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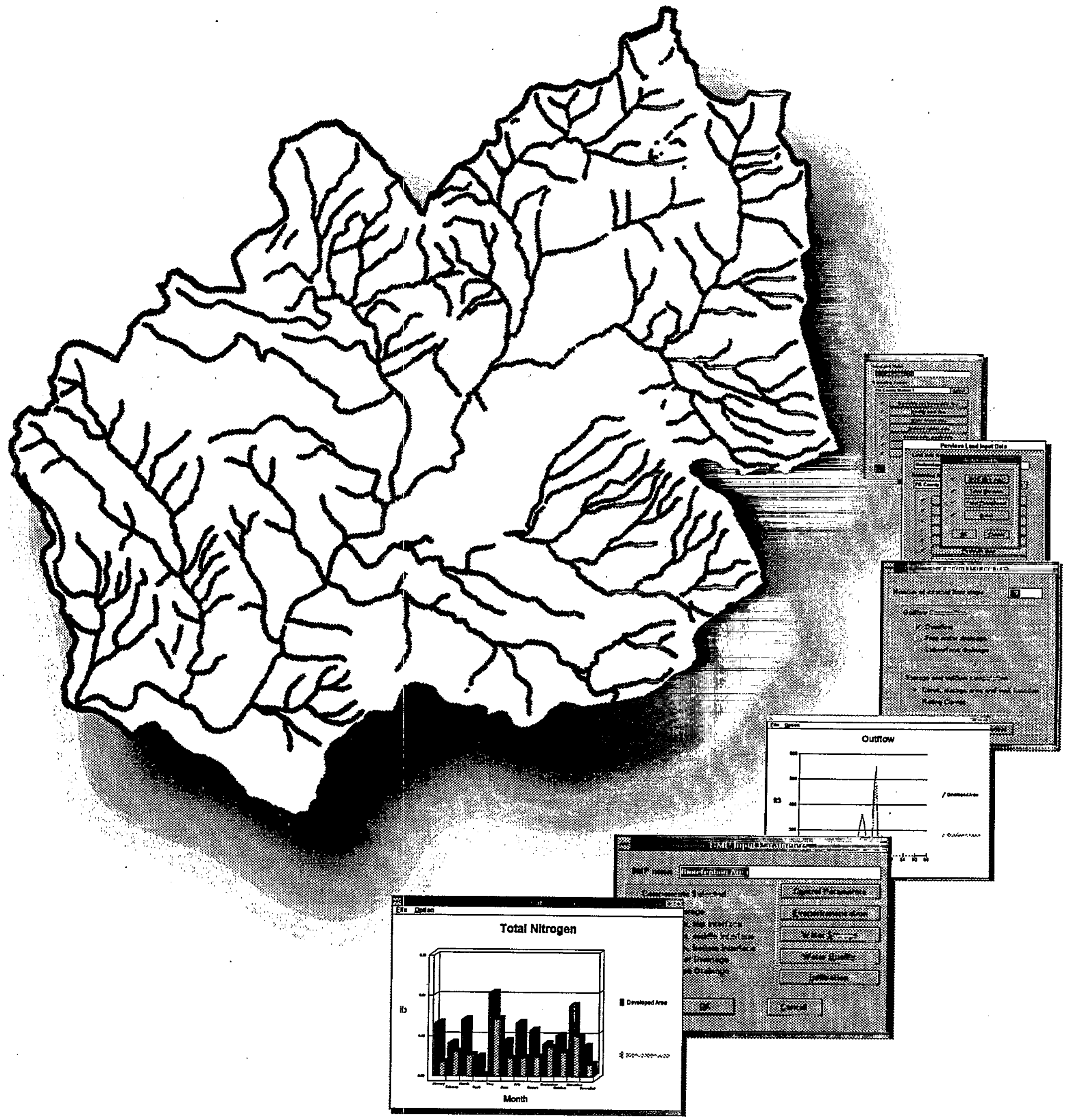

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Compendium of Tools for Watershed Assessment and TMDL Development

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Disclaimer

The information contained in this compendium is based on publications and literature provided by model developers. No verification or testing of model accuracy or function is implied by this review. The U.S. Environmental Protection Agency does not provide support for any model unless explicitly mentioned. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

Foreword

This document represents an update to and expansion of a previous EPA publication, *Compendium of Watershed-scale Models for TMDL Development*, EPA 841-R-92-002 (USEPA, Office of Water, 1992). The revised manual, renamed *Compendium of Tools for Watershed Assessment and TMDL Development*, broadens the review of models and techniques from solely watershed loading models to include receiving water models and ecological assessment techniques and models.

As EPA has recognized with the promotion of the Watershed Protection Approach, water quality managers today face complex water resource problems that require integrated solutions across traditional program areas. *Compendium of Tools for Watershed Assessment and TMDL Development* supports the Watershed Protection Approach by summarizing available techniques and models that assess and predict physical, chemical, and biological conditions in waterbodies. It is intended to provide watershed managers and other users with information helpful for selecting models appropriate to their needs and resources. Specifically, this document includes information regarding:

- A wide range of watershed-scale loading models. (This section has been updated from the previous *Compendium* to include new models and references).
- Field-scale loading models.
- Receiving water models, including eutrophication/water quality models, toxics models, and hydrodynamic models.
- Integrated modeling systems that, for example, link watershed-scale loading with receiving water processes.
- Ecological techniques and models that can be used to assess and/or predict the status of habitat, single species, or biological community.

Comments and suggestions from the user community help us in improving our publications, and we invite the user community to send their comments and suggestions to:

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Contents

VI

List of Tables

Acknowledgments

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Acronyms

AGNPS: Agricultural Nonpoint Source Pollution Model
ANSWERS: Areal Nonpoint Source Watershed Environment Response Simulation
ARS: Agricultural Research Services
AUTO-QI: Automated Q-ILLUDAS

BMP: Best management practice
BOD: Biochemical oxygen demand

CE-QUAL-ICM: Three-dimensional, time-variable, integrated-compartment eutrophication model
CE-QUAL-RIV: Hydrodynamic and water quality model for streams
CE-QUAL-W2: Two-dimensional, laterally averaged hydrodynamic and water quality model
CEAM: Center for Exposure Assessment Modeling
CNE: Curve Number Equation
COD: Chemical oxygen demand
COE: Corps of Engineers
CORMIX: Cornell Mixing Zone Expert System
CREAMS: Chemicals, Runoff and Erosion from Agricultural Management Systems
CSO: Combined sewer overflows
CSTR: Continuously Stirred Tank Reactor
CU: Catalog Unit
CWA: Clean Water Act

DECAL: Deposition Calculation for organic accumulation near marine outfalls
DEM: Digital Elevation Model
DO: Dissolved oxygen
DR3M or DR3M-QUAL: Distributed Routing Rainfall Runoff Model
DYNHYD5: Link-node tidal hydrodynamic model
DYNTOX: Dynamics Toxics model

EFDC: Environmental Fluid Dynamics Computer Code
EMC: Event mean concentrations
EPA/OST: Environmental Protection Agency, Office of Science and Technology
EPA/OWOW: Environmental Protection Agency, Office of Wetlands, Oceans, and Watersheds
EPA: Environmental Protection Agency
EPT: Ephemeroptera, Plecoptera, and Trichoptera
EUTROMOD: Eutrophication Model
EXAMSII: Exposure Analysis Modeling System

FGETS: Food and Gill Exchange of Toxic Substances
FHWA: Federal Highway Administration

GIS: Geographic information system
GLEAMS: Groundwater Loading Effects of Agricultural Management Systems
GWLF: Generalized Watershed Loading Function

HEC: Hydraulic Engineering Center (U.S. Army Corps of Engineers)
HEP: Habitat Evaluation Procedure
HES: Habitat Evaluation System
HGM: Hydrogeomorphic Assessment
HMEM: Habitat Management Evaluation Method System
HQI: Habitat Quality Index
HSI: Habitat Suitability Index
HSPF: Hydrologic Simulation Program-FORTRAN
HU: Habitat Unit
HUC: Hydrologic Unit Code
HUMUS: Hydrologic Unit Model for the United States
HUSLE: Hydrogeomorphic Universal Soil Loss Equation
HUV: Habitat Unit Values

IBI: Index of Biotic Integrity
ICI: Invertebrate Community Index
IFIM: Instream Flow Incremental Methodology
IWB: Index of Well-Being

LA: Load Allocation
LC: Load Capacity

NALMS: North American Lake Management Society
NOAA: National Oceanic and Atmospheric Administration
NPDES: National Pollutant Discharge Elimination System
NPS: Nonpoint source
NPSMAP: Nonpoint Pollution Source Model for Analysis and Planning
NRCS: U.S. Department of Agriculture Natural Resources Conservation Service
NURP: National Urban Runoff Program

P8-UCM: P8-Urban Catchment Model
PHABSIM: Physical Habitat Simulation System
PVA: Population Viability Analysis

QHEI: Qualitative Habitat Evaluation Index
QUAL2E: Enhanced Stream Water Quality Model

RBP: Rapid Bioassessment Protocols

SCS: Soil Conservation Service (USDA) (Now NRCS)
SITEMAP: Stormwater Intercept and Treatment Evaluation Model for Analysis and Planning
SLAMM: Source Loading and Management Model
SLOSS-PHOSPH: Sediment and Phosphorous Prediction
SMPTOX4: Simplified Method Program - Variable complexity stream toxics model
SNTEMP: Stream Network Temperature Model
SOD: Sediment Oxygen Demand
SSTEMP: Stream Segment Temperature Model
STORM: Storage, Treatment, Overflow, Runoff Model
SWAT: Soil and Water Assessment Tool
SWM: Stanford Watershed Model
SWMM: Storm Water Management Model
SWRRB-WQ: Simulation for Water Resources in Rural Basins - Water Quality

TMDL: Total maximum daily load
TPM: Tidal Prism Model
TSLIB: Time-Series Library
TSS: Total suspended solids

USDA-ARS: United States Department of Agriculture, Agricultural Research Service
USDA: United States Department of Agriculture
USEPA: United States Environmental Protection Agency
USFWS: United States Fish and Wildlife Service
USGS: United States Geological Survey
USLE: Universal Soil Loss Equation

VIMS: Virginia Institute of Marine Sciences
VirGIS: Virginia Geographic Information System

WASP5: Water Quality Analysis Simulation Program
WEPP: Water Erosion Prediction Project
WES: U.S. Army Corps of Engineers Waterways Experiment Station
WETII: Wetland Evaluation Technique (version 2.0)
WLA: Wasteload allocations
WMM: Watershed Management Model
WQS: Water Quality Standards
WSM: Watershed Screening Model
WUA: Weighted Usable Area

1 Introduction and Purpose

Simulation models are used extensively in water quality planning and pollution control. Models are applied to answer a variety of questions, support watershed planning and analysis, and develop total maximum daily loads (TMDLs). Some models are highly specialized to simulate environmental phenomena and components of pollution problems; others incorporate more comprehensive assessment techniques. For example, there are specialized models to predict localized pollutant transport, at the field scale, and comprehensive watershed-scale models that simulate pollutant loading, transport and transformation. Historically, models have been used to support the analysis of wastewater discharges by modeling biochemical oxygen demand (BOD) and resulting in-stream dissolved oxygen (DO) concentrations.

