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Office of Water
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Prepared jointly by:

The U.S. Environmental Protection Agency
Health and Ecological Criteria Division (Office of Science and Technology)

and

Wetlands Division (Office of Wetlands, Oceans, and Watersheds)

Notice

The material in this document has been subjected to U.S. Environmental Protection Agency (EPA) technical review and has been approved for publication as an EPA document. The information contained herein is offered to the reader as a review of the "state of the science" concerning wetland bioassessment and nutrient enrichment and is not intended to be prescriptive guidance or firm advice. Mention of trade names, products or services does not convey, and should not be interpreted as conveying official EPA approval, endorsement, or recommendation.

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This entire document can be downloaded from the following U.S. EPA websites:

http://www.epa.gov/water science/criteria/wetlands/

http://www.epa.gov/owow/wetlands/bawwg/publicat.html

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Foreword

In 1999, the U.S. Environmental Protection Agency (EPA) began work on this series of reports entitled *Methods for Evaluating Wetland Condition*. The purpose of these reports is to help States and Tribes develop methods to evaluate (1) the overall ecological condition of wetlands using biological assessments and (2) nutrient enrichment of wetlands, which is one of the primary stressors damaging wetlands in many parts of the country. This information is intended to serve as a starting point for States and Tribes to eventually establish biological and nutrient water quality criteria specifically refined for wetland waterbodies.

This purpose was to be accomplished by providing a series of "state of the science" modules concerning wetland bioassessment as well as the nutrient enrichment of wetlands. The individual module format was used instead of one large publication to facilitate the addition of other reports as wetland science progresses and wetlands are further incorporated into water quality programs. Also, this modular approach allows EPA to revise reports without having to reprint them all. A list of the inaugural set of 20 modules can be found at the end of this section.

This last set of reports is the product of a collaborative effort between EPA's Health and Ecological Criteria Division of the Office of Science and Technology (OST) and the Wetlands Division of the Office of Wetlands, Oceans and Watersheds (OWOW). The reports were initiated with the support and oversight of Thomas J. Danielson then of OWOW, Amanda K. Parker and Susan K. Jackson (OST), and seen to completion by Ifeyinwa F. Davis (OST). EPA relied on the input and expertise of the contributing authors to publish the remaining modules.

More information about biological and nutrient criteria is available at the following EPA website:

http://www.epa.gov/ost/standards

More information about wetland biological assessments is available at the following EPA website:

http://www.epa.gov/owow/wetlands/bawwg

LIST OF "METHODS FOR EVALUATING WETLAND CONDITION" MODULES

Nutrient Loading

The purpose of this module is to describe and discuss the general hydrologic properties that make wetlands unique, and to provide an overview of the processes that control wetland hydrologic behavior. The intent is to provide a general discussion of wetland hydrologic processes and methods in the hope of fostering an understanding of the important attributes of wetland hydrology relevant to the monitoring and assessment of these systems. As such, it is not intended to address the narrower definition of wetland hydrology for jurisdictional or classification purposes. Also, this module should not replace more advanced wetland texts. If the need arises to obtain more specific information, the reader is advised to refer to wetland books or articles, including those referenced within this document.

Summary

Nutrient loading to wetlands is determined primarily by surface and subsurface transport from the contributing landscape, and varies significantly as a function of weather and landscape characteristics such as soils, topography, and land use. In the absence of sufficient measurements, nutrient loading can only be estimated using an appropriate loading model. This module provides an overview of hydrologic and contaminant transport models that can be used to estimate nutrient loads to wetlands.

Purpose

The purpose of this module is to provide an overview of hydrologic and contaminant transport models that can be used to estimate nutrient loads to wetlands.

Introduction

Over the past three decades, considerable effort has been expended in developing models to simulate watershed hydrology and nutrient transport, particularly the estimation of cumulative field/watershed contributions of flow, sediment, nutrients, and other contaminants of interest. Appropriately used, existing models may apply when in evaluating wetland reference conditions or establishing nutrient criteria for wetlands or guiding management decisions once nutrient criteria are established.

Several reviews have summarized the characteristics, features, strengths, and limitations of models that are used for estimating watershed hydrology and water quality (Donigian, et al., et al. 1991b, 1995b; DeVries and Hromadka 1993; Novotny and Olem 1994; Tim 1996a, 1996b). These models vary widely in structure and in spatial and temporal scale, and can be classified as (i) empirical or semi-empirical loading function models and ii) process-oriented simulation models.

Loading Function Models

Loading function models are based on empirical or semi-empirical relationships that provide estimates of pollutant loads based on long-term measurements of flow and contaminant concentration. They provide for rapid estimation of critical pollutant loads with minimal effort and data requirements. Loading function models are widely used to estimate pollutant loads in areas where limited data sets are available for process-based modeling. A major advantage of loading function models is their simplicity. Generally, loading function models contain procedures for estimating pollutant load based on either heuristics or on the empirical relationships between landscape physiographic characteristics and phenomena that control pollutant export.

McElroy et al. (1976) and Mills (1985) described components of several screening models developed by EPA's Environmental Research Laboratory at Athens, Georgia to facilitate estimation of nutrient loads from point and nonpoint sources and to enhance preliminary assessment of water quality. The model contains simple empirical expressions that relate the magnitude of nonpoint pollutant load to readily available or measurable input parameters such as soils, land use and land cover, land management practices, and topography. This model is attractive because it can be applied to very large watersheds often with minimal effort and little or no calibration is required.

Regression modeling, an approach based on statistical descriptions of historic flow and pollutant concentration data, is an alternative to the screening model Regression models are used to obtain preliminary estimates of pollutant load under limiting and incomplete data. These models require primary input parameters such as drainage area, percent imperviousness, mean annual precipitation, land use pattern, and ambient temperature. Regression models can determine storm-event mean pollutant load with confidence intervals for the estimated loads.

In addition to regression modeling, several less complex, process-based models have been used to estimate flow and contaminant transport in terrestrial environments. Examples of process-based models include the Generalized Watershed Loading Function (GWLF), the Spatially Referenced Regressions on Watersheds (SPARROW), and the Pollutant Load model (PLOAD).

GENERALIZED WATERSHED LOADING FUNCTION MODEL

The Generalized Watershed Loading Function Model (GWLF), developed at Cornell University, estimates stream flow, nutrient load and sediment load from watersheds management areas. The model allows simulation of point and nonpoint loadings of nutrients and pesticides from urban and agricultural watersheds, including septic systems. The model also provides data to evaluate the effectiveness of certain land use management practices. The GWLF is a temporally-continuous simulation model with daily time steps, but it is not spatially distributed. It simulates overland flow and channel flow using a water balance approach based on measurements of daily precipitation and average temperature. Precipitation is partitioned into direct surface runoff and infiltration using the SCS Curve

Number technique. Here, the Curve Number determines the amount of precipitation that runs off directly, adjusted for antecedent soil moisture based on total precipitation during the previous five days. A separate Curve Number is specified for each combination of land use types and soil hydrologic groups. The amount of water available to the shallow groundwater zone is influenced by evapo-transpiration. This is estimated in GWLF using the available moisture in the unsaturated zone, the evapo-transpiration potential, and a cover coefficient. Potential evapo-transpiration is estimated from a relationship to mean daily temperature and the number of daylight hours. GWLF calculates the groundwater discharge by performing a lumped parameter water balance on the saturated and shallow saturated zones.

Soil erosion is modeled by the Revised Universal Soil-loss Equation (RULSE). Nutrient fluxes in GWLF are estimated empirically using daily nutrient fluxes from surface runoff from pervious and impervious surfaces, sediment erosion, groundwater base-flow, and septic runoff. The monthly nutrient load is calculated by totaling the daily nutrient fluxes. In GWLF, the nitrogen and phosphorus loads from surface runoff are estimated by multiplying excess runoff by their flow-weighted average concentrations, respectively.

The model assumes that each specific land-cover type has unique event-mean-concentration processes that affect transport and storage, and are unique to the land use. The nutrient-loading model for urban land use is based on an accumulation/wash off model. Nutrient fluxes from impervious surfaces and urban lands are estimated using chemical build-up and wash-off parameterization. Both nitrogen and phosphorus from eroded sediments are estimated using the sediment load, enrichment ratio, and the concentration of nitrogen and phosphorus in the top layer of the soil. As with many mid-range terrestrial models, GWLF calculates concentrations of dissolved and sediment-bound nitrogen and phosphorus in stream flow as the sum total of base flow, stream flow (overland flow) and point sources. Groundwater only contributes dissolved nitrogen and phosphorus values reflecting the effects of local land use. Nutrient losses in urban runoff are assumed to be entirely in the solid-phase, while point source losses are assumed to be dissolved.

The GWLF requires three categories of input parameters: meteorological; hydrology and landscape; and chemical and biophysical (see Table 1). The model requires daily precipitation and temperature. The GWLF also requires information related to land use, land cover, soil, and parameters that govern runoff, erosion, and nutrient load generation. The strength of GWLF model is that data required by this model are readily available from most resource management agency databases.

In general, GWLF is an empirically derived, statistically based process that uses daily inputs of precipitation and temperatures to compute nutrient fluxes. A major strength of GWLF is its simplicity in estimating pollutant load. Because of this, the model has been used for screening landscapes according to their pollutant delivery potentials or for identifying critical areas of nonpoint pollution. However, it does not account for rainfall intensity or storage along channels. Because it uses a simplified technique for estimating base flow, the model cannot reproduce the precise history of overland flow and fluxes as

TABLE 1: INPUT PARAMETERS REQUIRED BY GWLF MODEL

1.Meteorological:	
	Precipitation
	Temperature
2.Hydrology and Landscape:	
	Basin/watershed size
	Land use and land cover distribution
	Curve Number by source area
	USLE factors by source area
	ET cover coefficient
	Erosivity coefficients
	Daylight hours by month
	Growing season months
	Initial saturated storage
	Initial unsaturated storage
	Recession coefficient
	Seepage coefficient
	Initial snow amount
	Sediment delivery ratio
	Soil water available capacity
3.Chemical and Biophysical:	
	Dissolved N and P in runoff by land cover type
	N and P concentrations in manure runoff
	N and P buildup in urban areas
	N and P from point sources
	Background N and P in groundwater
	Background N and P in top soil layer
	Duration of manure spreading
	Population on septic systems
	Per capita septic system loads for N and P

do event-based models. It can, however, reproduce the frequency and magnitude of monthly nutrient fluxes from undisturbed watersheds. The GWLF model does not have a sufficiently long history of application and may not be applicable to land areas with a high degree of altered hydrology.

