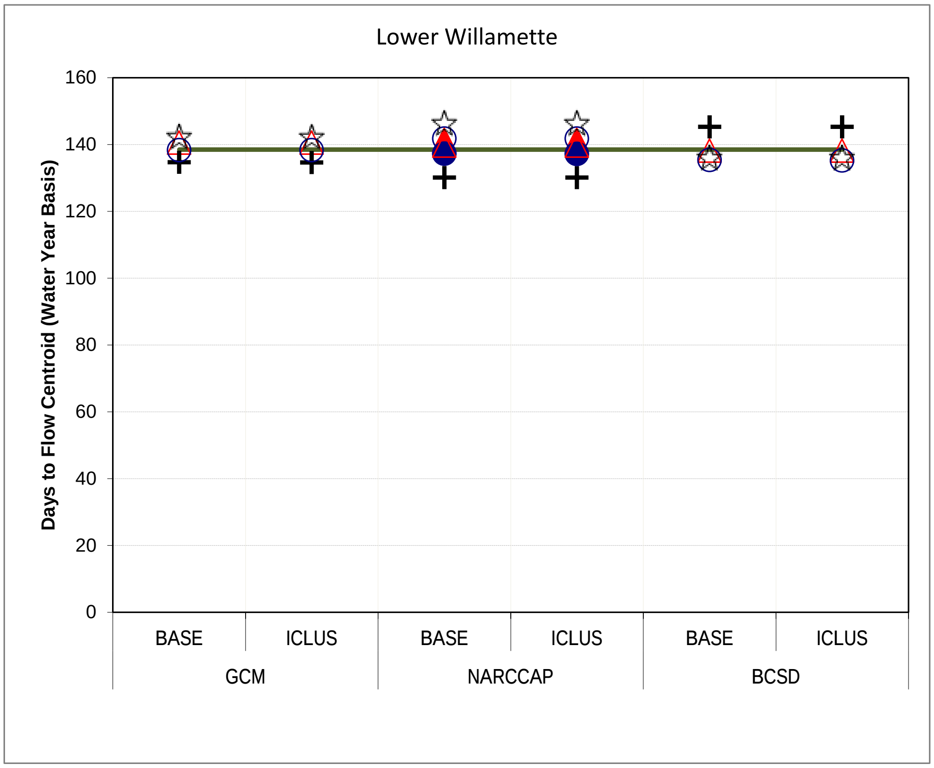


Figure 251. Days to Flow Centroid, Lower Willamette River (SWAT)

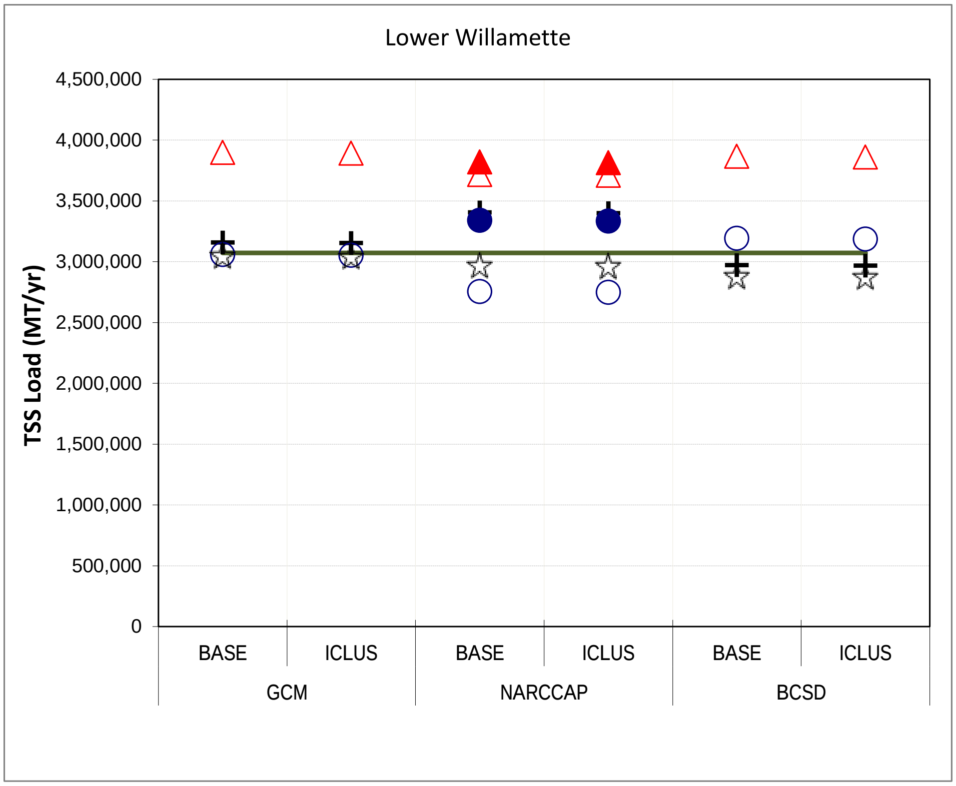


Figure 252. TSS Load, Lower Willamette River (SWAT)

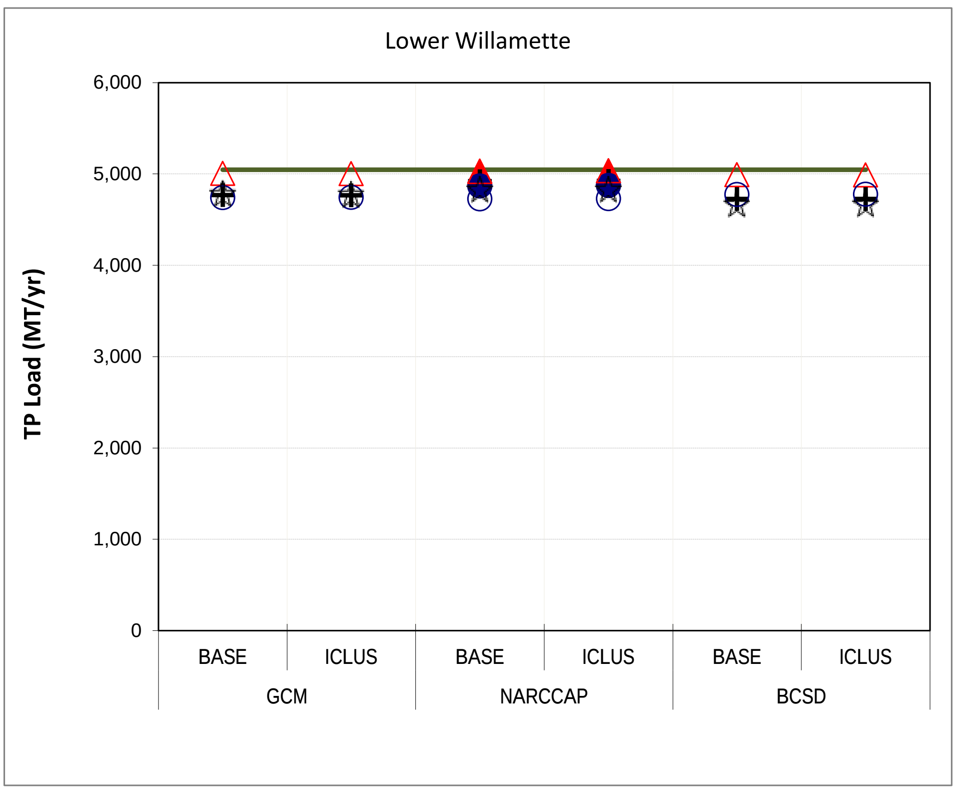


Figure 253. TP Load, Lower Willamette River (SWAT)

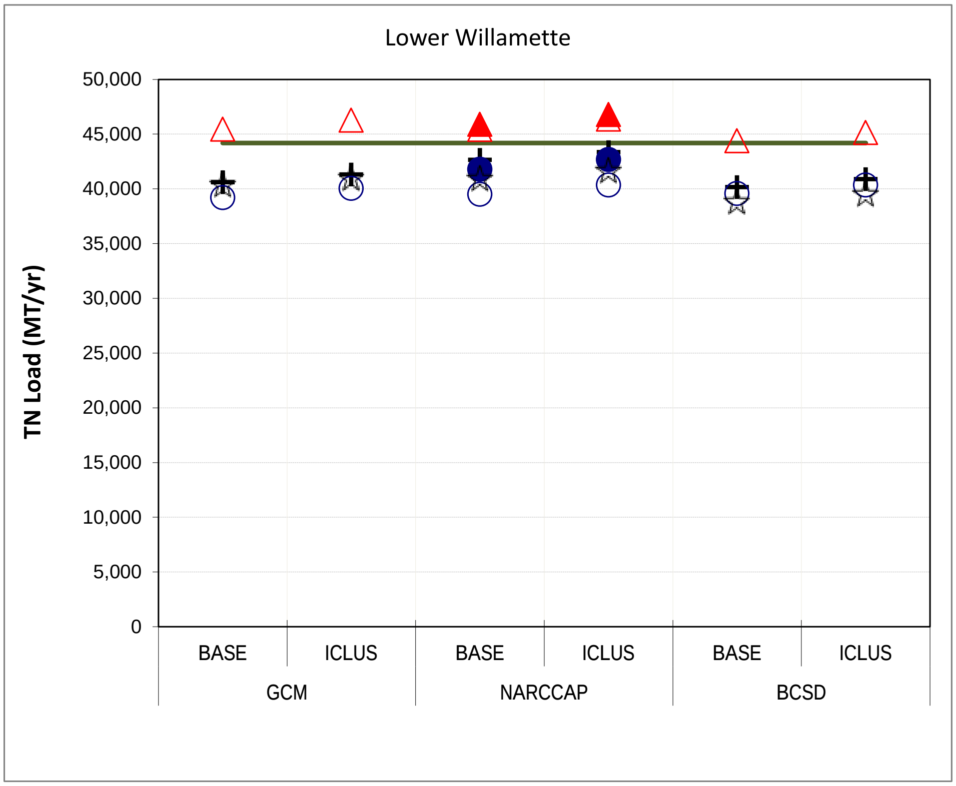


Figure 254. TN Load, Lower Willamette River (SWAT)

Results at Multiple Stations

Table 10. Summary of Range of Change Relative to Existing Conditions for NARCCAP Dynamically Downscaled Scenarios, Willamette River Basin (SWAT)

	Results without LU Change				Results with LU Change			
	Min	Median	Mean	Max	Min	Median	Mean	Max
Middle Fork Willamette HUC 17090001								
Flow	-17.51%	0.03%	-1.70%	10.39%	-17.51%	0.03%	-1.69%	10.40%
TSS	91.02%	132.96%	135.57%	177.73%	91.33%	133.31%	135.95%	178.19%
TN	49.94%	84.32%	82.64%	110.23%	48.72%	82.46%	80.90%	108.15%
TP	86.17%	142.56%	140.77%	183.53%	83.96%	139.23%	137.48%	179.48%
Coast Fork Willamette HUC 17090002								
Flow	-4.95%	6.37%	7.28%	19.55%	-4.98%	6.34%	7.26%	19.53%
TSS	-4.93%	29.49%	31.31%	63.92%	-4.65%	29.73%	31.54%	64.12%
TN	-14.77%	2.84%	4.93%	24.75%	-15.48%	1.50%	3.68%	23.30%
TP	-19.61%	5.31%	6.77%	31.82%	-19.46%	5.08%	6.60%	31.67%
Upper Willamette HUC 17090003								
Flow	-10.42%	3.89%	2.92%	12.86%	-10.43%	3.89%	2.91%	12.85%
TSS	-1.01%	13.58%	15.18%	31.82%	-0.99%	13.61%	15.20%	31.85%
TN	-7.23%	2.07%	3.41%	13.70%	-7.45%	1.78%	3.13%	13.40%
TP	-10.15%	-0.27%	-0.29%	7.20%	-10.21%	-0.32%	-0.32%	7.20%
McKenzie HUC 17090004								
Flow	-12.39%	5.32%	2.24%	10.76%	-12.39%	5.32%	2.24%	10.76%
TSS	-0.95%	114.25%	105.67%	218.42%	-0.94%	114.53%	105.97%	219.11%
TN	-1.52%	27.74%	22.02%	36.83%	-1.70%	27.11%	21.48%	35.94%
TP	-10.56%	35.02%	24.38%	48.46%	-10.63%	34.55%	24.02%	47.80%
North Santiam HUC 17090005								
Flow	-9.28%	5.21%	5.32%	16.94%	-9.29%	5.21%	5.31%	16.94%
TSS	-7.60%	6.79%	9.26%	29.41%	-7.14%	7.29%	9.76%	29.96%
TN	-14.08%	-3.80%	-3.19%	5.72%	-14.56%	-4.43%	-3.77%	5.07%
TP	-19.42%	-7.42%	-7.20%	1.44%	-19.68%	-7.63%	-7.41%	1.15%
South Santiam HUC 17090006								

	Results without LU Change				Results with LU Change			
	Min	Median	Mean	Max	Min	Median	Mean	Max
Flow	-7.77%	4.90%	6.28%	18.21%	-7.77%	4.90%	6.28%	18.21%
TSS	-8.09%	9.51%	11.57%	32.22%	-8.09%	9.51%	11.57%	32.23%
TN	-15.63%	-5.85%	-4.99%	5.14%	-15.62%	-5.90%	-5.02%	5.08%
TP	-19.81%	-8.02%	-7.75%	3.02%	-19.76%	-8.05%	-7.74%	3.01%
Middle Willamette HUC 17090007								
Flow	-8.45%	4.70%	4.53%	15.28%	-8.49%	4.69%	4.51%	15.27%
TSS	-9.71%	8.31%	8.06%	24.61%	-9.65%	8.42%	8.17%	24.70%
TN	-11.45%	-4.78%	-3.64%	3.94%	-11.71%	-5.36%	-4.16%	3.37%
TP	-7.59%	-3.62%	-3.50%	-0.47%	-7.42%	-3.43%	-3.33%	-0.31%
Yamhill HUC 17090008								
Flow	-3.30%	7.65%	9.71%	23.21%	-3.33%	7.64%	9.69%	23.20%
TSS	-8.27%	9.81%	11.30%	30.05%	-8.26%	9.86%	11.35%	30.13%
TN	-14.22%	-6.23%	-5.40%	3.24%	-14.41%	-6.57%	-5.69%	2.98%
TP	-18.00%	-8.13%	-7.82%	0.31%	-18.03%	-8.09%	-7.75%	0.39%
Pudding River at Aurora (gage 14202000)								
Flow	1.31%	5.72%	6.17%	12.04%	1.19%	5.65%	6.09%	11.96%
TSS	0.39%	5.98%	6.80%	15.12%	0.24%	5.94%	6.62%	14.68%
TN	-23.37%	-19.63%	-19.35%	-15.64%	-23.55%	-20.07%	-19.75%	-16.04%
TP	-20.73%	-13.83%	-14.92%	-11.96%	-19.81%	-12.77%	-13.98%	-10.77%
Tualatin HUC 17090010								
Flow	-5.04%	6.49%	8.24%	22.16%	-5.34%	6.31%	8.07%	22.08%
TSS	-7.91%	8.21%	10.43%	29.32%	-8.05%	8.02%	10.51%	29.99%
TN	-12.32%	-7.81%	-6.10%	0.58%	-11.86%	-8.34%	-6.41%	0.15%
TP	-11.04%	-2.89%	-2.18%	5.07%	-10.48%	-2.70%	-1.79%	5.34%
Clackamas HUC 17090011								
Flow	-8.10%	9.04%	7.61%	20.18%	-8.13%	9.01%	7.58%	20.15%
TSS	-8.89%	10.94%	9.11%	27.42%	-8.86%	10.91%	9.10%	27.41%
TN	-7.16%	1.37%	1.83%	9.21%	-7.05%	1.34%	1.88%	9.16%

	Results without LU Change				Results with LU Change			
	Min	Median	Mean	Max	Min	Median	Mean	Max
TP	-7.68%	0.66%	-0.08%	4.89%	-7.28%	1.31%	0.55%	5.60%
Lower Willamette HUC 17090012								
Flow	-8.35%	5.20%	4.91%	15.89%	-8.39%	5.18%	4.89%	15.87%
TSS	-10.38%	9.78%	8.57%	24.33%	-10.31%	9.90%	8.68%	24.49%
TN	-10.62%	-4.47%	-3.33%	3.87%	-10.86%	-4.99%	-3.80%	3.36%
TP	-6.34%	-3.02%	-2.86%	-0.32%	-6.16%	-2.84%	-2.68%	-0.14%
Williamette River at Salem (gage 14191000)								
Flow	-9.99%	4.30%	3.70%	14.23%	-10.00%	4.30%	3.70%	14.23%
TSS	-9.58%	11.57%	9.93%	24.93%	-9.51%	11.67%	10.03%	25.04%
TN	-9.63%	-0.42%	0.79%	10.54%	-9.95%	-0.83%	0.41%	10.15%
TP	-13.20%	-3.34%	-3.23%	4.13%	-13.30%	-3.34%	-3.24%	4.19%
Mohawk River nr Springfield (gage 14165000)								
Flow	-8.80%	3.09%	2.34%	12.39%	-8.80%	3.09%	2.34%	12.39%
TSS	6.65%	2391.16 %	2875.55 %	8244.24 %	17.29%	2396.01 %	2878.21 %	8232.58 %
TN	8.19%	80.12%	63.54%	102.34%	6.78%	76.20%	60.19%	97.67%
TP	-1.08%	132.86%	101.95%	165.98%	-2.24%	128.33%	98.19%	160.61%

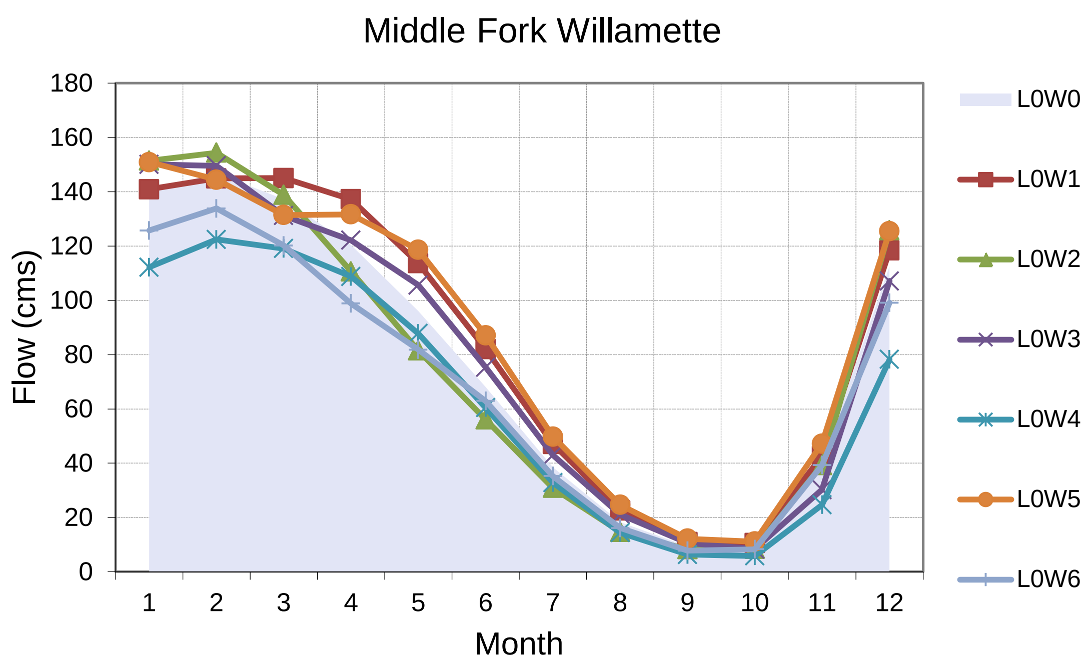


Figure 255. Monthly Average Flows, Middle Fork Willamette River (SWAT)

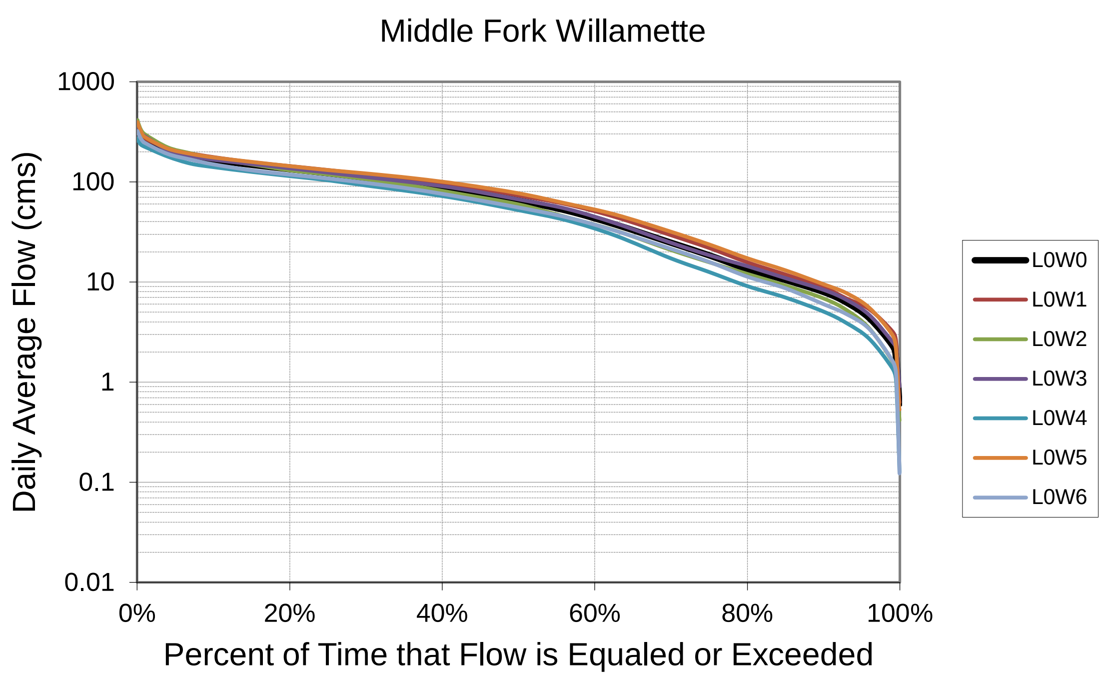


Figure 256. Flow Duration, Middle Fork Willamette River (SWAT)

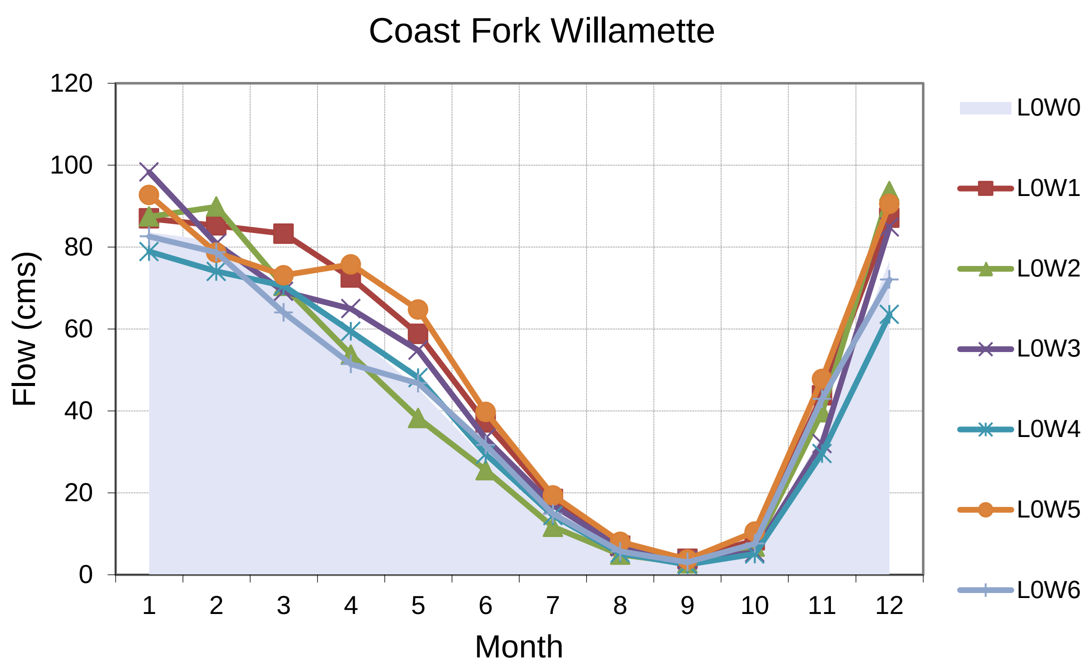


Figure 257. **Monthly Average Flows, Coast Fork Willamette River (SWAT)**

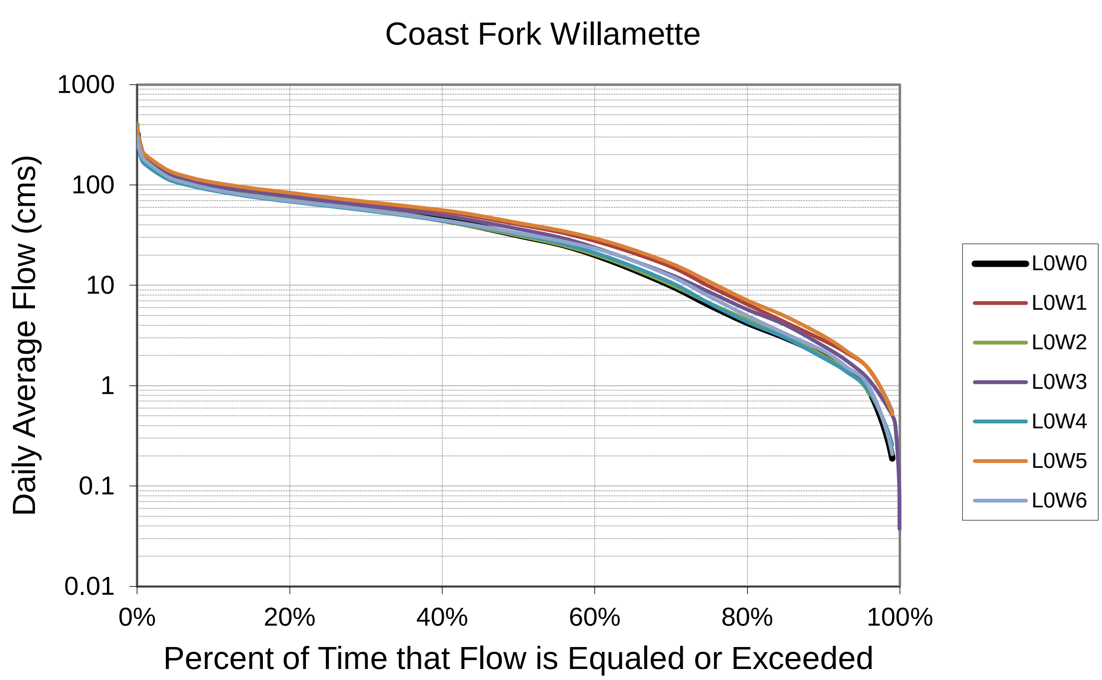


Figure 258. **Flow Duration, Coast Fork Willamette River (SWAT)**

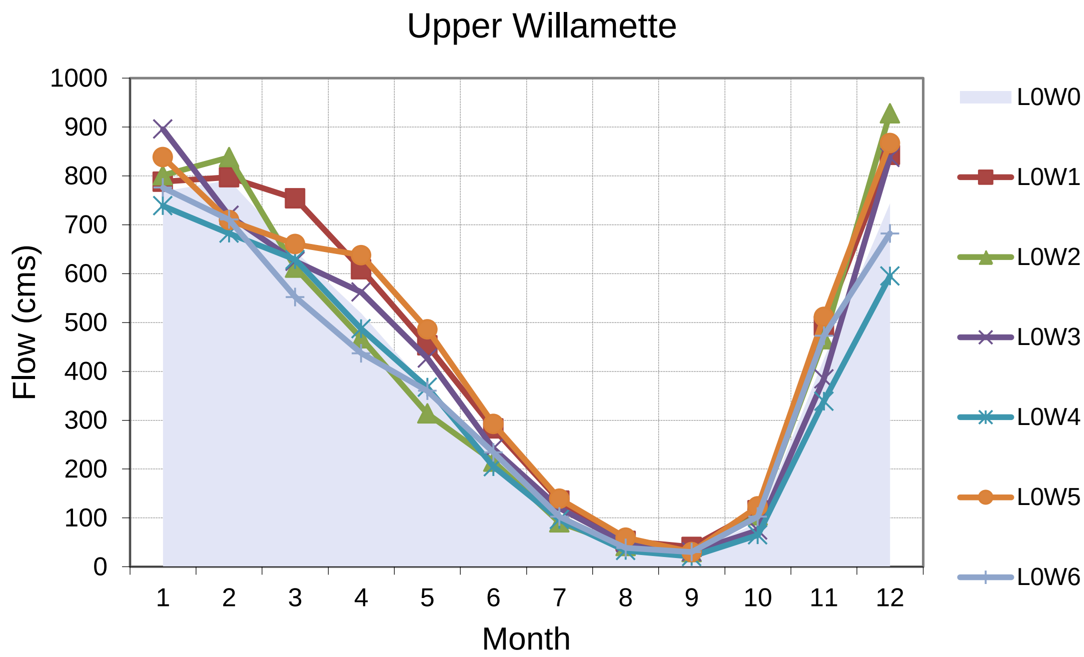


Figure 259. Monthly Average Flows, Upper Willamette River (SWAT)

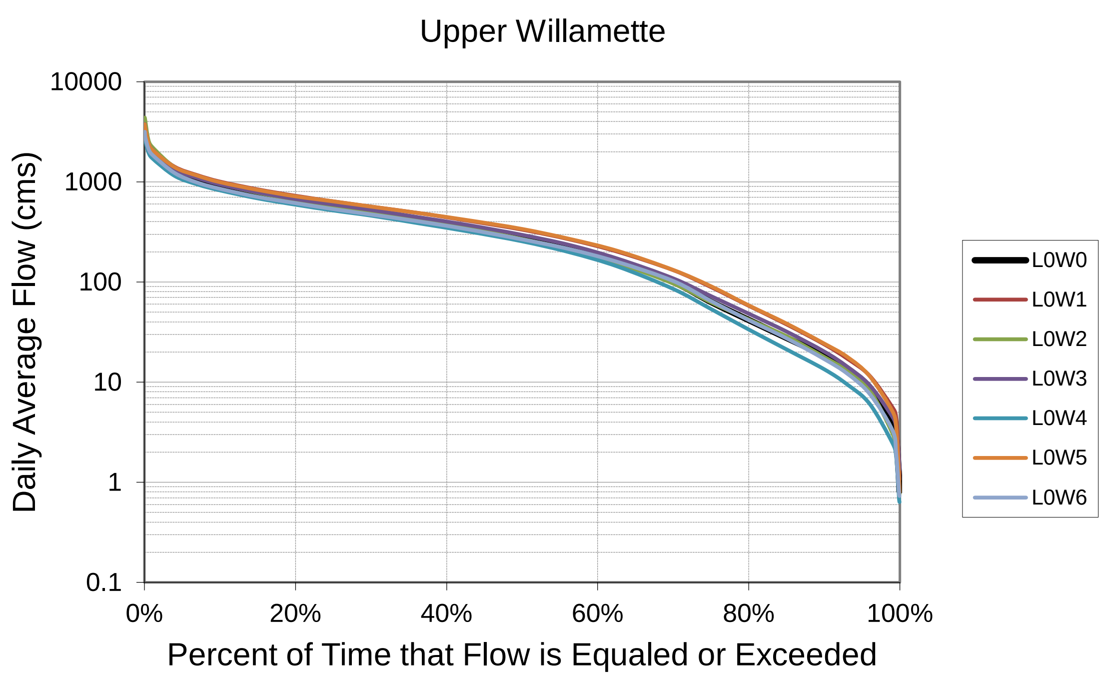


Figure 260. Flow Duration, Upper Willamette River (SWAT)

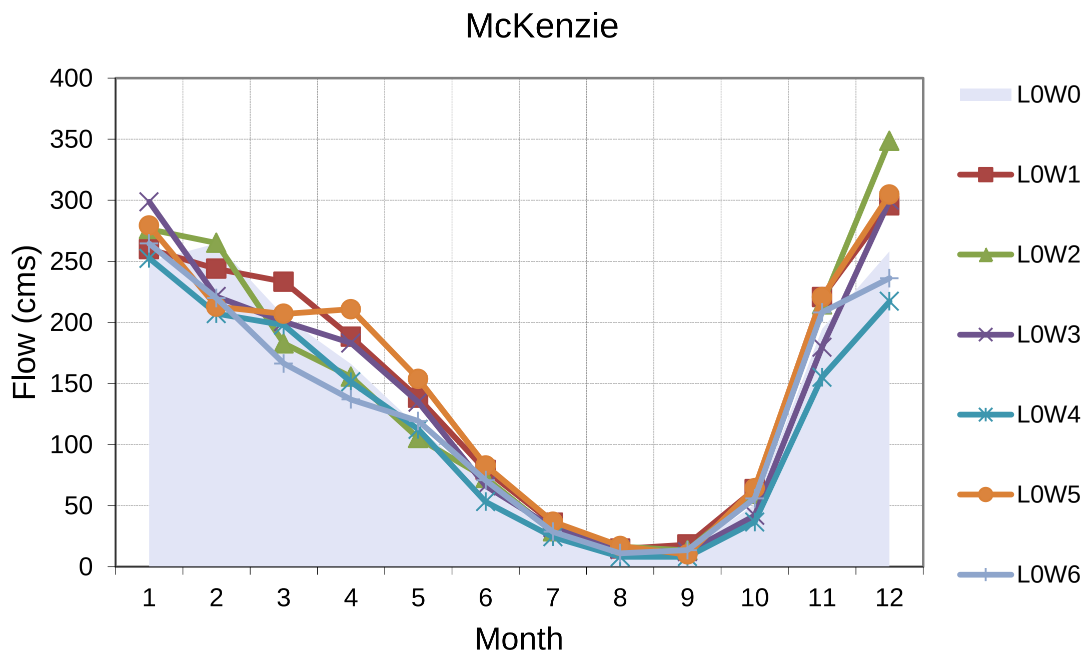


Figure 261. **Monthly Average Flows, McKenzie River (SWAT)**

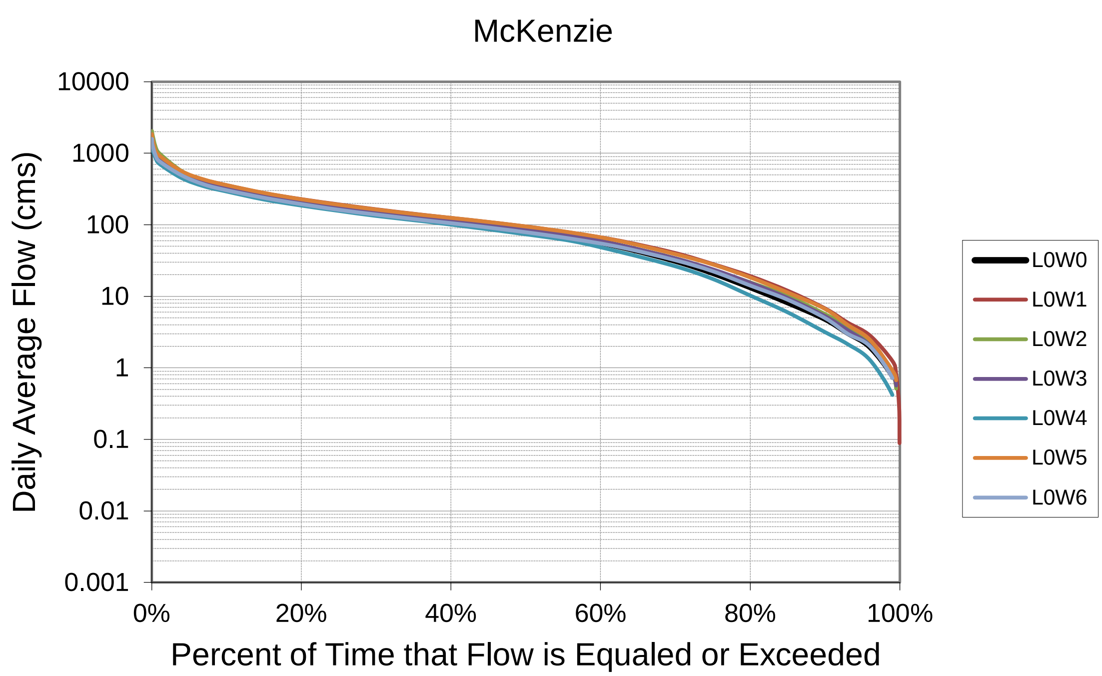


Figure 262. **Flow Duration, McKenzie River (SWAT)**

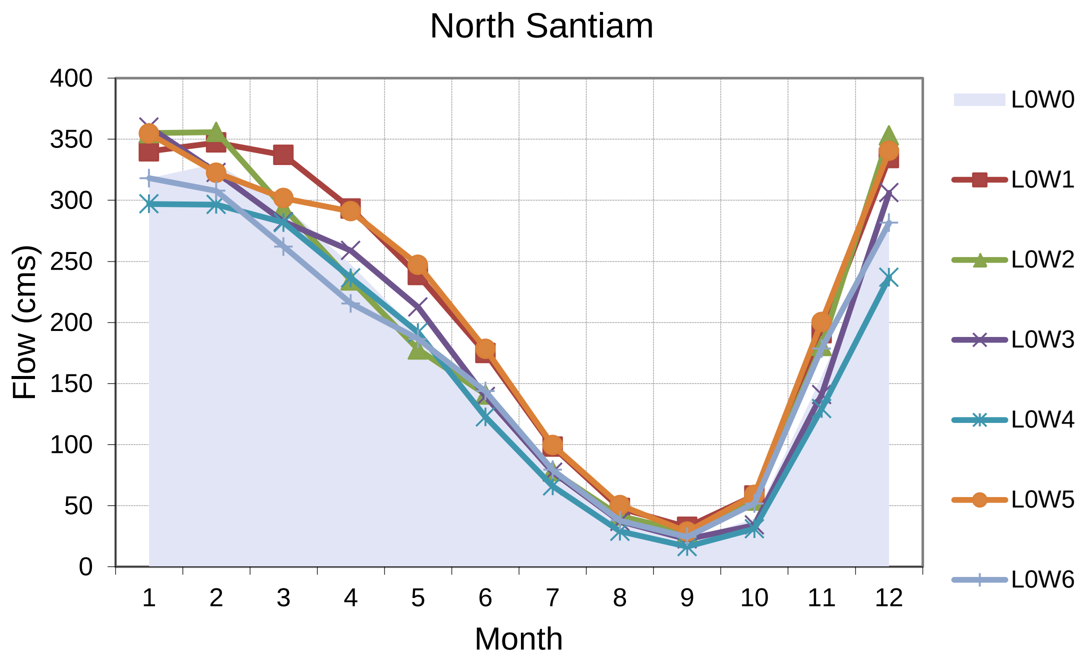


Figure 263. **Monthly Average Flows, North Santiam River (SWAT)**

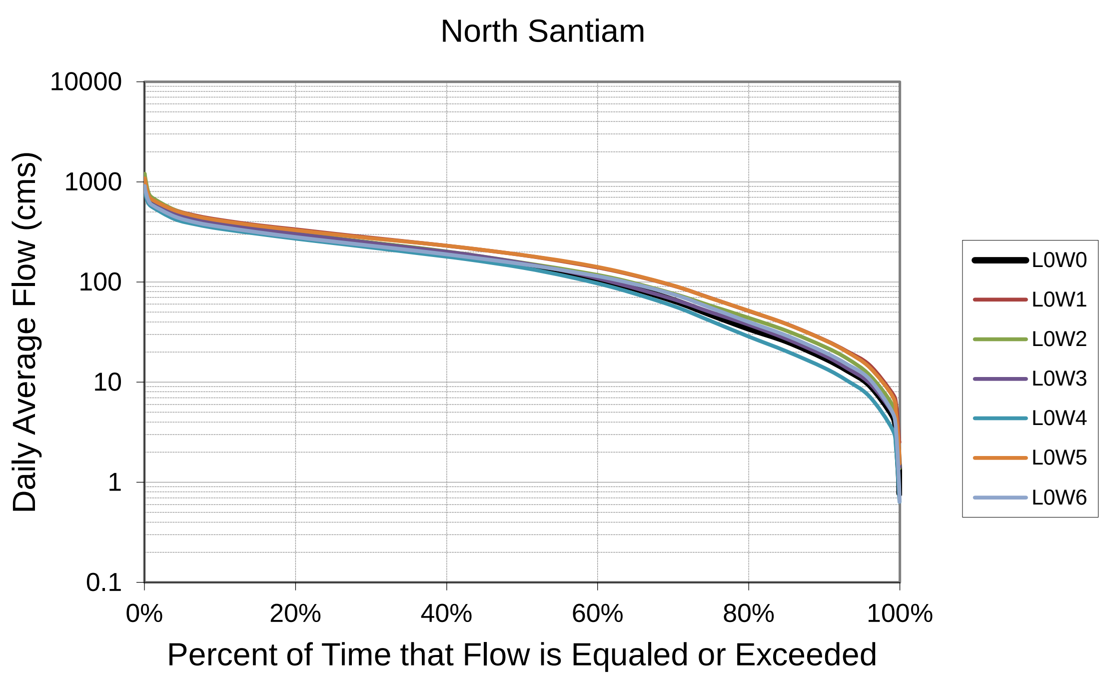


Figure 264. **Flow Duration, North Santiam River (SWAT)**

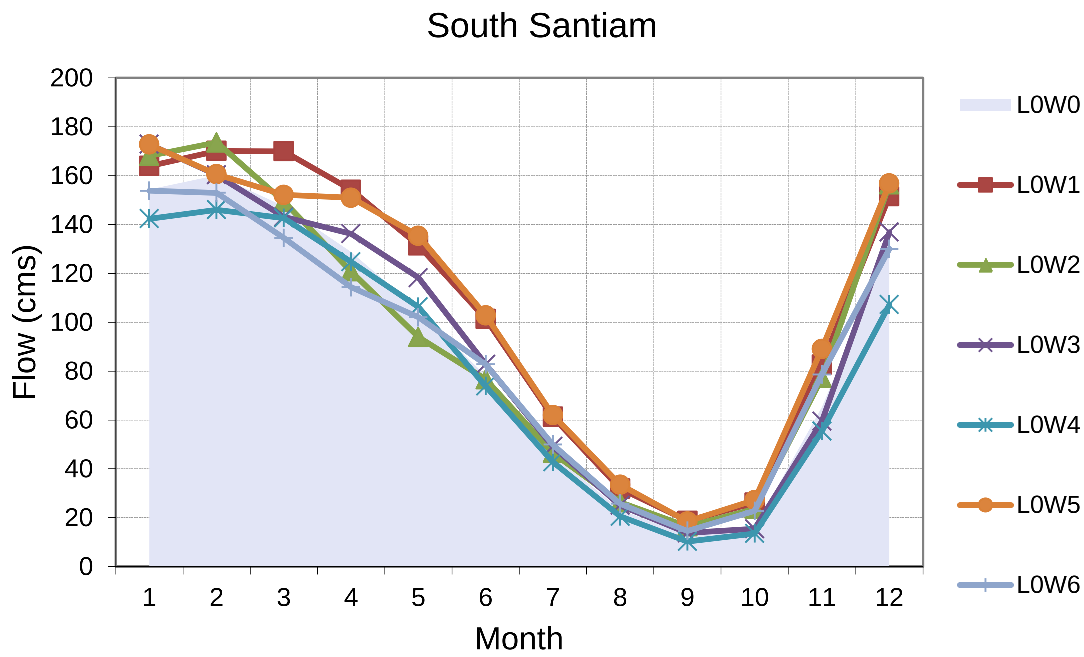


Figure 265. Monthly Average Flows, South Santiam River (SWAT)

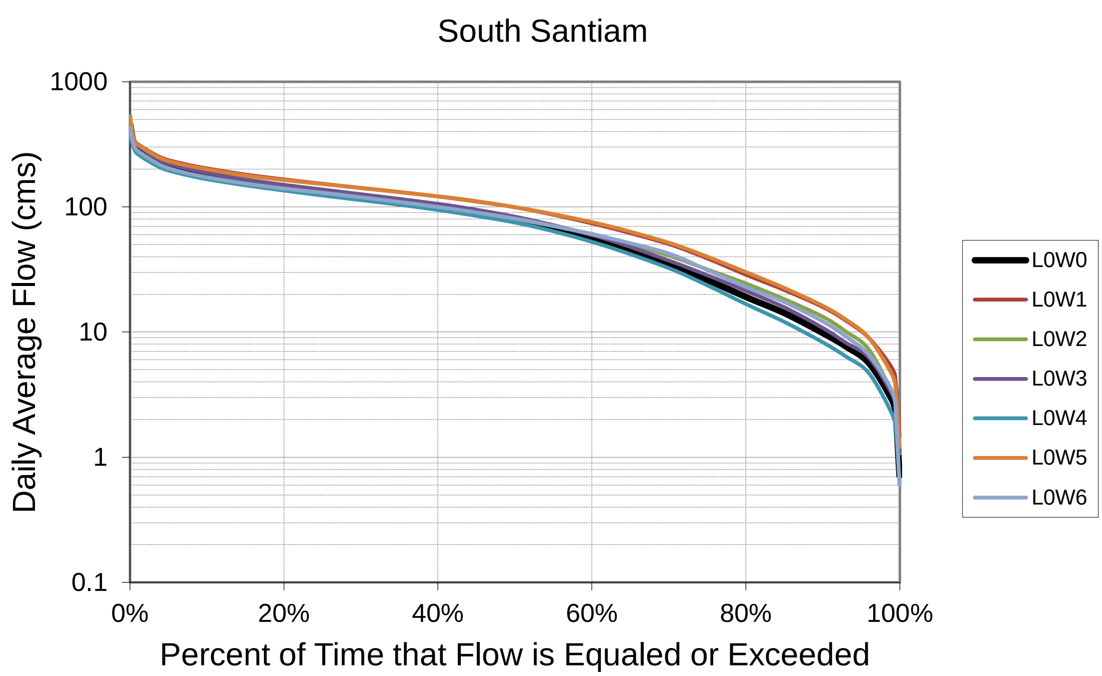


Figure 266. Flow Duration, South Santiam River (SWAT)

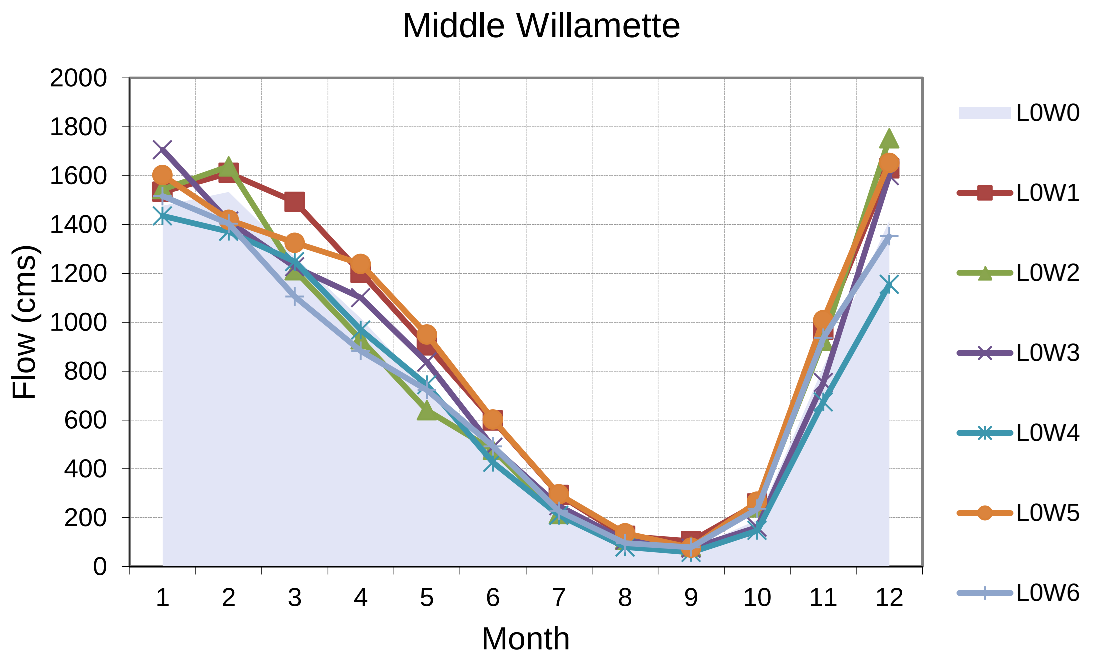


Figure 267. Monthly Average Flows, Middle Willamette River (SWAT)

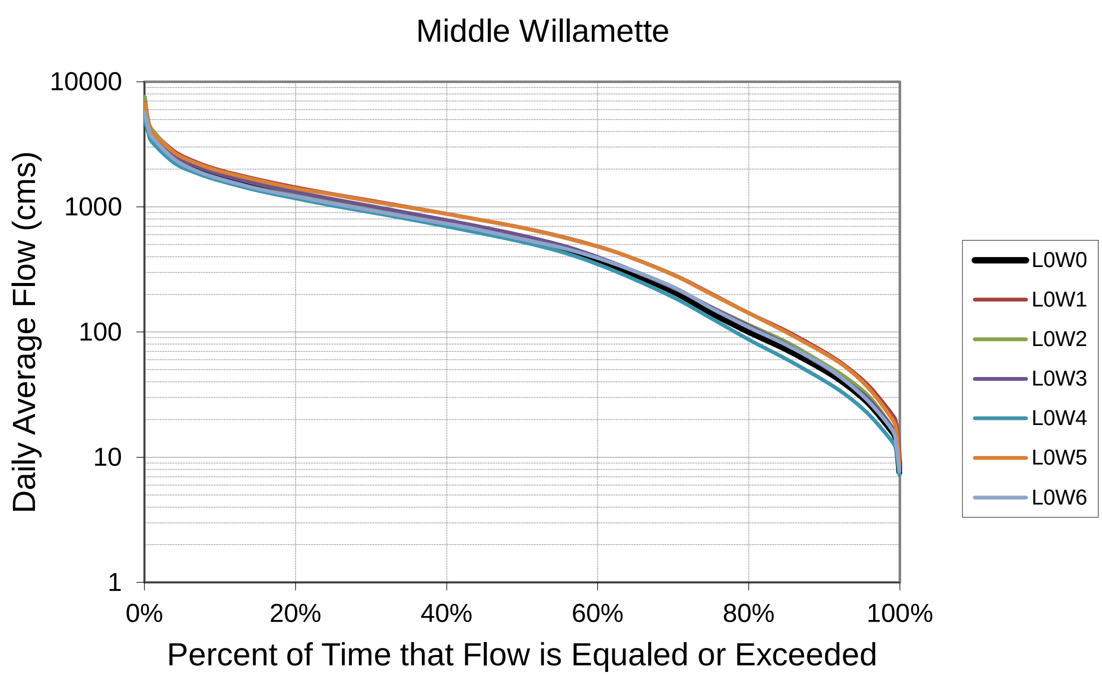


Figure 268. Flow Duration, Middle Willamette River (SWAT)

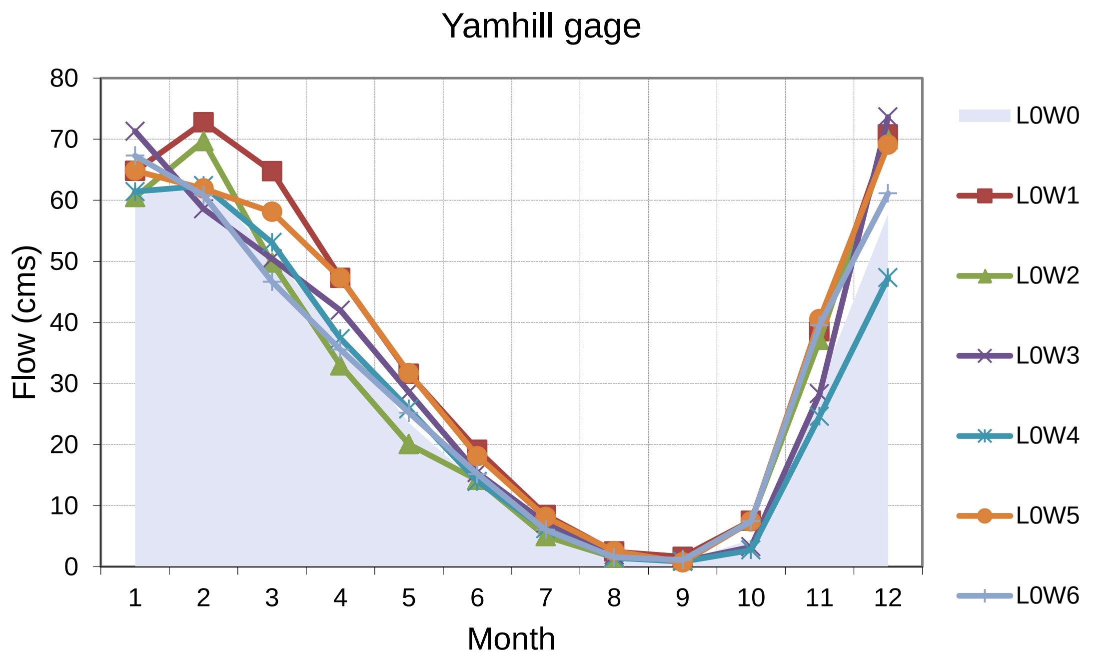


Figure 269. **Monthly Average Flows, Yamhill River (SWAT)**

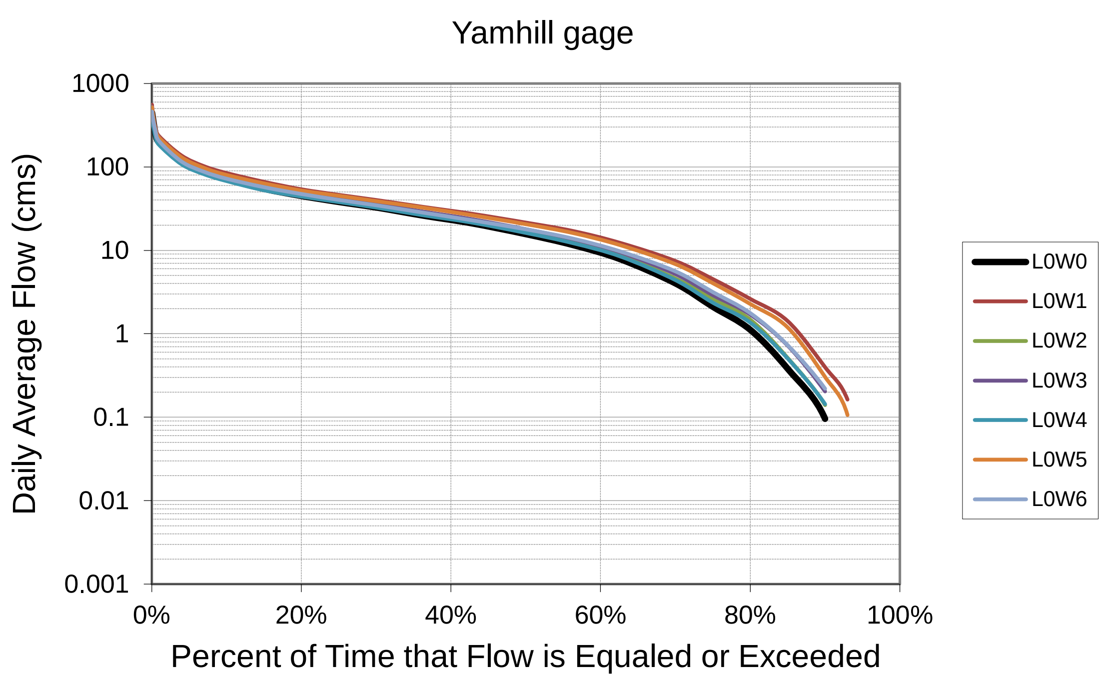


Figure 270. **Flow Duration, Yamhill River (SWAT)**

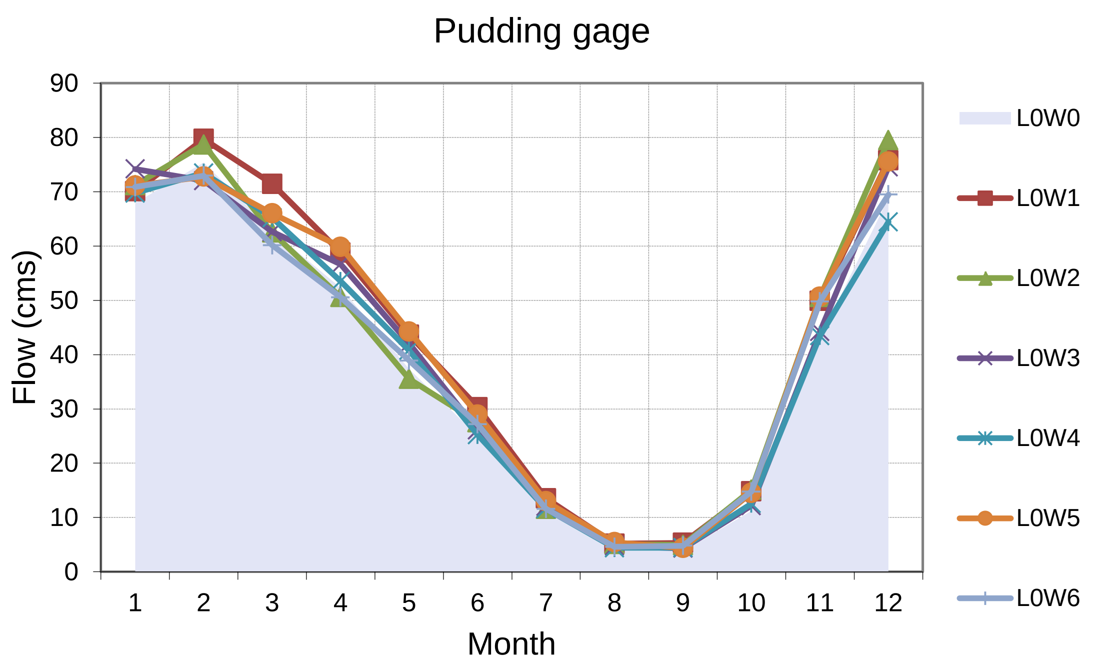


Figure 271. **Monthly Average Flows, Pudding River (SWAT)**

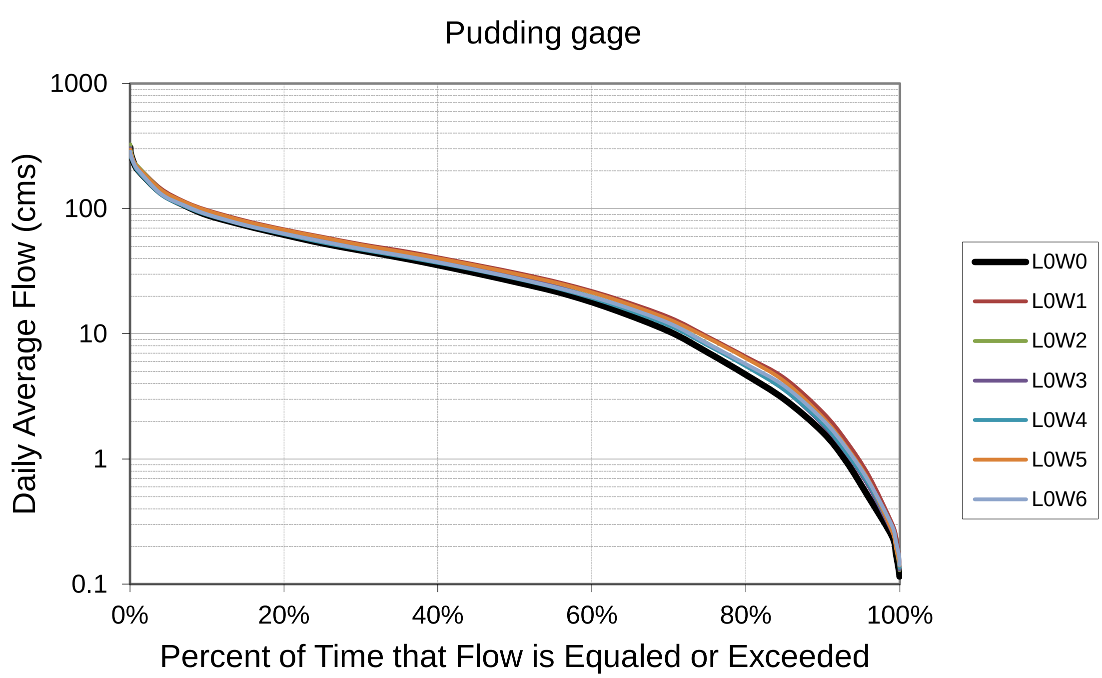


Figure 272. **Flow Duration, Pudding River (SWAT)**

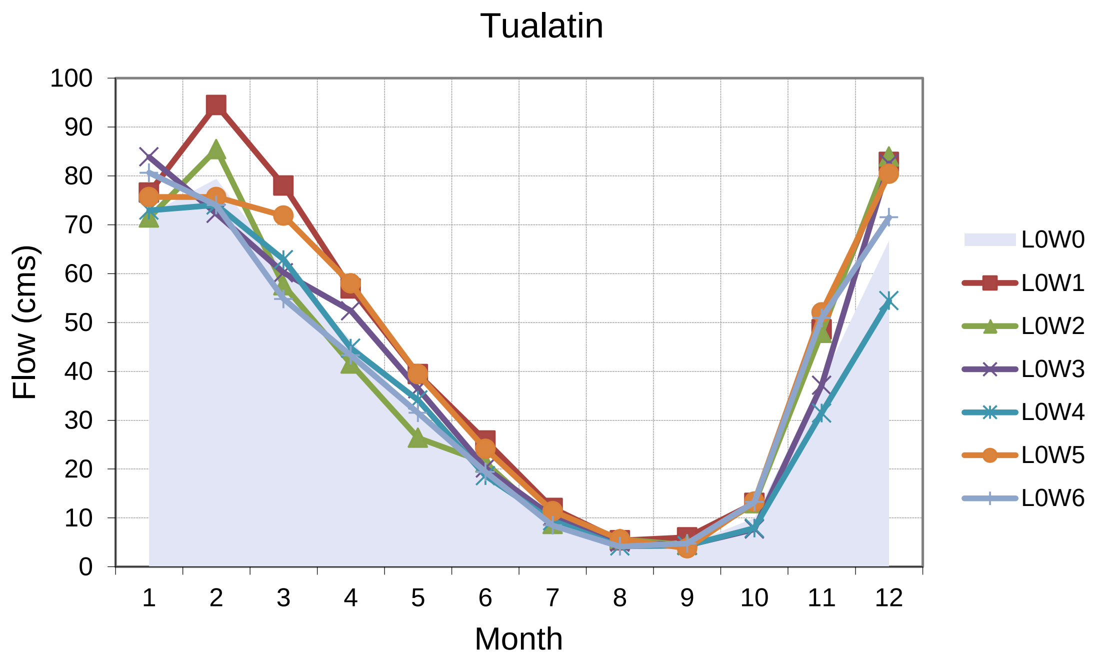


Figure 273. Monthly Average Flows, Tualatin River (SWAT)

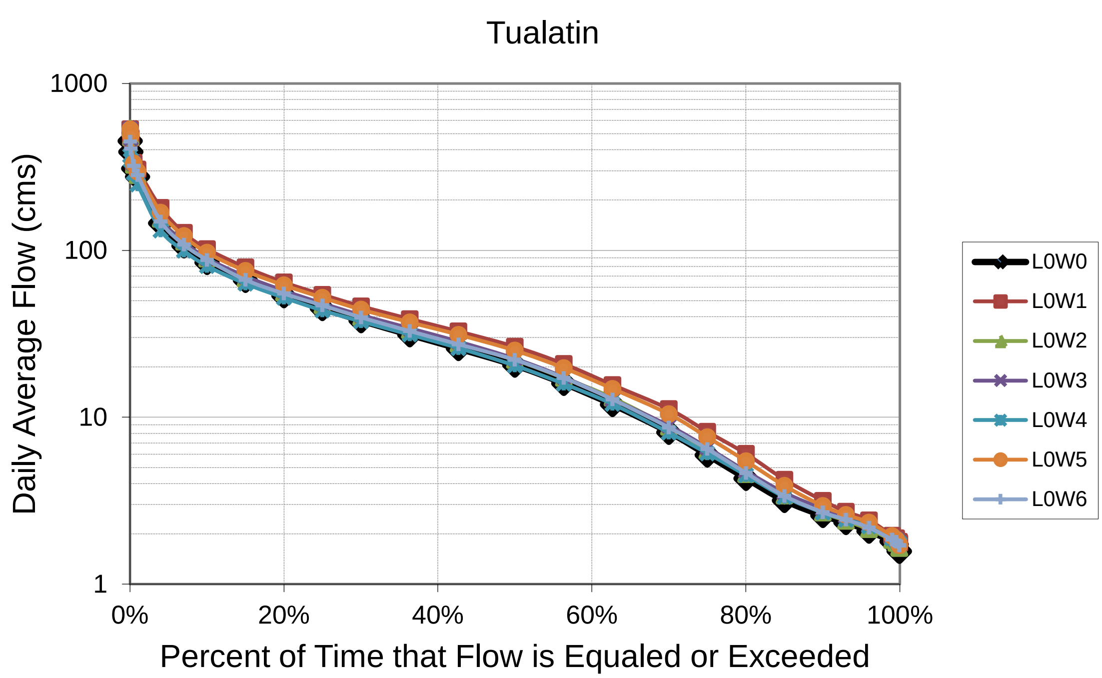


Figure 274. Flow Duration, Tualatin River (SWAT)

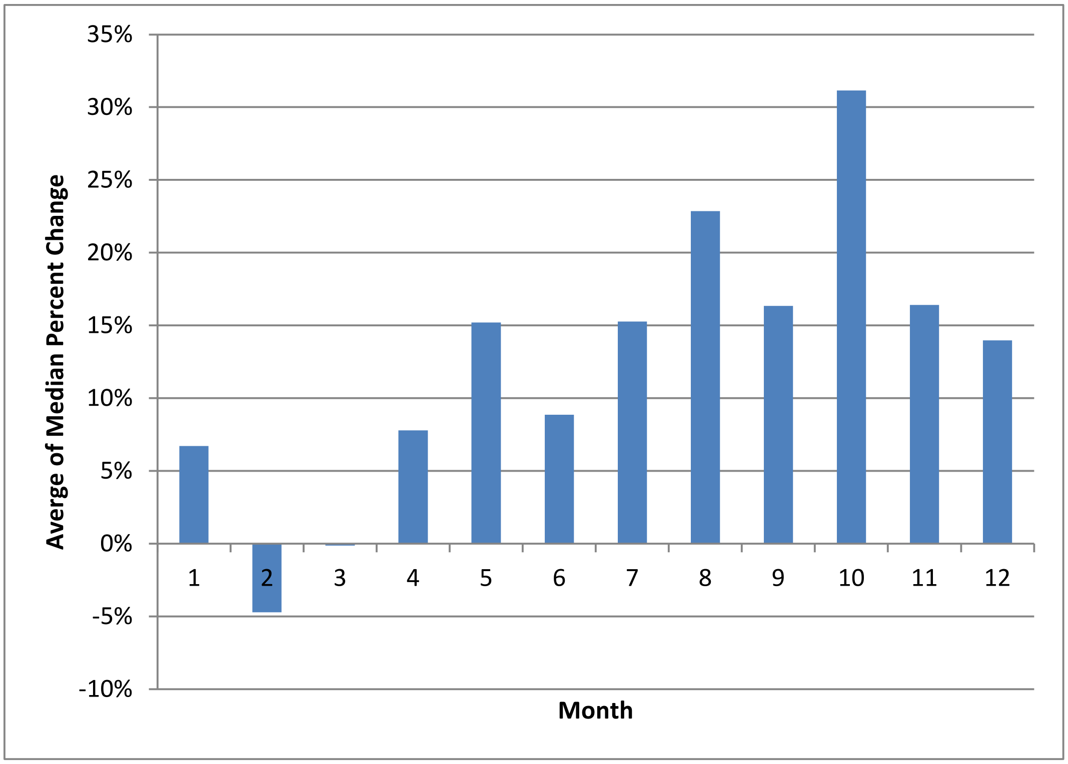
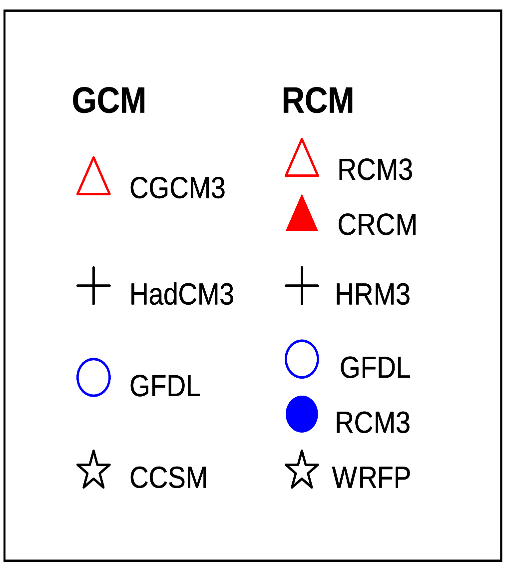


Figure 275. **Average of Median Percent Change in Flow; NARCCAP Scenarios W1-W6 at all Stations, Willamette River Basin (SWAT)**

Appendix Y

Scenario Results for the Non-Pilot Watersheds

LEGEND:



Southern California Coastal Watersheds

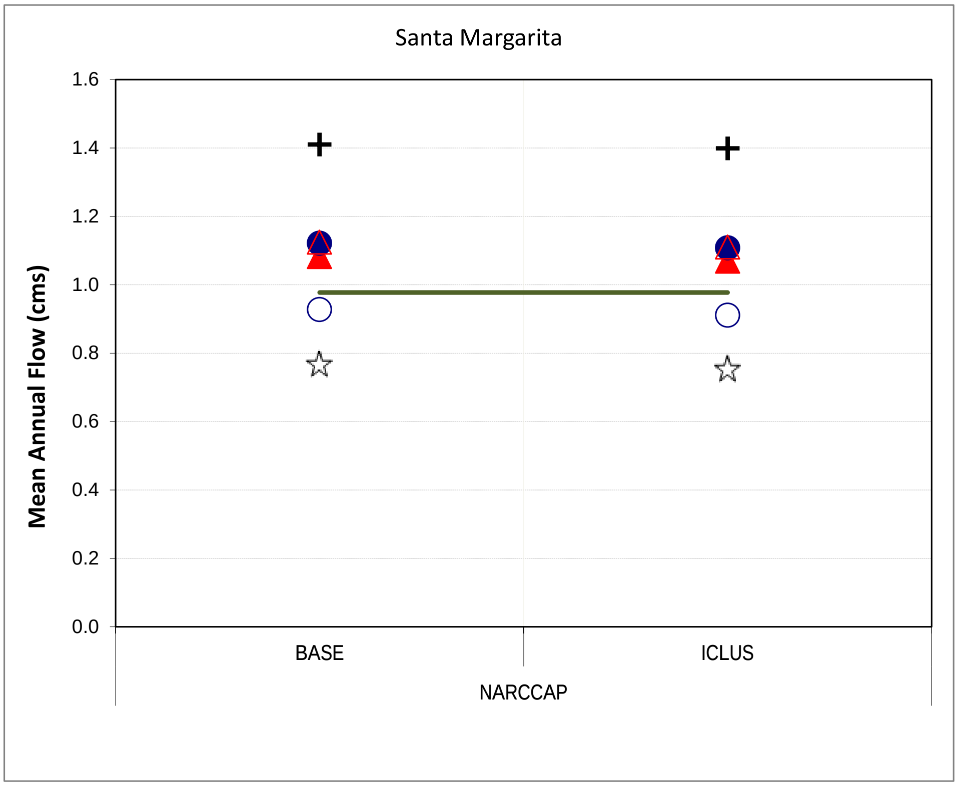
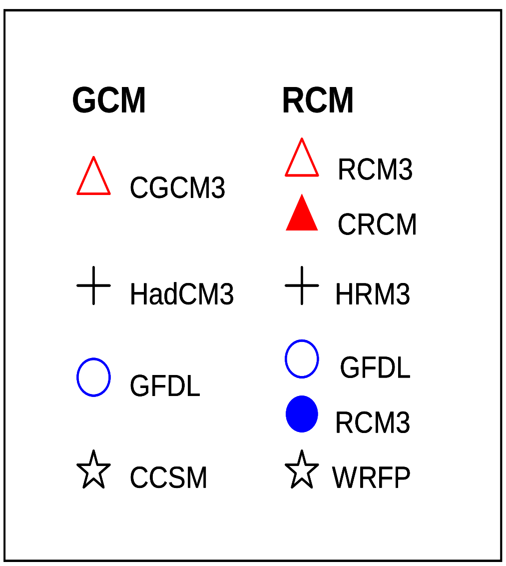


Figure 1. Mean annual flow (cms), Santa Margarita River (SWAT)



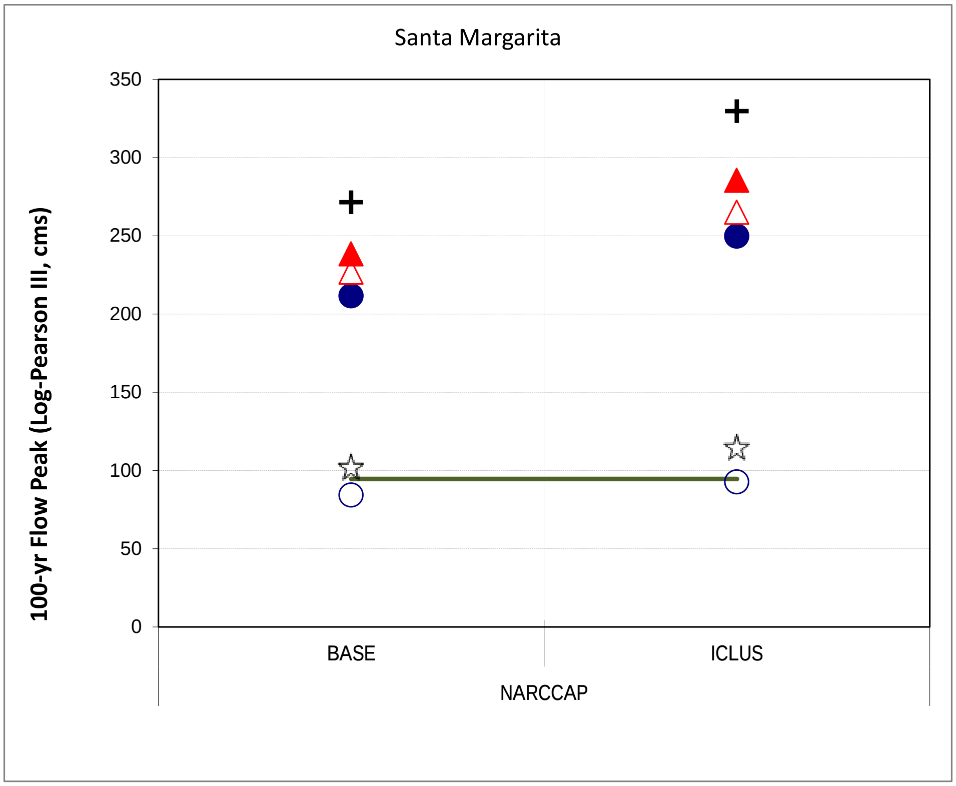


Figure 2. **100-yr Flow Peak (Log-Pearson III, cms), Santa Margarita River (SWAT)**

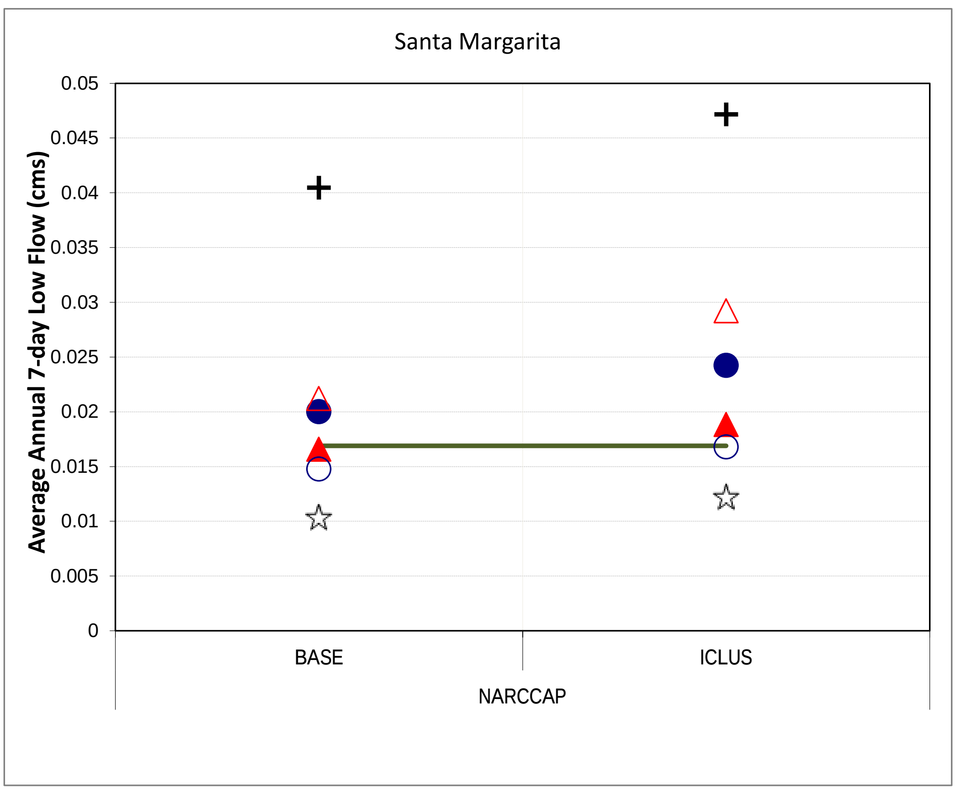


Figure 3. **Average Annual 7-day Low Flow (cms), Santa Margarita River (SWAT)**

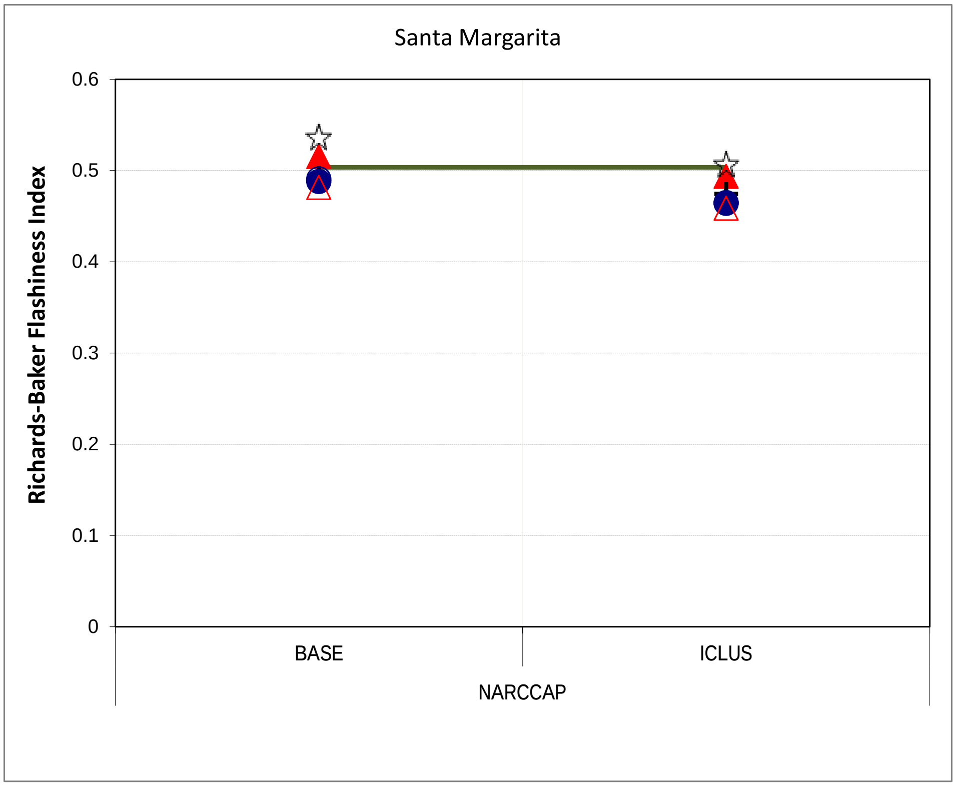


Figure 4. **Richards-Baker Flashiness Index, Average Annual 7-day Low Flow (cms), Santa Margarita River (SWAT)**

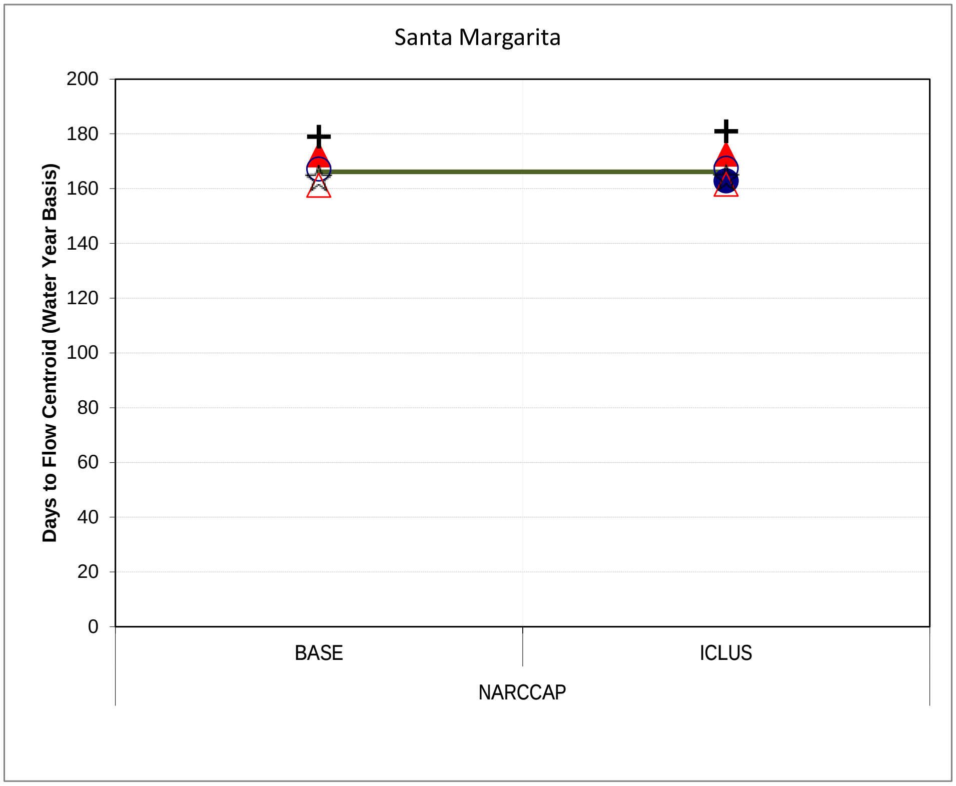


Figure 5. **Days to Flow Centroid (Water Year Basis), Santa Margarita River (SWAT)**

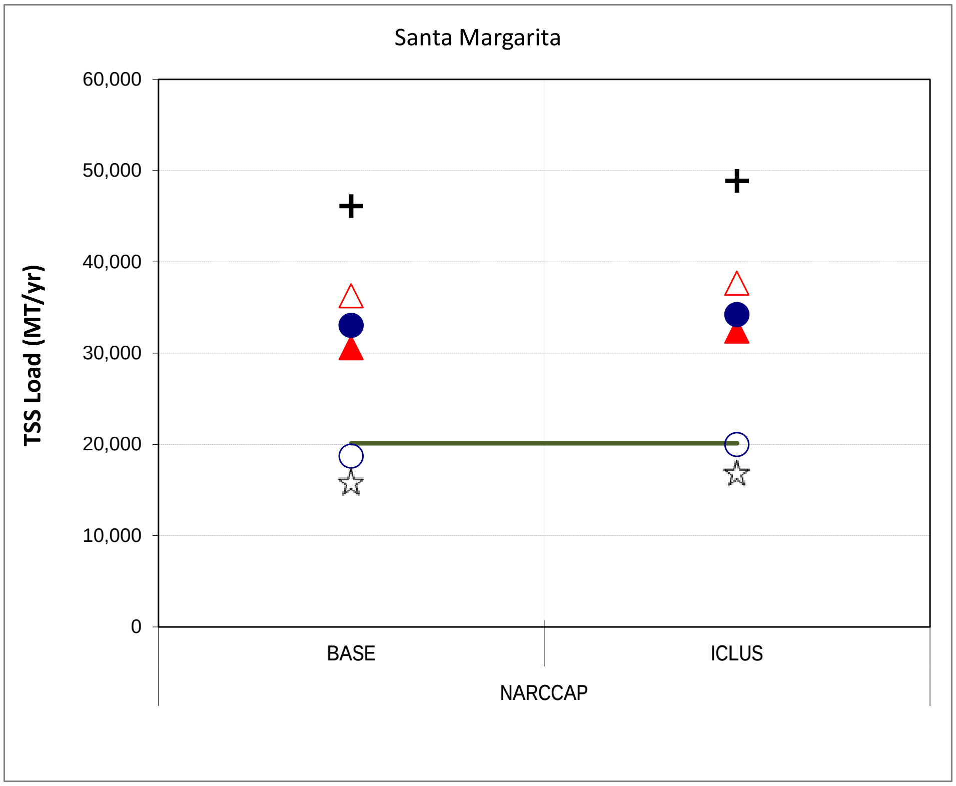


Figure 6. **TSS Load (MT/yr), Santa Margarita River (SWAT)**

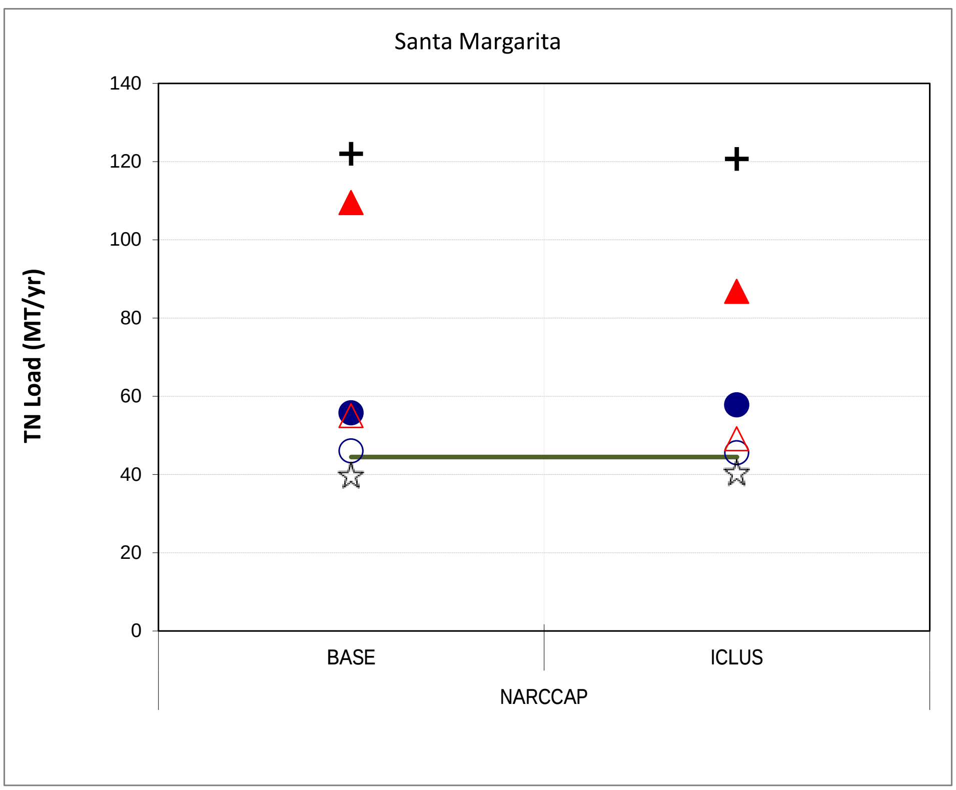


Figure 7. **TN Load (MT/yr), Santa Margarita River (SWAT)**

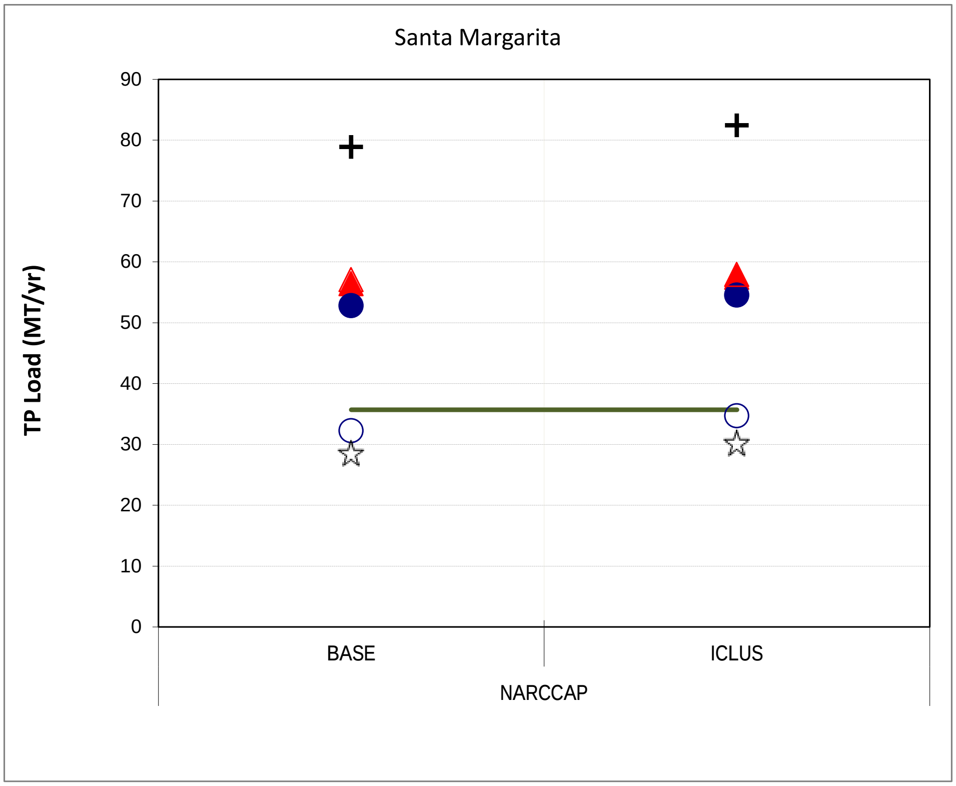


Figure 8. **TP Load (MT/yr), Santa Margarita River (SWAT)**

Table 1. Summary of range of change relative to existing conditions for NARCCAP dynamically downscaled scenarios, Southern California Coastal basins SWAT model

	Results without LU change				Results with LU change			
	Min	Median	Mean	Max	Min	Median	Mean	Max
Ventura River HUC 1807010								
Flow	-6.97%	-4.45%	1.93%	24.41%	-8.98%	-6.25%	-0.14%	21.98%
TSS	-18.83%	-9.61%	4.66%	61.06%	-11.51%	-3.99%	10.99%	70.69%
TN	1.40%	16.53%	19.95%	41.86%	-4.32%	15.73%	14.87%	34.38%
TP	-10.69%	6.90%	11.25%	36.48%	-9.83%	12.42%	10.00%	32.22%
Santa Clara HUC 18070102								
Flow	-9.40%	0.69%	2.81%	21.67%	-13.62%	-4.41%	-2.00%	16.57%
TSS	-31.29%	-19.22%	-17.82%	5.53%	-36.07%	-25.28%	-23.92%	-2.31%
TN	-10.46%	-6.48%	-6.37%	-0.23%	-13.77%	-10.86%	-9.61%	0.15%
TP	-70.02%	-66.08%	-65.68%	-57.92%	-70.63%	-67.29%	-66.64%	-58.83%
Calleguas HUC 18070103								
Flow	-11.30%	0.42%	2.33%	24.17%	-17.87%	-7.20%	-5.14%	14.72%
TSS	-4.20%	2.99%	12.58%	70.34%	-9.45%	-2.67%	5.66%	56.17%
TN	-0.79%	3.25%	8.41%	38.23%	-1.50%	2.41%	5.36%	23.31%
TP	-10.49%	2.85%	9.60%	59.30%	-17.10%	-4.53%	1.04%	40.75%
Los Angeles HUC 18070105								
Flow	-15.87%	2.80%	4.30%	37.89%	-18.50%	-0.63%	1.11%	34.64%
TSS	-35.29%	-19.33%	-18.02%	10.98%	-36.71%	-21.50%	-19.74%	10.97%
TN	-9.75%	-0.09%	9.06%	39.81%	-17.07%	-2.52%	5.67%	36.96%
TP	-46.85%	-38.86%	-35.25%	-12.03%	-47.04%	-35.50%	-31.18%	-3.79%
San Gabriel HUC 18070106								
Flow	-10.97%	2.25%	3.71%	25.91%	-12.23%	0.68%	2.20%	24.32%
TSS	-46.48%	-33.68%	-30.44%	-0.95%	-46.72%	-34.15%	-30.68%	-0.68%
TN	-4.55%	-3.02%	-2.06%	3.79%	-5.60%	-4.09%	-3.12%	2.80%
TP	-31.36%	-18.19%	-15.99%	9.90%	-33.83%	-21.16%	-18.30%	9.20%
San Jacinto HUC 18070202								
Flow	-26.91%	13.96%	13.70%	62.19%	-33.66%	4.16%	3.95%	48.71%
TSS	-29.47%	30.18%	32.03%	115.28%	-38.69%	14.54%	16.01%	89.84%
TN	52.93%	114.81%	163.48%	473.72%	43.09%	128.20%	164.27%	466.14%
TP	-16.17%	40.99%	48.26%	148.01%	-18.05%	22.10%	31.58%	124.47%
Santa Ana HUC 18070203								
Flow	-17.57%	11.28%	13.34%	56.22%	-22.45%	4.51%	6.64%	46.75%
TSS	-17.88%	14.58%	16.54%	64.12%	-22.71%	6.92%	9.40%	52.57%
TN	14.95%	49.96%	56.12%	144.14%	32.98%	77.79%	88.47%	208.75%
TP	-11.22%	25.87%	28.55%	88.59%	-9.68%	30.87%	31.92%	97.83%
Newport Bay HUC 18070204								
Flow	-16.15%	0.13%	3.74%	37.46%	-18.48%	-3.44%	-0.03%	31.52%

	Results without LU change				Results with LU change			
	Min	Median	Mean	Max	Min	Median	Mean	Max
TSS	-21.33%	3.64%	8.69%	55.79%	-21.50%	-1.30%	3.39%	44.39%
TN	7.48%	23.29%	45.09%	174.31%	9.53%	24.60%	50.29%	190.28%
TP	-10.91%	12.80%	25.25%	111.24%	-6.18%	11.34%	26.90%	122.82%
Santa Margarita HUC 18070302								
Flow	-21.03%	12.76%	9.79%	44.30%	-24.27%	8.77%	5.84%	39.81%
TSS	-20.57%	58.05%	49.64%	129.12%	-24.97%	47.01%	39.83%	115.71%
TN	-10.04%	24.47%	60.42%	174.21%	-17.61%	8.10%	35.06%	144.07%
TP	-19.56%	53.00%	42.96%	121.01%	-21.32%	45.06%	37.06%	113.56%
Santa Ana at MWD (Gage 11066460)								
Flow	-10.41%	2.18%	3.62%	21.08%	-12.23%	0.43%	1.73%	18.88%
TSS	-22.83%	-2.88%	-1.15%	21.77%	-23.01%	-2.98%	-1.69%	20.54%
TN	0.13%	3.40%	3.29%	5.51%	1.65%	6.08%	6.13%	8.87%
TP	-10.55%	0.59%	2.69%	20.77%	-7.75%	2.48%	4.30%	21.85%
Santa Clara at Piru (Gage 11109000)								
Flow	-13.99%	3.78%	4.73%	34.04%	-18.83%	-1.35%	-0.26%	29.08%
TSS	-18.30%	3.45%	8.02%	53.98%	-21.49%	-0.85%	3.55%	47.19%
TN	-3.07%	2.19%	6.65%	33.14%	-12.87%	-7.62%	-0.49%	40.07%
TP	-21.57%	1.53%	10.96%	69.37%	-25.97%	-4.58%	4.45%	61.09%
Santa Margarita nr Temecula (Gage 1104400)								
Flow	-21.99%	31.46%	26.94%	81.69%	-28.25%	21.51%	17.40%	69.34%
TSS	-20.54%	49.13%	41.71%	110.32%	-24.68%	36.25%	30.04%	91.47%
TN	-14.68%	70.49%	96.33%	289.14%	-24.59%	46.71%	68.34%	231.33%
TP	-22.14%	61.06%	53.75%	141.38%	-22.61%	56.67%	50.73%	142.63%

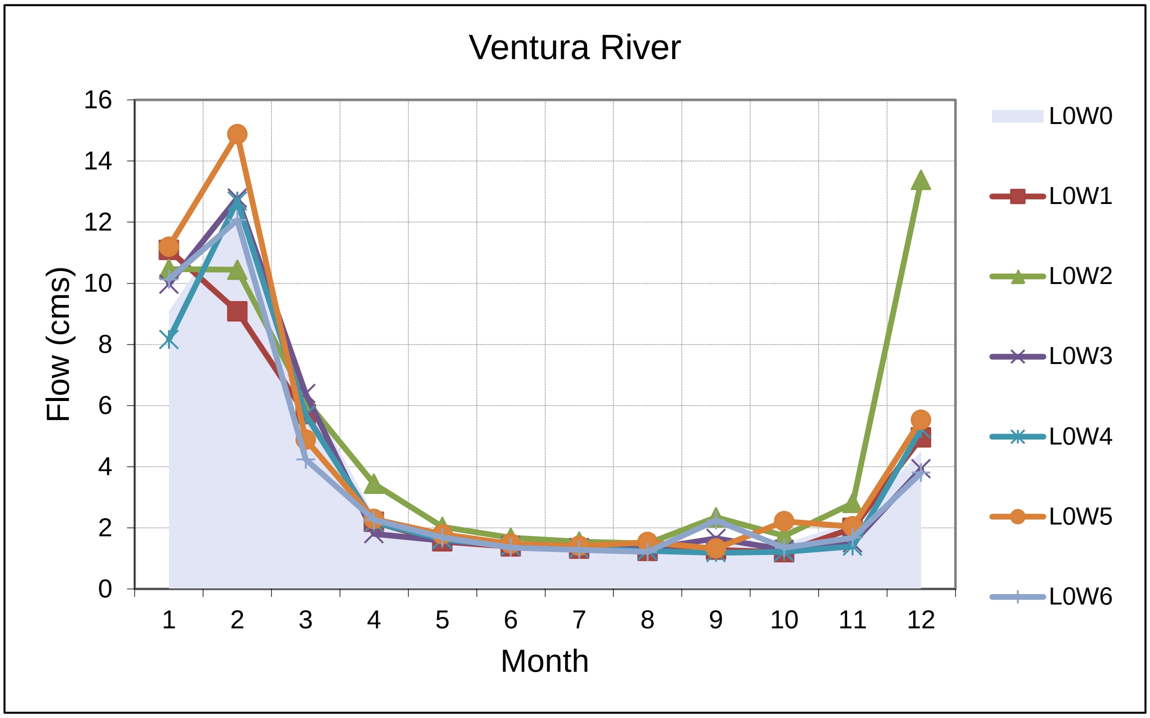


Figure 9. **Monthly average flows, Ventura River (SWAT)**

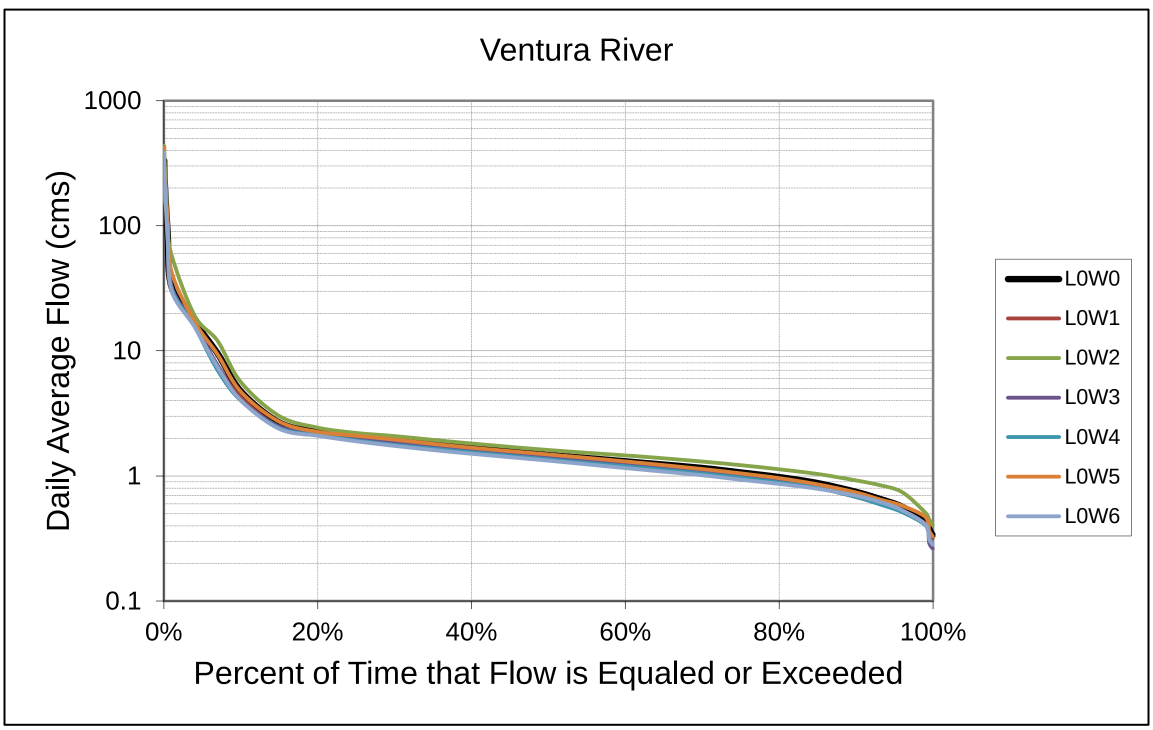


Figure 10. **Flow duration, Ventura River (SWAT)**

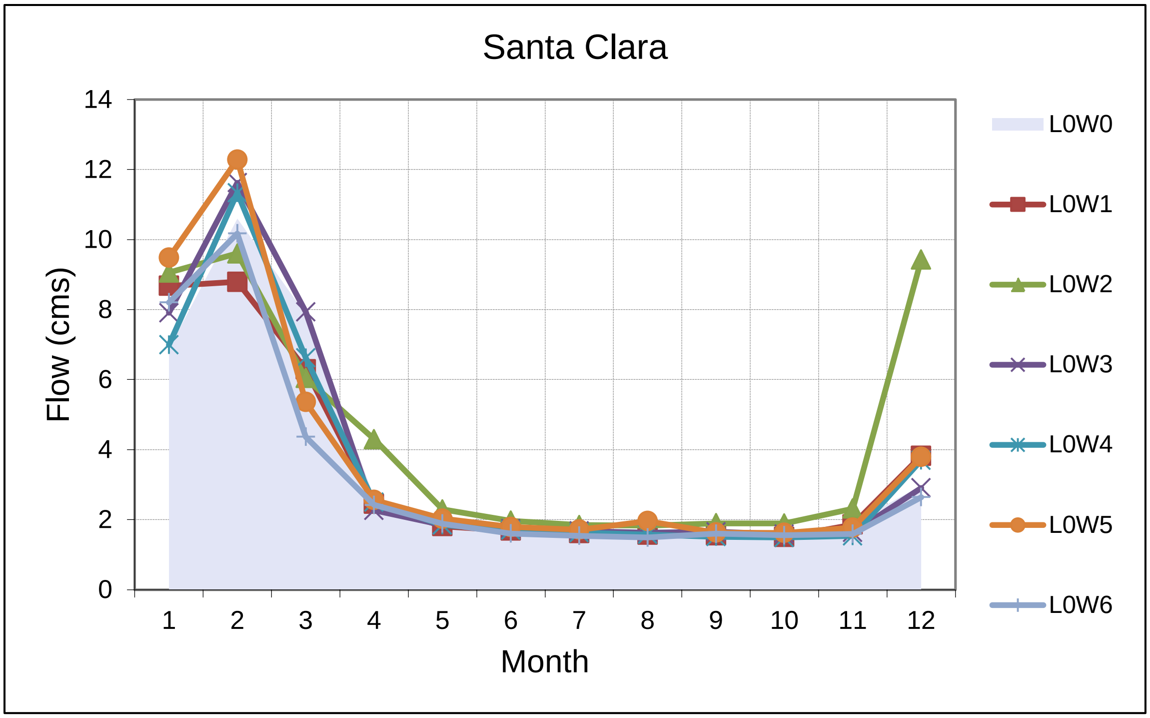


Figure 11. Monthly average flows, Santa Clara River (SWAT)

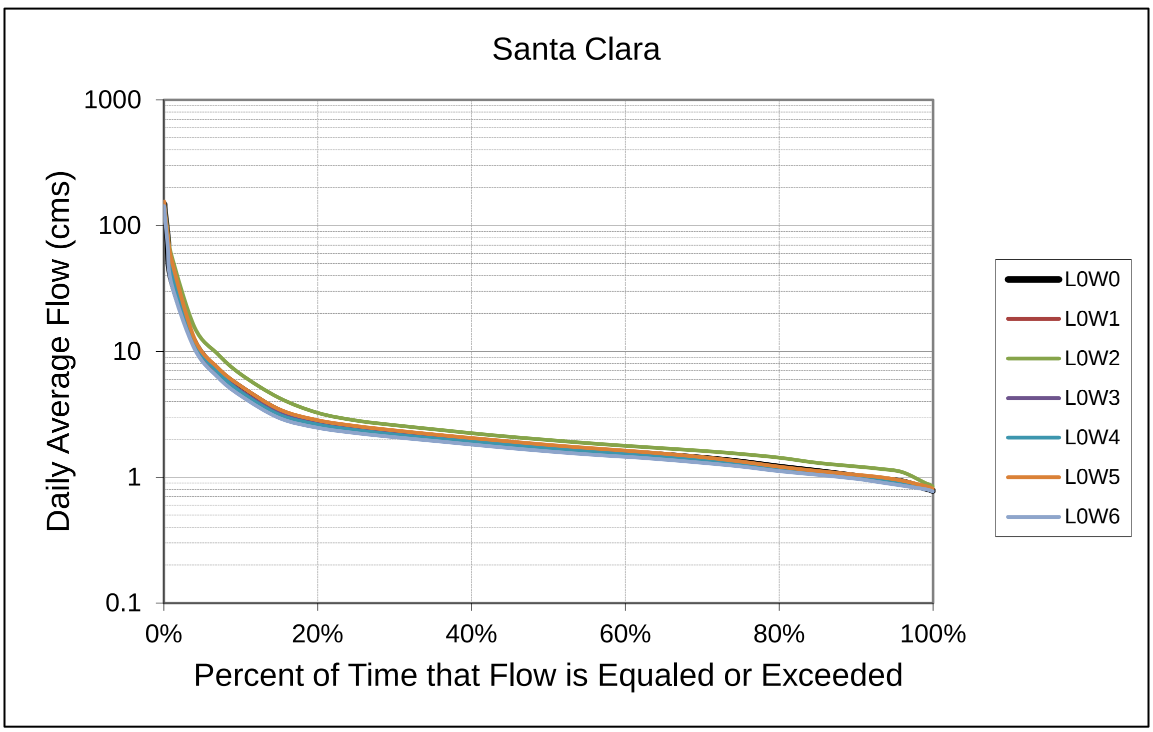


Figure 12. Flow duration, Santa Clara River (SWAT)

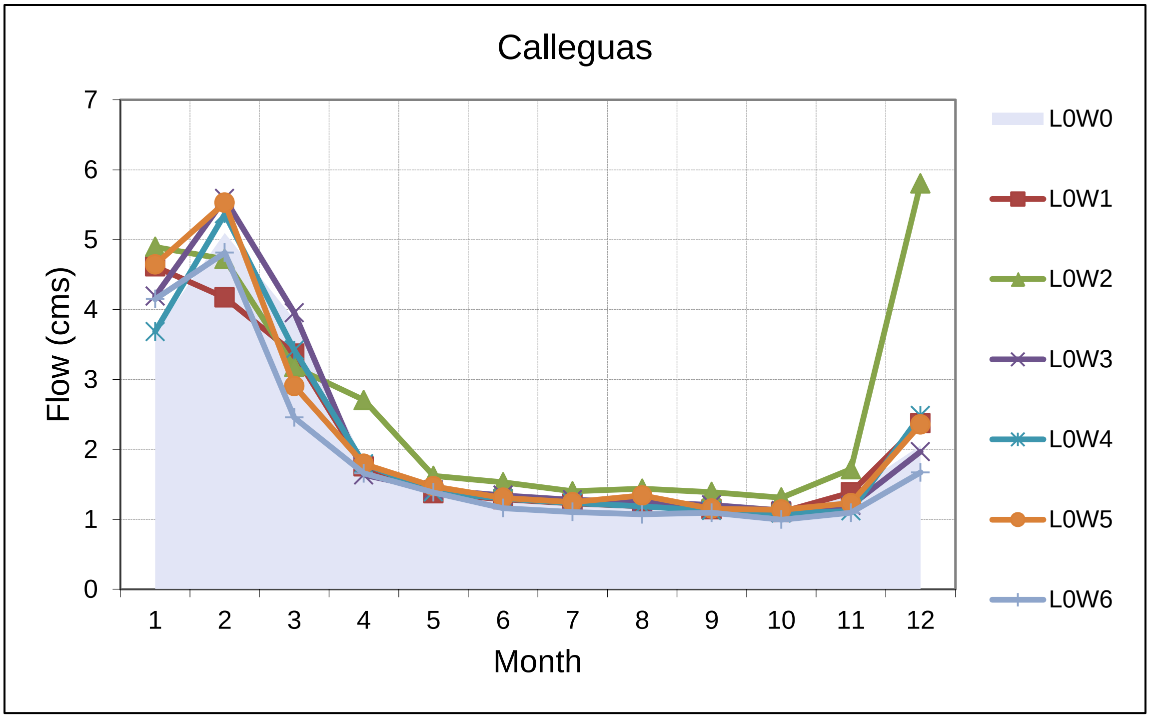


Figure 13. **Monthly average flows, Calleguas River (SWAT)**

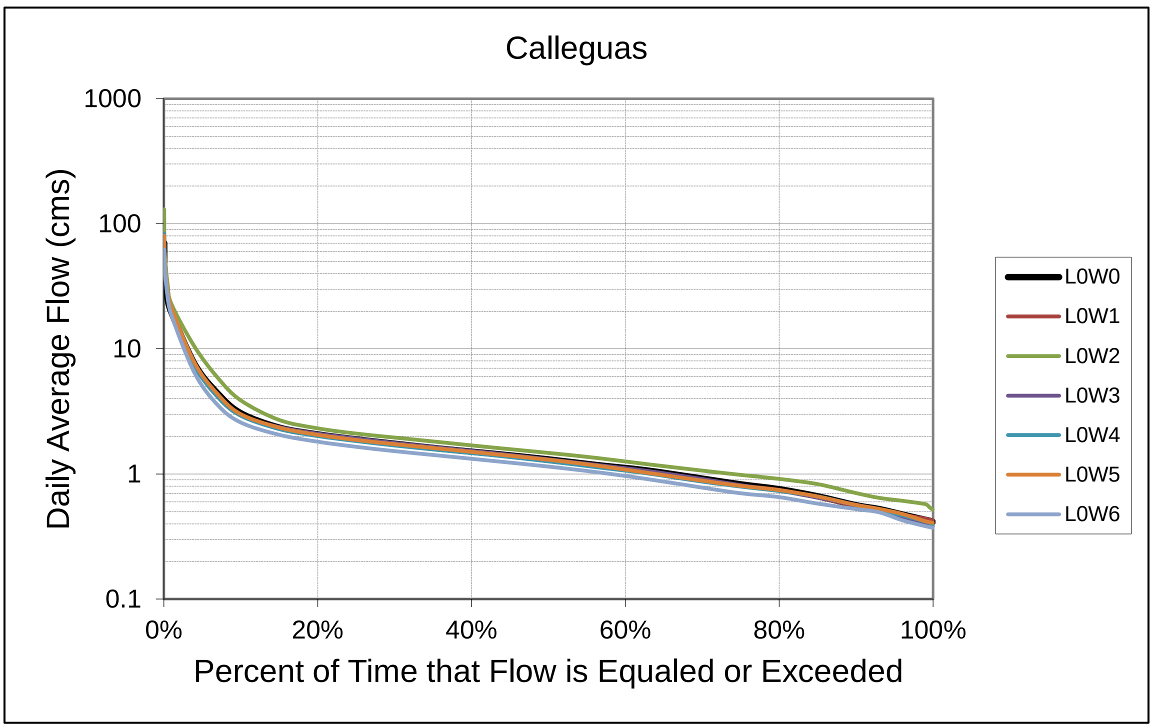


Figure 14. **Flow duration, Calleguas River (SWAT)**

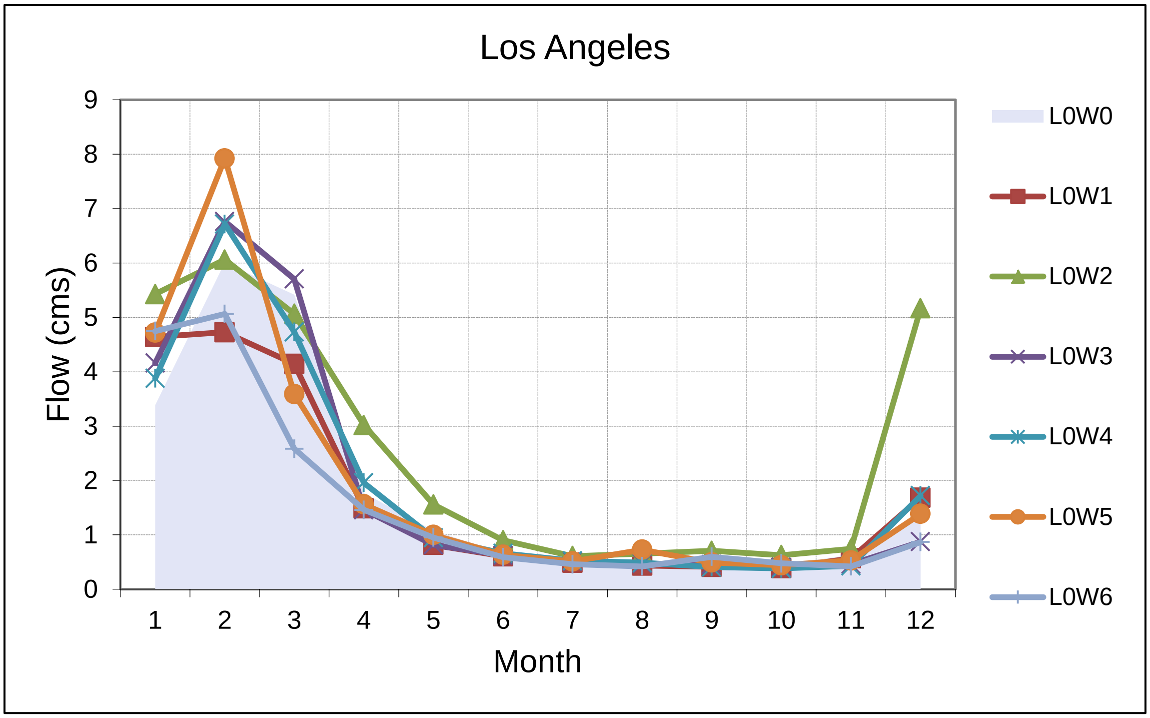


Figure 15. Monthly average flows, Los Angeles River (SWAT)

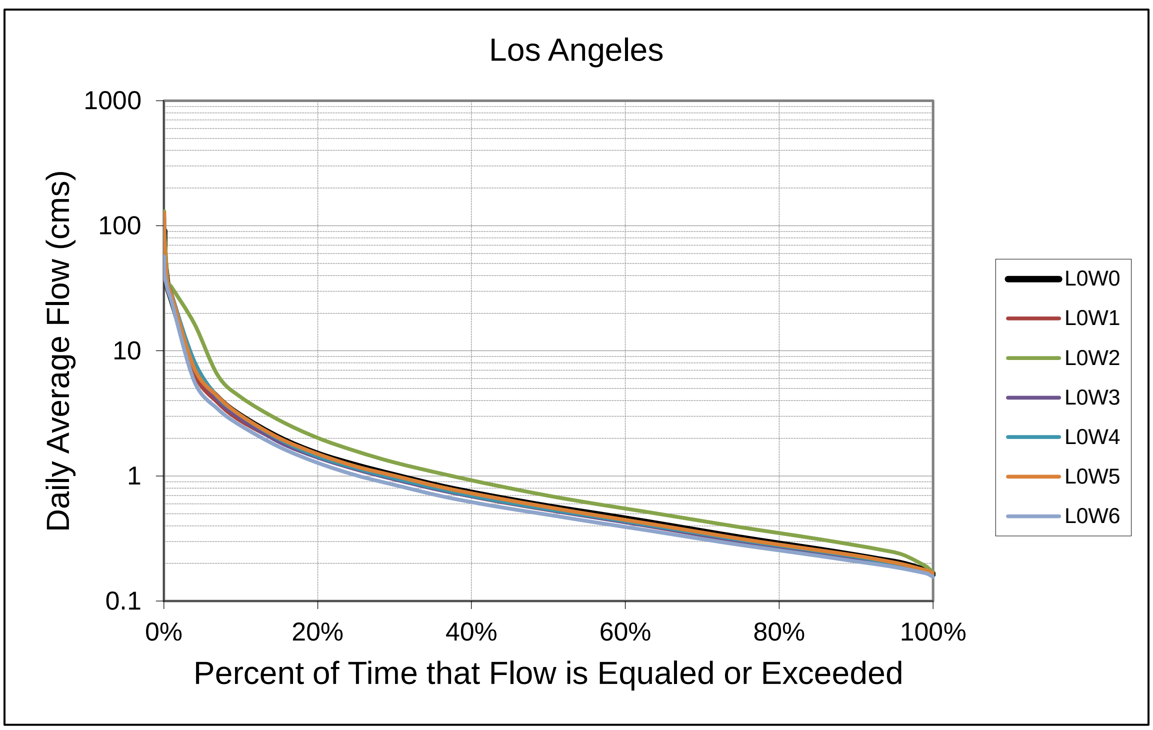


Figure 16. Flow duration, Los Angeles River (SWAT)

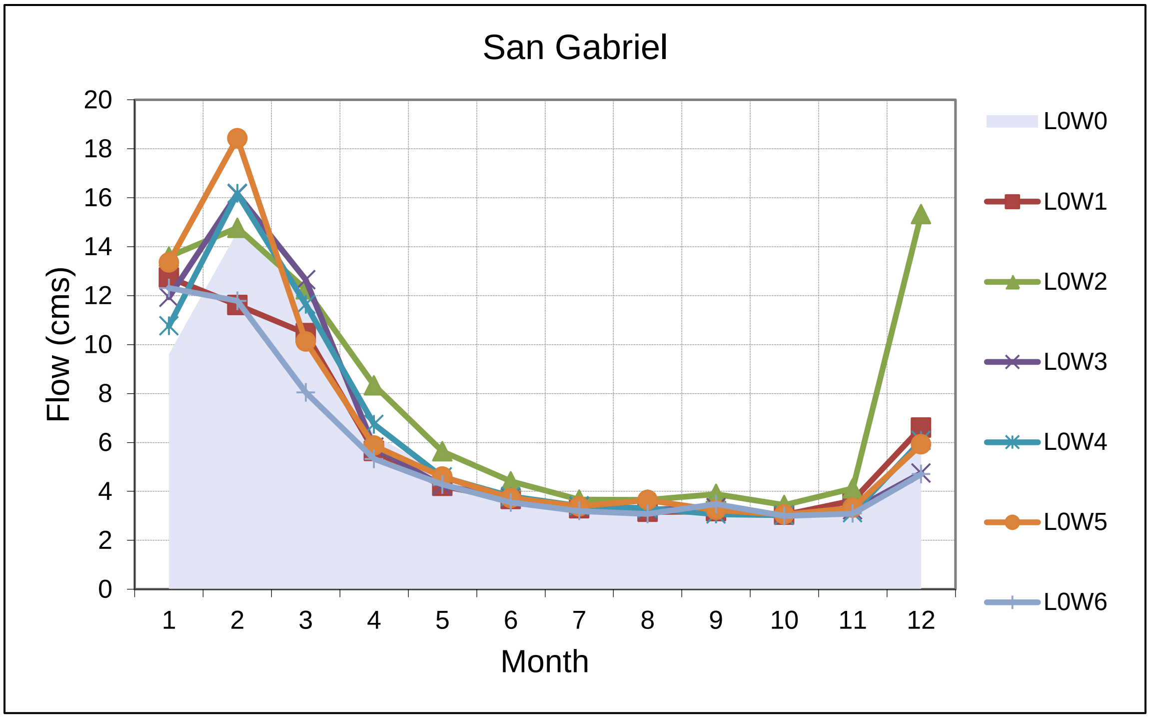


Figure 17. **Monthly average flows, San Gabriel River (SWAT)**

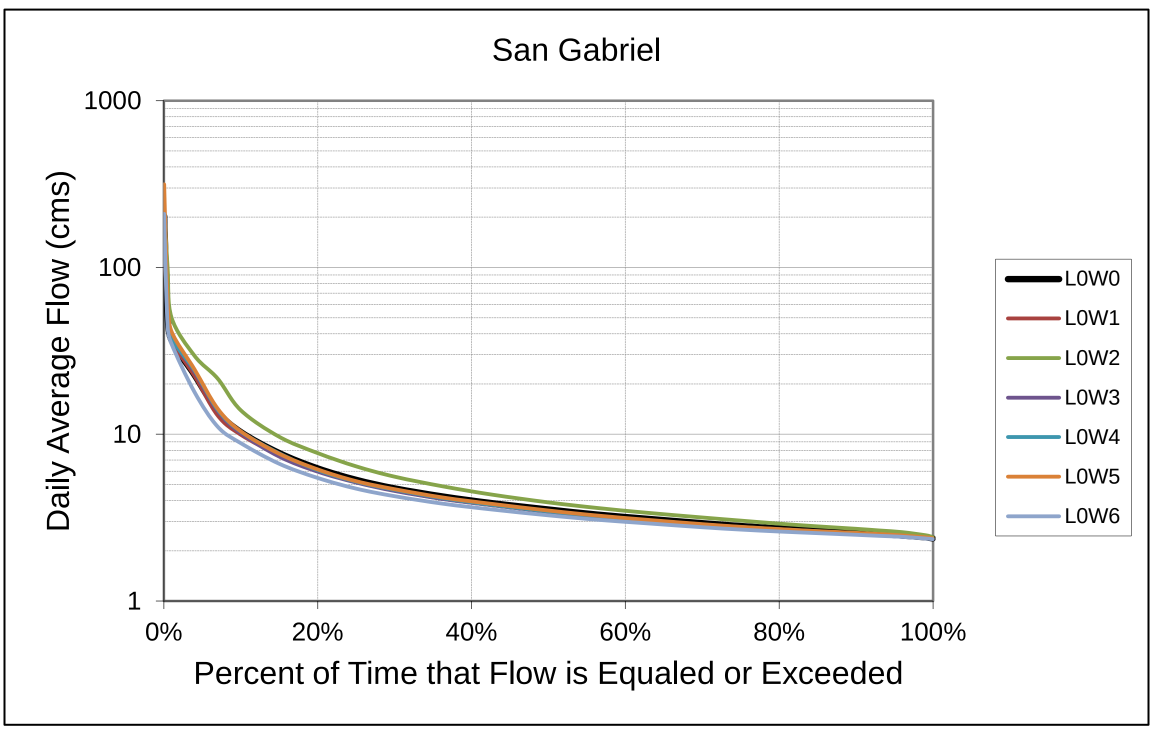


Figure 18. **Flow duration, San Gabriel River (SWAT)**

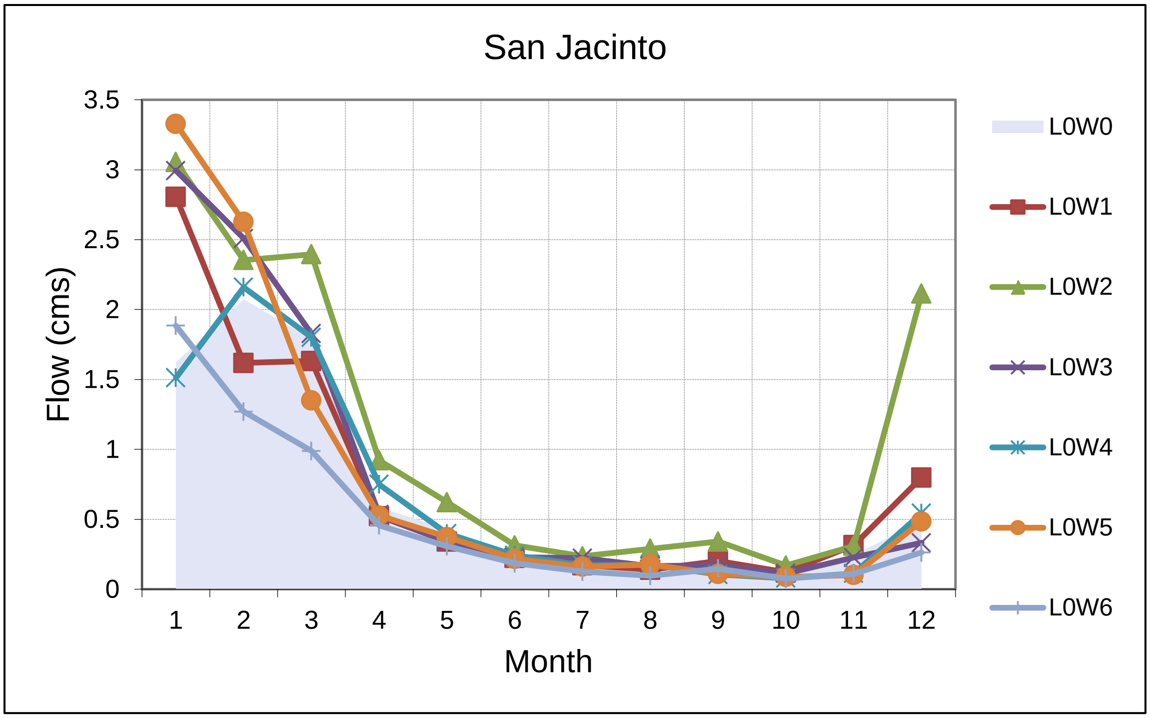


Figure 19. Monthly average flows, San Jacinto River (SWAT)

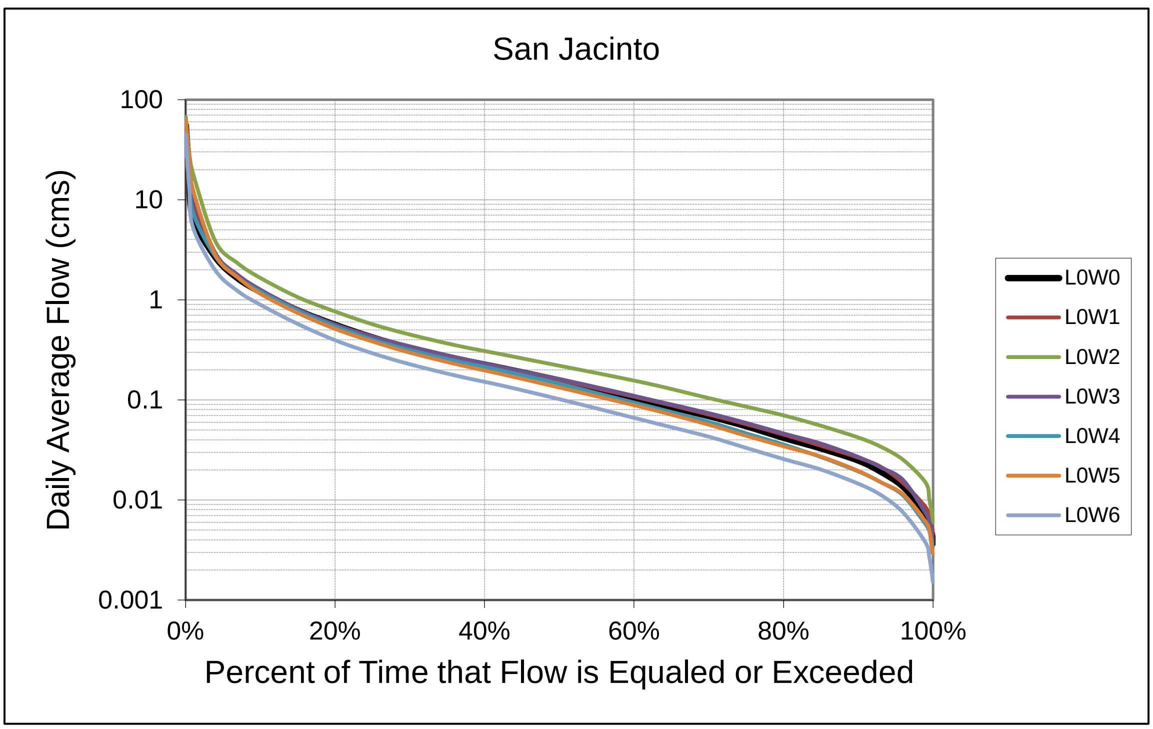


Figure 20. Flow duration, San Jacinto River (SWAT)

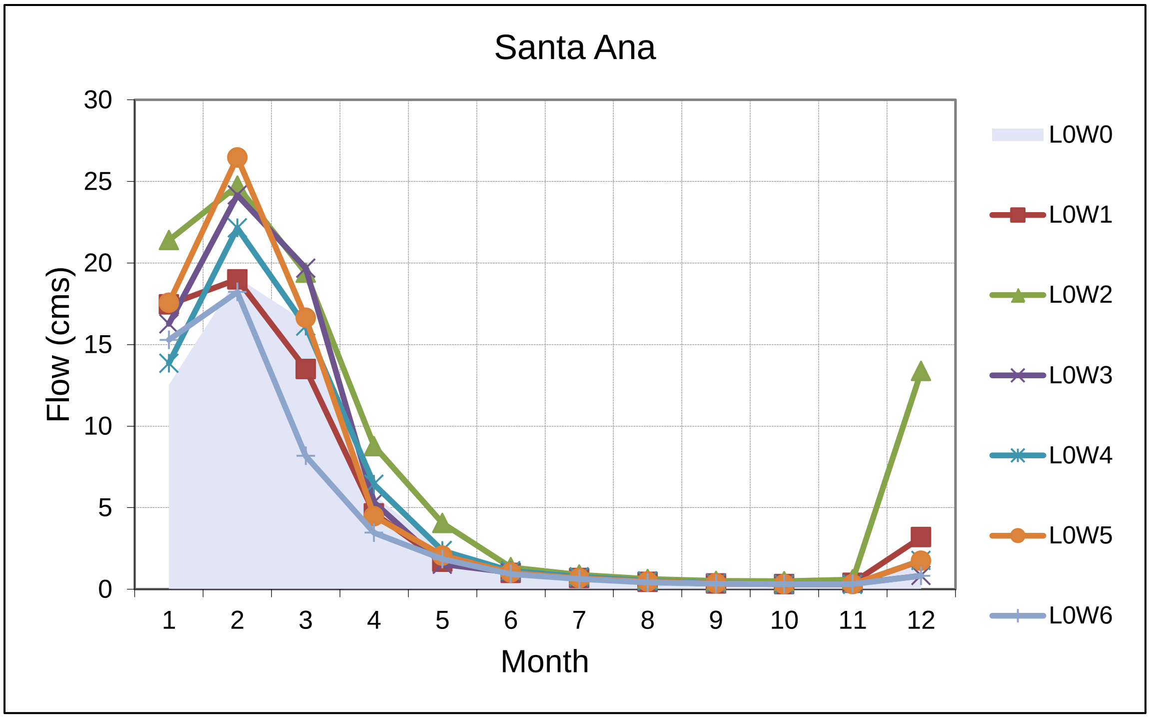


Figure 21. Monthly average flows, Santa Ana River (SWAT)

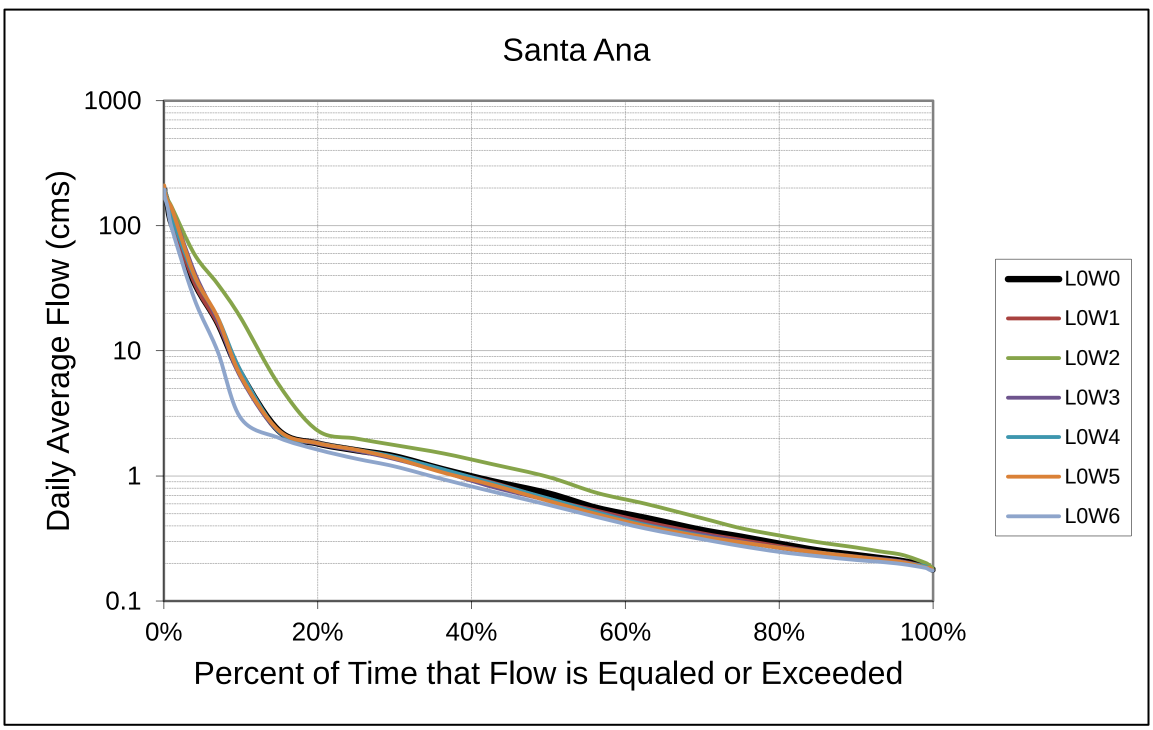


Figure 22. Flow duration, Santa Ana River (SWAT)

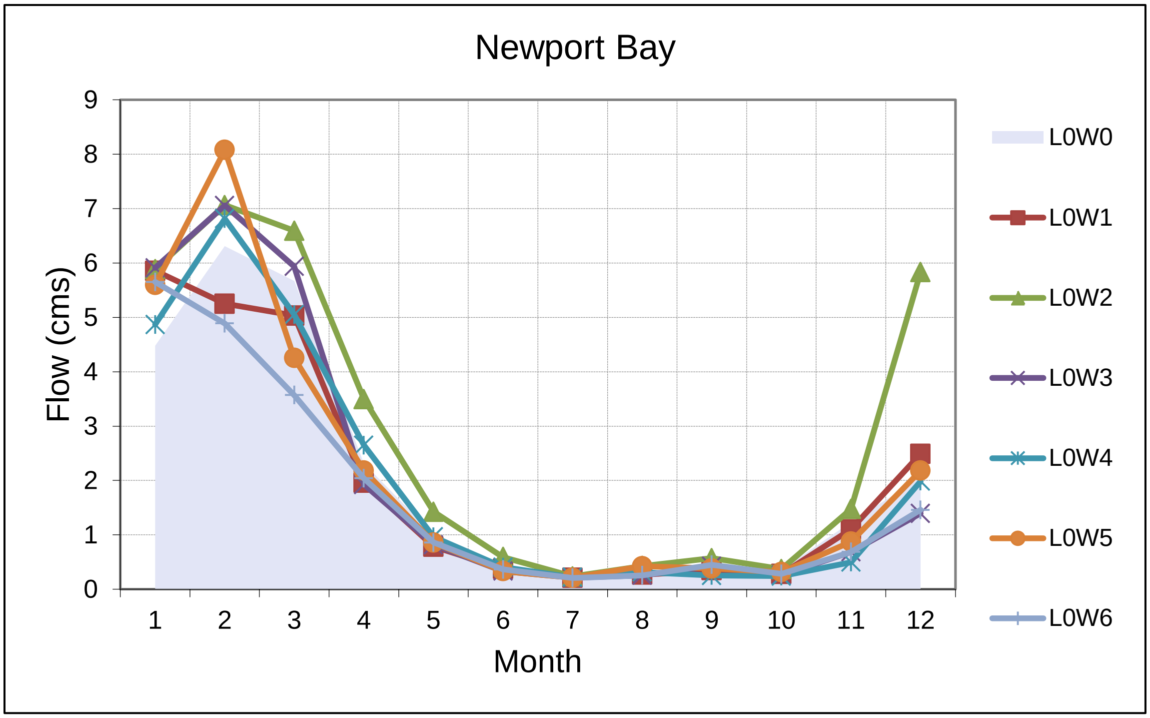


Figure 23. Monthly average flows, Newport Bay HUC8 (SWAT)

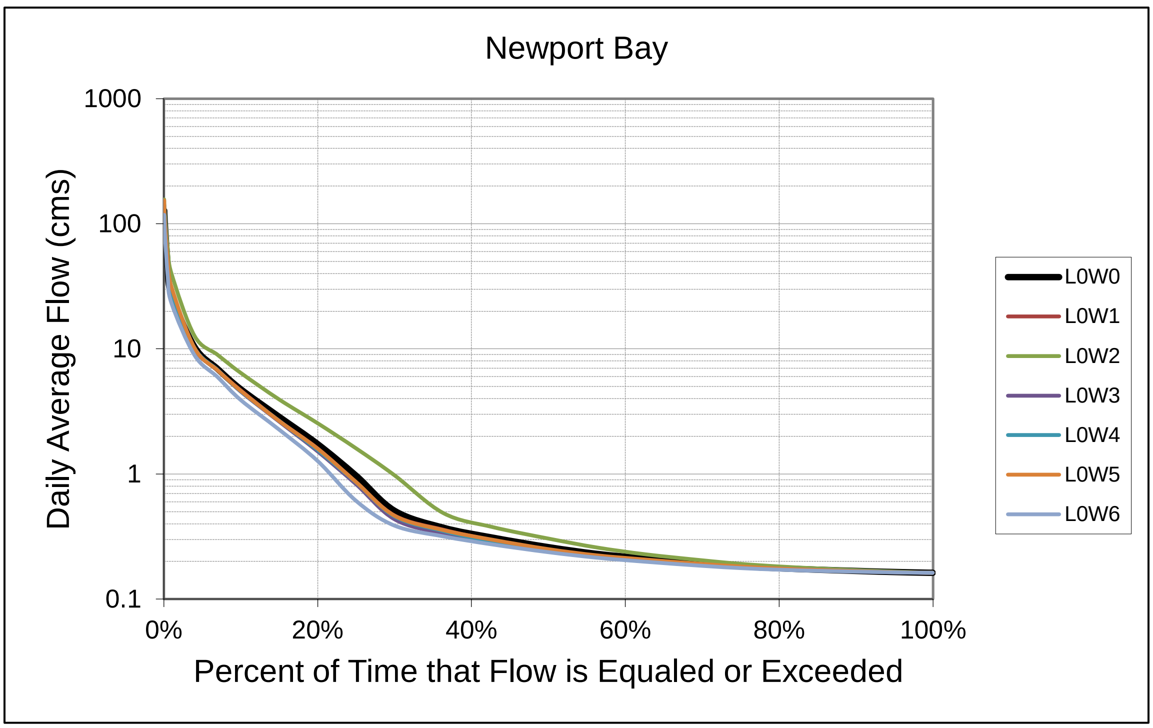


Figure 24. Flow duration, Newport Bay HUC8 (SWAT)

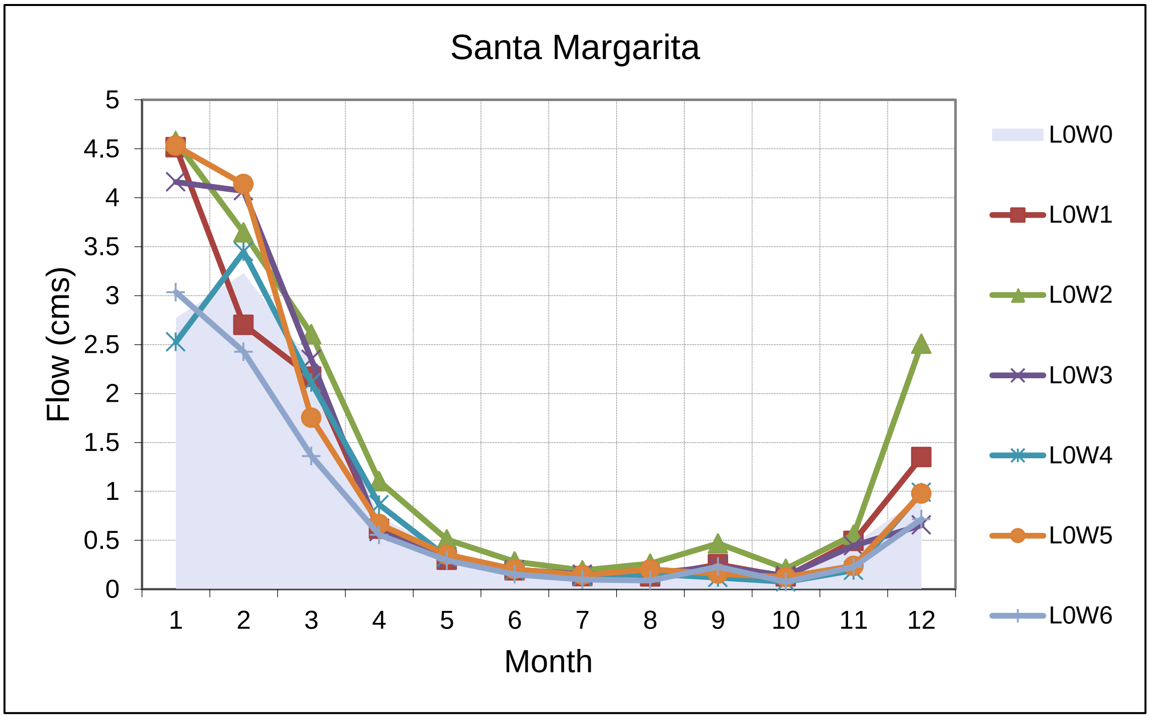


Figure 25. Monthly average flows, Santa Margarita River (SWAT)

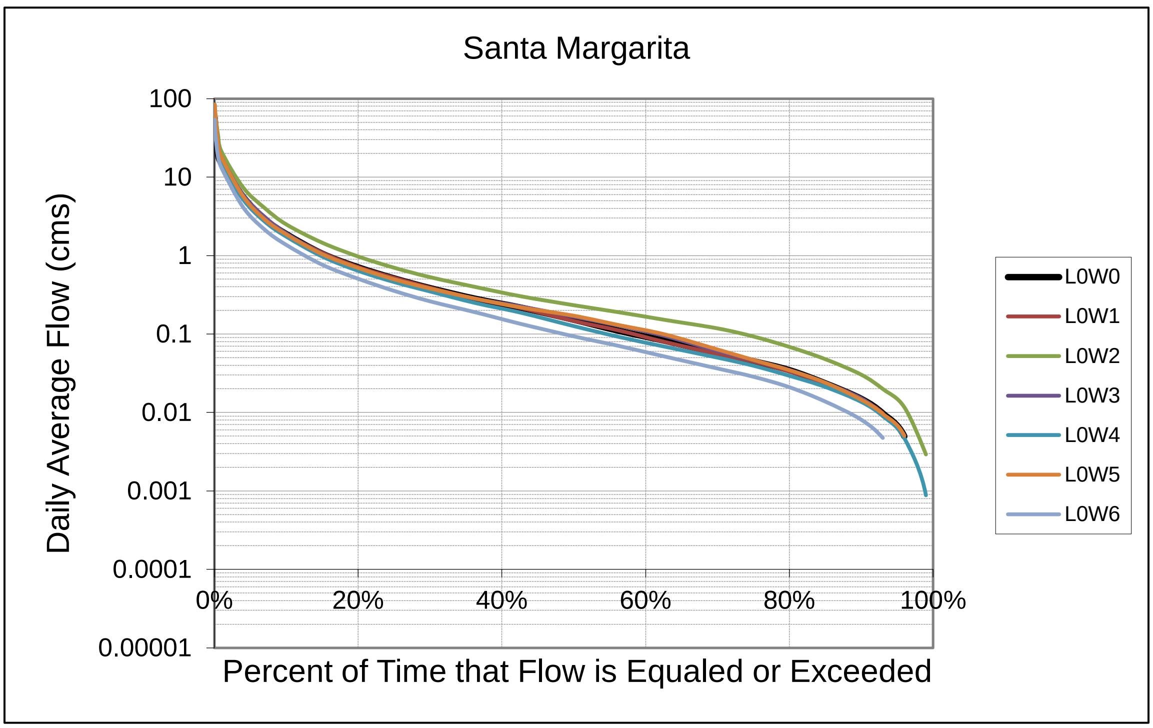


Figure 26. Flow duration, Santa Margarita River (SWAT)

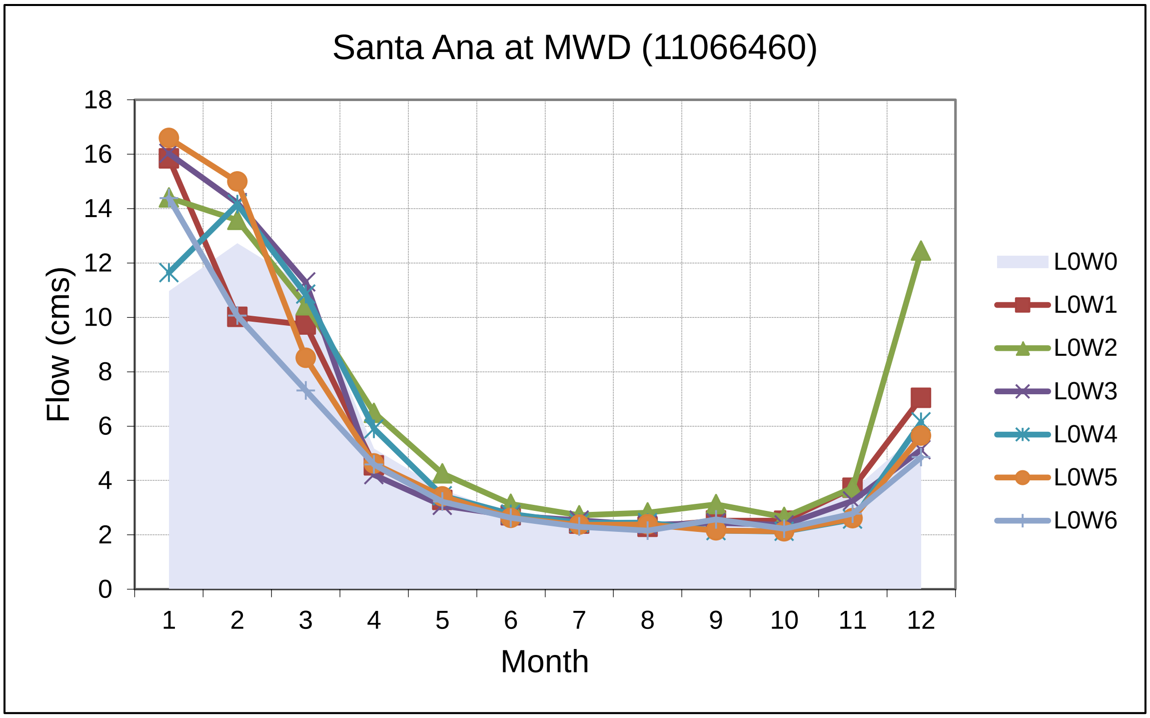


Figure 27. Monthly average flows, Santa Ana River at MWD (SWAT)

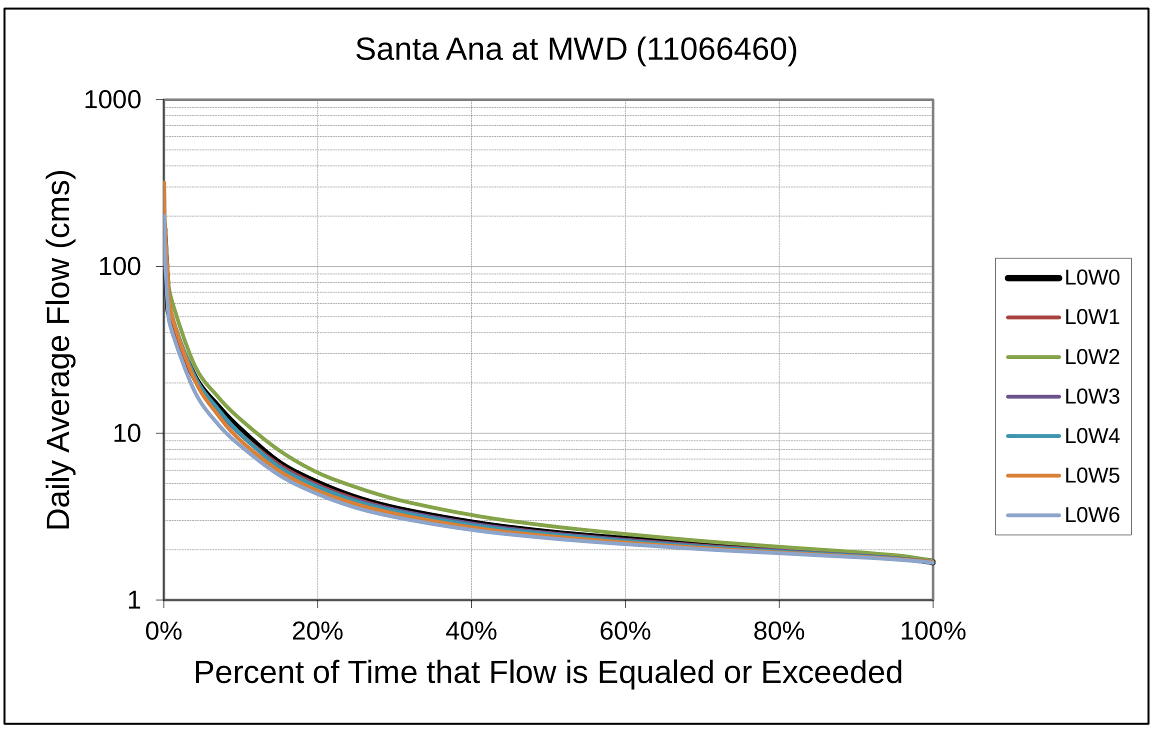


Figure 28. Flow duration, Santa Ana River at MWD (SWAT)

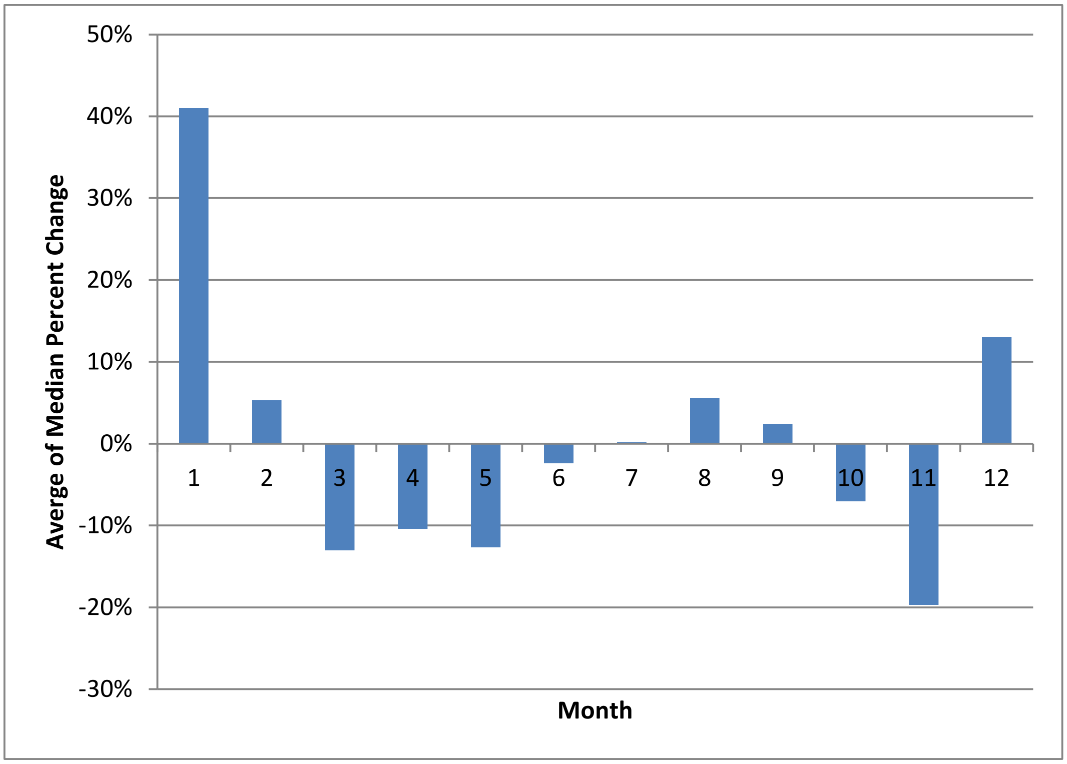


Figure 29. Average of median percent change in flow; NARCCAP Scenarios W1-W6 at all stations, Southern California Coastal basins (SWAT)

Cook Inlet Basin

Note: Coverage for the Cook Inlet basin is provided by only three of the six NARCCAP downscaled scenario outputs. In addition, the ICLUS land use change analysis does not cover Alaska.

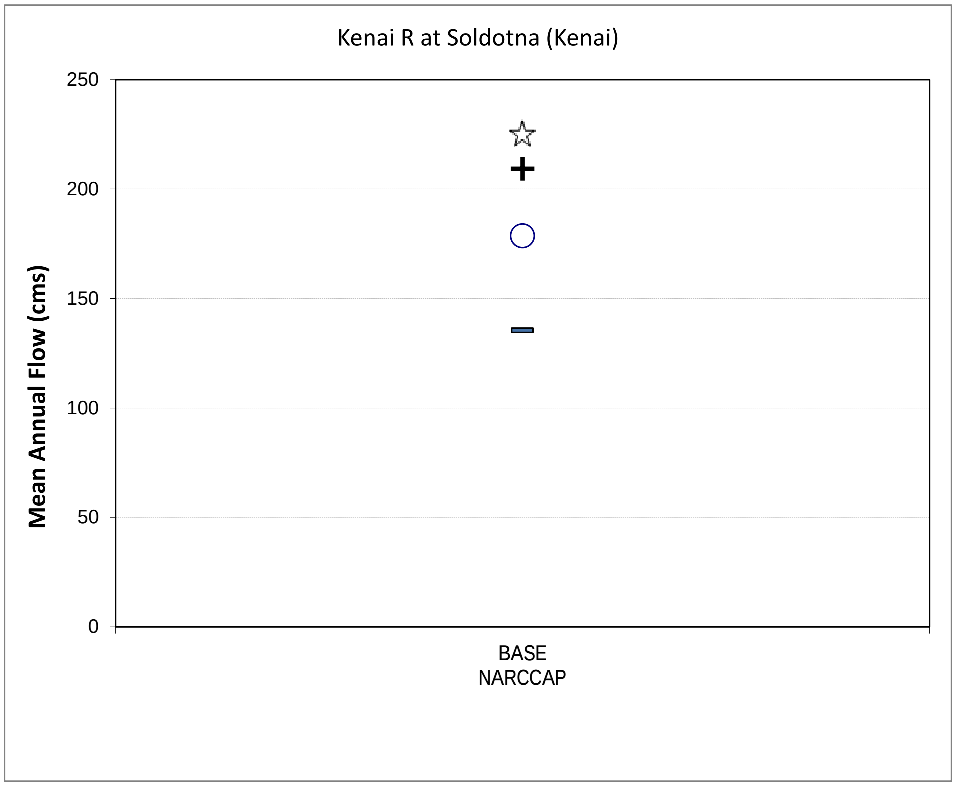


Figure 30. Mean annual flow (cms), Kenai River at Soldotna (SWAT)

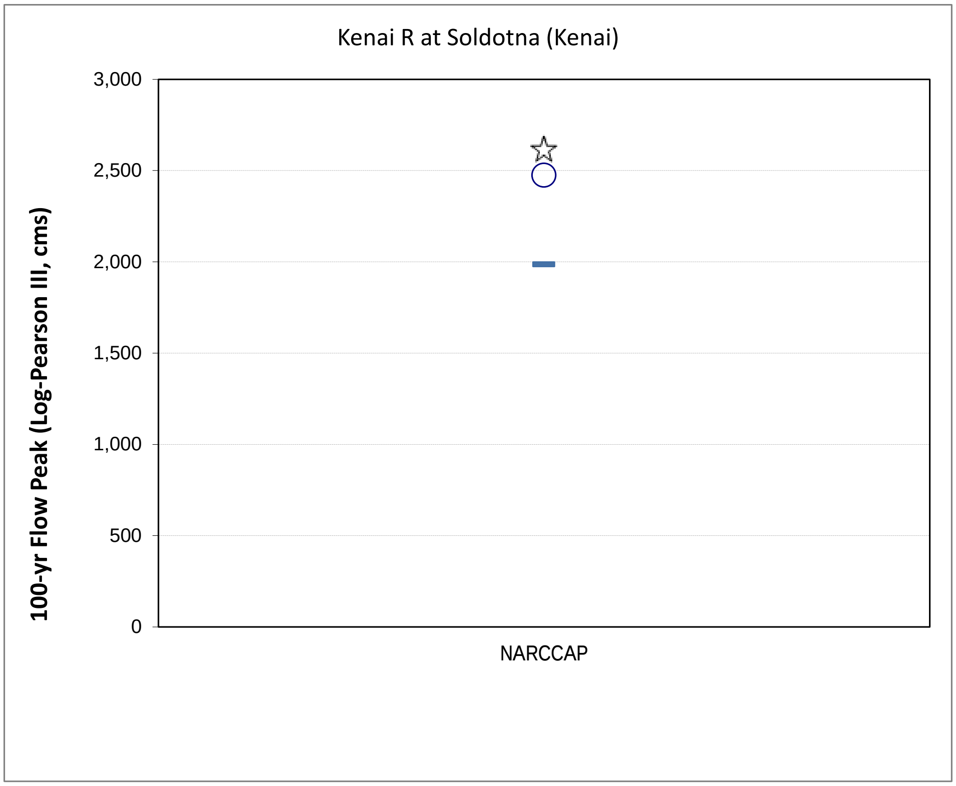


Figure 31. **100-yr Flow Peak (Log-Pearson III, cms), Kenai River at Soldotna (SWAT)**

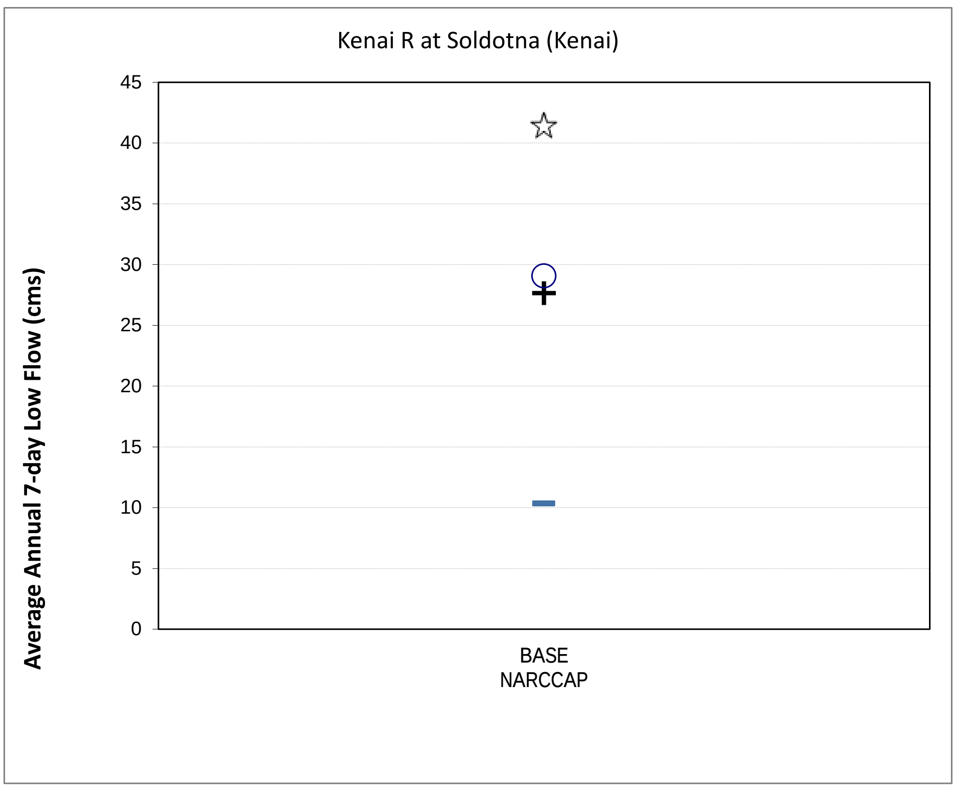


Figure 30. **Average Annual 7-day Low Flow (cms), Kenai River at Soldotna (SWAT)**

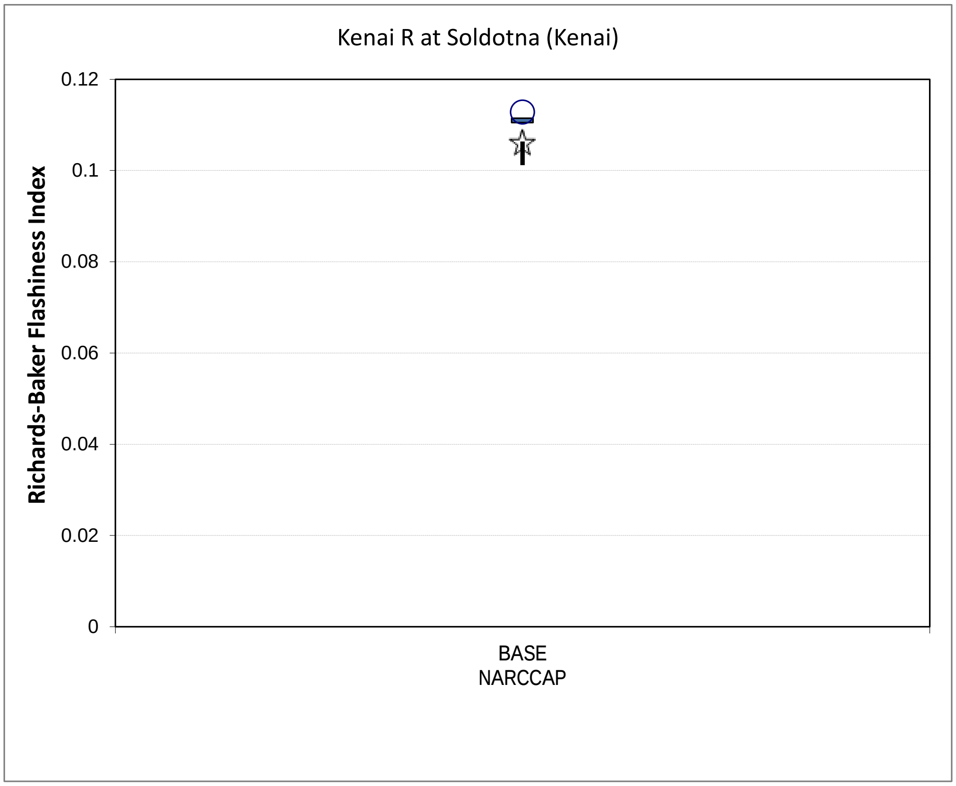


Figure 31. **Richards-Baker Flashiness Index, Average Annual 7-day Low Flow (cms), Kenai River at Soldotna (SWAT)**

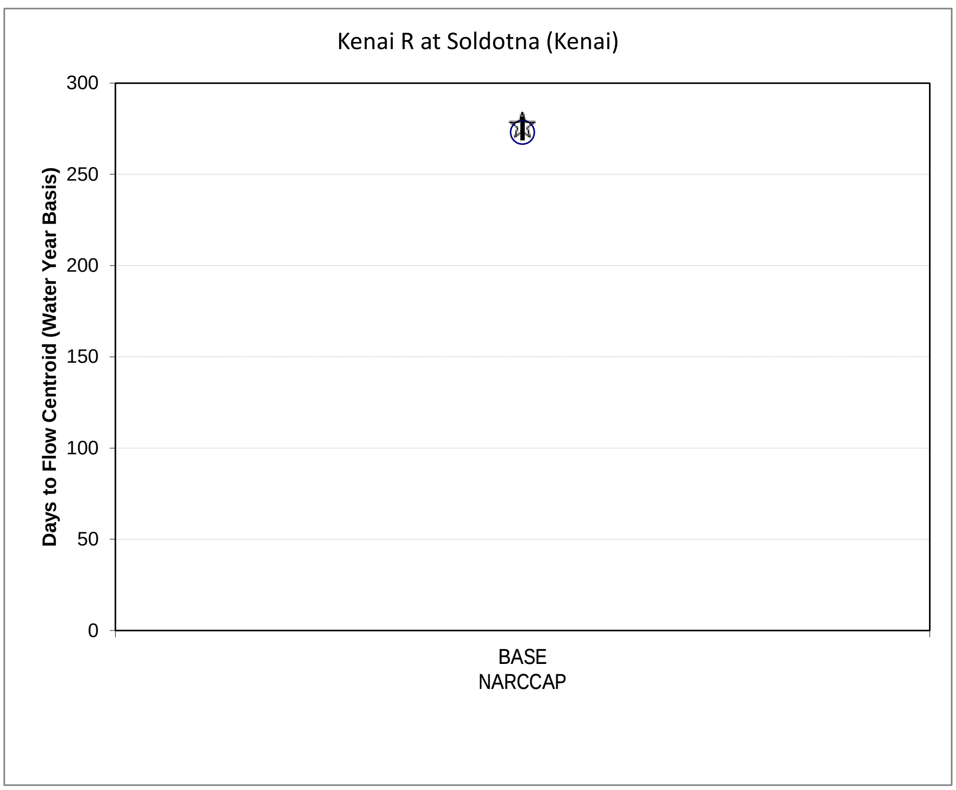


Figure 32. **Days to Flow Centroid (Water Year Basis), Kenai River at Soldotna (SWAT)**

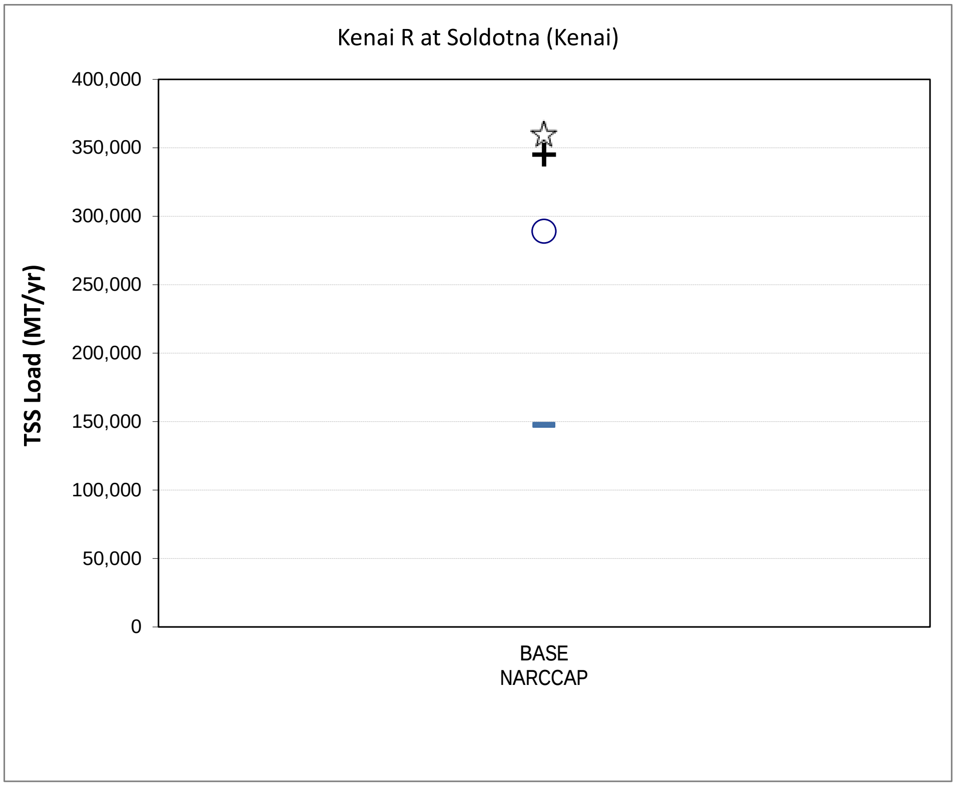


Figure 33. **TSS Load (MT/yr), Kenai River at Soldotna (SWAT)**

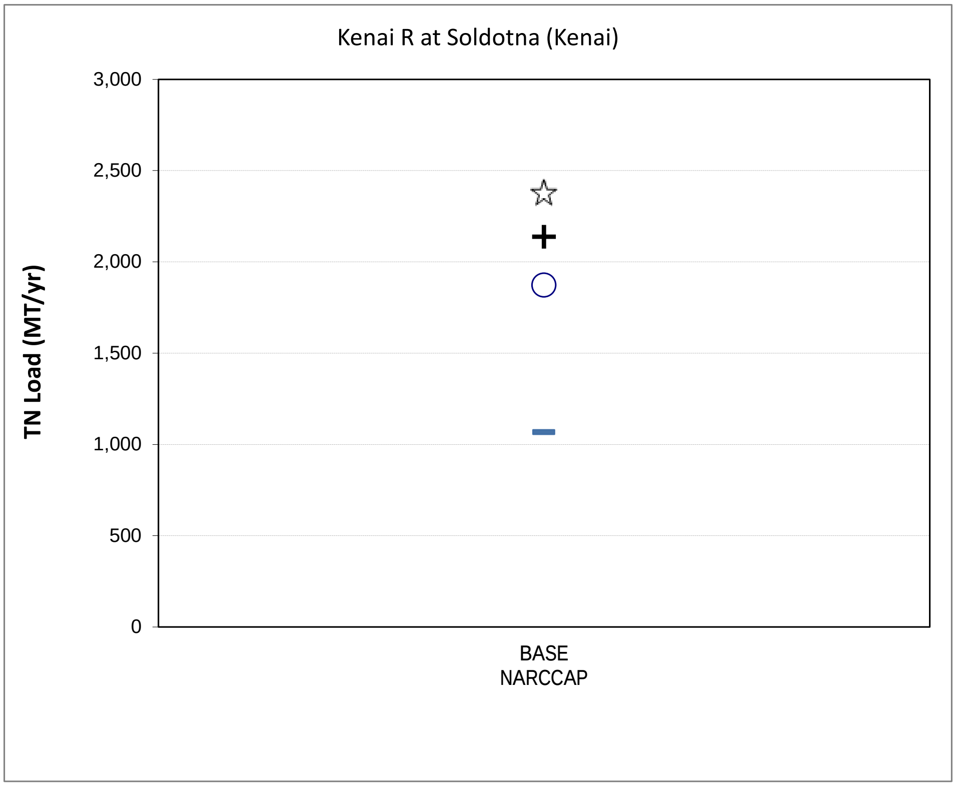


Figure 34. **TN Load (MT/yr), Kenai River at Soldotna (SWAT)**

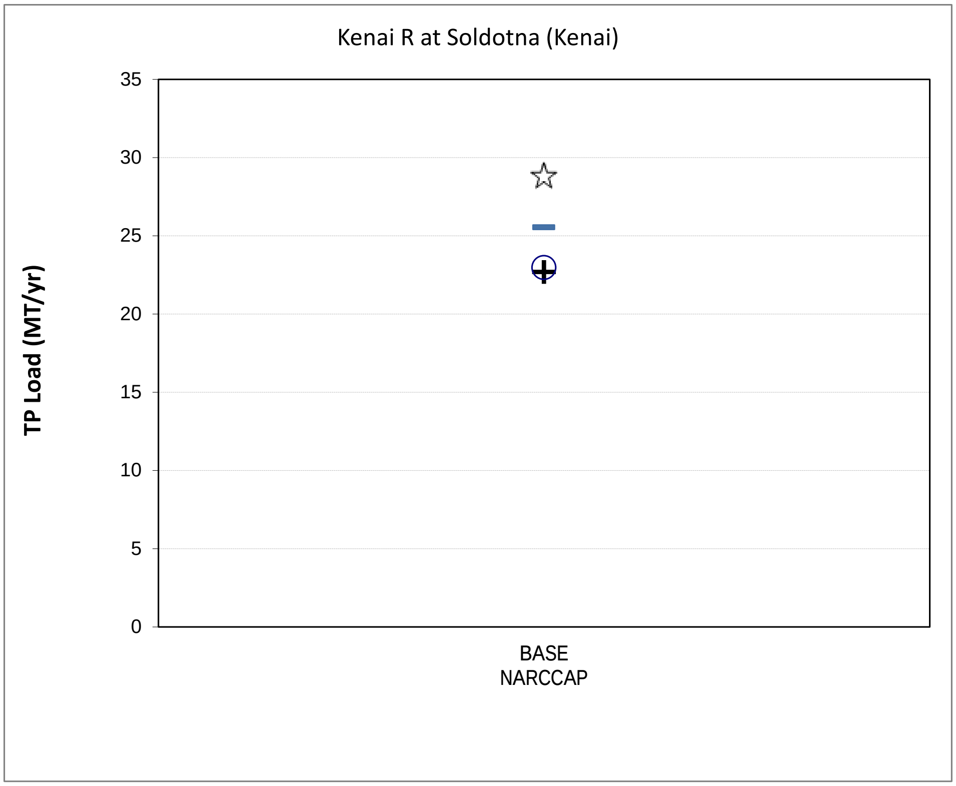


Figure 35. **TP Load (MT/yr), Kenai River at Soldotna (SWAT)**

Table 2. Summary of range of change relative to existing conditions for NARCCAP dynamically downscaled scenarios, Cook Inlet basin SWAT model

	Results without LU change			
	Min	Median	Mean	Max
Kenai R at Soldotna (Kenai)				
Flow	31.74%	54.35%	50.89%	66.56%
TSS	95.66%	133.64%	124.56%	144.37%
TN	75.39%	100.25%	99.69%	123.44%
TP	-11.23%	-10.13%	-2.72%	13.18%
Talkeetna R. near Talkeetna				
Flow	19.47%	27.66%	26.18%	31.42%
TSS	79.65%	97.68%	94.21%	105.28%
TN	11.74%	17.74%	17.20%	22.13%
TP	-13.52%	-8.28%	-9.72%	-7.37%
Upper Susitna HUC 19020501				
Flow	9.12%	26.59%	23.33%	34.27%
TSS	60.09%	97.28%	91.60%	117.41%
TN	1.83%	7.02%	10.31%	22.07%
TP	-21.37%	-11.77%	-14.06%	-9.04%
Matanuska HUC 19020402				
Flow	10.16%	19.90%	16.81%	20.35%
TSS	70.16%	90.58%	84.52%	92.81%
TN	39.83%	49.58%	46.85%	51.12%
TP	-20.66%	-9.76%	-12.96%	-8.47%
Lower Susitna HUC 19020505				
Flow	12.06%	19.42%	18.59%	24.29%
TSS	75.34%	94.99%	91.77%	104.99%
TN	15.63%	17.88%	19.96%	26.36%
TP	-22.65%	-14.35%	-16.84%	-13.52%
Chulitna HUC 19020502				
Flow	8.57%	14.12%	13.78%	18.65%
TSS	45.01%	57.93%	54.52%	60.63%
TN	23.36%	25.87%	27.33%	32.77%
TP	-19.45%	-12.57%	-14.57%	-11.69%
Talkeetna River Mouth HUC 19020503				
Flow	16.46%	23.87%	22.75%	27.92%
TSS	76.83%	92.96%	90.59%	101.99%
TN	12.13%	17.86%	17.60%	22.81%
TP	-14.71%	-9.99%	-11.39%	-9.46%

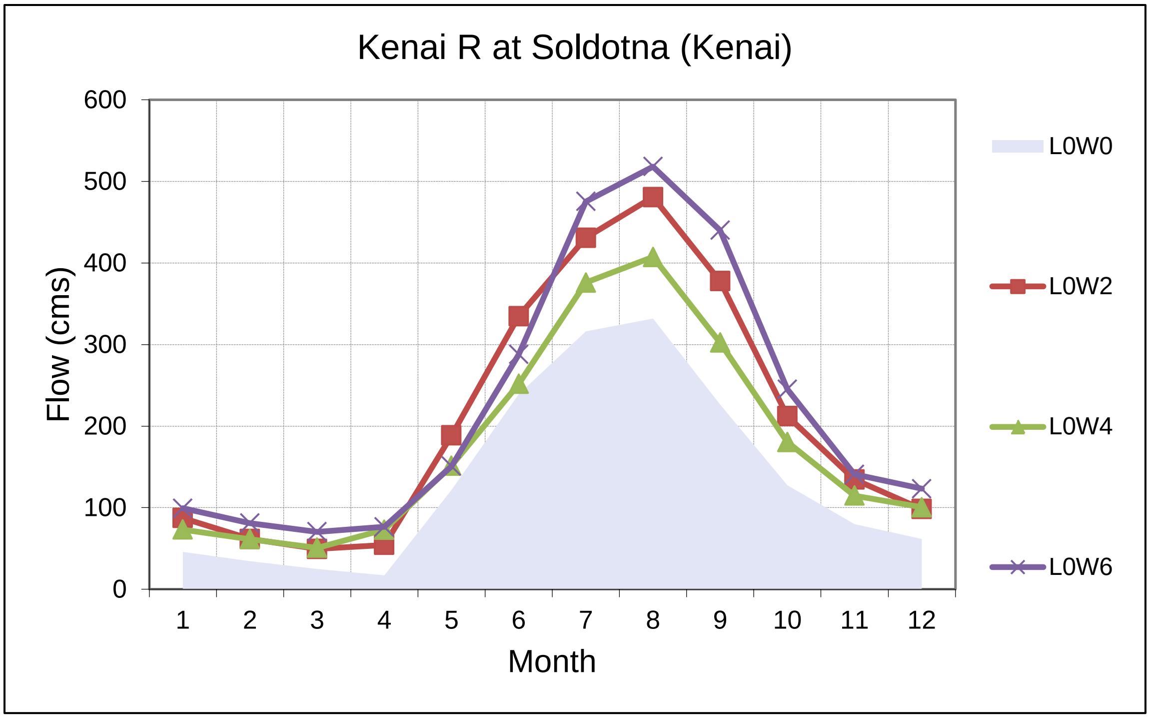


Figure 36. Monthly average flows, Kenai River at Soldotna (SWAT)

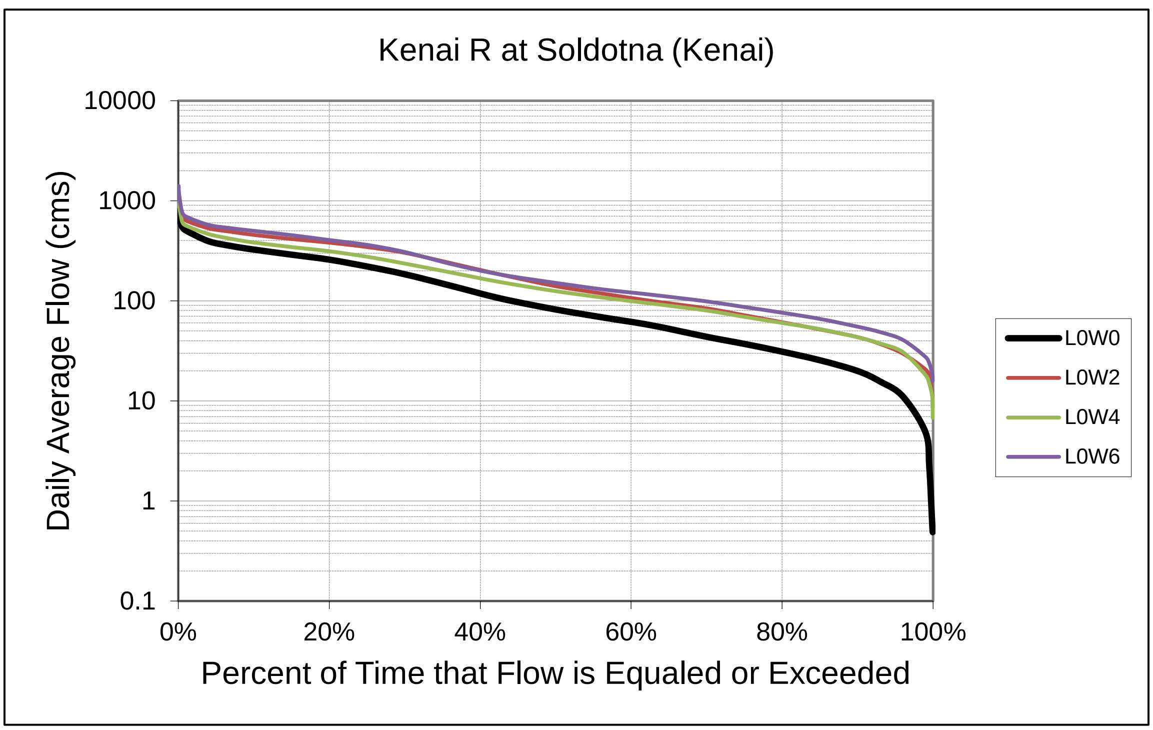


Figure 37. Flow duration, Kenai River at Soldotna (SWAT)