As the Environmental Protection Agency's (EPA's) water programs and their counterparts in state pollution control agencies have increasingly emphasized watershed-based assessment and integrated analysis of point and nonpoint sources, modeling has been used to evaluate a wider range of pollutant transport and environmental response issues. Most recently, attention has been focused on assessing "ecosystems," resulting in a more holistic assessment of watershed systems. This emphasis on ecosystems offers new challenges for the use of models, indices, and classification systems to assess and manage watershed systems.

This document discusses three major categories of models—watershed loading, receiving water, and ecological. Watershed loading models simulate the generation and movement of pollutants from the point of origin (source) to discharge into receiving waters. Receiving water models simulate the movement and transformation of pollutants through lakes, streams, rivers, estuaries, or nearshore ocean areas. Some receiving water models also include eutrophication processes such as algal and macrophyte life cycles. Ecological assessment techniques can include habitat and species classification and index systems, as well as ecological and toxicological models that explicitly simulate biological communities and their response to stressors such as toxics and habitat modification.

The models differ in how capabilities, detail, and accuracy are incorporated into specific processes. The selection of the appropriate model depends on the application needs. The definition of modeling objectives is an essential first step in the development of a modeling approach. In some cases, objectives will be best met by using a combination of models. In other cases, very simplified assessment techniques might be sufficient to support decision-making needs. The selection of the model can be based on criteria such as value of resource considered, data needs, application cost, accuracy required, type of pollutants/stressors considered, management considerations, and user experience. Selection and application of a watershed model or analysis tool is often part of the consensus-building process in development of a watershed plan. Stakeholder involvement in the model selection process can help in the acceptance of model results, and in making ensuing decisions based on those results.

This document summarizes the available models and tools that can be used to support watershed assessment and TMDL development. The document includes a wide range of tools and offers selection criteria to assist the user in choosing the model(s) appropriate for a particular application. Many of the models reviewed were developed or sponsored by federal or state agencies; however, a few models included here were developed by universities or private companies. Available models and assessment techniques were identified based on user experience, case studies, and literature searches. Key distributors were contacted for information on current model distribution and availability. The models that were acquired and reviewed are available through the public domain or at minimal cost and are generally recognized in the literature. Each model was reviewed with respect to its theoretical basis, range of applicability, and input requirements. Recent references on model application, testing, and support were also compiled. The review materials were used as the basis for generating model summaries, tables, and fact sheets.

By providing information on technical tools for developing and implementing watershed projects and TMDLs within a broader water quality-based management strategy, this document supports state and federal agencies in establishing ecologically based controls on a watershed basis. Although this document focuses on the available tools and selection criteria, model selection and application are only a portion of the framework for developing a successful watershed management program or TMDL. This document focuses on the availability of models, their characteristics and selection of candidate models for watershed assessment and TMDL development. The scope of this document does not include broader features of model use including monitoring, calibration, validation and modeling design/application. More information is available in other publications and in the respective user's guides and documentation of the various models. Additional information on watershed planning and TMDL development can be found in the references cited in Table 1.

1.1 Background

The Watershed Protection Approach (WPA) is a strategy for effectively protecting and restoring aquatic ecosystems and protecting human health (USEPA, 1995a, 1995b). The WPA has four major features: targeting priority problems, a high level of stakeholder involvement, integrated solutions that make use of the expertise and authority of multiple agencies, and measuring success through monitoring and other data gathering. The WPA brings a vision of water quality protection programs that feature watersheds as the fundamental management unit. Management is targeted to priority watersheds. WPA projects are designed to be consistent with state regulatory programs such as total maximum daily loads (TMDLs). The WPA provides an opportunity for states to share resources and expertise across multiple agencies to protect water quality and public health.

The EPA document *Watershed Protection: A Statewide Focus* describes the elements of a successful watershed project as building a project team and public support, defining the problem, setting goals and identifying solutions, implementing controls, and measuring success and making adjustments. The elements of the WPA process are interconnected, and each is important to the process, although the elements are not necessarily addressed sequentially.

Modeling and analysis can be instrumental to the development of successful watershed projects. Models can be used to assist in targeting watersheds, developing goals and objectives, defining solutions, developing plans for management implementation, and tracking progress toward achieving goals. Actions taken in a watershed or basin should draw on the full range of methods and tools available, integrating them into a coordinated, multiorganization process focusing on the problems. Selection of appropriate models will be guided by the needs of the specific watershed project. Within a watershed project context, models might be needed to address multiple stressors and interrelation

Table 1. Available EPA Guidance and Other References Helpful for Watershed Assessment and TMDL Development

Guidance for Water Quality-based Decisions: The TMDL Process (EPA 440/4-91-001)

This document defines and clarifies the requirements under section 303(d) of the Clean Water Act. Its purpose is to help state water quality program managers understand the application of total maximum daily loads within the water quality-based approach to establish pollution control limits for waters not meeting water quality standards.

Inventory of EPA Headquarters Ecosystem Tools (EPA 230-S-95-001)

This document contains summaries of tools developed at EPA Headquarters relevant to the scientific/technical, economic, planning/management, and socio-political analyses of ecosystems.

Watershed Protection: A Statewide Approach (EPA 841-R-95-004)

This document discusses the process of establishing a statewide watershed approach that focuses on organizing and managing by basins. In a basin approach, activities such as water quality monitoring, planning, and permitting are coordinated on a set schedule within large watersheds or basins. Involvement of other natural resource agencies is actively sought to achieve water quality and ecosystem goals. The document presents examples from many states that have adopted or begun the transition to watershed management.

Watershed Protection: A Project Focus (EPA-841-R-95-003)

This document is a companion to the preceding report and focuses on developing watershed-specific programs or projects. It illustrates how the broader aspects of watershed management can be brought to bear on water quality and ecological concerns. The guide provides a blueprint for designing and implementing watershed projects, and it includes references and case studies for specific elements of the process.

A Quick Reference Guide: Developing Nonpoint Source Load Allocations for TMDLs (EPA 841-B-92-001)

This document directs TMDL developers to existing technical guidance from other programs while more detailed TMDL technical guidance is developed.

TMDL Case Study Series

This series of case studies published by EPA illustrates real-world TMDL applications that the user can consult when appropriate.

The following documents provide more detailed technical guidance and are available from the Office of Science and Technology (4305) or Office of Wetlands, Oceans and Watersheds (4503F), USEPA, 401 M Street, SW, Washington, DC 20460. Some documents are also available from the National Technical Information Service, phone (703) 487-4650, fax (703) 321-8547; and the National Center for Environmental Publications and Information, phone (513) 489-8190, fax (513) 569-7186.

Technical Guidance Manual for Performing Waste Load Allocations - Book II Streams and Rivers - Chapter 1, Biochemical Oxygen Demand/Dissolved Oxygen (EPA 440/4-84-020)

Technical Guidance Manual for Performing Waste Load Allocations - Book II Streams and Rivers - Chapter 2, Nutrient/Eutrophication Impacts (EPA 440/4-84-021)

Technical Guidance Manual for Performing Waste Load Allocations - Book II Streams and Rivers - Chapter 3, Toxic Substances (EPA 440/4-84-022)

Technical Guidance Manual for Performing Waste Load Allocations - Simplified Analytical Method for Determining NPDES Effluent Limitations for POTWs Discharging into Low-Flow Streams

Technical Guidance Manual for Performing Waste Load Allocations - Book IV Lakes and Impoundments - Chapter 2, Nutrient/Eutrophication Impacts (EPA 440/4-84-019)

Technical Guidance Manual for Performing Waste Load Allocations - Book IV Lakes, Reservoirs and Impoundments—Chapter 3, Toxic Substances Impact (EPA 440/4-87-002)

Technical Guidance Manual for Performing Waste Load Allocations - Book VI Design Conditions - Chapter 1, Stream Design Flow for Steady-State Modeling (EPA 440/4-87-004)

Technical Guidance Manual for performing Waste Load Allocations - Book VII: Permit Averaging (EPA 440/4-84-023)

Handbook - Stream Sampling for Waste Load Allocation Applications (EPA 625/6-86/013)

Technical Guidance Manual for Performing Waste Load Allocations - Book III Estuaries - Part 1 - Estuaries and Waste Load Allocation Models (EPA 823/R-92-002)

Technical Guidance Manual for Performing Waste Load Allocations Book III Estuaries - Part 2 - Application of Estuarine Waste Load Allocation Models (EPA 823-R-92-003)

Technical Guidance Manual for Performing Waste Load Allocations - Book III: Estuaries - Part 3 - Use of Mixing Zone Models in Estuarine Waste Load Allocations (EPA 823-R-92-004)

Technical Guidance Manual for Performing Waste Load Allocations - Book III - Estuaries - Part 4 - Critical Review of Coastal Embayment and Estuarine Waste Load Allocation Modeling (EPA 823-R-92-005)

Technical Support Document for Water Quality-based Toxics Control (EPA 505/2-90-001)

Processes, Coefficients and Models for Simulating Toxic Organics and Heavy Metals in Surface Water (EPA/600/3-87/015)

Rates, Constants, and Kinetics Formulations in Surface Water Quality Modeling (Bowie et al., 1985, EPA/600/3-85/040)

Water Quality Assessment: A Screening Procedure for Toxic and Conventional Pollutants in Surface and Groundwater, Parts I and II (Mills et al., 1985, EPA 600/6-85/002a and EPA 600/6-85/002b)

Watershed Tools Directory: A Collection of Watershed Tools (EPA/841-B-95-005)

Modeling of Nonpoint Source Water Quality in Urban and Non-urban Areas (Donigian and Huber, 1991, EPA/600/3-91/039) ships, evaluate management practice effectiveness, or assess receiving water response to changes in loadings. In some cases, modeling tools might not be available or practical to assess the range of stressors and complex systems present within the watershed system.