SPATIALLY REFERENCED REGRESSIONS ON WATERSHEDS

As described in Preston and Brakebill (1999) the Spatially Referenced Regressions on Watersheds (SPARROW) model was developed to relate the water quality conditions within a watershed to sources of nutrients as well as those factors that influence transport of the nutrients. Developed specifically for conditions within the Chesapeake Bay watershed, the SPARROW methodology utilizes statistical techniques and spatially distributed landscape data to estimate nutrient loads. Specifically, the SPARROW methodology was designed to provide statistically based relationships between water quality and anthropogenic factors (e.g., sources of contamination within the watershed), land surface characteristics that influence delivery of pollutants to the stream, and in-stream transformation of pollutants through chemical and biological pathways. The general form of the statistical regression model for SPARROW is (Preston and Brakebill 1999):

$$L_i = \sum_{n=1}^{N} \sum_{j \epsilon J(i)} \beta_n S_{n,j} \exp(-\alpha' z_j) \exp(-\delta' T_{i,j})$$

in which L_i = nutrient load in stream reach i; n, N = pollutant source index; N = total number of sources; J(i) = number of upstream stream reaches; $ß_n$ = estimated source parameter; $S_{n,j}$ = contaminant mass from source n in drainage to reach j; α = estimated vector of land-to-water delivery parameters; z_j = land surface characteristics associated with drainage reach j (e.g., temperature, slope, stream density, irrigated land, precipitation, and wetland); δ = estimated vector of in-stream loss parameter; and $T_{i,j}$ = channel transport characteristics. The source parameter β consists of point sources, nutrient applications in the form of animal manure, commercial fertilizer, and atmospheric deposition of pollutants. The parameter, α, determines the relative influence of different types of land-surface characteristics on the delivery of nutrients from land surfaces to stream channels.

The literature reports a number of applications of SPARROW model, primarily applied to the Chesapeake Bay ecosystem. These articles document water quality conditions and assess the effectiveness of best management practices in controlling nonpoint pollution. The results provided the basis for not only delineating watershed areas that are most critical to the export of nutrients, but also for targeting and prioritizing remedial control strategies and conservation programs (Smith, et al. 1997).

MIDRANGE MODELS

In addition to the GWLF and SPARROW models described above, other modeling approaches utilize a compromise between empiricism and more complex mechanistic approaches. Typical examples of such models include the Stormwater Intercept and Treatment Evaluation Model for Analysis and Planning (SITEMAP) (Omnicron Associates 1990) and Pollutant Load model or PLOAD. These models use daily time steps. Both can be used to examine seasonal variability and the load response to landscape characteristics of specific watersheds. Due to their complexity, they may have greater data requirements and may require more site-specific data.

SITEMAP is a dynamic simulation model developed to assist with simulating stream segment waste-load allocations from point and non-point sources. This model calculates daily runoff and pollutant loading and can be used for storm-event or continuous simulations (including probability distributions) of runoff, pollutant loads, infiltration, soil moisture, and evapo-transpiration. SITEMAP can be used in either single or mixed land uses, and for event-based or continuous simulation of surface runoff and pollutant load. Users of the model are able to assess the effectiveness of alternative management strategies and to estimate load and waste-load from point and nonpoint sources, respectively. The primary outputs from the model include probabilistic estimates of runoff volume and nutrient loadings. A typical example application of SITEMAP involved the assessment of pollutant load and surface runoff in the Tualatin River Basin and Fairview Creek watershed in Oregon.

PLOAD is a simplified GIS-based watershed-loading model. It can model combined point and non-point source loads in either small urban areas or in rural watersheds of any size. As a loading model, PLOAD provides annualized estimates of pollutant export to waterbodies. Pollutants most commonly analyzed include sediments (TSS and TDS), oxygen demand (BOD and COD), nutrients (nitrogen, nitrate plus nitrite, TKN, ammonia, phosphorous), metals (lead, zinc) and bacteria (fecal coliform), or any other user-specified pollutant. The model addresses pollutant loading by land use categories and sub-watersheds, but does not as certain individual non-point sources or at actual pollutant fate and transport processes. Additional features of the model include: (i) the ability to estimate average annual pollutant load, (ii) a user-friendly interface that enhances manipulation of input parameters and the assessment of alternative pollution control strategies, (iii) tools to facilitate evaluation of land use change impacts, and (iv) the ability to generate outputs at user-defined formats.

To use the PLOAD model, users are required to provide reasonably accurate values of input parameters describing watershed land use and land cover, pollutant loading functions—based on land cover types, location of point source inputs, land areas with specified BMPs, and other general watershed characteristics. When supplied with these input variables, PLOAD generates outputs that include average annual loads, aggregated by sub-watershed, and reported in tables and maps of loads by watershed. In addition, users of PLOAD can view and compare multiple loading scenarios simultaneously.

The PLOAD is a part of the comprehensive modeling tools in the EPA's Better Assessment Science Integrating Point and Nonpoint Sources (BASINS). The literature also reports the applications of the PLOAD model for assessing the effects of land use change and BMPs for watersheds in North Carolina and Maryland.

SUMMARY OF LOADING FUNCTION MODELS

In summary, the many and diverse loading function models developed to allow estimation of point and non-point source pollution loads are based on simplistic, functional and empirical expressions that integrate flow and pollutant concentration. Attractive features of these models are that they: (i) require very limited data and computer modeling experience; (ii) contain relatively simple procedures for estimating pollutant load; and, (iii) provide tools for rapid assessment of point and non-point contributions to the watershed pollutant load. However, these advantages come at some expense regarding accuracy, nature of environmental process and conceptualization of the physical system. In particular, most loading function models fail to incorporate the complex, nonlinear biogeochemical and physical processes that influence the physical system. Furthermore, loading function models are limited in how spatial and temporal processes are handled and how landscape variability is characterized. Despite these limitations, there are situations in which these models are logical and legitimate.

Process-Oriented Models

In contrast to the empirical and simplified loading function models described above, process-oriented simulation models integrate knowledge of physical, chemical, and biological processes with empirical data, and allow users to evaluate interactions among human, economic and societal factors. This section provides an overview of some of the process-oriented simulation models that have been used to predict watershed hydrology and water quality, and that could provide modeling tools for predicting nutrient loading to wetlands. These models include AGNPS and AnnAGNPS, HEC-HMS, HEC-5Q, HSPF, STORM, SWAT, SWMM, and SWRRB models.

AGRICULTURAL NONPOINT SOURCE MODEL

The Agricultural Non-Point Source Pollution Model (AGNPS) is event-based, as well as a continuous or annualized AGNPS (AnnAGNPS) simulation model. These models predict surface runoff, sediment yield, and nutrient transport primarily from agricultural watersheds. The two main nutrients simulated are nitrogen and phosphorus, which are essential plant nutrients and are major contributors to eutrophication and surface water pollution. The basic model components include hydrology, erosion, sediment, and chemical transport (primarily nutrients and pesticides). The model also considers point sources of water, sediment, nutrients, and chemical oxygen demand (COD from various sources including feedlots). Water impoundments are also considered as depositional areas for sediment-associated nutrients. The model also has the ability to output water quality characteristics at intermediate or user-defined points throughout the watershed stream network.

The AGNPS model uses a grid-cell-based subdivision of the watershed, in which each cell is considered homogeneous. The cells are linked together through the aspect or flow direction, and all watershed characteristics and primary biophysical inputs are expressed at the grid-cell level. The components of the model use equations and methodologies that have been well established in the water quality modeling literature and are extensively used by resource management agencies. For example, the runoff volume is estimated using the SCS curve number technique. The peak runoff rate for each grid-cell is estimated using an empirical relationship in the CREAMS model (Knisel 1980). Soil erosion and sediment yield are computed by using the USLE and a bedload equation, a relationship—developed by Foster et al. (1981) based on the continuity equation. In the model, feedlots are treated as point sources and pollutant contributions from these sources are estimated by using the feedlot pollution model developed by Young (1982). Other point sources are accounted for by incorporating incoming flow rates and concentrations of nutrients to the cells where they occur.

In the AGNPS model, the resolution for the individual grid cells can range from 2.5 acres to greater than 40 acres (or 1 ha to more than 10 ha) depending on the problem being addressed, the size and complexity of the watershed, and the technical expertise of the modeler. Smaller grid-cell sizes such as 10 acres (4 ha) are recommended for watershed less than 2000 acres (800 ha). However,

TABLE 2: INPUT PARAMETERS REQUIRED BY AGNPS MODEL

Watershed-level Input Parameters:
Watershed identification
Cell area (Acres)
Total number of grid cells
Precipitation (inches)
Energy-Intensity
Storm type
Cell-level Input Parameters:
Cell number
Aspect
SCS Curve Number
Average land slope (°o)
Slope shape factor (uniform, convex, concave)
Average field slope length
Manning roughness coefficient
Soil erodibility factor (K-USLE)
Cropping factor (C-USLE)
Practice (P-USLE)
Surface condition constant
Soil texture (sand, silt, clay, peat)
Fertilization level
Fertilization availability factor
Point source indication
Gully source level
Chemical oxygen demand factor

for watershed and catchments that are larger than 2000 acres (800 ha), grid-cell sizes of 40 acres (16 ha) are normally used. The calculation of flow and transport processes in AGNPS occurs in three stages based on a set of twenty or more parameters for each grid cell, with the initial calculations for all cells in the watershed made in the first stage. The second stage calculates the runoff volume and sediment yield for each of the cells containing impoundments and the sediment yields for primary cells. A primary cell is one into which no other cell drains.

The non-point source pollution component of the model estimates transport and transformation of nitrogen, phosphorus, chemical oxygen demand, and pesticides. Pollutant transport is subdivided into soluble or dissolved phase and the sediment-attached or sediment-bound phase. Soluble nitrogen and phosphorus compounds are calculated using a relationship adapted from the CREAMS model (Knisel 1980); along with sediment yield equations taken from the CREAMS and the WEPP models. The input parameters for the AGNPS model include: cell number, receiving cell number, SCS curve number, land slope, field slope length, channel slope, channel side-slope, soil erodibility factor, cover and management factor, support practice factor, surface condition constant, aspect, and many other parameters related to land cover, land topography, management practices, and climate. The watershed-level parameters required include: area, area of each grid-cell, characteristics of storm precipitation, and storm energy-intensity. Table 2 summarizes the major input parameters required by the AGNPS model.