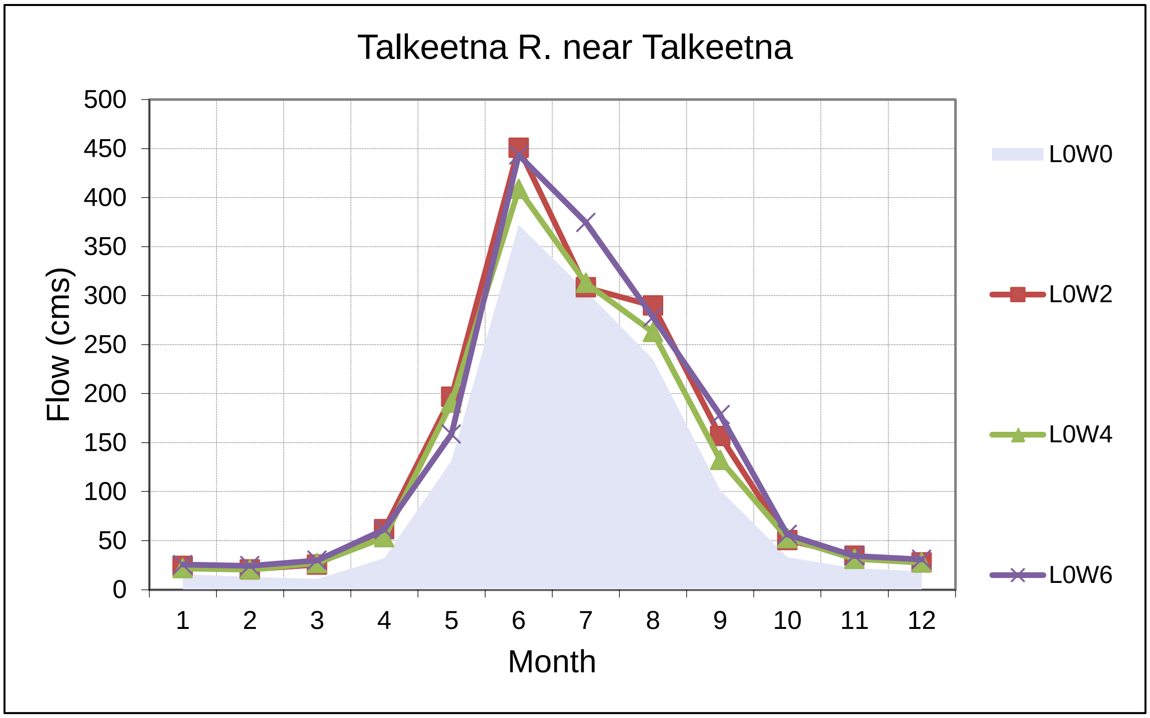


Figure 38. **Monthly average flows, Talkeetna River near Talkeetna (SWAT)**

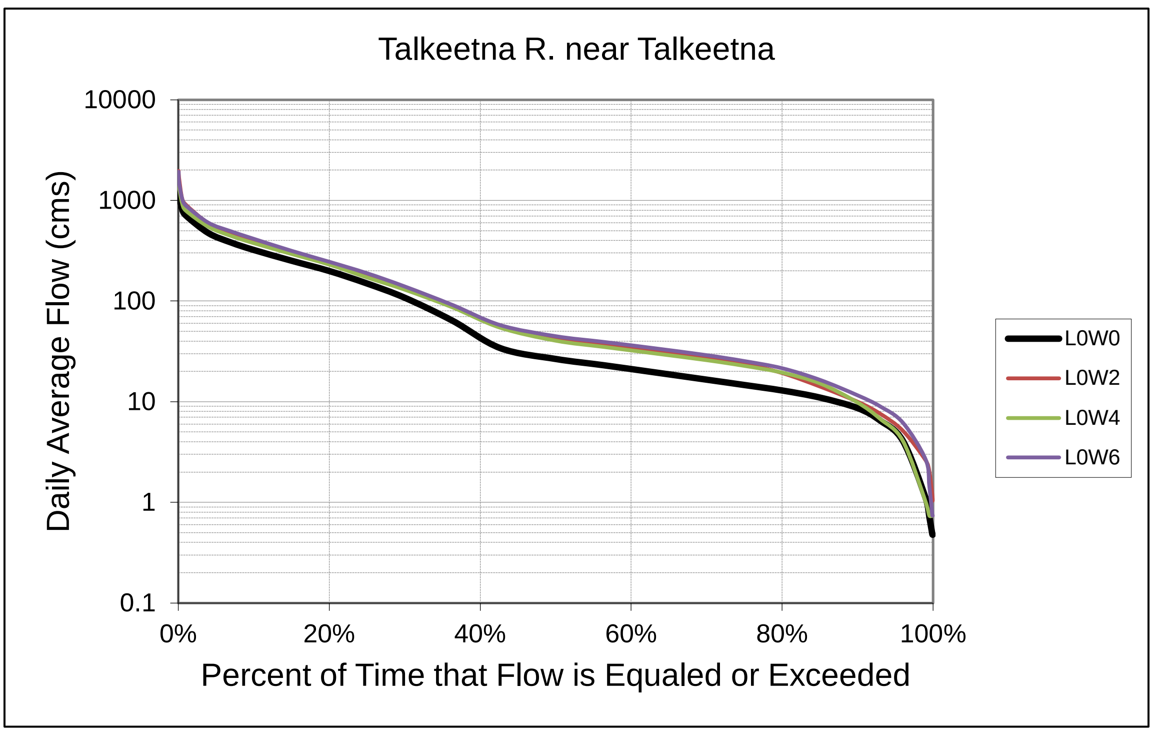


Figure 39. **Flow duration, Talkeetna River near Talkeetna (SWAT)**

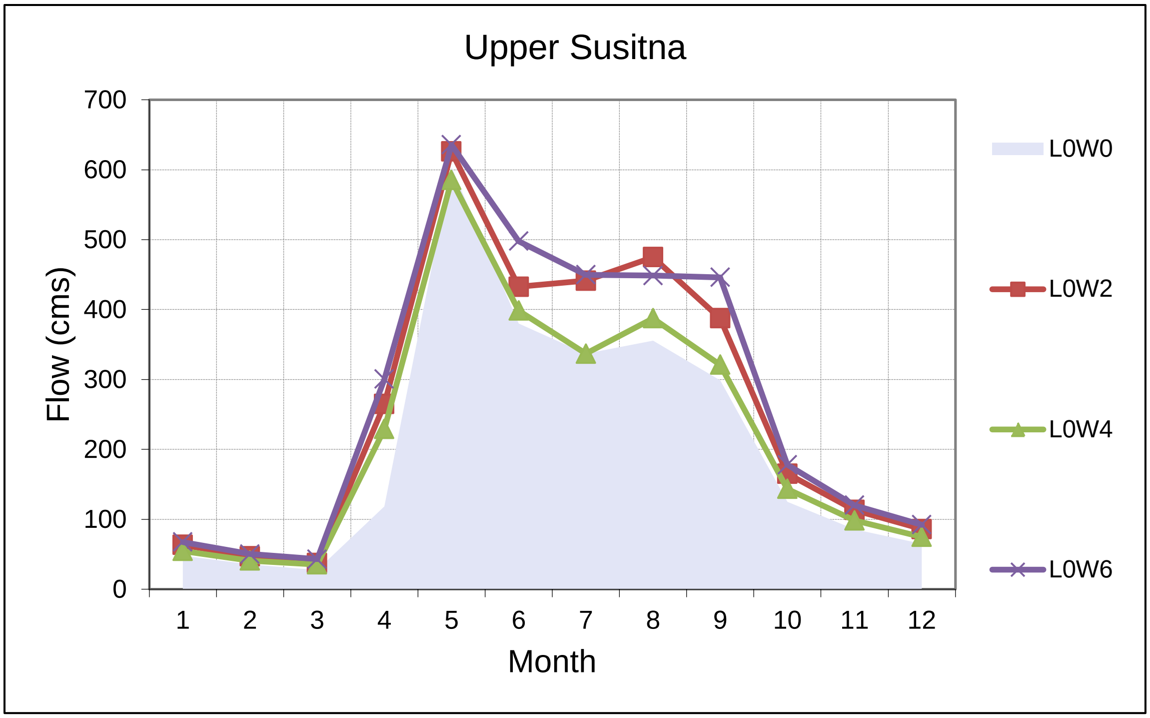


Figure 40. **Monthly average flows, Upper Susitna River (SWAT)**

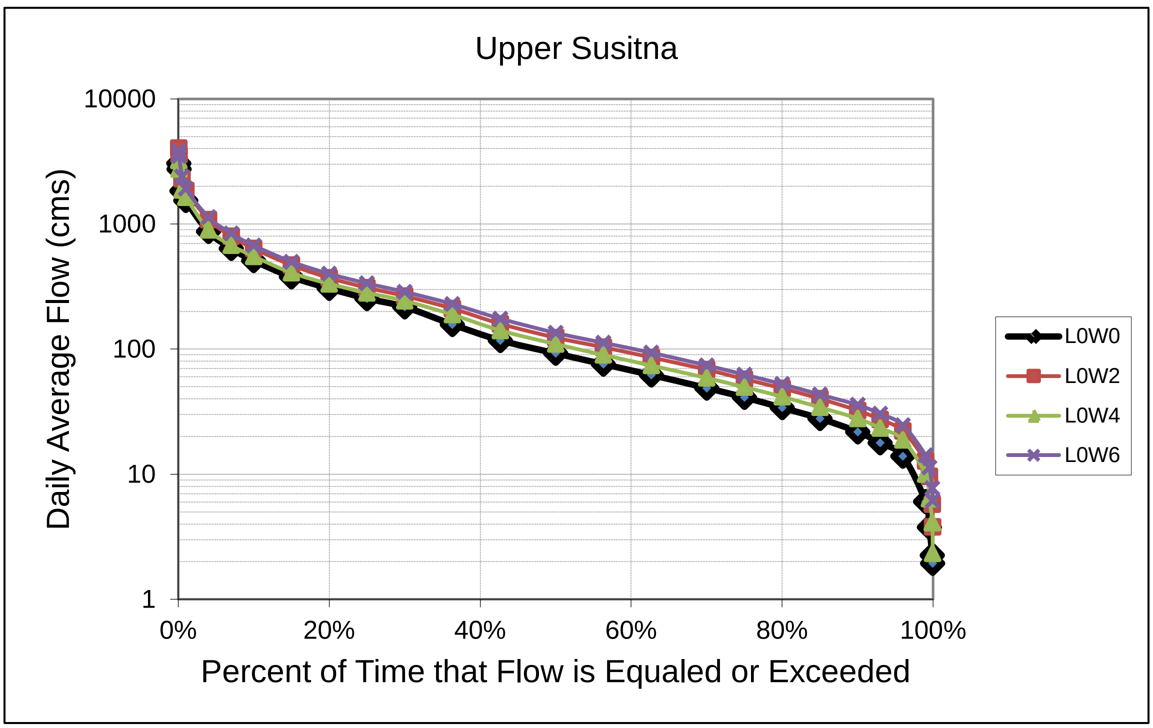


Figure 41. **Flow duration, Upper Susitna River (SWAT)**

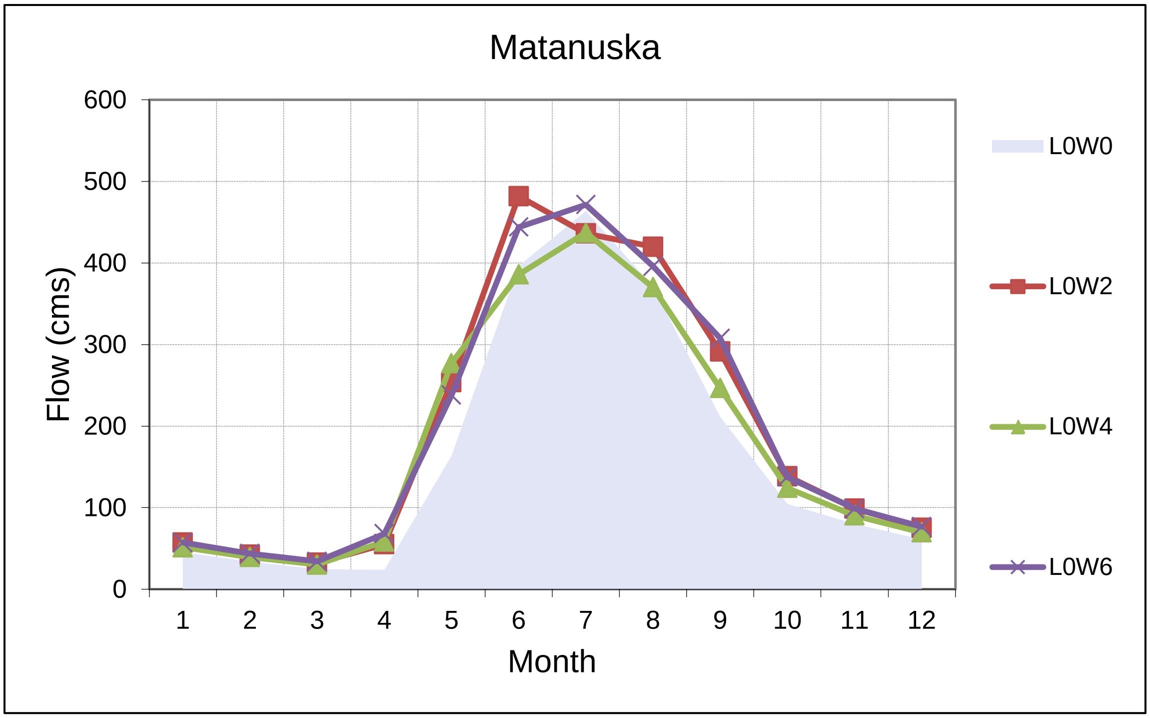


Figure 42. **Monthly average flows, Matanuska River (SWAT)**

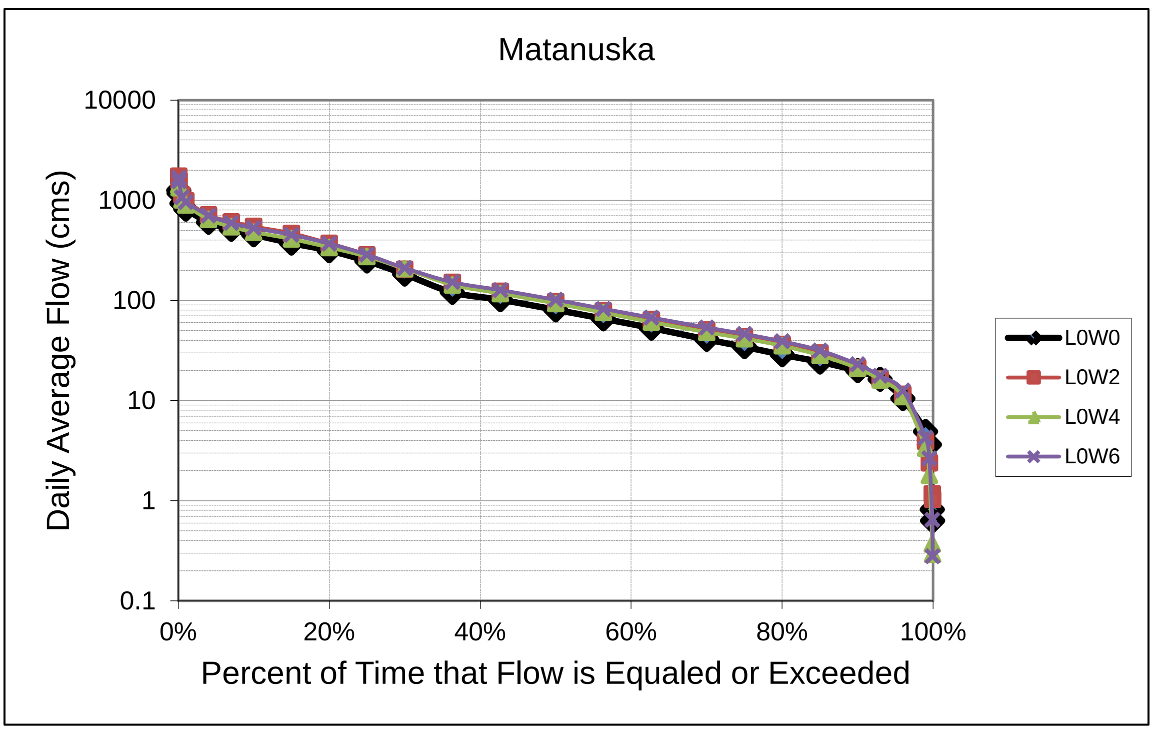


Figure 43. **Flow duration, Matanuska River (SWAT)**

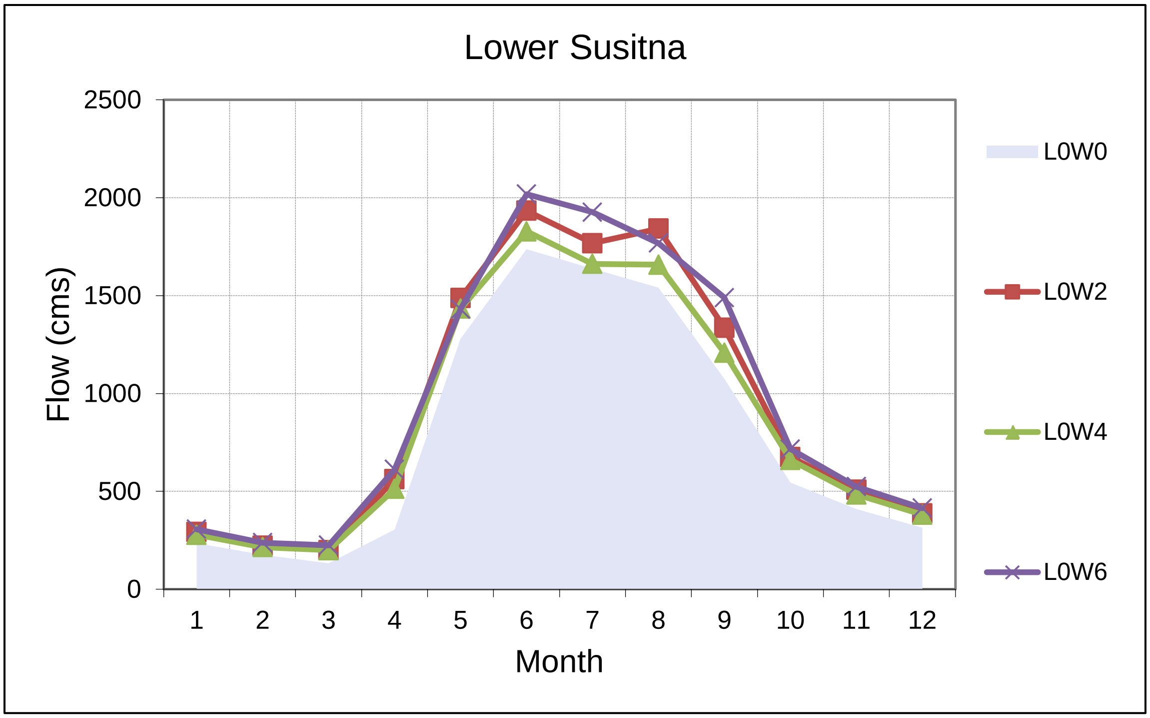


Figure 44. **Monthly average flows, Lower Susitna River (SWAT)**

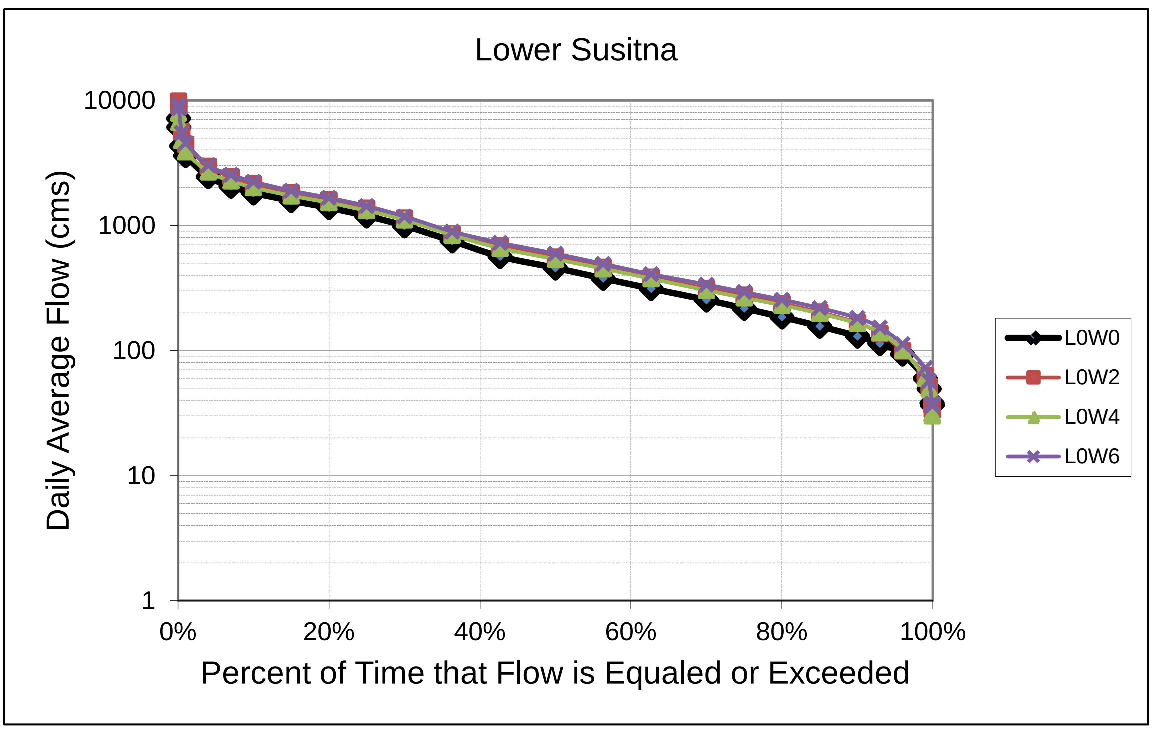


Figure 45. **Flow duration, Lower Susitna River (SWAT)**

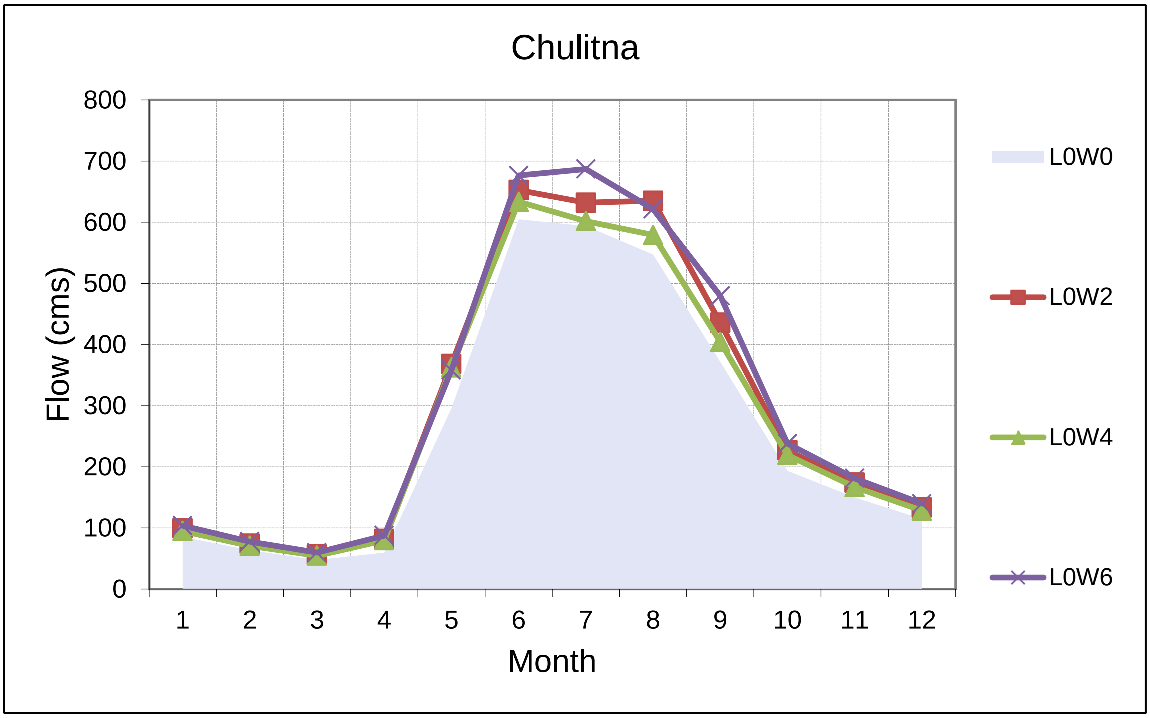


Figure 46. **Monthly average flows, Chulitna River (SWAT)**

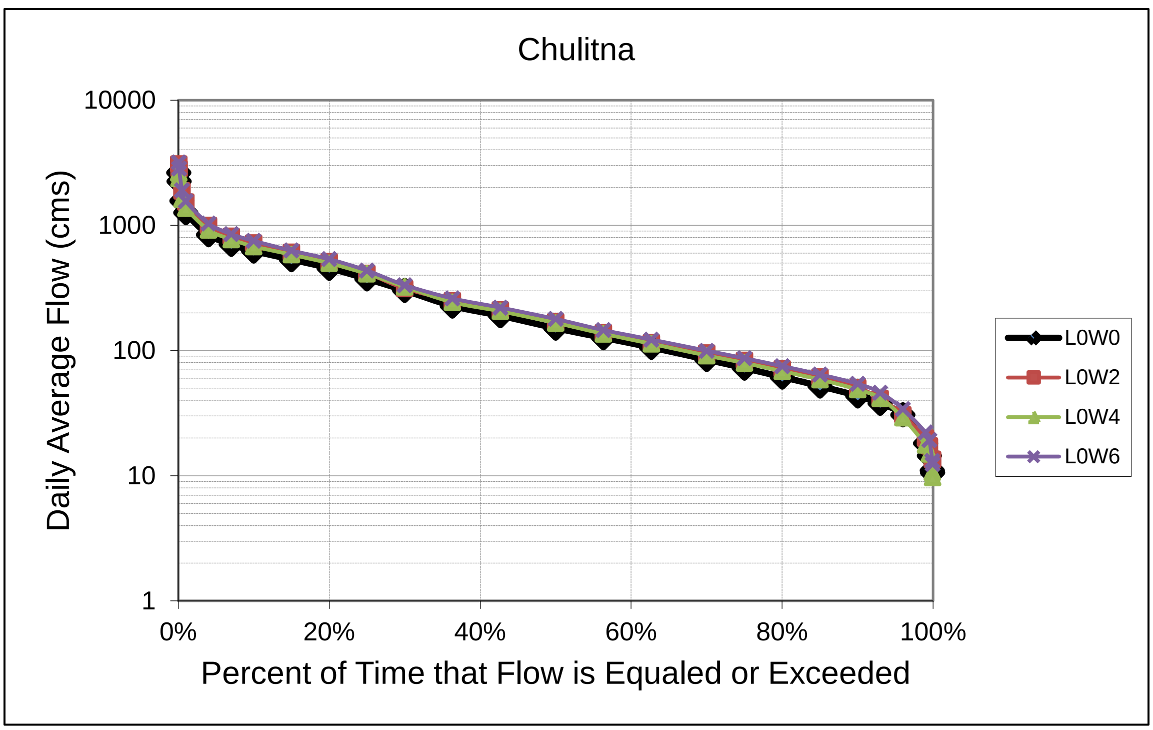


Figure 47. **Flow duration, Chulitna River (SWAT)**

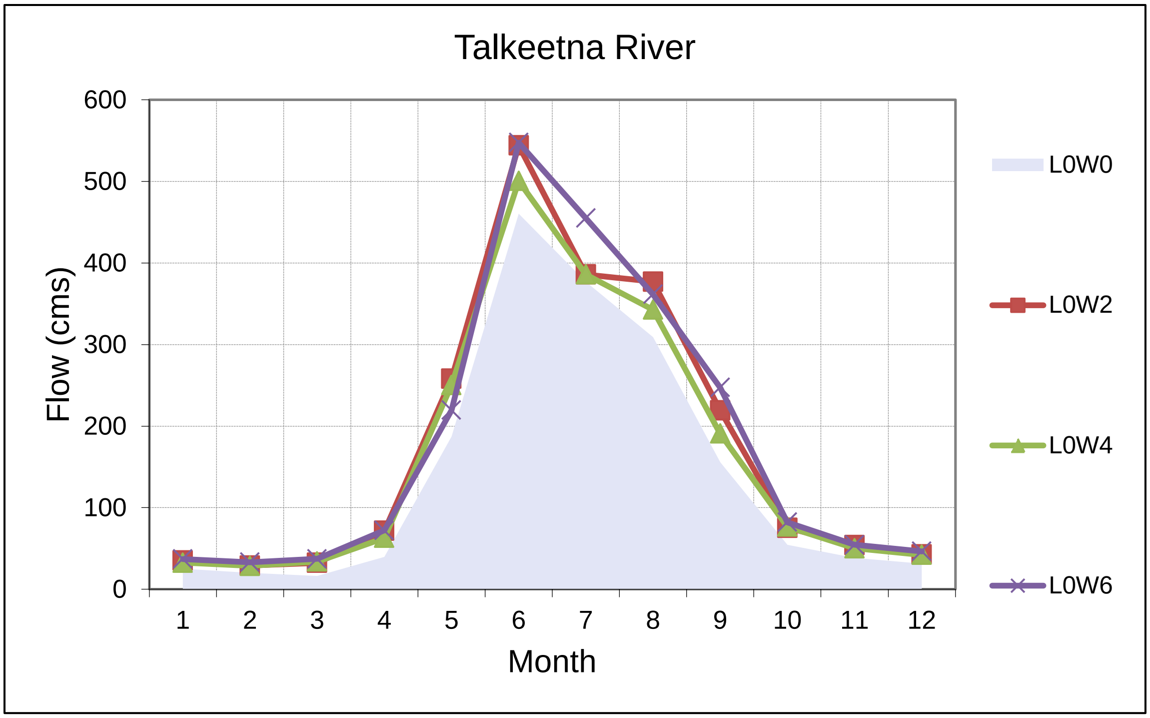


Figure 48. **Monthly average flows, Talkeetna River Mouth (SWAT)**

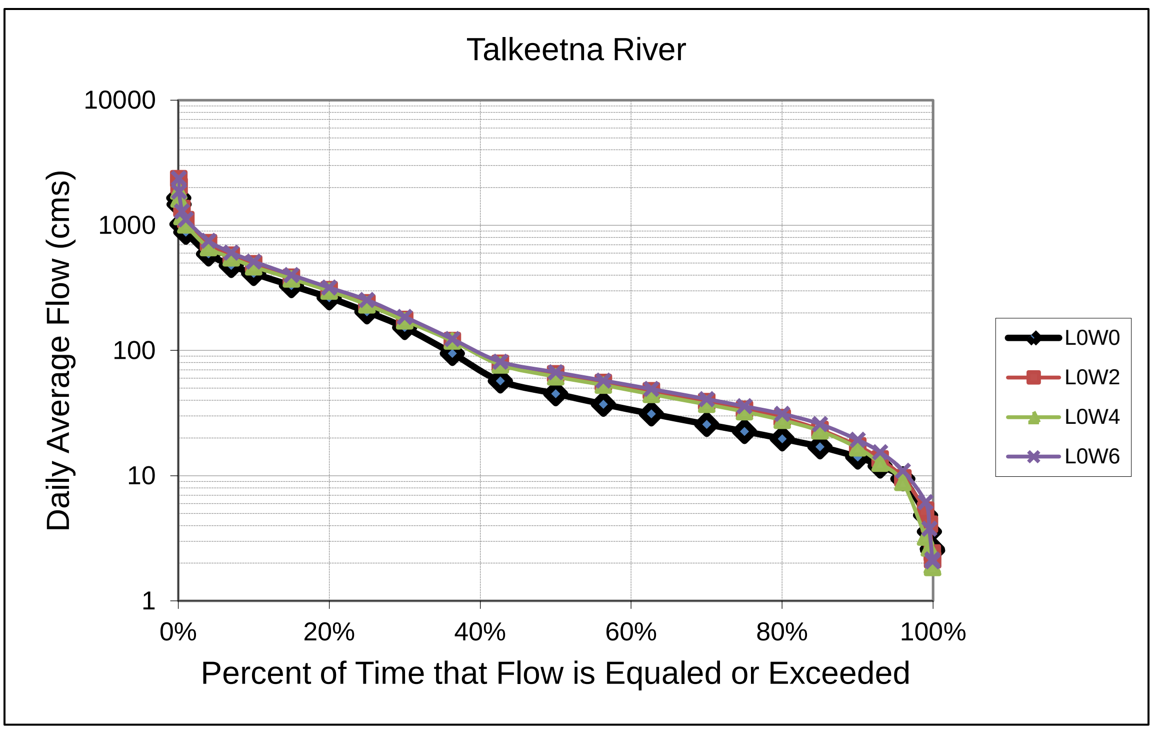


Figure 49. **Flow duration, Talkeetna River Mouth (SWAT)**

Georgia-Florida Coastal Basins

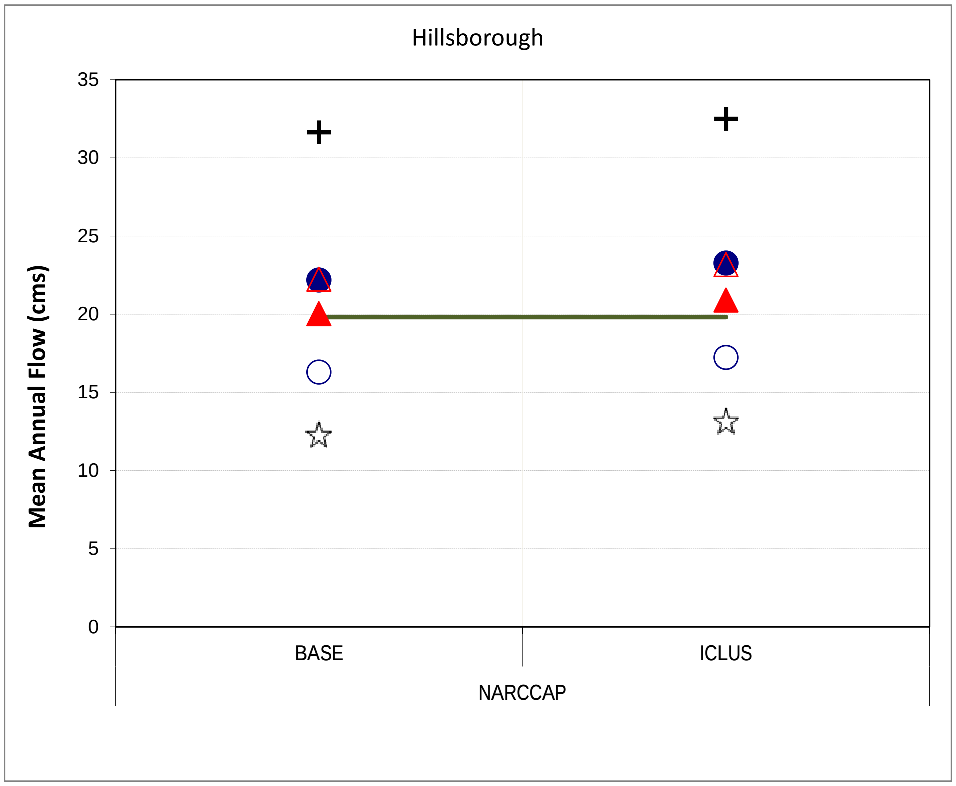


Figure 50. Mean annual flow (cms), Hillsborough River (SWAT)

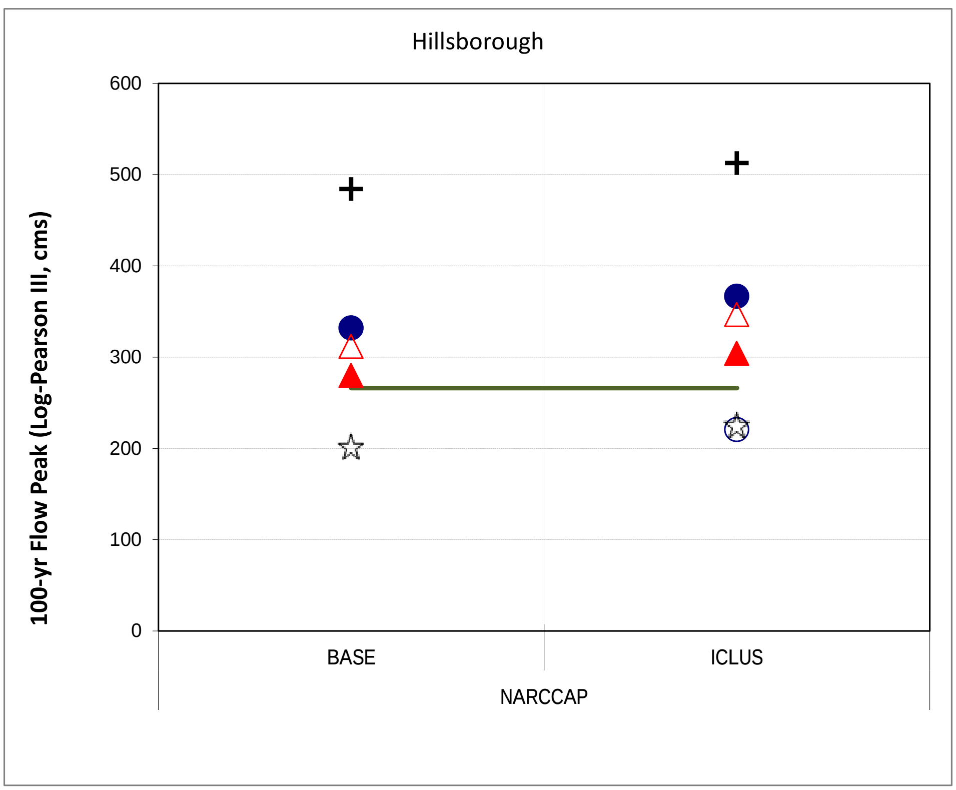


Figure 51. 100-yr Flow Peak (Log-Pearson III, cms), Hillsborough River (SWAT)

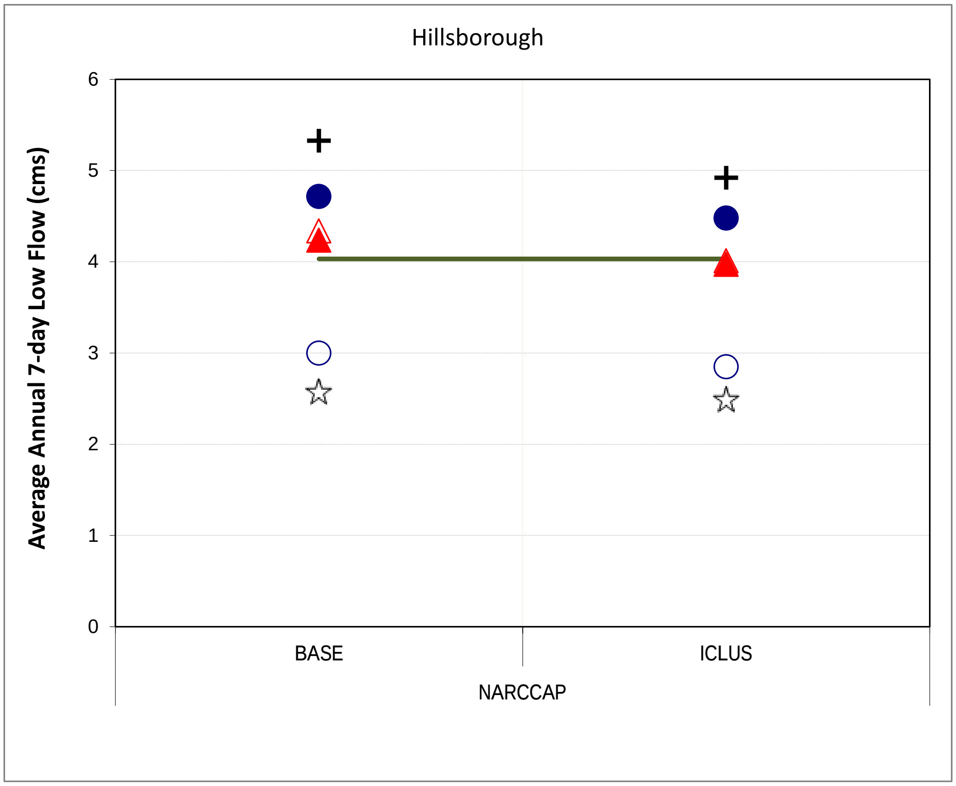


Figure 52. Average Annual 7-day Low Flow (cms), Hillsborough River (SWAT)

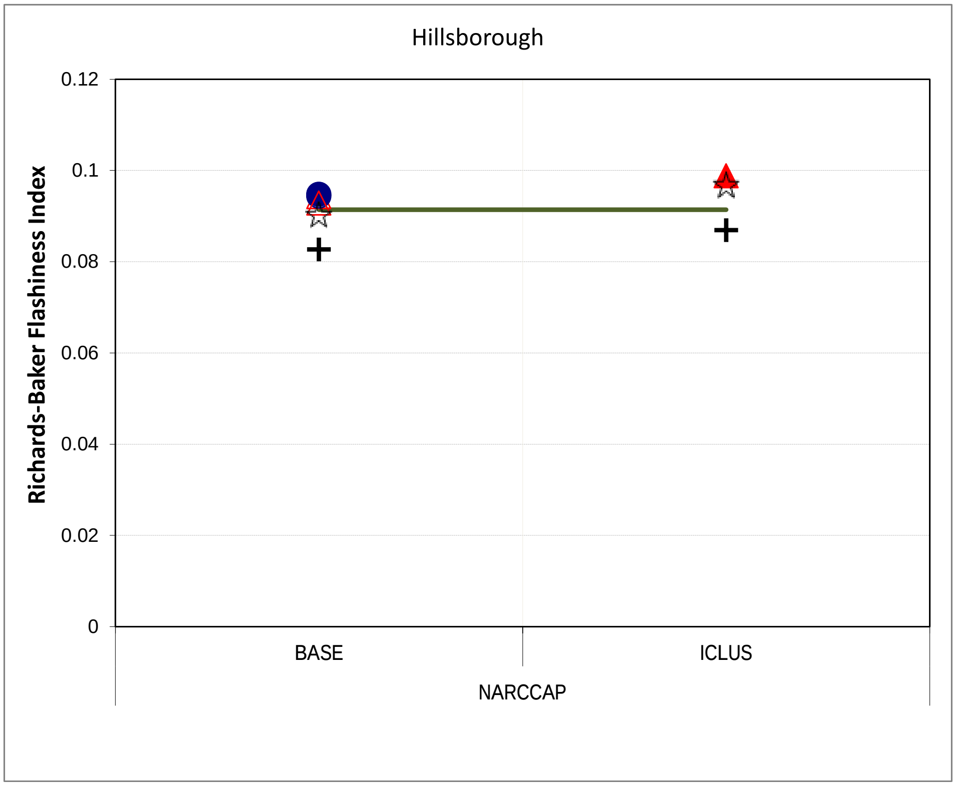


Figure 53. Richards-Baker Flashiness Index, Average Annual 7-day Low Flow (cms), Hillsborough River (SWAT)

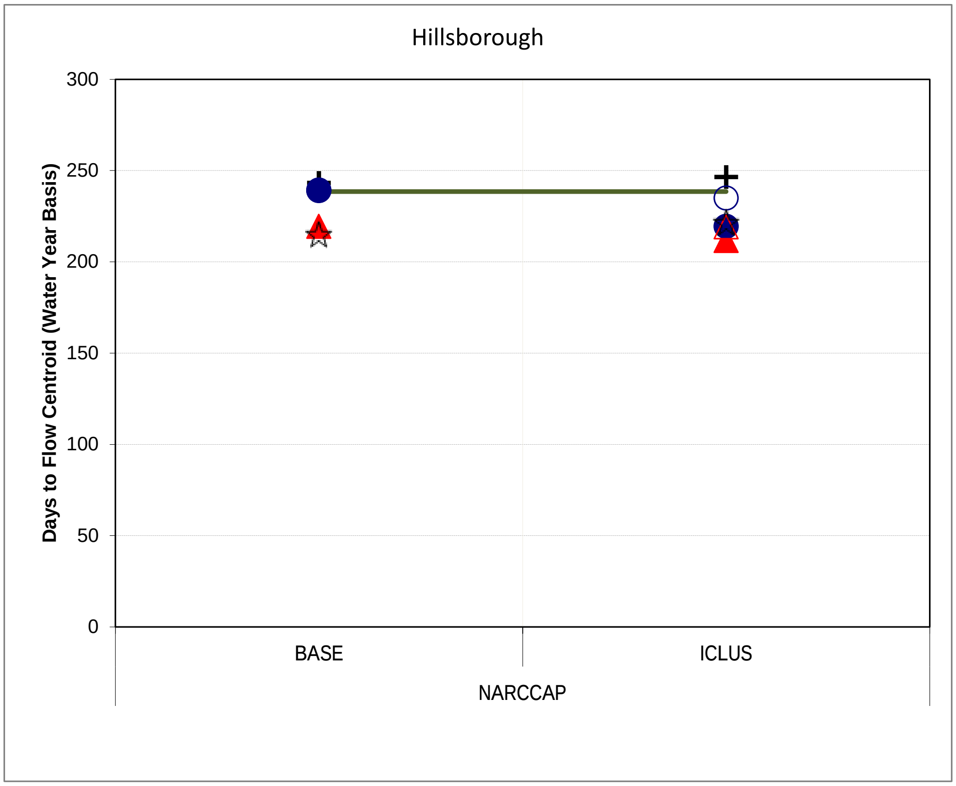


Figure 54. **Days to Flow Centroid (Water Year Basis), Hillsborough River (SWAT)**

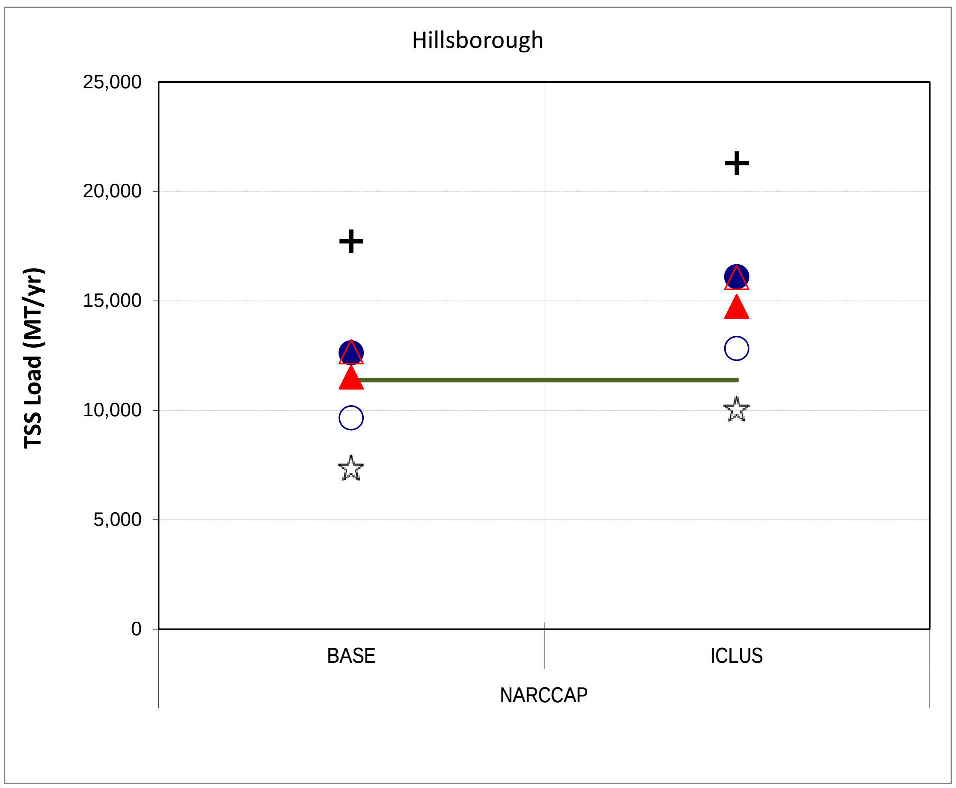


Figure 55. **TSS Load (MT/yr), Hillsborough River (SWAT)**

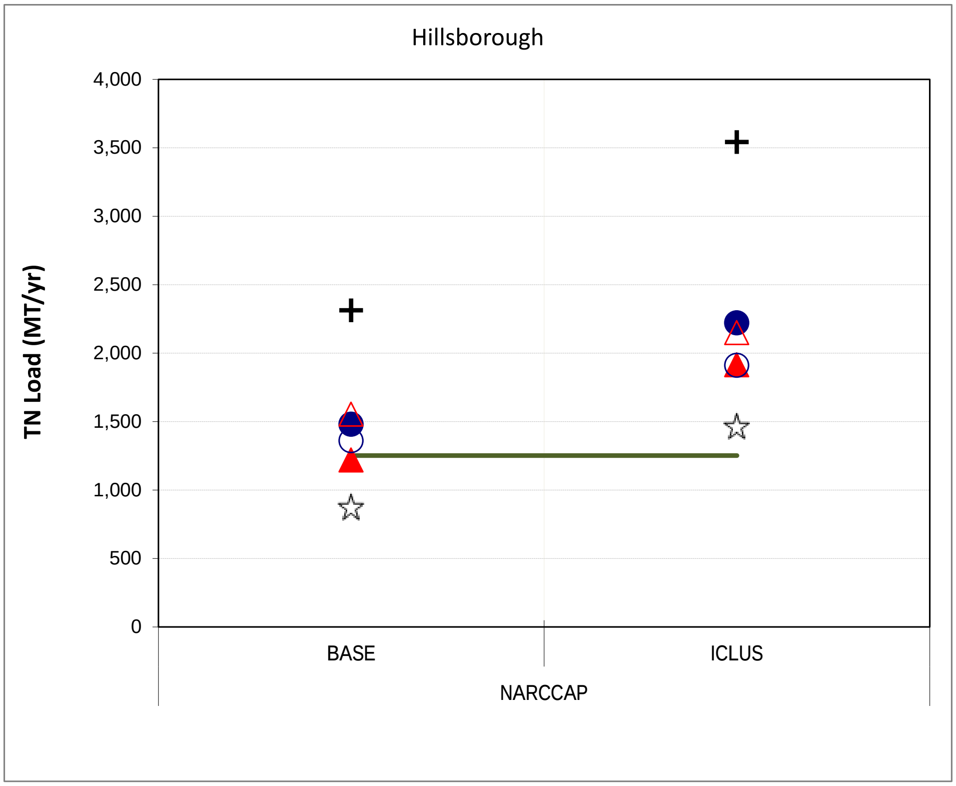


Figure 56. TN Load (MT/yr), Hillsborough River (SWAT)

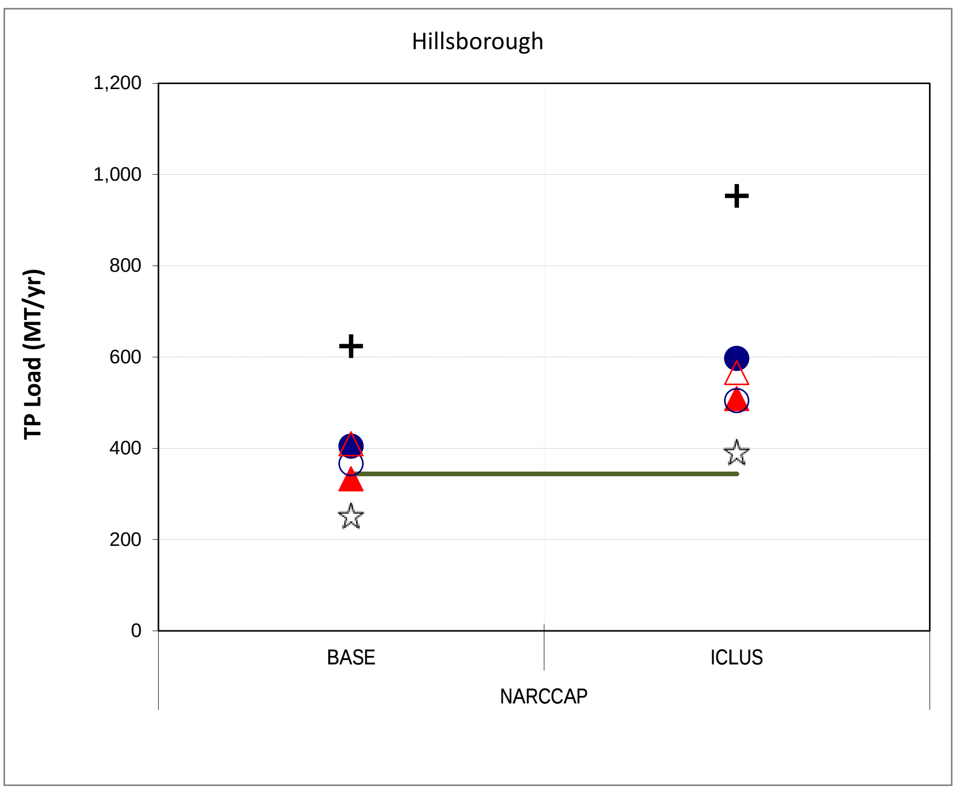


Figure 57. TP Load (MT/yr), Hillsborough River (SWAT)

Table 3. Summary of range of change relative to existing conditions for NARCCAP dynamically downscaled scenarios, Georgia-Florida basins SWAT model

	Results without LU change				Results with LU change			
	Min	Median	Mean	Max	Min	Median	Mean	Max
Aucilla HUC 03110103								
Flow	-23.75%	12.24%	13.58%	45.52%	-23.75%	12.23%	13.58%	45.52%
TSS	-20.42%	18.12%	22.64%	66.75%	-20.40%	18.10%	22.62%	66.73%
TN	-1.99%	12.71%	13.99%	24.82%	-2.06%	12.69%	13.99%	24.97%
TP	-18.40%	22.65%	33.35%	89.73%	-18.71%	22.48%	33.32%	90.36%
Upper Suwanee HUC 03110201								
Flow	-24.84%	28.79%	26.01%	68.81%	-24.81%	28.73%	25.97%	68.71%
TSS	-24.26%	39.56%	37.78%	98.24%	-24.23%	39.49%	37.72%	98.07%
TN	-23.50%	23.01%	22.03%	61.67%	-22.71%	23.87%	22.88%	62.43%
TP	-24.98%	25.16%	24.20%	69.24%	-23.70%	25.90%	25.02%	71.25%
Alapaha HUC 03110202								
Flow	-15.81%	25.16%	21.59%	57.95%	-15.78%	25.09%	21.53%	57.81%
TSS	-18.00%	31.27%	28.14%	76.14%	-17.97%	31.12%	28.01%	75.79%
TN	-11.17%	23.77%	20.63%	52.80%	-9.70%	24.31%	21.62%	53.11%
TP	-23.30%	13.11%	10.13%	43.22%	-21.52%	13.97%	11.48%	43.43%
Withlacoochee (nr Pinetta, FL)								
Flow	-21.49%	24.44%	21.42%	69.85%	-21.48%	24.34%	21.32%	69.60%
TSS	-25.76%	28.45%	26.79%	85.95%	-25.72%	28.36%	26.72%	85.78%
TN	-10.73%	32.23%	29.50%	85.42%	-11.02%	31.22%	28.96%	84.79%
TP	-21.61%	21.51%	20.29%	70.56%	-21.56%	21.14%	20.42%	71.62%
Little HUC 03110204								
Flow	-25.92%	24.76%	20.44%	67.92%	-25.89%	24.69%	20.37%	67.74%
TSS	-27.77%	24.16%	20.64%	69.75%	-27.74%	24.08%	20.61%	69.67%
TN	-11.90%	32.94%	27.78%	71.48%	-12.55%	32.45%	28.19%	73.81%
TP	-23.93%	23.99%	19.96%	59.29%	-24.05%	24.13%	21.23%	63.09%
Lower Suwanee HUC 03110205								
Flow	-24.77%	21.27%	19.99%	56.44%	-24.81%	21.19%	19.89%	56.27%
TSS	-26.02%	29.60%	30.11%	81.11%	-26.06%	29.50%	29.97%	80.86%
TN	-15.26%	30.76%	30.75%	66.08%	-15.75%	30.60%	31.00%	66.62%

	Results without LU change				Results with LU change			
	Min	Median	Mean	Max	Min	Median	Mean	Max
TP	-24.37%	25.22%	26.51%	73.14%	-25.00%	25.58%	27.00%	74.17%
Santa Fe HUC 03110206								
Flow	-26.50%	15.44%	12.31%	37.17%	-26.64%	15.29%	12.14%	36.95%
TSS	-34.97%	24.34%	21.88%	63.75%	-34.48%	23.78%	21.33%	62.17%
TN	0.76%	34.95%	34.17%	52.87%	-2.79%	33.01%	31.08%	50.12%
TP	-30.13%	19.26%	16.36%	52.01%	-32.41%	21.55%	15.81%	49.06%
Apalachee Bay - St. Marks HUC 03120001								
Flow	-25.80%	10.87%	12.84%	45.59%	-25.92%	10.36%	12.20%	44.44%
TSS	-20.78%	13.04%	17.60%	55.25%	-20.01%	10.39%	13.52%	45.25%
TN	-3.33%	18.02%	18.73%	38.17%	-7.19%	15.56%	17.39%	39.98%
TP	-27.82%	11.78%	15.72%	59.93%	-30.89%	8.01%	13.45%	57.31%
Upper Ochlockonee HUC 03120002								
Flow	-25.04%	26.32%	19.62%	61.25%	-25.03%	26.30%	19.61%	61.22%
TSS	-38.65%	34.32%	27.93%	82.94%	-38.65%	34.31%	27.92%	82.92%
TN	-22.80%	29.48%	24.54%	77.46%	-22.12%	30.39%	25.48%	79.43%
TP	-31.13%	13.95%	9.86%	51.03%	-30.52%	14.76%	10.75%	53.16%
Lower Ochlockonee HUC 03120003								
Flow	-30.24%	14.32%	13.81%	50.41%	-30.23%	14.11%	13.56%	49.94%
TSS	-31.40%	20.86%	21.26%	69.71%	-31.52%	20.58%	20.90%	69.17%
TN	-16.07%	22.06%	22.91%	59.18%	-17.77%	21.60%	22.00%	57.25%
TP	-34.99%	16.34%	18.35%	74.66%	-36.39%	15.54%	16.71%	69.16%
Little Manatee HUC 03100203								
Flow	-39.73%	-1.06%	0.44%	47.18%	-39.16%	-1.25%	-0.05%	44.98%
TSS	-45.87%	-2.45%	3.26%	67.43%	-41.56%	-2.06%	0.73%	52.77%
TN	-35.64%	17.99%	27.11%	109.29%	-33.32%	0.81%	11.16%	74.13%
TP	-42.97%	7.04%	17.11%	98.78%	-37.23%	-3.02%	7.99%	75.35%
Alafia HUC 03100204								
Flow	-35.01%	4.37%	1.61%	46.53%	-34.18%	4.30%	1.29%	43.89%
TSS	-35.63%	6.13%	3.28%	51.25%	-33.45%	5.77%	2.78%	46.56%
TN	-20.18%	13.29%	30.43%	123.07%	-7.94%	14.11%	30.90%	95.91%
TP	-26.24%	5.15%	1.69%	31.06%	-24.25%	5.79%	3.49%	32.00%

	Results without LU change				Results with LU change			
	Min	Median	Mean	Max	Min	Median	Mean	Max
Hillsborough HUC 03100205								
Flow	-37.66%	6.42%	4.82%	59.53%	- 36.21%	6.31%	4.77%	56.79%
TSS	-34.82%	6.04%	4.86%	55.70%	- 30.98%	5.05%	3.58%	45.17%
TN	-29.58%	13.41%	17.23%	84.71%	- 24.74%	3.81%	12.50%	80.96%
TP	-26.00%	12.06%	15.92%	81.45%	- 25.62%	1.54%	10.93%	80.06%

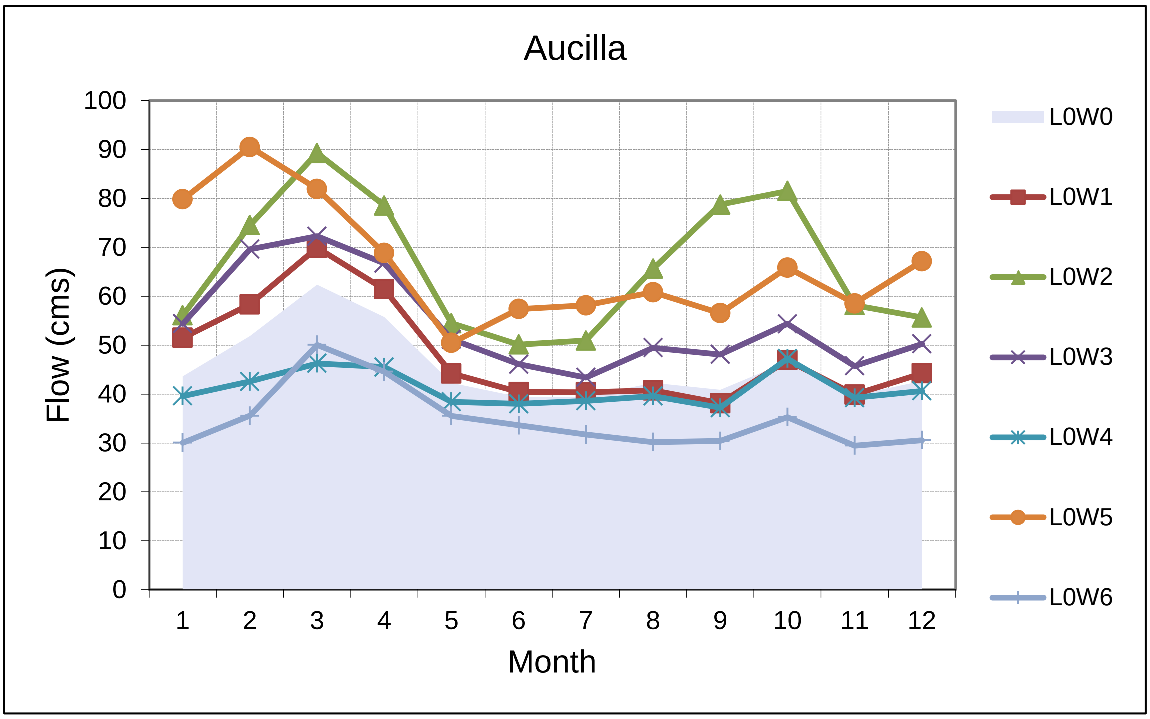


Figure 58. **Monthly average flows, Aucilla River (SWAT)**

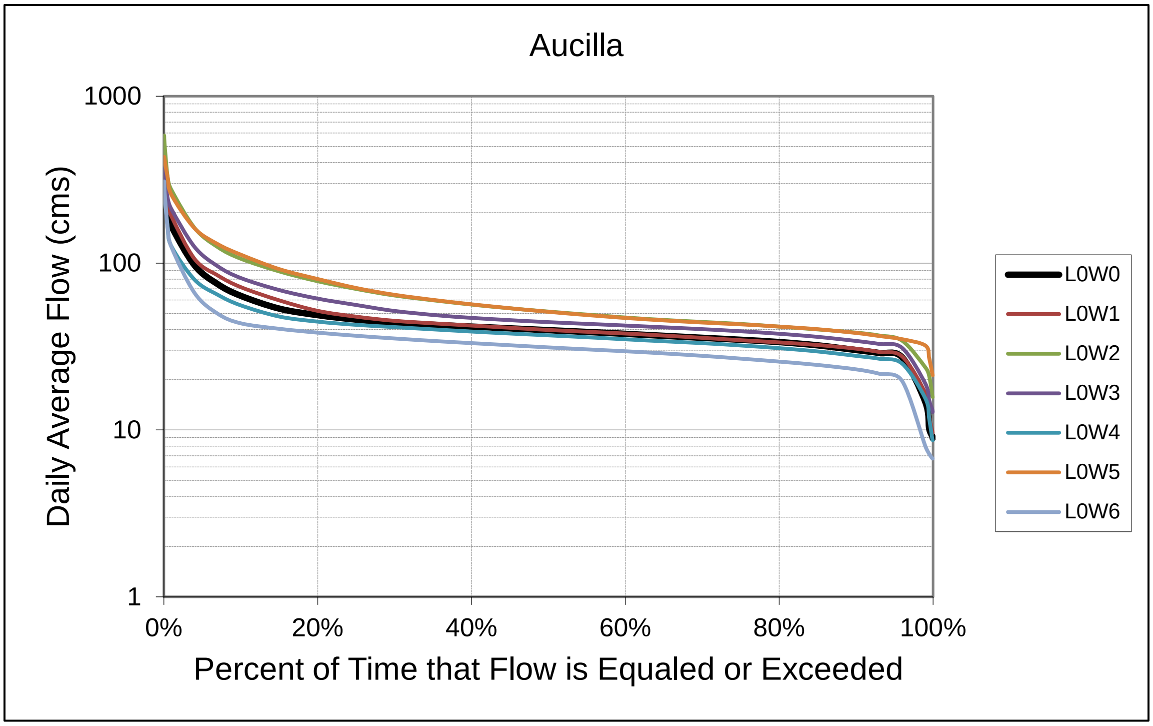


Figure 59. Flow duration, Aucilla River (SWAT)

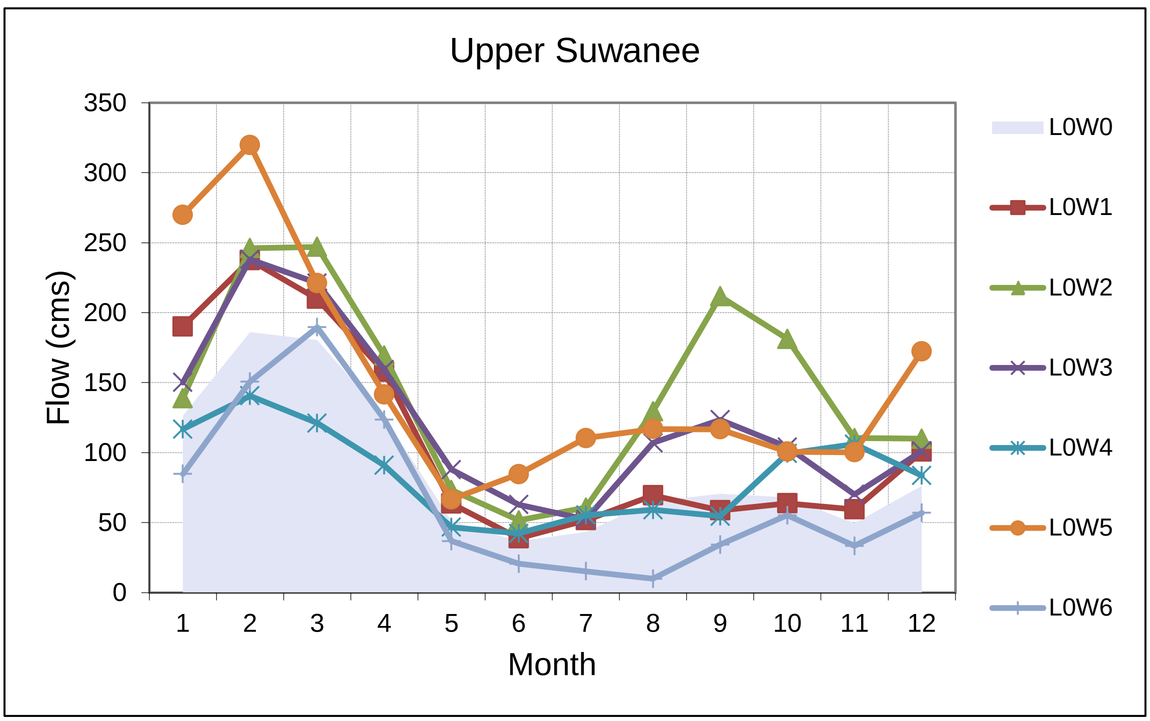


Figure 60. Monthly average flows, Upper Suwanee River (SWAT)

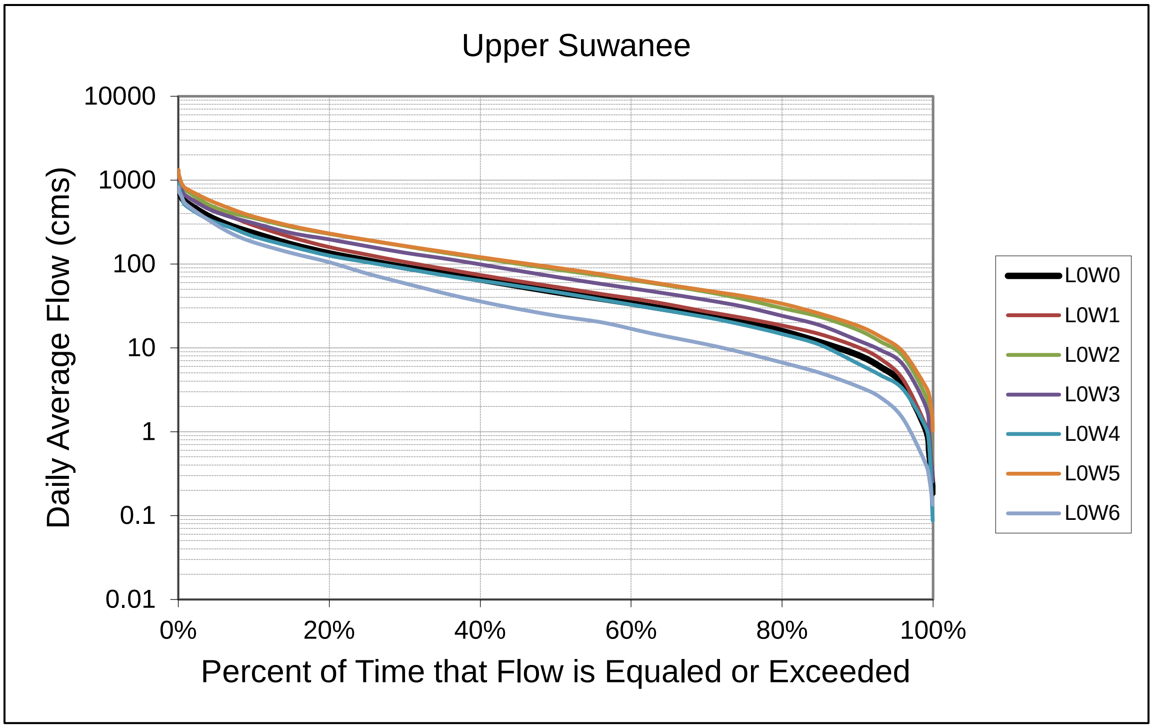


Figure 61. **Flow duration, Upper Suwanee River (SWAT)**

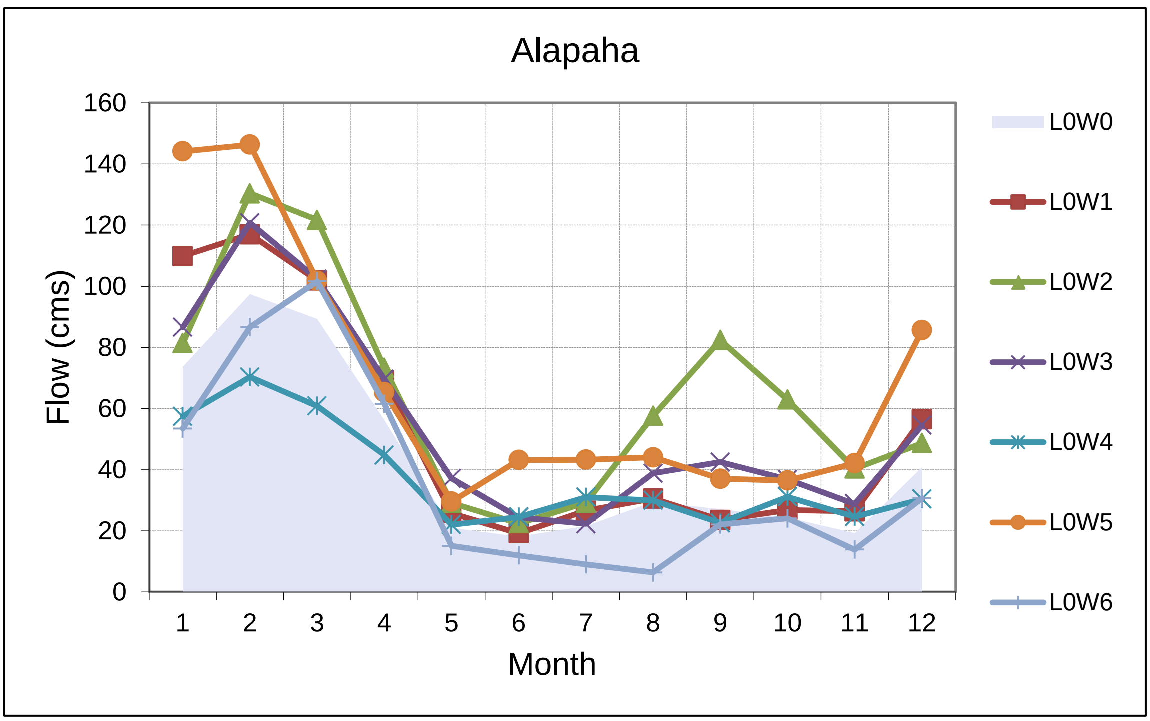


Figure 62. **Monthly average flows, Alapaha River (SWAT)**

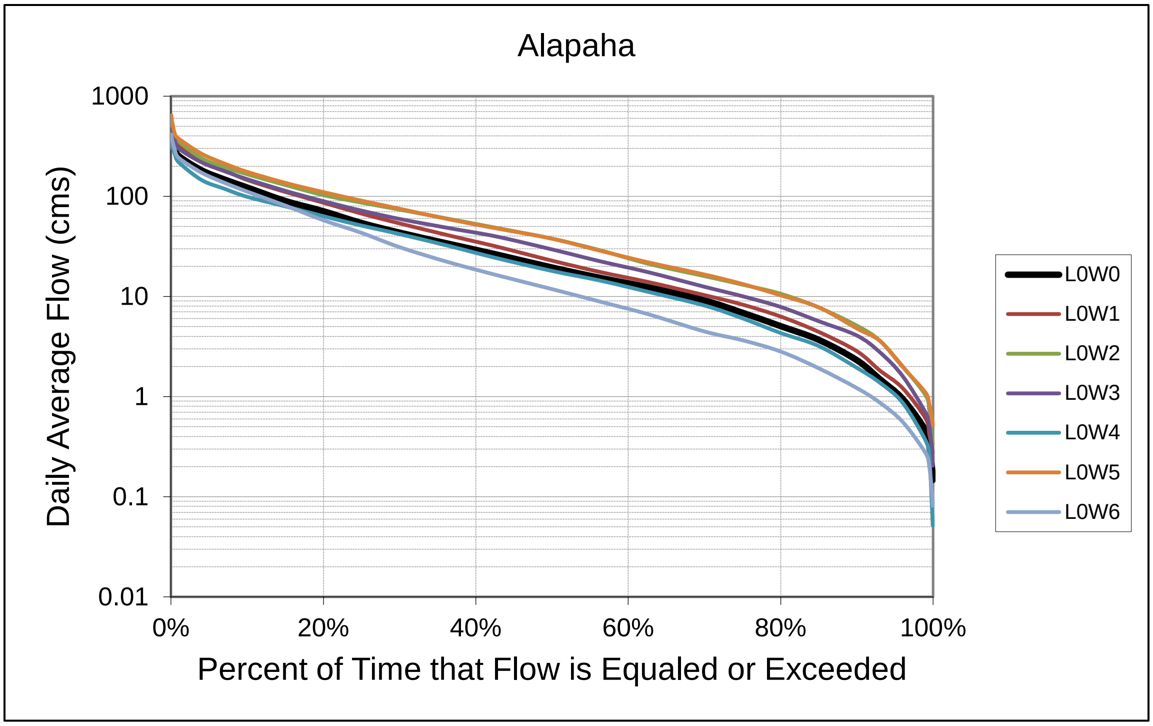


Figure 63. **Flow duration, Alapaha River (SWAT)**

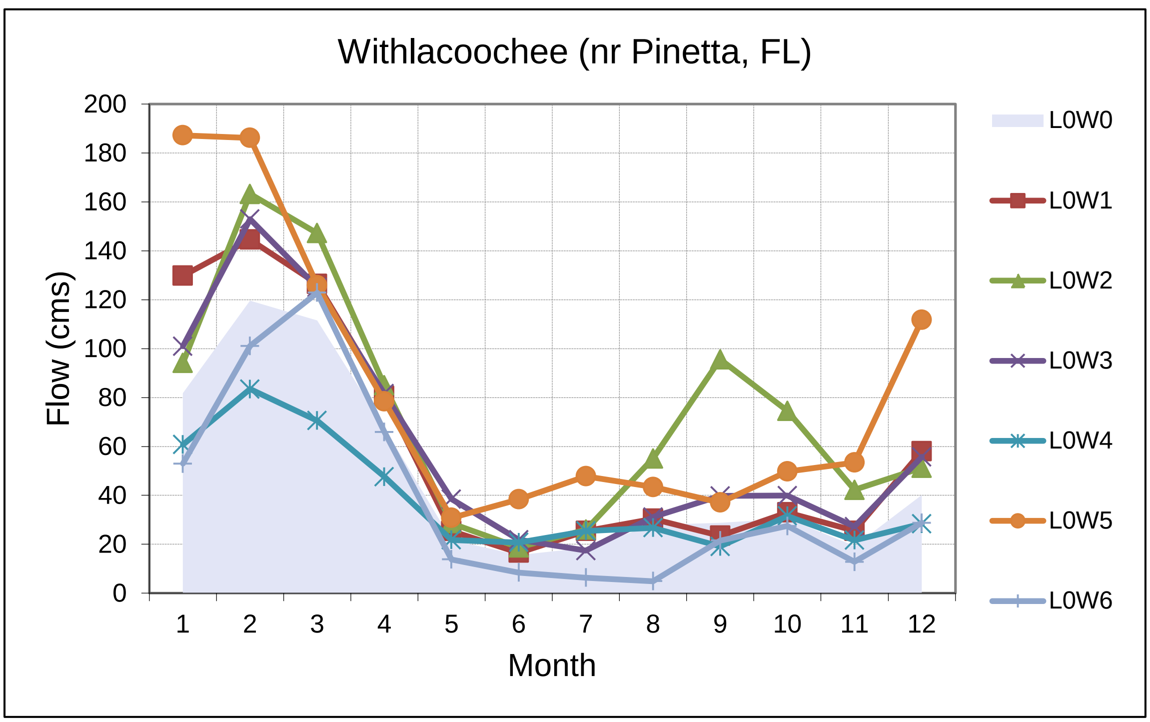


Figure 64. **Monthly average flows, Withlacoochee River near Pinetta, FL (SWAT)**

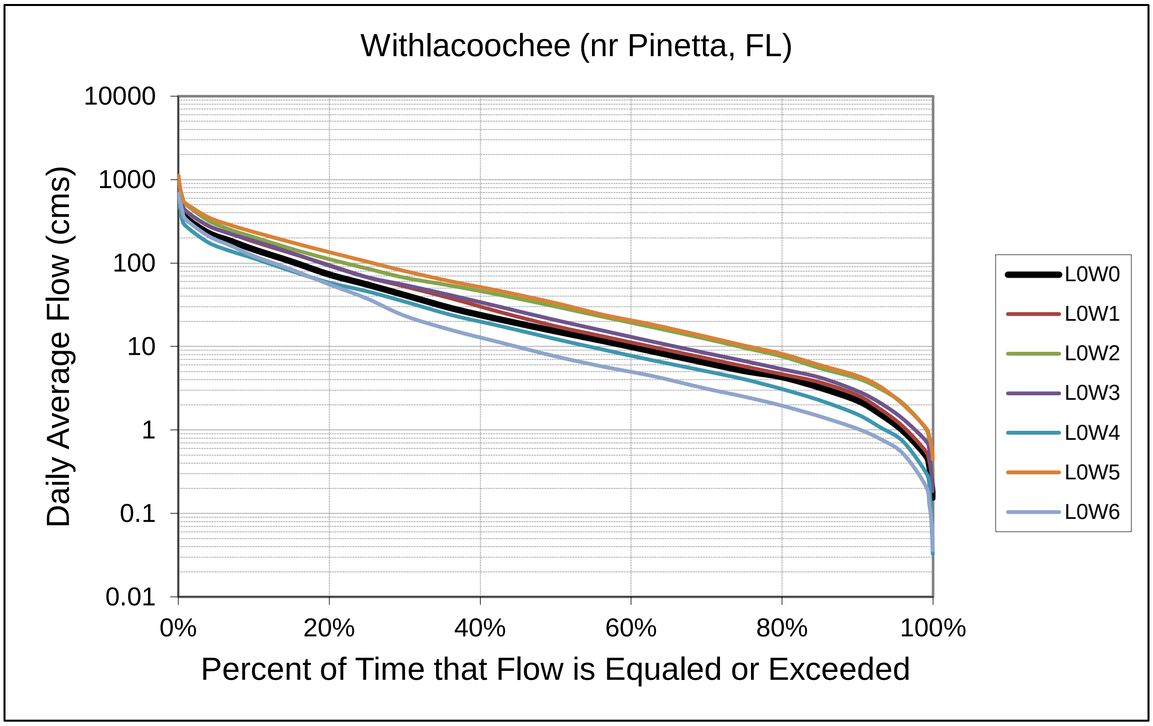


Figure 65. **Flow duration, Withlacoochee River near Pinetta, FL (SWAT)**

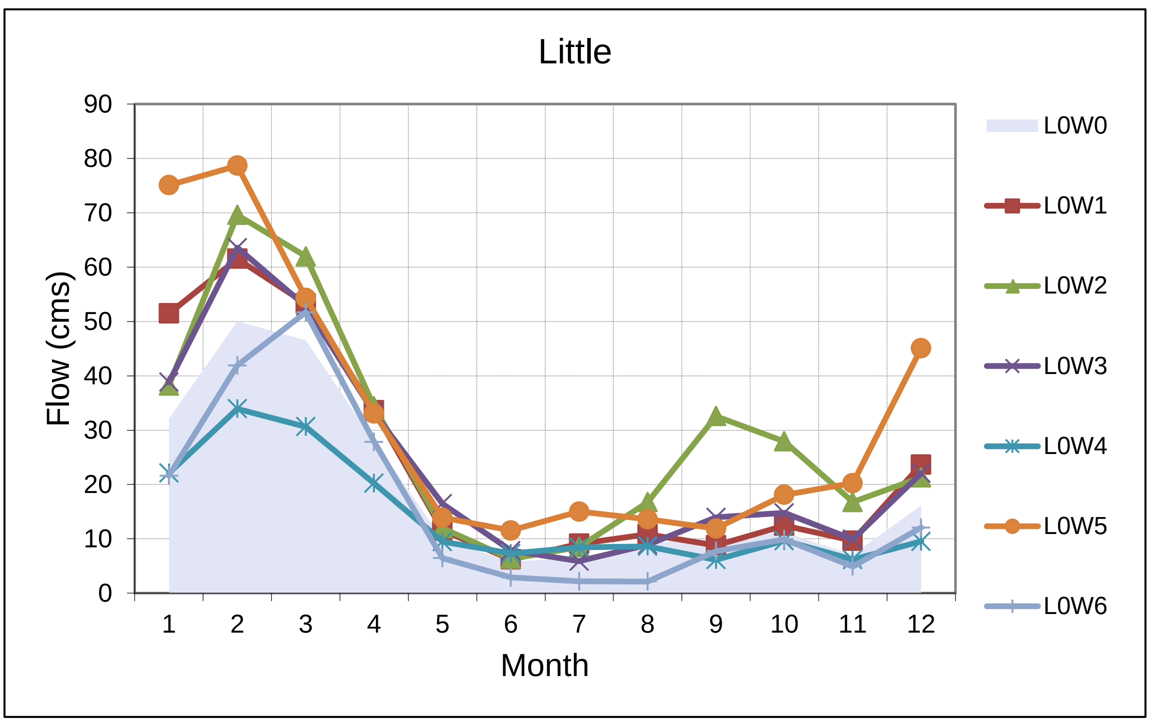


Figure 66. **Monthly average flows, Little River (SWAT)**

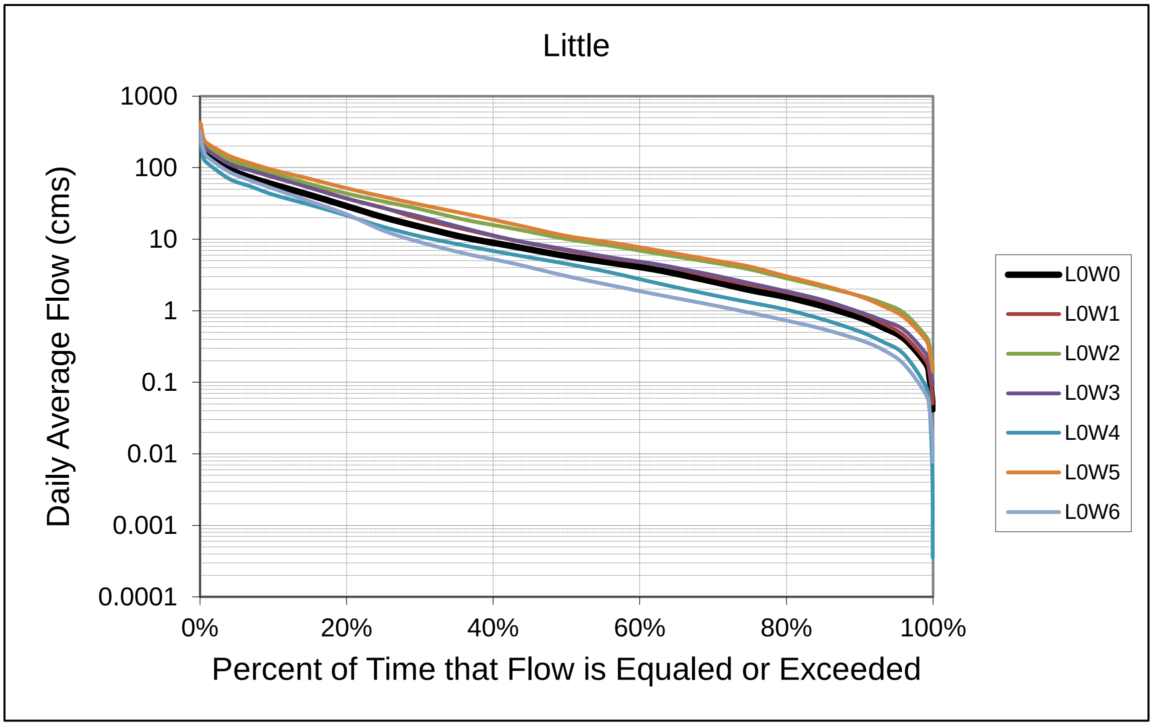


Figure 67. **Flow duration, Little River (SWAT)**

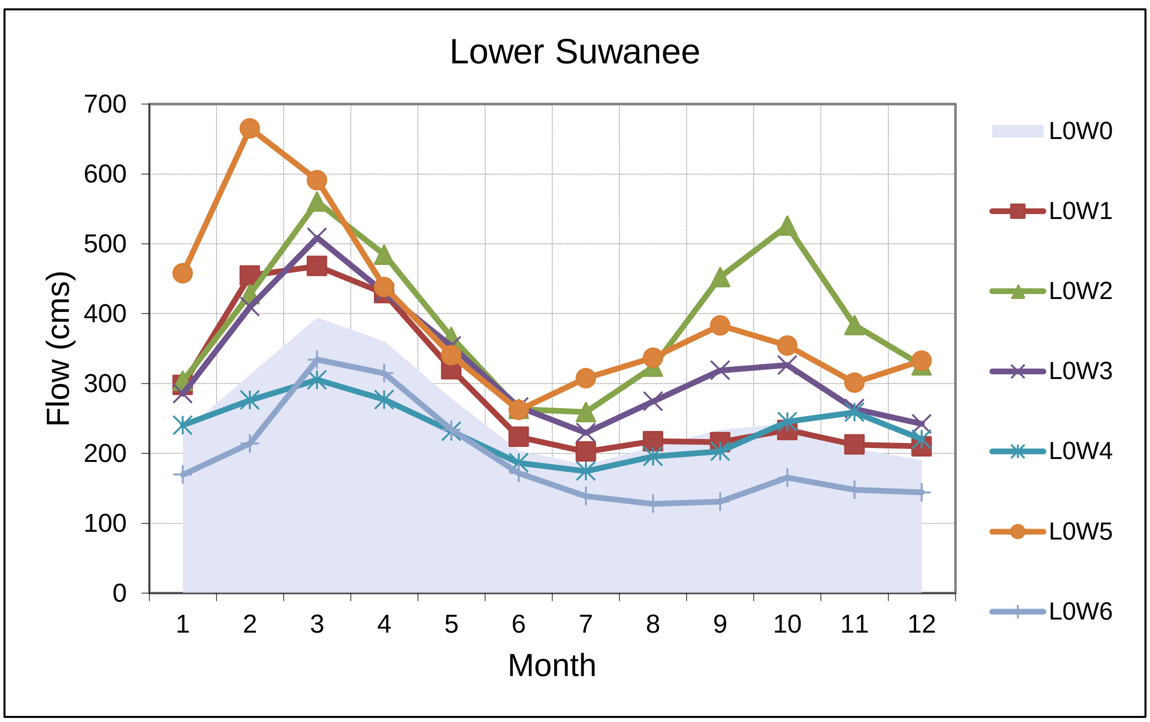


Figure 68. **Monthly average flows, Lower Suwanee River (SWAT)**

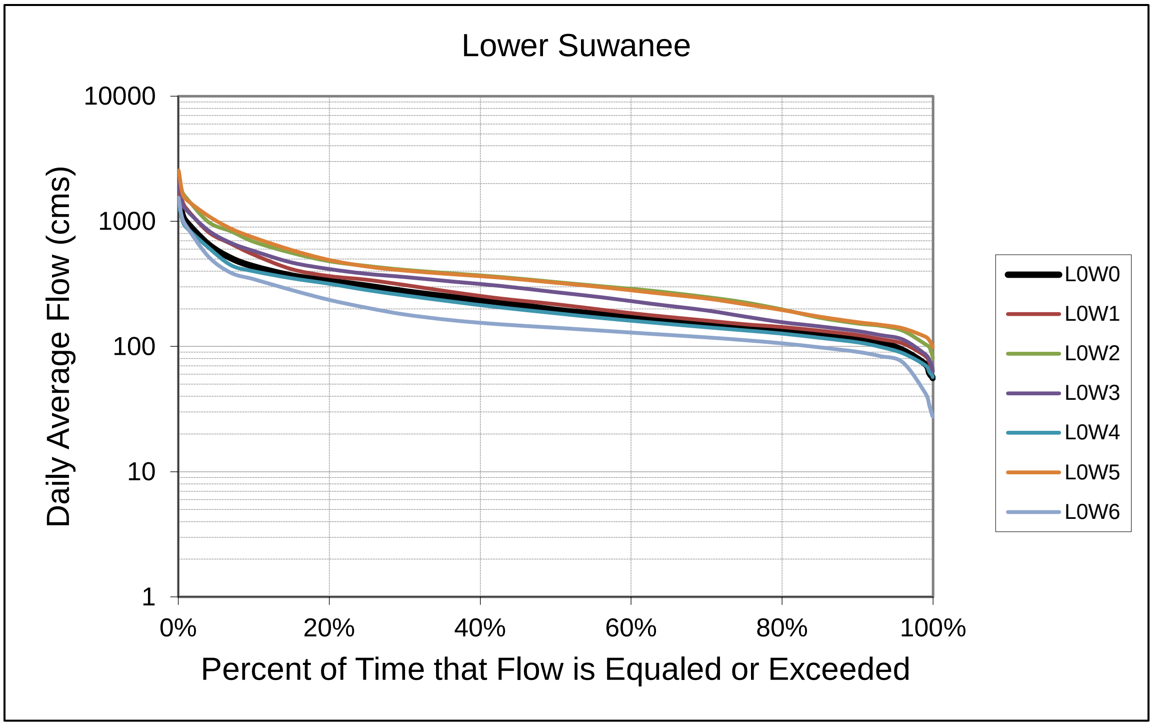


Figure 69. **Flow duration, Lower Suwanee River (SWAT)**

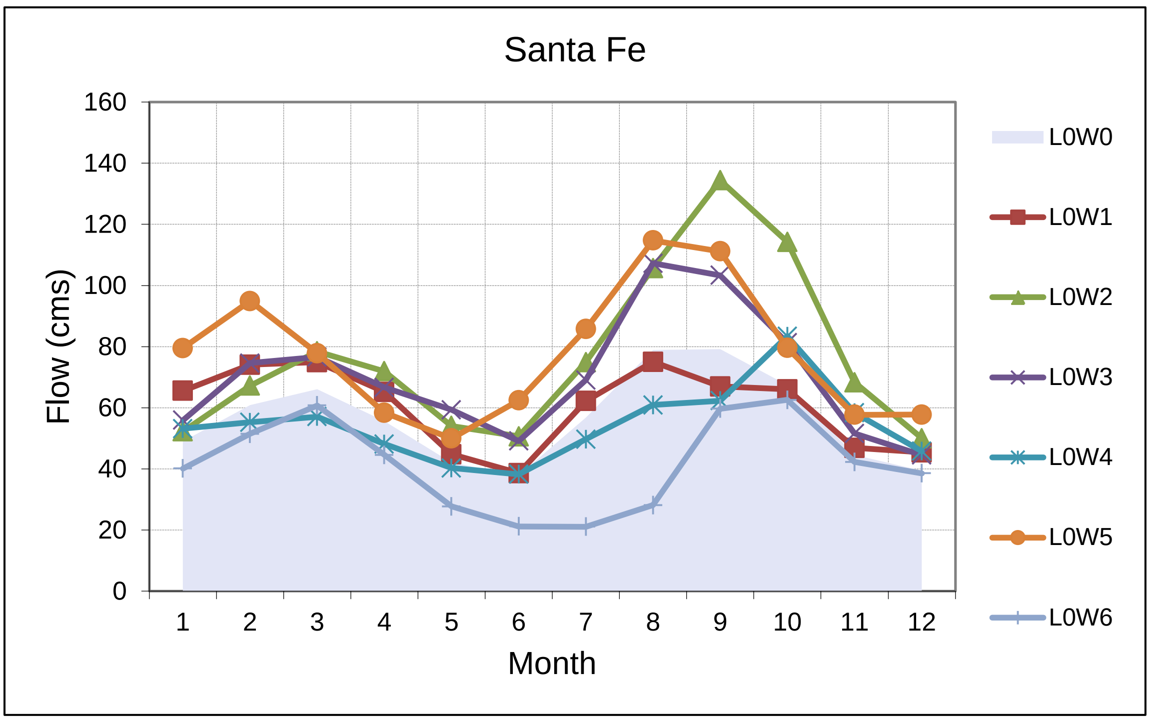


Figure 70. **Monthly average flows, Santa Fe River (SWAT)**

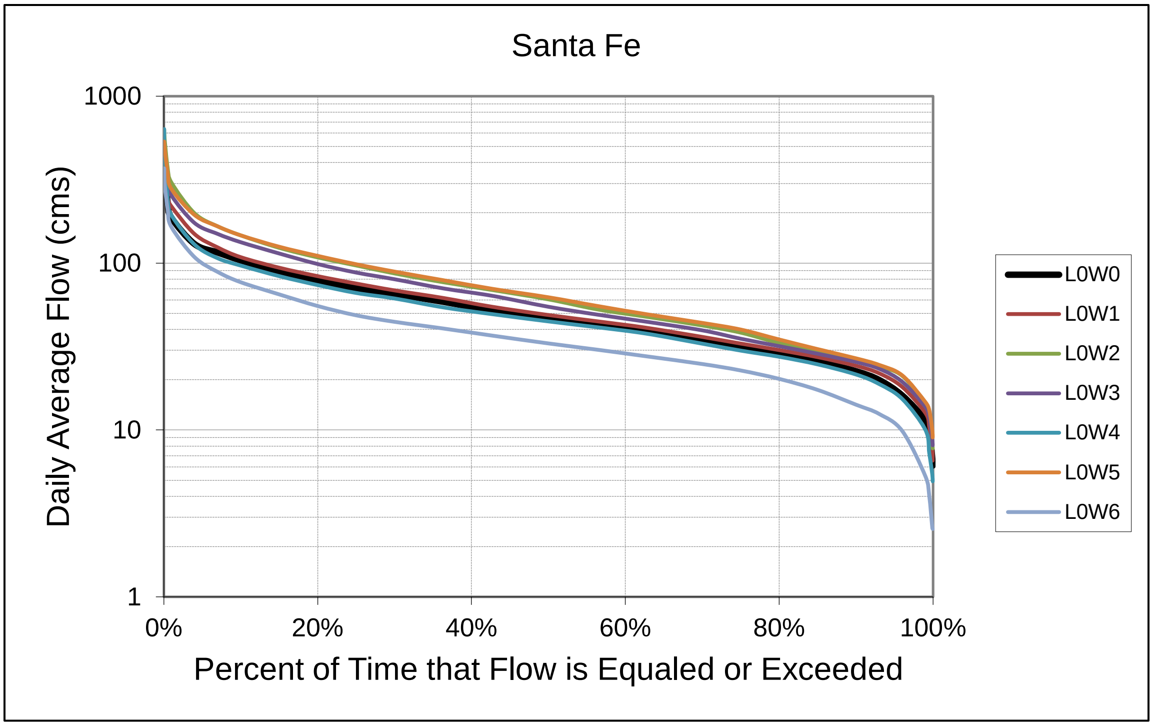


Figure 71. **Flow duration, Santa Fe River (SWAT)**

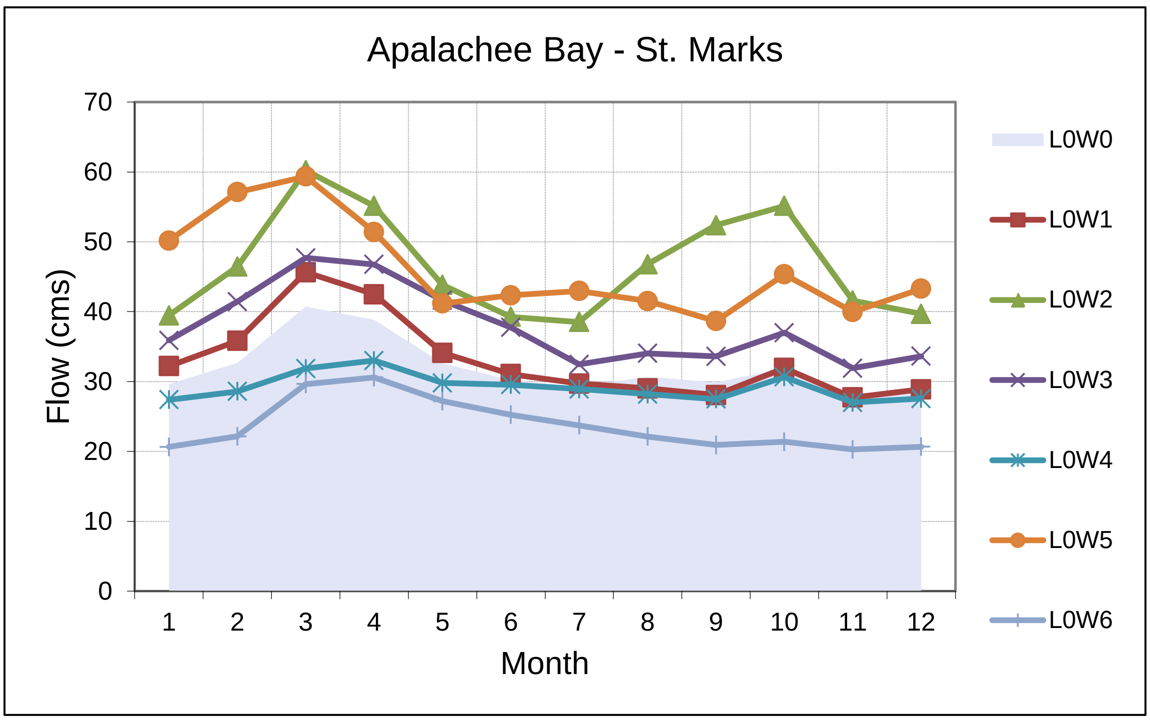


Figure 72. **Monthly average flows, Apalachee Bay at St. Marks HUC8 (SWAT)**

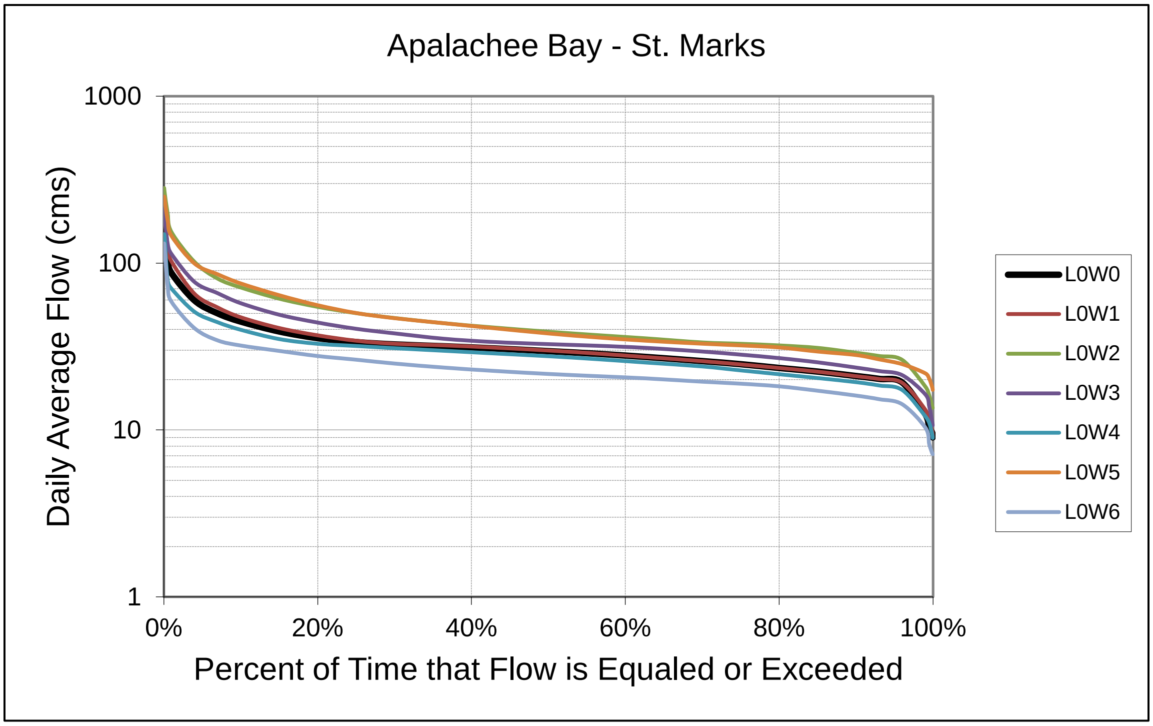


Figure 73. **Flow duration, Apalachee Bay at St. Marks HUC8 (SWAT)**

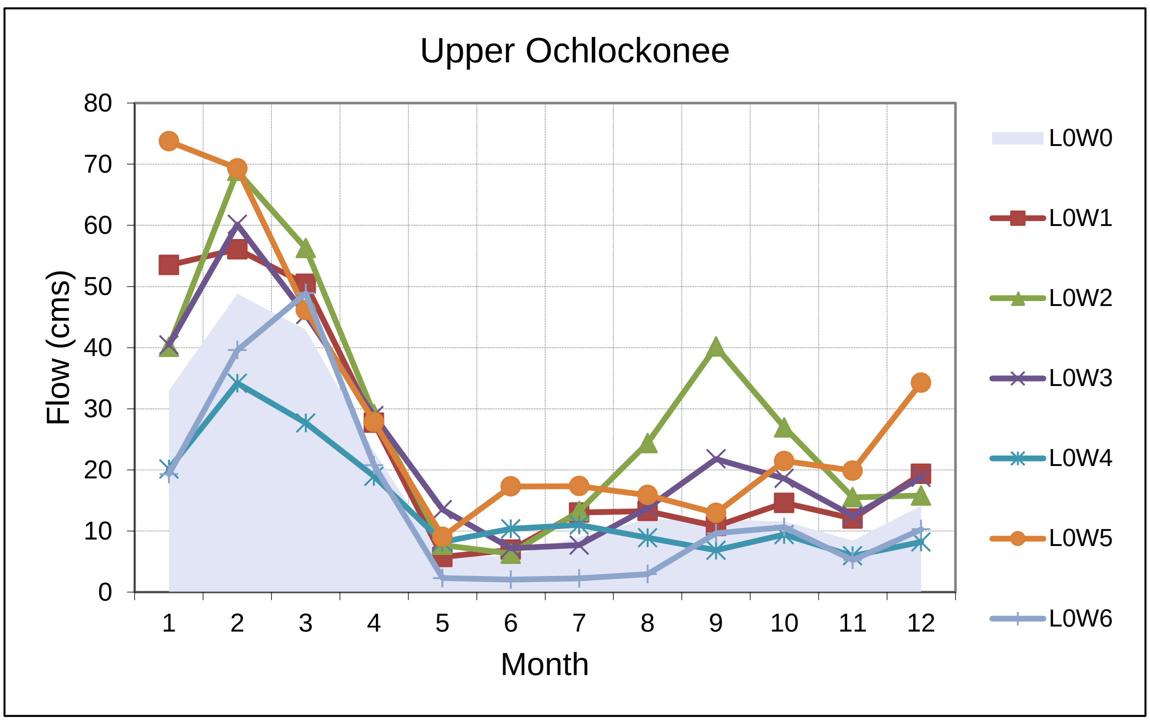


Figure 74. **Monthly average flows, Upper Ochlockonee River (SWAT)**

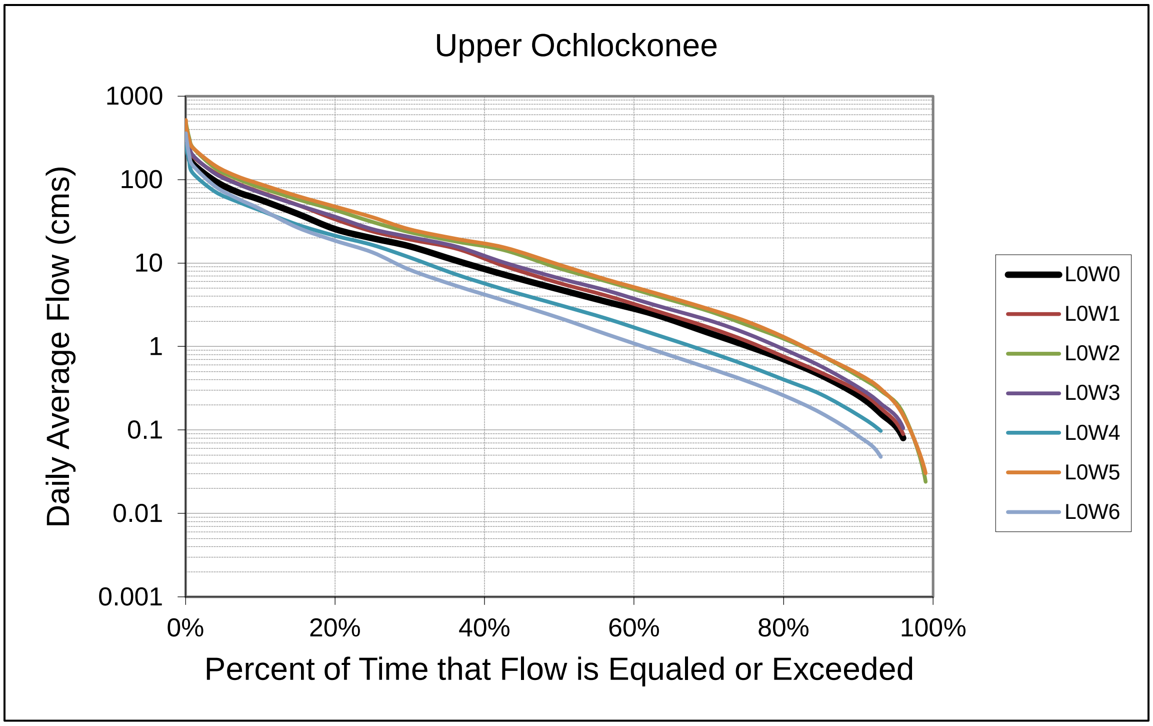


Figure 75. **Flow duration, Upper Ochlockonee River (SWAT)**

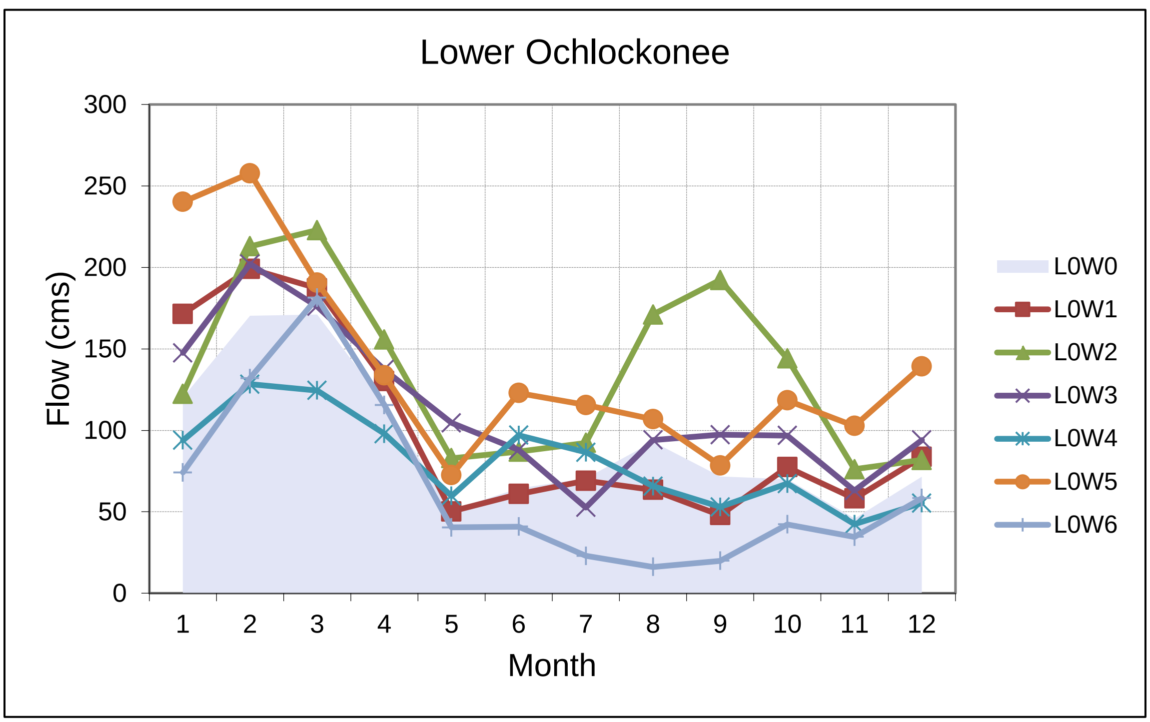


Figure 76. **Monthly average flows, Lower Ochlockonee River (SWAT)**

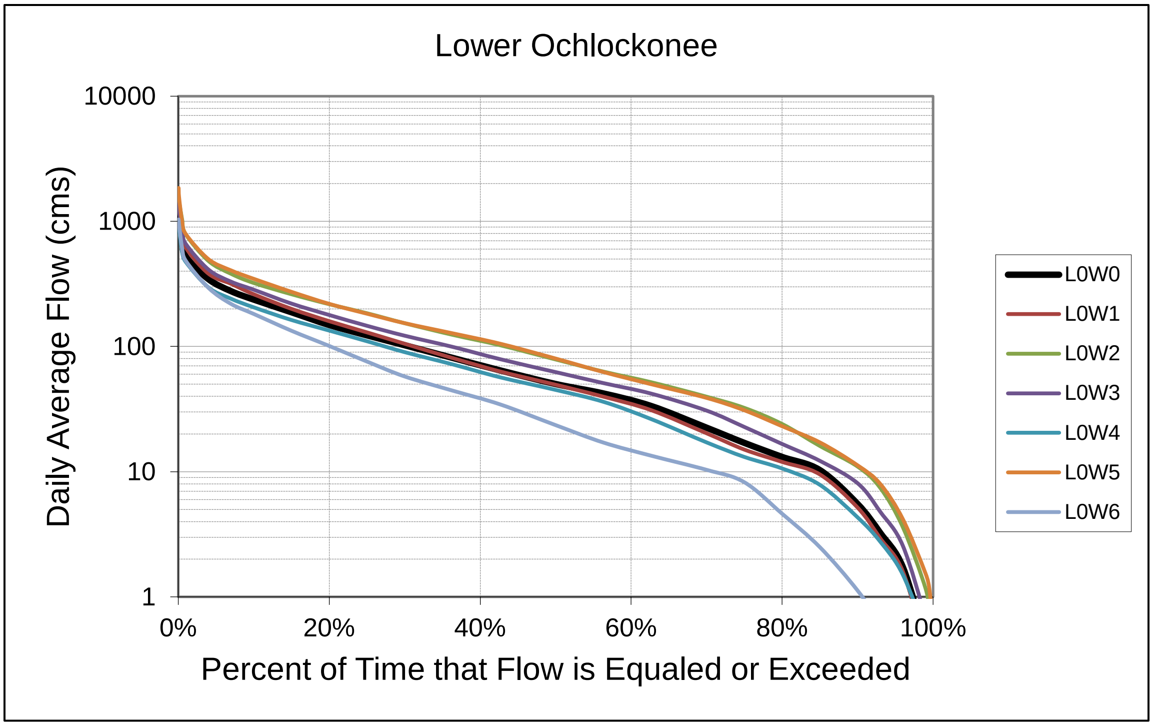


Figure 77. **Flow duration, Lower Ochlockonee River (SWAT)**

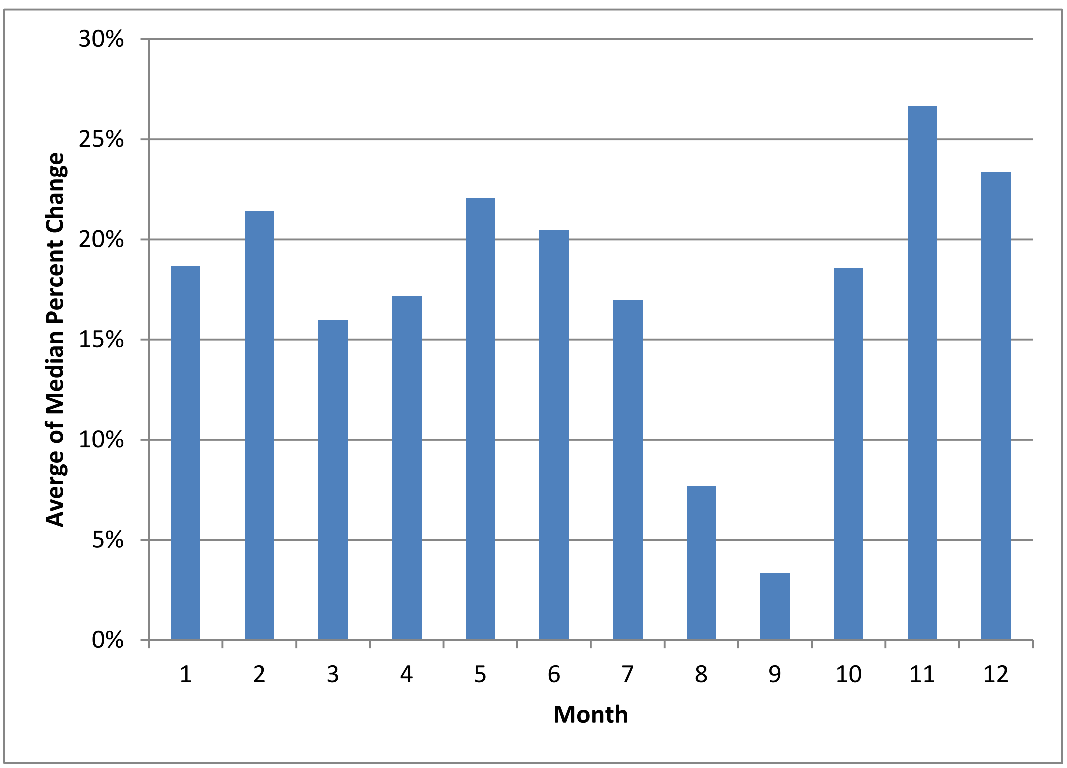


Figure 78. **Average of median percent change in flow; NARCCAP Scenarios W1-W6 at all stations, Georgia-Florida basins (SWAT)**

Illinois River Basin

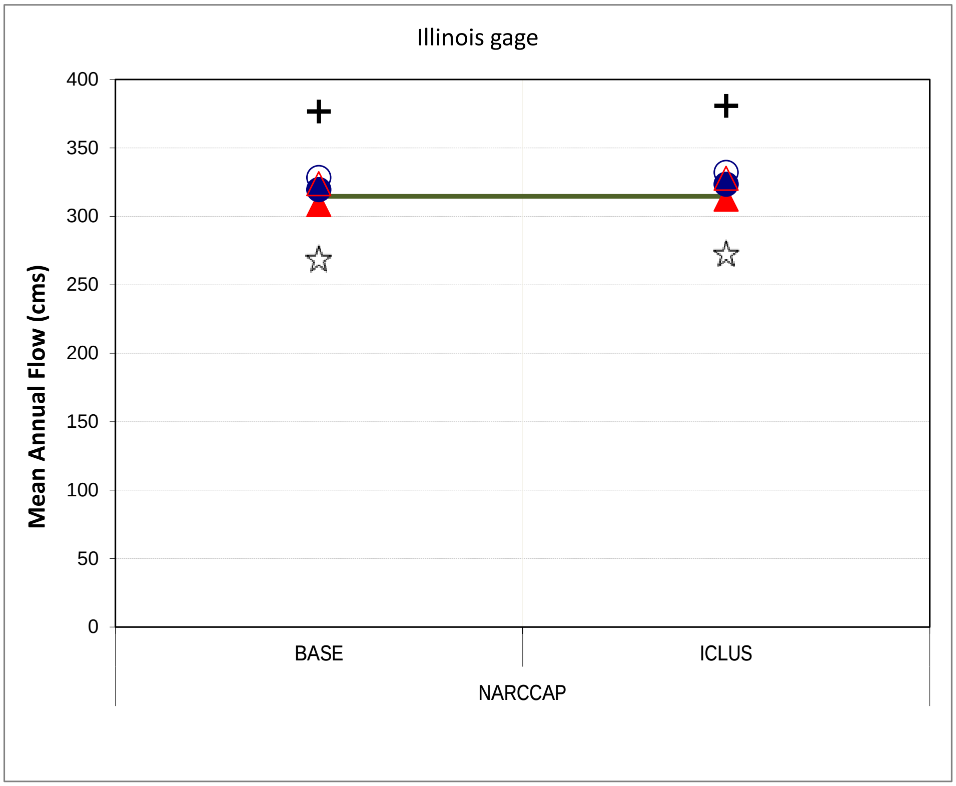


Figure 79. Mean annual flow (cms), Illinois River at Marseilles Gage (SWAT)

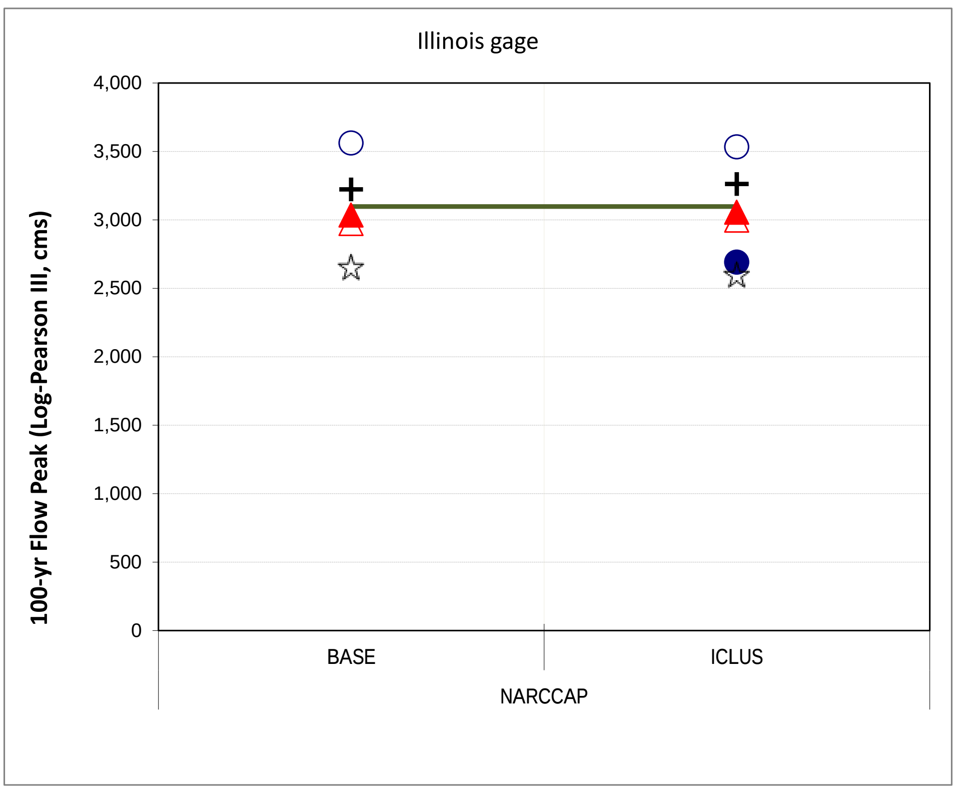


Figure 80. 100-yr Flow Peak (Log-Pearson III, cms), Illinois River at Marseilles Gage (SWAT)

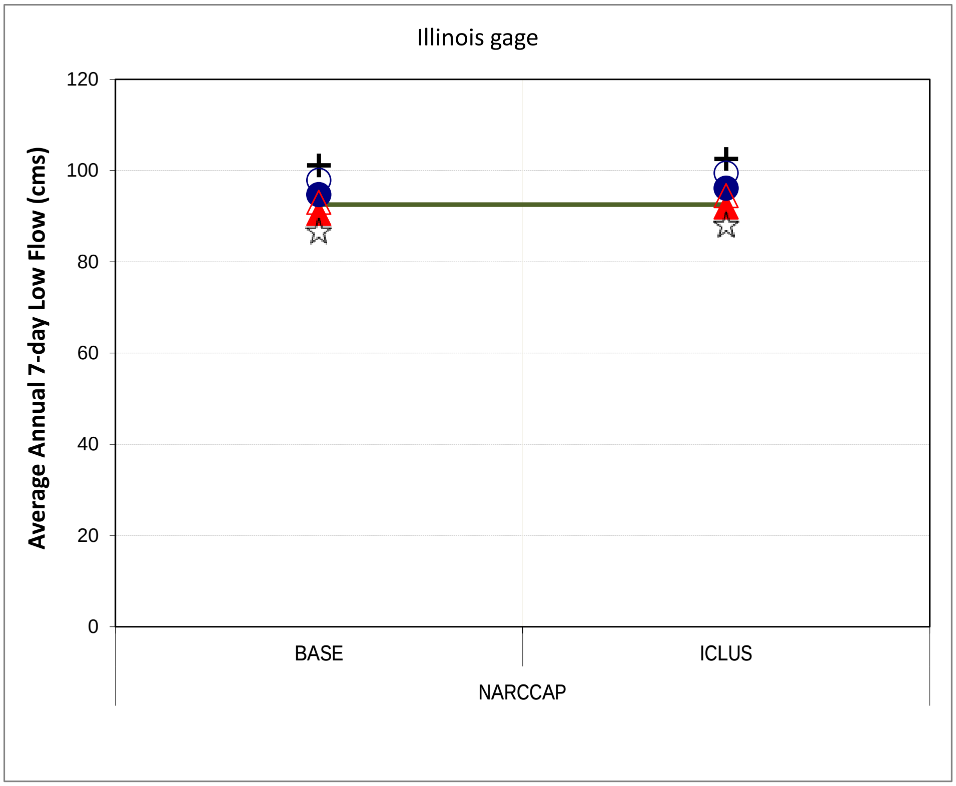


Figure 81. **Average Annual 7-day Low Flow (cms), Illinois River at Marseilles Gage (SWAT)**

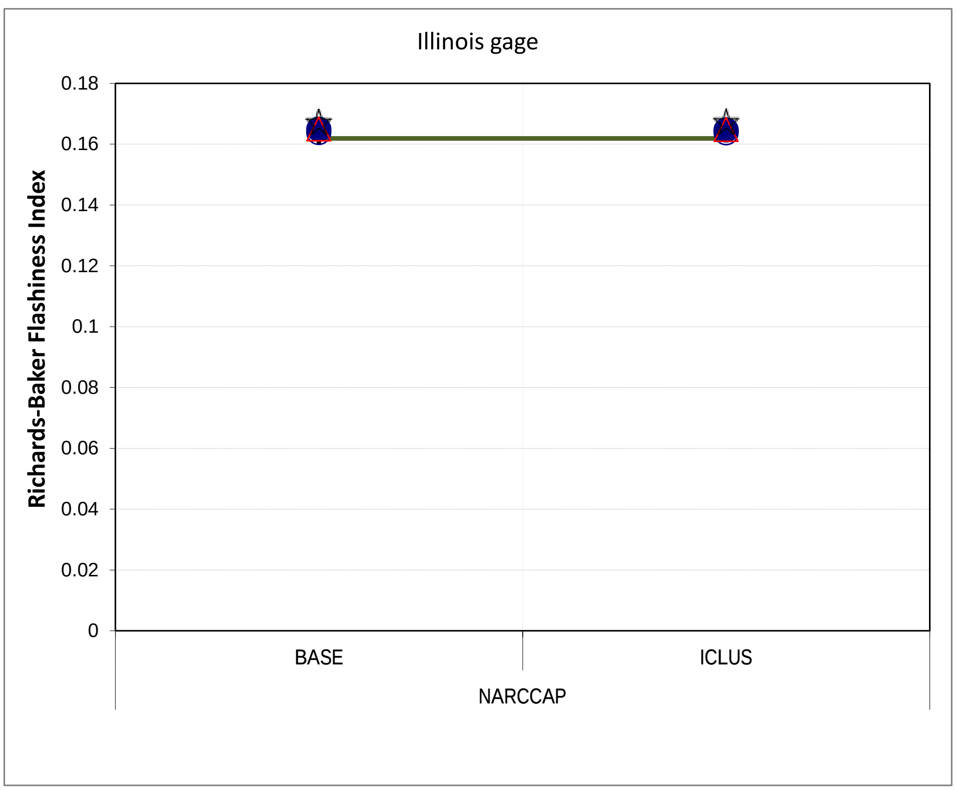


Figure 82. **Richards-Baker Flashiness Index, Average Annual 7-day Low Flow (cms), Illinois River at Marseilles Gage (SWAT)**

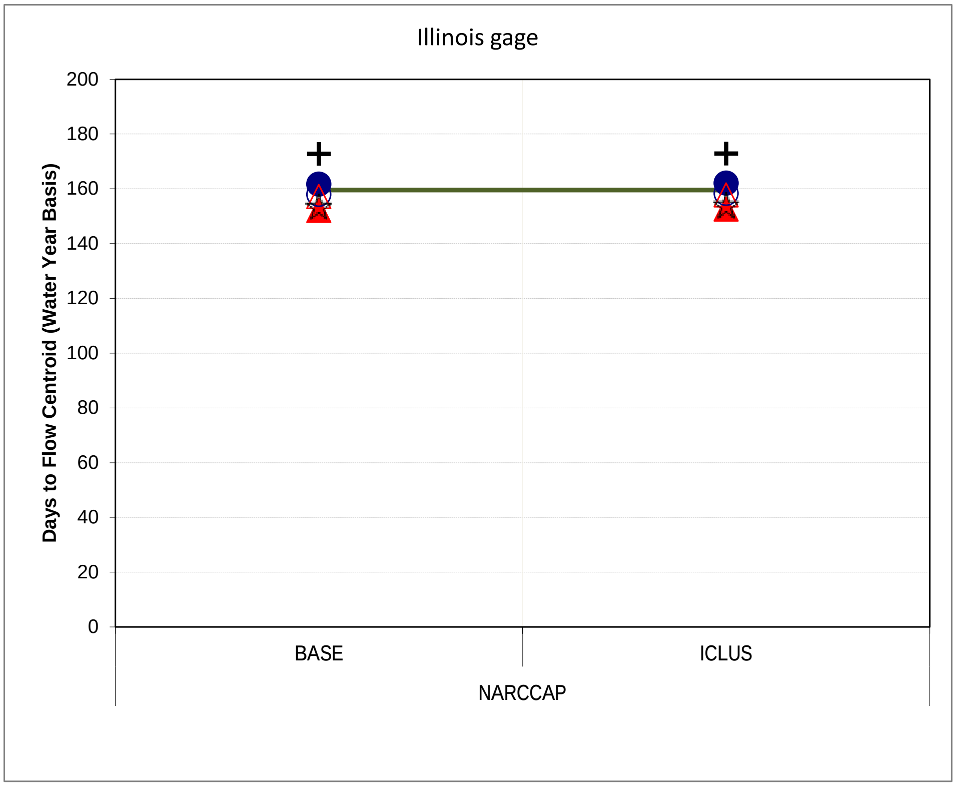


Figure 83. **Days to Flow Centroid (Water Year Basis), Illinois River at Marseilles Gage (SWAT)**

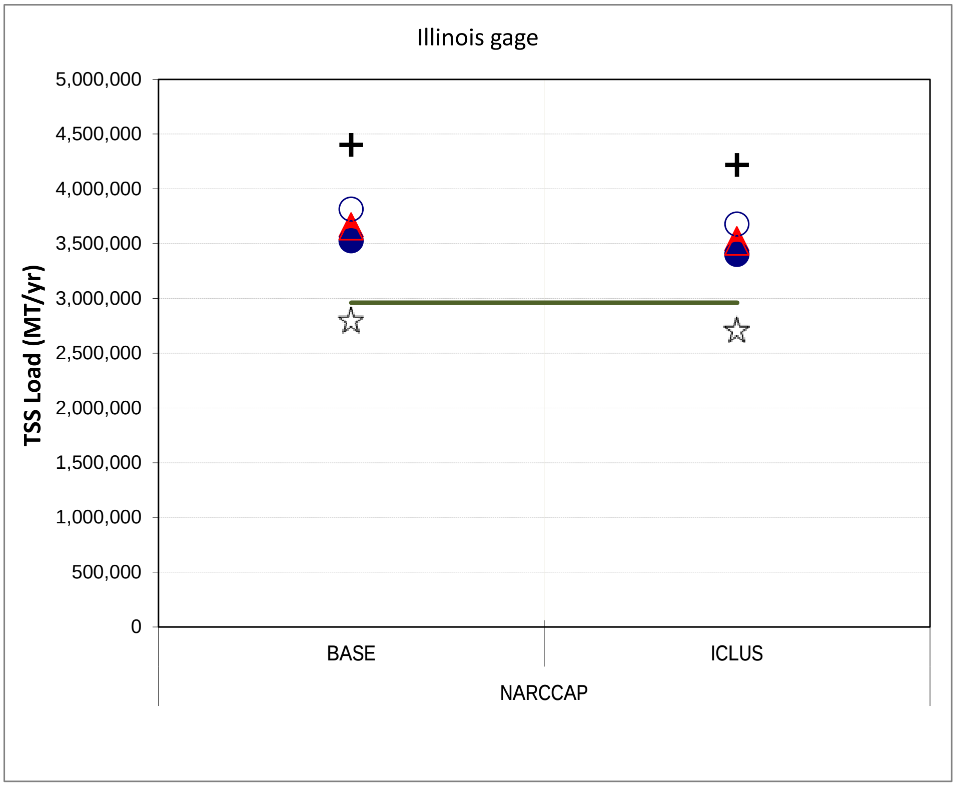


Figure 84. **TSS Load (MT/yr), Illinois River at Marseilles Gage (SWAT)**

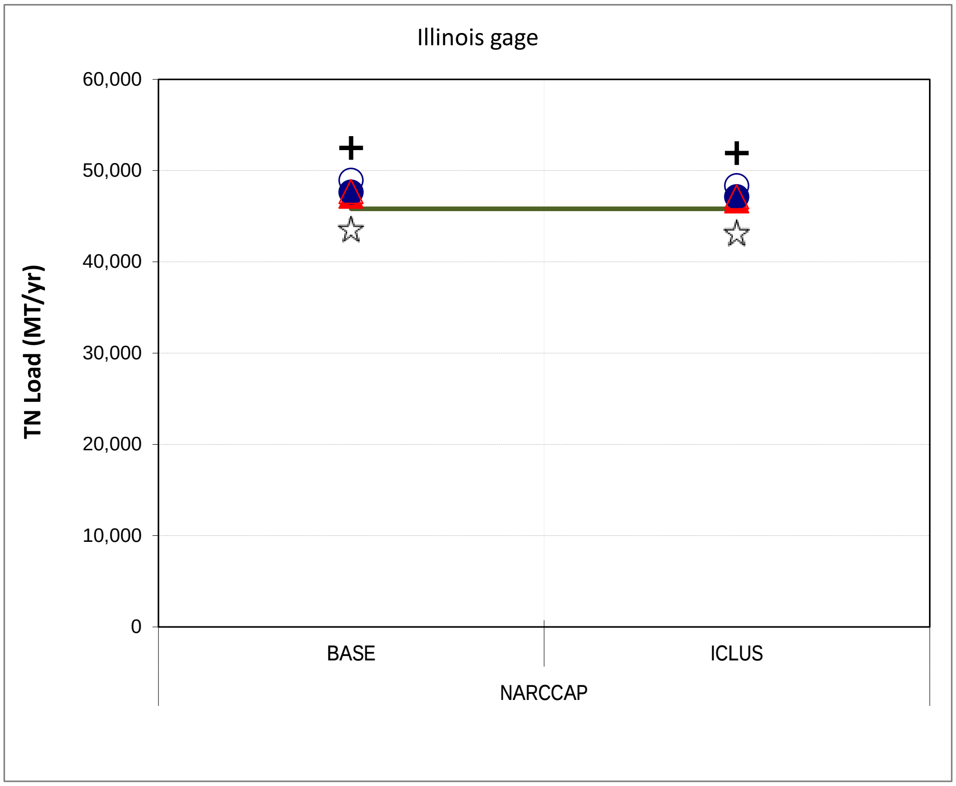


Figure 85. TN Load (MT/yr), Illinois River at Marseilles Gage (SWAT)

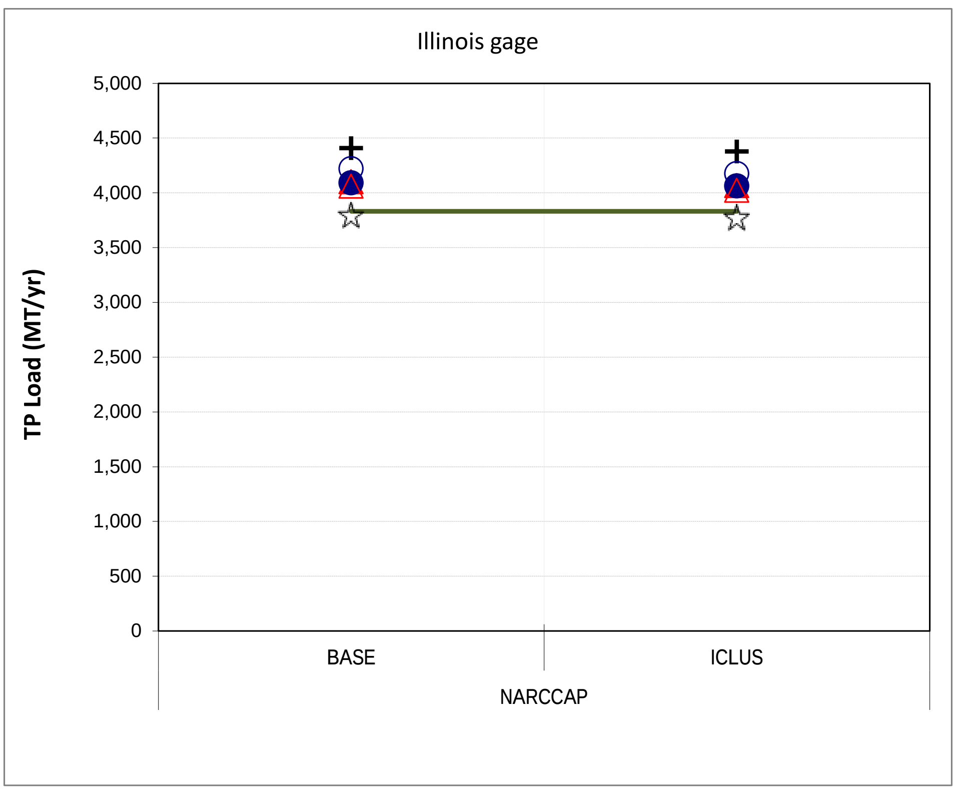


Figure 86. TP Load (MT/yr), Illinois River at Marseilles Gage (SWAT)

Table 4. Summary of range of change relative to existing conditions for NARCCAP dynamically downscaled scenarios, Illinois River basin SWAT model

	Results without LU change				Results with LU change			
	Min	**Median**	**Mean**	**Max**	**Min**	**Median**	**Mean**	**Max**
Kankakee HUC 07120001								
Flow	-21.45%	2.47%	3.59%	29.22%	-21.59%	2.08%	3.19%	28.55%
TSS	-4.70%	23.89%	25.87%	55.44%	-4.99%	23.13%	25.18%	54.44%
TN	-11.22%	4.31%	6.39%	24.79%	-10.86%	4.52%	6.74%	25.60%
TP	1.71%	20.63%	22.77%	41.20%	1.25%	19.38%	21.99%	41.12%
Iroquois HUC 07120002								
Flow	-19.02%	1.08%	2.38%	24.71%	-19.02%	1.08%	2.38%	24.71%
TSS	-1.36%	19.70%	22.64%	46.79%	-1.36%	19.69%	22.63%	46.77%
TN	-9.61%	3.63%	5.93%	22.43%	-9.63%	3.62%	5.93%	22.44%
TP	6.98%	25.45%	27.23%	43.90%	6.94%	25.43%	27.21%	43.90%
Des Plaines HUC 07120004								
Flow	-15.37%	1.06%	2.90%	30.24%	-16.38%	-0.98%	0.87%	26.80%
TSS	-7.59%	3.38%	3.87%	19.58%	-7.27%	3.11%	3.40%	17.52%
TN	1.54%	3.17%	4.01%	8.33%	2.72%	3.89%	4.89%	9.12%
TP	-0.95%	0.97%	1.77%	6.25%	-0.10%	1.29%	2.27%	6.67%
Upper Illinois HUC 07120005								
Flow	-13.76%	1.92%	1.90%	18.95%	-14.07%	1.39%	1.35%	18.13%
TSS	-3.34%	23.58%	23.64%	48.18%	-3.11%	22.89%	22.91%	46.20%
TN	-4.84%	3.04%	3.59%	12.71%	-4.34%	3.28%	3.90%	13.11%
TP	-0.78%	6.23%	6.67%	13.81%	-0.91%	5.75%	6.22%	13.47%
Upper Fox HUC 0120006								
Flow	-15.30%	6.91%	7.15%	34.00%	-16.54%	3.58%	3.85%	28.15%
TSS	-0.89%	27.24%	28.25%	59.62%	-6.85%	16.85%	17.17%	43.56%
TN	-3.41%	5.50%	5.56%	15.65%	-2.54%	5.69%	5.87%	15.56%
TP	-3.84%	4.68%	4.58%	13.37%	-4.29%	3.56%	3.52%	11.83%
Lower Fox HUC 0120007								
Flow	-19.24%	3.40%	3.91%	29.74%	-20.41%	0.54%	1.06%	24.97%
TSS	-5.98%	28.20%	27.28%	58.02%	-6.48%	26.05%	25.05%	53.73%
TN	-3.68%	8.72%	8.80%	21.69%	-2.70%	9.00%	9.09%	21.61%
TP	-4.31%	8.80%	8.09%	19.62%	-5.22%	6.76%	6.12%	17.14%
Lower Illinois-Senachwine HUC 07130001								
Flow	-15.36%	3.02%	2.39%	21.65%	-15.85%	2.05%	1.45%	20.22%
TSS	-5.82%	25.70%	24.77%	52.66%	-5.81%	24.84%	23.91%	50.68%
TN	-4.57%	5.67%	5.54%	16.21%	-4.02%	5.89%	5.83%	16.48%
TP	-1.58%	6.95%	7.40%	15.77%	-2.01%	6.15%	6.56%	14.90%
Vermillion HUC 07130002								
Flow	-17.02%	5.33%	4.19%	25.88%	-17.02%	5.33%	4.18%	25.88%
TSS	-0.45%	20.30%	22.43%	46.88%	-0.53%	20.21%	22.34%	46.82%

	Results without LU change				Results with LU change			
	Min	**Median**	**Mean**	**Max**	**Min**	**Median**	**Mean**	**Max**
TN	-7.19%	9.15%	9.13%	24.45%	-7.19%	9.09%	9.10%	24.48%
TP	9.87%	24.75%	26.19%	38.87%	9.85%	24.68%	26.13%	38.88%
Lower Illinois-Chatauqua HUC 07130003								
Flow	-22.22%	1.49%	0.68%	24.55%	-22.56%	0.73%	-0.06%	23.37%
TSS	-9.74%	18.25%	18.44%	41.52%	-9.81%	18.21%	18.27%	41.03%
TN	-7.11%	6.95%	6.38%	18.30%	-6.71%	7.09%	6.59%	18.40%
TP	-0.59%	7.55%	7.84%	13.24%	-0.73%	7.25%	7.56%	12.97%
Mackinaw HUC 07130004								
Flow	-14.96%	5.97%	5.18%	21.81%	-14.97%	5.92%	5.13%	21.73%
TSS	-0.53%	20.39%	21.41%	34.77%	-0.41%	20.45%	21.44%	34.76%
TN	-0.05%	12.48%	12.33%	20.57%	0.30%	12.61%	12.60%	20.92%
TP	8.38%	23.27%	24.11%	38.81%	8.52%	23.15%	24.06%	38.53%
Kankakee gage 05520500								
Flow	-23.05%	3.44%	5.13%	33.23%	-23.18%	3.03%	4.68%	32.45%
TSS	-8.32%	20.60%	24.03%	51.31%	-8.56%	19.71%	23.18%	50.16%
TN	-12.85%	4.24%	6.82%	26.37%	-12.08%	4.78%	7.56%	27.42%
TP	-2.31%	18.25%	21.51%	42.18%	-2.24%	17.52%	21.12%	42.26%
Illinois River at Marseilles gage 05543500								
Flow	-14.29%	2.23%	2.05%	19.70%	-14.56%	1.73%	1.54%	18.92%
TSS	-5.10%	23.52%	23.10%	48.70%	-4.89%	23.03%	22.59%	47.25%
TN	-4.61%	4.07%	4.64%	14.55%	-4.14%	4.31%	4.96%	14.94%
TP	-0.61%	6.93%	7.41%	15.05%	-0.80%	6.51%	6.97%	14.71%

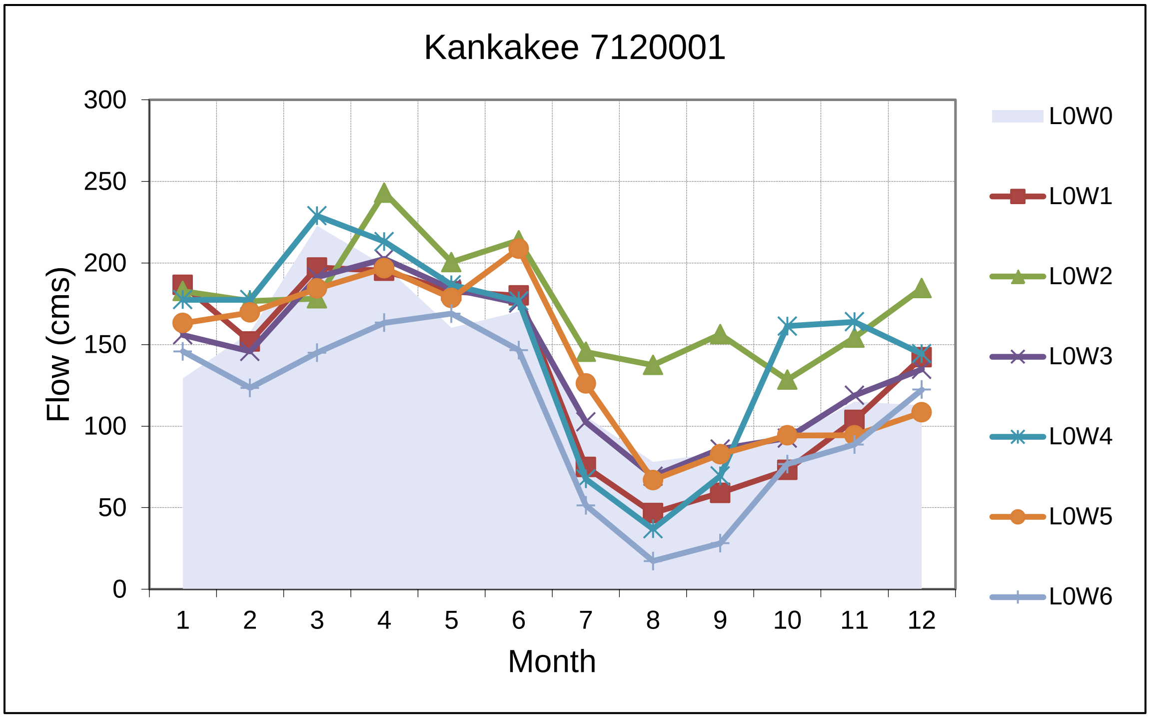


Figure 87. Monthly average flows, Kankakee River (SWAT)

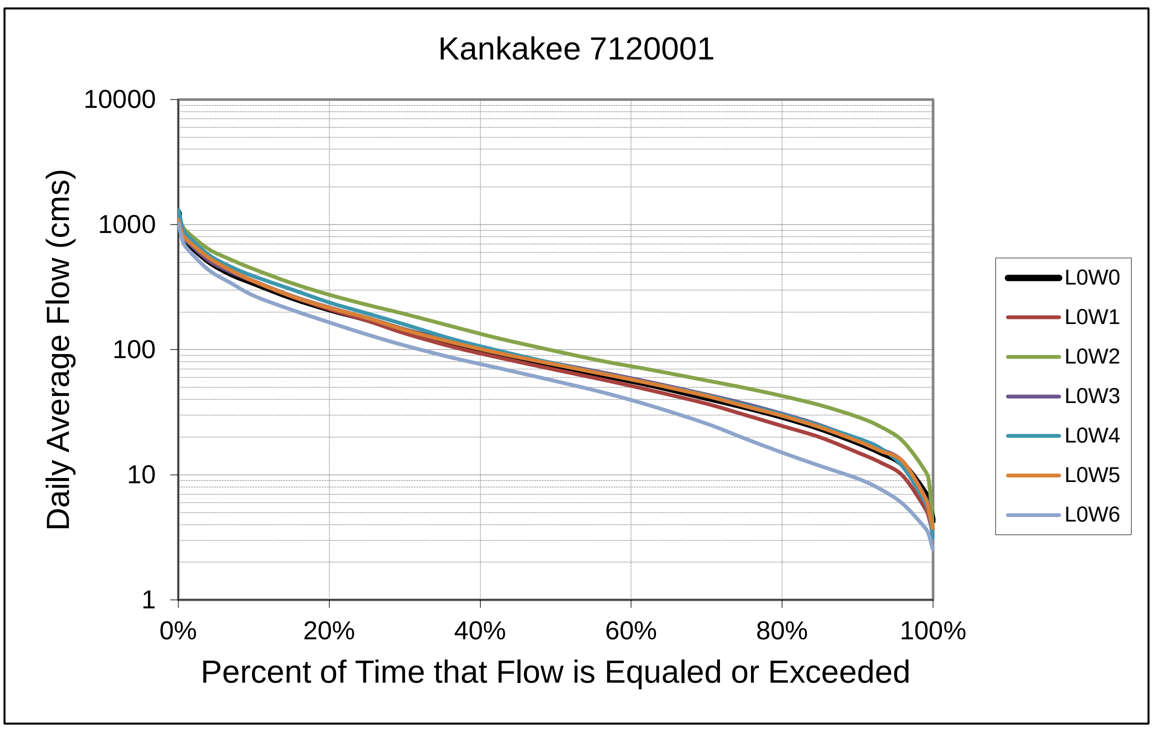


Figure 88. Flow duration, Kankakee River (SWAT)

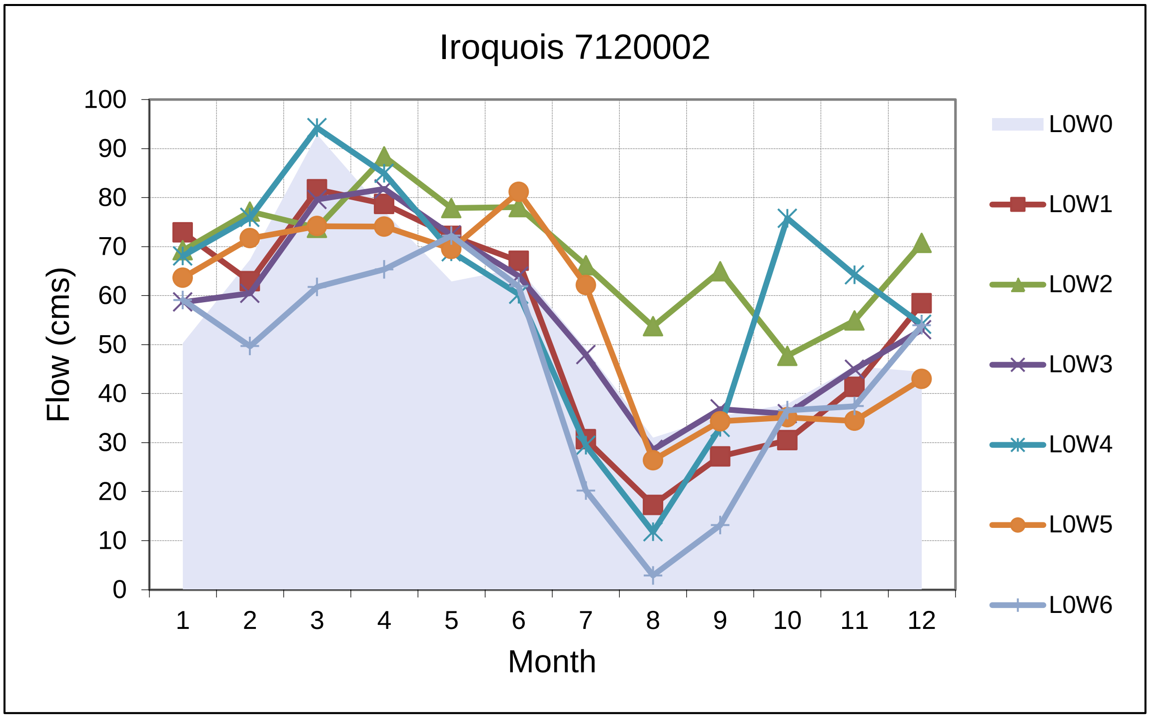


Figure 89. Monthly average flows, Iroquois River (SWAT)

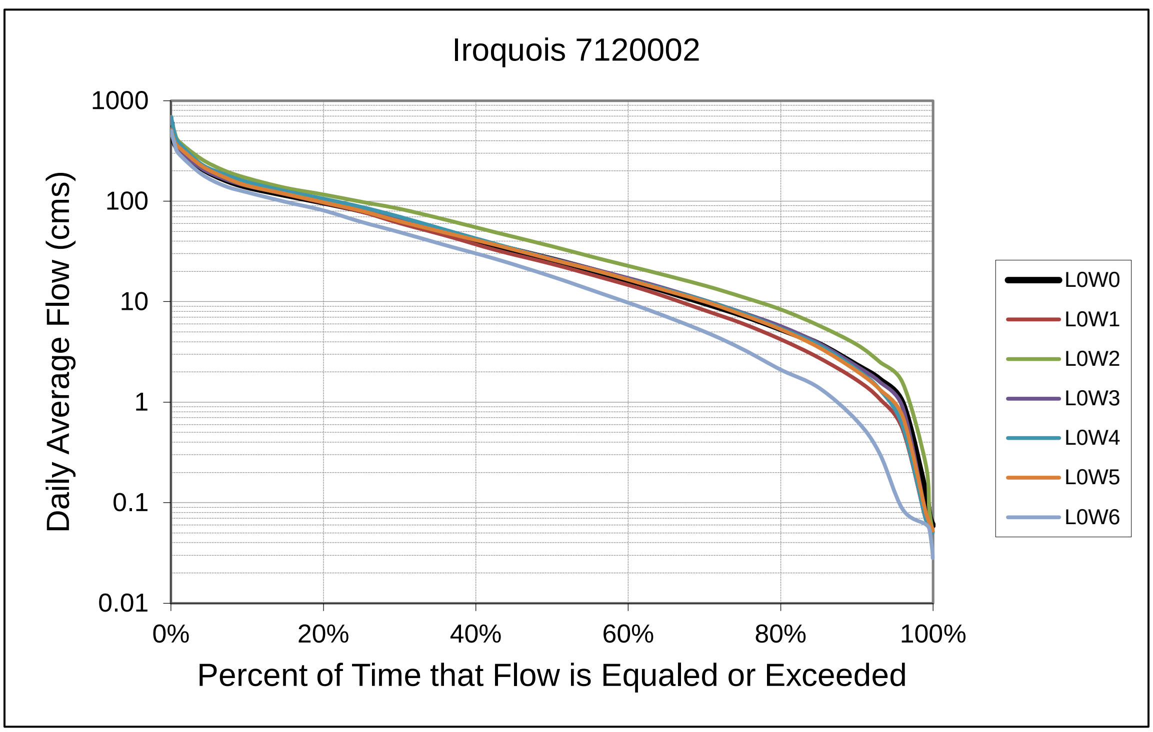


Figure 90. Flow duration, Iroquois River (SWAT)

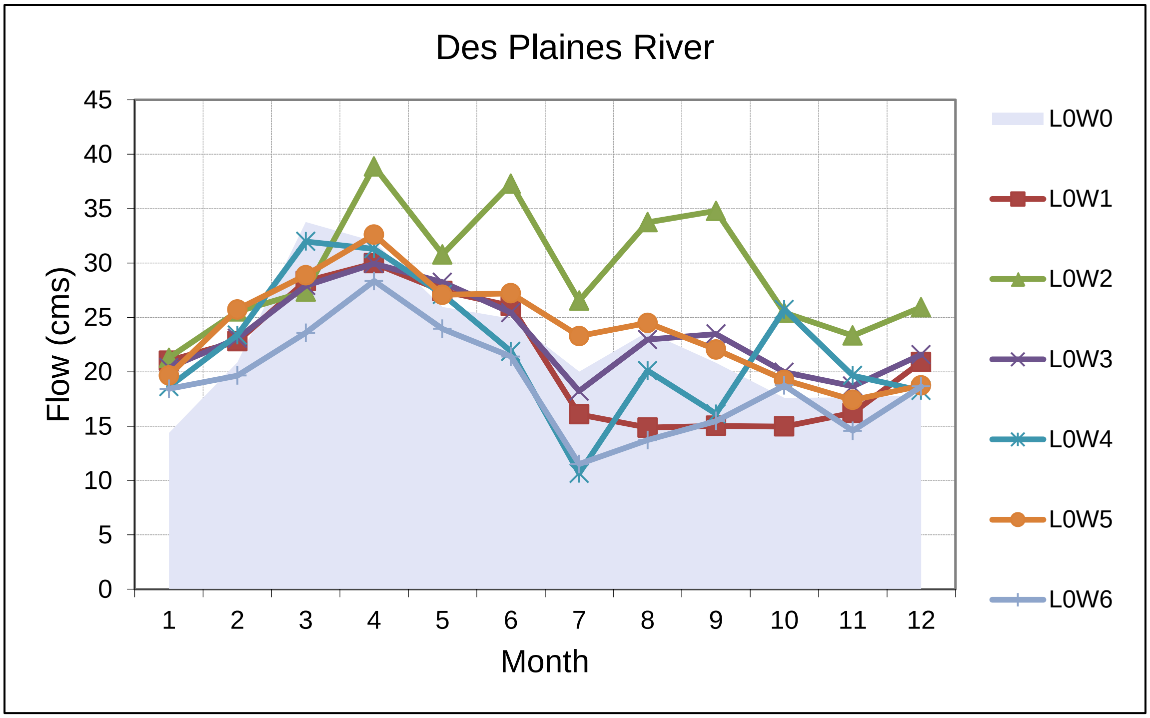


Figure 91. **Monthly average flows, Des Plaines River (SWAT)**

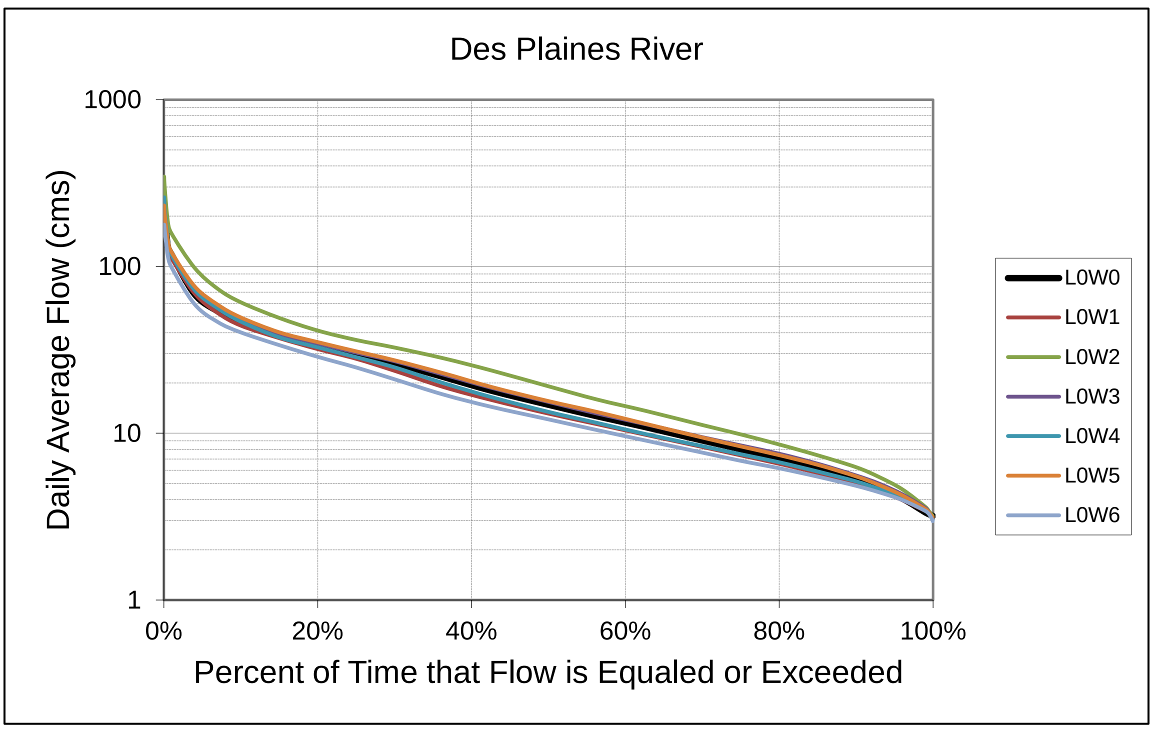


Figure 92. **Flow duration, Des Plaines River (SWAT)**

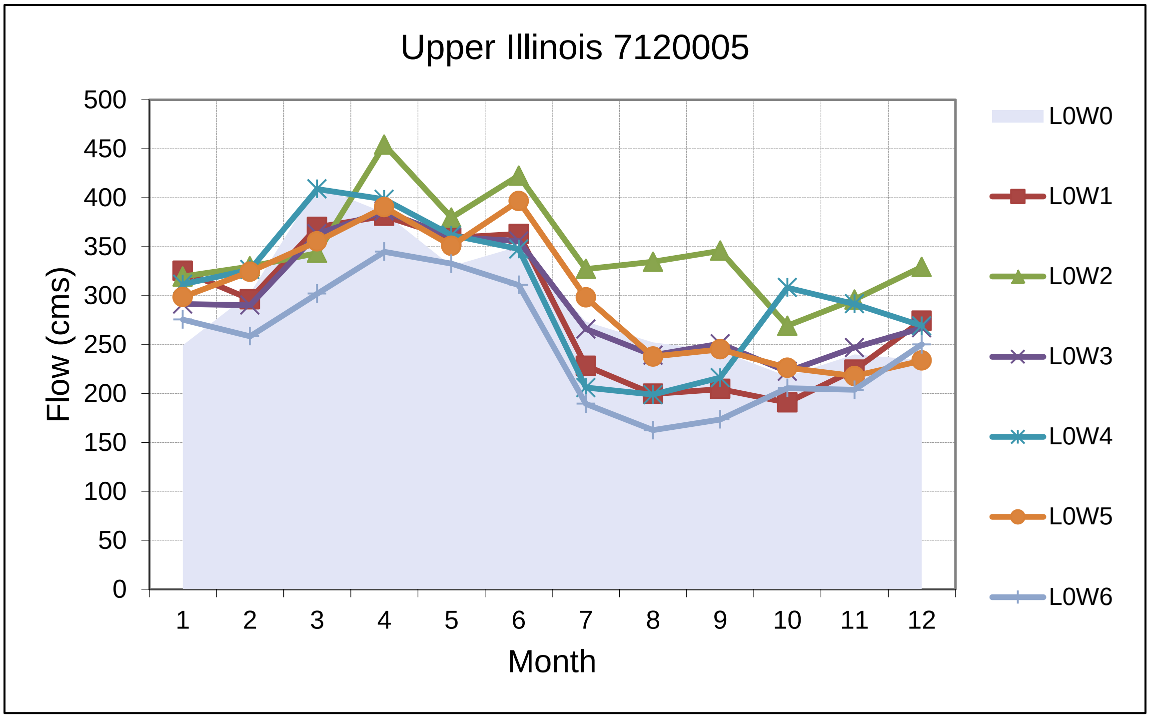


Figure 93. Monthly average flows, Upper Illinois River (SWAT)

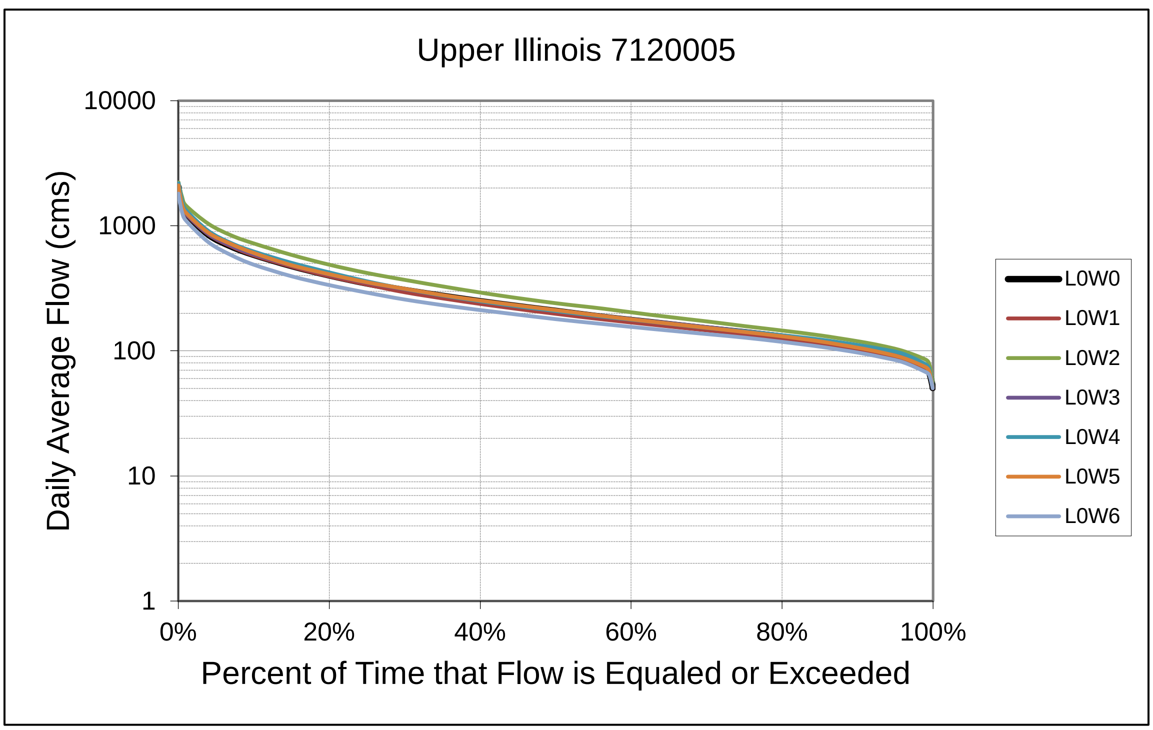


Figure 94. Flow duration, Upper Illinois River (SWAT)

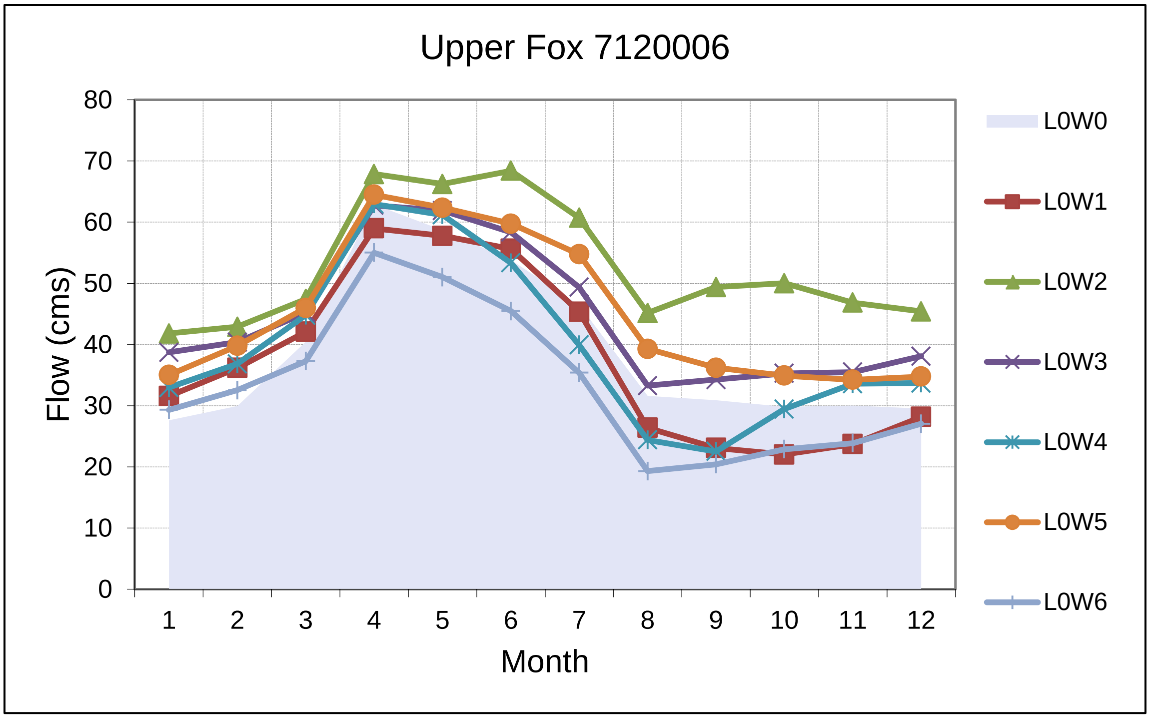


Figure 95. **Monthly average flows, Upper Fox River (SWAT)**

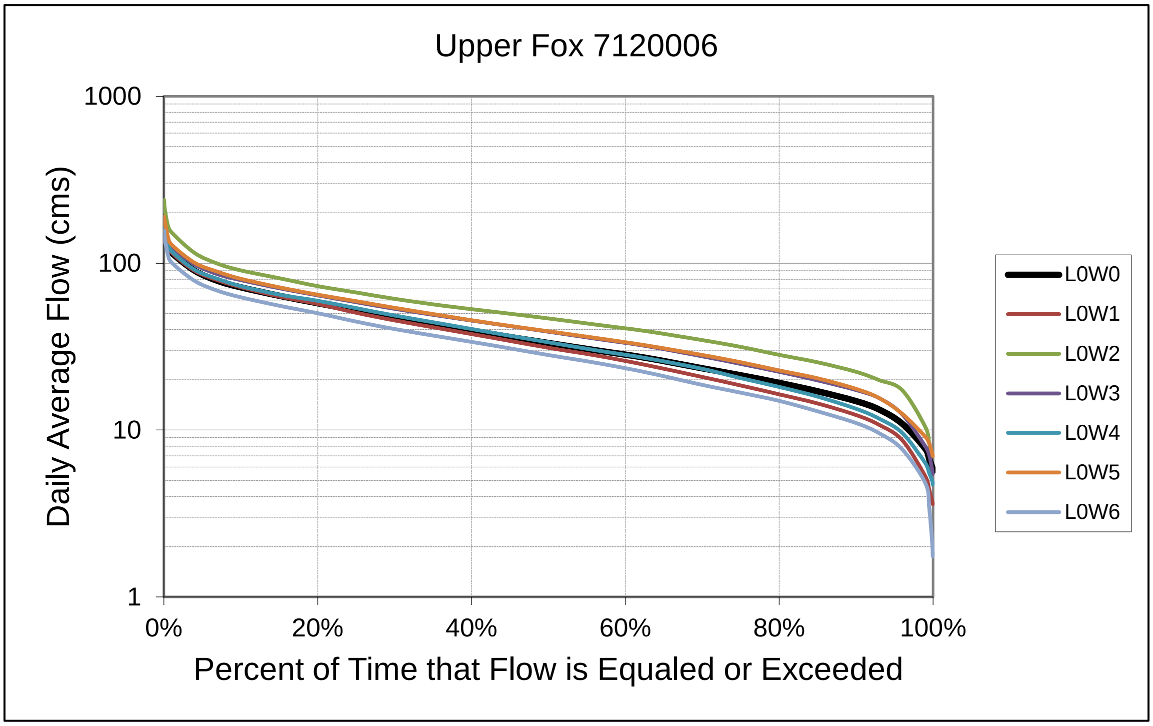


Figure 96. **Flow duration, Upper Fox River (SWAT)**

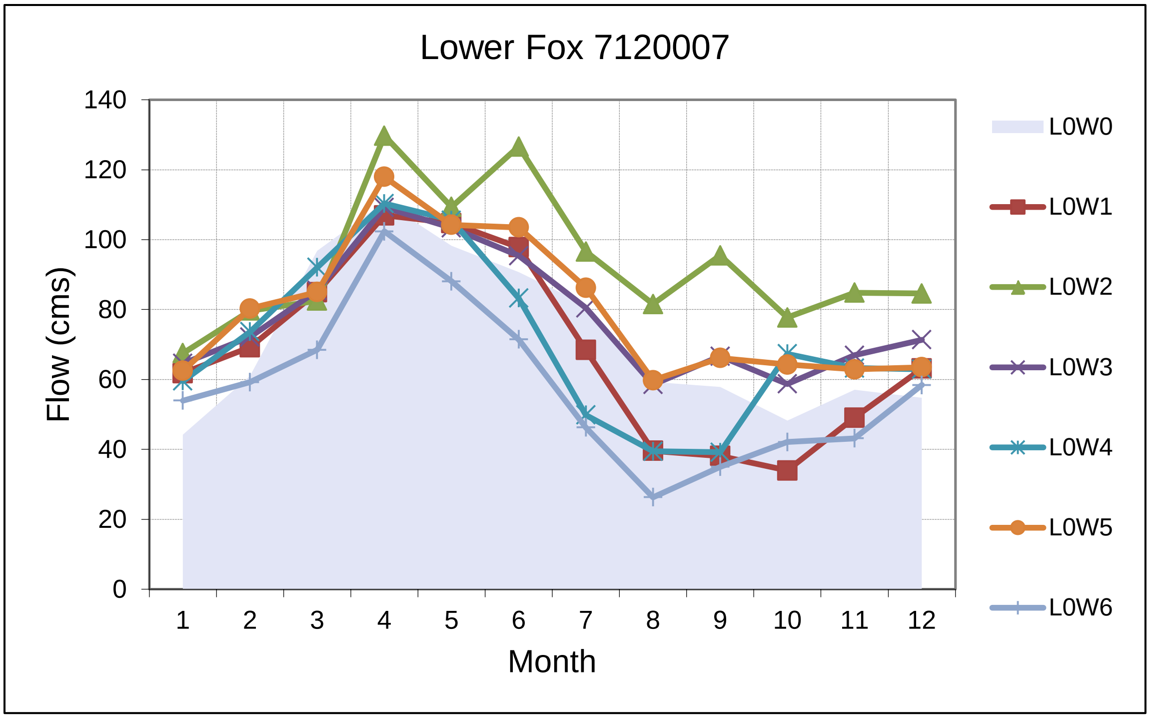


Figure 97. **Monthly average flows, Lower Fox River (SWAT)**

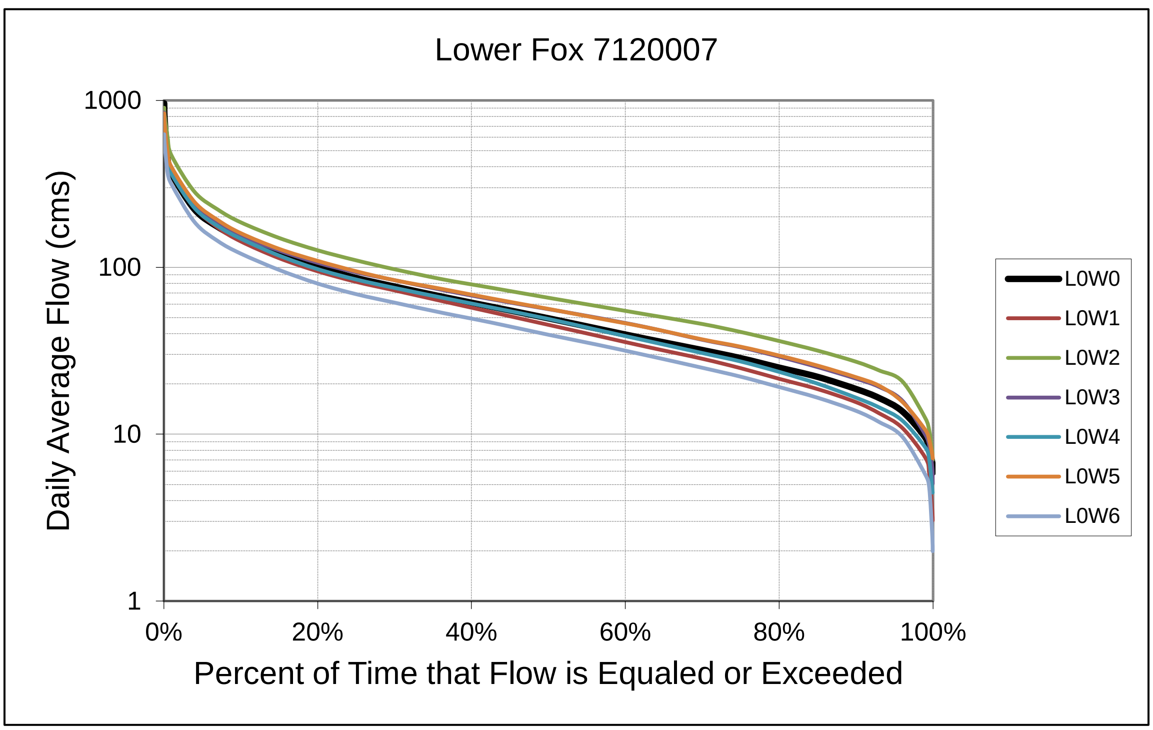


Figure 98. **Flow duration, Lower Fox River (SWAT)**

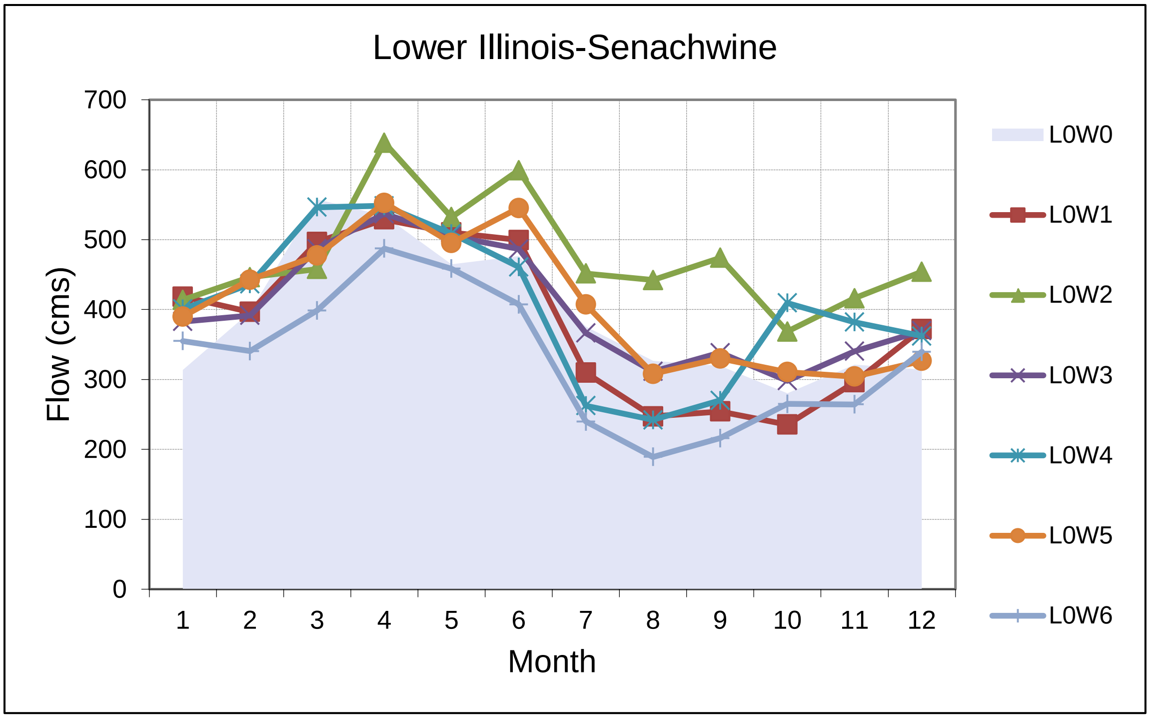


Figure 99. Monthly average flows, Lower Illinois-Senachwine River (SWAT)

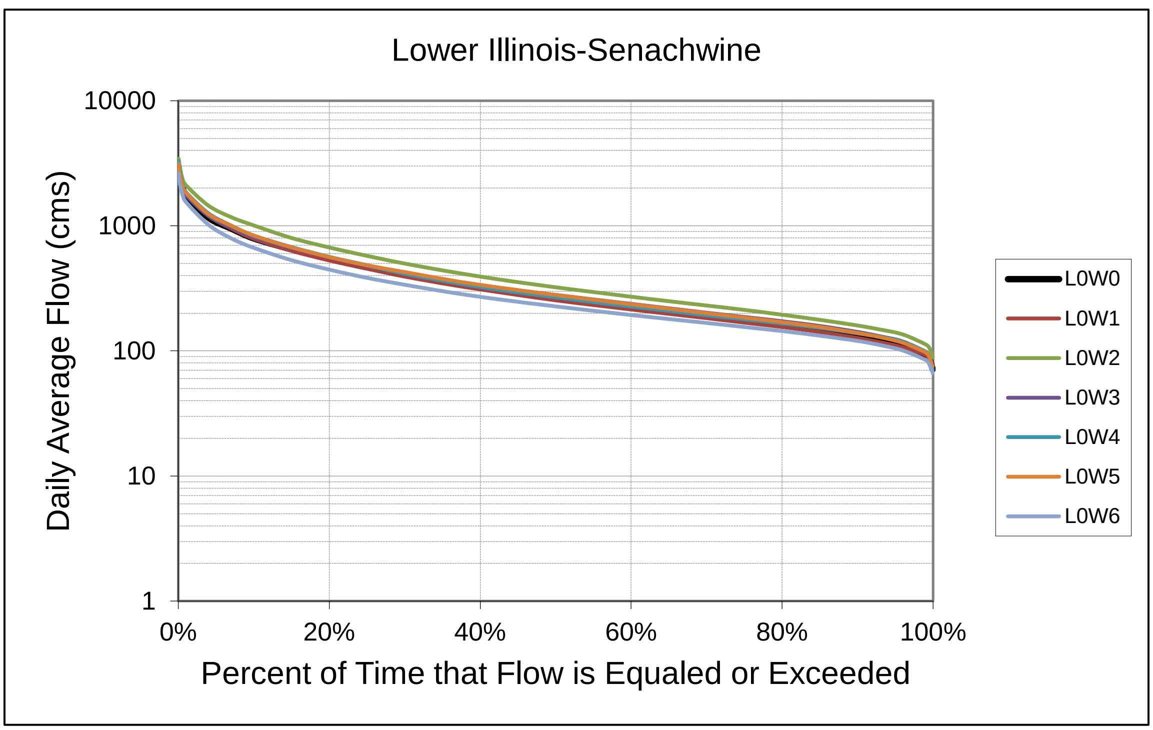


Figure 100. Flow duration, Lower Illinois-Senachwine River (SWAT)

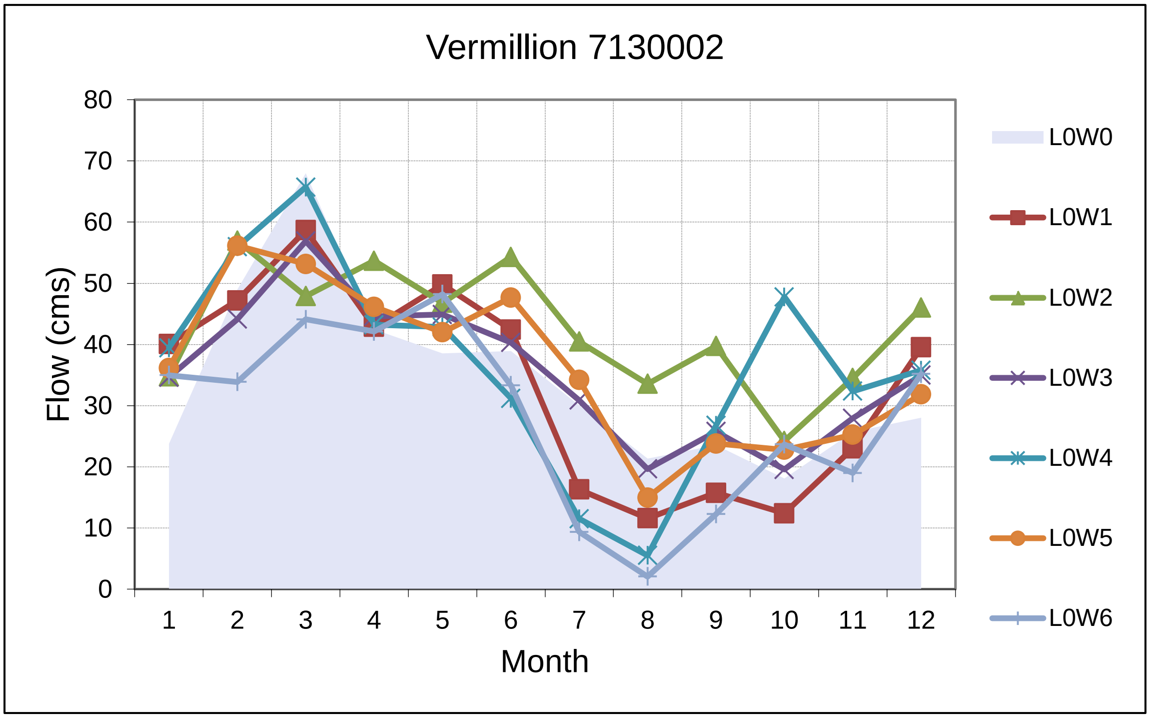


Figure 101. **Monthly average flows, Vermillion River (SWAT)**

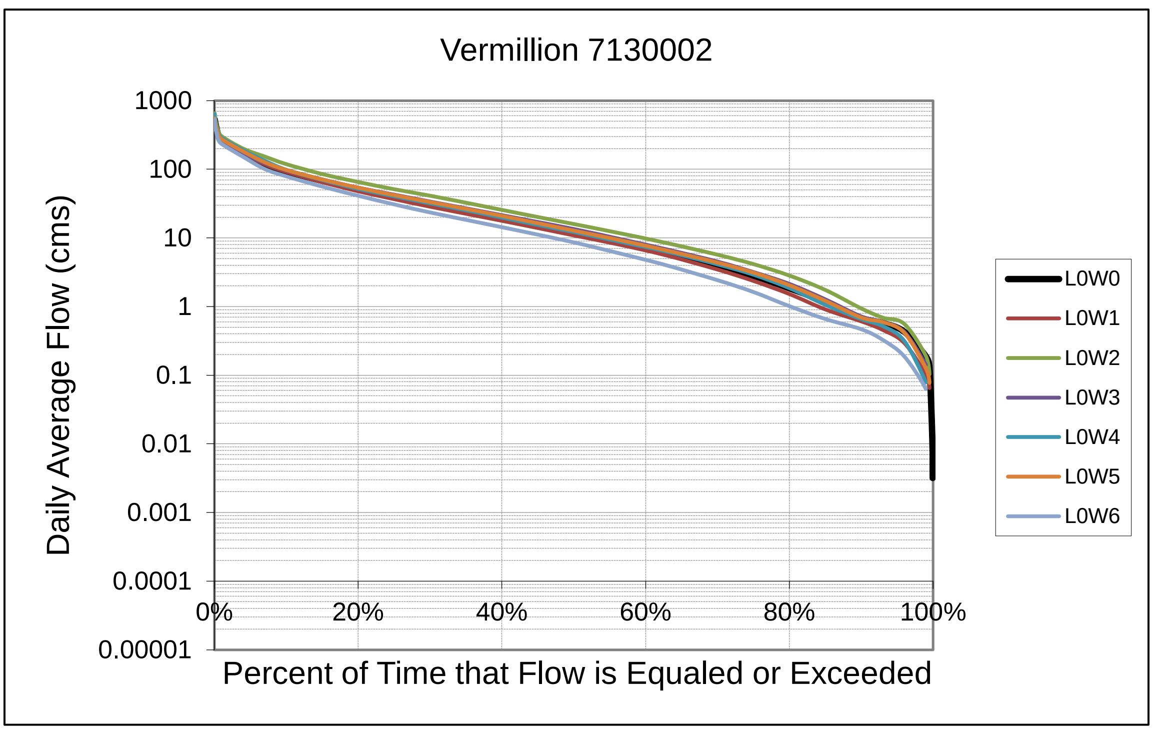


Figure 102. **Flow duration, Vermillion River (SWAT)**

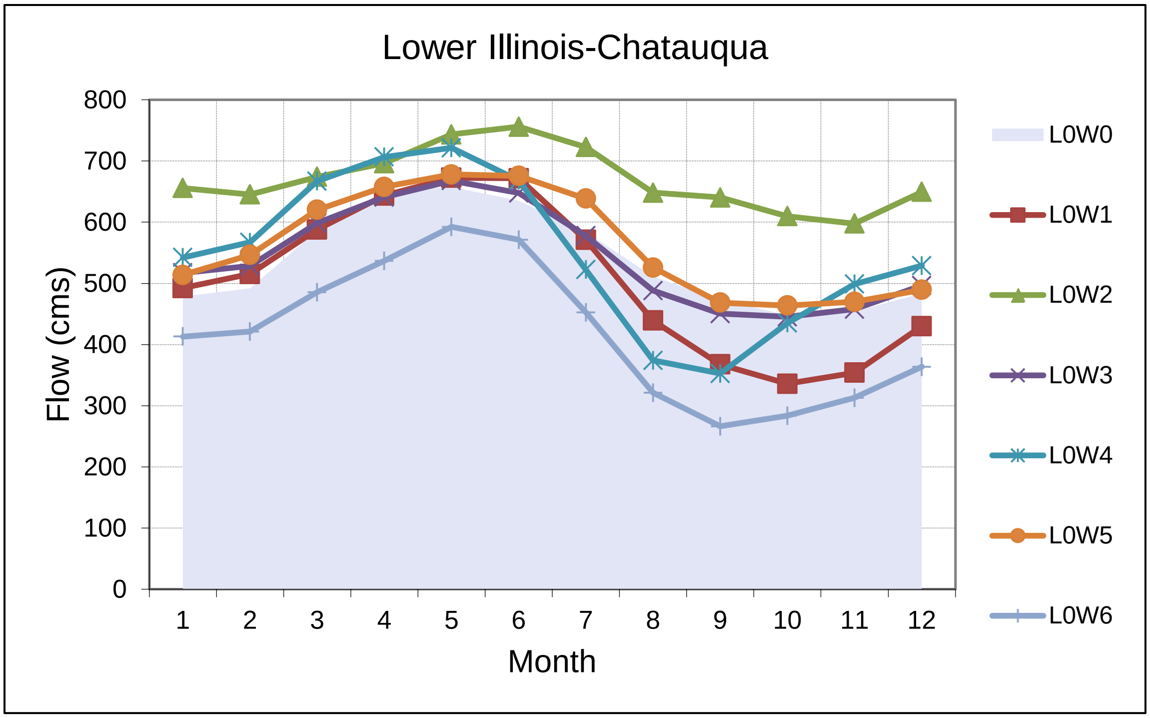


Figure 103. **Monthly average flows, Lower Illinois River – Lake Chatauqua (SWAT)**

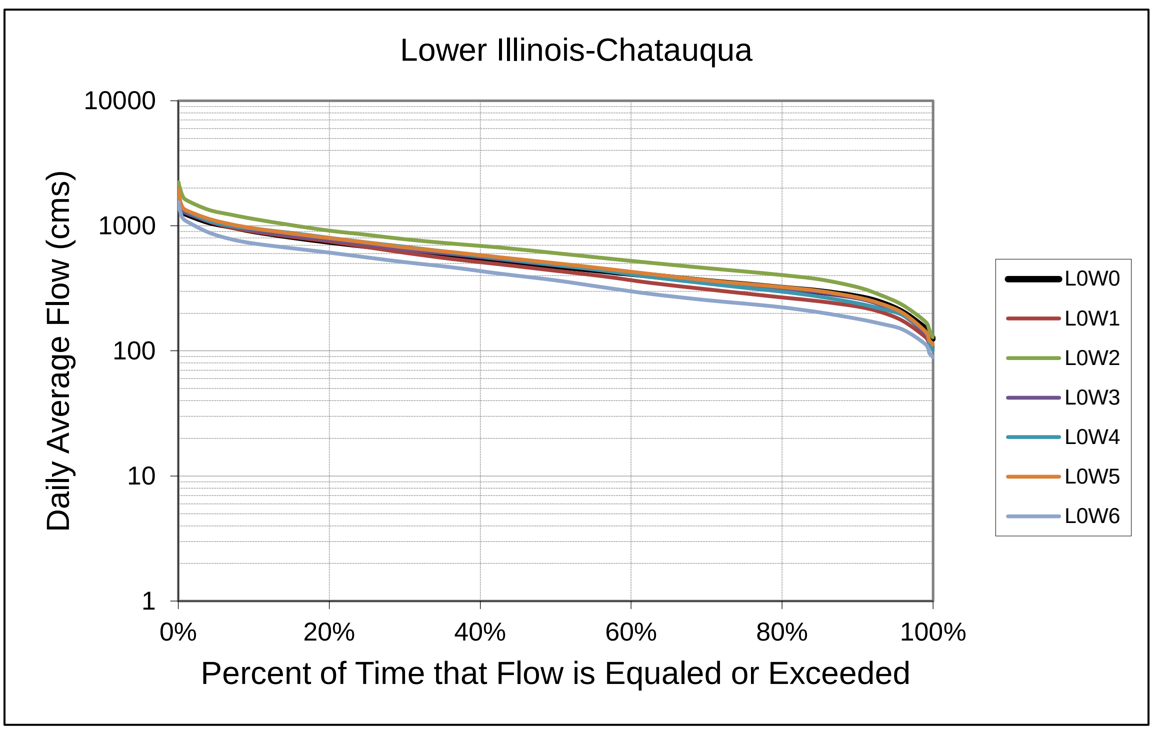


Figure 104. **Flow duration, Lower Illinois River – Lake Chatauqua (SWAT)**

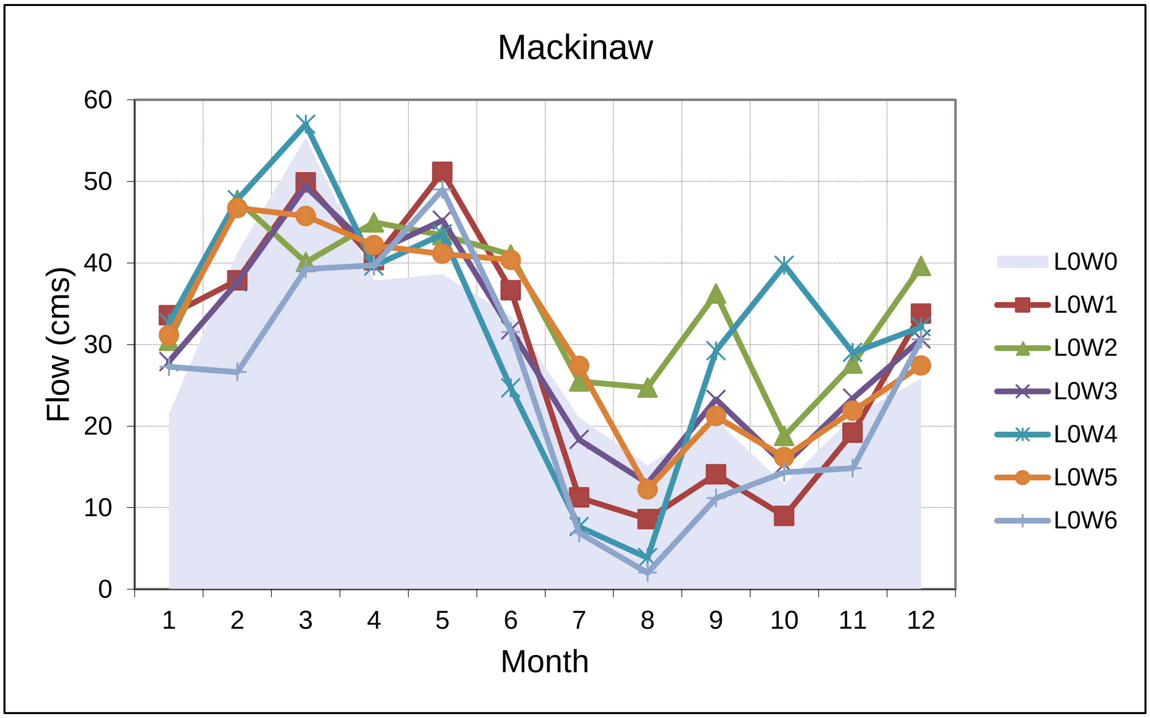


Figure 105. Monthly average flows, Mackinaw River (SWAT)

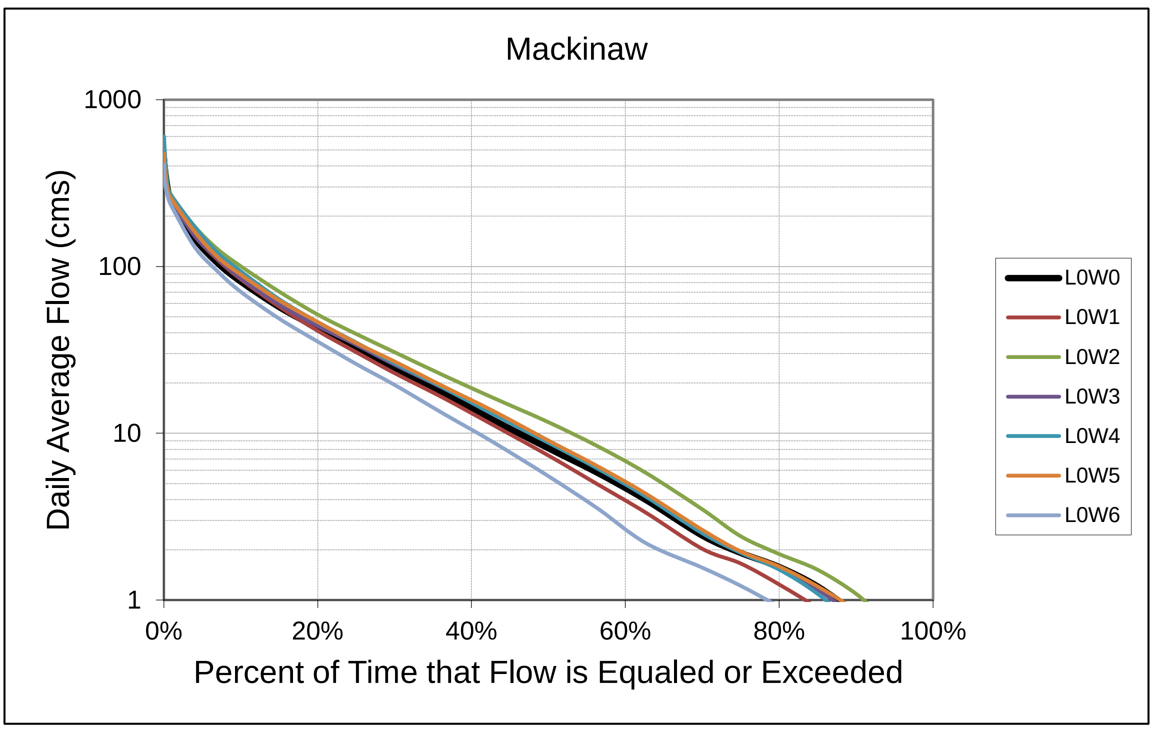


Figure 106. Flow duration, Mackinaw River (SWAT)

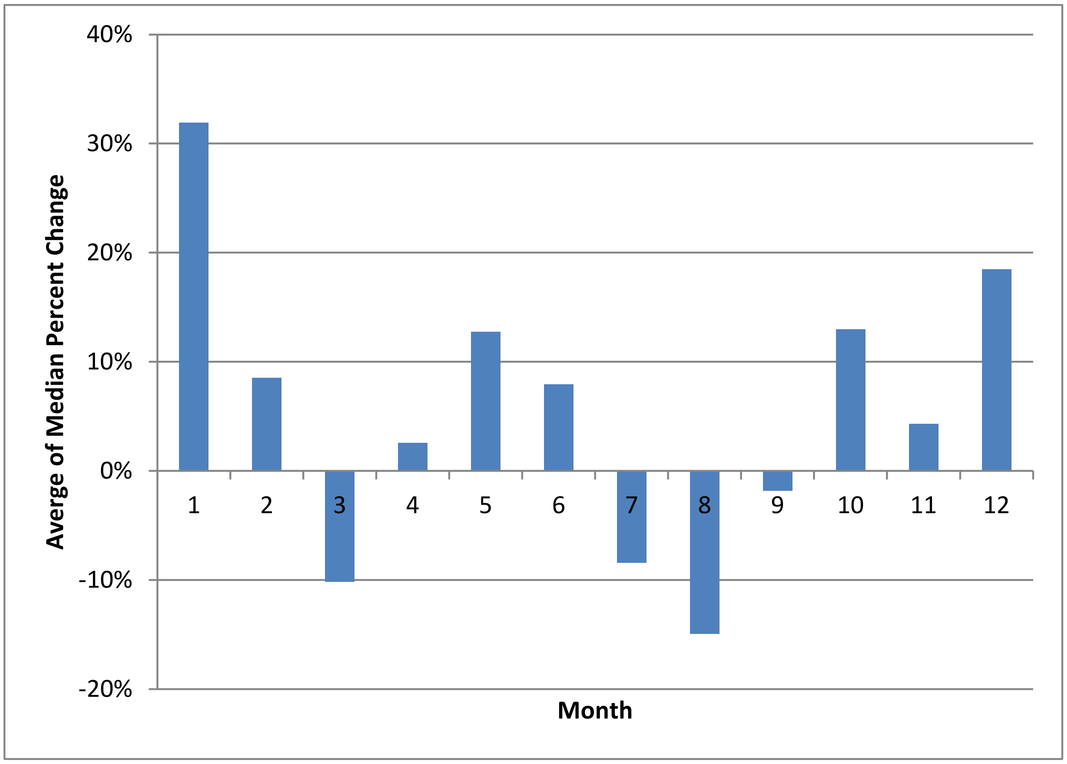


Figure 107. Average of median percent change in flow; NARCCAP Scenarios W1-W6 at all stations, Illinois River basin (SWAT)

Lake Erie Drainages

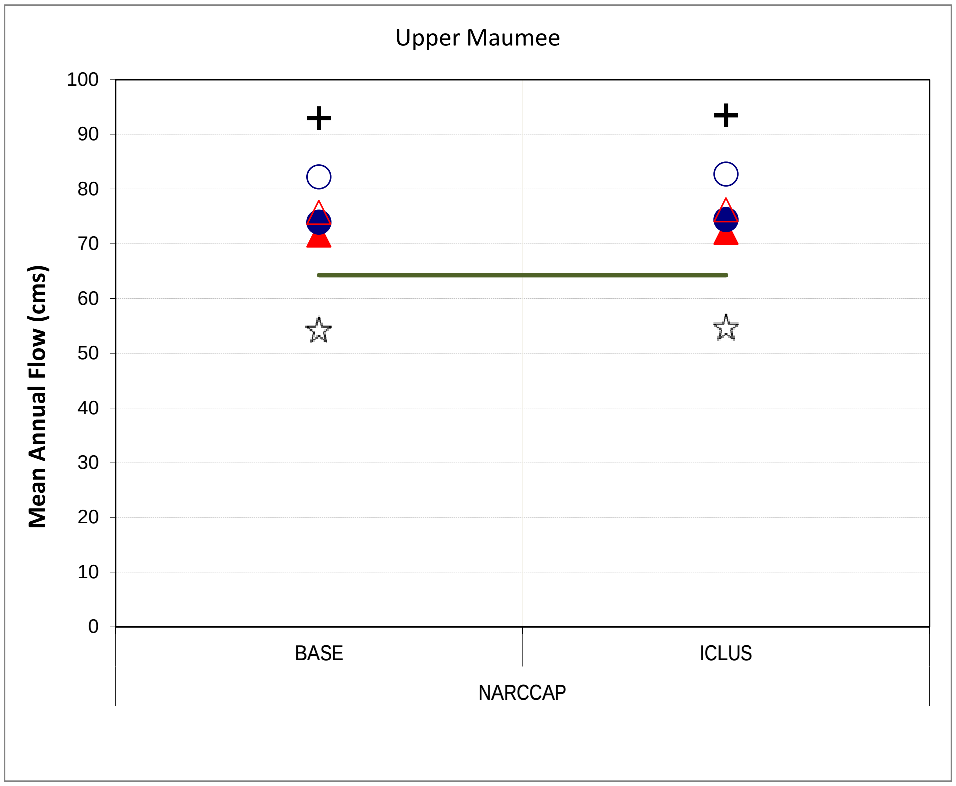


Figure 108. Mean annual flow (cms), Upper Maumee River (SWAT)