For those water quality-limited waters where existing or proposed controls do not or are not expected to result in attainment and/or maintenance of the applicable water quality standards (WQSs), section 303(d) of the Clean Water Act (CWA) requires states to develop TMDLs (USEPA, 1991b). The water quality-based approach consists of five steps, the first three of which constitute the TMDL process: (1) identification of water quality-limited waters that require TMDLs and the pollutants causing impairment, (2) priority ranking and targeting of identified waters,
(3) TMDL development, (4) implementation of pollution control actions, and
(5) monitoring and assessment of control effectiveness.

In complex situations or where nonpoint source reductions are part of the TMDL, a "phased approach" may be used. Under this approach, the best available data for water quality conditions and control actions are used to develop TMDLs that consider point and nonpoint sources of pollution, with the stipulation that additional monitoring and evaluation will be performed to assess and revise, if necessary, the initial TMDL allocations. In fact, the final step of the water quality-based approach provides for continuous evaluation and improvement of a TMDL and associated control actions. Models and data analysis techniques can be used in the implementation of each phase of the water quality-based approach, including the initial evaluation, ranking and targeting, TMDL development, evaluation of controls, and program tracking.

1.2 Models and analytical tools for watershed assessment and TMDL development

One challenge faced by water quality managers is the lack of integrated, scientifically sound approaches to identify problems in watersheds and to predict the results of potential control actions on receiving water quality and aquatic habitat. In setting priorities and gathering information for the development of a TMDL, it might be necessary to use several techniques, models, or analytical tools in assessing different components of the complex watershed system. Because of the limitations on applicability and predictive capabilities, care must be taken when selecting a model or analytical tool for watershed assessment and TMDL development.

A review of selected watershed loading models and receiving water models is presented in Chapter 2. The review provides an evaluation of each models features and capabilities. Models are compared based on complexity, capabilities, and interface characteristics. Chapter 2 also includes a brief overview of field-scale loading models (which can be useful for assessing nonpoint source loading changes corresponding to alternative land-use strategies) and integrated modeling systems (which link different model types and data sources to provide more comprehensive watershed assessment tools). Refer to Figure 1 for an overview of the models described in Chapter 2.

To address the CWA's challenge to restore and maintain the *biological* quality of the Nation's waters, a variety of ecological assessment techniques and models have been included in Chapter 3 of this document. These approaches are different from the loading and receiving water models described in Chapter 2 because they focus on evaluating a waterbody by directly examining or predicting the status of a habitat, biological population, or biological community. Biological resources like benthic macroinvertebrates and fish have the ability to integrate the effects of different stressors over space and time, thereby providing an overall measure of the impacts from these stressors. Many of the techniques reviewed compare the results of assessments to empirically defined reference conditions in a similar ecological region; others attempt to predict the effects of changes in hydrology or water chemistry on a habitat or species. Ecological assessment techniques and models can support comprehensive watershed assessments and implementation of controls, and thereby provide valuable insights during the TMDL process.

Chapter 4 provides a more detailed discussion of the selection of models for watershed assessment and TMDL development. Decision criteria and factors to be considered for the various components included in the watershed loading, receiving water, and ecological assessment techniques are reviewed. The information provided in Chapter 4 can be used to assess the suitability of the models for a specific situation. Appendices A, B, and C include detailed fact sheets for each of the watershed, receiving water, and ecological technique or models reviewed, respectively. The fact sheets identify contact points, key features of the model, and recent references. A list of acronyms and a glossary of terminology used for discussing modeling and model features are also included.

Figure 1. Overview of Models Described in Chapter 2.

Watershed-scale loading Models (Section 2.3)

Simple Methods

- EPA Screening
- Simple Method
- Regression Method
- SLOSS-PHOSPH
- Watershed
- Federal Highway Aministration Model
- Watershed Management Model

Mid-Range Models

- SITEMAP
- GWLF
- Urban Catchment Model
- Automated Q-ILLUDAS
- AGNPS
- SLAMM

Detailed Models

- STORM
- ANSWERS
- DR3M-QUAL
- SWRRBWQ
- SWMM
- HSPF

Field-Scale Loading Models (Section 2.4)

- CREAM/GLEAMS
- Opus
- WEPP

Integrated Modeling Systems (Section 2.6)

- PC-VIRGIS
- WSTT
- LWMM
- GISPLM
- BASINS

Receiving Water Models (Section 2.5)

Hydrodynamic Models

- RIVMOD-H
- DYNHYD 5
- EFDC
- CH3D-WES

Steady-State Models

- EPA Screening Procedures
- EUTROMOD
- PHOSMOD
- BATHTUB
- QUAL2E
- EXAMS II
- TOXMOD
- SMPTOX3
- Tidal Prism Model
- DECAL

Dynamic Water-Quality Models

- DYNTOX
- WASPS
- CE-QUAL-RIV1
- CE-QUAL-W2
- CE-QUAL-ICM
- HSPF

Mixing Zone Models

- CORMIX
- PLUME

2 Review of Selected Loading and Receiving Water Models

2.1 Introduction

During the last 20 years, numerous loading and receiving water quality models have been developed. Loading models include techniques primarily designed to predict pollutant movement from the land surface to waterbodies. Loading models can include simple loading rate assessments in which loads are a function of land use type. Loading models can also be complex simulation techniques that more explicitly describe the processes of rainfall, runoff, sediment detachment, and transport to receiving waters. Some loading models operate on a watershed scale, integrating all loads within a watershed. Some watershed models allow for the subdivision of the watershed into contributing subbasins. For the purposes of this document, primary emphasis is given to loading models that analyze systems on a watershed scale. Field-scale models are loading models that are designed to operate on a smaller, more localized scale. Field-scale models have traditionally included models that specialize in agricultural systems. Field-scale models have also been used to answer local management questions or to support the selection of best management practices. A brief discussion of field-scale models is included in Section 2.3.

Empirical formulations: Simple mathematical relationship based upon observed data rather than theoretical relationships.

Deterministic models: Mathematical models designed to produce system responses or outputs (e.g., runoff) to temporal or spatial inputs (e.g., precipitation).

Steady-state model: Mathematical model of fate and transport that uses constant values of input variables to predict constant values (e.g., receiving water quality concentrations).

Dynamic model: A mathematical formulation describing the physical behavior of a system or process and its temporal variability.

Hydrodynamic Model: Mathematical formulation used in describing circulation, transport, and deposition processes in receiving water.

Receiving water models emphasize the response of a waterbody to pollutant loadings, flows, and ambient conditions. Again, a range of complexity is encompassed from simple **empirical** formulations to **deterministic** models. Receiving water assessments can include examination of flow (hydrodynamics), as well as chemical and biological processes. The emphasis of the receiving water models discussed here is on "far-field" models, or models that assess impacts after initial mixing across larger areas. The three general categories of receiving water models discussed include hydrodynamic models, **steady-state** water quality models, and **dynamic** water quality models. More localized impact analysis, assessed by "near-field" models, is addressed in a brief section on mixing zone models.

In some cases models that internally link the loading and receiving water response have been developed. Often watershed management planning requires that both the loading and receiving water response be assessed. For example, in the development of a TMDL for a lake, a receiving water model can be used to determine the phosphorus loading capacity that will protect the lake from accelerated eutrophication. A loading model can be used to determine the sources of the phosphorus loads, the magnitude of the loads, and the potential reductions under a variety of management scenarios. Ultimately, the loading and receiving water models can be used to determine the optimum combination of loads for for the protection of water quality.

Integrated modeling systems link the models, data, and user interface within a single system. New developments in modeling systems have increasingly relied on geographic information systems (GISs) and database management systems to support modeling and analysis. Section 2.5 describes some of the currently available modeling systems and the trends in new modeling system development.

2.2 Watershed loading and receiving water model development and distribution

Some of the models developed over the past two decades have been (and still are) used successfully by watershed and receiving water managers. Other models have had limited use or have been incorporated into larger and more comprehensive modeling systems. Some models have been used solely for highly specialized research and development purposes. The emphasis of this review is on those models which are typically available and are being used for the assessment and management of watersheds and receiving waters. In addition, watershed and receiving water models are constantly being updated, revised, and modified to meet current needs. Many of the models reviewed were developed or sponsored by federal or state agencies; however, a few models were developed by universities or private companies.

2.2.1 USEPA

The U.S. EPA, through the Center for Exposure Assessment Modeling (CEAM), currently distributes and provides limited support for several commonly applied watershed loading and receiving water models. The Hydrologic Simulation Program - FORTRAN (HSPF) is a highly versatile model capable of simulating mixed-land-use watersheds (urban and rural). The Storm Water Management Model (SWMM) provides detailed simulation capabilities for assessing primarily urban watersheds. The versatility of HSPF and SWMM for simulating a wide range of land uses and their continual upgrading make these models two of the most detailed and widely applied to watershed studies. Receiving water models distributed by CEAM include QUAL2E, WASP5, and SMPTOX4. QUAL2E is widely applied for assessment of BOD and nutrient loading to rivers and streams under steady-state conditions. WASP5 provides more detailed and comprehensive analysis of receiving waters under steady-state or time-variable conditions. SMPTOX4 provides simplified steady-state assessment of toxics concentrations in rivers and streams. WASP5 and QUAL2E are widely applied to address watershed-based receiving water issues and development of TMDLs. Other models distributed by CEAM include CORMIX, a mixing zone model; EXAMSII, a fate and exposure model for assessing toxics in receiving waters; and PLUMES, a model interface for preparing and running both new-field and far-field plume models.

EPA's Office of Science and Technology (OST) has also sponsored the development of user interfaces and integrated modeling systems to facilitate the use of the SWMM, SWRRBWQ, HSPF, and QUAL2E models. Windows versions of the SWMM, SWRRBWQ and QUAL2E models are distributed by OST and are available on the OST web site at www.epa.gov/ost/tools. An integrated modeling system, Better Assessment Science Integrating Point and Nonpoint Sources (BASINS), is distributed by OST. OST also distributes the Dynamic Toxics (DYNTOX) model, which can assess instream toxicity based on a range of effluent discharge levels. EPA's Office of Wetlands, Oceans and Watersheds (OWOW) distributes the Watershed Screening and Targeting Tool (WSTT), an integrated modeling system that includes the Watershed Screening Model (WSM).