The AGNPS model is, by far one of the more widely used water quality models for estimating the relative effects of agricultural management practices in small to large watersheds. However, the model has many limitations, including: lack of process-level description of nutrient transformation processes or the biochemical cycling of major plant elements to document the biochemical cycling during transport; inability to characterize the transport and transformation of nutrients and pesticides in stream channels or similar waterbodies; inability to handle sub-surface flow and transport processes, as well as sub-surface interactions; the lack of a process to route flow or pollutants from individual grid-cells to the watershed outlet; and the model is event-based.

ANNUAL AGNPS

To eliminate some of these limiting factors, the AGNPS model has undergone numerous refinements. The term "AGNPS" now refers to the system of modeling components instead of the single-event AGNPS described above. These enhancements made to the event-based AGNPS of the 1980s and early 1990s are intended to improve the capability of the program and to automate many of the input data preparation steps needed for use with large watershed systems. The current version of the model is called AnnAGNPS, which is virtually the same computer program as AGNPS 5.*x* except that it allows for continuous simulations of surface runoff, peak flow rate, and pollutant transport for longer time periods and on a daily basis. AnnAGNPS is designed to handle watershed areas of up to 300,000 ha, and it divides the watershed area into subdivisions of homogenous cells with respect to soil type, land use, and land management.

In contrast to the event-based model, AnnAGNPS operates on a daily time step. It simulates water, sediment, nutrients, and pesticide transport at the cell and watershed levels. Special components are included to handle concentrated sources of nutrients from feedlots and point sources, concentrated sediment sources with attached chemicals from gullies, and irrigation (water with dissolved chemicals and sediment with attached chemicals). Each day the applied water and resulting runoff are routed through the watershed system before the next day is considered. The model partitions soluble nutrients and pesticides between surface runoff and infiltration. Sediment-transported nutrients and pesticides are estimated and equilibrated within the stream system, with the sediment assumed to consist of five particle size classes (clay, silt, sand, small aggregate, and large aggregate).

The soil profile is divided into two layers. For estimating surface runoff, infiltration and soil water storage. The top 200 mm are used as a tillage layer whose properties can change; the second layer's properties remain static. A daily soil moisture water budget considers applied water (rainfall, irrigation, and snowmelt), runoff, evapo-transpiration, and percolation. Surface runoff is estimated by using the SCS Runoff Curve Number equation where the Curve Number can be modified daily, based on tillage operations, soil moisture, and crop stage. Evapotranspiration is estimated as a function of potential evapotranspiration by using the Penman equation

(Penman 1948) and soil moisture content. Erosion and sediment transport is predicted within a watershed landscape according to RUSLE (Renard, et al. 1997).

For each day and each grid cell, the model calculates mass balances of nutrients (primarily nitrogen, phosphorous), and organic carbon. The model considers plant uptake of nitrogen and phosphorus, fertilization, residue decomposition, and nutrient transport. Soluble and sediment-adsorbed nutrients are estimated, and they are further partitioned into organic and mineral phases. Each nutrient component is decayed based upon the reach travel time, water temperature, and appropriate decay-constant. The soluble nutrients are decreased further by infiltration. Attached nutrients are adjusted for deposition of clay particles Based on a first-order relationship, equilibrium concentrations are calculated at both the upstream and downstream points of reach. Plant uptake of nutrients is modeled through a simple crop growth stage index. A daily mass balance adapted from GLEAMS (Leonard , et al. 1987) is estimated for each pesticide. The pesticides have unique chemodynamic properties, including half-life and organic matter partitioning coefficient. Major components of the pesticide model include foliage wash-off, vertical transport in the soil profile, and degradation. Soluble and sediment adsorbed fractions are calculated for each grid cell on a daily basis.

AnnAGNPS also contains simplified methods to route sediment, nutrients, and pesticides through the watershed. Peak flow for each reach is calculated using an extension of the TR-55 graphical peak-discharge method. Sediment routing is calculated based upon transport capacity relationships using the Bagnold stream power equation. Sediments are routed by particle size class, where each particular size class can be deposited, more entrained, or transported unchanged; depending upon the amount entering the reach, the availability of that size class in the channel and banks, and the transport capacity of each size class. If the sum of all incoming sediment is greater than the sediment transport capacity, then the sediment is deposited. If that sum is less than the sediment transport capacity, the sediment discharge at the downstream end of the reach will include bed and bank material (if it is an erodible reach). Nutrients and pesticides are subdivided into soluble and sediment attached components for routing. Attached phosphorus is further subdivided into organic and inorganic. Each nutrient component is decayed based upon the reach travel time, water temperature, and appropriate decay constant. Soluble nutrients are further reduced by infiltration. Attached nutrients are adjusted for deposition of clay particles. Based on a first-order relationship, equilibrium concentrations are calculated at both the upstream and downstream points of the reach.

AnnAGNPS includes 34 different input data categories, which can be grouped into climate, landscape characterization, agricultural management, chemical characteristics, and feedlot operations. The climatic data consist of precipitation, maximum and minimum air temperature, relative humidity, sky cover, and wind speed. Land characterization data include soil characterization, curve number, RUSLE parameters, and watershed drainage characterization. Agricultural management relates to data on tillage, planting, harvest, rotation, chemical operations, and irrigation schedules. Feedlot operations include daily manure production rates, times of manure removal, and residual amount from previous operations. Indeed, there are over 400 separate input parameters necessary for model execution. Some of these parameters are repeated for each cell, soil type, land use, feedlot, and/or channel reach. Separate parameters are necessary for the model verification section. Default values are available for some of the input parameters. The daily climate data input set includes twenty-two parameters, eight of which are repeated for each day simulated. A climate generator, GEM, can be used to generate the precipitation and minimum/maximum air temperatures for AnnAGNPS. The development of other input data can be simplified because of duplication over a given watershed. Some of the geographical inputs including cell boundaries, land slope, slope direction, and land use, can be generated by GIS and digital elevation models. Model input is facilitated by an input editor, which is currently available with the model. The input editor interface provides a page format for data input, with each of the 34 major data categories on a separate input page. Input and output can be in either all English or all metric units. Separate input files for watershed and climate data allow for quickly changing climatic input.

Extensive data checks (with appropriate error messages) are performed as data are entered and, to a lesser extent, after all data are read. Output is expressed on an event basis for selected stream channel reaches and as source accounting from land or reach components over the simulation period. Primary outputs parameters generated by the model relate to soluble and attached sediment-nutrients and pesticides, surface runoff volume and peak flow, and sediment yield based on particle size classes. Each output parameters can be selected by the user for the desired watershed source locations (specific cells, reaches, feedlots, point sources, and gullies) and for any simulation period. Source accounting indicates the fraction of a pollutant load passing through any reach in the stream network that came from the user-identified watershed source location. In addition, event quantities for user-selected parameters can be extracted at desired stream reach locations.

A major limitation of the AnnAGNPS is that it does not estimate transport of pesticide metabolites or daughter products. Other limitations of AnnAGNPS models include: (1) they lack a nutrient transformation component for both nutrient, and pesticides; (2) they lack a subsurface or near-surface water flow components; (3) they lack flow and contaminant routing component; (4) all runoff and associated pollutant (sediment, nutrient, and pesticide) loads for a single day are routed to the watershed outlet before the next day simulation begins (regardless of how many days this may actually take); (5) there are no mass balance calculations tracking inflow and outflow of water; (6) there is no tracking of sediment-bound pollutants in the stream reaches; (7) point sources are limited to constant loading rates (water and nutrients); and, (8) there is no provision for using spatially variable rainfall inputs. Detailed information on AGNPS and AnnAGNPS can be found at http://www.sedlab.olemiss.edu/PLM/ AnnAGNPS.html.

HYDROLOGIC ENGINEERING COMPUTATION- HYDROLOGIC MODELING SYSTEM

The Hydrologic Engineering Computation – Hydrologic Modeling System or HEC-HMS, developed by the U.S. Army Corps of Engineers, is a physically-based model designed to simulate precipitation runoff processes of dendritic watersheds. The model was developed to allow the simulation of large river basins and flood hydrology, as well as small urban watersheds. HEC-HMS is the latest version of the HEC-1 model and exhibits a number of similar options for simulating precipitation-runoff processes. In addition to unit hydrographic and hydrologic routing functions, capabilities available with HEC-HMS include a linear-distributed runoff transformation that can be applied with gridded rainfall data, a simple "moisture-depletion" option that can be used for simulations over extended time periods, and a versatile parameter optimization option.

HEC-HMS also provides the capability for continuous soil moisture accounting and reservoir routing operations. Several options are included in HEC-HMS to compute overland flow and infiltration. These include the SCS Curve Number equation, gridded SCS Curve Number equation, and the Green-Ampt equation. In addition to unit hydrographic and hydrologic routing options, other capabilities of the model include: linear quasi-distributed runoff transformation for use with gridded precipitation and terrain data such as DEM; continuous simulation with either one layer or a more complex five layer soil moisture method; and, a versatile parameter estimation option. The modified Clark method, ModClark, is a linear quasi-distributed unit hydrograph method that can be applied with gridded precipitation. A variety of flow routing schemes are included in the model. Hydrographs produced by the model can be used directly or in conjunction with other model for studies of water quality, urban drainage, flow forecasting, reservoir spillway design, flood mitigation, and flood management.

The HEC-HMS modeling environment has been enhanced by geospatial technologies. For example, the GEOspatial Hydrologic Modeling Extension or HEC-GEOHMS is a software package that integrates HEC-HMS with ArcView GIS. GEOHMS also incorporates ArcView Spatial Analyst Extension to allow users to generate model inputs for HEC-HMS. Using the digital terrain data from GIS databases, HEC-GEOHMS transforms the drainage paths and watershed boundaries into a hydrologic data structure that represents watershed response to precipitation. It provides an integrated, spatially-explicit simulation environment with data management and customized toolkit capabilities. Other interactive capabilities allow users to construct a hydrologic schematic of the watershed at stream gages, hydraulic structures, and control points within the waterbody.