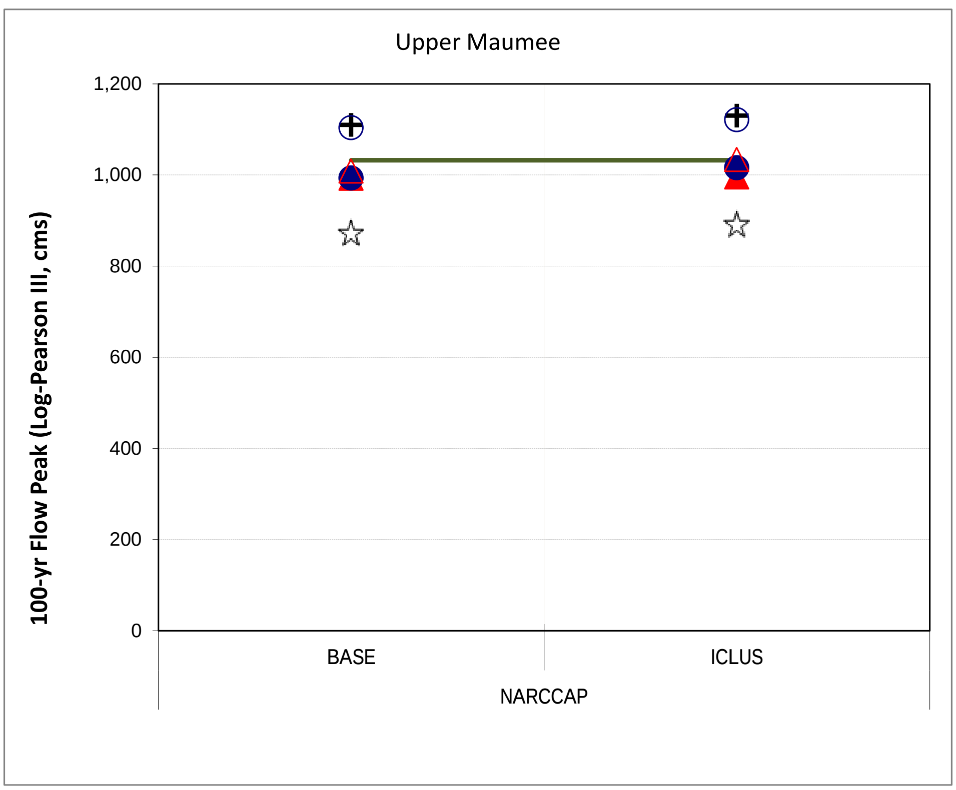


Figure 109. 100-yr Flow Peak (Log-Pearson III, cms), Upper Maumee River (SWAT)

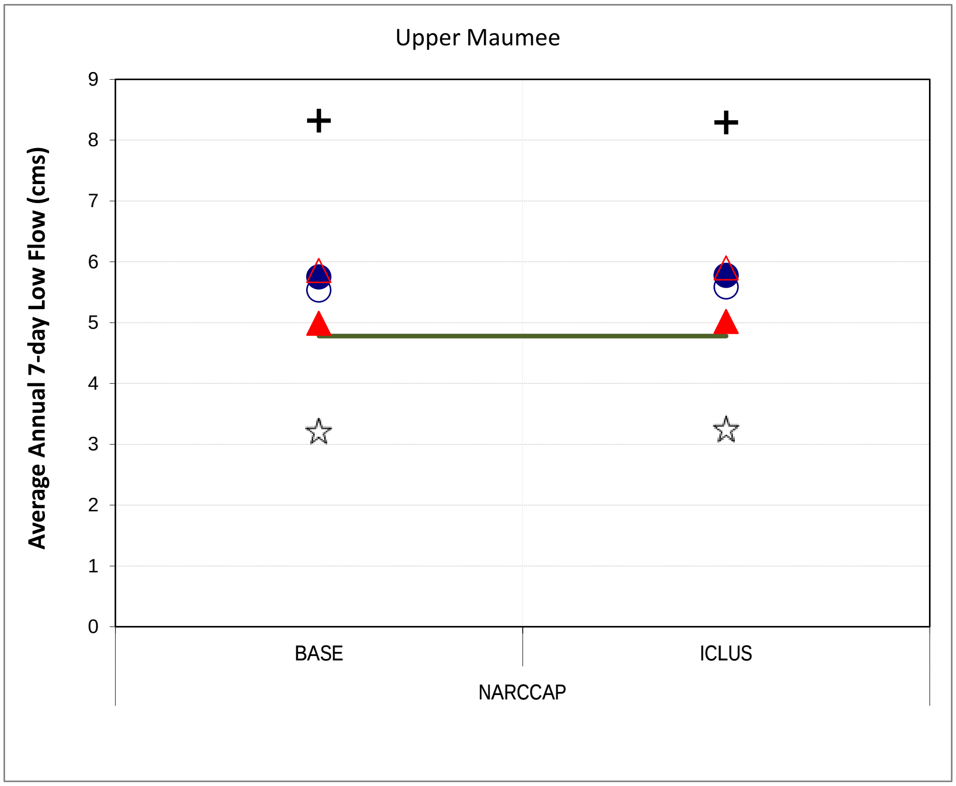


Figure 110. **Average Annual 7-day Low Flow (cms), Upper Maumee River (SWAT)**

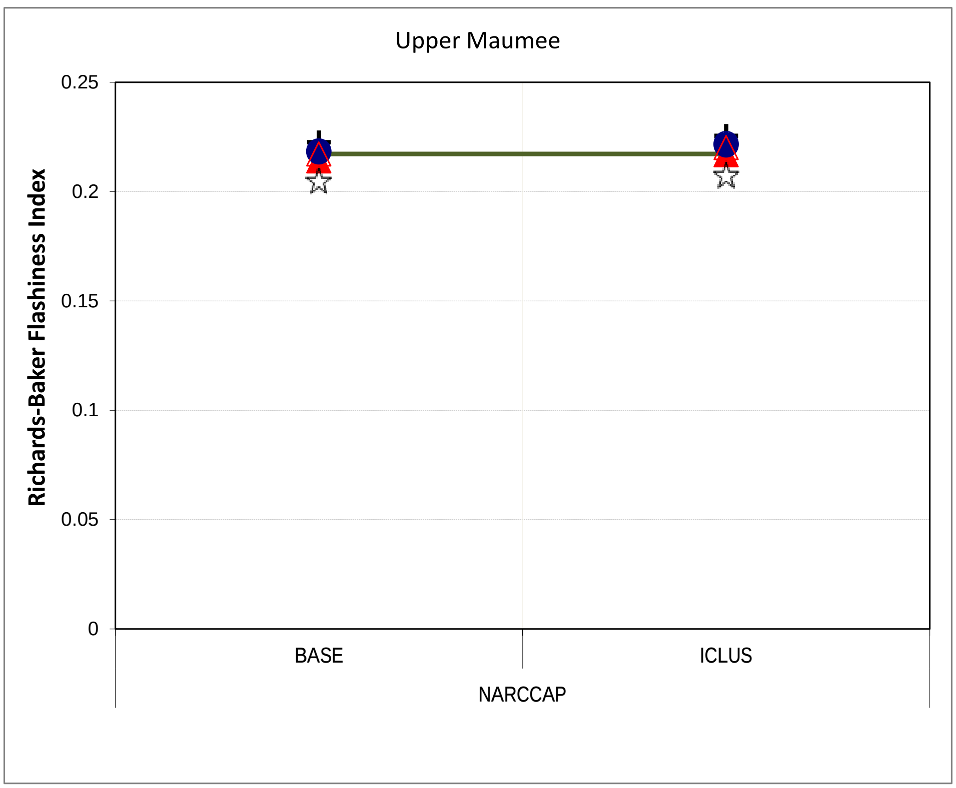


Figure 111. **Richards-Baker Flashiness Index, Average Annual 7-day Low Flow (cms), Upper Maumee River (SWAT)**

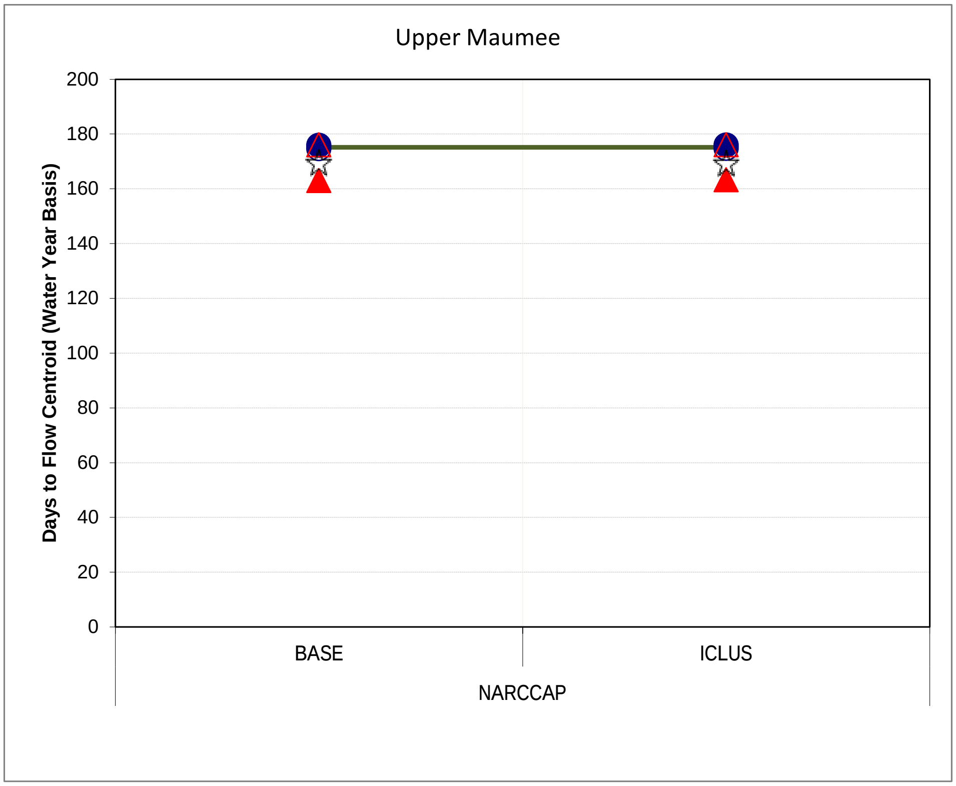


Figure 112. **Days to Flow Centroid (Water Year Basis), Upper Maumee River (SWAT)**

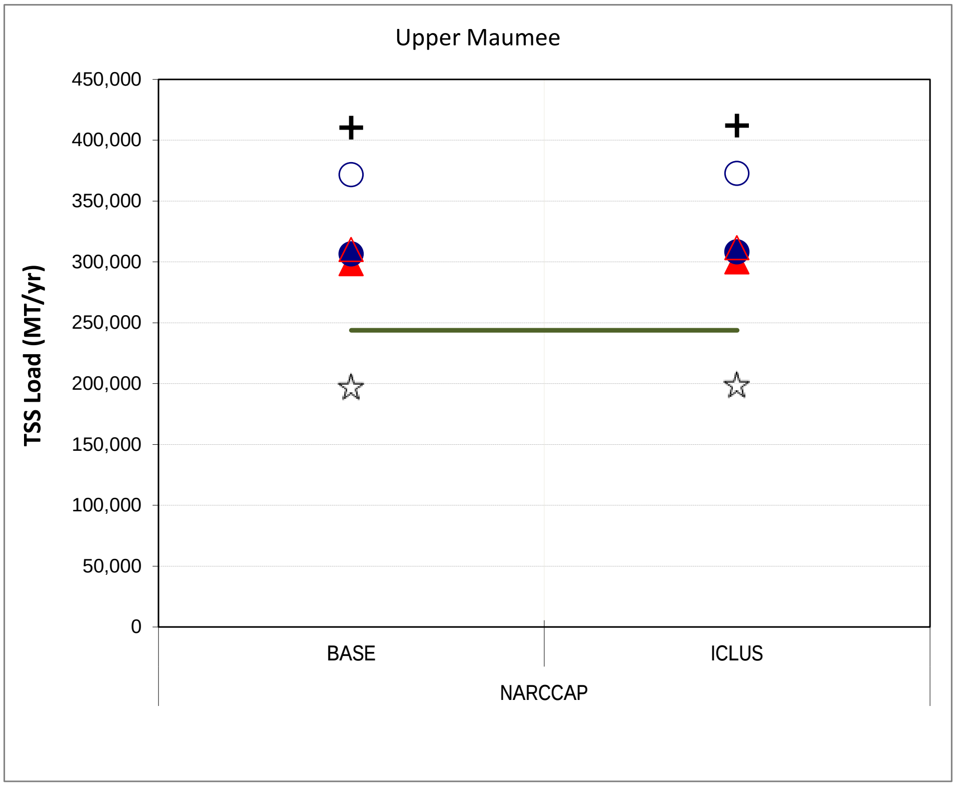


Figure 113. **TSS Load (MT/yr), Upper Maumee River (SWAT)**

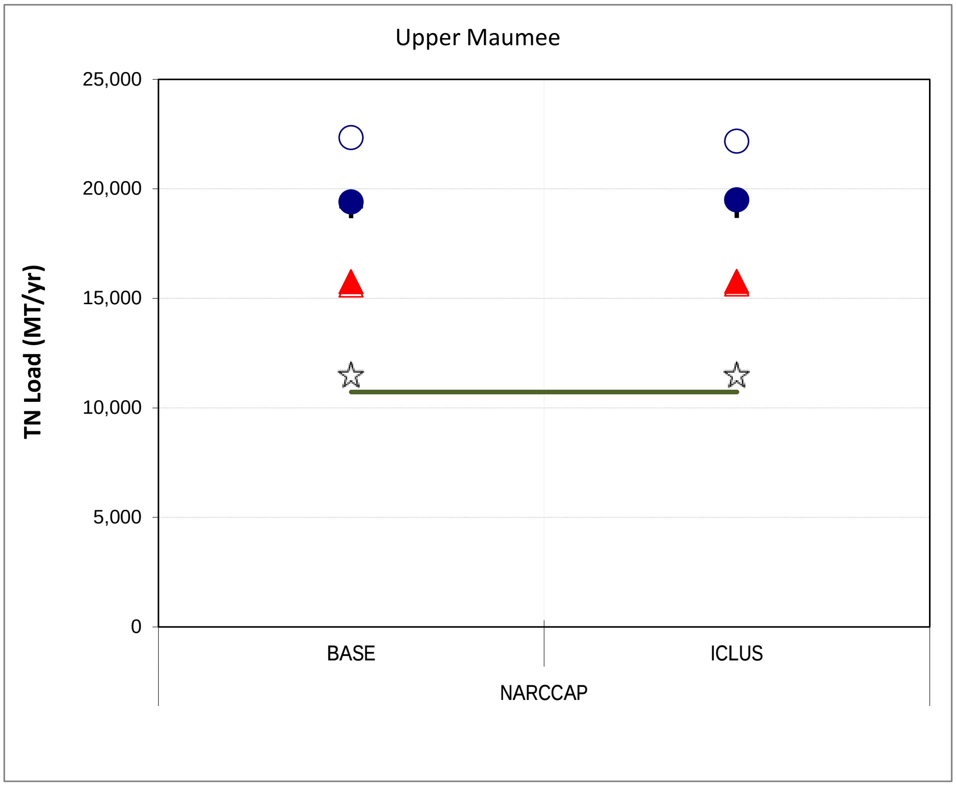


Figure 114. TN Load (MT/yr), Upper Maumee River (SWAT)

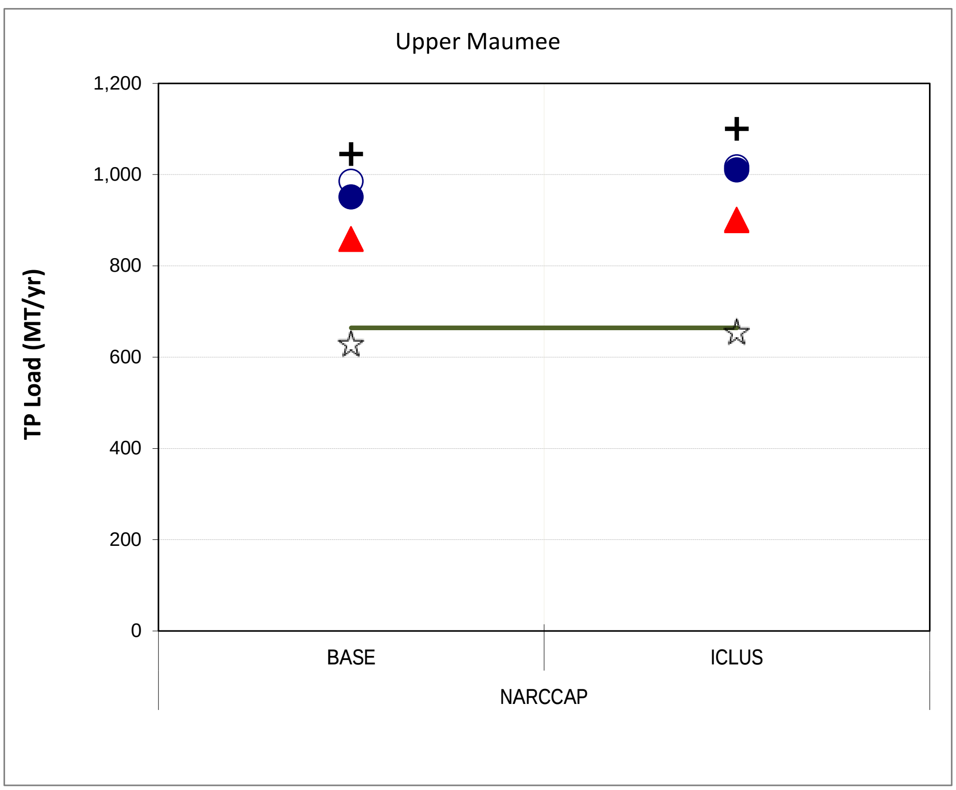


Figure 115. TP Load (MT/yr), Upper Maumee River (SWAT)

Table 5. Summary of range of change relative to existing conditions for NARCCAP dynamically downscaled scenarios, Lake Erie Drainages SWAT model

	Results without LU change				Results with LU change			
	Min	Median	Mean	Max	Min	Median	Mean	Max
St. Joseph HUC 04100003								
Flow	-22.89%	12.80%	10.51%	33.57%	-22.79%	12.71%	10.43%	33.34%
TSS	-25.64%	16.90%	14.96%	43.07%	-25.50%	16.73%	14.94%	43.09%
TN	25.95%	77.70%	77.53%	105.26%	26.28%	77.52%	77.11%	104.36%
TP	-8.66%	23.49%	21.83%	42.97%	-7.76%	24.07%	22.14%	43.21%
St. Marys HUC 04100004								
Flow	-4.24%	28.80%	30.53%	72.13%	-4.34%	28.42%	30.13%	71.35%
TSS	-3.73%	41.27%	44.47%	91.08%	-2.98%	41.22%	44.40%	90.43%
TN	-16.79%	18.83%	34.44%	104.97%	-15.82%	20.67%	35.94%	105.37%
TP	-6.10%	43.32%	37.39%	61.91%	-3.21%	48.43%	42.73%	68.63%
Upper Maumee HUC 04100005								
Flow	-15.25%	16.41%	16.93%	44.67%	-15.22%	16.21%	16.71%	44.22%
TSS	-18.67%	26.44%	29.55%	68.27%	-18.62%	26.10%	29.16%	67.68%
TN	7.69%	62.93%	61.35%	108.23%	8.41%	64.07%	62.32%	107.87%
TP	-4.90%	36.28%	33.75%	57.36%	-3.07%	40.80%	37.14%	62.09%
Tiffin HUC 04100006								
Flow	-13.80%	21.85%	20.13%	44.42%	-13.86%	21.85%	20.11%	44.37%
TSS	-17.44%	27.37%	25.32%	50.60%	-17.48%	27.35%	25.30%	50.56%
TN	-9.81%	62.88%	58.46%	111.70%	-9.58%	63.13%	58.57%	111.71%
TP	-17.53%	32.57%	27.38%	52.46%	-17.64%	32.17%	27.09%	51.51%
Lower Maumee HUC 04100009								
Flow	-11.71%	21.11%	22.12%	50.16%	-11.68%	20.98%	21.98%	49.87%
TSS	-13.77%	27.92%	31.24%	69.34%	-13.79%	27.75%	31.05%	68.96%
TN	-6.13%	42.66%	42.80%	90.76%	-6.02%	43.03%	42.95%	90.45%
TP	-12.30%	25.08%	25.60%	50.32%	-11.70%	26.38%	26.85%	52.88%
Sandusky HUC 04100011								
Flow	-0.95%	25.32%	25.96%	52.06%	-0.95%	25.32%	25.96%	52.06%
TSS	-8.31%	29.94%	33.12%	67.69%	-8.31%	29.94%	33.12%	67.69%
TN	-31.81%	1.59%	7.79%	53.03%	-31.81%	1.59%	7.79%	53.03%
TP	-12.38%	17.28%	16.17%	33.74%	-12.38%	17.28%	16.17%	33.74%
Huron-Vermillion HUC 04100012								
Flow	-1.54%	23.92%	25.09%	52.60%	-1.54%	23.92%	25.09%	52.60%
TSS	-4.89%	27.39%	28.15%	62.82%	-4.88%	27.40%	28.15%	62.82%
TN	-11.76%	21.83%	25.71%	60.68%	-11.76%	21.88%	25.73%	60.70%
TP	-6.58%	19.66%	17.61%	32.56%	-6.58%	19.66%	17.61%	32.57%
Black-Rocky HUC 04110001								
Flow	-3.80%	15.11%	13.38%	28.15%	-3.45%	15.31%	13.58%	28.20%
TSS	-4.59%	24.78%	22.34%	46.53%	-4.30%	25.05%	22.45%	46.22%

	Results without LU change				Results with LU change			
	Min	Median	Mean	Max	Min	Median	Mean	Max
TN	5.43%	23.11%	24.65%	47.06%	10.90%	28.63%	30.45%	54.90%
TP	8.64%	29.40%	30.01%	60.10%	15.60%	36.56%	37.41%	69.39%
Cuyahoga HUC 04110002								
Flow	-3.53%	8.57%	8.88%	21.12%	-3.54%	8.52%	8.84%	21.06%
TSS	-4.69%	12.57%	13.09%	30.95%	-4.72%	12.49%	13.03%	30.83%
TN	25.29%	39.35%	42.79%	61.17%	25.92%	39.69%	43.26%	63.33%
TP	19.28%	33.47%	35.85%	58.22%	20.90%	35.07%	37.31%	61.39%
Grand HUC 04110004								
Flow	-0.30%	8.34%	10.17%	26.75%	-0.28%	8.35%	10.18%	26.76%
TSS	-2.32%	9.20%	10.80%	31.03%	-2.31%	9.14%	10.78%	31.07%
TN	9.67%	19.91%	21.34%	39.53%	9.98%	19.53%	21.27%	40.15%
TP	5.95%	17.69%	19.39%	42.00%	6.56%	17.82%	19.46%	42.58%
Auglaize HUC 04100007								
Flow	-7.88%	22.58%	25.44%	55.81%	-7.86%	22.57%	25.44%	55.79%
TSS	-9.63%	30.52%	36.15%	76.22%	-9.60%	30.54%	36.11%	75.94%
TN	-8.36%	33.77%	35.11%	84.13%	-8.30%	33.71%	35.04%	84.06%
TP	-12.16%	23.93%	25.75%	53.96%	-12.13%	23.76%	25.70%	54.09%
Blanchard HUC 04100008								
Flow	-10.08%	20.91%	22.64%	51.46%	-10.03%	20.90%	22.63%	51.42%
TSS	-7.81%	31.52%	35.53%	74.47%	-7.76%	31.50%	35.52%	74.43%
TN	0.65%	41.36%	41.39%	83.21%	0.83%	41.31%	41.34%	83.25%
TP	-7.93%	31.74%	30.58%	55.72%	-7.84%	31.43%	30.52%	55.81%

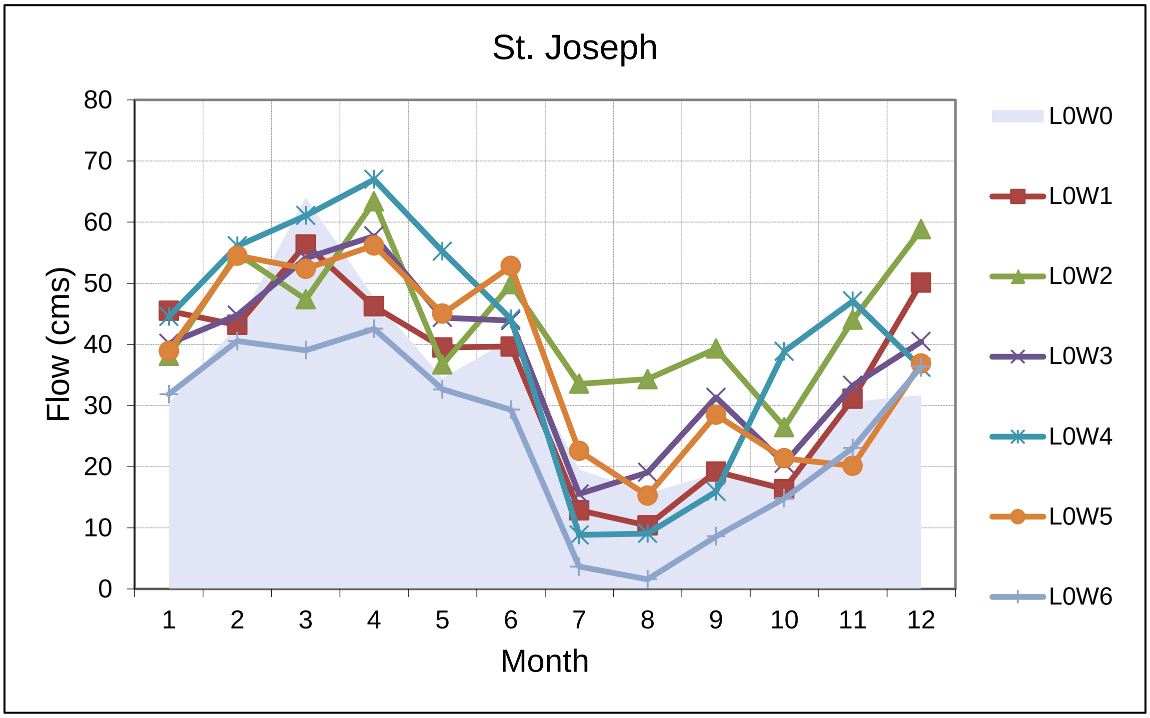


Figure 116. Monthly average flows, St. Joseph River (SWAT)

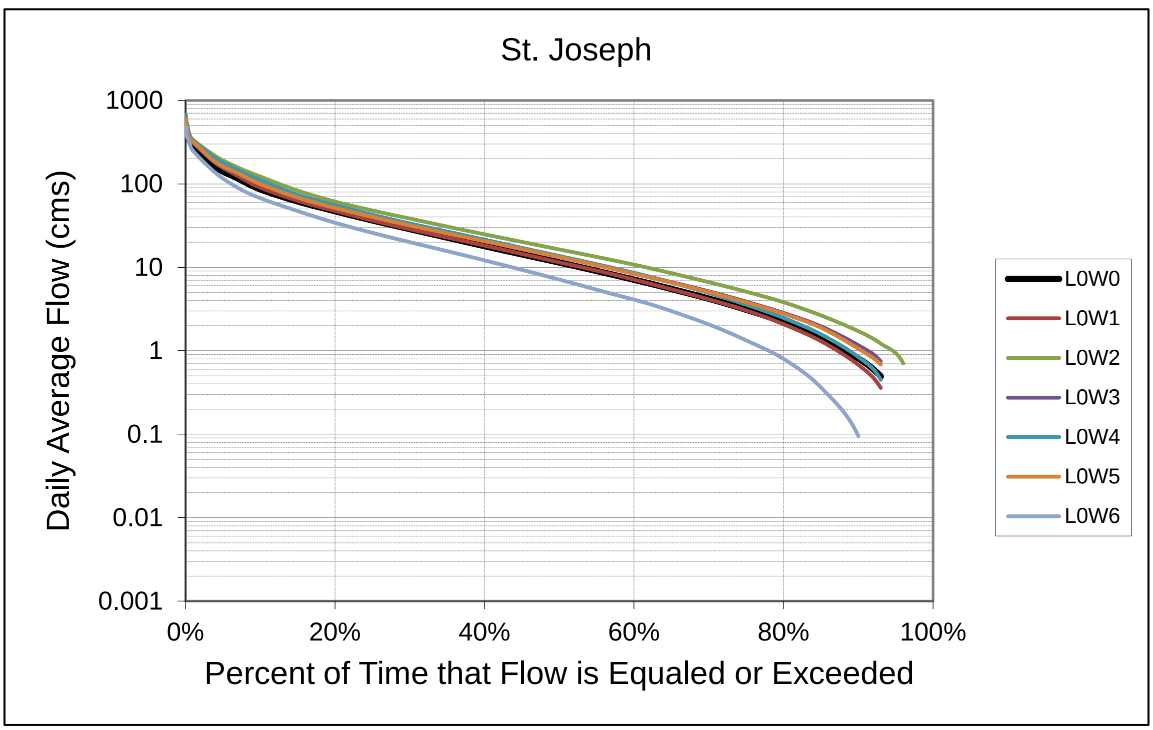


Figure 117. Flow duration, St. Joseph River (SWAT)

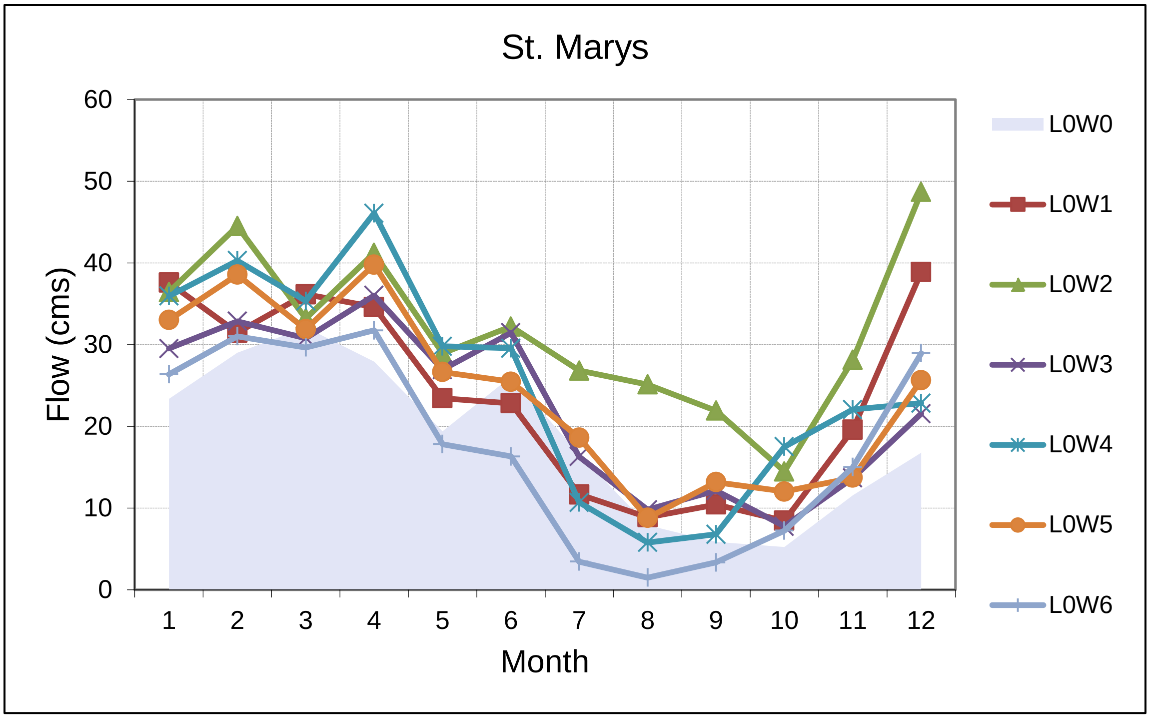


Figure 118. **Monthly average flows, St. Marys River (SWAT)**

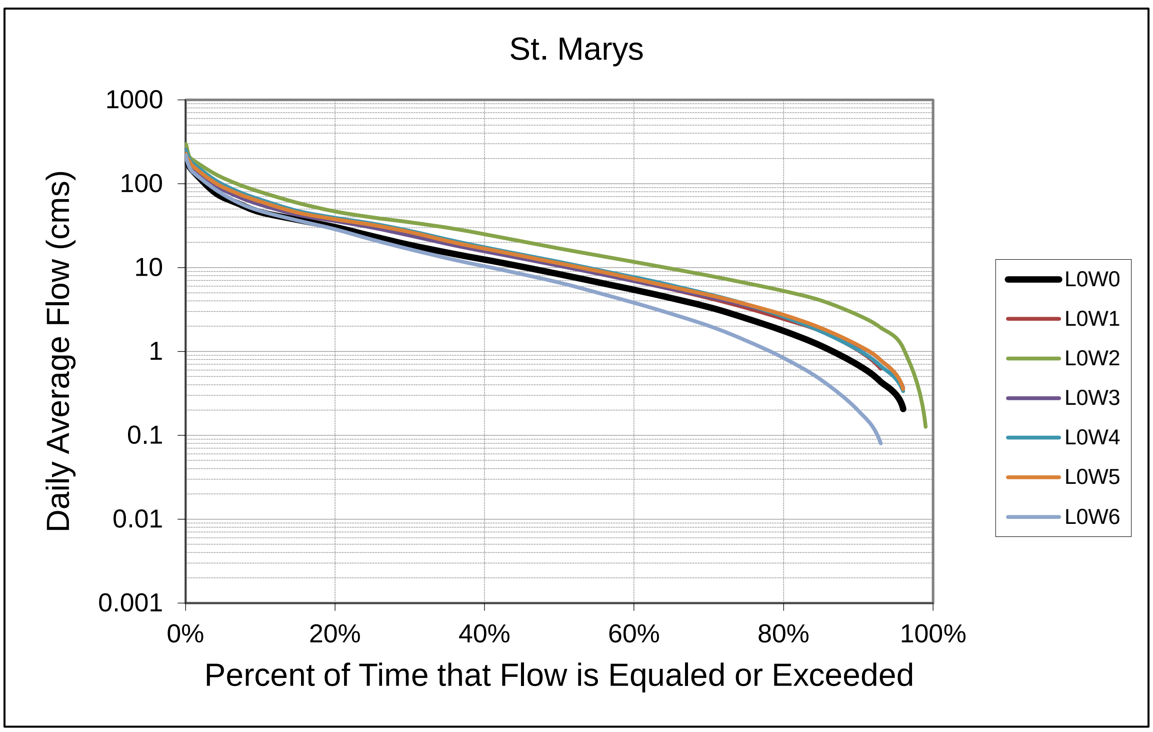


Figure 119. **Flow duration, St. Marys River (SWAT)**

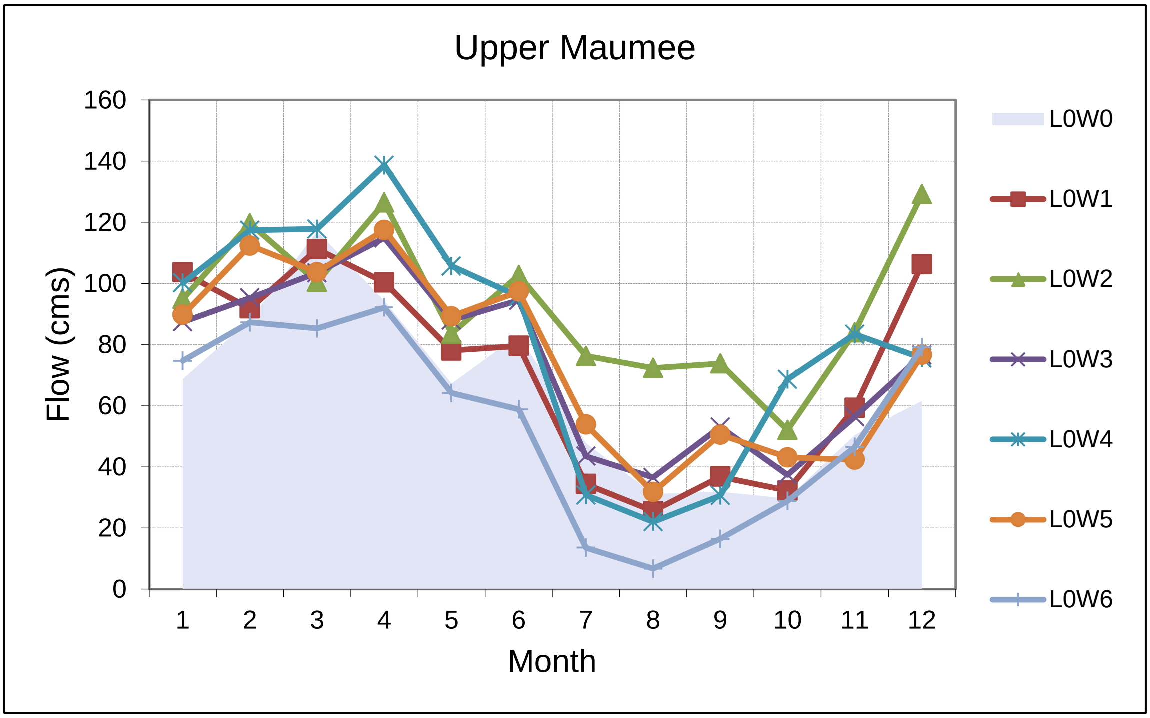


Figure 120. Monthly average flows, Upper Maumee River (SWAT)

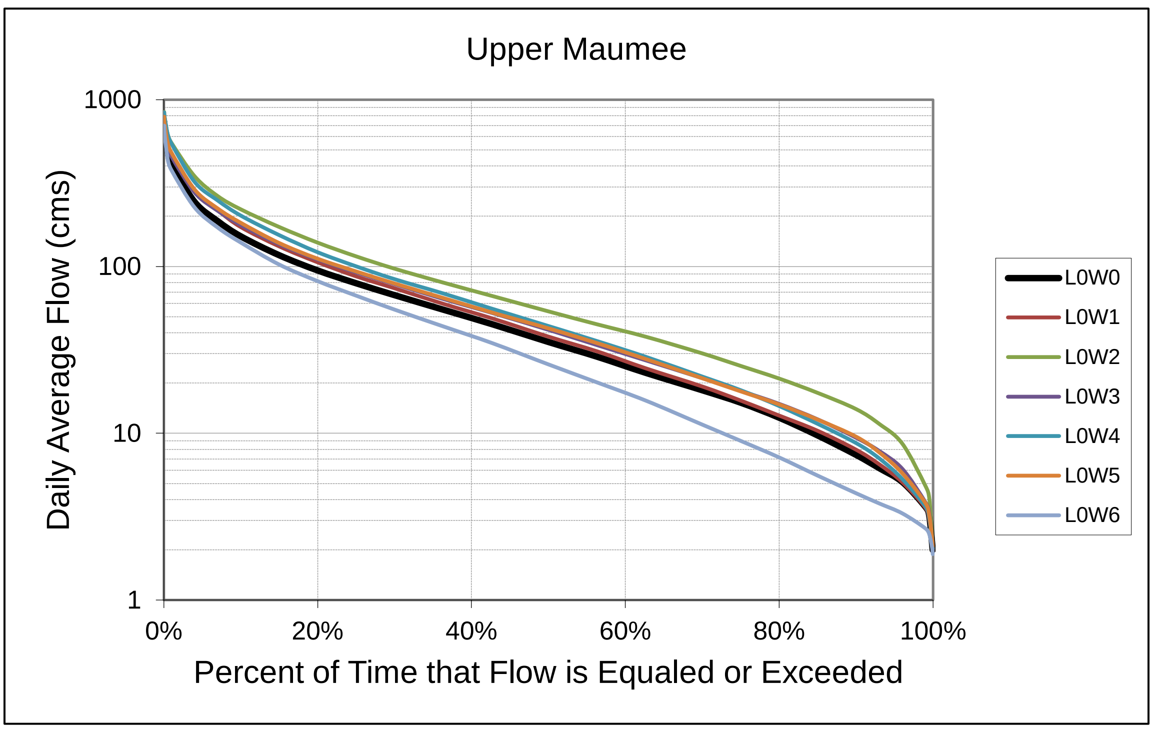


Figure 121. Flow duration, Upper Maumee River (SWAT)

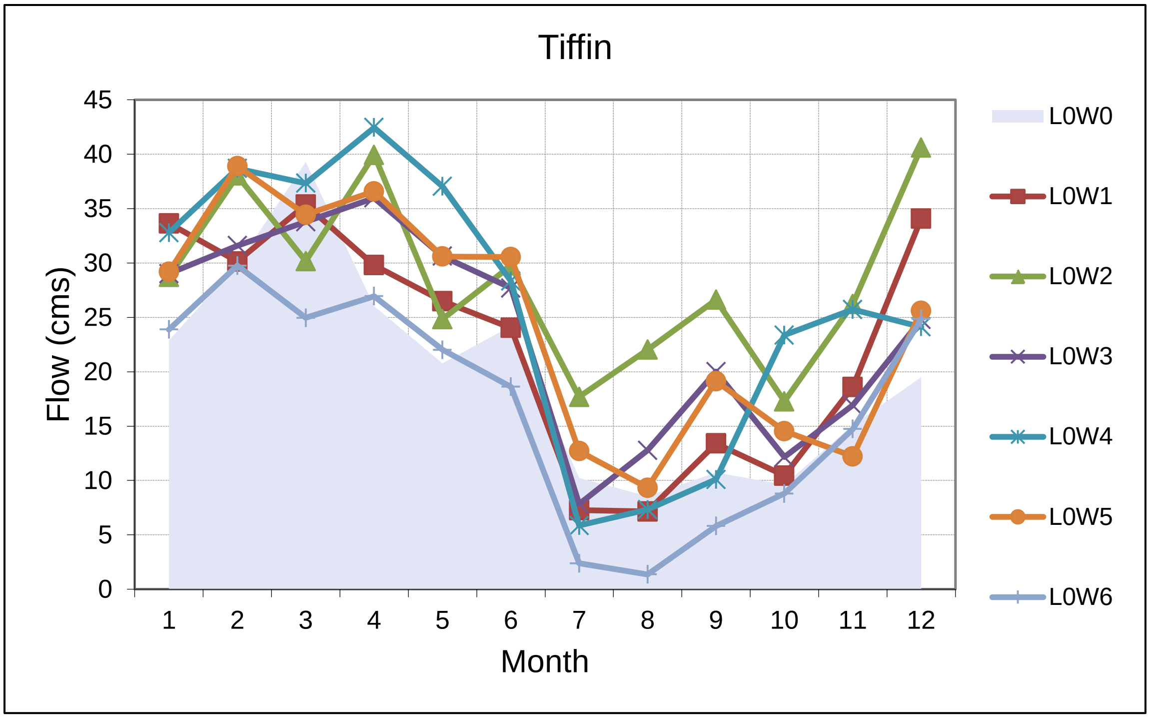


Figure 122. Monthly average flows, Tiffin River (SWAT)

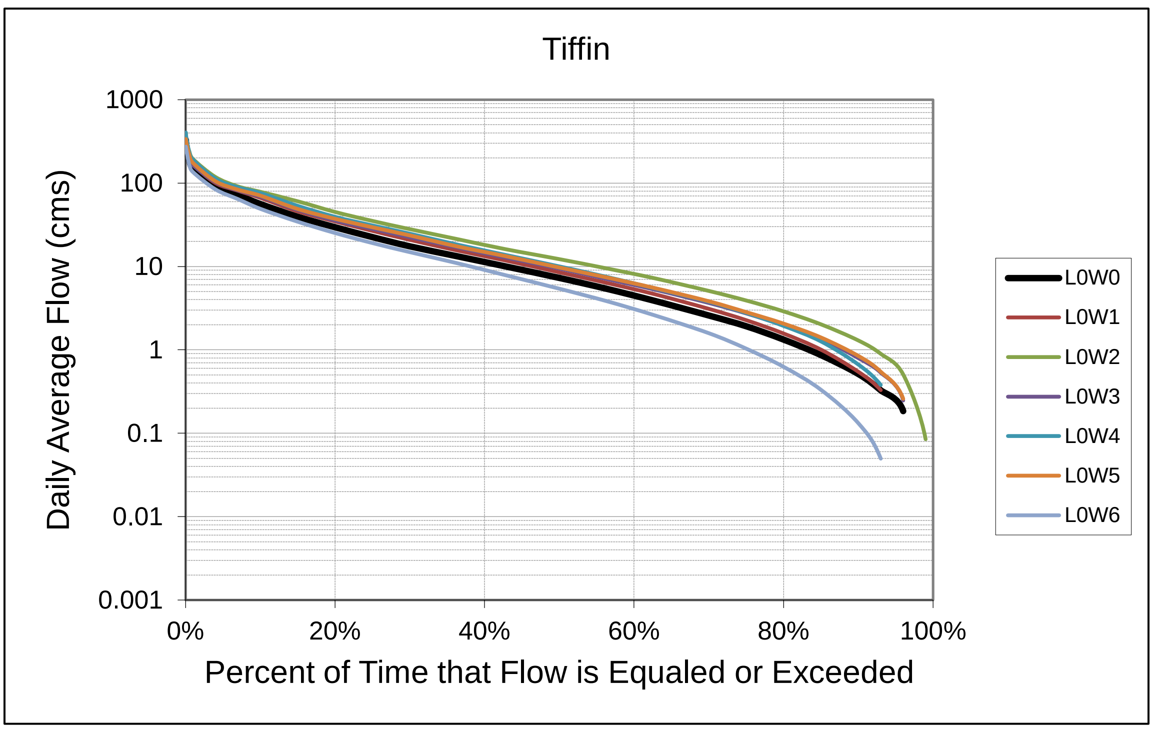


Figure 123. Flow duration, Tiffin River (SWAT)

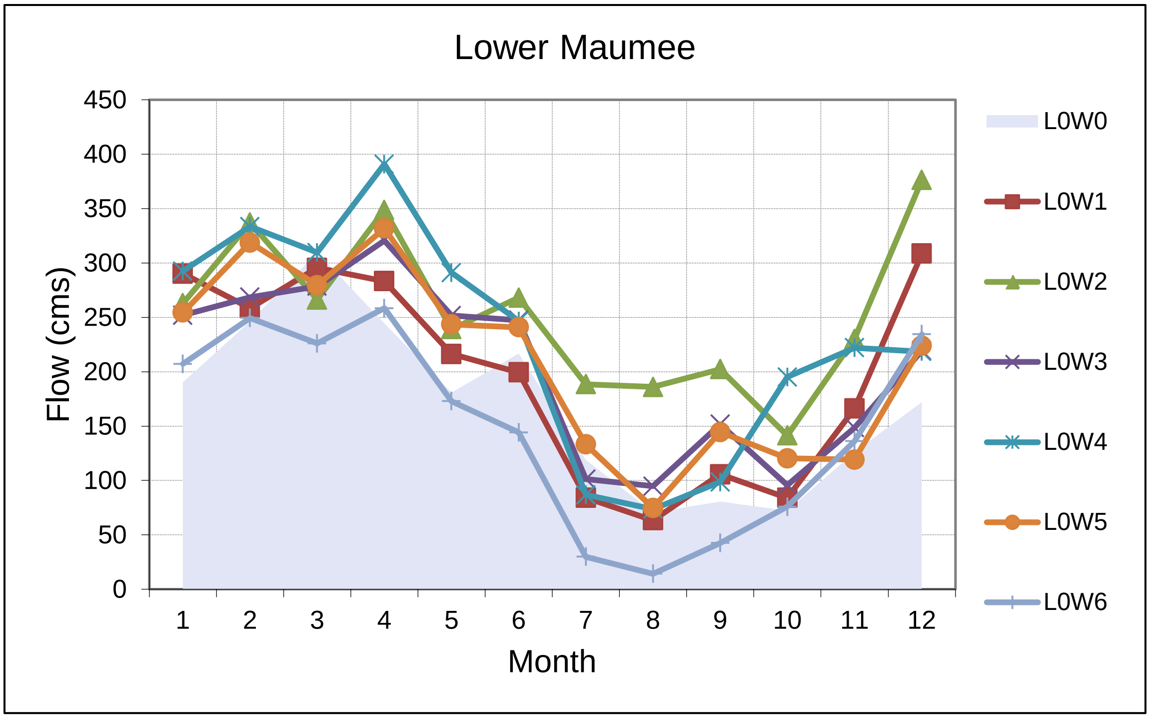


Figure 124. Monthly average flows, Lower Maumee River (SWAT)

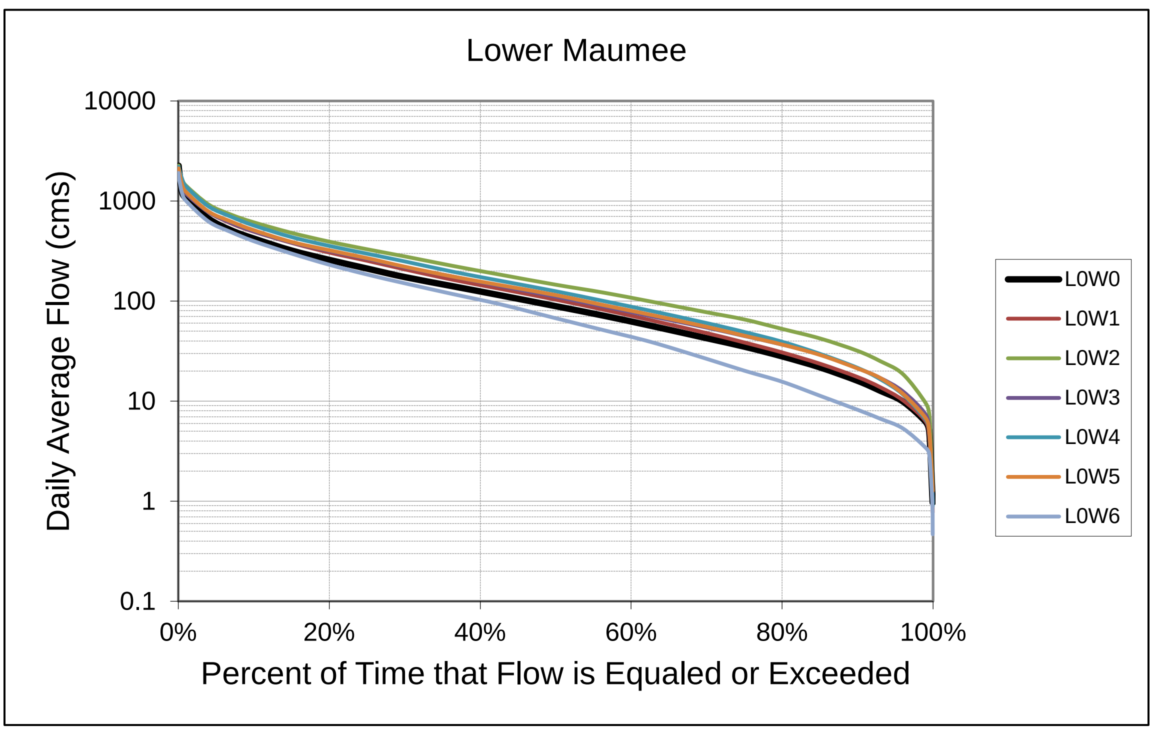


Figure 125. Flow duration, Lower Maumee River (SWAT)

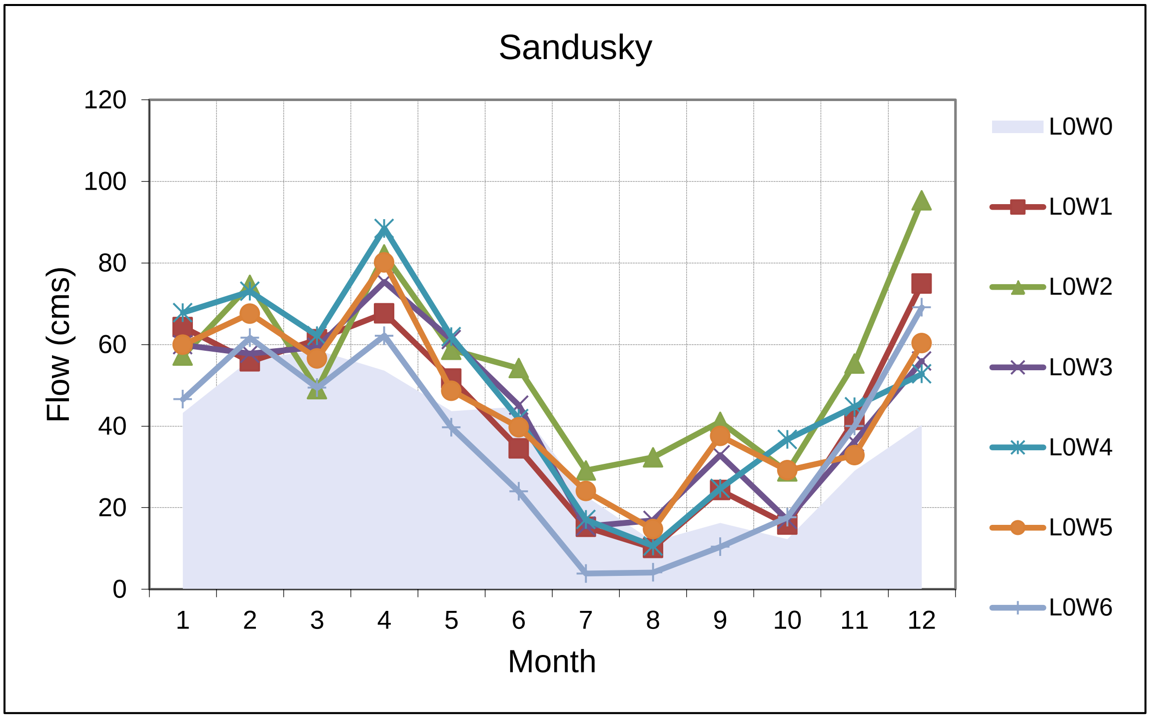


Figure 126. **Monthly average flows, Sandusky River (SWAT)**

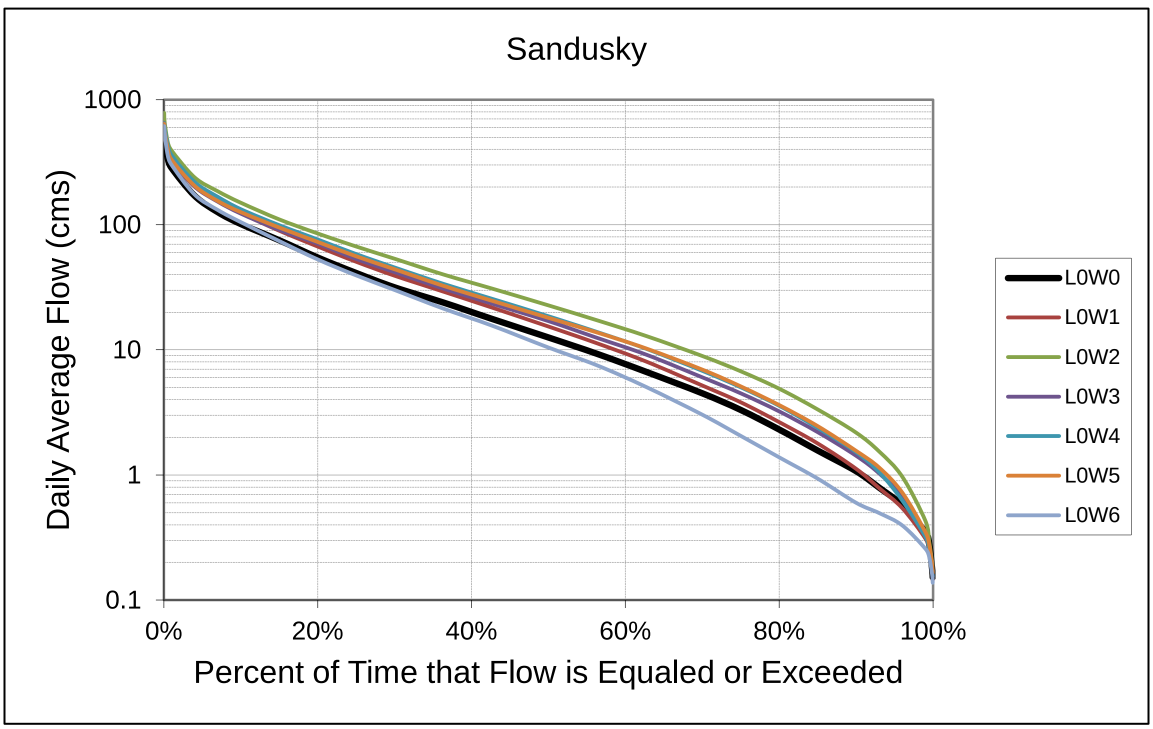


Figure 127. **Flow duration, Sandusky River (SWAT)**

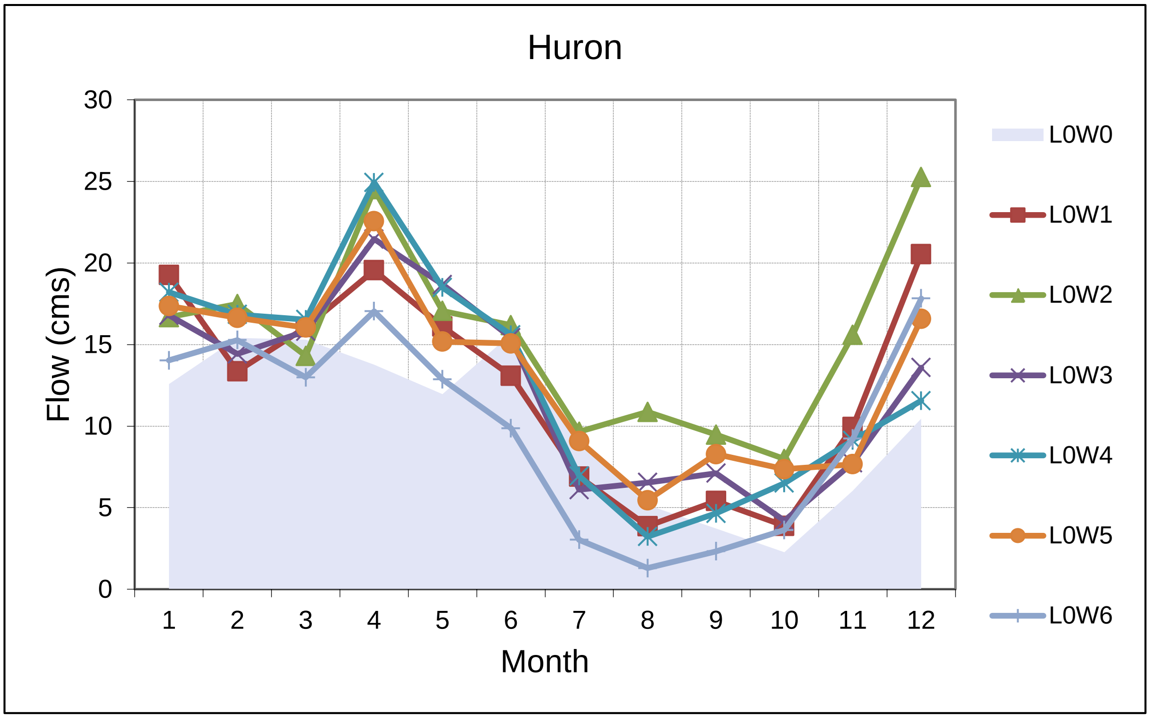


Figure 128. **Monthly average flows, Huron River (SWAT)**

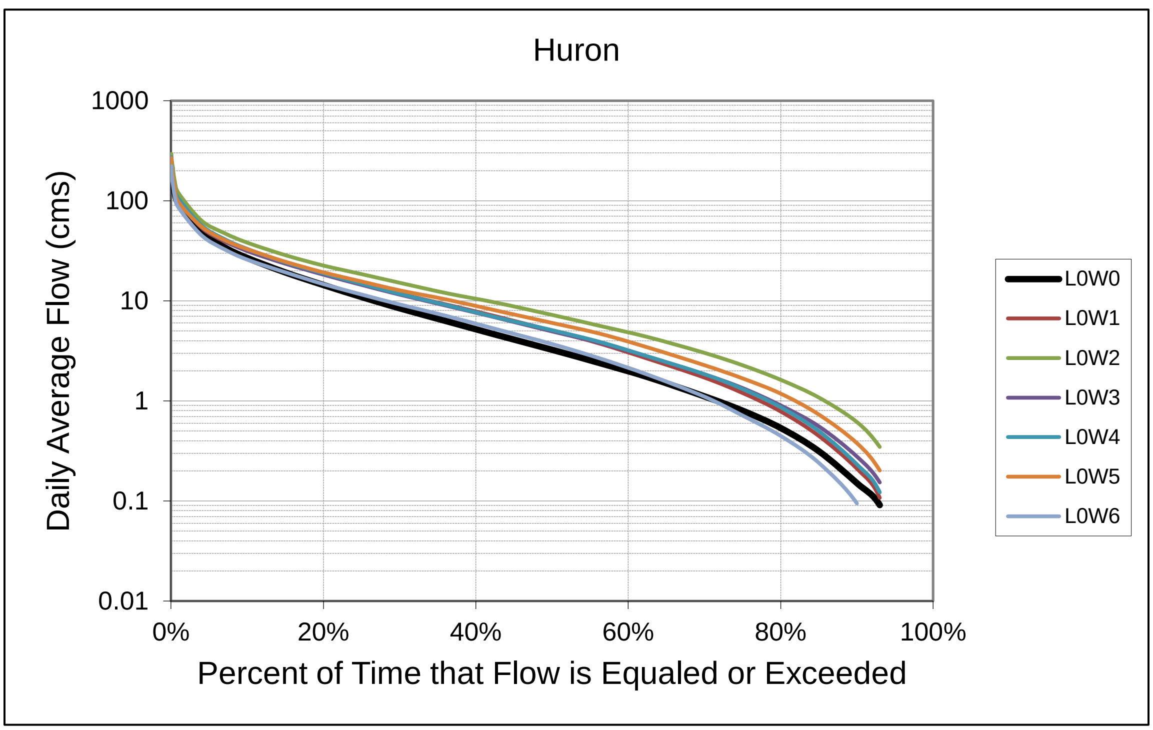


Figure 129. **Flow duration, Huron River (SWAT)**

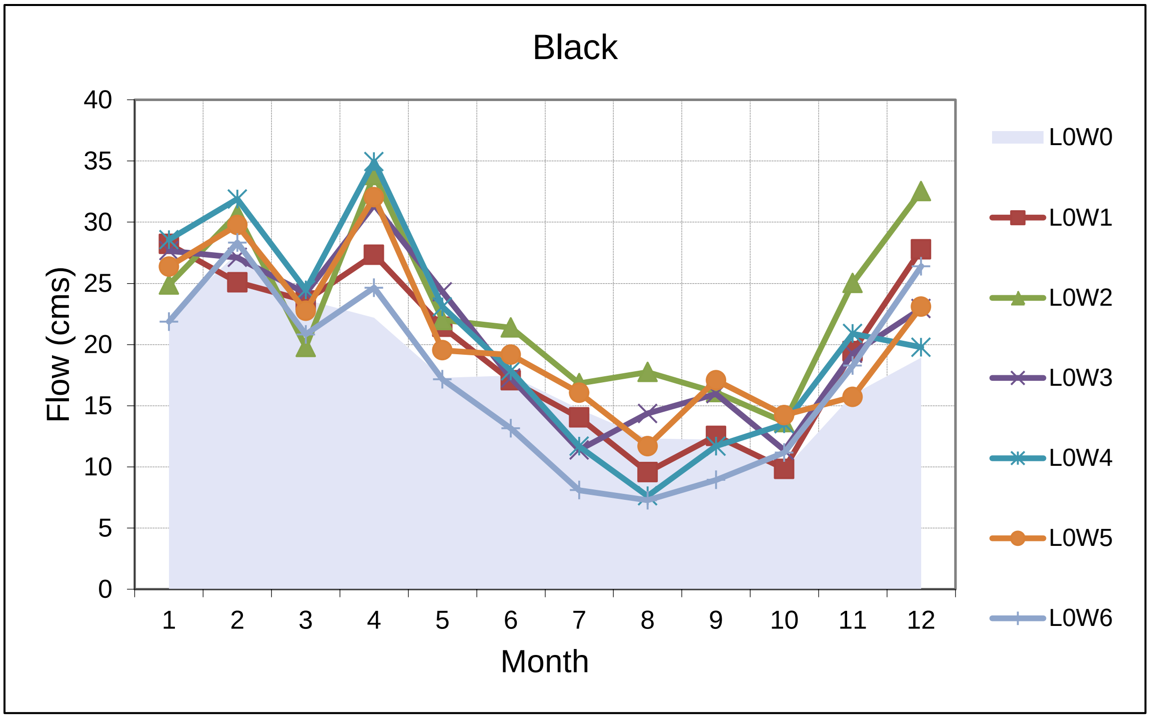


Figure 130. **Monthly average flows, Black River (SWAT)**

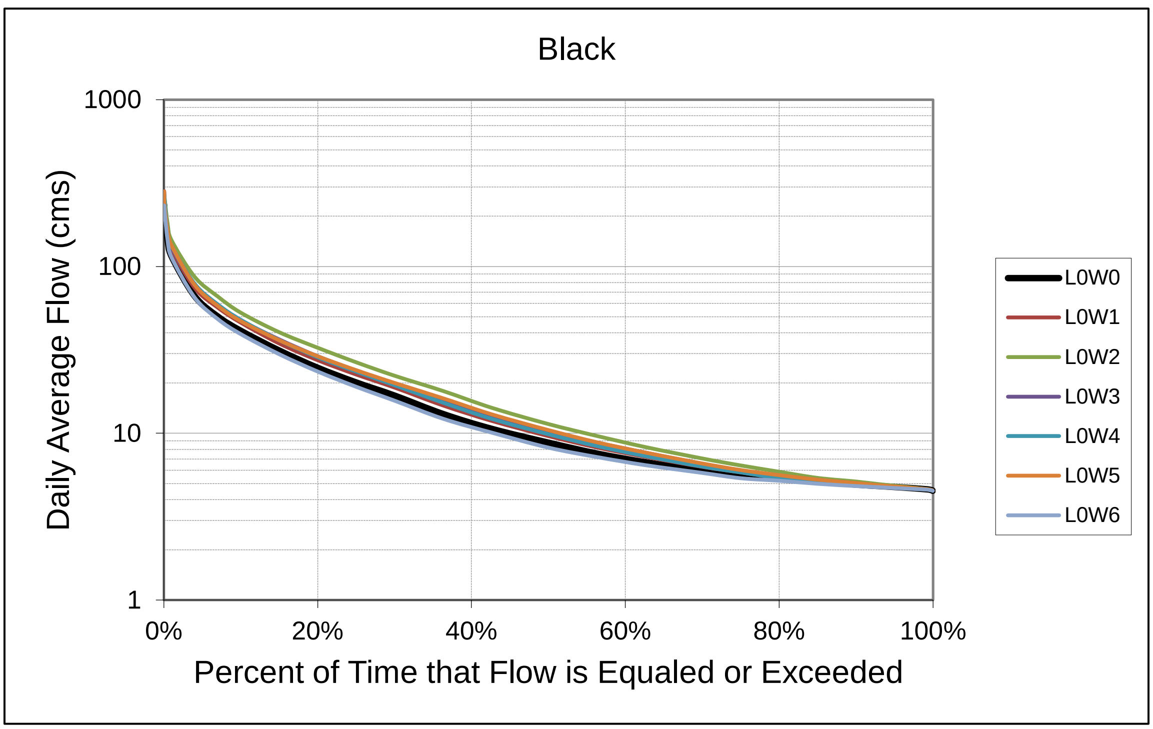


Figure 131. **Flow duration, Black River (SWAT)**

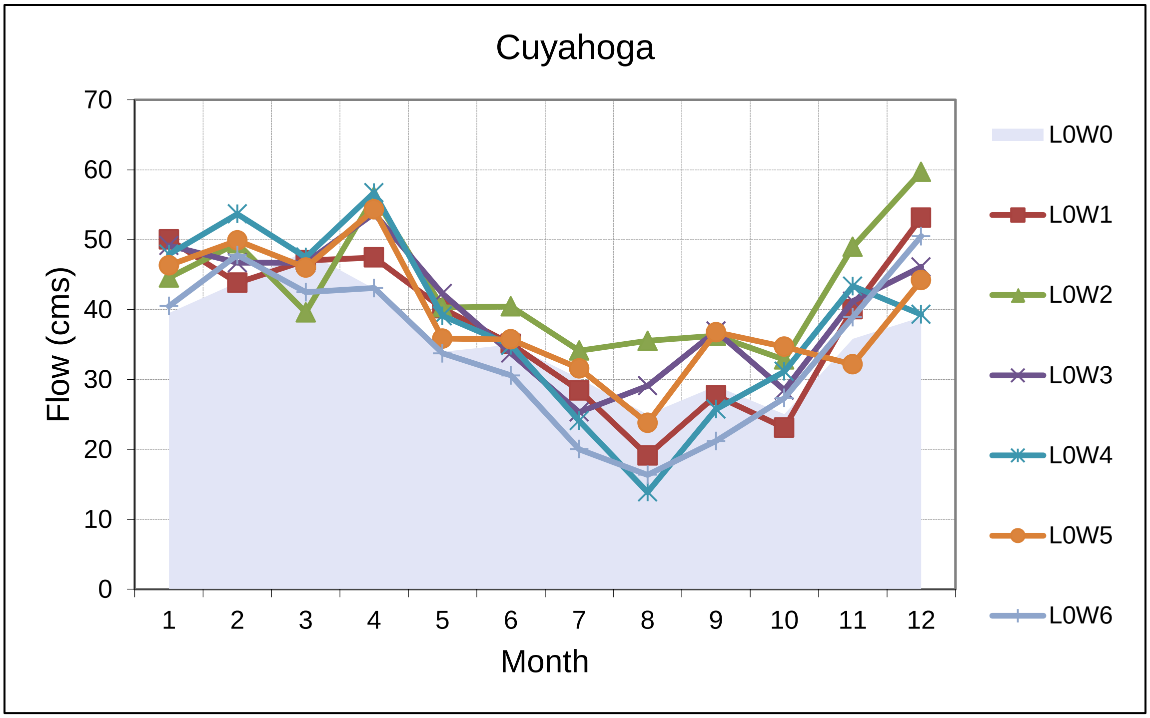


Figure 132. **Monthly average flows, Cuyahoga River (SWAT)**

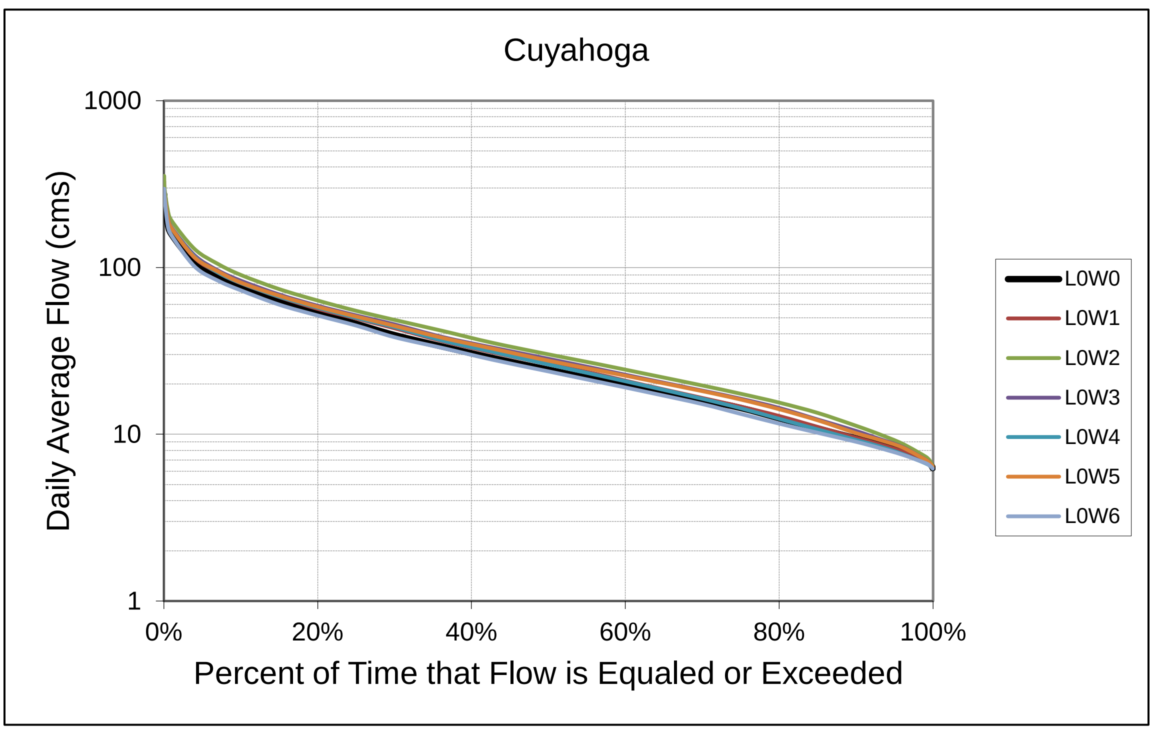


Figure 133. **Flow duration, Cuyahoga River (SWAT)**

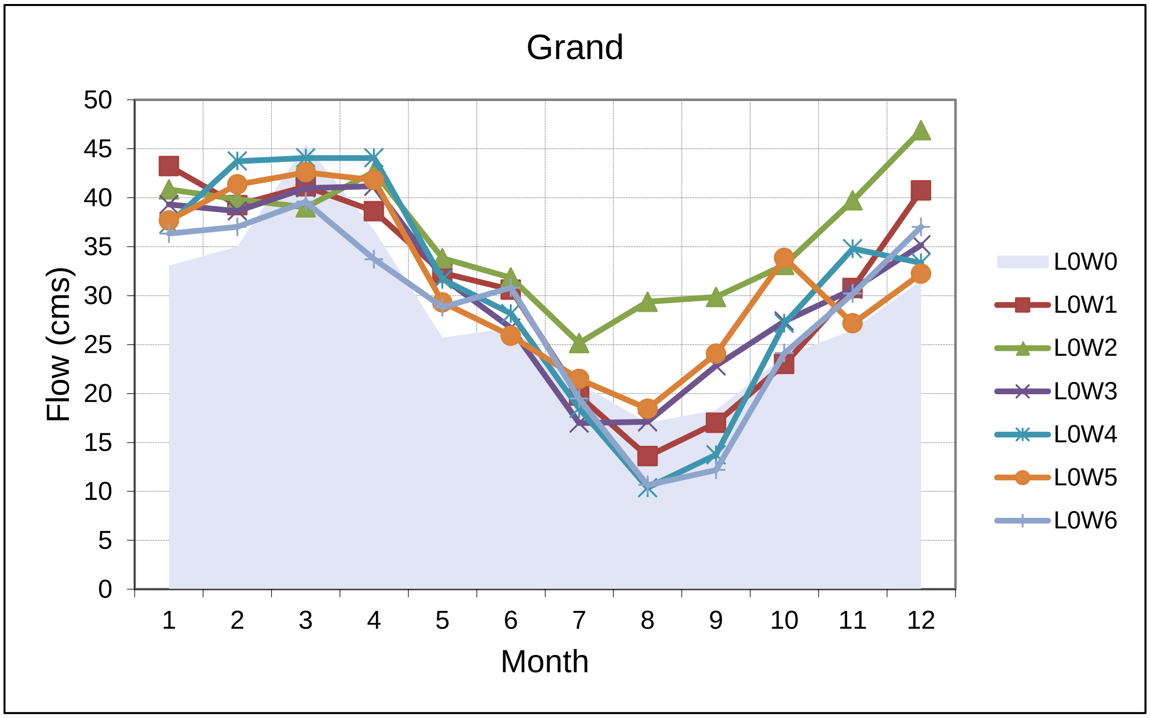


Figure 134. **Monthly average flows, Grand River (SWAT)**

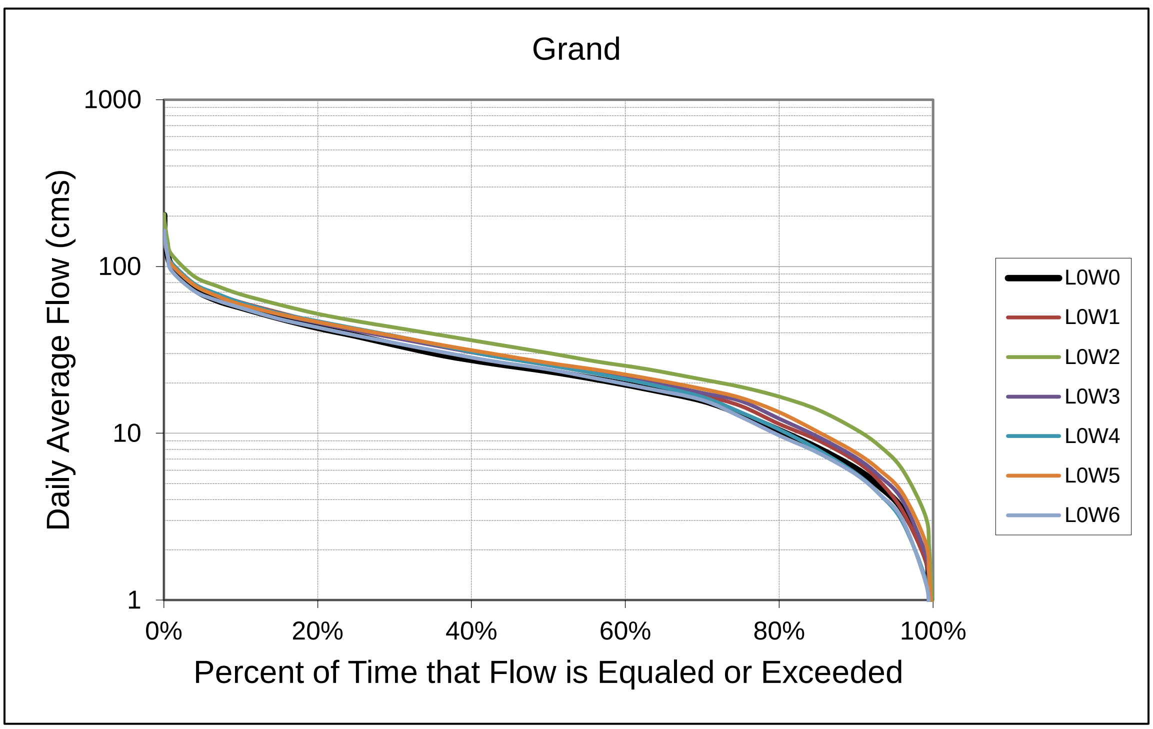


Figure 135. **Flow duration, Grand River (SWAT)**

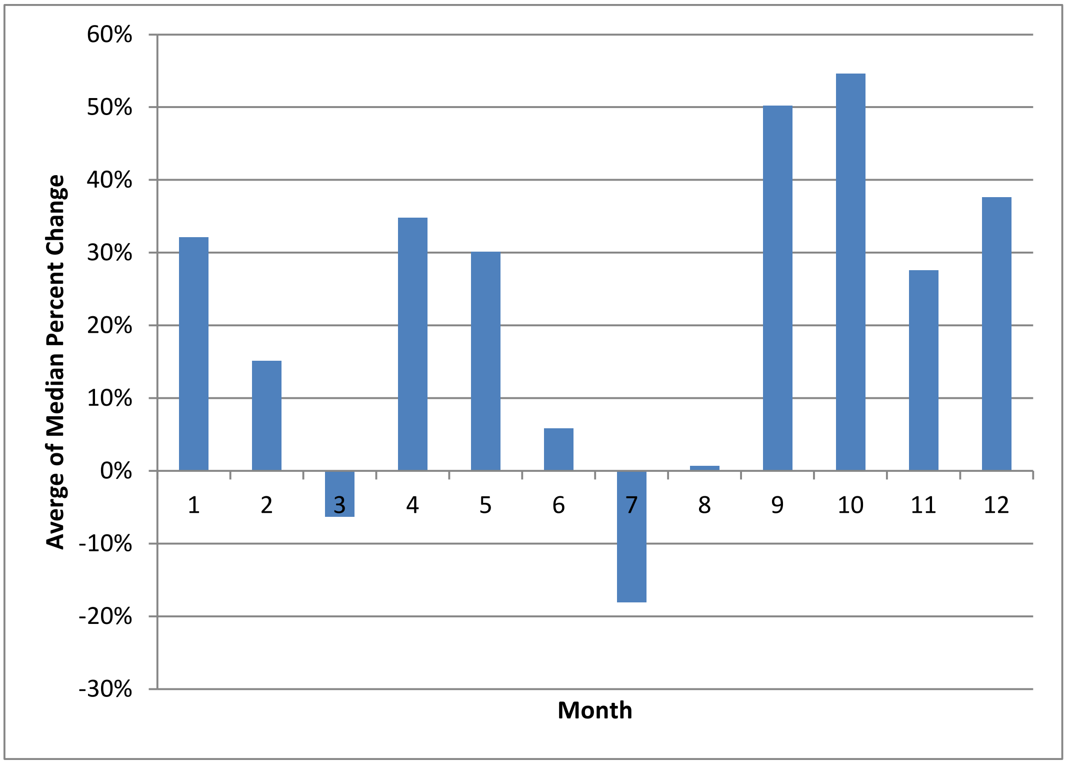


Figure 136. Average of median percent change in flow; NARCCAP Scenarios W1-W6 at all stations, Lake Erie drainages (SWAT)

Nebraska: Loup and Elkhorn River Basins

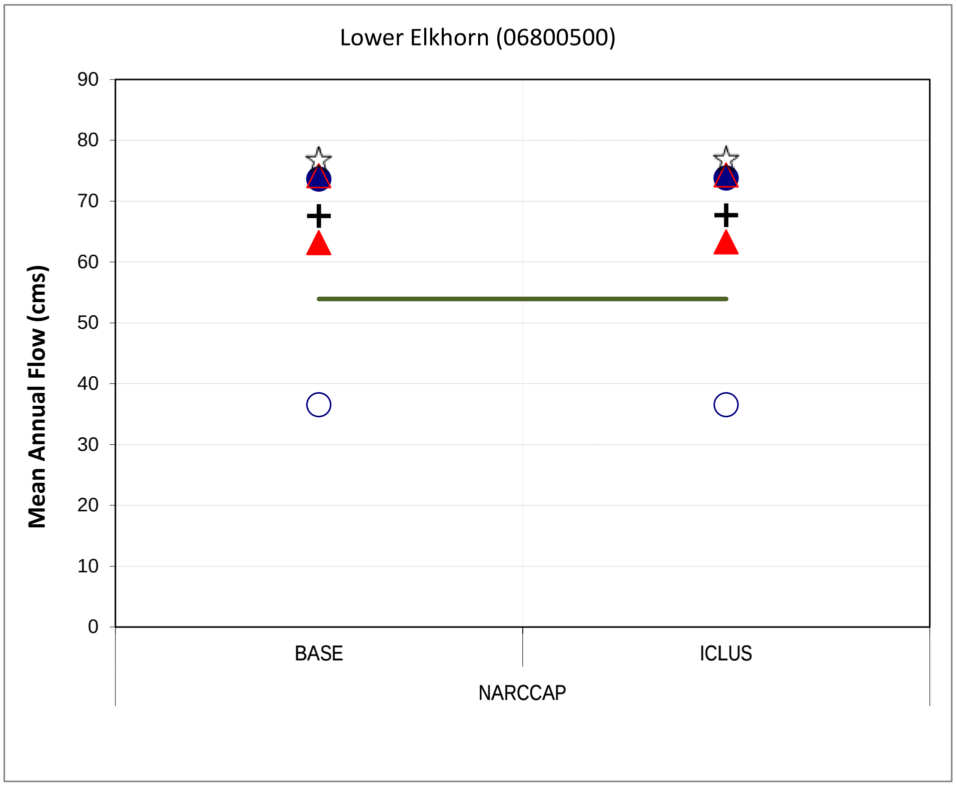


Figure 137. Mean annual flow (cms), Lower Elkhorn River (SWAT)

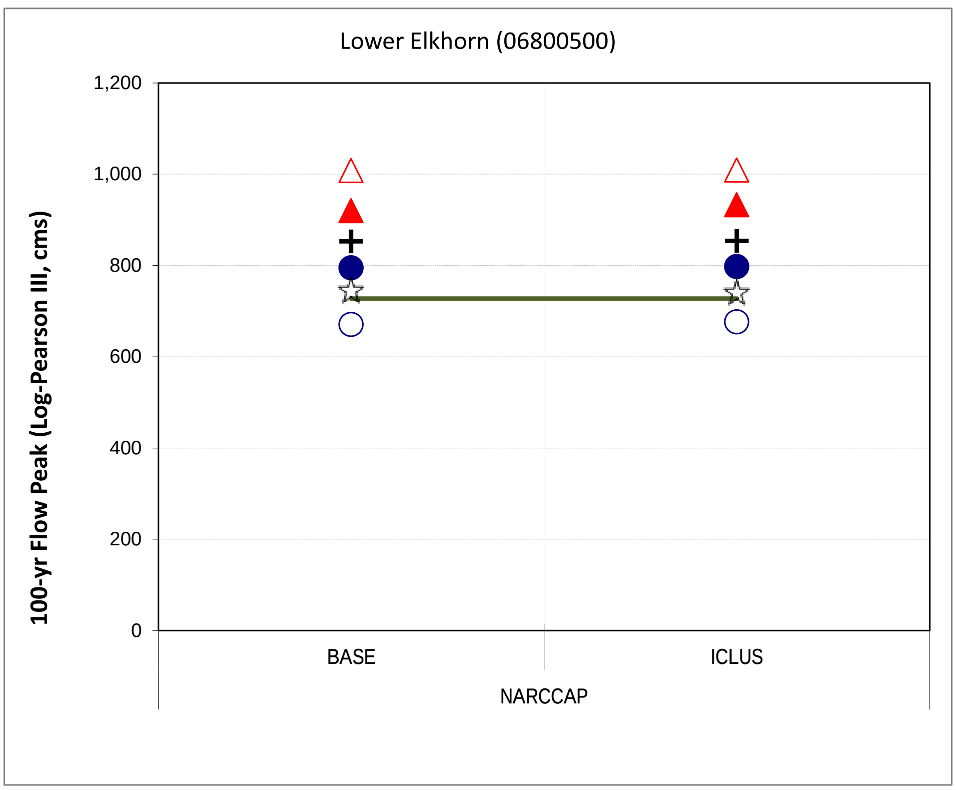


Figure 138. 100-yr Flow Peak (Log-Pearson III, cms), Lower Elkhorn River (SWAT)

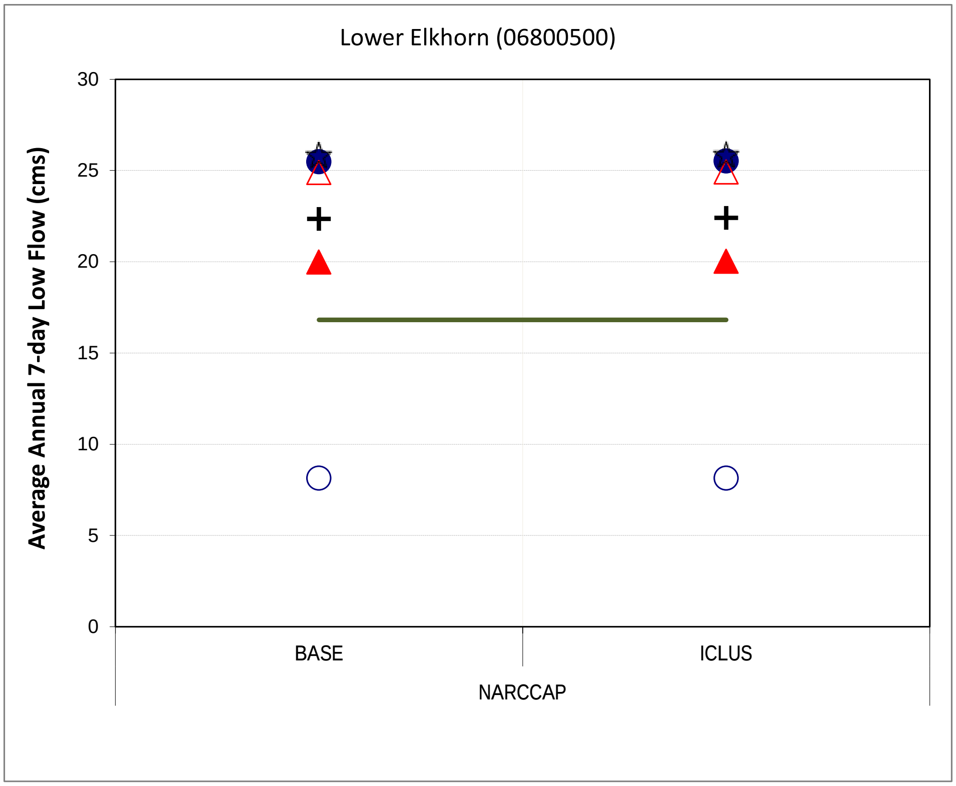


Figure 139. Average Annual 7-day Low Flow (cms), Lower Elkhorn River (SWAT)

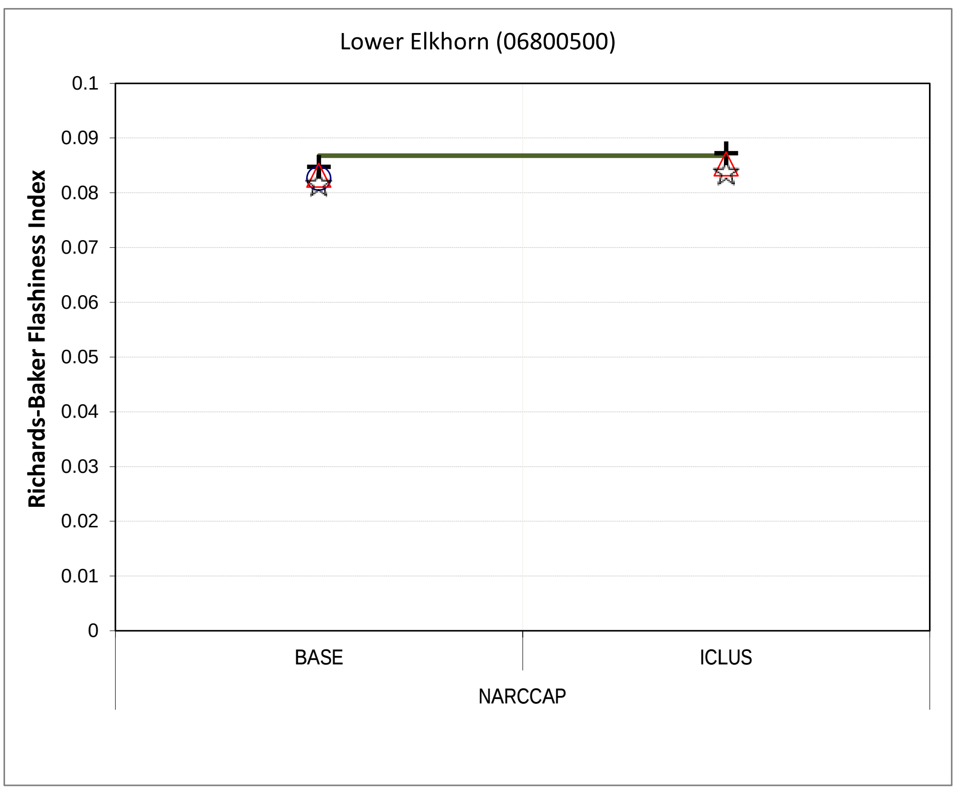


Figure 140. Richards-Baker Flashiness Index, Average Annual 7-day Low Flow (cms), Lower Elkhorn River (SWAT)

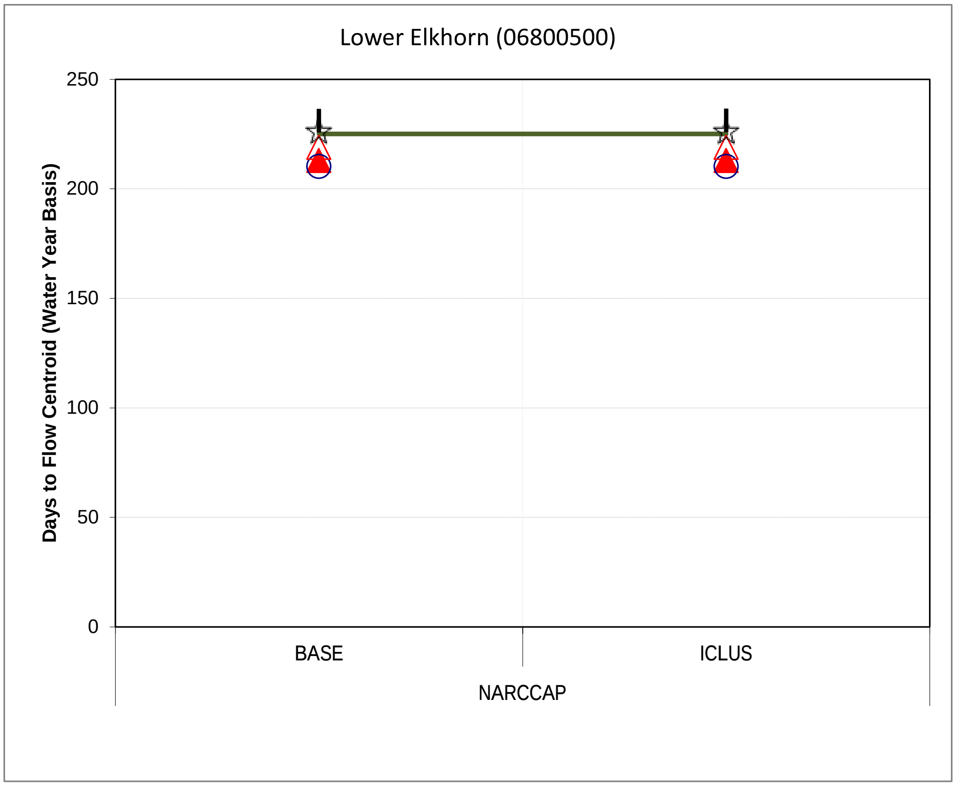


Figure 141. **Days to Flow Centroid (Water Year Basis), Lower Elkhorn River (SWAT)**

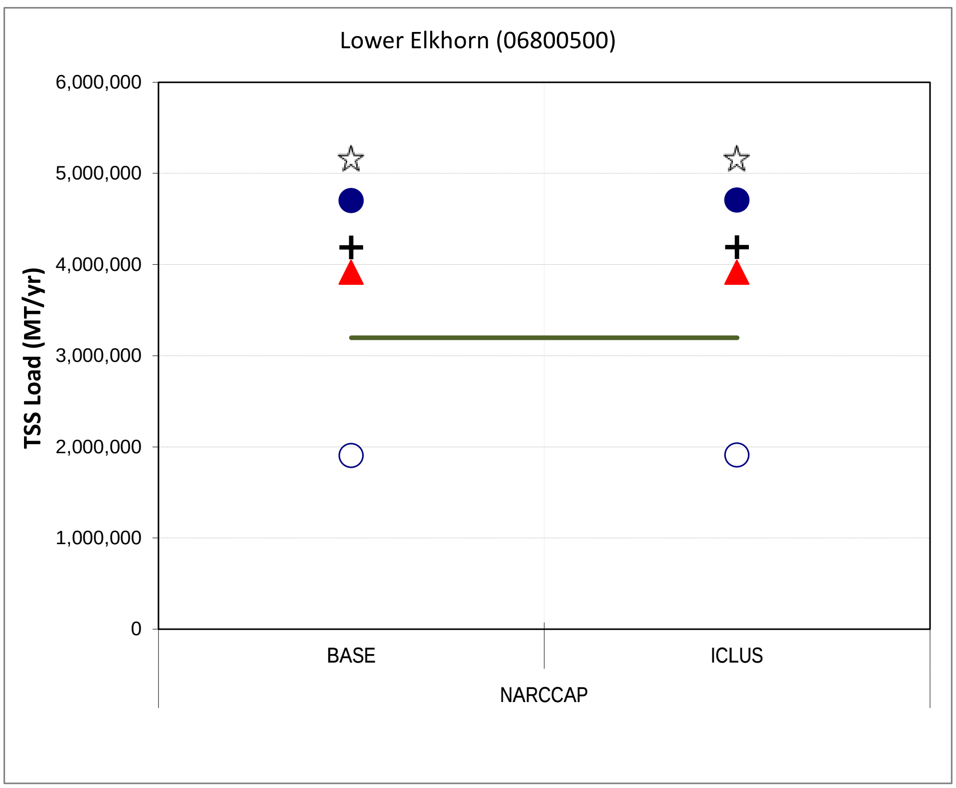


Figure 142. **TSS Load (MT/yr), Lower Elkhorn River (SWAT)**

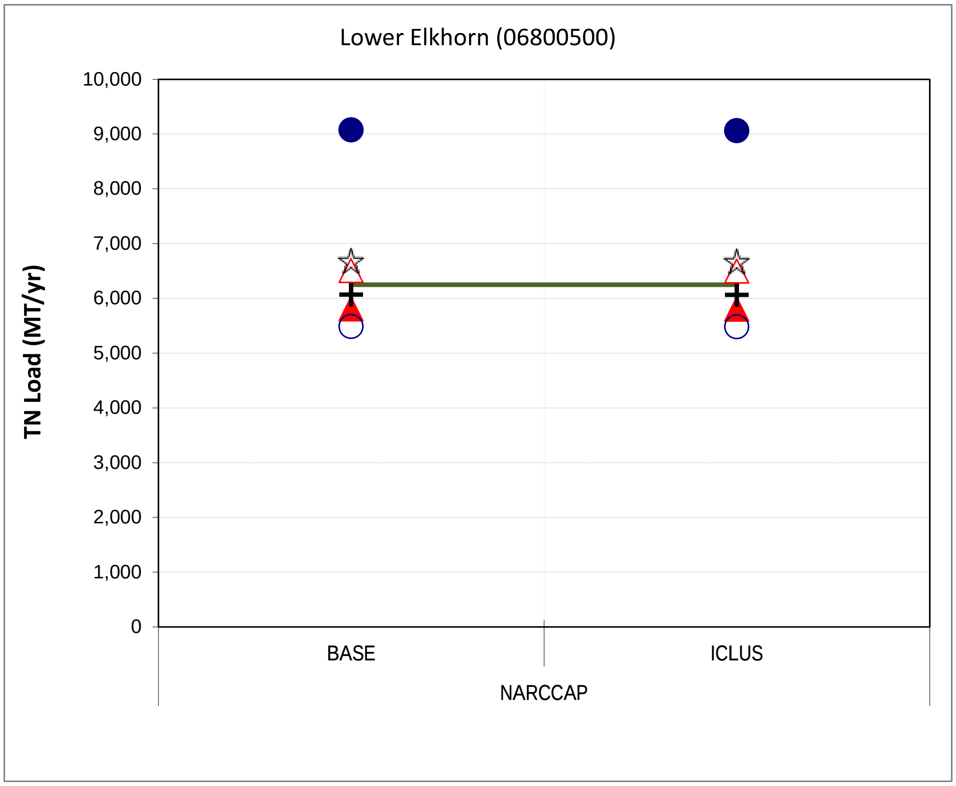


Figure 143. **TN Load (MT/yr), Lower Elkhorn River (SWAT)**

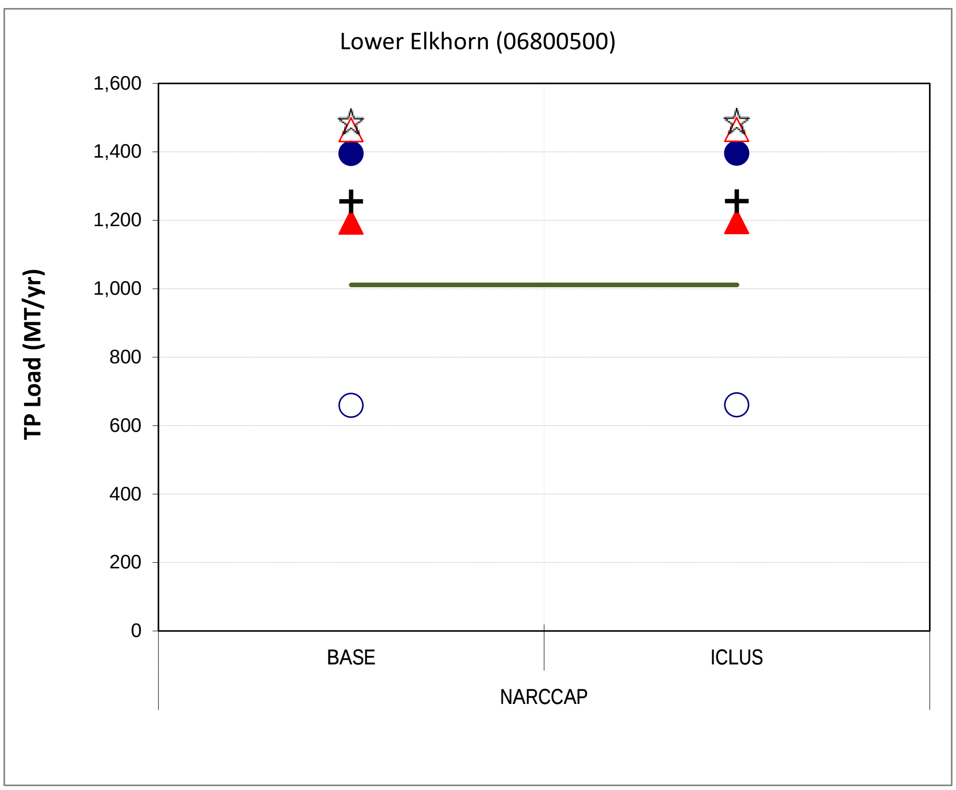


Figure 144. **TP Load (MT/yr), Lower Elkhorn River (SWAT)**

Table 6. Summary of range of change relative to existing conditions for NARCCAP dynamically downscaled scenarios, Loup and Elkhorn basins SWAT model

	Results without LU change				Results with LU change			
	Min	Median	Mean	Max	Min	Median	Mean	Max
Upper Elkhorn gage 06799500								
Flow	-37.25%	21.57%	15.15%	41.00%	-37.25%	21.57%	15.16%	41.00%
TSS	-44.79%	24.89%	17.52%	49.08%	-44.78%	24.89%	17.52%	49.08%
TN	-43.55%	20.04%	12.19%	34.53%	-43.55%	20.04%	12.20%	34.53%
TP	-46.94%	26.75%	18.98%	52.58%	-46.94%	26.75%	18.98%	52.58%
Lower Elkhorn gage 06800500								
Flow	-32.28%	30.92%	21.17%	42.81%	-32.43%	30.87%	21.07%	42.68%
TSS	-40.44%	39.06%	30.60%	61.82%	-40.27%	39.05%	30.61%	61.79%
TN	-12.24%	0.60%	5.73%	45.26%	-12.14%	0.67%	5.78%	45.29%
TP	-34.81%	31.02%	22.92%	47.40%	-34.77%	30.99%	22.89%	47.34%
N Fork Elkhorn HUC 10220002								
Flow	-31.27%	29.04%	20.62%	45.97%	-31.27%	29.04%	20.61%	45.97%
TSS	-24.86%	33.74%	26.77%	58.16%	-24.86%	33.73%	26.76%	58.15%
TN	-18.98%	-10.03%	-2.74%	38.44%	-18.99%	-10.04%	-2.75%	38.44%
TP	-17.12%	16.74%	12.21%	27.10%	-17.14%	16.74%	12.21%	27.11%
Logan HUC 10220004								
Flow	-19.06%	42.44%	37.19%	65.62%	-19.08%	42.43%	37.17%	65.60%
TSS	-13.69%	51.04%	46.72%	82.44%	-13.62%	51.03%	46.73%	82.41%
TN	-2.33%	9.36%	16.70%	63.74%	-2.33%	9.36%	16.71%	63.74%
TP	-16.58%	43.36%	39.08%	68.01%	-16.64%	43.33%	39.04%	67.96%
Upper Middle Loup HUC 10210001								
Flow	-37.61%	-2.34%	-2.01%	19.17%	-37.61%	-2.34%	-2.01%	19.17%
TSS	-52.72%	-3.93%	-2.13%	32.01%	-52.72%	-3.93%	-2.13%	32.01%
TN	-37.66%	2.22%	3.01%	28.82%	-37.66%	2.22%	3.01%	28.82%
TP	-44.06%	-3.10%	-2.28%	25.00%	-44.06%	-3.10%	-2.28%	25.00%
Dismal HUC 10210002								
Flow	-37.63%	-4.76%	-2.46%	22.50%	-37.63%	-4.76%	-2.46%	22.50%
TSS	-50.64%	-8.78%	-2.99%	34.85%	-50.64%	-8.78%	-2.99%	34.85%
TN	-33.01%	16.90%	9.58%	29.34%	-33.01%	16.90%	9.58%	29.34%
TP	-43.47%	-7.38%	-3.30%	27.23%	-43.47%	-7.38%	-3.30%	27.23%
Lower Middle Loup HUC 10210003								
Flow	-46.33%	-0.33%	0.47%	30.89%	-46.33%	-0.32%	0.48%	30.89%
TSS	-58.53%	-1.37%	3.49%	52.73%	-58.53%	-1.35%	3.50%	52.72%
TN	-48.22%	3.34%	1.68%	36.42%	-48.23%	3.38%	1.66%	36.36%
TP	-50.20%	-2.70%	0.27%	35.49%	-50.20%	-2.68%	0.28%	35.52%
South Loup HUC 10210004								
Flow	-54.05%	11.97%	7.96%	49.17%	-54.05%	11.99%	7.97%	49.17%

	Results without LU change				Results with LU change			
	Min	Median	Mean	Max	Min	Median	Mean	Max
TSS	-66.37%	18.77%	19.46%	109.14%	-66.39%	18.68%	19.52%	108.95%
TN	-51.14%	3.28%	-3.42%	31.16%	-51.32%	3.02%	-3.73%	30.26%
TP	-53.12%	9.04%	6.19%	49.11%	-53.09%	9.14%	6.18%	49.15%
Mud HUC 10210005								
Flow	-73.10%	17.49%	10.94%	62.36%	-73.10%	17.50%	10.95%	62.36%
TSS	-80.86%	17.09%	22.51%	139.63%	-81.00%	16.21%	21.59%	137.83%
TN	-55.02%	-1.14%	-5.38%	23.61%	-55.33%	-2.01%	-6.19%	22.60%
TP	-73.53%	15.40%	10.07%	67.06%	-73.34%	15.90%	10.57%	67.80%
Upper North Loup HUC 10210006								
Flow	-30.62%	0.69%	1.14%	21.30%	-30.62%	0.69%	1.14%	21.30%
TSS	-40.02%	11.50%	9.20%	38.49%	-40.02%	11.50%	9.20%	38.49%
TN	-14.84%	34.51%	30.67%	74.21%	-14.84%	34.51%	30.67%	74.21%
TP	-3.50%	3.97%	3.47%	7.56%	-3.50%	3.97%	3.47%	7.56%
Lower North Loup HUC 10210007								
Flow	-52.42%	3.86%	1.34%	33.63%	-52.42%	3.86%	1.34%	33.64%
TSS	-57.69%	5.14%	5.07%	49.86%	-57.69%	5.14%	5.07%	49.85%
TN	-46.98%	19.48%	11.79%	48.95%	-46.94%	19.51%	11.84%	49.11%
TP	-52.85%	2.62%	3.18%	41.57%	-52.84%	2.63%	3.19%	41.59%
Calamus HUC 10210008								
Flow	-38.44%	2.00%	0.37%	23.41%	-38.44%	2.00%	0.37%	23.41%
TSS	-49.76%	2.13%	2.00%	36.20%	-49.76%	2.13%	2.00%	36.20%
TN	-29.90%	25.52%	14.71%	32.65%	-29.90%	25.52%	14.71%	32.65%
TP	-40.65%	1.14%	0.63%	26.62%	-40.65%	1.14%	0.63%	26.62%
Loup HUC 10210009								
Flow	-79.17%	12.46%	11.64%	72.64%	-79.17%	12.47%	11.64%	72.64%
TSS	-88.67%	24.15%	25.48%	116.93%	-88.67%	24.17%	25.49%	116.94%
TN	-65.58%	17.51%	11.07%	58.25%	-65.59%	17.34%	11.03%	58.30%
TP	-69.16%	8.65%	10.32%	67.53%	-69.16%	8.66%	10.33%	67.55%
Cedar HUC 10210010								
Flow	-47.10%	15.83%	7.21%	28.46%	-47.10%	15.83%	7.21%	28.46%
TSS	-58.97%	26.40%	13.94%	42.11%	-58.96%	26.41%	13.94%	42.11%
TN	-47.53%	4.25%	-2.56%	16.16%	-47.53%	4.19%	-2.37%	16.06%
TP	-47.44%	15.72%	7.19%	28.71%	-47.43%	15.73%	7.19%	28.71%

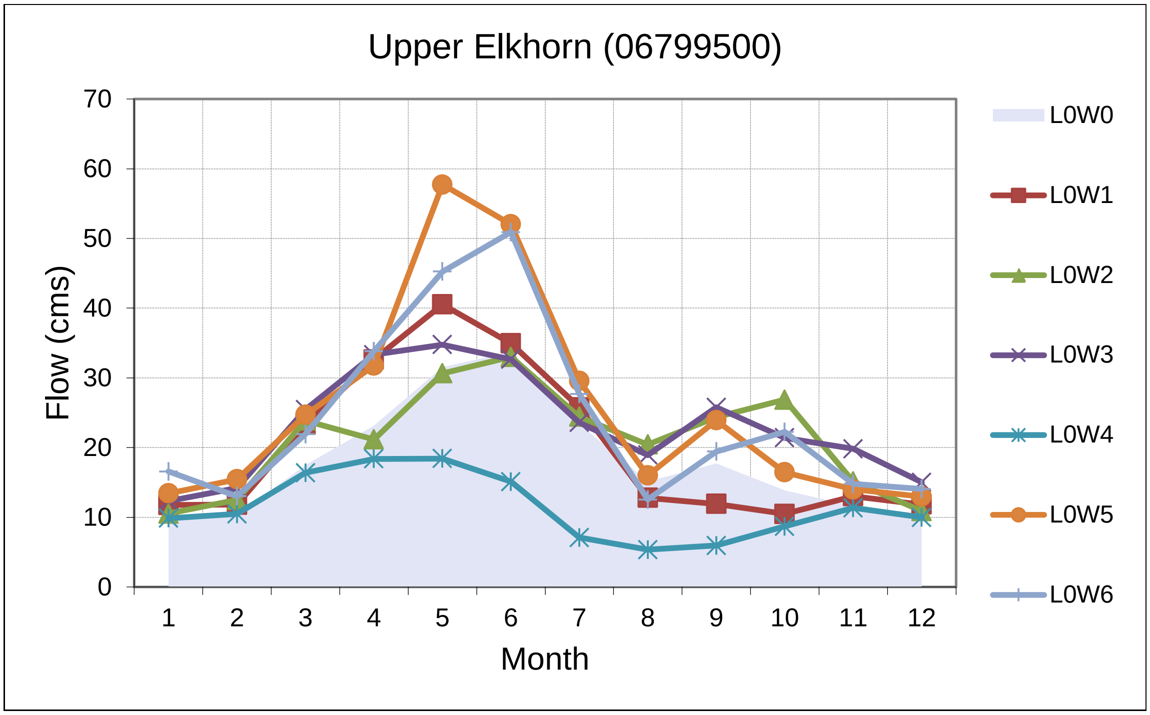


Figure 145. **Monthly average flows, Upper Elkhorn River (SWAT)**

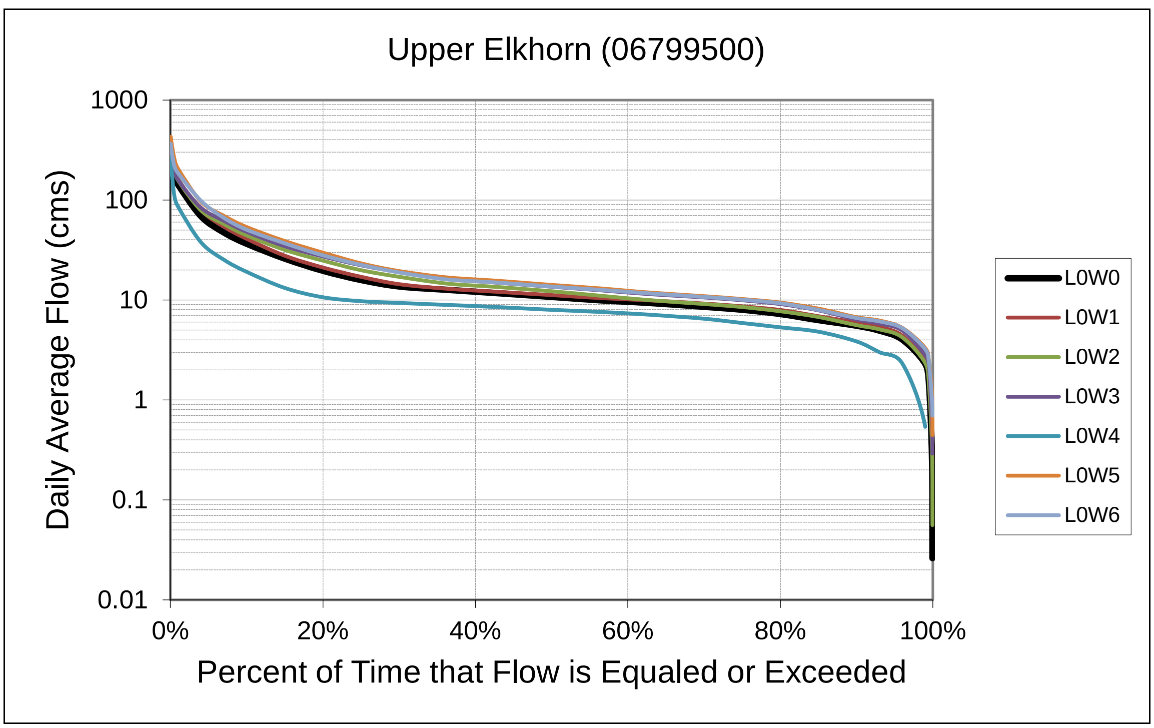


Figure 146. **Flow duration, Upper Elkhorn River (SWAT)**

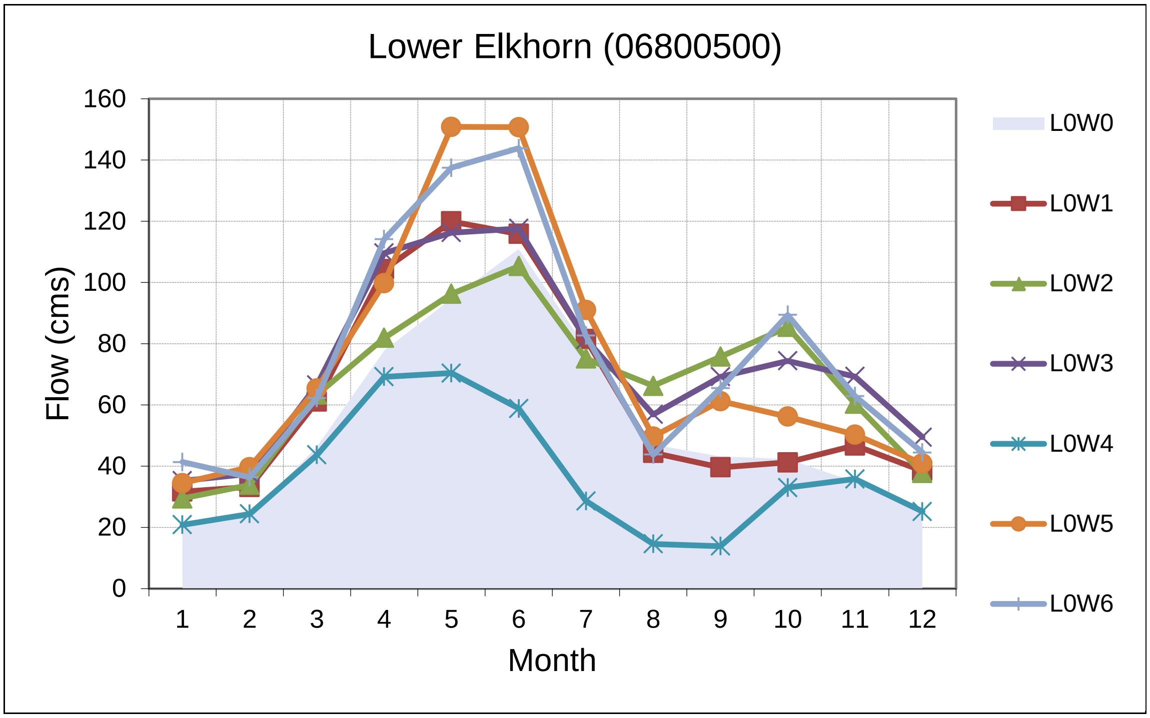


Figure 147. **Monthly average flows, Lower Elkhorn River (SWAT)**

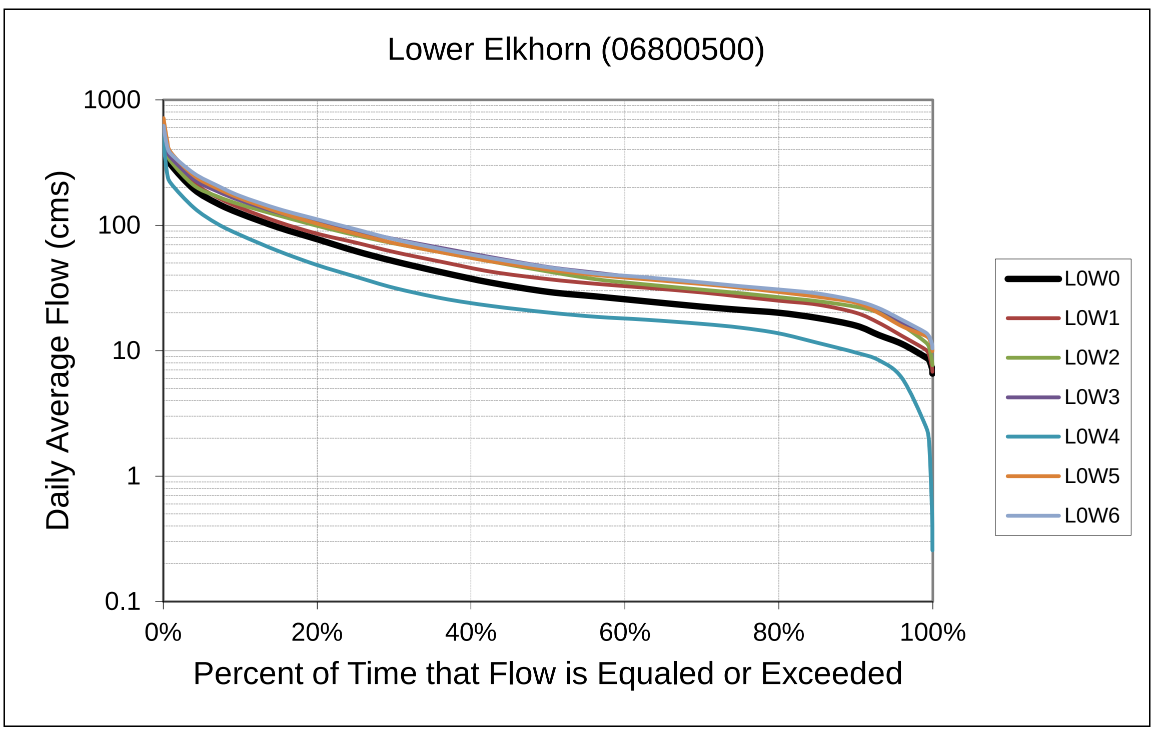


Figure 148. **Flow duration, Lower Elkhorn River (SWAT)**

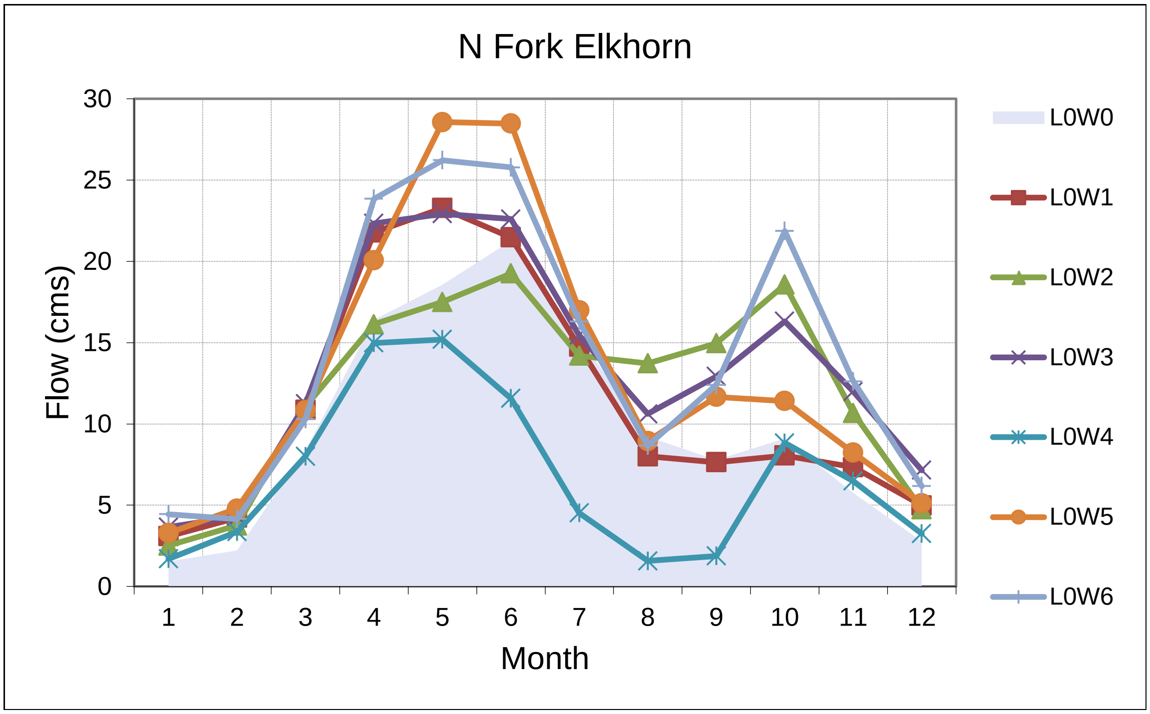


Figure 149. **Monthly average flows, North Fork Elkhorn River (SWAT)**

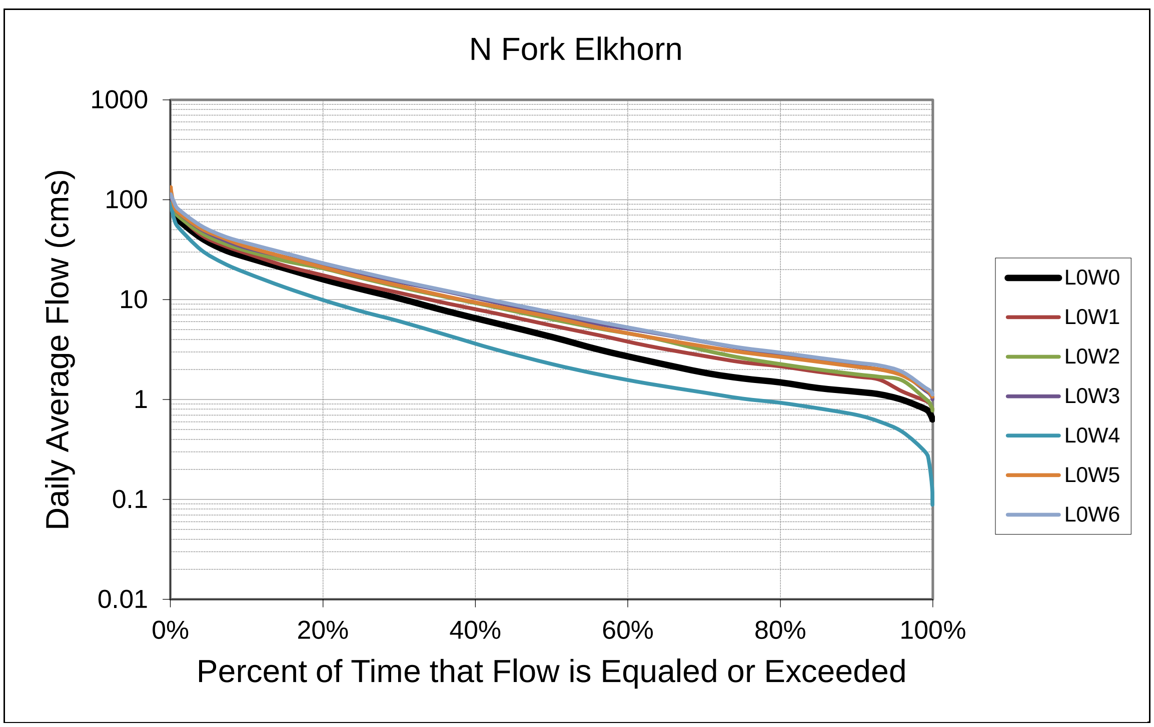


Figure 150. **Flow duration, North Fork Elkhorn River (SWAT)**

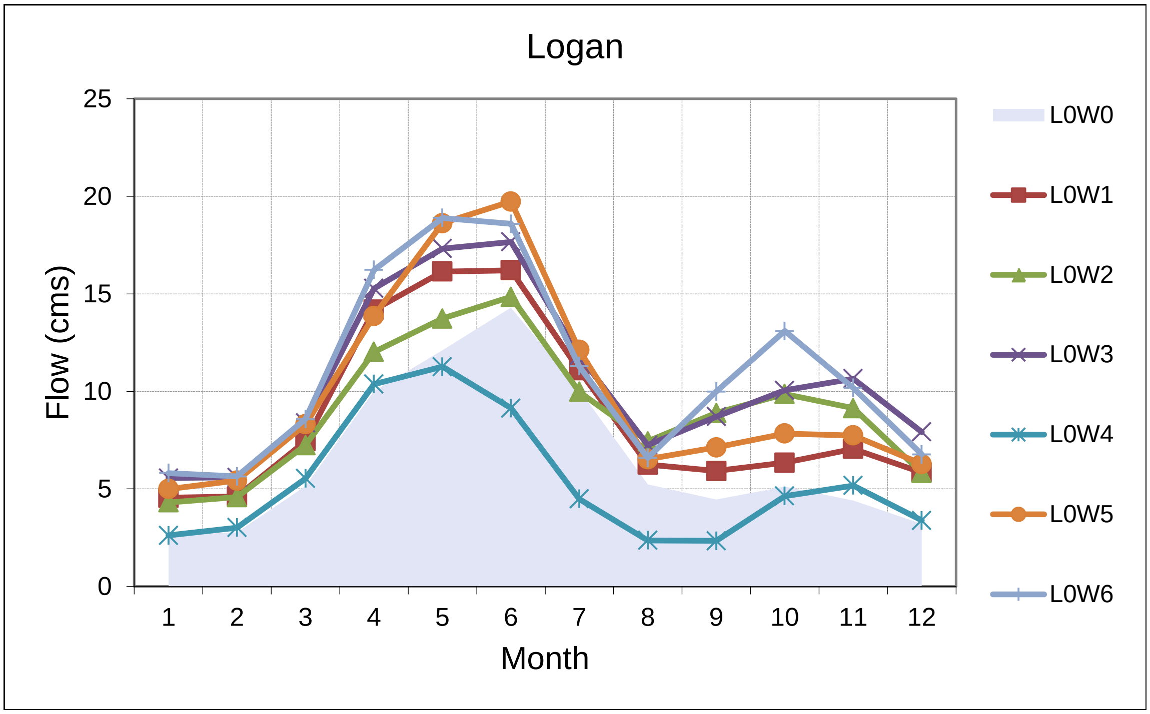


Figure 151. Monthly average flows, Logan River (SWAT)

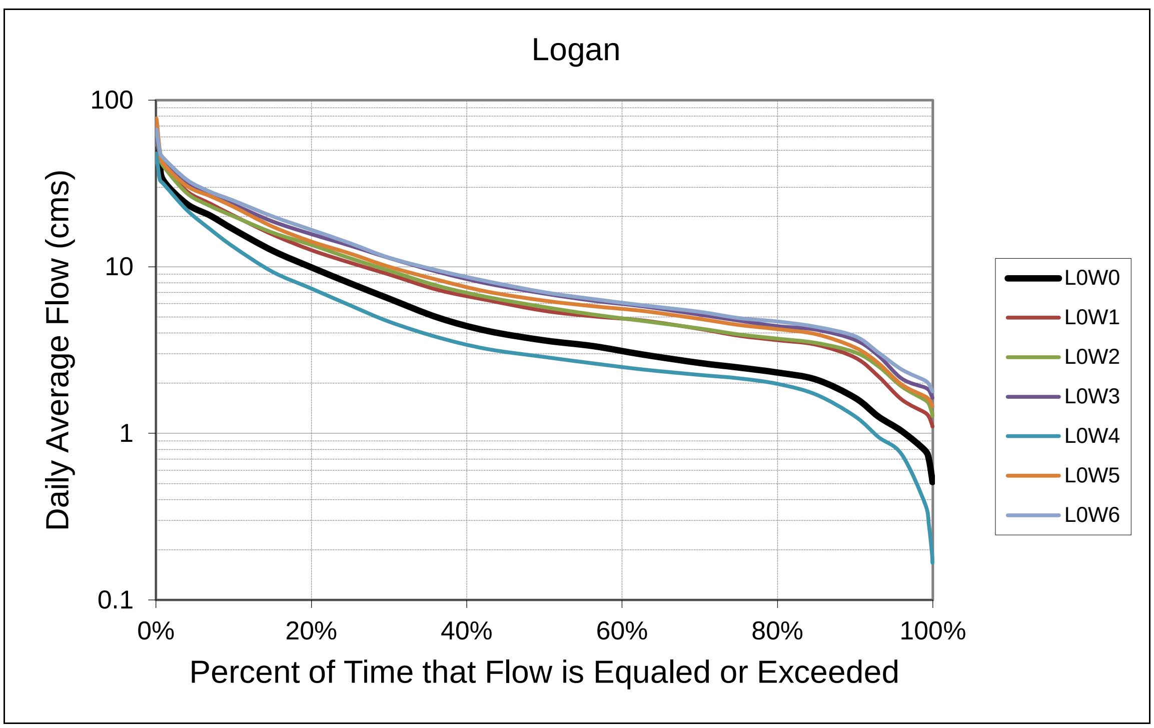


Figure 152. Flow duration, Logan River (SWAT)

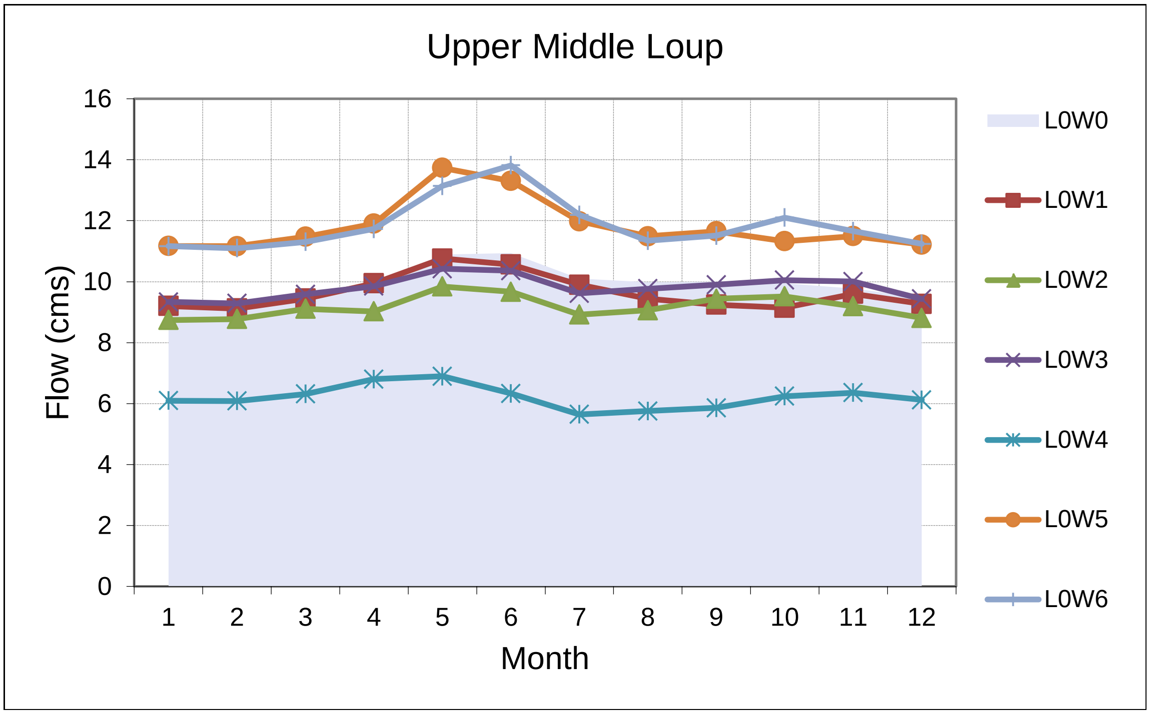


Figure 153. **Monthly average flows, Upper Middle Loup River (SWAT)**

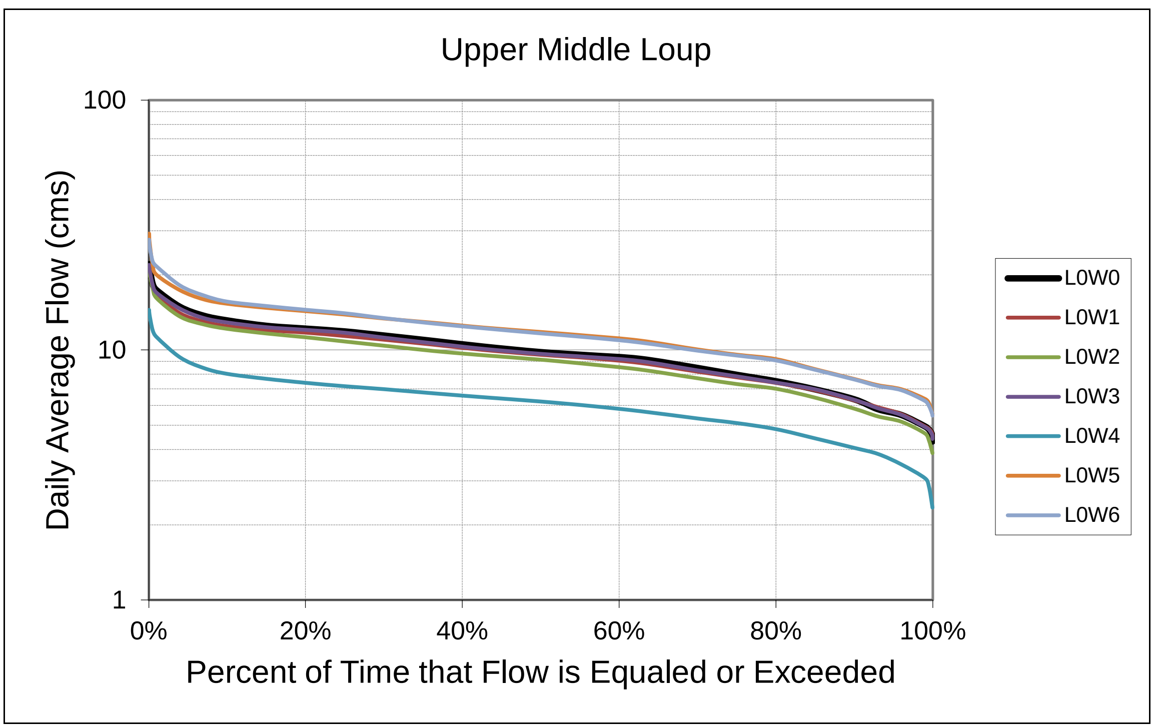


Figure 154. **Flow duration, Upper Middle Loup River (SWAT)**

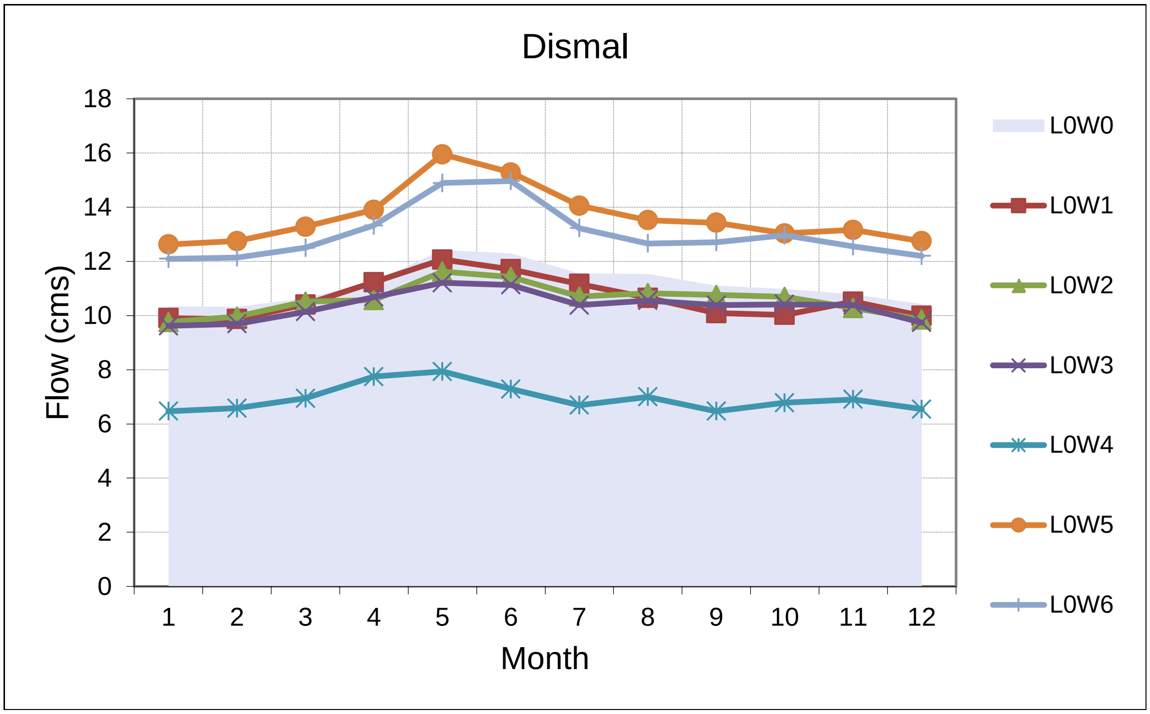


Figure 155. Monthly average flows, Dismal River (SWAT)

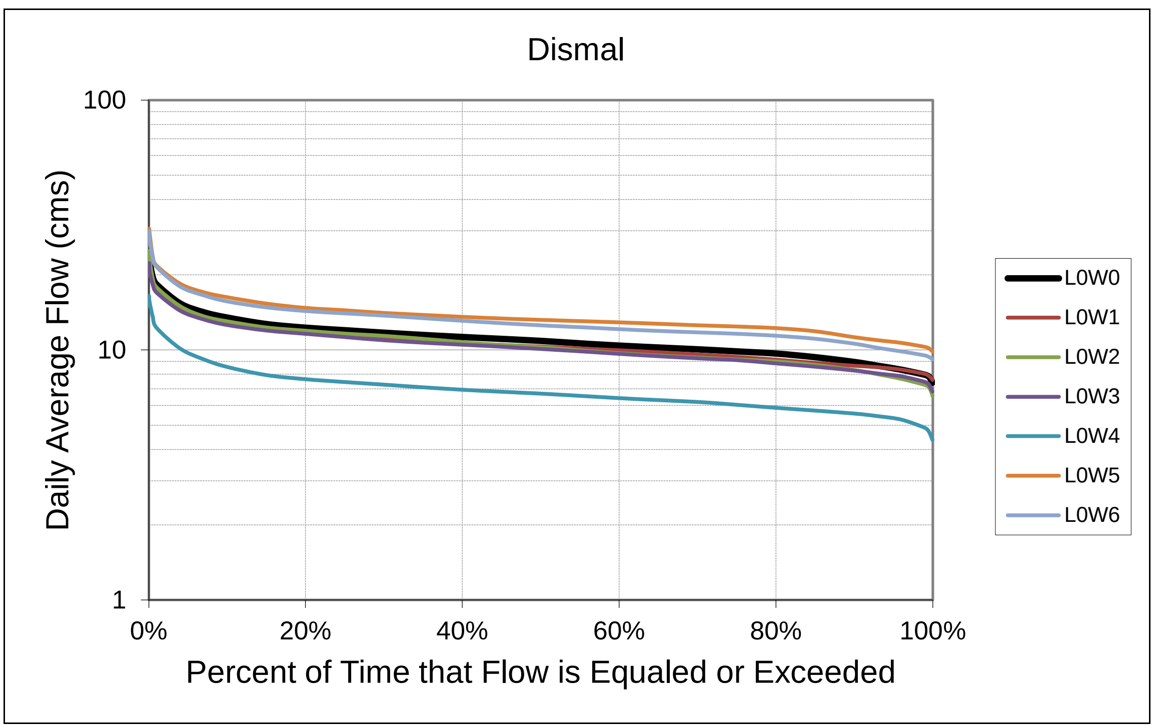


Figure 156. Flow duration, Dismal River (SWAT)

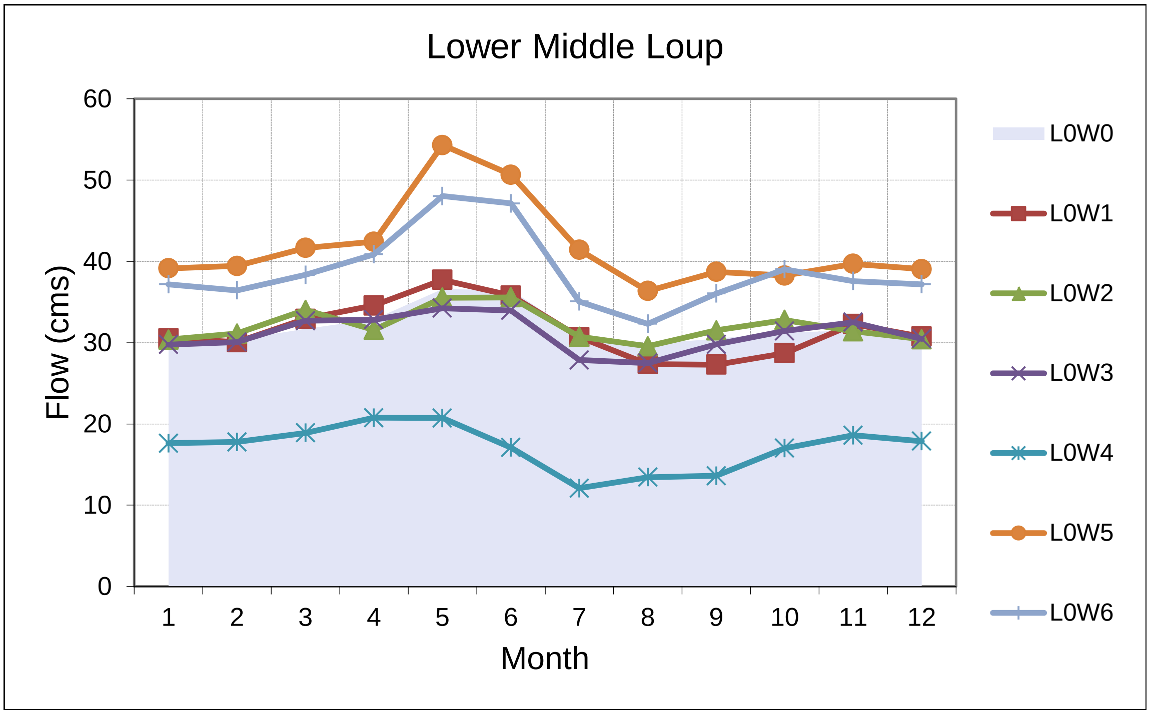


Figure 157. Monthly average flows, Lower Middle Loup River (SWAT)

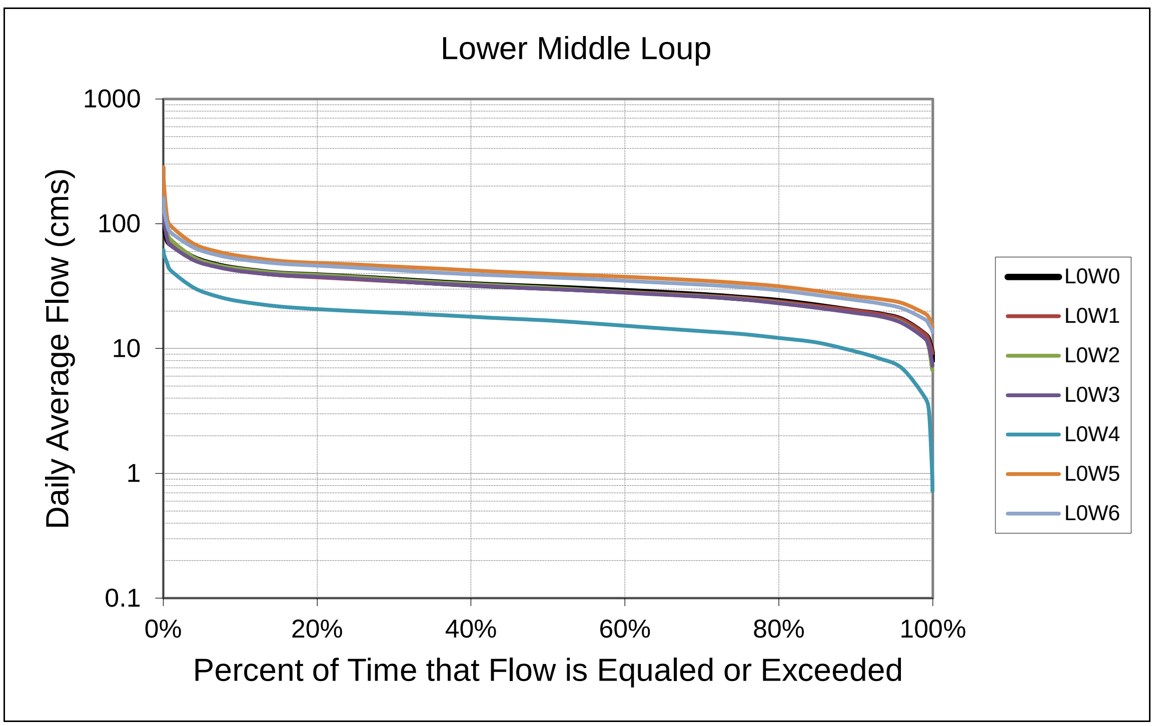


Figure 158. Flow duration, Lower Middle Loup River (SWAT)

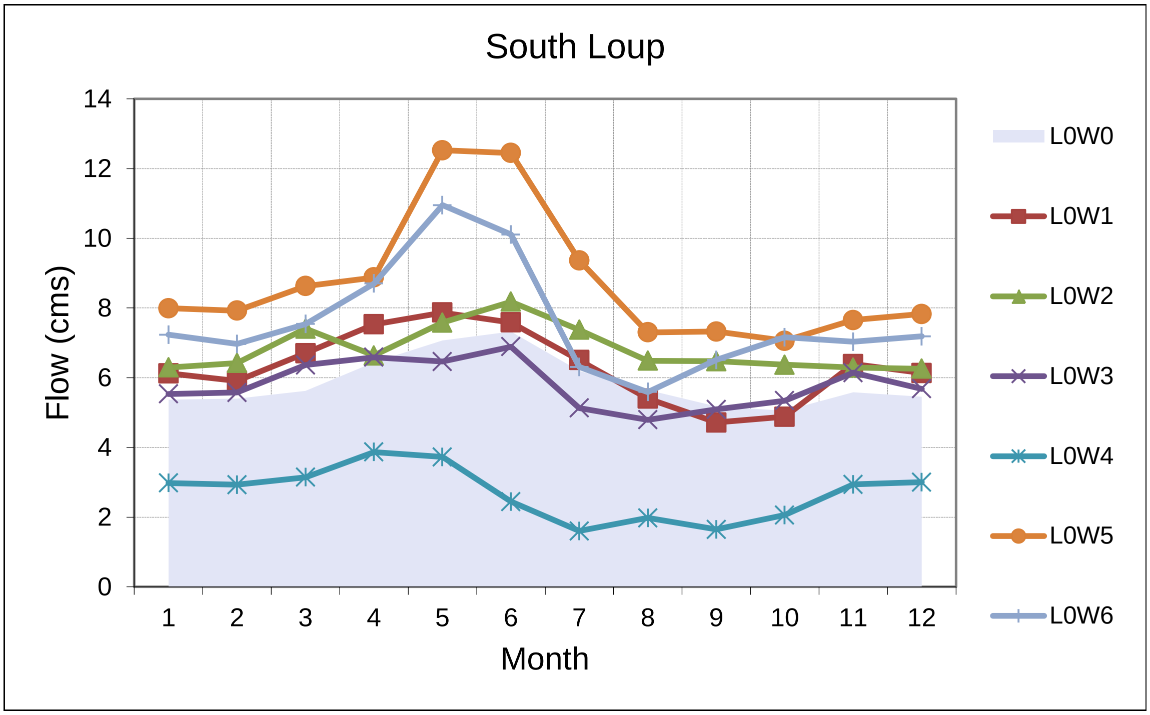


Figure 159. Monthly average flows, South Loup River (SWAT)

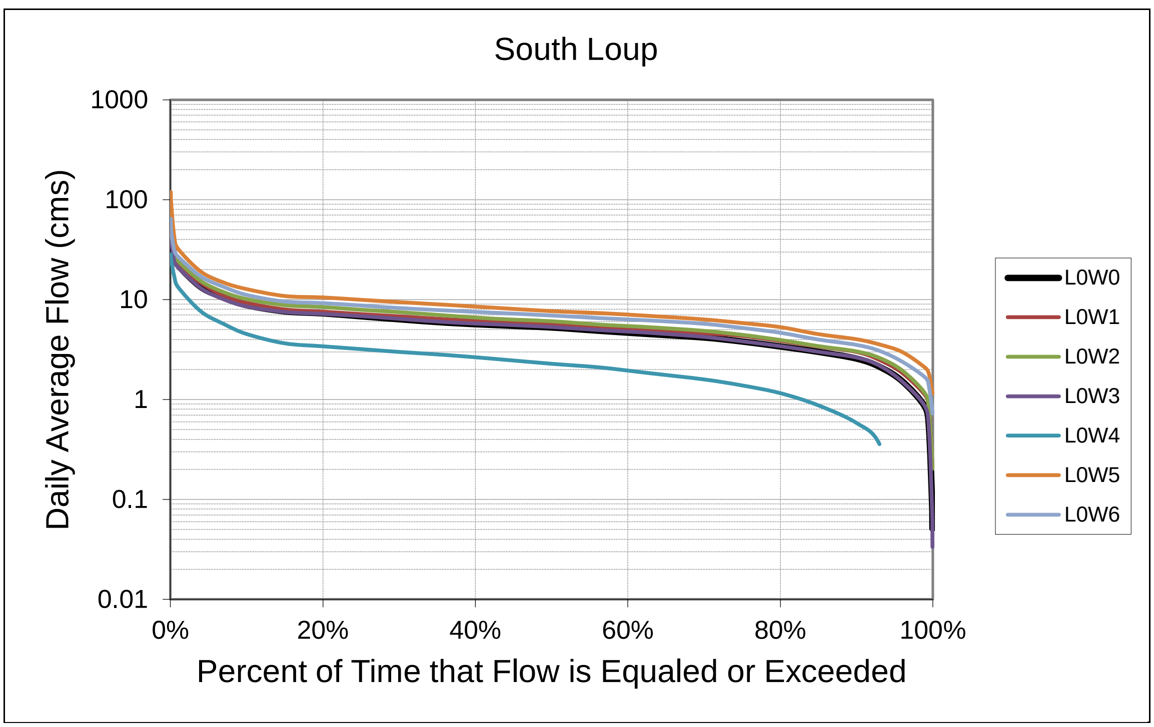


Figure 160. Flow duration, South Loup River (SWAT)

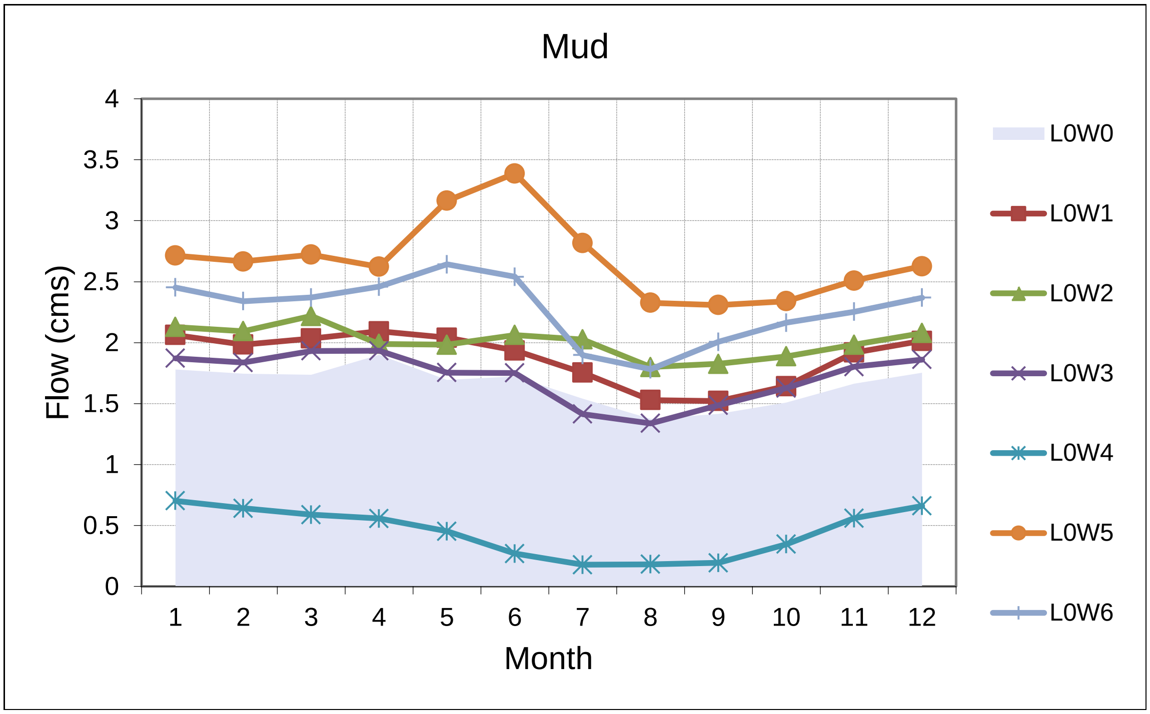


Figure 161. Monthly average flows, Mud River (SWAT)

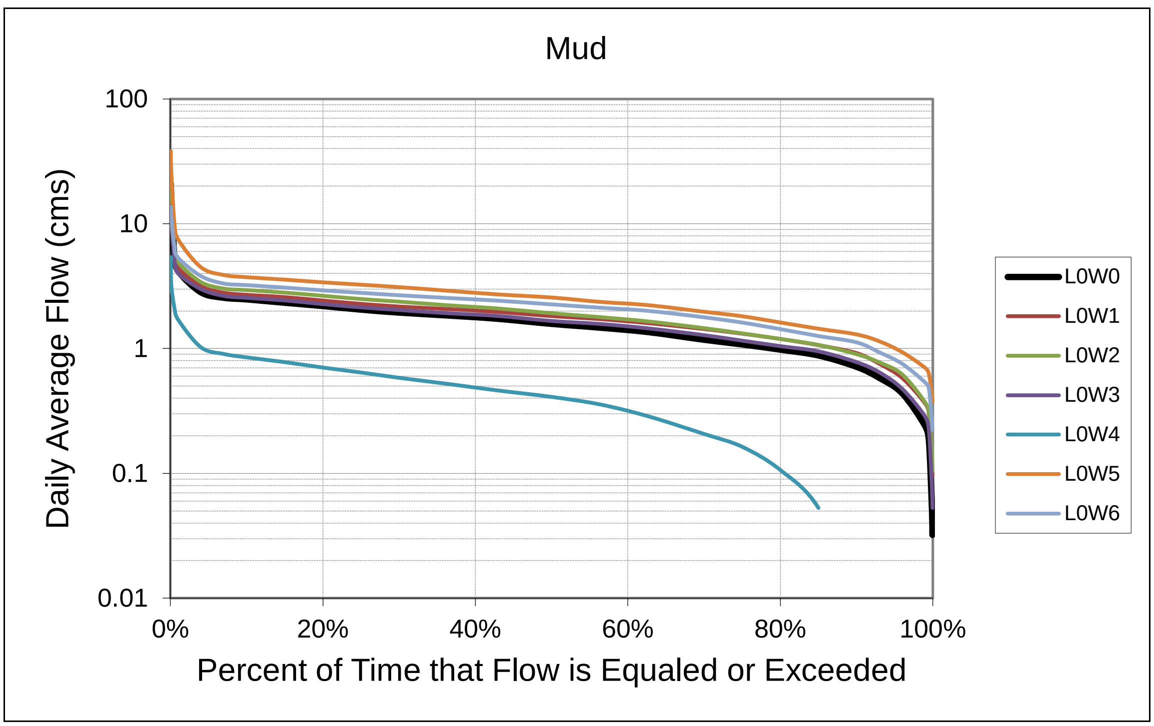


Figure 162. Flow duration, Mud River (SWAT)

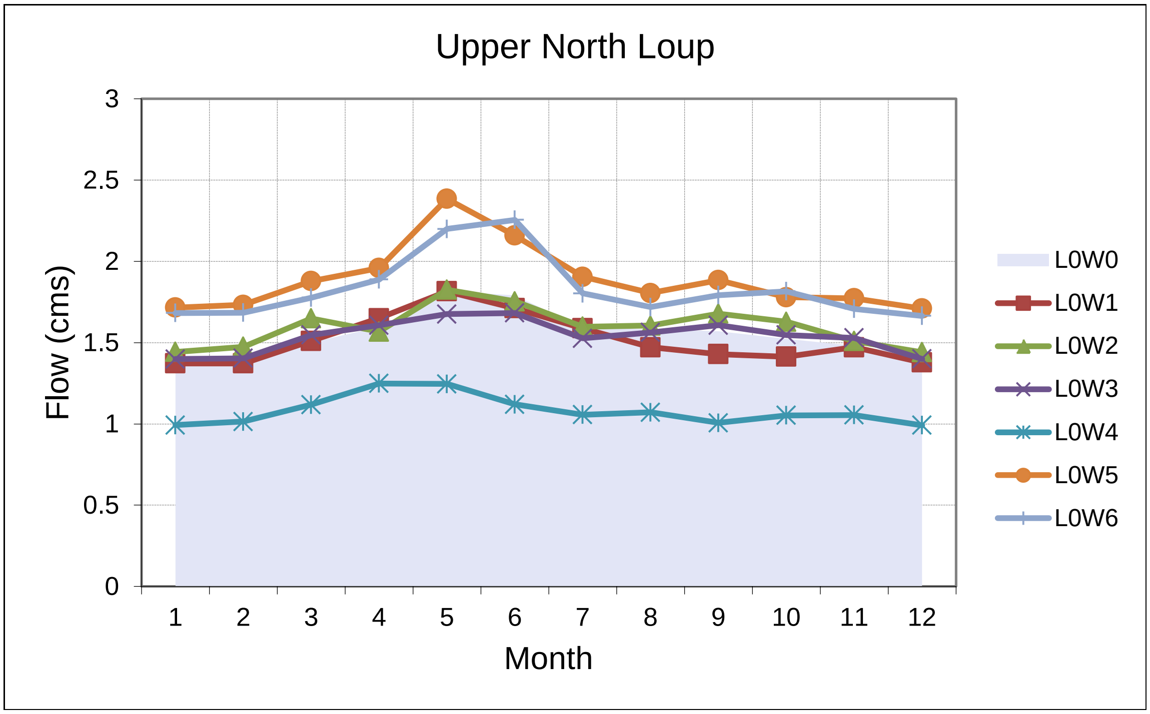


Figure 163. Monthly average flows, Upper North Loup River (SWAT)

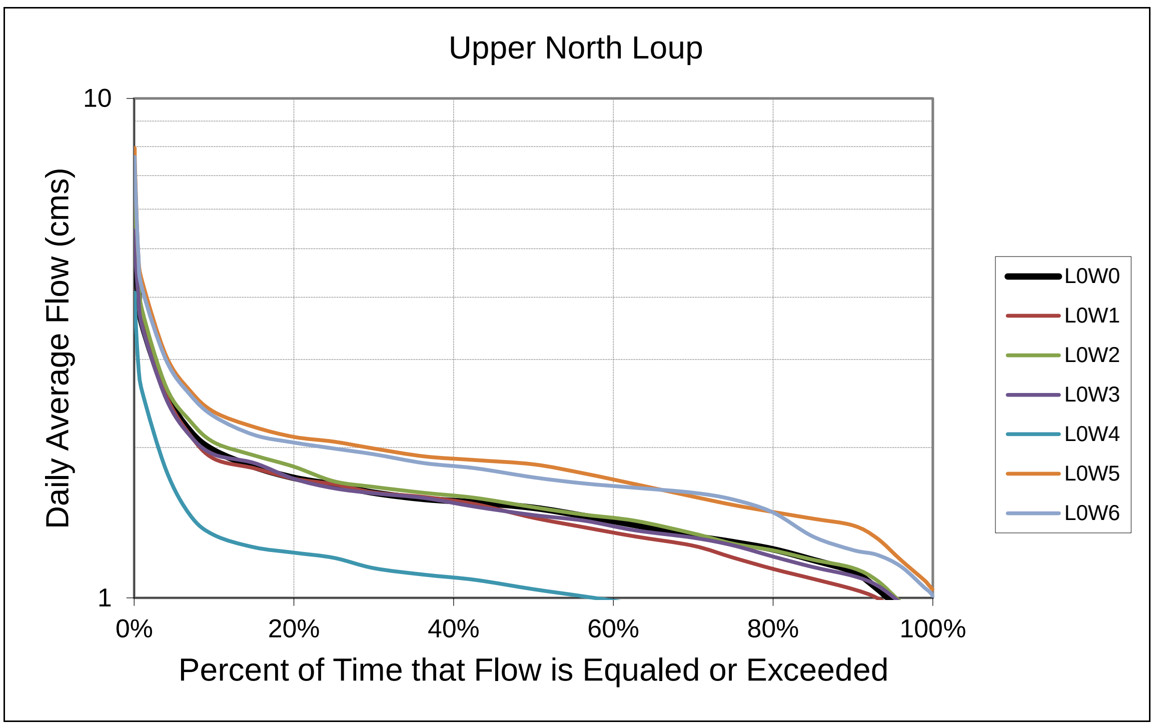


Figure 164. Flow duration, Upper North Loup River (SWAT)

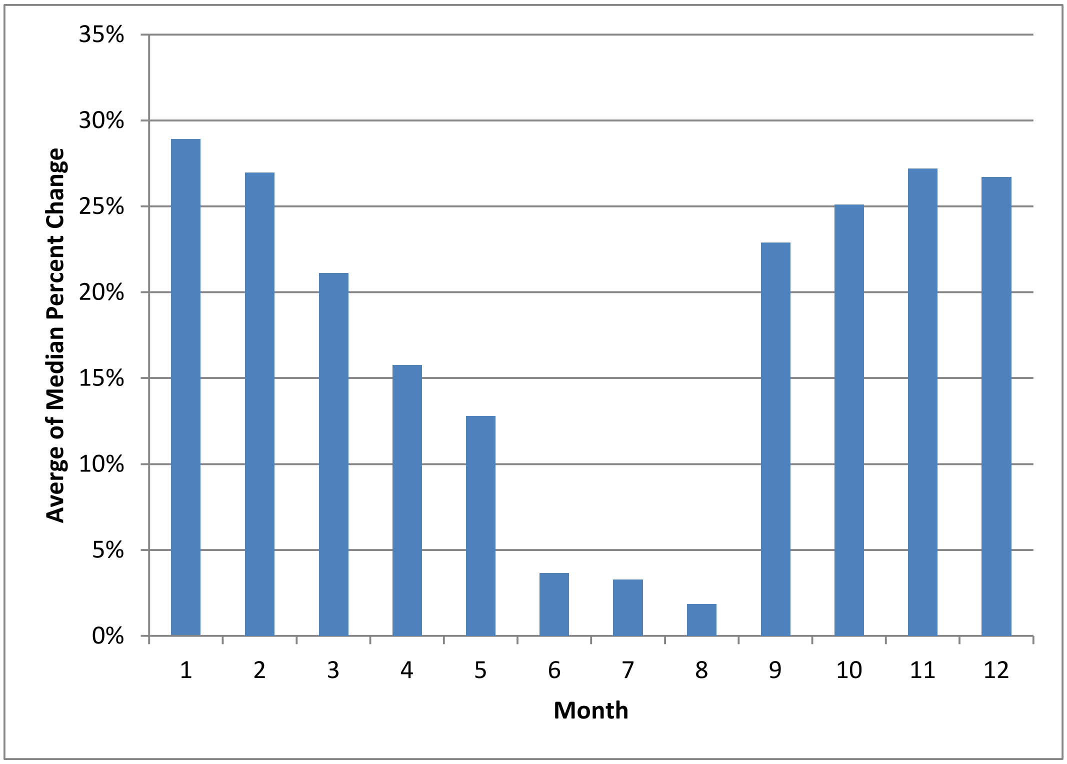


Figure 165. Average of median percent change in flow; NARCCAP Scenarios W1-W6 at all stations, Loup-Elkhorn basins (SWAT)

Tar and Neuse River Basins

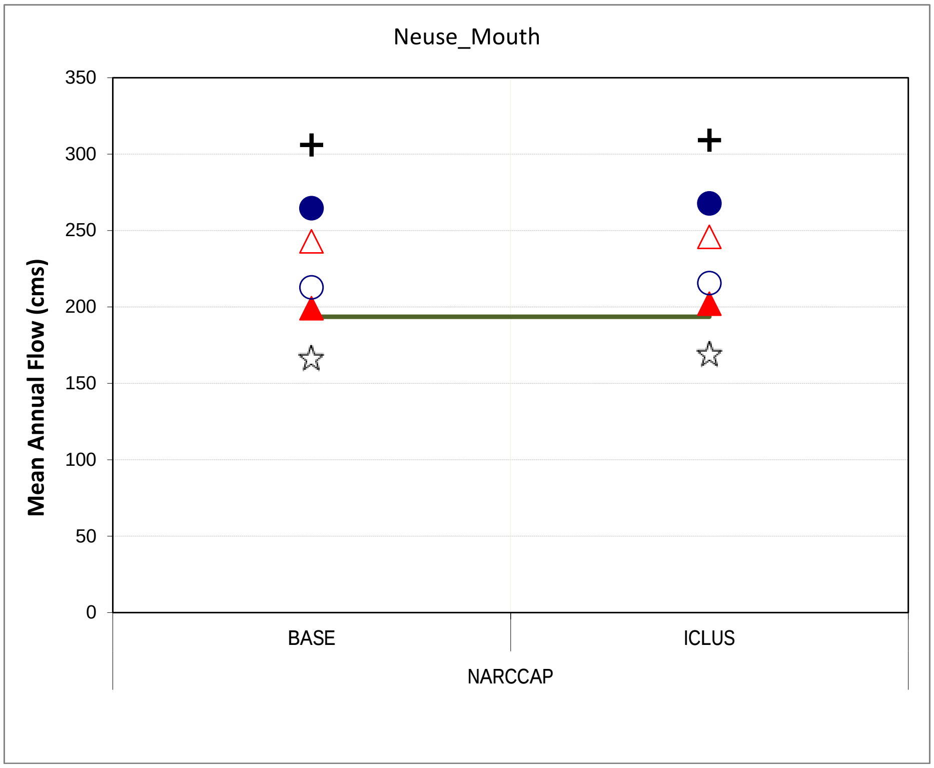


Figure 166. Mean annual flow (cms), mouth of Neuse River (SWAT)

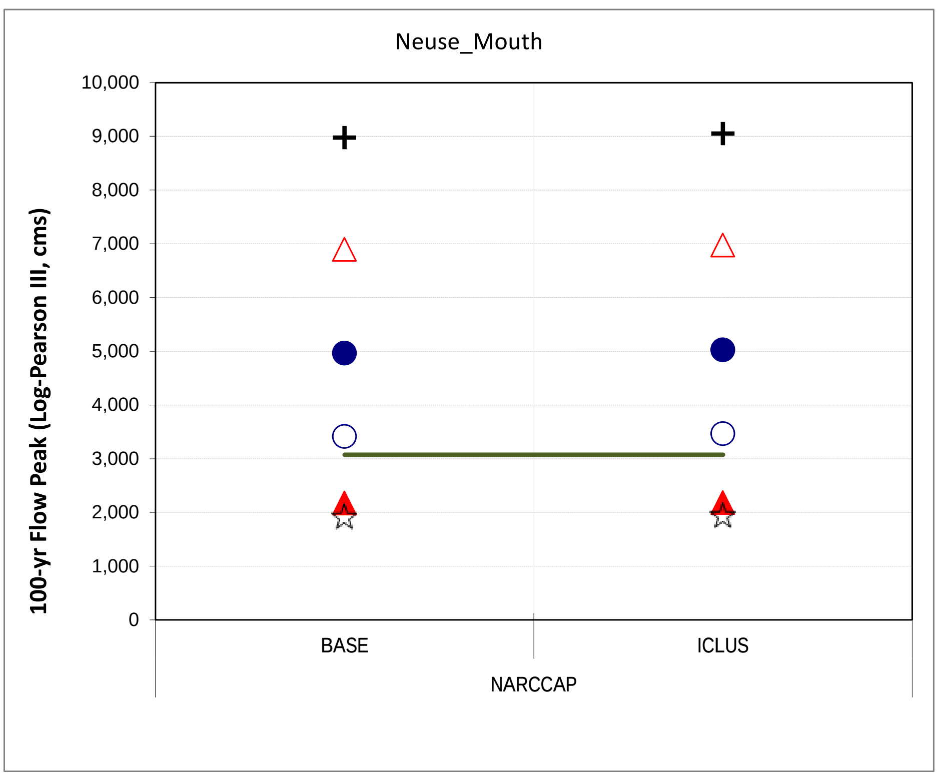


Figure 167. 100-yr Flow Peak (Log-Pearson III, cms), mouth of Neuse River (SWAT)

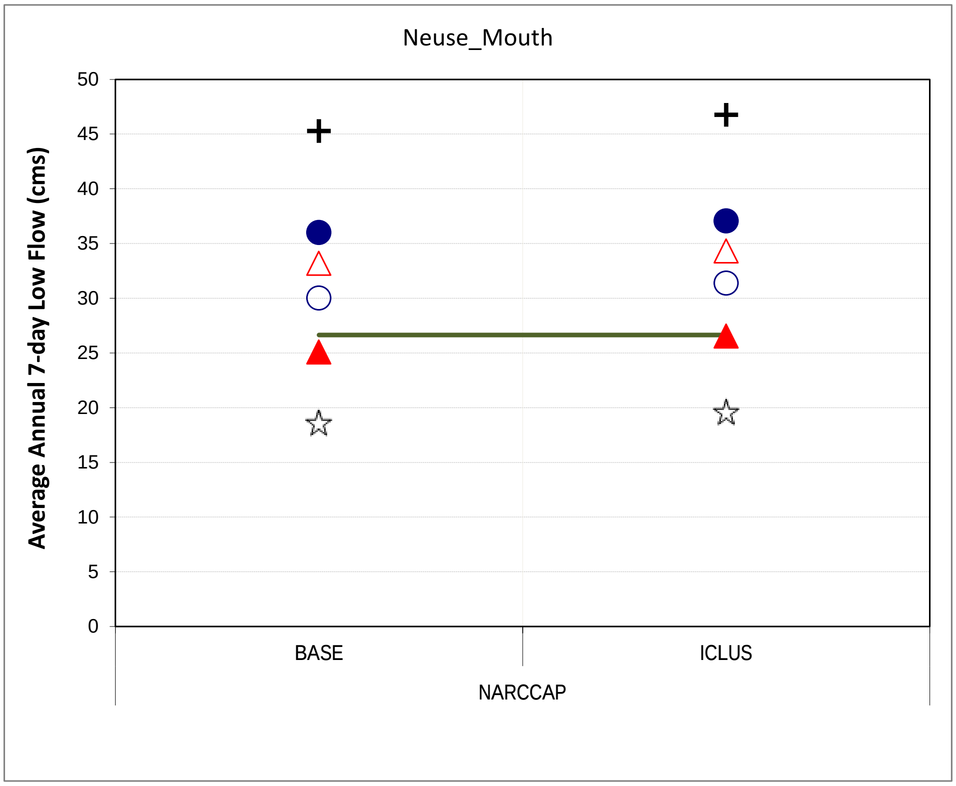


Figure 168. Average Annual 7-day Low Flow (cms), mouth of Neuse River (SWAT)

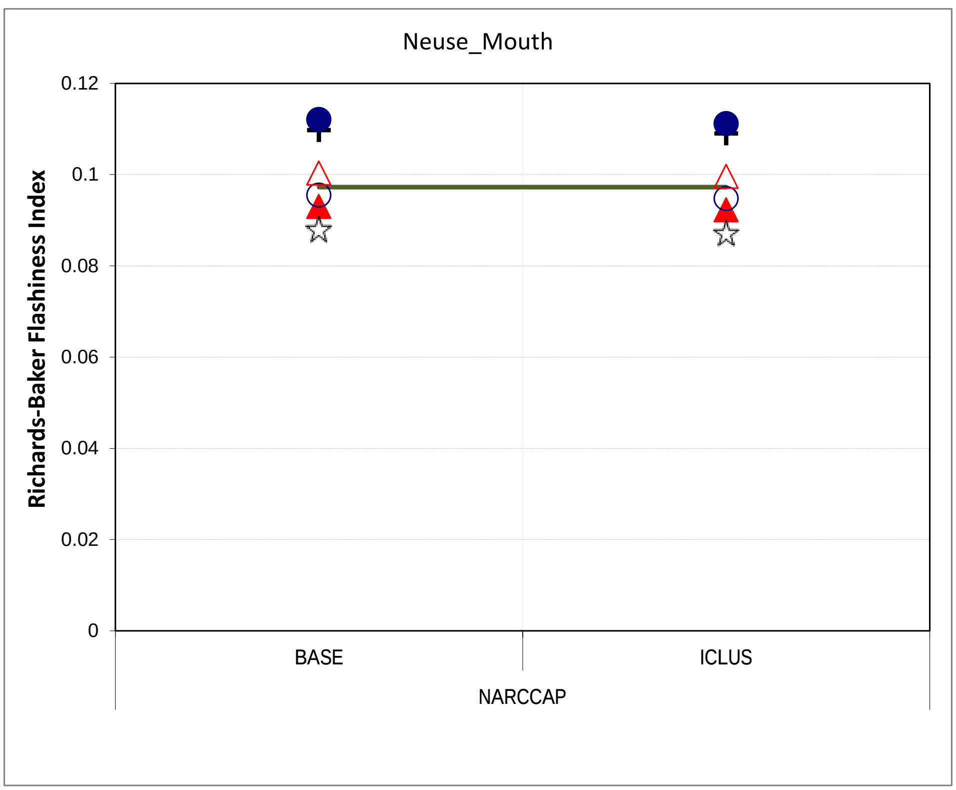


Figure 169. Richards-Baker Flashiness Index, Average Annual 7-day Low Flow (cms), mouth of Neuse River (SWAT)

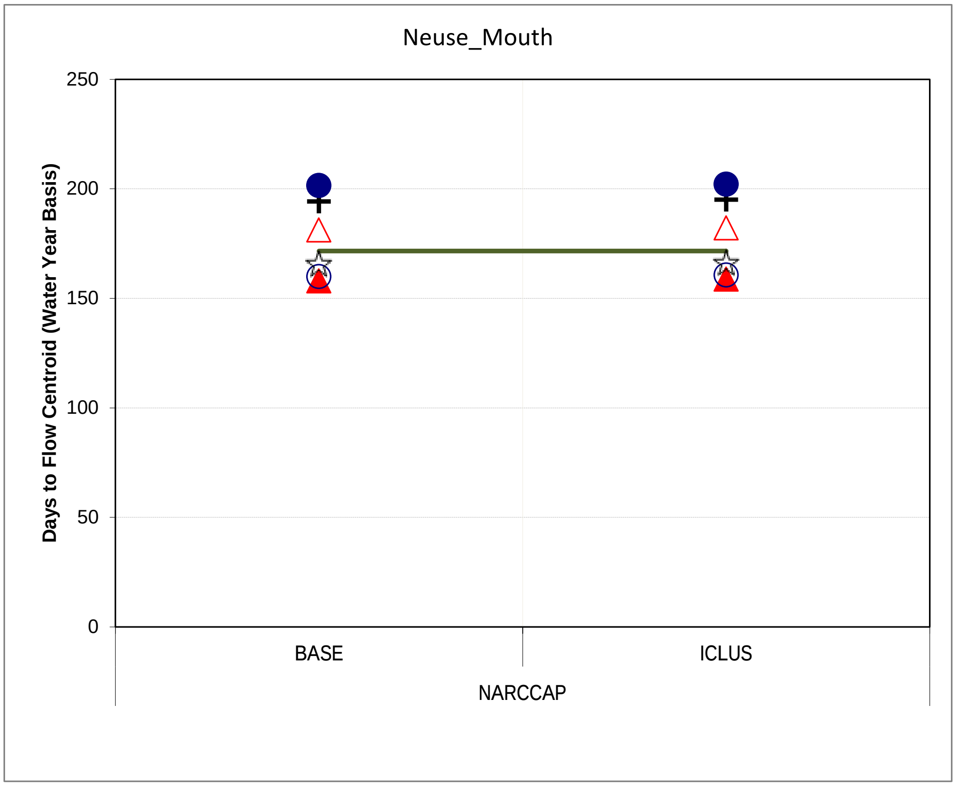


Figure 170. Days to Flow Centroid (Water Year Basis), mouth of Neuse River (SWAT)

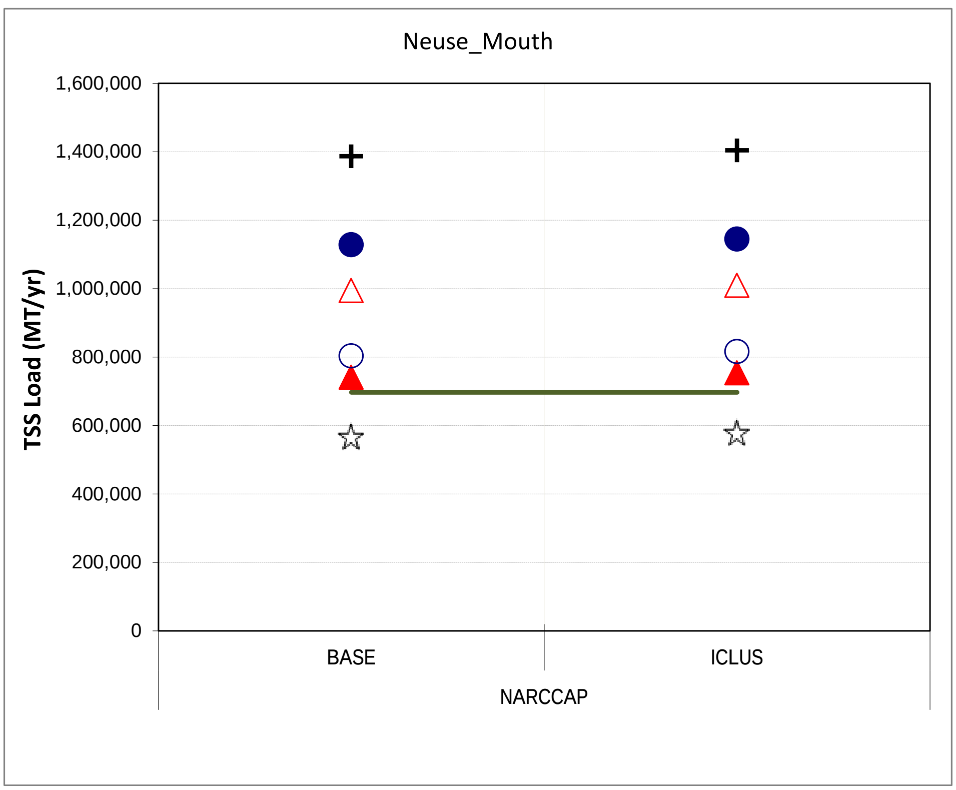


Figure 171. TSS Load (MT/yr), mouth of Neuse River (SWAT)

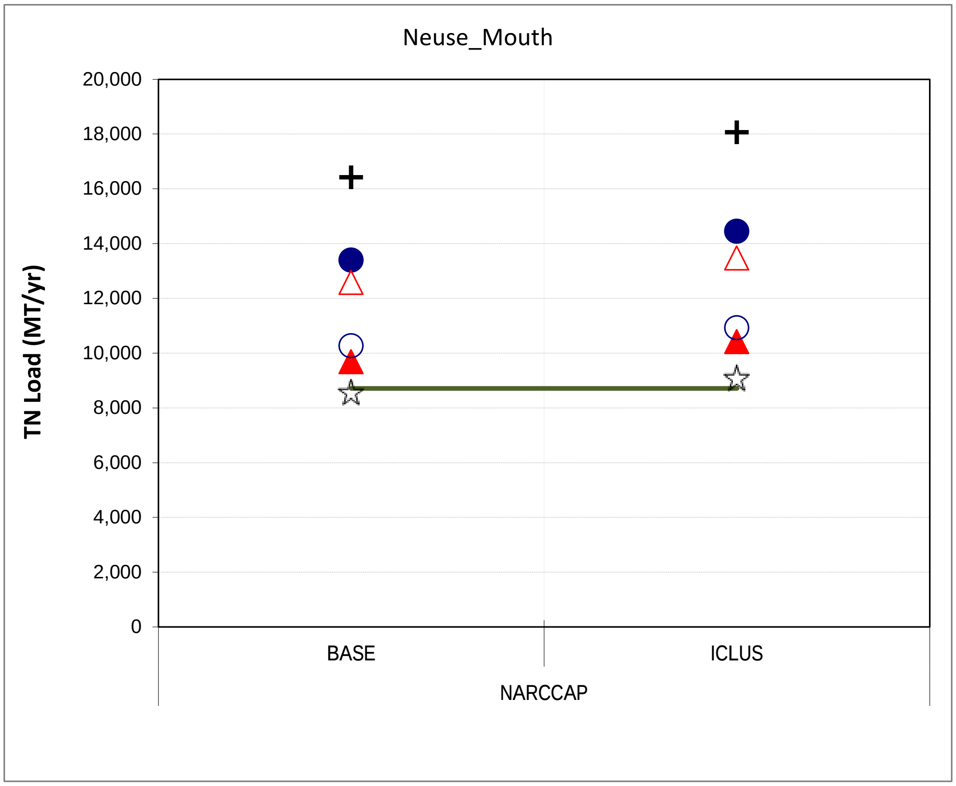


Figure 172. **TN Load (MT/yr), mouth of Neuse River (SWAT)**

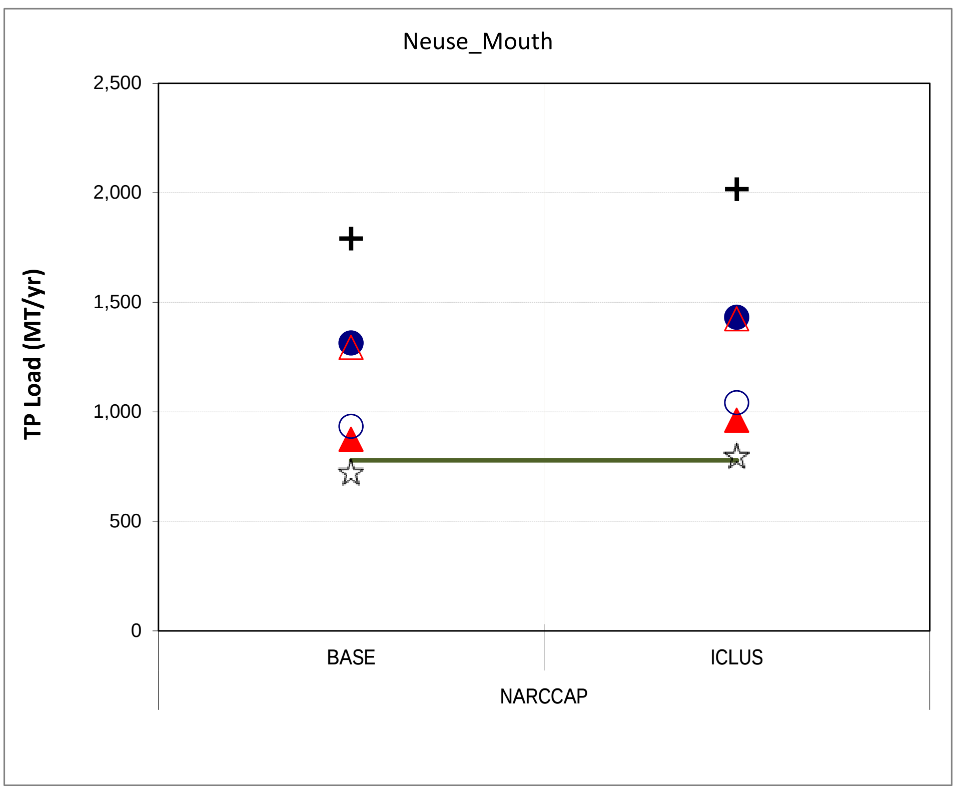


Figure 173. **TP Load (MT/yr), mouth of Neuse River (SWAT)**

Table 7. Summary of range of change relative to existing conditions for NARCCAP dynamically downscaled scenarios, Tar-Neuse watershed SWAT model

	Results without LU change				Results with LU change			
	Min	Median	Mean	Max	Min	Median	Mean	Max
Contentnea Creek (gage 02091500)								
Flow	-11.95%	20.12%	21.63%	61.83%	-11.94%	19.88%	21.40%	61.34%
TSS	-22.15%	49.06%	58.45%	190.18%	-22.13%	48.83%	58.05%	188.94%
TN	-3.11%	44.81%	53.26%	141.32%	-2.79%	46.27%	54.87%	143.00%
TP	-10.80%	47.10%	57.60%	166.11%	-10.45%	47.50%	57.59%	164.93%
Neuse River at Kinston (gage 02089500)								
Flow	-7.77%	20.31%	22.01%	59.34%	-8.12%	19.10%	20.76%	56.94%
TSS	-10.52%	30.82%	36.31%	107.02%	-10.56%	30.00%	35.40%	105.08%
TN	5.65%	40.64%	43.90%	97.93%	14.33%	52.17%	57.70%	127.50%
TP	1.69%	43.42%	50.77%	120.14%	7.85%	53.00%	61.64%	146.07%
Neuse at Mouth HUC 03020204								
Flow	-13.65%	17.69%	19.90%	58.08%	-13.71%	17.15%	19.35%	56.99%
TSS	-18.16%	29.00%	34.52%	99.03%	-18.37%	28.07%	33.50%	96.92%
TN	-1.17%	31.19%	35.80%	88.54%	1.51%	35.54%	41.61%	100.72%
TP	-6.45%	42.94%	48.33%	129.77%	-3.23%	48.33%	53.95%	142.56%
Tar River at Tarboro (Upper Tar, Fishing); HUCs 03020101 and 03020102								
Flow	-4.58%	20.27%	23.15%	61.50%	-4.61%	20.18%	23.05%	61.30%
TSS	-7.85%	31.12%	42.58%	126.63%	-7.79%	31.07%	42.51%	126.44%
TN	8.65%	27.11%	31.52%	61.86%	8.00%	28.37%	32.58%	64.49%
TP	2.23%	29.91%	31.09%	71.26%	1.98%	31.64%	32.55%	74.33%
Pamlico (Tar Mouth) HUC 03020104								
Flow	-9.47%	19.57%	20.91%	57.03%	-9.49%	19.45%	20.79%	56.79%
TSS	-13.29%	31.58%	34.71%	96.24%	-13.32%	31.41%	34.52%	95.77%
TN	-1.21%	28.35%	30.96%	58.91%	-0.27%	30.32%	34.42%	64.57%
TP	-8.97%	31.05%	34.74%	77.35%	-7.62%	33.21%	38.10%	83.03%
Lower Tar HUC 03020103								
Flow	-7.29%	20.69%	22.12%	60.12%	-7.32%	20.51%	21.94%	59.75%
TSS	-14.95%	40.55%	46.67%	144.39%	-14.96%	40.38%	46.43%	143.72%
TN	3.23%	30.57%	34.36%	72.61%	5.11%	36.84%	40.96%	82.45%
TP	-6.89%	31.72%	35.75%	92.03%	-3.73%	39.27%	42.98%	103.36%
Upper Neuse HUC 03020201								
Flow	-6.73%	20.35%	21.98%	58.69%	-7.16%	19.03%	20.56%	55.96%
TSS	-8.38%	31.16%	40.77%	118.63%	-8.99%	29.65%	38.81%	114.27%
TN	7.82%	36.82%	43.72%	102.65%	22.37%	55.25%	64.51%	143.10%
TP	5.87%	39.80%	49.61%	122.46%	18.41%	54.61%	67.38%	158.17%
Middle Neuse HUC 03020202								
Flow	-11.22%	19.38%	21.18%	59.87%	-11.38%	18.63%	20.42%	58.38%

	Results without LU change				Results with LU change			
	Min	Median	Mean	Max	Min	Median	Mean	Max
TSS	-18.29%	38.51%	45.11%	140.27%	-18.42%	37.61%	44.13%	137.90%
TN	0.24%	35.61%	38.59%	89.70%	5.27%	41.60%	47.52%	107.46%
TP	-5.32%	39.93%	42.78%	108.29%	-0.99%	46.18%	50.37%	124.56%
Contentnea HUC 03020203								
Flow	-12.43%	20.47%	21.42%	61.60%	-12.43%	20.17%	21.13%	60.97%
TSS	-20.96%	42.94%	49.15%	160.75%	-20.88%	42.63%	48.77%	159.54%
TN	-4.11%	37.92%	43.31%	111.71%	-3.82%	38.47%	45.60%	114.03%
TP	-9.95%	38.83%	43.97%	124.92%	-9.31%	37.67%	44.44%	123.57%