2.2.2 USDA

The U.S. Department of Agriculture's Agricultural Research Service (ARS) has developed several well-documented models that can be used for watershed assessment and development of TMDLs in predominantly agricultural areas. Watershed loading models developed by the USDA include the Agricultural Non-Point Source Pollution Model (AGNPS) and Simulator for Water Resources in Rural Basin-Water Quality (SWRRBWQ). Due to its distributed design, in which the simulation area is divided into cells, the AGNPS model is well suited to linkage with geographic information systems (GISs). Although currently still limited to design storm simulations, AGNPS has been widely applied to watershed-based assessment of agricultural nonpoint sources. The SWRRBWQ model provides watershed-scale assessment using continuous simulation. The SWRRBWQ model has been incorporated into the Soil and Water Assessment Tool (SWAT) under development by the USDA Agricultural Research Services in Temple, Texas. SWAT is currently being applied to a national-scale modeling project, Hydrologic Unit Model for the United States (HUMUS), scheduled for completion in 1997 (Srinivasan et al., 1995).

The SWAT model allows for simulation of larger and more complex watersheds with numerous subbasins. Some of the relevant field-scale models supported by the USDA include Chemicals, Runoff, Erosion from Agricultural Management Systems (CREAMS); Groundwater Loading Effects of Agricultural Management Systems (GLEAMS); Opus; Water Erosion Prediction Project (WEPP); Environmental Policy Integrated Climate (EPIC); and the Nitrate Leaching and Economic Analysis Program (NLEAP). Field-scale models can provide site-specific analysis of management practice alternatives and effectiveness. In some cases field-scale models can be used to support broader watershed management planning needs.

2.2.3 USCOE

The U.S. Army Corps of Engineers distributes models through the Hydraulic Engineering Center (HEC) in Davis, CA and the Waterways Experiment Station (WES) in Vicksburg, Mississippi. The HEC developed a continuous urban simulation model including dry-weather sewer flows, in the Storage, Treatment, Overflow, Runoff Model (STORM). With the support of HEC, STORM has been used extensively for planning purposes and for evaluating control strategies for combined sewer overflows. The U.S. Army Engineer WES distributes the BATHTUB, CE-QUAL-RIV1, CE-QUAL-W2, CE-QUAL-ICM, and CH3-HEM models. BATHTUB applies a series of empirical eutrophication models to morphologically complex lakes and reservoirs. The CE-QUAL-RIV1 model simulates one-dimensional dynamic transport and water quality in rivers and streams. The CE-QUAL-W2 simulates two-dimensional, laterally averaged hydrodynamics and transport in rivers, lakes, and reservoirs. The CE-QUAL-ICM model was developed for three-dimensional applications, such as the Chesapeake Bay, and is typically linked with the CH3-HEM hydrodynamic model.

2.2.4 Other Federal Agencies

The U.S. Geological Survey (USGS) has developed and applied the Distributed Routing Rainfall Runoff Model (DR3M-QUAL), which calculates runoff and pollutant loads in urban watersheds. The USGS has also developed a statistical method for estimating pollutant loads. The U.S. Federal Highway Administration (FHWA) developed and uses a statistically based approach for assessing stormwater runoff from highways and developing preliminary pollution control options.

2.2.5 Universities

A number of models have also been developed at universities or other research institutions. The Areal Nonpoint Source Watershed Environment Response Simulation (ANSWERS) model was developed at the University of Georgia to predict the movement of sediment through relatively large agricultural watersheds. Its cell-based design, similar to AGNPS, has resulted in research developing linked applications with GIS. Researchers at Virginia Polytechnic Institute have continued development and testing of the ANSWERS model. The Source Loading and Management Model (SLAMM) was developed at the University of Alabama for the purpose of evaluating urban management practices for sediment, nutrients, and other urban pollutants, including toxics and water-demanding substances. The Generalized Watershed Loading Functions (GWLF) model was developed at Cornell University. The GWLF model considers runoff from urban and agricultural land uses and integrated pollution from both point and nonpoint sources. WATERSHED is a simple nonpoint source model developed at the University of Wisconsin to assess the cost-effectiveness of stormwater control practices.

Universities have also been active in the development, testing, and application of receiving water models. For example, the Virginia Institute of Marine Sciences (VIMS) supports the development of the Environmental Fluid Dynamics Computer Code (EFDC) and related receiving water modeling tools. The EFDC is a three-dimensional hydrodynamic and salinity numerical model that has been linked with various water quality models for receiving water simulations. Most recently, researchers at VIMS have developed a fully linked water quality model, HEM-3D, which incorporates EFDC (Park et al., 1995).

2.2.6 Other

Several state and local agencies have participated in the development of nonpoint source models. The Illinois State Water Survey developed a watershed loading model, Auto-QI, for continuous simulation of pollutant loading from urban areas. The Washington Metropolitan Council of Governments developed a simplified approach, "the Simple Method," for estimating pollutant loads from urban land uses (Schueler, 1987). This approach relies on data from the National Urban Runoff Program (NURP) for default values. The Watershed Management Model (WMM) was developed for the Florida Department of Environmental Regulation to evaluate nonpoint source pollution loads and control strategies from mixed-land-use watersheds. The Urban Catchment Model (P8-UCM) was developed for the Narragansett Bay Project. The P8-UCM model predicts pollutant loading and transport of stormwater runoff from urban watersheds.

The North American Lake Management Society (NALMS) distributes models specially designed for the assessment of eutrophication and toxics in lakes. Models available from NALMS include EUTROMOD, PHOSMOD, and TOXMOD. EUTROMOD includes routines to estimate nutrient loadings and in-lake response. PHOSMOD evaluates the effects of seasonal and long-term phosphorus loads on lake condition.

Other models developed and supported by private companies include the Stormwater Intercept and Treatment Evaluation Model for Analysis and Planning (SITEMAP). SITEMAP is a spreadsheet-based model designed to simulate stream segment load capacities, point source wasteload allocations, and nonpoint source load allocations.

2.3 Watershed-scale loading models

Thoroughly assessing a watershed or developing a TMDL often requires the use of watershed loading models to evaluate the effects of land uses and practices on pollutant loading to waterbodies. For discussion purposes, loading models are divided into categories based on complexity, operation, time step, and simulation technique. Watershed-scale loading models can be grouped into three categories—simple methods, mid-range models, and detailed models. In addition to the different classes of models, the level of application of a given model can vary depending on the objectives of the analysis. The three categories of models and types of available models in each category are discussed below.

> **Simple methods** can be used to support an assessment of the relative significance of different sources, guide decisions for management plans, and focus continuing monitoring efforts.

Simple methods. The major advantage of simple methods is that they can provide a rapid means of identifying critical areas with minimal effort and data requirements. Simple methods are typically derived from empirical relationships between physiographic characteristics of the watershed and pollutant export. They can often be applied using a spreadsheet program or hand-held calculator. Simple methods are often used when data limitations and budget and time constraints preclude the use of complex models. They are used to diagnose nonpoint source pollution problems where relatively limited information is available. They can be used to support an assessment of the relative significance of different sources, guide decisions for management plans, and focus continuing monitoring efforts.

Typically, simple methods rely on large-scale aggregation and neglect important features of small patches of land. They rely on generalized sources of information and therefore have low to medium requirements for site-specific data. Default values provided for these methods are derived from empirical relationships that are evaluated based on regional or site-specific data. The estimations are usually expressed as mean annual values.

Simple methods provide only rough estimates of sediment and pollutant loadings and have very limited predictive capability. The empiricism contained in the models limits their transferability to other regions. Because they often neglect temporal variability, simple methods might not be adequate to model water quality problems for which loadings of shorter duration are important. They might be sufficient for problems such as nutrient loadings to and eutrophication of long-residence-time waterbodies (e.g., lakes, reservoirs).

As shown in Table 2, these methods use large simulation time steps to provide long-term averages or annual estimates. Although they can easily be adapted to estimate seasonal or storm event loadings, their accuracy decreases because they cannot capture the large fluctuations of pollutant loading or concentration usually observed at smaller time steps. Pollutant loads are determined from export coefficients (e.g., the Watershed model) or as a function of the sediment yield (e.g., EPA screening procedures, SLOSS-PHOSPH). The Simple Method, the USGS regression method, and the FHWA model are statistically based approaches developed from past monitoring information. Their application is limited to the areas for which they were developed and to watersheds with similar land uses or activities.

Mid-range models. The advantage of mid-range watershed-scale models is that they evaluate pollution sources and impacts over broad geographic scales and therefore can assist in defining target areas for pollution mitigation programs on a watershed basis. Several mid-range models are designed to interface with geographic information systems (GISs), which greatly facilitate parameter estimation. Greater reliance on site-specific data gives mid-range models a relatively broad range of regional applicability. However, the use of simplifying assumptions can limit the accuracy of their predictions to within about an order of magnitude (Dillaha, 1992) and can restrict their analysis to relative comparisons.

Table 2. Evaluation of Model Capabilities—Simple Models

Criteria		EPA Screening[1]	Simple Method[1]	Regression Method[1]	SLOSS-PHOSPH[2]	Watershed	FHWA	WMM
Land Uses	Urban	○	◒	◒	-	◒	○[3]	●
	Rural	◒	-	○	◒	◒	○	●
	Point Sources	-	-	-	-	○	-	○
Time Scale	Annual	●	●	●	●	●	●	●
	Single Event	○	○	○	-	-	○	-
	Continuous	-	-	-	-	-	-	-
Hydrology	Runoff	-[4]	◒	-	-	-	○	○
	Baseflow	-	-	-	-	-	-	○
Pollutant Loading	Sediment	◒	◒	◒	◒	◒	-	-
	Nutrients	◒	◒	◒	◒	◒	◒	◒
	Others	○	◒	◒	-	◒	◒	◒
Pollutant Routing	Transport	-	-	-	-	-	-	-
	Transformation	-	-	-	-	-	-	○
Model Output	Statistics	-	-	-	-	◒	○	○
	Graphics	-	-	-	-	◒	-	○
	Format Options	-	-	-	-	◒	-	○
Input Data	Requirements	○	○	○	○	○	○	○
	Calibration	-	-	-	○	◒	-	◒
	Default Data	●	●	◒	◒	○	◒	◒
	User Interface	-	-	-	-	◒	○	◒
BMPs	Evaluation	○	○	-	○	◒	◒	◒
	Design Criteria	-	-	-	-	-	-	-
Documentation		●	●	●	●	●	●	◒

1 Not a computer program.
2 Coupled with GIS.
3 Highway drainage basins.
4 Extended versions recommend use of SCS-curve number method for runoff estimation.