HEC-HMS also features a Windows-based graphical user interface (GUI), integrated hydrological analysis components, data storage and management capabilities, and graphics and reporting tools. The data storage and manipulation component is used for the storage and retrieval of time series, paired functions, and gridded data, in a manner that is largely transparent to the user. The HEC-HMS GUI provides a means for specifying watershed components, inputting data for each component, and examining the results interactively. It also contains global editors for entering or examining data for all applicable landscape elements.

Both HEC-HMS and HEC-GEOHMS have long history of application as a quasidynamic hydrologic model. They are both in the public domain and their technical reference manuals contain useful information on how to model hydrological processes in general, and the implementation of HEC-HMS or HEC-GEOHMS in particular. In addition, technical and users supports are adequate. However, several factors limit the use of the model in many situations, particularly when assessing wetland hydrology. First, the model was developed to predict the hydrologic responses of rural landscapes due to precipitation and no water quality component is included. Second, the model is unsuitable for landscapes with significantly altered surface hydrology due to, for example, tiling or other landscape modification strategies. Finally, the model does not have an explicit subsurface modeling capability.

HYDROLOGIC ENGINEERING COMPUTATION-5 QUALITY

The Hydrologic Engineering Computation-5 Quality or HEC-5Q is a water quality model for use with U. S. Army Corps of Engineers' hydraulic model, HEC-5. The water flow simulation module, HEC-5, was developed to assist in planning studies for evaluating proposed reservoirs in a system and to assist in sizing the flood control and conservation storage requirements for each project recommended for the system. It can also be useful for selecting proper reservoir operational releases for hydropower, water supply, and flood control.

The water quality simulation module, HEC-5Q, is used to simulate concentrations of various combinations of the following water quality constituents: temperature, dissolved oxygen, nitrate (NO_3) – nitrogen, phosphate (PO_4) – phosphorus, ammonia (NH_3) – nitrogen, phytoplankton, C-biochemical oxygen demand, benthic oxygen demand, benthic source for nitrogen, benthic source for phosphorus, chloride, alkalinity, pH, coliform bacteria, three user-specified conservative constituents, three user-specified non-conservative constituents, water column and sediment dissolved organic chemicals, water column and sediment heavy metals, water column and sediment dioxins and furans, organic and inorganic particulate matter, sulfur, iron and manganese.

Using estimates of system flows generated by HEC-5, the HEC-5Q model computes the distribution of temperature and other water quality constituents in the reservoir and in the associated downstream reaches. For those constituents modeled, the water quality module can be used in conjunction with the flow simulation module to determine concentrations resulting from operation of the reservoir system for flow and storage considerations, or alternately, for determination of flow rates necessary to meet water quality objectives.

HEC-5Q can be used to evaluate options for coordinating reservoir releases among projects to examine the effects on flow and water quality at a specified location in the system. Examples of applications of the flow simulation model include examination of reservoir capacities for flood control, hydropower, and reservoir release requirements to meet water supply and irrigation diversions. The model may be used in applications including the evaluation of in-stream temperatures and constituent concentrations at critical locations in the system, examination of the potential effects of changing reservoir operations on temperature, or water quality constituent concentrations.

Reservoirs equipped with selective withdrawal structures may be simulated to determine operations necessary to meet downstream water quality objectives. With these capabilities, planners could evaluate the effects on water quality of proposed reservoir-stream system modifications and determine how a reservoir intake structure could be operated to achieve desired water quality objectives within the system.

The 1997 version of HEC-5Q, modified by Resource Management Associates, Inc., under contract to the HEC, provides flexibility when applying it to systems consisting of multiple branches of streams flowing into or out of reservoirs, which may be placed in tandem or in parallel configurations. The user can specify the number of streams and reservoirs that can be modeled, and program dimensions can be increased to meet project needs.

HYDROLOGIC SIMULATION PROGRAM-FORTRAN

The Hydrologic Simulation Program-Fortran or HSPF (Johansen, et al. 1984; Bicknell, et al. 1993; Donigian, et al. 1995a) is a physically based, semi-distributed and deterministic model developed during the mid-1970's to predict watershed hydrology and water quality for both conventional and toxic organic pollutants. It provides an analytical tool for: (i) planning, design and operation of water resource systems; (ii) watershed, water-quality management and planning; (iii) point and non-point source pollution analyses; (iv) fate, transport exposure assessment and control of conventional and toxic pollutants; and, (v) evaluation of urban and rural agricultural management practices. HSPF combines three process-oriented models: the Agricultural Runoff Management Model or ARM (Donigian and Davis 1978); the Non-point Source Runoff Model or NPM (Donigian and Crawford 1979); and, the Hydrologic Simulation Program or HSP and its water quality component (Hydrocomp 1977). All of these components were seamlessly combined into a basin-scale framework for simulating water quantity and water quality conditions of terrestrial and aquatic systems (Bicknell , et al. 1993) and for integrated analysis of in-stream hydraulic process.

HSPF provides continuous simulations of hydrological water balance, chemical transport and fate in the terrestrial environment. It also includes an in-stream water quality component for evaluating nutrient fate and transport, biochemical oxygen demand, dissolved oxygen, phytoplankton, zooplankton, and benthic algae. In general, the model consists of three primary application modules: (1) PERLND, which simulates water budget and runoff processes, snowmelt and accumulation, sedimentation, nutrients (e.g., nitrogen, phosphorous) and pesticide fate and transport in runoff, and movement of a chemical tracer (e.g., bromide); (2) IMPLND, which simulates impervious land area runoff and water quality; and (3) RCHRES, which predicts movement of runoff water and water quality constituents in stream channels and mixed reservoirs.

The PERLND module includes process-based functions for predicting: (1) Ambient temperature as a function of elevation differences between land segment and weather station (ATEMP); (2) Water budget resulting from precipitation on each previous land segment (PWATER); (3) Sediment deposition and detachment from the land areas (SEDMNT);

TABLE 3: INPUT PARAMETERS REQUIRED BY HSPF

Watershed-level Data:	
	Soils
	Geology
	Land-surface elevation (DEM)
	Land use and land cover
	Hydrography/natural drainage network
	Artificial drainage network
	Drainage basin delineation
Input Time Series Data for Hydrologic Modeling:	
	Stream flow
	Precipitation (daily/breakpoint)
	Air Temperatures (Maximum/Minimum)
	Water use
Auxiliary Data for Hydrologic Modeling:	
	Channel geometry, roughness and gradient
	Discrete-sample data foe water quality modeling
	Nutrient concentrations
	Sediment concentrations (total suspended sediment)
	Sediment size distribution
	Field parameters (e.g., dissolved oxygen, pH, etc.)
GIS and Auxiliary data for Water Quality Modeling:	
	Cropland
	Pasture
	CAFOs
	Fertilizer application rates
	Manure application rates
	Atmospheric deposition
	Wetlands
	Point Sources

(4) Soil temperature for surface and subsurface layers and its impact on flow and contaminant transport, (PSTEMP); (5) Surface runoff water temperature and dissolved oxygen and carbon dioxide concentrations in overland flow (PWTGAS); (6) Water quality constituents in the surface and subsurface flows from each previous land segment (PQUAL); (7) Storage and moisture fluxes and solute transport in each soil layer or compartment (INSTLAY); and, (8) (Movement and behavior of pesticides (PEST), nitrogen (NITR), phosphorus (PHOS) and tracers (TRACER) through the top surface soil profile.

The IMPLND module of HSPF predicts relevant flow and transport processes in the impervious land segments. It contains compartment equations for simulating air temperature at different locations within the watershed or basin (ATEMP) as in the PERLND module, snow accumulation and snowmelt (SNOW), hydrologic water budget that includes infiltration and other interactions (IWATER), solids accumulation and removal (SOLIDS), surface runoff water temperature and gas concentrations (IWTGAS), and generalized water quality constituents. These modeling compartments are similar to the PERLND module except that little or no infiltration and other surface-subsurface interactions occur.

In the RCHRES module, constitutive equations are used to route runoff and water quaity constituents predicted by the PERLND and IMPLND modules through stream channel networks and reservoirs. The RCHRES module also simulates those processes that occur in open channels, such as sediment detachment and deposition; chemical phase partitioning and transformation (e.g., oxygen and biochemical oxygen demand); plankton population; nitrogen and phosphorus mass balances; and total carbon and carbon dioxide concentrations. Embedded within RCHRES module are compartment equations for describing channel flow hydrodynamics (HYDR), sediment transport (SEDTRN) advection of water quality constituents (ADCALC), transport of conservative chemicals and water quality constituents (CONS and EQUAL) and including synthetic organic chemicals and pesticides.

The HSPF modeling environment also contains five utility models that enhance access, manipulation and analysis of time-series of model parameters, including hourly precipitation, daily evaporation and daily stream flow (Table 3). These utility modules include the following: (i) COPY, which copies data residing in the time series store or watershed management titles to another file; (ii) PLTGEN, which creates an ASCII file for display on a plotter or for input to other programs; (iii) DISPLAY, which generates summary data in tabular form, (iv) DU RANL, a utility program for frequency, duration and statistical analyses; and, (v) GENER, which transforms one or more time series to produce a new or different time series. In addition to these utility programs, ancillary programs such as ANNIE (Lumb, et al. 1990) and HSPEXP (Lumb and Kittle 1993) are used with HSPF to interactively manipulate, store, retrieve, list, plot, and update spatial, parametric and time-series data. ANNIE and other similar interactive pre and post-processing software programs greatly reduce the massive data size and intensive data demands of HSPF. HSPEXP is a stand-alone land-surface hydrologic computation module that incorporates an expert system component for model calibration and for other modeling support.

Since its debut in the early 1980s, HSPF has undergone a number of enhancements. Some of these improvements were in direct response to changes in computer operating systems (e.g., shift from DOS to Windows), computing environment (e.g., from mainframe to minicomputer), human-computer interaction (e.g., paradigm shift from command line interfaces to GUIs), and user requirements (e.g., the need to predict hydrology and water quality of mixed land-use watersheds.) Today, HSPF can be implemented on most computer platforms, from laptops to the largest supercomputers using DOS, Windows, UNIX, or other platforms. Depending on the size of the watershed or basin, an HSPF simulation can be efficiently executed on a 486-based microcomputer or a Pentium III (or greater) microcomputer with/without extended memory. Overall, the HSPF modeling code accommodates a wide range of operating environments and user competencies. However, for watersheds and basins with complex land-use and significant spatial heterogeneity, powerful computing resources and high levels of modeling competency are required.