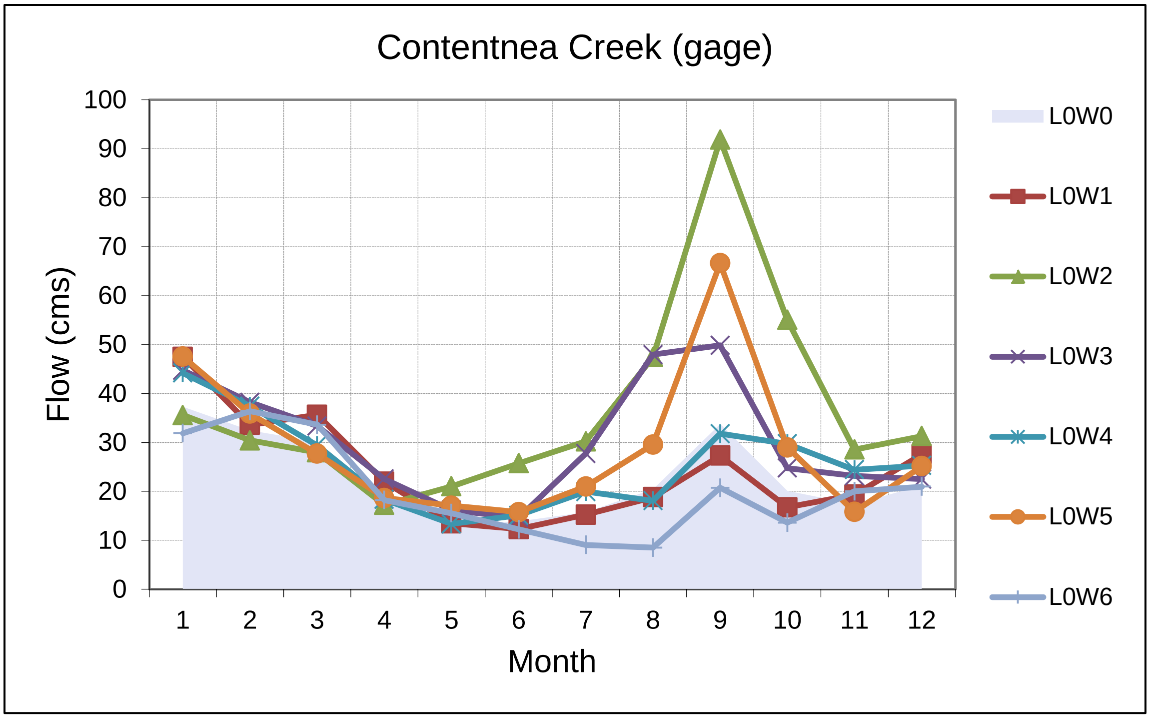


Figure 174. **Monthly average flows, Contentnea Creek gage (SWAT)**

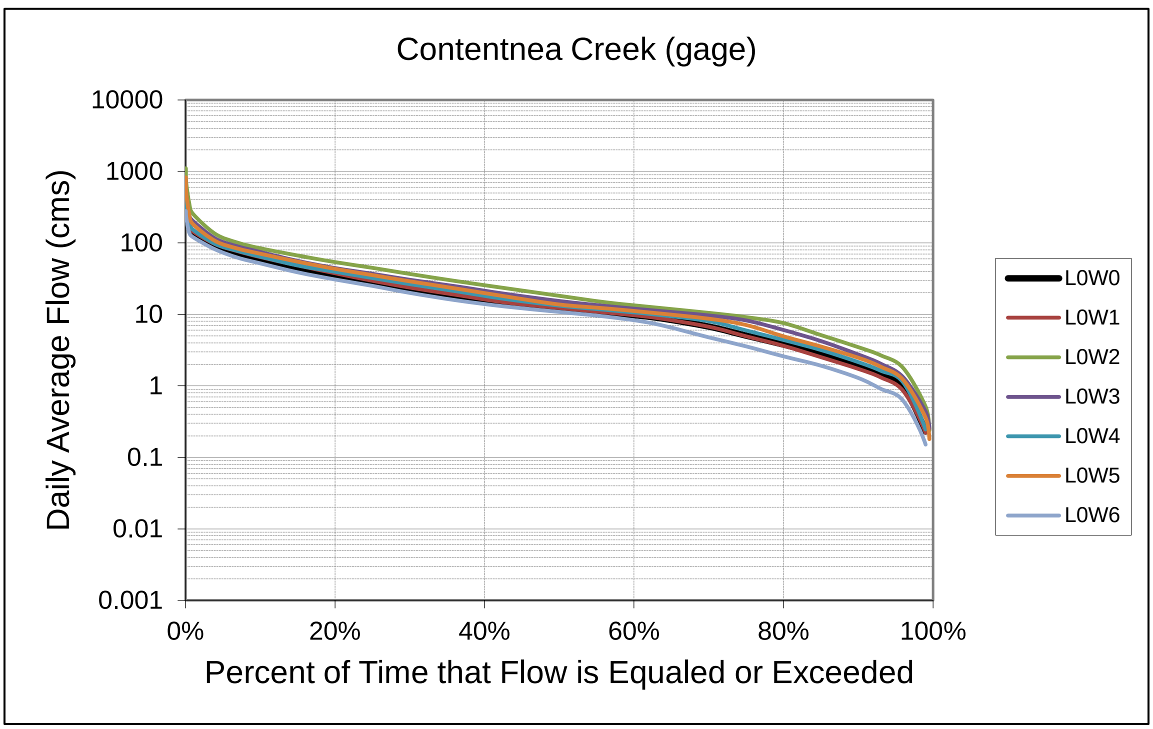


Figure 175. **Flow duration, Contentnea Creek gage (SWAT)**

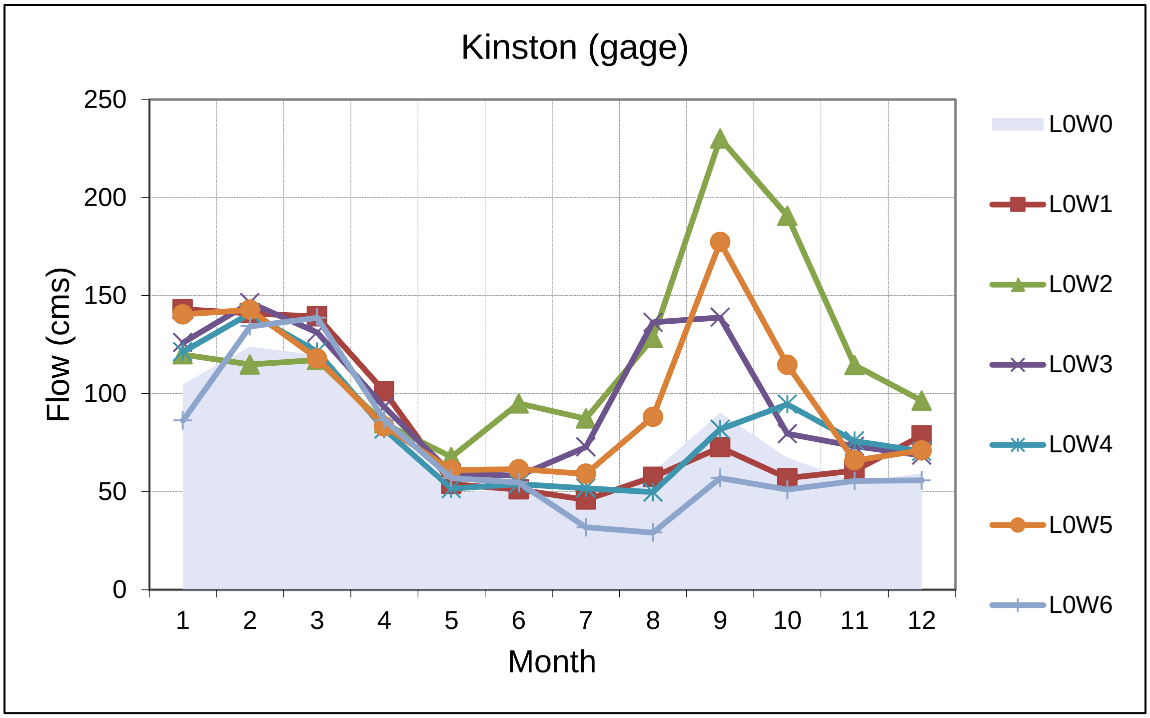


Figure 176. Monthly average flows, Neuse River at Kinston (SWAT)

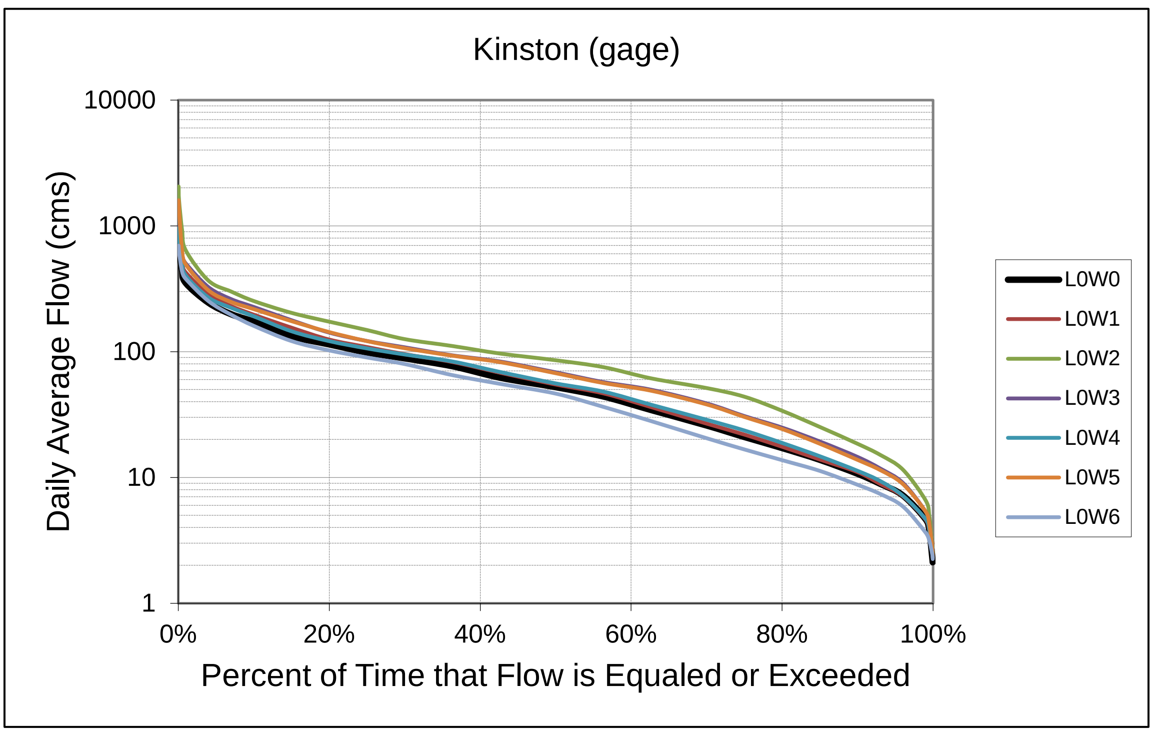


Figure 177. Flow duration, Neuse River at Kinston (SWAT)

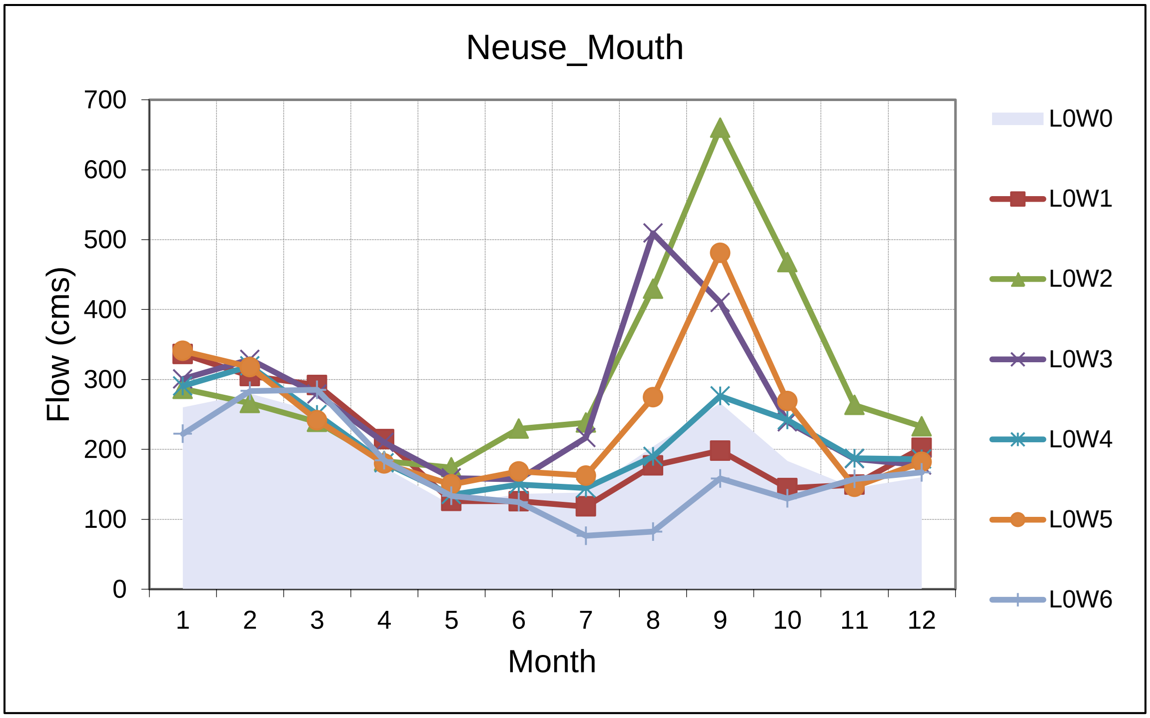


Figure 178. Monthly average flows, mouth of Neuse River (SWAT)

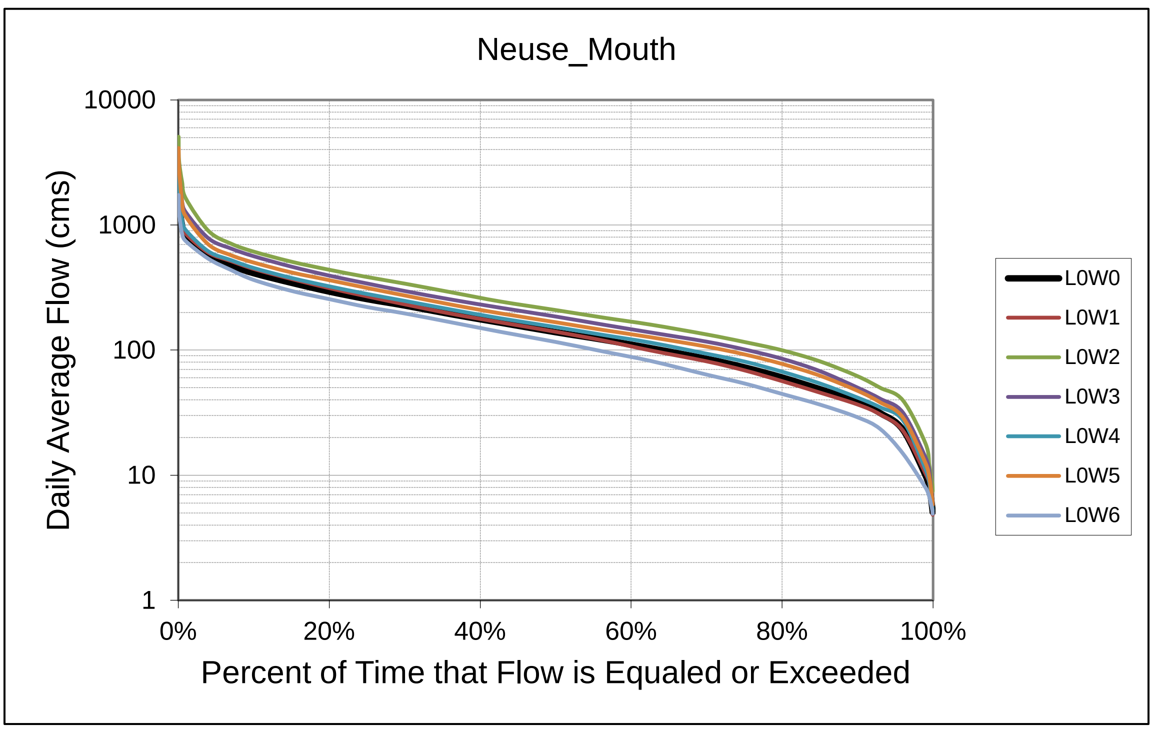


Figure 179. Flow duration, mouth of Neuse River (SWAT)

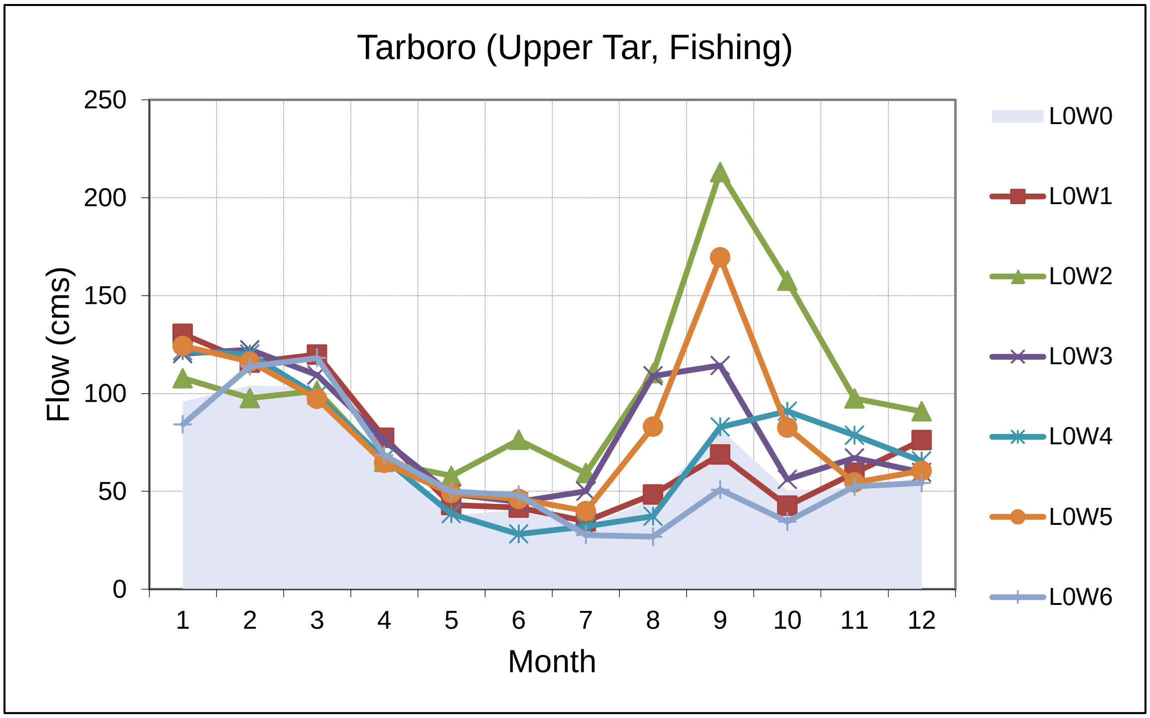


Figure 180. **Monthly average flows, Upper Tar River at Tarboro (SWAT)**

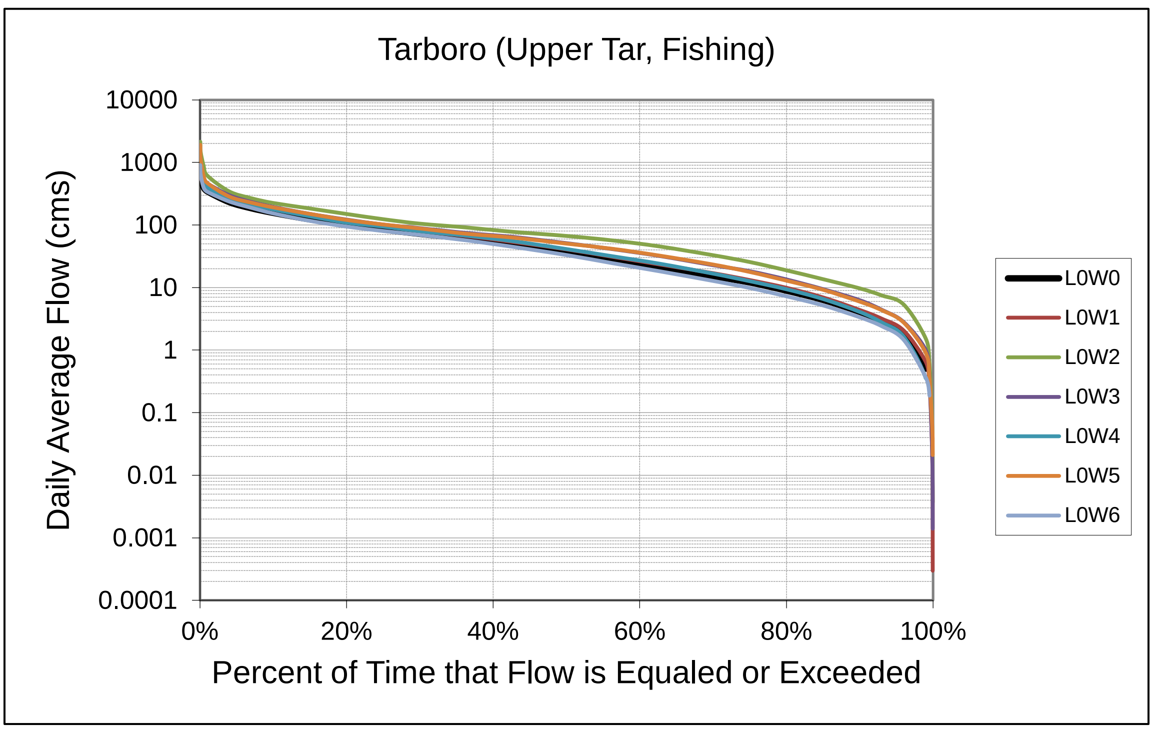


Figure 181. **Flow duration, Upper Tar River at Tarboro (SWAT)**

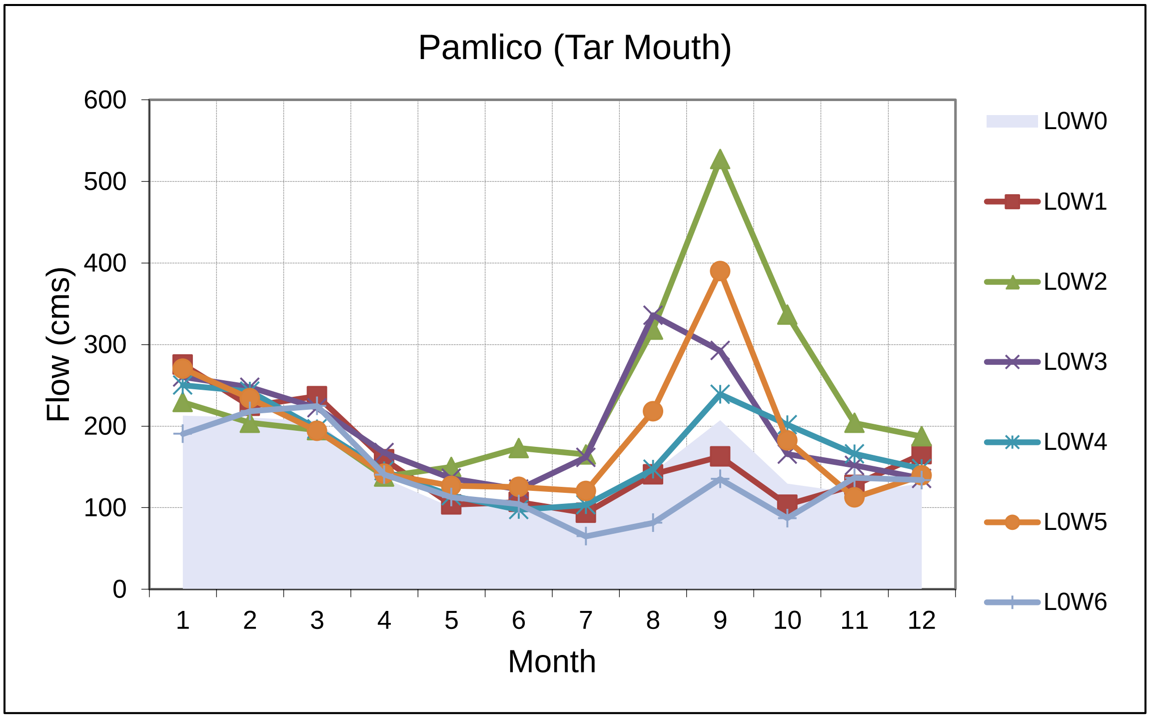


Figure 182. **Monthly average flows, mouth of Tar River at Pamlico (SWAT)**

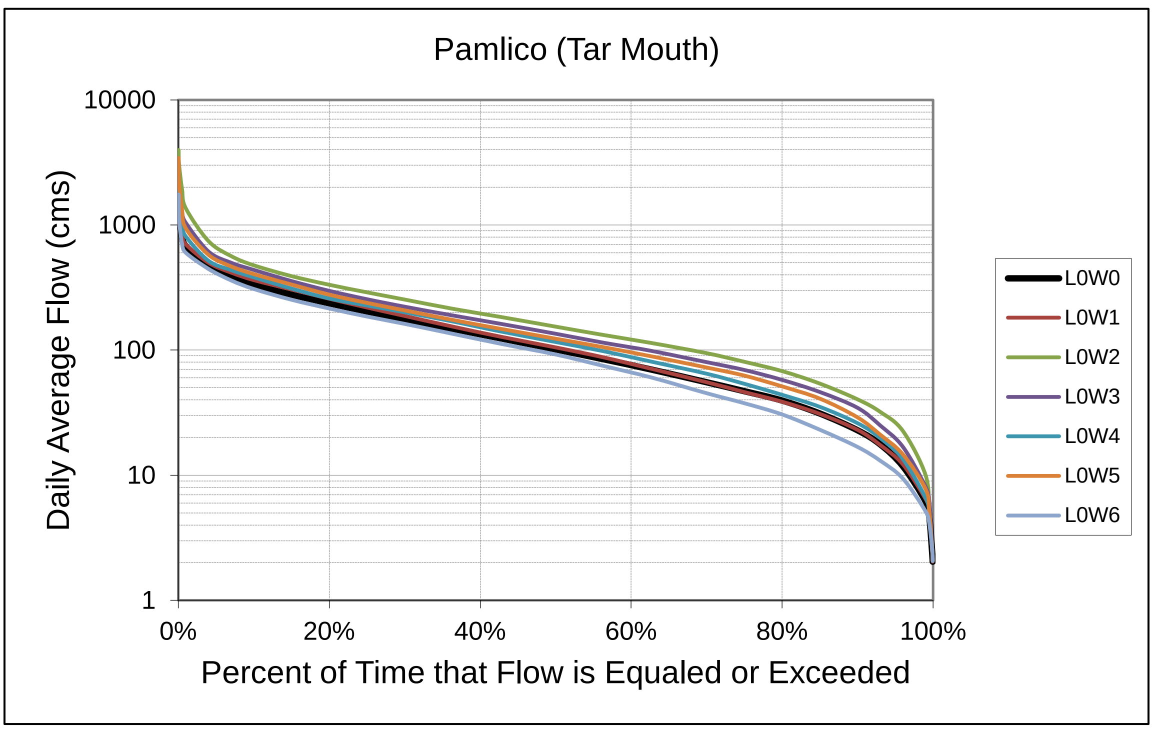


Figure 183. **Flow duration, mouth of Tar River at Pamlico (SWAT)**

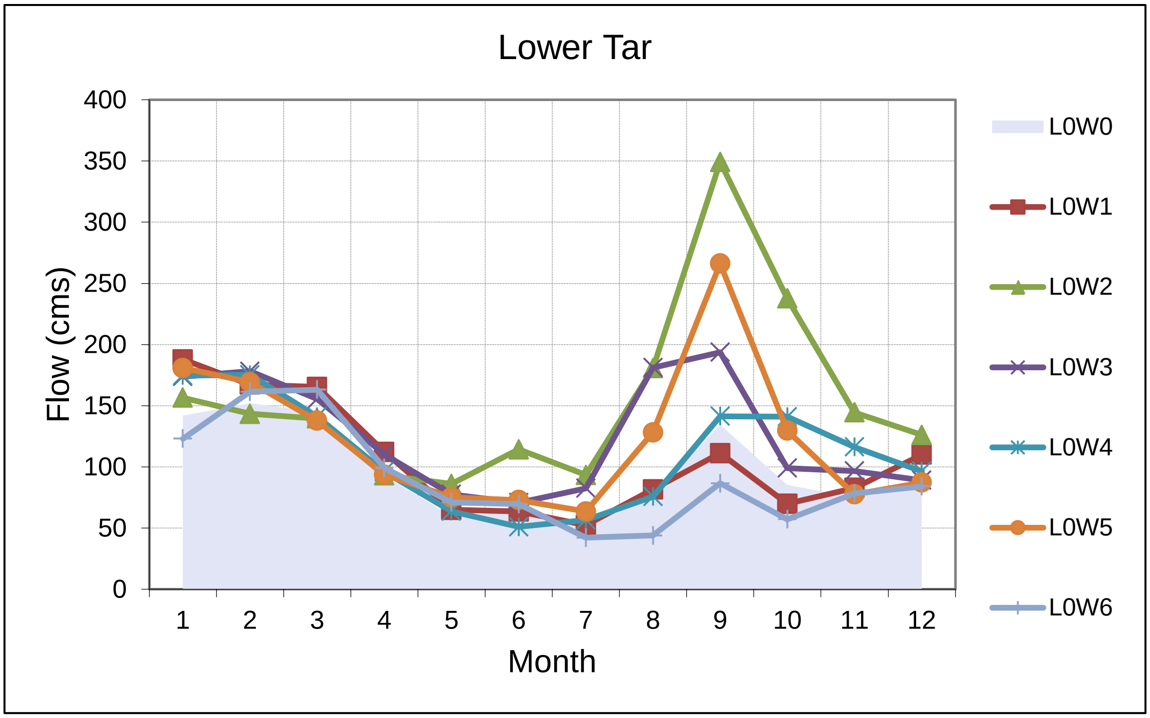


Figure 184. **Monthly average flows, Lower Tar River (SWAT)**

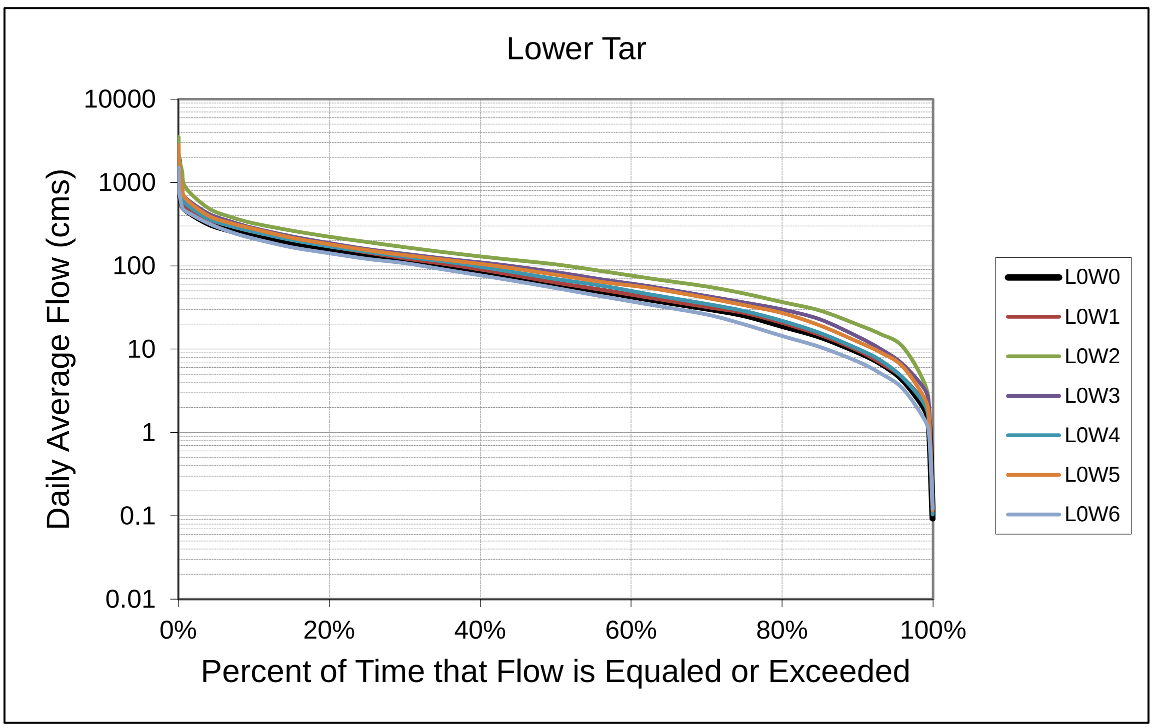


Figure 185. **Flow duration, Lower Tar River (SWAT)**

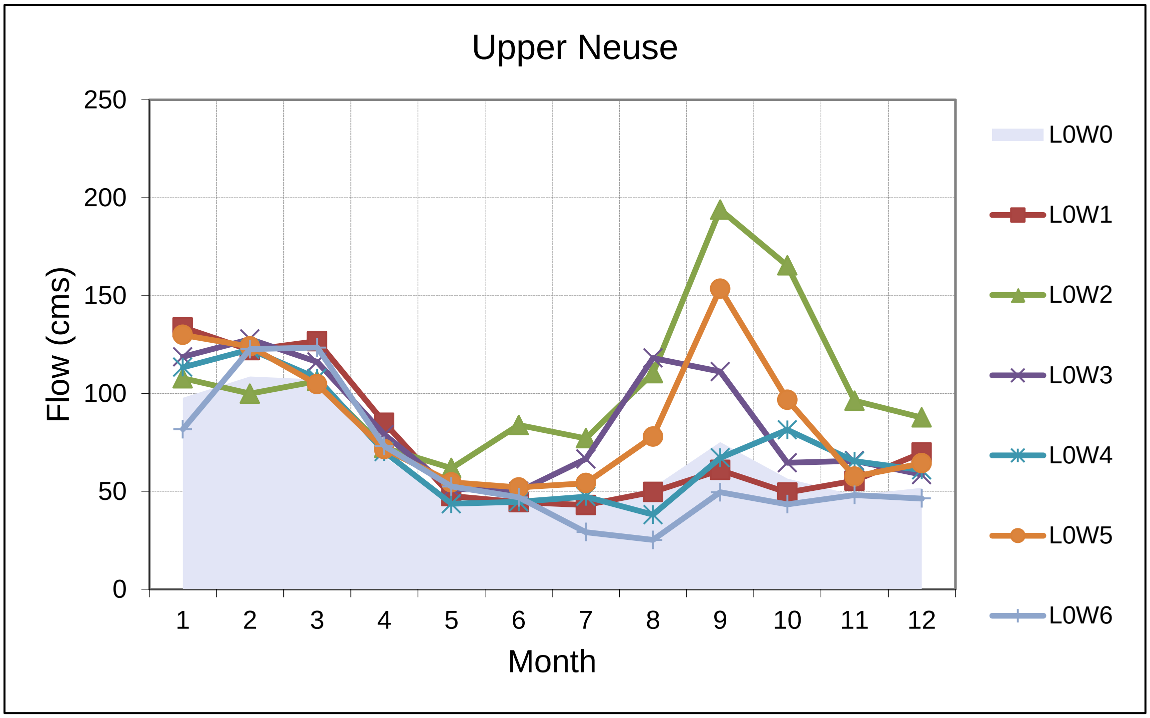


Figure 186. Monthly average flows, Upper Neuse River (SWAT)

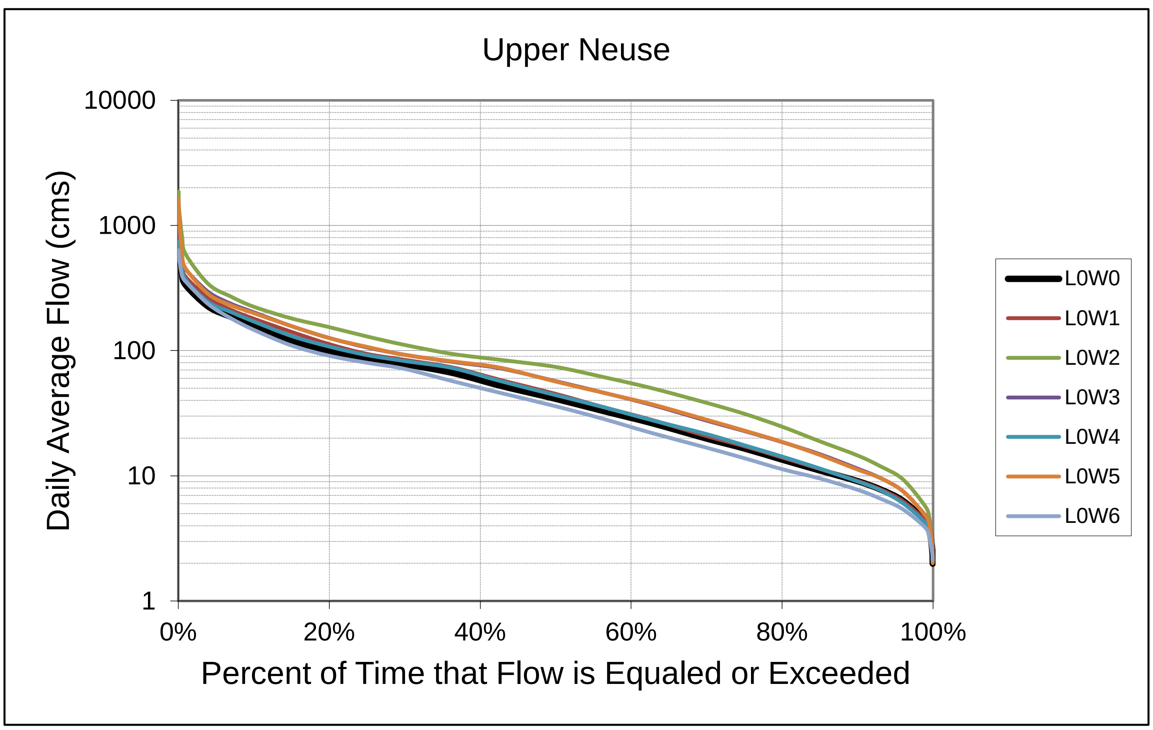


Figure 187. Flow duration, Upper Neuse River (SWAT)

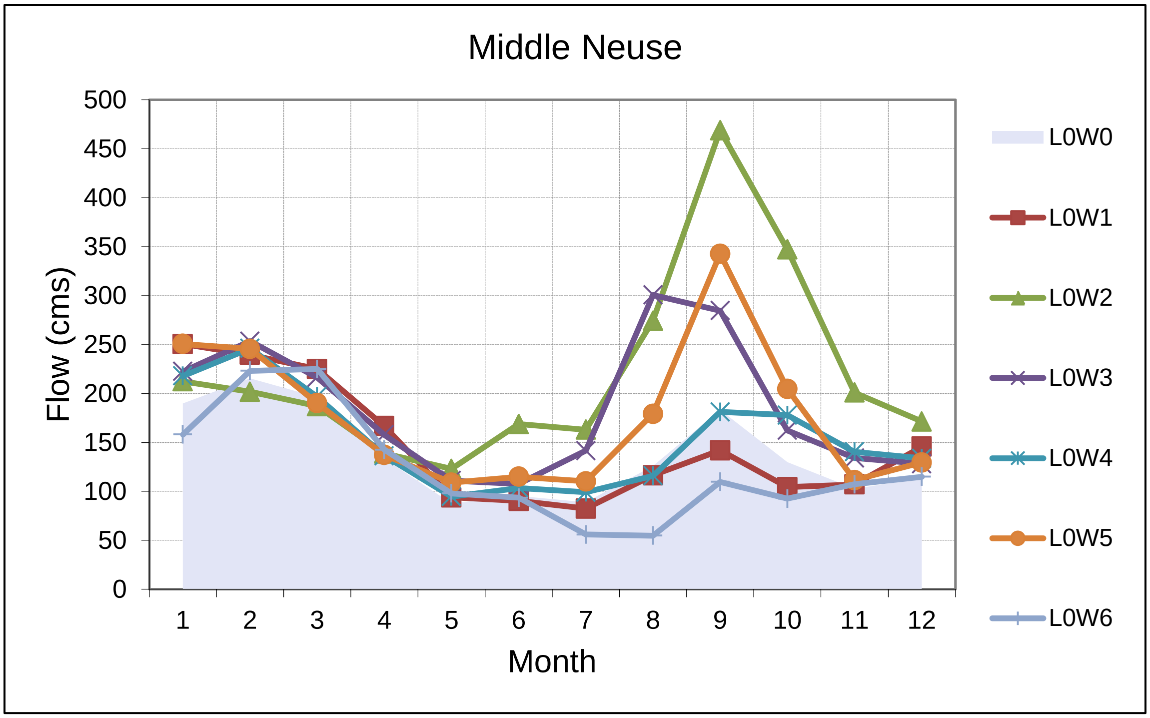


Figure 188. **Monthly average flows, Middle Neuse River (SWAT)**

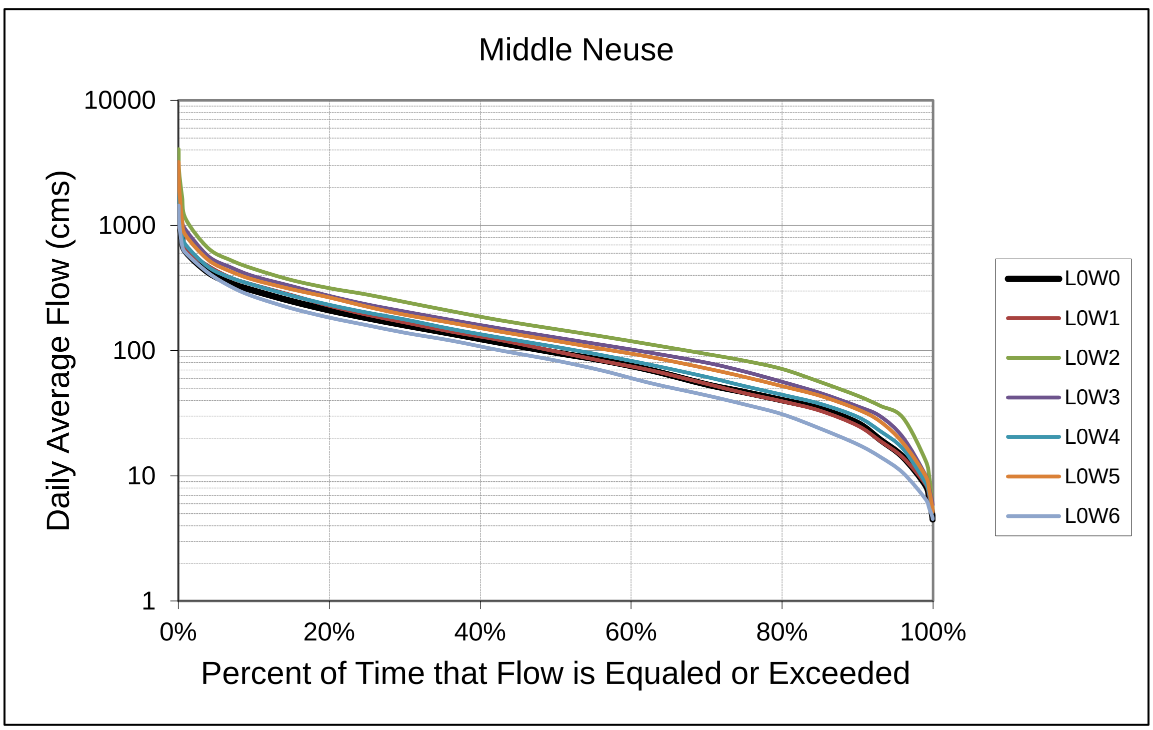


Figure 189. **Flow duration, Middle Neuse River (SWAT)**

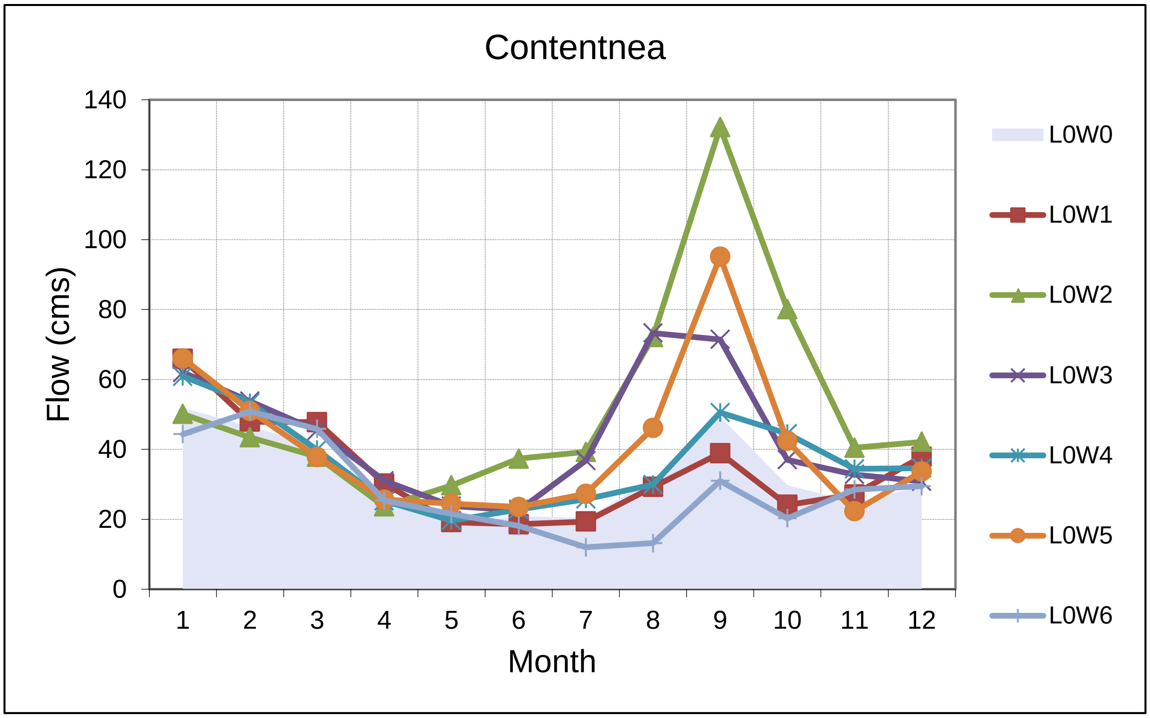


Figure 190. **Monthly average flows, Contentnea Creek (SWAT)**

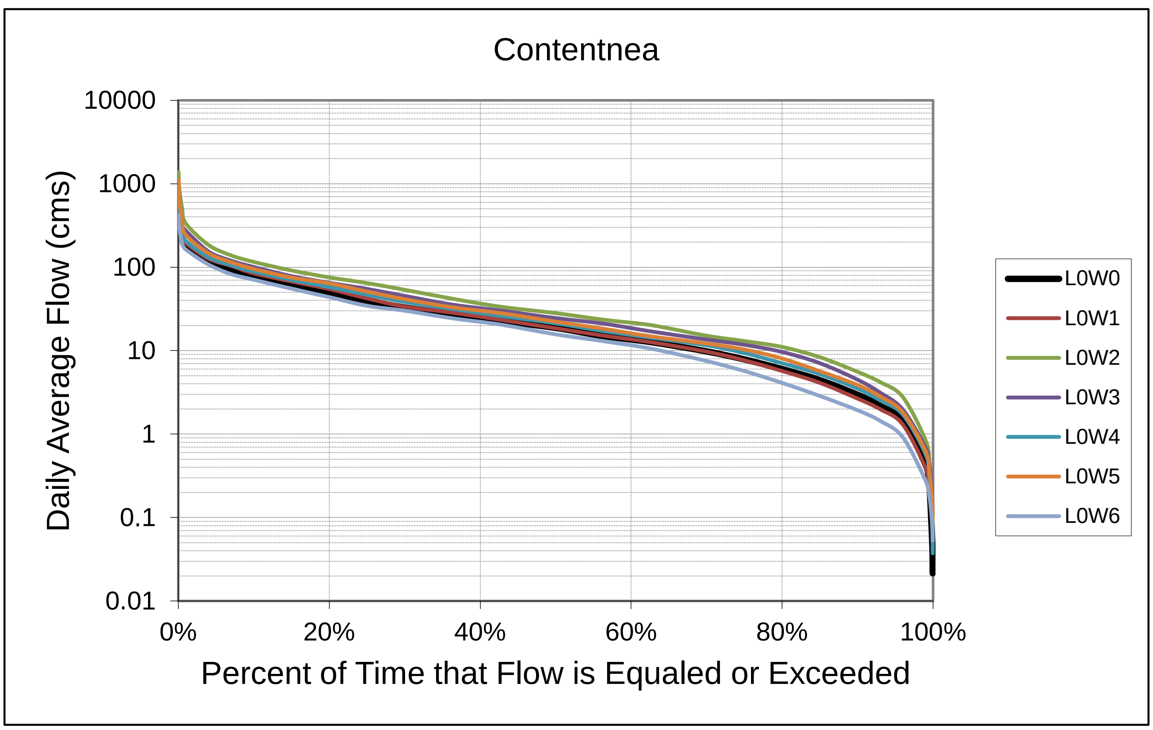


Figure 191. **Flow duration, Contentnea Creek (SWAT)**

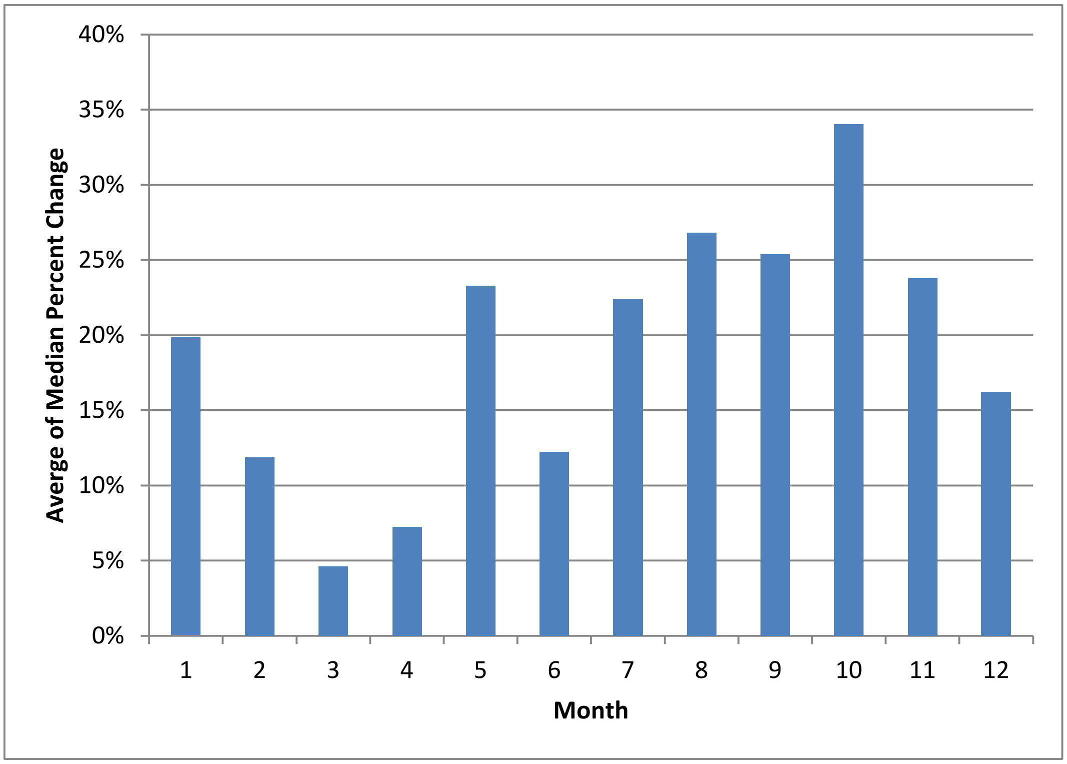


Figure 192. Average of median percent change in flow; NARCCAP Scenarios W1-W6 at all stations, Neuse-Tar watershed (SWAT)

New England Coastal Basins

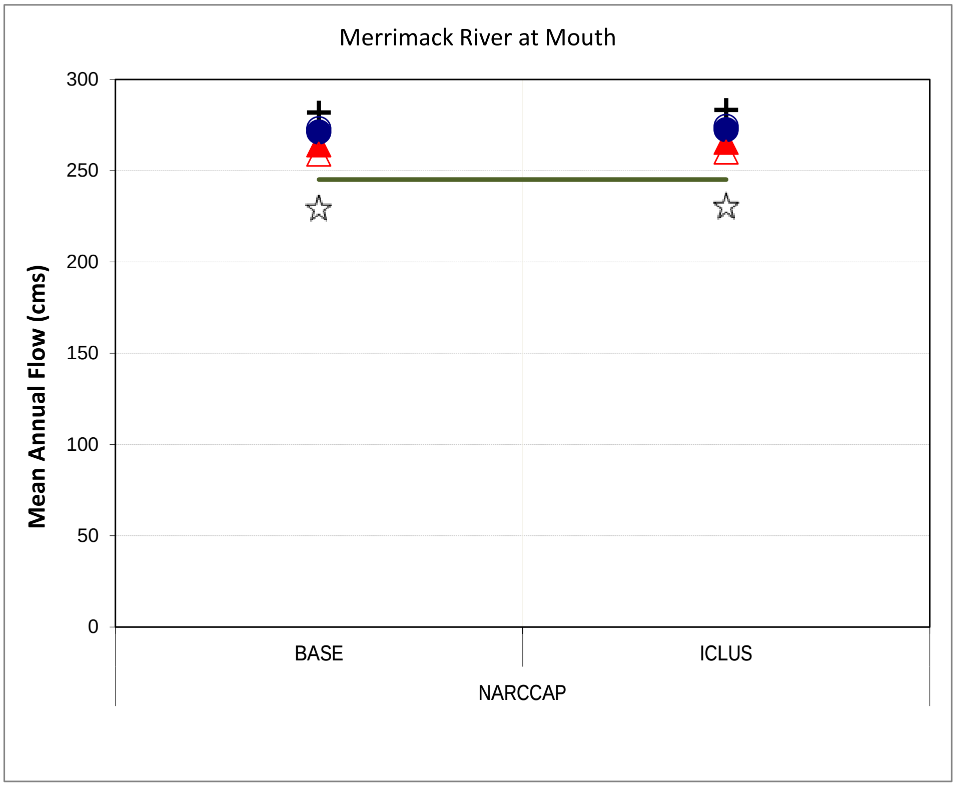


Figure 193. Mean annual flow (cms), mouth of the Merrimack River (SWAT)

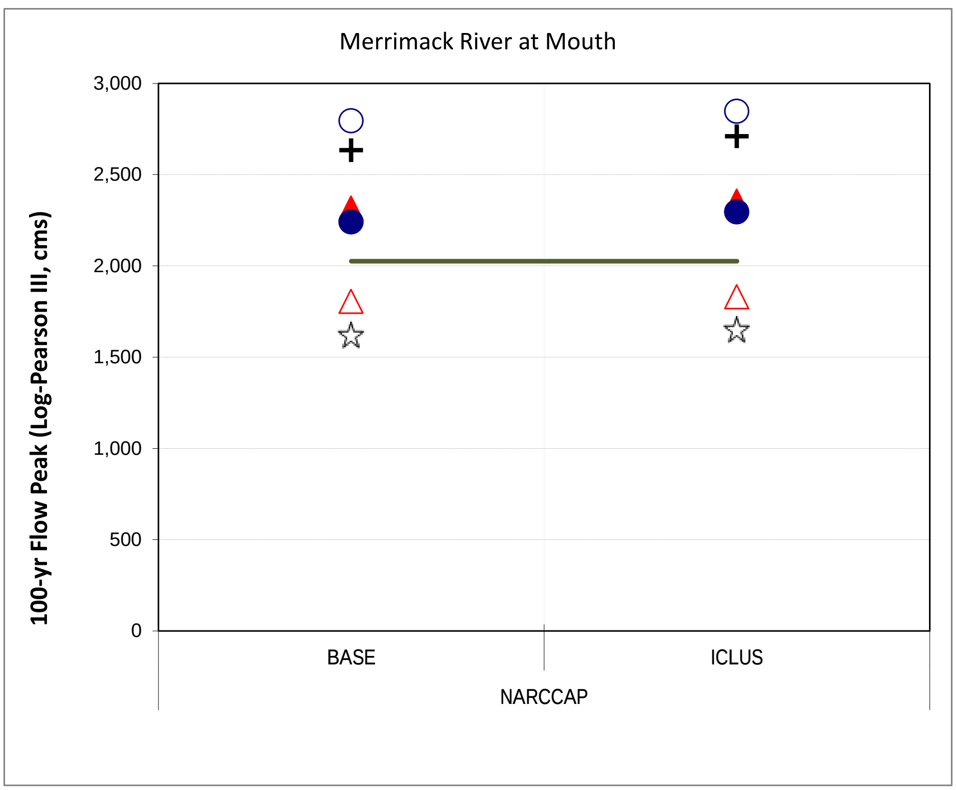


Figure 194. 100-yr Flow Peak (Log-Pearson III, cms), mouth of the Merrimack River (SWAT)

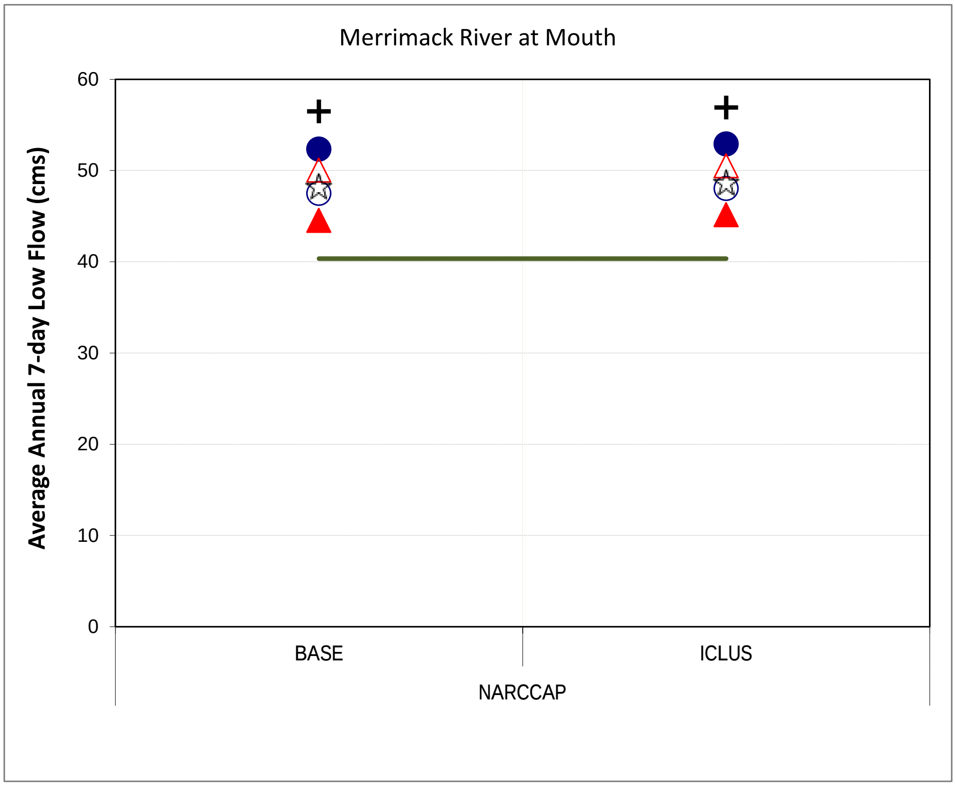


Figure 195. Average Annual 7-day Low Flow (cms), mouth of the Merrimack River (SWAT)

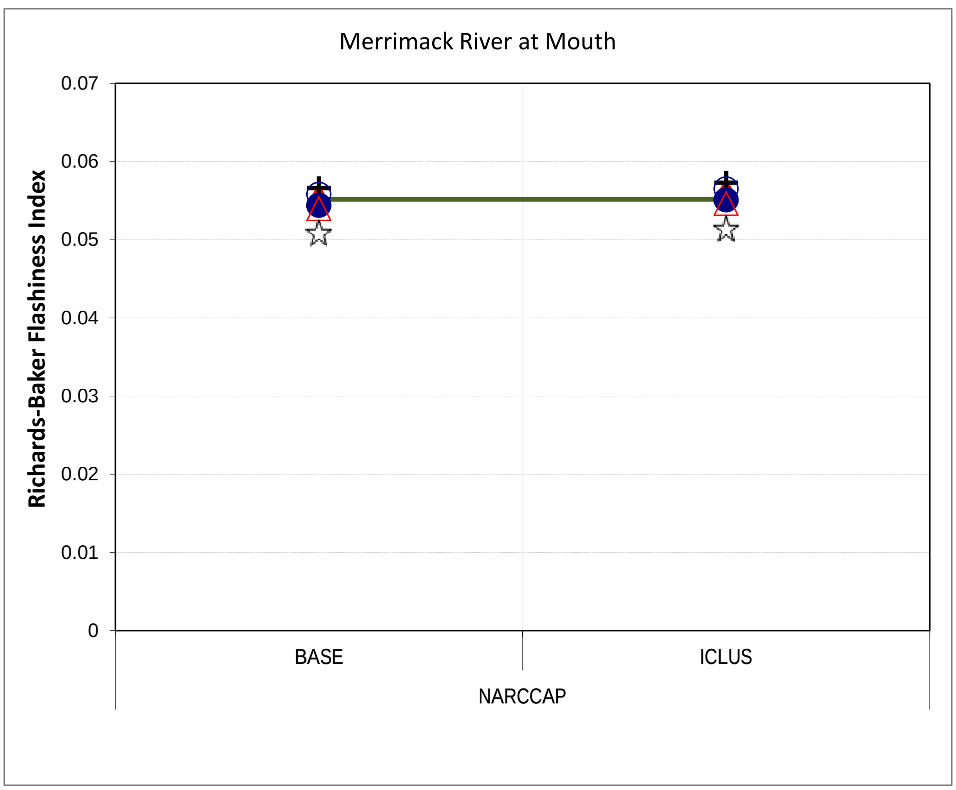


Figure 196. Richards-Baker Flashiness Index, Average Annual 7-day Low Flow (cms), mouth of the Merrimack River (SWAT)

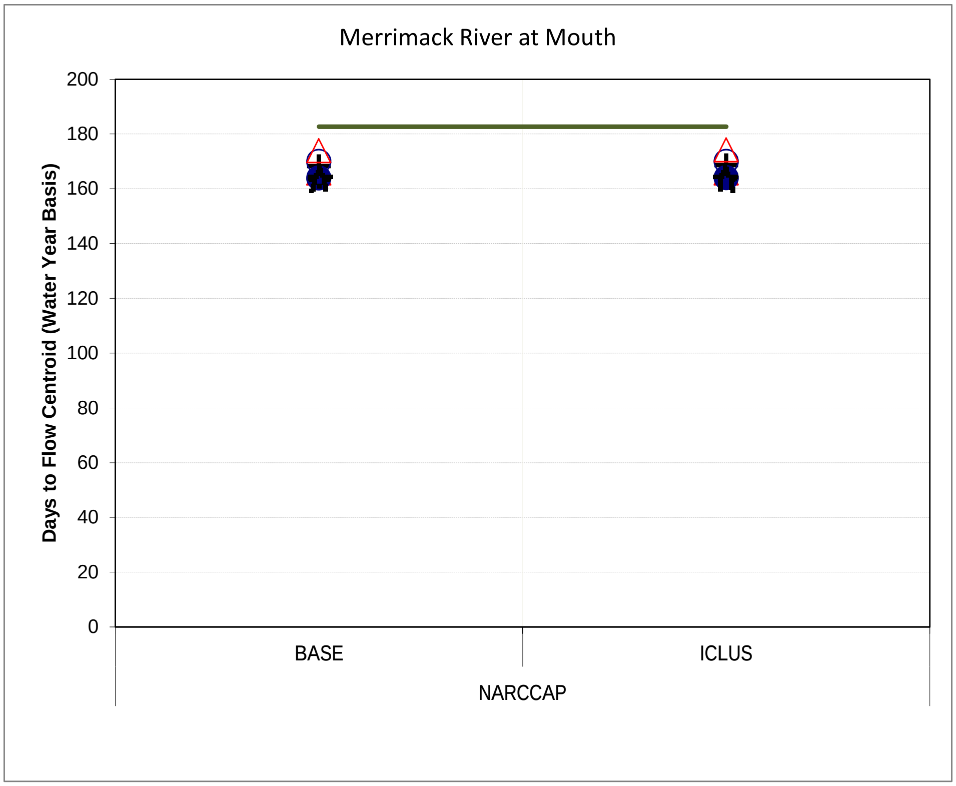


Figure 197. **Days to Flow Centroid (Water Year Basis), mouth of the Merrimack River (SWAT)**

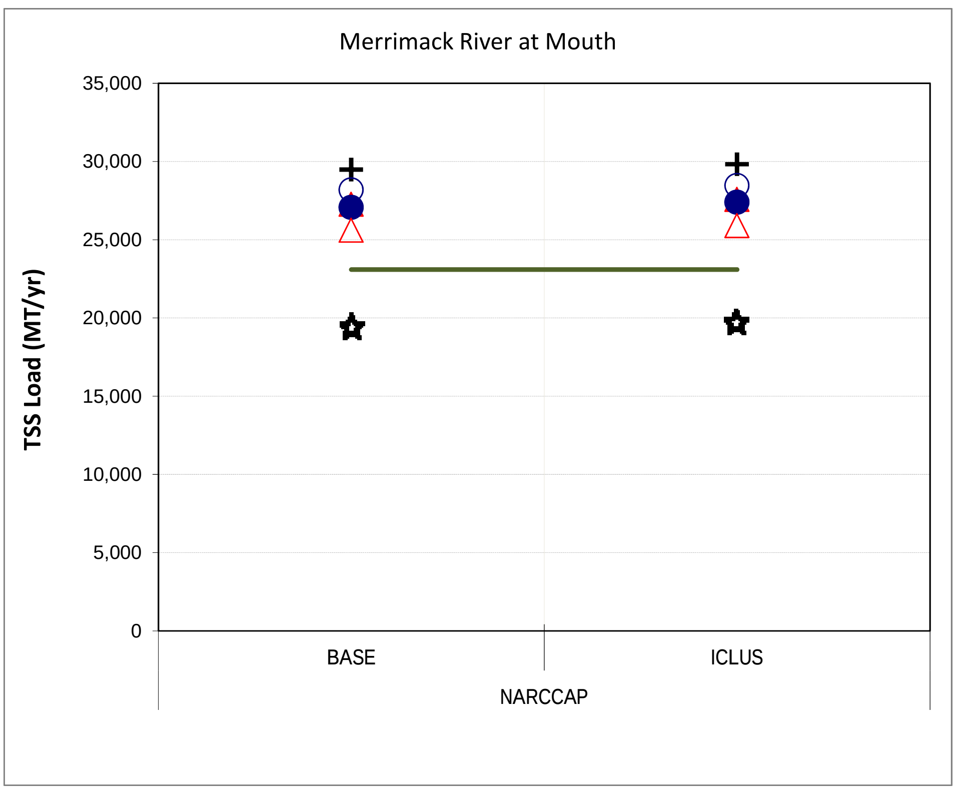


Figure 198. **TSS Load (MT/yr), mouth of the Merrimack River (SWAT)**

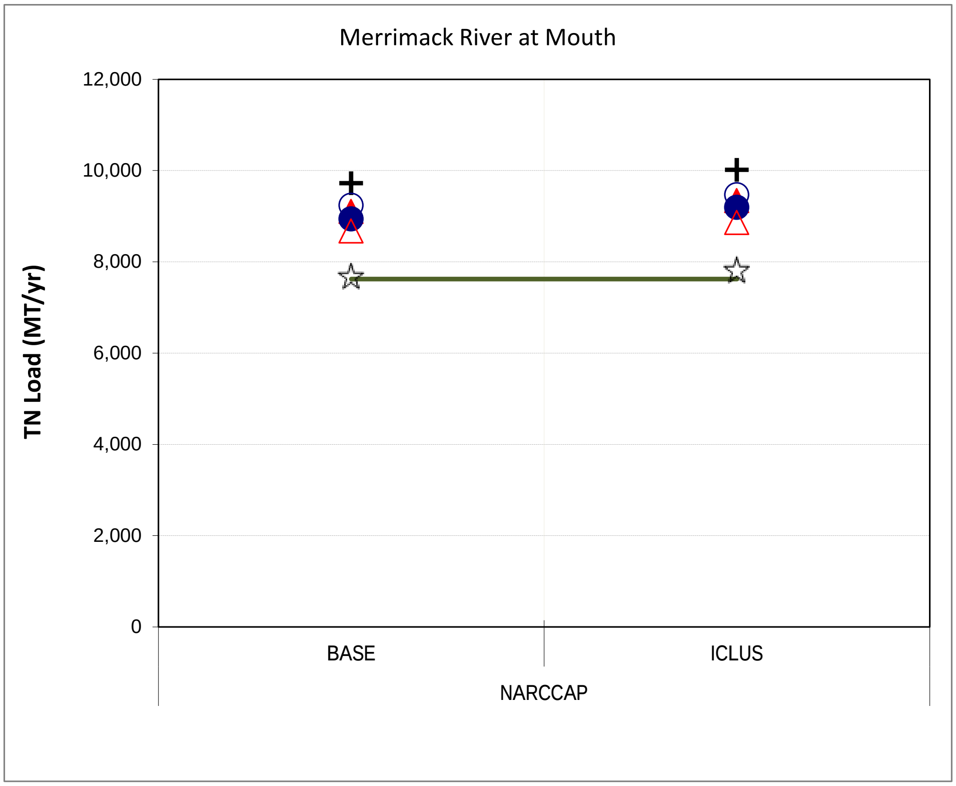


Figure 199. TN Load (MT/yr), mouth of the Merrimack River (SWAT)

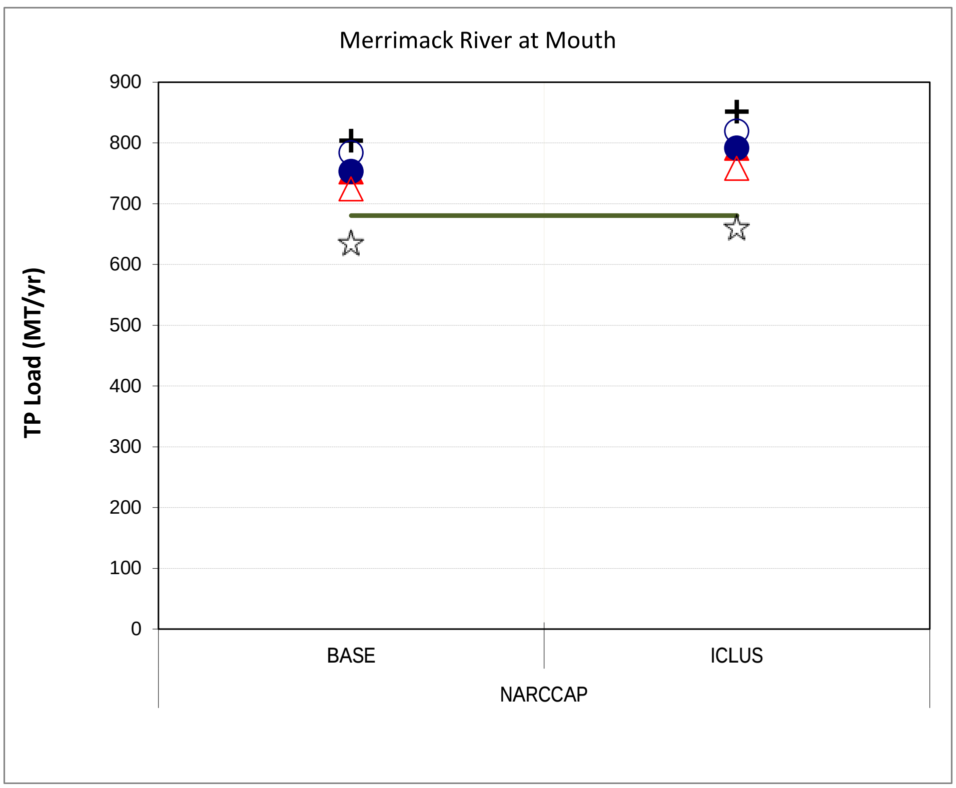


Figure 200. TP Load (MT/yr), mouth of the Merrimack River (SWAT)

Table 8. Summary of range of change relative to existing conditions for NARCCAP dynamically downscaled scenarios, New England Coastal basins SWAT model

	Results without LU change				Results with LU change			
	Min	Median	Mean	Max	Min	Median	Mean	Max
Presumpscot HUC 01060001								
Flow	-7.72%	14.77%	10.95%	18.05%	-7.63%	14.73%	10.92%	17.95%
TSS	-12.76%	11.99%	7.38%	15.10%	-12.60%	11.68%	7.27%	15.01%
TN	-19.40%	-6.11%	-8.73%	-0.88%	-19.60%	-6.61%	-9.41%	-3.23%
TP	-12.75%	15.74%	16.55%	39.60%	-12.11%	13.87%	14.07%	31.27%
Saco River at Mouth HUC 01060002								
Flow	-4.46%	9.65%	7.57%	12.18%	-4.45%	9.64%	7.57%	12.18%
TSS	33.26%	55.66%	55.69%	68.36%	32.52%	54.78%	54.82%	67.47%
TN	6.42%	19.19%	17.66%	23.73%	6.10%	18.81%	17.28%	23.29%
TP	-19.05%	-6.74%	-7.37%	-0.59%	-18.81%	-6.54%	-7.16%	-0.43%
Piscataqua HUC 01060003								
Flow	-6.78%	9.38%	7.23%	14.73%	-6.65%	9.48%	7.32%	14.83%
TSS	-13.21%	12.41%	8.98%	21.98%	-12.85%	12.83%	9.36%	22.47%
TN	21.60%	40.51%	41.00%	60.85%	19.49%	40.86%	39.95%	57.88%
TP	3.69%	35.38%	34.78%	64.83%	1.36%	35.37%	32.89%	56.81%
Merrimack River at Mouth HUC 01070006								
Flow	-6.14%	9.19%	7.37%	14.98%	-6.04%	9.25%	7.44%	15.08%
TSS	-15.05%	17.65%	13.49%	27.68%	-14.87%	17.60%	13.44%	27.62%
TN	1.14%	18.37%	16.74%	27.55%	0.97%	19.24%	17.37%	28.90%
TP	-6.32%	10.57%	9.09%	18.08%	-6.15%	12.02%	10.27%	20.51%
Pemigewasset HUC 01070001								
Flow	-1.75%	8.56%	7.53%	12.70%	-1.74%	8.57%	7.54%	12.71%
TSS	-27.46%	-12.23%	-14.35%	-9.88%	-27.37%	-12.12%	-14.23%	-9.74%
TN	-11.26%	-8.86%	-6.92%	5.57%	-11.14%	-8.79%	-6.89%	5.29%
TP	-21.25%	-18.27%	-17.02%	-5.49%	-20.95%	-17.94%	-16.77%	-5.63%
Concord River at Lowell HUC 01070005								
Flow	-12.55%	10.86%	7.20%	16.86%	-12.39%	10.88%	7.27%	17.02%
TSS	-15.37%	15.26%	10.51%	25.17%	-15.49%	14.90%	10.41%	25.57%
TN	5.83%	14.53%	15.28%	24.74%	5.14%	14.19%	14.77%	24.48%
TP	-1.17%	4.47%	4.09%	9.02%	-1.64%	4.56%	4.15%	9.92%
Charles River at Mouth HUC 01090001								
Flow	-4.45%	5.63%	4.62%	9.16%	-4.41%	5.63%	4.63%	9.21%
TSS	-5.04%	6.85%	5.78%	11.94%	-5.01%	6.90%	5.87%	12.20%
TN	-0.09%	0.64%	0.60%	1.31%	-0.10%	0.63%	0.59%	1.29%
TP	-0.05%	0.31%	0.26%	0.41%	-0.05%	0.32%	0.27%	0.43%
Winnepesaukee River HUC 01070002								
Flow	0.03%	9.88%	9.07%	15.35%	0.05%	9.89%	9.08%	15.37%
TSS	-16.55%	-7.60%	-7.98%	-0.32%	-16.27%	-7.27%	-7.68%	0.02%

	Results without LU change				Results with LU change			
	Min	Median	Mean	Max	Min	Median	Mean	Max
TN	5.98%	22.17%	24.11%	54.33%	5.00%	21.40%	23.31%	53.52%
TP	-14.58%	3.20%	9.24%	55.01%	-15.18%	2.89%	8.43%	53.36%
Contoocook HUC 01070003								
Flow	-8.43%	8.37%	6.64%	15.65%	-8.32%	8.45%	6.72%	15.75%
TSS	-28.90%	-3.23%	-5.16%	10.29%	-28.72%	-3.07%	-4.97%	10.65%
TN	9.99%	30.28%	28.91%	42.92%	7.95%	28.21%	27.29%	42.17%
TP	-12.86%	7.33%	4.32%	14.57%	-13.04%	8.78%	4.94%	13.78%
Nashua HUC 01070004								
Flow	-11.94%	11.04%	8.60%	19.79%	-11.80%	11.06%	8.65%	19.93%
TSS	-29.14%	4.66%	0.81%	14.13%	-28.65%	4.81%	1.11%	14.54%
TN	-19.12%	1.95%	4.28%	31.83%	-19.59%	2.34%	5.62%	35.57%
TP	-31.88%	-7.56%	-2.98%	24.15%	-31.27%	-5.86%	-0.54%	30.43%
Nashua River at East Pepperell gage 01096500								
Flow	-11.75%	10.34%	8.32%	20.33%	-11.65%	10.35%	8.36%	20.42%
TSS	-27.21%	10.65%	6.67%	23.02%	-26.93%	10.66%	6.79%	23.44%
TN	-20.27%	-4.91%	-1.04%	26.21%	-21.80%	-6.15%	-2.21%	25.33%
TP	-34.88%	-16.51%	-13.16%	12.60%	-35.84%	-17.26%	-13.77%	12.04%
Saco River at Cornish gage 01066000								
Flow	-4.01%	8.86%	6.87%	10.80%	-4.01%	8.86%	6.87%	10.80%
TSS	-30.52%	-22.56%	-23.95%	-20.95%	-30.45%	-22.48%	-23.88%	-20.88%
TN	-0.09%	11.06%	9.71%	15.89%	-0.18%	10.94%	9.58%	15.73%
TP	-30.86%	-15.88%	-16.73%	-9.98%	-30.22%	-15.43%	-16.29%	-9.72%

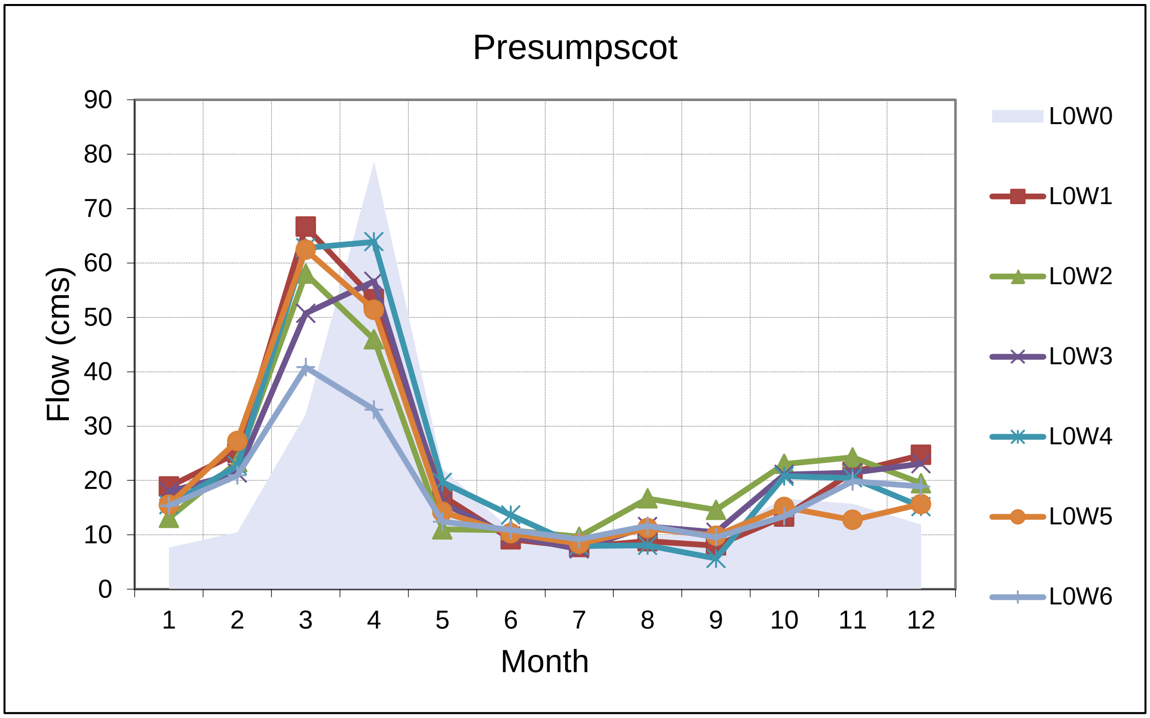


Figure 201. Monthly average flows, Presumpscot River (SWAT)

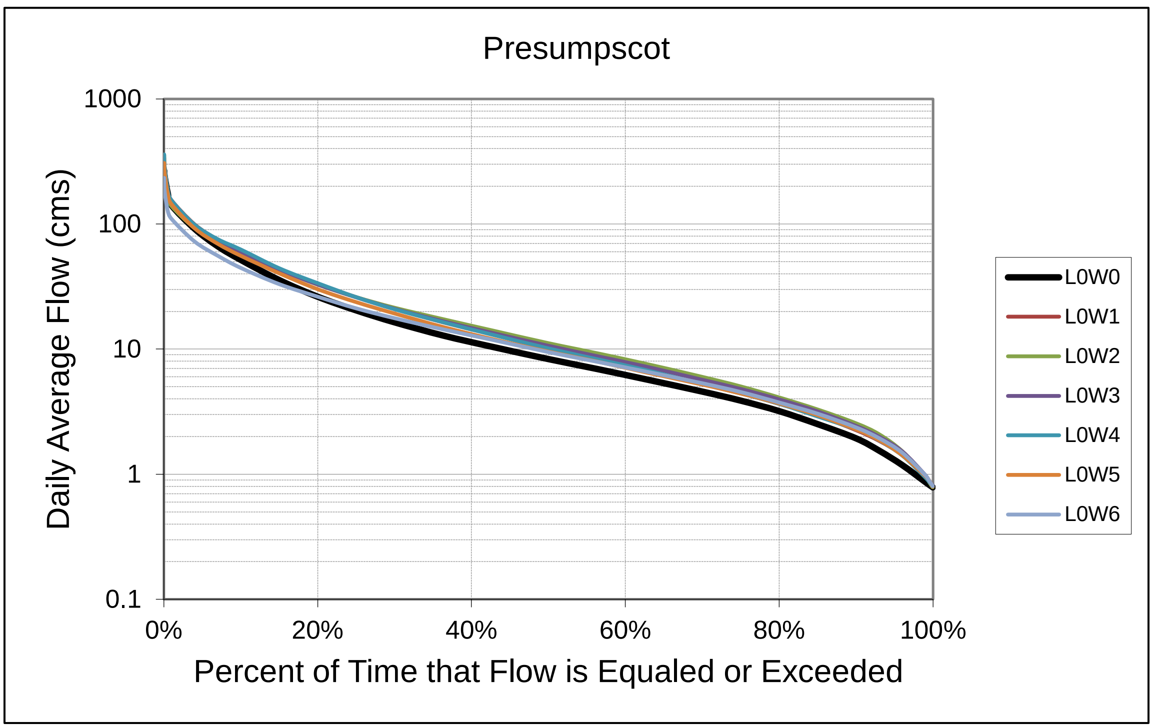


Figure 202. Flow duration, Presumpscot River (SWAT)

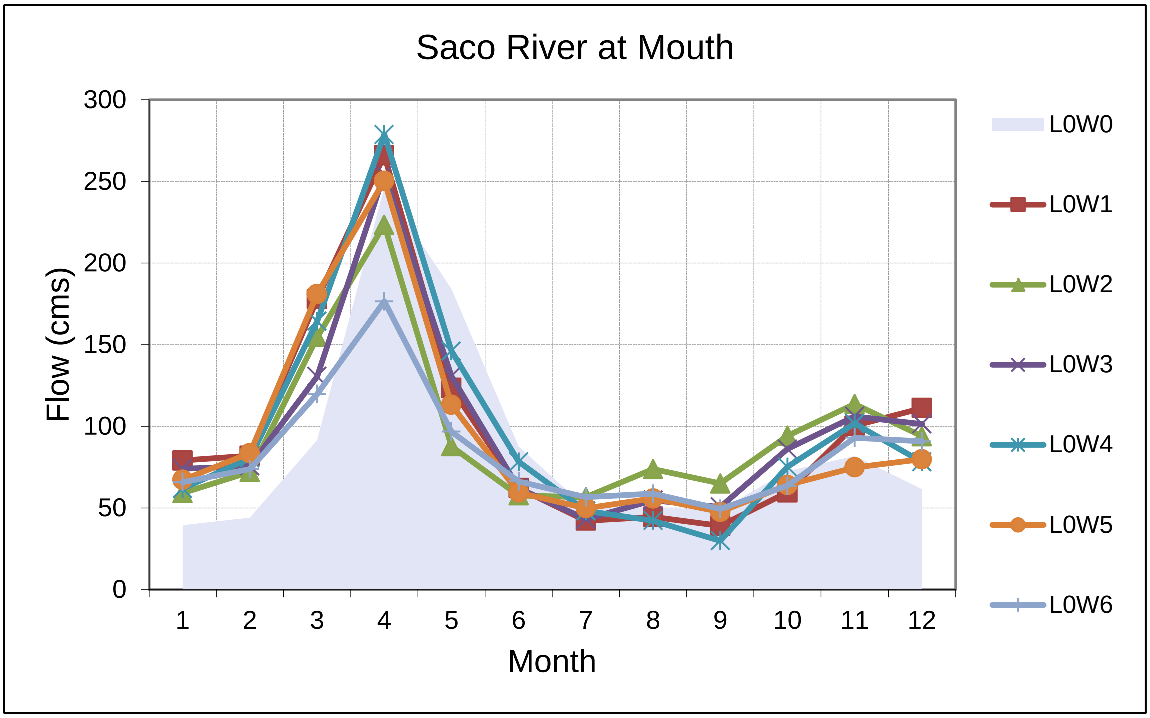


Figure 203. Monthly average flows, mouth of the Saco River (SWAT)

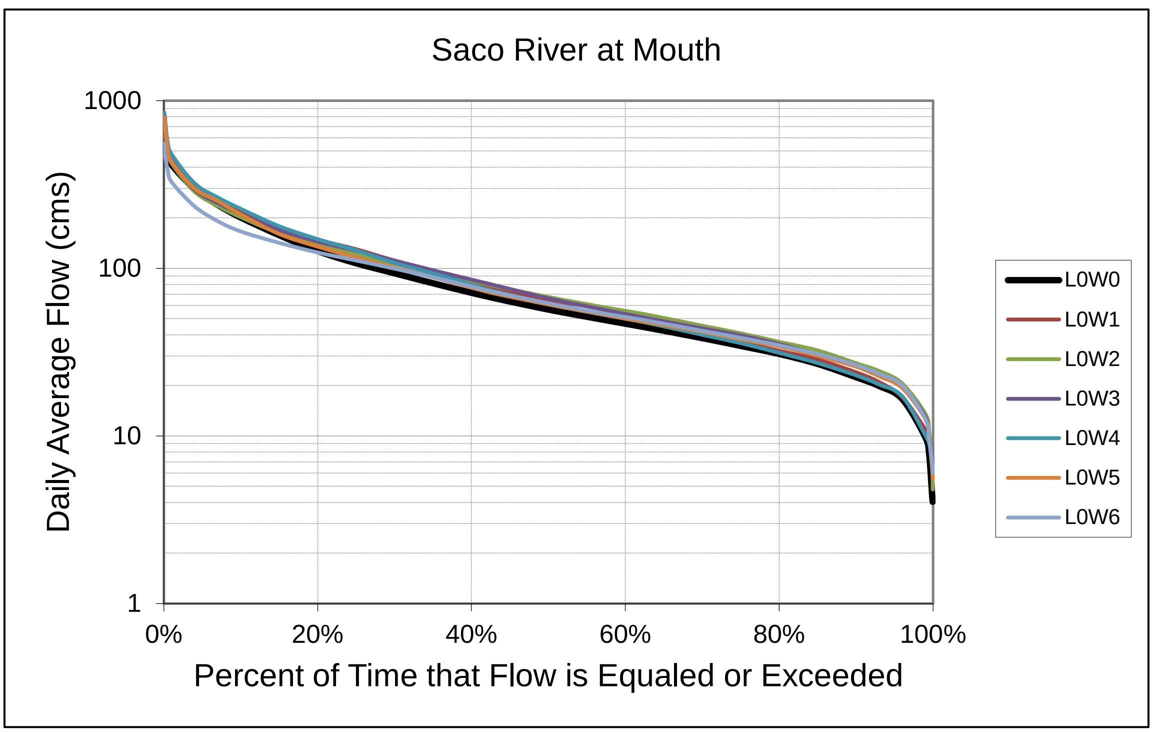


Figure 204. Flow duration, mouth of the Saco River (SWAT)

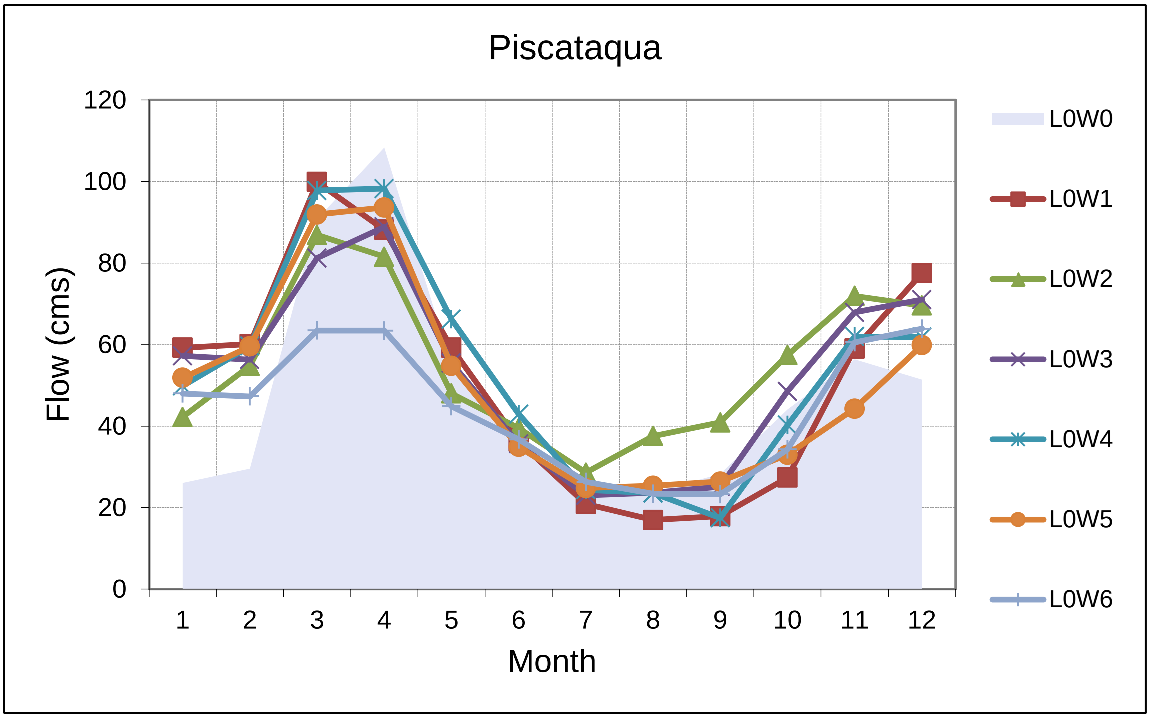


Figure 205. **Monthly average flows, Piscataqua River (SWAT)**

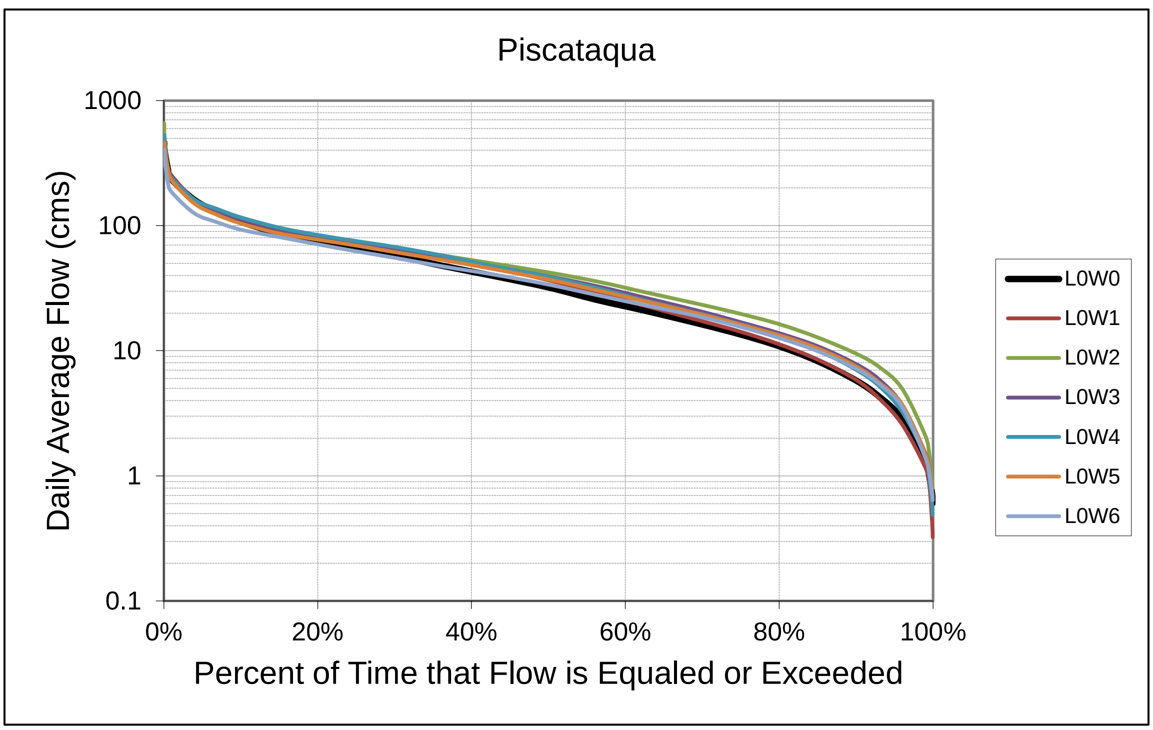


Figure 206. **Flow duration, Piscataqua River (SWAT)**

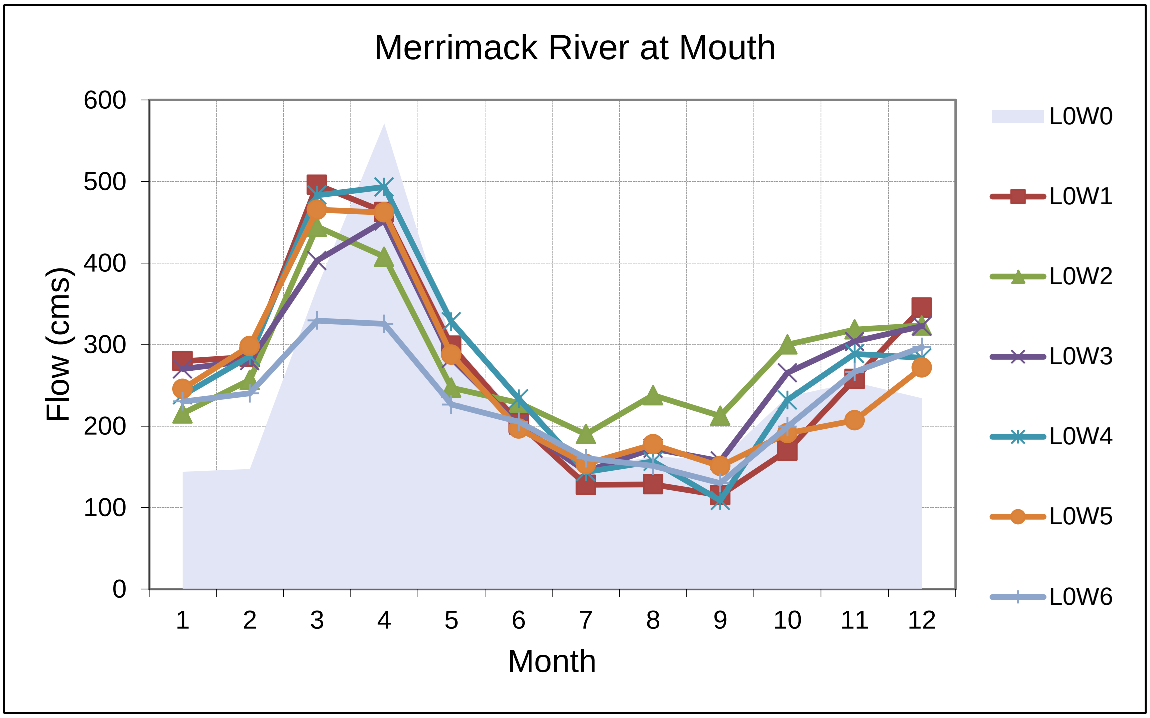


Figure 207. Monthly average flows, mouth of the Merrimack River (SWAT)

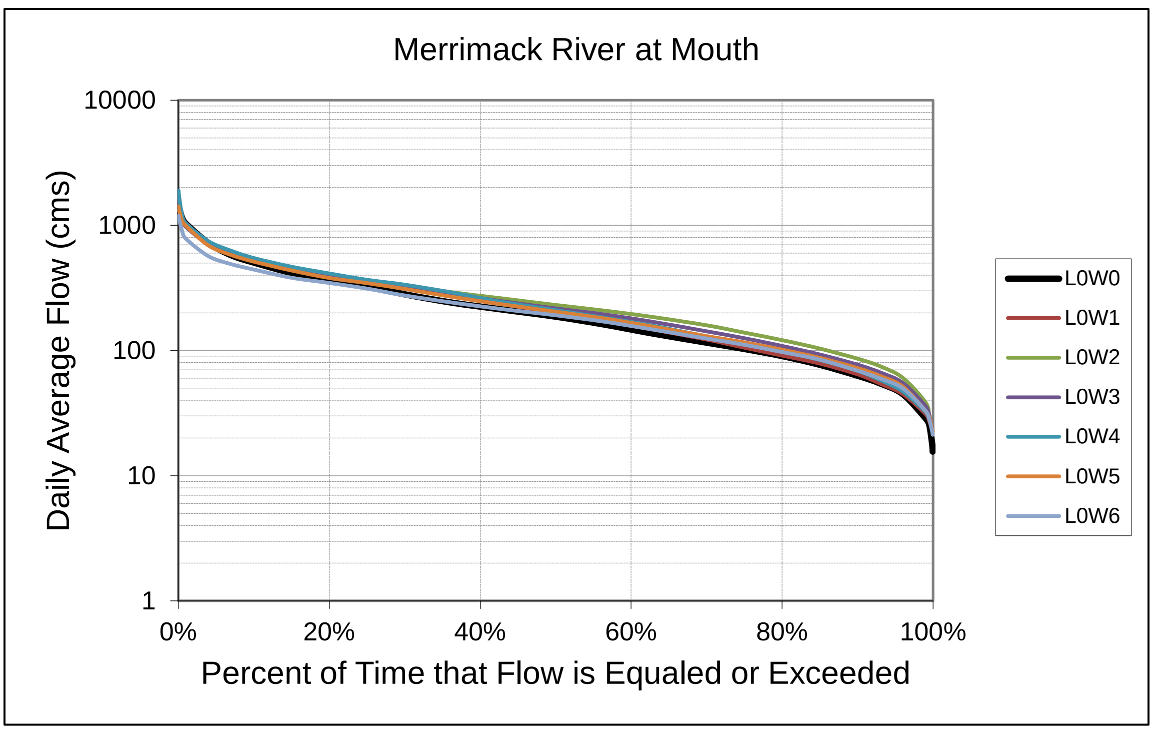


Figure 208. Flow duration, mouth of the Merrimack River (SWAT)

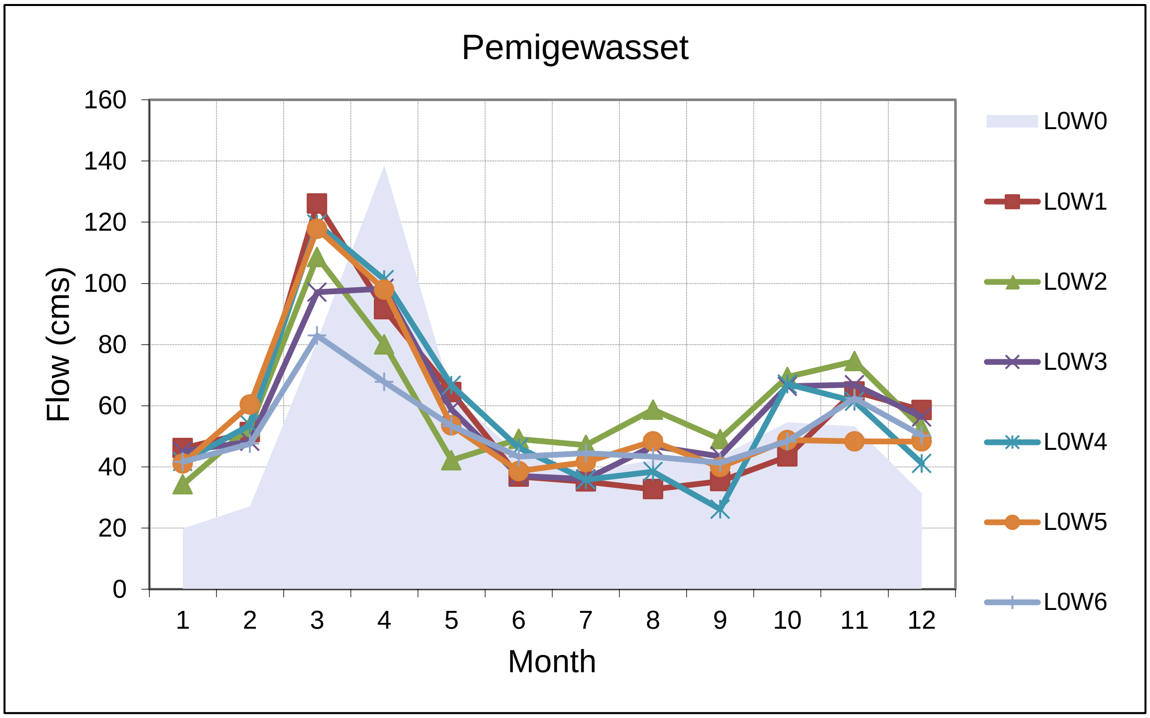


Figure 209. **Monthly average flows, Pemigewasset River (SWAT)**

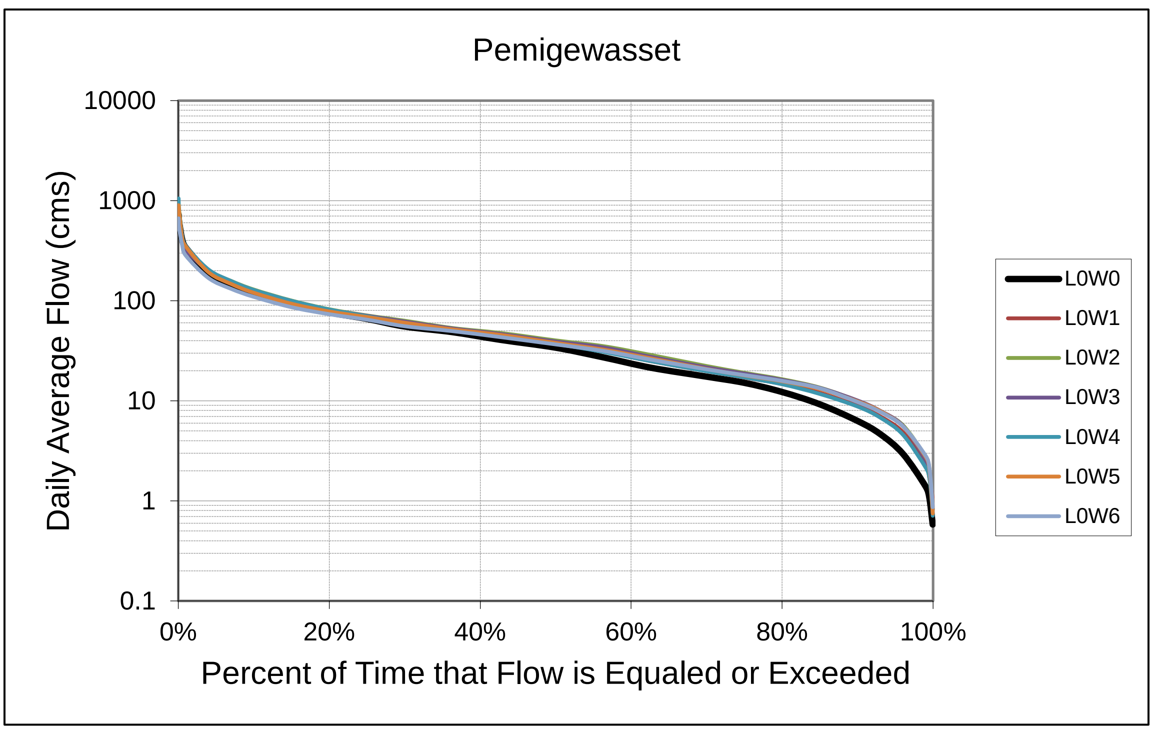


Figure 210. **Flow duration, Pemigewasset River (SWAT)**

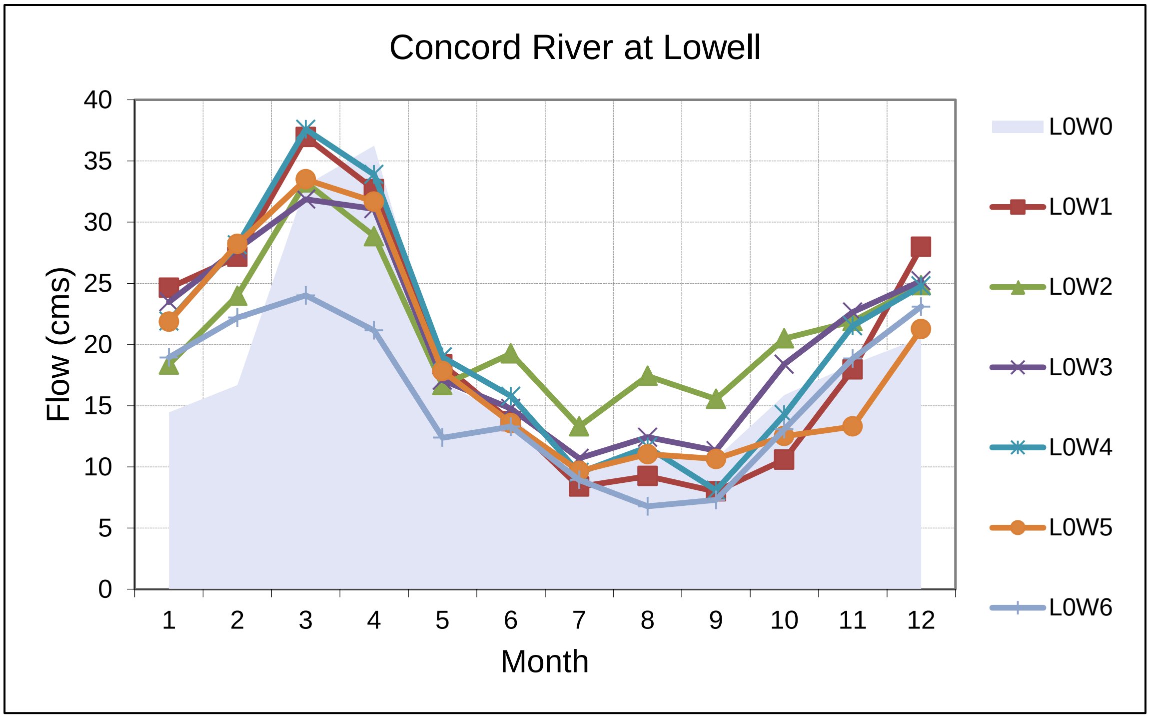


Figure 211. **Monthly average flows, Concord River at Lowell (SWAT)**

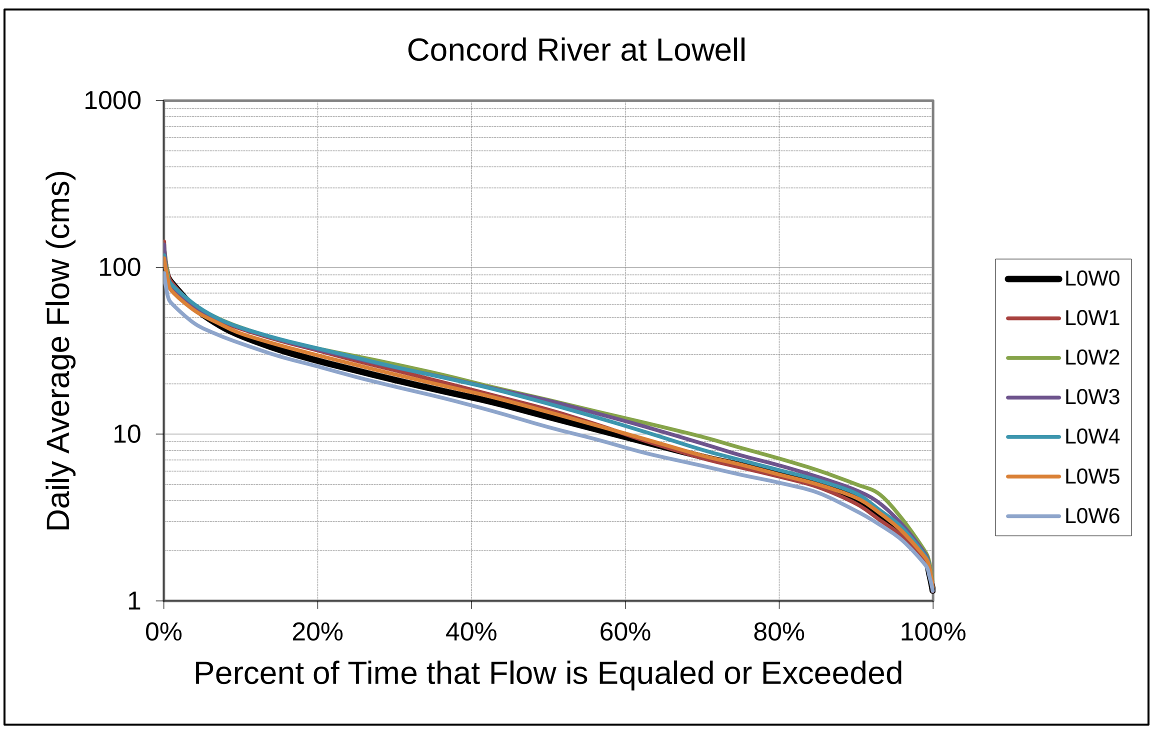


Figure 212. **Flow duration, Concord River at Lowell (SWAT)**

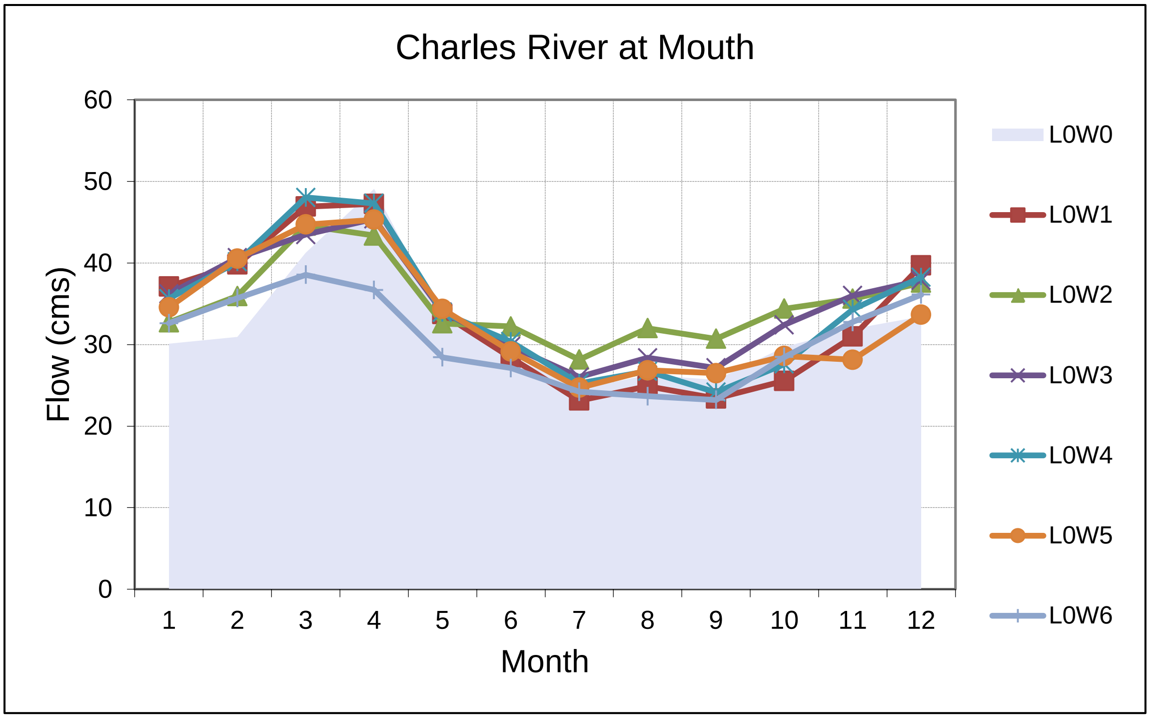


Figure 213. **Monthly average flows, mouth of the Charles River (SWAT)**

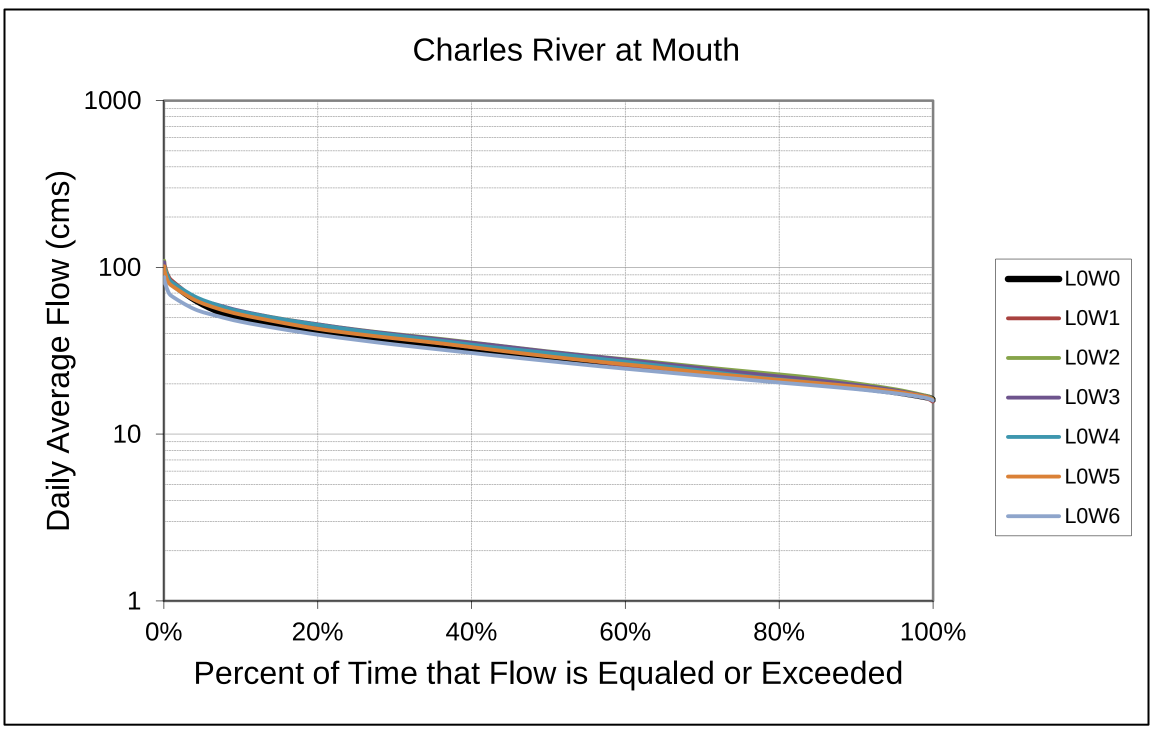


Figure 214. **Flow duration, mouth of the Charles River (SWAT)**

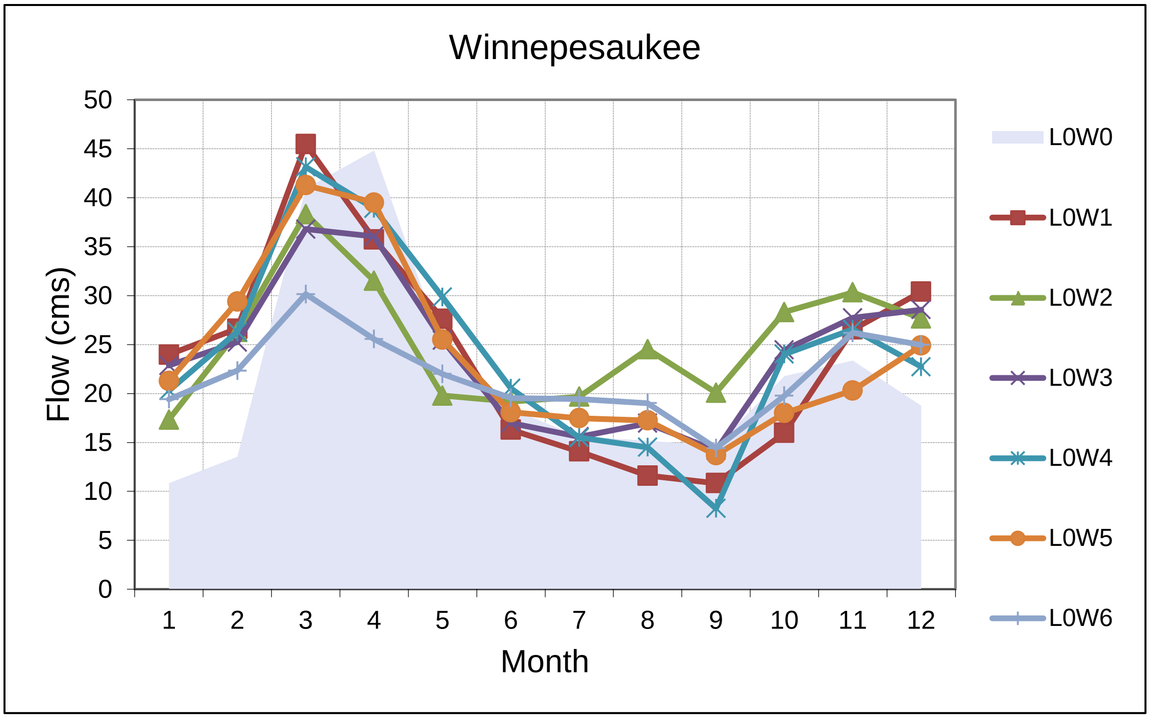


Figure 215. **Monthly average flows, Winnepesaukee River (SWAT)**

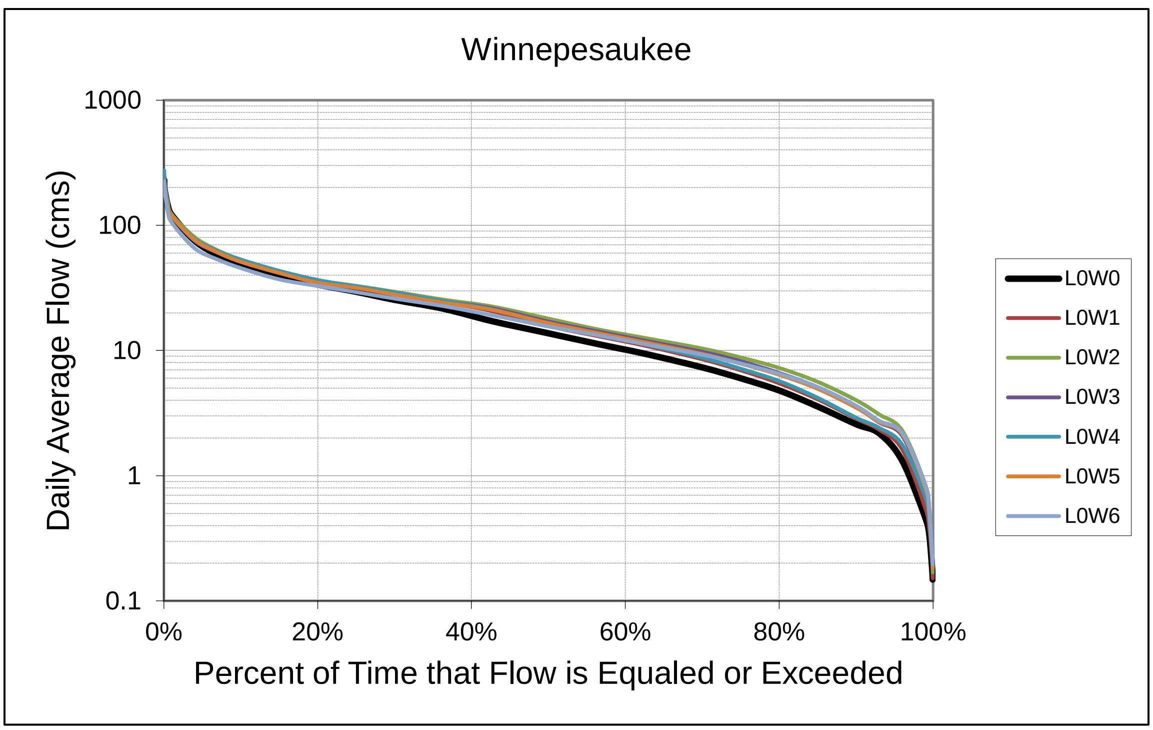


Figure 216. **Flow duration, Winnepesaukee River (SWAT)**

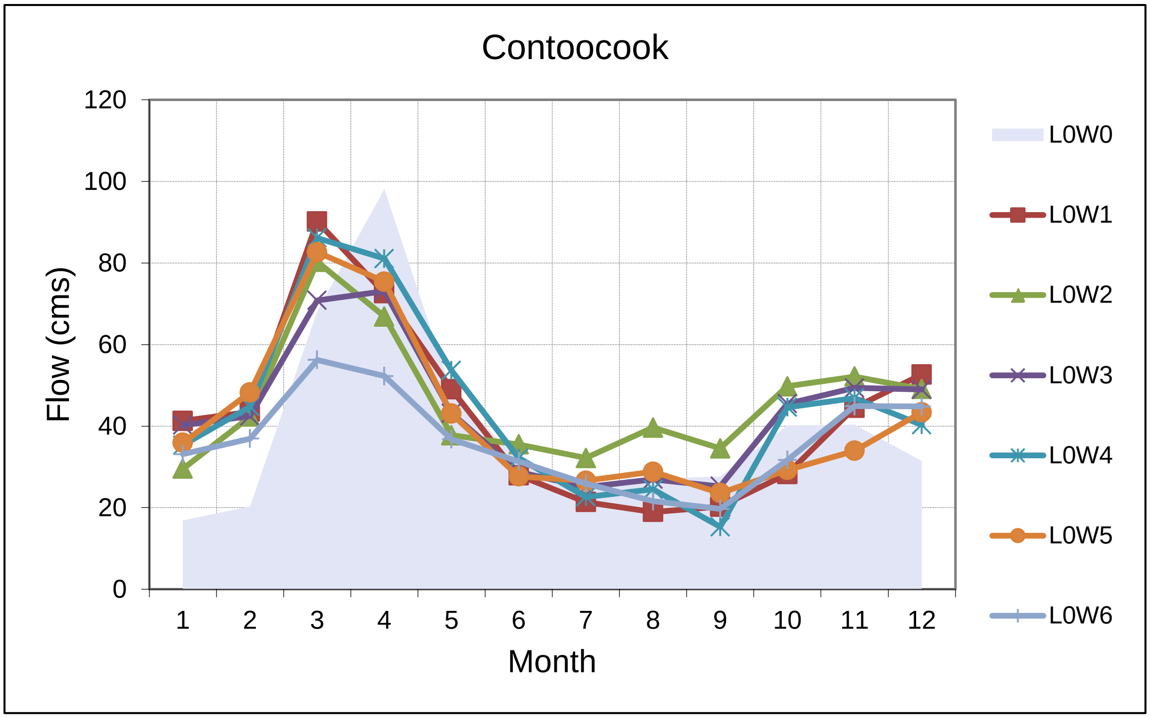


Figure 217. Monthly average flows, Contoocook River (SWAT)

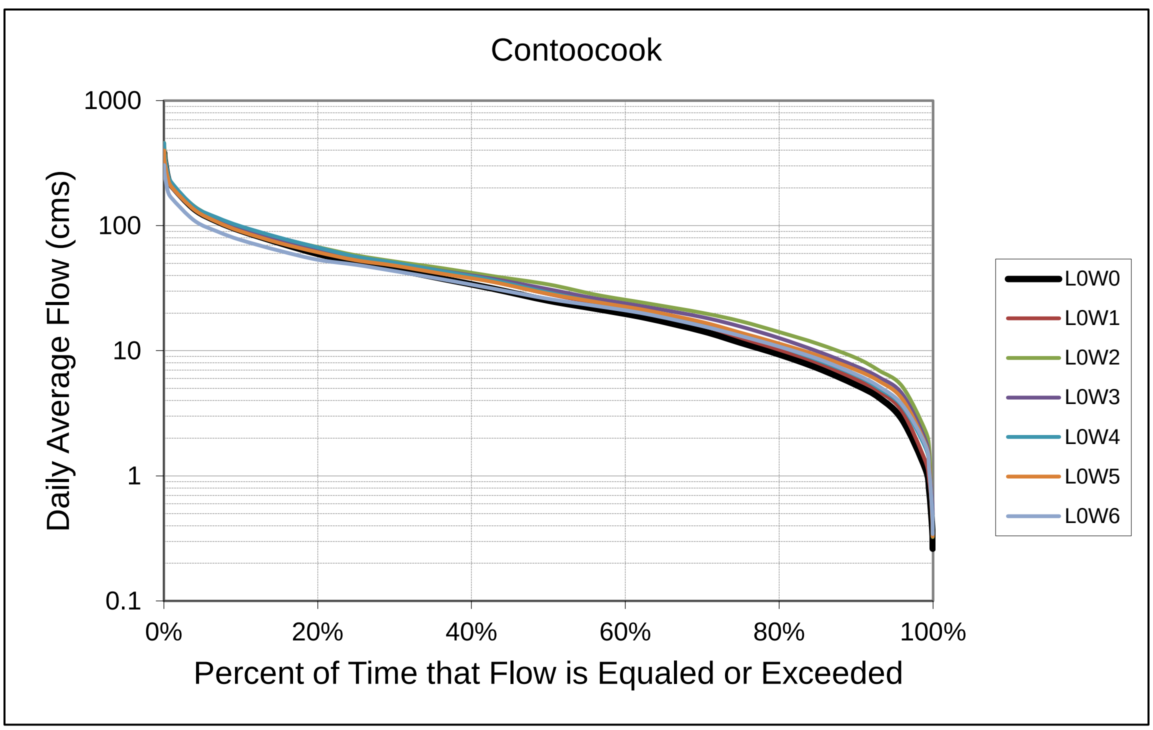


Figure 218. Flow duration, Contoocook River (SWAT)

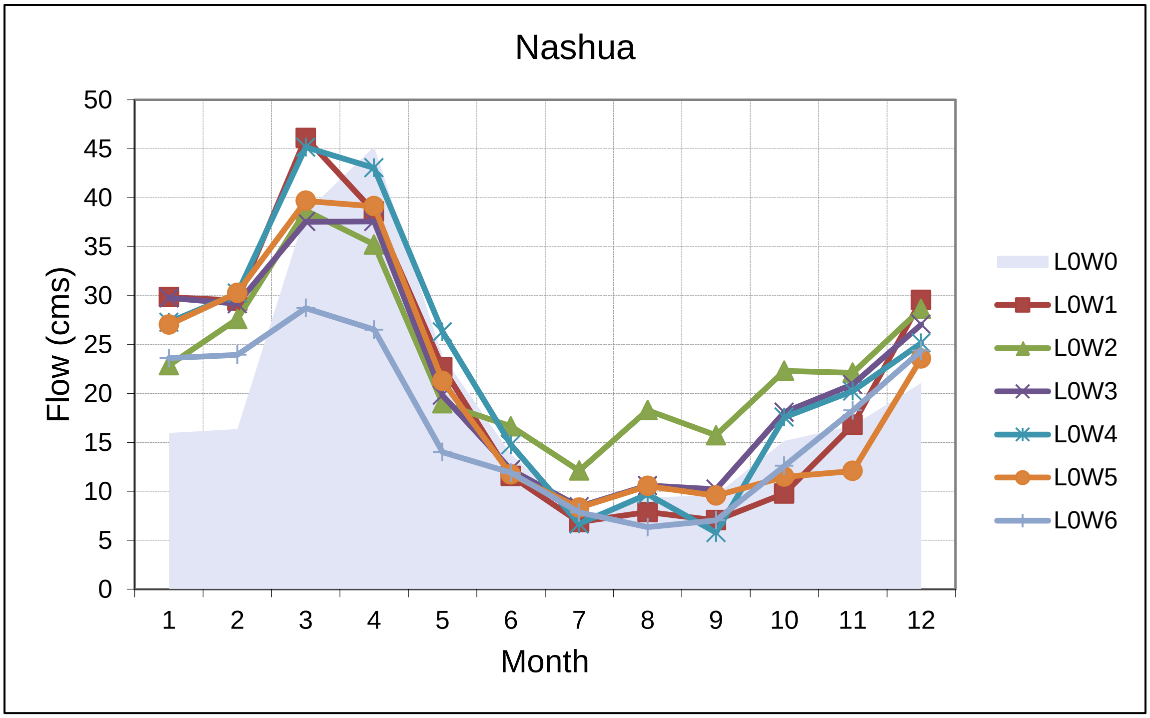


Figure 219. **Monthly average flows, Nashua River (SWAT)**

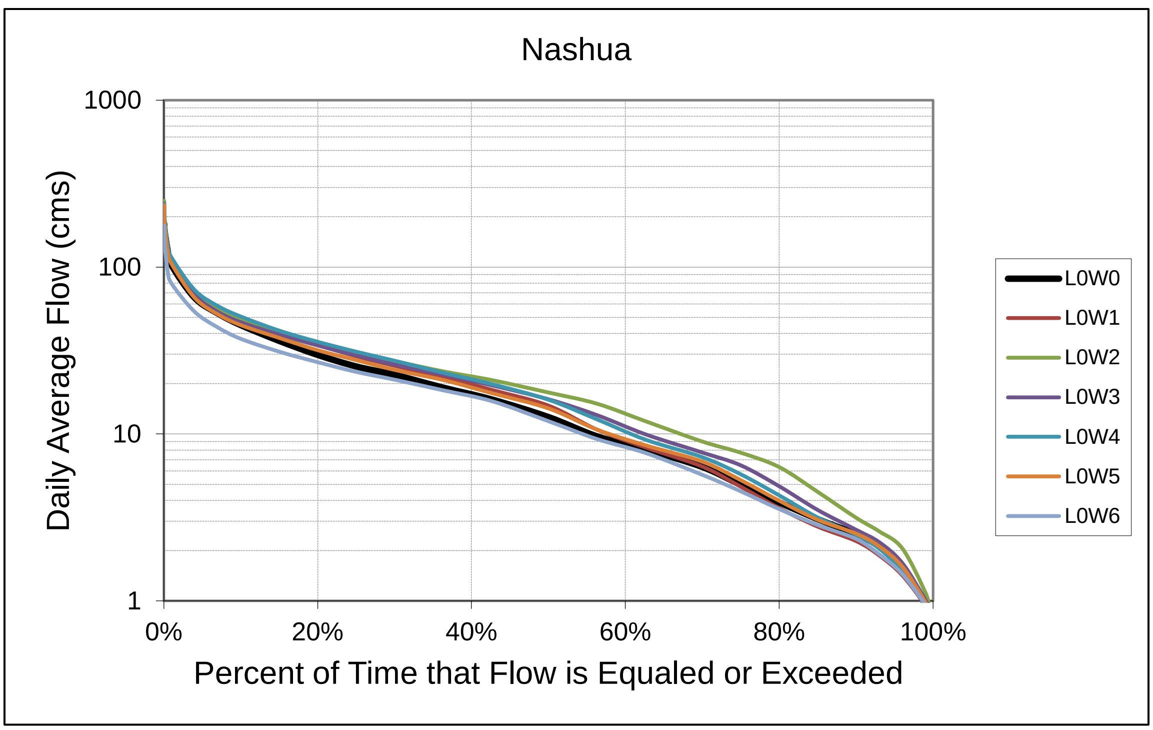


Figure 220. **Flow duration, Nashua River (SWAT)**

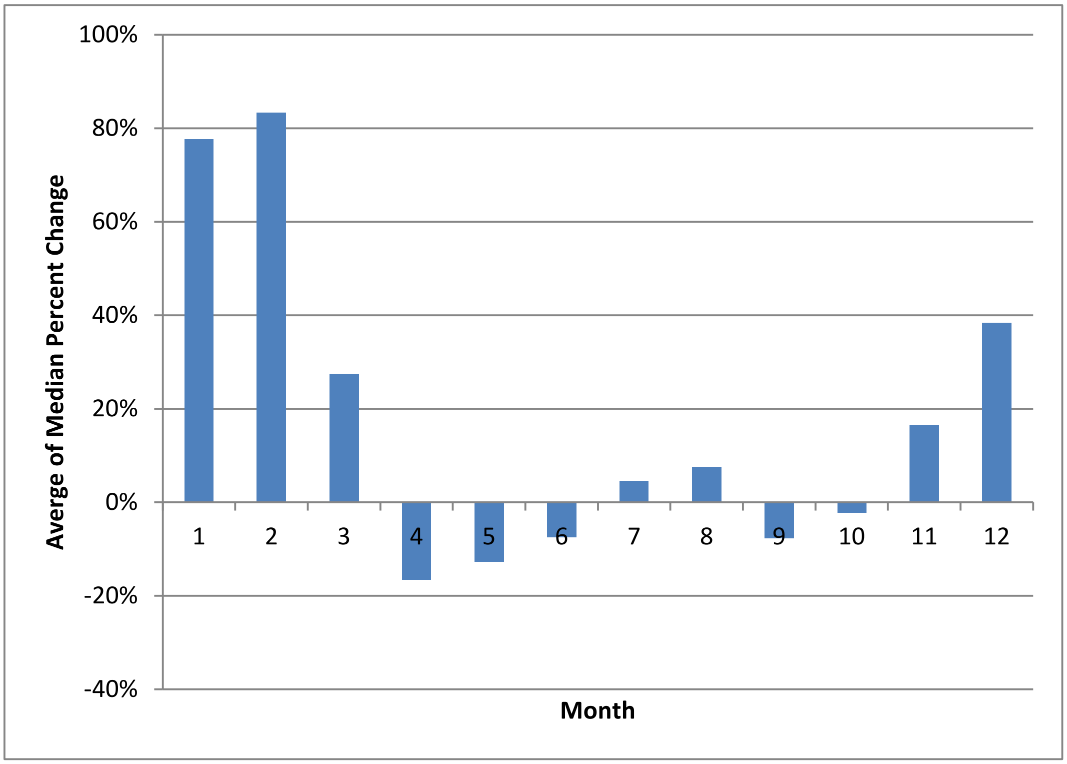


Figure 221. Average of median percent change in flow; NARCCAP Scenarios W1-W6 at all stations, New England Coastal basins (SWAT)

Lake Pontchartrain Drainage

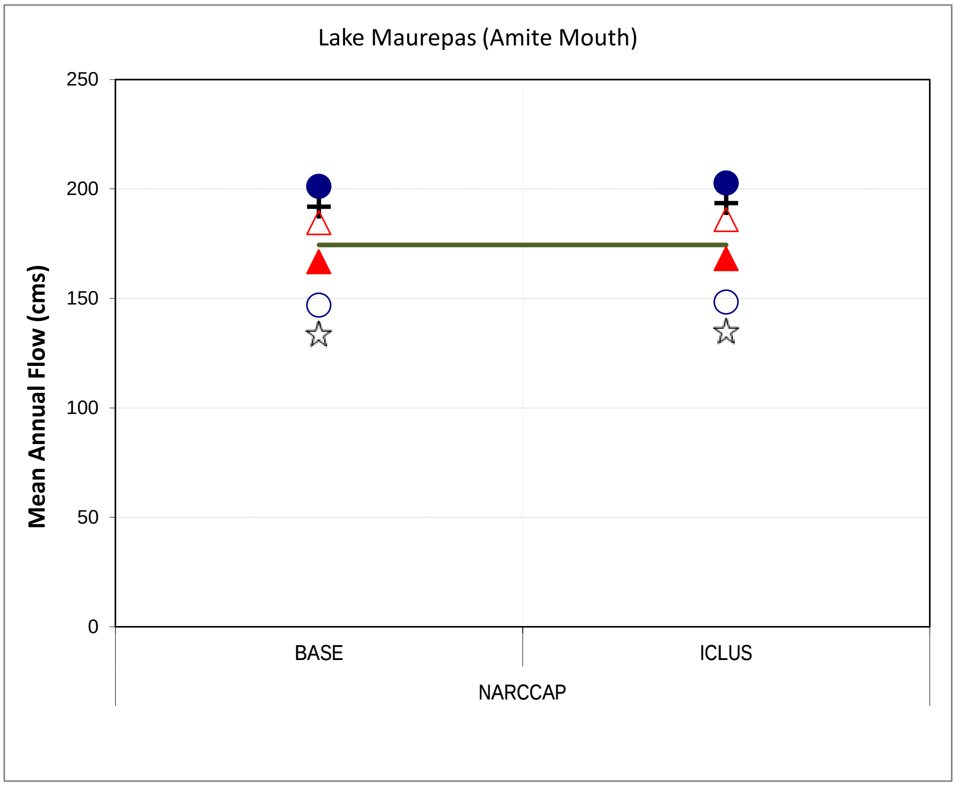


Figure 222. Mean annual flow (cms), mouth of the Amite River at Lake Maurepas (SWAT)

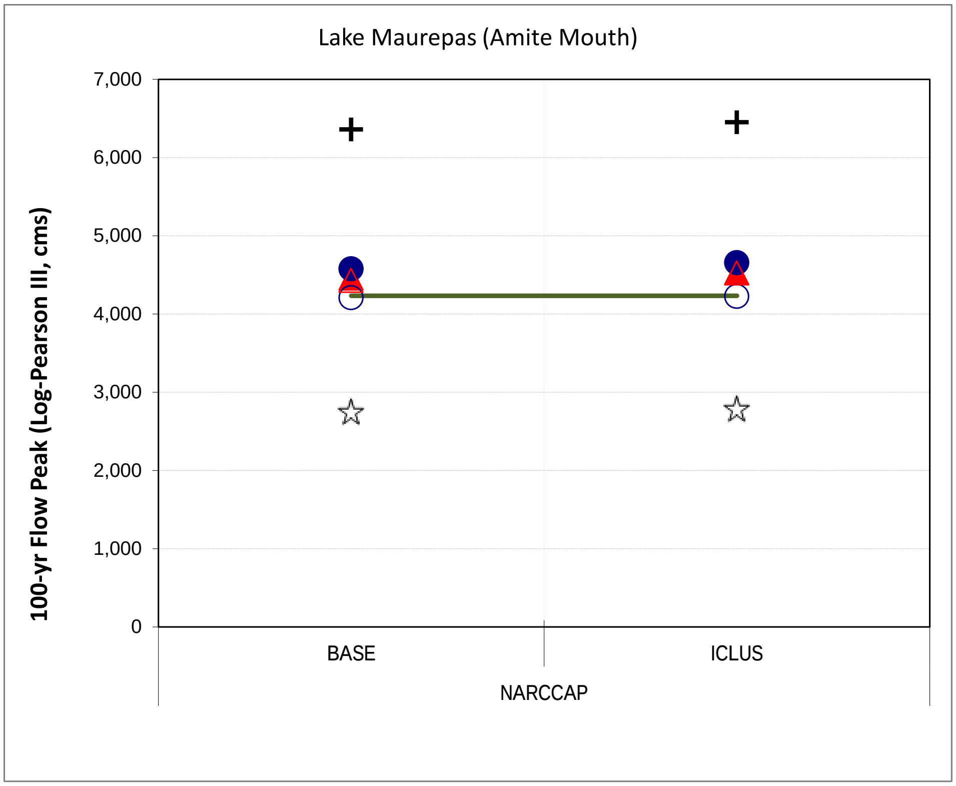


Figure 223. **100-yr Flow Peak (Log-Pearson III, cms), mouth of the Amite River at Lake Maurepas (SWAT)**

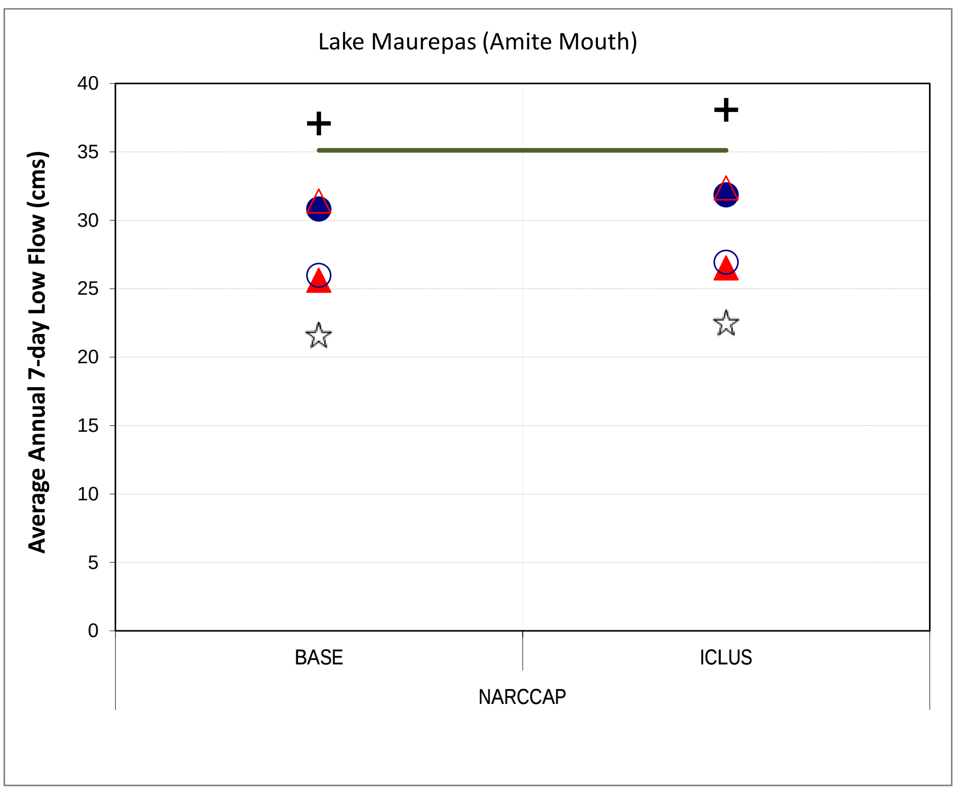


Figure 224. **Average Annual 7-day Low Flow (cms), mouth of the Amite River at Lake Maurepas (SWAT)**

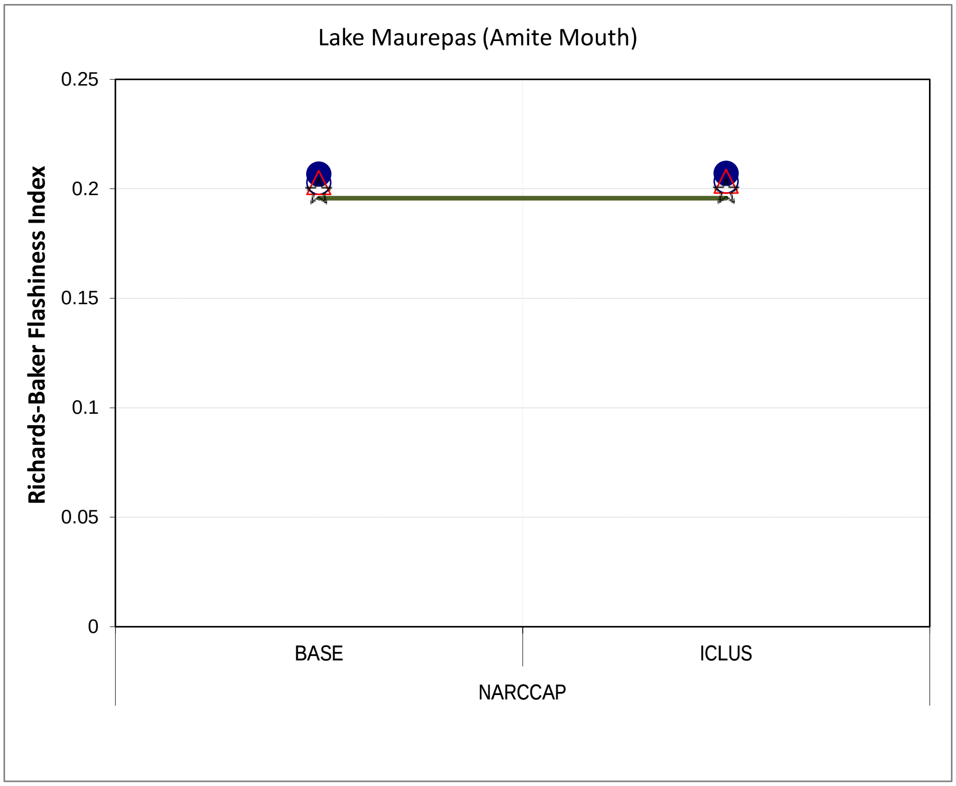


Figure 225. **Richards-Baker Flashiness Index, Average Annual 7-day Low Flow (cms), mouth of the Amite River at Lake Maurepas (SWAT)**

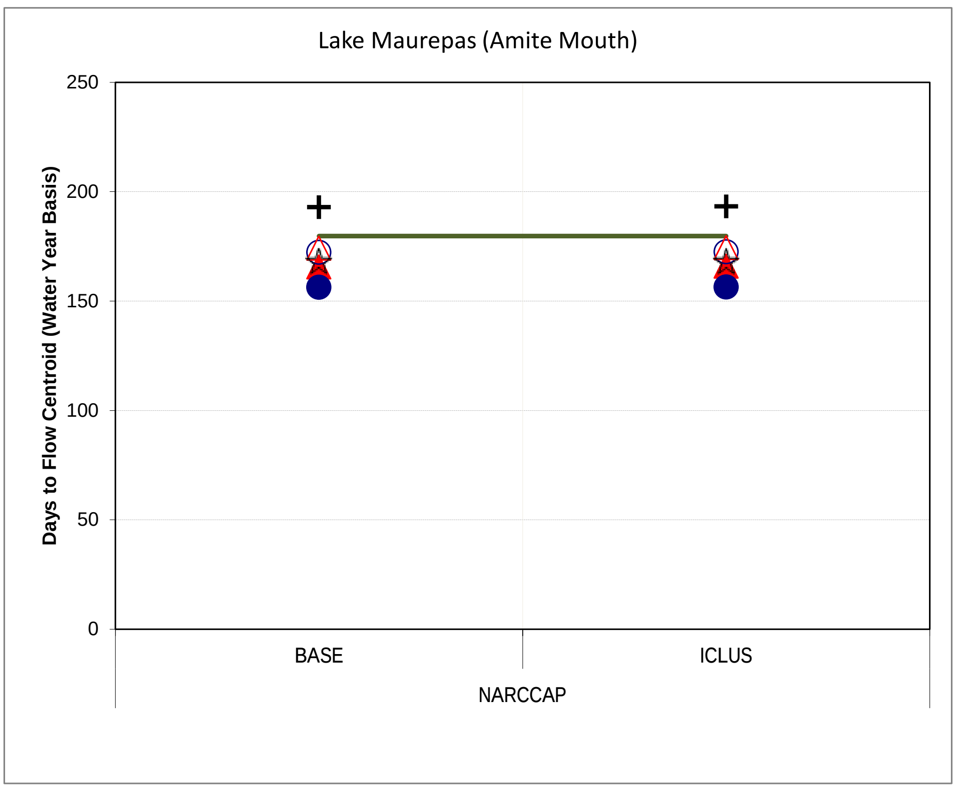


Figure 226. **Days to Flow Centroid (Water Year Basis), mouth of the Amite River at Lake Maurepas (SWAT)**

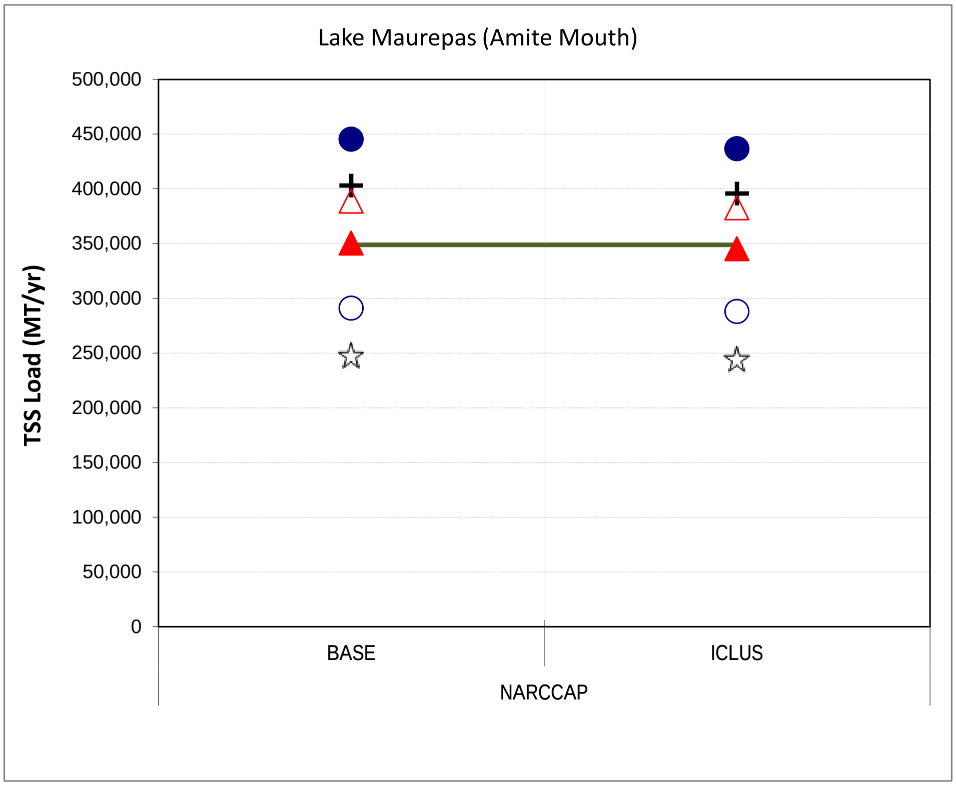


Figure 227. TSS Load (MT/yr), mouth of the Amite River at Lake Maurepas (SWAT)

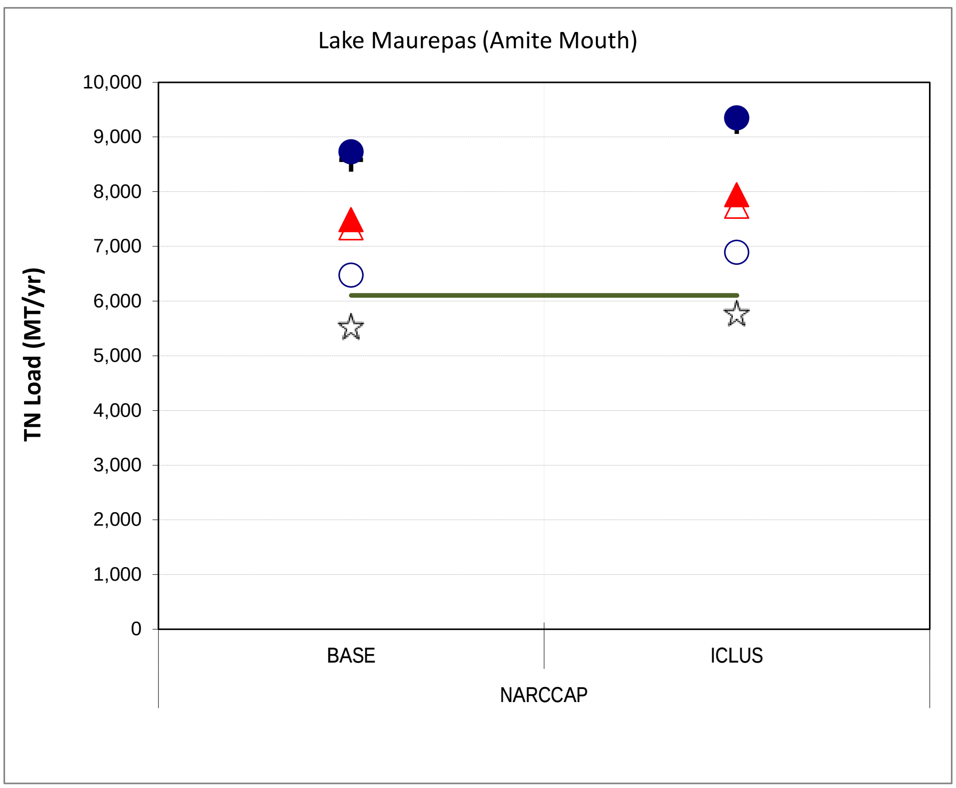


Figure 228. TN Load (MT/yr), mouth of the Amite River at Lake Maurepas (SWAT)

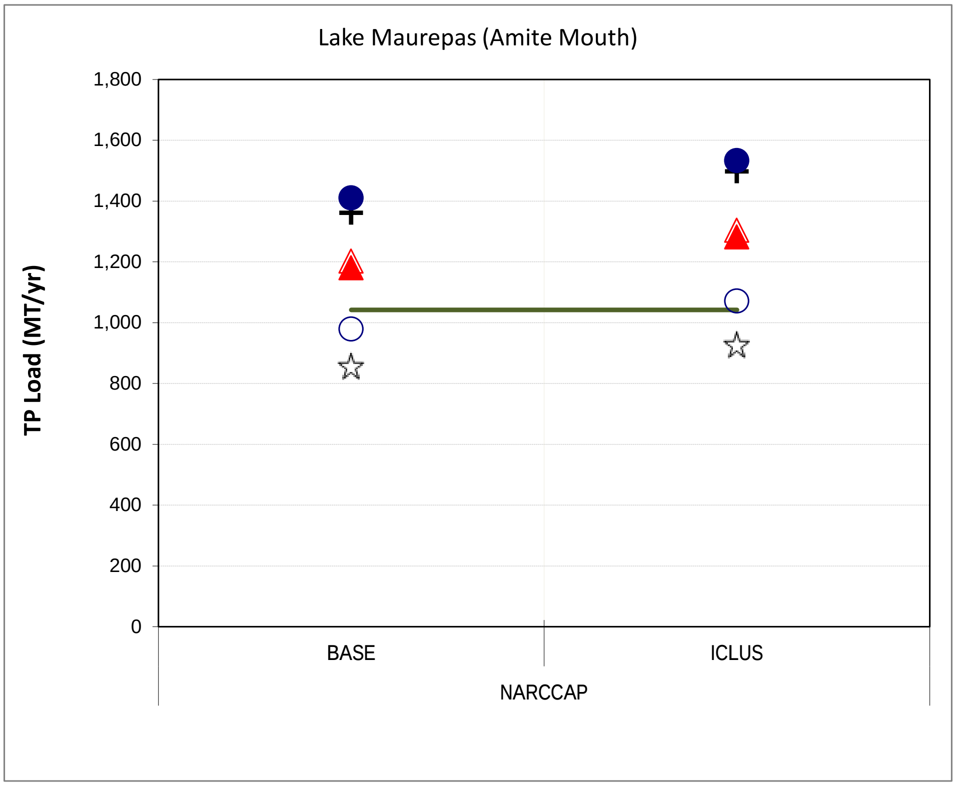


Figure 229. **TP Load (MT/yr), mouth of the Amite River at Lake Maurepas (SWAT)**

Table 9. Summary of range of change relative to existing conditions for NARCCAP dynamically downscaled scenarios, Neuse-Tar watershed SWAT model

	Results without LU change				Results with LU change			
	Min	Median	Mean	Max	Min	Median	Mean	Max
Amite HUC 08070202								
Flow	-23.29%	2.10%	-1.82%	16.57%	-23.15%	2.10%	-1.81%	16.43%
TSS	-29.86%	7.74%	1.98%	30.26%	-29.85%	7.63%	1.83%	29.43%
TN	-11.70%	21.07%	21.52%	49.95%	-10.61%	23.62%	25.14%	54.81%
TP	-12.27%	15.19%	16.20%	41.72%	-10.96%	17.45%	19.30%	46.13%
Tickfaw HUC 08070203								
Flow	-24.75%	3.41%	-1.67%	15.82%	-24.71%	3.40%	-1.66%	15.79%
TSS	-26.07%	5.13%	0.10%	20.01%	-25.91%	4.91%	-0.01%	19.80%
TN	-20.05%	32.79%	28.86%	60.83%	-22.31%	32.67%	30.15%	65.51%
TP	-26.81%	17.23%	12.52%	39.32%	-27.78%	17.23%	13.31%	41.83%
Lake Maurepas (Amite Mouth) HUC 08070204								
Flow	-23.02%	0.74%	-1.98%	15.38%	-22.87%	0.71%	-1.96%	15.27%
TSS	-28.77%	5.89%	1.57%	27.60%	-28.67%	5.68%	1.33%	26.78%
TN	-9.04%	21.42%	20.56%	42.96%	-8.62%	23.61%	23.48%	47.41%
TP	-17.45%	14.34%	11.87%	35.37%	-16.30%	16.20%	14.15%	37.83%
Tangipahoa R at Robert (gage 07375500)								
Flow	-20.43%	3.61%	-0.44%	14.97%	-20.43%	3.59%	-0.45%	14.96%
TSS	-26.21%	9.45%	3.89%	26.57%	-26.11%	9.61%	4.17%	27.03%
TN	-6.20%	36.55%	26.90%	52.22%	-6.27%	39.25%	28.94%	55.30%
TP	-14.39%	29.94%	20.14%	46.75%	-14.44%	32.14%	21.73%	48.91%
Tchefuncte HUC 08090201								
Flow	-24.68%	-0.53%	-4.23%	15.81%	-24.58%	-0.70%	-4.30%	15.58%
TSS	-25.36%	0.12%	-2.99%	18.15%	-24.63%	-0.40%	-3.27%	16.74%
TN	-14.60%	12.84%	11.39%	32.27%	-16.77%	13.50%	12.23%	36.97%
TP	-19.34%	5.16%	3.52%	24.08%	-19.97%	6.36%	4.76%	28.24%
Tickfaw R at Holden (gage 07376000)								
Flow	-22.01%	7.63%	2.06%	21.82%	-22.01%	7.63%	2.06%	21.82%
TSS	-29.60%	15.24%	9.61%	49.72%	-29.60%	15.24%	9.61%	49.69%
TN	-9.61%	17.93%	12.33%	29.33%	-9.56%	17.98%	12.38%	29.41%
TP	-18.53%	11.44%	5.48%	24.36%	-18.52%	11.48%	5.51%	24.42%
Amite R nr Denham Sprs (gage 07378500)								
Flow	-22.67%	3.18%	-1.05%	16.97%	-22.60%	3.16%	-1.05%	16.90%
TSS	-30.85%	4.21%	-1.11%	24.24%	-30.64%	4.33%	-0.88%	24.28%
TN	-10.47%	16.89%	15.87%	43.35%	-8.72%	18.39%	18.66%	47.57%
TP	-8.75%	13.46%	14.21%	39.65%	-6.61%	15.27%	17.41%	44.42%

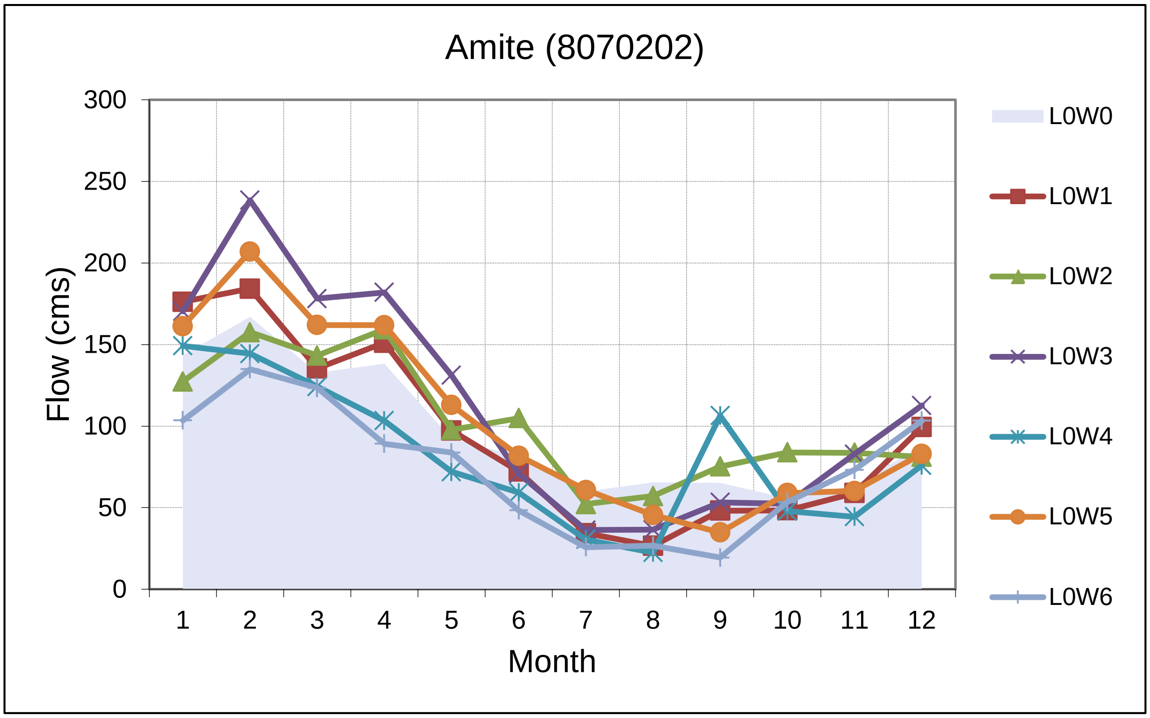


Figure 230. **Monthly average flows, Amite River (SWAT)**

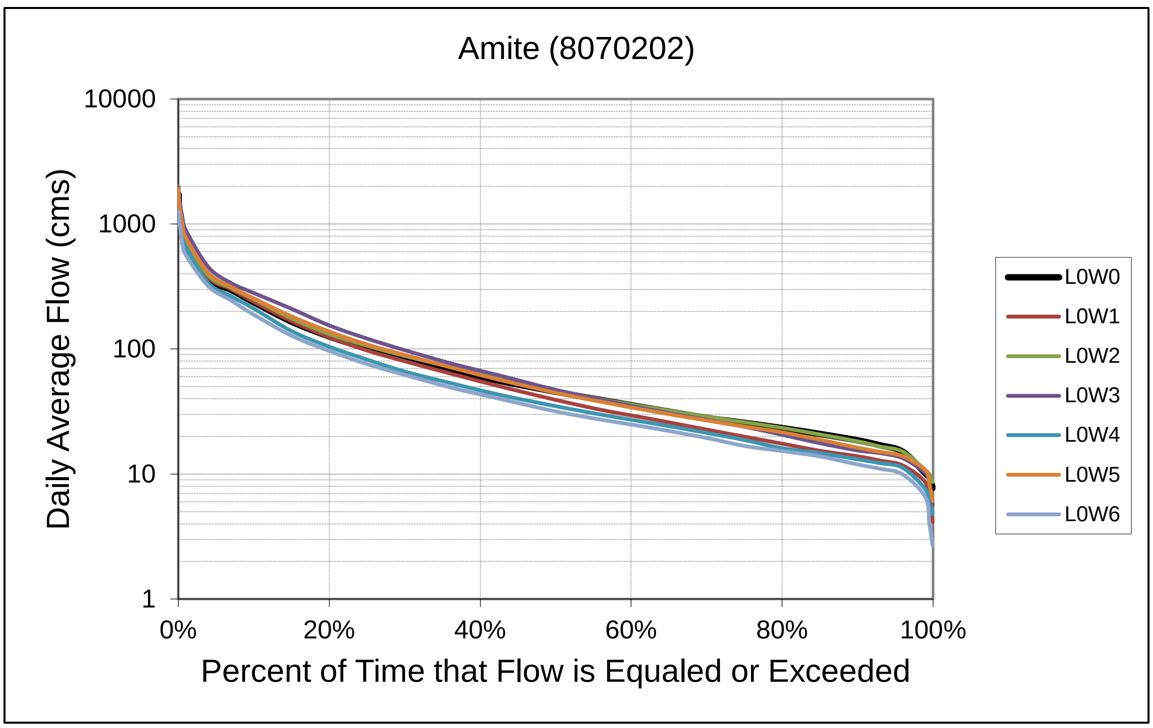


Figure 231. **Flow duration, Amite River (SWAT)**

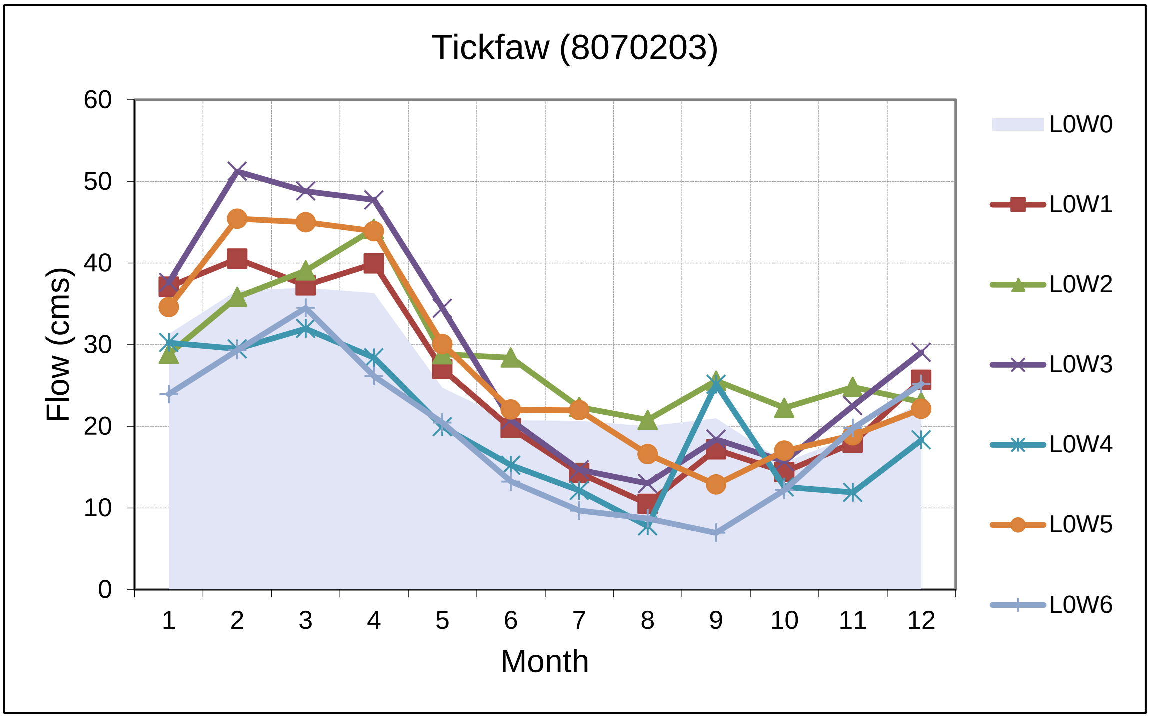


Figure 232. Monthly average flows, Tickfaw River (SWAT)

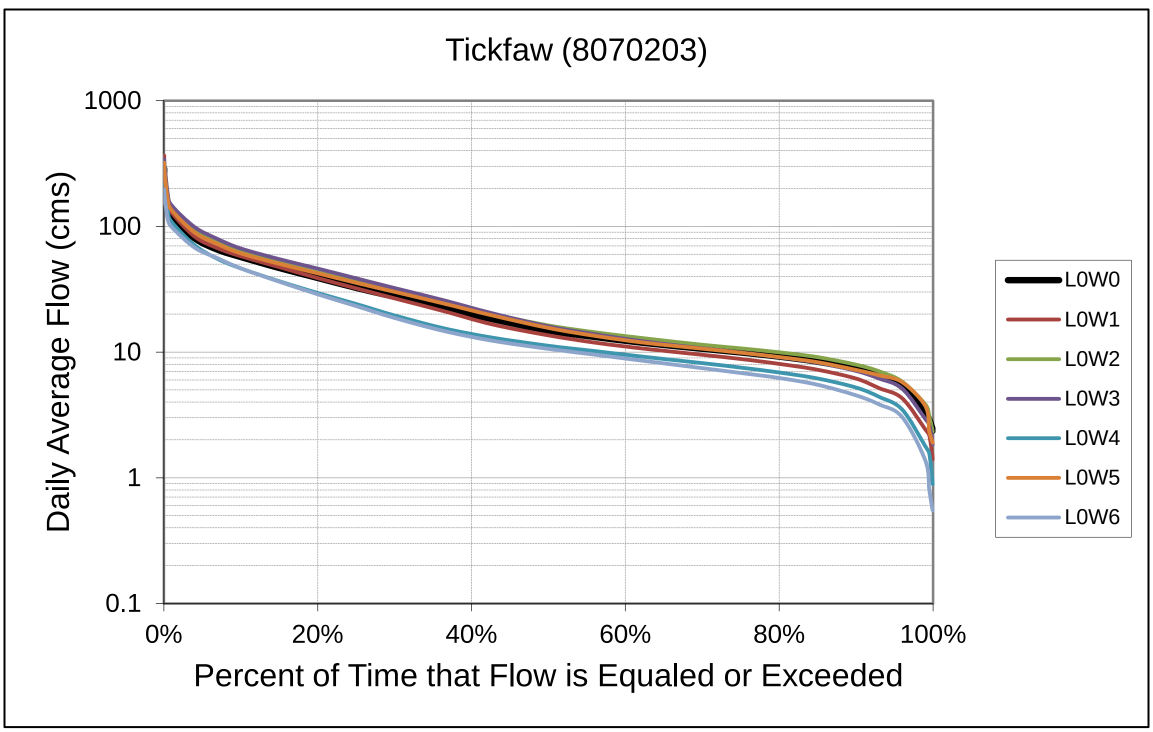


Figure 233. Flow duration, Tickfaw River (SWAT)

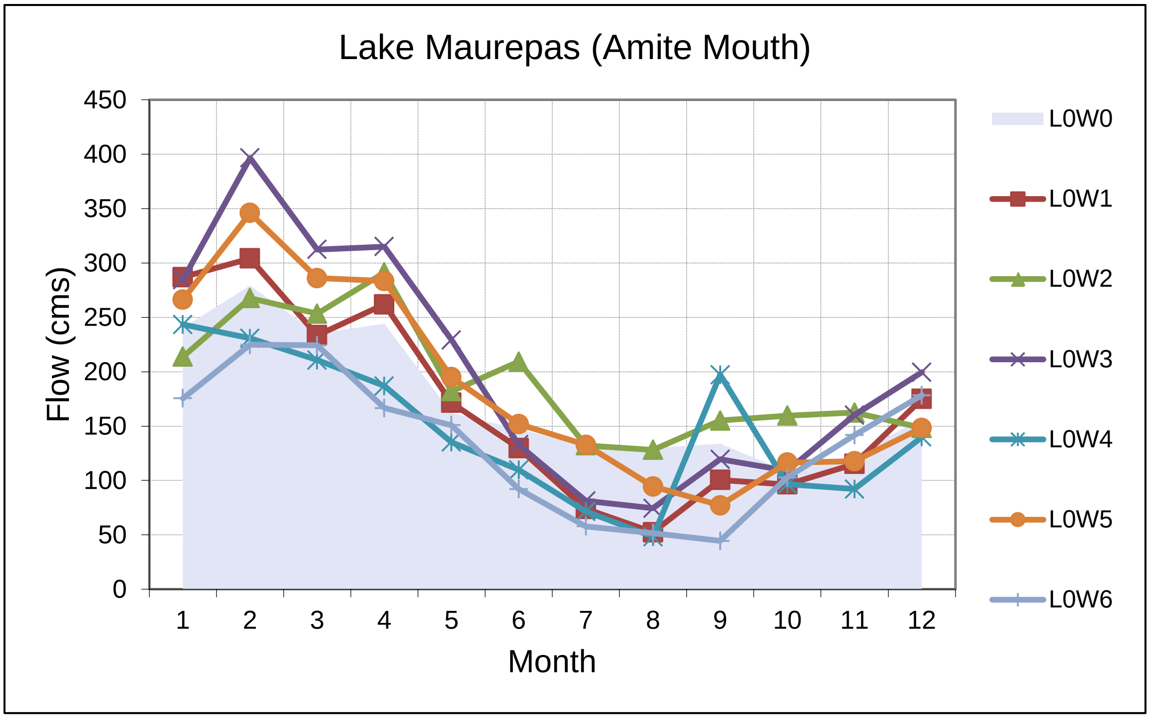


Figure 234. **Monthly average flows, Amite River Mouth (SWAT)**

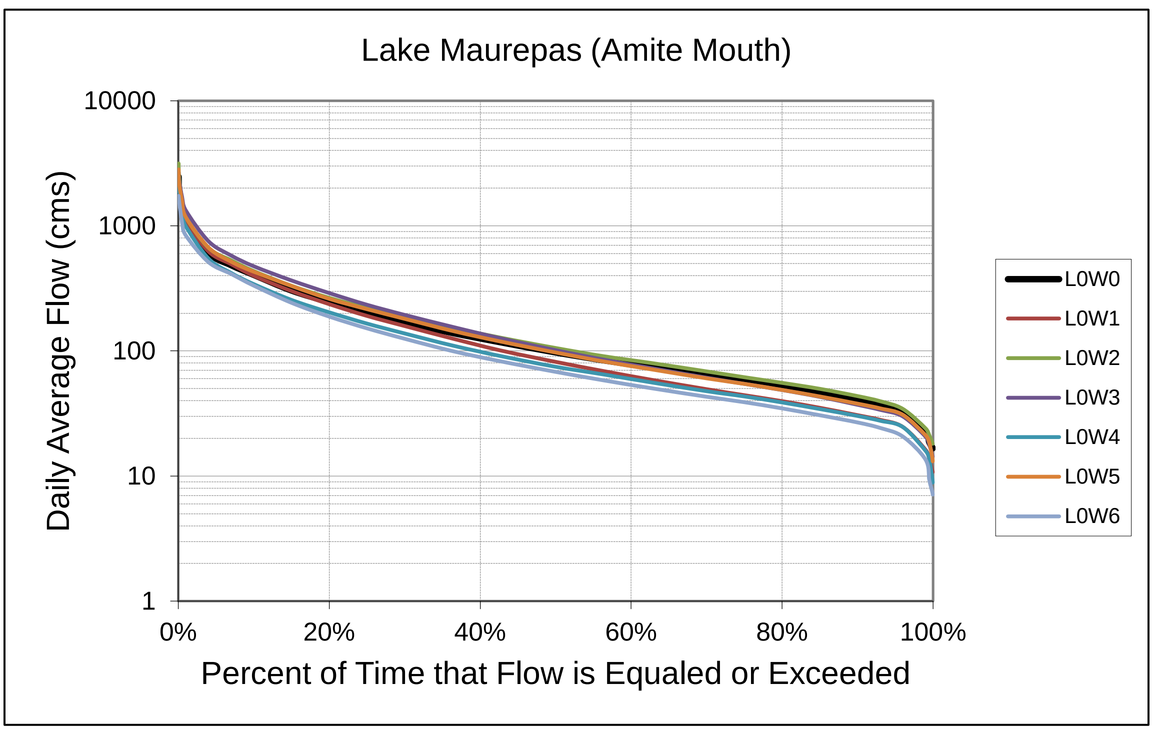


Figure 235. **Flow duration, Amite River Mouth (SWAT)**

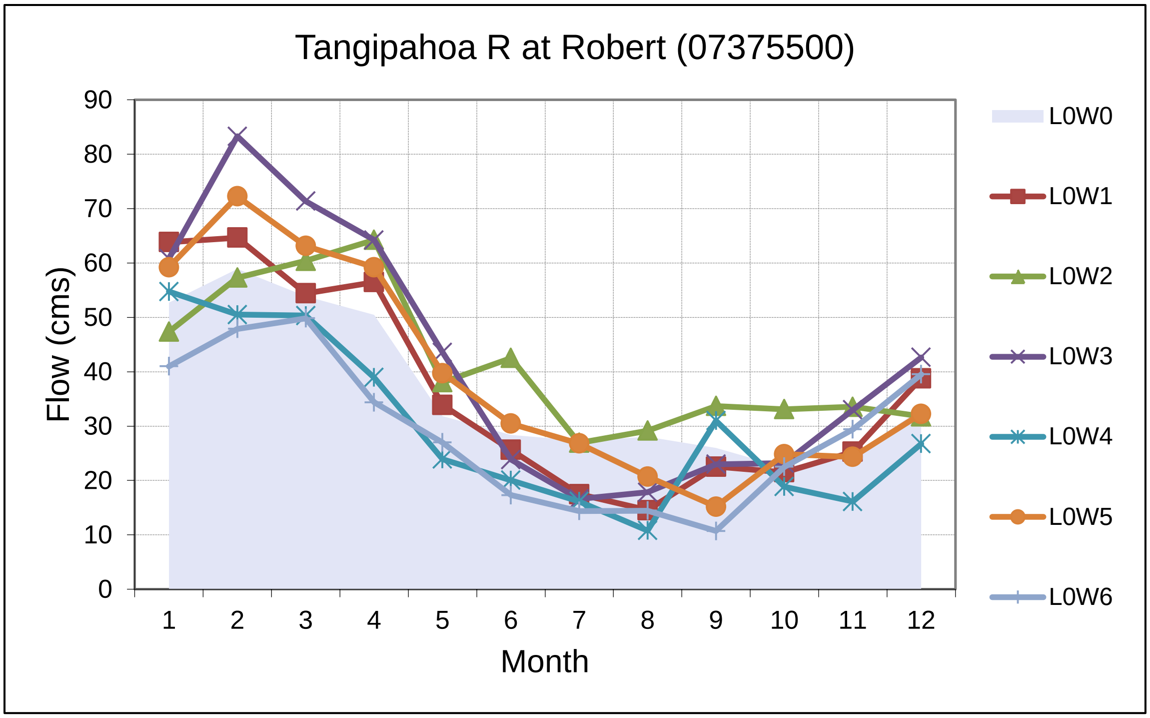


Figure 236. **Monthly average flows, Tangipahoa River at Robert (SWAT)**

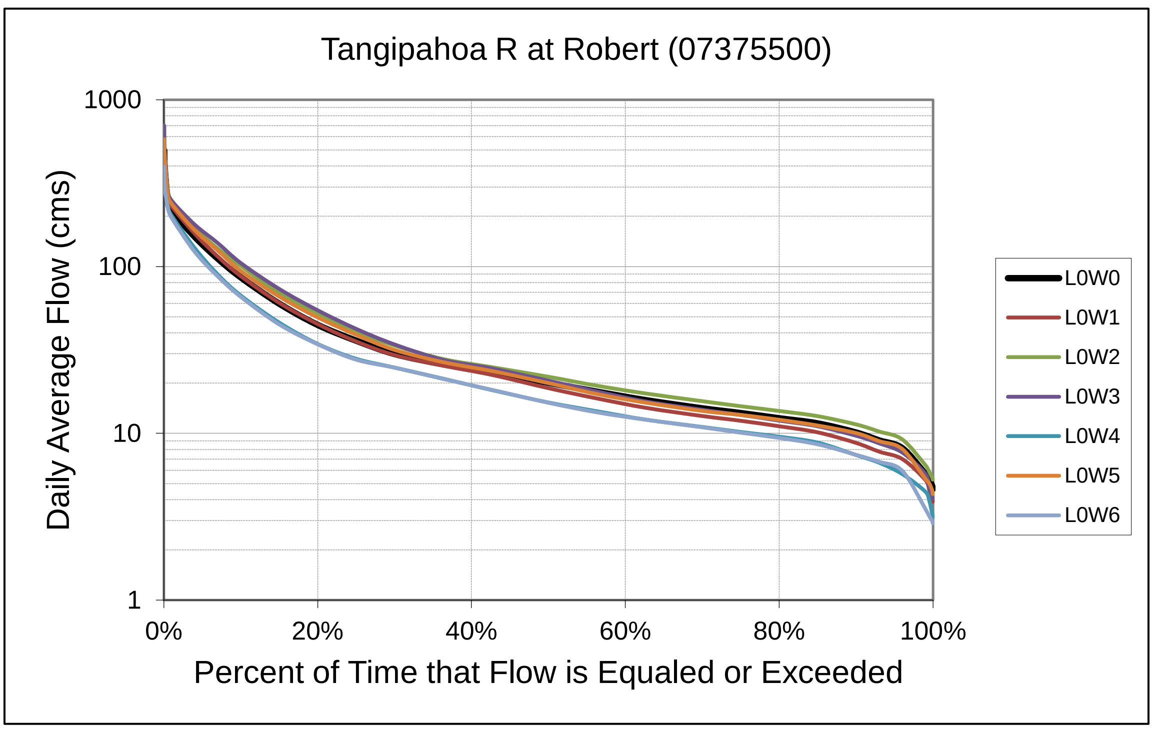


Figure 237. **Flow duration, Tangipahoa River at Robert (SWAT)**

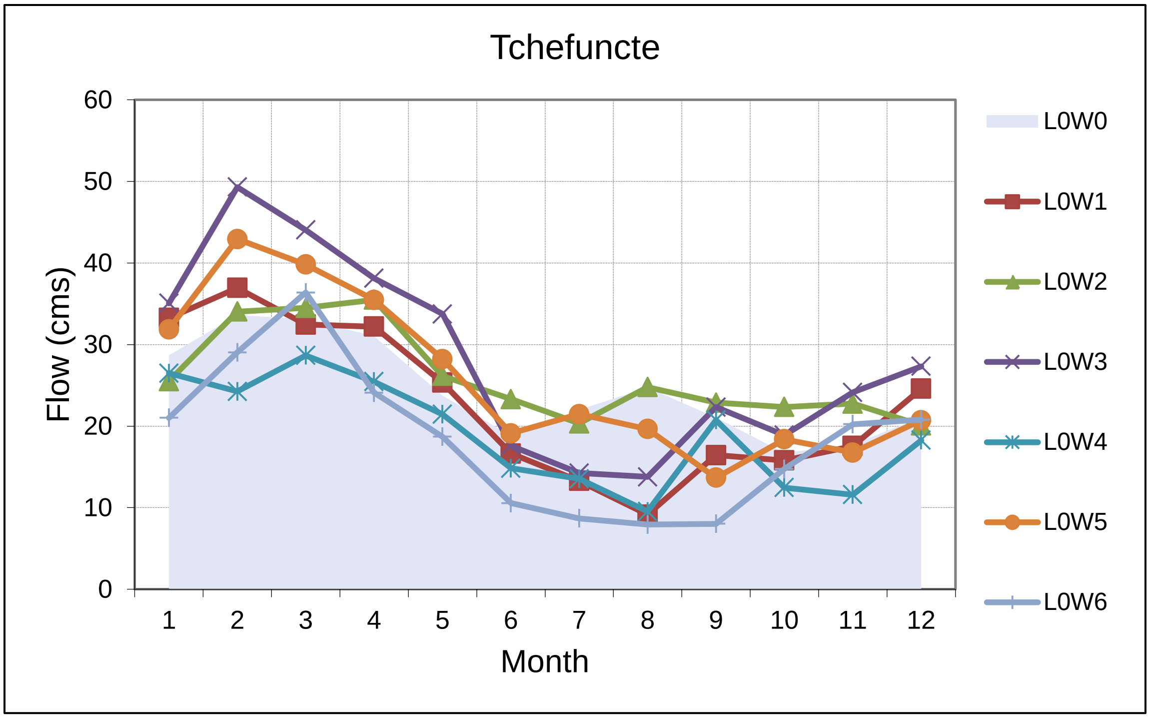


Figure 238. **Monthly average flows, Tchefuncte River (SWAT)**

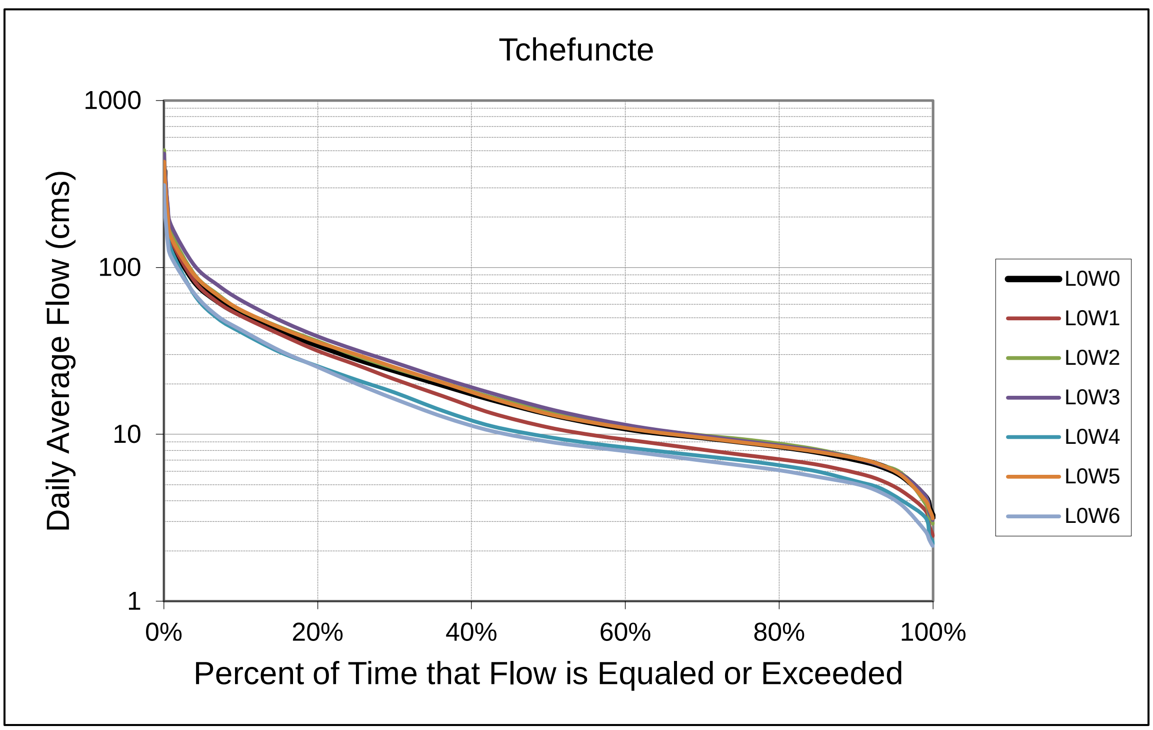


Figure 239. **Flow duration, Tchefuncte River (SWAT)**

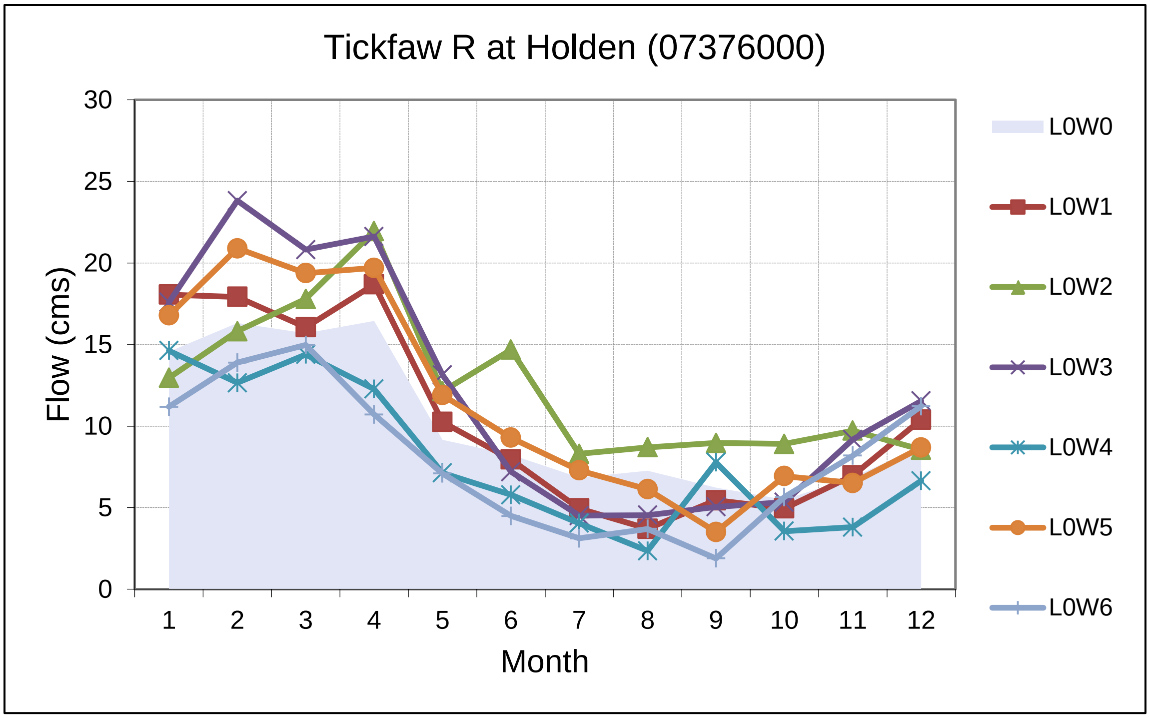


Figure 240. **Monthly average flows, Tickfaw River at Holden (SWAT)**

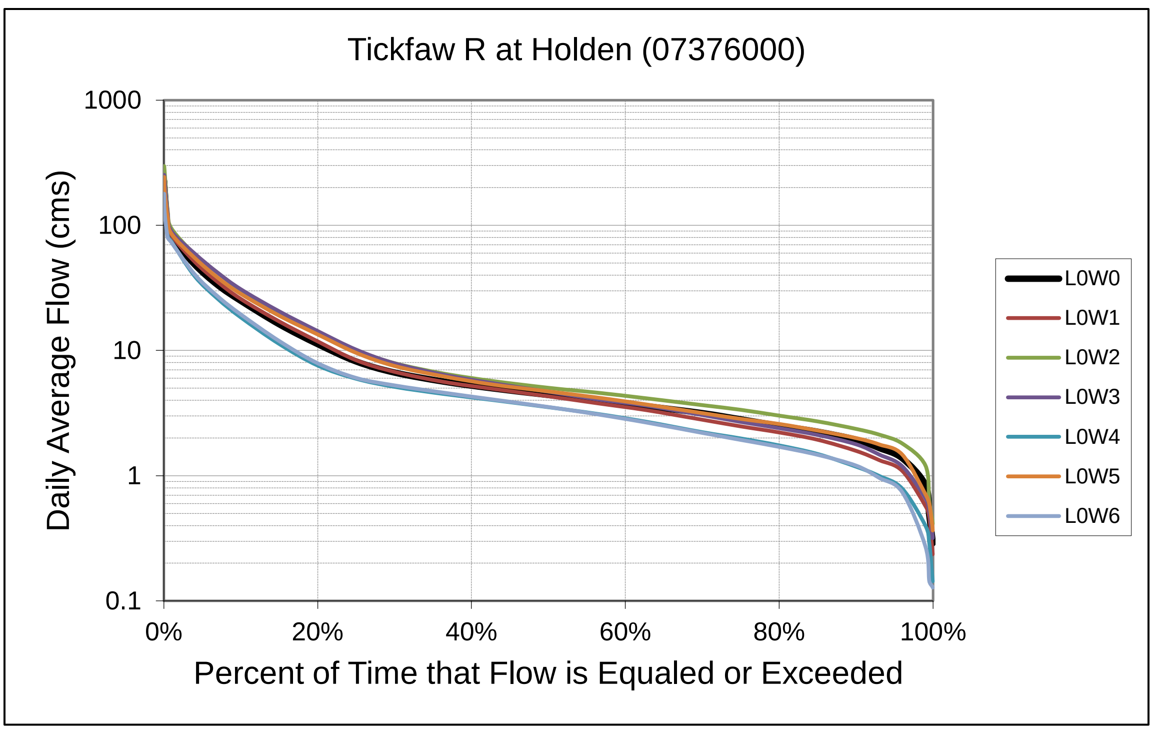


Figure 241. **Flow duration, Tickfaw River at Holden (SWAT)**

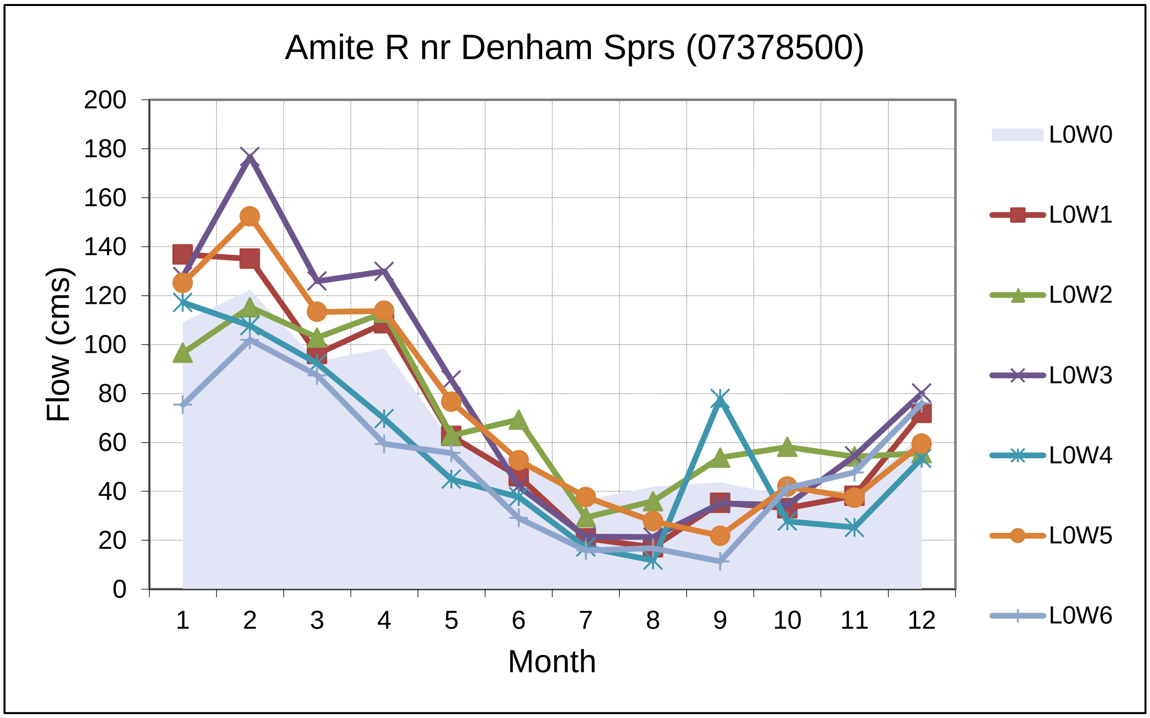


Figure 242. **Monthly average flows, Amite River near Denham Springs (SWAT)**

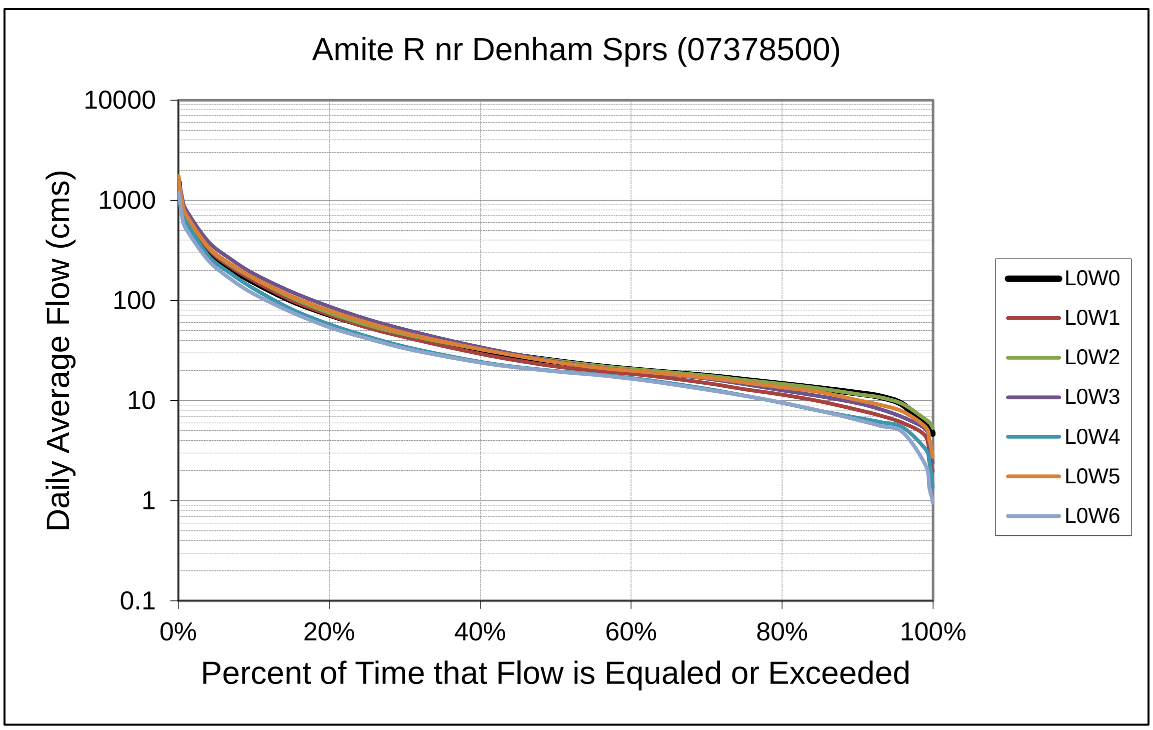


Figure 243. **Flow duration, Amite River near Denham Springs (SWAT)**

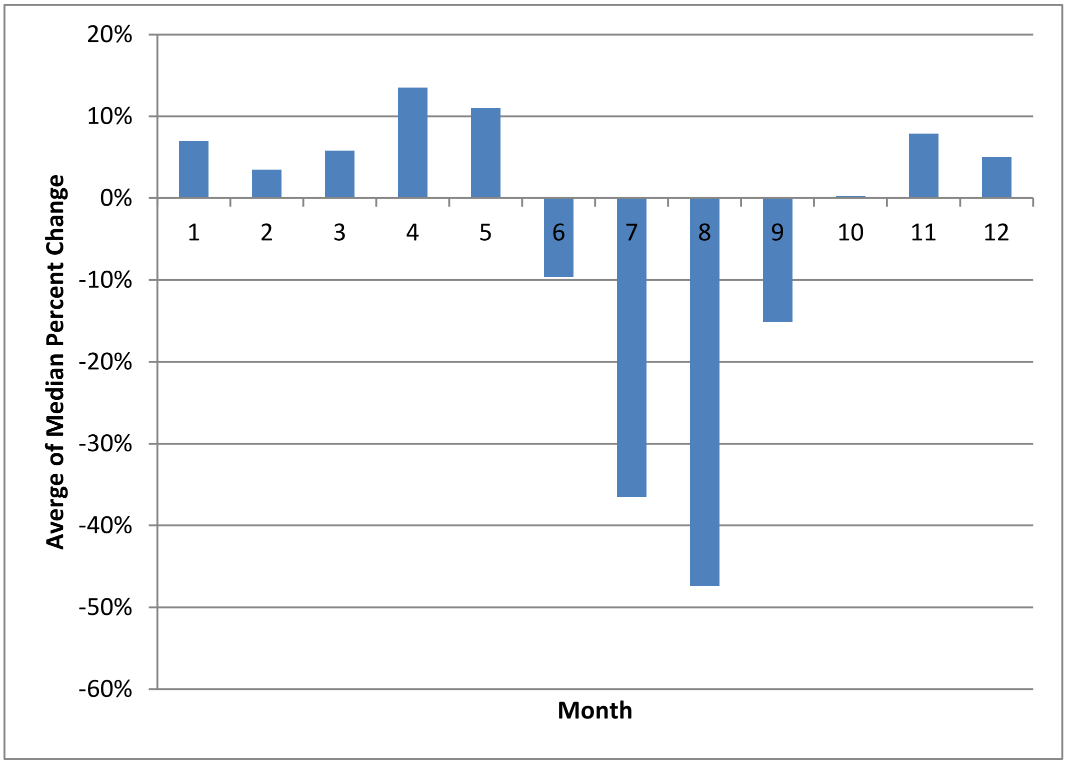


Figure 244. **Average of median percent change in flow; NARCCAP Scenarios W1-W6 at all stations, Lake Pontchartrain watershed (SWAT)**