● High ◒ Medium ○ Low - Not incorporated

> **Mid-range models** attempt a compromise between the empiricism of the simple methods and the complexity of detailed mechanistic models.

This class of model attempts a compromise between the empiricism of the simple methods and the complexity of detailed mechanistic models. Mid-range models use a management-level approach to assess pollutant sources and transport in watersheds by incorporating simplified relationships for the generation and transport of pollutants. Mid-range models, however, still retain responsiveness to management objectives and actions appropriate to watershed management planning (Clark et al., 1979). They are relatively simple and are intended to be used to identify problem areas within large drainage basins or to make preliminary, qualitative evaluations of BMP alternatives (Dillaha, 1992).

Unlike the simple methods, which are restricted to predictions of annual or storm loads, mid-range tools can be used to assess the seasonal or interannual variability of nonpoint source pollutant loadings and to assess long-term water quality trends. Also, they can be used to address land use patterns and landscape configurations in actual watersheds.

Table 3. Evaluation of Model Capabilities—Mid-Range Models

Criteria		SITEMAP	GWLF	P8-UCM	Auto-QI	AGNPS	SLAMM
Land Uses	Urban	●	●	●	●	-	●
	Rural	●	●	-	-	●	-
	Point Sources	◒	◒	●	-	●	●
Time Scale	Annual	-	-	-	-	-	-
	Single Event	○	-	●	-	●	-
	Continuous	●	●	●	●	-	●
Hydrology	Runoff	●	●	●	●	●	●
	Baseflow	○	●	○	○	-	○
Pollutant Loading	Sediment	-	●	●	●	●	●
	Nutrients	●	●	●	●	●	●
	Others	-	-	●	●	-	●
Pollutant Routing	Transport	○	○	○	◒	●	◒
	Transformation	-	-	-	-	-	-
Model Output	Statistics	◒	○	-	-	-	○
	Graphics	◒	◒	●	-	●	○
	Format Options	●	●	●	○	●	●
Input Data	Requirements	◒	◒	◒	◒	◒	◒
	Calibration	○	○	○	◒	○	◒
	Default Data	●	●	◒	○	◒	◒
	User Interface	●	●	●	◒	◒	●
BMPs	Evaluation	○	○	●	◒	◒	◒
	Design Criteria	-	-	●	◒	◒	○
Documentation		●	●	●	◒	●	◒

● High ◒ Medium ○ Low - Not Incorporated

They are based primarily on empirical relationships and default values. In addition, they typically require some site-specific data and calibration.

Mid-range models are designed to estimate the importance of pollutant contributions from multiple land uses and many individual source areas in a watershed. Thus, they can be used to target important areas of pollution generation and identify areas best suited for controls on a watershed basis. Moreover, the continuous simulation furnished by some of these models provides an analysis of the relative importance of sources for a range of storm events or conditions. In an effort to reduce complexity and data requirements, these models are often developed for specific applications. For instance, mid-range models can be designed for application to agricultural, urban, or mixed watersheds. Some mid-range models simplify the description of transport processes while emphasizing possible reductions available with controls; others simplify the description of control options and emphasize changes in concentrations as pollutants move through the watershed.

Table 3 describes the key features of mid-range models. Because mid-range models attempt to use smaller time steps in order to represent temporal variability, they require additional meteorologic data (e.g., daily weather data for the GWLF, hourly rainfall for SITEMAP). They also attempt to relate pollutant loadings to hydrologic (e.g., runoff) and erosion (e.g., sediment yield) processes. These models usually include detailed input-output features (e.g., AGNPS, GWLF), making applications easier to process. Several of these models (SITEMAP, Auto-QI) were developed in existing computing environments (e.g., Lotus 1-2-3) to make use of their built-in graphical and statistical capabilities. It should be noted from Tables 2 and 3 that neither the simple nor the mid-range models consider degradation and transformation processes, and few incorporate detailed representation of pollutant transport within and from the watershed. Although their applications might be limited to relative comparisons, they can often provide water quality managers with useful information for watershed-level planning decisions.

If properly applied and calibrated, detailed models can provide relatively accurate predictions of variable flows and water quality at any point in a watershed.

Detailed models. Detailed models best represent the current understanding of watershed processes affecting pollution generation. Detailed models are best able to identify causes of problems rather than simply describing overall conditions. If properly applied and calibrated, detailed models can provide relatively accurate predictions of variable flows and water quality at any point in a watershed. The additional precision they provide, however, comes at the expense of considerable time and resource expenditure for data collection and model application.

Detailed models use storm event or continuous simulation to predict flow and pollutant concentrations for a range of flow conditions. The models are complex and were not designed with emphasis on their potential use by the typical state or local planner. Many of these models were developed for research into the fundamental land surface and instream processes that influence runoff and pollutant generation rather than to communicate information to decision makers faced with planning watershed management.

Detailed models incorporate the manner in which watershed processes change over time in a continuous fashion rather than relying on simplified terms for rates of change (Addiscott and Wagenet, 1985). They tend to require rate parameters for flow velocities and pollutant accumulation, settling, and decay instead of capacity terms. The length of time steps is variable and depends on the stability of numerical solutions as well as the response time for the system (Nix, 1991). Algorithms in detailed models more closely simulate the physical processes of infiltration, runoff, pollutant accumulation, instream effects, and groundwater/surface water interaction. The input and output of detailed models also have greater spatial and temporal resolution. Moreover, the manner in which physical characteristics and processes differ over space is incorporated within the governing equations (Nix, 1991). Linkage to biological modeling is possible because of the comprehensive nature of continuous simulation models. In addition, detailed hydrologic simulations can be used to design potential control actions.

Table 4 shows that these models use small time steps to allow for continuous and storm event simulations. However, input data file preparation and calibration require professional training and adequate resources. Some of these models (e.g., STORM, SWMM, ANSWERS) were developed not only to support planning-level evaluations but also to provide design criteria for pollution control practices. If appropriately applied, state-of-the-art models such as HSPF and SWMM can provide accurate estimations of pollutant loads and the expected impacts on water quality. New interfaces developed for HSPF and SWMM, and links with GISs, can facilitate the use of complex models for environmental decision making. However, their added accuracy might not always justify the amount of effort and resources they require. Application of such detailed models is more cost-effective when used to address complex situations or objectives.

A qualitative description of each model is presented in the following section to supplement the information reported in Tables 2, 3, and 4. For a more technical description of each of the watershed loading models, refer to Appendix A.

Table 4. Evaluation of Model Capabilities—Detailed Models

Criteria		STORM	ANSWERS	DR3M-QUAL	SWRRBWQ/ SWAT	SWMM	HSPF
Land Uses	Urban	●	-	●	○	●	●
	Rural	-	●	-	●	○	●
	Point Sources	●	-	●	●	●	●
Time Scale	Annual	-	-	-	-	-	-
	Single Event	○	●	○	○	●	●
	Continuous	●	-	●	●	●	●
Hydrology	Runoff	●	●	●	●	●	●
	Baseflow	○	-	○	●	●	●
Pollutant Loading	Sediment	●	●	●	●	●	●
	Nutrients	●	●	●	●	●	●
	Others	●	-	-	●	●	●
Pollutant Routing	Transport	-	◒	●	●	○	●
	Transformation	-	-	-	-	○	●
Model Output	Statistics	○	-	●	●	●	●
	Graphics	-	-	◒	◒	○	○
	Format Options	●	●	●	●	●	●
Input Data	Requirements	◒	●	●	◒	●	●
	Calibration	○	○	◒	◒	●	●
	Default Data	◒	○	●	●	◒	◒
	User Interface	●	-	◒	●	●	-
BMPs	Evaluation	◒	◒	●	◒	●	●
	Design Criteria	◒	◒	◒	-	●	●
Documentation		●	◒	◒	●	●	●

● High ◒ Medium ○ Low - Not Incorporated

2.3.1 Simple methods

EPA Screening Procedures (fact sheet, page A.9). The EPA Screening Procedures, developed by the EPA Environmental Research Laboratory in Athens, Georgia, (McElroy et al., 1976; Mills et al., 1985) include methodologies to calculate pollutant loads from point and nonpoint sources, including atmospheric deposition, for preliminary assessment of water quality. The procedures consist of loading functions and simple empirical expressions relating nonpoint pollutant loads to other readily available parameters. Data required generally include information on land use/land cover, management practices, soils, and topography. Although these procedures are not coded into a computer program, several computer-based models have adapted the loading function concept to predict pollutant loadings. An advantage of this approach is the possibility of using readily available data as default values when site-specific information is lacking. Application of these procedures requires minimum personnel training and practically no calibration. However, application to large, complex watersheds should be limited to pre-planning activities. Many of the techniques included in the manual were incorporated into current models such as GWLF.

The Simple Method (fact sheet, page A.21). The Simple Method is an empirical approach developed for estimating pollutant export from urban development sites in the Washington, DC, area (Schueler, 1987). It is used at the site-planning level to predict pollutant loadings under a variety of development scenarios. Its application is limited to small drainage areas of less than one square mile. Pollutant concentrations of phosphorus, nitrogen, chemical oxygen demand, biochemical oxygen demand (BOD), and metals are calculated from flow-weighted concentration values for new suburban areas, older urban areas, central business districts, hardwood forests, and urban highways. The method relies on the National Urban Runoff Program (NURP) data for default values (USEPA, 1983). A graphical relationship is used to determine the event mean sediment concentration based on readily available information. This method is not coded into a computer program but can be easily implemented with a hand-held calculator.

USGS Regression Approach (fact sheet, page A.33). The regression approach developed by USGS researchers is based on a statistical description of historic records of storm runoff responses on a watershed level (Tasker and Driver, 1988). This method may be used for rough preliminary calculations of annual pollutant loads when data and time are limited. Simple regression equations were developed using available monitoring data for pollutant discharges at 76 gaging stations in 20 states. Separate equations are given for 10 pollutants, including dissolved and total nutrients, chemical oxygen demand, and metals. Input data include drainage area, percent imperviousness, mean annual rainfall, general land use pattern, and mean minimum monthly temperature. Application of this method provides storm-mean pollutant loads and corresponding confidence intervals. The use of this method as a planning tool at a regional or watershed level might require preliminary calibration and verification with additional, more recent monitoring data.