The capabilities, strengths, and weaknesses of HSPF have been demonstrated by its many applications to urban and rural watersheds (e.g., Donigian, et al. 1990; Moore, et al. 1992; and Ball, et al. 1993). Some applications have featured more comprehensive and innovative uses of the model, particularly its ability to handle complex landscapes and environmental conditions. For example, Donigian et al. (1990, 1991a) and Donigian and Patwardhan (1992) describe the application of HSPF within the framework of the Chesapeake Bay program to determine total contributions of flow, sediment, and other water quality constituents (e.g., dissolved oxygen and nutrients) to the tidal region of the Chesapeake Bay estuary. They use HSPF to estimate total loads of nitrogen and phosphorus entering the Chesapeake Bay from contributing sub-basins under a range of land management scenarios and to evaluate the feasibility of the 40% reduction in non-point polluted loads to the Bay.

In another application of the model, the Maryland Department of the Environment use HSPF to quantify nonpoint source contributions to the water quality impairment in the Patuxent River and to evaluate alternative strategies for improving downstream water quality in the Patuxent River Estuary. In this application, the HSPF provides estimates of non-point pollution loads from complex mixed land-use areas of the drainage basin, and the in-stream water quality throughout the river system.

As part of the EPA's Better Assessment Science Integrating point and Nonpoint Sources (BASINS) tool, HSPF is being applied to watersheds and basins for watersheds and water-quality based assessment for developing the Clean Water Act Total Maximum Daily Loads. Linked to Windows-based user interface, HSPF constitutes the major component of BASINS' nonpoint source model (NPSM) that estimates land-use-specific nonpoint source loadings for selected pollutants within the watershed.

STORAGE TREATMENT OVERFLOW RUNOFF MODEL

The Storage Treatment Overflow Runoff Model or STORM is a model designed by the Hydrologic Engineering Center of the U.S. Army Corps of Engineers to simulate runoff from urbanized landscapes. This model consist of components that facilitate rainfall-runoff assessment, water quality simulation, and statistical and sensitivity analysis of the modeling results. In general, STORM's advantage over other continuous simulation models because of its relatively simple structure and moderate data requirements. It particularly addresses combined sewer outflows, although it may be used to simulate stormwater runoff quality and quantity. The hydrologic modeling procedures in STORM adopt a modified rational formula with a simplified runoff coefficient and depressive storage. Water quality constituents are estimated based on buildup or wash-off functions, and include total suspended and settled solids, BOD, total coliform, ortho-phosphate, and total nitrogen. The model does have capability of continuous and diffuse source release and uses the USLE to estimate soil erosion by water. Limitations of the STORM include minimal flexibility in parameters with which to calibrate model to observed hydrographs, lack of a desktop version that operates in desktop environment, and the large amount of input data required for its application.

SOIL AND WATER ASSESSMENT TOOL

The Soil and Water Assessment Tool or SWAT (Arnold, et al. 1995) was developed by the USDA,Agricultural Research Services by combining the modeling components of SWRRB-WQ, EPIC, and ROTO, with a weather generator. SWAT provides continuous, long-term simulation of the impact of land management practices on water, sediment, and agricultural chemical yields in large complex watersheds. The SWAT model assists resource planners in assessing non-point source pollution impacts on watersheds and large river basins. According to Arnold et al. (1998), the model: (i) is based on physical processes—associated with water flow, sediment detachment and transport, crop growth, nutrient cycling, and pesticide fate and transport; (ii) uses readily available input parameters and standard environmental databases; (iii) is computationally efficient and supports simulation of large basins or a variety of management scenarios and practices; and, (iv) enables users to examine long-term implications of current and alternatives agricultural management practices that can be juxtaposed on the rural landscape.

In the development of the SWAT model, emphasis was placed on: (i) reasonably accurate depiction and characterization of the agricultural land management and spatial variability; (ii) accurate prediction of pollutant load; (iii) flexibility in discretization of the watershed into homogeneous, manageable sub-basins; and, (iv) continuous, long-term simulations as opposed to discrete storm-event simulations of most quasi-distributed models.

The SWAT modeling code consists of eight major components: hydrology, weather, sedimentation, soil temperature, crop growth, nutrients, pesticides, and agricultural management. Hydrologic processes simulated by the model include surface runoff, estimated using the curve number methodology with an option to simulate infiltration on the basis of the Green-Ampt equation; percolation modeled with a layered storage routing technique combined with a crack flow model; lateral subsurface flow; groundwater flow to streams from shallow aquifers; potential evaporation by the Hargraves, Priestley-Taylor, and Penman-Montheith techniques; snow melt; transmission losses from stream; and, water storage losses from pond and reservoirs. Meteorological variables that drive the hydrologic modeling component of SWAT include: daily precipitation, daily minimum and maximum temperatures, solar radiation, relative humidity, and wind speed. For watersheds without historical or current measurements of these climatic data variables, a weather generator can be used to synthetically simulate all or some variables based on monthly historical statistics. Different climatic data can be associated with specific sections of the watershed.

Sediment yield from individual sub-basins and hydrologic response units is computed by using the modified Universal Soil Loss Equation. Crop growth is predicted by using algorithms from the EPIC model that characterizes plant phenological developments based on daily accumulation of heat units, harvest index for partitioning grain yield, Montheit's approach for potential biomass, and adjustments for temperature and water stress. Nitrate-N losses in runoff, deep percolation, and lateral subsurface flow are simulated using methodologies in CREAMS and SWRRB-WQ models. The transformation processes of nitrogen (N) considered in SWAT include mineralization (residue and humus), nitrification, denitrification, volatilization, and plant uptake. For phosphorus (P), the transformation processes include mineralization, soluble

TABLE 4: SWAT/SWAT 200 INPUT PARAMETERS

Watershed-level Parameters:
Sub-basins
Reach and main channels
Hydrologic response units
Groundwater aquifer data
Channel characteristics
General water quality information
Stream and lake water quality
Point sources
Ponds/wetlands/ reservoir days
Tributary channels
Hydro-meterological Data:
Precipitation (daily)
Solar radiation
Min/max temperatures
Solar radiation and wind speed
Relative humidity
Potential evapo-transpiration
Sub-basin level data:
Soils and soil properties
Management practices
Fertilizer application
Manure application
Pesticide application
Urban data

P in runoff, sediment-bound P, P fixation by soil particles, and crop uptake. Pesticide transport and transformation follow algorithms in the GLEAMS model and include equations for describing interception by crop canopy, volatilization, soil degradation, losses in runoff and sediment, and leaching. Agricultural management practices in the SWAT model include tillage effects on soil and residue mixing, bulk density and residue decomposition, irrigation, and chemical management.

In the SWAT model, the stream channel processes include channel routing (flood, sediment, nutrients, and pesticides) and reservoir routing (sediment, nutrients, pesticides, and water balance). Algorithms are included to characterize in-stream parameters such as chlorophyll, dissolved oxygen, organic N, ammonia-N, and biological oxygen demand. Within stream and reservoirs, the model facilitates the simulation of major processes including outflow, nutrient and pesticide loading, nutrient and pesticide transformations, volatilization, diffusive transport of chemical constituents, and chemical/sediment resuspension.

Because of its semi-distributed parameter nature, coupled with its extensive climatic, soil, and management databases, the SWAT model is probably one of the most widely used hydrologic and water quality model for large watersheds and basins. To enhance the use of the model, several interfaces that link the modeling code with geographic information systems (GIS) have been developed. For example, Srinivasan and Arnold (1994) describe an interface that links the SWAT model to the GRASS (Geographical Resources Analysis Support System), a raster-based GIS software package. This interface supports watershed delineation into hydrologically homogeneous units and enhances the extraction of appropriate soil, topographic, climate, agricultural management, and land use data for modeling and the display of the results in the results in the form of maps and graphs. Building on the popularity and the look and feel of the ArcView GIS (Environmental Systems Research Institute, Redlands, CA), another interface was developed for the SWAT model.

The SWAT-ArcView user interface contains appropriately structured components and functions for generating sub-basin topographic attributes and model parameters, editing of input coverages and data, running the SWAT model, and displaying model outputs in a user-defined format. With more than 500, 000 copies in use worldwide ArcView GIS is probably the most versatile desktop software for the manipulation, analysis, modeling, and visualization of geographically referenced data. The interface uses the many capabilities of ArcView GIS to offer users desirable housekeeping functions such as creating a new SWAT project (wherein a project refers to a set of model parameters and model application), editing of the modeling database, and opening, copying, and deleting of a SWAT project. In general, the interface consists of customized menus and dialog boxes that facilitate interactive manipulation of watershed and modeling database and for interrogating the modeling code.

As a quasi-distributed model, one of the many limitations of SWAT is that it is input data intensiveness andit requires the specification of an appropriate data format that ensures error-free simulation (see Table 4 for a partial list). The primary input parameters includes those that describe the watershed (e.g., area), the watershed landscape (e.g., number of hydrologic response units, number of sub-basins, average sub-basin slope, etc.), agricultural management (e.g., date of planting, chemical application, tillage, and harvesting), and the climatic conditions within the watershed. These input data categories are arranged in different hierarchically structured data files with definable extensions. For example, parameters that describe the different hydrologic response units within a sub-basin are constituted under the *.*sub* input file. They include tributary channels, amount of topographic relief and its influence on climatic conditions within a sub-basin, parameters affecting surface and subsurface water flow and contaminant transport. Likewise, the parameters describing soil physical and chemical properties within each hydrologic response unit are arranged as input files with *.*sol* and *.*chm* extension, respectively, while the 14 different types of agricultural management operations simulated by SWAT are defined in the *.*mgt* input file extension.

To further assist users in creating and organizing input data for modeling, a digital database and customized menus are provided with the modeling code. Users of SWAT can select and use the following data sets: (i) USDA-NRCS STATSGO soil-association database- consisting of soil map unit polygons and attribute data; (ii) digital elevation model (DEM) for the contiguous United States as derived from 1:250,000 scale USGS topographic data; (iii) Anderson Level III classified land use/land cover data created by using the 1:250,000-scale USGS LUDA; and, (iv) historical climatic database for 1130 weather stations located across the U.S.