Rio Grande Valley

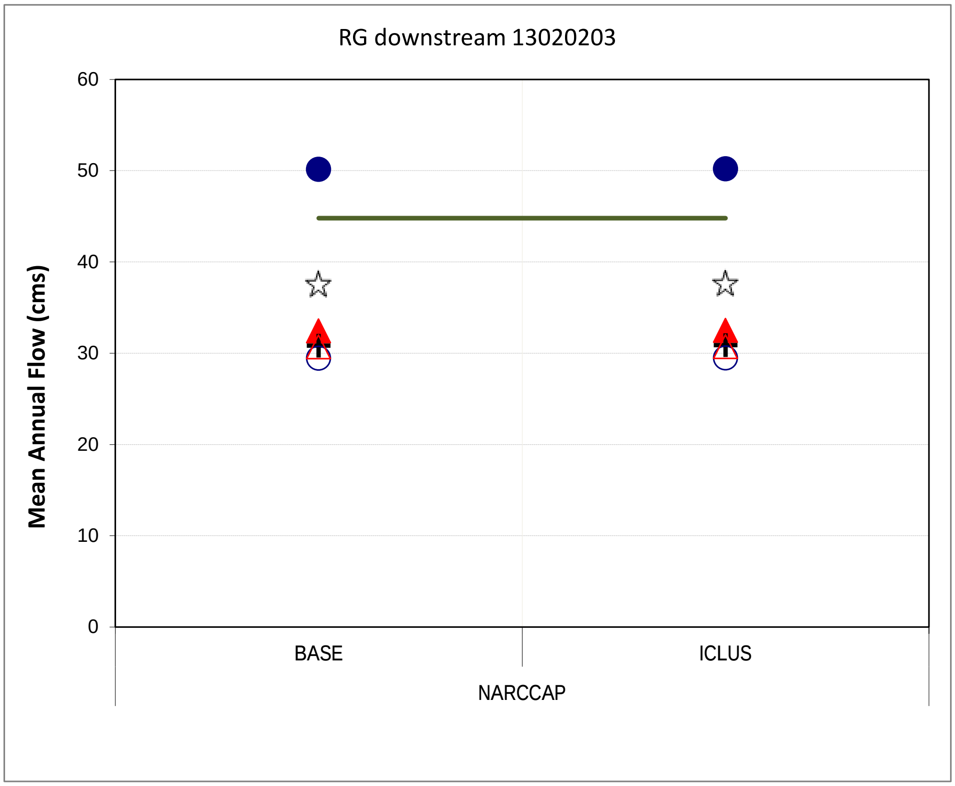


Figure 245. Mean annual flow (cms), Rio Grande downstream (SWAT)

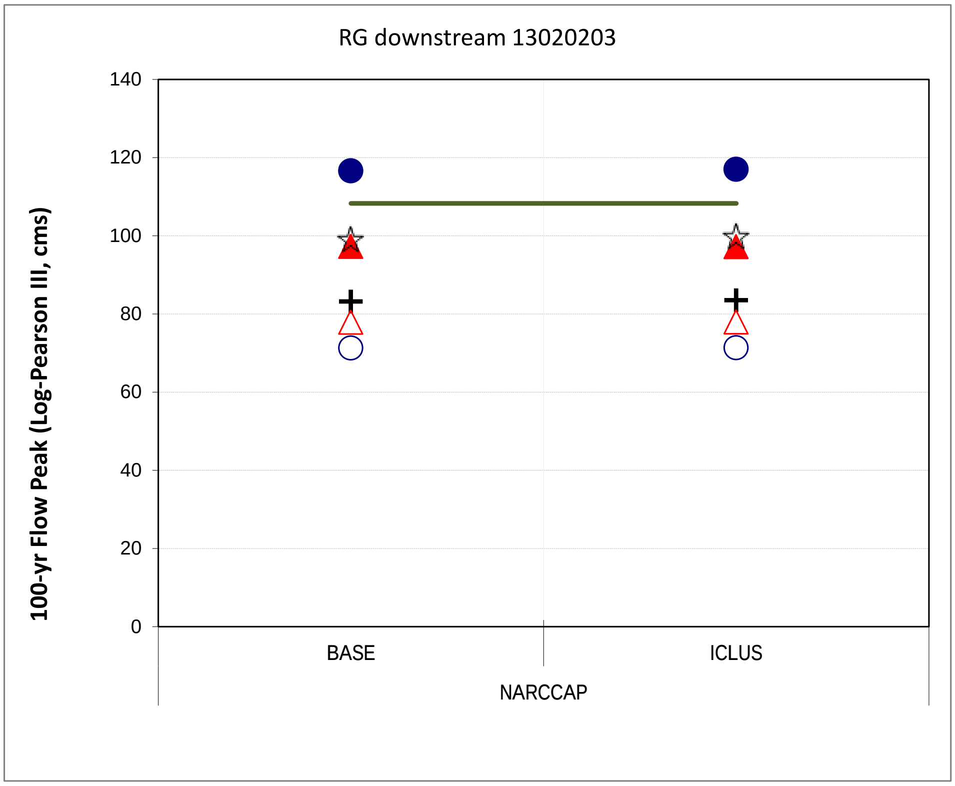


Figure 246. 100-yr Flow Peak (Log-Pearson III, cms), Rio Grande downstream (SWAT)

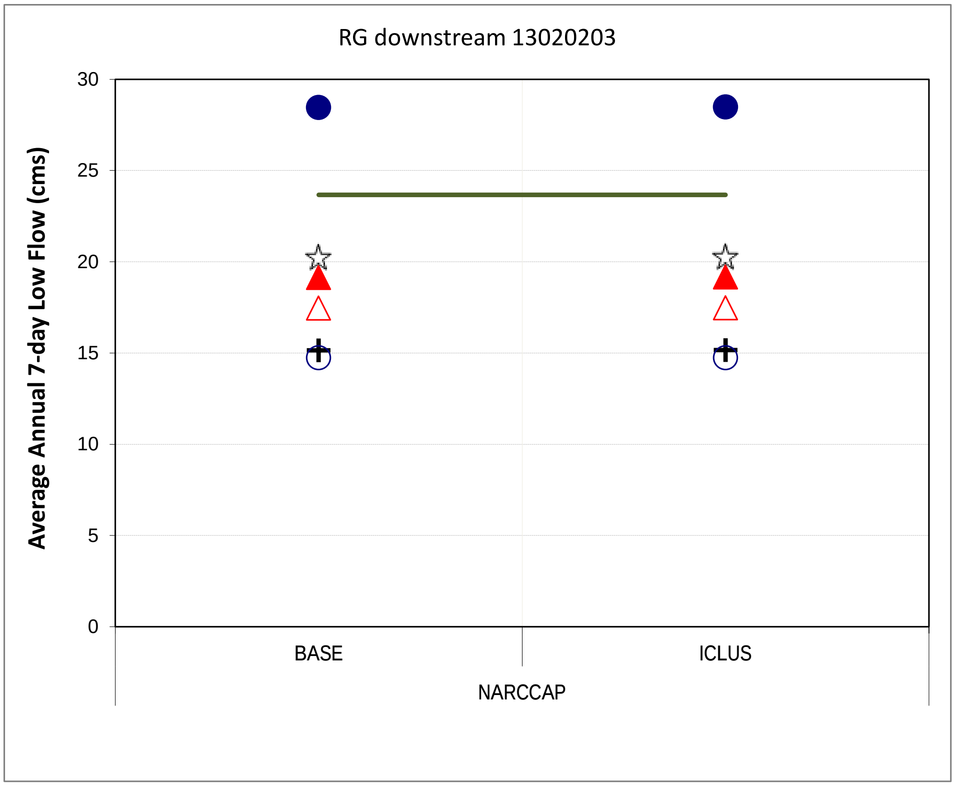


Figure 247. Average Annual 7-day Low Flow (cms), Rio Grande downstream (SWAT)

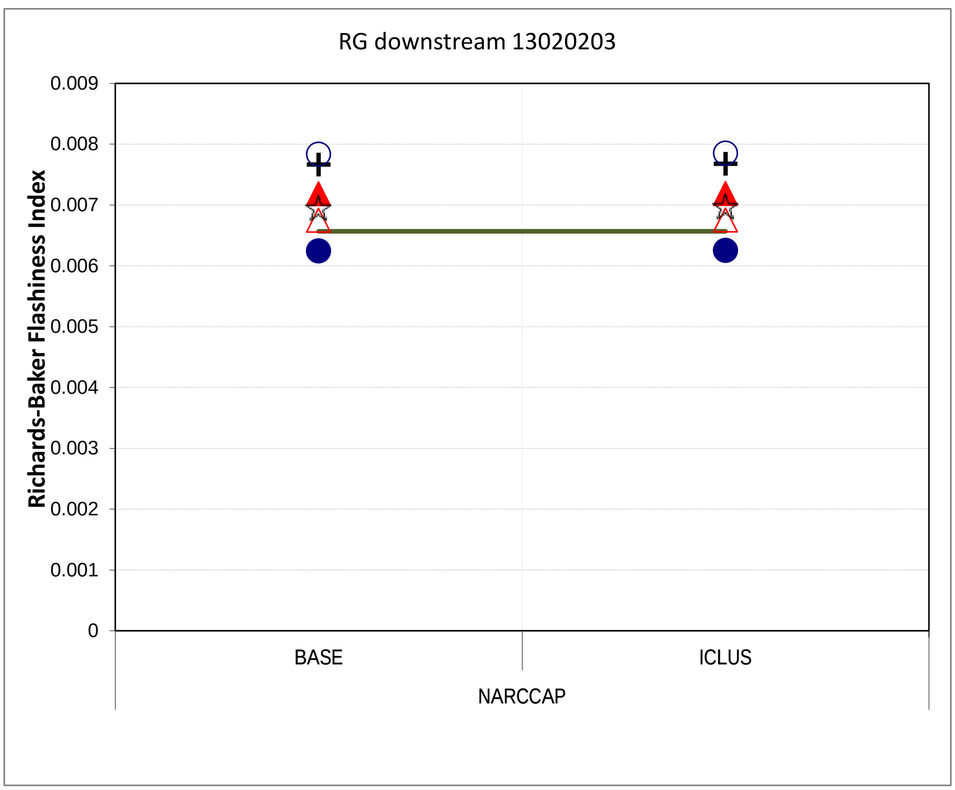


Figure 248. Richards-Baker Flashiness Index, Average Annual 7-day Low Flow (cms), Rio Grande downstream (SWAT)

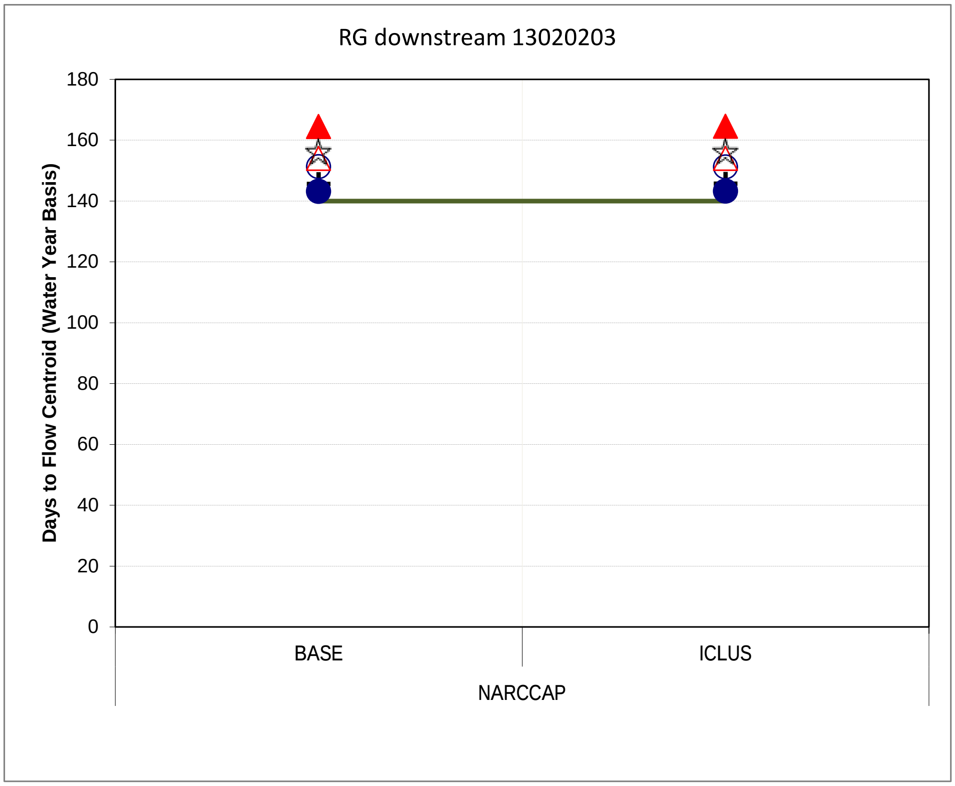


Figure 249. Days to Flow Centroid (Water Year Basis), Rio Grande downstream (SWAT)

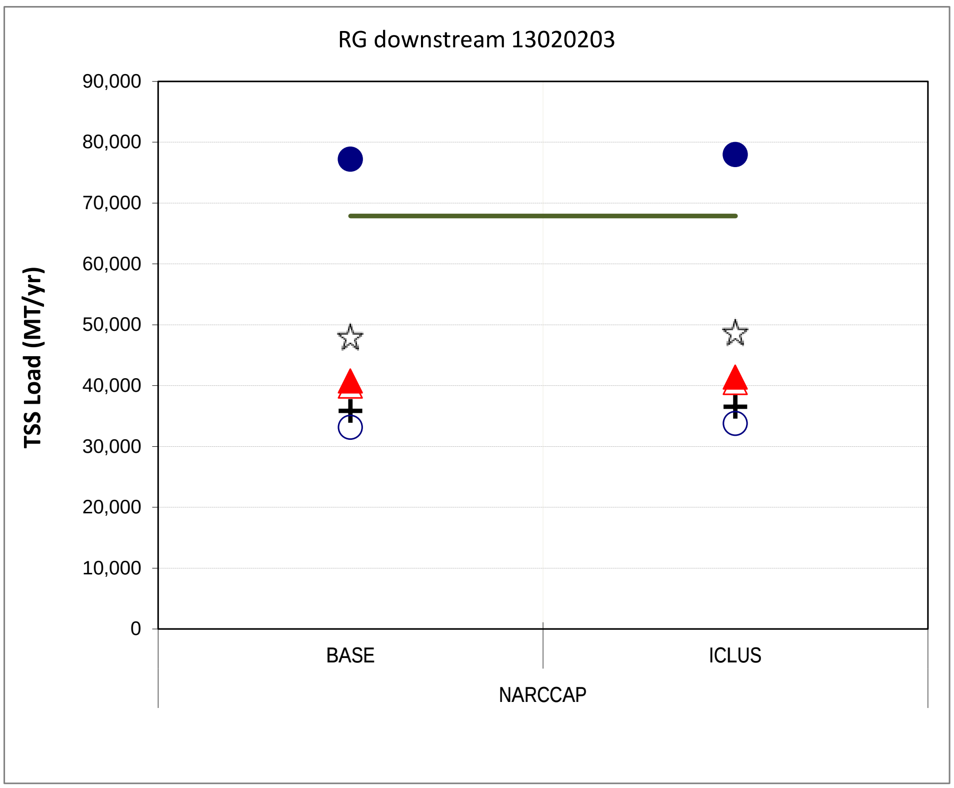


Figure 250. TSS Load (MT/yr), Rio Grande downstream (SWAT)

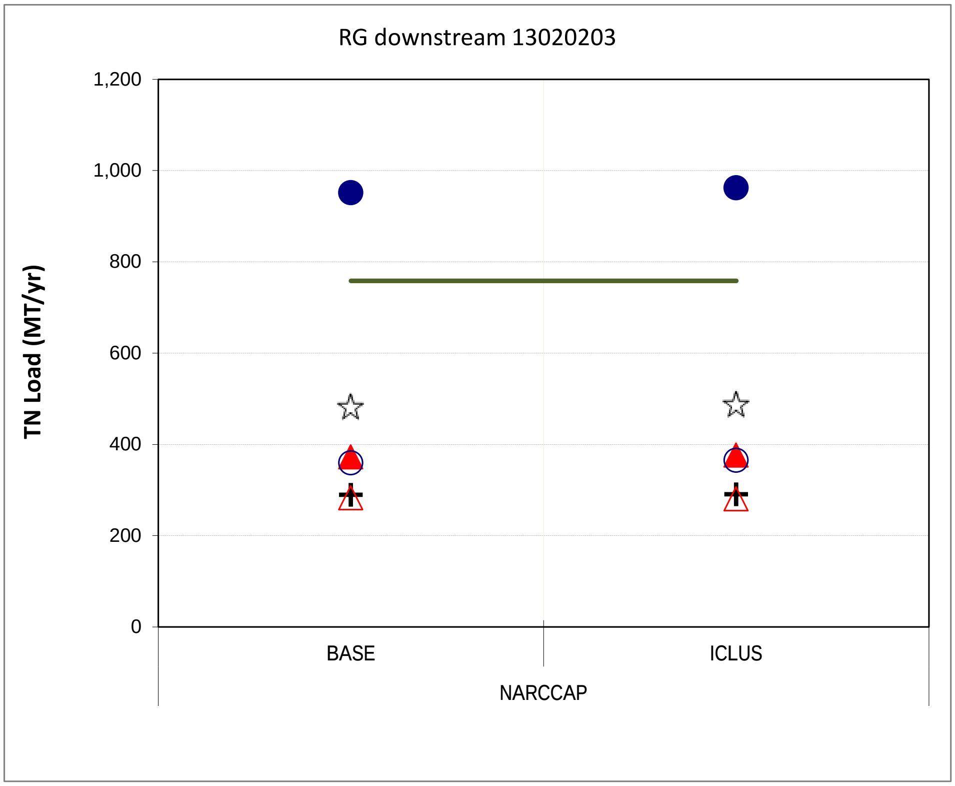


Figure 251. TN Load (MT/yr), Rio Grande downstream (SWAT)

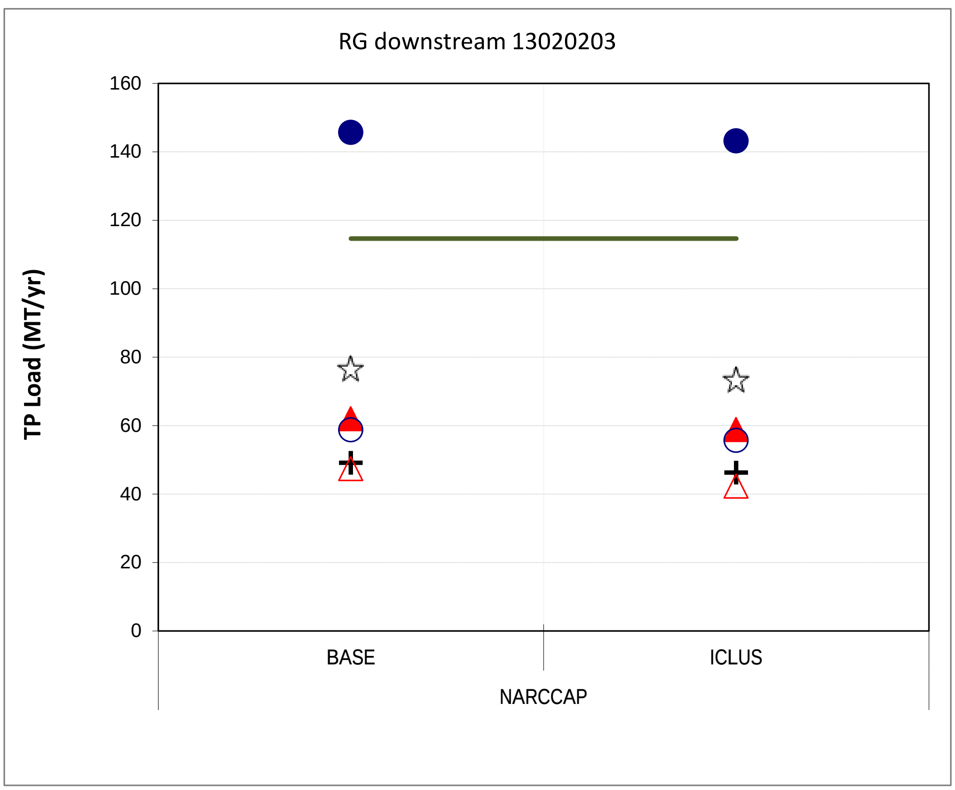


Figure 252. TP Load (MT/yr), Rio Grande downstream (SWAT)

Table 10. Summary of range of change relative to existing conditions for NARCCAP dynamically downscaled scenarios, Rio Grande Valley SWAT model

	Results without LU change				Results with LU change			
	Min	Median	Mean	Max	Min	Median	Mean	Max
Rio Grande Headwaters HUC 13010001								
Flow	-41.70%	-35.70%	-29.64%	9.07%	-41.70%	-35.70%	-29.64%	9.07%
TSS	-63.67%	-50.43%	-42.25%	15.46%	-63.66%	-50.43%	-42.25%	15.46%
TN	-41.87%	-29.09%	-24.31%	5.88%	-41.87%	-29.10%	-24.31%	5.88%
TP	-52.61%	-32.42%	-29.60%	5.96%	-52.58%	-32.41%	-29.59%	5.96%
Alamosa-Trinchera HUC 13010002								
Flow	-40.07%	-36.14%	-27.91%	9.87%	-40.07%	-36.15%	-27.91%	9.87%
TSS	-57.38%	-45.99%	-38.83%	12.28%	-57.33%	-45.97%	-38.80%	12.26%
TN	-71.34%	-58.93%	-41.48%	51.02%	-73.16%	-59.77%	-41.57%	55.40%
TP	-61.33%	-50.08%	-34.79%	46.04%	-65.50%	-52.36%	-36.08%	51.65%
Saguache HUC 13010004								
Flow	-42.18%	-36.97%	-29.84%	8.55%	-42.18%	-36.97%	-29.84%	8.55%
TSS	-62.77%	-38.71%	-36.89%	12.34%	-62.69%	-38.67%	-36.86%	12.32%
TN	-34.54%	-21.18%	-19.94%	4.40%	-34.52%	-21.18%	-19.93%	4.40%
TP	-23.33%	-11.96%	-12.07%	4.13%	-23.38%	-12.10%	-12.14%	4.11%
Conejos HUC13010005								
Flow	-45.38%	-34.01%	-27.42%	9.88%	-45.38%	-34.01%	-27.42%	9.87%
TSS	-42.45%	-35.94%	-32.35%	-10.53%	-39.84%	-34.05%	-30.27%	-9.05%
TN	-78.09%	-60.90%	-45.43%	1.30%	-78.04%	-61.06%	-45.56%	0.42%
TP	-70.37%	-46.54%	-37.75%	8.32%	-70.40%	-46.86%	-37.95%	8.49%
Rio Grande at Otowi Br (Upper RG – HUC 13020101)								
Flow	-38.59%	-33.16%	-24.68%	12.64%	-38.60%	-33.17%	-24.69%	12.64%
TSS	-54.20%	-43.49%	-35.54%	14.20%	-54.11%	-43.43%	-35.48%	14.17%
TN	-63.74%	-51.99%	-40.58%	22.83%	-64.49%	-51.84%	-40.21%	25.09%
TP	-55.72%	-44.23%	-34.55%	22.51%	-59.91%	-45.38%	-35.22%	26.21%
Rio Chama HUC13020102								
Flow	-37.82%	-29.36%	-22.58%	19.86%	-37.83%	-29.37%	-22.58%	19.86%
TSS	-25.35%	-18.19%	-12.24%	22.72%	-25.34%	-18.19%	-12.25%	22.65%
TN	-48.02%	-35.10%	-27.69%	16.32%	-47.94%	-35.11%	-27.72%	16.26%
TP	-41.88%	-28.21%	-22.28%	22.51%	-41.81%	-28.20%	-22.29%	22.39%
Rio Grande-Santa Fe HUC 13020201								
Flow	-37.74%	-32.46%	-23.89%	12.53%	-37.76%	-32.48%	-23.90%	12.53%
TSS	-53.44%	-43.76%	-34.99%	14.55%	-53.24%	-43.61%	-34.84%	14.48%
TN	-63.48%	-52.32%	-40.32%	25.45%	-63.86%	-51.88%	-39.80%	27.72%
TP	-58.17%	-47.21%	-36.06%	26.77%	-61.85%	-47.93%	-36.38%	30.85%
Jemez HUC 13020202								
Flow	-31.19%	-15.25%	-13.97%	11.66%	-31.23%	-15.28%	-13.98%	11.68%
TSS	-60.50%	-32.22%	-28.38%	3.78%	-59.73%	-31.87%	-28.05%	3.53%

	Results without LU change				Results with LU change			
	Min	Median	Mean	Max	Min	Median	Mean	Max
TN	-10.06%	1.78%	6.61%	45.15%	-12.22%	1.09%	0.21%	6.36%
TP	-19.00%	-0.67%	-4.09%	5.32%	-10.21%	0.50%	-0.76%	5.17%
Rio Grande Albuquerque (downstream) HUC 13020203								
Flow	-34.27%	-29.35%	-21.38%	11.94%	-34.26%	-29.35%	-21.38%	11.92%
TSS	-51.16%	-40.58%	-32.46%	13.77%	-50.78%	-40.32%	-32.21%	13.63%
TN	-62.68%	-51.75%	-39.76%	25.50%	-62.85%	-50.88%	-38.95%	27.46%
TP	-58.63%	-47.32%	-36.02%	27.09%	-61.33%	-47.61%	-35.97%	30.97%
Saguache Creek HUC 13010004								
Flow	-40.98%	-35.20%	-29.12%	7.83%	-40.98%	-35.20%	-29.12%	7.83%
TSS	-70.73%	-47.18%	-43.79%	2.23%	-70.73%	-47.18%	-43.79%	2.23%
TN	-34.66%	-26.24%	-21.98%	3.51%	-34.66%	-26.24%	-21.98%	3.51%
TP	-35.28%	-21.06%	-20.06%	3.34%	-35.28%	-21.06%	-20.06%	3.34%
RG near Lobatos (gage 08251500)								
Flow	-40.04%	-36.01%	-27.86%	9.81%	-40.04%	-36.01%	-27.86%	9.81%
TSS	-57.43%	-45.68%	-38.80%	12.26%	-57.38%	-45.66%	-38.77%	12.25%
TN	-70.93%	-58.84%	-41.24%	51.49%	-72.92%	-59.72%	-41.37%	55.93%
TP	-60.88%	-49.85%	-34.42%	45.97%	-64.89%	-52.14%	-35.75%	51.63%
RG near Taos (gage 08276500)								
Flow	-39.40%	-34.47%	-25.67%	11.72%	-39.40%	-34.47%	-25.67%	11.72%
TSS	-56.65%	-45.24%	-37.43%	13.35%	-56.60%	-45.21%	-37.40%	13.33%
TN	-67.53%	-54.17%	-41.83%	26.31%	-68.66%	-54.18%	-41.63%	28.55%
TP	-57.67%	-45.76%	-35.16%	25.51%	-62.55%	-47.22%	-36.14%	29.20%
RG at Albuquerque (gage 08330000)								
Flow	-36.80%	-31.36%	-22.95%	12.68%	-36.79%	-31.37%	-22.95%	12.66%
TSS	-52.87%	-41.39%	-33.72%	13.67%	-52.56%	-41.18%	-33.52%	13.57%
TN	-61.72%	-51.00%	-39.20%	25.36%	-62.24%	-50.29%	-38.57%	27.44%
TP	-57.89%	-46.82%	-35.70%	26.81%	-61.16%	-47.29%	-35.83%	30.90%

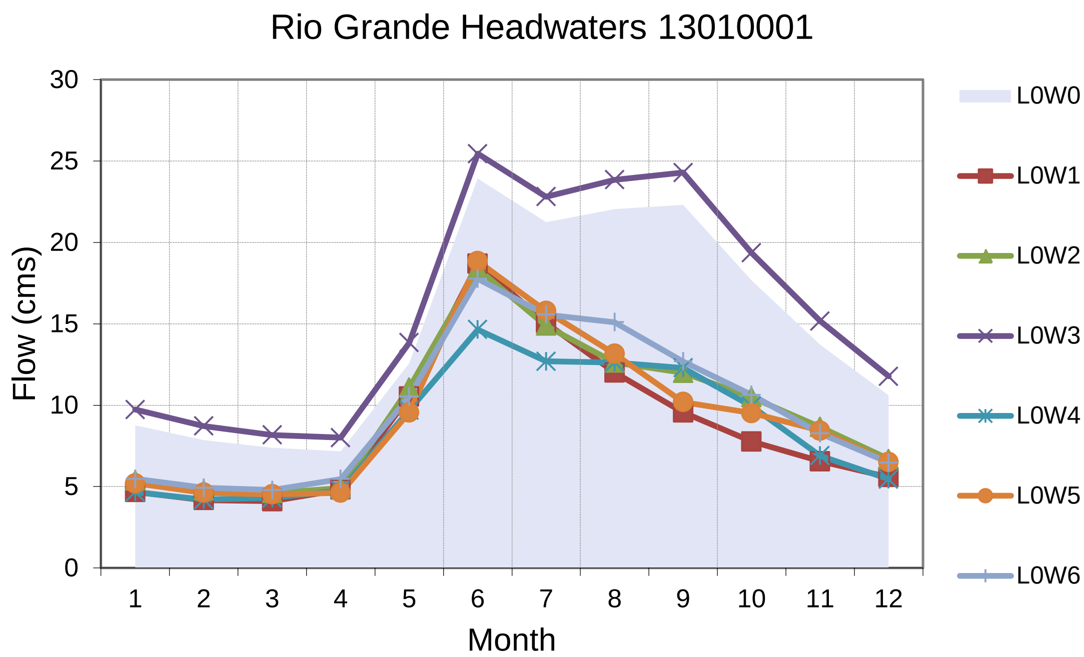


Figure 253. **Monthly average flows, Rio Grande Headwaters (SWAT)**

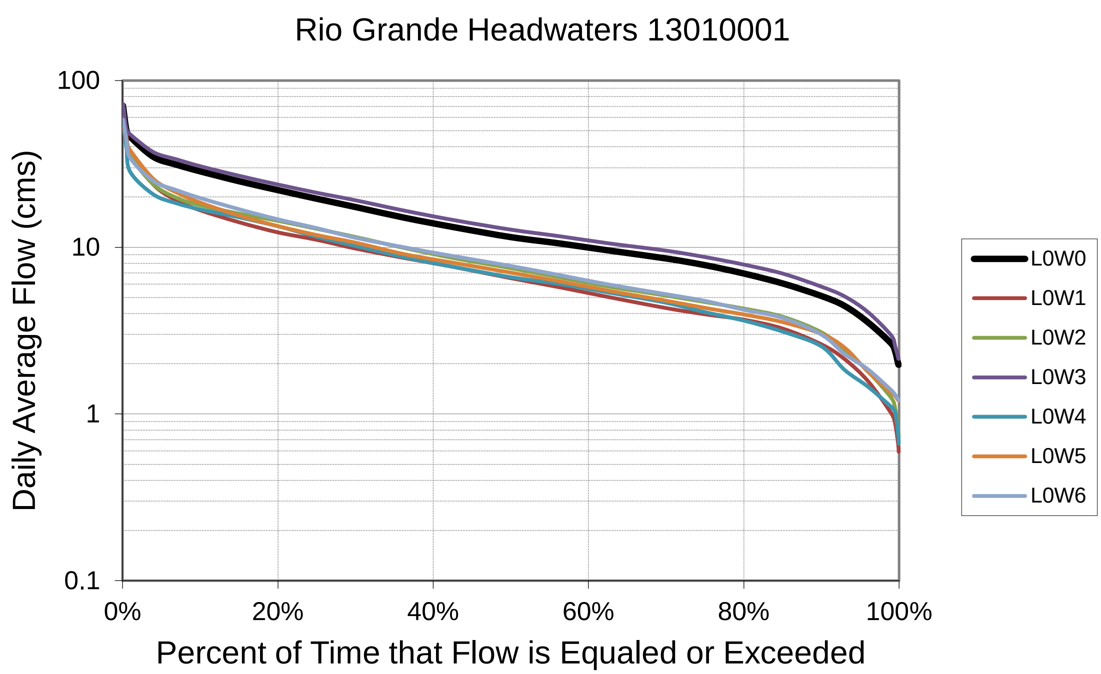


Figure 254. **Flow duration, Rio Grande Headwaters (SWAT)**

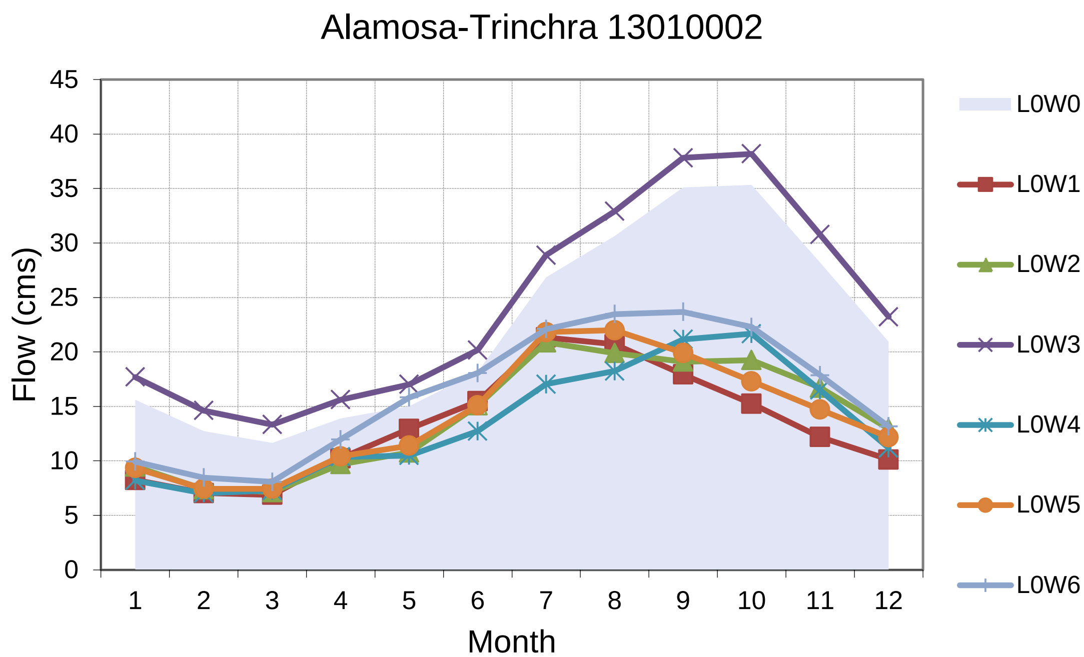


Figure 255. Monthly average flows, Alamosa River (SWAT)

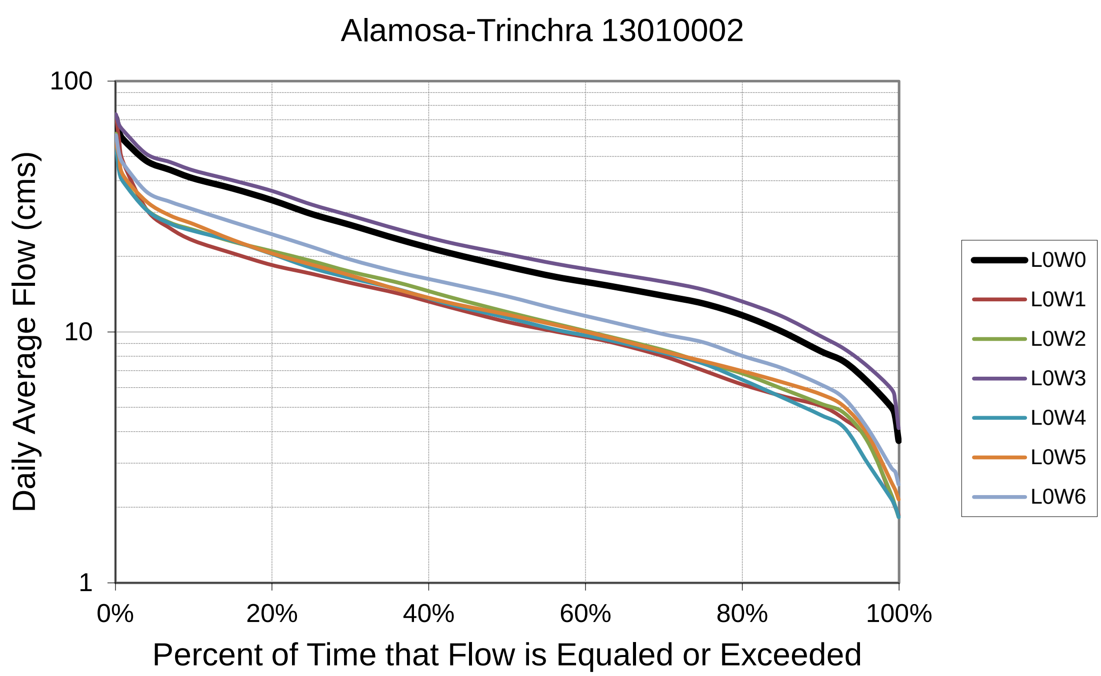


Figure 256. Flow duration, Alamosa River (SWAT)

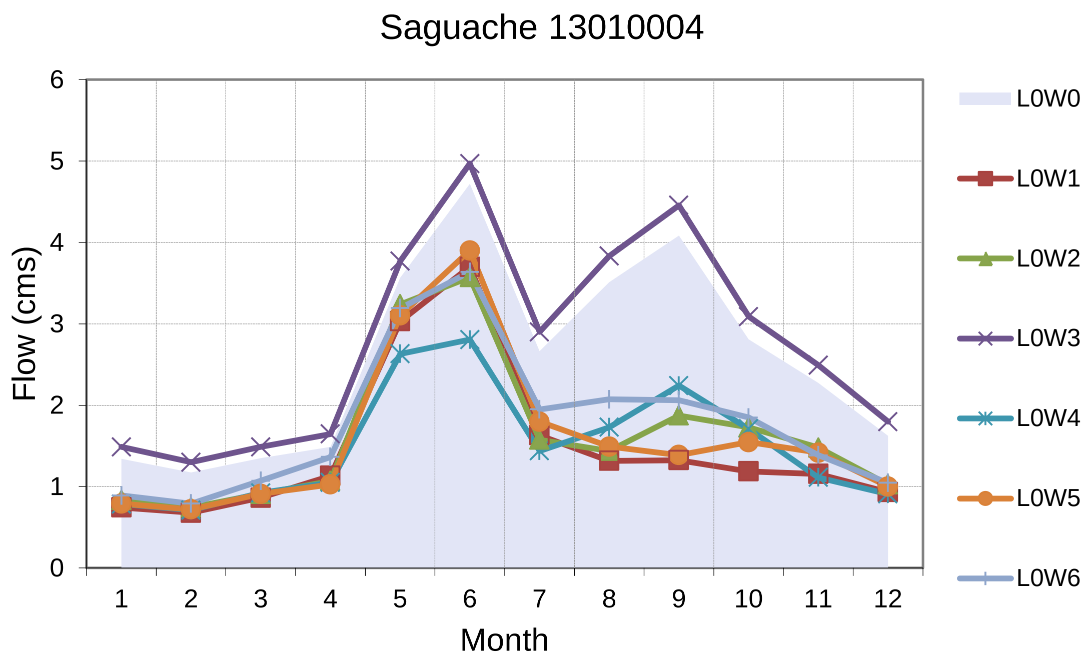


Figure 257. **Monthly average flows, Saguache River (SWAT)**

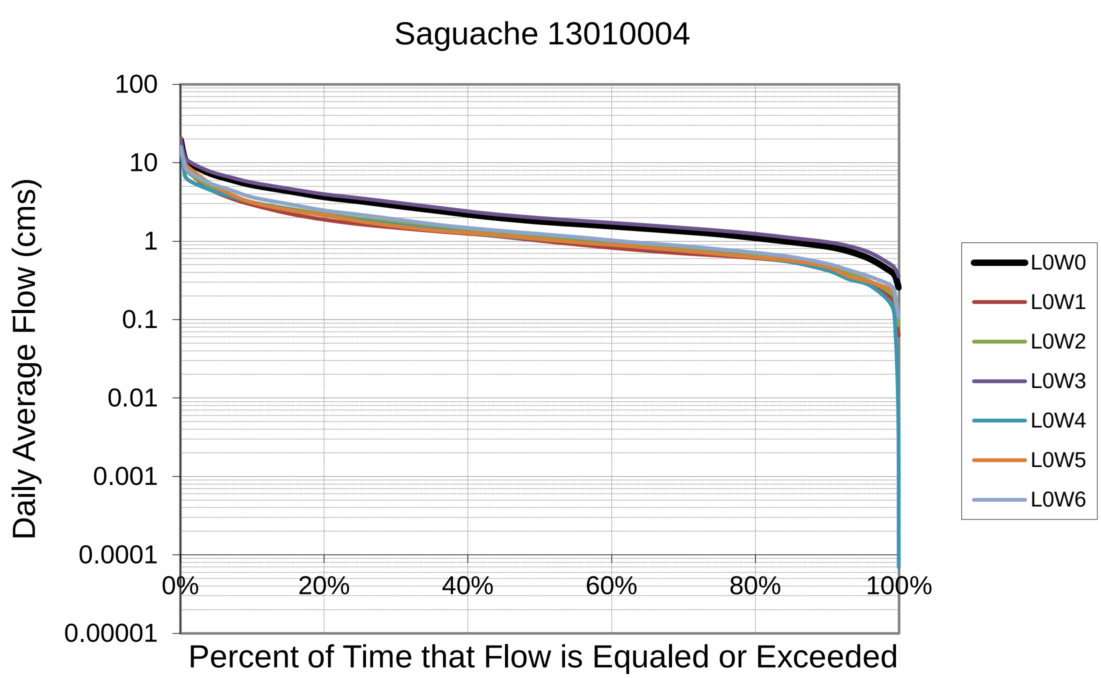


Figure 258. **Flow duration, Saguache River (SWAT)**

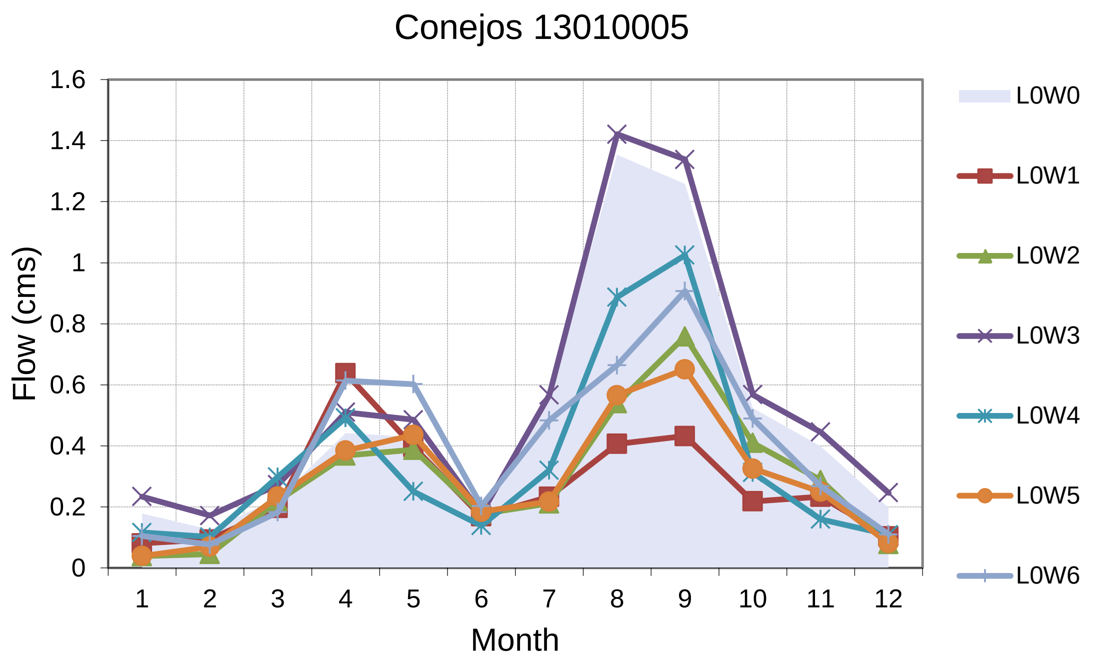


Figure 259. **Monthly average flows, Conejos River (SWAT)**

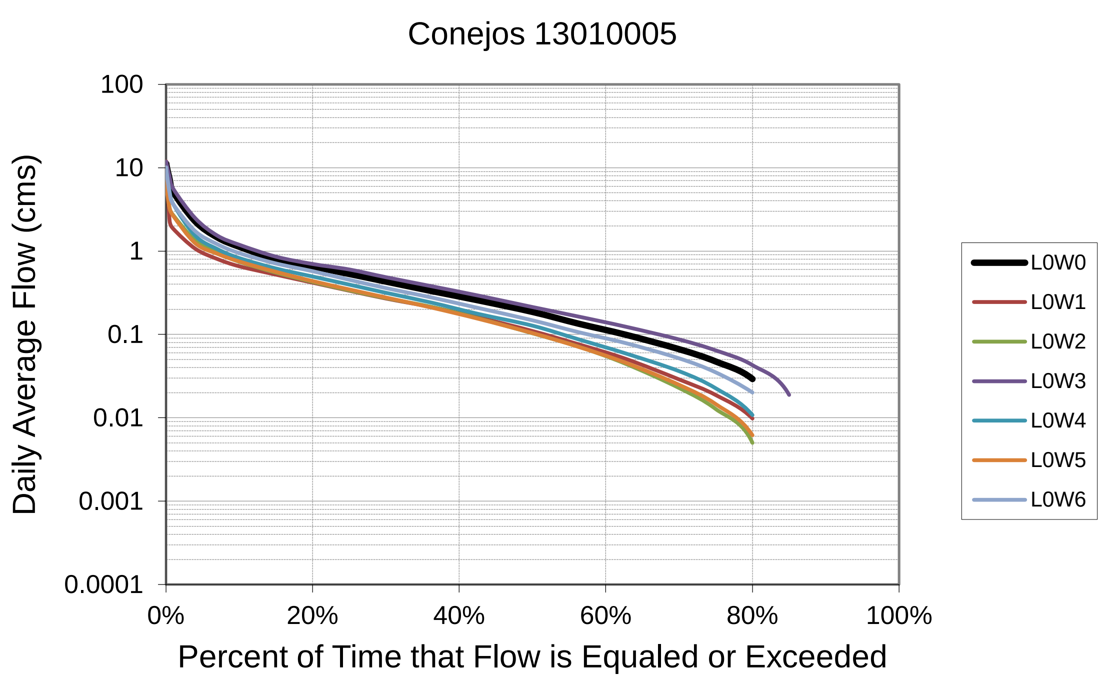


Figure 260. **Flow duration, Conejos River (SWAT)**

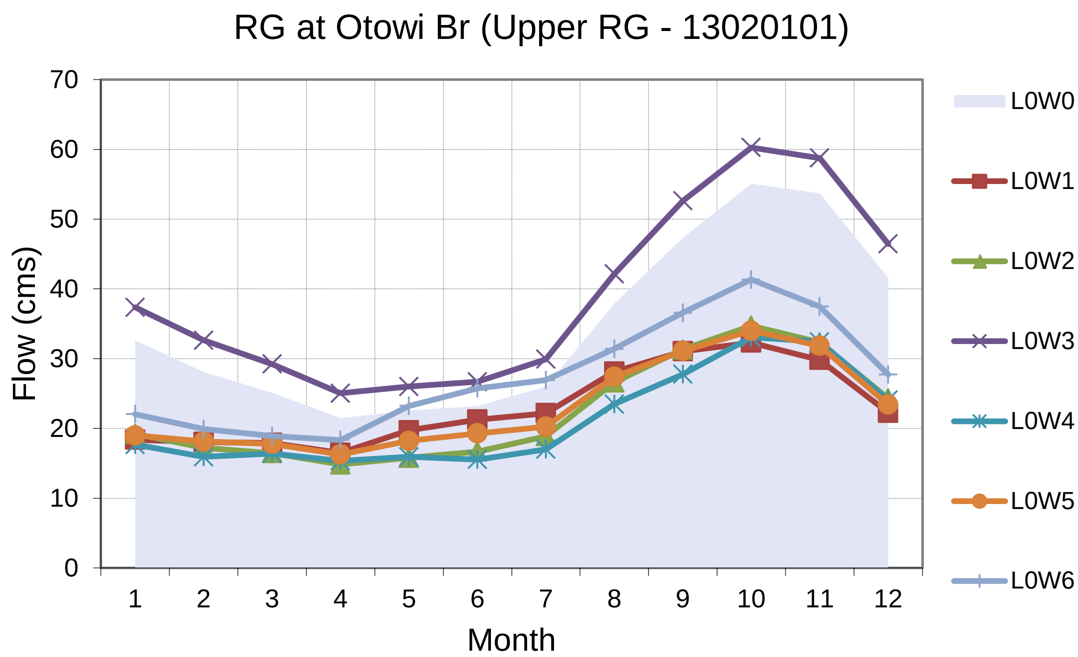


Figure 261. **Monthly average flows, Upper Rio Grande at Otowi Bridge (SWAT)**

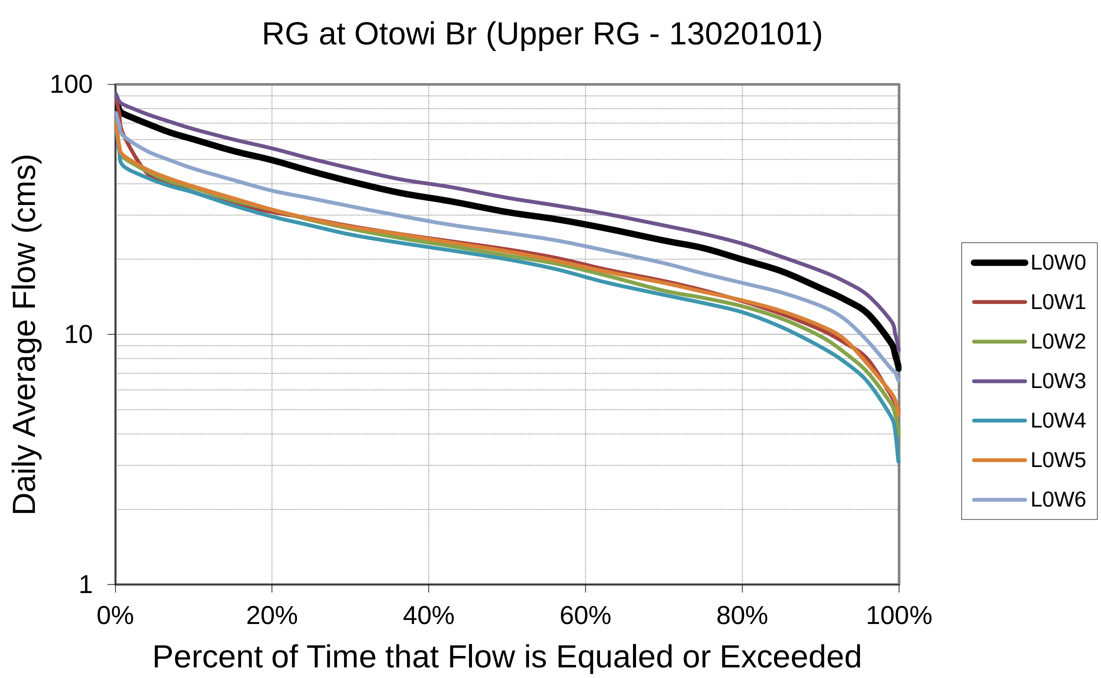


Figure 262. **Flow duration, Upper Rio Grande at Otowi Bridge (SWAT)**

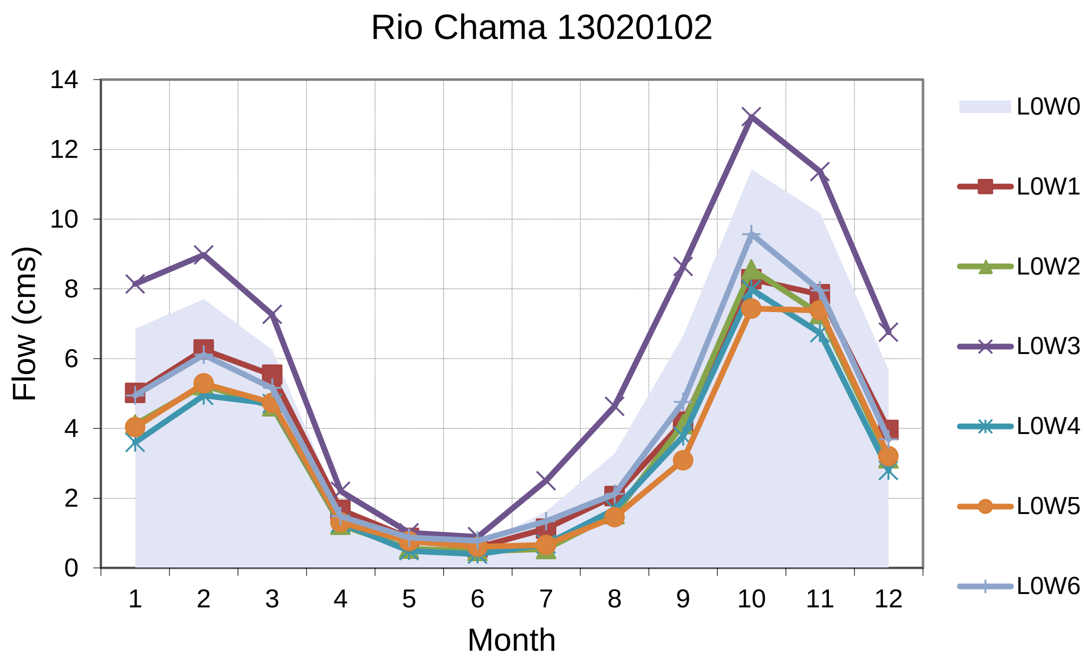


Figure 263. **Monthly average flows, Rio Chama (SWAT)**

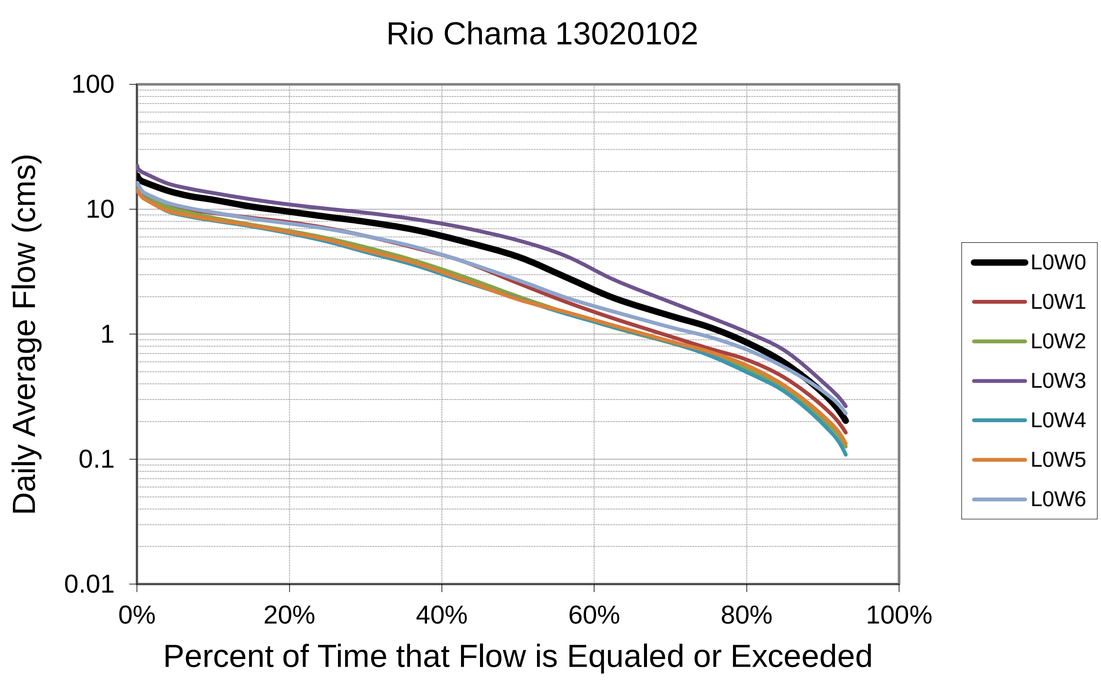


Figure 264. **Flow duration, Rio Chama (SWAT)**

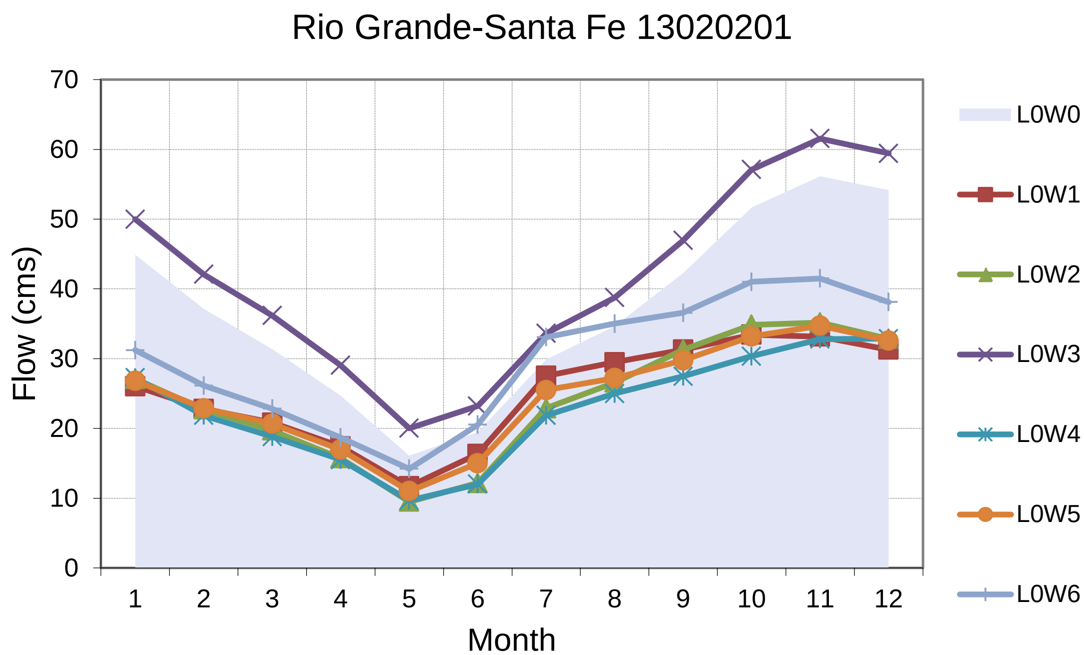


Figure 265. **Monthly average flows, Rio Grande at Santa Fe (SWAT)**

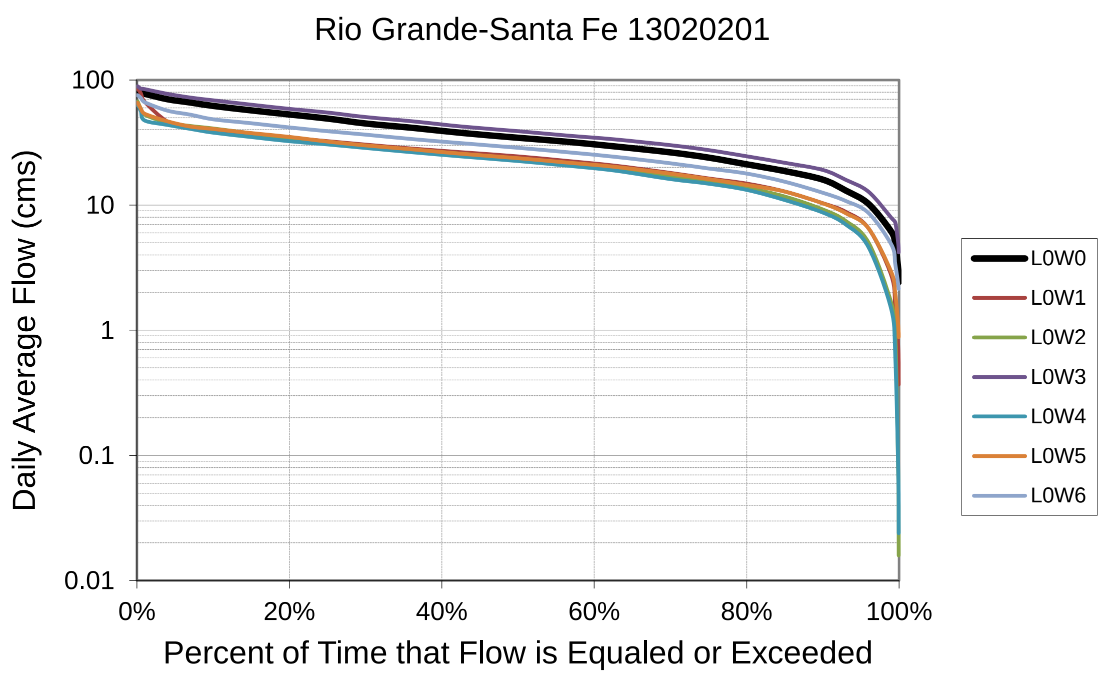


Figure 266. **Flow duration, Rio Grande at Santa Fe (SWAT)**

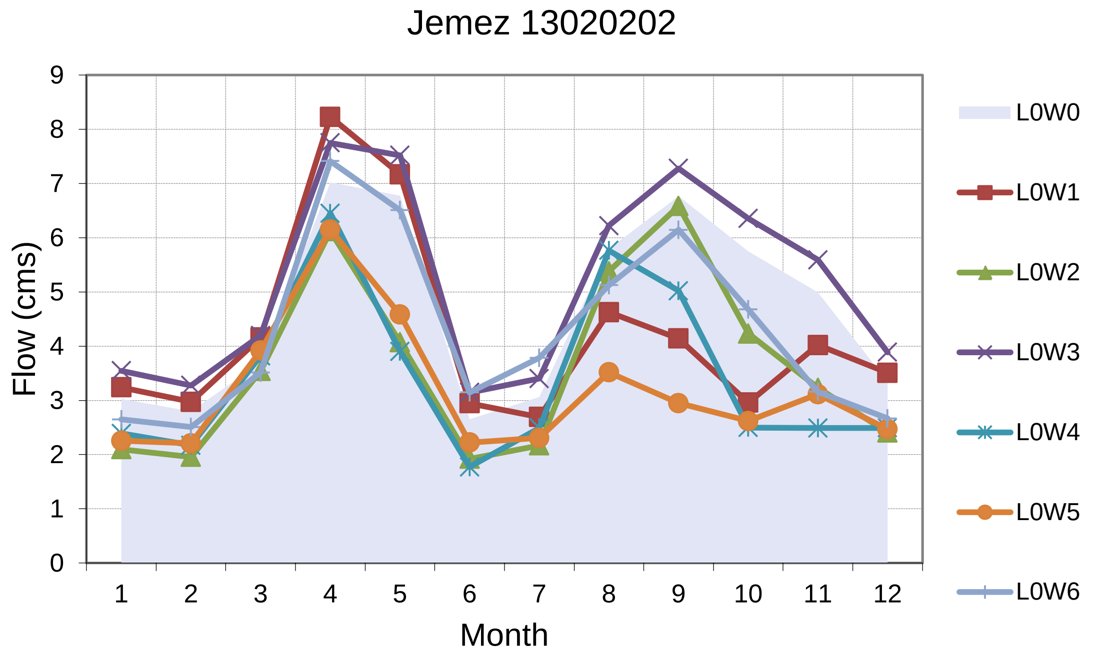


Figure 267. Monthly average flows, Jemez River (SWAT)

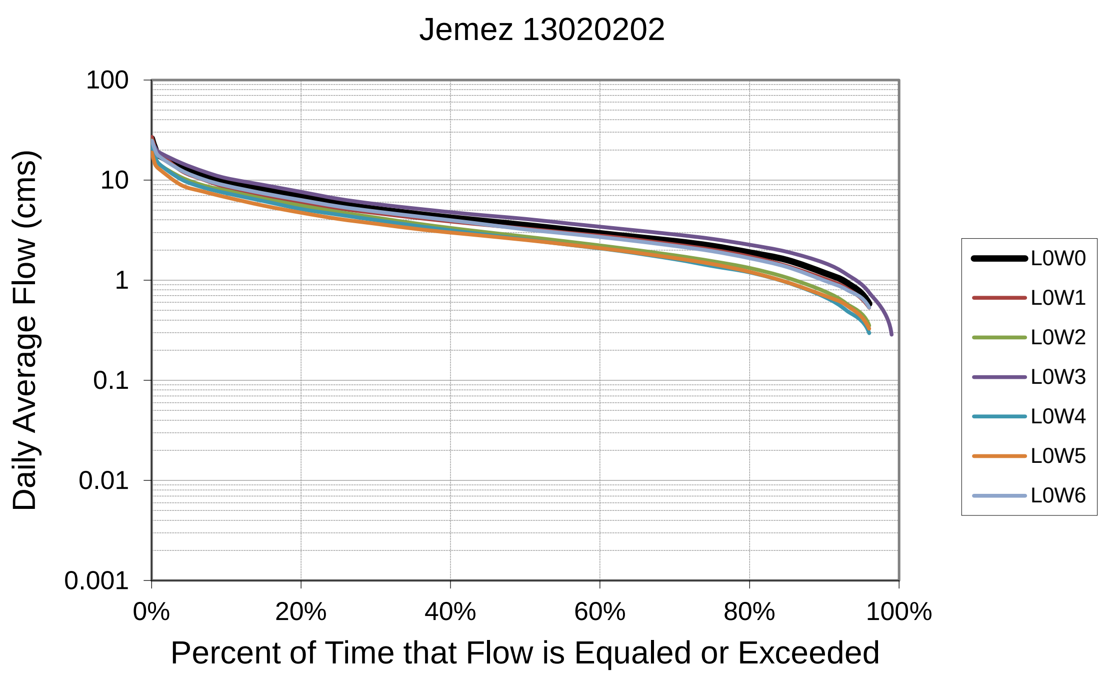


Figure 268. Flow duration, Jemez River (SWAT)

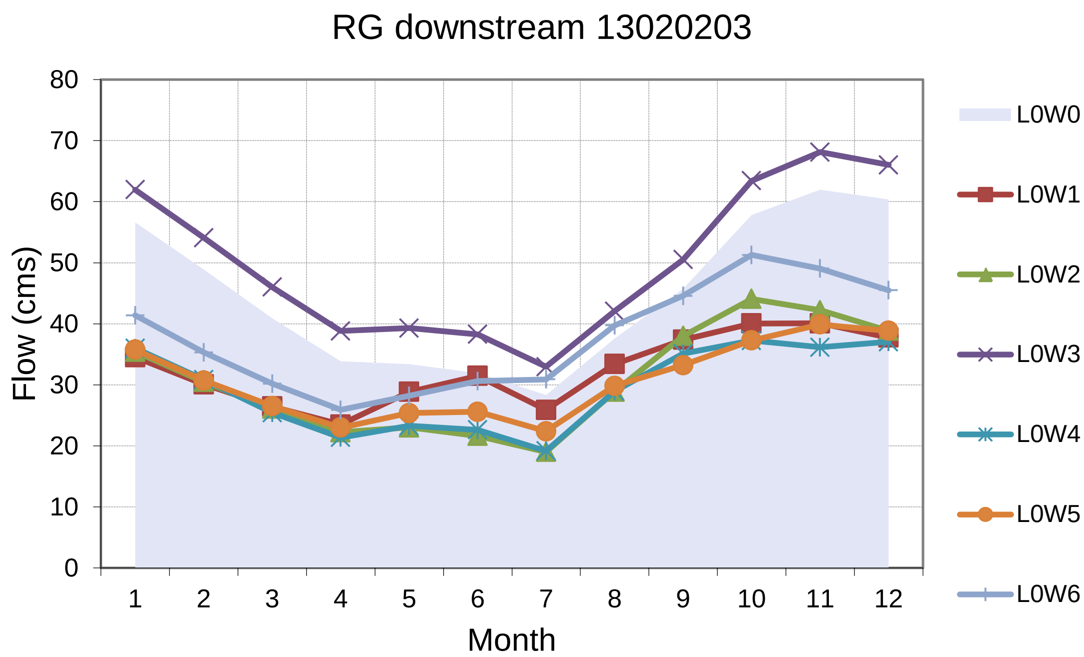


Figure 269. **Monthly average flows, Rio Grande downstream (SWAT)**

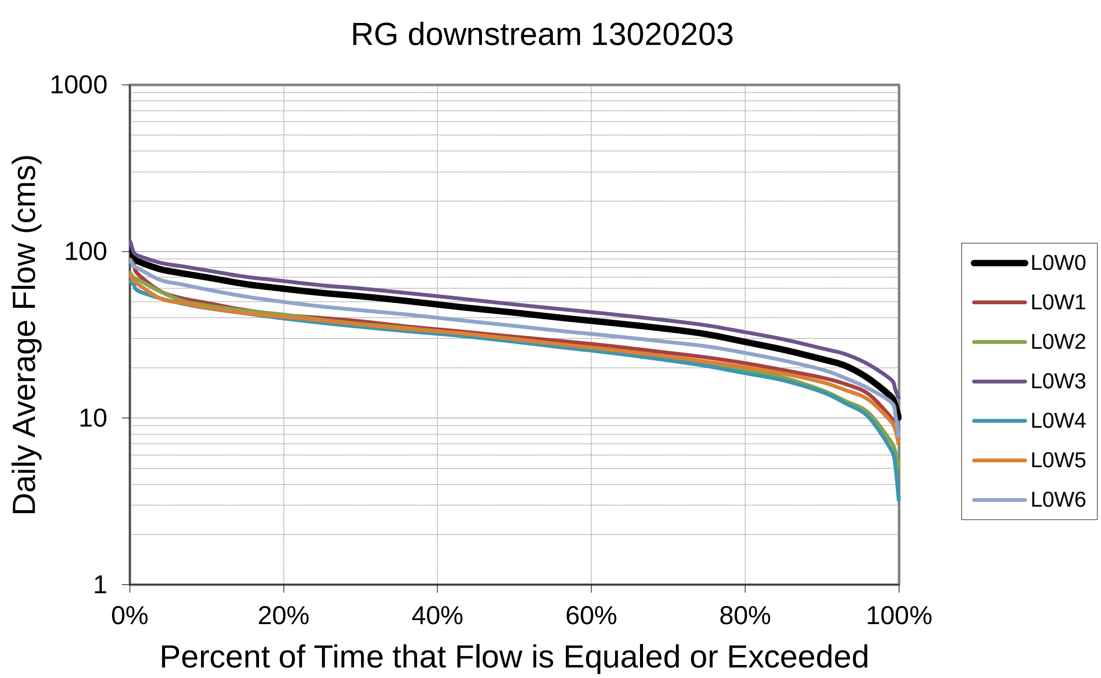


Figure 270. **Flow duration, Rio Grande downstream (SWAT)**

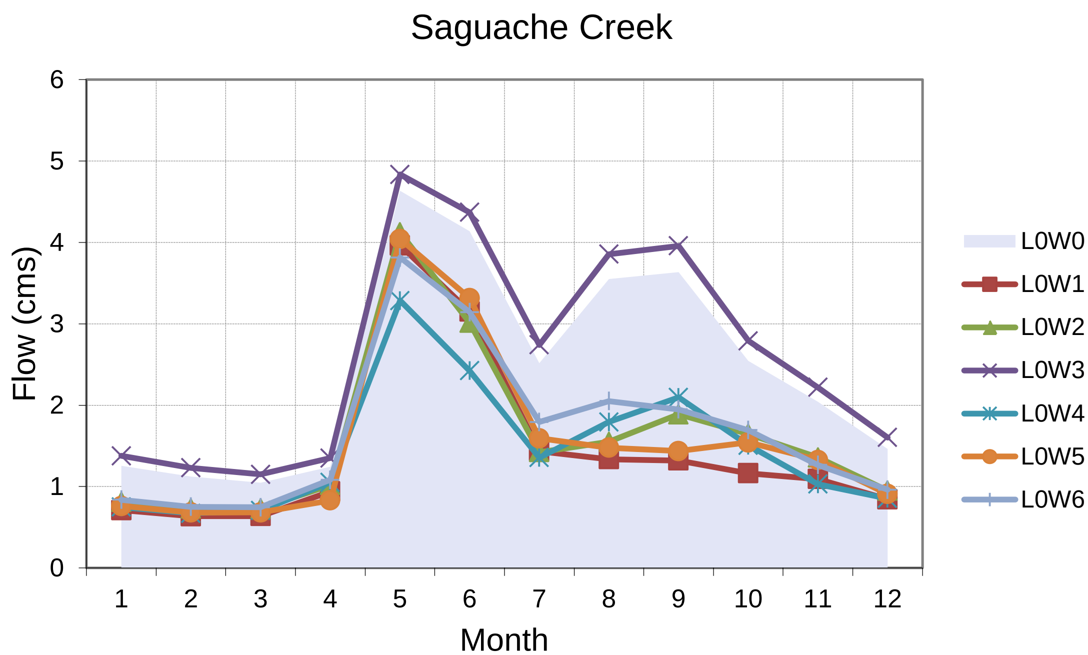


Figure 271. Monthly average flows, Saguache Creek (SWAT)

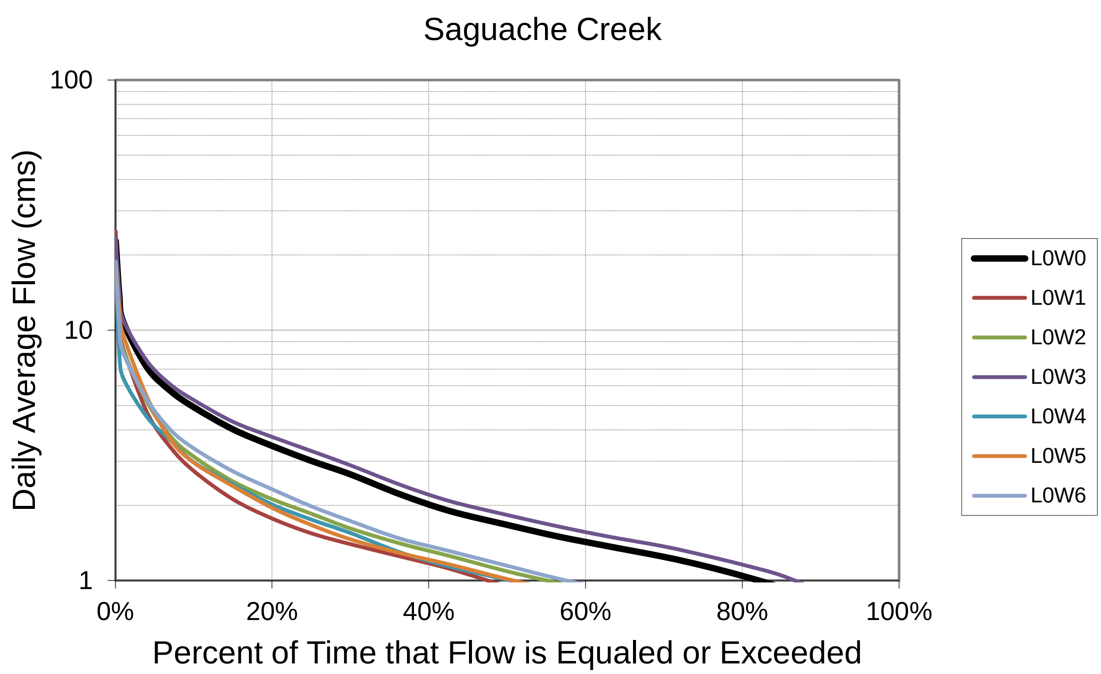


Figure 272. Flow duration, Saguache Creek (SWAT)

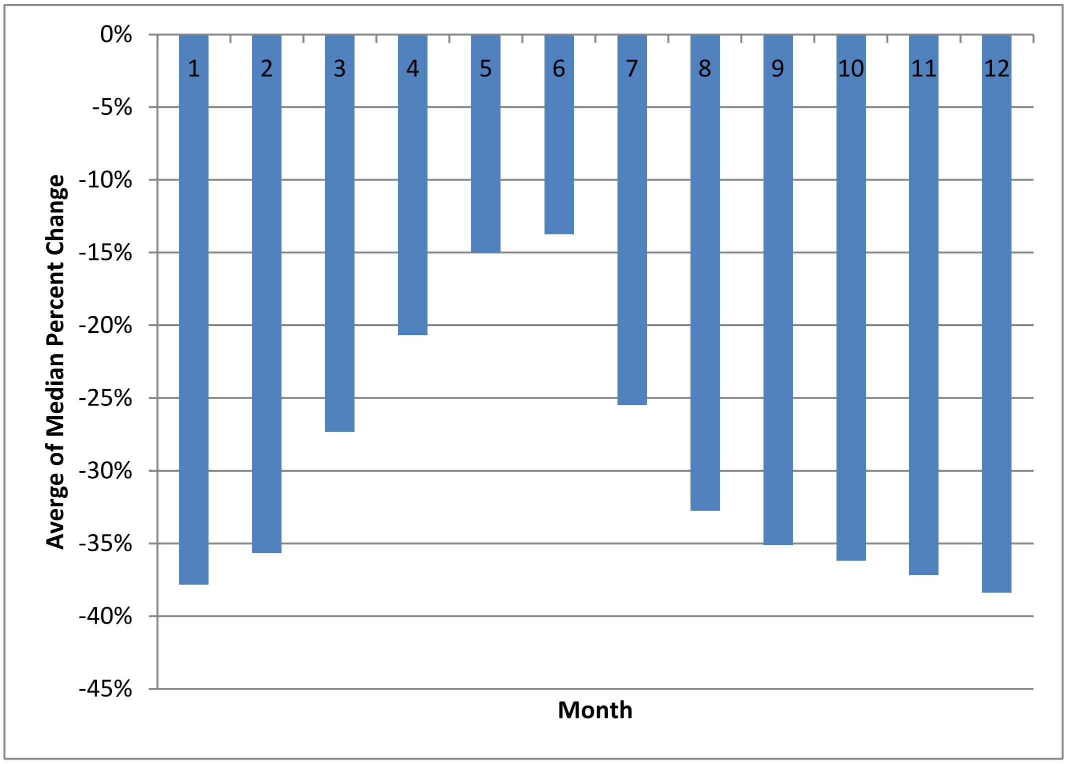


Figure 273. Average of median percent change in flow; NARCCAP Scenarios W1-W6 at all stations, Rio Grande Valley (SWAT)

Sacramento River Watershed

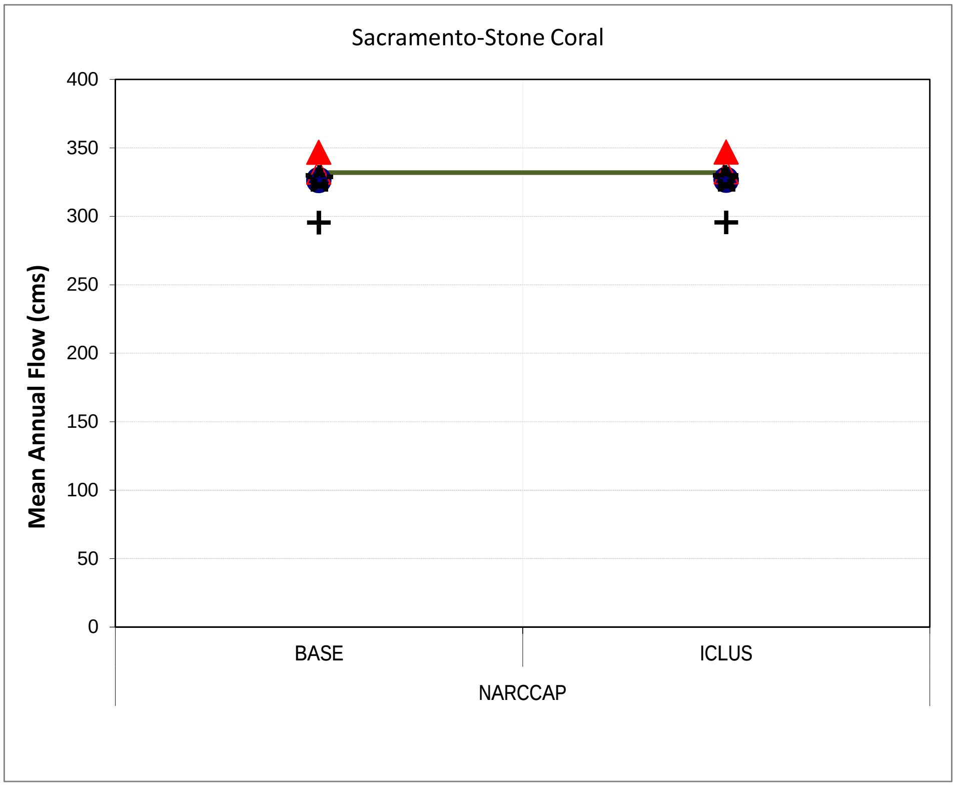


Figure 274. Mean annual flow (cms), Sacramento River at Stone Corral (SWAT)

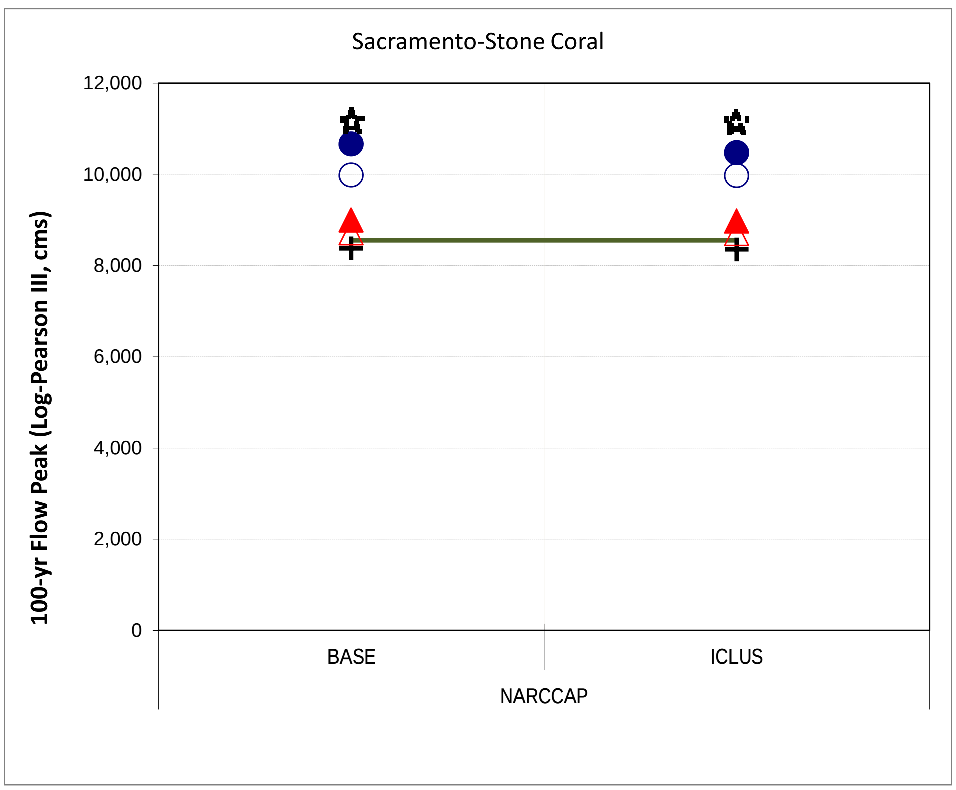


Figure 275. 100-yr Flow Peak (Log-Pearson III, cms), Sacramento River at Stone Corral (SWAT)

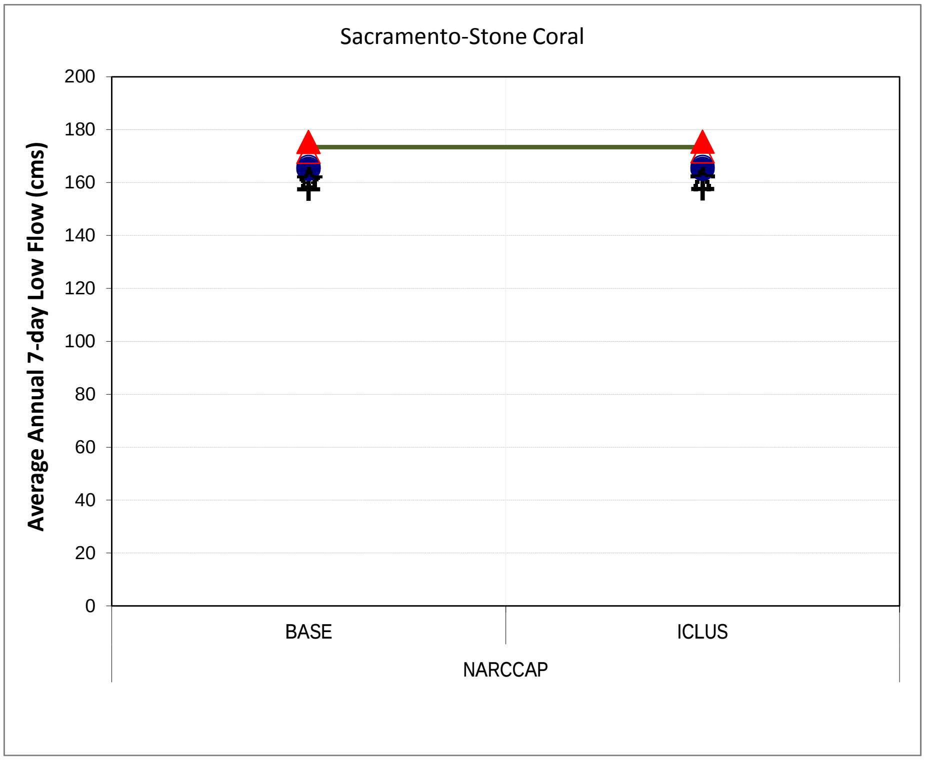


Figure 276. **Average Annual 7-day Low Flow (cms), Sacramento River at Stone Corral (SWAT)**

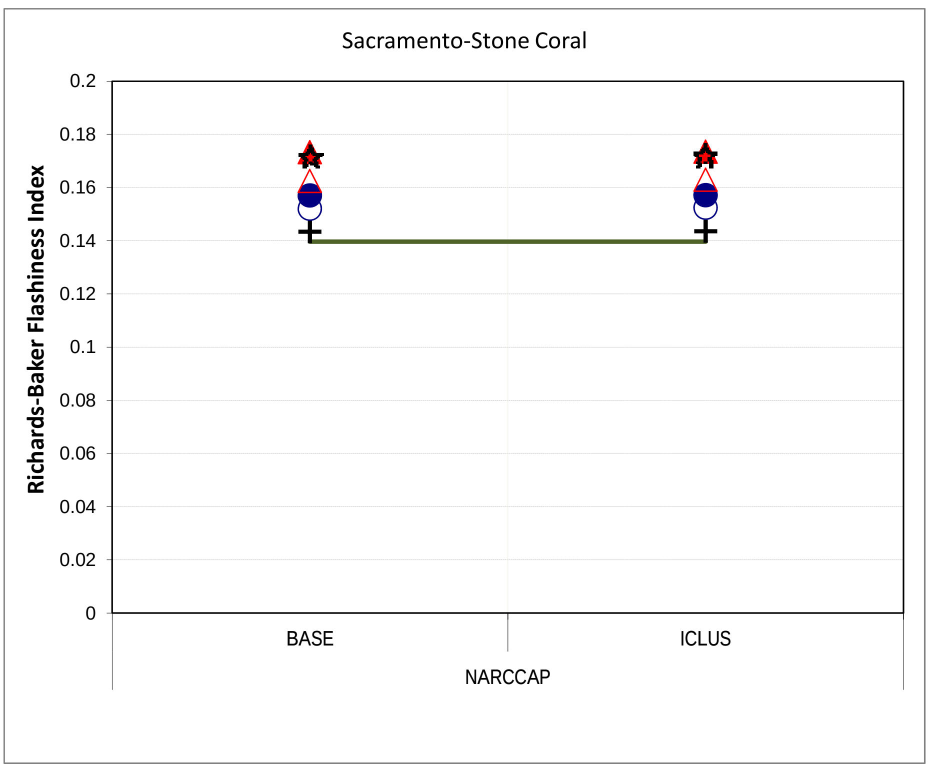


Figure 277. Richards-Baker Flashiness Index, Average Annual 7-day Low Flow (cms), Sacramento River at Stone Corral (SWAT)

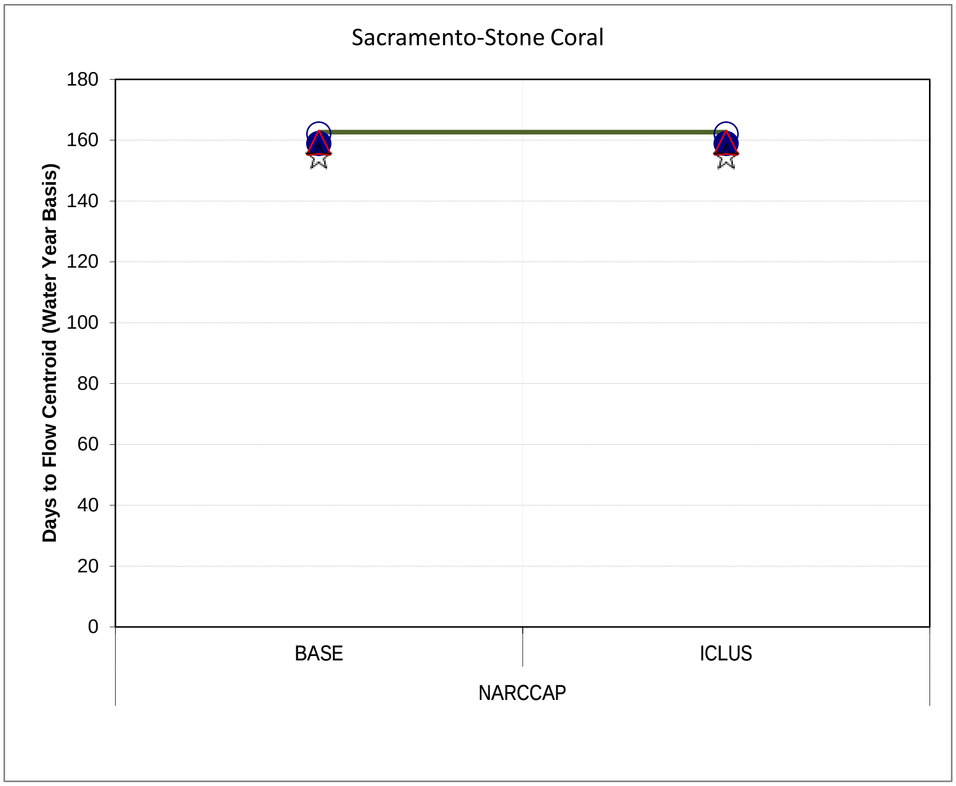


Figure 278. Days to Flow Centroid (Water Year Basis), Sacramento River at Stone Corral (SWAT)

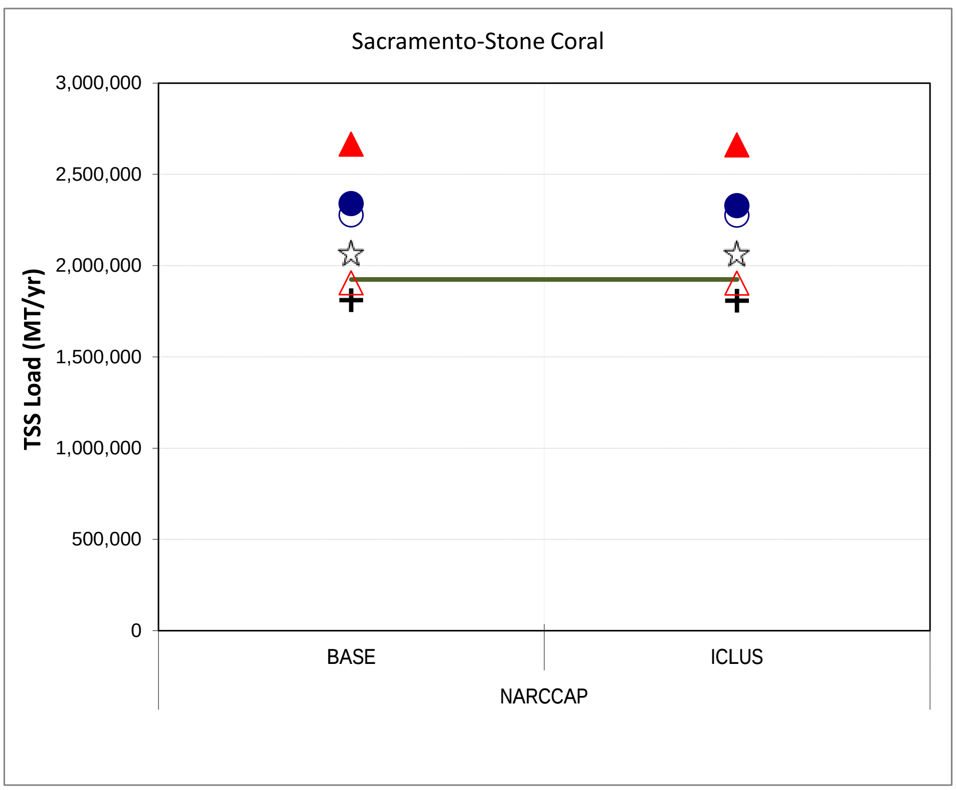


Figure 279. TSS Load (MT/yr), Sacramento River at Stone Corral (SWAT)

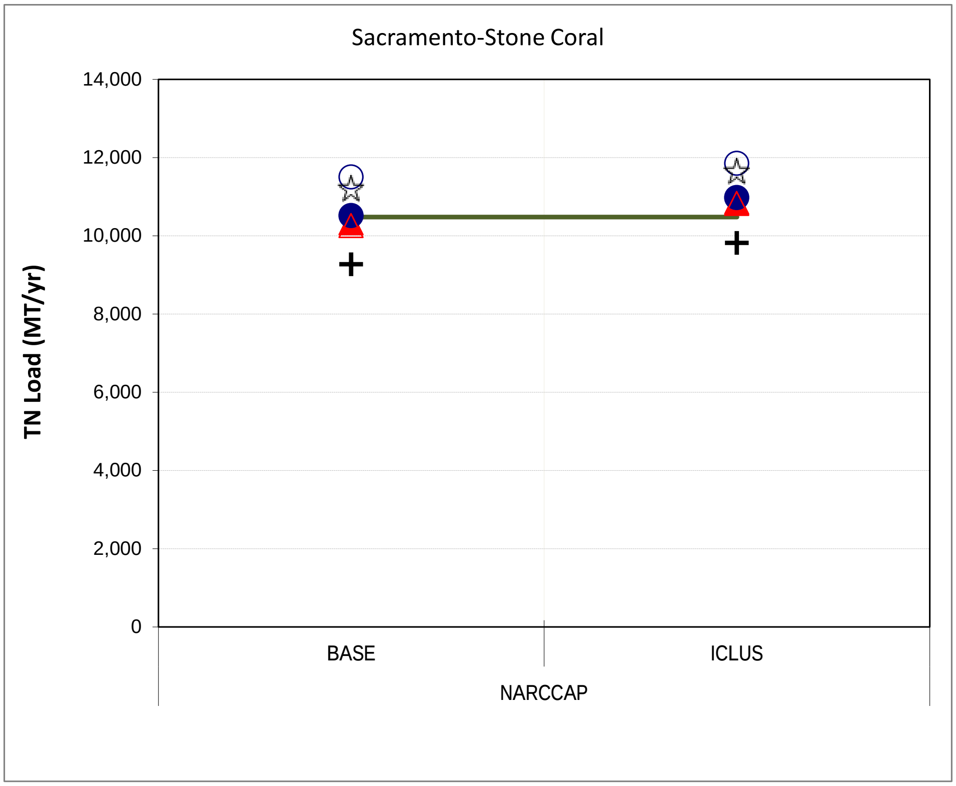


Figure 280. **TN Load (MT/yr), Sacramento River at Stone Corral (SWAT)**

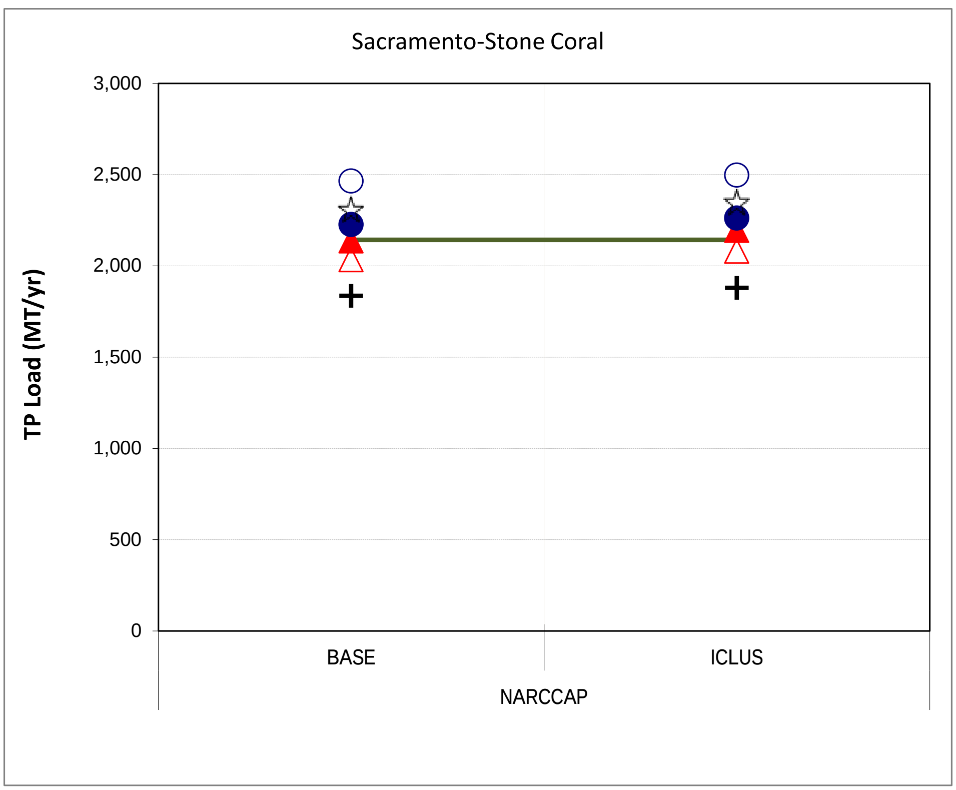


Figure 281. **TP Load (MT/yr), Sacramento River at Stone Corral (SWAT)**

Table 11. Summary of range of change relative to existing conditions for NARCCAP dynamically downscaled scenarios, Sacramento River watershed SWAT model

	Results without LU change				Results with LU change			
	Min	Median	Mean	Max	Min	Median	Mean	Max
Sacramento-Stone Corral HUC 18020104								
Flow	-11.03%	-1.23%	-1.80%	4.45%	-11.05%	-1.25%	-1.82%	4.41%
TSS	-5.89%	13.09%	13.25%	38.51%	-5.76%	13.33%	13.38%	38.72%
TN	-11.49%	-0.49%	0.42%	9.80%	-10.50%	-0.46%	0.31%	8.08%
TP	-14.30%	1.78%	1.18%	14.99%	-14.08%	1.83%	1.06%	14.14%
Lower Cow HUC 18020101 (Bend Bridge)								
Flow	-5.09%	-0.95%	-1.28%	1.76%	-5.09%	-0.94%	-1.27%	1.76%
TSS	-10.94%	-1.09%	1.53%	20.73%	-10.89%	-0.82%	1.72%	20.78%
TN	3.12%	6.47%	5.95%	9.12%	2.46%	5.85%	5.57%	8.62%
TP	1.00%	7.26%	6.24%	10.78%	0.44%	7.13%	5.97%	10.27%
Lower Cottonwood HUC 18020102								
Flow	-16.68%	-2.01%	-4.01%	5.32%	-16.68%	-2.01%	-4.02%	5.31%
TSS	-15.40%	4.05%	3.22%	18.85%	-15.36%	4.07%	3.22%	18.80%
TN	3.76%	10.14%	12.05%	27.24%	3.62%	10.07%	11.96%	26.97%
TP	-2.35%	7.52%	8.98%	24.84%	-2.20%	7.52%	8.96%	24.61%
Sacramento-Lower Thomes HUC 18020103								
Flow	-10.37%	-1.24%	-1.77%	4.18%	-10.38%	-1.24%	-1.77%	4.16%
TSS	-1.83%	16.40%	16.85%	43.90%	-1.54%	16.67%	17.10%	44.16%
TN	-11.31%	-1.74%	-0.43%	9.19%	-10.33%	-1.68%	-0.43%	7.88%
TP	-14.39%	0.25%	-0.21%	14.44%	-14.27%	0.16%	-0.27%	14.02%
Lower Butte HUC 18020105								
Flow	-20.79%	-1.86%	-3.05%	8.08%	-20.94%	-2.09%	-3.28%	7.80%
TSS	-30.11%	6.33%	3.17%	24.54%	-30.00%	7.06%	3.71%	24.88%
TN	-16.48%	3.62%	2.23%	15.25%	-15.09%	1.49%	1.84%	18.61%
TP	-13.12%	7.94%	6.42%	19.27%	-12.03%	5.69%	5.81%	22.50%
Upper Stony HUC 18020115								
Flow	-14.78%	3.16%	1.86%	10.29%	-14.76%	3.18%	1.88%	10.32%
TSS	-4.98%	47.36%	43.92%	68.51%	-4.98%	47.34%	43.91%	68.49%
TN	5.30%	31.33%	29.96%	48.92%	4.87%	30.64%	29.28%	47.91%
TP	16.29%	58.23%	55.38%	91.07%	15.67%	57.29%	54.50%	89.89%
Upper Cow HUC 18020118								
Flow	-14.84%	-6.38%	-5.66%	3.04%	-14.81%	-6.35%	-5.63%	3.06%
TSS	-35.74%	-17.12%	-11.08%	19.48%	-35.73%	-17.15%	-11.11%	19.44%
TN	-11.70%	-4.16%	-3.37%	5.96%	-14.94%	-9.06%	-8.87%	-2.00%
TP	-18.32%	-9.79%	-9.29%	-1.08%	-19.03%	-11.34%	-10.47%	-2.76%
Sacramento River, Keswick gage								
Flow	-0.31%	-0.09%	-0.11%	0.04%	-0.31%	-0.09%	-0.12%	0.04%
TSS	-14.51%	3.16%	2.19%	14.94%	-14.13%	3.52%	2.56%	15.33%

	Results without LU change				Results with LU change			
	Min	Median	Mean	Max	Min	Median	Mean	Max
TN	-0.40%	0.23%	0.19%	0.49%	-0.63%	0.20%	0.07%	0.31%
TP	-0.80%	0.26%	0.18%	0.73%	-1.21%	0.14%	-0.03%	0.39%

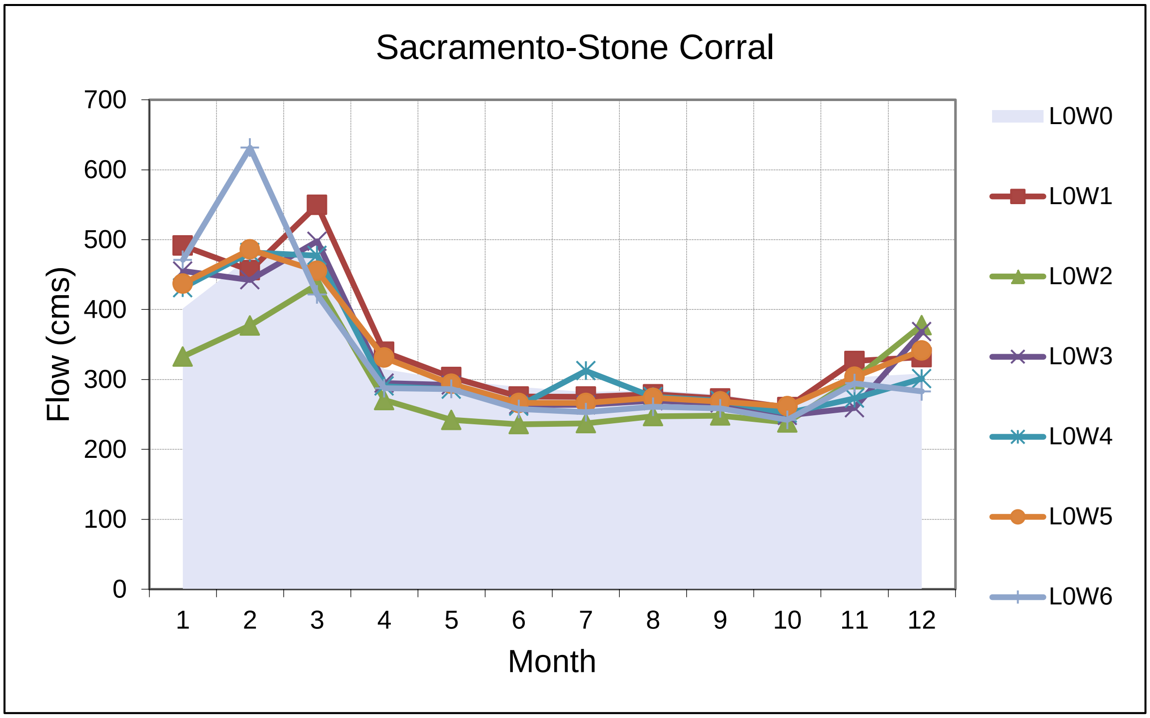


Figure 282. **Monthly average flows, Sacramento River at Stone Corral (SWAT)**

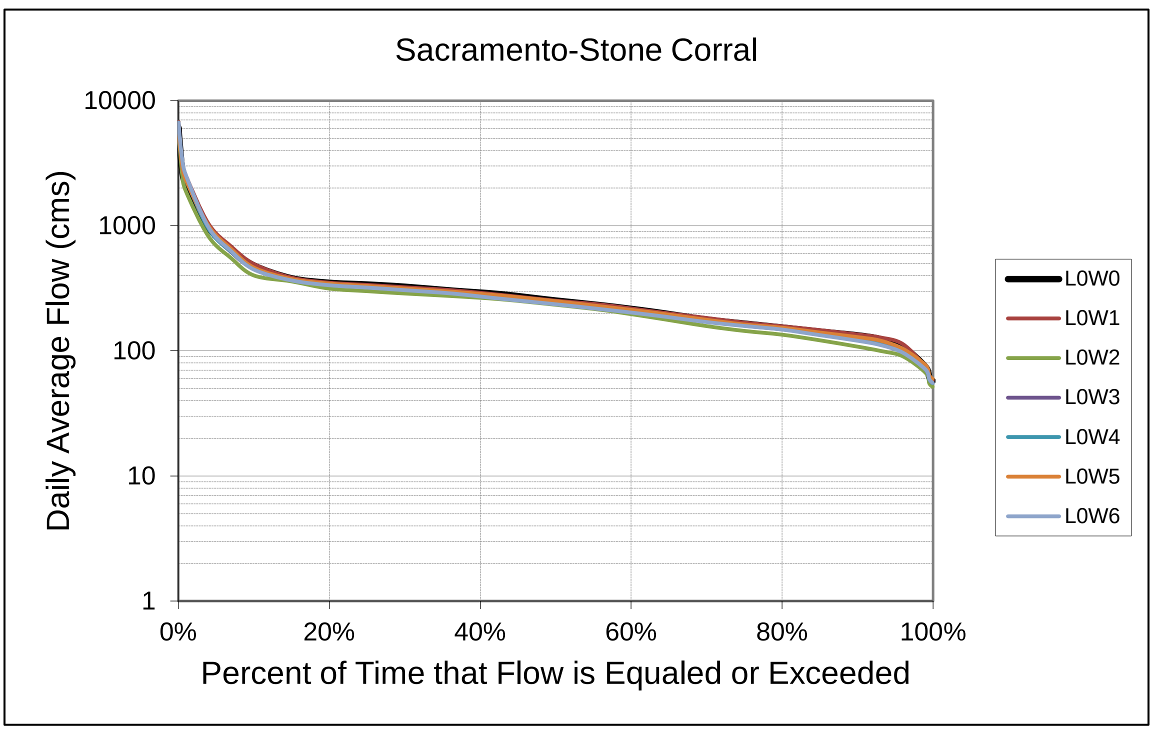


Figure 283. Flow duration, Sacramento River at Stone Corral (SWAT)

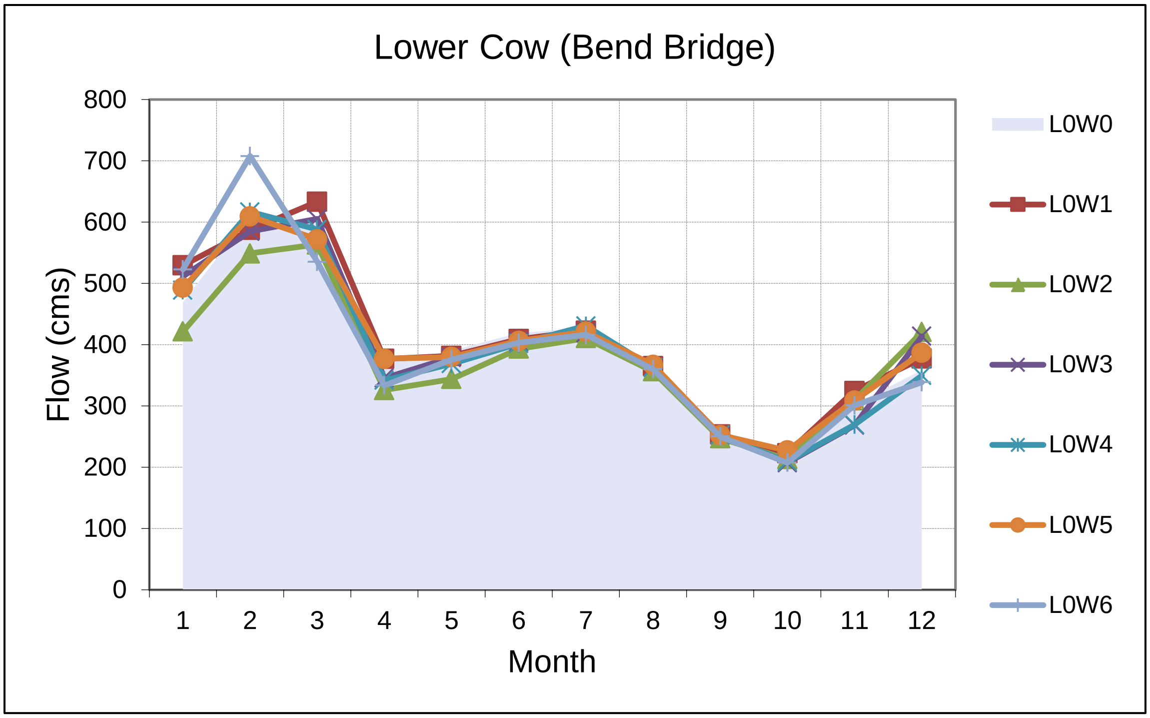


Figure 284. **Monthly average flows, Sacramento River at Bend Bridge (SWAT)**

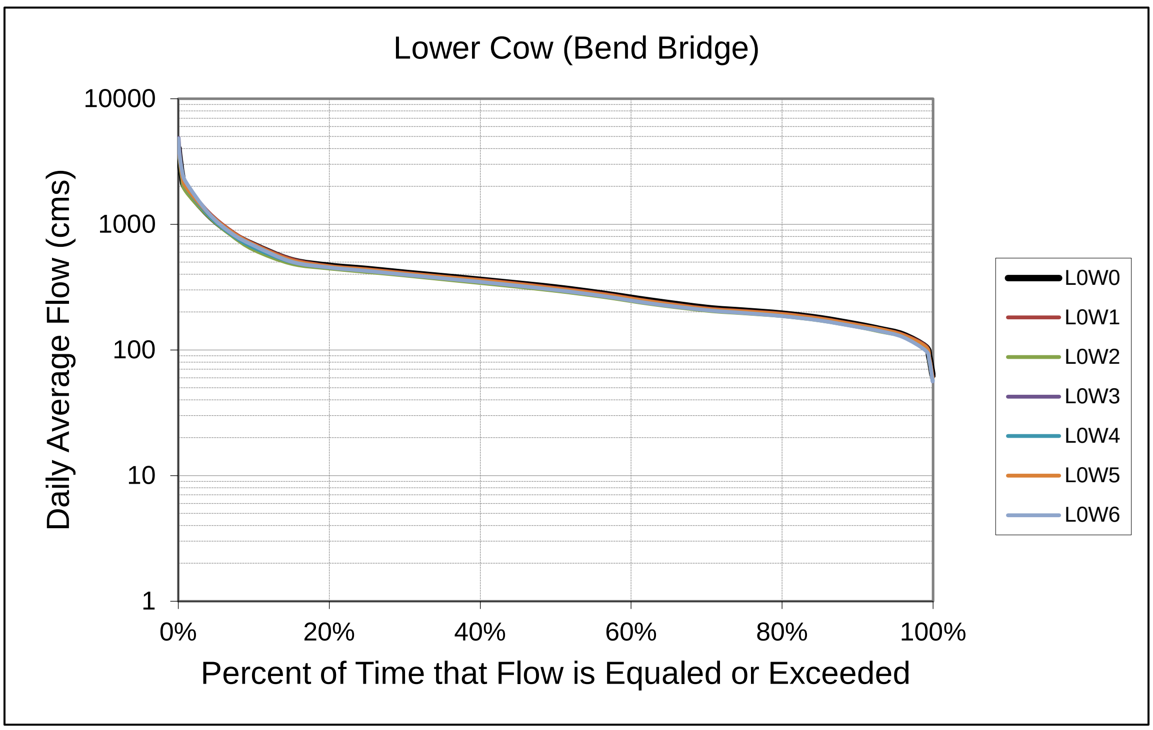


Figure 285. **Flow duration, Sacramento River at Bend Bridge (SWAT)**

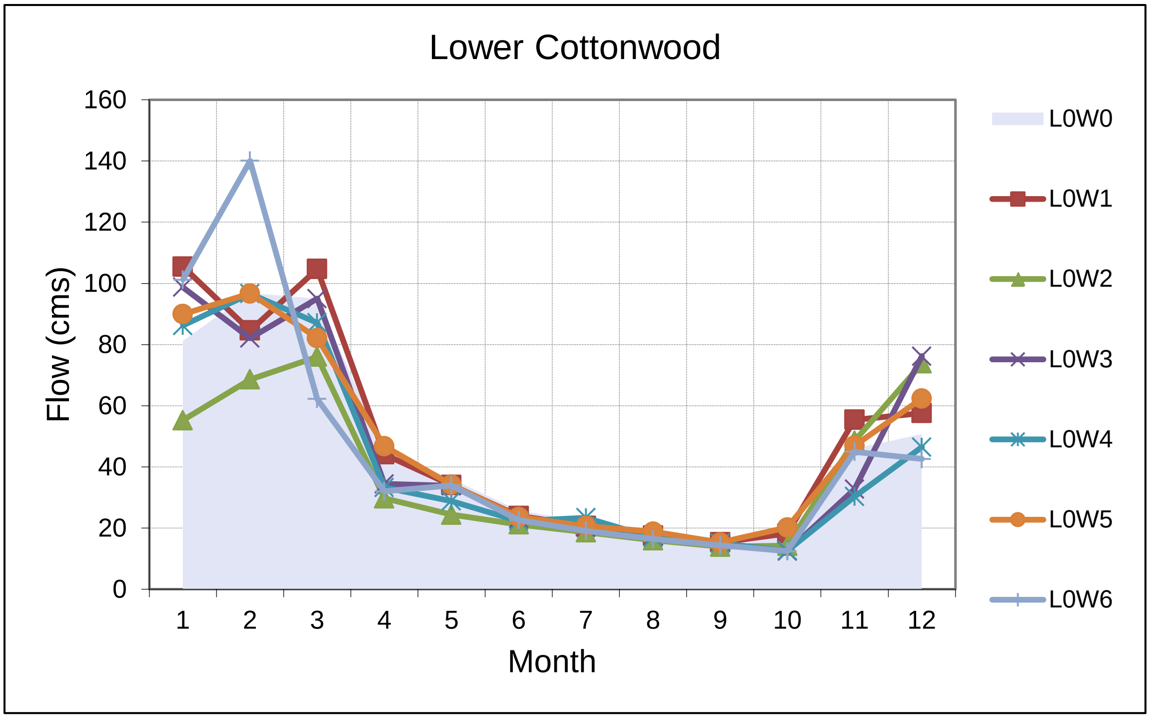


Figure 286. Monthly average flows, Lower Cottonwood (SWAT)

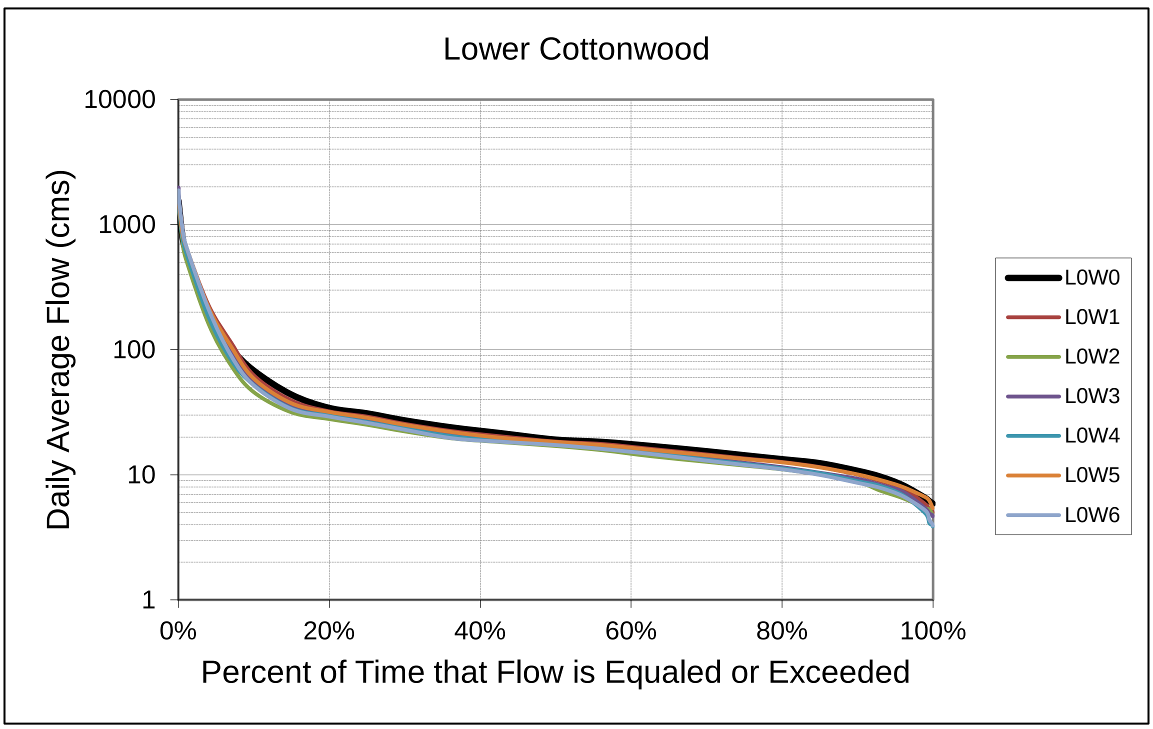


Figure 287. Flow duration, Lower Cottonwood (SWAT)

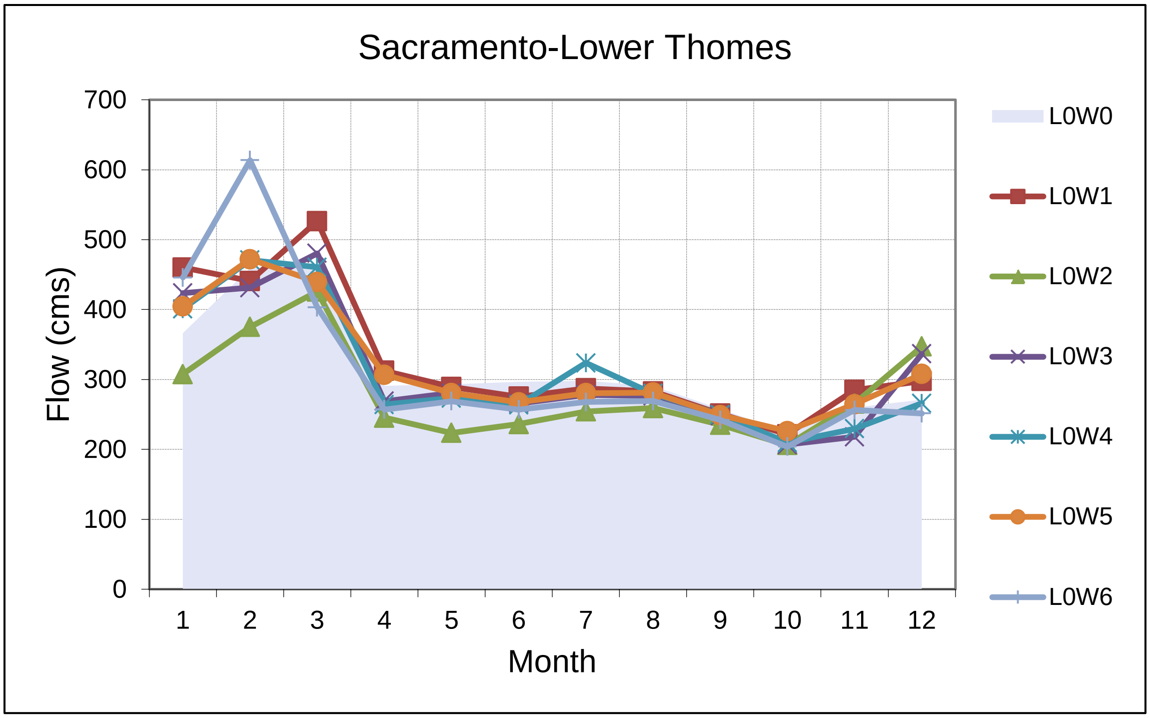


Figure 288. **Monthly average flows, Sacramento - Lower Thomes (SWAT)**

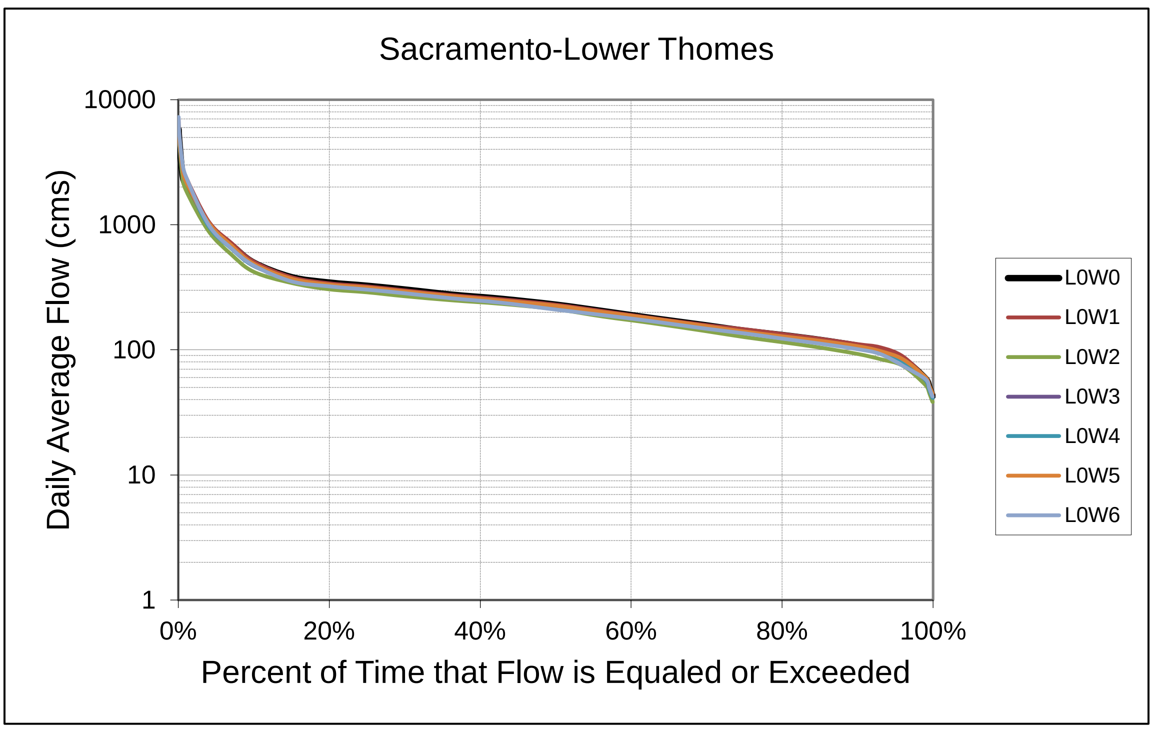


Figure 289. **Flow duration, Sacramento -Lower Thomes (SWAT)**

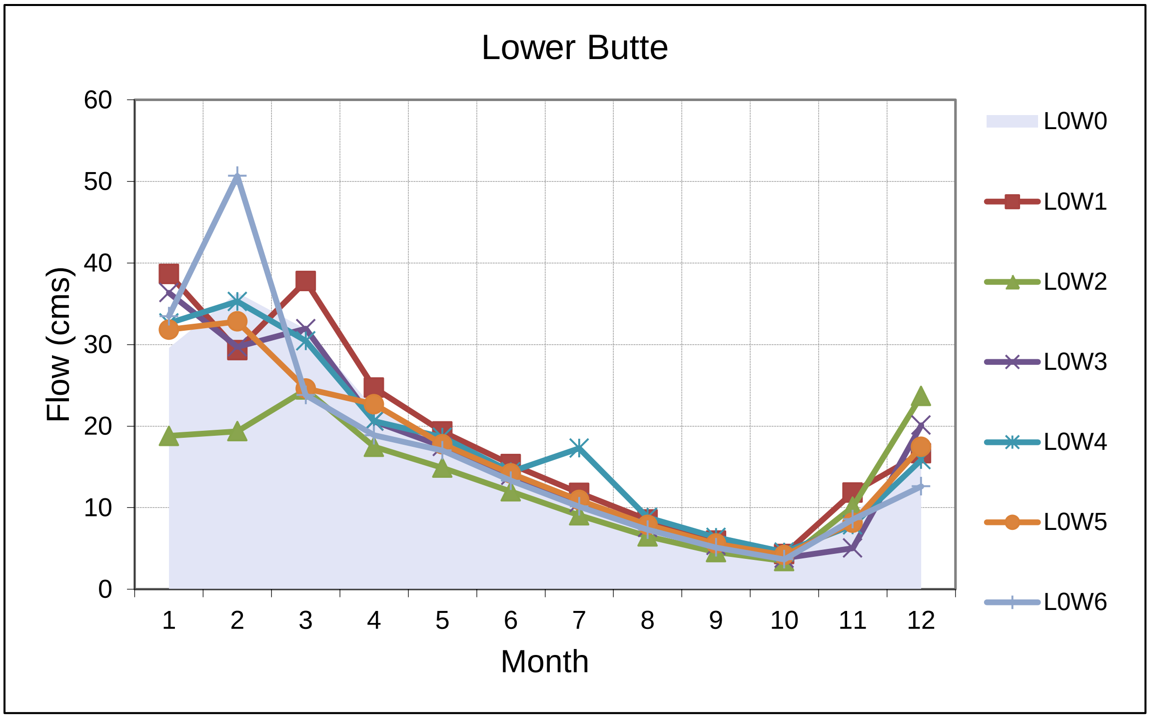


Figure 290. **Monthly average flows, Lower Butte (SWAT)**

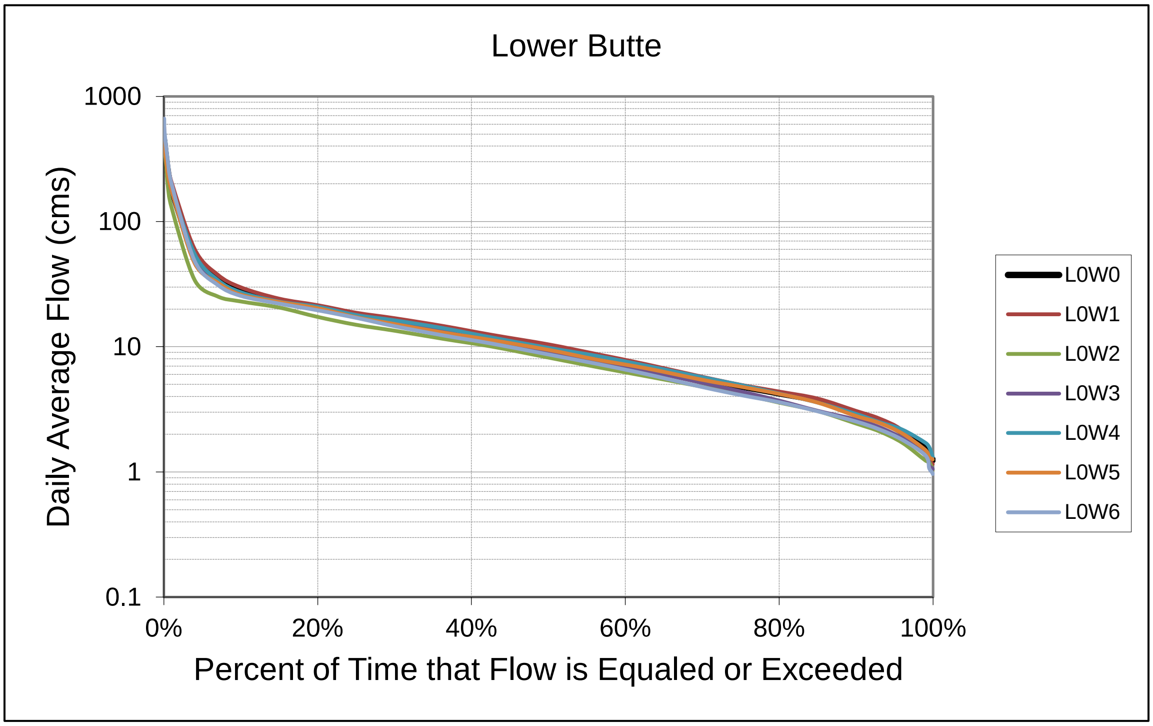


Figure 291. **Flow duration, Lower Butte (SWAT)**

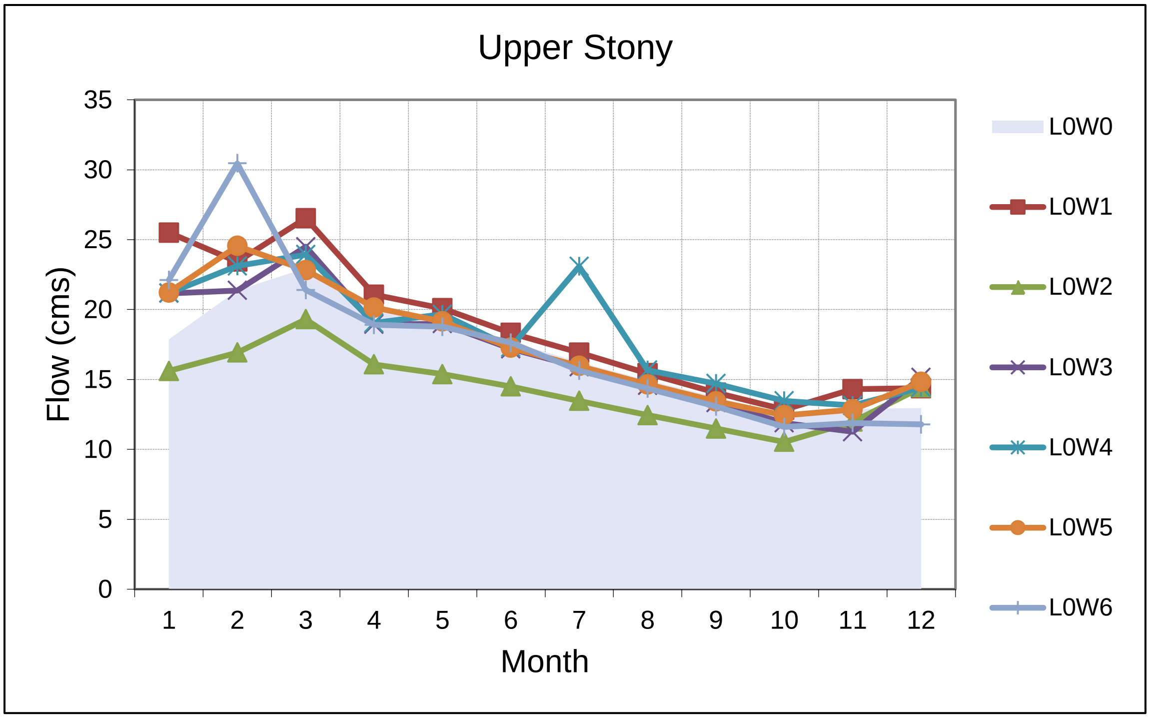


Figure 292. Monthly average flows, Upper Stony (SWAT)

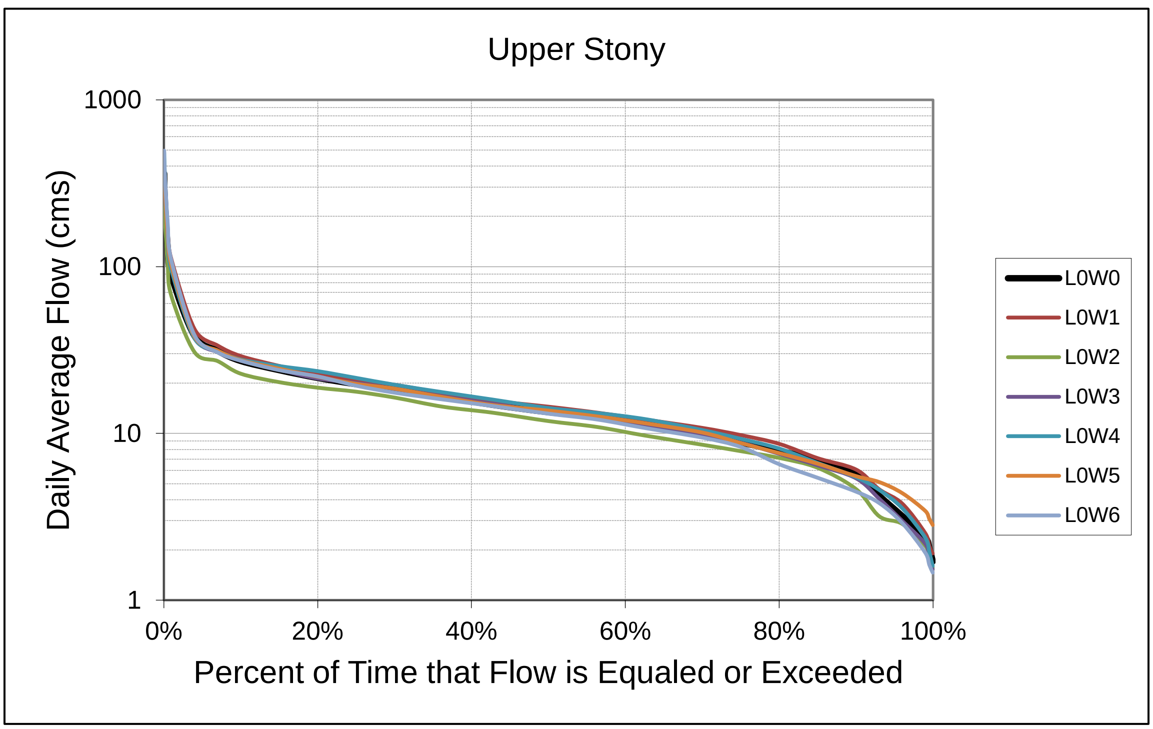


Figure 293. Flow duration, Upper Stony (SWAT)

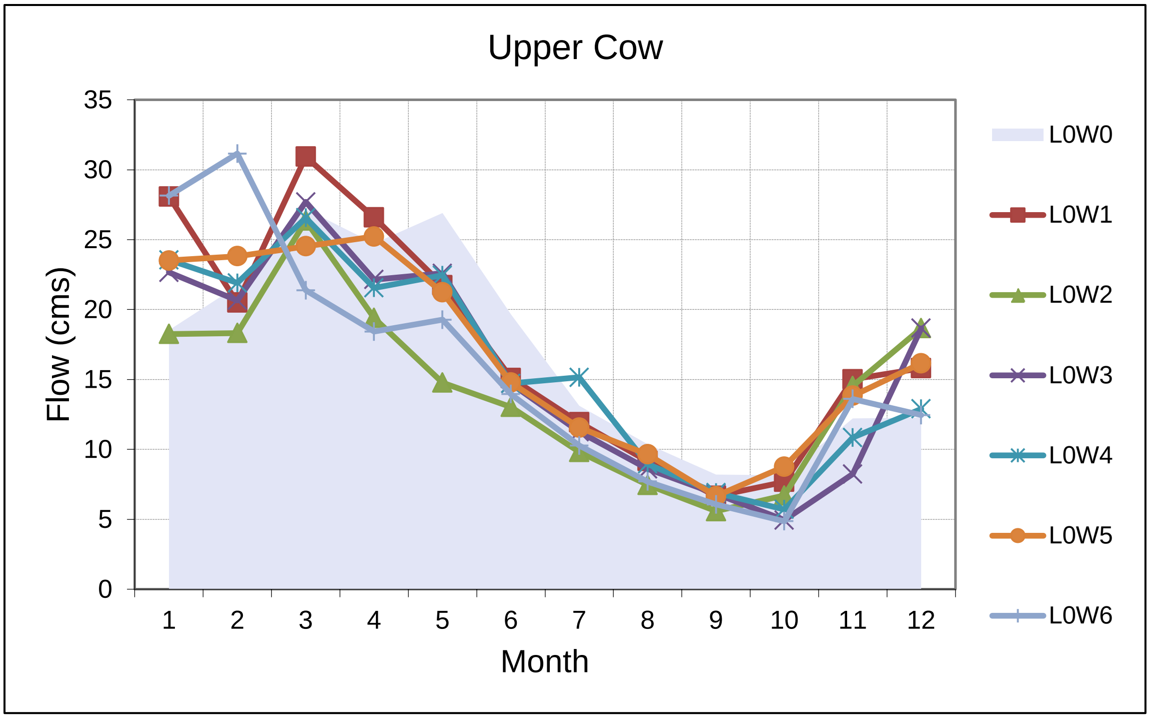


Figure 294. Monthly average flows, Upper Cow (SWAT)

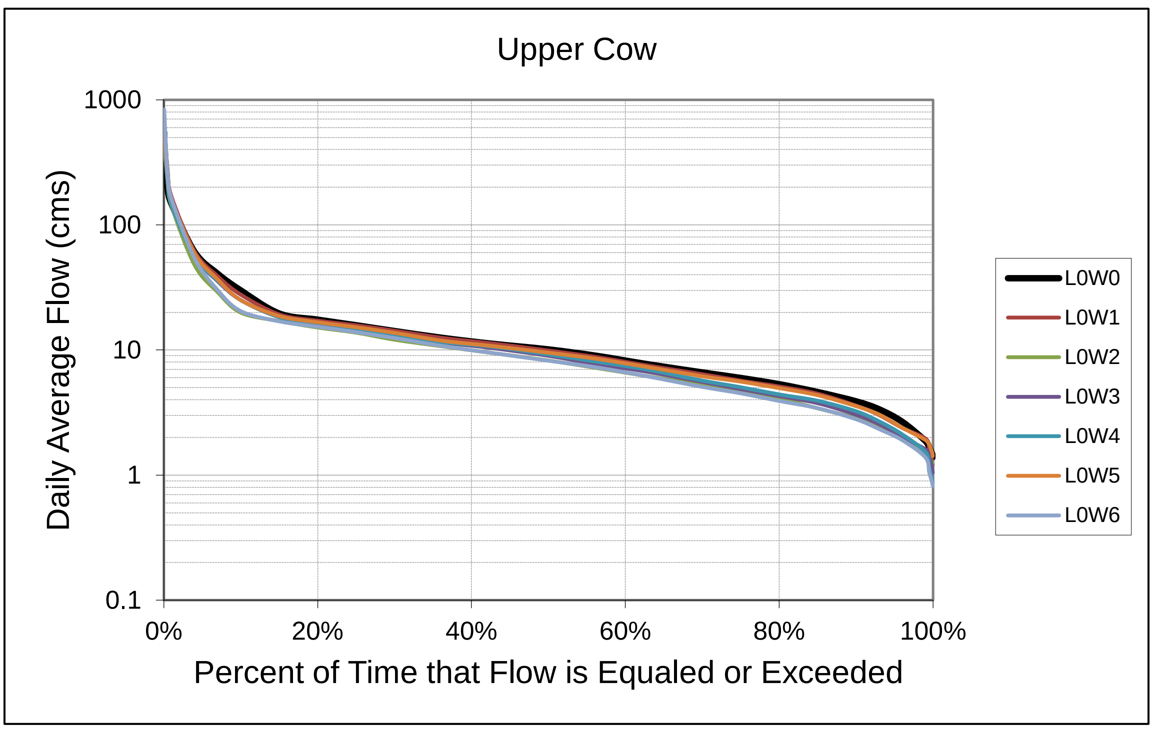


Figure 295. Flow duration, Upper Cow (SWAT)

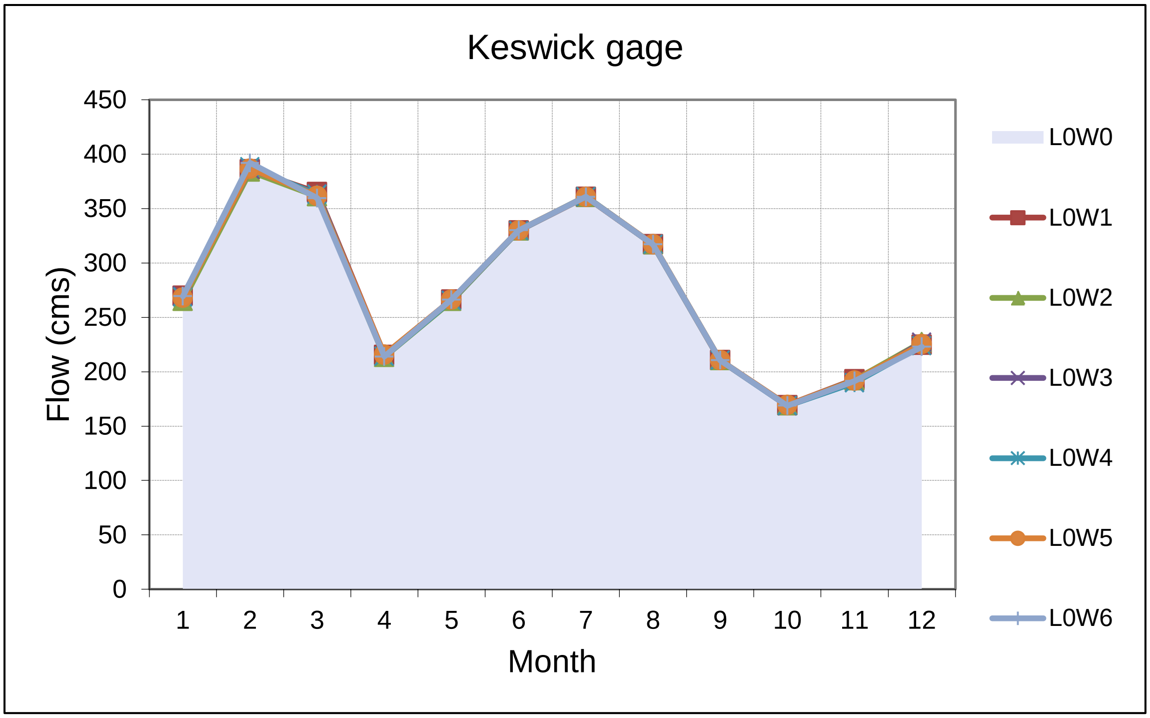


Figure 296. **Monthly average flows, Sacramento River at Keswick Gage (SWAT)**

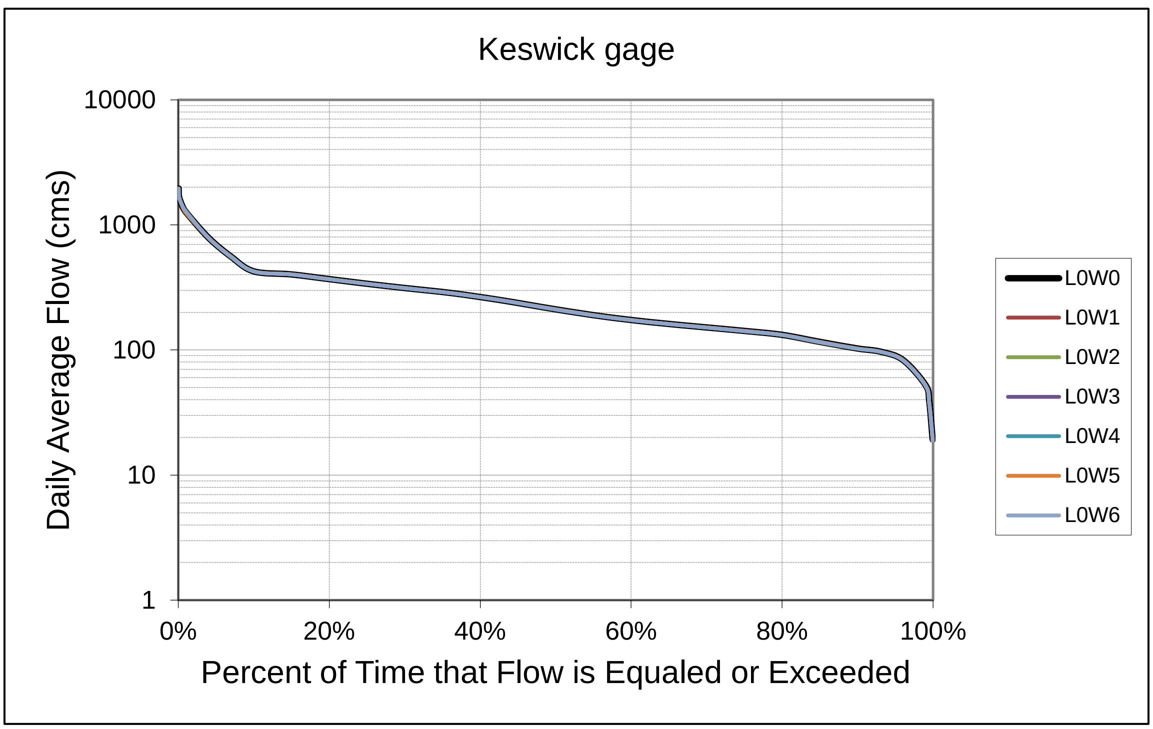


Figure 297. **Flow duration, Sacramento River at Keswick Gage (SWAT)**

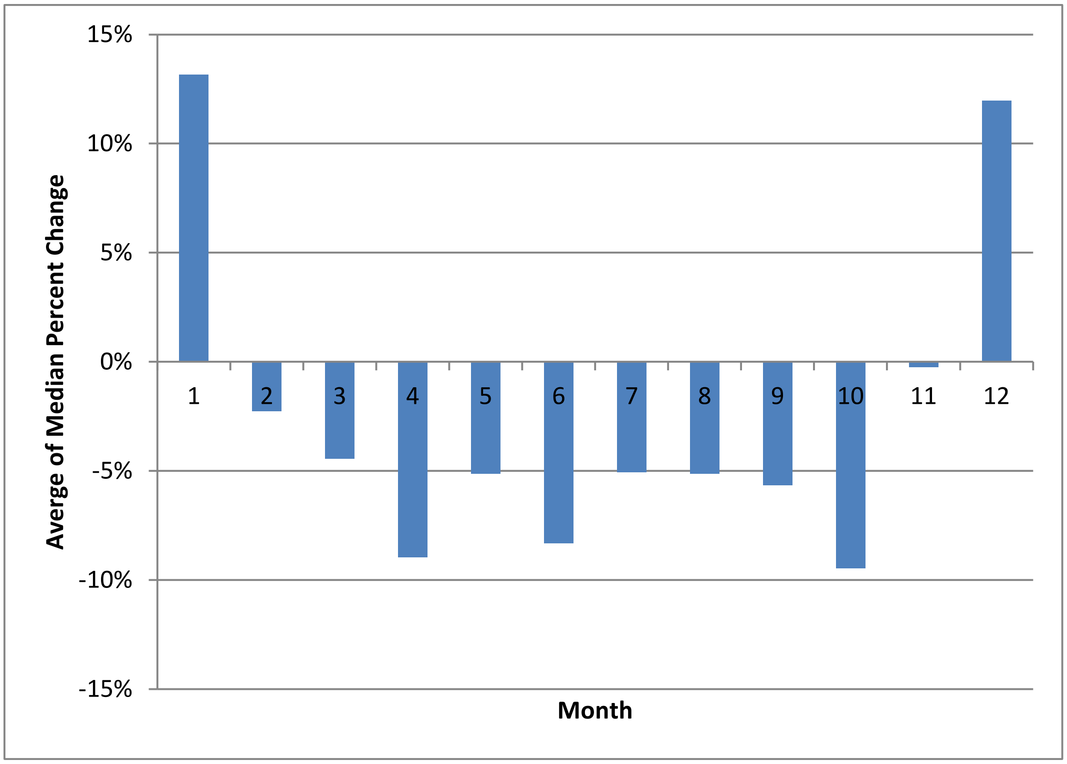


Figure 298. **Average of median percent change in flow; NARCCAP Scenarios W1-W6 at all stations, Sacramento River watershed (SWAT)**

South Platte River Basin

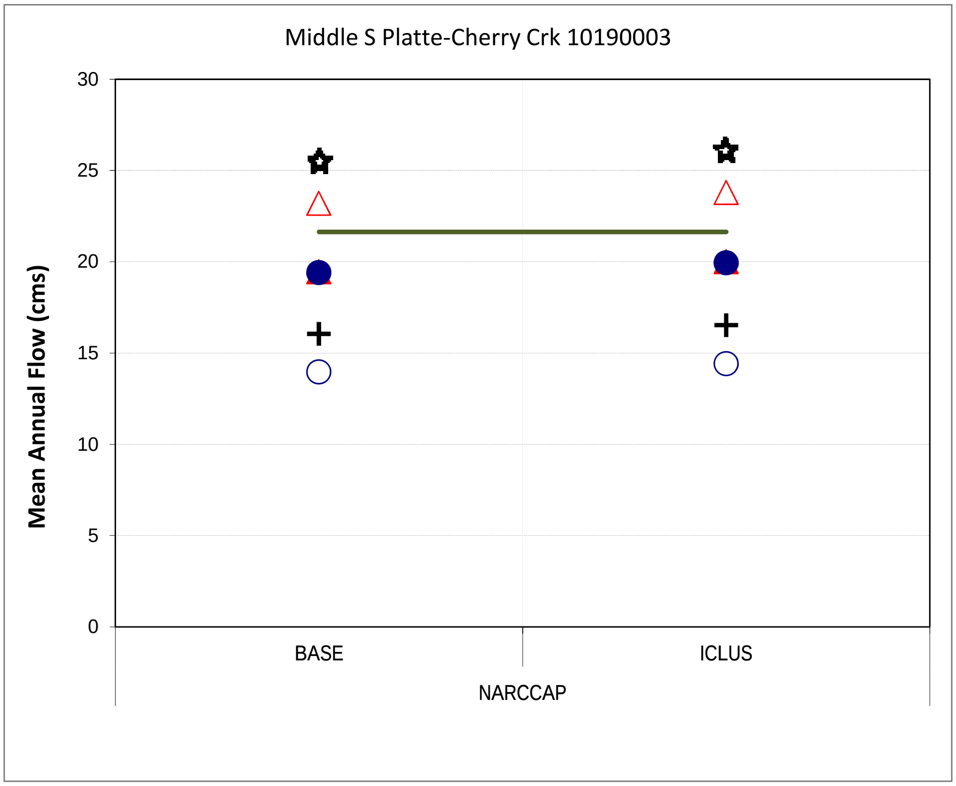


Figure 299. Mean annual flow (cms), Middle South Platte River at Cherry Creek (SWAT)

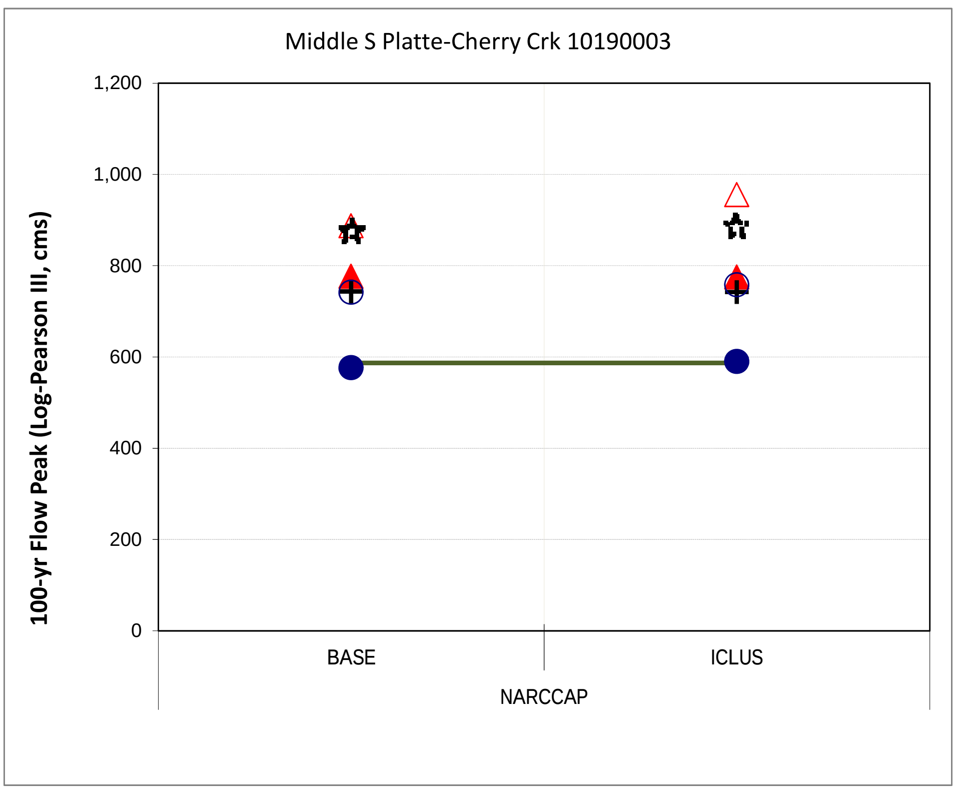


Figure 300. 100-yr Flow Peak (Log-Pearson III, cms), Middle South Platte River at Cherry Creek (SWAT)

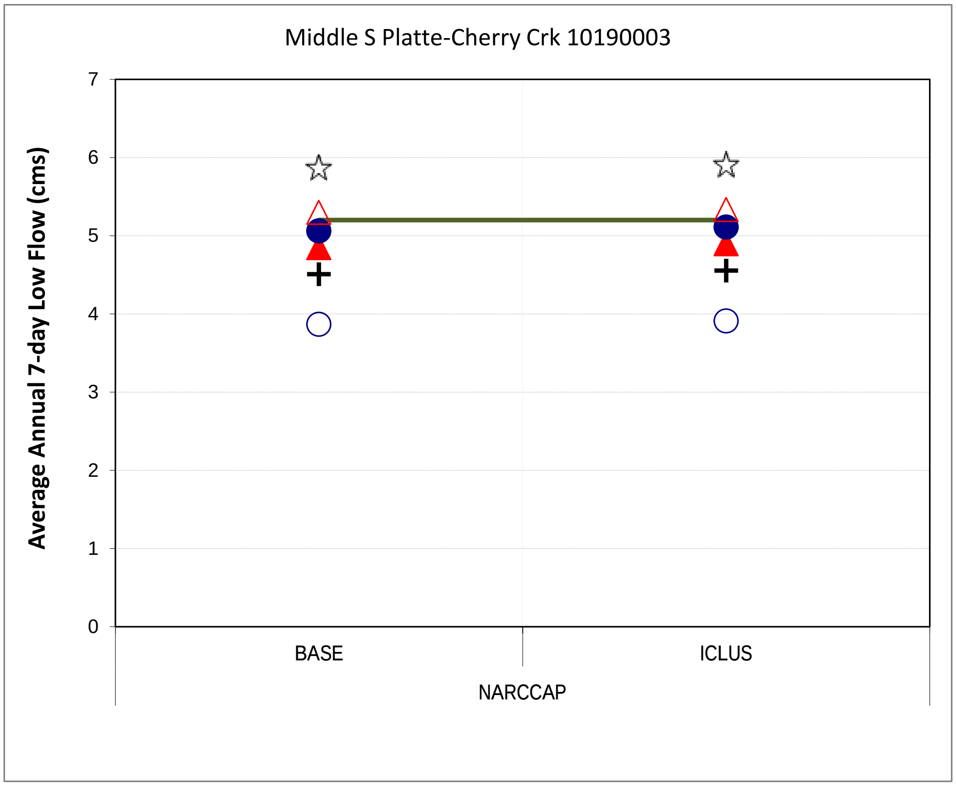


Figure 301. **Average Annual 7-day Low Flow (cms), Middle South Platte River at Cherry Creek (SWAT)**

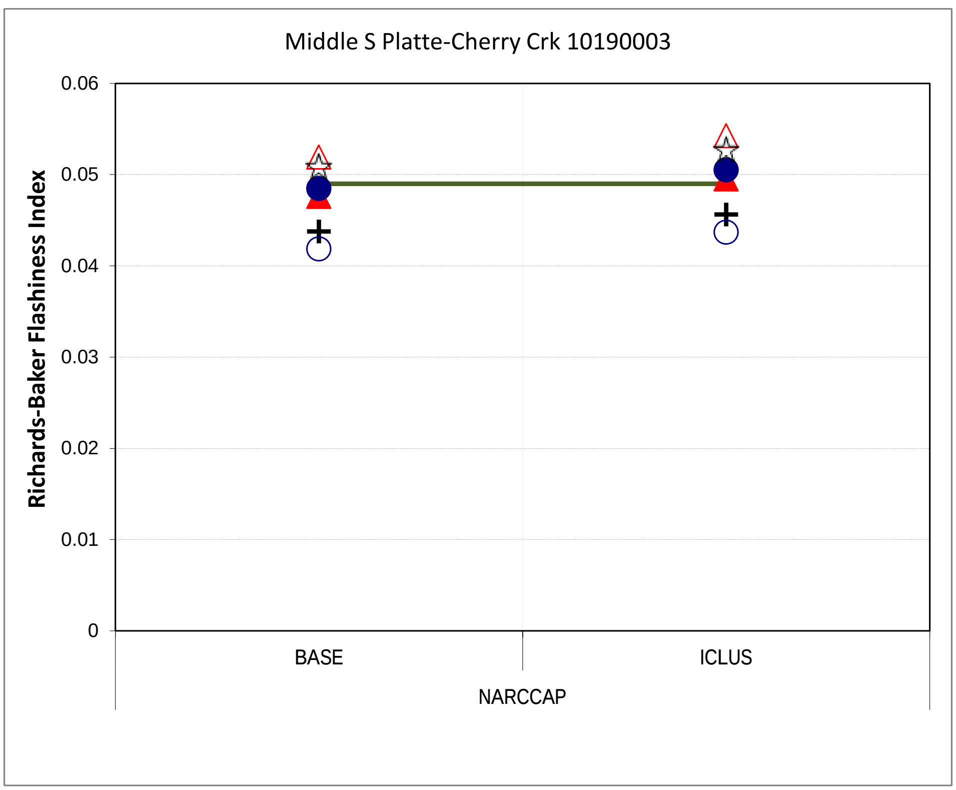


Figure 302. **Richards-Baker Flashiness Index, Average Annual 7-day Low Flow (cms), Middle South Platte River at Cherry Creek (SWAT)**

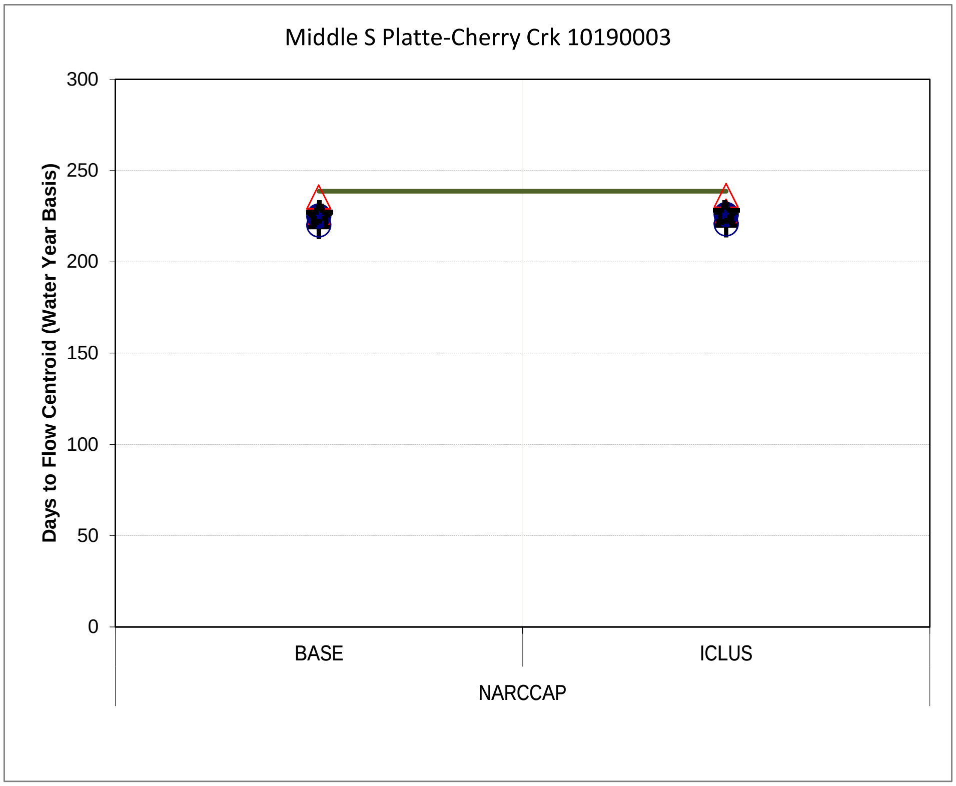


Figure 303. Days to Flow Centroid (Water Year Basis), Middle South Platte River at Cherry Creek (SWAT)

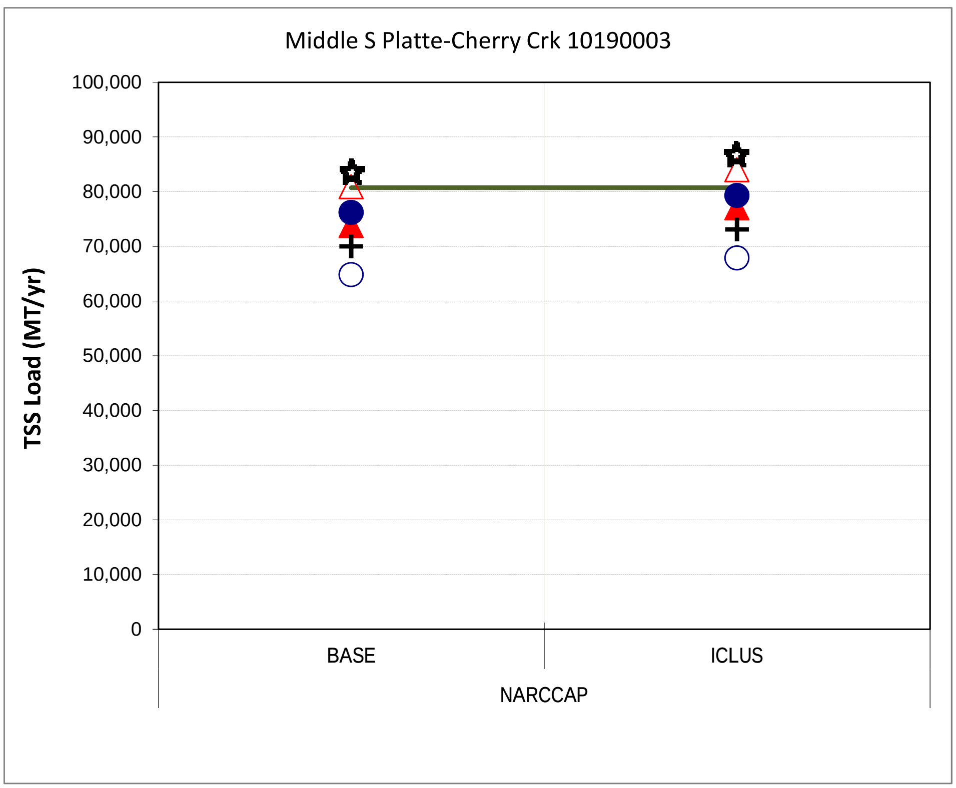


Figure 304. TSS Load (MT/yr), Middle South Platte River at Cherry Creek (SWAT)

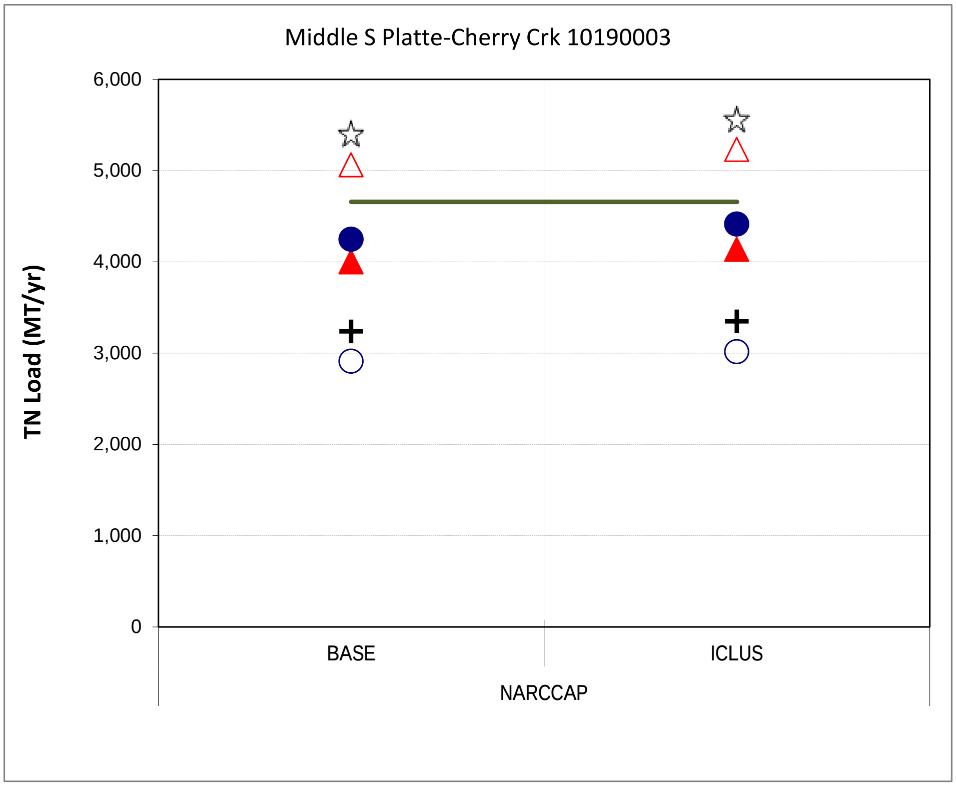


Figure 305. **TN Load (MT/yr), Middle South Platte River at Cherry Creek (SWAT)**

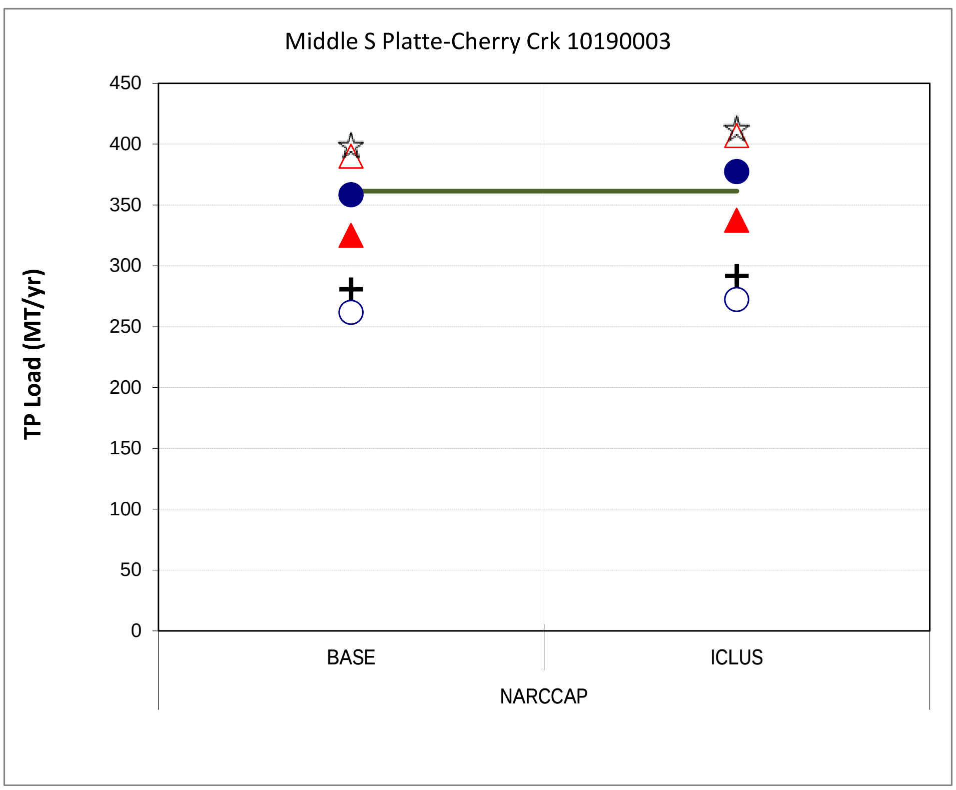


Figure 306. **TP Load (MT/yr), Middle South Platte River at Cherry Creek (SWAT)**

Table 12. Summary of range of change relative to existing conditions for NARCCAP dynamically downscaled scenarios, South Platte River watershed SWAT model

	Results without LU change				Results with LU change			
	Min	Median	Mean	Max	Min	Median	Mean	Max
S Platte Headwaters HUC 10190001								
Flow	-36.89%	-20.62%	-20.43%	0.84%	-36.93%	-20.69%	-20.51%	0.73%
TSS	-65.57%	-54.01%	-53.01%	-36.33%	-65.71%	-54.51%	-53.56%	-37.43%
TN	-65.33%	-47.10%	-48.90%	-31.36%	-65.35%	-47.33%	-48.97%	-31.43%
TP	-44.99%	-31.42%	-28.35%	-3.42%	-44.93%	-31.00%	-28.14%	-3.24%
Upper S Platte HUC 10190002								
Flow	-35.38%	-13.10%	-15.35%	-0.68%	-35.01%	-13.20%	-15.34%	-1.02%
TSS	-41.89%	-15.38%	-19.00%	-1.21%	-39.28%	-14.59%	-17.98%	-1.77%
TN	-37.36%	-19.15%	-19.82%	-4.91%	-37.33%	-19.33%	-19.67%	-3.59%
TP	-30.52%	-15.11%	-15.22%	-1.63%	-30.26%	-14.82%	-14.66%	0.19%
Middle S Platte-Cherry Crk HUC 10190003								
Flow	-35.48%	-10.22%	-9.34%	18.52%	-35.22%	-10.26%	-9.43%	18.01%
TSS	-19.67%	-7.10%	-7.12%	4.16%	-19.08%	-6.82%	-6.90%	4.06%
TN	-37.48%	-11.45%	-10.98%	16.28%	-37.35%	-11.20%	-10.98%	15.73%
TP	-27.54%	-5.46%	-7.04%	10.56%	-27.59%	-4.92%	-6.92%	10.07%
Clear HUC 10190004								
Flow	-19.59%	-8.28%	-7.78%	6.48%	-19.56%	-8.37%	-7.80%	6.53%
TSS	-68.91%	-57.70%	-58.62%	-49.02%	-68.76%	-57.54%	-58.48%	-48.91%
TN	-19.10%	-10.15%	-8.96%	5.27%	-19.10%	-10.20%	-8.92%	5.48%
TP	-28.01%	-14.79%	-12.76%	9.07%	-27.94%	-14.75%	-12.58%	9.58%
St Vrain HUC 10190005								
Flow	-18.59%	-4.98%	-6.21%	5.80%	-18.69%	-5.10%	-6.34%	5.62%
TSS	-25.25%	-12.08%	-13.12%	-2.27%	-25.27%	-11.94%	-13.16%	-2.75%
TN	-21.67%	-8.97%	-10.09%	0.52%	-21.23%	-8.43%	-9.69%	0.92%
TP	-5.28%	-1.28%	-1.89%	1.15%	-5.39%	-1.19%	-1.86%	1.19%
Big Thompson HUC 10190006								
Flow	-10.44%	-2.98%	-3.31%	3.12%	-10.49%	-2.98%	-3.33%	3.12%
TSS	-25.70%	-19.72%	-19.67%	-14.31%	-25.37%	-19.32%	-19.32%	-13.94%
TN	-11.23%	-4.28%	-3.87%	2.26%	-11.62%	-4.66%	-4.31%	1.92%
TP	-6.65%	-3.26%	-2.64%	1.88%	-6.57%	-3.12%	-2.56%	1.42%
Cache La Poudre HUC 10190007								
Flow	-26.87%	-5.02%	-6.79%	9.01%	-26.28%	-4.89%	-6.59%	9.00%
TSS	-39.12%	-18.89%	-20.53%	-4.98%	-37.64%	-18.03%	-19.68%	-4.65%
TN	-23.68%	-1.27%	-4.69%	15.28%	-21.68%	-0.65%	-3.58%	18.09%
TP	-4.55%	2.79%	3.36%	13.28%	-4.30%	2.41%	3.97%	15.42%
Lone Tree-Owl HUC 10190008								
Flow	-29.85%	-2.46%	1.93%	32.81%	-29.79%	-2.45%	1.92%	32.73%
TSS	-30.31%	-0.91%	5.36%	39.21%	-29.94%	-1.06%	5.04%	38.13%

	Results without LU change				Results with LU change			
	Min	Median	Mean	Max	Min	Median	Mean	Max
TN	-31.92%	-7.24%	-3.57%	33.36%	-31.77%	-7.12%	-3.44%	33.46%
TP	-29.46%	-7.93%	-3.07%	30.23%	-29.21%	-7.78%	-3.06%	29.70%
Crow HUC 10190009								
Flow	-53.04%	-27.95%	-16.36%	25.26%	-53.04%	-27.95%	-16.36%	25.26%
TSS	-47.25%	-18.53%	-9.23%	27.06%	-47.16%	-18.49%	-9.21%	27.01%
TN	-35.94%	-17.32%	-8.94%	18.73%	-35.93%	-17.31%	-8.90%	18.93%
TP	-7.34%	-2.93%	-1.72%	4.22%	-7.34%	-2.93%	-1.72%	4.23%
Kiowa HUC 10190010								
Flow	-20.20%	7.02%	13.17%	59.23%	-20.20%	7.02%	13.17%	59.23%
TSS	-17.09%	6.16%	14.66%	60.82%	-17.09%	6.16%	14.65%	60.81%
TN	11.20%	24.69%	26.70%	42.80%	11.20%	24.69%	26.70%	42.80%
TP	-3.07%	2.35%	3.96%	14.21%	-3.07%	2.35%	3.96%	14.21%
Bijou HUC 10190011								
Flow	-44.46%	-5.63%	-6.93%	31.10%	-44.41%	-5.65%	-6.95%	31.01%
TSS	-57.62%	-14.14%	-14.33%	27.79%	-56.46%	-13.94%	-14.20%	27.13%
TN	-59.50%	-40.45%	-38.73%	-22.22%	-59.50%	-40.42%	-38.74%	-22.28%
TP	-43.73%	-8.30%	-9.95%	23.06%	-43.25%	-8.14%	-9.78%	22.76%
S Platte at Henderson (gage 06720500)								
Flow	-26.13%	-7.87%	-10.17%	1.35%	-26.12%	-8.32%	-10.46%	0.66%
TSS	-45.93%	-27.09%	-29.11%	-19.72%	-43.64%	-26.28%	-27.83%	-18.24%
TN	-21.50%	-9.07%	-9.18%	2.21%	-21.73%	-9.19%	-9.02%	3.48%
TP	-16.10%	-6.24%	-6.35%	2.56%	-16.42%	-6.34%	-6.22%	3.71%
Box Elder Creek								
Flow	-60.45%	-11.87%	-16.04%	17.00%	-59.20%	-11.53%	-15.60%	17.00%
TSS	-59.18%	-12.68%	-15.39%	20.95%	-51.55%	-10.83%	-13.45%	17.55%
TN	-45.23%	-34.61%	-32.63%	-19.49%	-45.66%	-34.34%	-32.33%	-19.12%
TP	-46.68%	-7.23%	-10.58%	17.85%	-43.35%	-5.83%	-9.03%	18.07%
S Platte at Denver (gage 06714000)								
Flow	-35.68%	-10.19%	-13.61%	3.07%	-34.68%	-10.75%	-13.81%	1.71%
TSS	-40.75%	-9.77%	-16.06%	1.64%	-37.20%	-10.76%	-14.94%	3.33%
TN	-36.98%	-17.73%	-18.82%	-4.22%	-36.48%	-17.70%	-18.46%	-3.44%
TP	-30.63%	-14.00%	-14.57%	-1.40%	-30.04%	-13.35%	-13.68%	0.43%

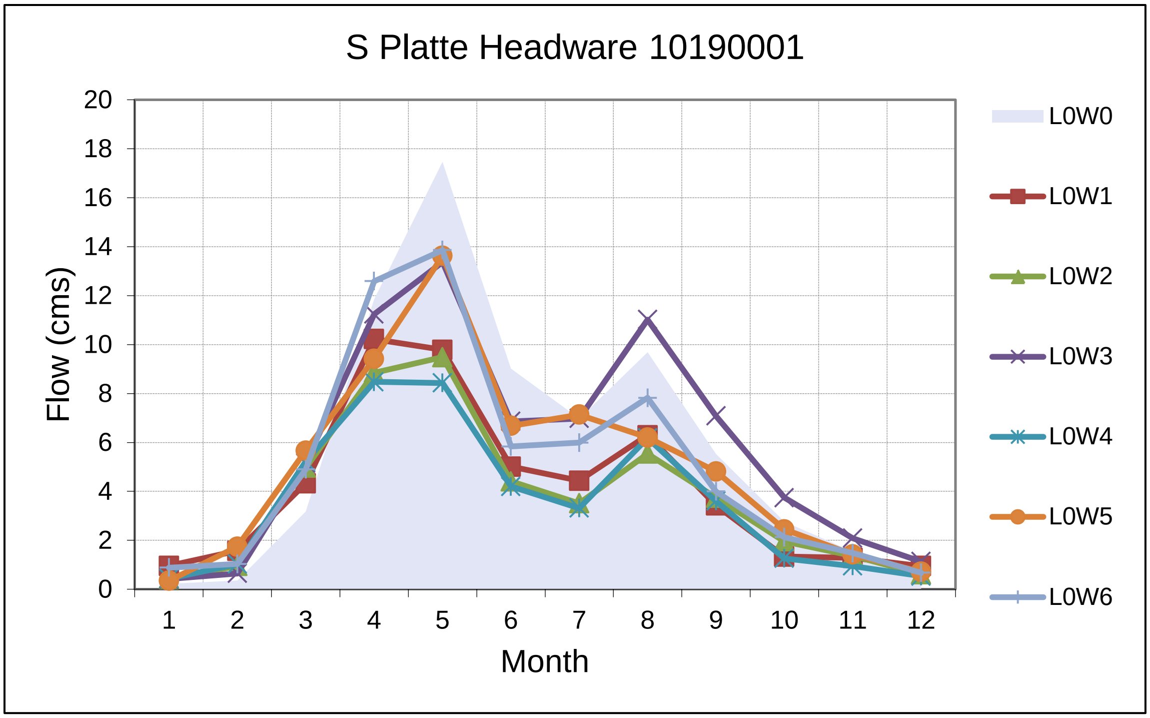


Figure 307. **Monthly average flows, South Platte Headwaters (SWAT)**

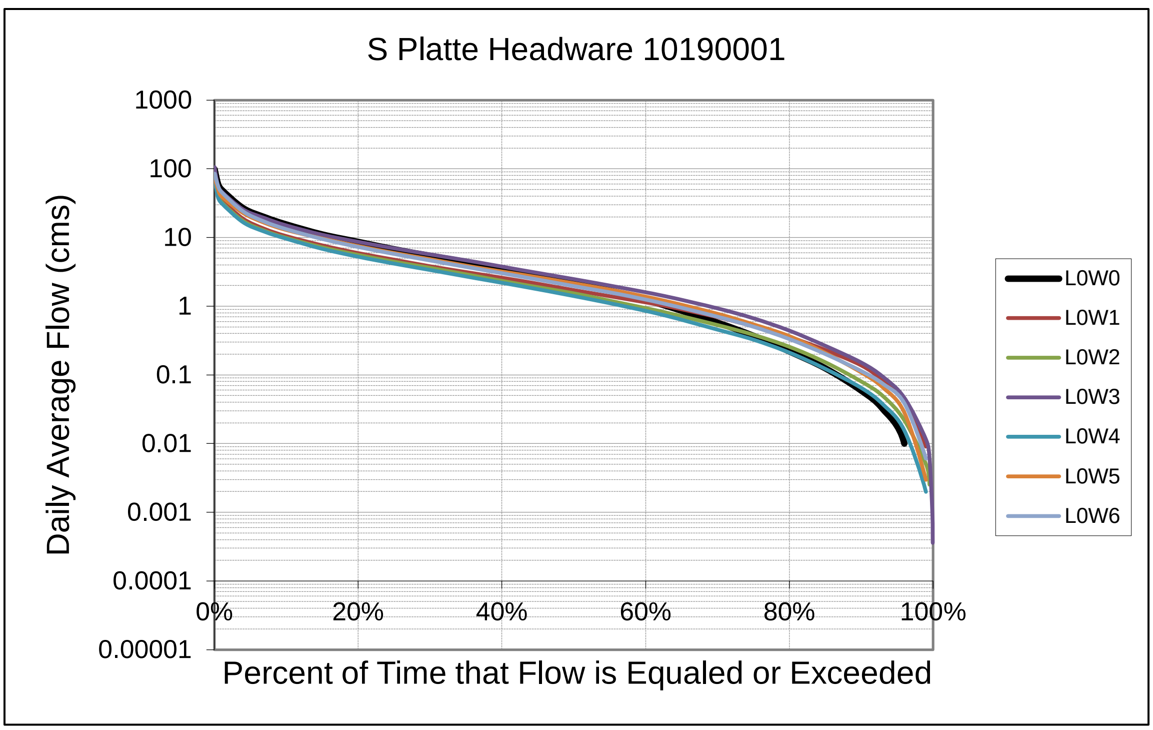


Figure 308. Flow duration, South Platte Headwaters (SWAT)