Simplified Pollutant Yield Approach (SLOSS-PHOSPH) (fact sheet, page A.19). This method uses two simplified loading algorithms to evaluate soil erosion, sedimentation, and phosphorus transport from distributed watershed areas. The SLOSS algorithm provides estimates of sediment yield, whereas the PHOSPH algorithm uses a loading function to evaluate the amount of sediment-bound phosphorus. Application to watershed and subwatershed levels was developed by Tim et al. (1991) based on an integrated approach coupling these algorithms with the Virginia Geographical Information System (VirGIS). The approach was applied to the Nomini Creek watershed, Westmoreland County, Virginia, to target critical areas of nonpoint source pollution at the subwatershed level (USEPA, 1992c). In this application, analysis was limited to phosphorus loading; however, other pollutants for which input data or default values are available can be modeled in a similar fashion. The approach requires full-scale GIS capability and trained personnel.

Watershed (fact sheet, page A.35). Watershed is a spreadsheet model developed at the University of Wisconsin to calculate phosphorus loading from point sources, combined sewer overflows (CSOs), septic tanks, rural croplands, and other urban and rural sources. It can be used to evaluate the trade-offs between control of point and nonpoint sources (Walker et al., 1989). It uses an annual time step to calculate total pollution loads and to evaluate the cost-effectiveness of pollution control practices in terms of cost per unit load reduction. The program uses a series of worksheets to summarize watershed characteristics and to estimate pollutant loadings for uncontrolled and controlled conditions. Because of the simple formulation describing the various pollutant loading processes, the model can be applied using available default values with minimum calibration effort. Watershed was applied to study the trade-offs between controlling point and nonpoint sources in the Delavan Lake watershed in Wisconsin.

The Federal Highway Administration (FHWA) Model (fact sheet, page A.11). The FHWA's Office of Engineering and Highway Operations has developed a simple statistical spreadsheet procedure to estimate pollutant loading and impacts to streams and lakes that receive highway stormwater runoff (Federal Highway Administration, 1990). The procedure uses several worksheets to tabulate site characteristics and other input parameters, as well as to calculate runoff volumes, pollutant loads, and the magnitude and frequency of occurrence of instream pollutant concentrations. The FHWA model uses a set of default values for pollutant event-mean concentrations that depend on traffic volume and the rural or urban setting of the highway's pathway. The Federal Highway Administration uses this method to identify and quantify the constituents of highway runoff and their potential effects on receiving waters and to identify areas that might require controls.

Watershed Management Model (WMM) (fact sheet, page A.37). The Watershed Management Model was developed for the Florida Department of Environmental Regulation for watershed management planning and estimation of watershed pollutant loads (Camp, Dresser, and McKee, 1992). Pollutants simulated include nitrogen, phosphorus, lead, and zinc from point and nonpoint sources. The model is implemented in the Lotus 1-2-3 spreadsheet environment and will thus calculate standard statistics and produce plots and bar charts of results. Although it was developed to predict annual loadings, this model can be adapted to predict seasonal loads provided that seasonal event mean concentration data are available. In the absence of site-specific information, the event concentrations derived from the NURP surveys may be used as default values. The model includes computational components for stream and lake water quality analysis using simple transport and transformation formulations based on travel time. The WMM has been applied to several watersheds including the development of a master plan for Jacksonville, Florida, and the Part II estimation of watershed loadings for the NPDES stormwater permitting process. It has also been applied in Norfolk County, Virginia; to a Watershed Management Plan for North Carolina; to a wasteload allocation study for Lake Tohopekaliga, near Orlando, Florida; and for water quality planning in Austin, Texas (Pantalion et al., 1995).

2.3.2 Mid-range models

Stormwater Intercept and Treatment Evaluation Model for Analysis and Planning (SITEMAP) (fact sheet, page A.23). SITEMAP, previously distributed under the name NPSMAP, is a dynamic simulation program that computes, tabulates, and displays daily runoff, pollutant loadings, infiltration, soil moisture, irrigation water demand, evapotranspiration, drainage to groundwater, and daily outflows, water and residual pollutant levels in retention basins or wetland systems (Omicron Associates, 1990). The model can be used to evaluate user-specified alternative control strategies, and it simulates stream segment load capacities (LCs) in an attempt to develop point source wasteload allocations (WLAs) and nonpoint source load allocations (LAs). Probability distributions for runoff and nutrient loadings can be calculated by the model based on either single-event or continuous simulations. The model can be applied in urban, agricultural, or complex watershed simulations. SITEMAP operates within the Lotus 1-2-3 programming environment and is capable of producing graphic output. Although this model requires a minimum calibration effort, it requires moderate effort to prepare input data files. The current version of the program considers only nutrient loading; sediment and other pollutants are not yet incorporated into the program. The model is easily interfaced with GIS (ARC/INFO) to facilitate preparation of land use files. SITEMAP has been applied as a component of a full watershed model to the Tualatin River basin for the Oregon Department of Environmental Quality, and to the Fairview Creek watershed for the Metropolitan Service District in Portland, Oregon.

Generalized Watershed Loading Functions (GWLF) Model (fact sheet, page A.13). The GWLF model was developed at Cornell University to assess the point and nonpoint loadings of nitrogen and phosphorus from urban and agricultural watersheds, including septic systems, and to evaluate the effectiveness of certain land use management practices (Haith et al., 1992). One advantage of this model is that it was written with the express purpose of requiring no calibration, making extensive use of default parameters. The GWLF model includes rainfall/runoff and erosion and sediment generation components, as well as total and dissolved nitrogen and phosphorus loadings. The current version of this model does not account for loadings of toxics and metals. The GWLF model uses daily time steps and allows analysis of annual and seasonal time series. The model also uses simple transport routing, based on the delivery ratio concept. In addition, simulation results can be used to identify and rank pollution sources and evaluate basinwide management programs and land use changes. The most recent update of the model incorporates a septic (on-site wastewater disposal) system component. The model also includes several reporting and graphical representations of simulation output to aid in interpretation of the results. This model was successfully tested on a medium-sized watershed in New York (Haith and Shoemaker, 1987). A version of the model with an enhanced user interface and linkages to national databases, WSM (Watershed Screening Model), has recently become available and is distributed with the EPA Office of Wetlands, Oceans and Watersheds' (OWOW's) computer program Watershed Screening and Targeting Tool (WSTT).

Urban Catchment Model (P8-UCM) (fact sheet, page A.17). The P8-UCM program was developed for the Narragansett Bay Project to simulate the generation and transport of stormwater runoff pollutants in small urban catchments and to assess impacts of development on water quality, with minimum site-specific data. It includes several routines for evaluating the expected removal efficiency for particular site plans, selecting or siting best management practices (BMPs) necessary to achieve a specified level of pollutant removal, and comparing the relative changes in pollutant loads as a watershed develops (Palmstrom and Walker, 1990). Default input parameters can be derived from NURP data and are available as a function of land use, land cover, and soil properties. However, without calibration, the use of model results should be limited to relative comparisons. Spreadsheet-like menus and on-line help documentation make extensive user interface possible. On-screen graphical representations of output are developed for a better interpretation of simulation results. The model also includes components for performing monthly or cumulative frequency distributions for flows and pollutant loadings.

Automated Q-ILLUDAS (AUTO-QI) (fact sheet, page A.5). AUTO-QI is a watershed model developed by the Illinois State Water Survey to perform continuous simulations of stormwater runoff from pervious and impervious urban lands (Terstriep et al., 1990). It also allows the examination of storm events or storm sequence impacts on receiving water. Critical events are also identified by the model. However, hourly weather input data are required. Several pollutants, including nutrients, chemical oxygen demand, metals, and bacteria, can be analyzed simultaneously. This model also includes a component to evaluate the relative effectiveness of best management practices. An updated version of AUTO-QI, with an improved user interface and linkage to a geographic information system (ARC/INFO on PRIME computer), has been completed by the Illinois State Water Survey. This interface is provided to generate the necessary input files related to land use, soils, and control measures. AUTO-QI was verified on the Boneyard Creek in Champaign, Illinois, and applied to the Calumet and Little Rivers to determine annual pollutant loadings.

Agricultural Nonpoint Source Pollution Model (AGNPS) (fact sheet, page A.1). Developed by the USDA Agricultural Research Service, AGNPS addresses concerns related to the potential impacts of point and nonpoint source pollution on water quality (Young et al., 1989). It was designed to quantitatively estimate pollution loads from agricultural watersheds and to assess the relative effects of alternative management programs. The model simulates surface water runoff along with nutrient and sediment constituents associated with agricultural nonpoint sources, as well as point sources such as feedlots, wastewater treatment plants, and stream bank or gully erosion. The available version of AGNPS is event-based; however, a continuous version is under active development (Needham and Young, 1993). The structure of the model consists of a square grid cell system to represent the spatial distribution of watershed properties. This grid system allows the model to be connected to other software such as GIS and digital elevation models (DEMs). This connectivity can facilitate the development of a number of the model's input parameters. Two new terrain-enhanced versions of the model— AGNPS-C, a contour-based version, and AGNPS-G, a grid-based version—have been developed to automatically generate the grid network and the required topographic parameters (Panuska et al., 1991). Vieux and Needham (1993) describe a GIS-based analysis of the sensitivity of AGNPS predictions to grid-cell size. Engel et al. (1993) present GRASS-based tools to assist with the preparation of model inputs and visualization and analysis of model results. Tim and Jolly (1994) used AGNPS with ARC/INFO to evaluate the effectiveness of several alternative management strategies in reducing sediment pollution in a 417 hectare watershed in southern Iowa. The model also includes enhanced graphical representations of input and output information.

Source Loading and Management Model (SLAMM) (fact sheet, page A.25). The SLAMM model (Pitt, 1993) can identify pollutant sources and evaluate the effects of a number of different stormwater control practices on runoff. The model performs continuous mass balances for particulate and dissolved pollutants and runoff volumes. Runoff is calculated by a method developed by Pitt (1987) for small-storm hydrology. Runoff is based on rainfall minus initial abstraction and infiltration and is calculated for both pervious and impervious areas. Triangular hydrographs, parameterized by a statistical approach, are used to simulate flow. Exponential buildup and rain wash-off and wind removal functions are used for pollutant loadings. Water and sediment from various source areas are tracked by source area as they are routed through various treatment devices. The program considers how particulates filter or settle out in control devices. Particulate removal is calculated based on the design characteristics of the basin or other removal device. Storage and overflow of devices are also considered. At the outfall locations, the characteristics of the source areas are used to determine pollutant loads in solid and dissolved phases. Loads from various source areas are summed. SLAMM has been used in conjunction with a receiving water quality model (HSPF) to examine the ultimate effects on urban runoff from Toronto for the Ontario Ministry of the Environment. SLAMM was also used to evaluate control options for controlling urban runoff in Madison, Wisconsin, using GIS information (Thum et al., 1990). The State of Wisconsin uses SLAMM as part of its Priority Watershed Program. It was used in Portland, Oregon, for a study evaluating CSOs.