The SWAT model and the ArcView GIS modeling interface are available to users worldwide through the model's Web site (http://www.brc.tamu.edu/swat/swatdoc.html) or by sending an e-mail request to the principals at the Blackland Research Center, Temple, TX. The SWAT models runs on a number of operating environments including Windows (95, 98, NT, and 2000) as well as Unix workstations. Version 99.2 of the SWAT model, for example, requires about 16 MB of RAM, a 486 or Pentium processor, and 10 to 15 MB of disk storage.

The SWAT model has found widespread application in many modeling studies that involve systemic evaluation of the impact of agricultural management on water quality. Several case studies are available in the literature that demonstrate the reliability of the model. For example, as part of the national Coastal Pollutant Discharge Inventory, the National Oceanic and Atmospheric Administration utilized the SWAT model to estimate nonpoint source loading into all U.S. coastal areas. Srinivasan et al. (1998) describe the application of SWAT to selected watersheds in the Upper Trinity River Basin in Texas. Manguerra and Engel (1998) report the use of SWAT model to evaluate runoff from two agricultural watersheds in west central Indiana. More recent applications of the SWAT model include watershed assessments and nonpoint source pollution control in Texas (Rosenthal , et al. 1995), Mississippi (Bingner 1996), and Indiana (Engel and Arnold 1991). The U.S. Environmental Protection Agency is considering adopting SWAT as a nonpoint source modeling component of its BASINS (Better Assessment Science Integrating Point and Nonpoint Sources) modeling environment. The current version of BASINS uses the HSPF model to assist in delineating impaired and critical watersheds and for analyzing baseline nonpoint source loadings and for examining total maximum daily load allocation scenarios and TMDL compliance assessment within watersheds.

STORM WATER MANAGEMENT MODEL

The Storm Water Management Model or SWMM is a comprehensive computer model used for the analysis of water quantity and quality of runoff. The model has been widely used to perform either single event or continuous simulation (i.e. long-term) of hydrologic and hydraulic problems of both combined and separate sewer systems, as well as for assessing urban nonpoint pollution problems. The model predicts flows, stages, and pollution concentrations. SWMM also simulates all components of the hydrologic cycle including, rainfall, snowmelt, surface runoff and subsurface flow, flow/flood routing through drainage networks, storage, and treatment.

SWMM can be used both for planning and designing sewers and for evaluating the hydrology of urban watersheds including those with wetlands. In planning mode, the model can be used as an overall assessment of the urban runoff problems and potential pollutant abatement options. This mode is realized by continuous simulation of hydrology and hydrologic conditions using long-term precipitation data. Users can perform frequency analysis of predicted hydrographs and pollutographs, and examine hydrological events of specific interest. In design mode, event simulation may also be performed using a detailed watershed schematization and shorter time steps for the precipitation input. SWMM is structured around six different, but related, modules or blocks including: (i) RAIN, which processes precipitation data for input into the RUNOFF block; (ii) RUNOFF, which generates runoff volume and quality from precipitation on the watershed; (iii) TEMP, which processes are temperature data for snowmelt computations; (iv) TRANSPORT, which is based on kinematic wave routing of flow and quality, base flow generation, and infiltration; (v) STORAGE and TREATMENT, which handles detention; and, (vi) EXTRAN, which handles dynamic flow routing equations (Saint Venant's equations) for accurate simulation of backwater, looped connections, surcharging, and pressure flow. Within the EXTRAN block, users can perform sophisticated hydraulic analysis of urban drainage networks using either the Saint Venant's hydrodynamic equations or the kinematic wave equations. The RAIN block facilitates the processing of hourly and 15-minute (breakpoint) precipitation time series for input to continuous simulation. It also includes the statistical analysis procedures of the EPA SYNOP model used to characterize storm events. By using these blocks, users can simulate all aspects of the urban hydrologic and quality cycles, including rainfall, snowmelt, surface and subsurface runoff, flow routing through the drainage network, storage and treatment.

In SWMM, the watershed/basin is divided into basic spatial units called sub-watersheds or subbasins. Each sub-watershed requires specification of a number of parameters characterizing its landscape. Data requirements for hydraulic and hydrologic simulation include area, imperviousness, slope, surface roughness, and depression storage and infiltration parameters. Land use information is used to determine type of ground cover for each model sub-area. Depression storage can be estimated from rainfall and stream flow data or from published literature values. Soil infiltration parameters are calculated from either the Horton equation or the Green-Ampt equation. Manning roughness values for previous and impervious areas are estimated form published values for each land cover type. Water quality processes in SWMM are simulated by a variety of options, including constant concentrations, regression relationships (load vs. flow), buildup and wash-off. Other water quality processes in SWMM are those associated with precipitation, land surface, erosion, sedimentation, soil, deposition and treatment. SWMM can predict up to ten different pollutants during a single simulation session. Pollutants that can be simulated include total nitrogen, total phosphorus, ortho-phosphate, copper and zinc. Ten different land uses can be simulated and land uses are grouped as appropriate. The event-mean concentration can be calculated for each pollutant and each land use.

Depending on the objective of the model application, the input data requirements by SWMM can be minimal or extensive. The data collection and data preparation activities for simulation modeling can be intensive, particularly for large watersheds and drainage networks. For example, the simulation of sewer hydraulics requires expensive and time-consuming field verification of sewer invert elevations. Extensive data is also needed for the model calibration and validation.

The outputs generated from SWMM consist of hydrographs and pollutographs (concentration vs. time) at any desired point within the drainage system. Users can output depths and velocities of flow as well as summary statistics defining surcharging, volumes, continuity, and other water quality parameters. The statistics block can be used to separate the hydrographs and pollutographs into storm events and to compute summary statistics on parameters such as volume, duration, inter-event time, load, average concentration, and peak concentration. Model outputs can be in tabular or geographical format. There are options for dynamic plots of the hydraulic grade line produced by the EXTRAN module. Linkages have also been developed between SWMM and GIS.

SWMM is perhaps one of the most widely used models developed by the EPA for urban runoff simulations. Originally developed between 1969 and 1971, SWMM has withstood many verification tests. It continues to be used in countries throughout the world including the United States as well as in Australia, Canada and Europe. A large body of literature exists describing the applicability of the model. Within the United States, applications of SWMM are many and varied Spanning states as varied as California, Florida, and Virginia. The U.S. Geological Survey has used the model to predict hydrology of a watershed in Rolla, Missouri. The model was applied to the Winter Haven chain of lakes and its watersheds to predict pollutant loading to the lake and to examine the effects of human activities on lake water quality.

One of the major strengths of SWMM is its ability to predict hydraulic systems such as drains, detention basins, wetlands, sewers, and related flow controls. The SWMM, however, does have a number of limitations including: (i) the lack of component equations and functions to route subsurface flow and water quality; (ii) limited interactions between the relevant biophysical and chemical processes; (iii) the reliance on first-order rate kinetics to describe pollutant transformation in the TRANSPORT block; and, (- iv) the lack of explicit functional components to predict biogeochemical cycling in receiving waterbodies and control structures.

One drawback, when using of earlier versions of SWMM, is the lack of an appropriate user interface. Over the past decade developers have worked to enhance the "look-and-feel" of the model's interface using interfaces such as MIKE-SWMM, PC_SWMM, and XP-SWMM. In response to EPAs clients' need for improved computational tools for managing urban runoff and wet weather water quality problems, the agency has supported development of a new version of SWMM that incorporates recent advancements in software engineering methods and updated computational techniques. In this new version, the architecture of SWMM's computational scheme has been revised by using object-oriented programming techniques. This revision of SWMM resulted from a collaborative effort between EPA-NRMRL's Water Supply and Water Resources Division and Camp Dresser McKee, Inc. New features include: improved prediction of infiltration, soil moisture accounting, functions for estimating groundwater flow and energy balance, and techniques for routing surface water flow. They also incorporated features such as—Lagrangian water quality transport model, bed/suspended load sediment transport model, and interactive real-time control of sewer flow routing.

SIMULATION OF WATER RESOURCES IN RURAL BASINS-WATER QUALITY

The Simulation of Water Resources in Rural Basins-Water Quality (SWRRB-WQ) (Arnold, et al. 1990) adapts the CREAMS (Knisel 1980) model to provide predictions of hydrologic, sedimentation, nutrient and pesticide transport in large, complex rural watersheds and basins. The primary objective of the model is to predict the effects of alternative management decisions on water flow, sediment yields, and chemical transport with an acceptable level of accuracy for un-gauged rural basins and watersheds. The major modifications to the CREAMS model which resulted in the SWRRB-WQ are: (i) the modeling code now allows simultaneous computation of several sub basins to predict water and sediment yields and chemical loading, and each sub-basin was considered a homogeneous entity; (ii) a return flow component appropriately simulates the soil water balances; (iii) reservoir storage routing component provides estimates of effects of ponds and reservoirs on water flow and sediment yield; (iv) a weather simulation model provides statistical, daily estimates of weather inputs such as precipitation, solar radiation, and minimum and maximum temperatures; (v) plant growth model provides predictions of management and natural and anthropogenic inputs on variation in crop growth; and, (vi) components are incorporated to enable simulation of sediment movement in ponds, reservoirs and streams. In general, the SWRRB-WQ handles the major biophysical processes including surface runoff, percolation, return flow, evapo-transpiration, transmission losses, pond and reservoir storage, sedimentation, nutrient cycling, pesticides fate and transport, and plant growth.

In the SWRRB-WQ model, the water balance in the soil-plant-water atmosphere system is represented by the hydrologic modeling component. Thus, the hydrological cycle, particularly the soil water balance, is described by the equation:

$$SW_t - SW = \sum_{i=1}^{t} (R_i - Q_i - ET_i - P_i - QR_i)$$

in which SW = soil-water content less 15-bar water content; t = time in days; R, Q, ET, P and QR = daily amount of precipitation, runoff, evapo-transpiration, percolation, and return flow, respectively surface runoff, Q is estimated by using modified form of the runoff curve number technique and sediment yield is predicted by using modified USLE (Williams and Berndt 1977).