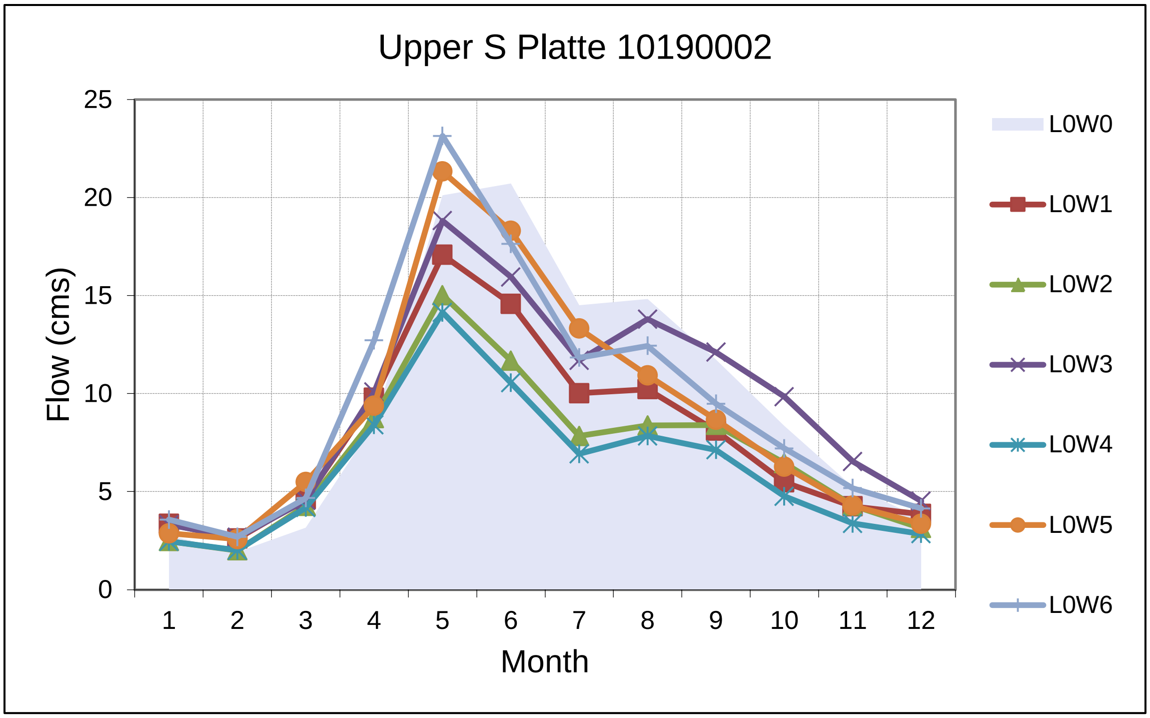


Figure 309. **Monthly average flows, Upper South Platte River (SWAT)**

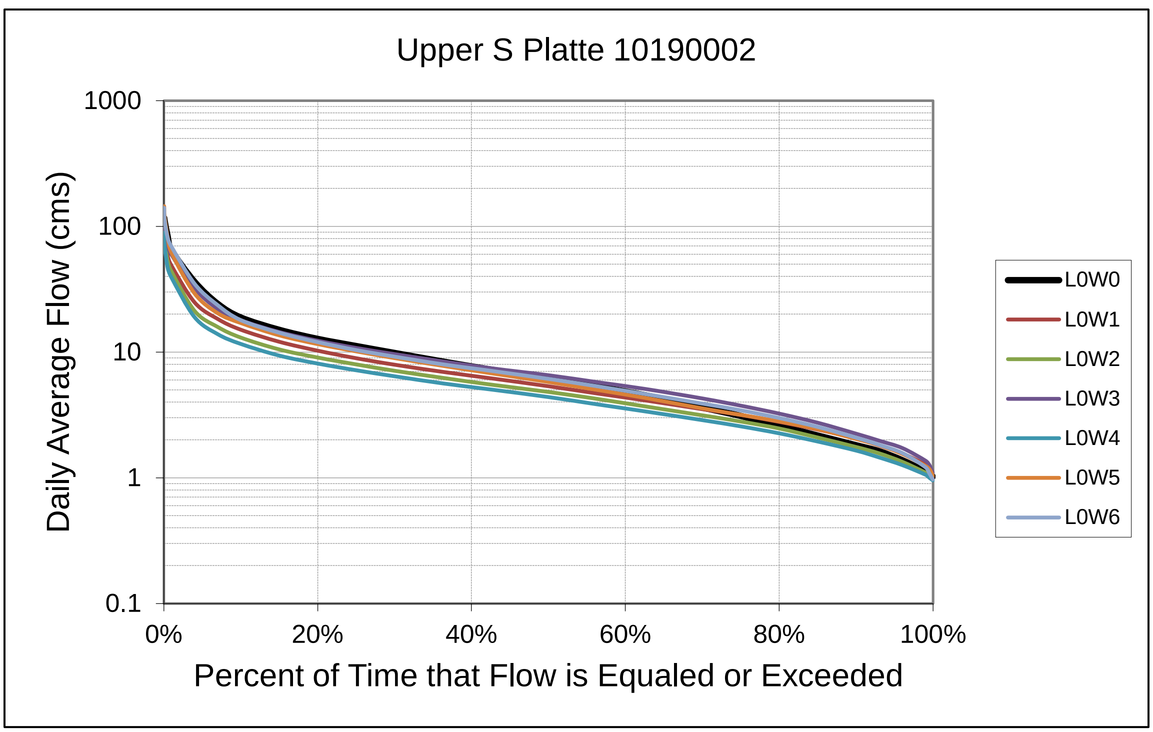


Figure 310. **Flow duration, Upper South Platte River (SWAT)**

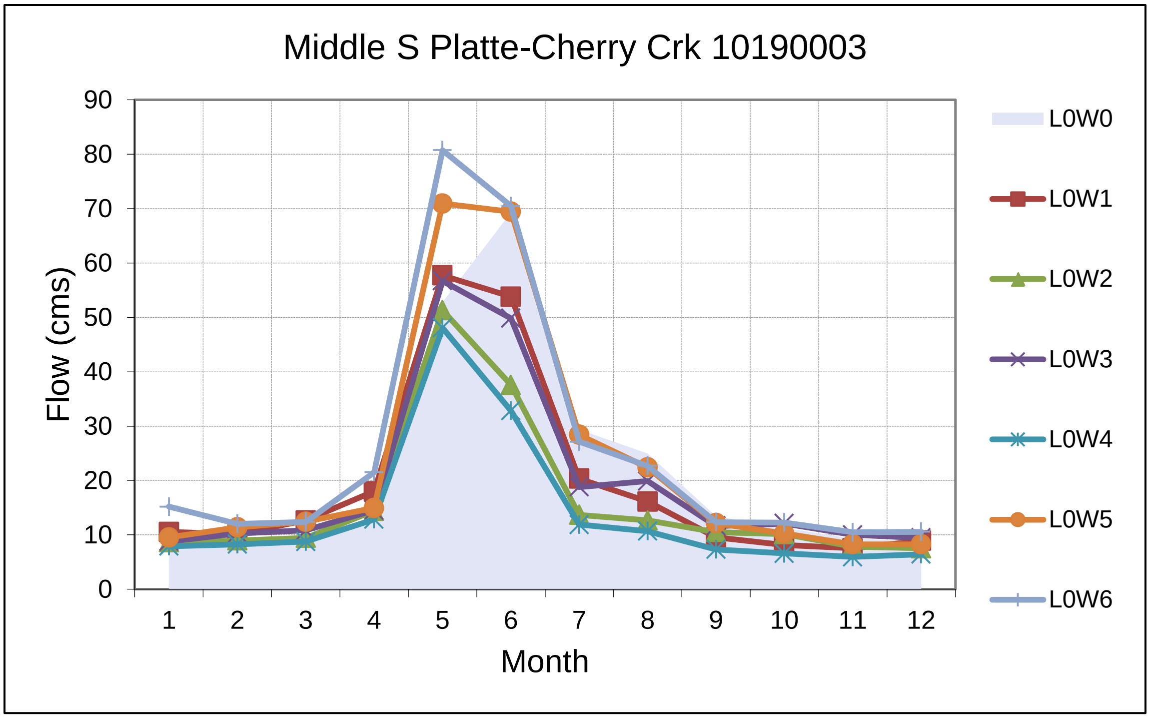


Figure 311. **Monthly average flows, Middle South Platte River at Cherry Creek (SWAT)**

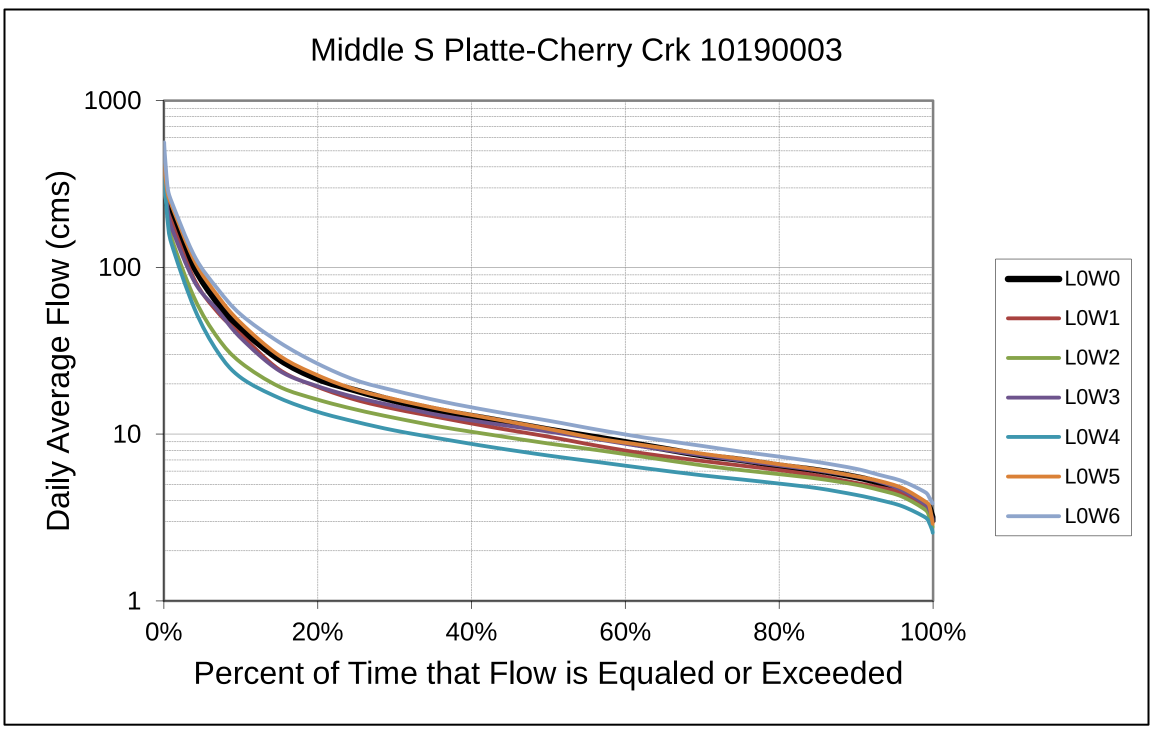


Figure 312. **Flow duration, Middle South Platte River at Cherry Creek (SWAT)**

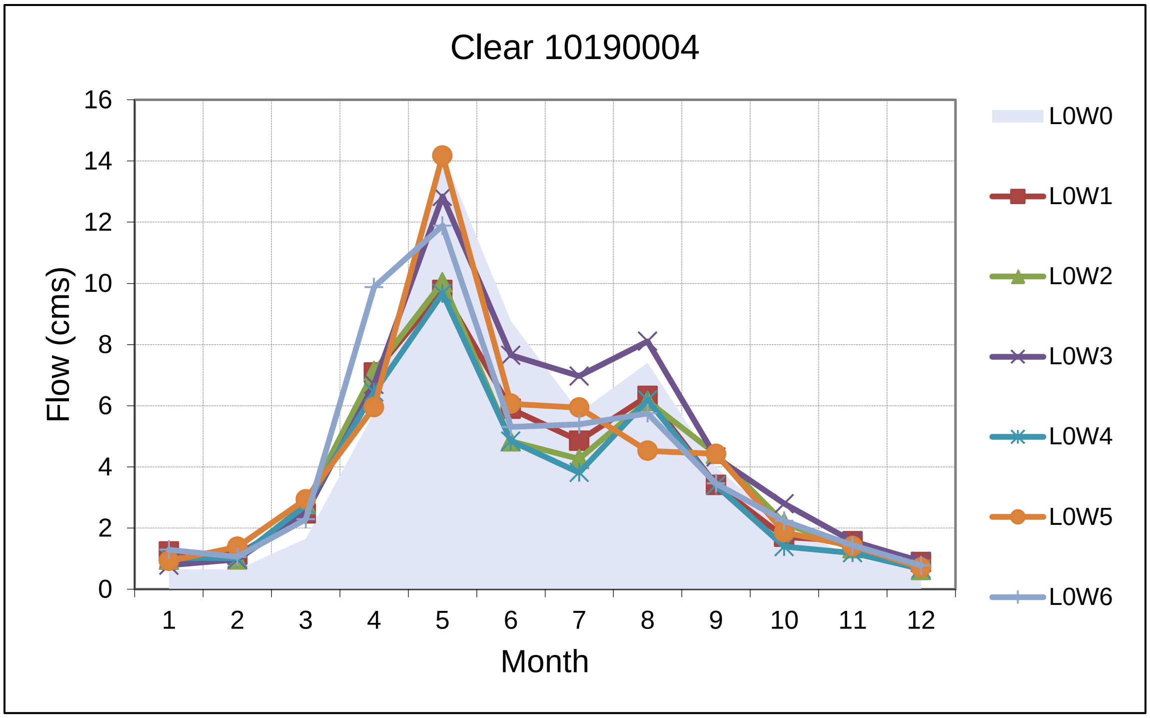


Figure 313. Monthly average flows, Clear Creek (SWAT)

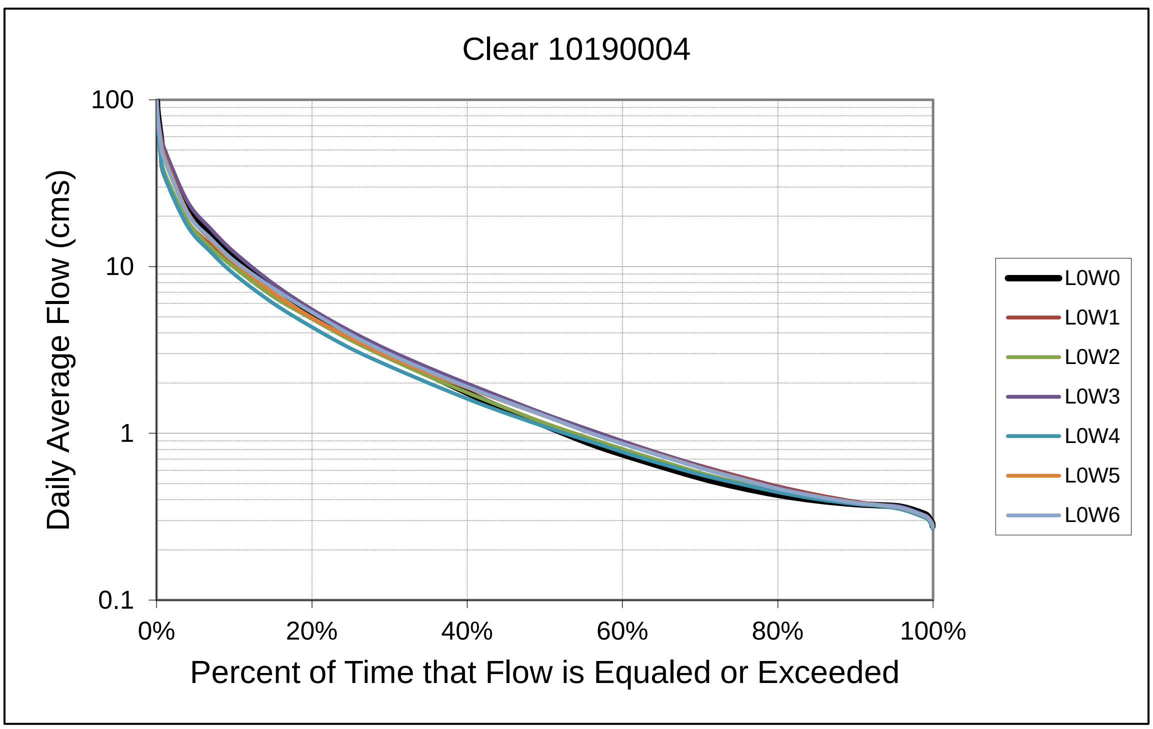


Figure 314. Flow duration, Clear Creek (SWAT)

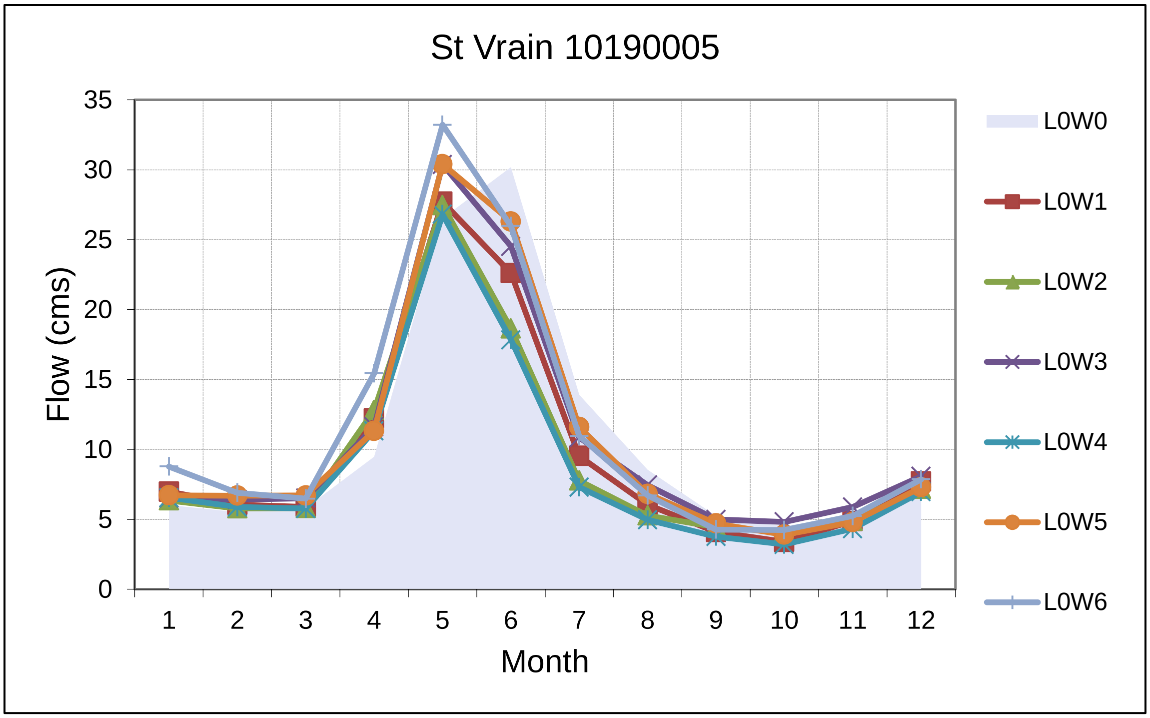


Figure 315. **Monthly average flows, St Vrain River (SWAT)**

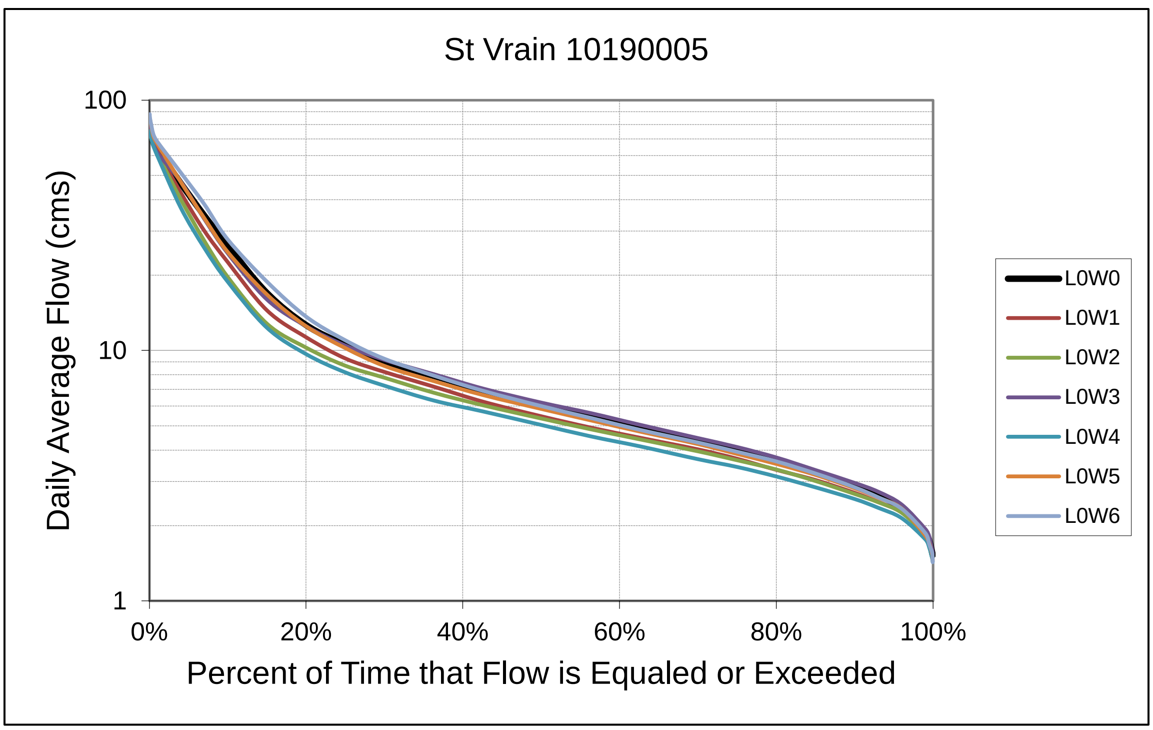


Figure 316. **Flow duration, St Vrain River (SWAT)**

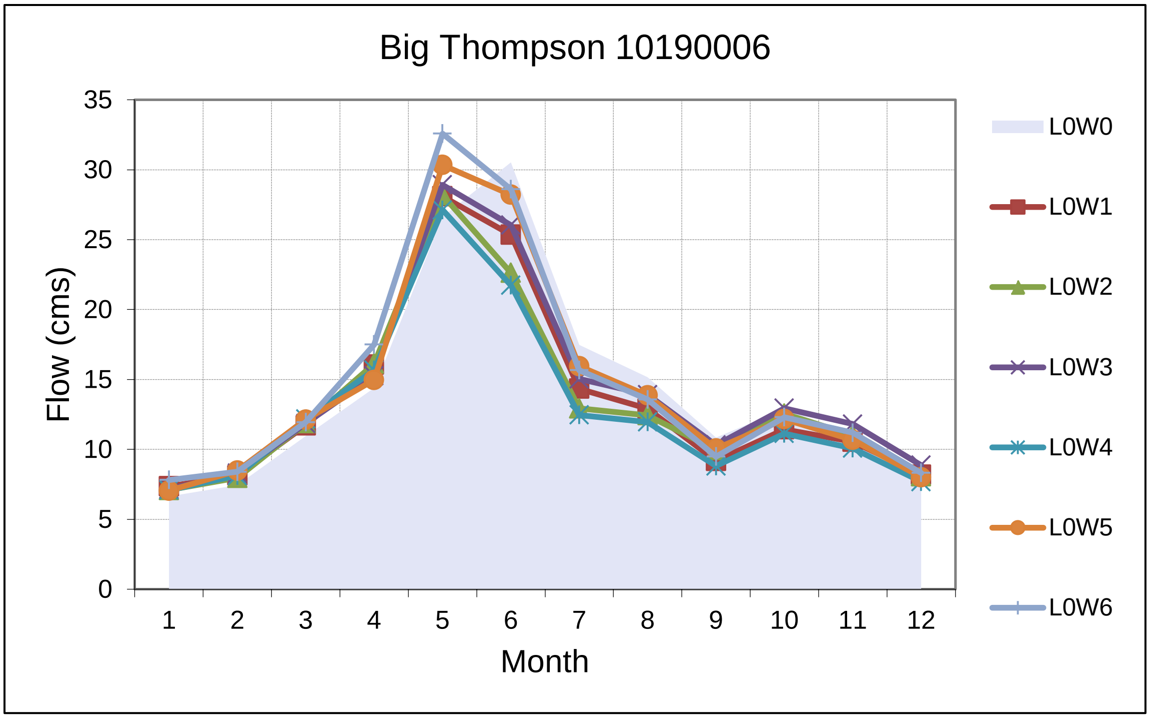


Figure 317. Monthly average flows, Big Thompson River (SWAT)

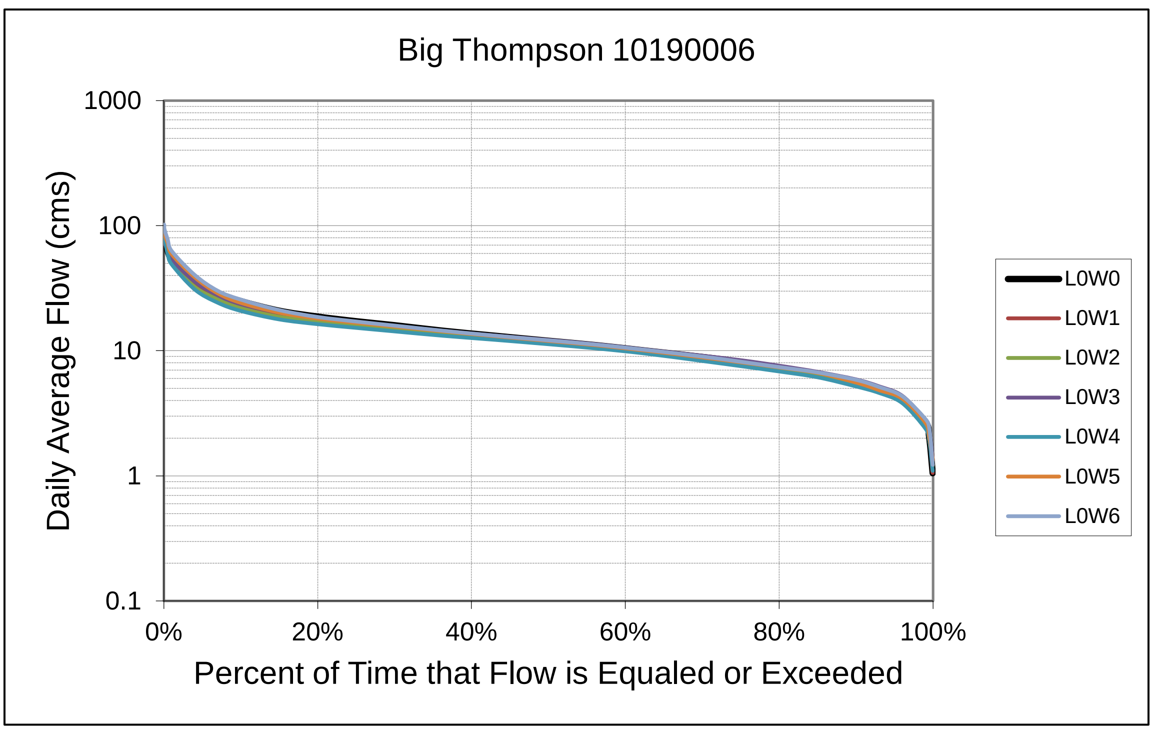


Figure 318. Flow duration, Big Thompson River (SWAT)

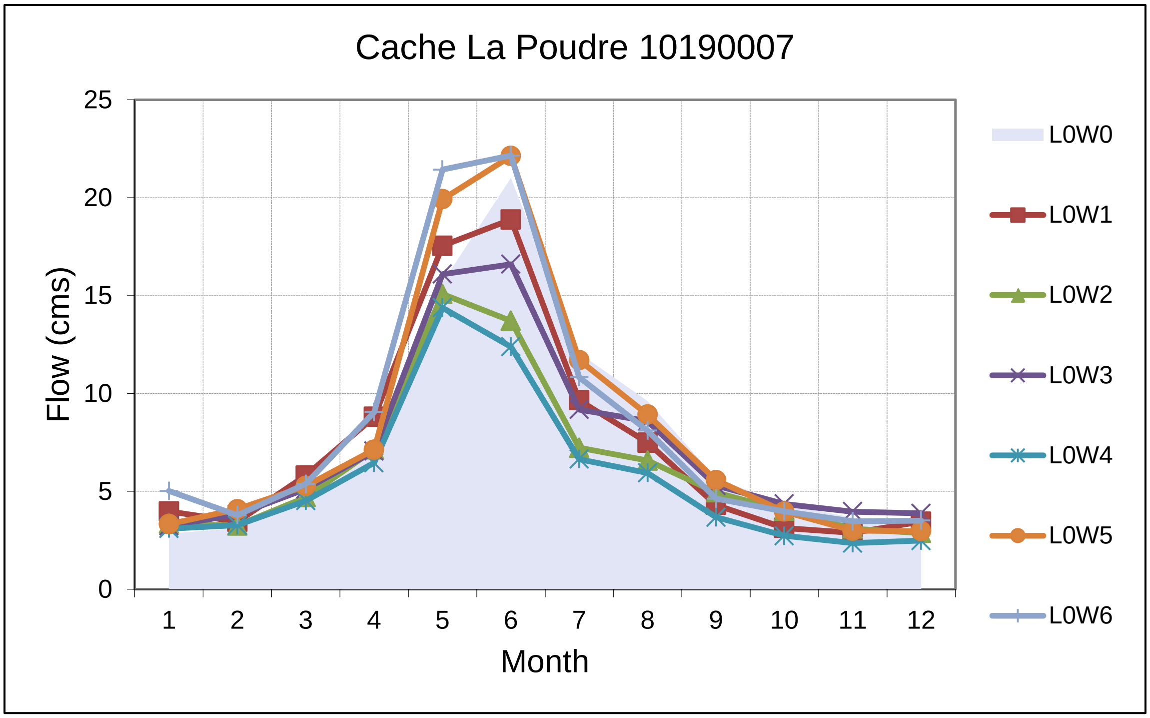


Figure 319. Monthly average flows, Cache La Poudre River (SWAT)

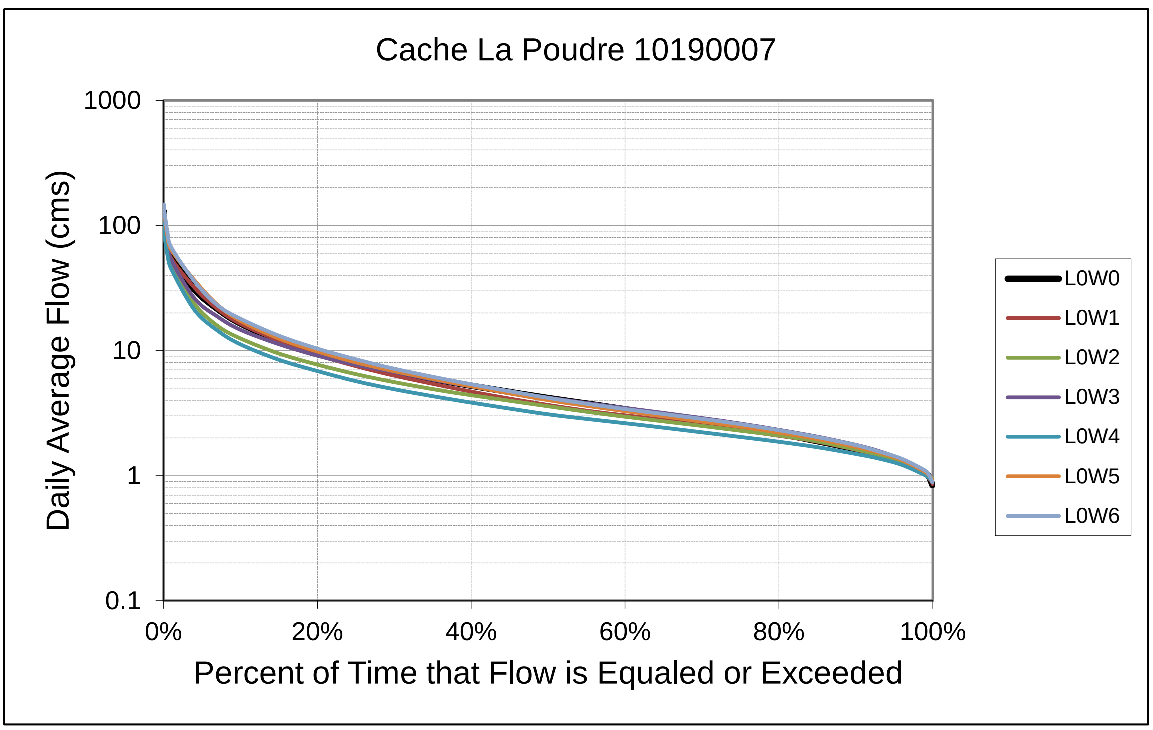


Figure 320. Flow duration, Cache La Poudre River (SWAT)

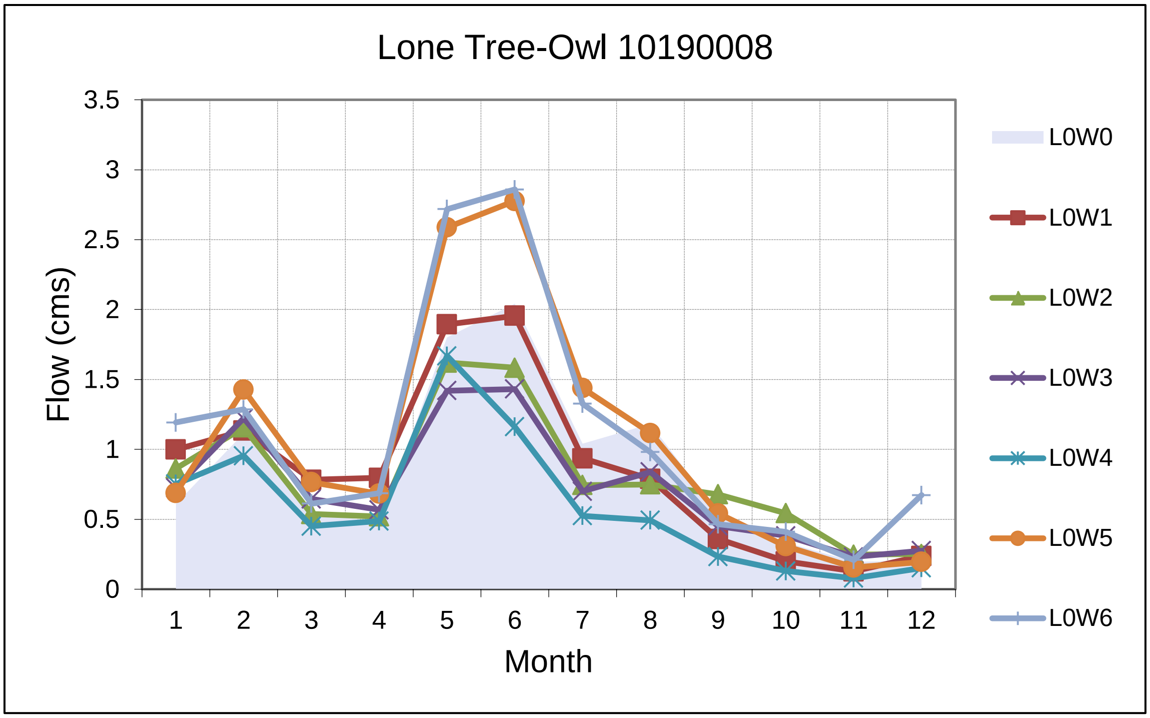


Figure 321. **Monthly average flows, Lone Tree - Owl (SWAT)**

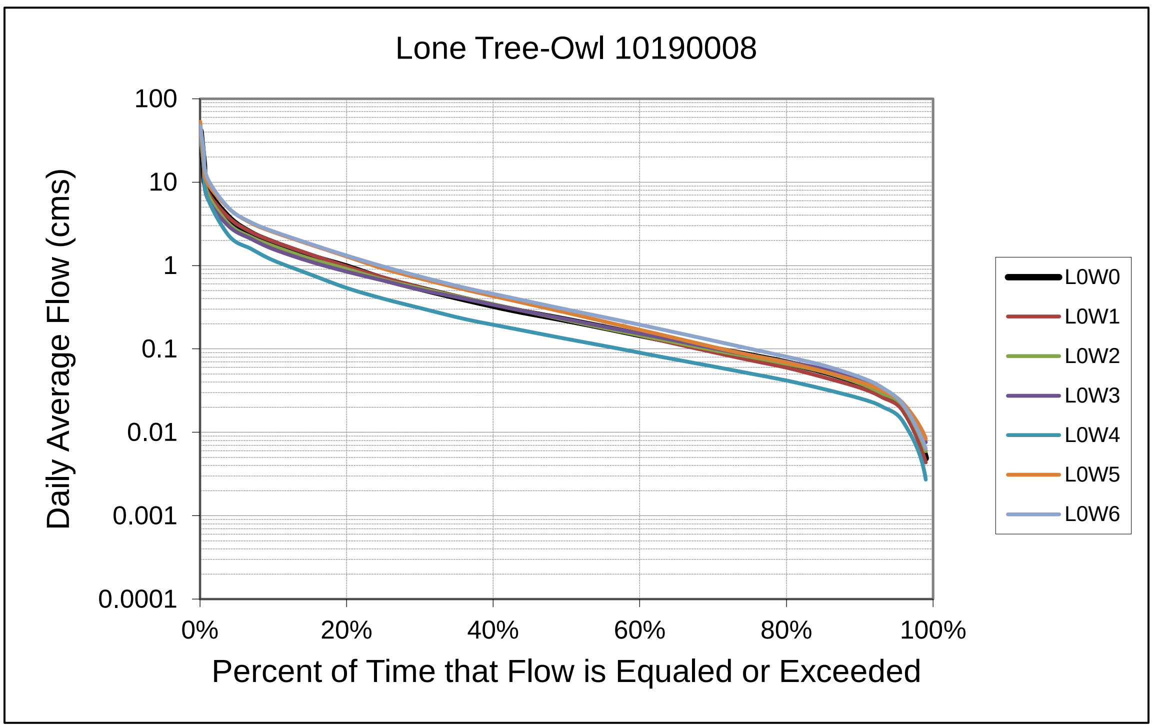


Figure 322. **Flow duration, Lone Tree - Owl (SWAT)**

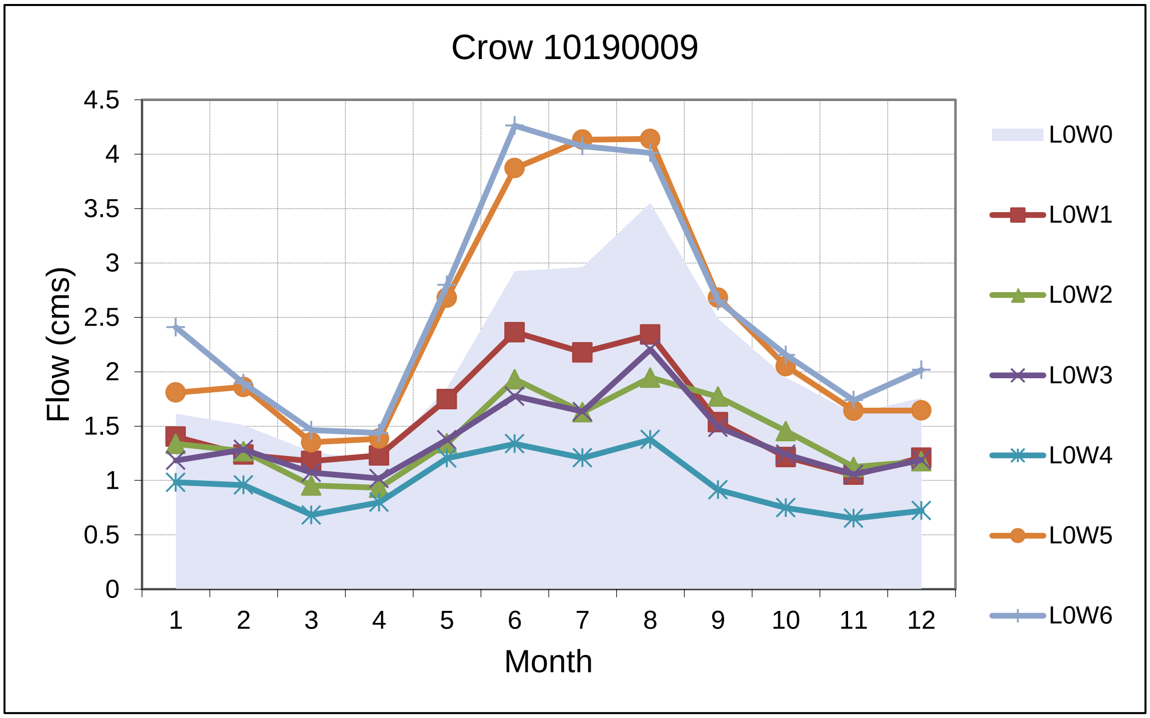


Figure 323. **Monthly average flows, Crow River (SWAT)**

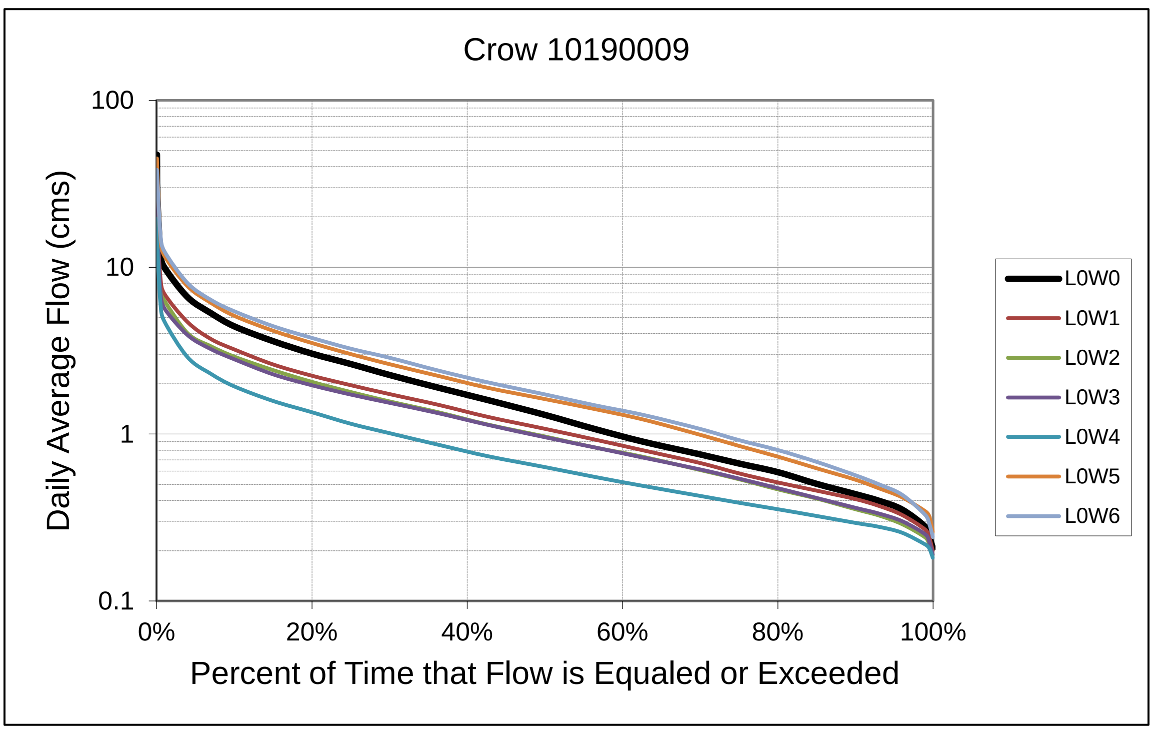


Figure 324. **Flow duration, Crow River (SWAT)**

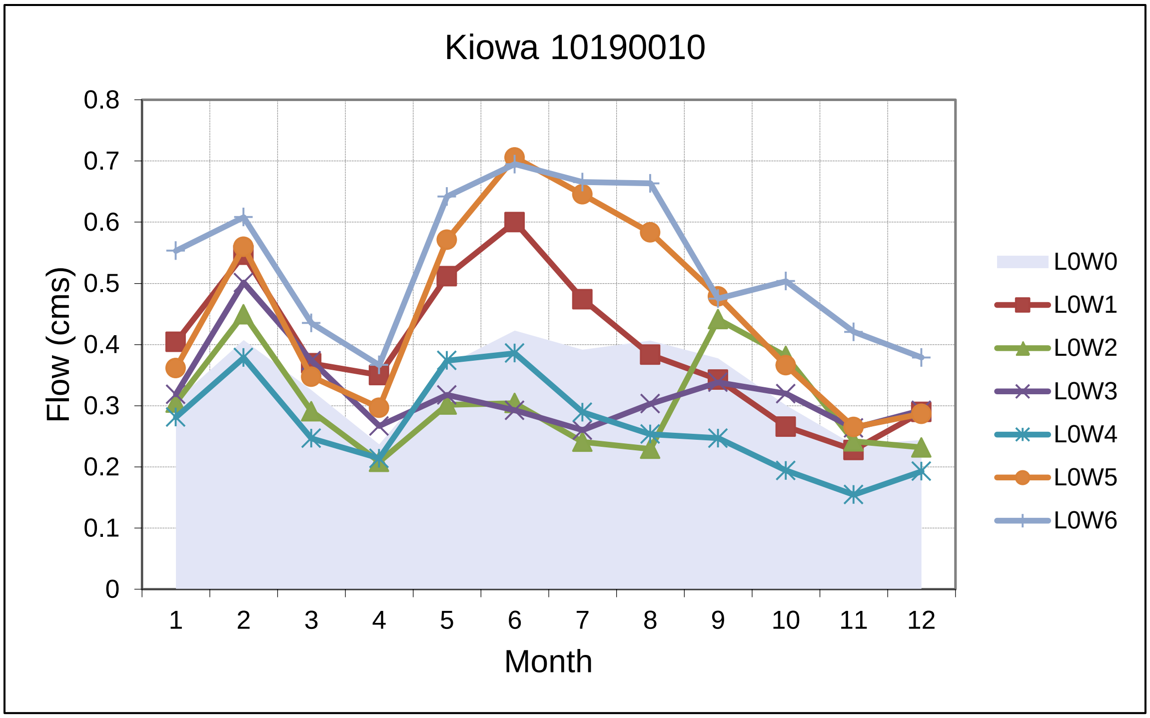


Figure 325. **Monthly average flows, Kiowa River (SWAT)**

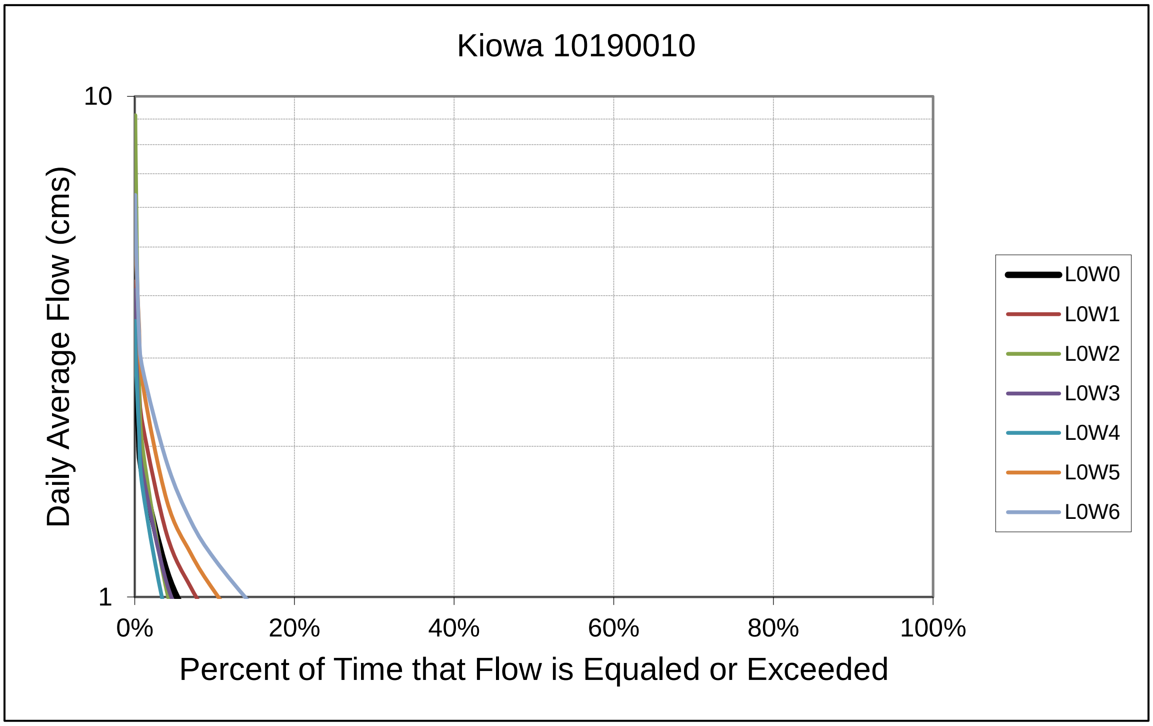


Figure 326. **Flow duration, Kiowa River (SWAT)**

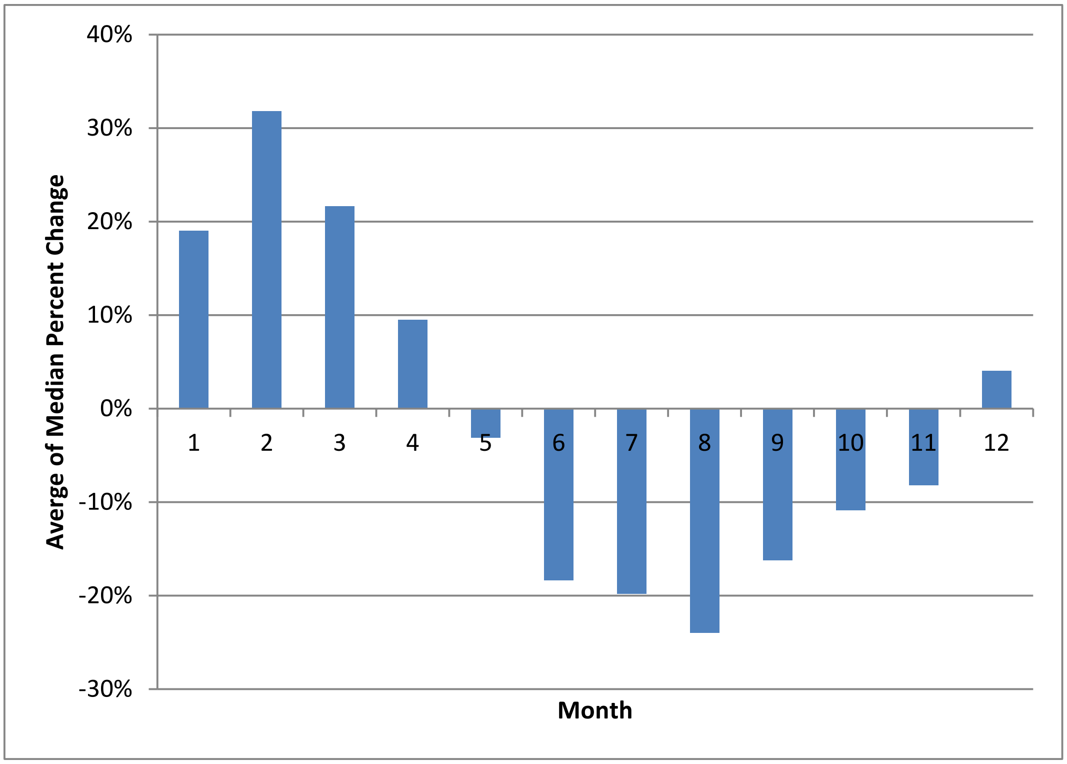


Figure 327. Average of median percent change in flow; NARCCAP Scenarios W1-W6 at all stations, South Platte River watershed (SWAT)

Powder and Tongue Rivers Basins

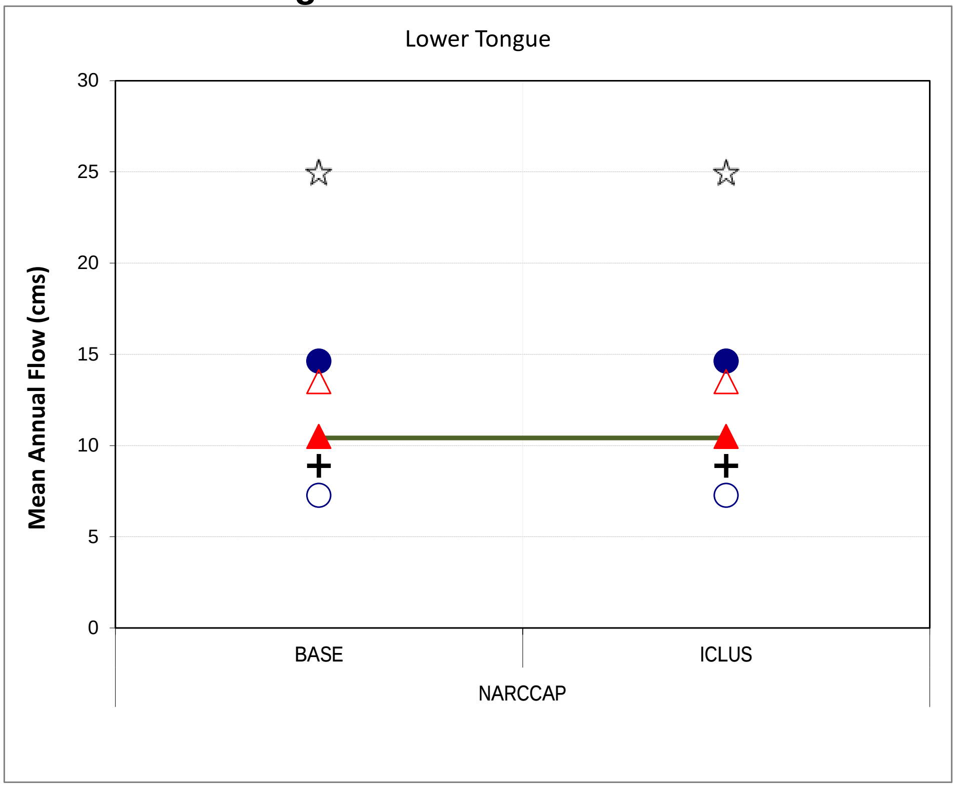


Figure 328. Mean annual flow (cms), Lower Tongue River (SWAT)

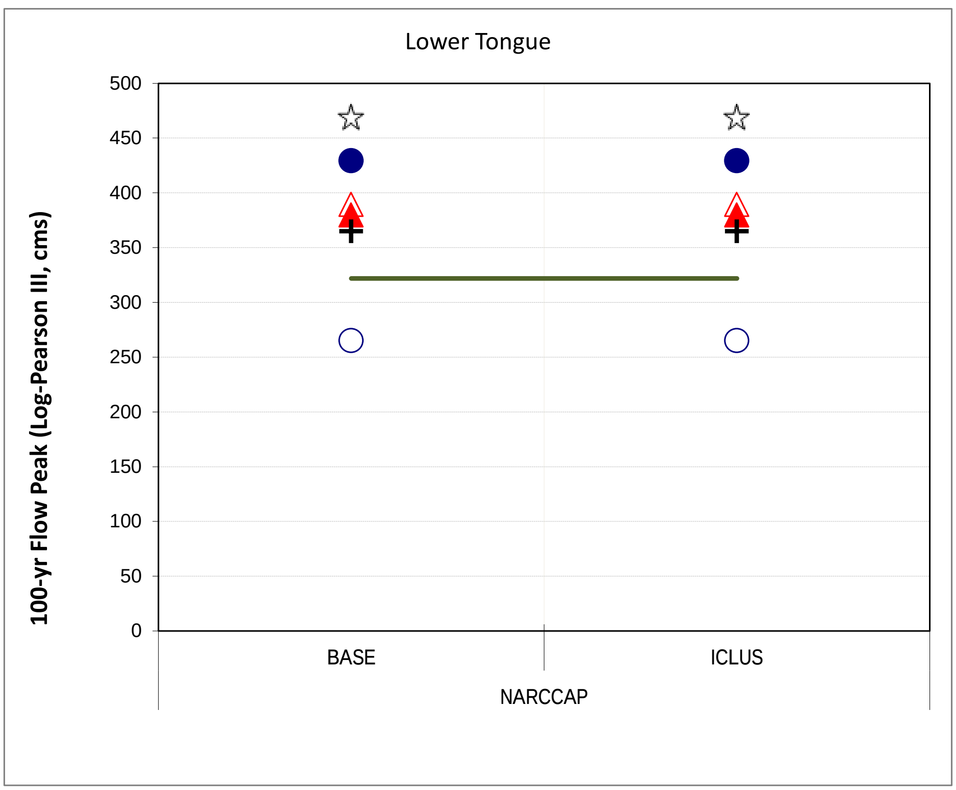


Figure 329. 100-yr Flow Peak (Log-Pearson III, cms), Lower Tongue River (SWAT)

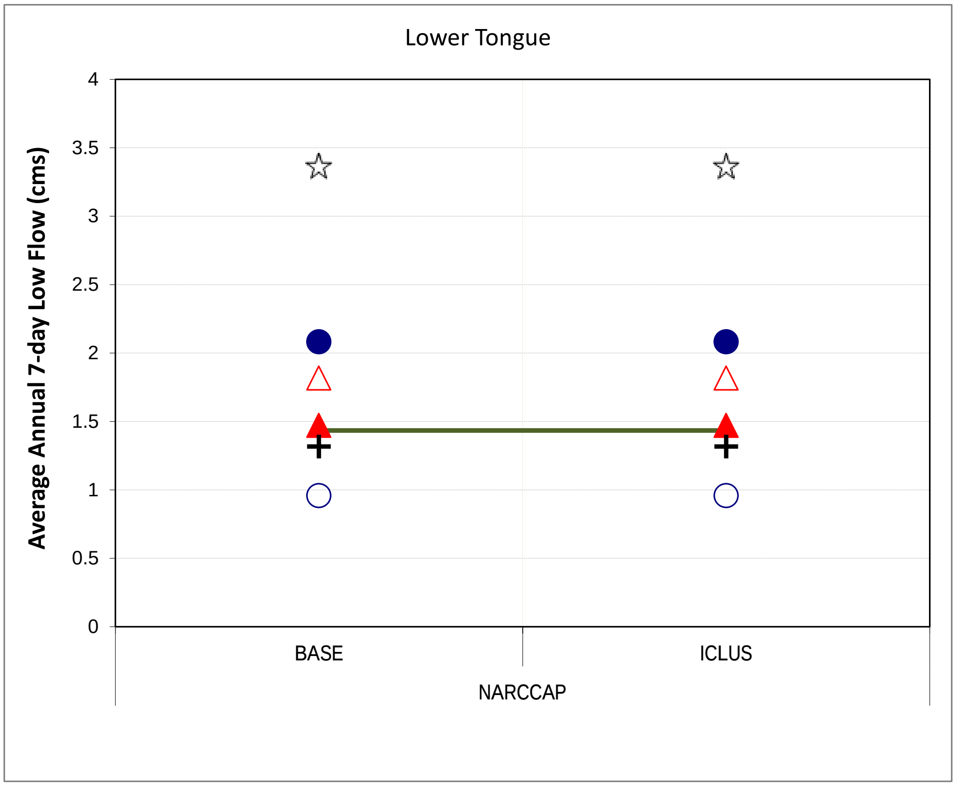


Figure 330. **Average Annual 7-day Low Flow (cms), Lower Tongue River (SWAT)**

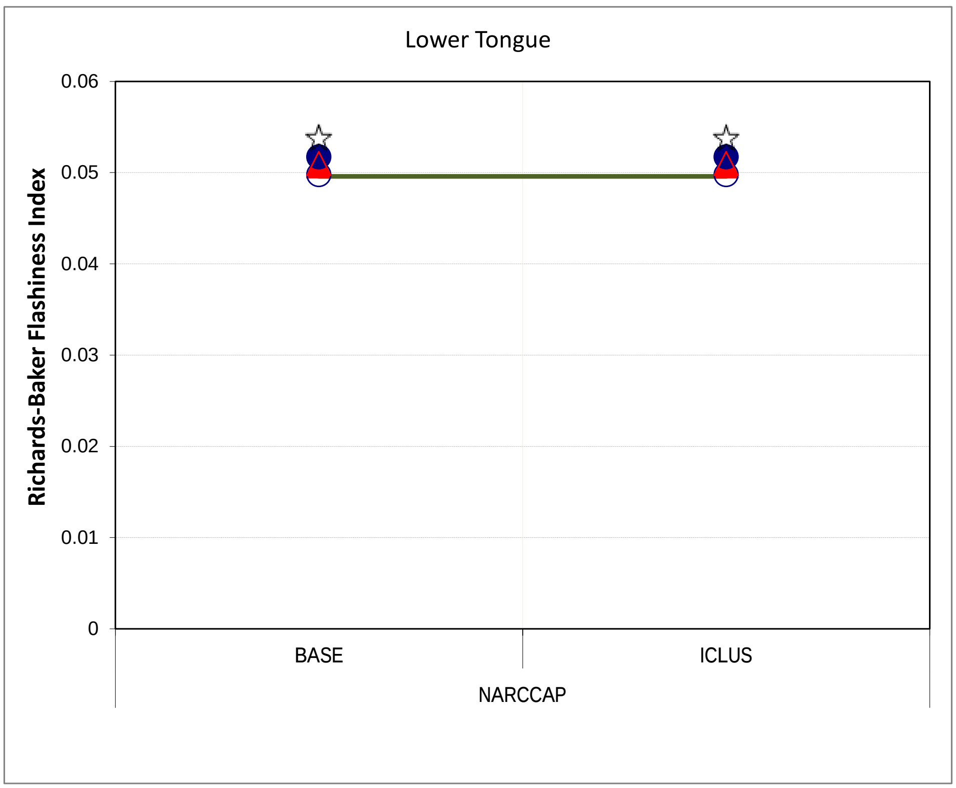


Figure 331. **Richards-Baker Flashiness Index, Average Annual 7-day Low Flow (cms), Lower Tongue River (SWAT)**

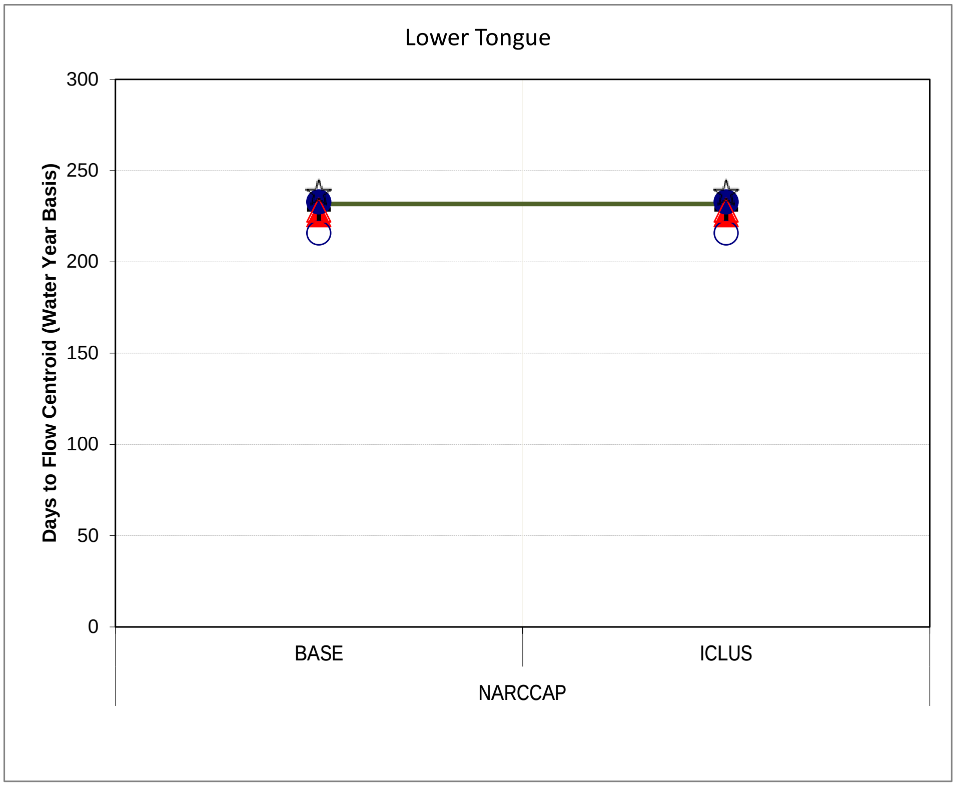


Figure 332. Days to Flow Centroid (Water Year Basis), Lower Tongue River (SWAT)

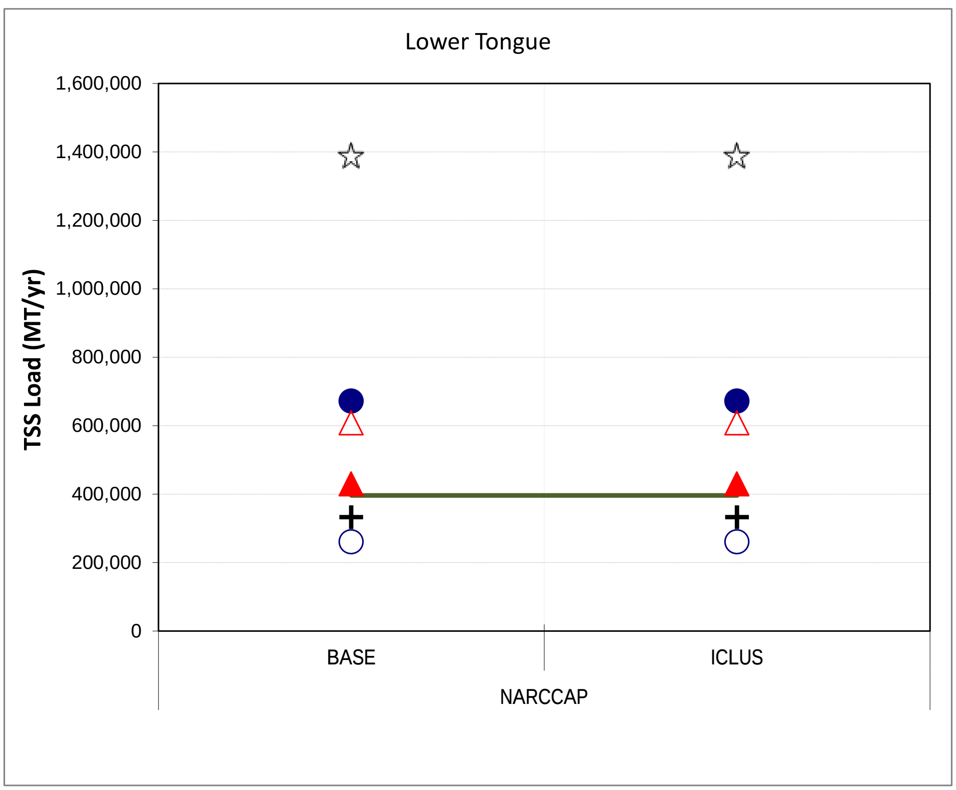


Figure 333. TSS Load (MT/yr), Lower Tongue River (SWAT)

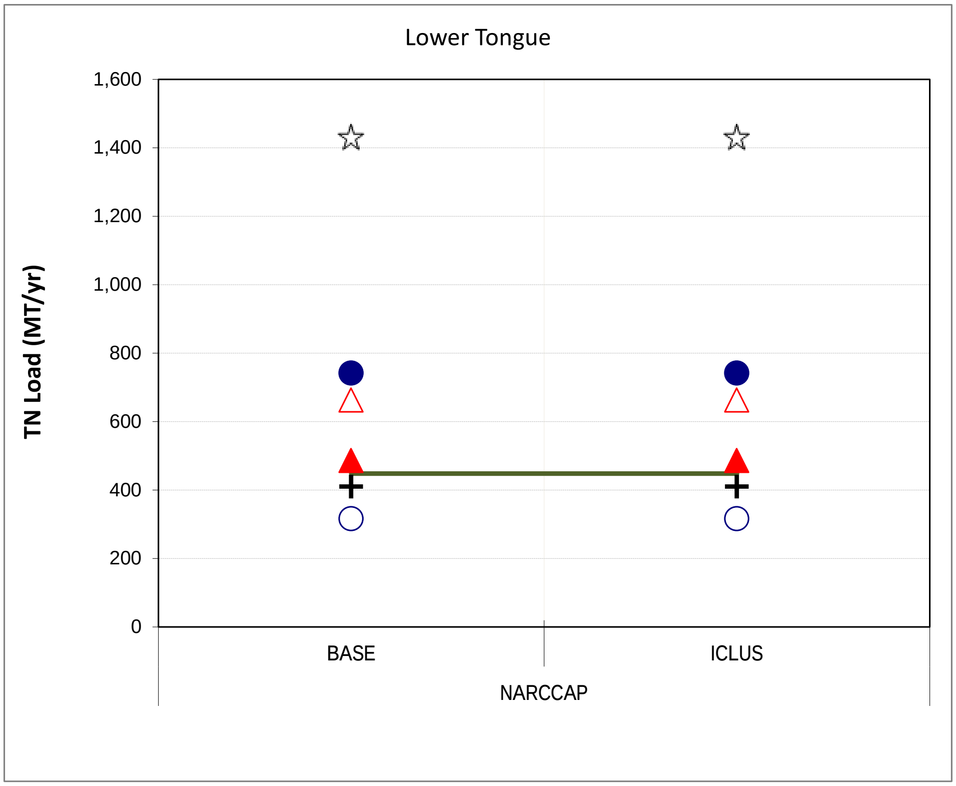


Figure 334. **TN Load (MT/yr), Lower Tongue River (SWAT)**

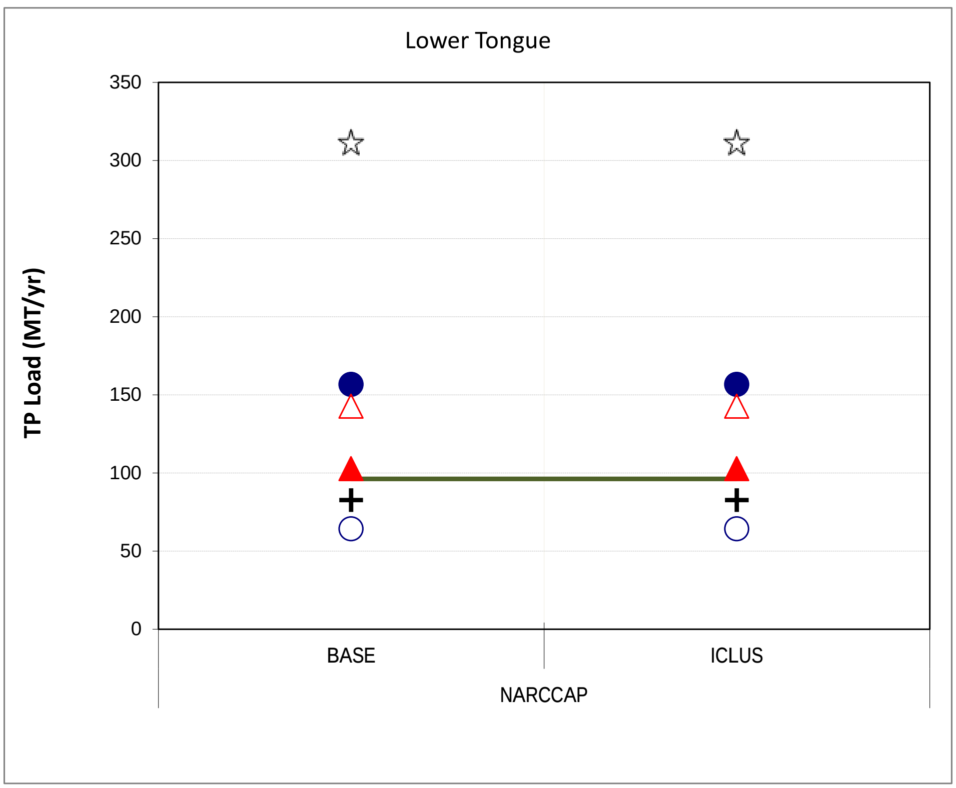


Figure 335. **TP Load (MT/yr), Lower Tongue River (SWAT)**

Table 13. Summary of range of change relative to existing conditions for NARCCAP dynamically downscaled scenarios, Tongue and Powder Rivers watershed SWAT model

	Results without LU change				Results with LU change			
	Min	Median	Mean	Max	Min	Median	Mean	Max
Lower Powder, Mizpah HUCs 10090209 and 10090210								
Flow	-40.04%	39.41%	54.43%	206.01%	-40.04%	39.41%	54.43%	206.01%
TSS	-59.86%	49.18%	85.32%	334.52%	-59.86%	49.18%	85.32%	334.52%
TN	-56.12%	50.82%	84.84%	330.85%	-56.12%	50.82%	84.84%	330.85%
TP	-56.62%	50.83%	84.75%	330.05%	-56.62%	50.83%	84.75%	330.05%
Clear								
Flow	-19.63%	4.99%	4.82%	29.73%	-19.63%	4.99%	4.82%	29.73%
TSS	-5.88%	12.61%	62.14%	301.52%	-5.88%	12.61%	62.14%	301.52%
TN	11.60%	25.40%	27.42%	48.89%	11.60%	25.40%	27.42%	48.89%
TP	15.41%	35.94%	34.72%	49.70%	15.41%	35.94%	34.72%	49.70%
Little Powder HUC 10090208								
Flow	-42.49%	35.37%	36.98%	126.23%	-42.49%	35.37%	36.98%	126.23%
TSS	78.30%	118.86 %	151.59%	256.12%	78.30%	118.86 %	151.59%	256.12%
TN	10.22%	60.13%	92.36%	309.15%	10.22%	60.13%	92.36%	309.15%
TP	24.32%	53.31%	76.22%	217.07%	24.32%	53.31%	76.22%	217.07%
Middle Powder HUC 10090207								
Flow	-30.51%	12.35%	16.60%	78.80%	-30.51%	12.35%	16.60%	78.80%
TSS	124.73%	401.48 %	476.52%	1109.71 %	124.73 %	401.48 %	476.52%	1109.71 %
TN	41.30%	54.59%	72.29%	168.12%	41.30%	54.59%	72.29%	168.12%
TP	47.19%	56.45%	67.49%	122.45%	47.19%	56.45%	67.49%	122.45%
Crazy Woman HUC 10090205								
-28.57%	12.33%	15.34%	72.52%	-28.57%	12.33%	15.34%	72.52%	-28.57%
-34.19%	4.31%	5.63%	49.86%	-34.19%	4.31%	5.63%	49.86%	-34.19%
-19.99%	-11.98%	1.35%	63.51%	-19.99%	-11.98%	1.35%	63.51%	-19.99%
-35.99%	-6.97%	1.35%	59.84%	-35.99%	-6.97%	1.35%	59.84%	-35.99%
Upper Powder HUC 10090202								
Flow	-32.36%	7.45%	10.07%	61.02%	-32.36%	7.45%	10.07%	61.02%
TSS	27.05%	832.76 %	1020.30 %	2449.84 %	27.05%	832.76 %	1020.30 %	2449.84 %
TN	31.22%	59.06%	74.50%	135.51%	31.22%	59.06%	74.50%	135.51%
TP	28.92%	65.83%	68.23%	133.36%	28.92%	65.83%	68.23%	133.36%
Middle Fork Powder HUC 10090201								
Flow	-21.44%	4.03%	2.38%	23.91%	-21.44%	4.03%	2.38%	23.91%
TSS	-48.68%	-32.66%	-31.99%	-9.05%	-48.68%	-32.66%	-31.99%	-9.05%
TN	-17.76%	-4.76%	3.38%	34.70%	-17.76%	-4.76%	3.38%	34.70%
TP	-20.86%	-5.68%	1.39%	38.72%	-20.86%	-5.68%	1.39%	38.72%

S Fork Powder, Salt HUCs 10090203 and 10090204								
Flow	-30.63%	6.62%	7.66%	50.62%	-30.63%	6.62%	7.66%	50.62%
TSS	-20.89%	30.09%	363.91%	2018.84 %	-20.89%	30.09%	363.91%	2018.84 %
TN	3.98%	39.37%	32.25%	62.00%	3.98%	39.37%	32.25%	62.00%
TP	0.86%	49.86%	37.93%	67.49%	0.86%	49.86%	37.93%	67.49%
Lower Tongue HUC10090102								
Flow	-30.29%	15.13%	27.64%	140.14%	-30.29%	15.13%	27.64%	140.14%
TSS	-34.27%	30.86%	55.34%	251.20%	-34.27%	30.86%	55.34%	251.20%
TN	-29.42%	28.19%	50.61%	219.77%	-29.42%	28.19%	50.61%	219.77%
TP	-33.26%	27.48%	49.13%	224.40%	-33.26%	27.48%	49.13%	224.40%
Upper Tongue HUC 10090101								
Flow	-21.39%	0.45%	1.96%	38.77%	-21.39%	0.45%	1.96%	38.77%
TSS	6.84%	32.12%	43.35%	110.24%	6.84%	32.12%	43.35%	110.24%
TN	-19.96%	-4.64%	3.63%	51.81%	-19.96%	-4.64%	3.63%	51.81%
TP	-15.22%	-1.98%	8.30%	63.19%	-15.22%	-1.98%	8.30%	63.19%
Powder at Moorhead (gage 06324500)								
Flow	-26.90%	6.09%	7.84%	47.48%	-26.90%	6.09%	7.84%	47.48%
TSS	121.64%	375.40 %	510.94%	1317.64 %	121.64 %	375.40 %	510.94%	1317.64 %
TN	31.50%	46.23%	51.80%	90.53%	31.50%	46.23%	51.80%	90.53%
TP	33.81%	56.51%	53.93%	73.64%	33.81%	56.51%	53.93%	73.64%
Powder at Locate (gage 06326500)								
Flow	-40.81%	36.36%	50.16%	192.44%	-40.81%	36.36%	50.16%	192.44%
TSS	-58.53%	46.17%	79.14%	309.85%	-58.53%	46.17%	79.14%	309.85%
TN	-54.12%	47.52%	78.69%	304.85%	-54.12%	47.52%	78.69%	304.85%
TP	-54.91%	47.42%	78.49%	303.61%	-54.91%	47.42%	78.49%	303.61%
Tongue at State Line (gage 06306300)								
Flow	-19.50%	-4.37%	-3.34%	21.00%	-19.50%	-4.37%	-3.34%	21.00%
TSS	-78.56%	-73.08%	-69.76%	-57.96%	-78.56%	-73.08%	-69.76%	-57.96%
TN	-51.92%	-33.13%	-26.82%	18.82%	-51.92%	-33.13%	-26.82%	18.82%
TP	-47.25%	-28.61%	-20.26%	33.03%	-47.25%	-28.61%	-20.26%	33.03%

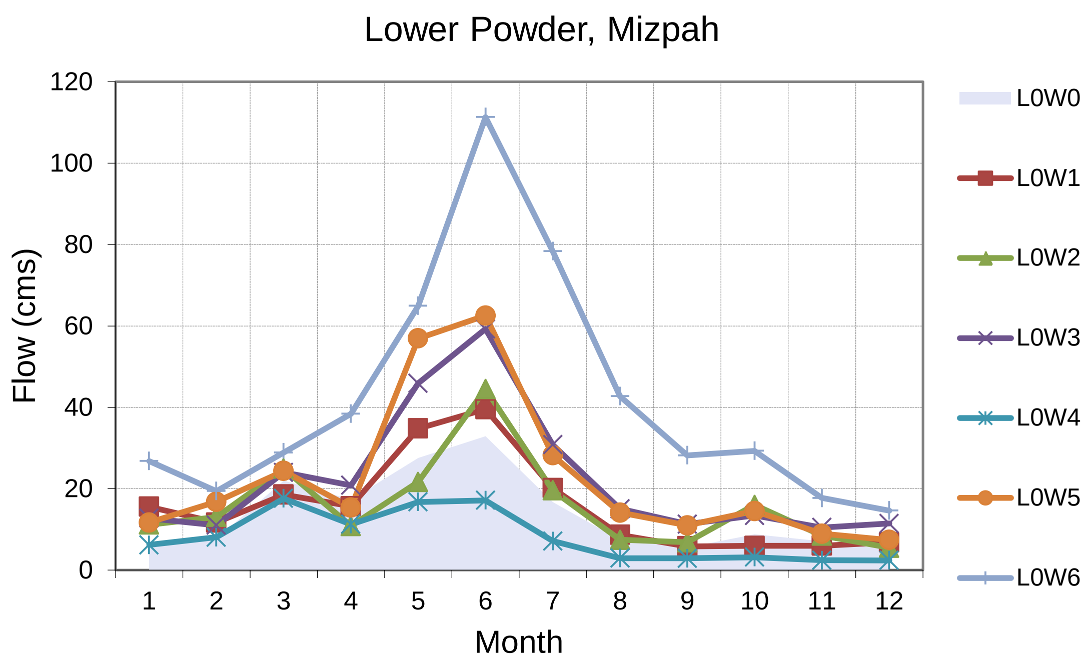


Figure 336. **Monthly average flows, Lower Powder River (SWAT)**

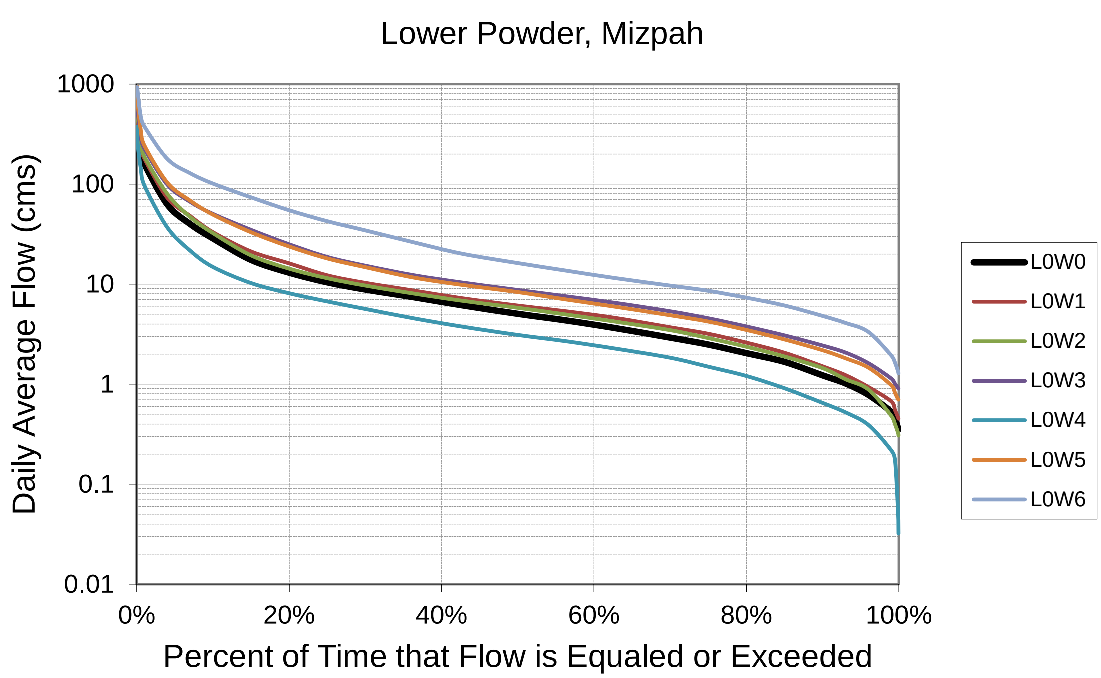


Figure 337. **Flow duration, Lower Powder River (SWAT)**

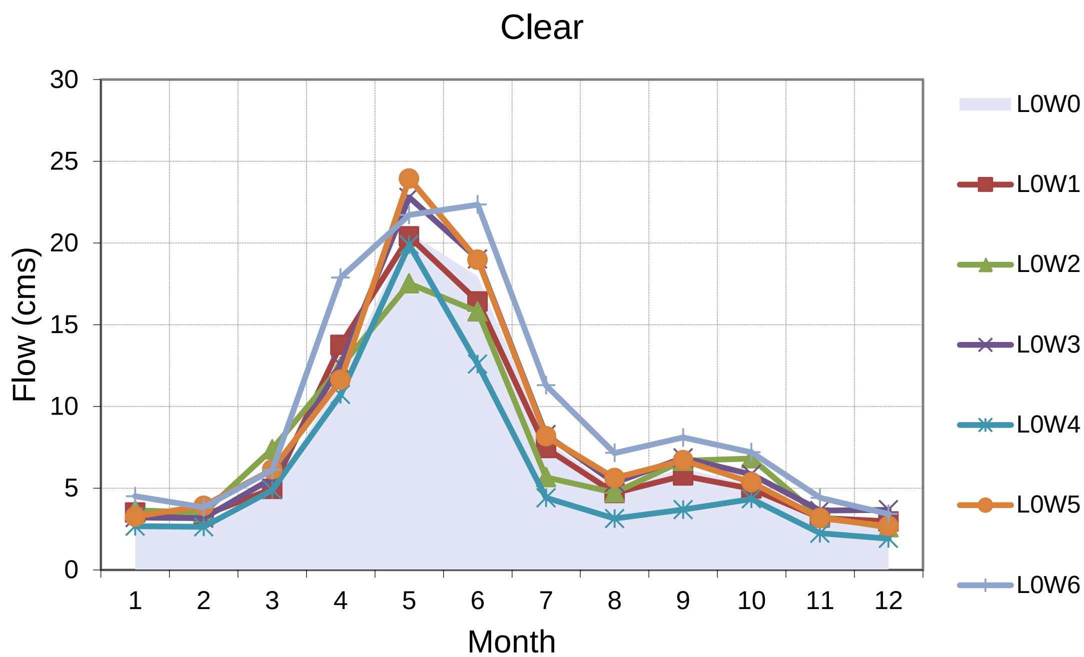


Figure 338. Monthly average flows, Clear Creek (SWAT)

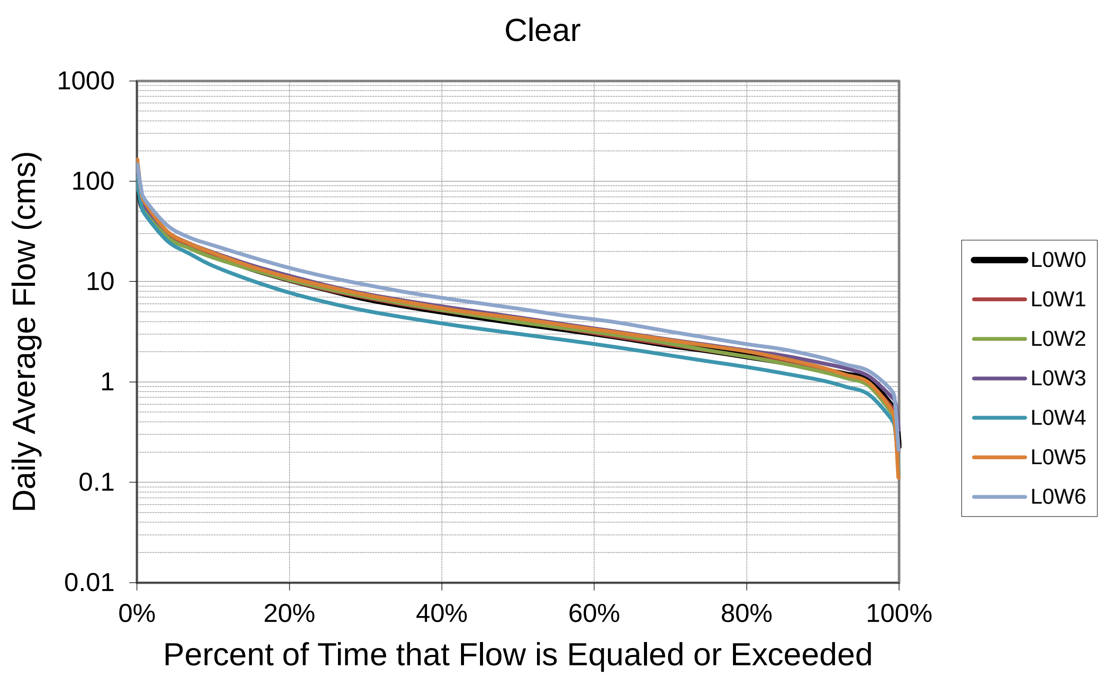


Figure 339. Flow duration, Clear Creek (SWAT)

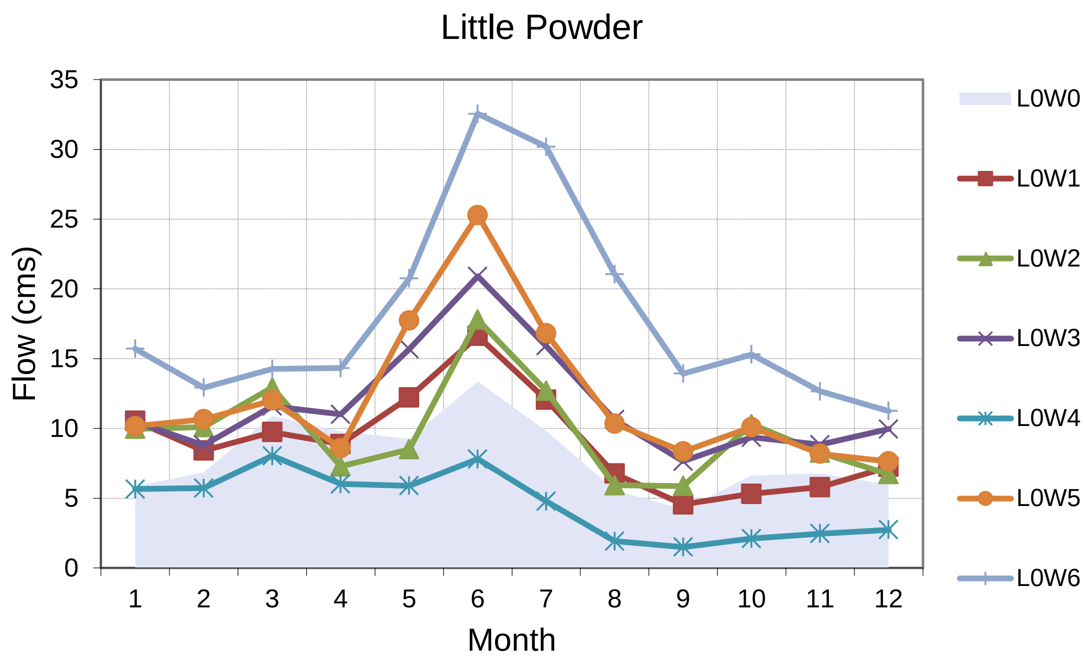


Figure 340. **Monthly average flows, Little Powder River (SWAT)**

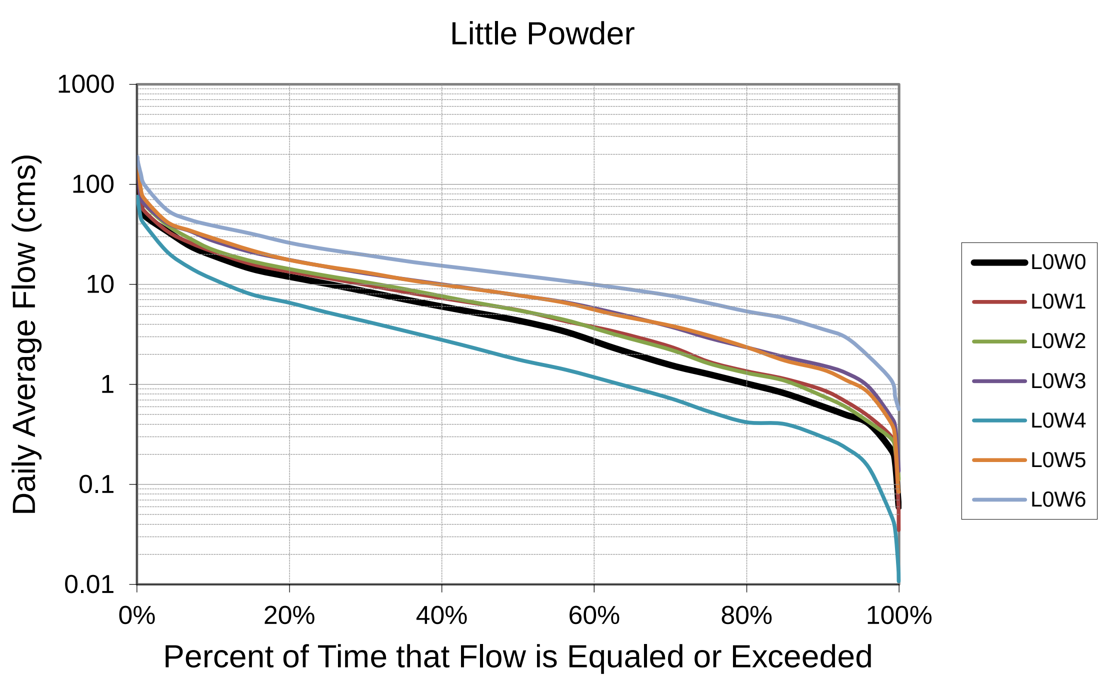


Figure 341. **Flow duration, Little Powder River (SWAT)**

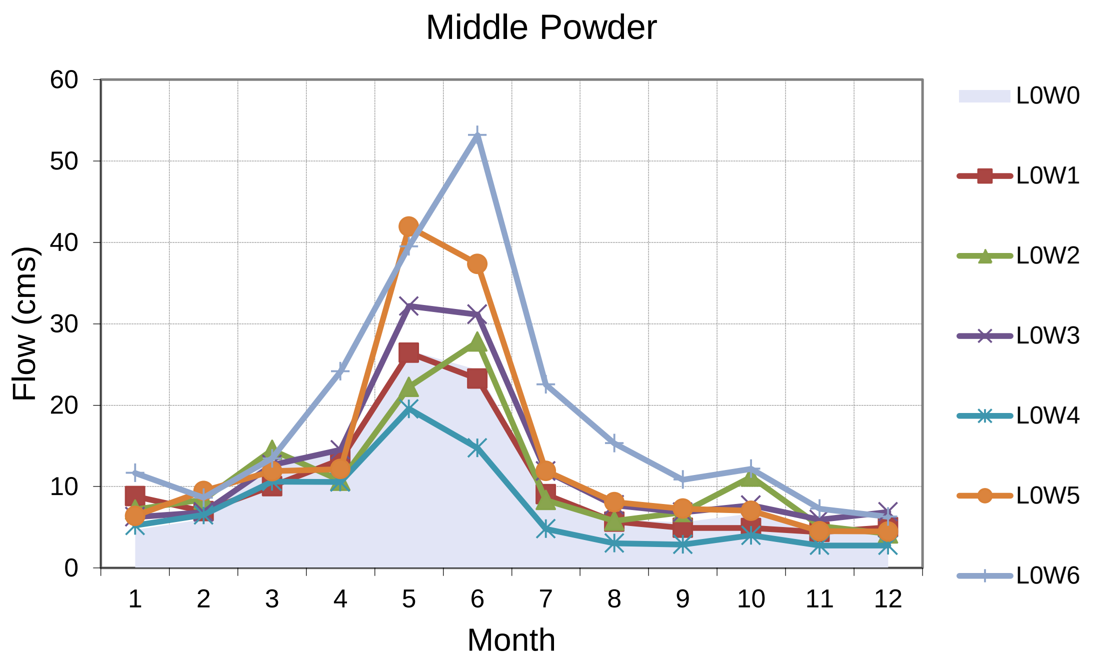


Figure 342. **Monthly average flows, Middle Powder River (SWAT)**

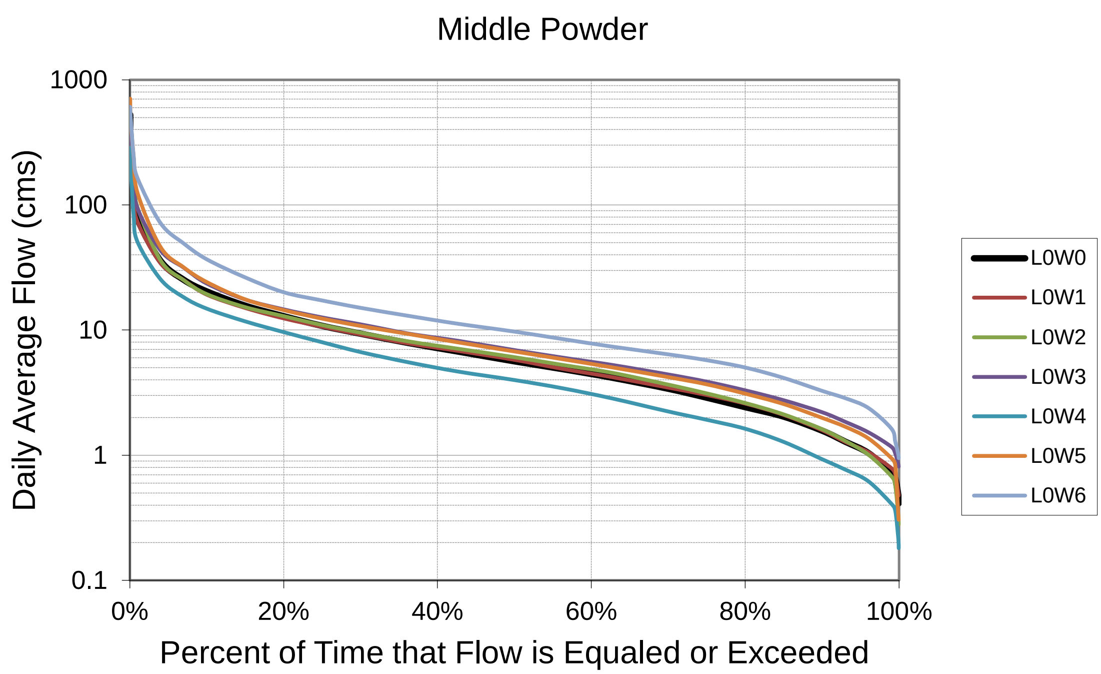


Figure 343. **Flow duration, Middle Powder River (SWAT)**

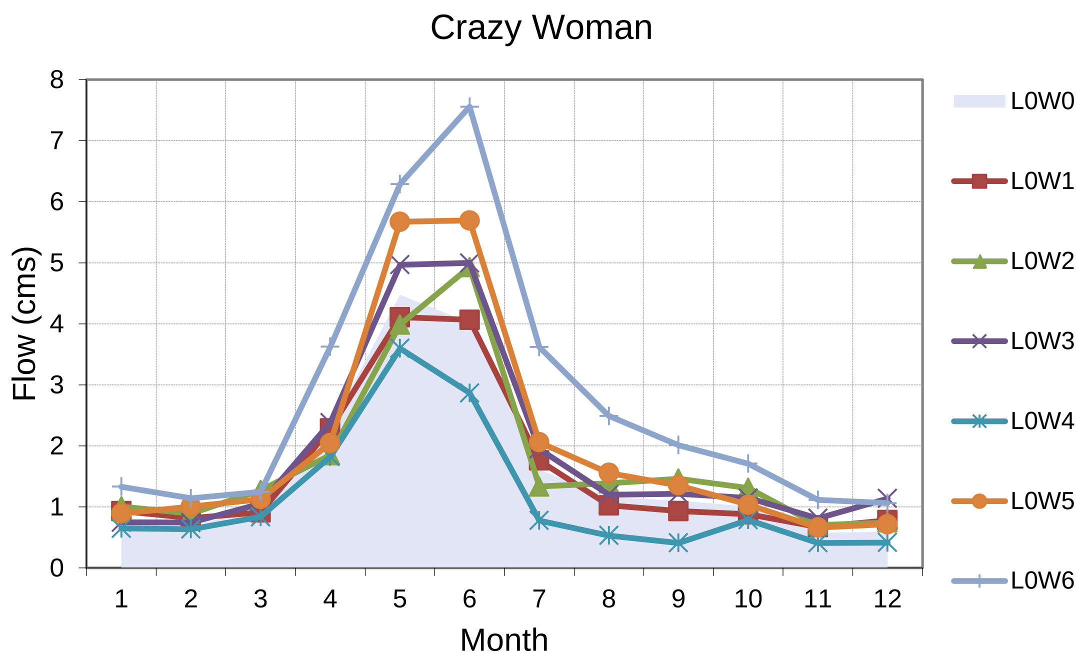


Figure 344. **Monthly average flows, Crazy Woman Creek (SWAT)**

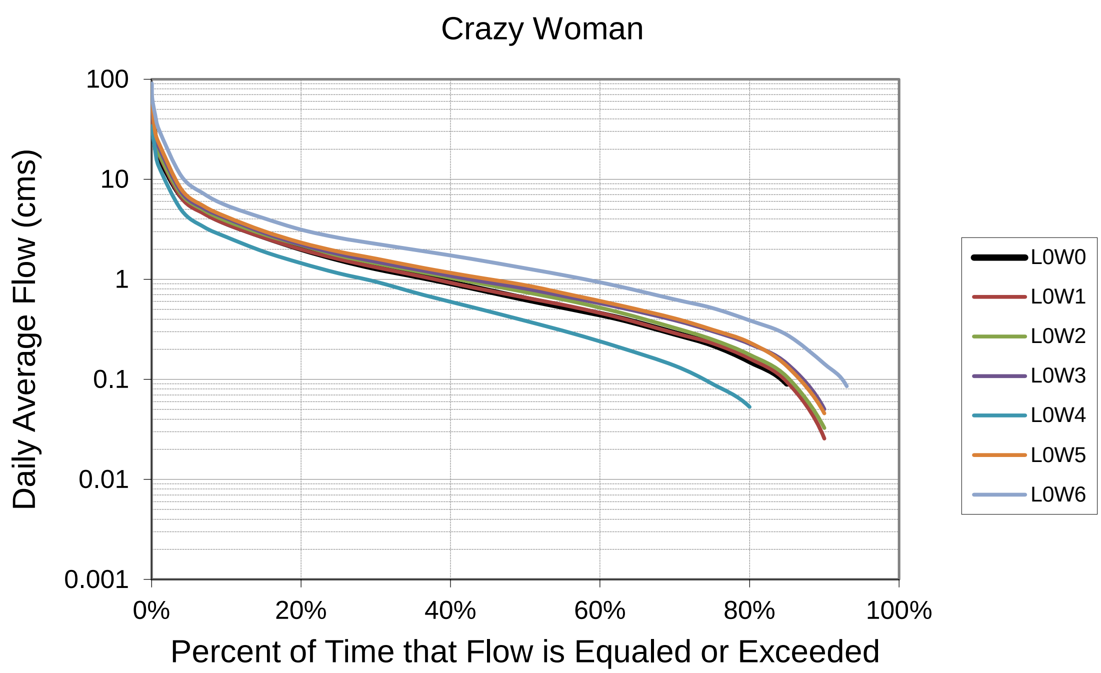


Figure 345. **Flow duration, Crazy Woman Creek (SWAT)**

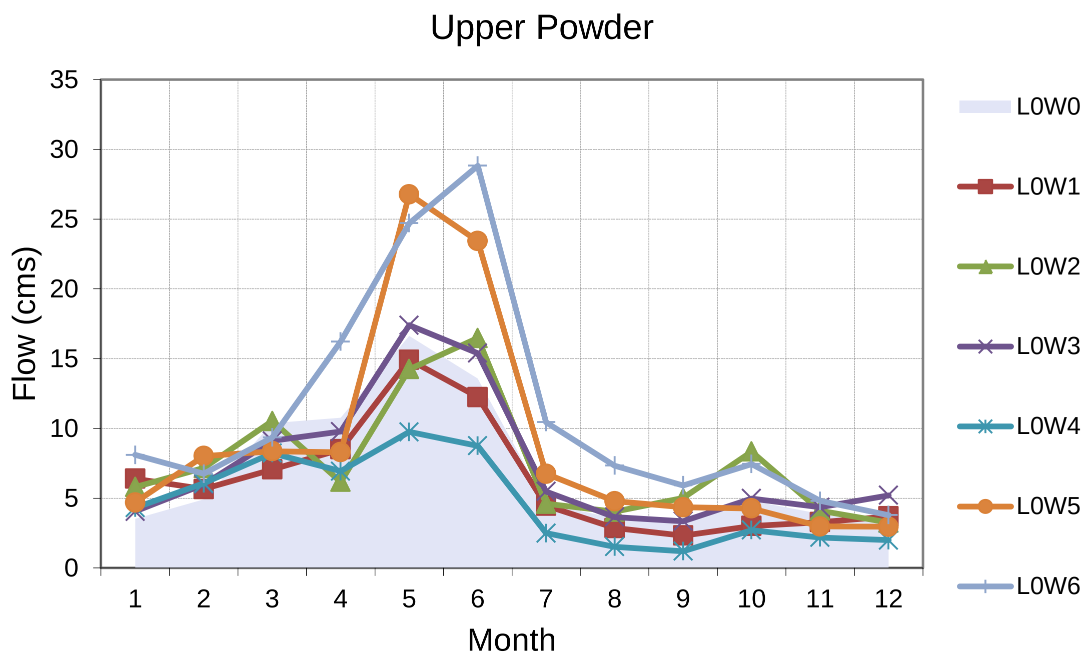


Figure 346. Monthly average flows, Upper Powder River (SWAT)

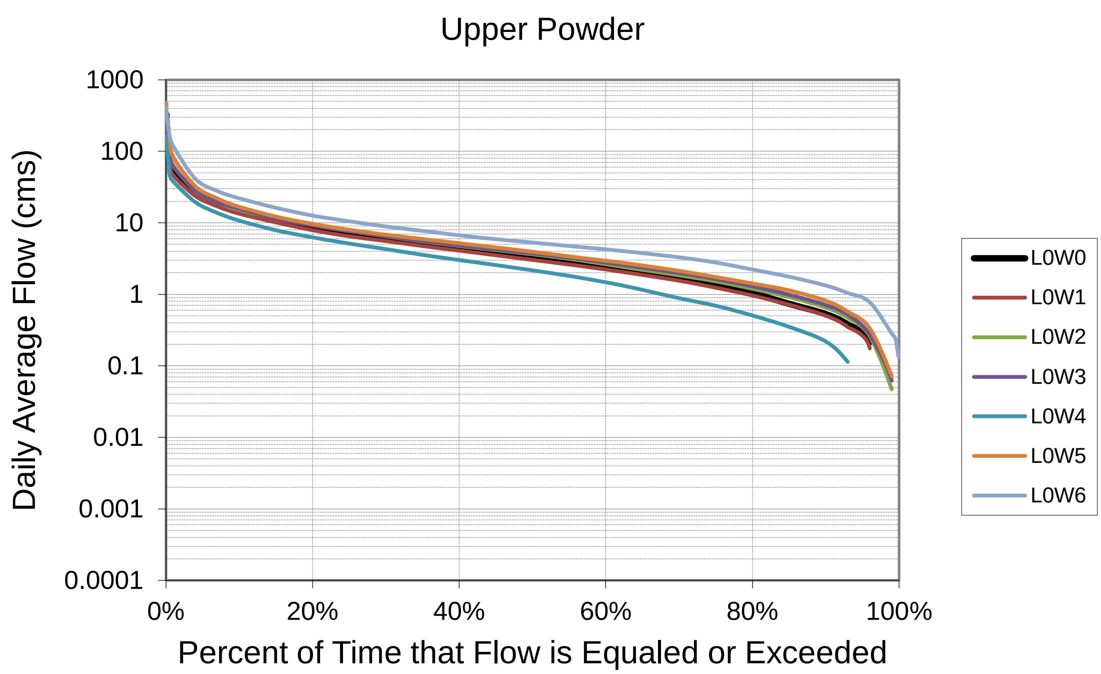


Figure 347. Flow duration, Upper Powder River (SWAT)

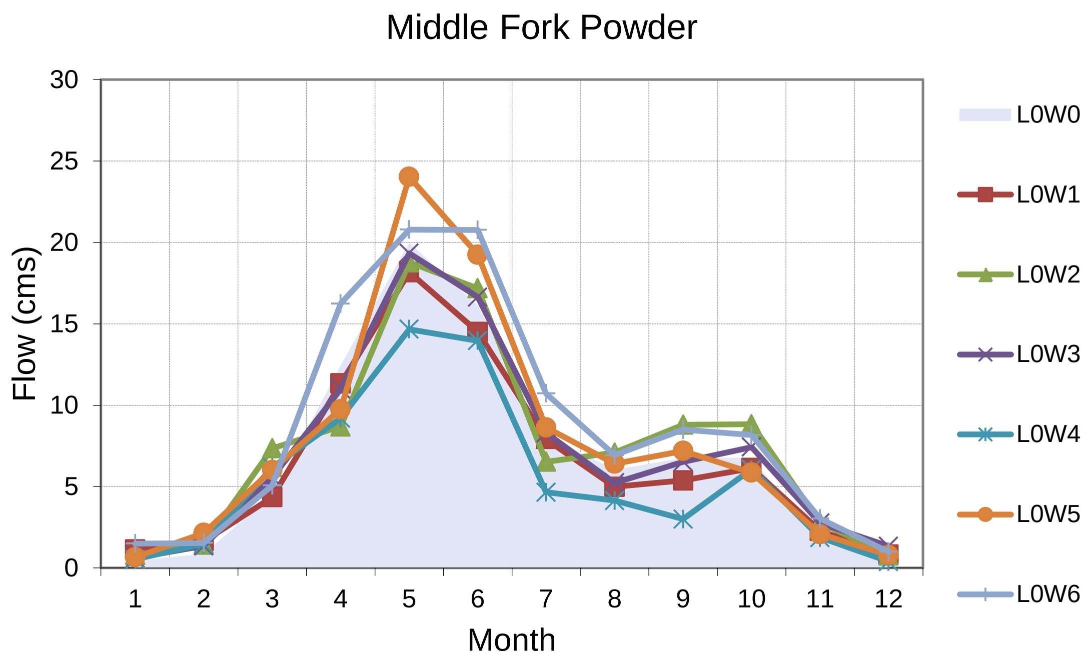


Figure 348. **Monthly average flows, Middle Fork Powder River (SWAT)**

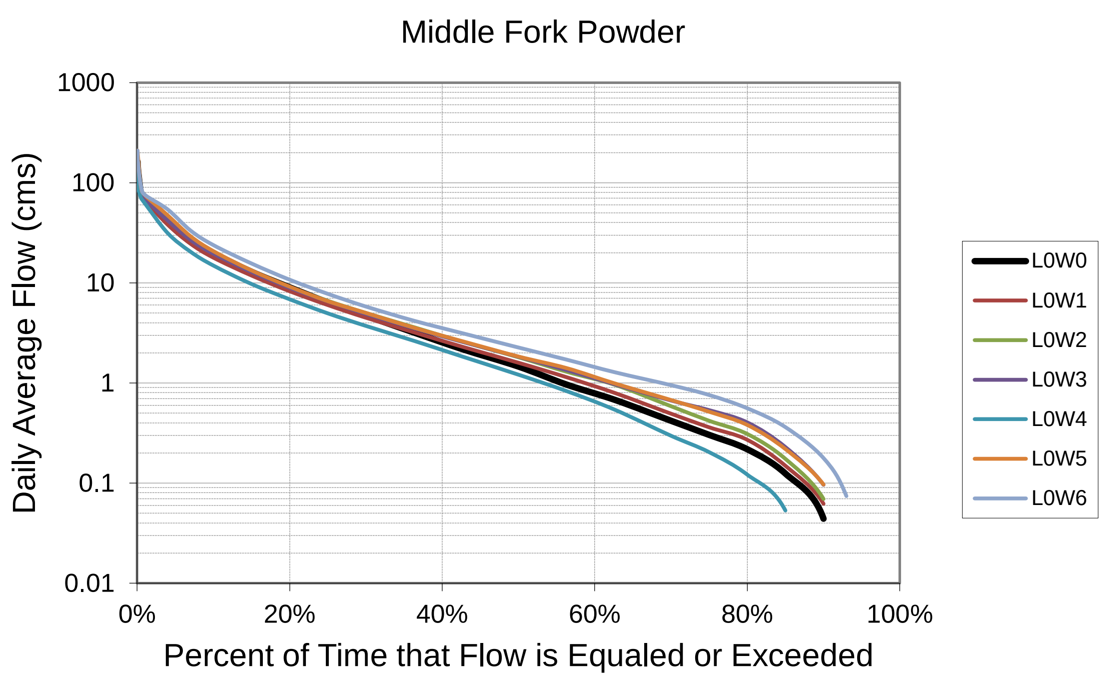


Figure 349. **Flow duration, Middle Fork Powder River (SWAT)**

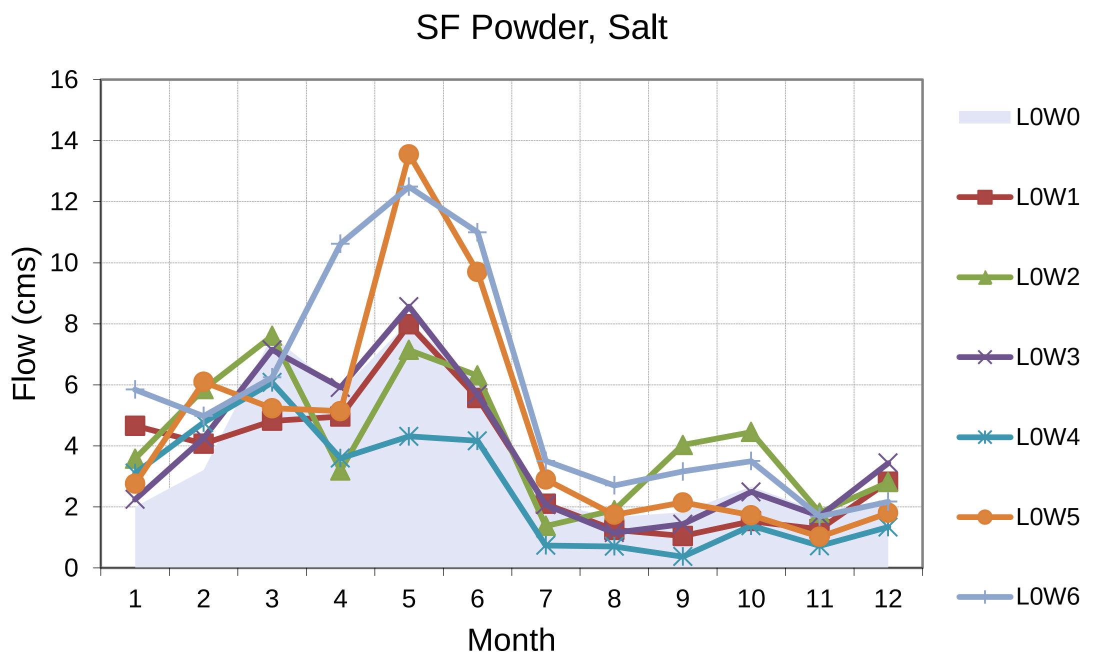


Figure 350. **Monthly average flows, South Fork Powder River (SWAT)**

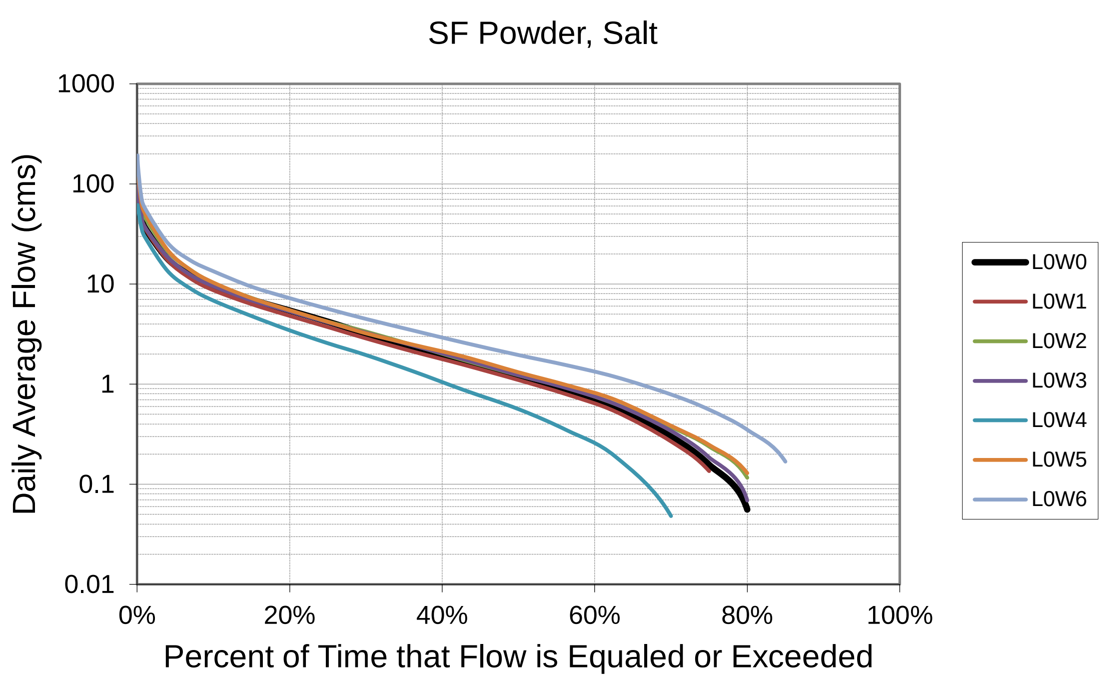


Figure 351. **Flow duration, South Fork Powder River (SWAT)**

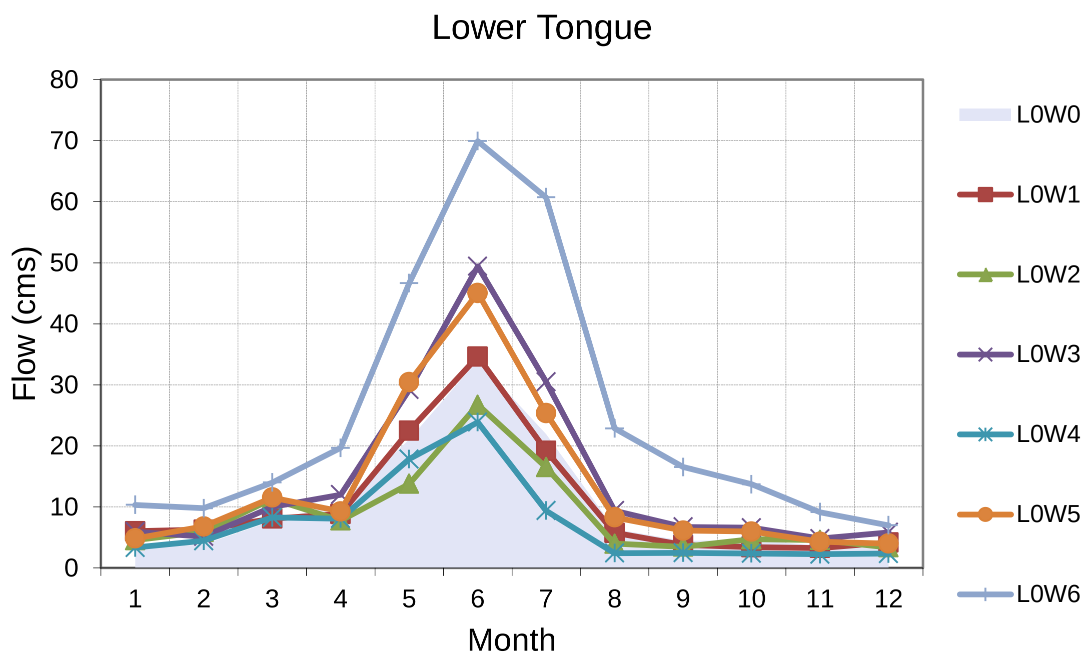


Figure 352. **Monthly average flows, Lower Tongue River (SWAT)**

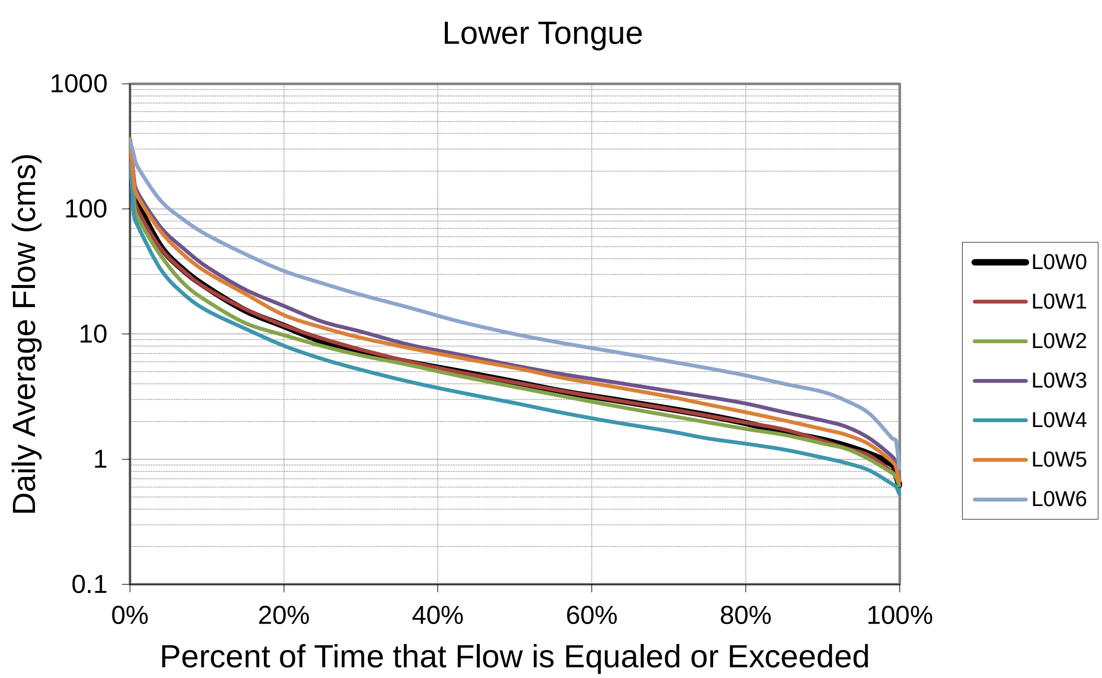


Figure 353. **Flow duration, Lower Tongue River (SWAT)**

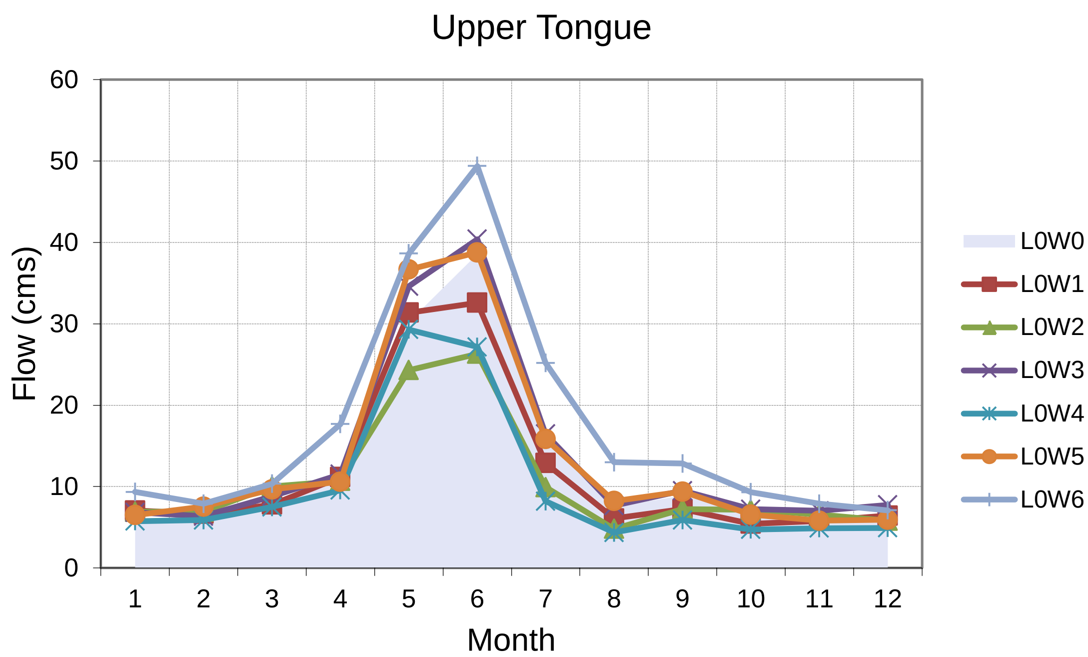


Figure 354. **Monthly average flows, Upper Tongue River (SWAT)**

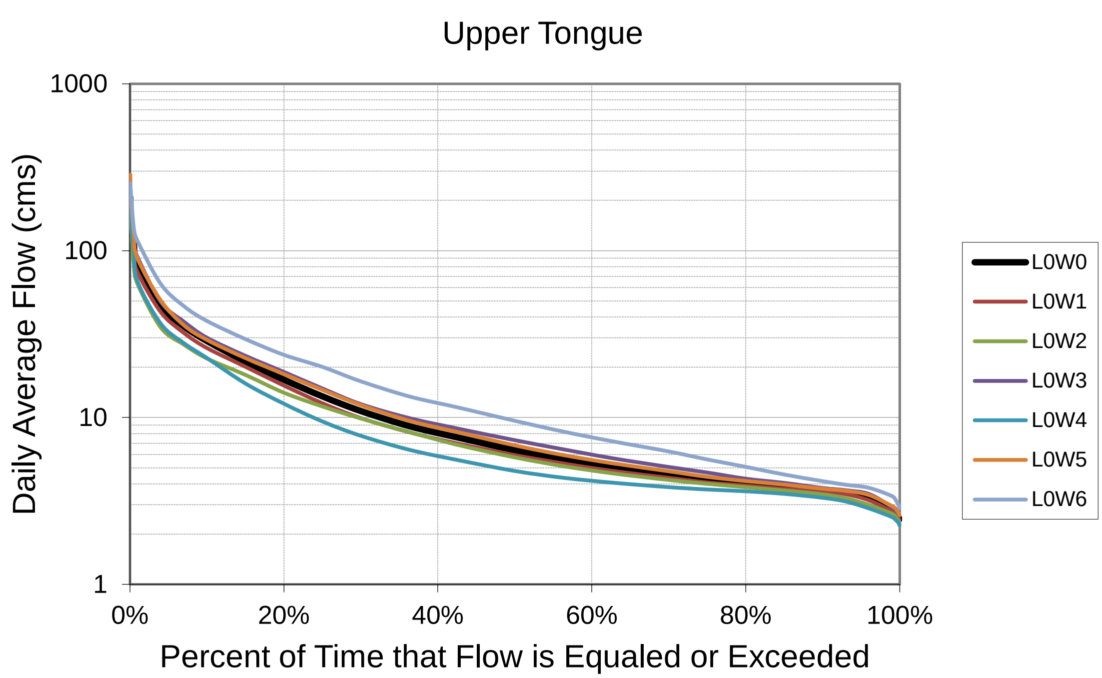


Figure 355. **Flow duration, Upper Tongue River (SWAT)**

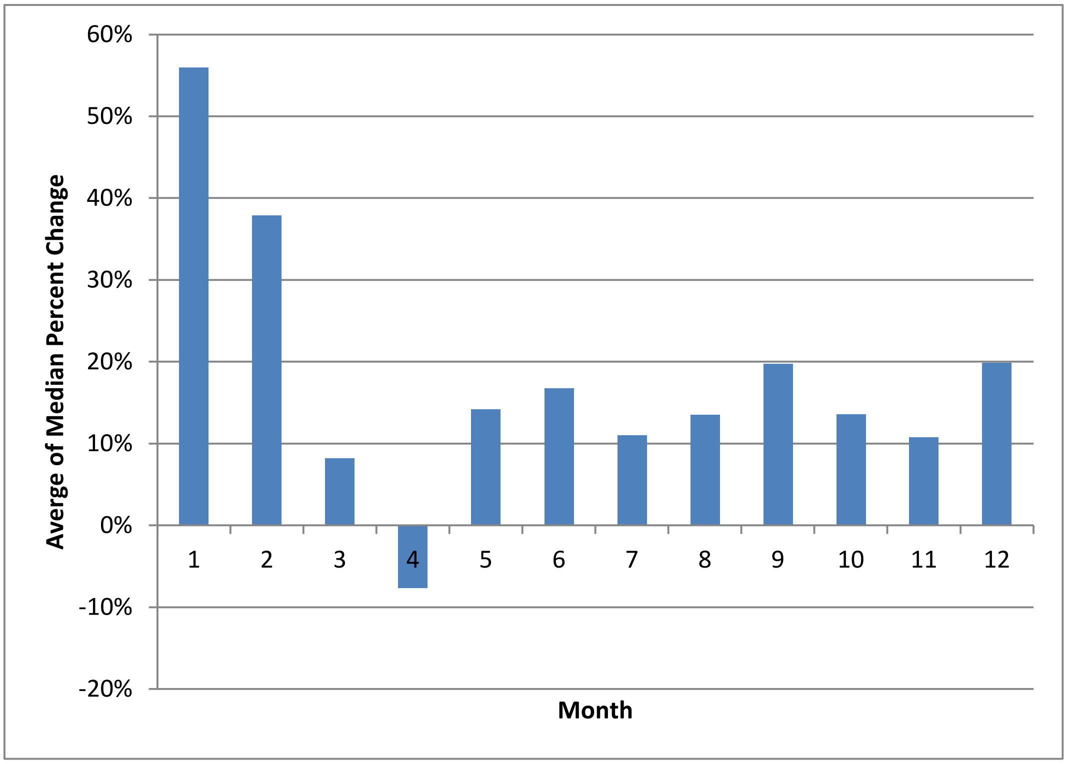


Figure 356. **Average of median percent change in flow; NARCCAP Scenarios W1-W6 at all stations, Tongue and Powder Rivers watershed (SWAT)**

Trinity River Watershed

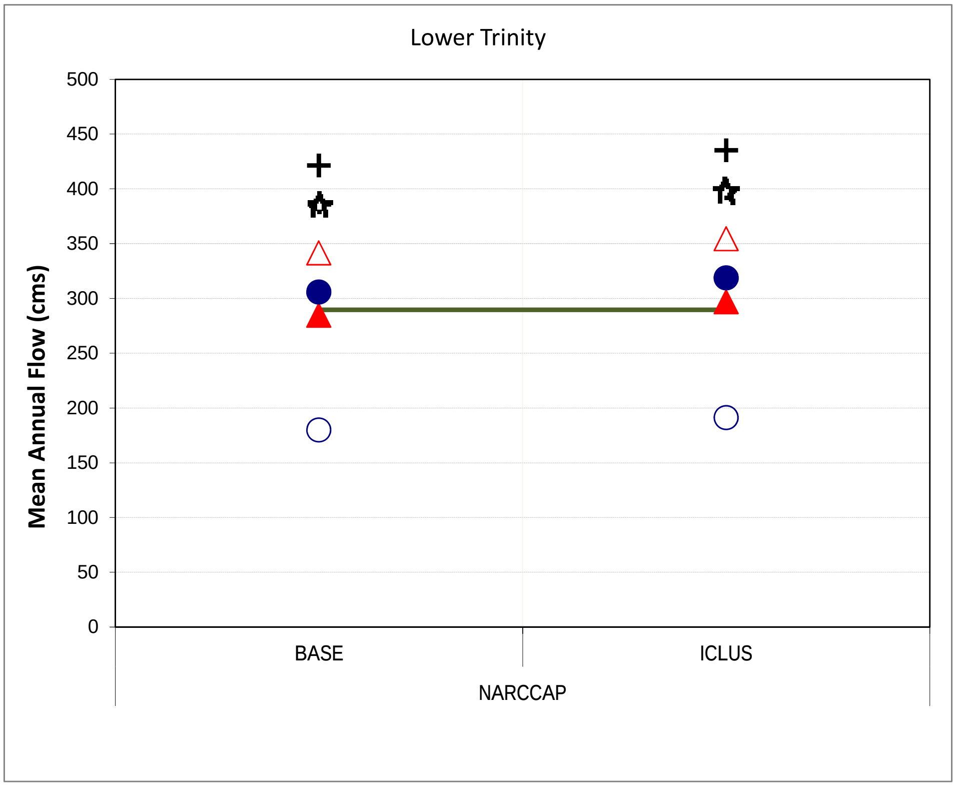


Figure 357. Mean annual flow (cms), Lower Trinity River (SWAT)

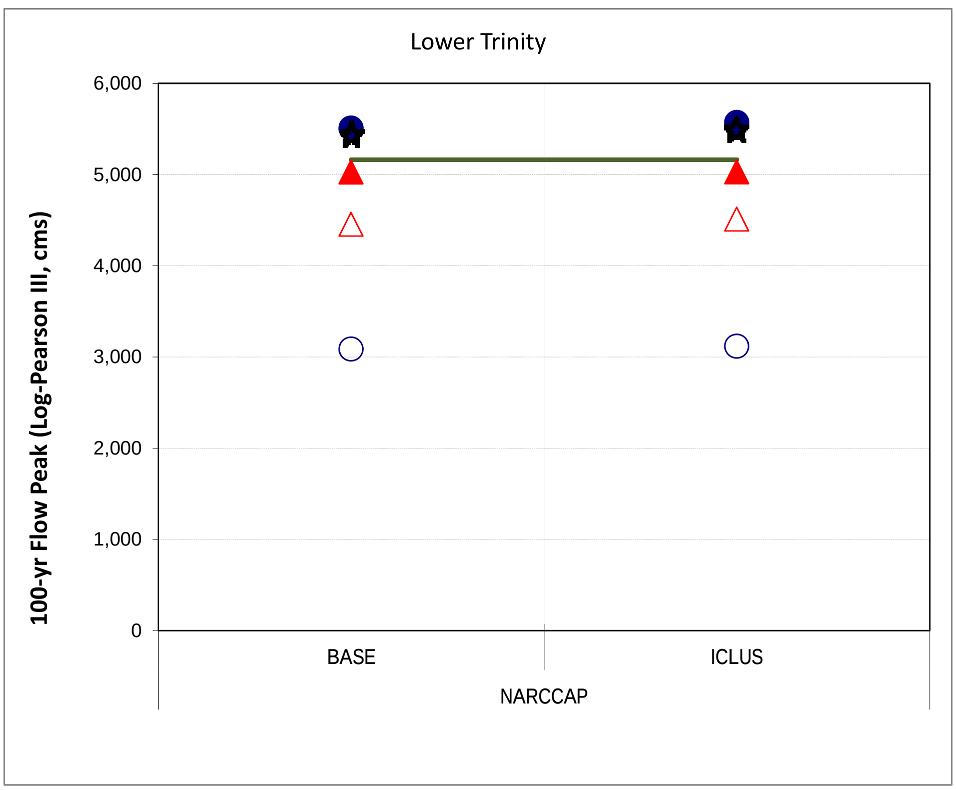


Figure 358. 100-yr Flow Peak (Log-Pearson III, cms), Lower Trinity River (SWAT)

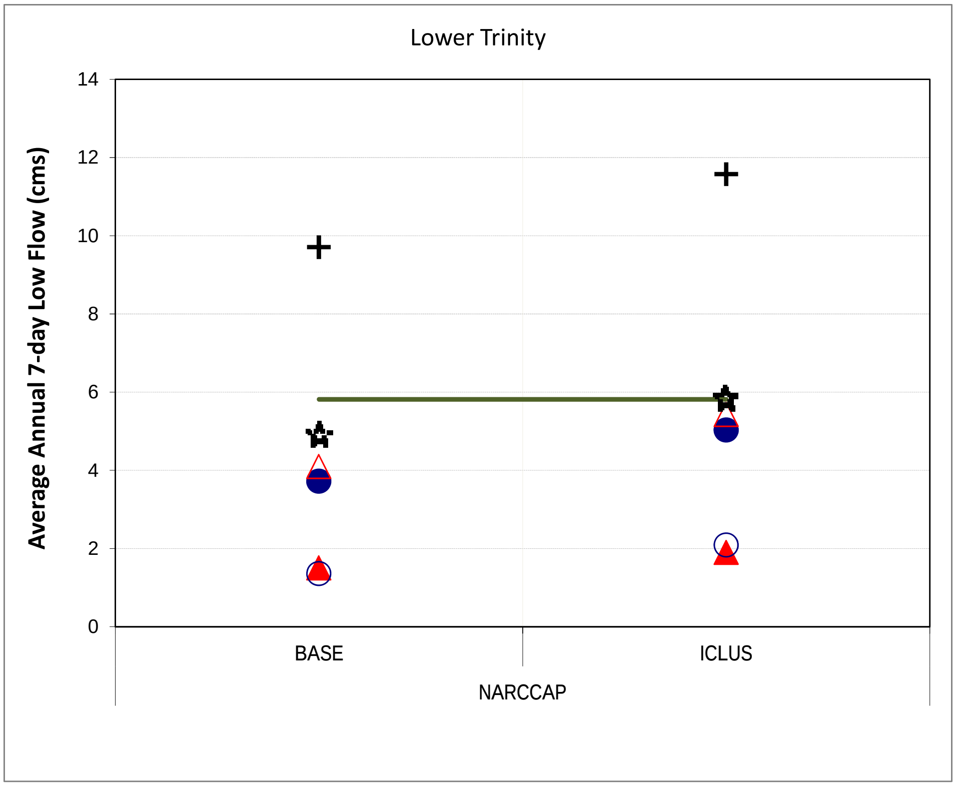


Figure 359. Average Annual 7-day Low Flow (cms), Lower Trinity River (SWAT)

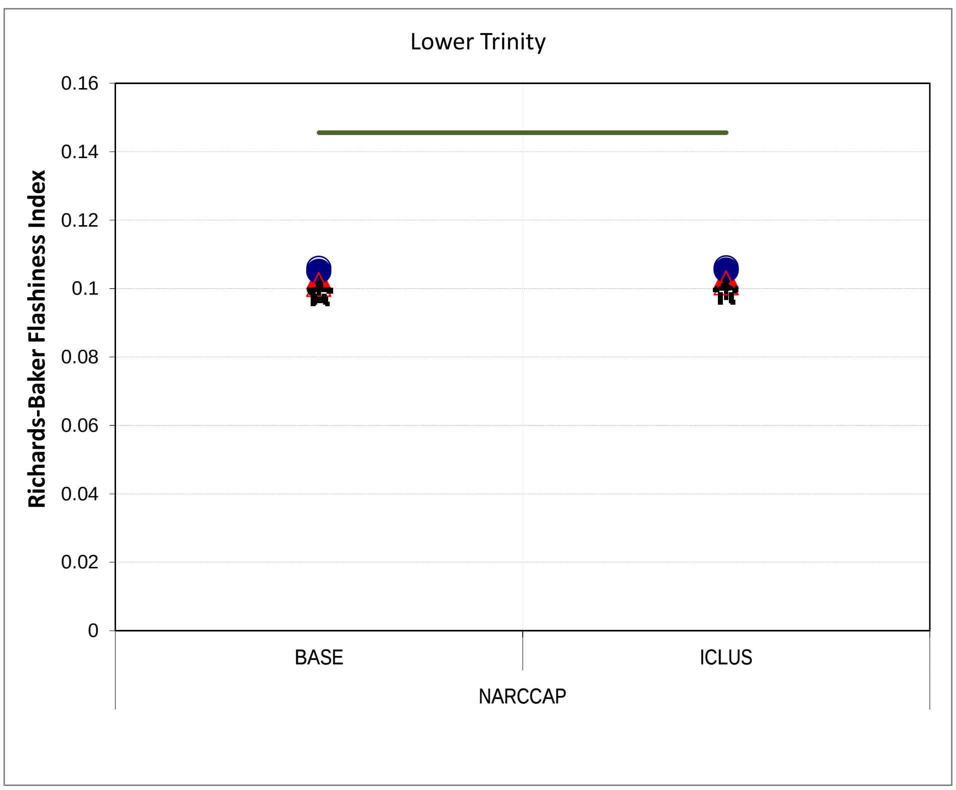


Figure 360. Richards-Baker Flashiness Index, Average Annual 7-day Low Flow (cms), Lower Trinity River (SWAT)

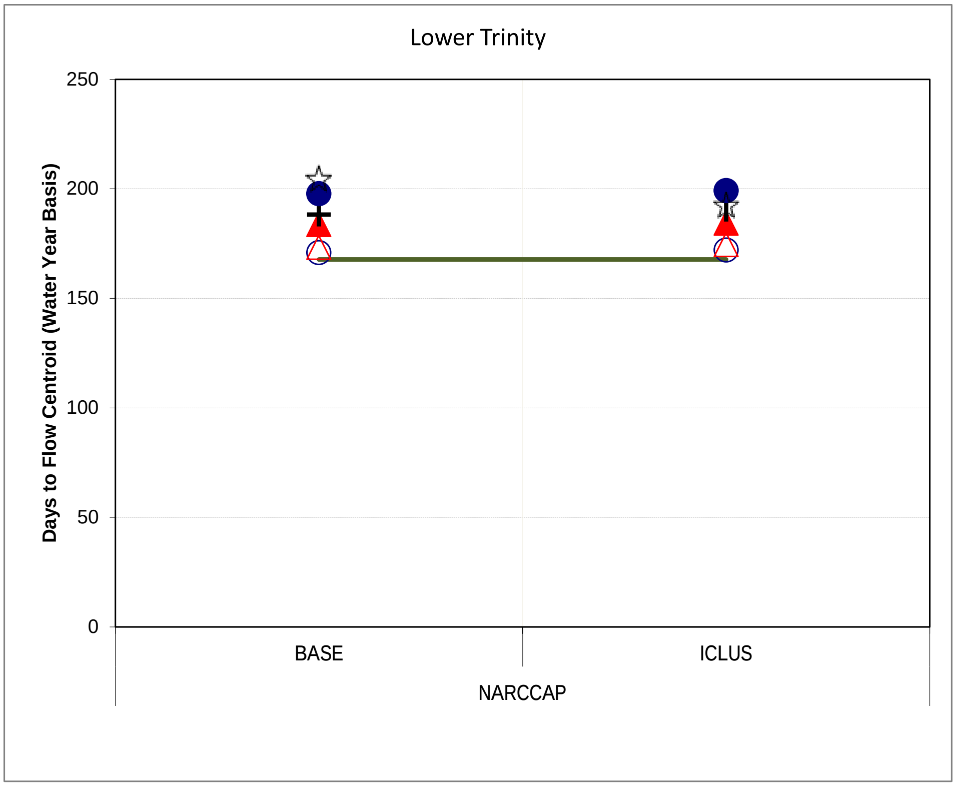


Figure 361. **Days to Flow Centroid (Water Year Basis), Lower Trinity River (SWAT)**

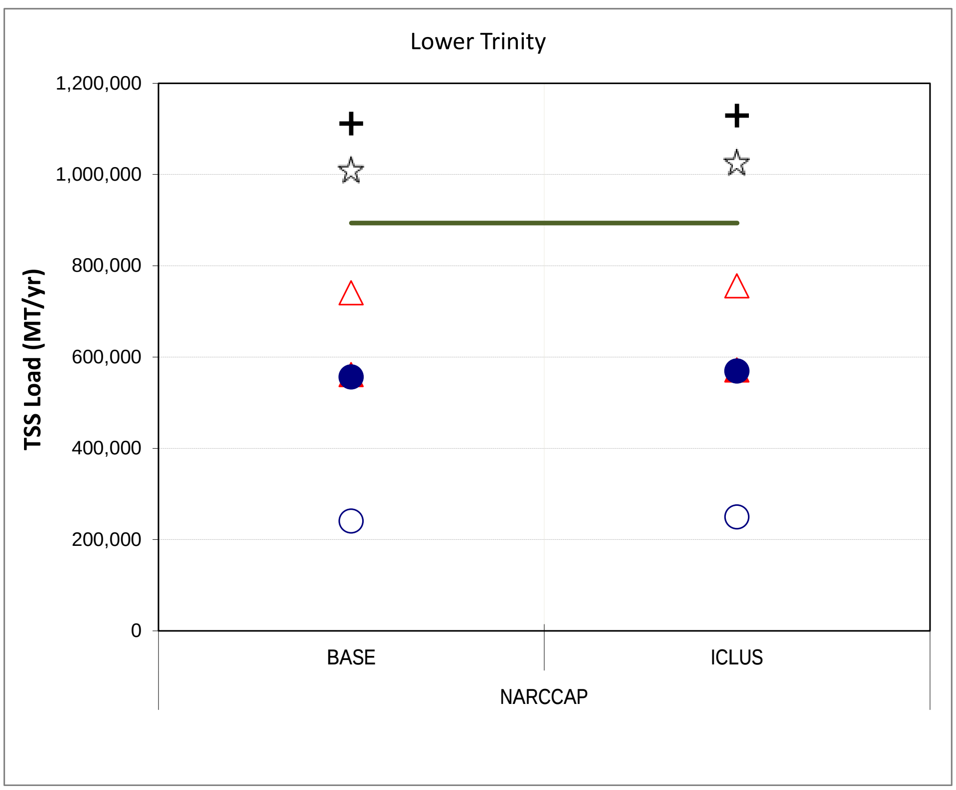


Figure 362. **TSS Load (MT/yr), Lower Trinity River (SWAT)**

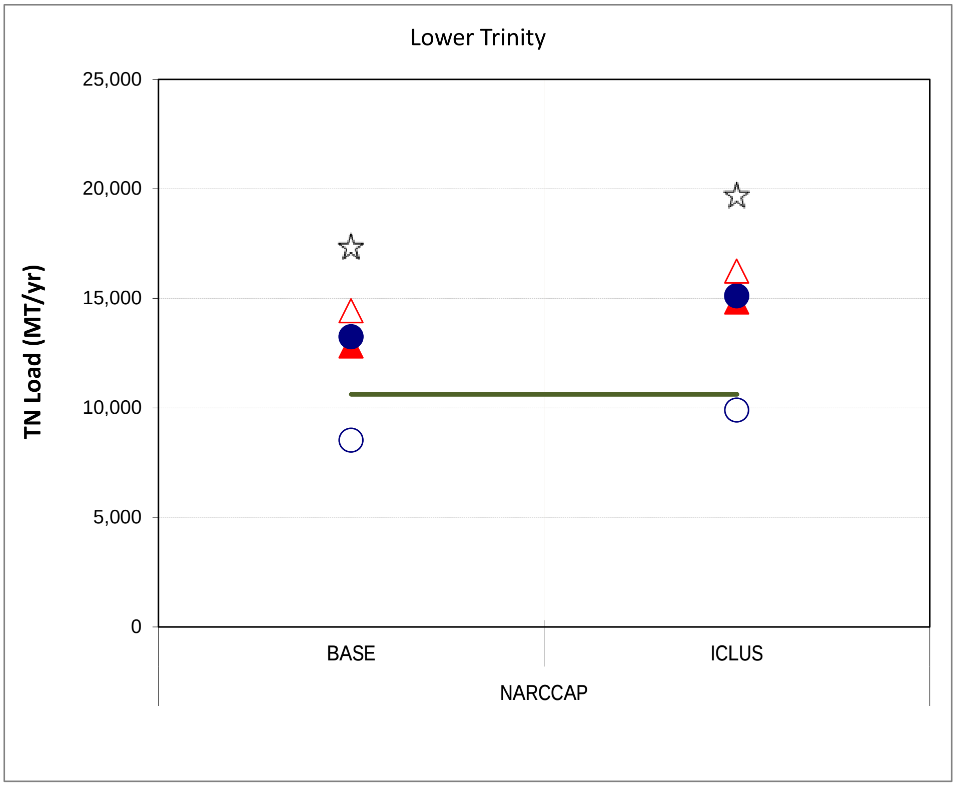


Figure 363. **TN Load (MT/yr), Lower Trinity River (SWAT)**

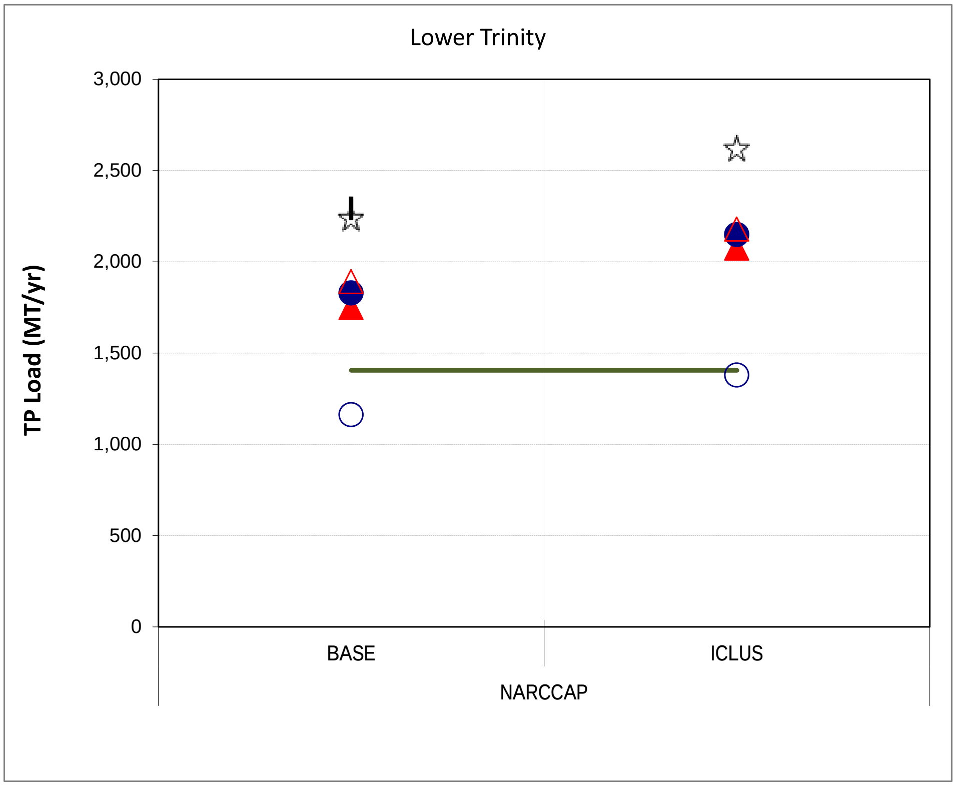


Figure 364. **TP Load (MT/yr), Lower Trinity River (SWAT)**

Table 14. Summary of range of change relative to existing conditions for NARCCAP dynamically downscaled scenarios, Neuse-Tar watershed SWAT model

	Results without LU change				Results with LU change			
	Min	**Median**	**Mean**	**Max**	**Min**	**Median**	**Mean**	**Max**
Upper WF Trinity HUC12030101								
Flow	-60.57%	27.48%	38.78%	125.65%	-61.73%	9.22%	17.28%	84.08%
TSS	-70.32%	-5.70%	8.70%	93.85%	-61.87%	16.81%	34.02%	136.66%
TN	-45.92%	77.86%	128.00%	350.37%	-48.06%	54.80%	79.90%	235.62%
TP	-46.01%	50.23%	87.80%	255.66%	-43.74%	46.22%	67.76%	203.40%
Lower W. Fk Trinity River HUC 12030102								
Flow	-48.48%	7.94%	12.11%	59.28%	-45.86%	7.22%	10.72%	53.80%
TSS	-69.49%	-9.50%	-0.92%	61.32%	-58.95%	15.37%	25.41%	100.51%
TN	3.18%	35.04%	30.56%	45.98%	6.44%	41.92%	37.42%	57.61%
TP	0.13%	23.81%	20.82%	33.52%	1.34%	27.54%	24.49%	38.39%
Elm Fork Trinity HUC 12030103								
Flow	-52.26%	9.17%	8.56%	51.00%	-48.83%	6.67%	5.96%	43.74%
TSS	-55.37%	10.34%	9.74%	57.00%	-52.17%	7.82%	7.25%	50.47%
TN	-26.19%	45.35%	51.60%	136.69%	-18.99%	50.11%	56.27%	139.44%
TP	-29.16%	47.68%	55.43%	151.86%	-24.85%	49.68%	56.59%	149.99%
Denton HUC 12030104								
Flow	-50.19%	15.40%	16.70%	64.10%	-48.72%	8.72%	9.88%	50.85%
TSS	-52.29%	14.44%	16.07%	65.77%	-50.30%	9.58%	11.07%	55.79%
TN	-26.26%	68.20%	57.38%	102.85%	-31.30%	70.11%	56.69%	118.52%
TP	-28.75%	57.76%	50.63%	98.07%	-33.30%	57.86%	49.04%	111.53%
Upper Trinity HUC 12030105								
Flow	-43.89%	6.25%	8.45%	43.88%	-41.40%	5.10%	7.19%	39.68%
TSS	-65.26%	-13.20%	-9.53%	34.16%	-53.88%	10.22%	15.09%	69.42%
TN	-13.18%	12.31%	13.12%	35.69%	-7.31%	20.08%	20.89%	44.30%
TP	-13.87%	8.86%	9.82%	29.72%	-10.00%	14.56%	15.78%	36.11%
East Fork Trinity HUC 12030106								
Flow	-41.81%	3.94%	6.03%	40.43%	-38.87%	4.89%	6.63%	38.77%
TSS	-60.79%	-2.11%	0.38%	47.87%	-54.02%	8.76%	11.36%	62.36%
TN	-6.13%	10.22%	11.36%	27.67%	-1.96%	16.18%	17.14%	34.34%
TP	-6.82%	6.94%	7.87%	21.76%	-4.36%	10.46%	11.54%	26.38%
Cedar HUC 12030107								
Flow	-38.90%	13.92%	16.65%	51.89%	-40.35%	7.41%	9.92%	41.82%
TSS	-60.77%	-17.57%	-14.89%	16.22%	-48.05%	7.30%	10.90%	50.55%
TN	-2.97%	18.60%	17.67%	32.43%	-0.38%	23.77%	22.29%	38.59%
TP	-3.75%	13.31%	12.57%	24.60%	-2.66%	16.78%	15.64%	28.27%
Richland HUC 12030108								
Flow	-42.84%	21.39%	26.82%	86.52%	-46.58%	11.32%	16.22%	70.02%
TSS	-59.43%	-15.89%	-9.71%	37.07%	-46.56%	10.09%	18.00%	78.52%

	Results without LU change				Results with LU change			
	Min	**Median**	**Mean**	**Max**	**Min**	**Median**	**Mean**	**Max**
TN	-32.71%	30.99%	31.84%	80.39%	-26.36%	46.01%	45.48%	94.84%
TP	-30.63%	33.38%	34.04%	81.94%	-24.58%	47.05%	46.47%	94.70%
Chambers HUC 12030109								
Flow	-41.69%	21.72%	27.12%	84.62%	-44.71%	11.62%	16.42%	67.47%
TSS	-59.45%	-16.76%	-10.10%	37.50%	-44.92%	11.87%	20.66%	83.60%
TN	-32.92%	30.34%	30.34%	68.18%	-20.65%	56.62%	55.72%	100.53%
TP	-30.47%	31.72%	32.13%	70.61%	-19.05%	55.36%	54.92%	99.28%
Lower Trinity-Tehuacana HUC 12030201								
Flow	-44.39%	7.60%	10.82%	51.69%	-43.33%	5.00%	8.03%	45.99%
TSS	-69.01%	-20.17%	-15.73%	24.85%	-54.89%	12.46%	18.79%	75.04%
TN	-15.65%	14.82%	17.33%	42.46%	-9.75%	22.50%	24.90%	50.98%
TP	-15.88%	10.31%	12.50%	33.51%	-11.88%	15.68%	18.07%	39.58%
Lower Trinity-Kickapoo HUC 12030202								
Flow	-40.67%	10.74%	10.86%	47.61%	-40.54%	8.09%	8.11%	42.79%
TSS	-69.05%	-20.58%	-16.24%	25.93%	-54.16%	14.74%	21.02%	81.13%
TN	-24.79%	25.51%	27.06%	64.32%	-19.76%	30.19%	32.84%	71.60%
TP	-26.83%	24.45%	24.40%	60.68%	-24.03%	25.86%	26.87%	64.21%
Lower Trinity (at mouth) HUC 12030203								
Flow	-37.90%	11.73%	10.53%	45.51%	-37.98%	9.23%	8.01%	41.24%
TSS	-73.07%	-27.12%	-21.23%	24.42%	-54.90%	19.88%	29.60%	103.95%
TN	-19.77%	30.25%	31.77%	65.38%	-12.28%	39.02%	41.39%	75.79%
TP	-17.32%	32.30%	32.42%	63.07%	-10.76%	39.98%	40.71%	70.90%
Clear Creek nr Sanger (gage 05317000)								
Flow	-38.27%	14.86%	17.51%	61.53%	-39.47%	5.66%	7.64%	44.03%
TSS	-59.35%	-17.40%	-15.83%	22.09%	-46.40%	8.19%	10.18%	58.96%
TN	-1.43%	30.94%	48.37%	118.20%	-13.68%	21.07%	33.83%	119.75%
TP	-8.77%	24.70%	40.07%	103.05%	-15.96%	20.54%	32.24%	112.33%

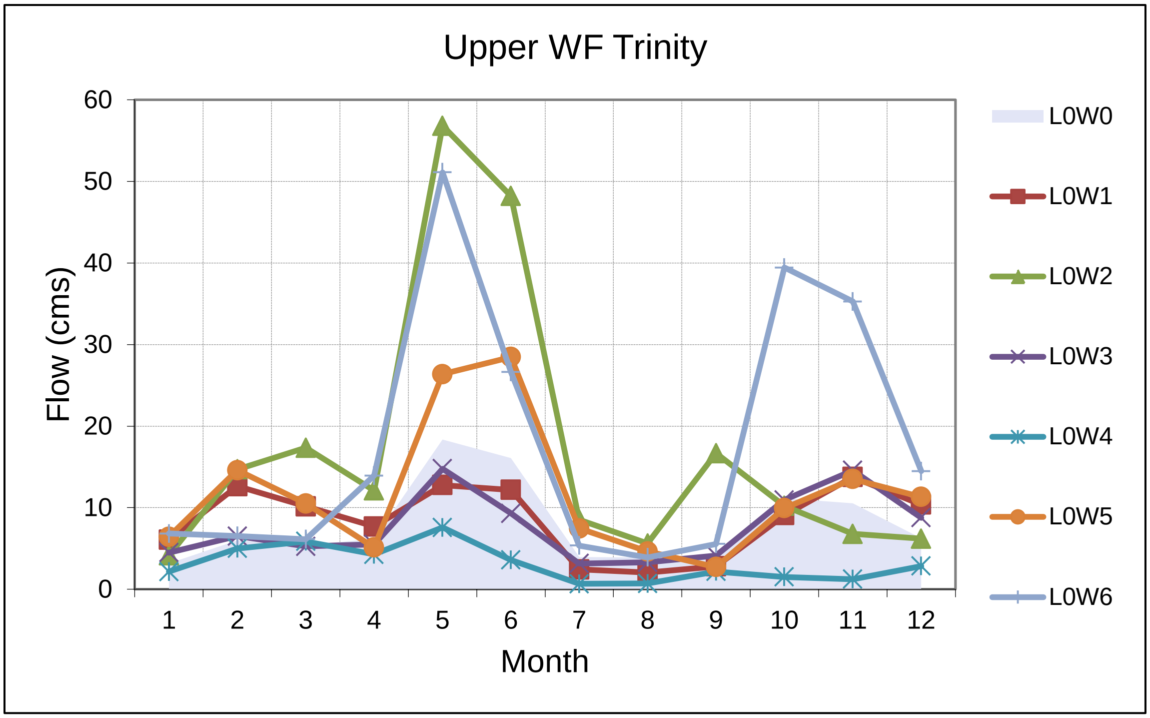


Figure 365. **Monthly average flows, Upper WF Trinity River (SWAT)**

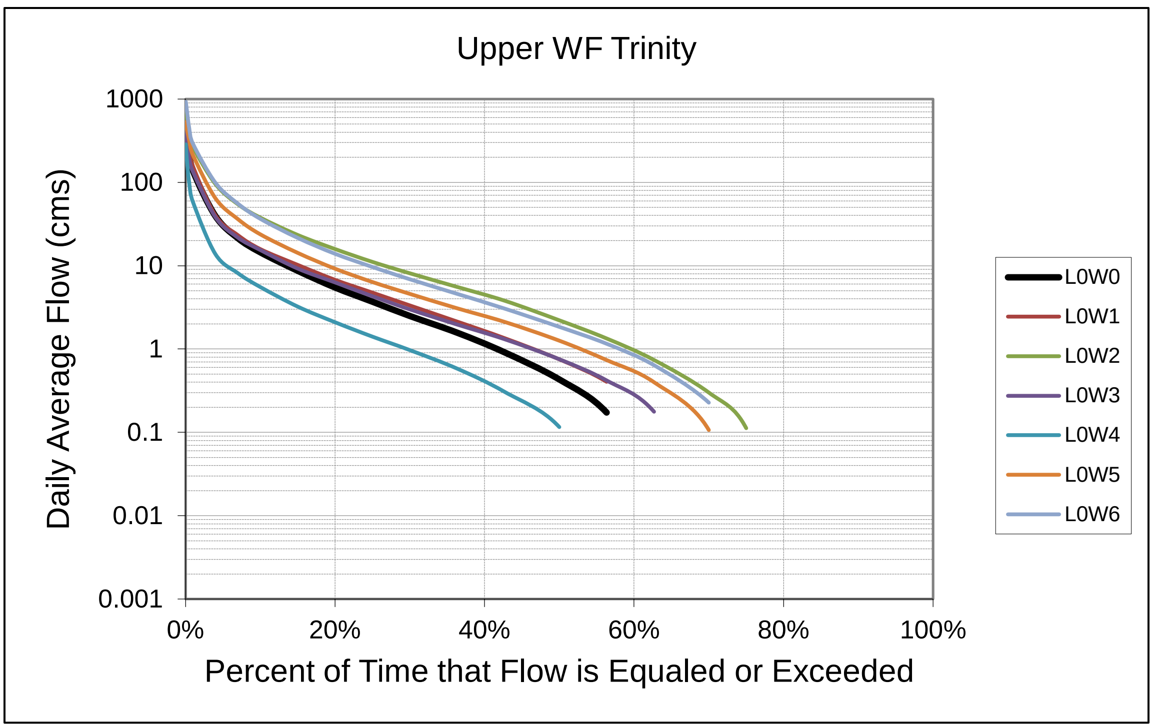


Figure 366. Flow duration, Upper WF Trinity River (SWAT)

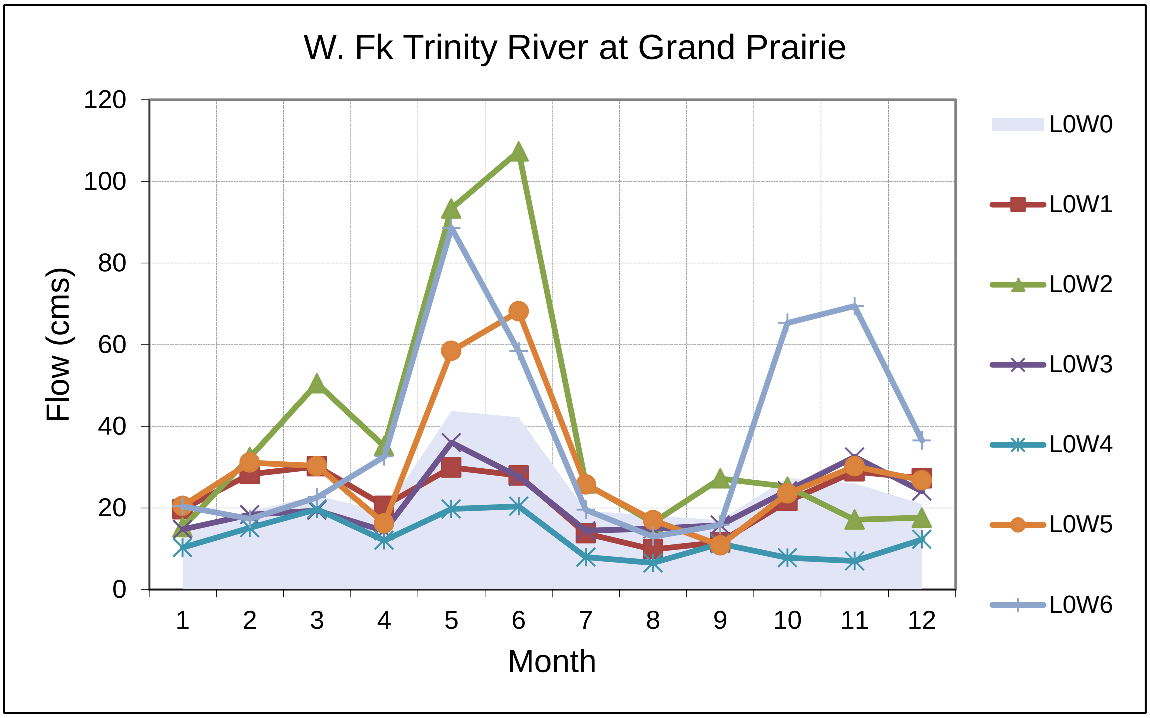


Figure 367. **Monthly average flows, Lower West Fork Trinity River at Grand Prairie (SWAT)**

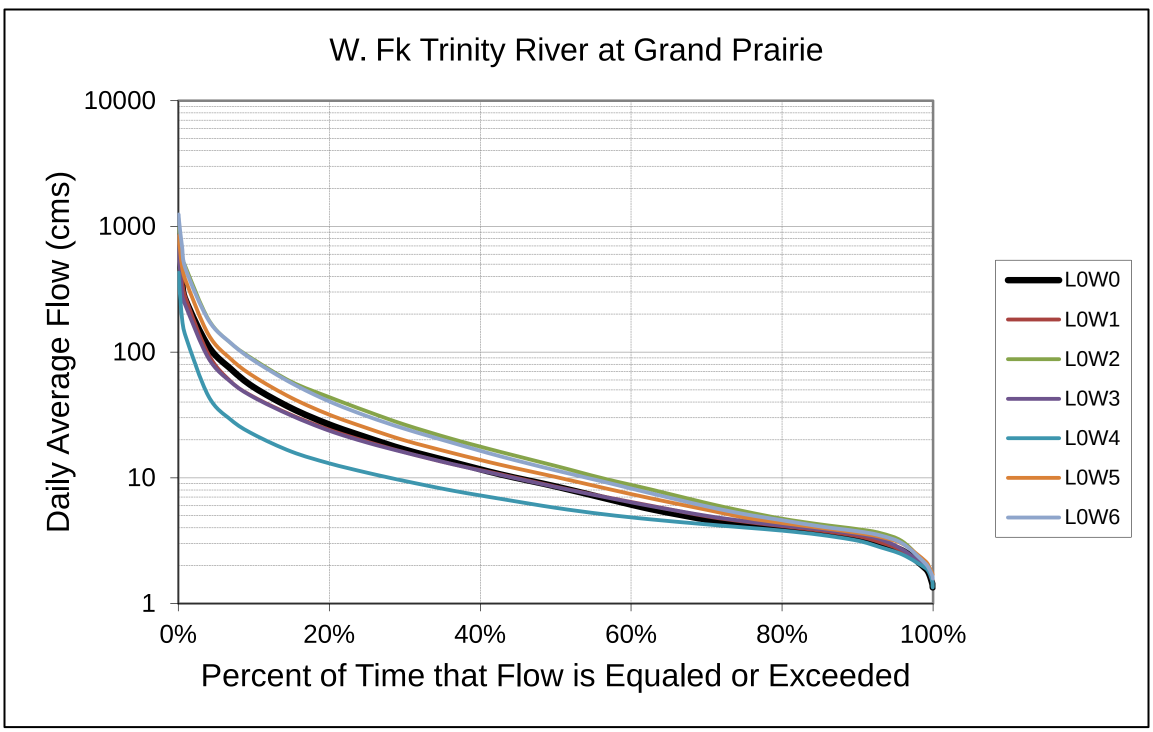


Figure 368. **Flow duration, Lower West Fork Trinity River at Grand Prairie (SWAT)**

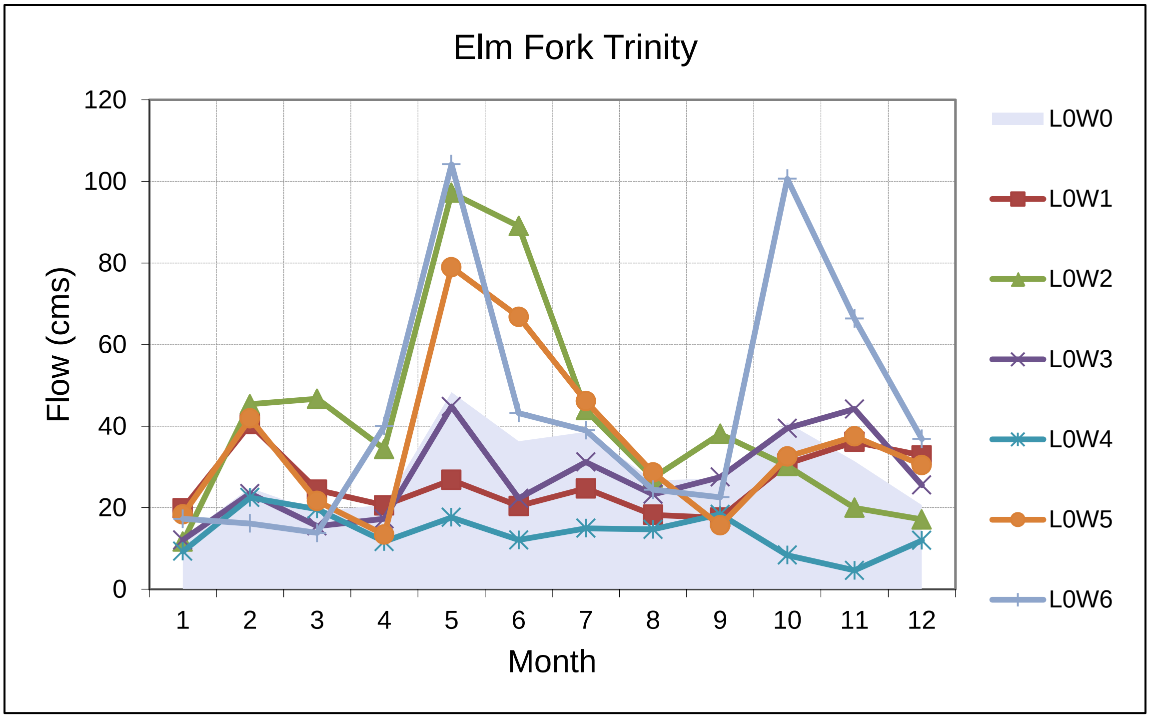


Figure 369. **Monthly average flows, Elm Fork Trinity River (SWAT)**

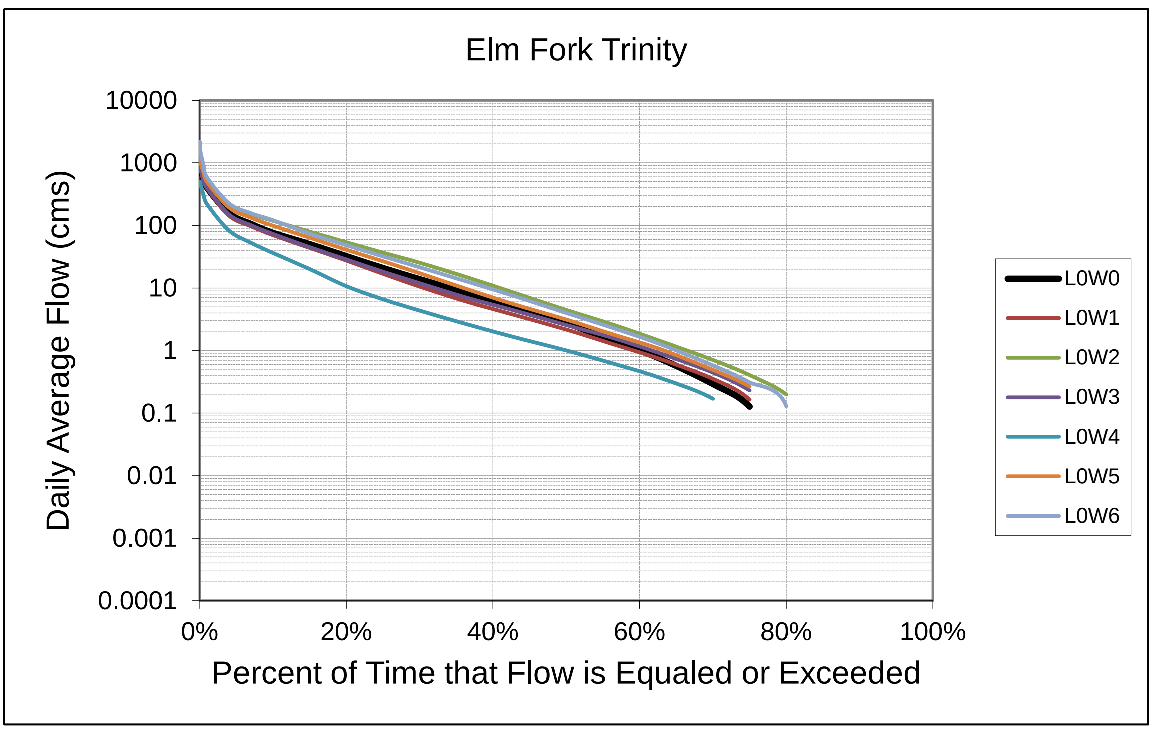


Figure 370. **Flow duration, Elm Fork Trinity River (SWAT)**

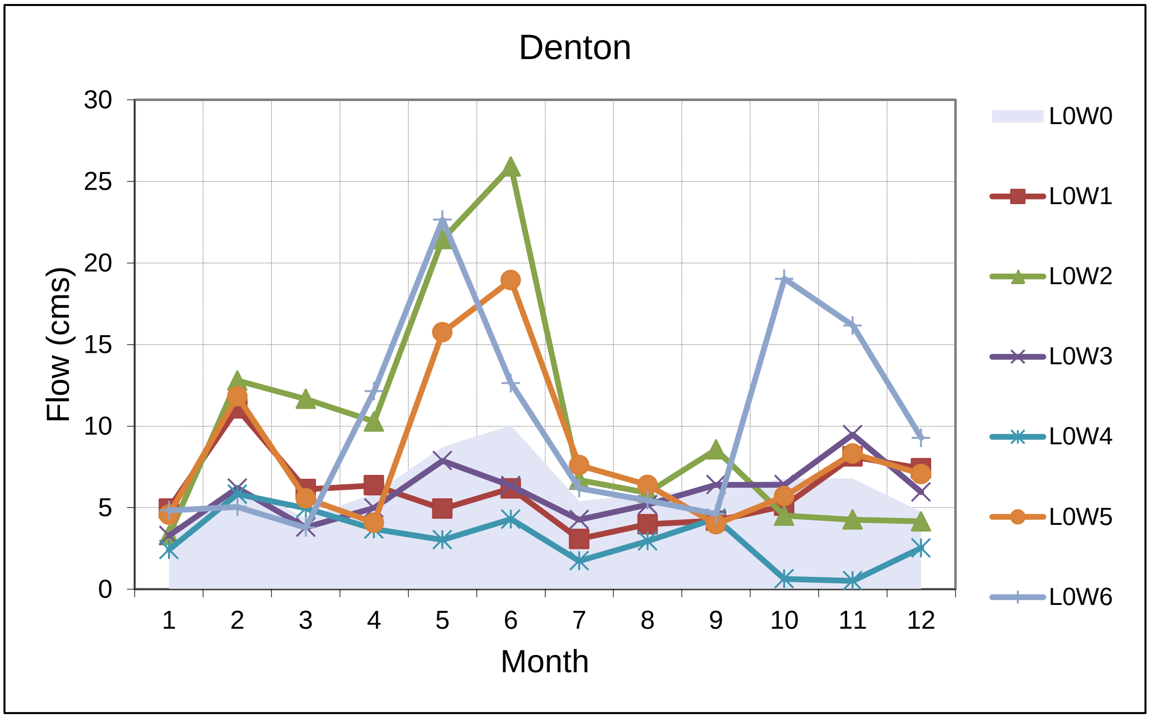


Figure 371. **Monthly average flows, Denton River (SWAT)**

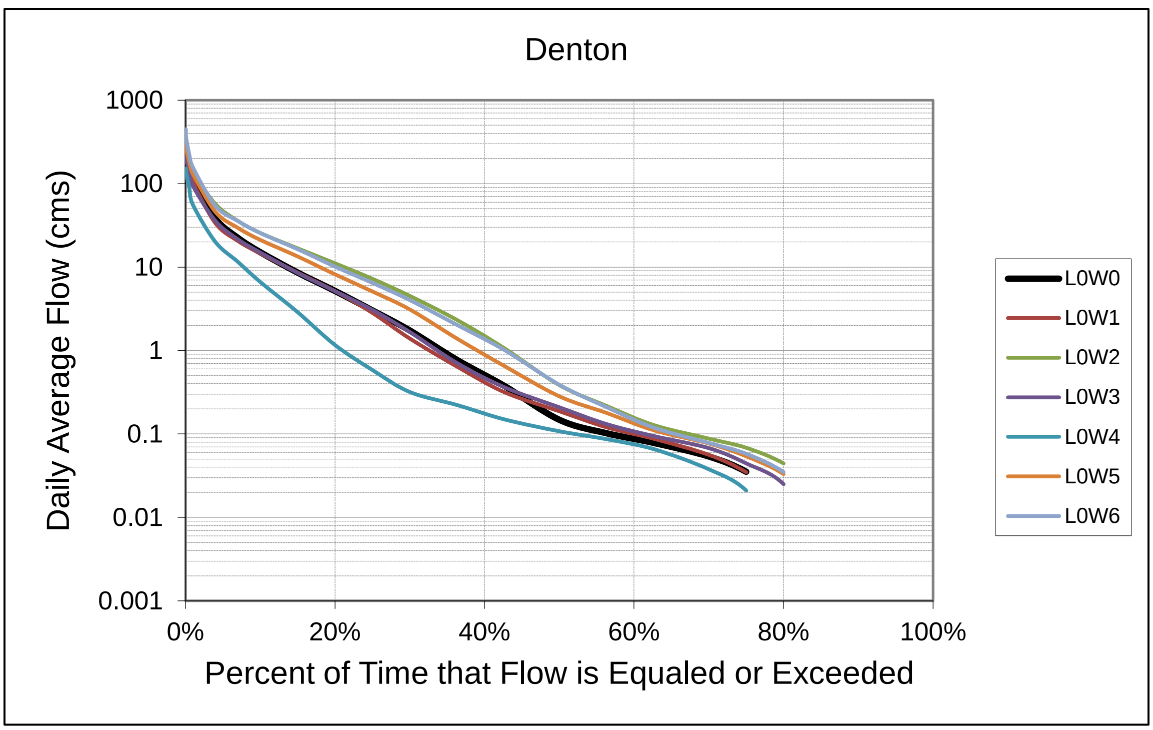


Figure 372. **Flow duration, Denton River (SWAT)**

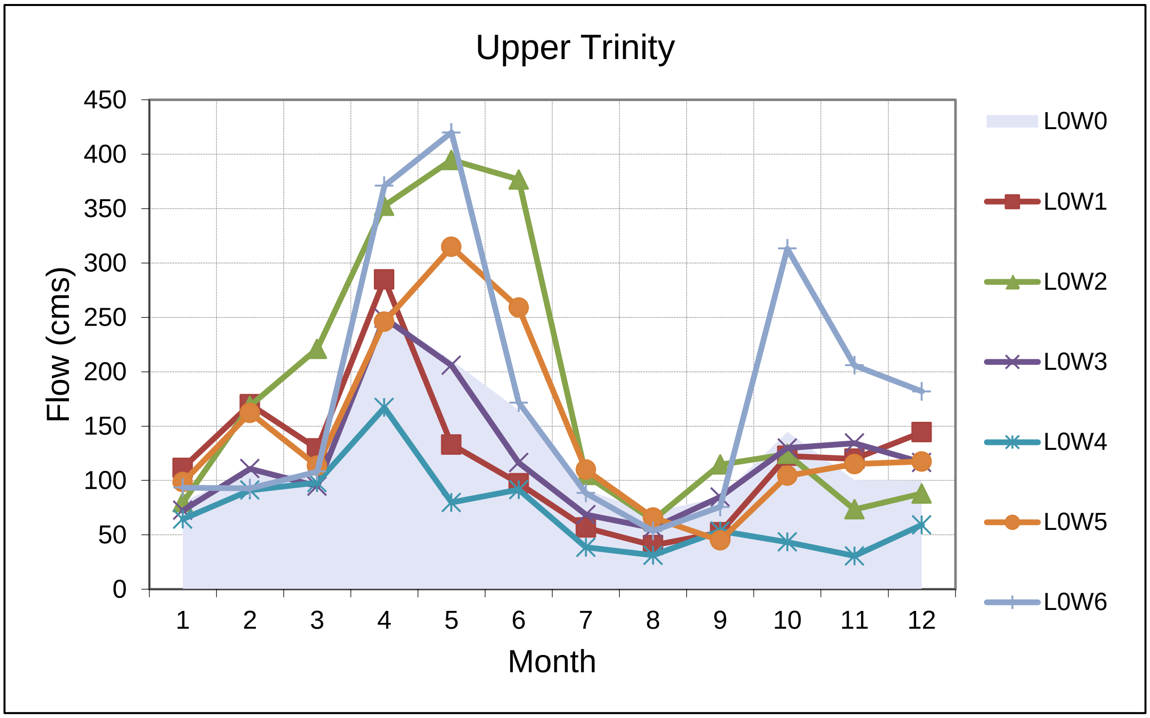


Figure 373. **Monthly average flows, Upper Trinity River (SWAT)**

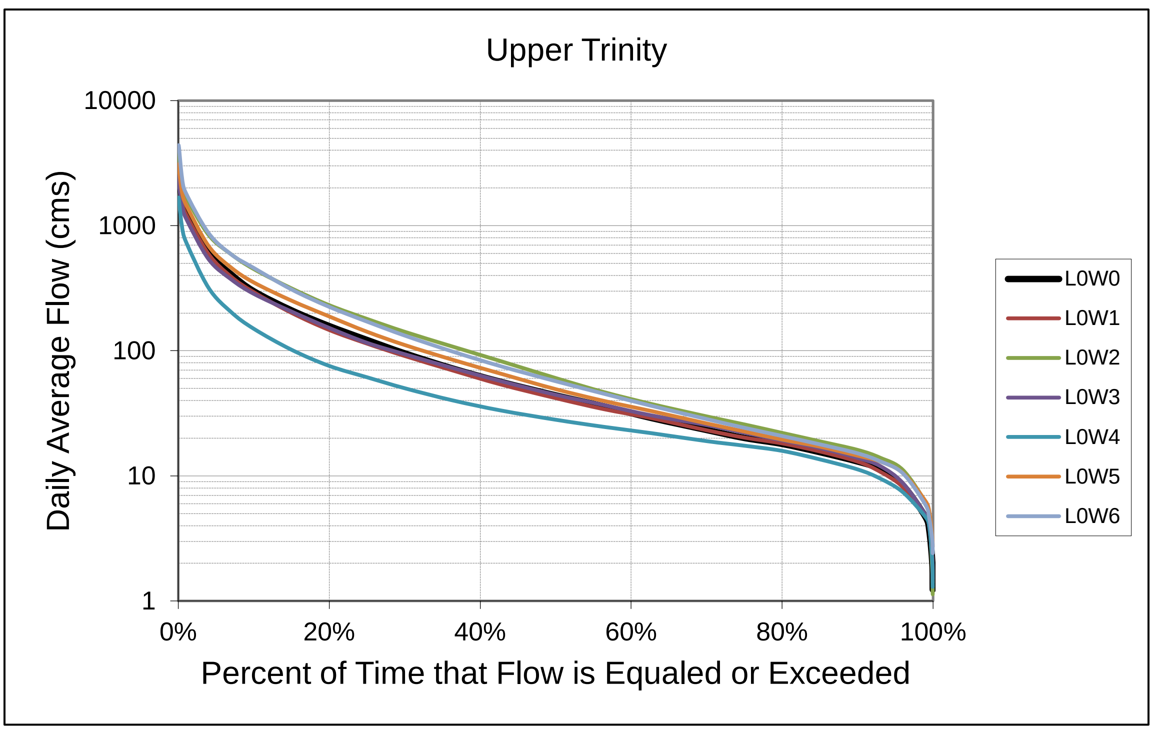


Figure 374. **Flow duration, Upper Trinity River (SWAT)**

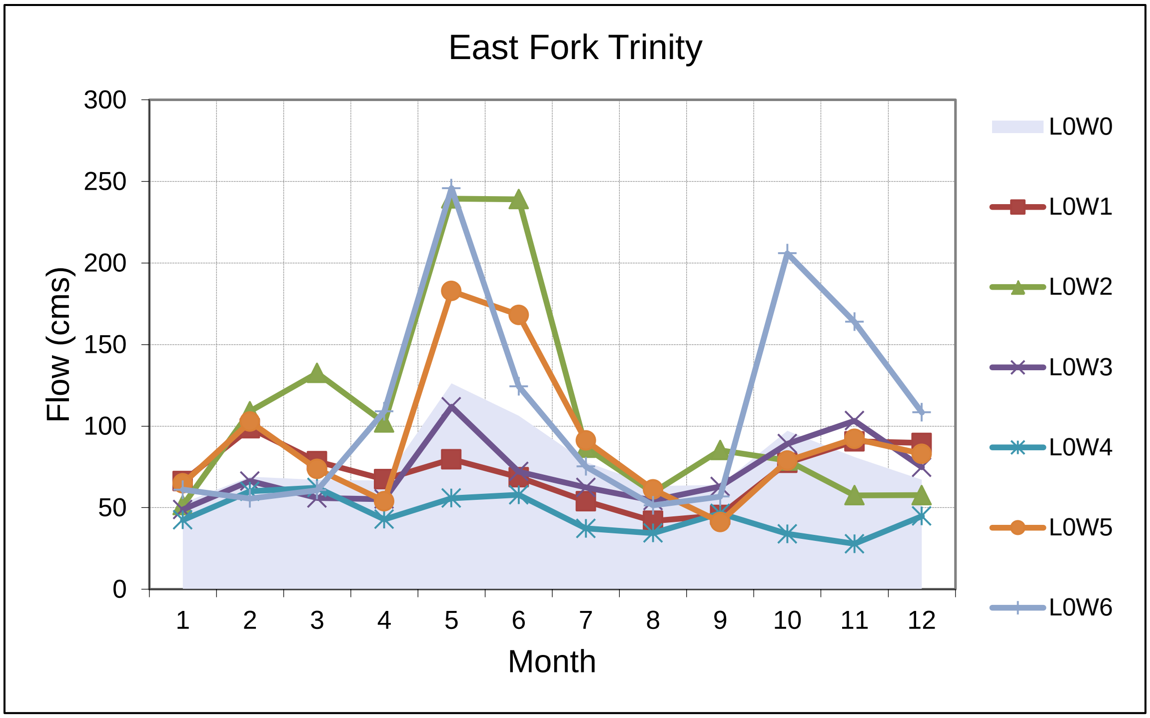


Figure 375. Monthly average flows, East Fork Trinity River (SWAT)

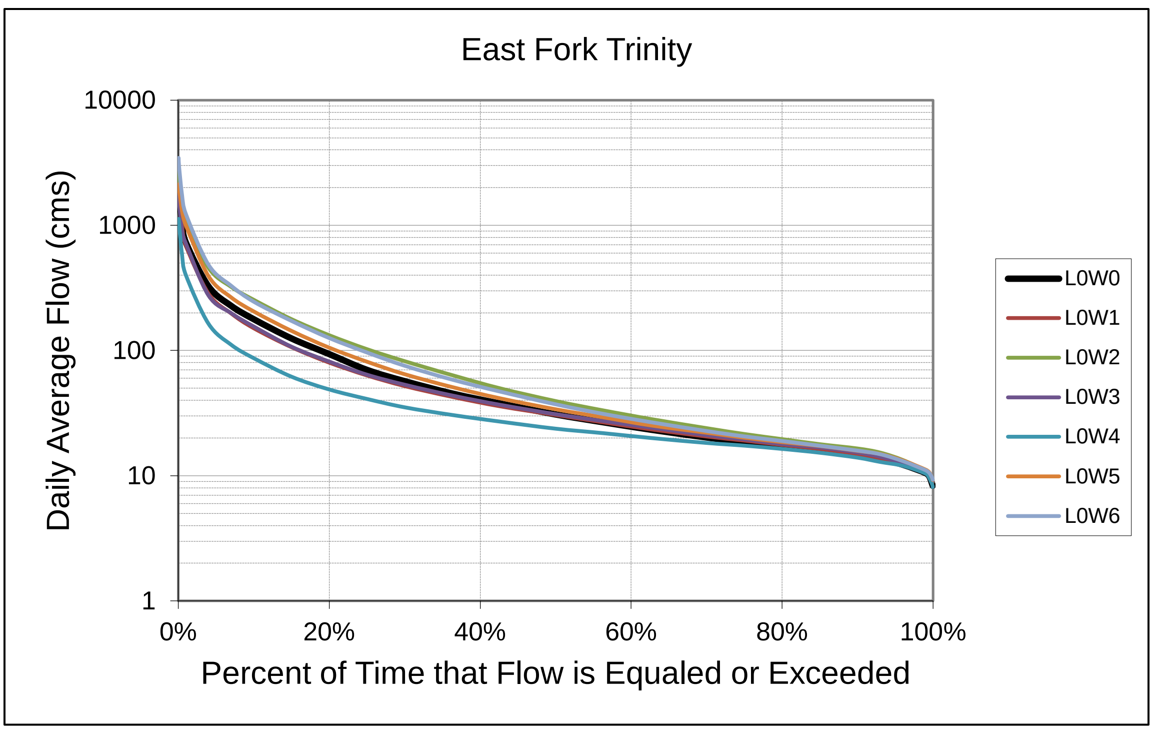


Figure 376. Flow duration, East Fork Trinity River (SWAT)

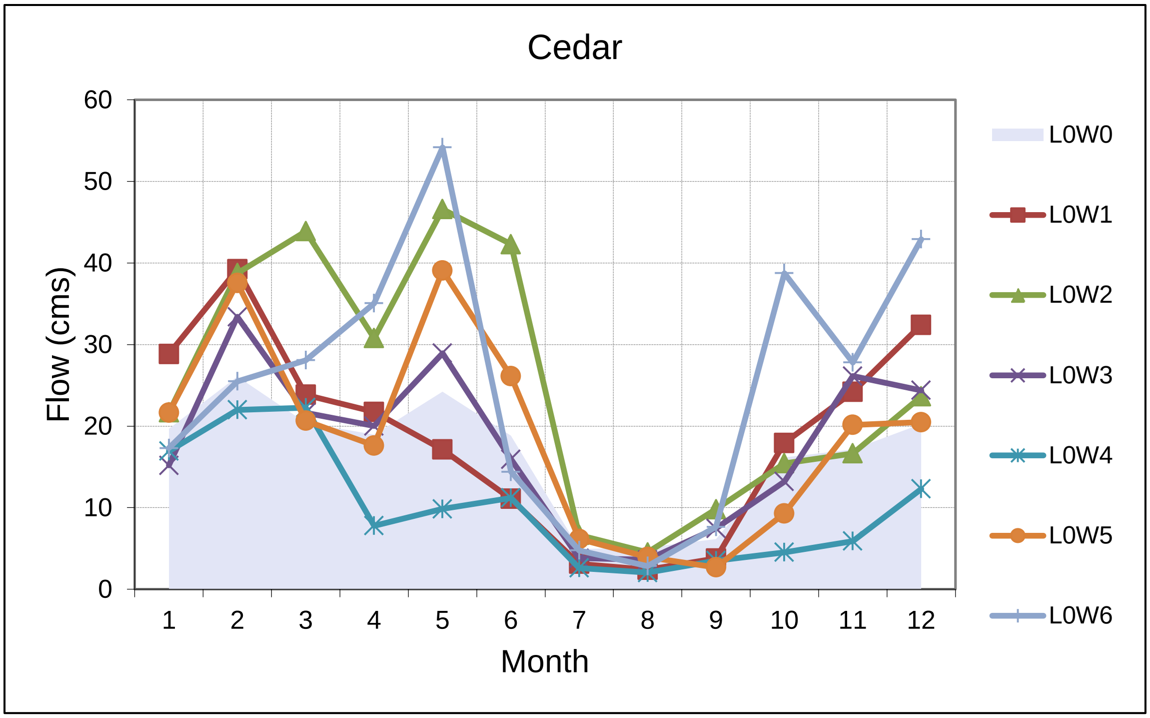


Figure 377. Monthly average flows, Cedarr (SWAT)