2.3.3 Detailed models

Storage, Treatment, Overflow Runoff Model (STORM) (fact sheet, page A.27). STORM is a U.S. Army Corps of Engineers (COE) model developed for continuous simulation of runoff quantity and quality, including sediments and several conservative pollutants. It also simulates combined sewer systems (Hydrologic Engineering Center, 1977). STORM has been widely used for planning and evaluation of the trade-off between treatment and storage control options for CSOs. Long-term simulations of runoff quantity and quality can be used for the construction of duration-frequency diagrams. These diagrams are useful in developing urban planning alternatives and designing structural control practices. STORM was primarily designed for modeling stormwater runoff from urban areas. It requires relatively moderate to high calibration and input data. STORM was initially developed for mainframe computer usage; however, several versions have been adapted by various individual consultants for use on microcomputers. The model has been applied recently to water quality planning in the City of Austin, Texas (Pantalion et al., 1995).

Areal Nonpoint Source Watershed Environment Response Simulation Model (ANSWERS) (fact sheet, page A.3). ANSWERS is a comprehensive model developed to evaluate the effects of land use, management schemes, and conservation practices or structures on the quantity and quality of water from both agricultural and nonagricultural watersheds (Beasley, 1986). The distributed structure of this model allows for a better analysis of the spatial as well as temporal variability of pollution sources and loads. It was initially developed on a storm event basis to enhance the physical description of erosion and sediment transport processes. Data file preparation for the ANSWERS program is rather complex and requires mainframe capabilities, especially when dealing with large watersheds. The output routines are quite flexible; results may be obtained in several tabular and graphical forms. The program has been used to evaluate management practices for agricultural watersheds and construction sites in Indiana. It has been combined with extensive monitoring programs to evaluate the relative importance of point and nonpoint source contributions to Saginaw Bay. This application involved the computation of unit area loadings under different land use scenarios for evaluation of the trade-offs between load allocations (LAs) and wasteload allocations (WLAs). Recent model revisions include improvements to the nutrient transport and transformation subroutines (Dillaha et al., 1988). Bouraoui et al. (1993) describe the development of a continuous version of the model.

Multi-event urban runoff quality model (DR3M-QUAL) (fact sheet, page A.7). DR3M is a watershed model for routing storm runoff through a branched system of pipes and/or natural channels using rainfall as input. The model provides detailed simulation of storm-runoff periods selected by the user and a daily soil-moisture accounting between storms. Kinematic wave theory is used for routing flows over contributing overland-flow areas and through the channel network. Storm hydrographs may be saved for input to DR3M-QUAL, which simulates the quality of surface runoff from urban watersheds. The model simulates impervious areas, pervious area, and precipitation contributions to runoff quality, as well as the effects of street sweeping and/or detention storage. Variations of runoff quality are simulated for user-specified storm-runoff periods. Between these storms, a daily accounting of the accumulation and wash-off of water-quality constituents on effective impervious areas is maintained. Input to the model includes the storm hydrographs, usually from DR3M. The program has been extensively reviewed within the USGS and applied to several urban modeling studies (Brabets, 1986; Guay, 1990; Lindner-Lunsford and Ellis, 1987).

Simulation for Water Resources in Rural Basins - Water Quality (SWRRBWQ) (fact sheet, page A.31). The SWRRBWQ model was adapted from the field-scale CREAMS model by USDA to simulate hydrologic, sedimentation, nutrient, and pesticide movement in large, complex rural watersheds (Arnold et al., 1989). SWRRBWQ uses a daily time step to evaluate the effect of management decisions on water, sediment yields, and pollutant loadings. The processes simulated within this model include surface runoff, percolation, irrigation return flow, evapotranspiration, transmission losses, pond and reservoir storage, sedimentation, and crop growth. The model is useful for estimation of the order of magnitude of pollutant loadings from relatively small watersheds or watersheds with fairly uniform properties. Input requirements are relatively high, and experienced personnel are required for successful simulations. SWRRBWQ was used by the National Oceanic and Atmospheric Administration (NOAA) to evaluate pollutant loadings to coastal estuaries and embayments as part of its national Coastal Pollution Discharge Inventory. The model has been run for all major estuaries on the east coast, west coast, and Gulf coast for a wide range of pollutants (Donigian and Huber, 1991). Although SWRRBWQ is no longer under active development, the technology is being incorporated into the Soil and Water Assessment Tool (SWAT) as part of the Hydrologic Unit Model for the United States (HUMUS) project at Temple, Texas (Arnold et al., 1993; Srinivasan and Arnold, 1994). EPA's Office of Science and Technology (OST) has recently developed a Microsoft Windows-based interface for SWRRBWQ to allow convenient access to temperature, precipitation, and soil data files.

Storm Water Management Model (SWMM) (fact sheet, page A.29). SWMM is a comprehensive watershed-scale model developed by EPA (Huber and Dickinson, 1988). It was initially developed to address urban stormwater and assist in storm-event analysis and derivation of design criteria for structural control of urban stormwater pollution, but it was later upgraded to allow continuous simulation and application to complex watersheds and land uses. SWMM can be used to model several types of pollutants provided that input data are available. Recent versions of the model can be used for either continuous or storm event simulation with user-specified variable time steps. The model is relatively data-intensive and requires special effort for validation and calibration. Its application in detailed studies of complex watersheds might require a team effort and highly trained personnel. SWMM has been applied to address various urban water quantity and quality problems in many locations in the United States and other countries (Donigian and Huber, 1991; Huber, 1992). In addition to developing comprehensive watershed-scale planning, typical uses of SWMM include predicting CSOs, assessing the effectiveness of BMPs, providing input to short-time-increment dynamic receiving water quality models, and interpreting receiving water quality monitoring data (Donigian and Huber, 1991). Warwick and Tadepalli (1991) describe calibration and verification of SWMM on a 10-square-mile urbanized watershed in Dallas, Texas. Tsihrintzis et al. (1995) describe SWMM applications to four watersheds in South Florida representing high- and low-density residential, commercial, and highway land uses. Ovbiebo and She (1995) describe another application of SWMM in a subbasin of the Duwamish River, Washington. EPA's Office of Science and Technology distributes a Microsoft Windows interface for SWMM that makes the model more accessible. A postprocessor allows tabular and graphical display of model results and has a special section to help in model calibration.

The Hydrological Simulation Program - FORTRAN (HSPF) (fact sheet, page A.15). HSPF is a comprehensive package developed by EPA for simulating water quantity and quality for a wide range of organic and inorganic pollutants from complex watersheds (Bicknell et al., 1993). The model uses continuous simulations of water balance and pollutant generation, transformation, and transport. Time series of the runoff flow rate, sediment yield, and user-specified pollutant concentrations can be generated at any point in the watershed. The model also includes instream quality components for nutrient fate and transport, biochemical oxygen demand (BOD), dissolved oxygen (DO), pH, phytoplankton, zooplankton, and benthic algae. Statistical features are incorporated into the model to allow for frequency-duration analysis of specific output parameters. Data requirements for HSPF are extensive, and calibration and verification are recommended. The program is maintained on IBM microcomputers and DEC/VAX systems. Because of its comprehensive nature, the HSPF model requires highly trained personnel. It is recommended that its application to real case studies be carried out as a team effort. The model has been extensively used for both screening-level and detailed analyses. HSPF is being used by the Chesapeake Bay Program to model total watershed contributions of flow, sediment, nutrients, and associated constituents to the tidal region of the Bay (Donigian et al., 1990; Donigian and Patwardhan, 1992). Moore et al. (1992) describe an application to model BMP effects on a Tennessee watershed. Scheckenberger and Kennedy (1994) discuss how HSPF can be used in subwatershed planning. Ball et al. (1993) describe an application of HSPF in Australia. Lumb et al. (1990) describe an interactive program for data management and analysis that can be effectively used with HSPF. Lumb and Kittle (1993) present an expert system that can be used for calibration and application of HSPF. Donigian et al. (1996) describe the use of HSPF to identify and quantify the relative pollutant contributions from both point and nonpoint sources and to evaluate agricultural BMPs for the LeSueur basin of southern Minnesota.

2.4 Field-scale loading models

While watershed-scale loading models consider relatively large areas at an abbreviated level of detail, field-scale loading models represent smaller, homogenous areas in more depth. **Field-scale models** can be used to support watershed projects and TMDL development, particularly in the areas of management practices assessment and testing. In some cases, field-scale modeling can be used as a basis for the selection of recommended practices for basinwide implementation. For example, the CREAMS model was applied to representative fields in the Chesapeake Bay watershed to assess the benefits of various BMPs (Shirmohammadi et al., 1992). Field-scale models can be used as part of a "nested" modeling analysis, where results from the field-scale analysis are incorporated into larger basin- or watershed-scale modeling efforts. Field-scale models can therefore be useful in assessing management practices on a microscale as part of designing plans to achieve nonpoint source load reductions for watershed studies and TMDLs.

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Field-scale loading models address many of the interactive processes that occur in a small catchment or field. They are generally continuous models that can be used to study the effects of alternative management scenarios on the movement of water and pollutants within and from a small catchment system. Four public-domain field-scale models developed by the U.S. Department of Agriculture's Agricultural Research Service (USDA-ARS) are presented here. Chemicals, Runoff, and Erosion from Agricultural Management Systems (CREAMS) and Groundwater Loading Effects of Agricultural Management Systems (GLEAMS) are well-documented models that have gained wide acceptance among users. Opus (not an acronym) is a state-of-the-art field-scale model that comprehensively represents both physical and chemical processes occurring in an agricultural field. The Water Erosion Prediction Project (WEPP) model was developed to provide predictions of water erosion based on fundamental hydrologic and erosion mechanics science.

Brief descriptions of each of the field-scale models are included below. Since field-scale models are of only limited applicability to watershed planning, no fact sheets are included for the models.

CREAMS/GLEAMS. CREAMS is a lumped-parameter, continuous simulation model that uses separate hydrology, erosion, and chemistry submodels connected by pass files. The hydrology component has two options, depending on availability of rainfall data. Option one uses daily rainfall with runoff estimated using the Soil Conservation Service (SCS) curve number, while option two requires hourly (breakpoint) rainfall with runoff estimated using the Green-Ampt equation. The erosion component uses the Universal Soil Loss Equation (USLE) parameters but considers the basic processes of soil detachment, transport, and deposition. The basic concepts for modeling treat nutrient transport as proceeding separately in adsorbed and dissolved phases. Soil nitrogen is modified by nitrification-denitrification processes and by plant uptake. Pesticides in runoff are partitioned between the solution and sediment phases using a simplified isotherm model.