Nutrient yield and nutrient cycling in SWRRB-WQ adopts the expressions developed in the EPIC model (Williams, et al. 1989) and the quantities calculated for each sub-watershed is routed to watershed outlet. The nutrient load is distributed between the soluble and sediment-bound phases. Pesticides fate and transport modeling in SWRRB-WQ adopts the methodology and equations in GLEAMS model (Leonard, et al. 1987). As with nutrients, the pesticides are distributed between the soluble and adsorbed phases according to the organic matter content of the soil.

Inputs parameters required for SWRRB-WQ model simulations are related to processes such as hydrology, sediment yield, chemical fate and transport, and channel routing. The basic inputs include time history of precipitation, meteorological data, characteristics of land surface including management practices, vegetation cover, and terrain, conversations and structural management practices within sub-basins, chemical characteristics of pollutants, stream channel characteristics, and point source impacts such as reservoirs and ponds. The SWRRB-WQ also requires input parameters that describe the entire drainage basin (e.g., total drainage area, basin slope, and field capacity), pesticide parameters (e.g., soil partition coefficient, wash-off fraction, soil biological half-life, and water solubility), and sub-basin characteristics (e.g., slope, area, curve number, and type of vegetation cover).

The hardware and software requirements for implementing the SWRRB-WQ model are fairly standard. Depending on the area of the watershed and the degree of variability in hydrologic (e.g., ponds, gullies, and reservoirs) and landscape features, the model can be expected to run efficiently on standard desktop computers operating under the Windows environment.

Several applications of SWRRB-WQ evaluate the hydrology and water quality of complex, large rural watersheds and basins and are reported in the literature. For example, the National Oceanic and Atmospheric Administration used SWRRB-WQ to estimate loading of nonpoint pollutants from rural basins in all coastal counties in the United States (Singer, et al. 1988). In this application, disparate data from the National Weather Service stations, Natural Resource Conservation Service (NRCS) Soils 5 database, the U.S. Geological Survey's digital land use land cover data, and other watershed parameters were used with the model to provide simulations of water quality variables for cropland, forest, and rangeland in about 770 watersheds that comprise the Gulf Coast, eastern, and western coastal zones of the United States. In another application, Arnold et al. (1987) predicted the effects of urbanization on watershed water yield and reservoir sedimentation. As a component of the HUMUS (Hydrologic Unit Model of the United States) project, the SWRRB-WQ model was integrated with EPIC and ROTO (Arnold, et al. 1995) to provide a tool for the 1997 Resource Conservation Assessment of the NRCS. Lastly, a Windows interface to enhance the use of the model was developed by the Office of Science and Technology of the U.S. EPA, to assist regional planning jurisdictions in developing the total maximum daily loads for agricultural watersheds. This can be found at http://www.epa.gov/docs/SWRRB_WINDOWS/metadata.txt.html.

Limitations and Model Validation

Mathematical models of ecological systems provide a simplified, approximate representation of real-world processes and phenomena. Indeed, researchers describe models as "metaphors for reality" or "deliberately simplified construct of nature erected for purposes of understanding a system or phenomena" (Batchelor 1994). Bear (1979) defines a model as: "a simplified version of a real investigated system that approximately simulates the latter's excitation-response relations that are relevant to the considered problems." Application of models to ecological problems

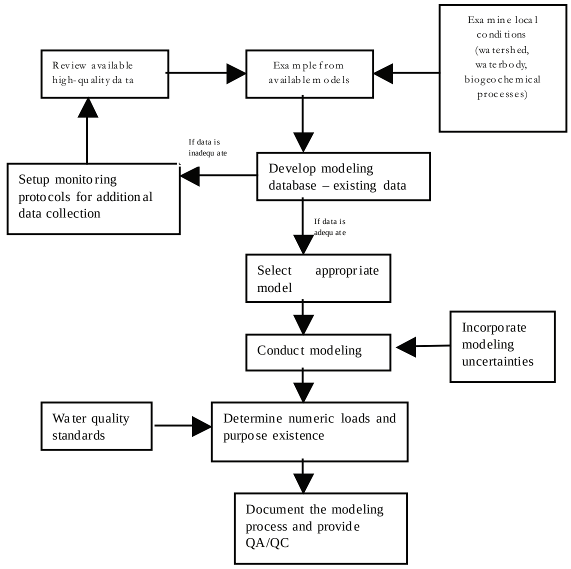

FIGURE 1: MODEL QUALITY ASSURANCE COMPONENTS

requires well-designed protocols for model reliability assessment and quality assurance, including model validation.

Mathematical models are routinely used in most disciplines and fields related to earth and environmental sciences. Their use in problem solving and decision-making is increasing. Examples abound in many application areas on the potential benefits of modeling. However, there is an area of concern to developers and users of these models as well as the decision makers using information derived from the output of the models. Indeed, the ability of models to replicate real-world processes and system responses is greatly influenced by (i) errors in the underlying theory upon which the model is based, (ii) uncertainty in the input parameters, and (iii) unpredictability of the system's phenomena. These factors not only affect the integrity of model outputs, but also the decisions that these outputs support. Because mathematical models are increasingly relied upon in environmental decision-making, it has become imperative to document their reliability. In addition, models used to describe earth system processes are becoming increasingly complex, often involving multiple media, multiple pathways and widely varying endpoints. This complexity could lead to errors and uncertainty in the predicted endpoints and outcomes, making it increasingly necessary to develop methodologies to convey critical uncertainties in environmental models. Techniques and approaches to convey errors and uncertainties in mathematical models fall under the domain of quality assurance and quality control (QA/QC). In modeling, components of a QA/QC protocol often include pre- and post-audit analyses that involve model verification, sensitivity analysis, model calibration and validation, and the assessment of model uncertainty (Figure 1).

In hydrologic and water quality modeling, a wide range of techniques are used to establish the veracity and reliability of environmental models. These include model verification, model sensitivity analysis, model calibration, model validation, and model uncertainty analysis.

MODEL VERIFICATION

Model verification constitutes the process of assessing the reliability of the modeling computer code in generating both accurate and "numerically stable" outputs that represent the conceptualized physical system. Often compared to or confused with model validation, verification of a model generally involves comparing the results of the numerical solution to those obtained using analytical or "closed-form" techniques. Through model verification, illogical statements in the computer code or incorrect assumptions that require significant model modifications can be identified and corrected. In the use of hydrodynamic models, for example, it is desirable that the computational scheme (e.g., numerical finite difference or finite element) be free of numerical dispersion due to the choice of input parameters for the advection component of flow. A model verification process assures that the numerical results are reasonably correct and matches prior specifications and assumptions.

SENSITIVITY ANALYSIS

For mathematical models, sensitivity analysis is required to help identify key input parameters and predictions errors. The aim of sensitivity analysis, in general is to estimate the rate of change in the predicted model output with respect to changes in the model inputs. Such information is important for: (i) assessing the range and limits of applicability of the model, (ii) determining parameters for which it is important to have highly accurate values, and, (iii) understanding the behavior of the physical system being modeled. The choice of method of sensitivity analysis depends largely on the sensitivity measure employed, the desired accuracy in the estimates of the sensitivity measure, and the computational demands and costs involved.

Methods of sensitivity analysis can be broadly divided into three main categories: (i) variations of parameters or model formulations in which the models is run for different combinations of input parameters of concern, or a straightforward change is made to the model structure; (ii) domain-wide sensitivity analysis involving the evaluation of the system behavior response over the entire range of parameter variations; and (iii) local sensitivity analysis which focuses on estimates of model sensitivity to input and parameter variation in the vicinity of a point. One widely used method of sensitivity analysis is the normalized gradient technique. For a mathematical model of the form:

$$F(u,k) = 0$$

where k is a set of m parameters, and u is a vector of n output variables. Thus the normalized gradient sensitivity analysis takes the form:

$$S_{i,j} = k_j / u_i(k) * (\partial u_i / \partial k_j)$$

Other techniques include the normalized response and the local gradient approximation represented mathematically as:

$$D_i = \partial u_i \,/\, u_i(k)$$

$$\partial u \cong [S_{ij}]\,\partial k;\ S_{ij} = \partial u_i / \partial k_j$$

in which S_{ij} and D_i are sensitivity coefficients.

MODEL CALIBRATION

This process of model QA involves adjusting model input parameters until the system output and the model output (predicted values) show an acceptable level of agreement. Typically, this level of agreement is measured using an objective function (or some aggregation function of the model residuals), usually supported by visual inspection of the computed or predicted time series. Thus, the modeling structure and parameter combination producing the best performance is commonly assumed to represent the conceptualized physical system.

Fundamentally, model calibration is an interactive process involving: (i) simulations using parameter sets from the search space to document model performance; (ii) determination of parameter sets that are likely to perform better than those used in the previous simulations, and model simulation using the new or revised parameter sets; and, (iii) repetition of step (ii) until a satisfactory measure of performance is obtained or until further improvements are negligible. During calibration, model performance is quantified by an objective function and coefficients. Some commonly used coefficients include the coefficient of determination, modeling error or bias, and the root mean square error. Graphical plots such as hydrographs (in hydrodynamic models) and scatter plots can be used. The three steps for model calibration could be undertaken manually or automatically using some form of optimization.

MODEL VALIDATION

An inherent issue in many modeling applications is what constitutes an acceptable bias or difference between model predictions and corresponding observations in the real-world. Model reliability and quality assurance can also be assessed through a validation process. Model validation is probably one technique of model performance assessment that has received the most attention in the modeling literature. Differing opinions exist as to the definition of model validation or what constitutes a model validation process. For example, the U.S. Department of Energy defines validation as the determination "that the model indeed reflects the behavior of the real world." The International Atomic Energy Agency (IAEA) defines a validated model as one that provides "a good representation of the actual process occurring in a real (physical) system". Furthermore, the IAEA, in its Radioactive Waste Management Glossary provides yet another definition of model validation as "a process carried out by comparison of model predictions with independent field observations and experimental measurements". Wigman (1972) defines validation as "the process of discriminating between sets of postulates by reference to fresh data not used in setting up, fitting, and a calibration process". From these definitions, the purposes of model validation are to: (i) objectively assess the performance and trustworthiness of the model, (ii) characterize the effects of parameter variability and parameter uncertainty on model outputs, and, (iii) evaluate the results of model simulations without human bias and interpretation.