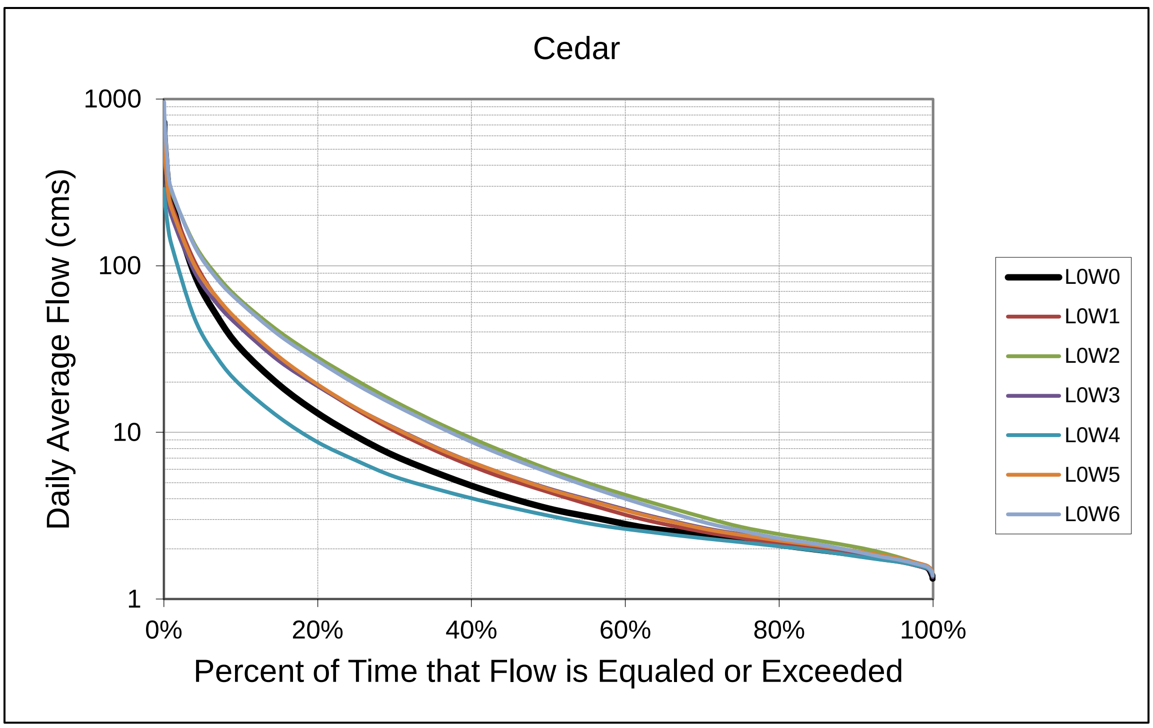


Figure 378. Flow duration, Cedar River (SWAT)

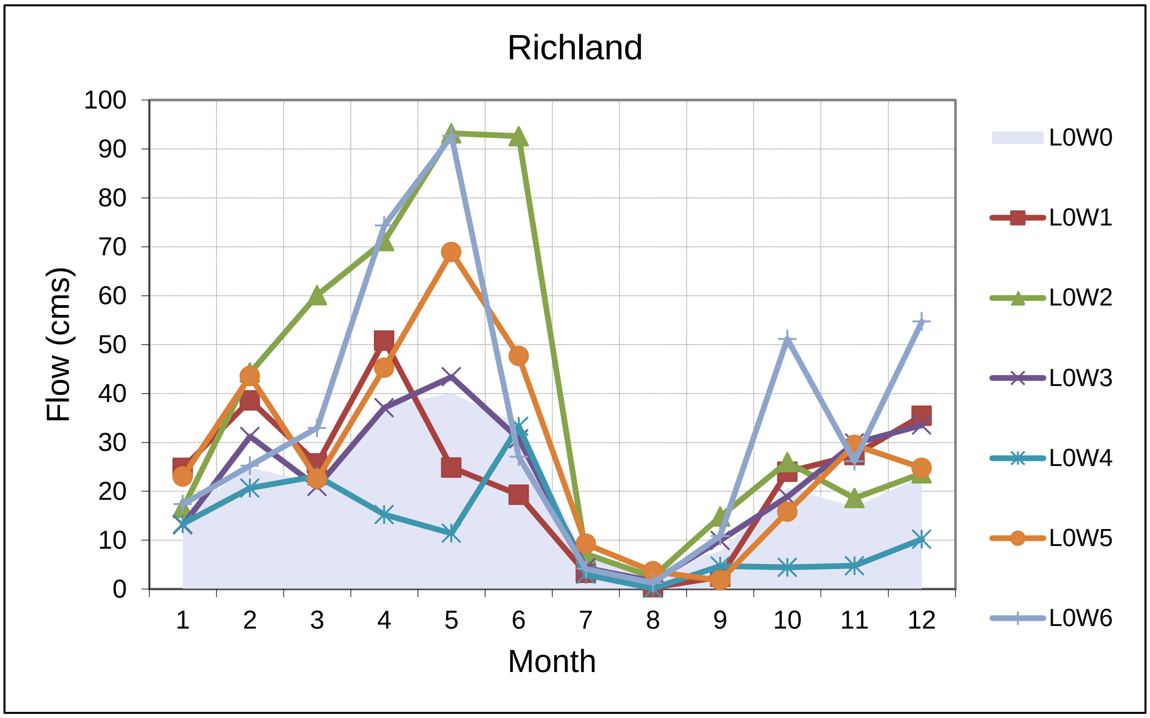


Figure 379. **Monthly average flows, Richland (SWAT)**

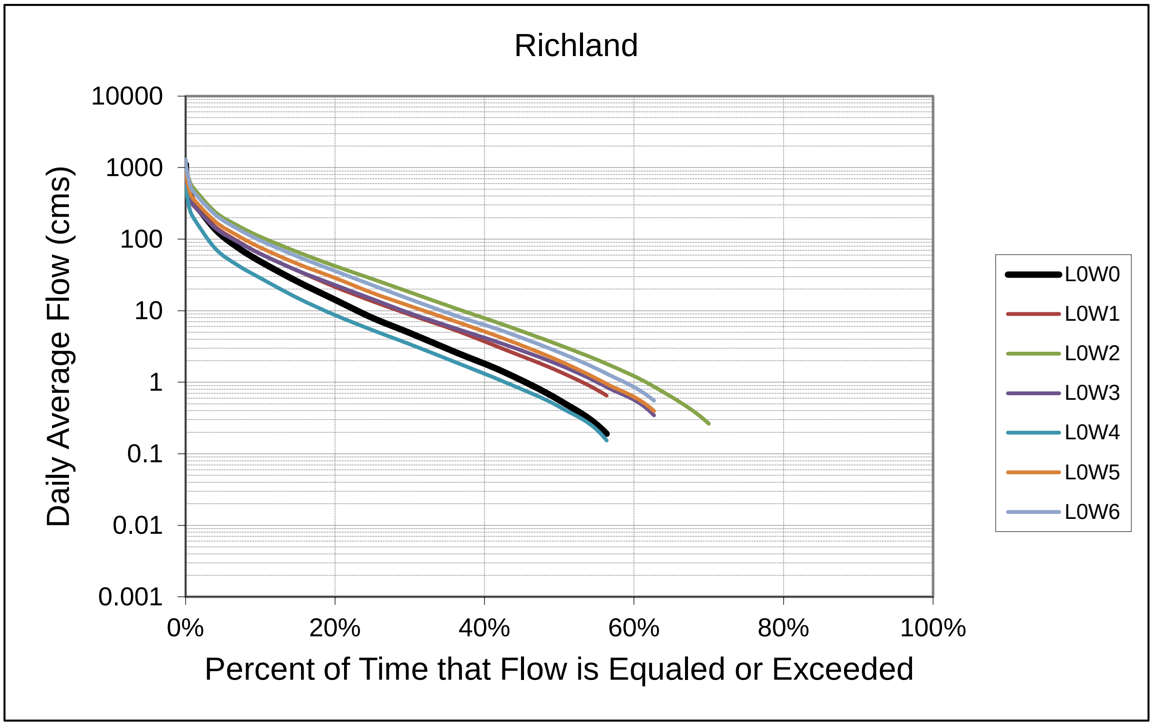


Figure 380. **Flow duration, Richland (SWAT)**

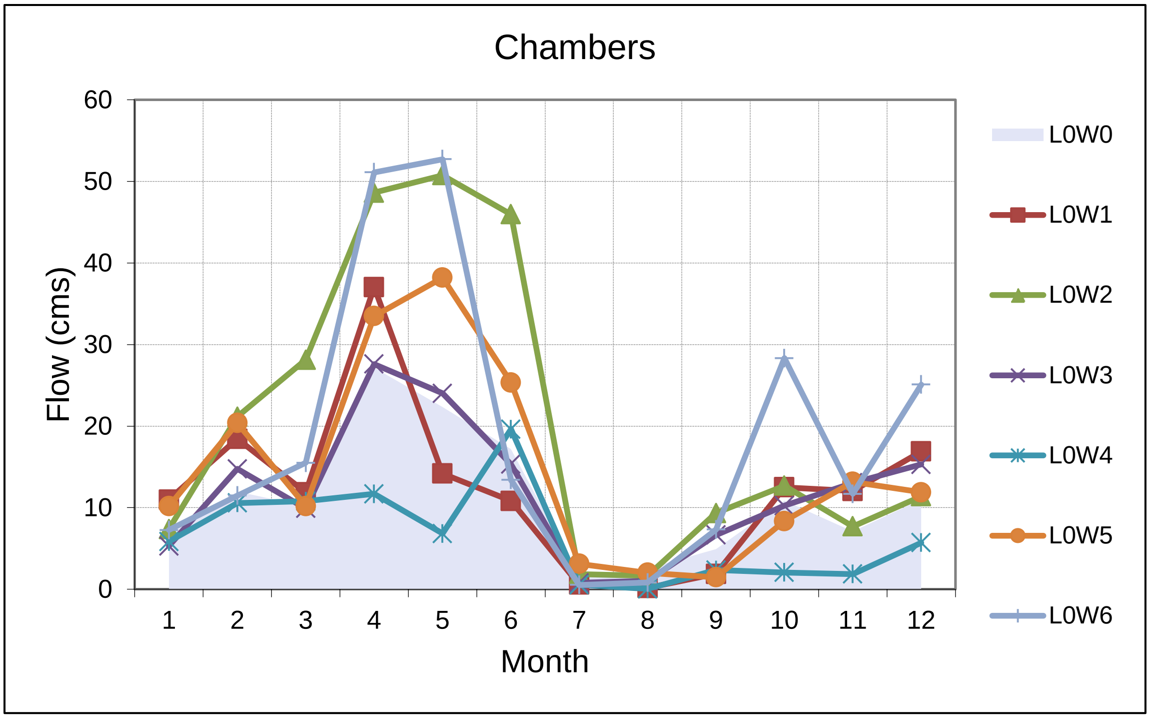


Figure 381. **Monthly average flows, Chambers (SWAT)**

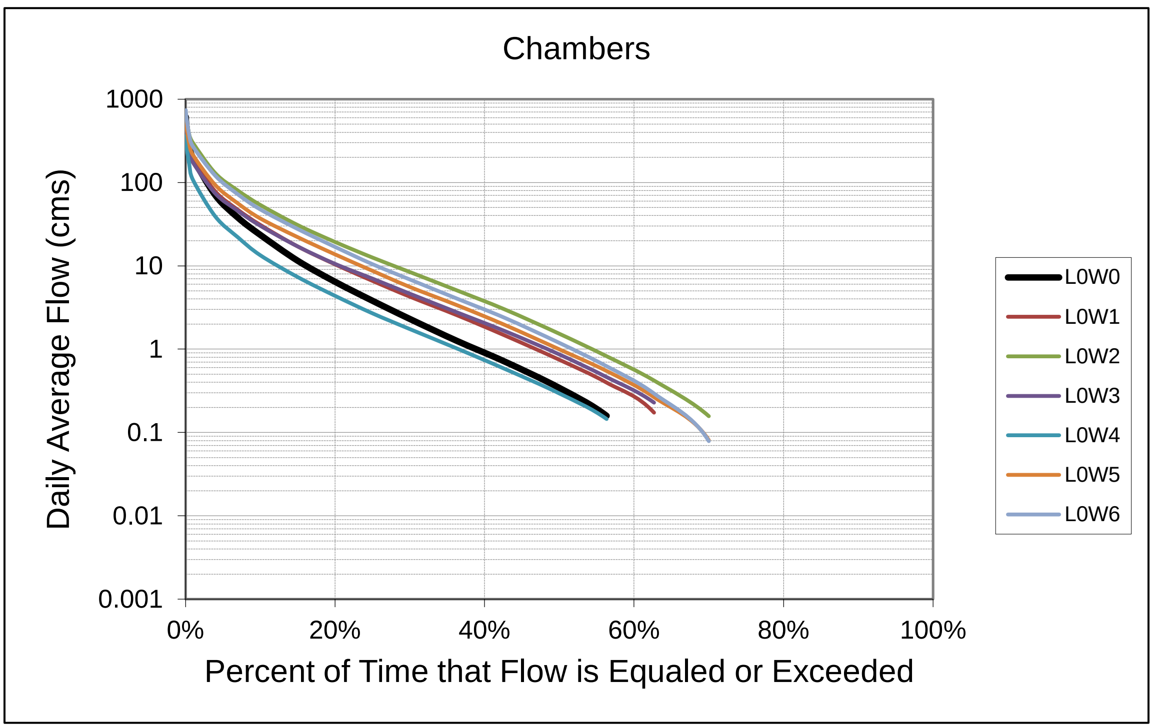


Figure 382. **Flow duration, Chambers (SWAT)**

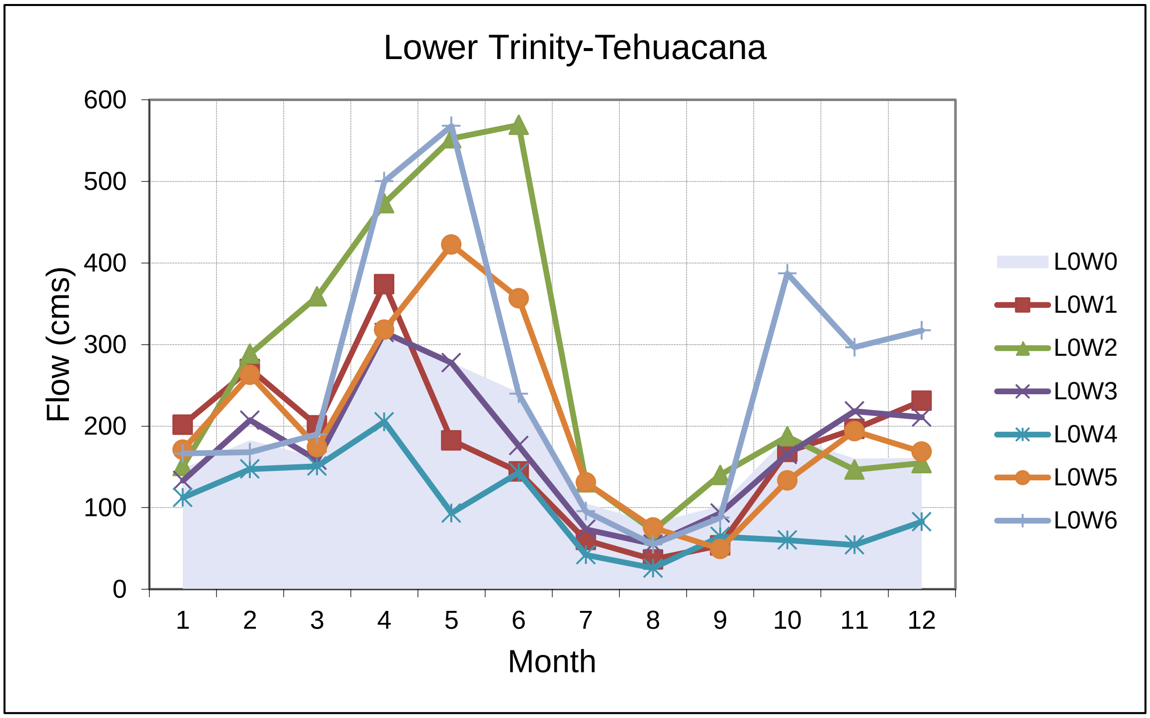


Figure 383. **Monthly average flows, Lower Trinity River - Tehuacana (SWAT)**

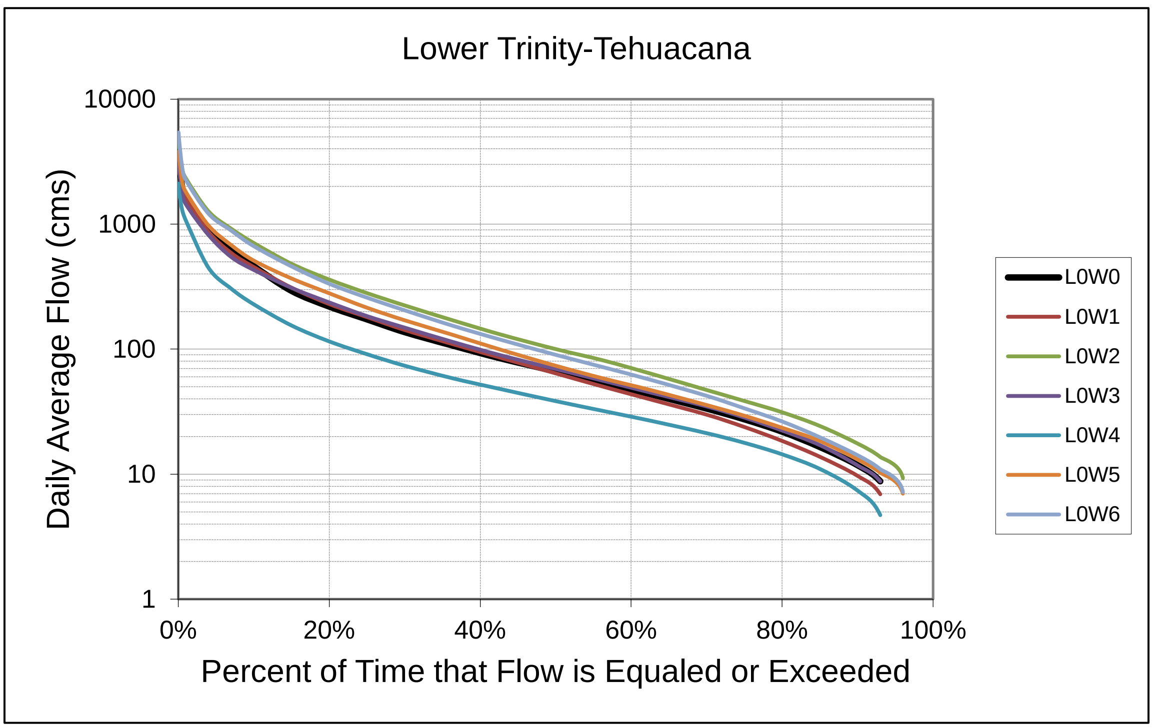


Figure 384. **Flow duration, Lower Trinity River - Tehuacana (SWAT)**

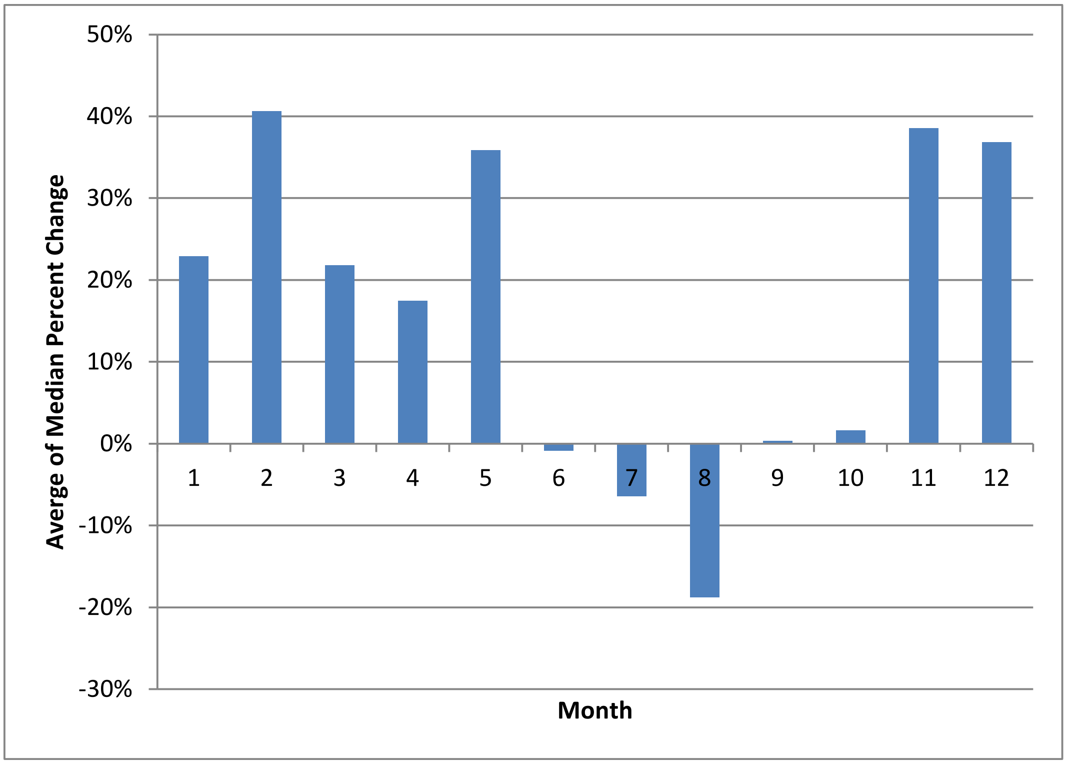


Figure 385. Average of median percent change in flow; NARCCAP Scenarios W1-W6 at all stations, Trinity River watershed (SWAT)

Upper Colorado River Basin

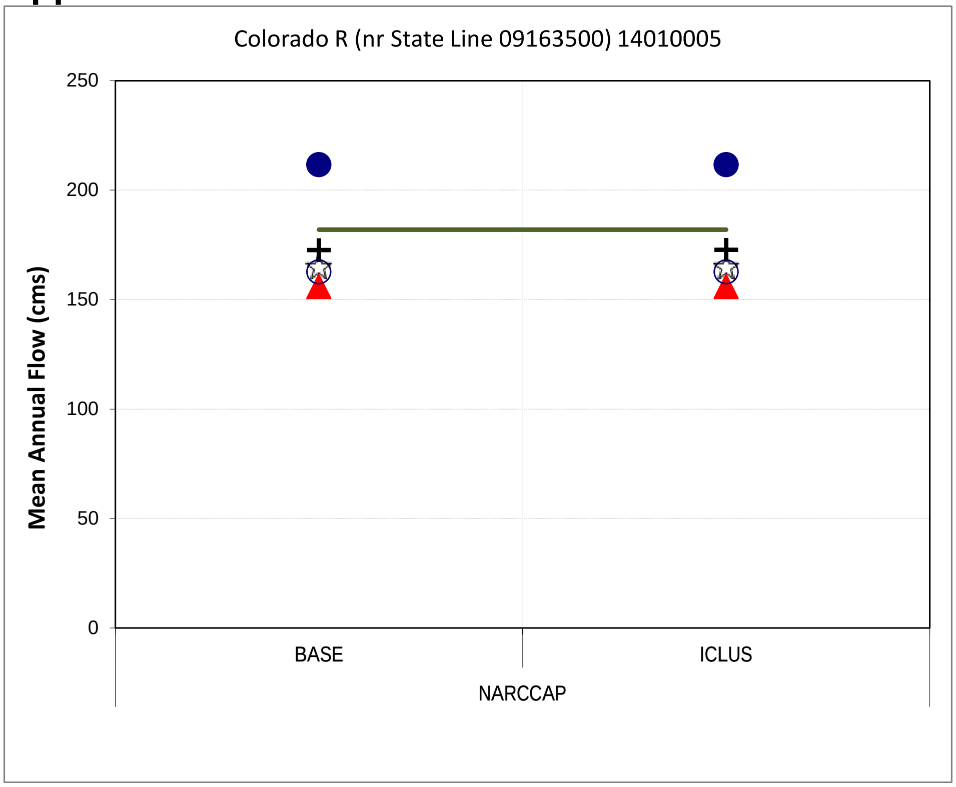


Figure 386. Mean annual flow (cms), Colorado River near State Line (SWAT)

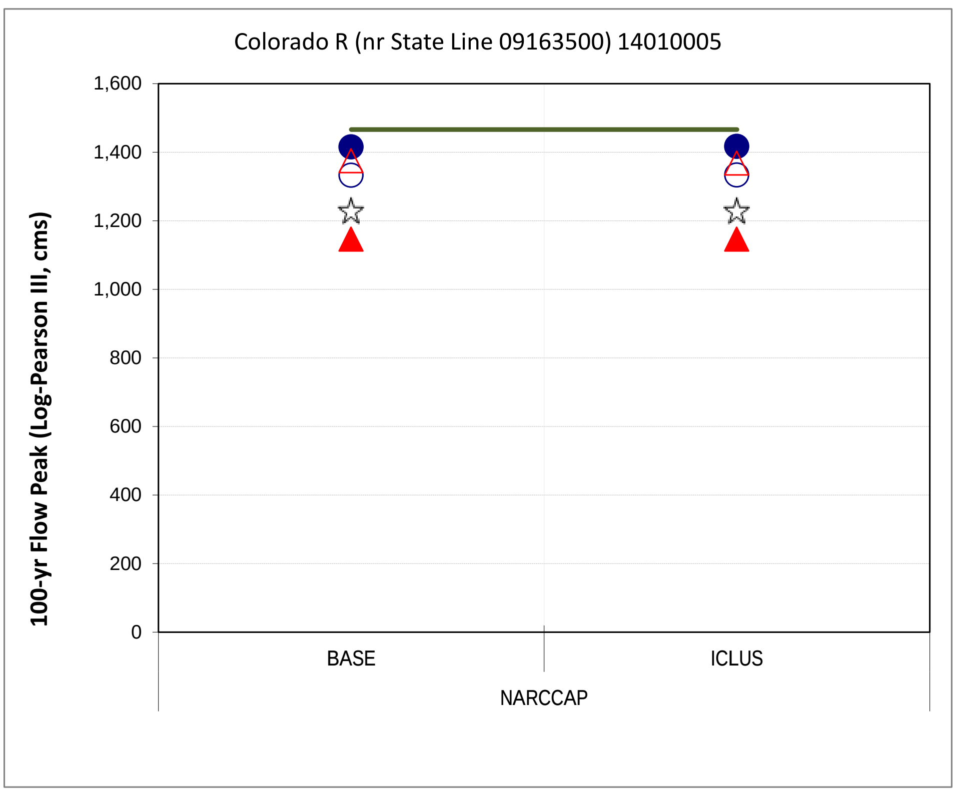


Figure 387. 100-yr Flow Peak (Log-Pearson III, cms), Colorado River near State Line (SWAT)

Upper Colorado River Basin

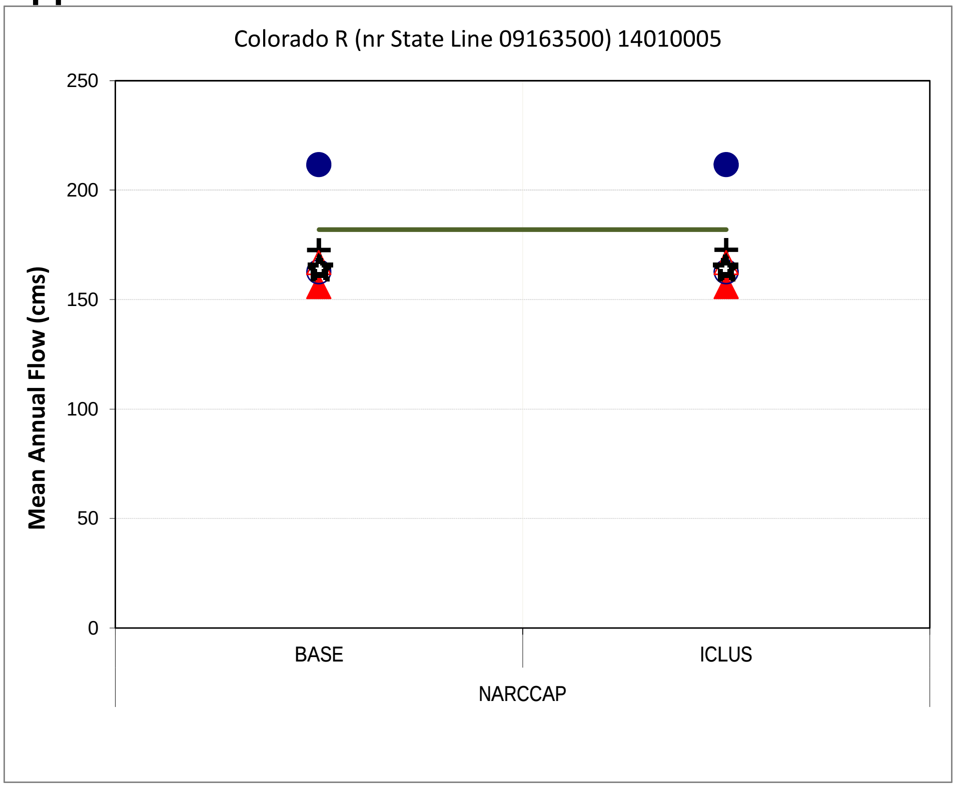


Figure 386. Mean annual flow (cms), Colorado River near State Line (SWAT)

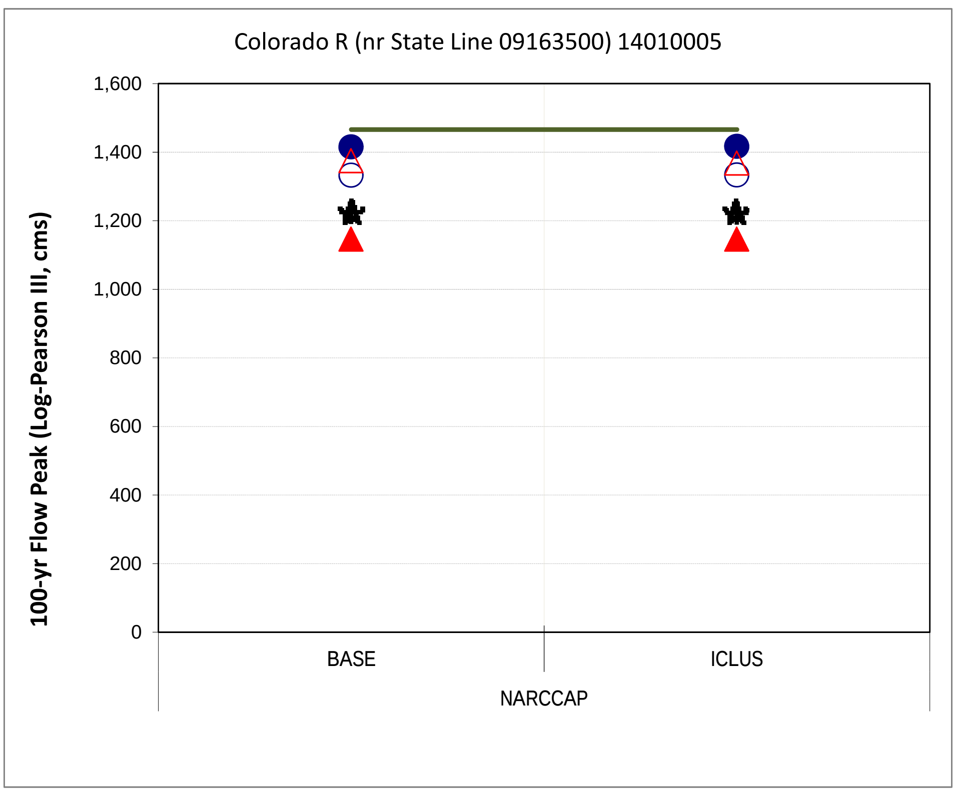


Figure 387. 100-yr Flow Peak (Log-Pearson III, cms), Colorado River near State Line (SWAT)

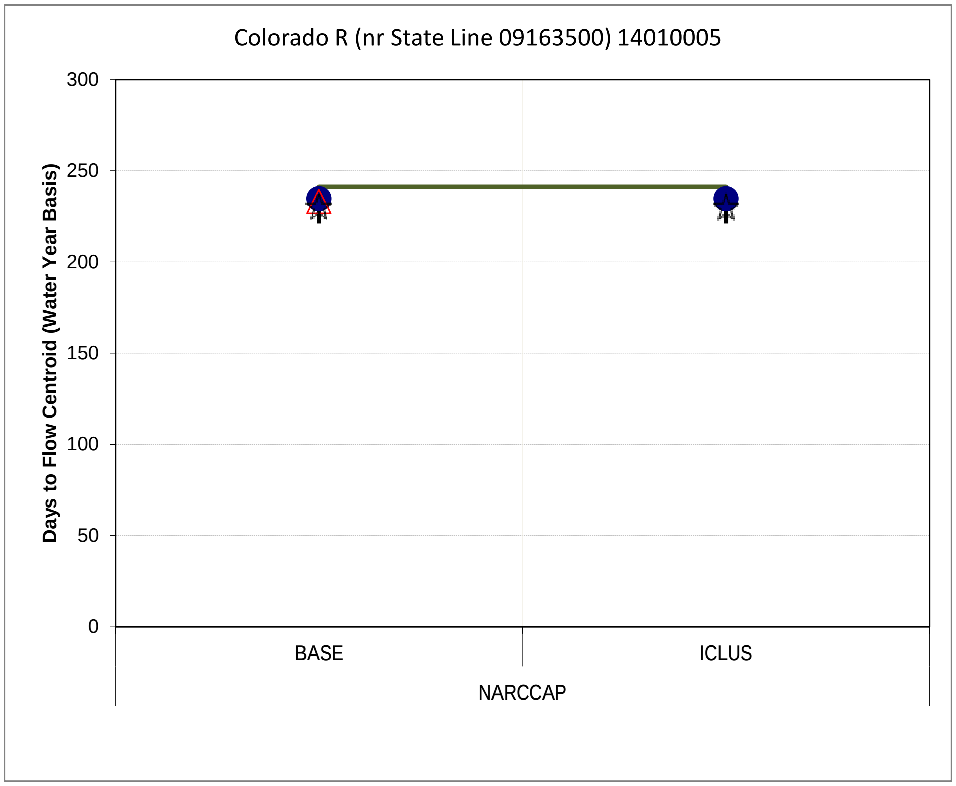


Figure 390. Days to Flow Centroid (Water Year Basis), Colorado River near State Line (SWAT)

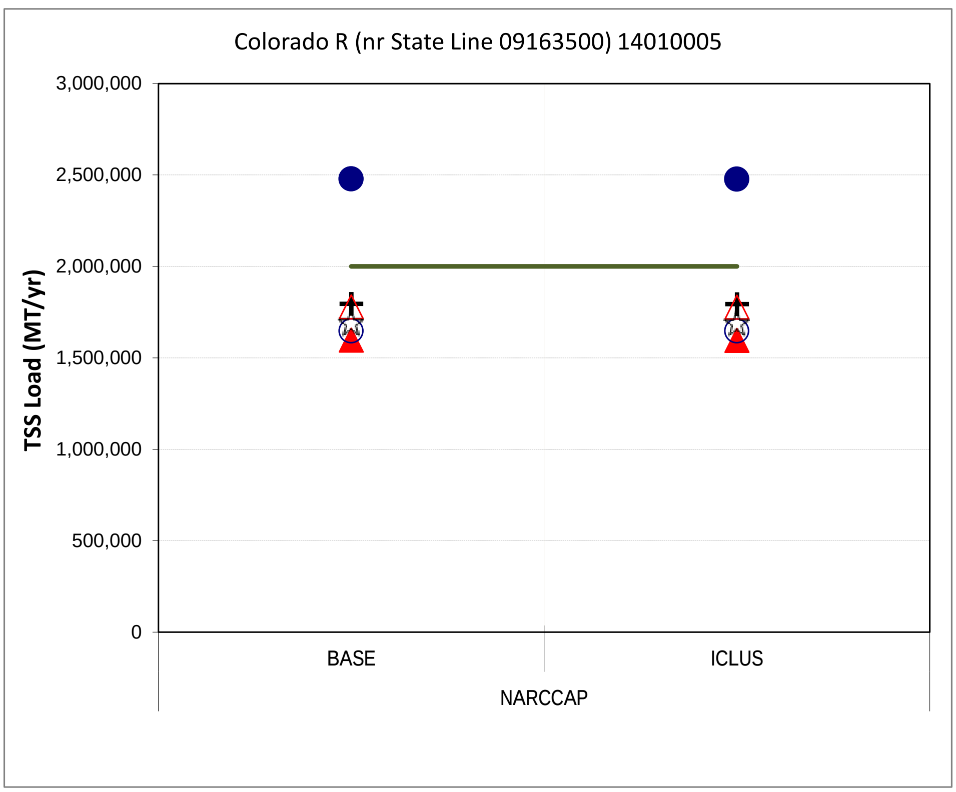


Figure 391. TSS Load (MT/yr), Colorado River near State Line (SWAT)

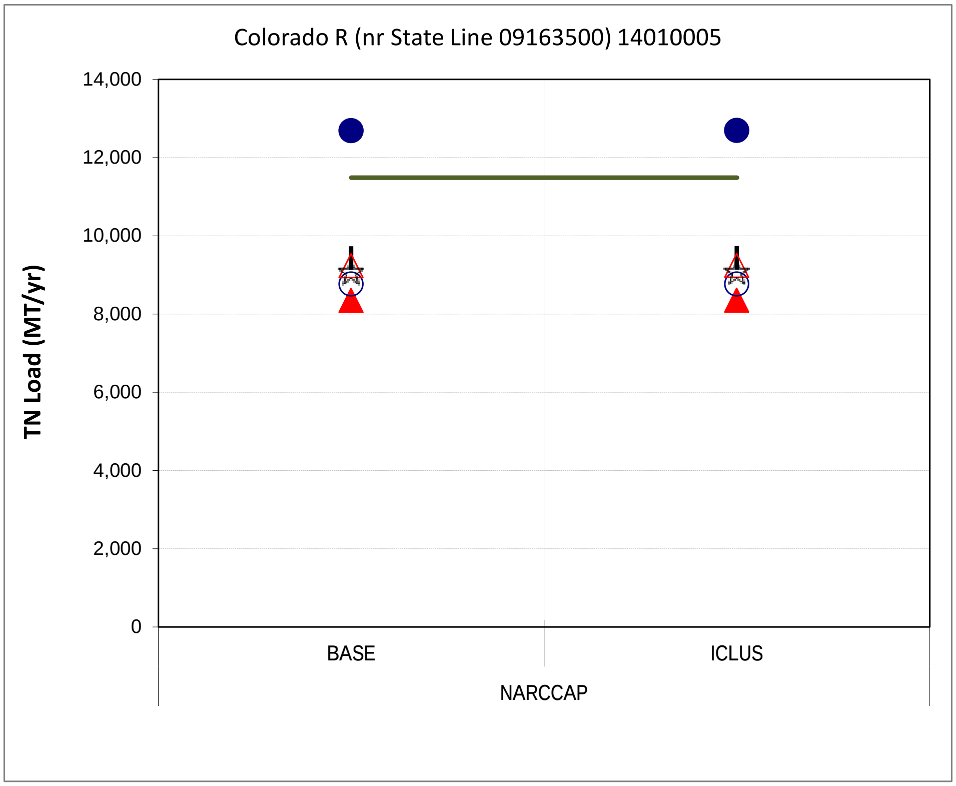


Figure 392. TN Load (MT/yr), Colorado River near State Line (SWAT)

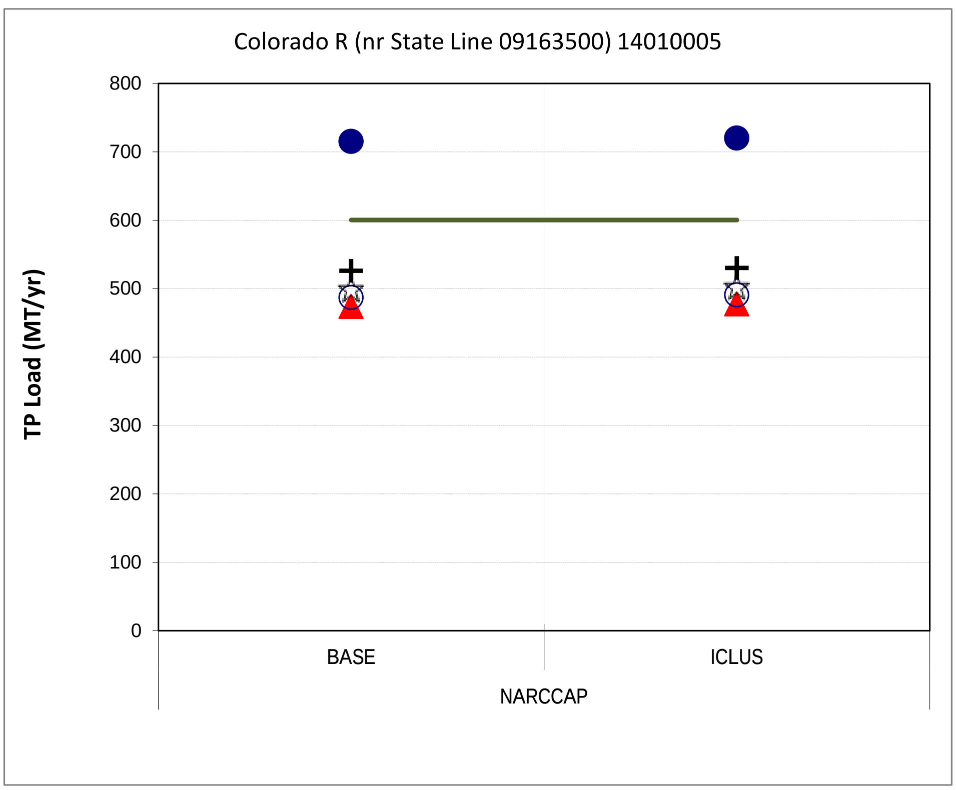


Figure 393. TP Load (MT/yr), Colorado River near State Line (SWAT)

Table 15. Summary of range of change relative to existing conditions for NARCCAP dynamically downscaled scenarios, Upper Colorado River watershed SWAT model

	Results without LU change				Results with LU change			
	Min	Median	Mean	Max	Min	Median	Mean	Max
Colorado Headwaters HUC 14010001								
Flow	-11.21%	-5.12%	-3.76%	9.05%	-11.33%	-5.23%	-3.87%	8.95%
TSS	-17.71%	-11.15%	-8.49%	8.20%	-17.84%	-11.27%	-8.60%	8.08%
TN	-33.36%	-31.12%	-30.12%	-24.81%	-33.56%	-31.36%	-30.34%	-24.89%
TP	-17.27%	-11.84%	-10.16%	1.22%	-17.73%	-12.40%	-10.64%	0.91%
Blue HUC 14010002								
Flow	-13.20%	-9.03%	-6.90%	5.58%	-13.41%	-9.25%	-7.10%	5.42%
TSS	-20.76%	-14.55%	-11.22%	8.17%	-21.03%	-14.84%	-11.49%	7.94%
TN	-38.27%	-29.63%	-29.88%	-22.73%	-39.68%	-30.50%	-30.91%	-23.50%
TP	-58.02%	-46.02%	-44.24%	-23.75%	-56.95%	-45.27%	-43.54%	-23.53%
Eagle HUC 14010003								
Flow	-13.35%	-5.88%	-4.09%	10.95%	-13.64%	-6.16%	-4.36%	10.66%
TSS	-19.38%	-12.82%	-9.29%	10.22%	-19.69%	-13.02%	-9.53%	9.91%
TN	-40.80%	-39.56%	-38.81%	-35.18%	-40.80%	-39.52%	-38.72%	-34.87%
TP	-1.23%	4.70%	4.27%	10.10%	-2.39%	3.69%	3.31%	9.62%
Roaring Fork (at Glenwood Sps, gage 09085000) HUC 14010004								
Flow	-15.92%	-8.48%	-6.20%	9.98%	-15.99%	-8.53%	-6.28%	9.88%
TSS	-21.86%	-13.97%	-10.93%	11.56%	-21.95%	-14.01%	-11.01%	11.43%
TN	-48.72%	-43.87%	-43.00%	-35.69%	-48.71%	-43.92%	-43.05%	-35.79%
TP	-26.80%	-18.36%	-17.13%	-0.78%	-26.65%	-18.13%	-16.99%	-0.77%
Colorado R (nr State Line gage 09163500) HUC 14010005								
Flow	-14.31%	-8.68%	-5.19%	16.29%	-14.36%	-8.74%	-5.25%	16.23%
TSS	-20.13%	-13.07%	-8.36%	23.96%	-20.21%	-13.13%	-8.42%	23.90%
TN	-27.32%	-20.18%	-16.46%	10.47%	-27.39%	-20.25%	-16.54%	10.37%
TP	-21.03%	-16.41%	-11.00%	19.13%	-21.07%	-16.45%	-11.06%	18.95%
East-Taylor HUC 14020001								
Flow	-12.05%	-6.00%	-4.71%	11.13%	-12.05%	-6.00%	-4.71%	11.13%
TSS	-96.05%	-95.62%	-95.27%	-93.33%	-96.05%	-95.62%	-95.27%	-93.33%
TN	-61.79%	-57.01%	-57.31%	-53.71%	-61.79%	-57.01%	-57.31%	-53.71%
TP	-21.02%	-14.28%	-13.31%	1.00%	-21.02%	-14.28%	-13.31%	1.00%
Upper Gunnison HUC 14020002								
Flow	-19.75%	-11.28%	-7.83%	20.26%	-19.75%	-11.28%	-7.83%	20.26%
TSS	-27.09%	-16.35%	-11.04%	31.07%	-27.09%	-16.35%	-11.04%	31.07%
TN	-37.82%	-29.31%	-25.21%	6.29%	-37.82%	-29.31%	-25.21%	6.29%
TP	-28.38%	-18.48%	-14.75%	17.46%	-28.38%	-18.48%	-14.75%	17.46%
Tomichi Cr (at Gunnison gage 09119000) HUC 14020003								
Flow	-20.21%	-10.45%	-7.52%	11.50%	-20.21%	-10.45%	-7.52%	11.50%

	Results without LU change				Results with LU change			
	Min	**Median**	**Mean**	**Max**	**Min**	**Median**	**Mean**	**Max**
TSS	-41.56%	-26.71%	-24.85%	-5.57%	-41.56%	-26.70%	-24.84%	-5.57%
TN	-86.43%	-76.90%	-78.26%	-71.70%	-86.43%	-76.90%	-78.26%	-71.70%
TP	-37.34%	-20.21%	-18.35%	6.59%	-37.33%	-20.21%	-18.35%	6.59%
N Fork Gunnison HUC 14020004								
Flow	-11.63%	-10.02%	-3.15%	22.93%	-11.63%	-10.02%	-3.15%	22.93%
TSS	-19.14%	-17.67%	-8.98%	24.86%	-19.14%	-17.67%	-8.98%	24.85%
TN	-28.19%	-25.74%	-18.51%	10.54%	-28.19%	-25.74%	-18.51%	10.54%
TP	-33.29%	-30.86%	-23.76%	5.35%	-33.28%	-30.86%	-23.75%	5.35%
Lower Gunnison HUC 1402000								
Flow	-18.22%	-12.13%	-7.15%	22.10%	-18.21%	-12.13%	-7.15%	22.10%
TSS	-25.82%	-18.37%	-11.08%	34.02%	-25.82%	-18.37%	-11.08%	34.02%
TN	-31.05%	-23.11%	-18.04%	16.64%	-31.05%	-23.11%	-18.04%	16.64%
TP	-25.82%	-18.81%	-14.10%	17.91%	-25.82%	-18.81%	-14.10%	17.91%
Uncompahgre HUC 14020006								
Flow	-14.92%	-10.82%	-5.51%	20.62%	-14.92%	-10.82%	-5.51%	20.62%
TSS	-21.21%	-16.35%	-9.45%	27.31%	-21.21%	-16.35%	-9.45%	27.32%
TN	-22.65%	-18.37%	-11.12%	25.59%	-22.65%	-18.37%	-11.11%	25.59%
TP	-12.34%	-7.34%	-2.57%	27.48%	-12.35%	-7.36%	-2.58%	27.45%
Gunnison R nr Gunnison (gage 09114500)								
Flow	-13.60%	-6.85%	-5.47%	11.45%	-13.60%	-6.85%	-5.47%	11.45%
TSS	-84.04%	-82.63%	-81.80%	-76.18%	-84.03%	-82.63%	-81.80%	-76.18%
TN	-63.22%	-58.80%	-59.06%	-55.93%	-63.22%	-58.80%	-59.06%	-55.93%
TP	-20.21%	-12.47%	-11.32%	4.71%	-20.21%	-12.47%	-11.32%	4.71%
Colorado R nr Cameo (gage 09095500)								
Flow	-11.74%	-5.96%	-3.89%	11.57%	-11.84%	-6.05%	-3.98%	11.47%
TSS	-15.94%	-9.86%	-6.37%	14.89%	-16.05%	-9.96%	-6.47%	14.77%
TN	-30.28%	-25.67%	-23.62%	-10.87%	-30.44%	-25.87%	-23.81%	-11.06%
TP	-12.74%	-9.90%	-5.57%	18.60%	-13.00%	-10.14%	-5.89%	18.10%

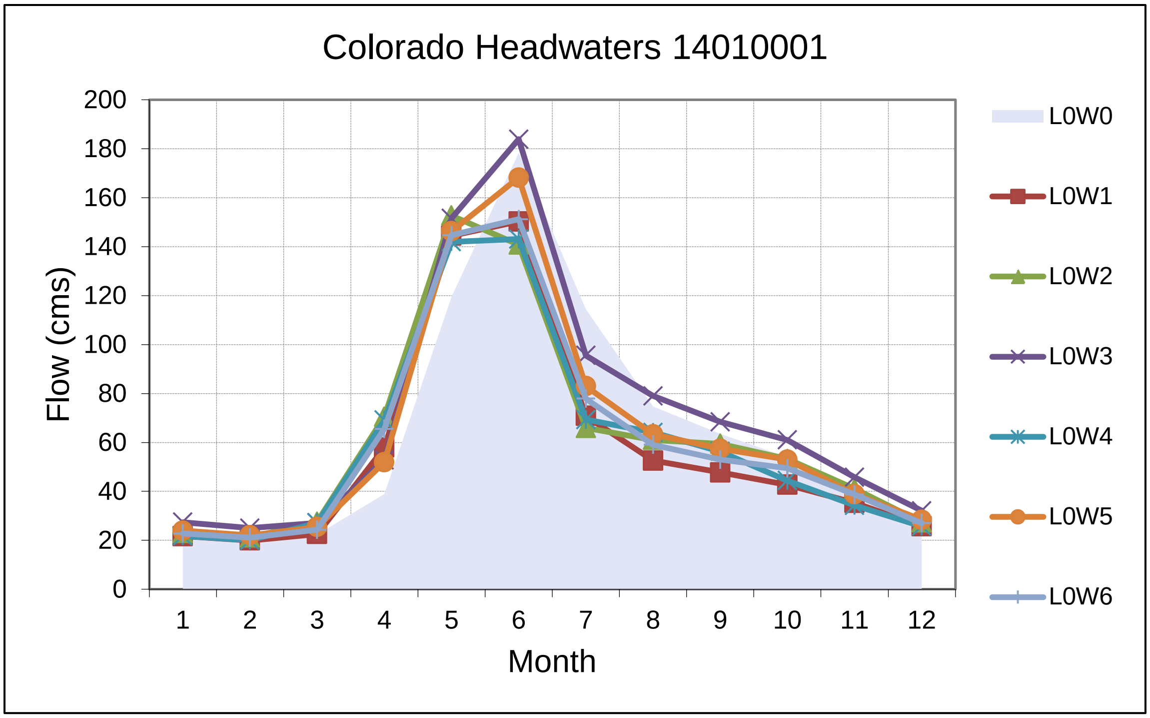


Figure 394. **Monthly average flows, Colorado River Headwaters (SWAT)**

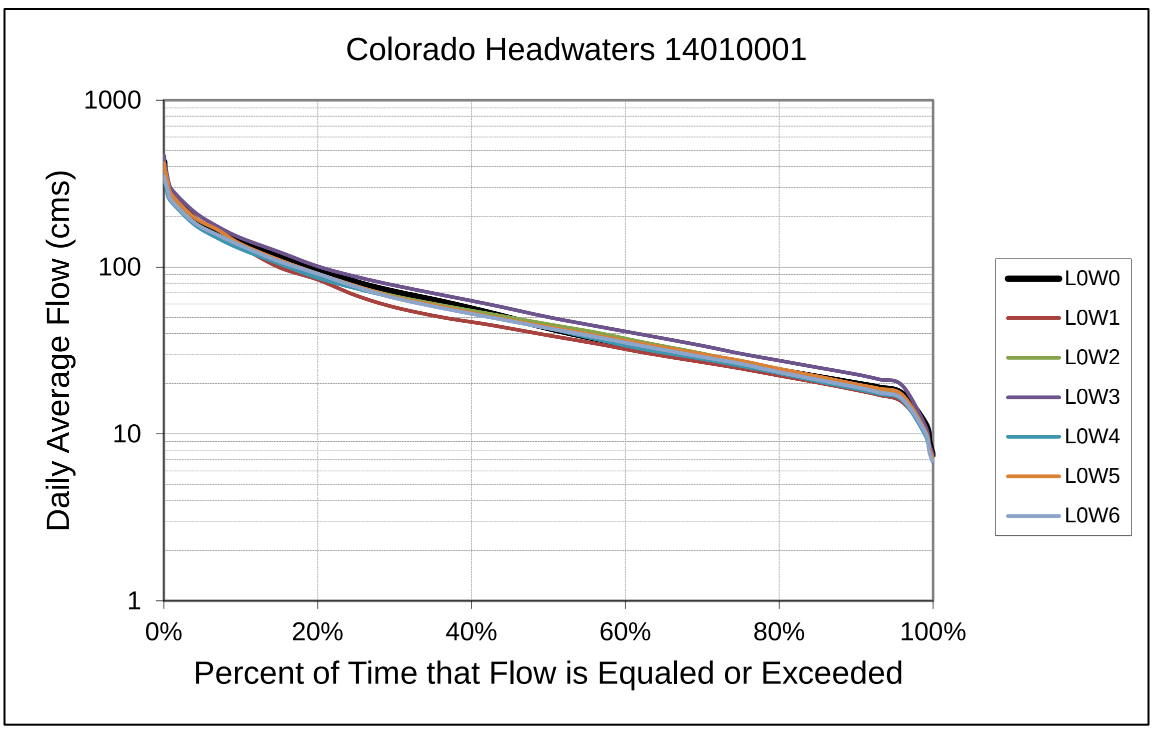


Figure 395. **Flow duration, Colorado River Headwaters (SWAT)**

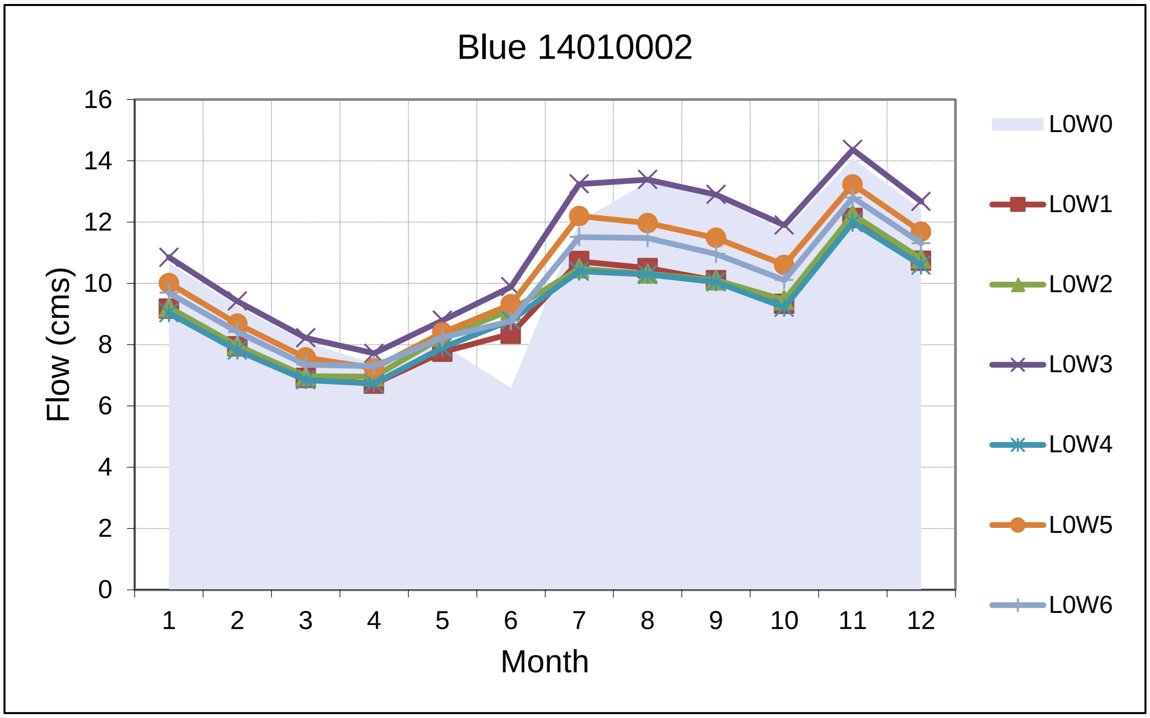


Figure 396. Monthly average flows, Blue River (SWAT)

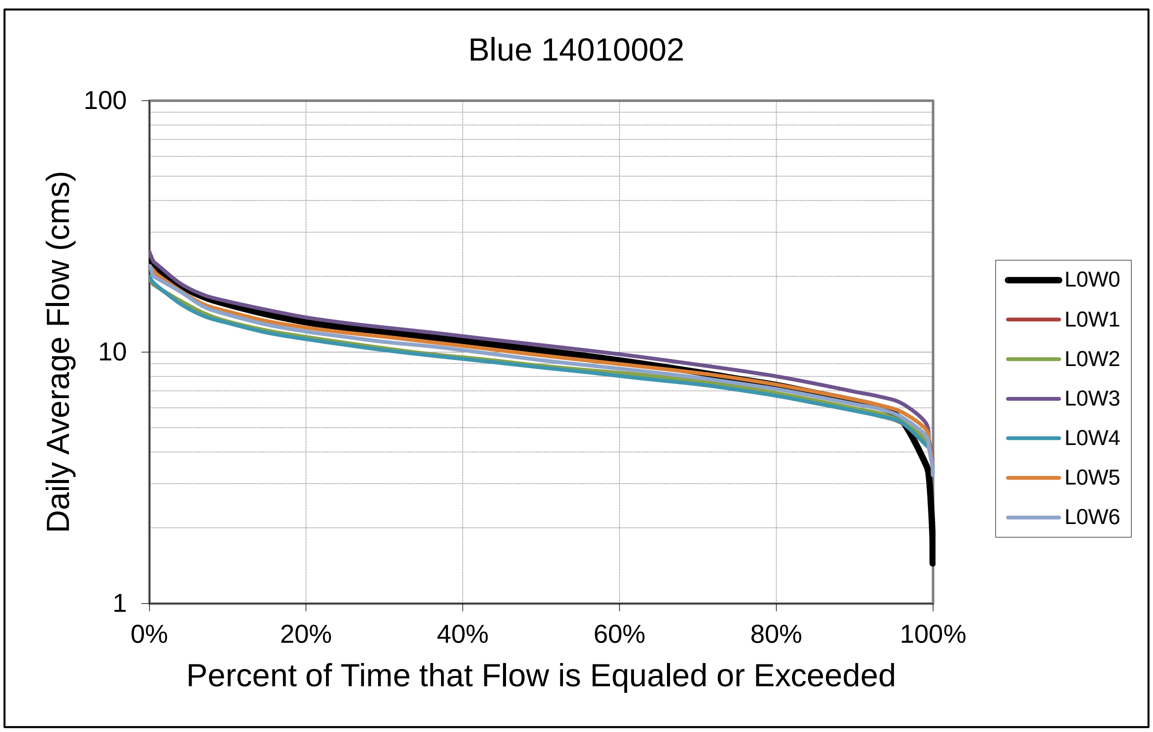


Figure 397. Flow duration, Blue River (SWAT)

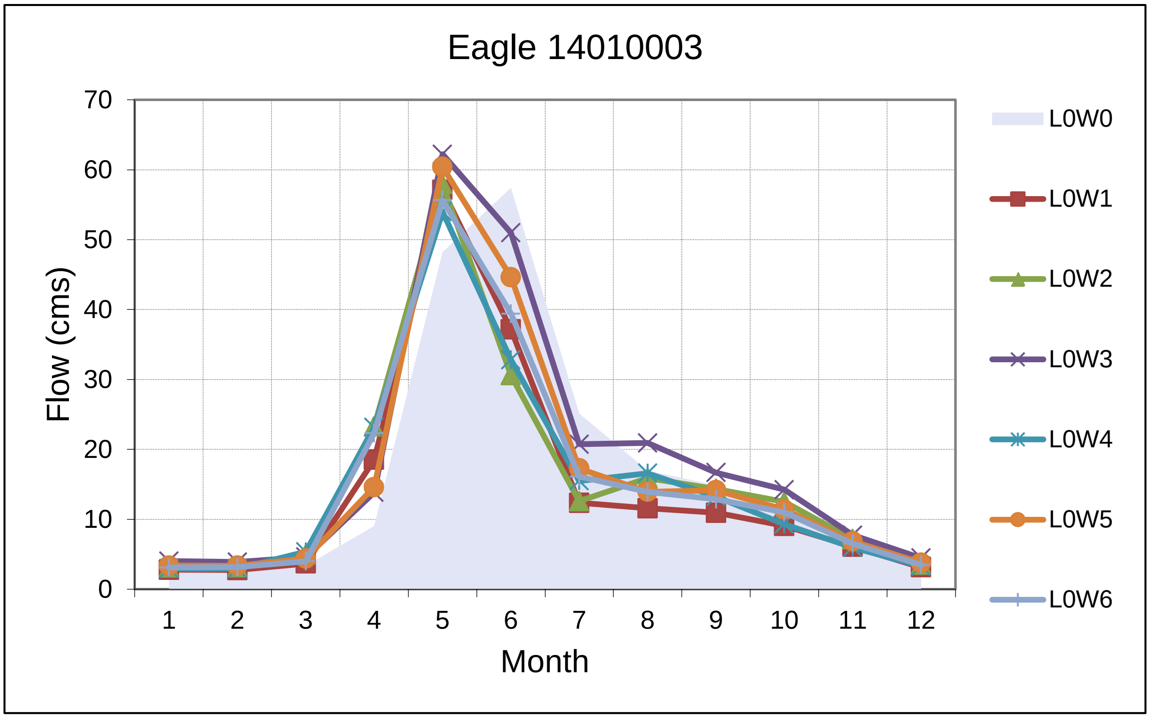


Figure 398. **Monthly average flows, Eagle River (SWAT)**

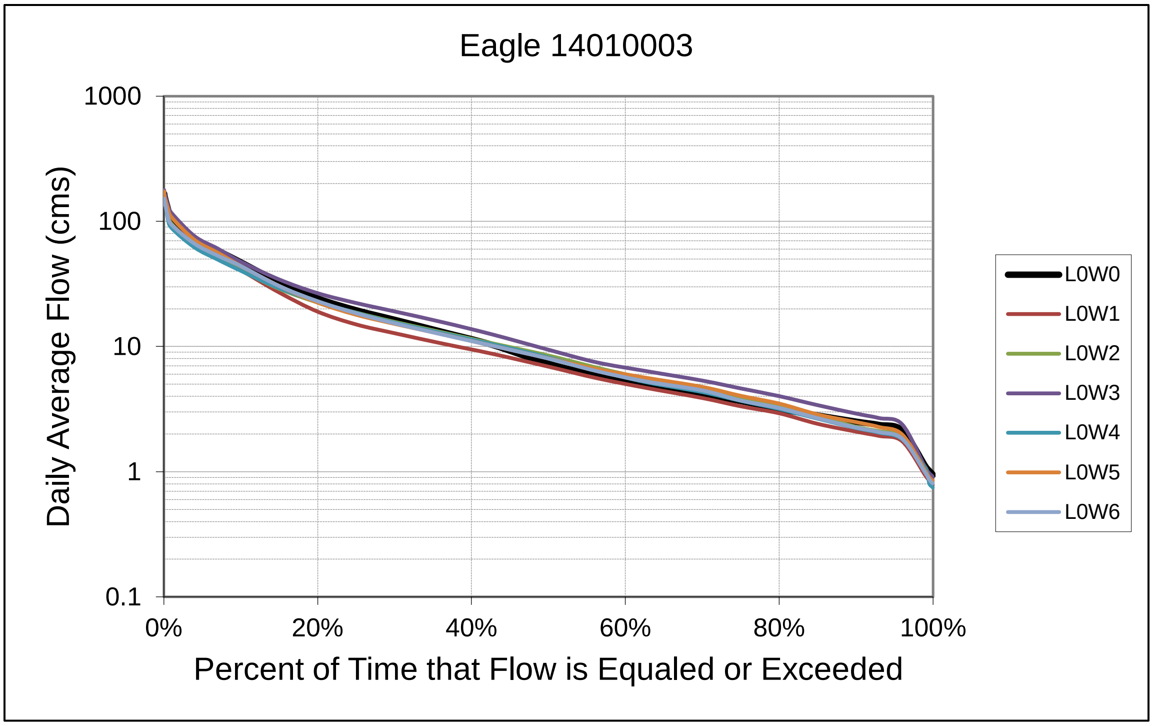


Figure 399. **Flow duration, Eagle River (SWAT)**

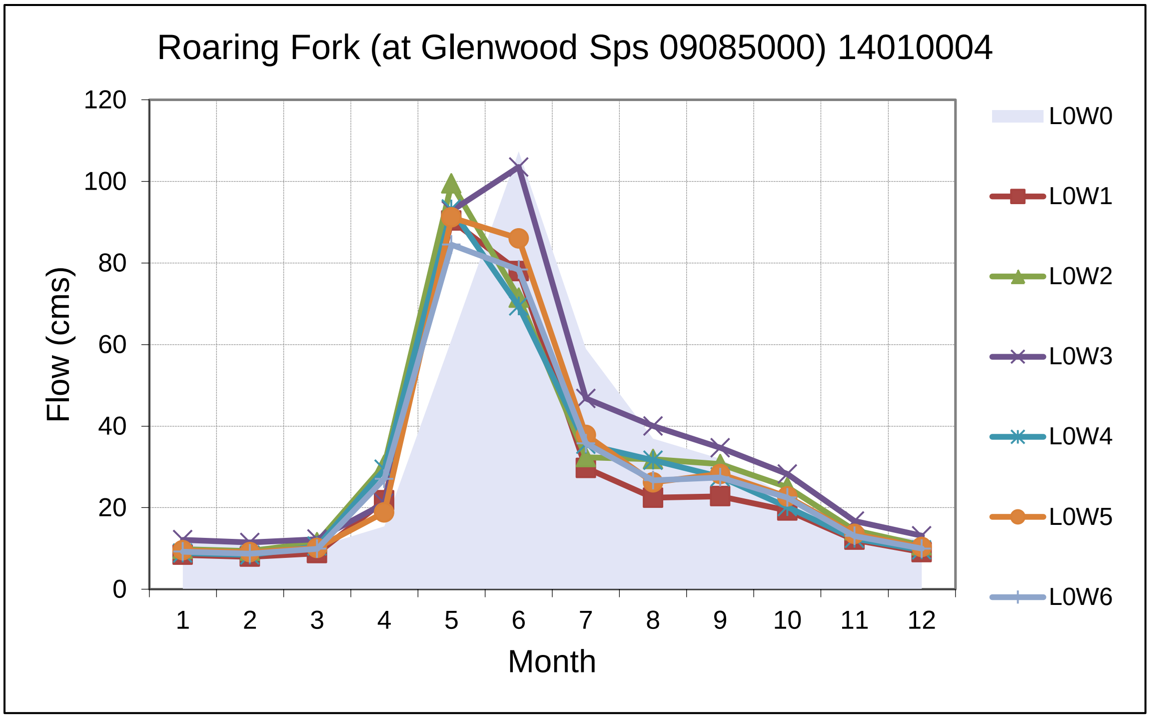


Figure 400. **Monthly average flows, Roaring Fork at Glenwood Springs (SWAT)**

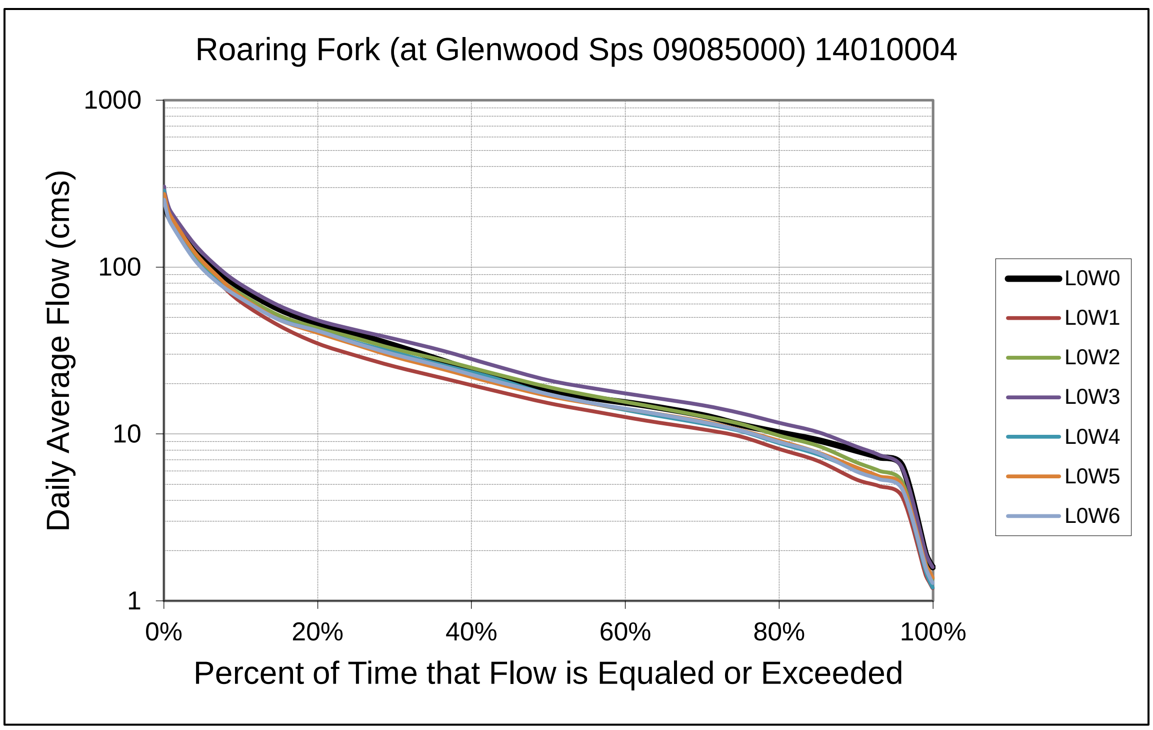


Figure 401. **Flow duration, Roaring Fork at Glenwood Springs (SWAT)**

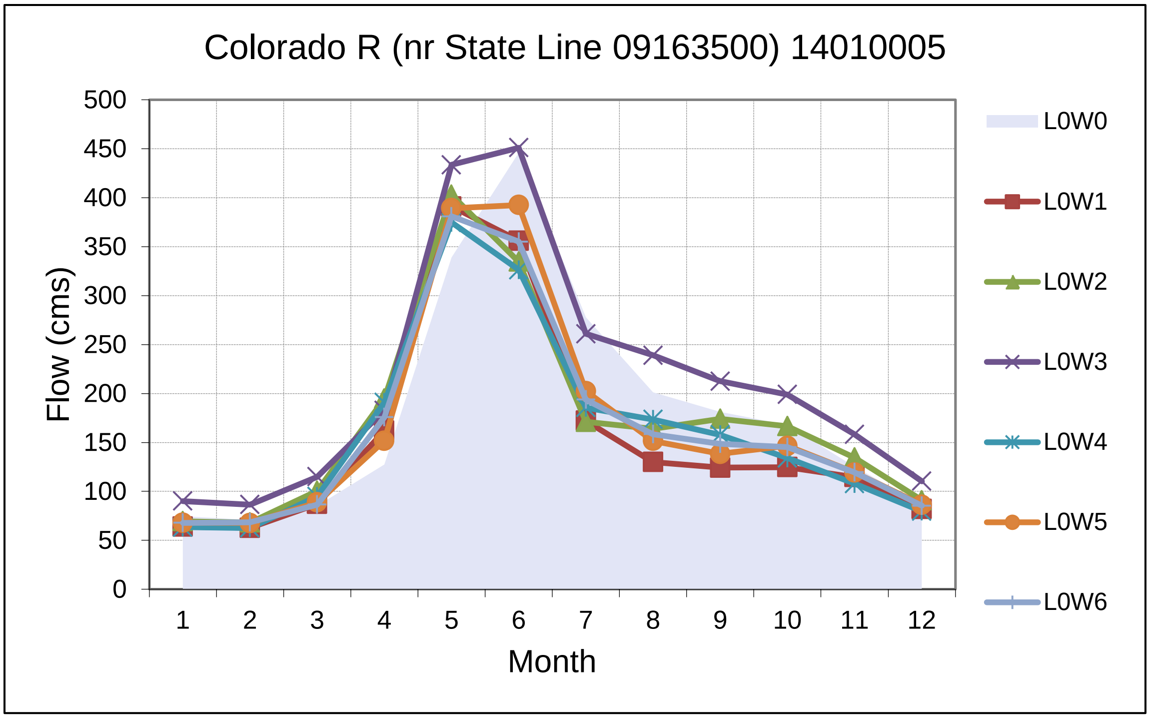


Figure 402. **Monthly average flows, Colorado River near State Line (SWAT)**

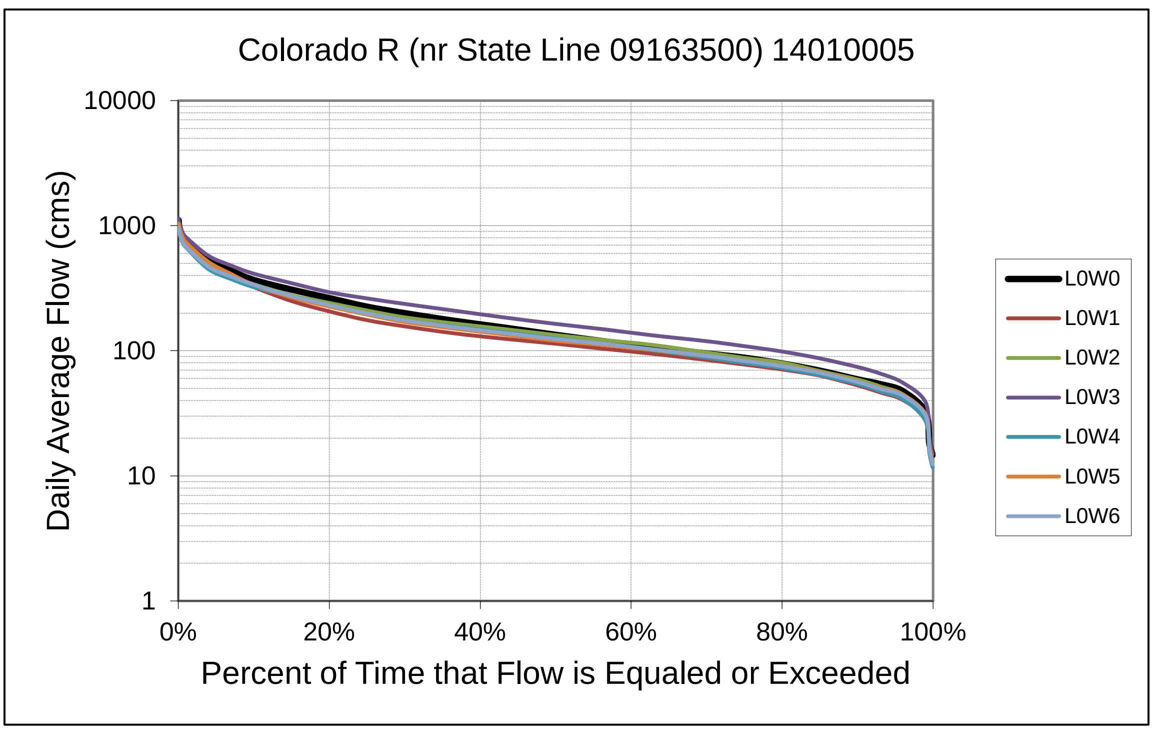


Figure 403. **Flow duration, Colorado River near State Line (SWAT)**

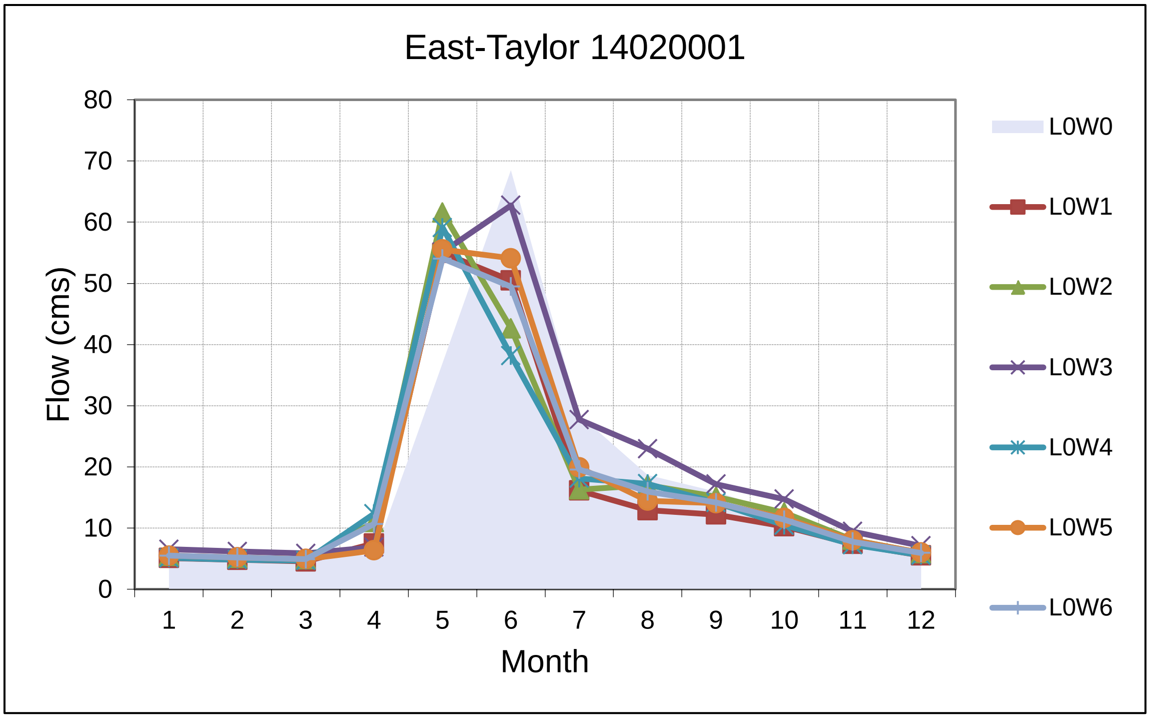


Figure 404. Monthly average flows, East - Taylor (SWAT)

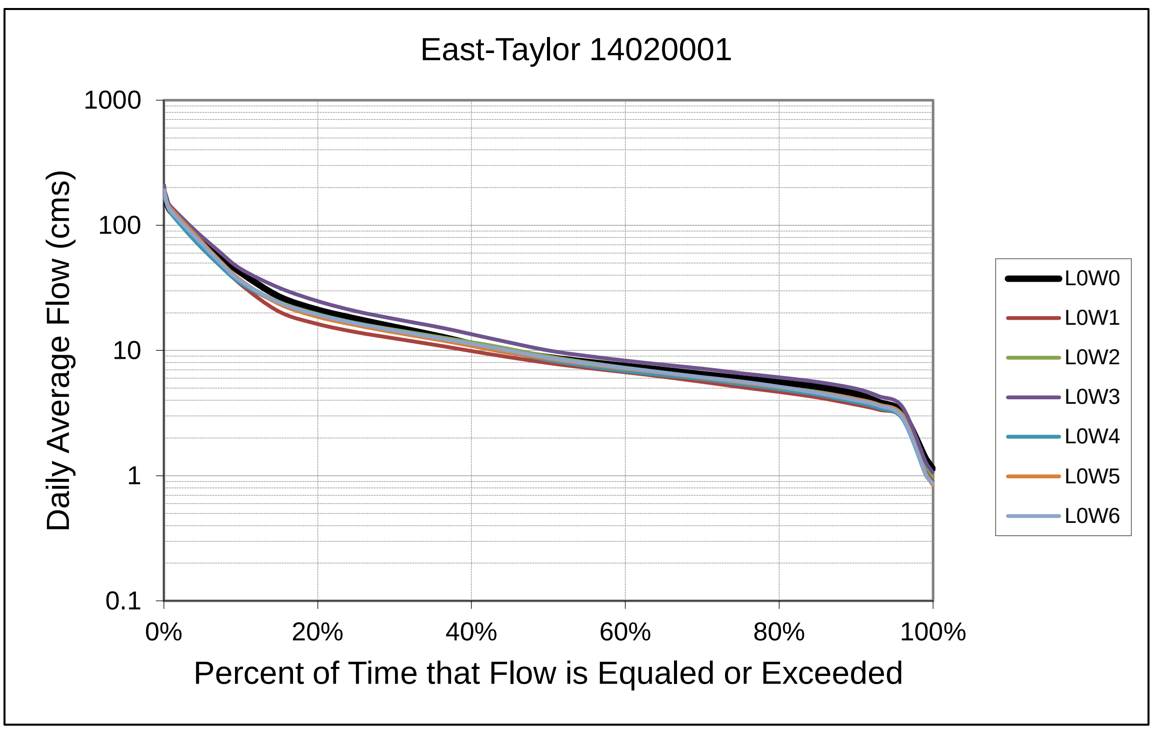


Figure 405. Flow duration, East - Taylor (SWAT)

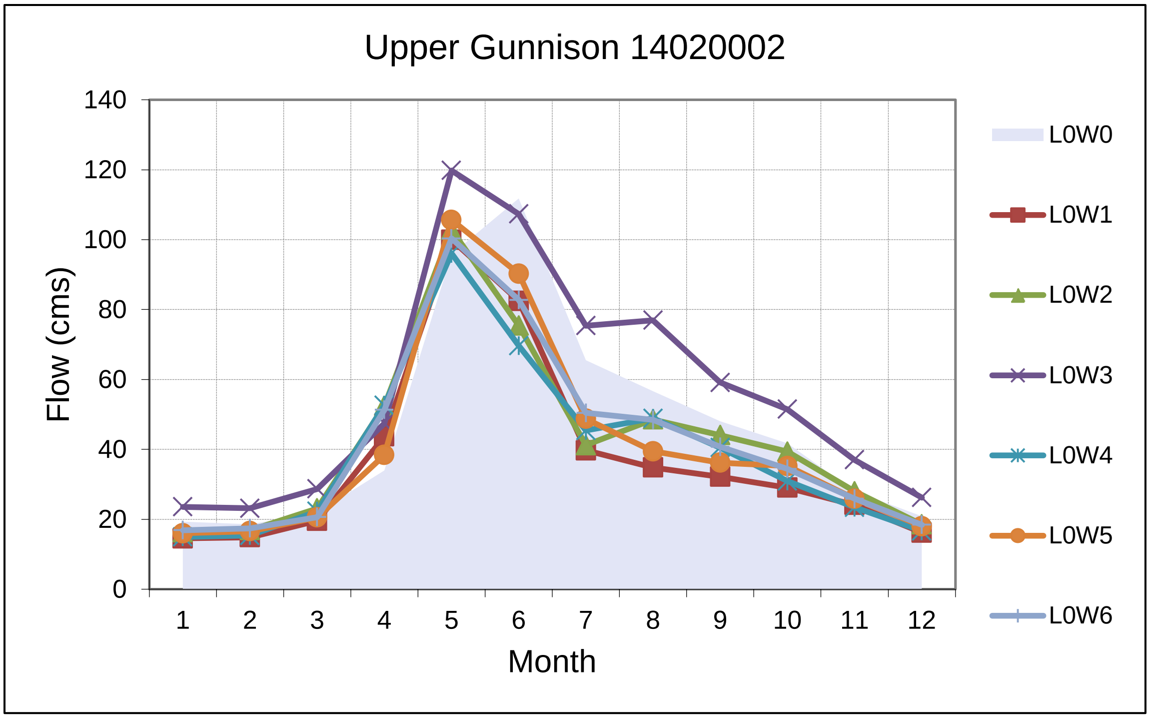


Figure 406. **Monthly average flows, Upper Gunnison River (SWAT)**

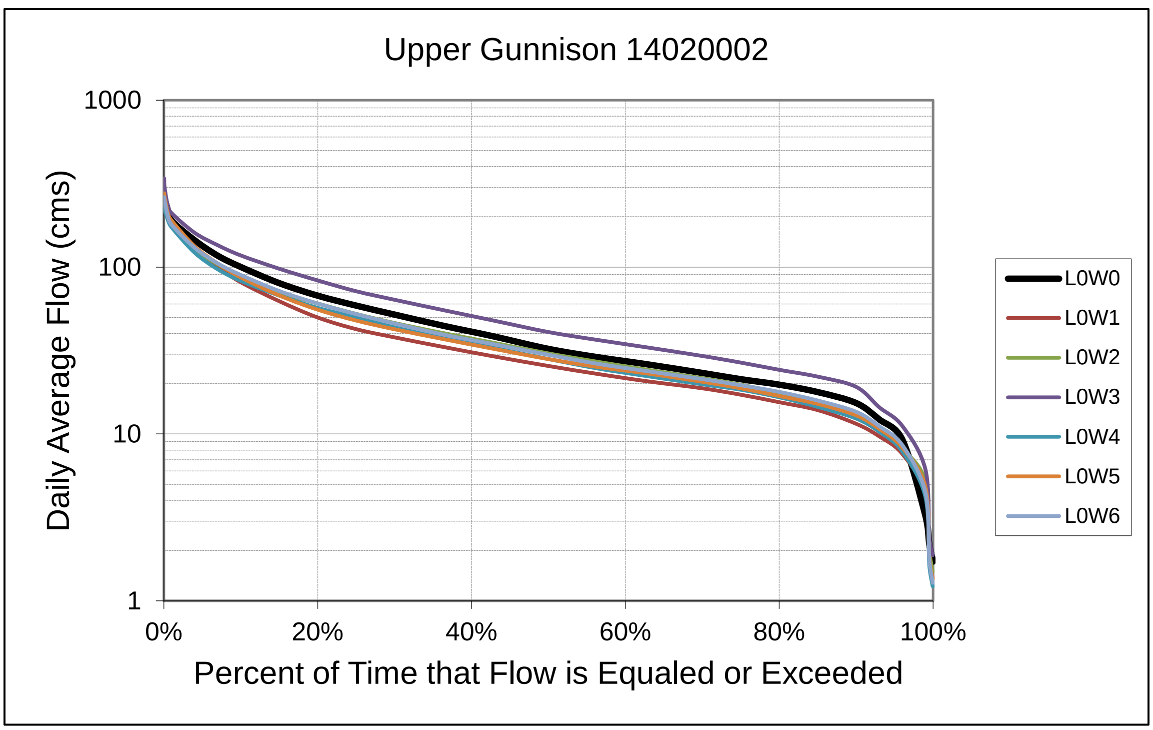


Figure 407. **Flow duration, Upper Gunnison River (SWAT)**

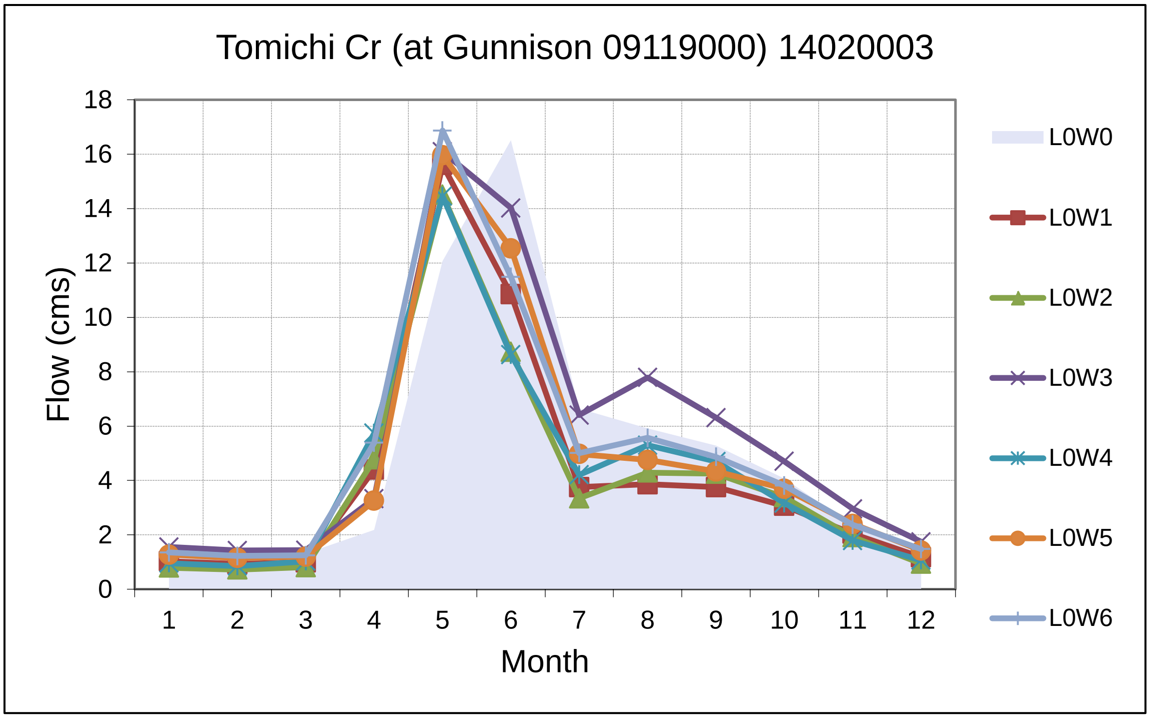


Figure 408. **Monthly average flows, Tomichi Creek at Gunnison (SWAT)**

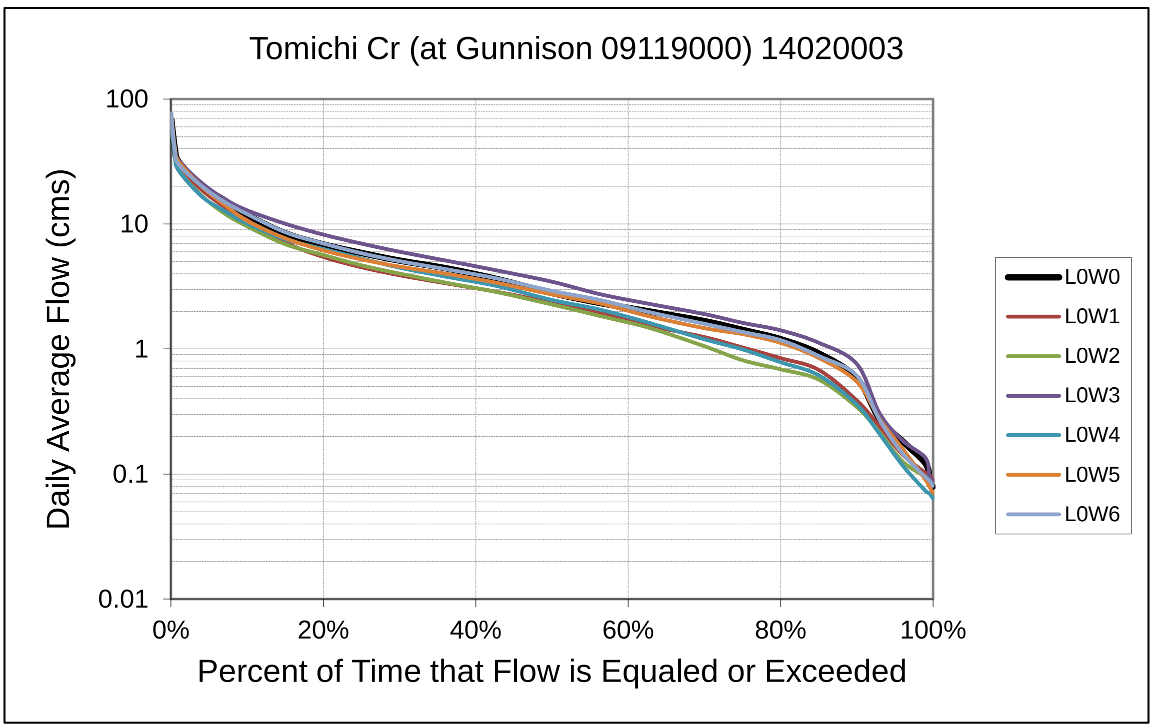


Figure 409. **Flow duration, Tomichi Creek at Gunnison (SWAT)**

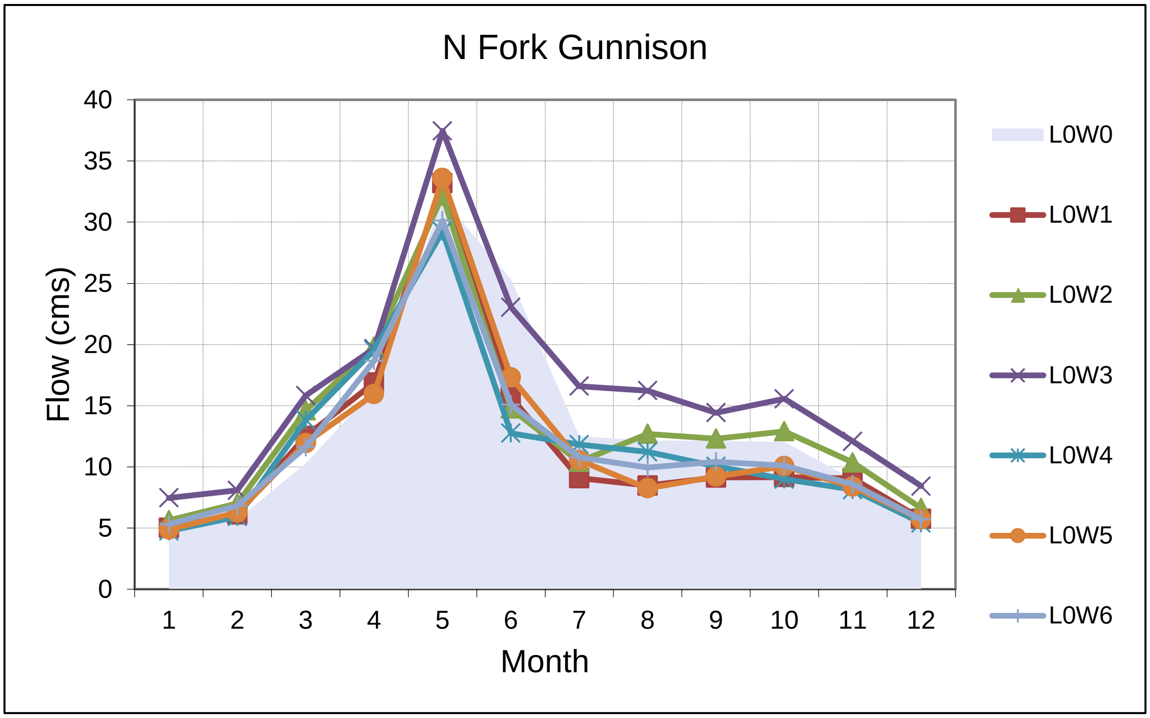


Figure 410. **Monthly average flows, North Fork Gunnison River (SWAT)**

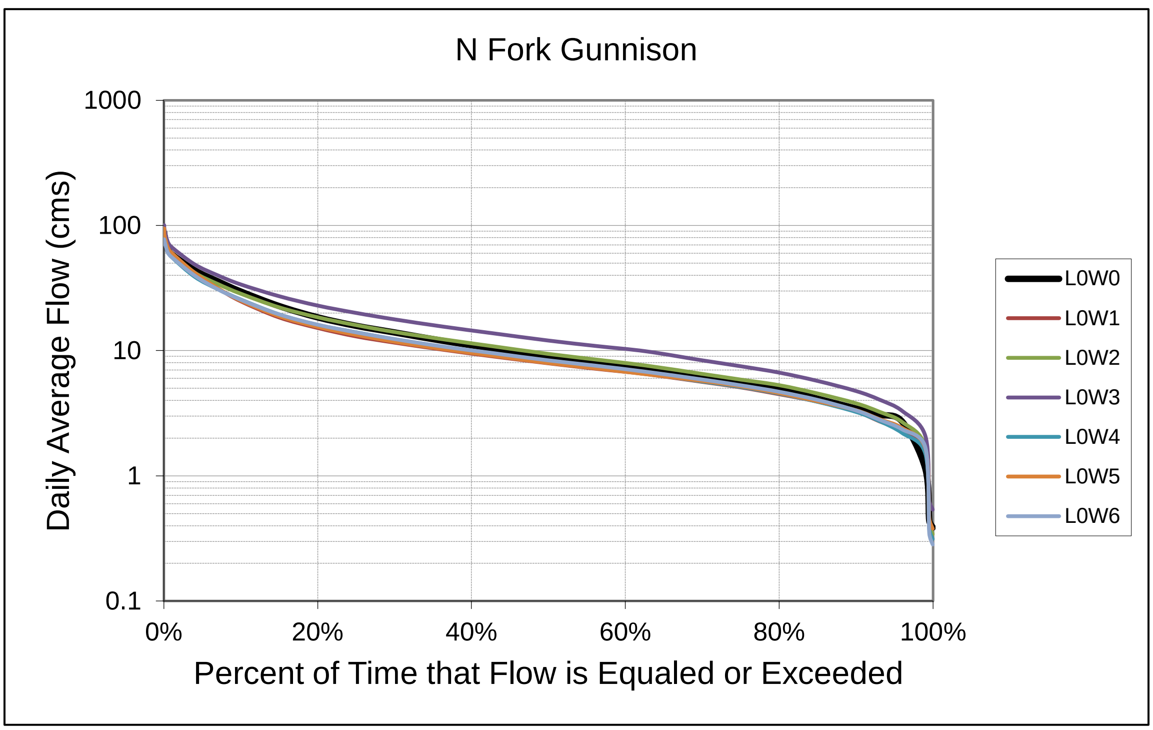


Figure 411. **Flow duration, North Fork Gunnison River (SWAT)**

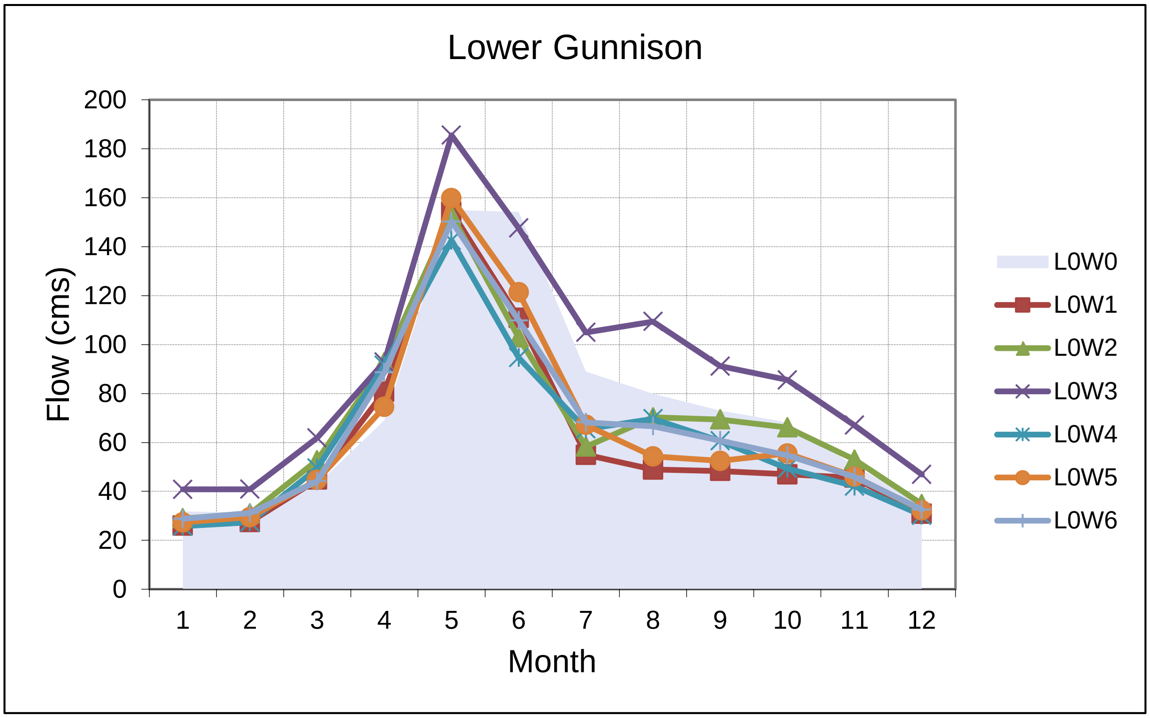


Figure 412. **Monthly average flows, Lower Gunnison River (SWAT)**

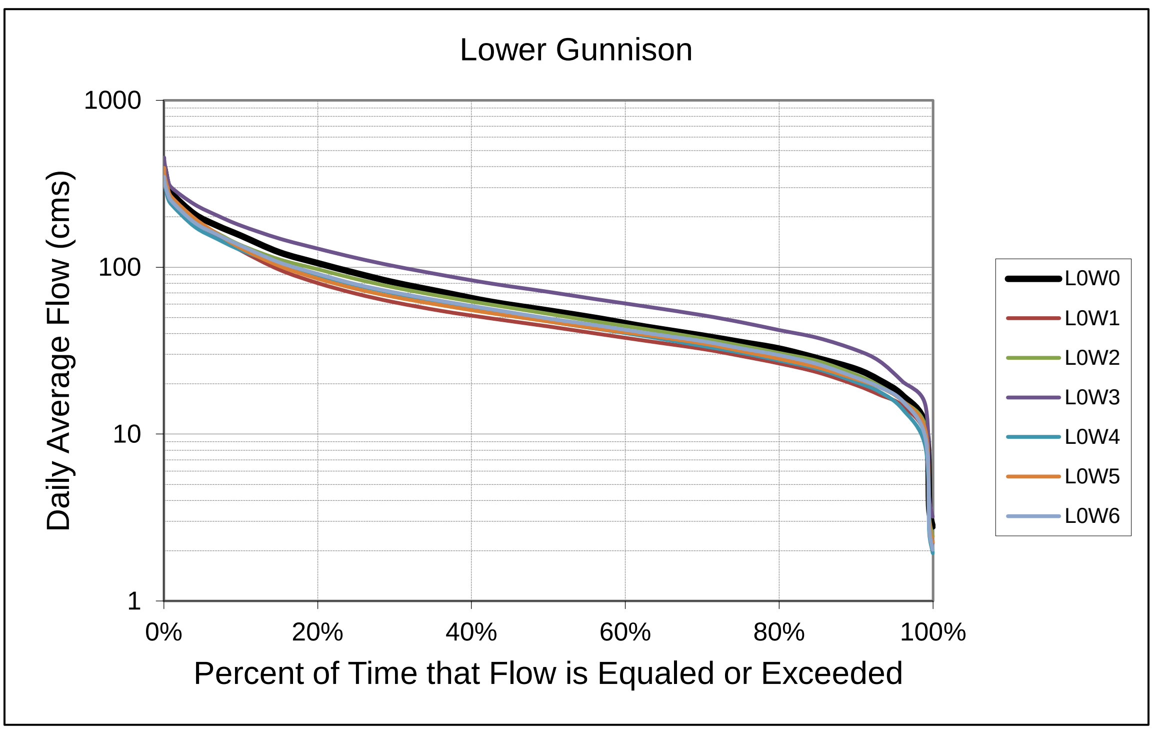


Figure 413. **Flow duration, Lower Gunnison River (SWAT)**

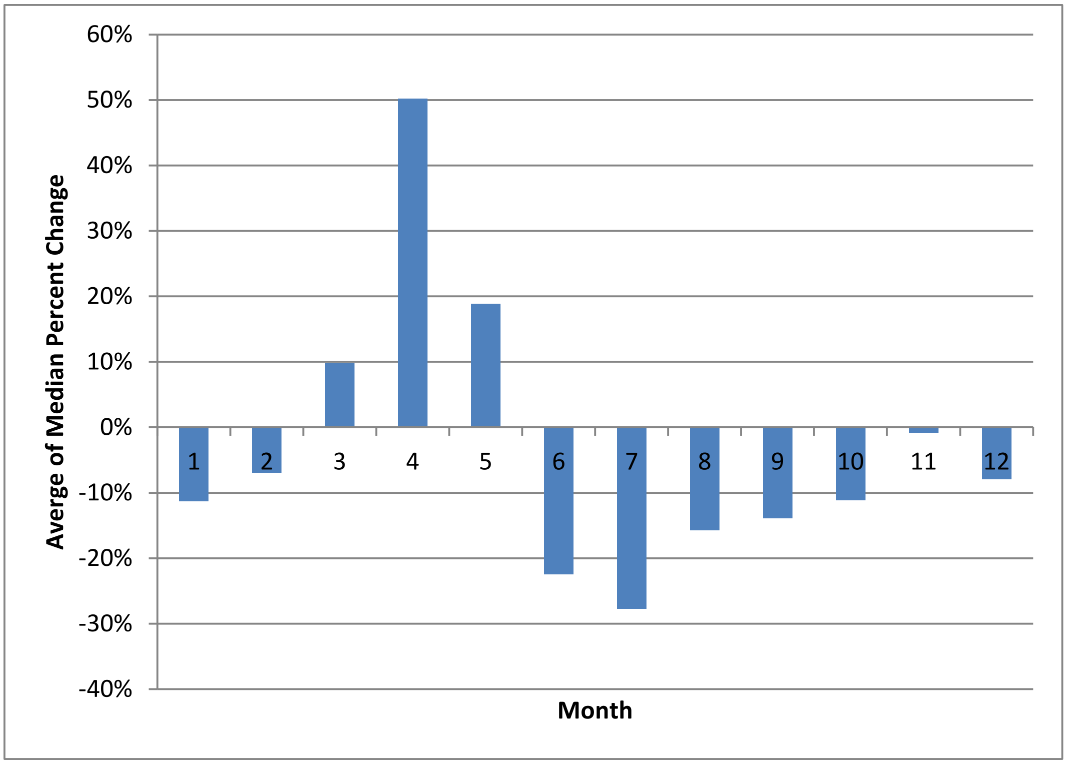
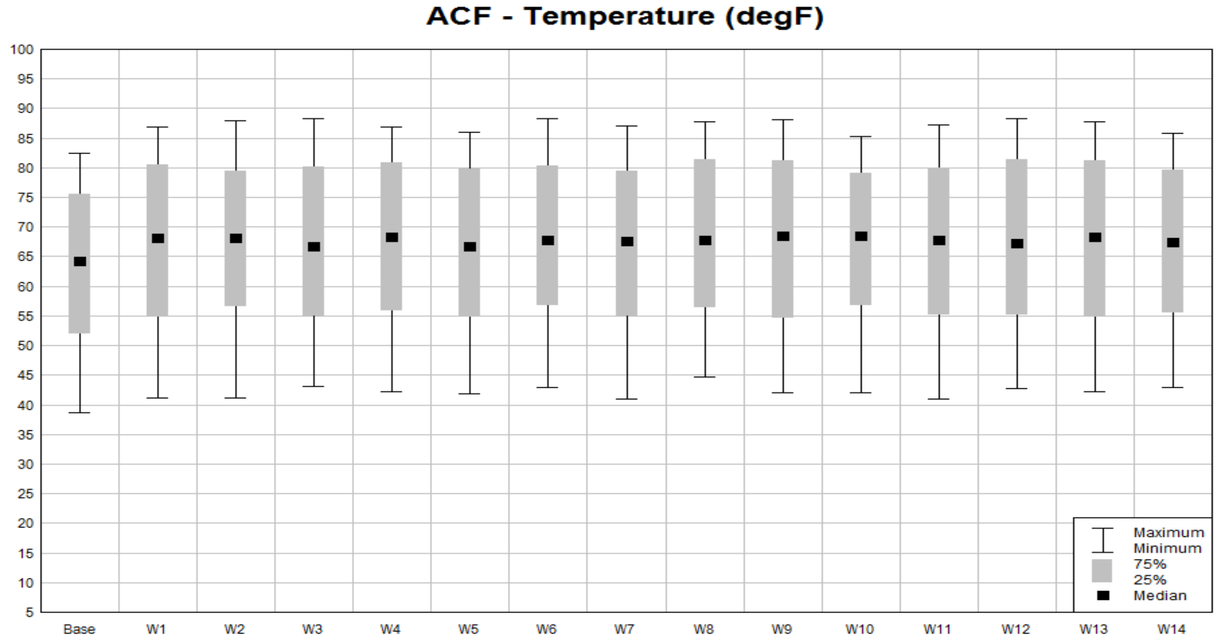


Figure 414. Average of median percent change in flow; NARCCAP Scenarios W1-W6 at all stations, Upper Colorado River watershed (SWAT)

APPENDIX Z.
OVERVIEW OF CLIMATE SCENARIO MONTHLY TEMPERATURE, PRECIPITATION, AND POTENTIAL EVAPOTRANSPIRATION

Table Z-1. Climate change scenarios evaluated

Scenario (W) #	Climate Model(s) (GCM / RCM)
NARCCAP dynamically downscaled scenarios	
1	**CGCM3 / CRCM**
2	**HadCM3 / HRM3**
3	**GFDL / RCM3**
4	**GFDL / GFDL high res**
5	**CGCM3 / RCM3**
6	**CCSM / WRFP**
Driving GCMs of the NARCCAP scenarios (without downscaling)	
7	**CGCM3**
8	**HadCM3**
9	**GFDL**
10	**CCSM**
BCSD statistically downscaled scenarios	
11	**CGCM3**
12	**HadCM3**
13	**GFDL**
14	**CCSM**



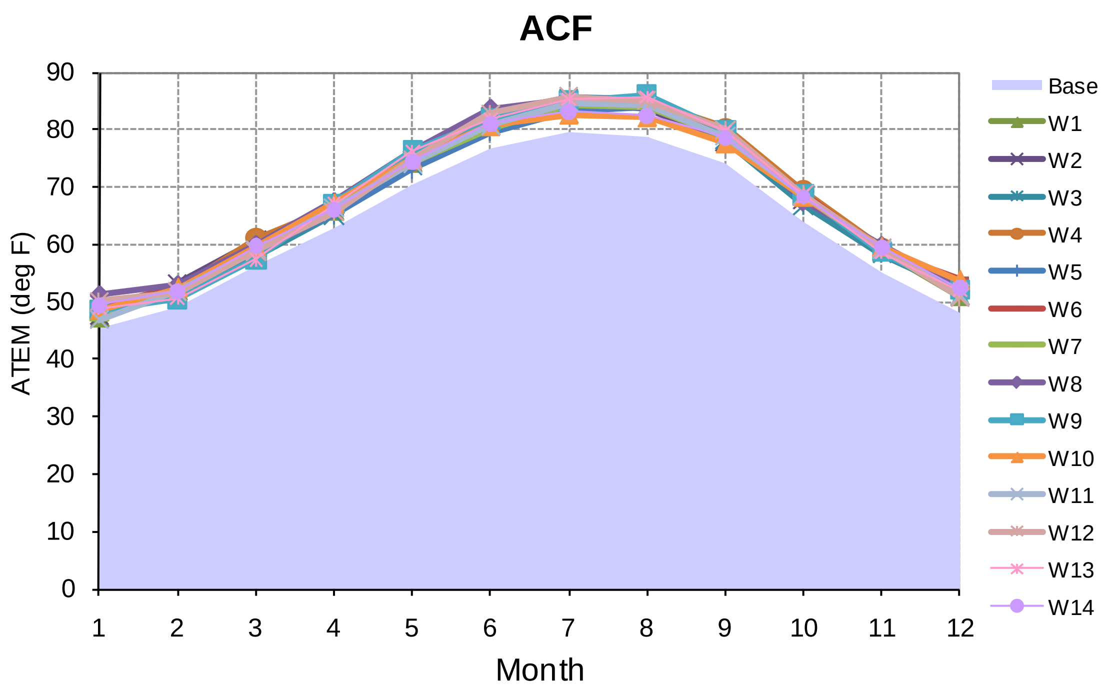
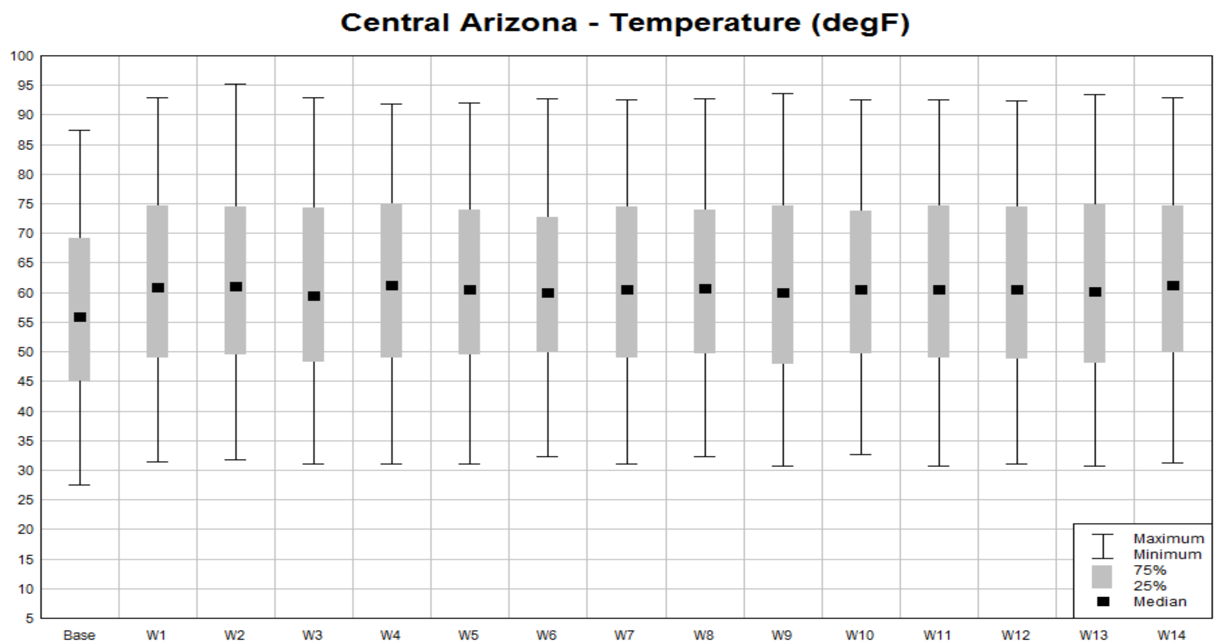


Figure Z-1. ACF: Comparison of climate scenario temperature for the ACF basin

Note: See Table Z-1 for key to climate scenarios.



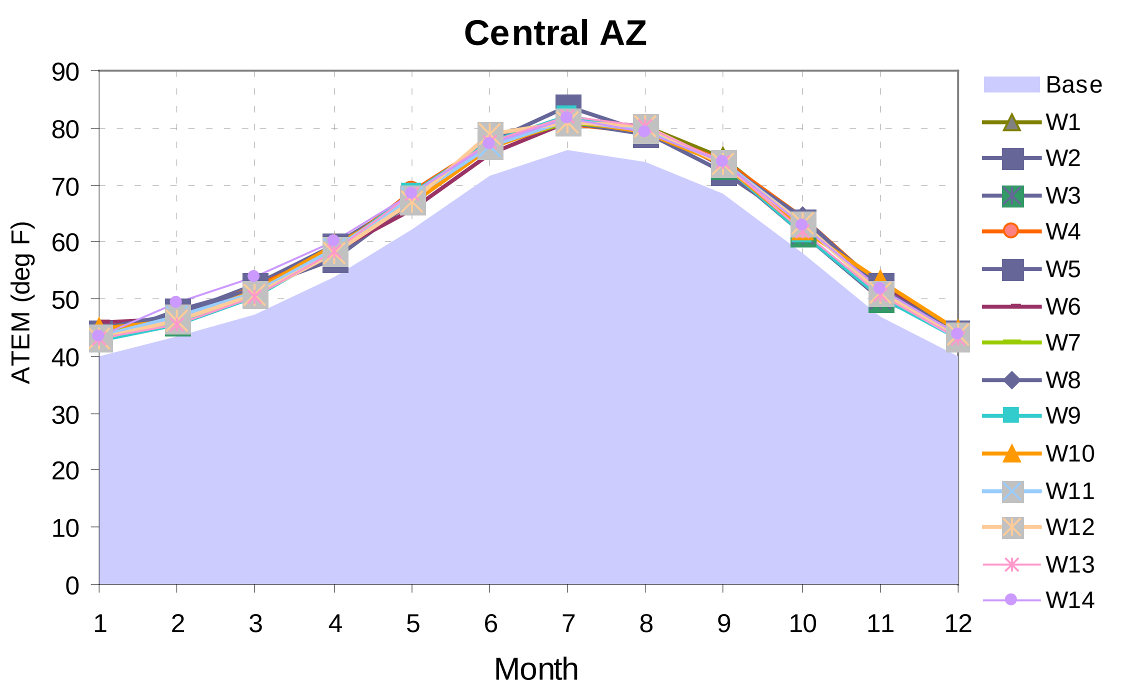
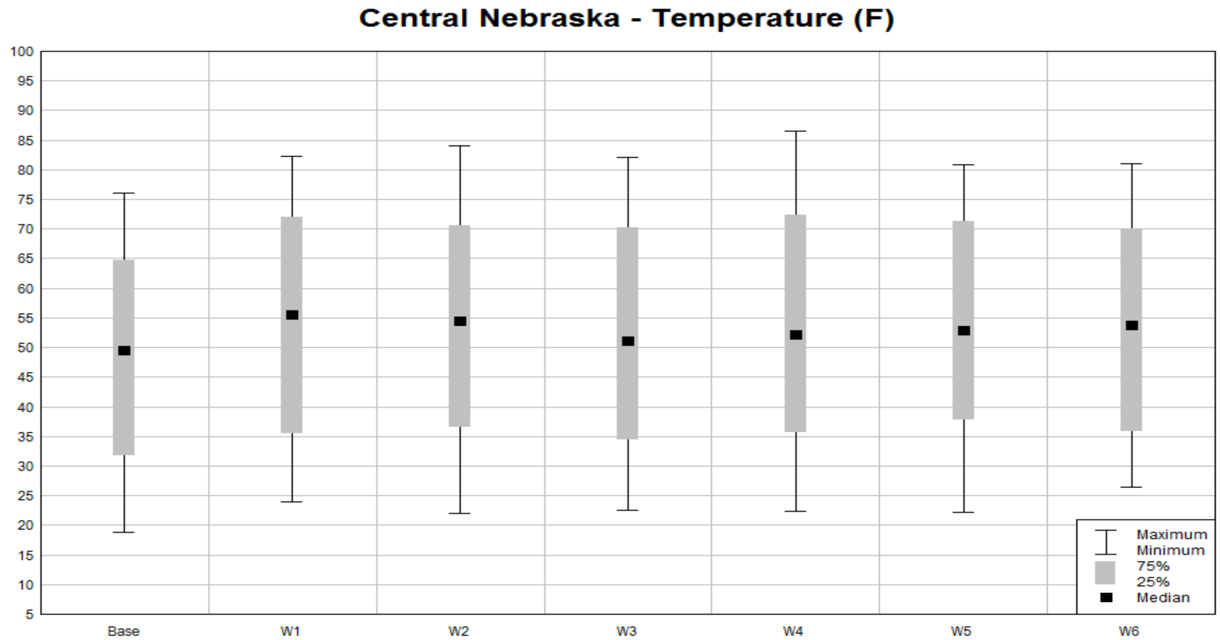


Figure Z-2. Ariz: Comparison of climate scenario temperature for the Salt, Verde, and San Pedro basins

Note: See Table Z-1 for key to climate scenarios.



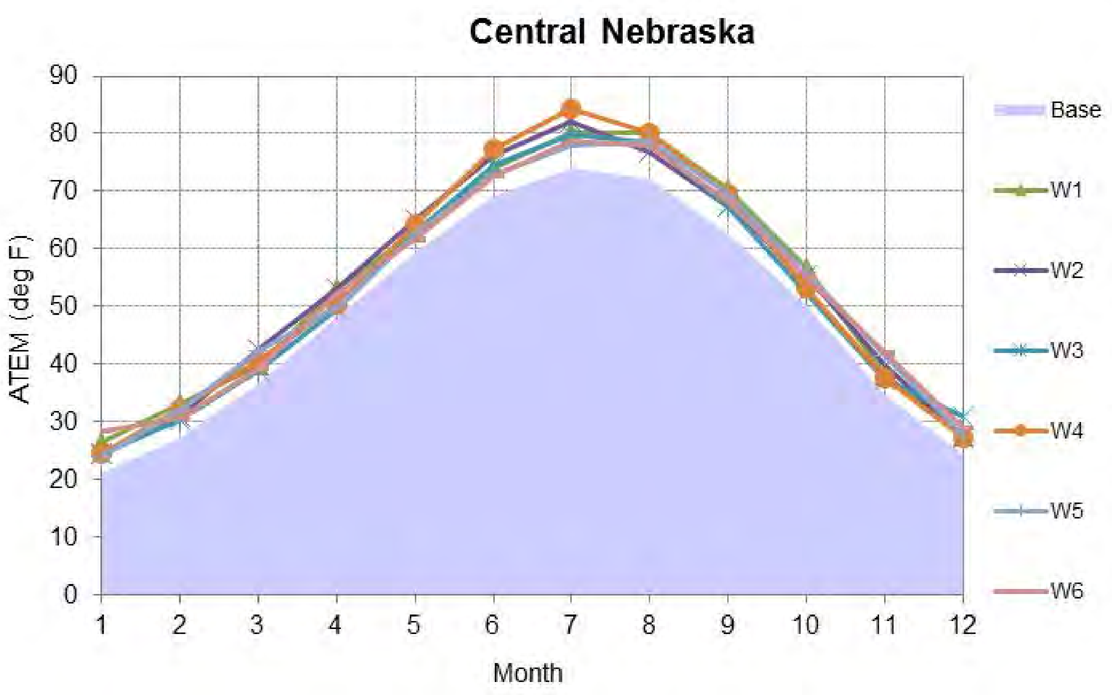


Figure Z-3. CenNeb: Comparison of climate scenario temperature for the Loup/Elkhorn River basins

Note: See Table Z-1 for key to climate scenarios.

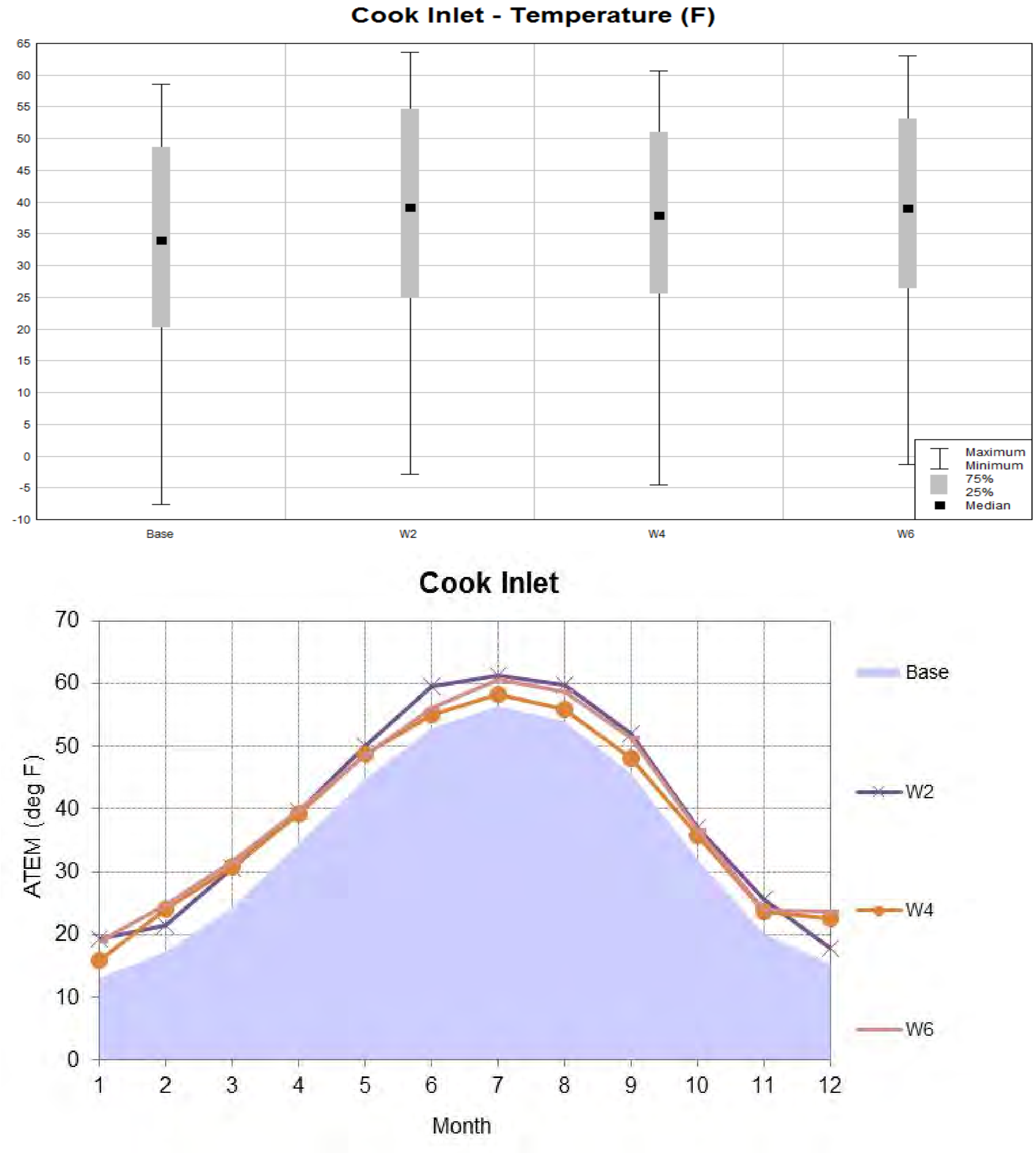


Figure Z-4. Cook: Comparison of climate scenario temperature for the Cook Inlet basin

Note: See Table Z-1 for key to climate scenarios.

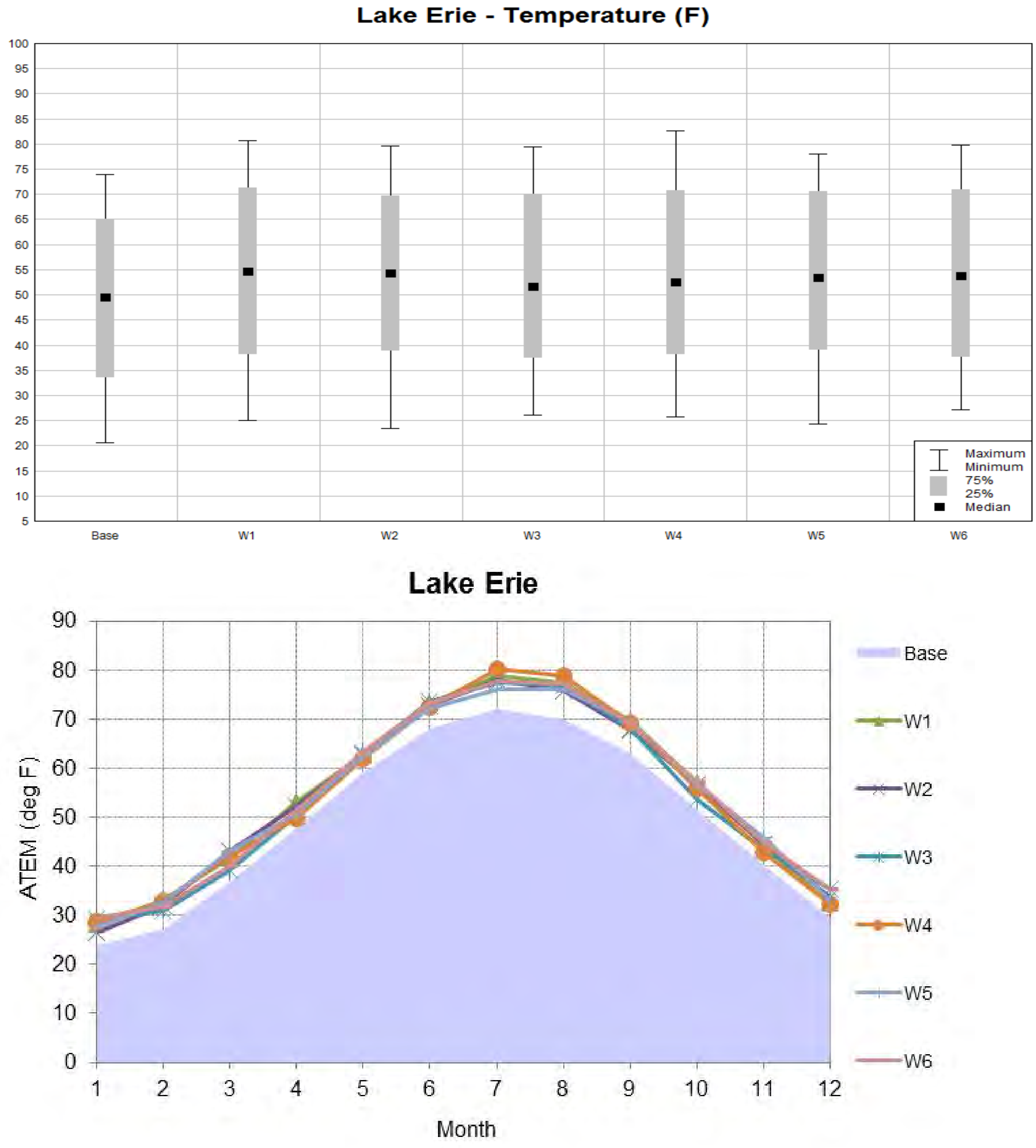


Figure Z-5. Erie: Comparison of climate scenario temperature for the Lake Erie Drainages

Note: See Table Z-1 for key to climate scenarios.

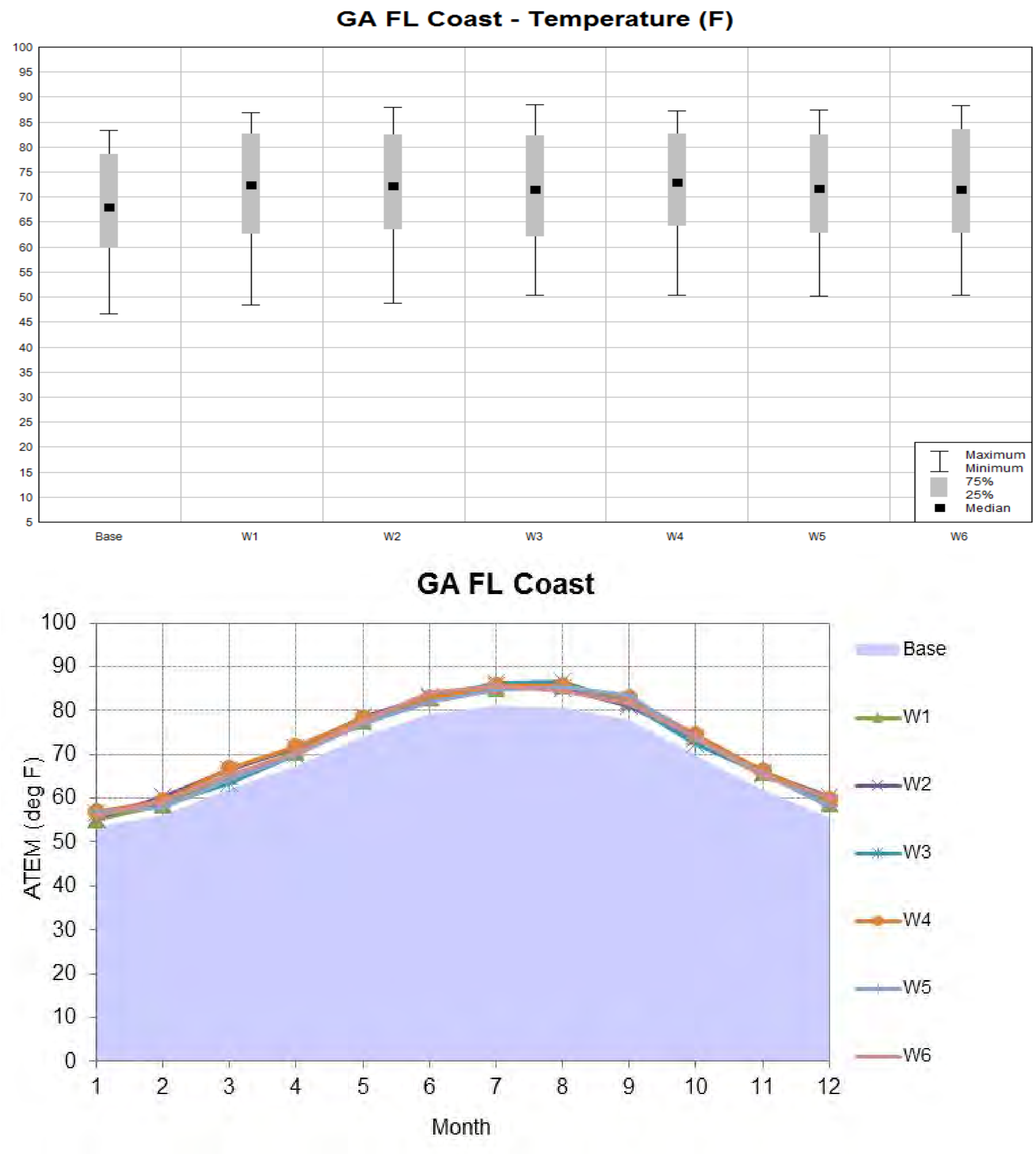


Figure Z-6. GaFla: Comparison of climate scenario temperature for the Georgia-Florida Coastal Plain

Note: See Table Z-1 for key to climate scenarios.

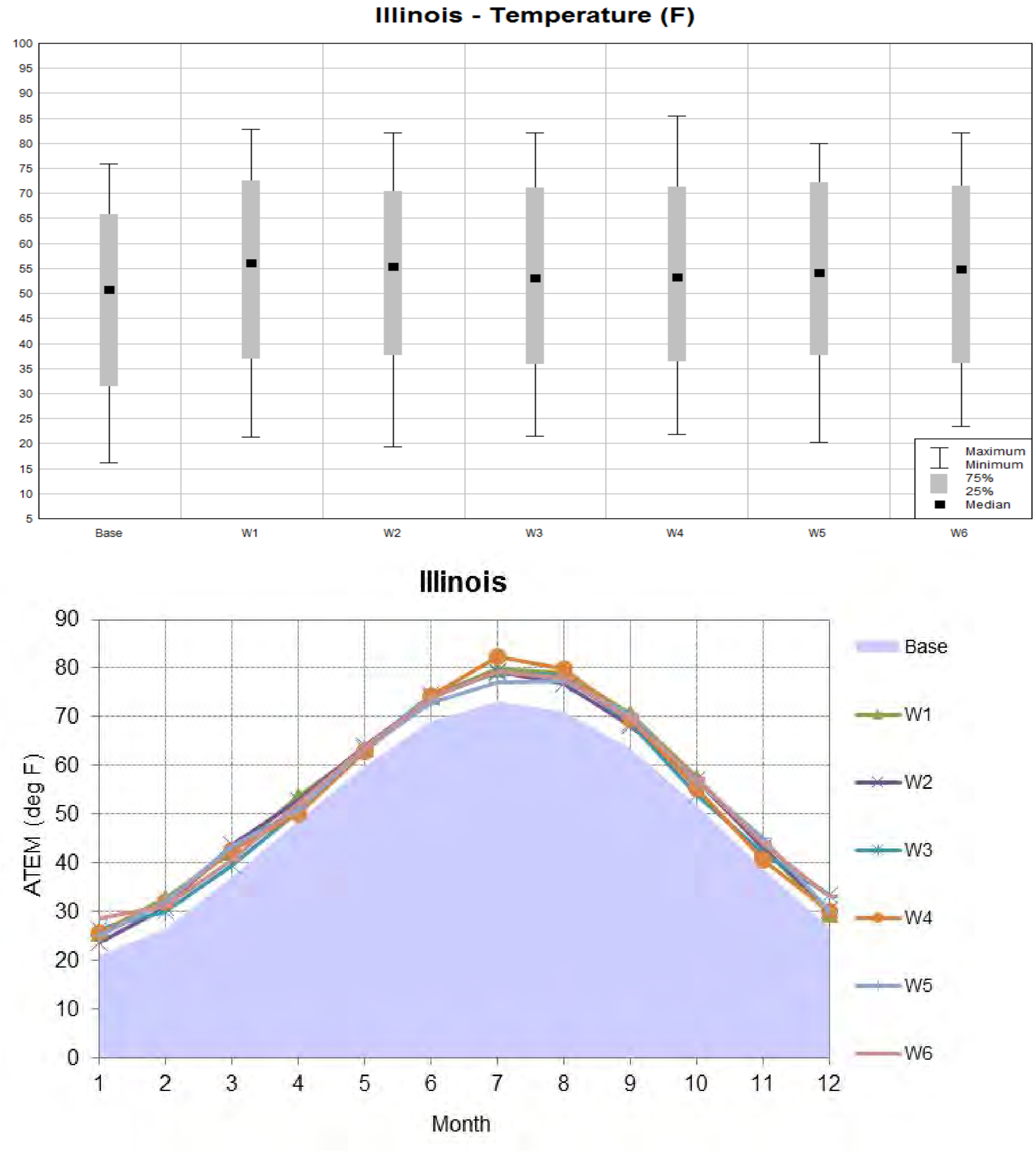
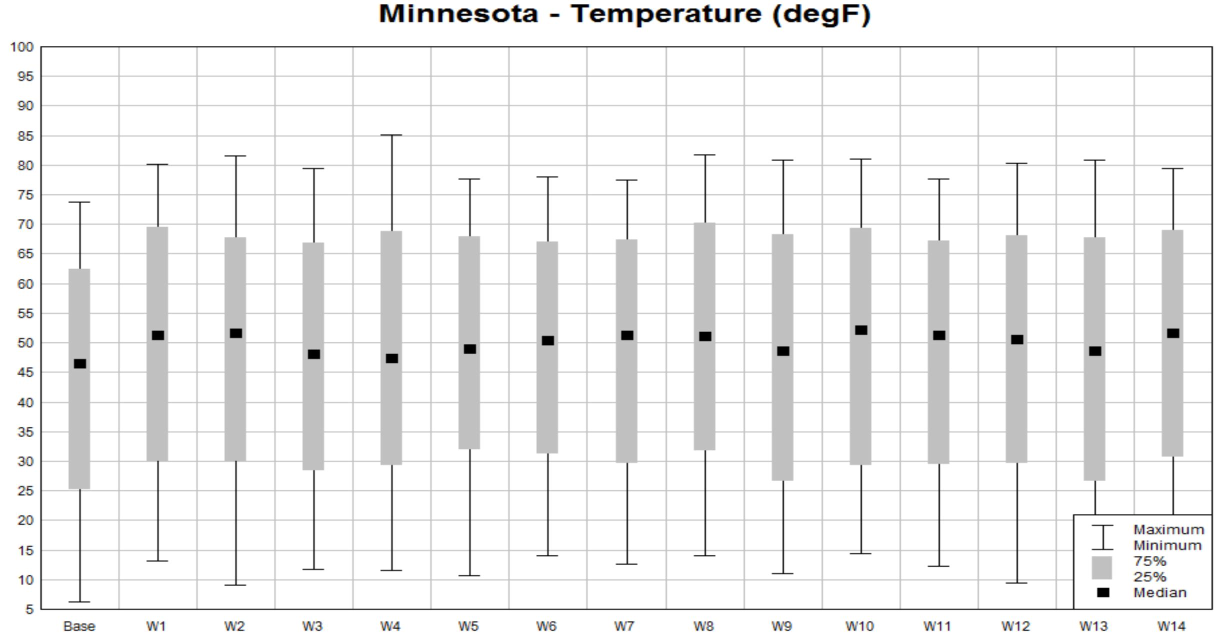


Figure Z- 7. Illin: Comparison of climate scenario temperature for the Illinois River basin

Note: See Table Z-1 for key to climate scenarios.



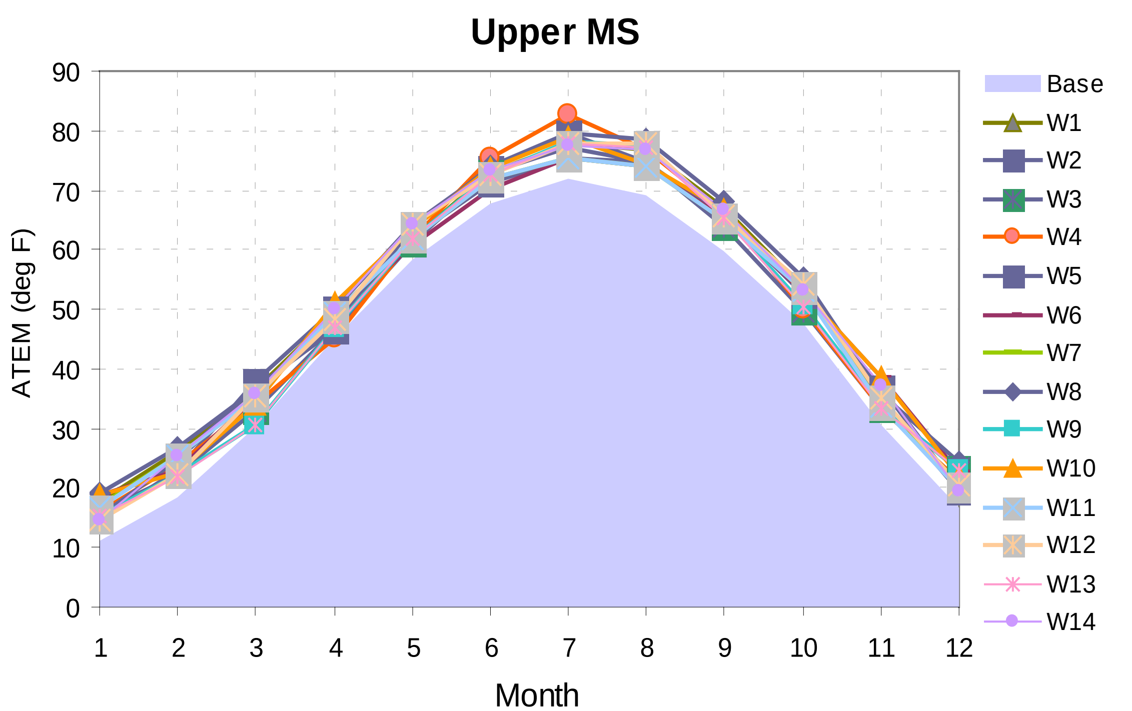
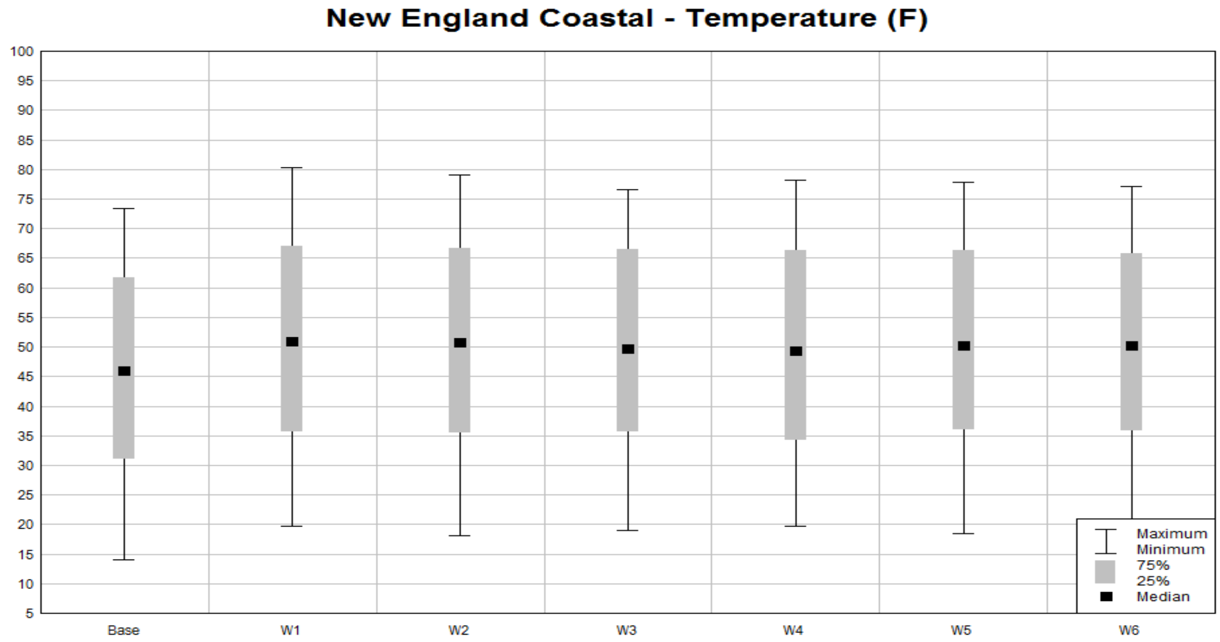


Figure Z-8. Minn: Comparison of climate scenario temperature for the Minnesota River (Upper Mississippi) basin

Note: See Table Z-1 for key to climate scenarios.



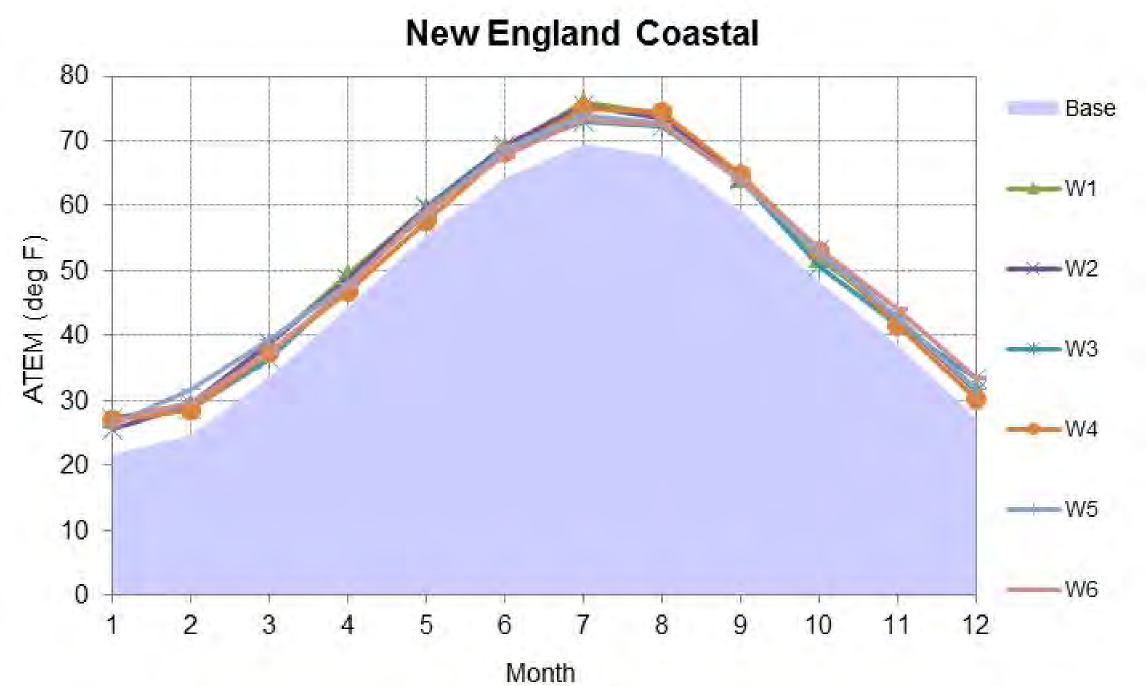
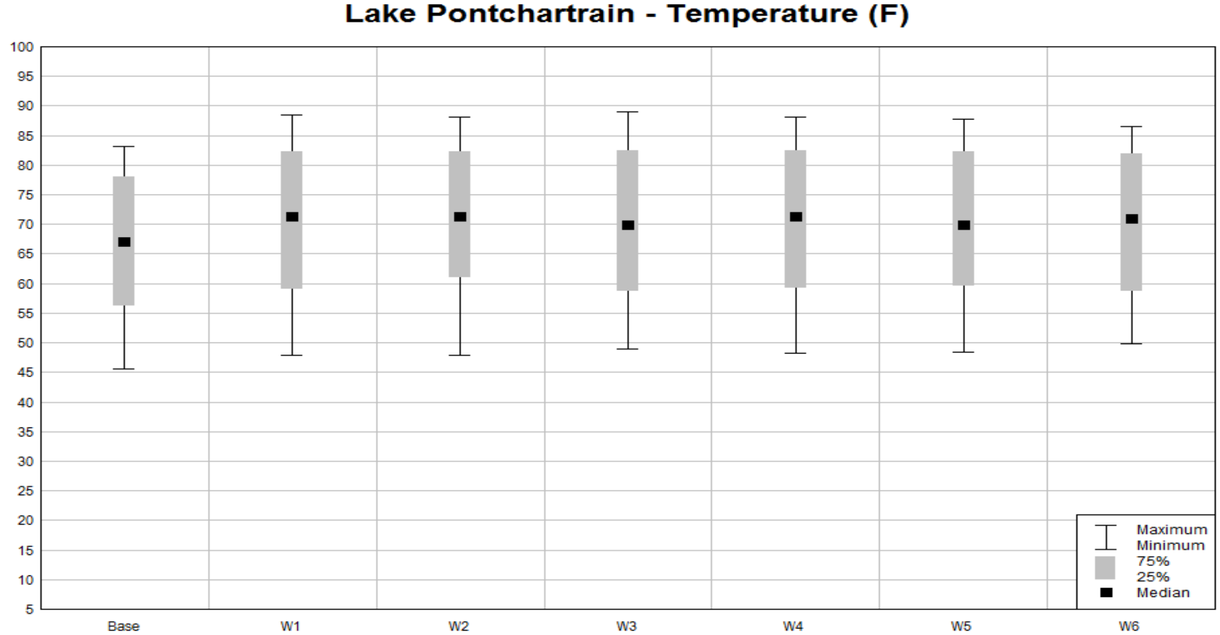


Figure Z- 9. NewEng: Comparison of climate scenario temperature for the New England Coastal basins

Note: See Table Z-1 for key to climate scenarios.



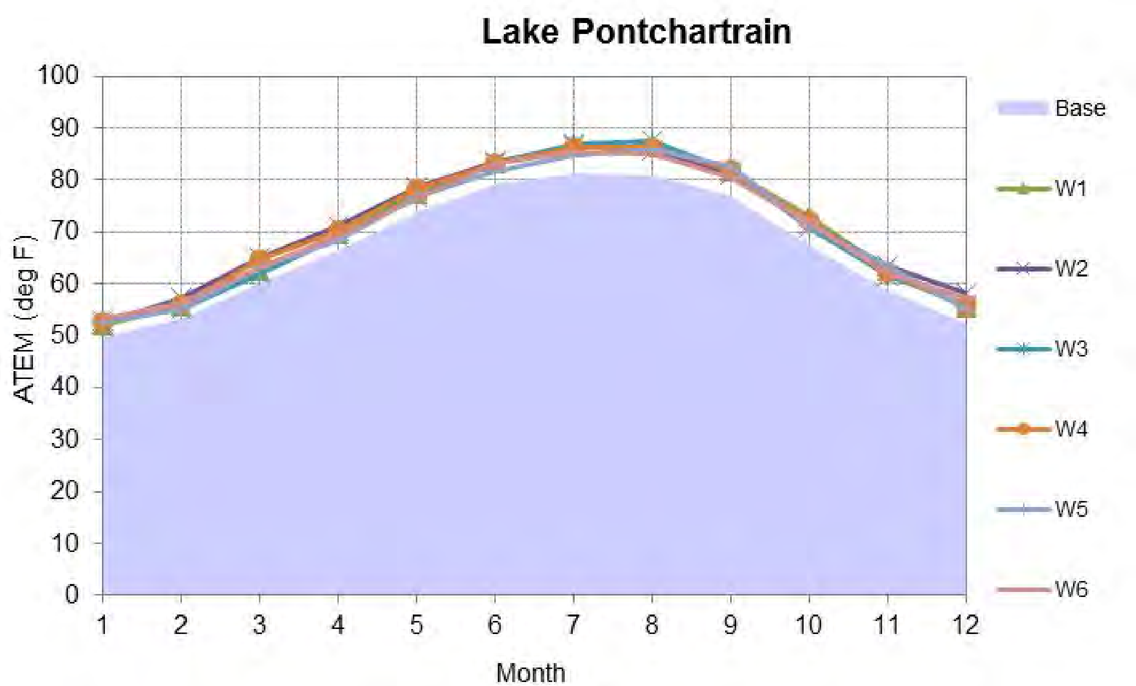


Figure Z-10. Pont: Comparison of climate scenario temperature for the Lake Pontchartrain drainage

Note: See Table Z-1 for key to climate scenarios.

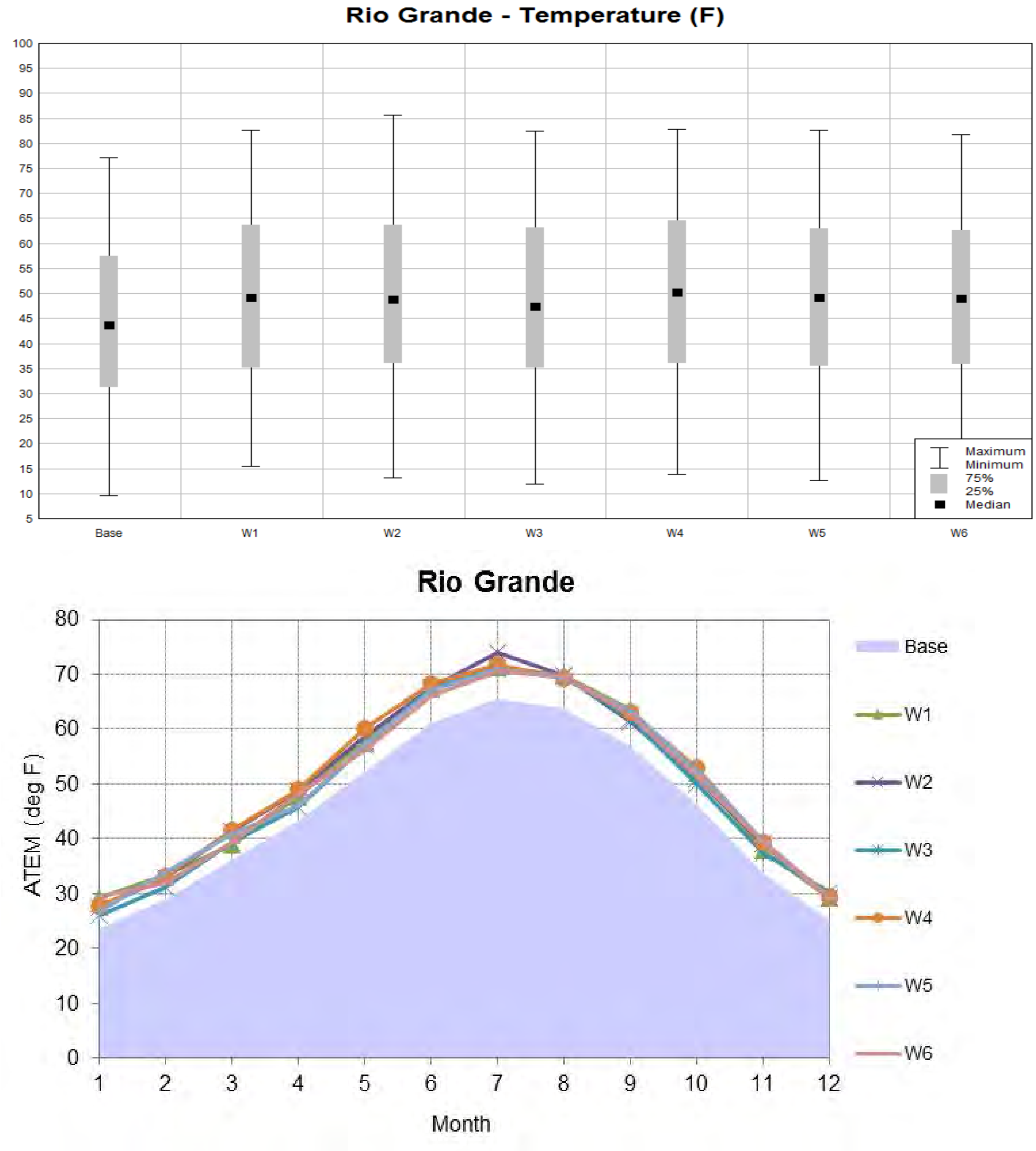
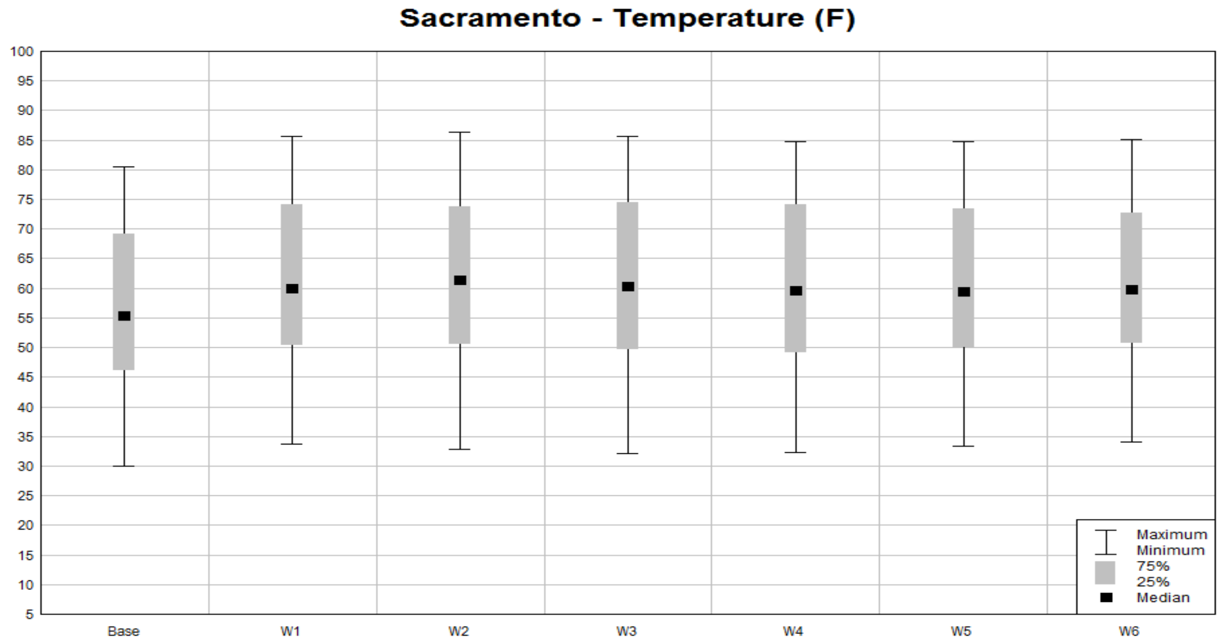


Figure Z-11. RioGra: Comparison of climate scenario temperature for the Rio Grande Valley

Note: See Table Z-1 for key to climate scenarios.



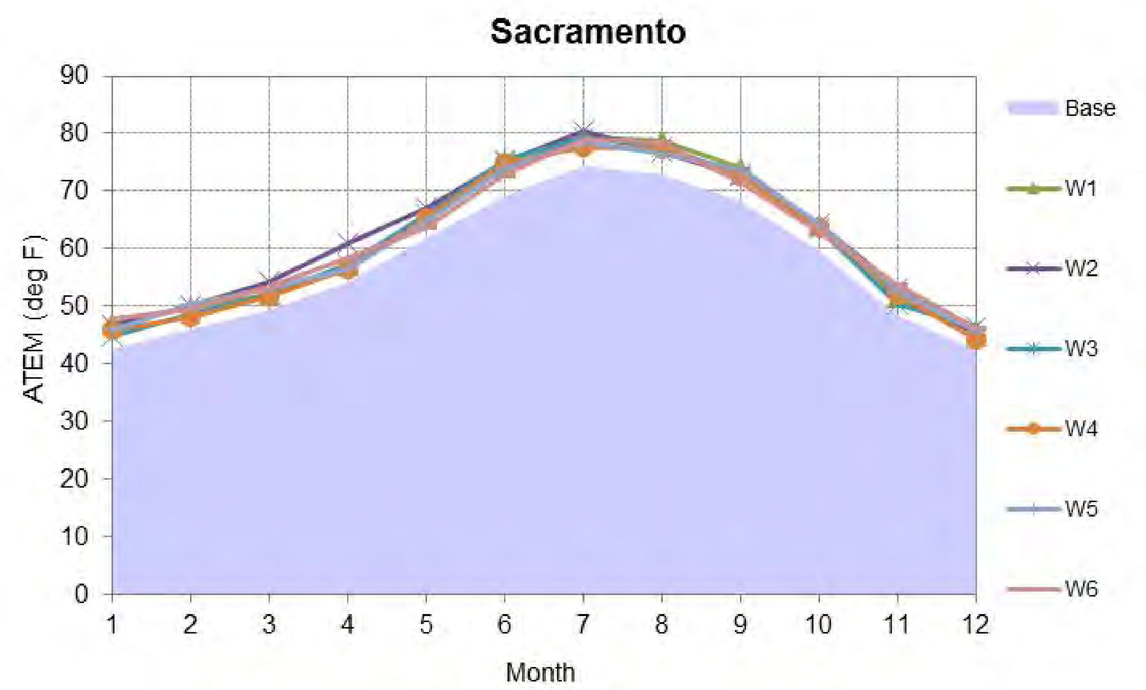


Figure Z-12. Sac: Comparison of climate scenario temperature for the Sacramento River basin

Note: See Table Z-1 for key to climate scenarios.

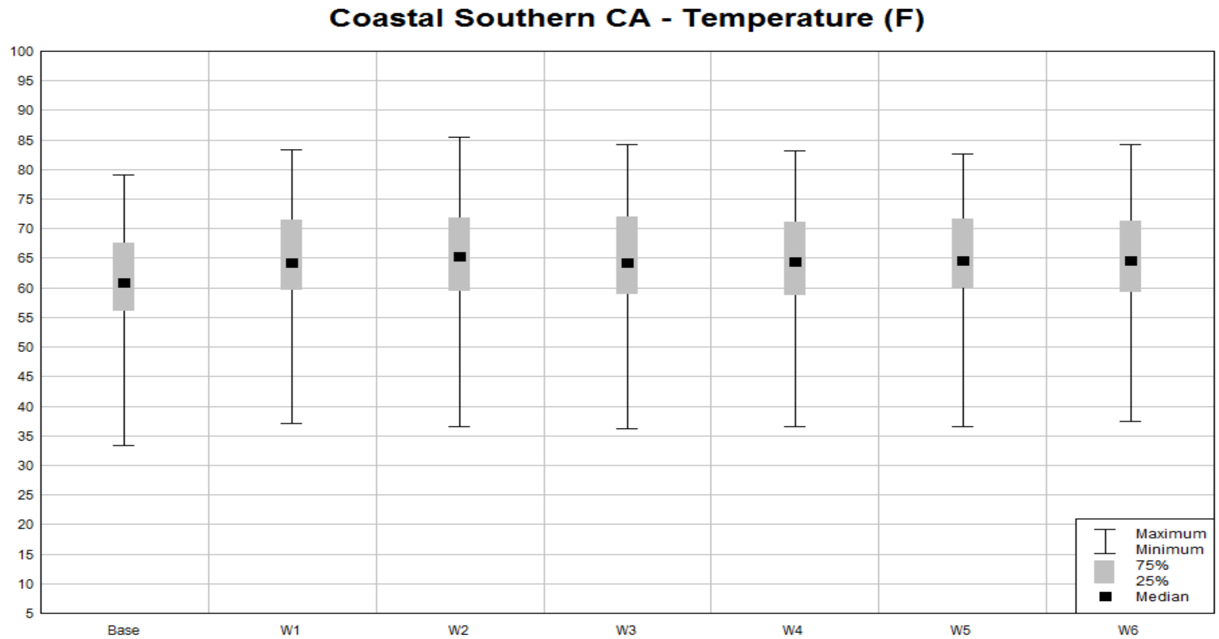
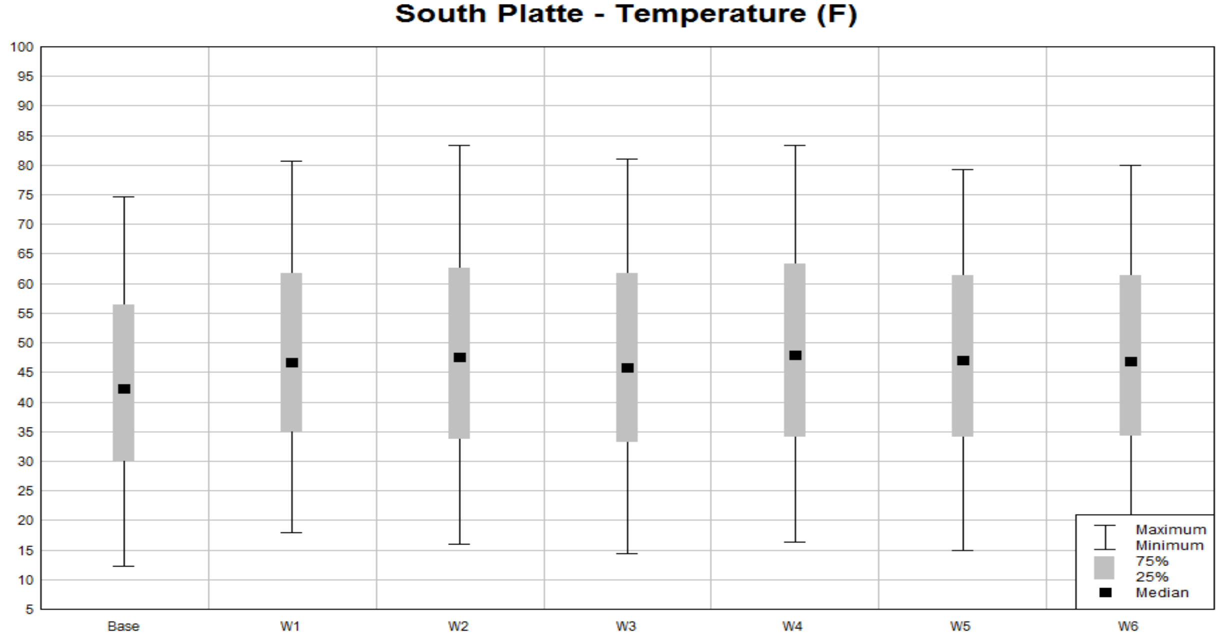


Figure Z-13. SoCal: Comparison of climate scenario temperature for the Coastal Southern California basins

Note: See Table Z-1 for key to climate scenarios.



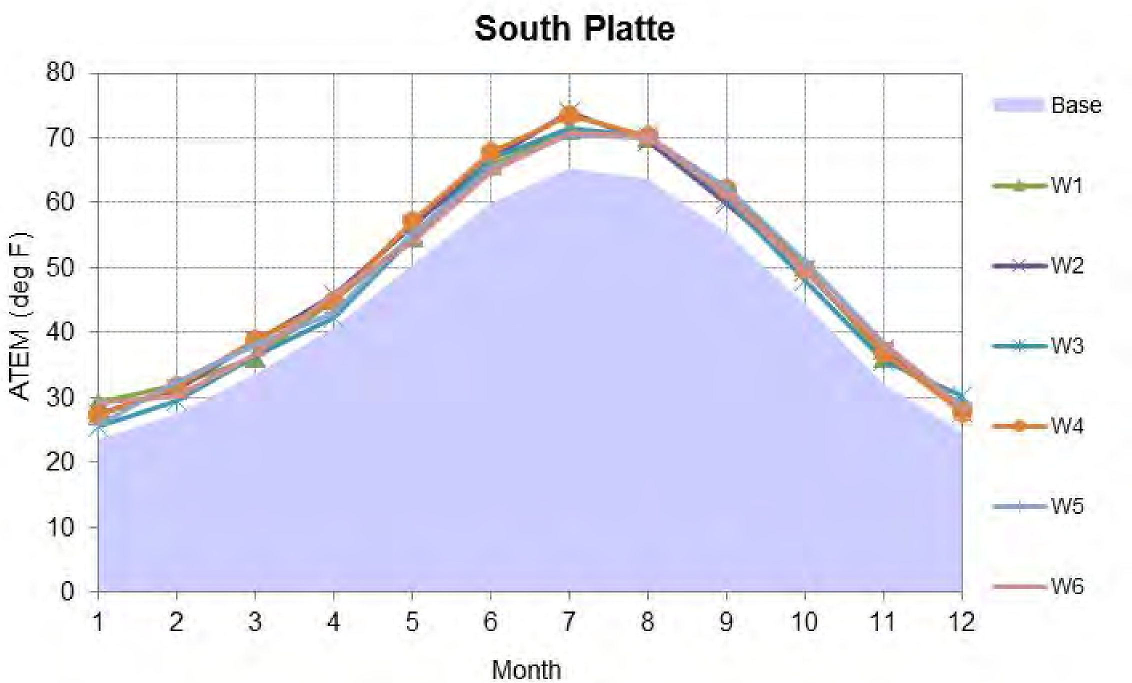
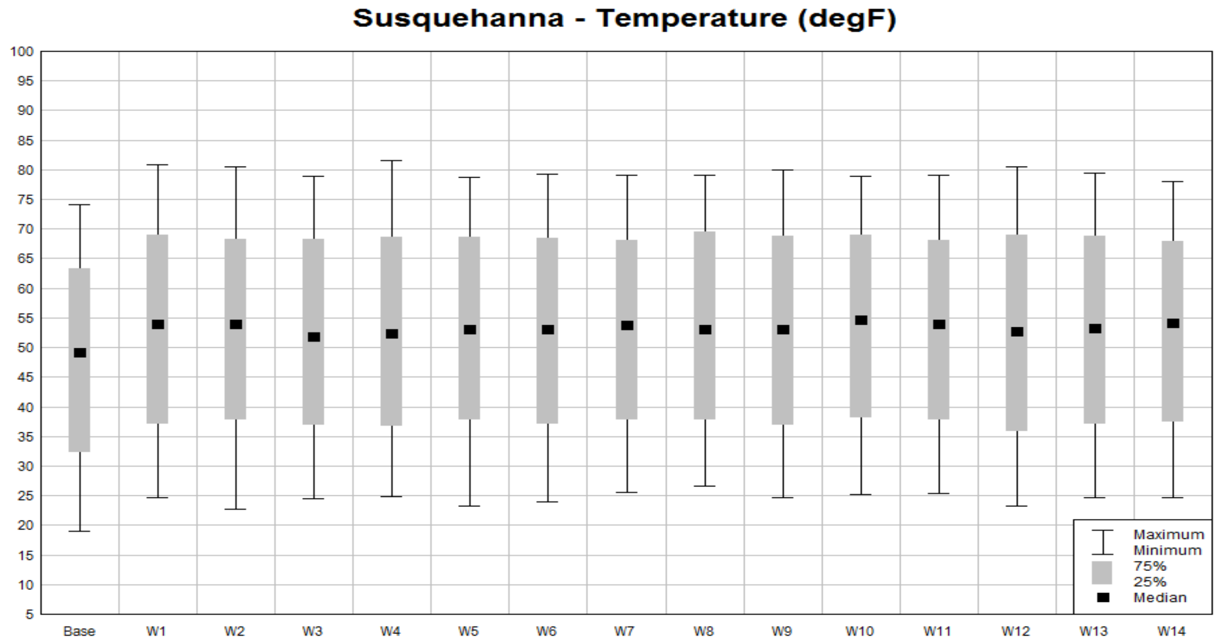


Figure Z-14. SoPlat: Comparison of climate scenario temperature for the South Platte River basin

Note: See Table Z-1 for key to climate scenarios.



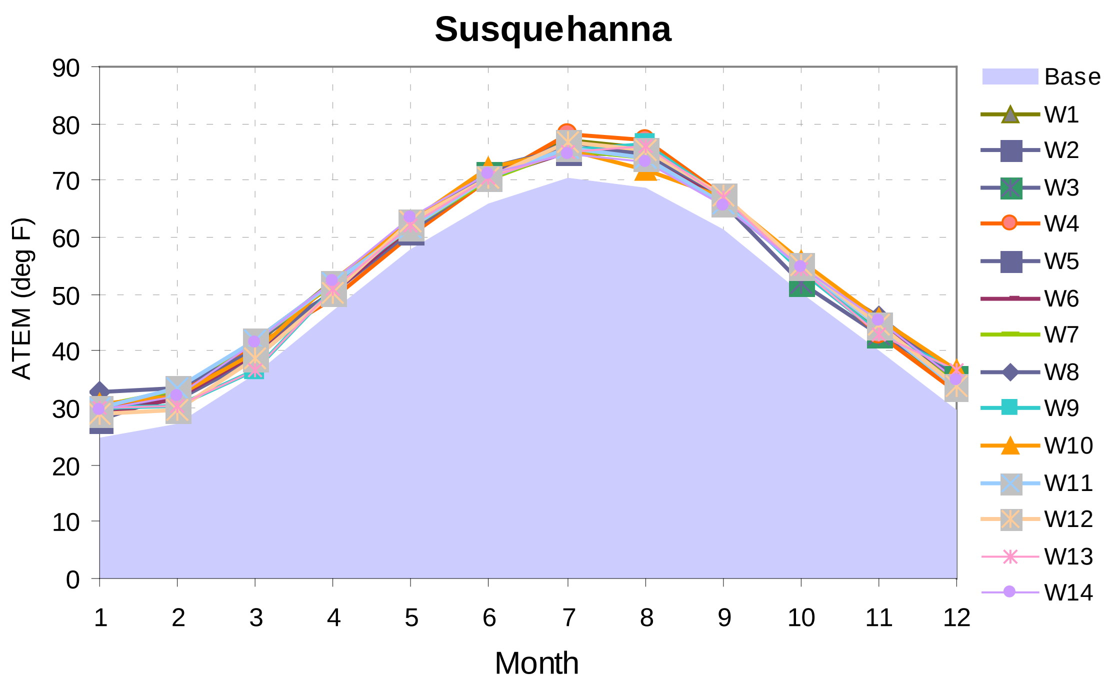
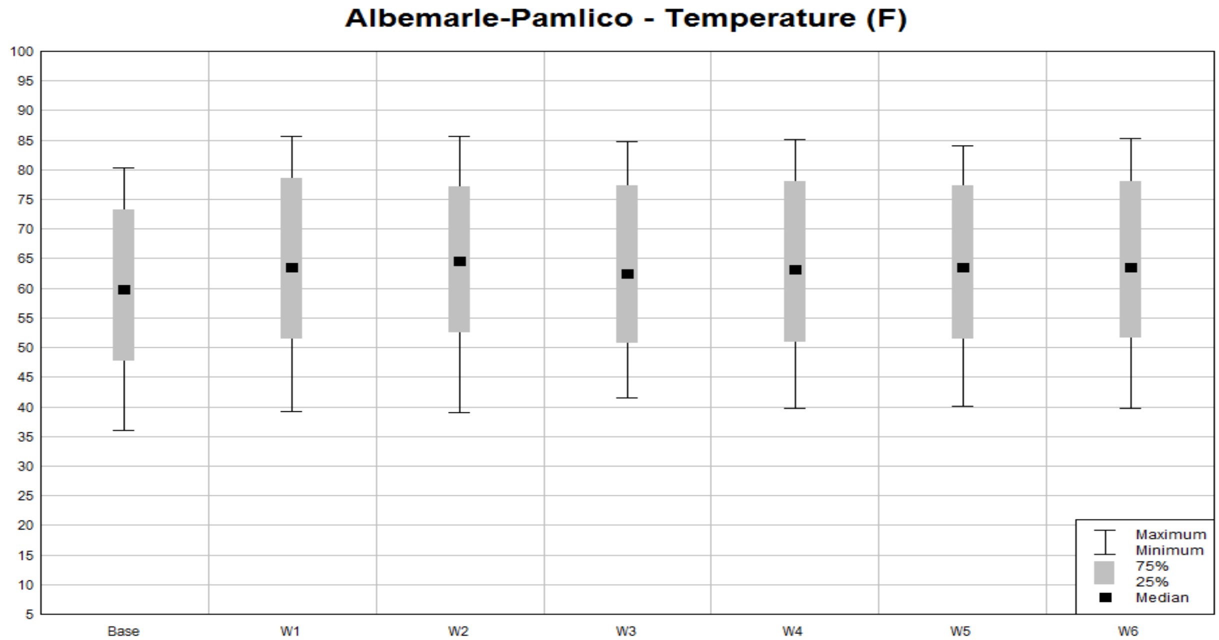


Figure Z-15. Susq: Comparison of climate scenario temperature for the Susquehanna River basin

Note: See Table Z-1 for key to climate scenarios.



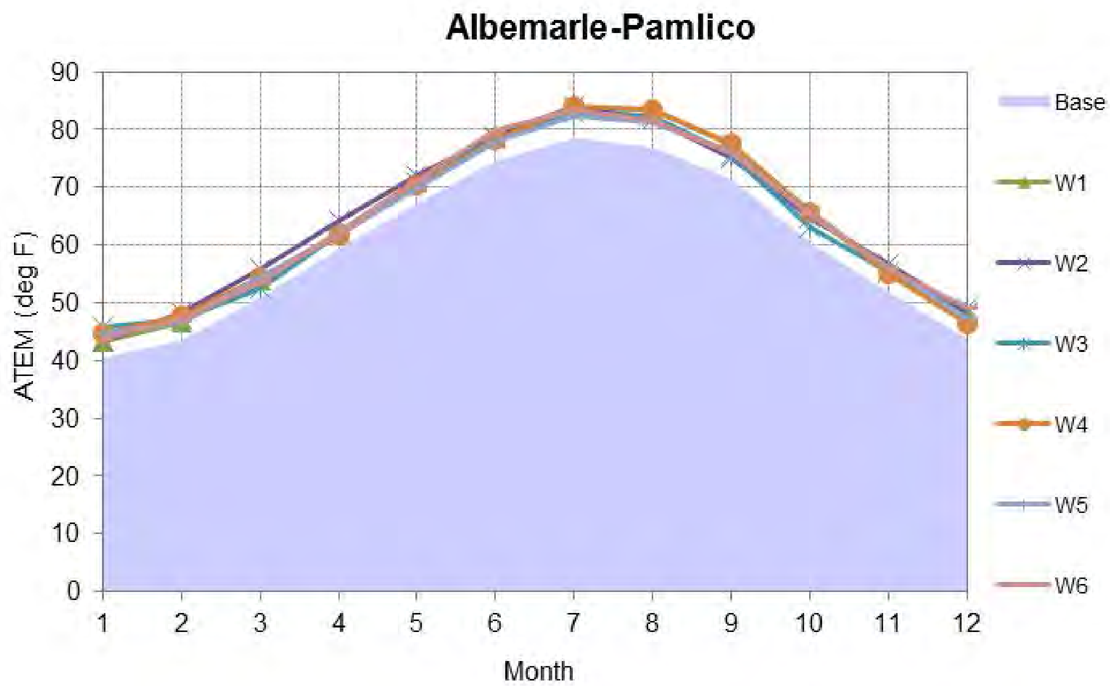


Figure Z-16. TarNeu: Comparison of climate scenario temperature for the Tar and Neuse River basins

Note: See Table Z-1 for key to climate scenarios.

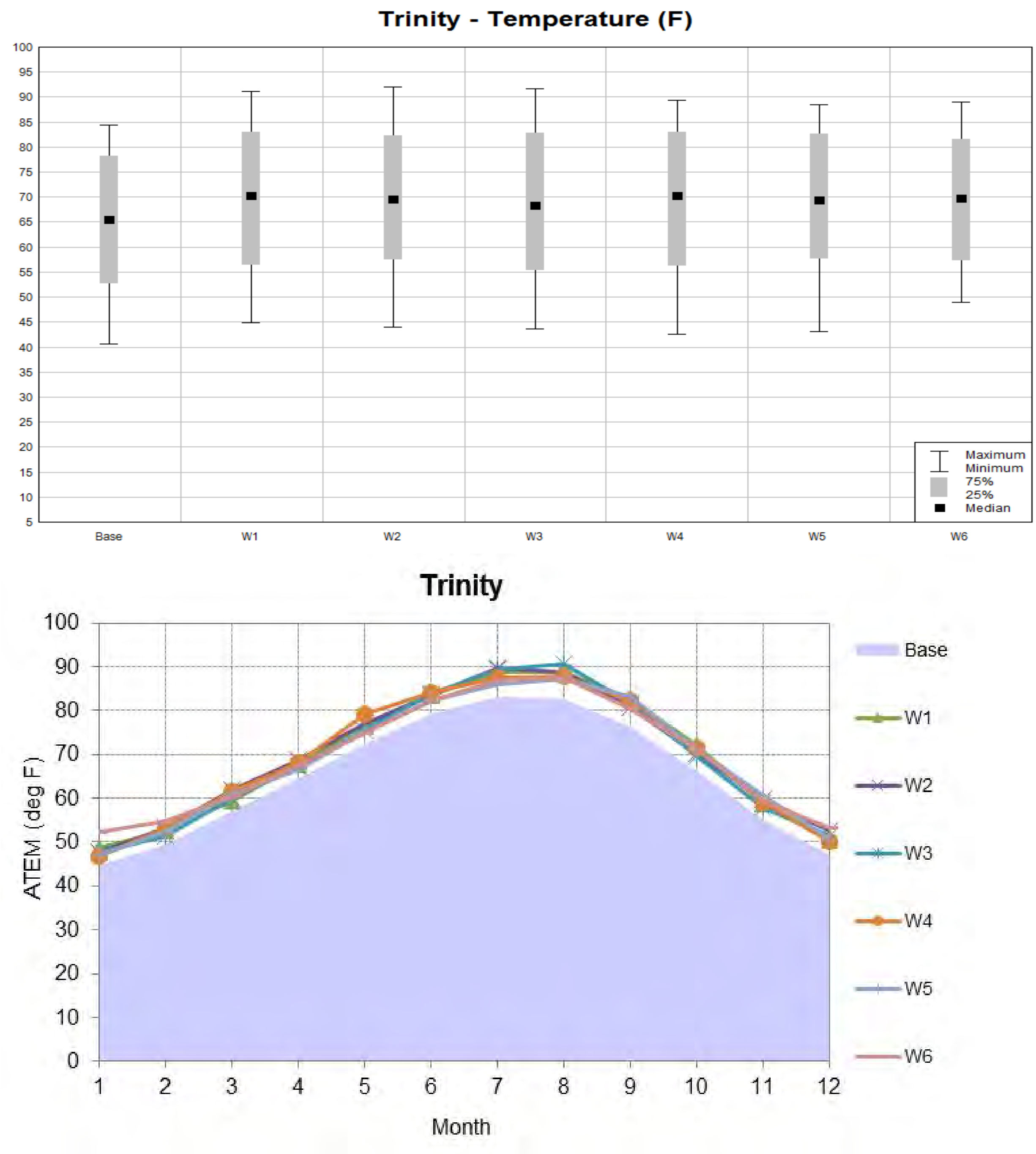


Figure Z-17. Trin: Comparison of climate scenario temperature for the Trinity River basin

Note: See Table Z-1 for key to climate scenarios.

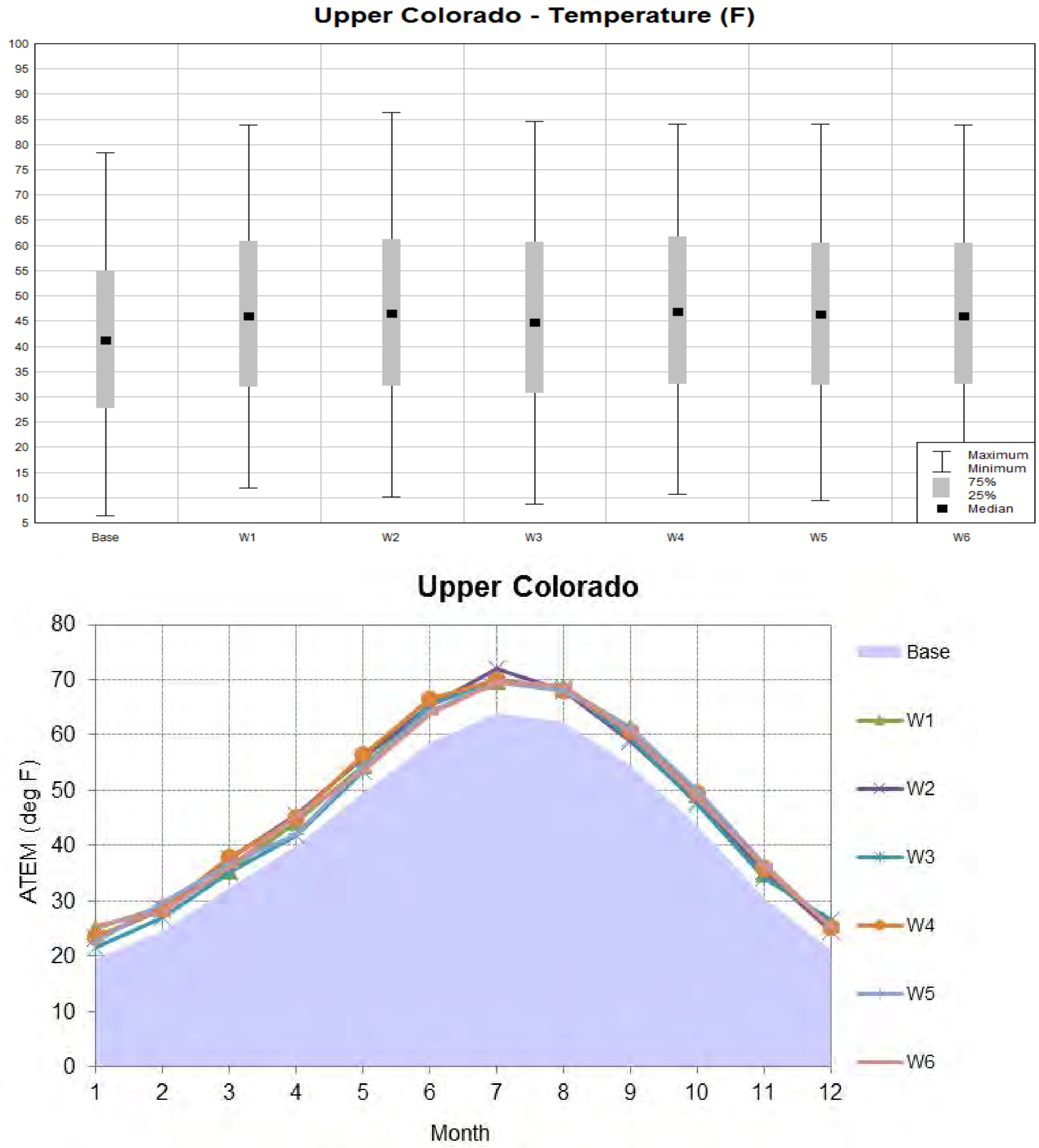
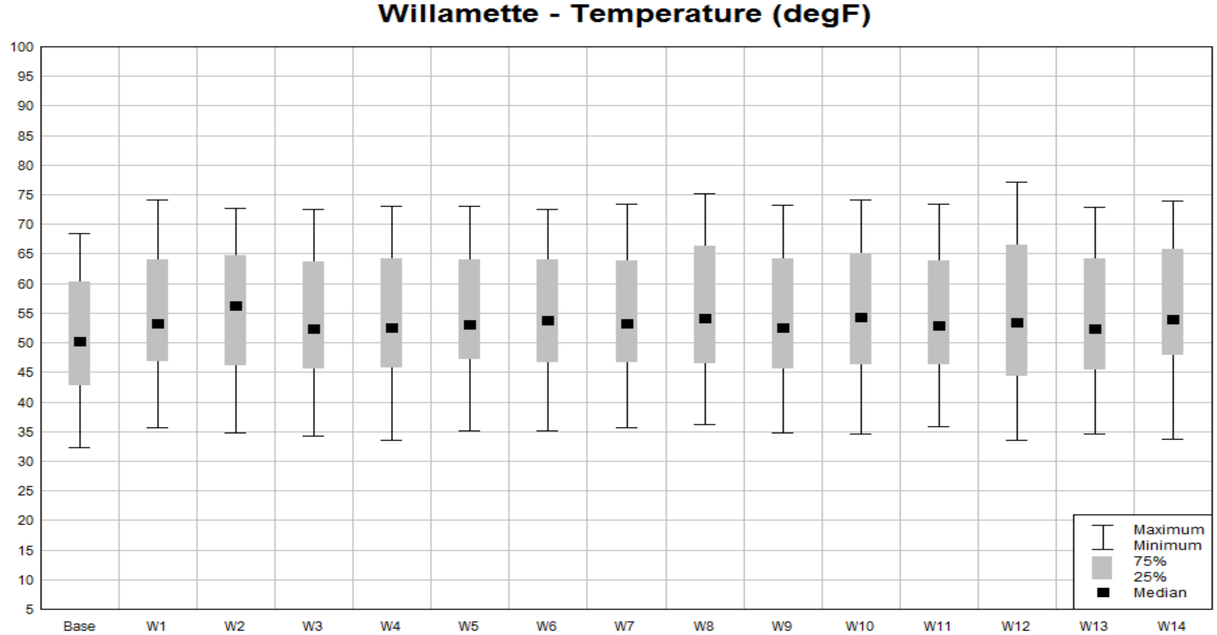


Figure Z-18. UppCol: Comparison of climate scenario temperature for the Upper Colorado River basin

Note: See Table Z-1 for key to climate scenarios.



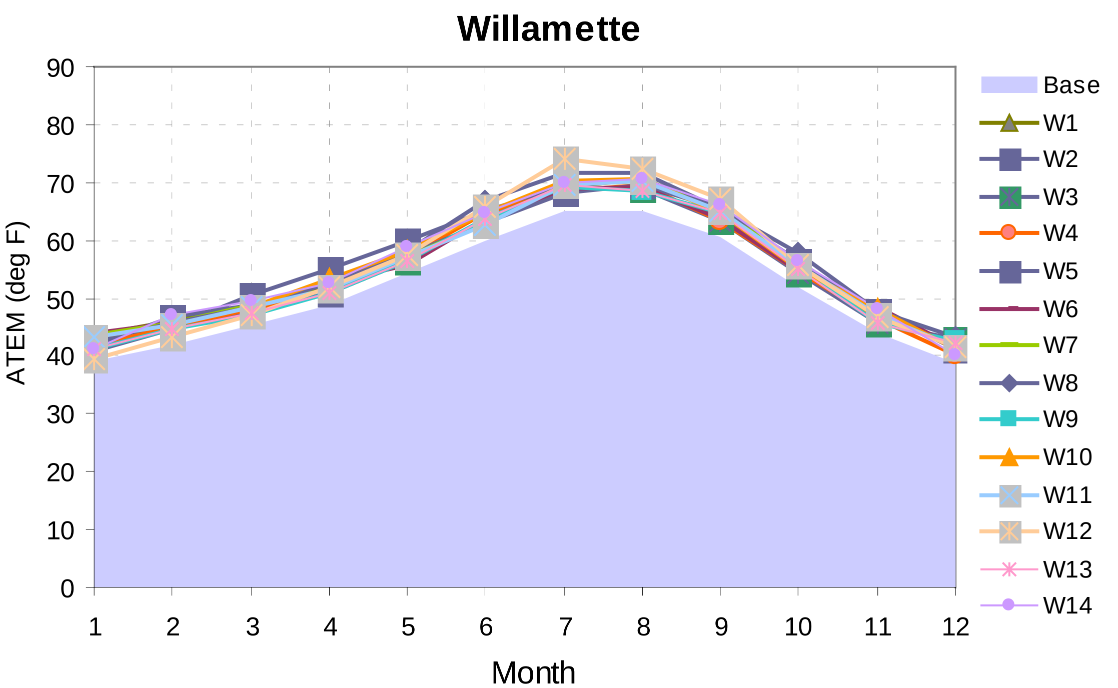
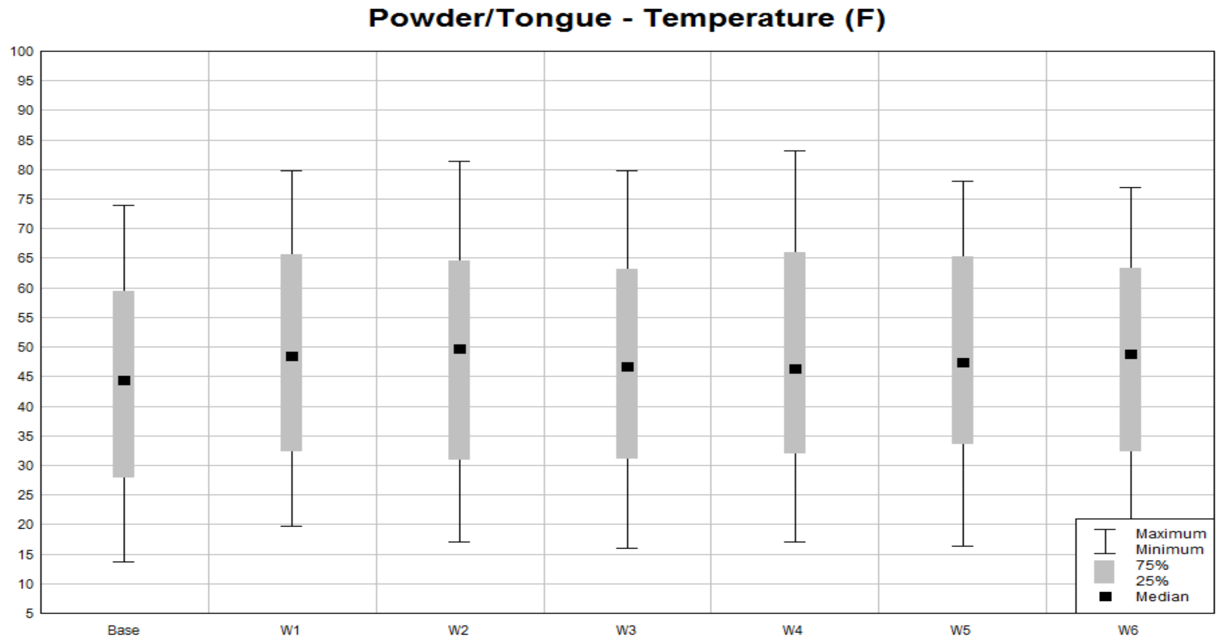


Figure Z-19. Willa: Comparison of climate scenario temperature for the Willamette River basin

Note: See Table Z-1 for key to climate scenarios.