In general, model validation is the process which determines the accuracy of a model by comparing model outputs to data measured from the natural world that the model is simulating. The initial conditions for the model are matched to those at the time of collection of the field (observed) data. From a collection of those comparisons, the overall model performance is analyzed, evaluated, and documented. Furthermore, model validation involves identifying those factors that contribute to differences between model predictions and field observations.

In model validation, numerous attempts have been made to develop practical and quantitative performance measures to establish whether to accept, modify, or refute a model. For example, Whitmore (1991) suggests a combination of graphical and statistical techniques for assessing model reliability. The discrepancy between model predictions and field observations, whether random or systematic, can be classified as space-time-independent residuals. The sum of the squares of the residual error is partitioned into two other sums of squares: one derived from random variations and the other due to systematic variation or mismatch between predictions and confirming real-world observations. The performance criteria for assessing model reliability based on replicated field experiments, as summarized by Whitman (1991) are as follows:

$$RSS = \sum \sum d_{ij}^2 = \sum\sum(y_{ij} - x_j)^2$$

$$SSE = \sum \sum(d_{ij} - d_j)^2 = \sum \sum[(y_{ij} - x_j) - (y_i - x_j)]^2$$

$$LOFIT = \sum n_j d_j^2 = \sum n_j (y_j - x_j)^2$$

in which RSS is the residual sum of squares; SSE is the sum of squares of the error; LOFIT (or lack of fit) is sum of squares attributed to the lack of fit, an indication of model bias; d_{ij} = deviation or residual error $(y_{ij} - x_j)$; d_j = the mean deviation $(y_j - x_j)$; y_j = mean of the measurements in the *j*th experiment; and, x_j = mean of the predictions of the *j*th experiment. Loague and Green (1991) and Green and Stephenson (1986) propose a combination of approaches for assessing model validity. They suggested the use of goodness-of-fit tests that include: maximum error (ME), not mean square error (RMSE), modeling efficiency (EF), coefficient of determination (CD) and coefficient of residual mass (CRM). The expressions for three performance measures are as follows:

$$ME = max\_x_i - y_{i\_for\ all\ i}$$

$$RMSE = 100/y[\ \sum(x_i - y_i)^2/N]^{0.5}$$

$$EF = [\ \sum(y_i - y)^2 - \sum(x_i - y_i)^2]\ /\ \{\sum(y_i - y)^2\}$$

$$CD = [\sum(y_i - y)^2]\ /\ \{\sum(x_i - y)^2\}$$

$$CRM = [\sum y_i - \sum x_i]\ /\ \sum y_i$$

where N is the number of pair of model-predicted (x_i) and field observed (y_i) values, and y is the mean value of the observations. For the models to be considered fully validated and representative of real-world physical system, values of ME, RMSE, EF, CD, and CRM must be equal to 0, 0, 1.0, 1.0, and 0, respectively.

MODEL UNCERTAINTY ANALYSIS

Analysis of model errors and uncertainty is rapidly becoming an acceptable practice in environmental modeling. It is essential for making reliable predictions of complex phenomena. Well informed and technically defensible environmental policy decisions based on model simulations demand that we identify and document: the significance of the inherent variability of the physical system, the impact of the approximations and simplifications made in formulating the model problem, the consequences of simulation errors, the sensitivity of the predictions to limited understanding of governing processes and system dynamics, and, the probabilistic implications of inherent stochastic effects that exist in most physical systems. A systematic analysis of model uncertainty provides valuable insights into the level of confidence in model predictions and assists in assessing how the model predictions should be weighed in any decision making process. Furthermore, model uncertainty analysis can suggest to model users reasons for strengthening or weakening their belief in the model results.

Increasingly, the reliability of mathematical models requires that we gain a better understanding of the simplifying assumptions in the model, the influence of potential modeling error and uncertainties on the response of the model, and the sources of the modeling uncertainty. A number of sources of model uncertainty have been reported in the literature, including uncertainties due to model structure, model comprehensibility, choice of boundary conditions, and model spatial and temporal resolution.

Uncertainty from modeling structure arises when there are alternative sets of scientific or technical assumptions for developing the model. Thus, when a competing model is used and the results are compared; similar conclusion could provide some level of confidence with the model. If, however, an alternate model formulation provides different conclusions, then further evaluation of model structure may be necessary.

In the development of mathematical models, processes that describe the dynamics of the physical system are simplified for purposes of tractability. Examples of model uncertainty due to comprehensibility include assumptions of nonlinearity, compressibility, unidirectional flow, or the conversion of nonlinear process to linear processes to allow simplified analytical solutions to be obtained. Uncertainty of predictions from simplified models can be characterized by comparing predictions to those obtained from more inclusive and detailed models.

Mathematical models that are validated for a section of the input space could be completely inappropriate when used for decisions in other regions of the parameter space. For example, in predicting components of the hydrologic cycle, models that are calibrated for certain precipitation events may not be appropriately verified if similar events are applied during the validation process.

Model uncertainty can arise from the selection of the spatial and temporal resolution. There is a trade-off between model prediction accuracy and the computation time. Trade-off also exists between the choice of the spatial resolution (e.g., lumped or distributed) and the validity of the governing equations. Quite often, coarse spatial resolution introduces approximations and uncertainties in the model results due to aggregation. However, a finer resolution, in some situations, does not necessarily result in predictions that are more accurate.

A number of techniques have been utilized to attempt to represent and/or reduce uncertainty in mathematical modeling. Some widely used techniques involve: (i) classical set theory, in which uncertainty is expressed by sets of mutually exclusive alternatives in situation where one alternative is desired, (ii) probability theory, where model uncertainty, notwithstanding its origin, is expressed in forms of a measure or subsets of a universal set of alternatives; and, (iii) fuzzy set theory, which unlike the classical set theory, is capable of incorporating vagueness that emerges from imprecision of definitions rather than from non-specificity. Modeling uncertainty using fuzzy set theory is expressed as a degree rather than an affirmation.

Choosing a Suitable Model

Models are increasingly used in many aspects of environmental management and planning, ranging from evaluating changes in watershed management to extending datasets to areas with little or no measurement, and to assessing impact of external influences such as climate change. While there are many mathematical models of hydrology and water quality in use, the skill in selecting the right model for an application and balancing the data requirements against the cost of model implementation is an art as well as science. For a critical and rigorous assessment of model suitability, users need to ask the following questions:

THE MODELING PROCESS

(a) Hydrology:

- Does the model have a built-in stochastic climate generator for constituting synthetic climate data if measurements are not available?
- Does the model compute overland flow (runoff) using a processes-oriented approach or physically-based approach (e.g. SCS Curve Number technique)?
- Does the model compute flow in a stream channel and route this downstream?
- What method of flow routing is used?
- Does the model account for flow into and out of artificial impoundments (e.g. lakes and wetlands)?
- Does the model explicitly incorporate flow into and out of marshes and ponds?
- Does the model contain specialized functions to deal with outflow or outfalls into estuaries, tidal flows, and saltwater intrusions?
- How does the model deal with irrigation water?

(b) Sedimentation:

- What technique is used in the model to estimate soil erosion by water? Is it USLE, MUSLE, or RUSLE?
- How is ephemeral gully erosion simulated?
- How is streambed and bank erosion predicted?

- What physically based or process-oriented approach is adopted by the model to predict sediment detachment, transport, and deposition?
- In estimating sediment yield, is an expression for the delivery ratio stated explicitly? If so, how does the model route sediment to the domain outlet point?

(c) Nutrient export

- How does the model handle the fate and transport of nutrients in the landscape?
- What forms of nutrients does the model handle? Nitrogen or phosphorus?
- Does the model contain components that predict the fate and movement of nitrogen in surface runoff?
- Does the model handle inorganic forms of nutrients?
- What forms of nitrogen does the model predict?
- Does the model include manure management and nitrogen transformation?
- How does the model handle the fate and transport of phosphorus in runoff?
- Are there component equations to differentiate between dissolved and particulate matter?
- What forms of phosphorus does the model predict?
- Does the model handle subsurface leaching losses of both nitrogen and phosphorus?
- Are there any provisions to handle other nutrient sources (e.g. organic wastes from municipal sludge and food processing residues or atmospheric inputs)?
- Are nitrogen and phosphorus predicted as total amounts or concentrations?

MODEL PARAMETERS

(a) Meteorological:

- Does the model require breakpoint, hourly, daily, or monthly values of precipitation?
- Does the model include a climate generator for constituting climate data where measurements are unavailable or inadequate?
- Does the model require air temperature for each time-step of the modeled period?
- Does the model require wind speed, relative humidity, and solar radiation data for each time-step?
- Is precipitation data considered spatially distributed or lumped?
- Does the model require information on percent cloud cover, sunshine hours, or other related surface air data?

(b) Landscape:

- What topographic information is required by the model (e.g. elevation, slope, aspect, drainage network)?
- What soil properties and characteristics does the model require?

- Does the model require users to specify the type of land cover, land-use and land management?
- Are the landscape-related parameters required by the model spatially distributed?
- What management factors (agricultural, urban, and forest) are considered in the model?
- In terms of tillage practices, are there any component of the model that incorporates the different effects of these practices in hydrology and water quality?
- Does the model handle crop rotation or changes in crop growth parameters with respect to time and location?
- Are irrigation practices (application rate, type of irrigation system) and chemigation handled by the model?
- Does the model accept data on artificial drainage of the subsurface soil and the associated effects on hydrology and water quality?
- What conservation practices can be adequately incorporated into the model?
- Does the model incorporate information on nutrient and pesticide management?

(c) Model Output Parameters

- At what time-step does the model produce flow and water quality results?
- Does the model incorporate information on nutrient and pesticide management?
- Does the model lump output results with respect to watershed area?
- In what time-space format does the model generate the outputs?
- For the spatially distributed models, can users examine outputs at specified locations within the landscape?
- For water quantity and quality variables, can users track the source of the contaminant?
- Can users evaluate or assess the effects of model and parameter uncertainty on the predicted outputs?
- Is the output generated in a tabular or graphical format?
- What output data format is provided in the model?

(d) Space and Time Scale

- Does the model simulate discrete events or can it utilize long-term continuous data?
- Is the model designed for the plot, field, whole-farm, or watershed-scale?
- Does the model allow the use of GIS in extending its spatial scale?
- Was the model developed for a specific geographical area?
- Is the modeling technology applicable on a national basis?

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