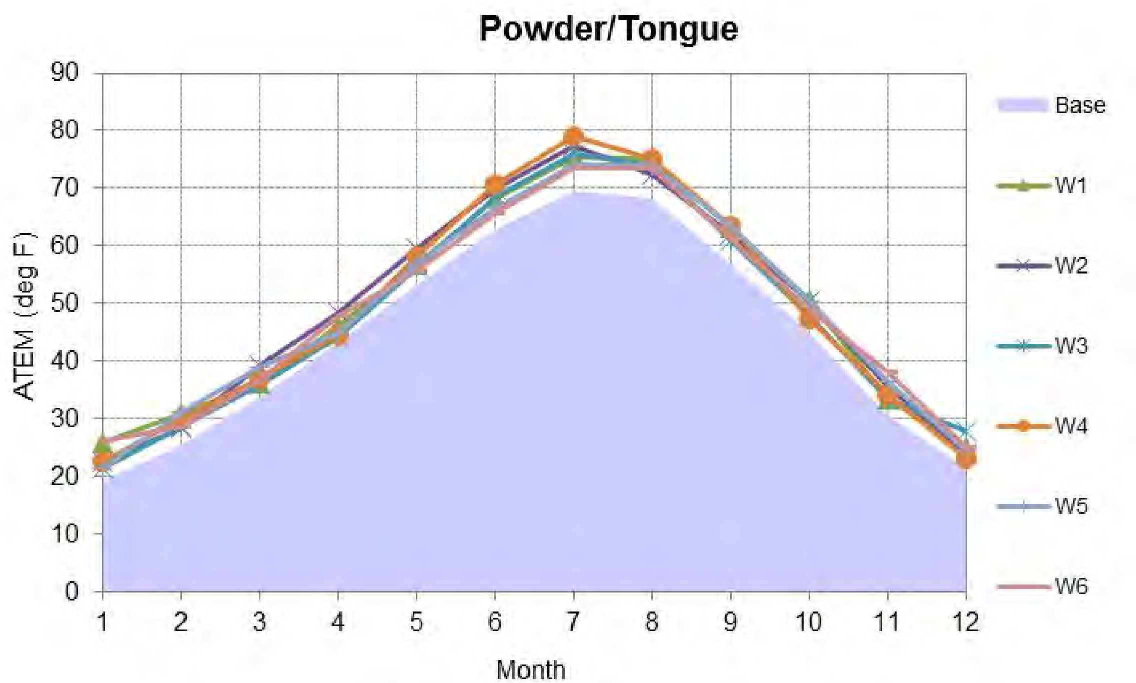
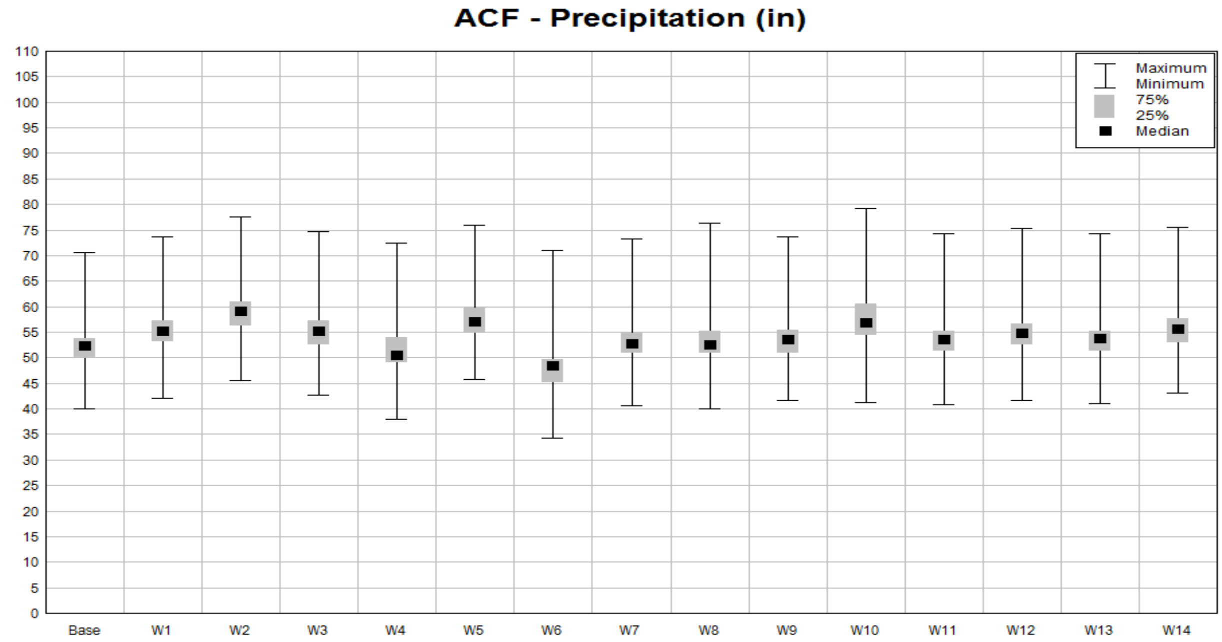


Figure Z-20. Yellow: Comparison of climate scenario temperature for the Powder/Tongue River basins

Note: See Table Z-1 for key to climate scenarios.



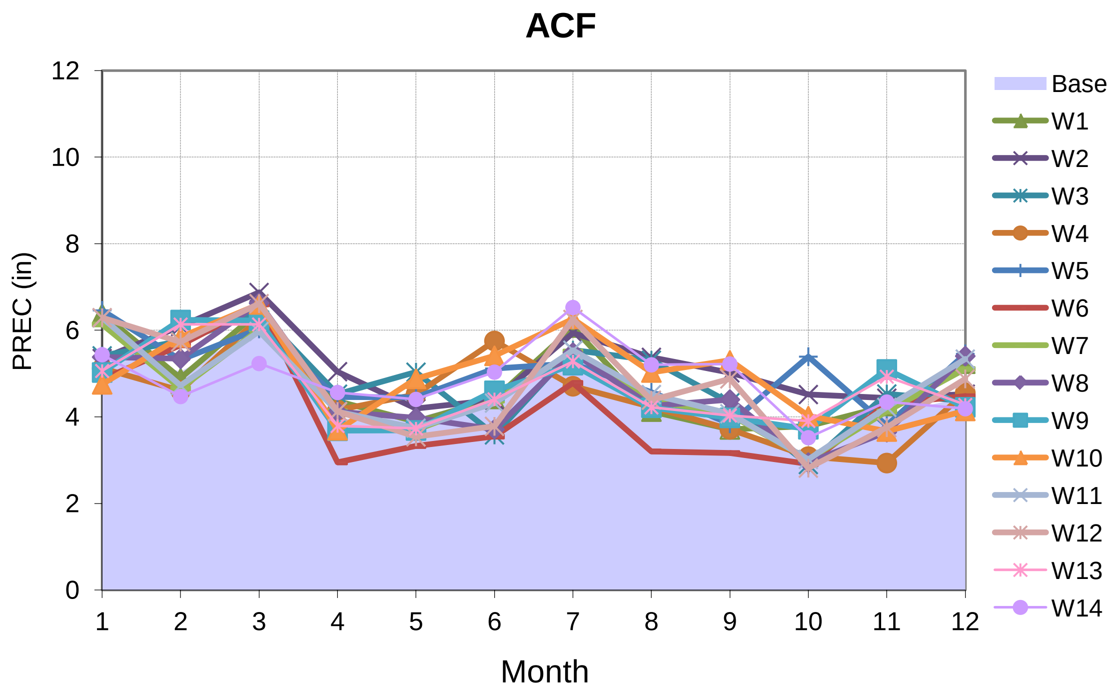
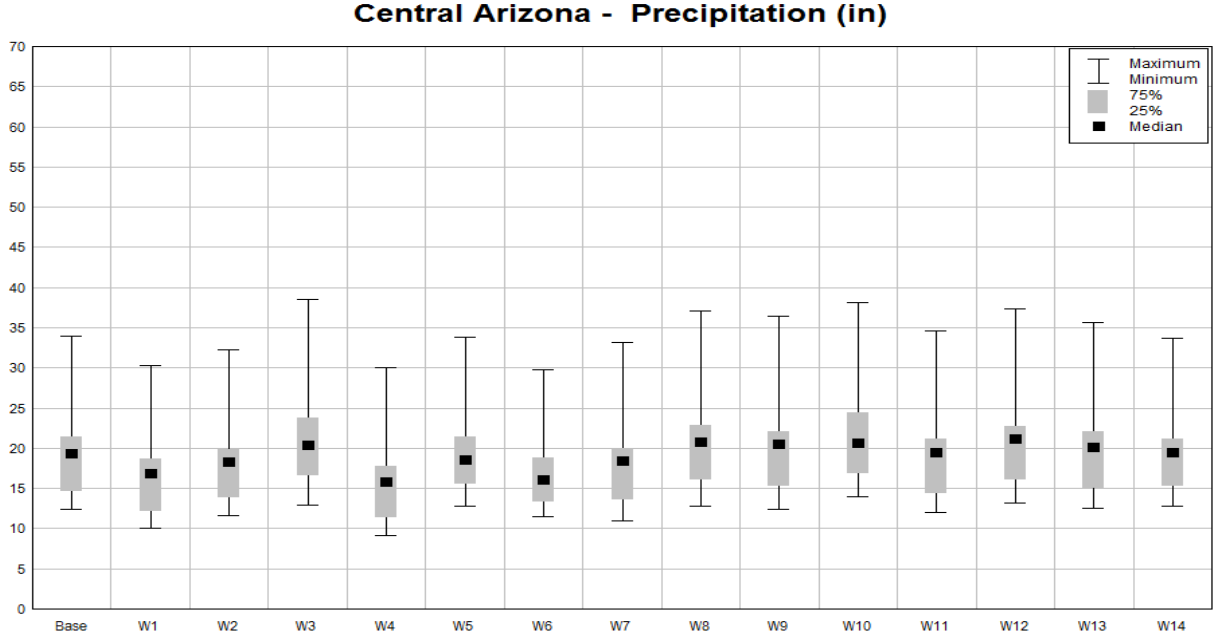


Figure Z-21. ACF: Comparison of climate scenario precipitation for the ACF basin

Note: See Table Z-1 for key to climate scenarios.



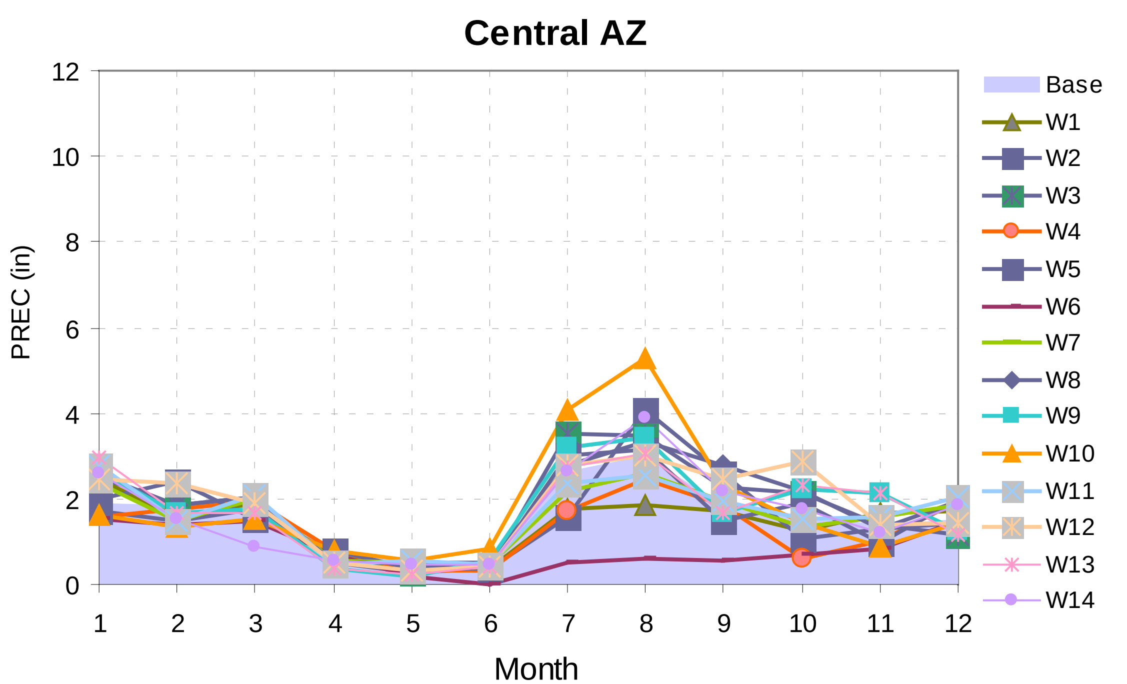


Figure Z-22. Ariz: Comparison of climate scenario precipitation for the Salt, Verde, and San Pedro basins

Note: See Table Z-1 for key to climate scenarios.

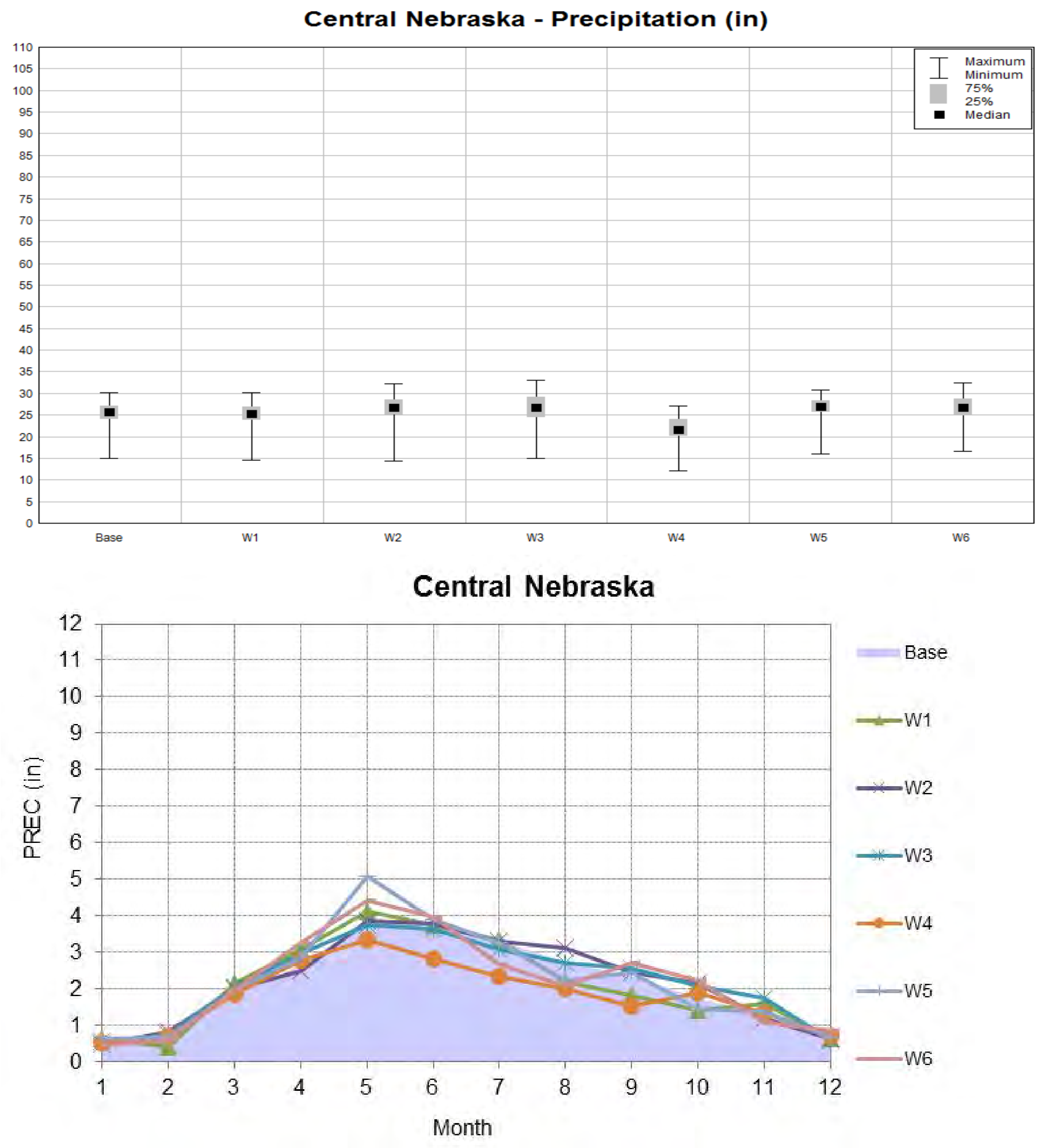
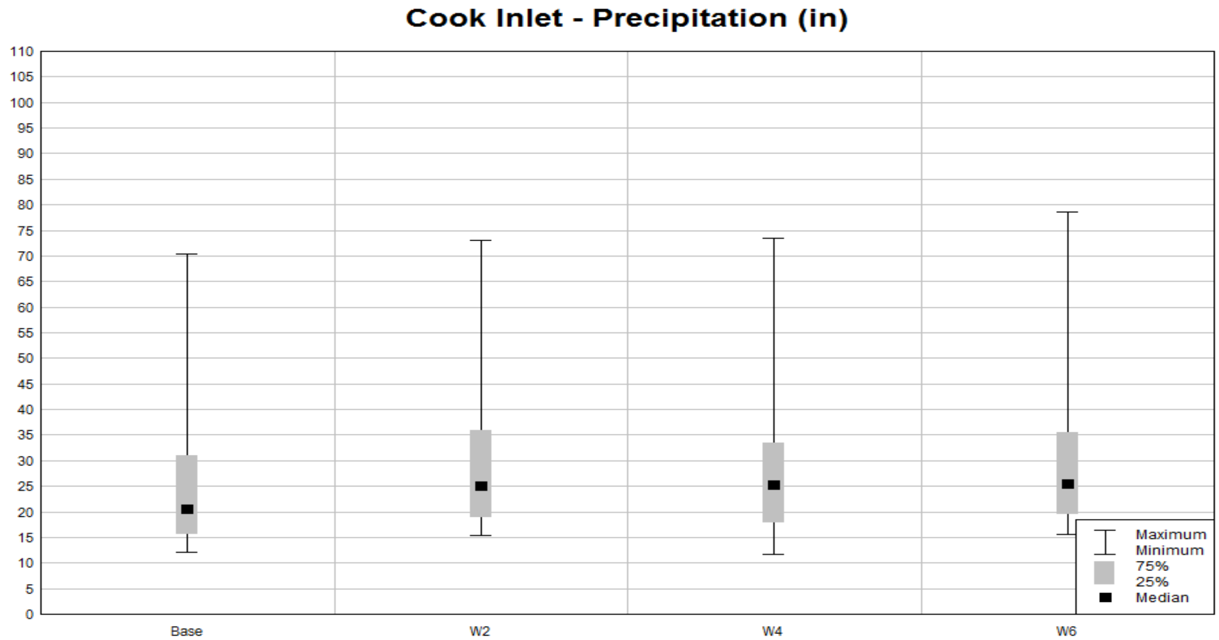


Figure Z-23. CenNeb: Comparison of climate scenario precipitation for the Loup/Elkhorn River basin

Note: See Table Z-1 for key to climate scenarios.



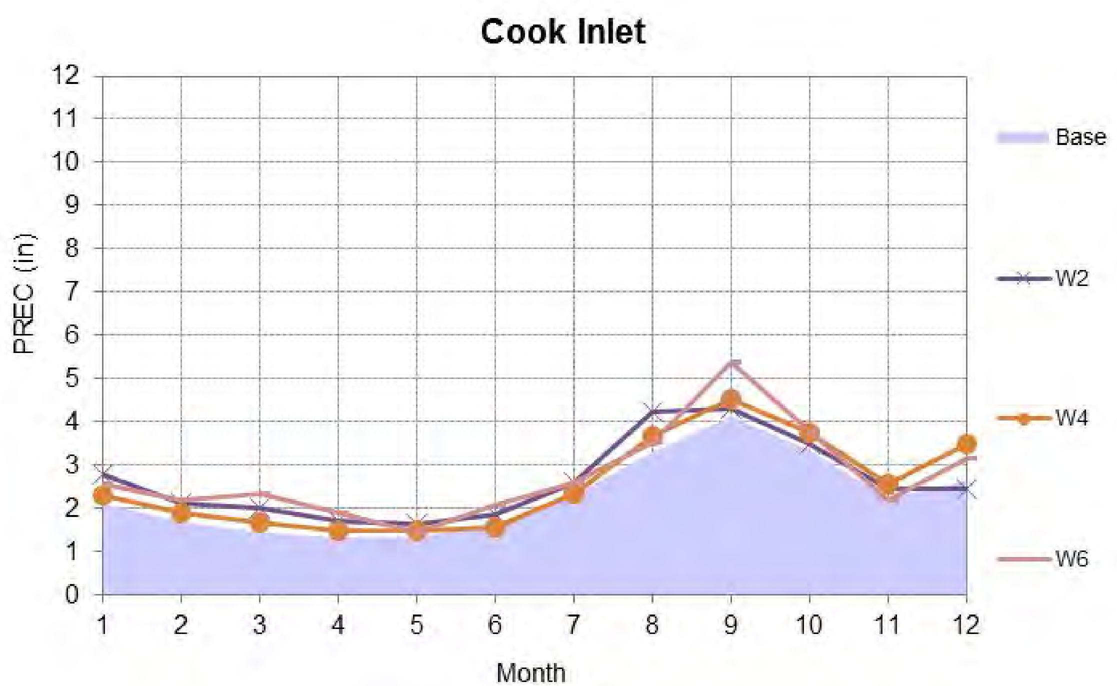
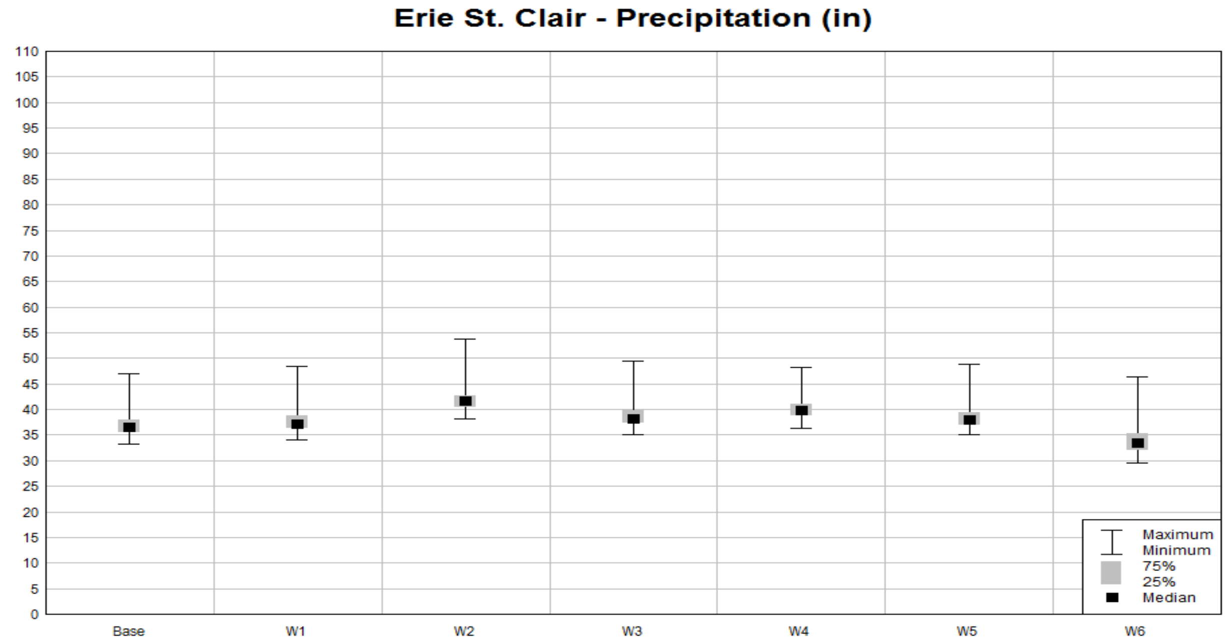


Figure Z-24. Cook: Comparison of climate scenario precipitation for the Cook Inlet basin

Note: See Table Z-1 for key to climate scenarios.



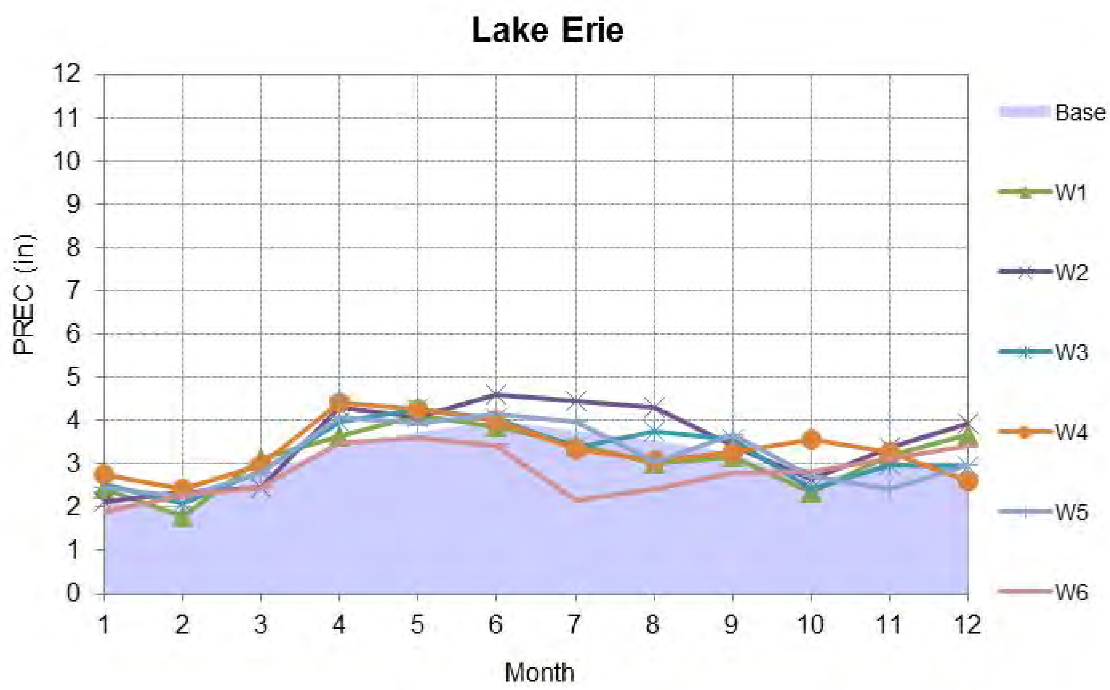


Figure Z-25. Erie: Comparison of climate scenario precipitation for the Lake Erie drainages

Note: See Table Z-1 for key to climate scenarios.

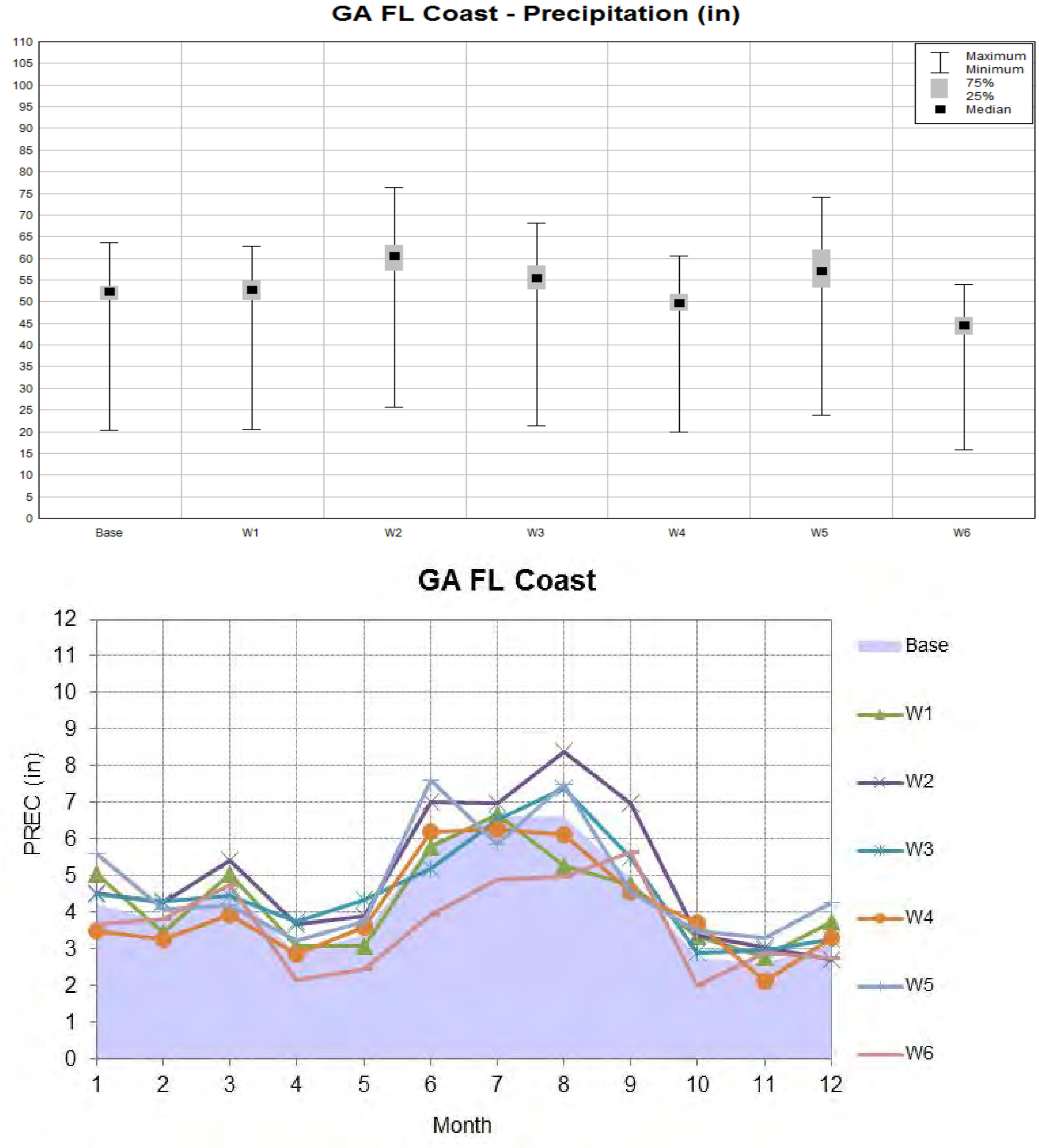
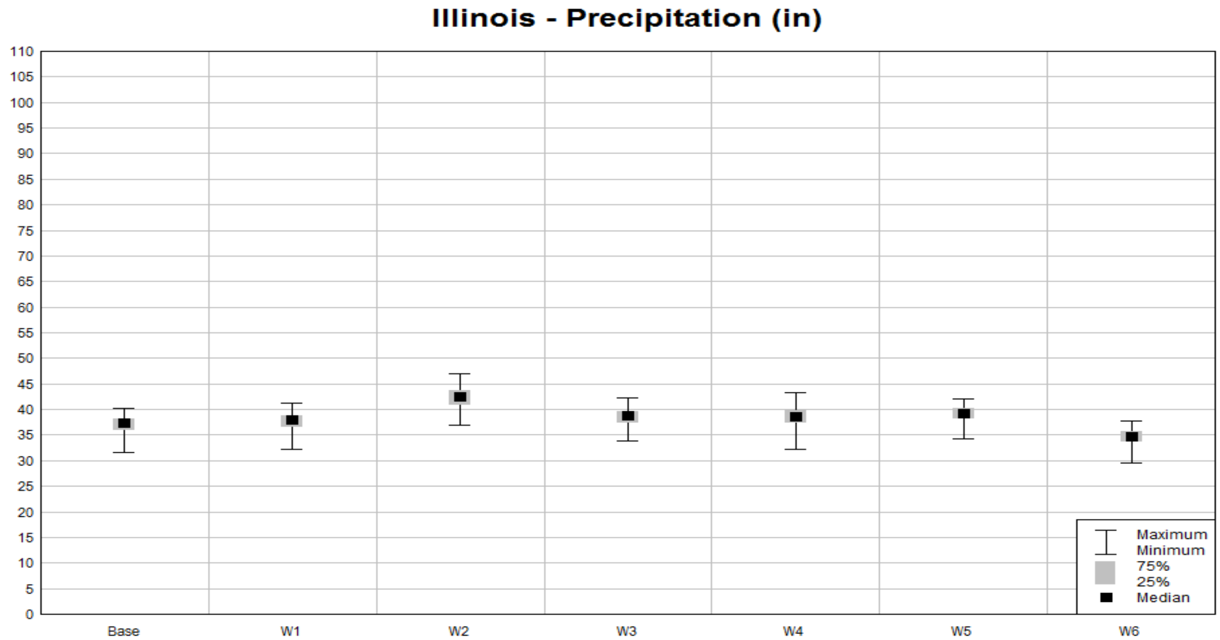


Figure Z-26. GaFla: Comparison of climate scenario precipitation for the Georgia-Florida Coastal Plain

Note: See Table Z-1 for key to climate scenarios.



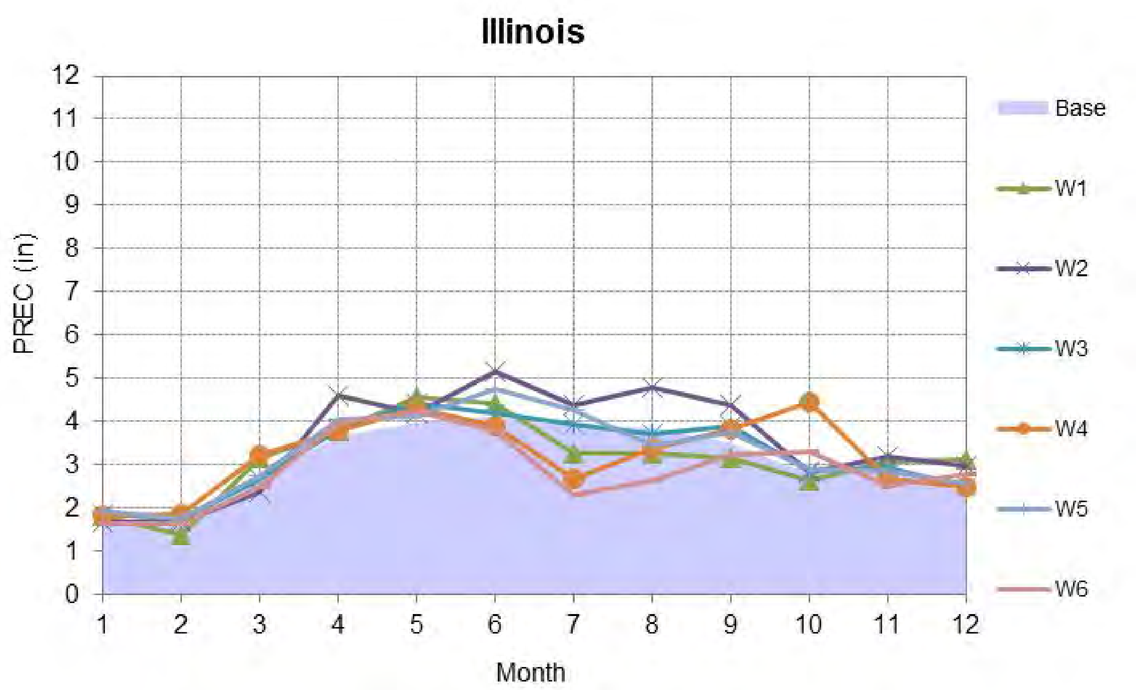
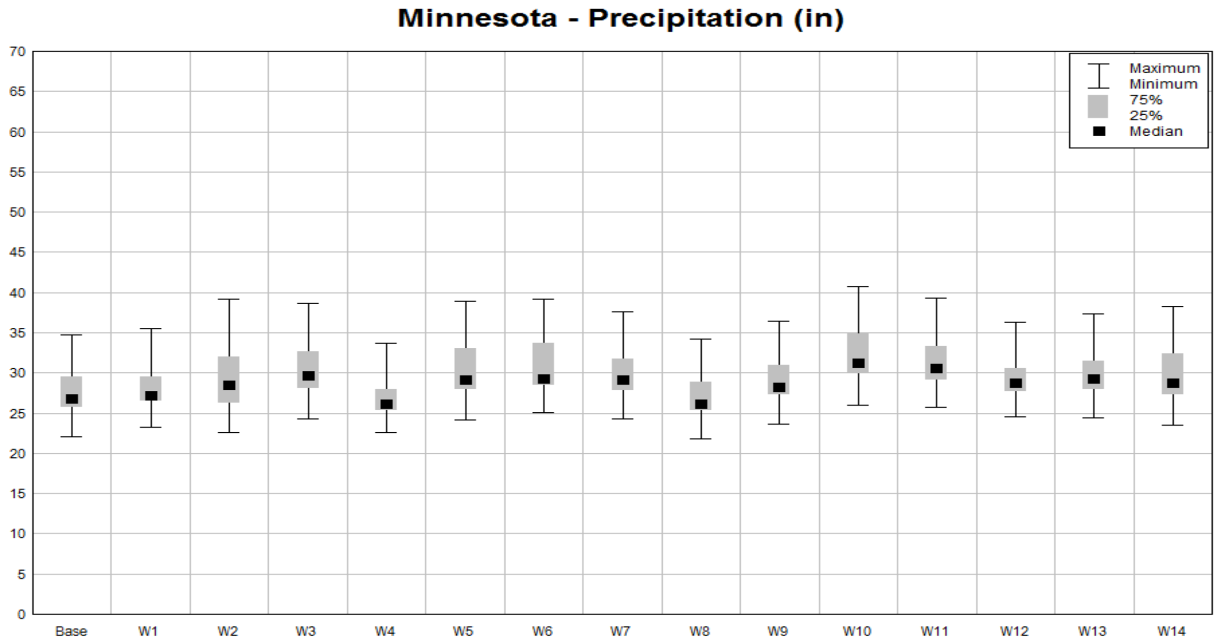


Figure Z-27. Illin: Comparison of climate scenario precipitation for the Illinois River basin

Note: See Table Z-1 for key to climate scenarios.



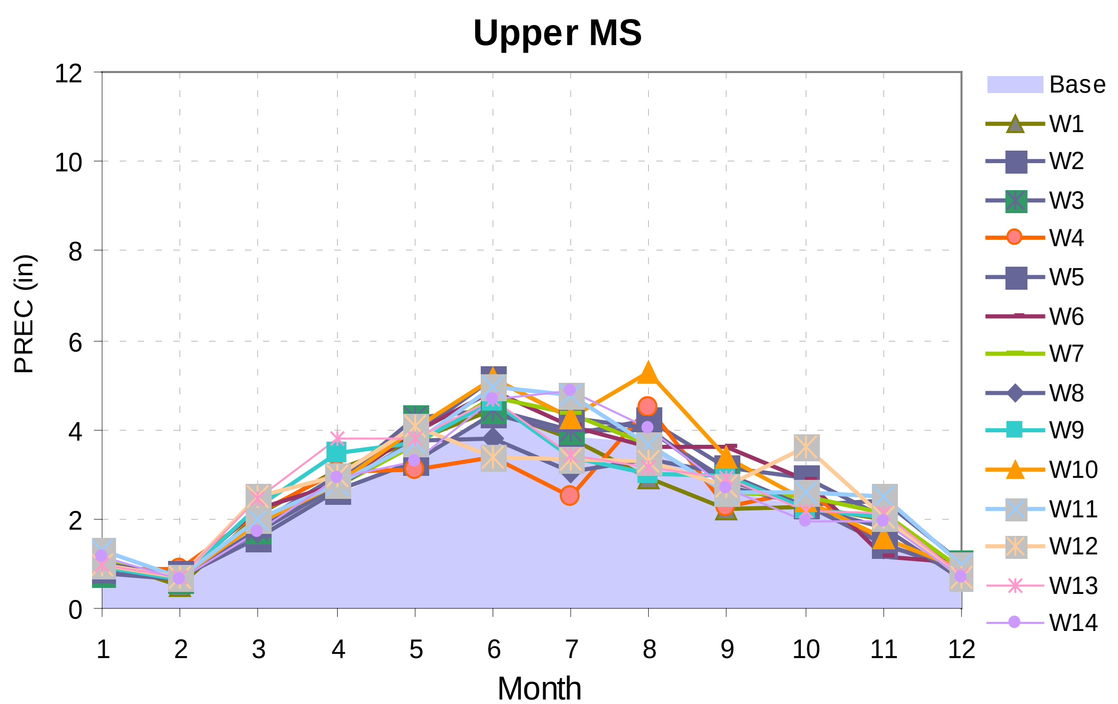


Figure Z-28. Minn: Comparison of climate scenario precipitation for the Minnesota River (Upper Mississippi) basin

Note: See Table Z-1 for key to climate scenarios.

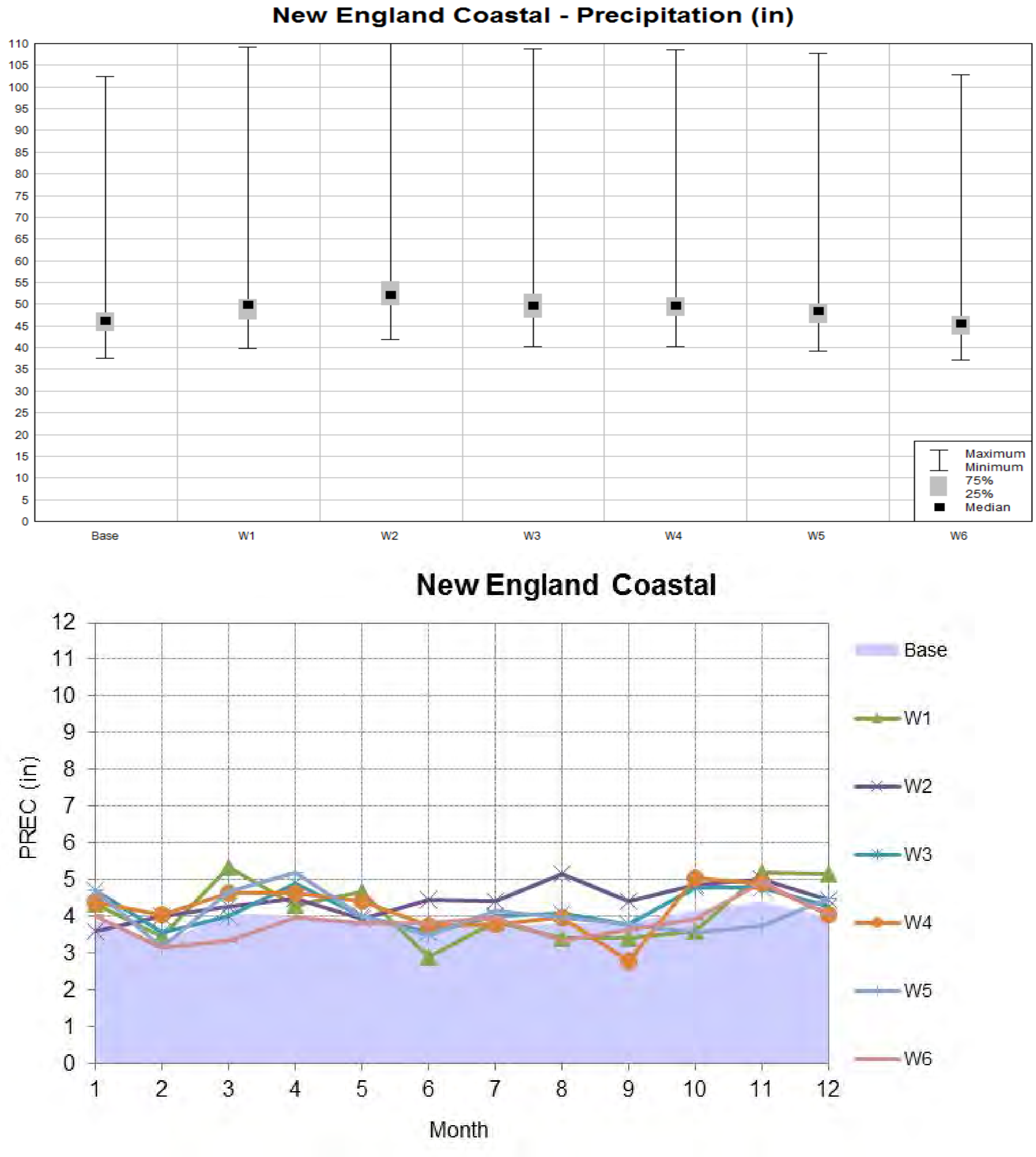
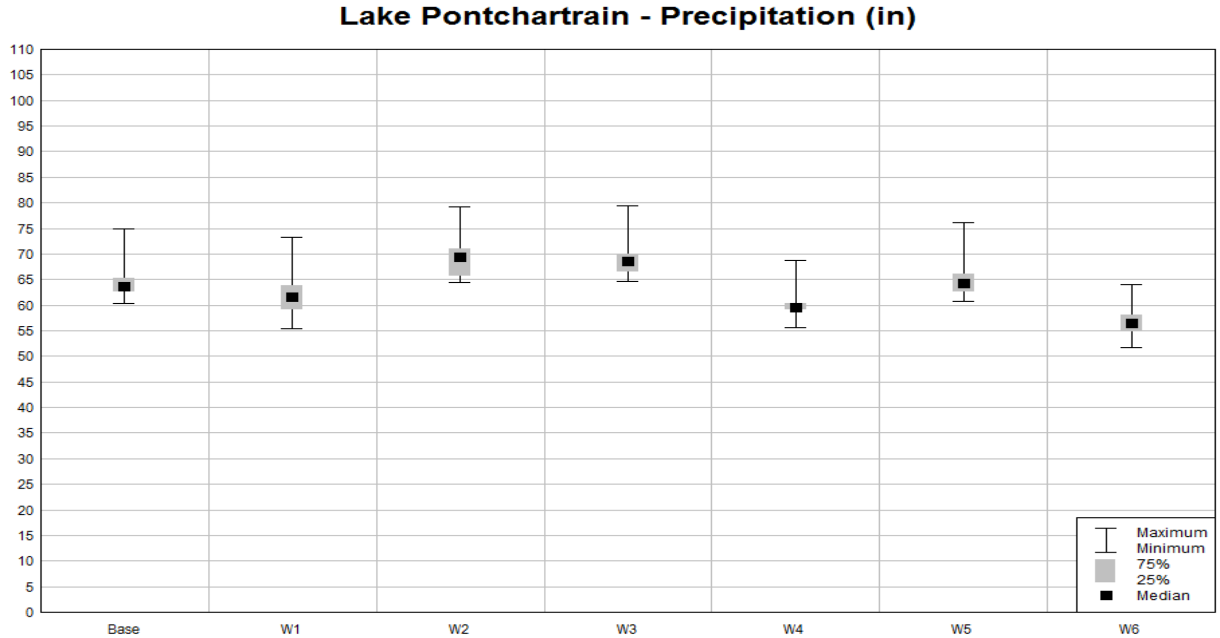


Figure Z-29. NewEng: Comparison of climate scenario precipitation for the New England Coastal basins

Note: See Table Z-1 for key to climate scenarios.



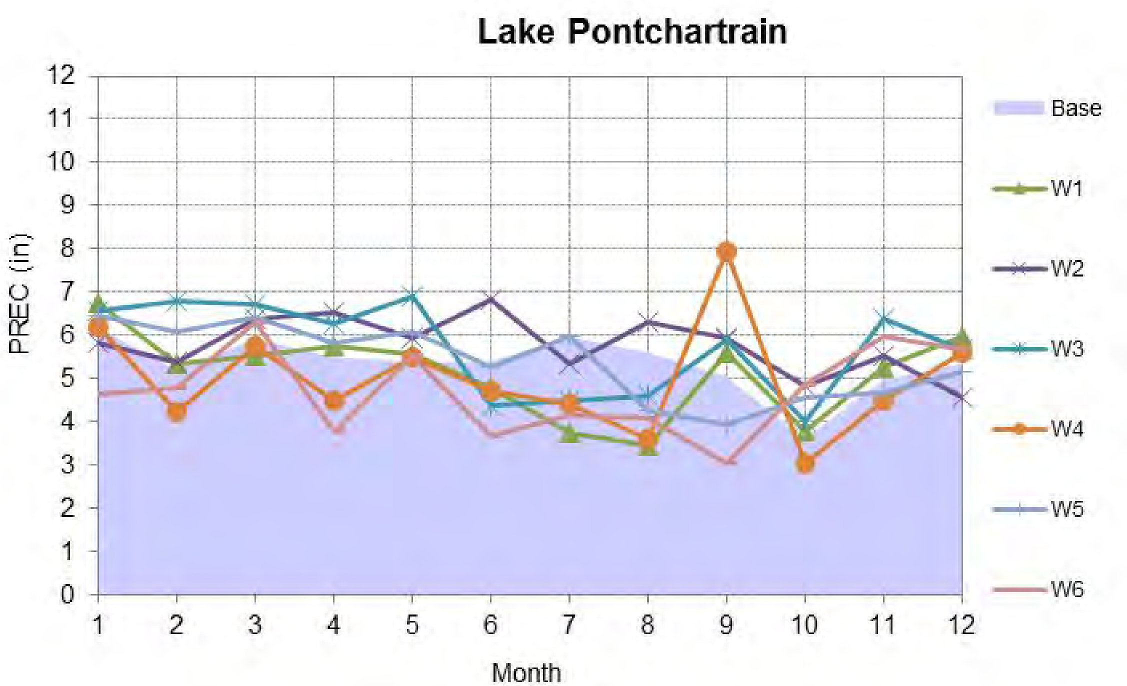
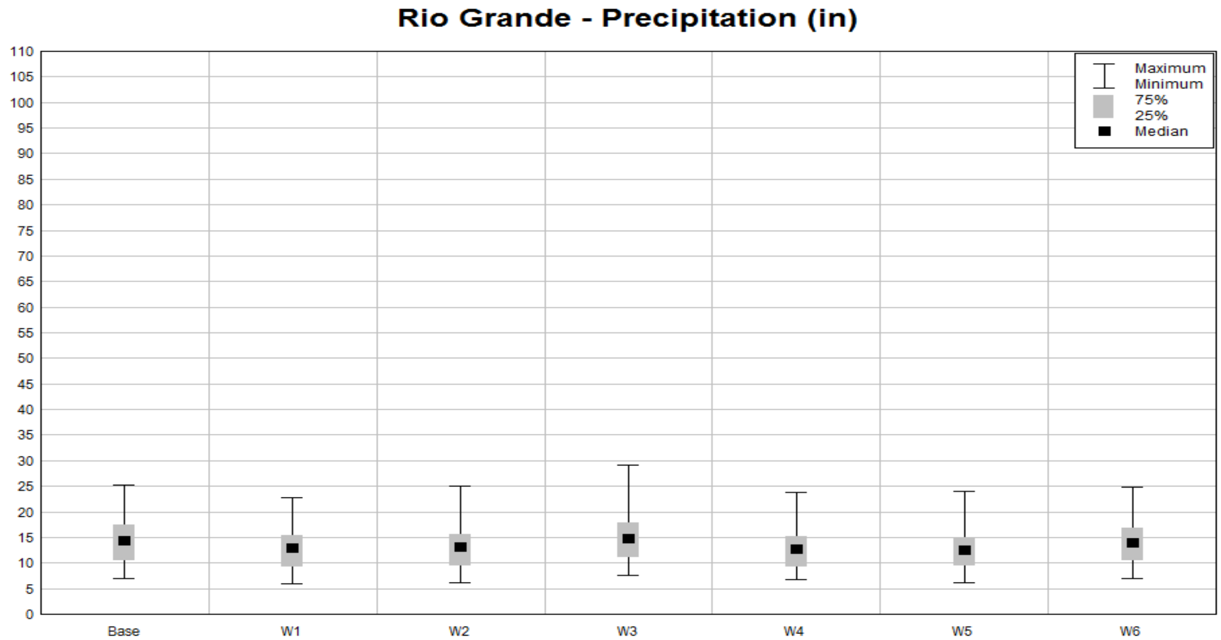


Figure Z-30. Pont: Comparison of climate scenario precipitation for the Lake Pontchartrain drainage

Note: See Table Z-1 for key to climate scenarios.



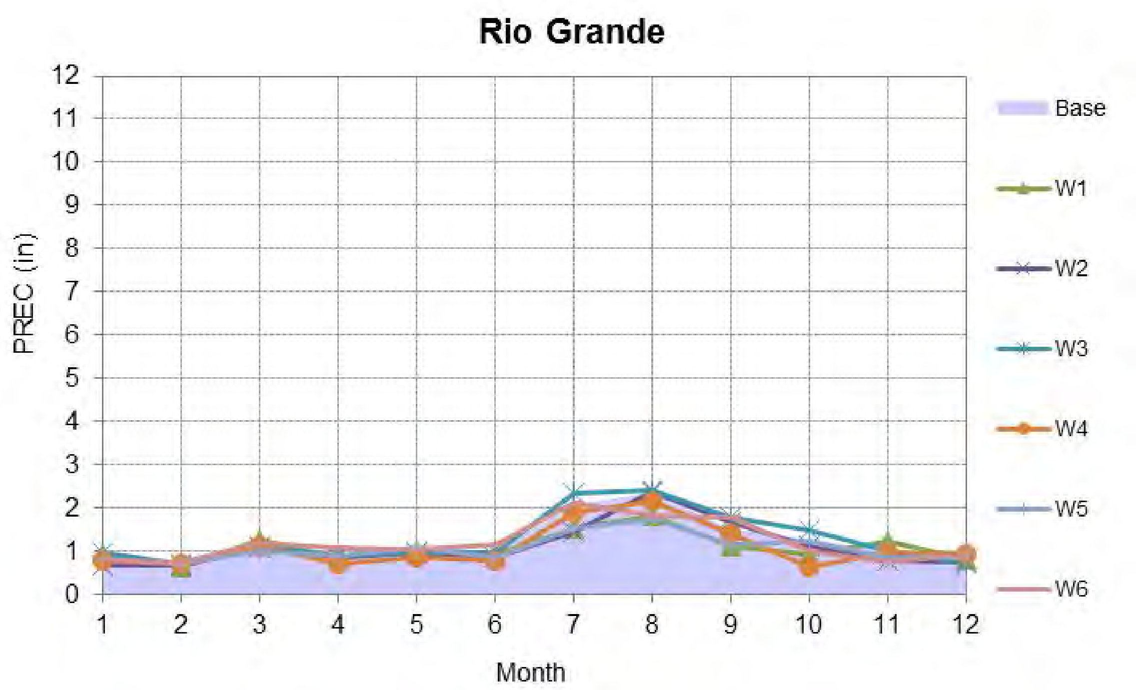


Figure Z-31. RioGra: Comparison of climate scenario precipitation for the Rio Grande Valley

Note: See Table Z-1 for key to climate scenarios.

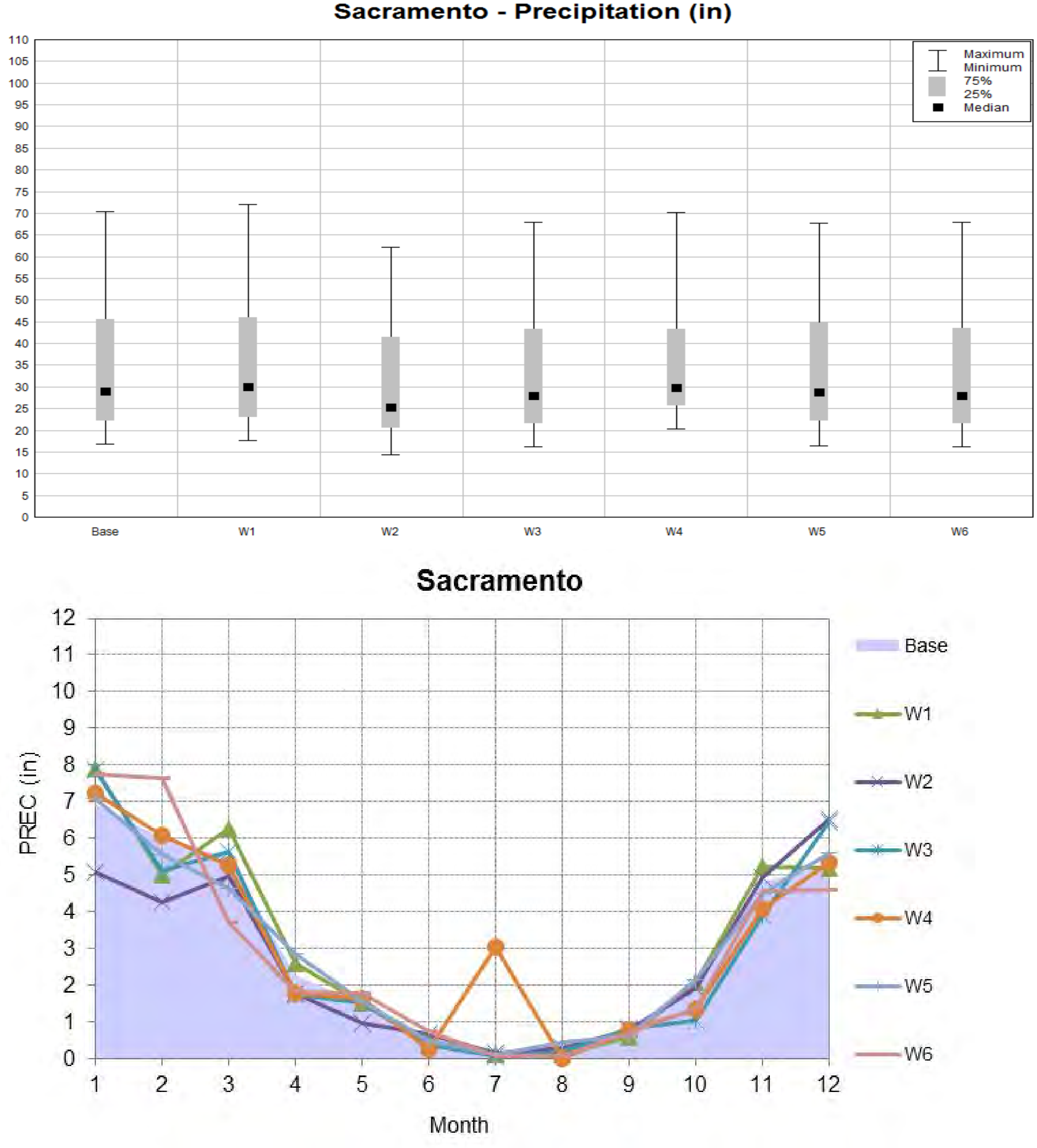


Figure Z-32. Sac: Comparison of climate scenario precipitation for the Sacramento River basin

Note: See Table Z-1 for key to climate scenarios.

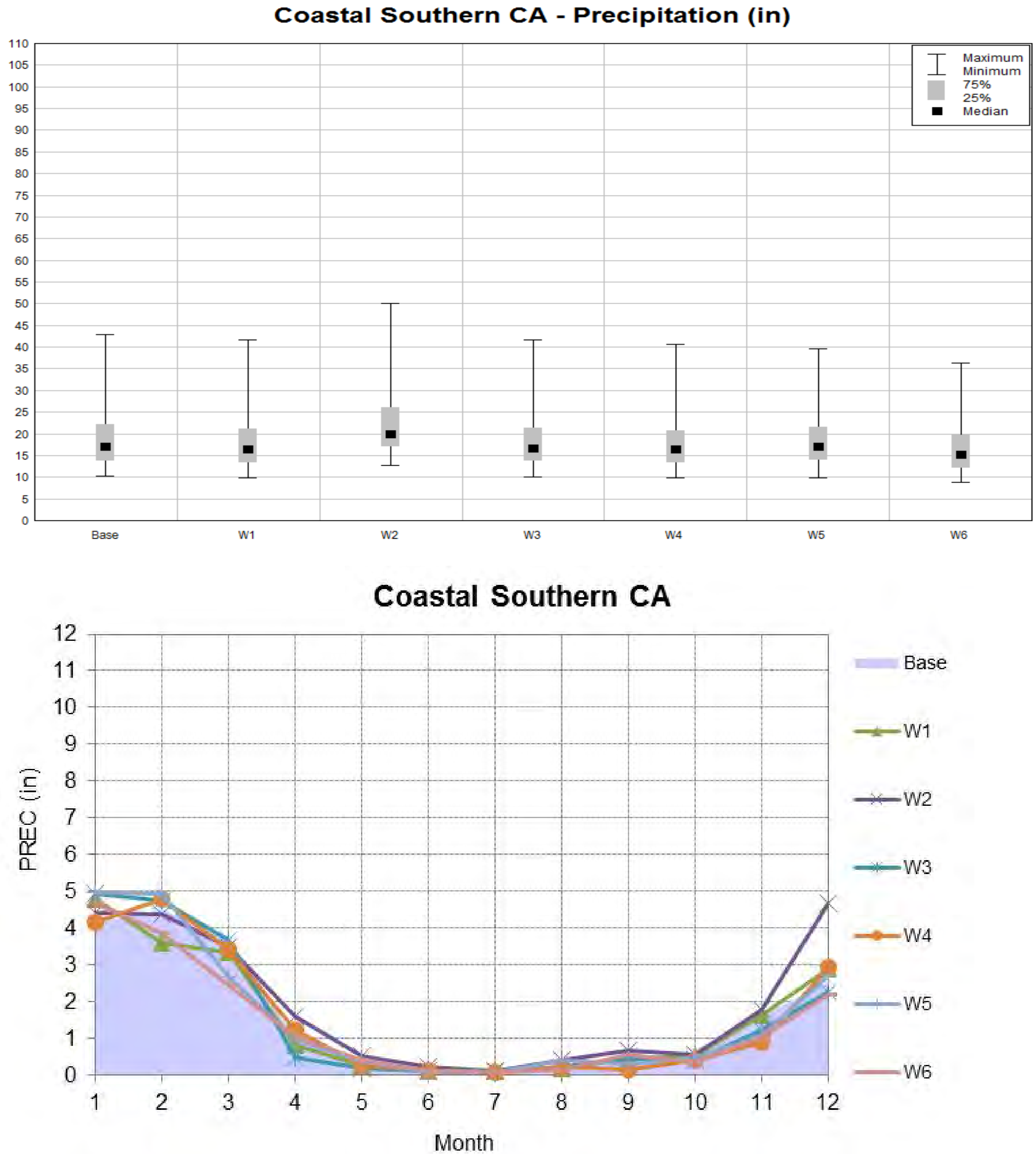
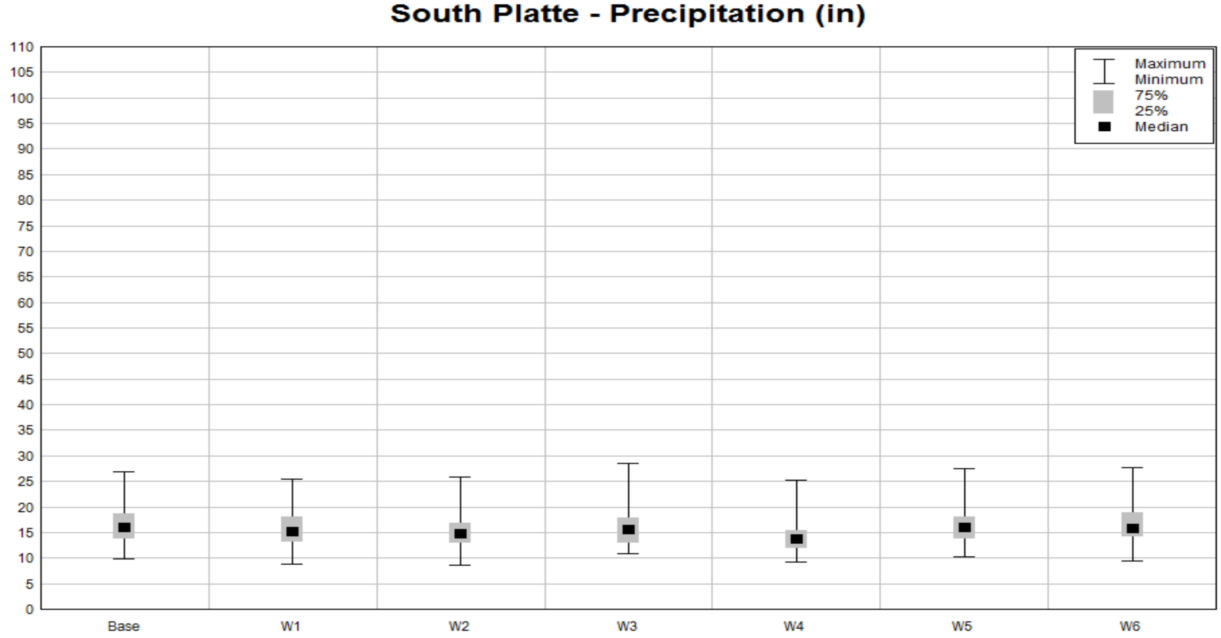


Figure Z-33. SoCal: Comparison of climate scenario precipitation for the Coastal Southern California basin

Note: See Table Z-1 for key to climate scenarios.



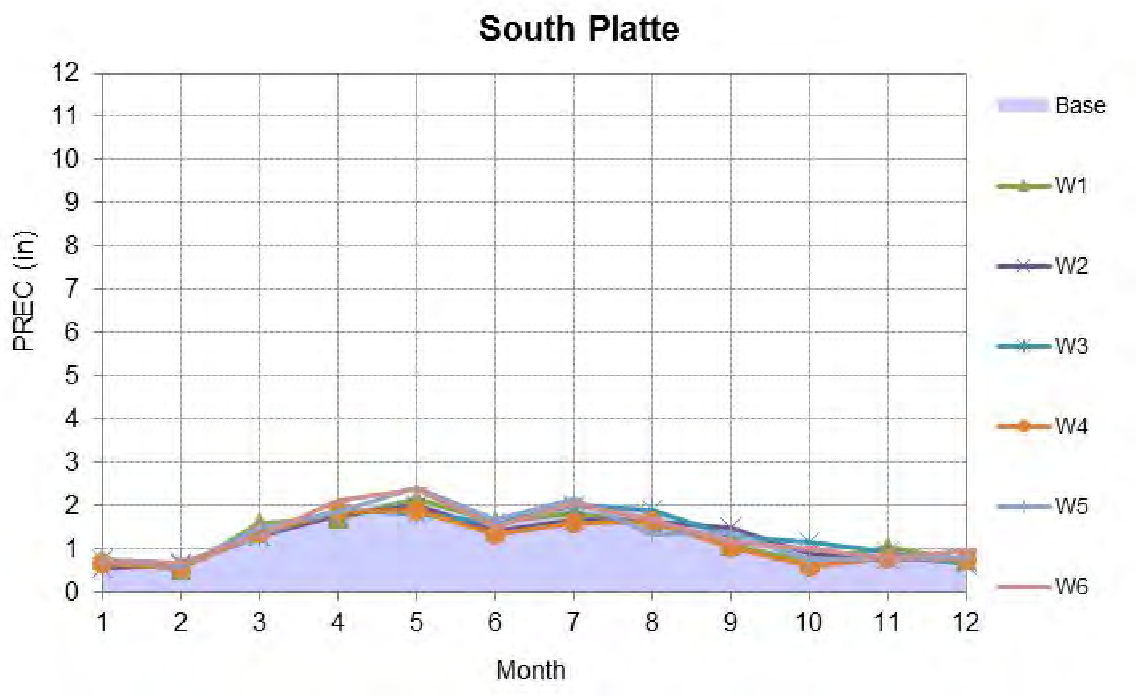
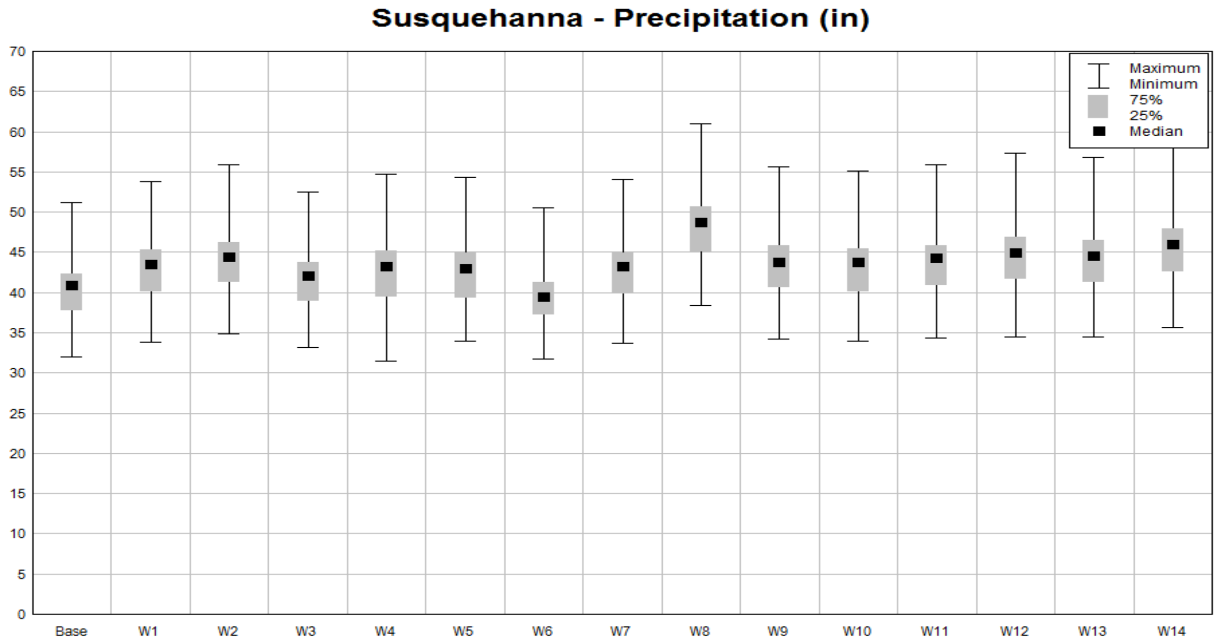


Figure Z-34. SoPlat: Comparison of climate scenario precipitation for the South Platte River basin

Note: See Table Z-1 for key to climate scenarios.



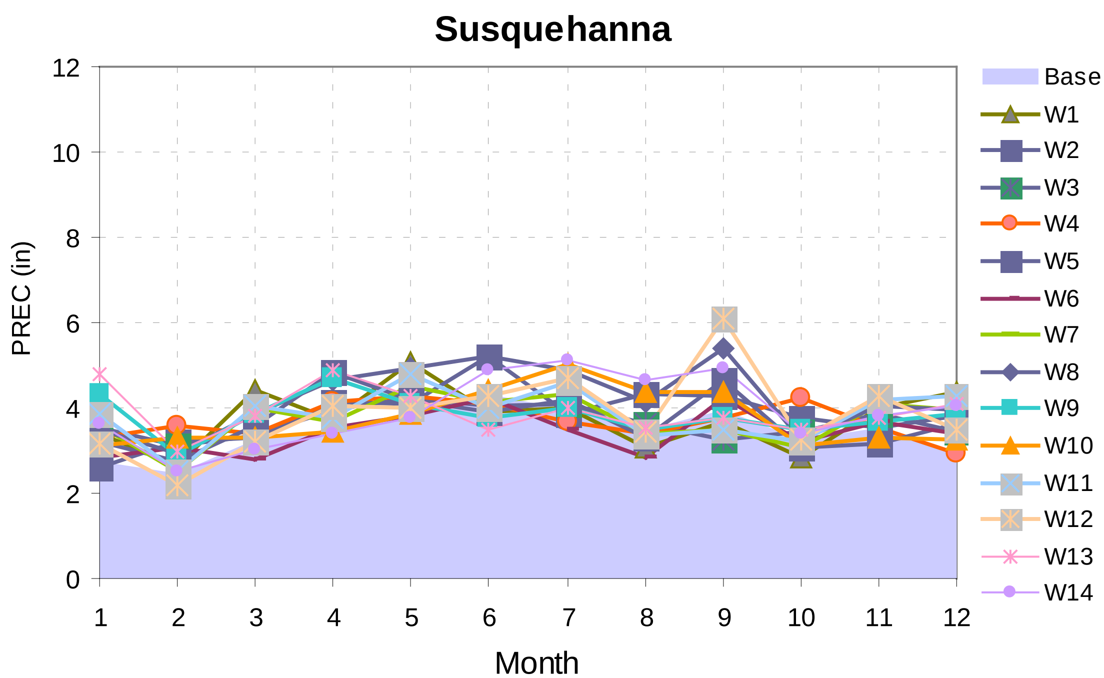
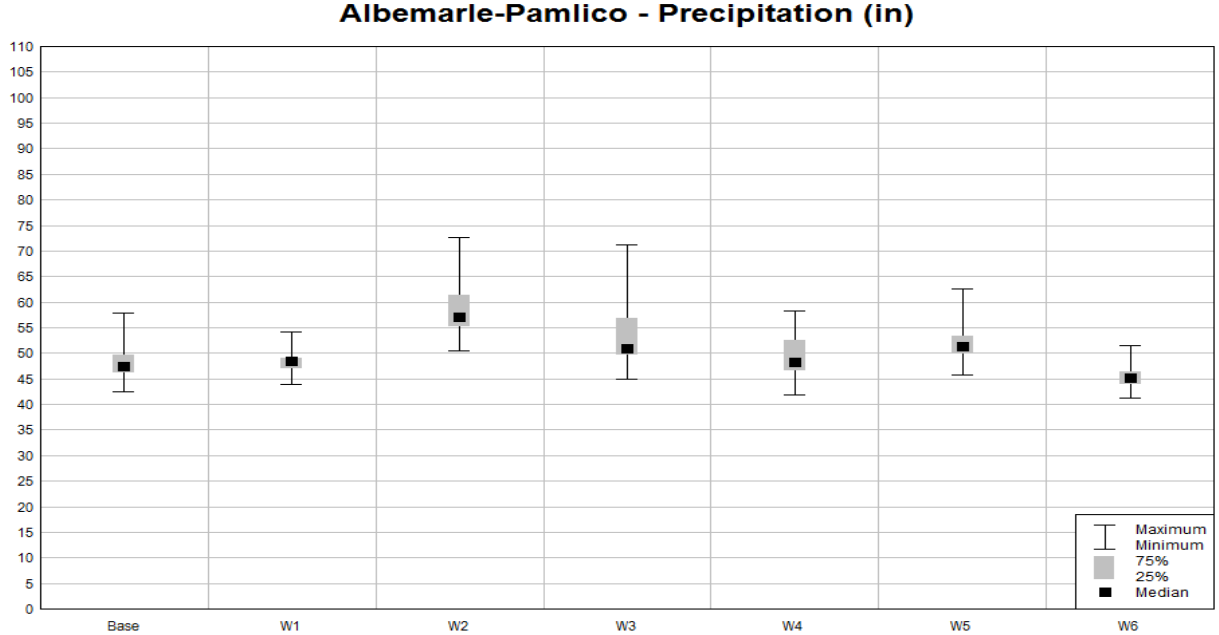


Figure Z-35. Susq: Comparison of climate scenario precipitation for the Susquehanna River basin

Note: See Table Z-1 for key to climate scenarios.



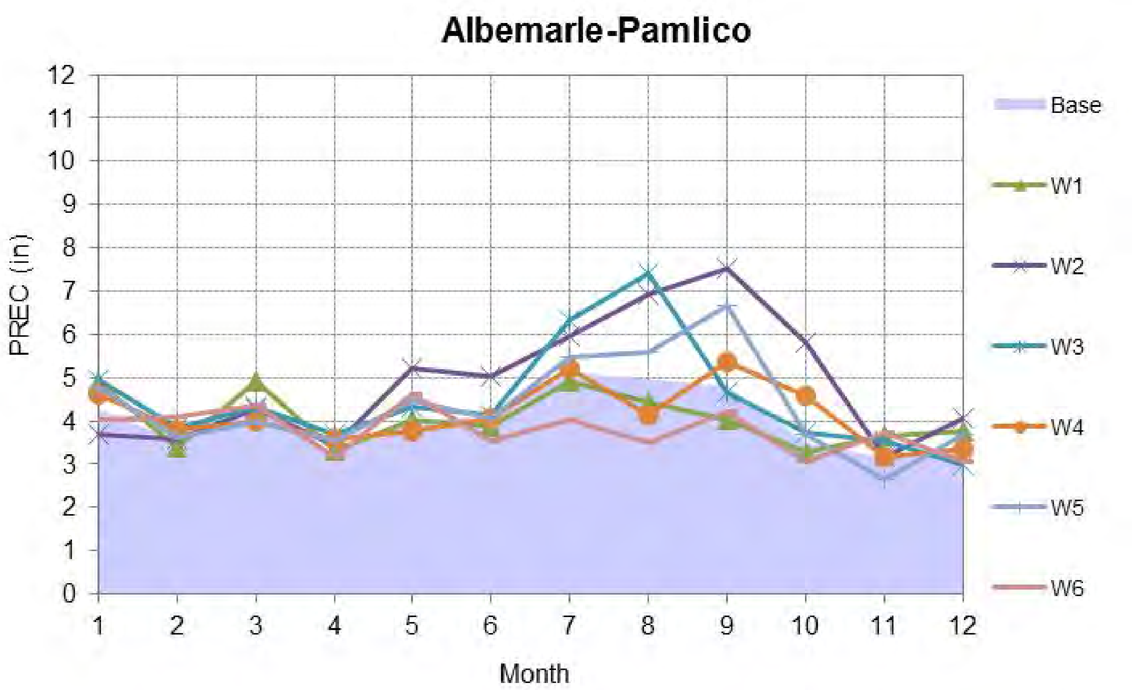
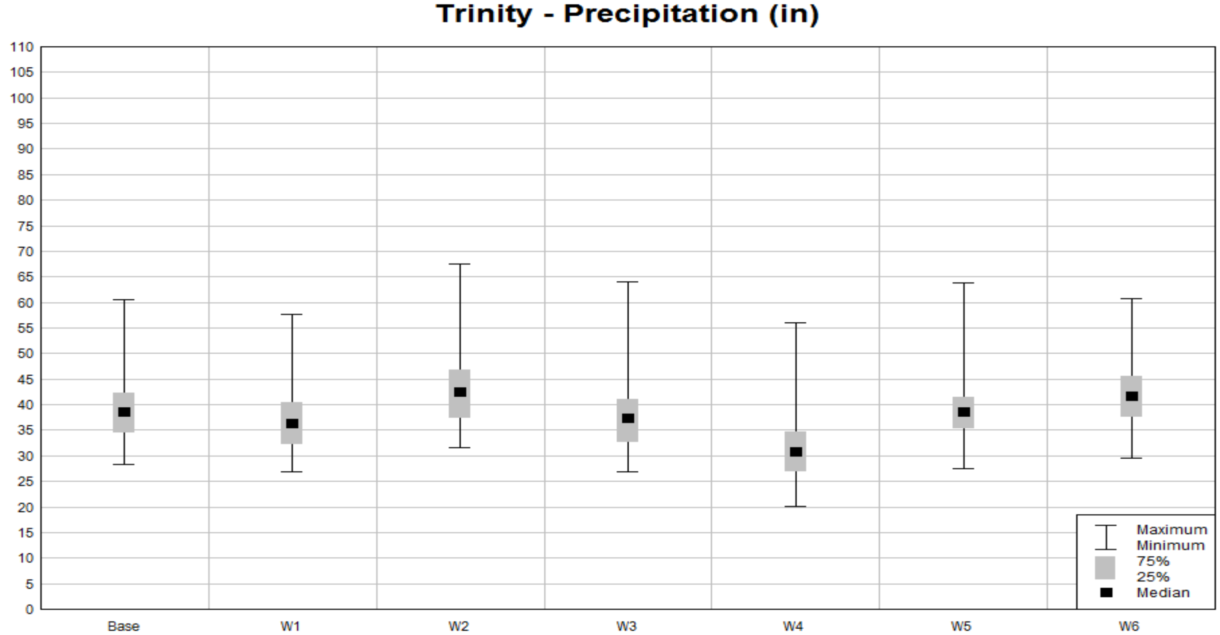


Figure Z-36. TarNeu: Comparison of climate scenario precipitation for the Tar and Neuse River basin

Note: See Table Z-1 for key to climate scenarios.



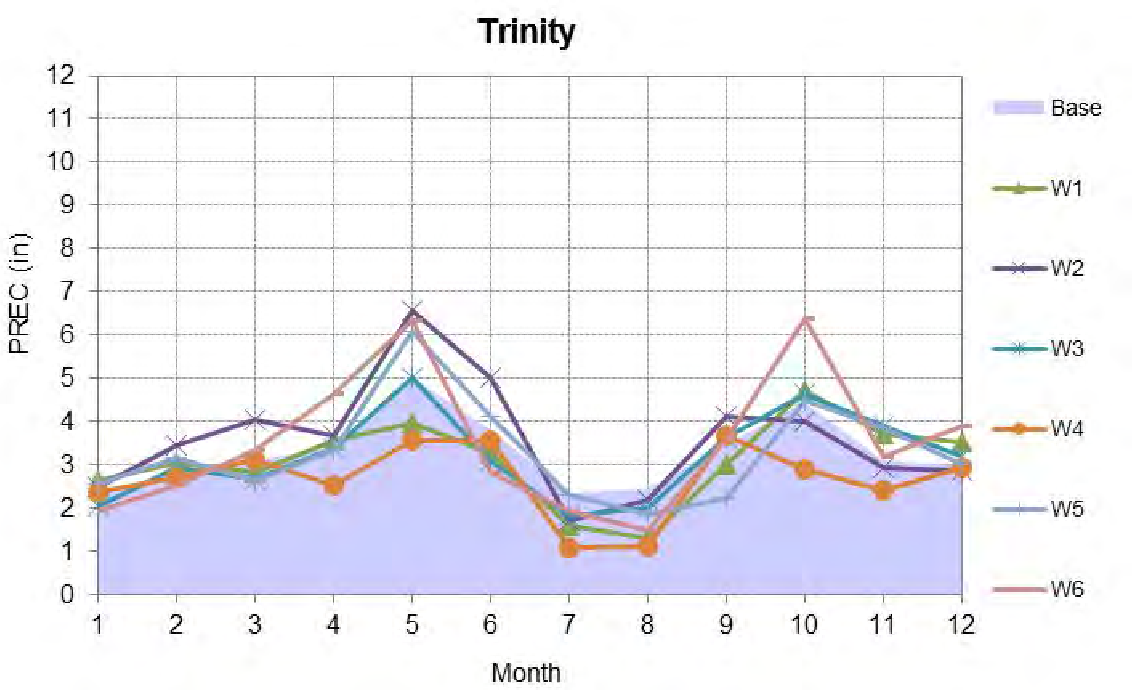
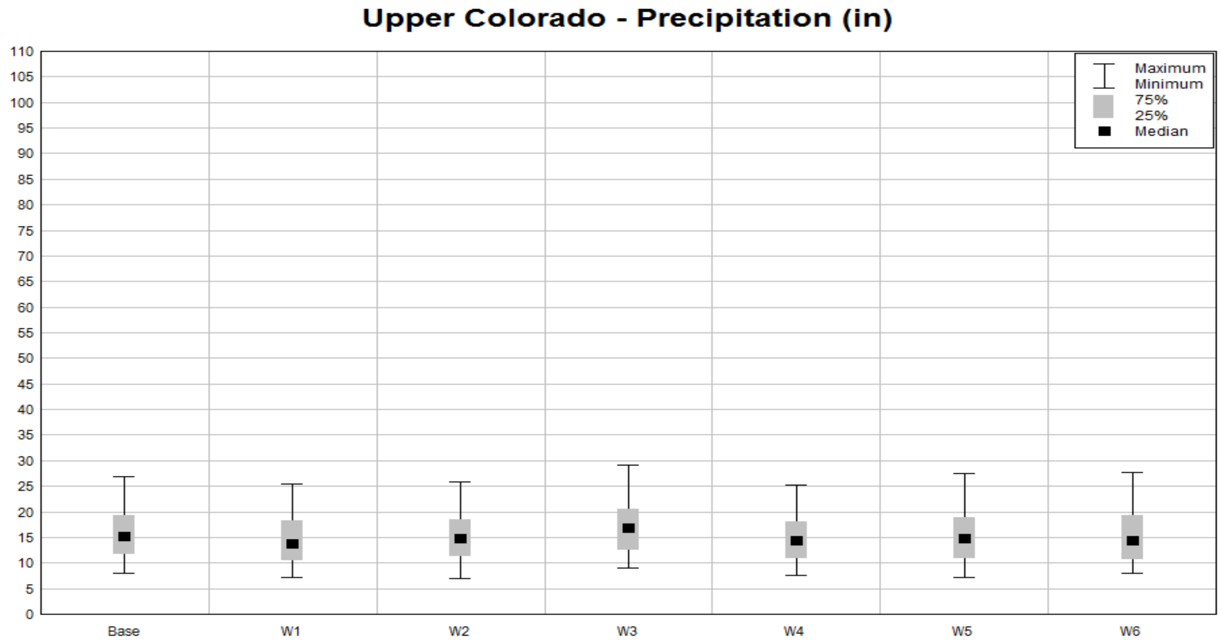


Figure Z-37. Trin: Comparison of climate scenario precipitation for the Trinity River basin

Note: See Table Z-1 for key to climate scenarios.



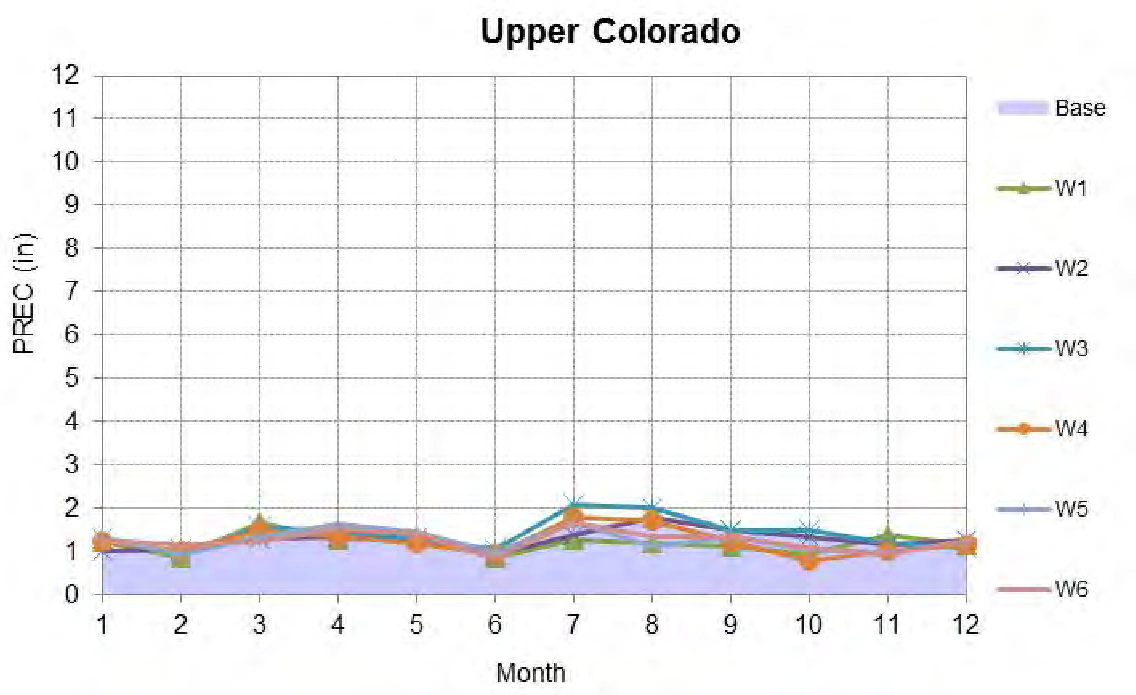
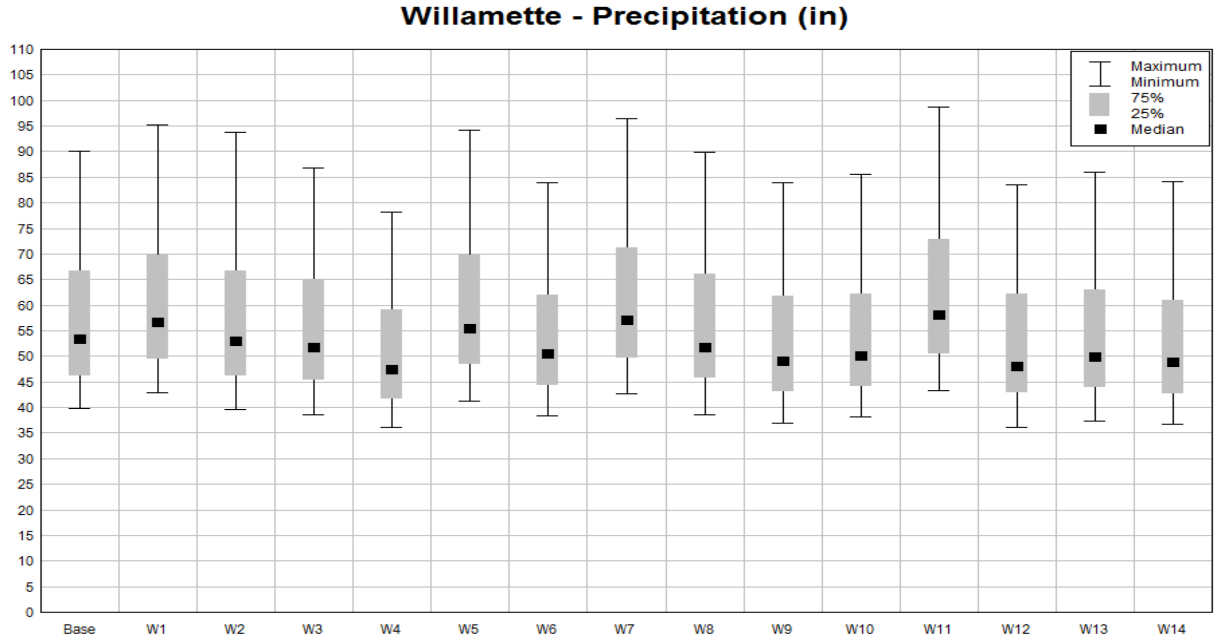


Figure Z-38. UppCol: Comparison of climate scenario precipitation for the Loup/Elkhorn River basin

Note: See Table Z-1 for key to climate scenarios.



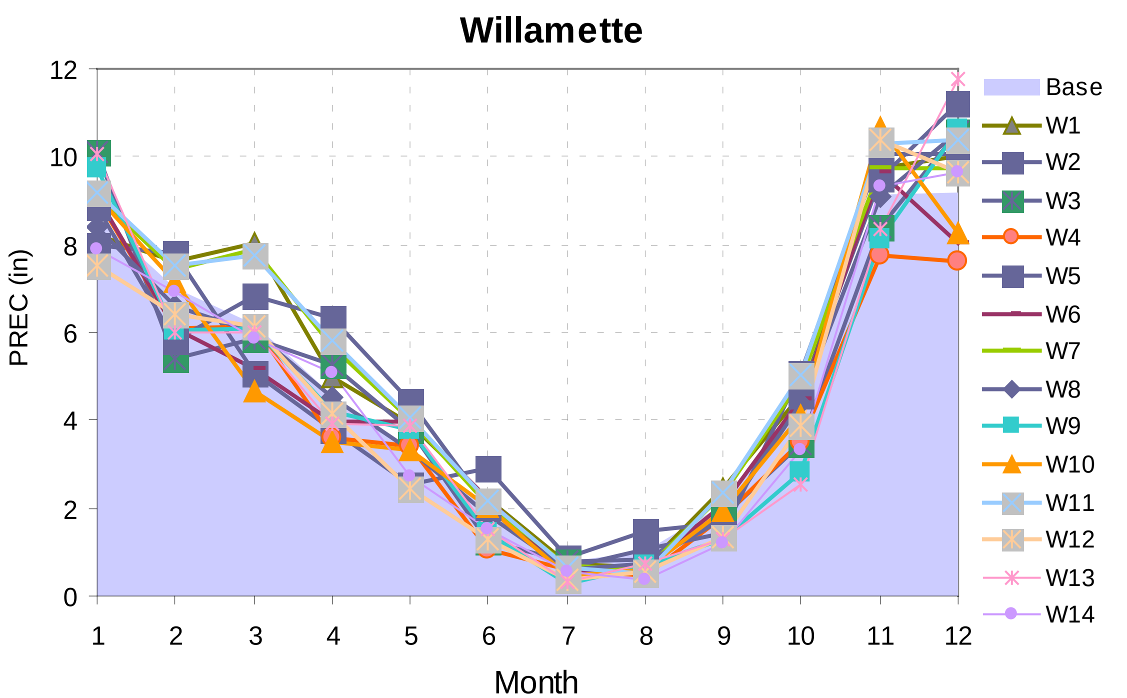


Figure Z-39. Willa: Comparison of climate scenario precipitation for the Willamette River basin

Note: See Table Z-1 for key to climate scenarios.

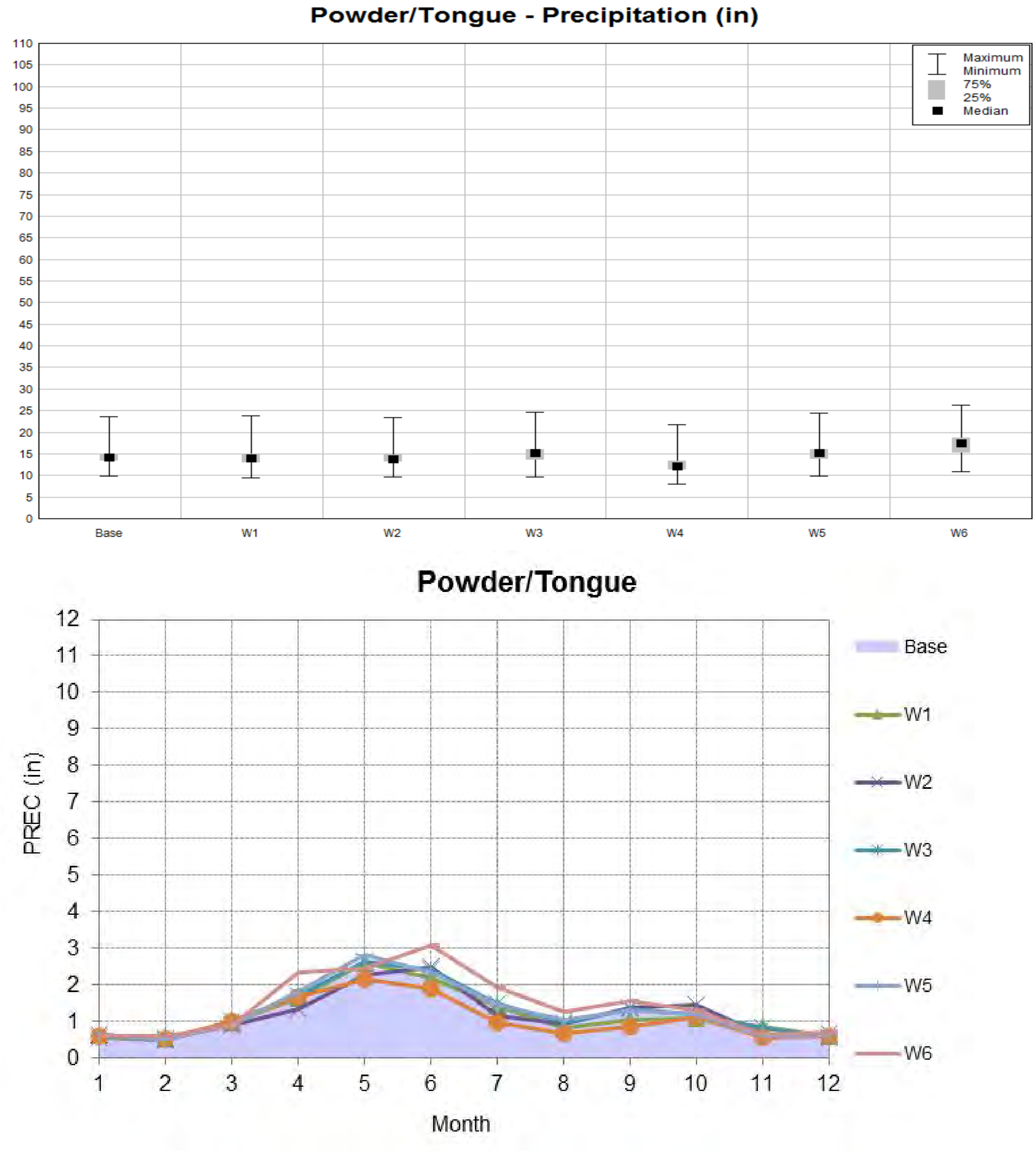
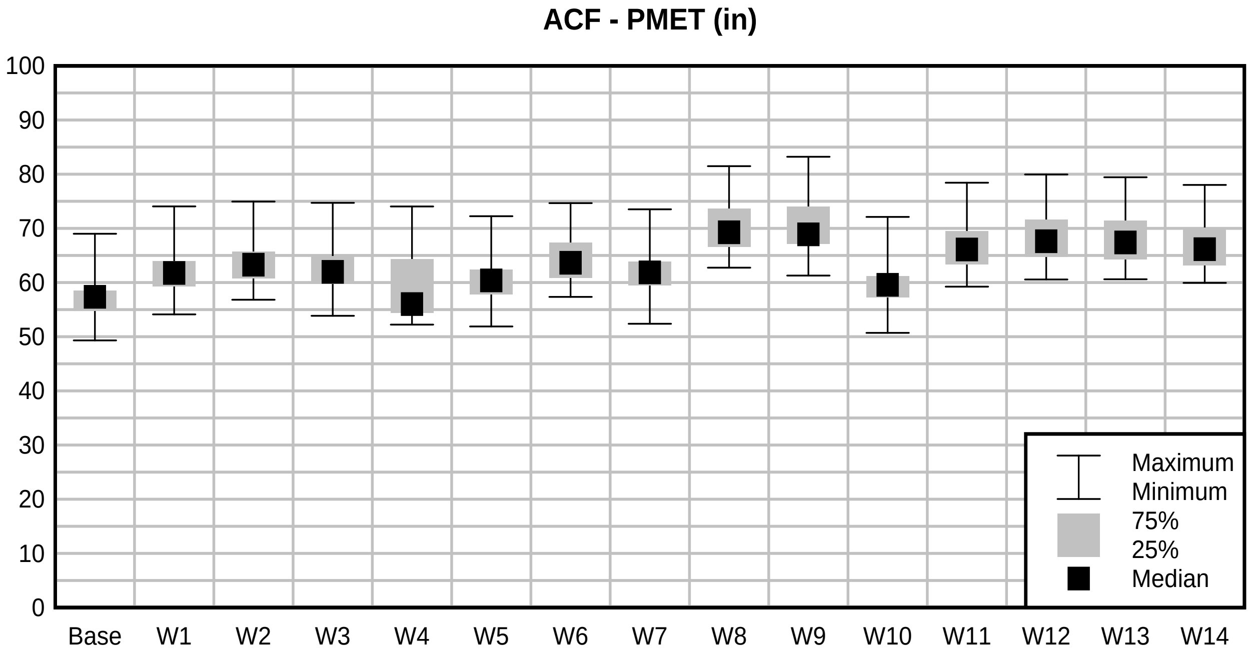


Figure Z-40. Yellow: Comparison of climate scenario precipitation for the Powder/Tongue River basin

Note: See Table Z-1 for key to climate scenarios.



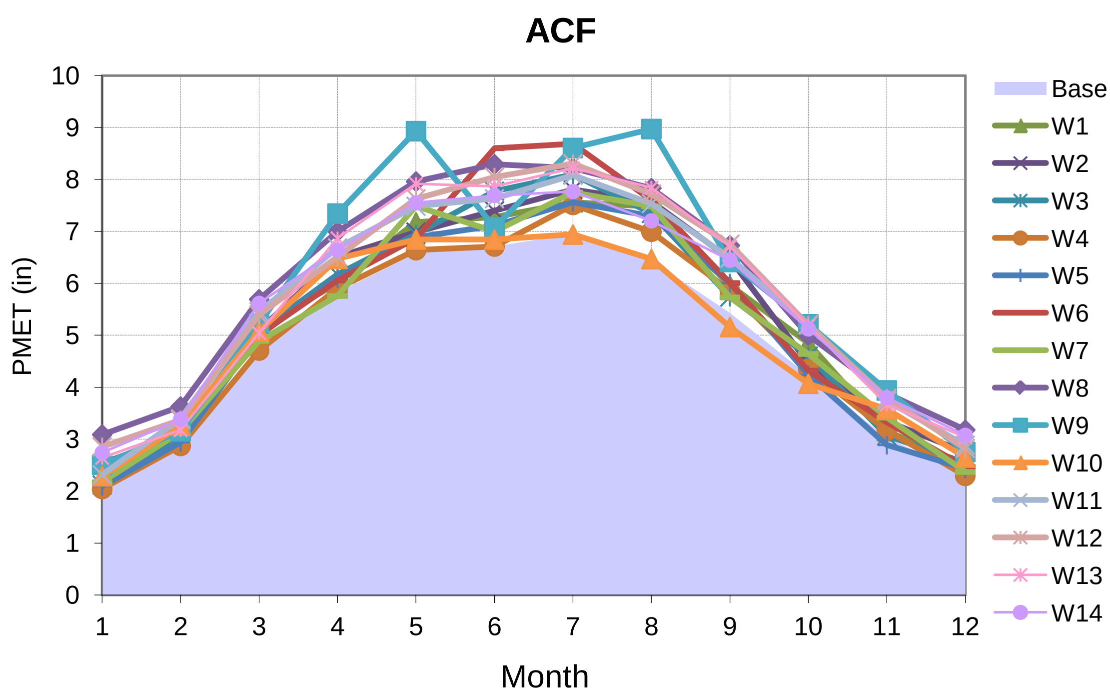
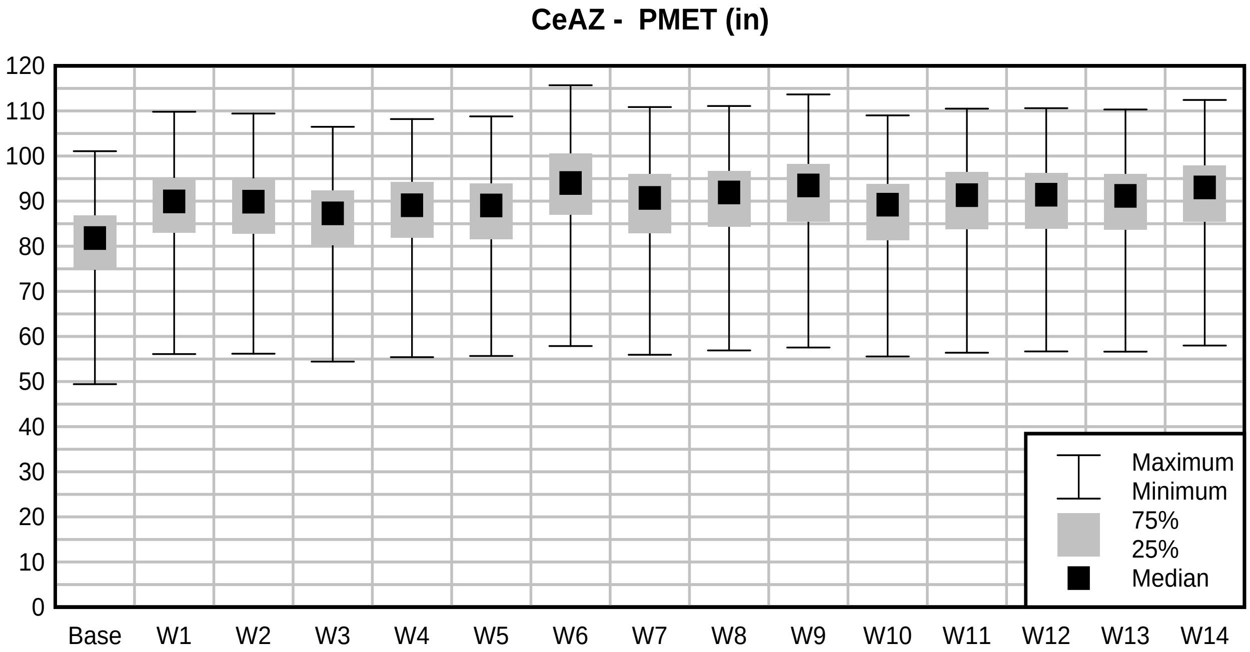


Figure Z-41. ACF: Comparison of climate scenario Penman-Monteith reference ET for the ACF basin

Note: See Table Z-1 for key to climate scenarios.



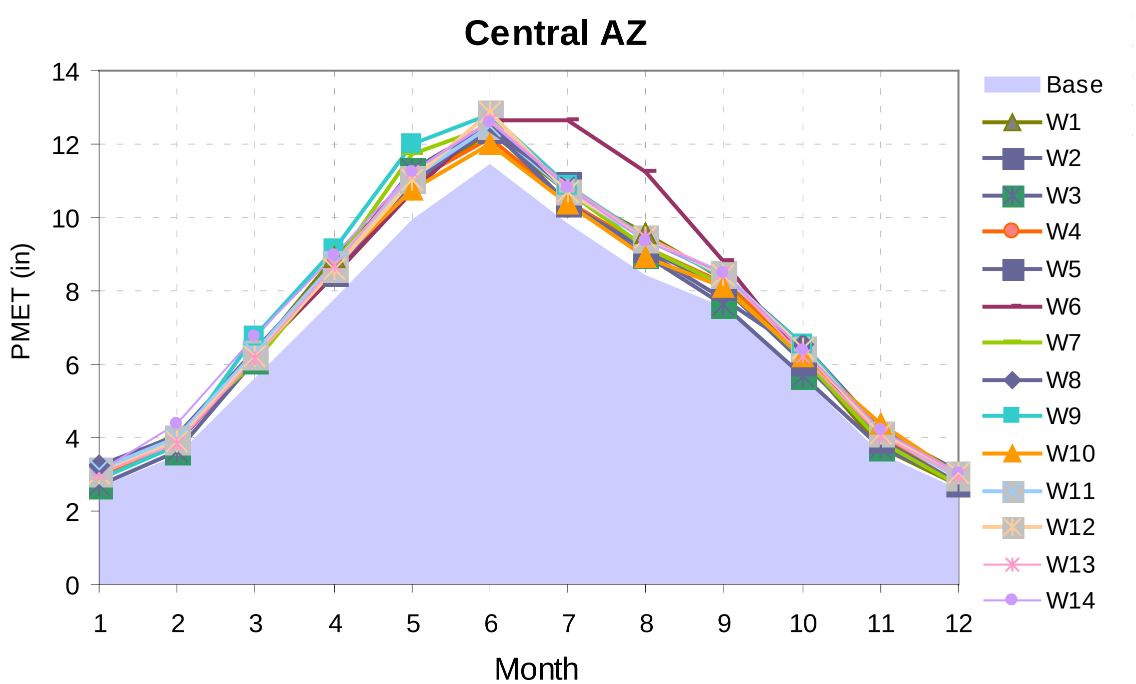
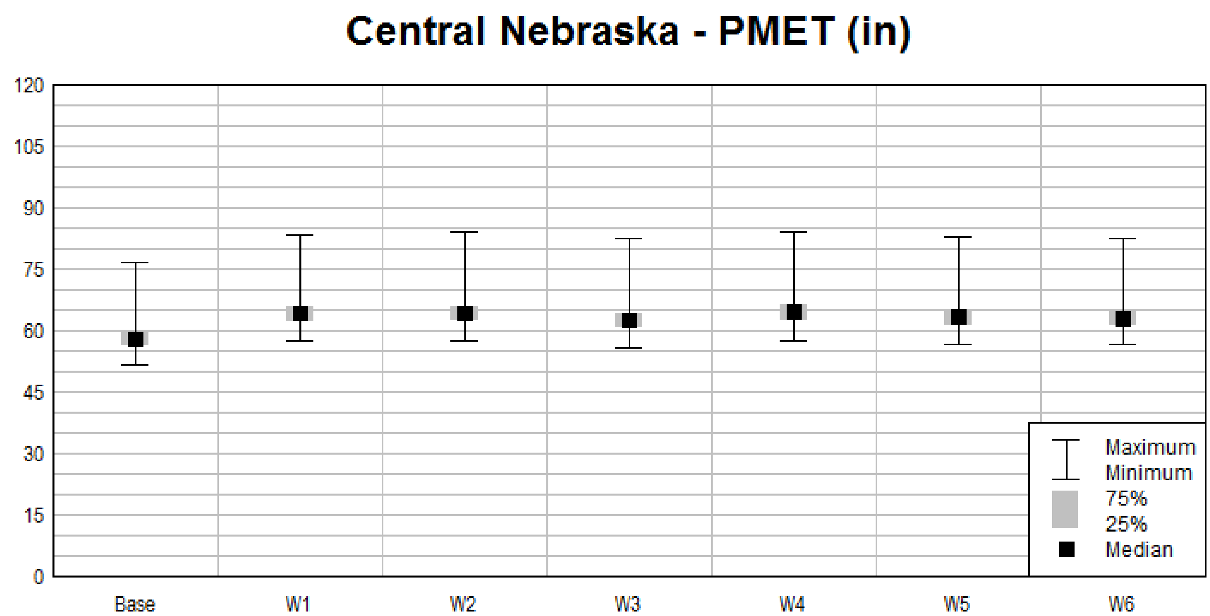


Figure Z-42. Ariz: Comparison of climate scenario Penman-Monteith reference ET for the Salt, Verde, and San Pedro basins

Note: See Table Z-1 for key to climate scenarios.



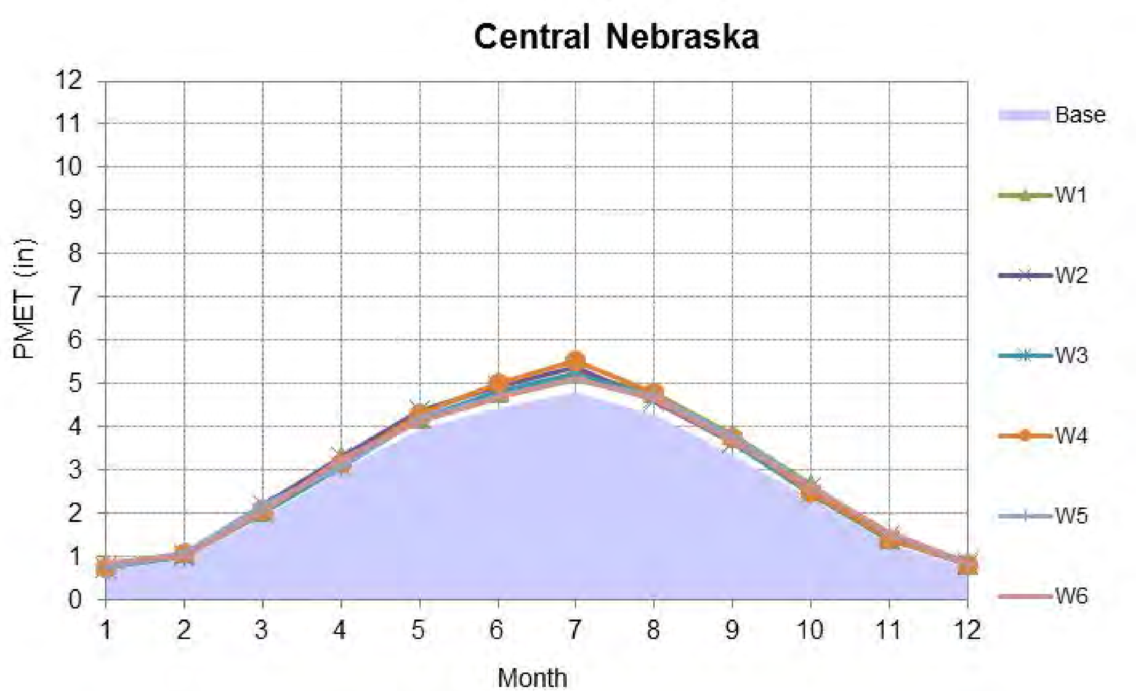


Figure Z-43. CenNeb: Comparison of climate scenario Penman-Monteith reference ET for the Loup/Elkhorn River basin

Note: See Table Z-1 for key to climate scenarios.

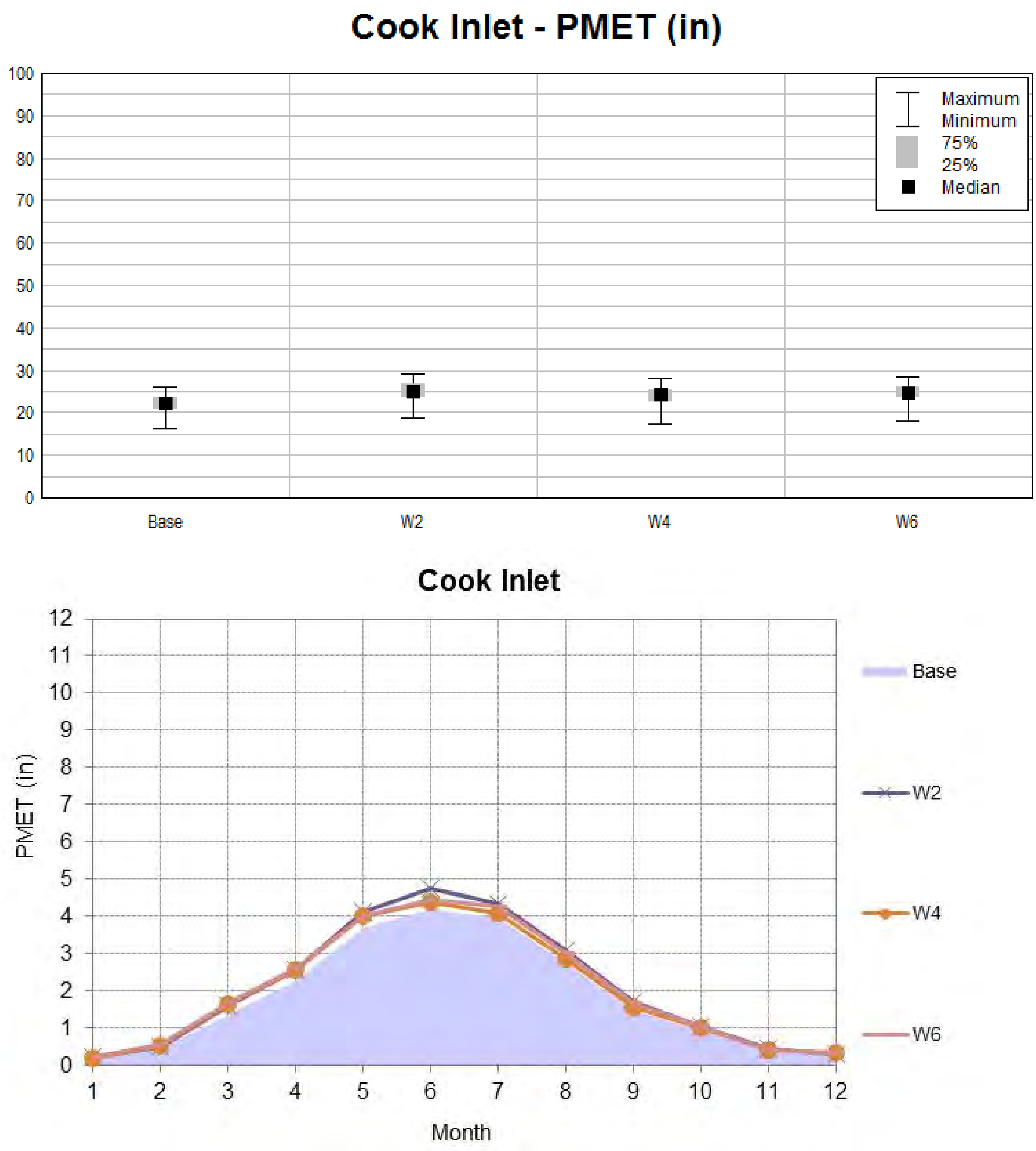
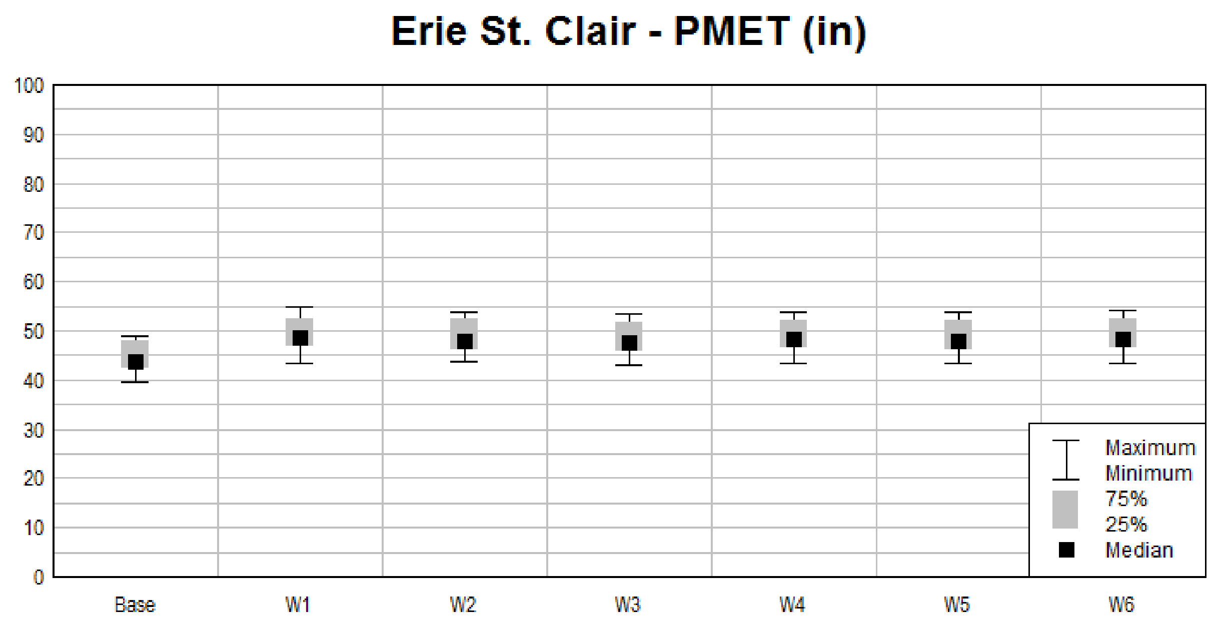


Figure Z-44. Cook: Comparison of climate scenario Penman-Monteith reference ET for the Cook Inlet basin

Note: See Table Z-1 for key to climate scenarios.



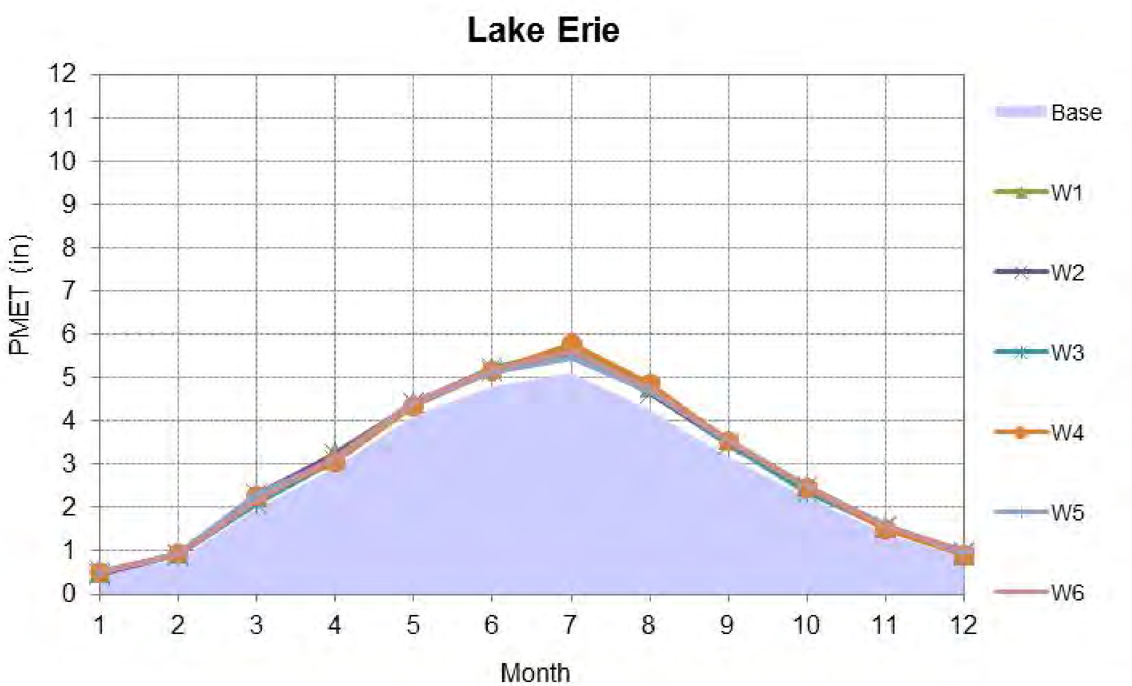
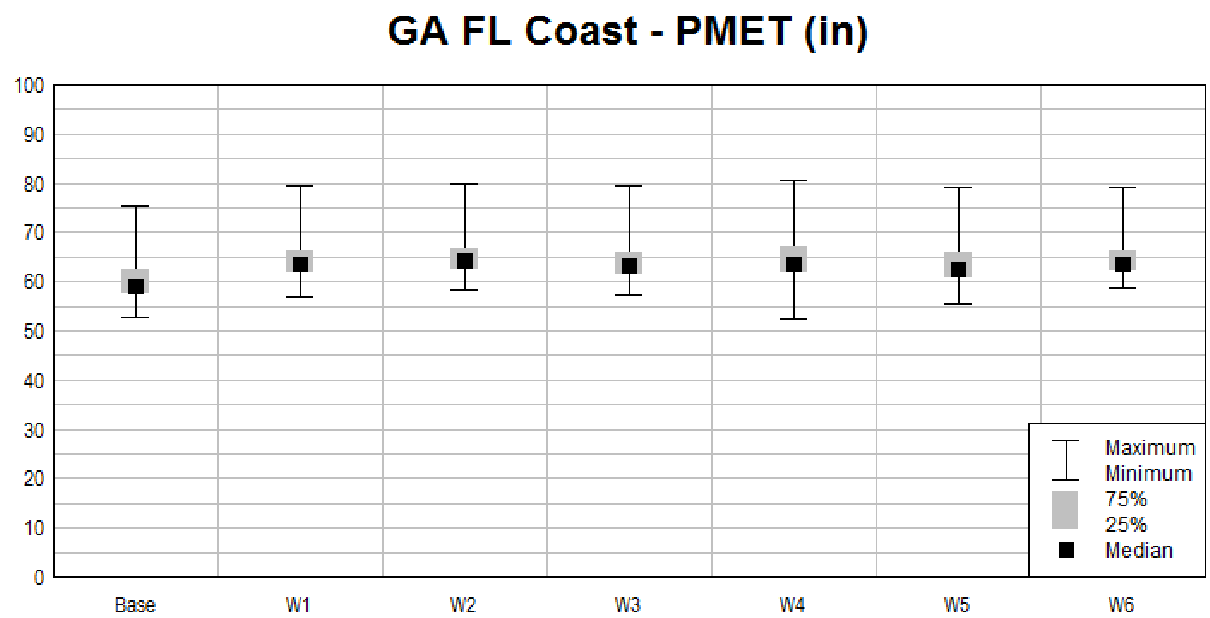


Figure Z-45. Erie: Comparison of climate scenario Penman-Monteith reference ET for the Lake Erie drainages

Note: See Table Z-1 for key to climate scenarios.



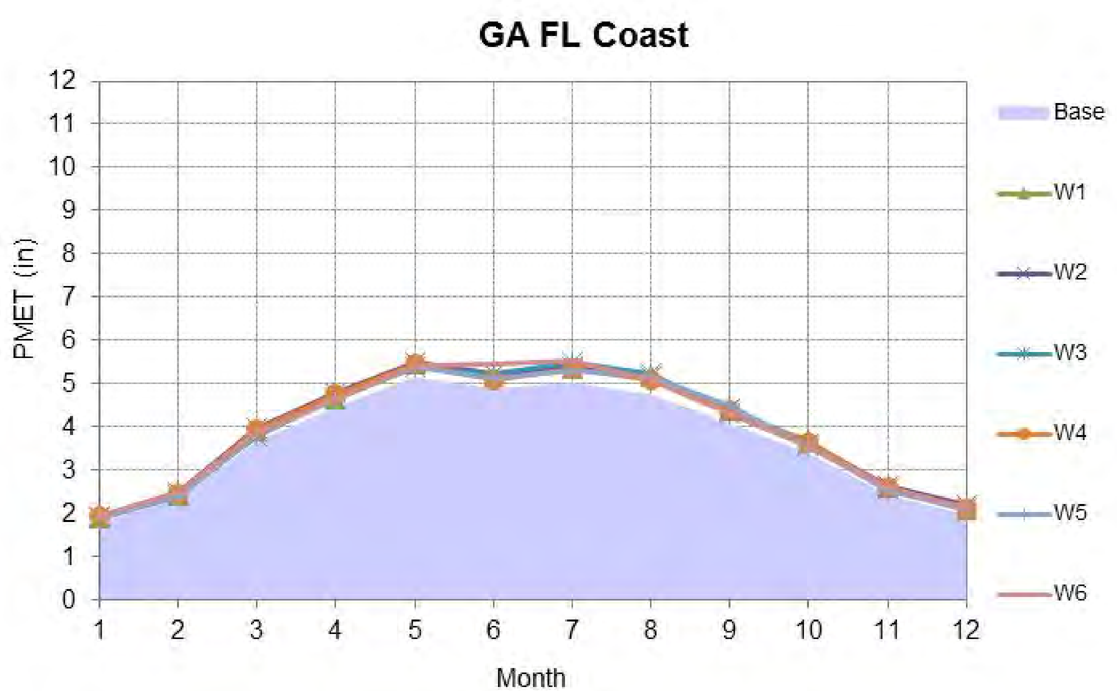


Figure Z-46. GaFla: Comparison of climate scenario Penman-Monteith reference ET for the Georgia-Florida Coastal Plain

Note: See Table Z-1 for key to climate scenarios.

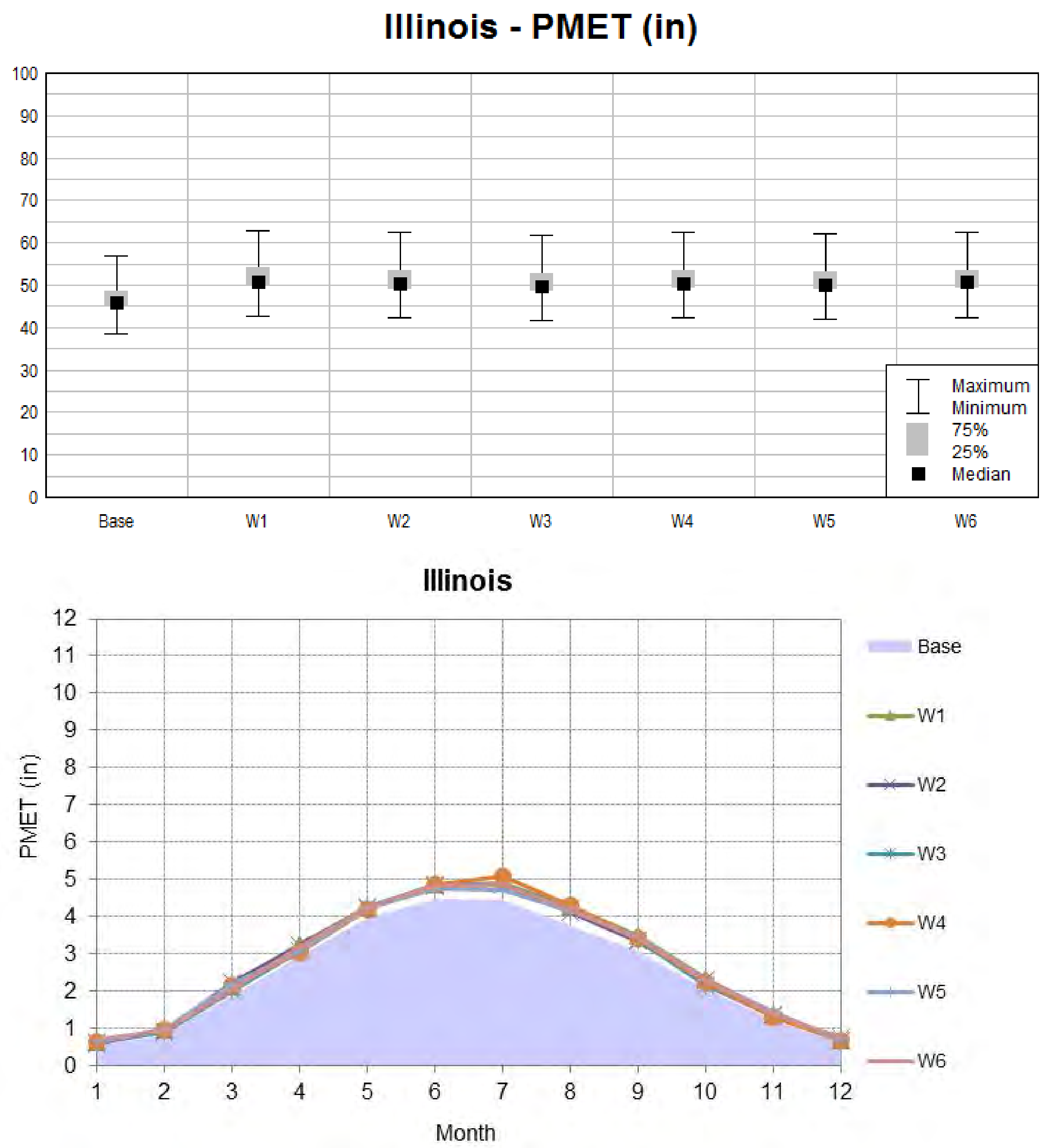
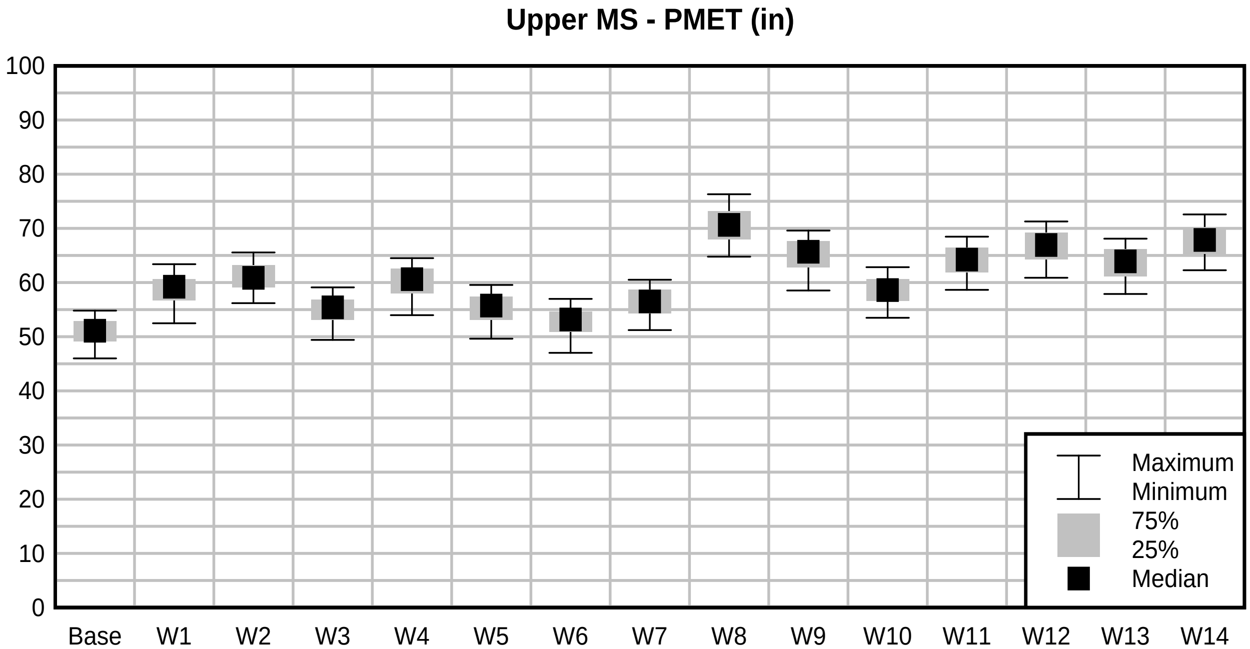


Figure Z-47. Illin: Comparison of climate scenario Penman-Monteith reference ET for the Illinois River basin

Note: See Table Z-1 for key to climate scenarios.



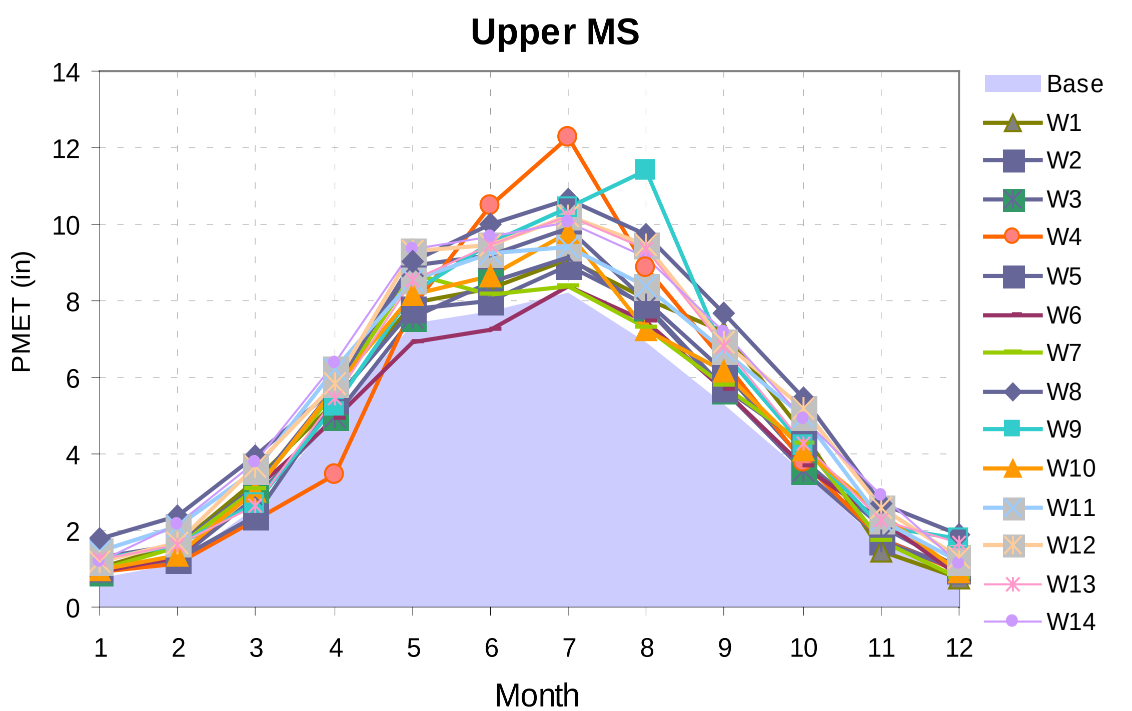
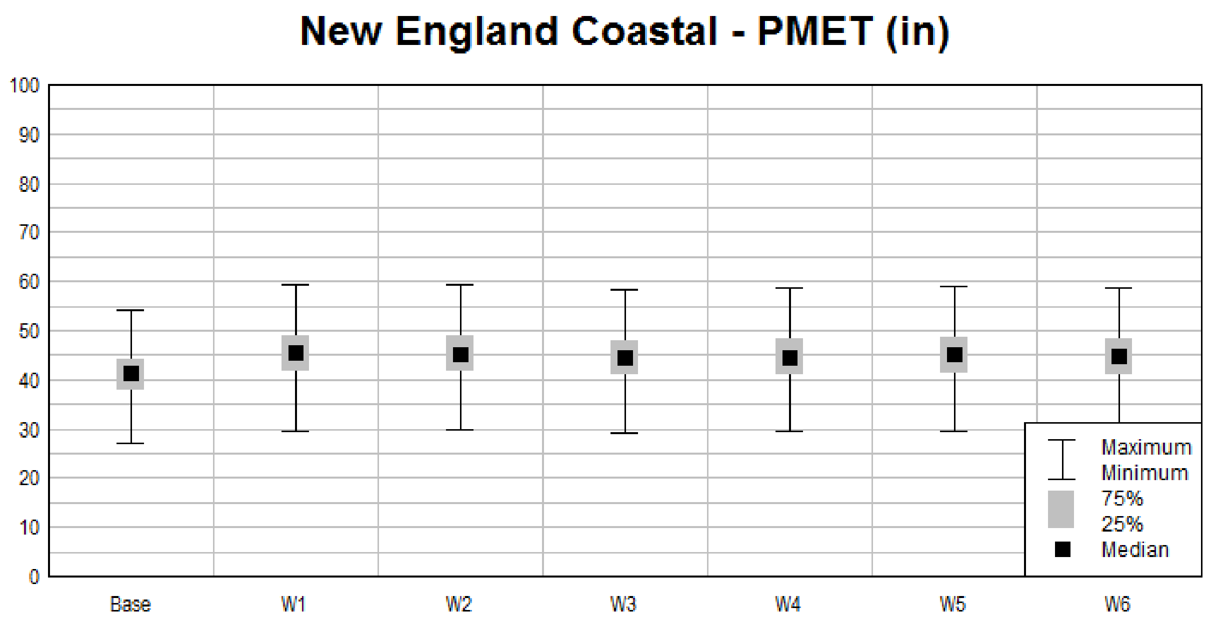


Figure Z-48. Minn: Comparison of climate scenario Penman-Monteith reference ET for the Minnesota River (Upper Mississippi) basin

Note: See Table Z-1 for key to climate scenarios.



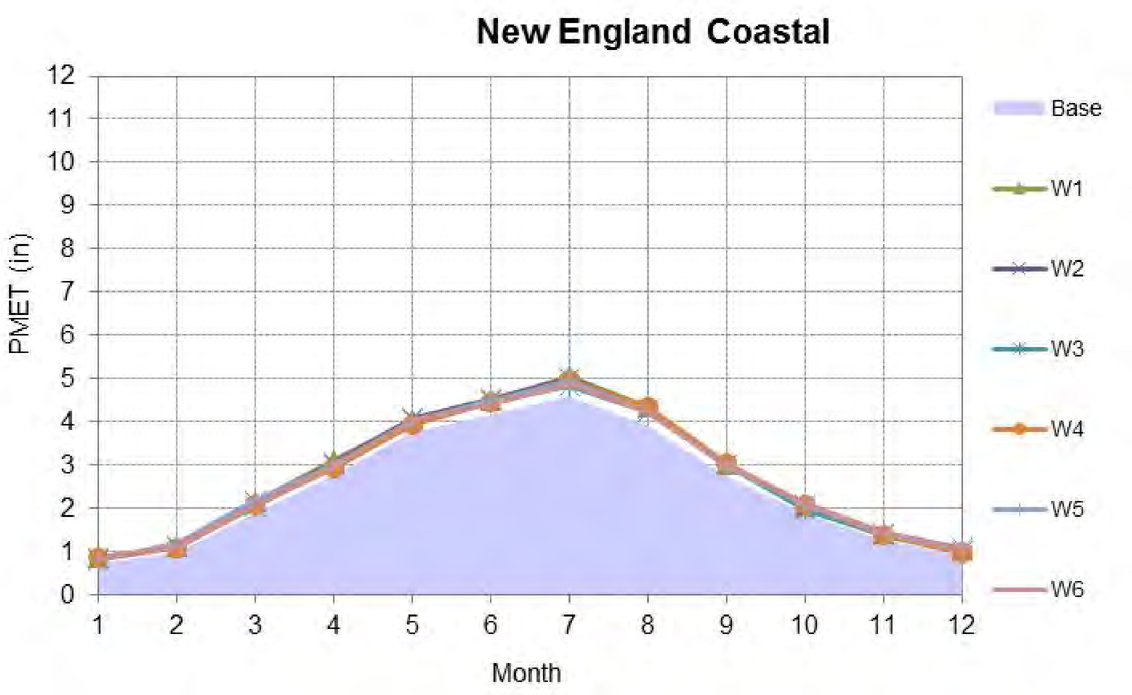
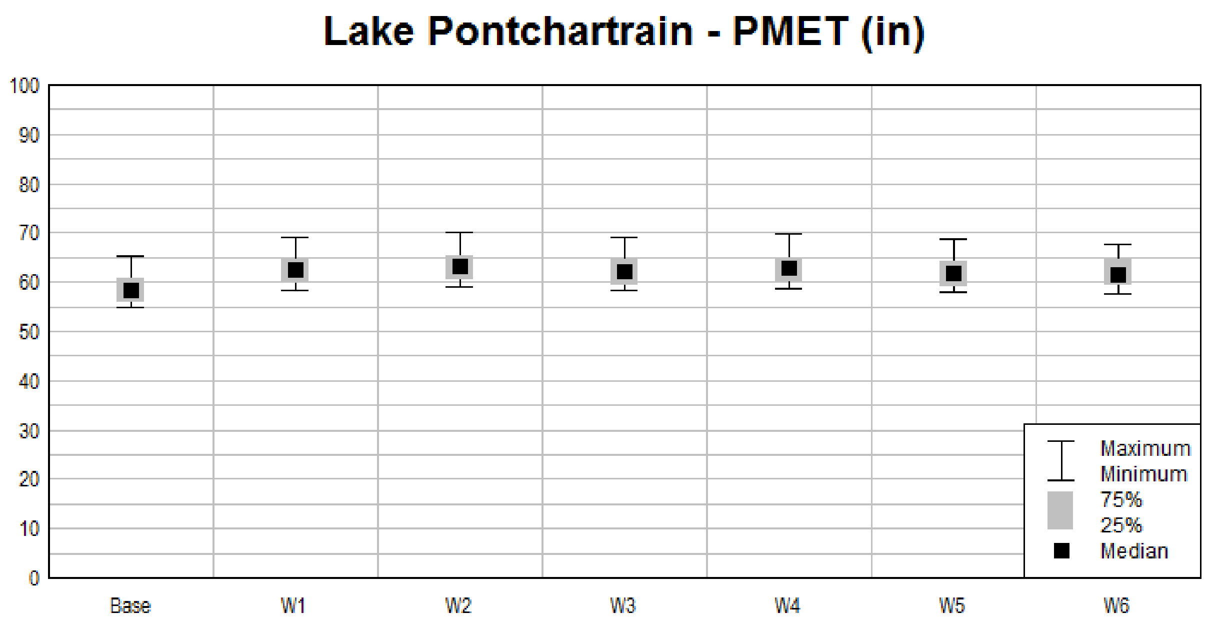


Figure Z-49. NewEng: Comparison of climate scenario Penman-Monteith reference ET for the New England Coastal basins

Note: See Table Z-1 for key to climate scenarios.



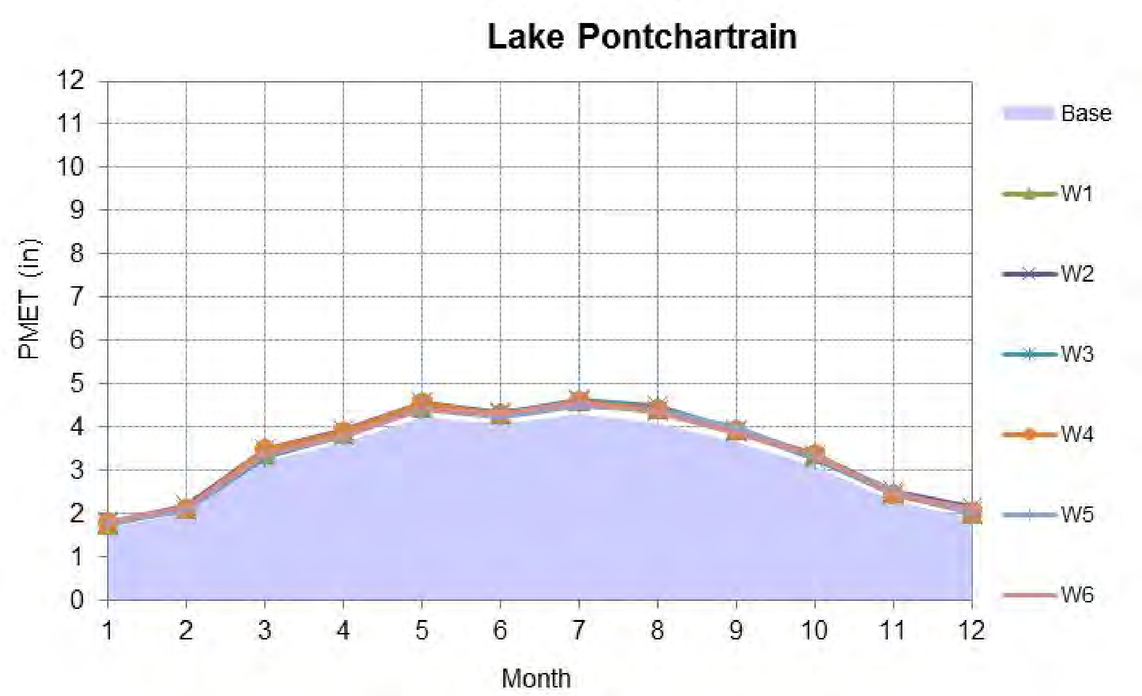
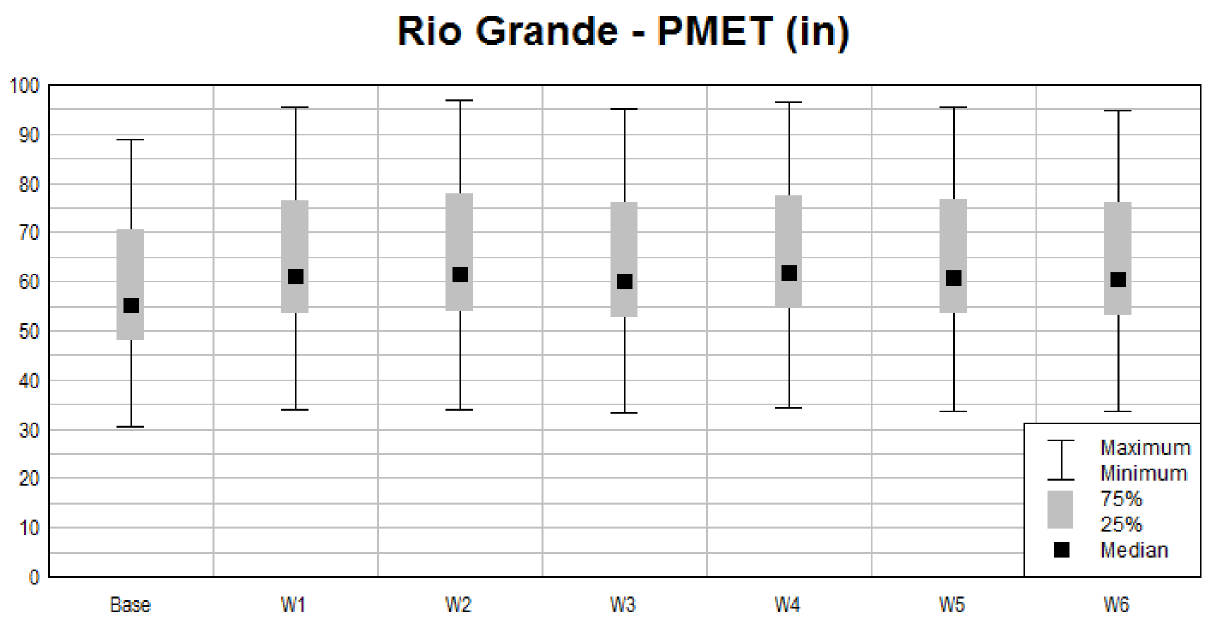


Figure Z-50. Pont: Comparison of climate scenario Penman-Monteith reference ET for the Lake Pontchartrain drainage

Note: See Table Z-1 for key to climate scenarios.



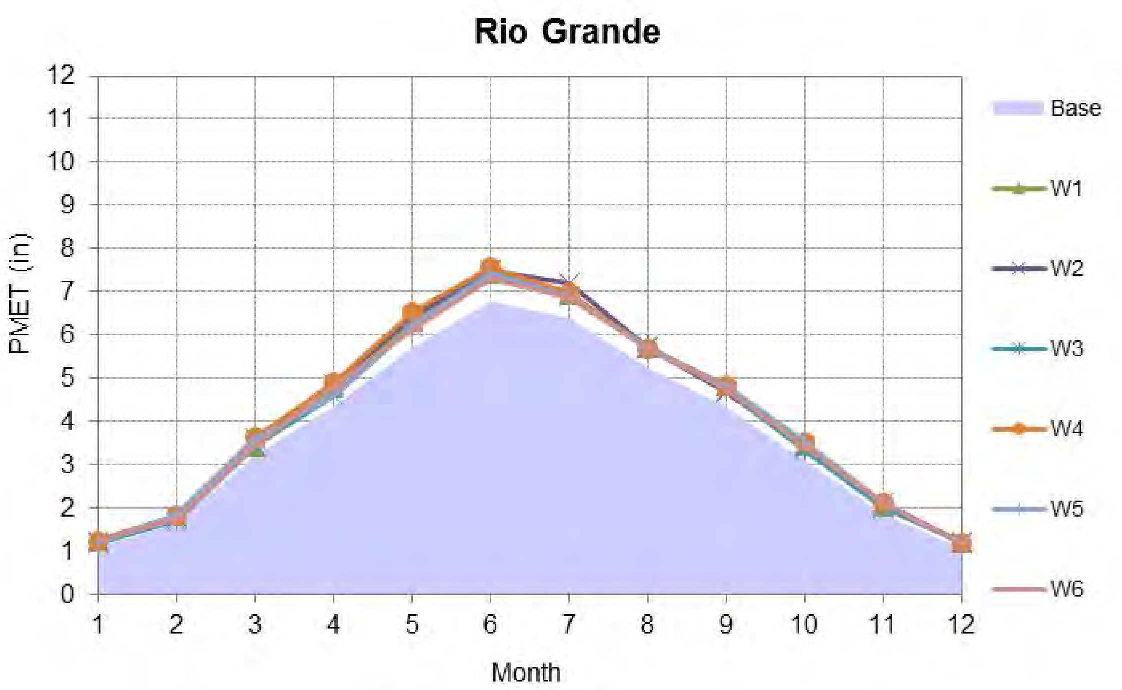


Figure Z-51. RioGra: Comparison of climate scenario Penman-Monteith reference ET for the Rio Grande Valley

Note: See Table Z-1 for key to climate scenarios.

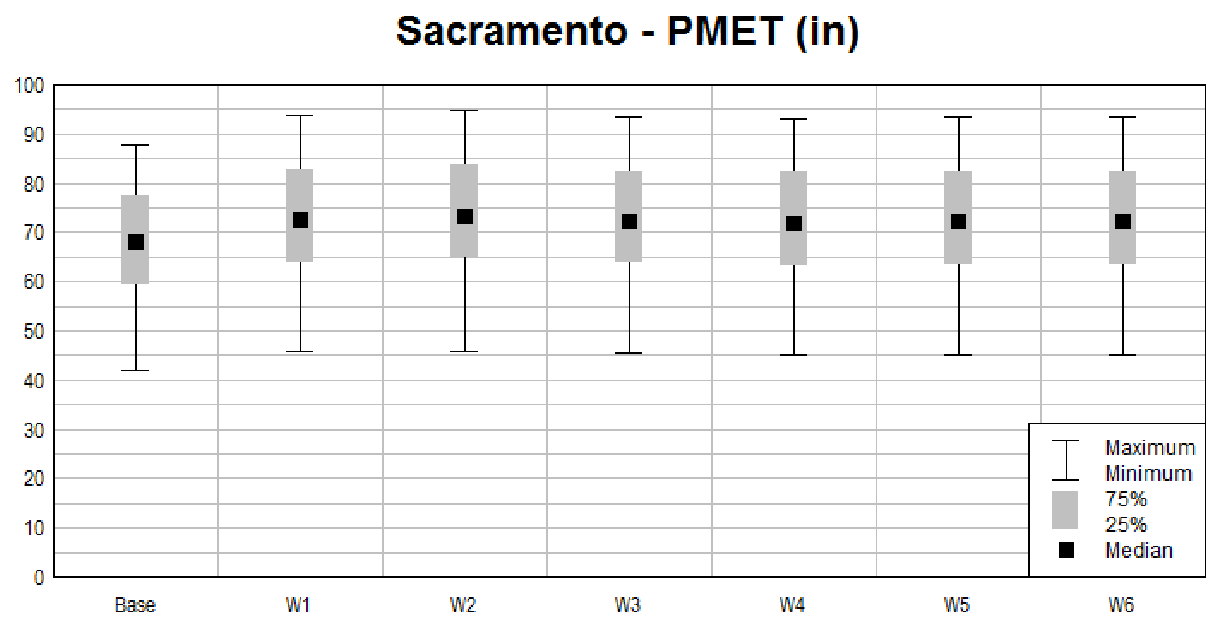
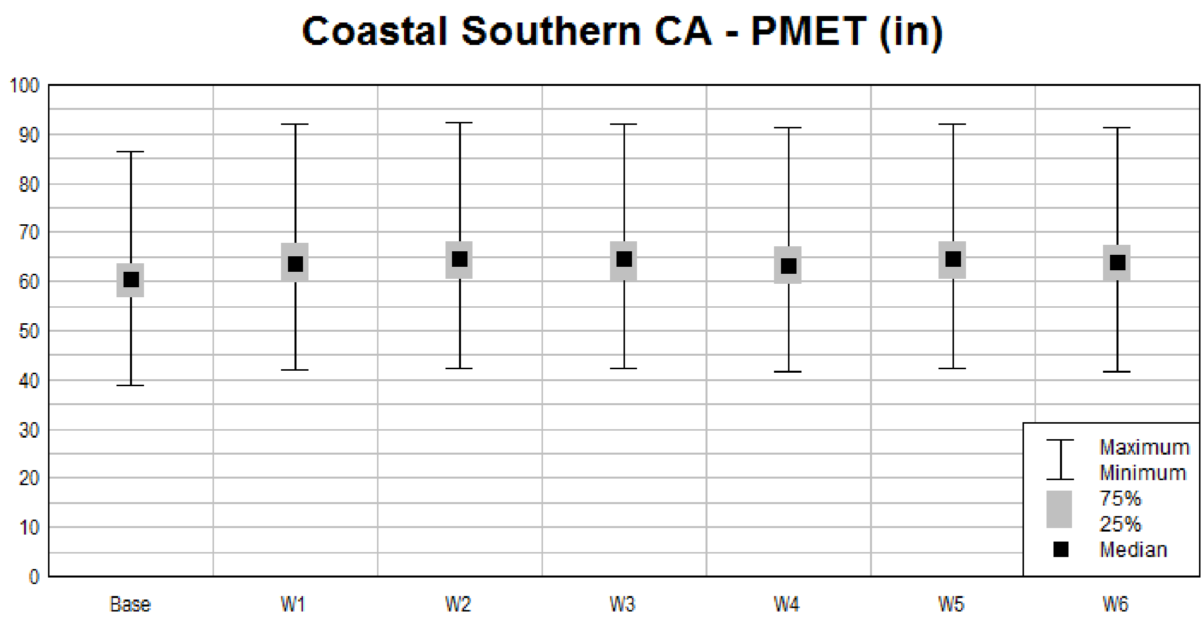


Figure Z-52. Sac: Comparison of climate scenario Penman-Monteith reference ET for the Sacramento River basin

Note: See Table Z-1 for key to climate scenarios.



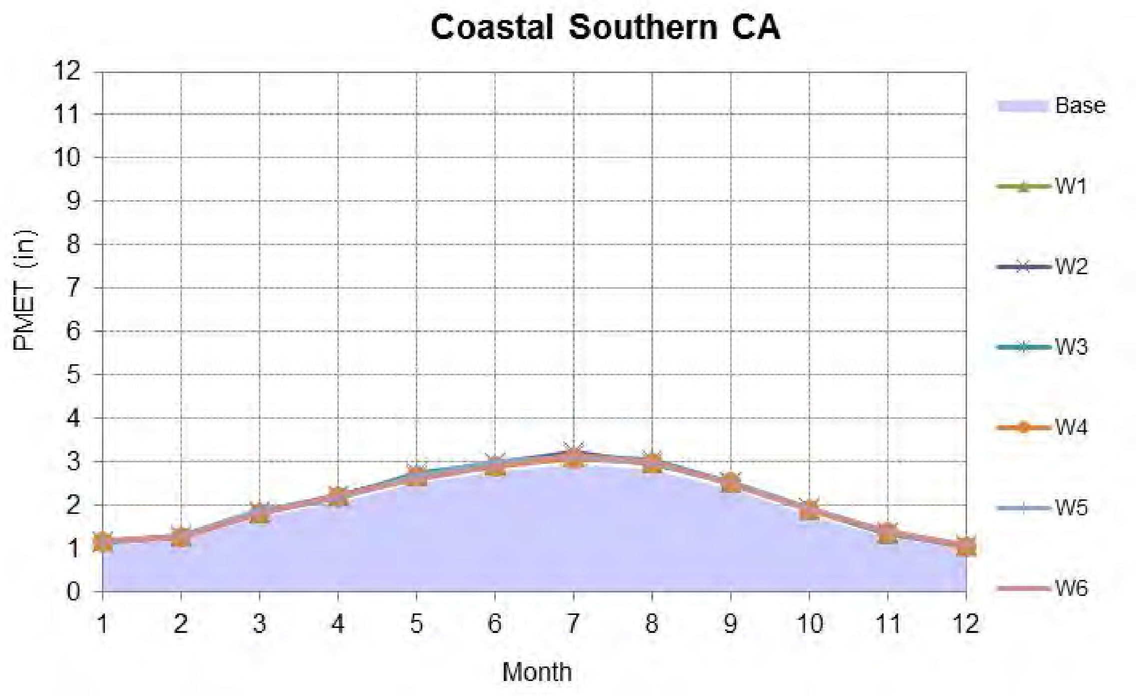
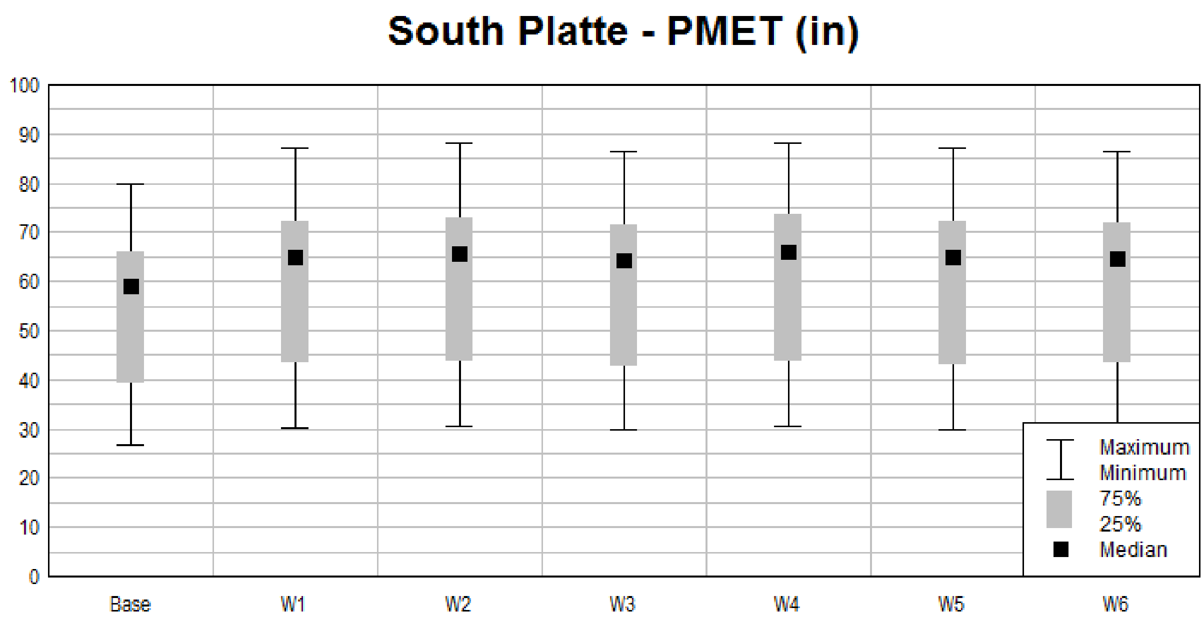


Figure Z-53. SoCal: Comparison of climate scenario Penman-Monteith reference ET for the Coastal Southern California basins

Note: See Table Z-1 for key to climate scenarios.



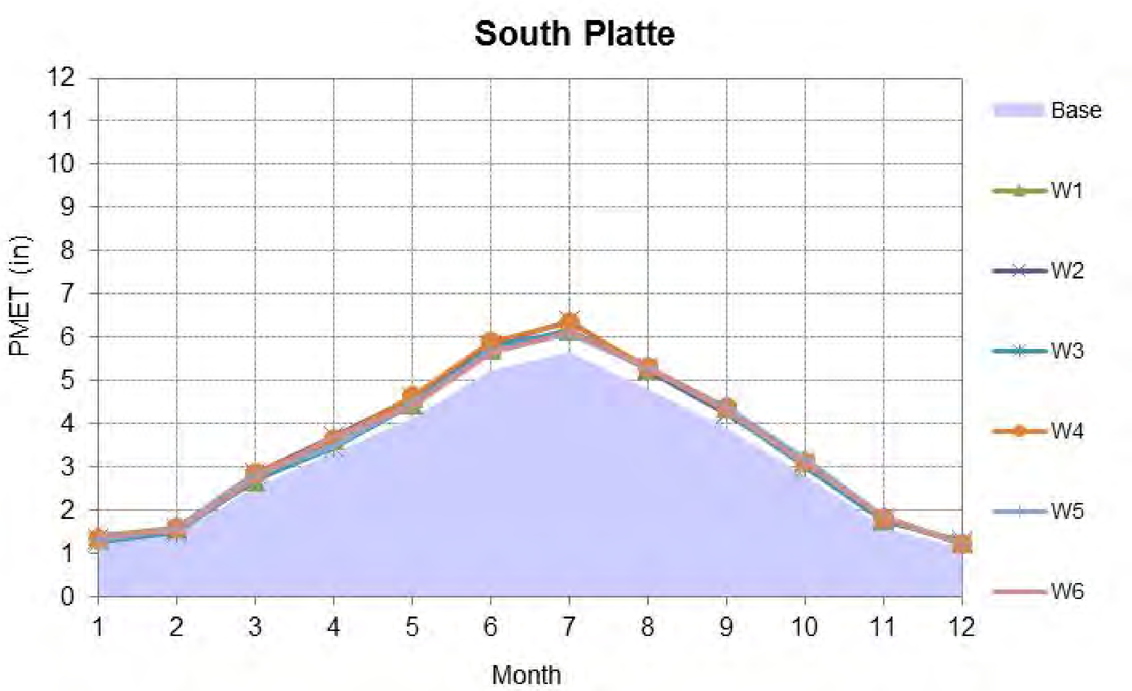
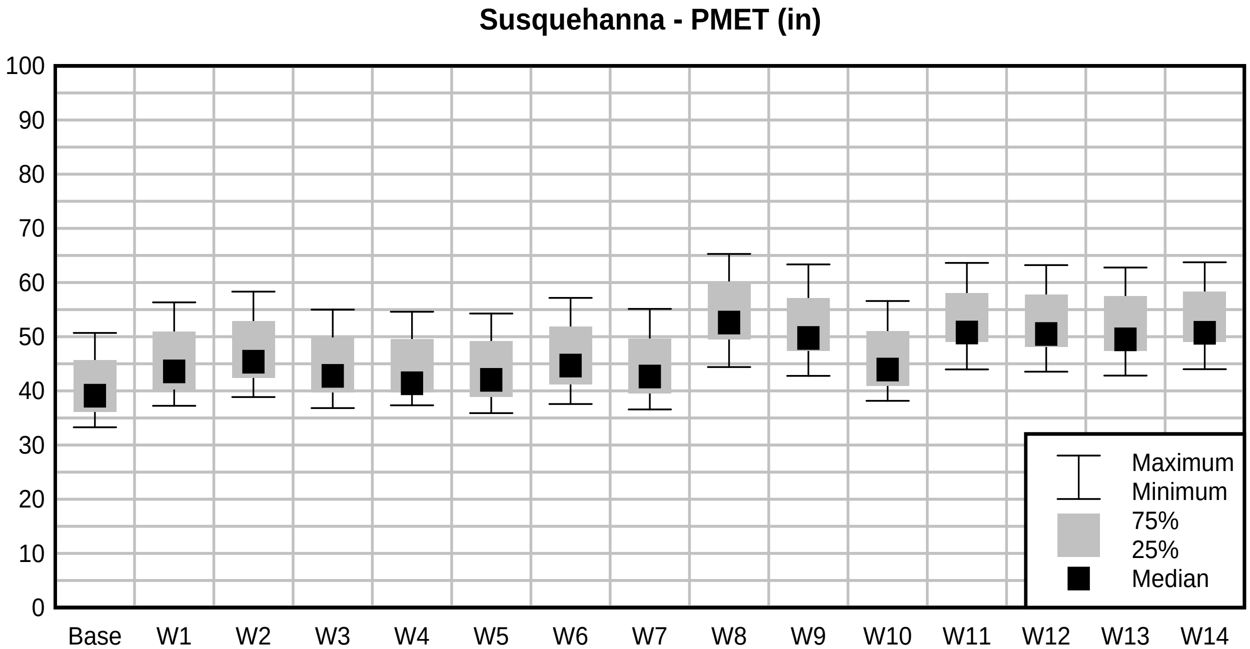


Figure Z-54. SoPlat: Comparison of climate scenario Penman-Monteith reference ET for the South Platte River basin

Note: See Table Z-1 for key to climate scenarios.



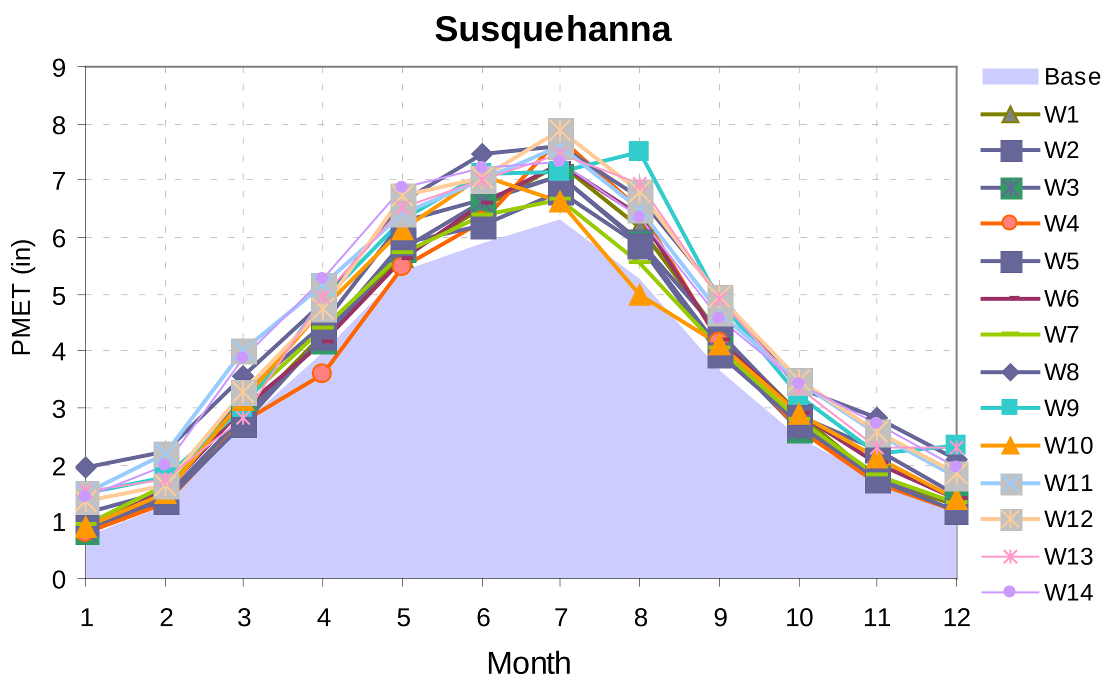


Figure Z-55. Susq: Comparison of climate scenario Penman-Monteith reference ET for the Susquehanna River basin

Note: See Table Z-1 for key to climate scenarios.

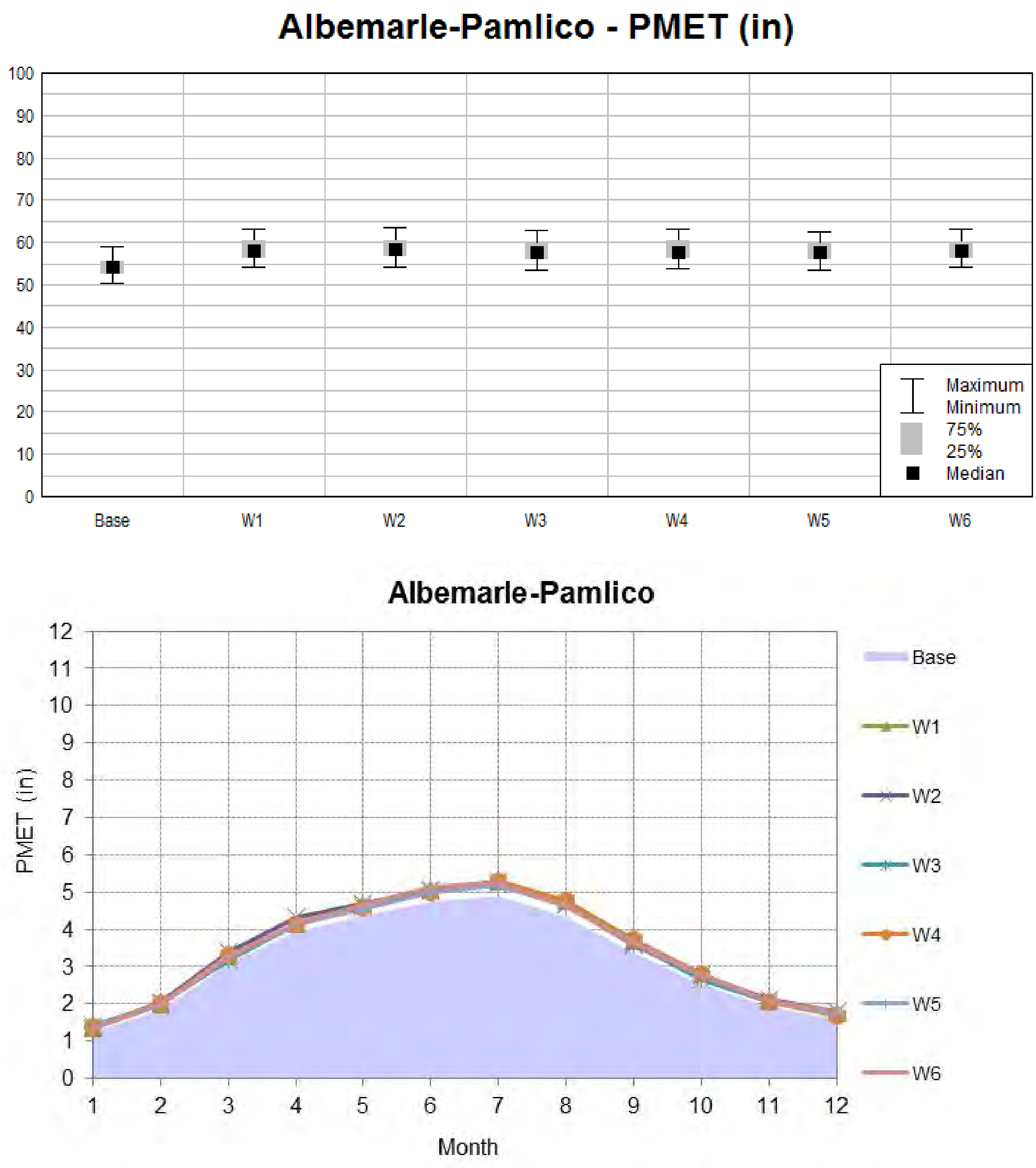
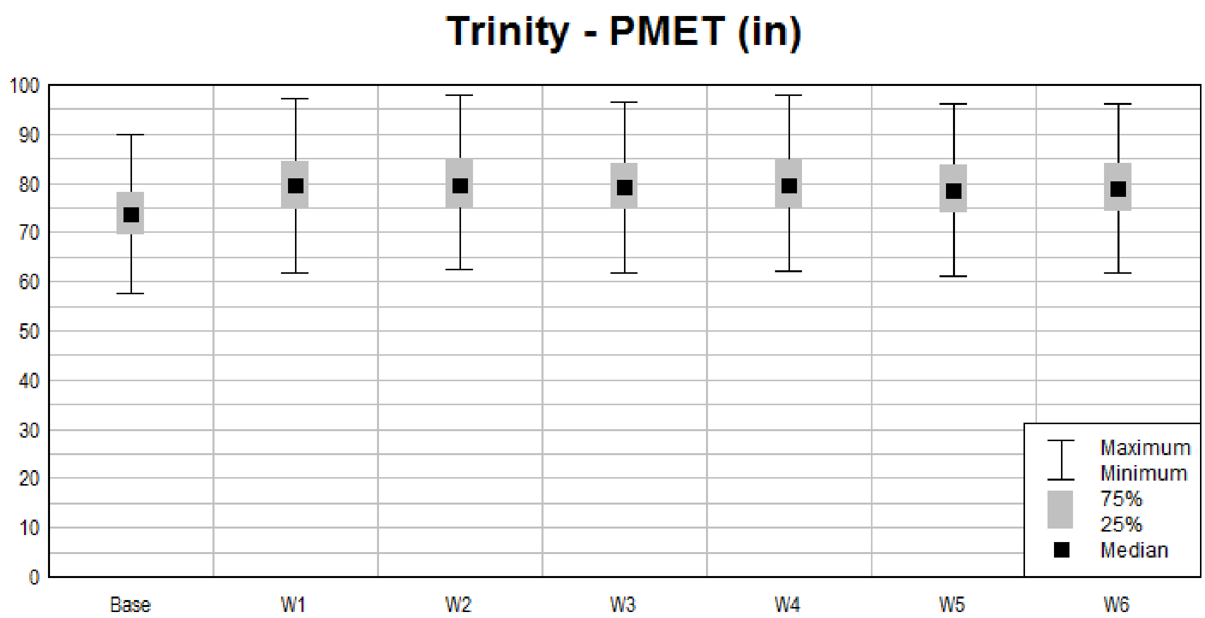


Figure Z-56. TarNeu: Comparison of climate scenario Penman-Monteith reference ET for the Tar and Neuse River basins

Note: See Table Z-1 for key to climate scenarios.



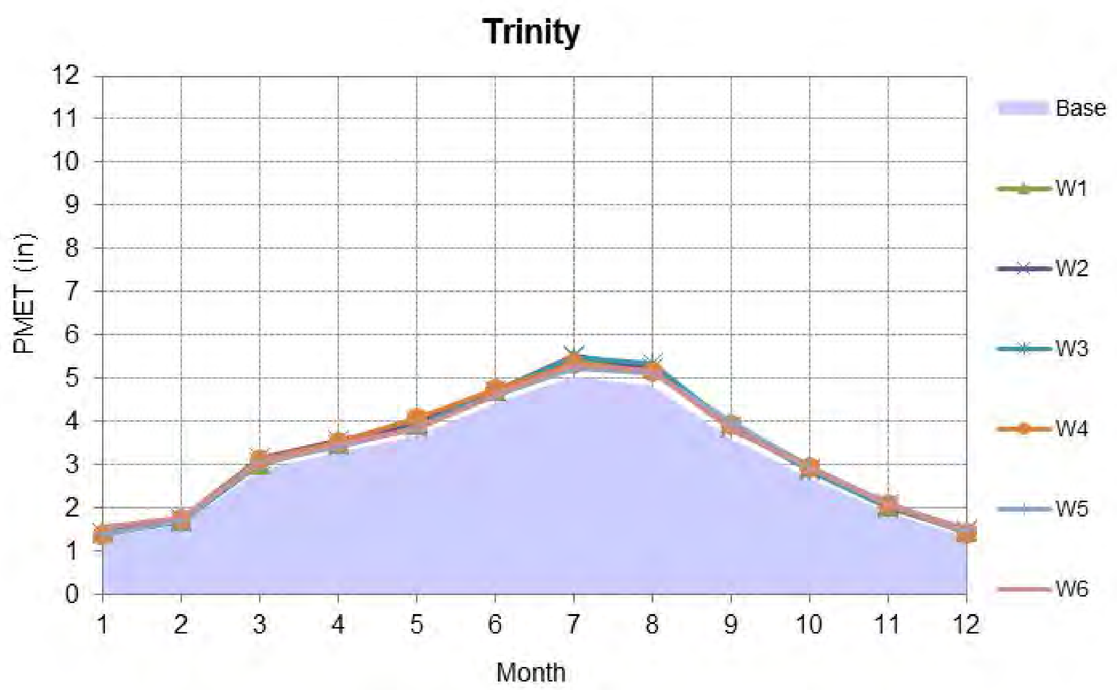


Figure Z-57. Trin: Comparison of climate scenario Penman-Monteith reference ET for the Trinity River basin

Note: See Table Z-1 for key to climate scenarios.

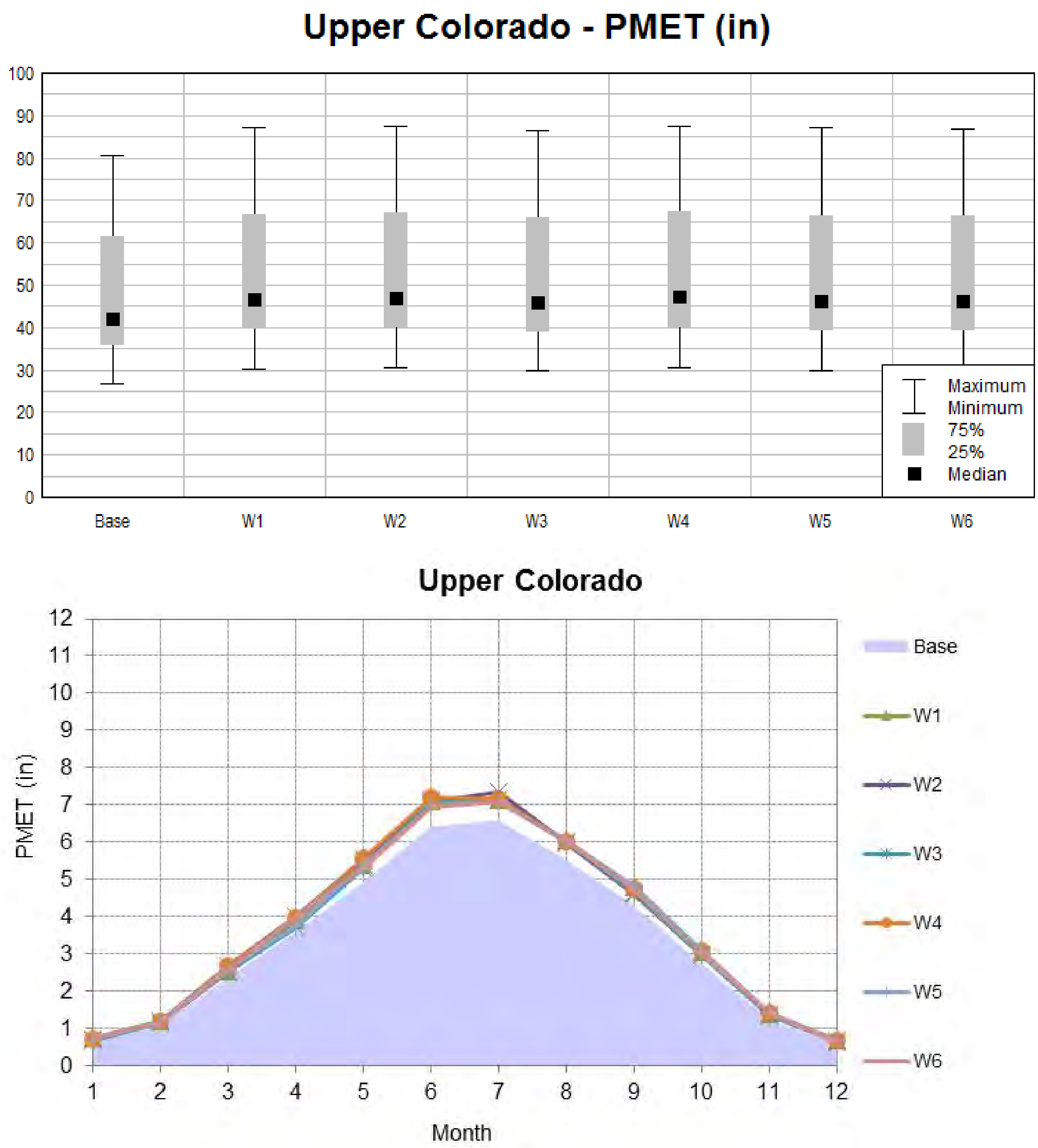
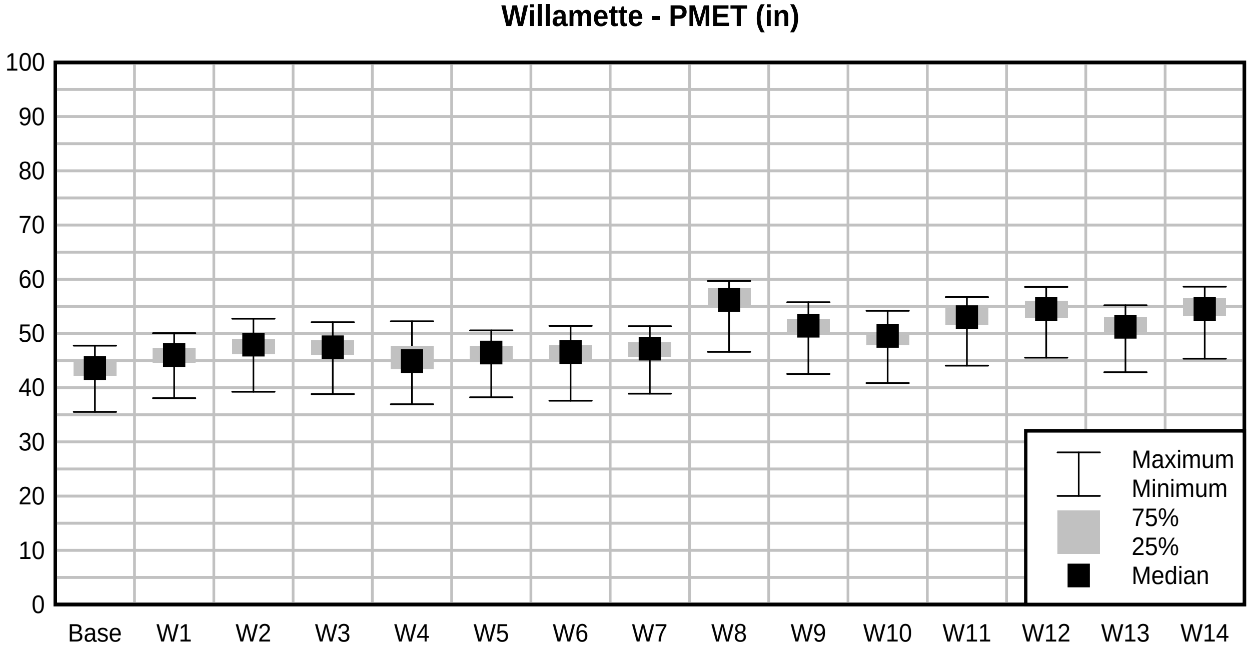


Figure Z-58. UppCol: Comparison of climate scenario Penman-Monteith reference ET for the Upper Colorado basin

Note: See Table Z-1 for key to climate scenarios.



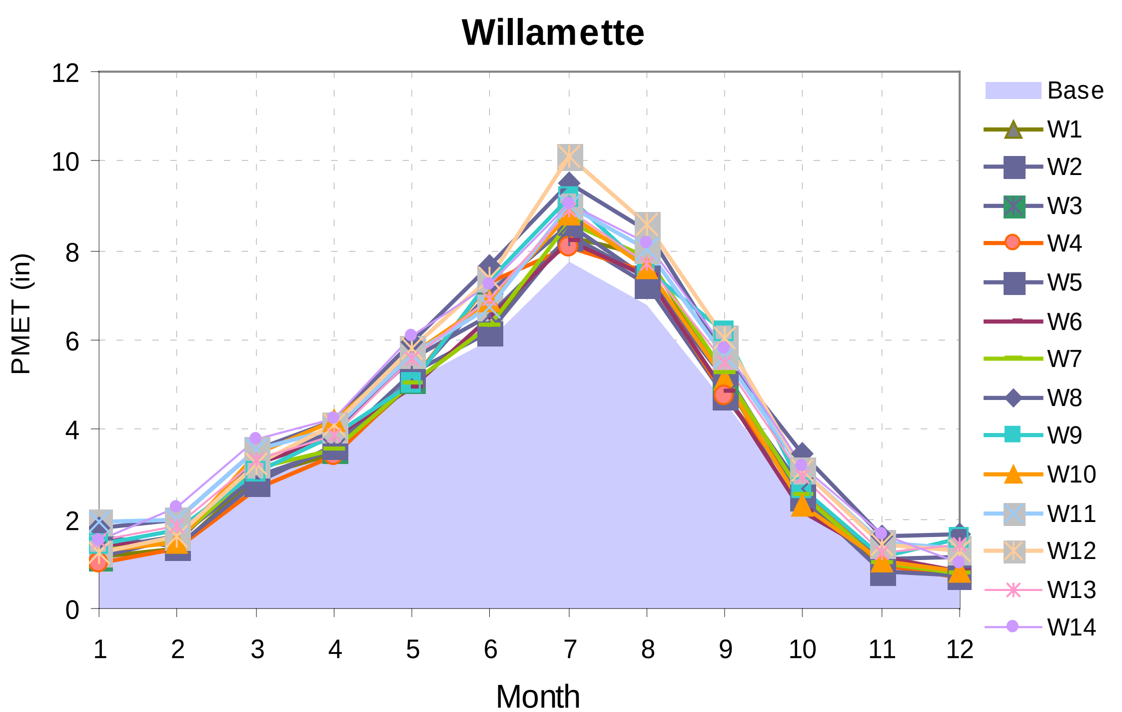
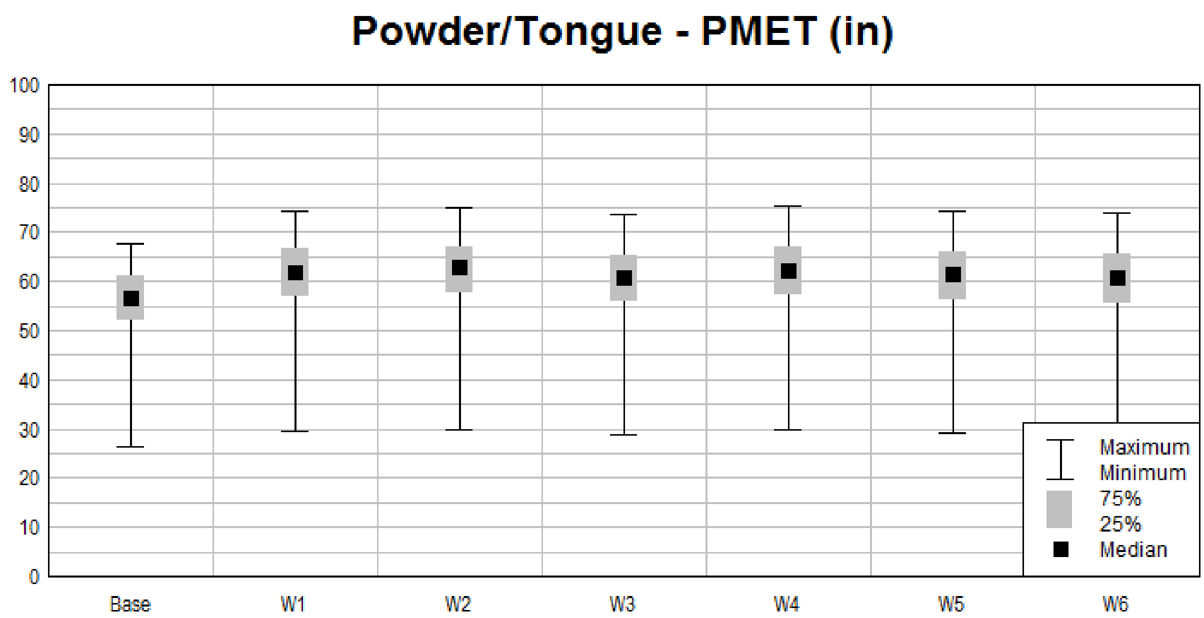


Figure Z-59. Willa: Comparison of climate scenario Penman-Monteith reference ET for the Willamette River basin

Note: See Table Z-1 for key to climate scenarios.



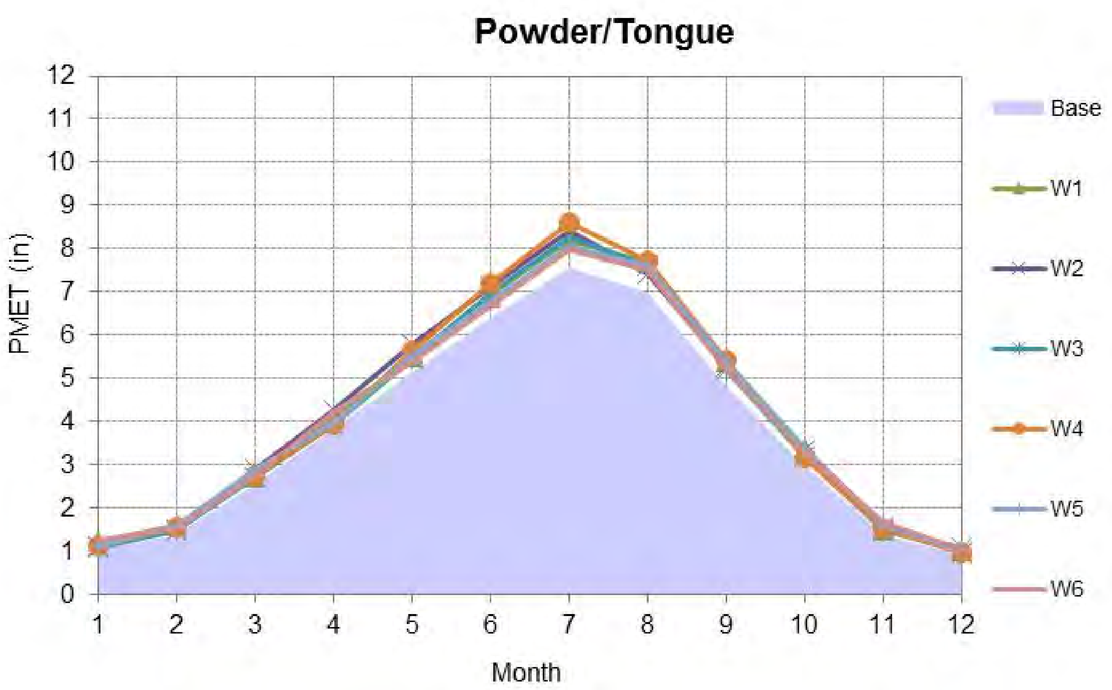


Figure Z-60. Yellow: Comparison of climate scenario Penman-Monteith reference ET for the Powder/Tongue River basins

Note: See Table Z-1 for key to climate scenarios.