CREAMS allows the simulation of user-defined agricultural BMPs including soil incorporation of pesticides and various conservation tillage practices. CREAMS is no longer under active development and has been replaced by the GLEAMS model.

The hydrology and erosion components in CREAMS and GLEAMS are very similar. However, option two in the hydrology component of CREAMS is not available in GLEAMS, and several erosion parameters that were user-specified in CREAMS are internally driven in GLEAMS. The nutrient component in GLEAMS contains significant enhancements over the CREAMS nutrient component, using detailed consideration of various nitrogen and phosphorus transformation processes. Animal waste applications can be explicitly modeled, with estimates of decomposition and disposition. GLEAMS also has a more comprehensive component for subsurface routing and mass-balance of pesticides and nutrients. Alternative land-use management options are typically specified by changes in the SCS curve number and Universal Soil Loss Equation (USLE) parameters.

Cooper et al. (1992) evaluated the ability of the CREAMS model to predict loadings of runoff, sediment, and nutrients from a New Zealand grazed pasture. They concluded that although CREAMS has limitations in representing the dynamics of grazed pastures, it shows potential as a water quality management tool in pastoral watersheds. Reyes et al. (1993) modified GLEAMS to account for shallow water table fluctuations and improve its ability to simulate nonpoint loadings in alluvial shallow water table soils. Yoon et al. (1994) applied GLEAMS to predict nutrient losses from land application of poultry litter.

The GLEAMS model can be obtained by writing to David C. Moffitt at the South National Technical Center, P.O. Box 6567, Fort Worth, TX 76115 or contacting him at (817) 334-5232 extension 3650.

Opus. Opus (not an acronym) is a lumped-parameter, continuous simulation model for studying the potential pollution from various agricultural management practices. The model simulates the effect of weather, soil type, crop, topography, and management action on nonpoint source pollutant losses. Processes modeled include hydrology, erosion, crop growth, agricultural management, nutrient cycling and transport, and pesticide fate and transport. The model allows detailed simulation using breakpoint data on the time-intensity pattern of rainfall or a more lumped approach using either recorded daily rainfall or stochastically generated rainfall. The field size in Opus is limited to catchments with a single rain gage record and a single soil profile. The simulation time step in Opus varies by process and conditions from fractions of a second in some hydrologic components to years in annual management cycles, with many processes proceeding on a daily time step.

Management options in Opus are specified as part of the field description. These include the type and direction of tillage, and the use of terracing, impoundments, and grass buffer strips. Management is assumed to occur on a multiyear rotation basis. The user can choose crops to grow, tillage procedures to use, and pesticide and nutrient (including animal waste) applications. Zacharias and Heatwole (1993) evaluated the ability of Opus to predict differences in pesticide losses from two plots under alternative tillage practices.

The Opus model may be obtained by contacting Roger E. Smith at USDA-ARS, Water Management Research Unit, AERC CSU, Fort Collins, CO 80523 or contacting him at (970) 491-8511 or roger@lily.aerc.colostate.edu.

Water Erosion Prediction Project (WEPP). The WEPP model is a distributed-parameter, continuous-simulation model developed to provide a new generation of water erosion prediction technology. The model requires inputs for rainfall amounts and intensity; soil textural qualities; plant growth parameters; residue decomposition parameters; effects of tillage implements on soil properties and residue amounts; slope shape, steepness, and orientation; and soil erodibility parameters. Parameters used for predicting erosion, including soil roughness, surface residue cover, canopy height, canopy cover, and soil moisture are updated on a daily basis. The basic output from WEPP consists of runoff and erosion summary information, which can be produced on a storm-by-storm, monthly, annual, or average annual basis. The time-integrated estimates of runoff, erosion, sediment delivery, and sediment enrichment are contained in this output, as well as the spatial distribution of erosion.

Tillage impacts on various soil properties and model parameters are simulated within the soils component of the WEPP model. Tillage activity during a simulation results in a decrease in soil bulk density, increase in soil porosity, changes in soil roughness and ridge height, rill destruction, increased infiltration, and changes in erodibility parameters. WEPP simulates consolidation, including its impacts on soil parameters due to time and rainfall after tillage. The plant growth component in WEPP predicts potential growth based on daily heat accumulation, with actual growth decreased depending on moisture and temperature stress, and actual nitrogen uptake. Several types of residue management may be represented in WEPP including residue removal, shredding, burning, and contact herbicide application. The most recent release of WEPP (version 95.7) allows watershed-scale simulation. The watershed simulation component combines results from each field (or hillslope) and routes sediment and runoff through channels and impoundments in the watershed. Additional inputs required for watershed applications include channel soils, topography, and hydraulic characteristics, and specification of impoundments if present.

Tiscareno-Lopez et al. (1993, 1994) present the results of a sensitivity analysis of WEPP for rangeland applications. Elliot et al. (1995) used WEPP to simulate erosion losses from timber harvest areas. They concluded that the model showed considerable promise as a tool to help forest managers predict the onsite erosion and offsite sedimentation due to timber harvest.

The WEPP model can be obtained by writing to Dennis Flanagan, USDA-ARS-NSERL, 1196 Building SOIL, Purdue University, West Lafayette, IN 47907-1196 or contacting him at (317) 494-8673 or Flanagan@soils.ecn.purdue.edu.

2.5 Receiving water models

The use of models to predict a receiving waterbody's response to various pollutant loading scenarios is often an important aspect of watershed assessment and TMDL development. Receiving water models are used to examine the interactions between loadings and response, evaluate loading capacities (LCs), and test various loading scenarios. As with watershed loading models, receiving water models vary widely in complexity. For traditional point source abatement, where biodegradable pollutant discharges are the major concern, simple, steady-state models of the dissolved oxygen (DO) balance are commonly used by planners and pollution control authorities. For assessment of eutrophication and toxics, more comprehensive models have evolved to incorporate a wider range of processes. Other recent reviews of receiving water models include Ambrose et al. (1995). For additional sources of information related to receiving water models, refer to the list of references in Table 1.

A fundamental concept for the analysis of receiving waterbody response to point and nonpoint source inputs is the principle of mass balance (or continuity). Receiving water models typically develop a mass balance for one or more interacting constituents, taking into account three factors: transport through the system, reactions within the system, and inputs into the system. The first factor describes the hydrologic and hydrodynamic regime of the water system; the second, the biological, chemical, and physical reactions that affect constituents; and the third, the inputs to or withdrawals from the system because of anthropogenic activities and natural phenomena (O'Conner et al., 1975). The complexity of a receiving water model depends on the way in which these three factors are incorporated. The simplest models use a steady-state, one-dimensional framework with steady inputs. The more complex models typically use hydrodynamic relationships, consider interactions between constituents, allow distributed nonpoint inputs, and are capable of providing dynamic, multidimensional simulations.

Receiving water models are used to examine the interactions between loadings and response, evaluate loading capacities (LCs), and test various loading scenarios.

The various physical, chemical, and biological processes considered by a receiving water model are represented mathematically by mechanistic and/or empirical relationships between forcing functions and state variables (Jorgensen, 1989). Forcing functions are variables or functions of an external nature that are regarded in the model formulation as directly influencing the state of the receiving waterbody. Point and nonpoint source loadings to the waterbody are examples of forcing functions; other examples are temperature and solar radiation. State variables, such as DO and chlorophyll *a* concentrations, define the state of the receiving waterbody. When the predicted values of state variables change because of changes to forcing functions, the state variables are regarded as model outputs. In the context of TMDL development, the typical situation would involve manipulating forcing functions that are controllable (e.g., point source loadings and, to an extent, nonpoint source loadings) and observing the effect on state variables of interest.

Receiving water models are typically described in terms of their representation of space (spatial domain), time (temporal domain), flow simulation (hydrodynamics), transport processes, inputs (forcing functions), and state variables. Other factors considered in the review of receiving water models include user interface and inherent application complexity. For discussion purposes, receiving water models are grouped into three classes—hydrodynamic models, steady-state water quality models, and dynamic water quality models. The features and evaluation criteria for each class are discussed below. Brief descriptions of each of the models included in each type of model follow this section. Near-field models, or mixing zone models, are briefly discussed in a separate section. Summary tables are not included for these models, although fact sheets are provided in Appendix B.

Hydrodynamic models. Surface water flow is fundamental to the simulation of pollutant transport and transformation in waterbodies. Some of the key physical factors affecting the health of a waterbody include the quantity and velocity of flow. Hydrodynamic models simulate the "dynamic" or time-varying features of water transport. For impoundments (lakes and reservoirs), the period of time the water is held within the system (or retention time) affects eutrophication and toxic-related processes. For estuarine systems, mixing and flushing due to tidal influences and external freshwater inputs are essential to understanding internal processes.

Hydrodynamic models can potentially represent the features of water movement in rivers, streams, lakes, reservoirs, estuaries, near-coastal waters, and wetland systems. Depending on the type of system and the model capabilities, spatial dimensions of the simulation can include 1-D longitudinal, 2-D in the vertical, 2-D in the horizontal, or fully 3-D formulations. Some 3-D models can be effectively "collapsed" to simulate systems as 1-D or 2-D. Hydrodynamic models employ numerical solutions of the fundamental governing equations in order to predict water movement based on bottom topography and shoreline geometry. Higher-order hydrodynamic models represent systems as a cartesian grid or a curvilinear orthogonal grid (Mobley and Stewart, 1980; Ryskin and Leal, 1983). Grid generation software can facilitate the interpolation of spatially varying model input data, such as bottom topography, initial water depth, and bottom roughness, into cell inputs. Physical processes that may be included in hydrodynamic models include tidal, wind, and buoyancy or density forcing, and turbulent momentum and mass transport. For shallow systems, such as some estuaries or wetlands, the ability of the model to represent wetting and drying is essential. The representation of vegetation resistance below and above the water surface can also be important in shallow surface water systems. The representation of flow control by hydraulic structures may need to be included for reservoir or managed river systems. Water balance components such as rainfall, evaporation, infiltration, and groundwater interactions can affect systems as well. For impounded waters, the ability of the model to perform thermal simulation with surface heat exchange is also desirable.

Hydrodynamic models simulate the "dynamic" or time-varying features of water transport.

Some hydrodynamic models (RIVMOD, DYNHYD5, EFDC, CH3D-WES) are distributed as stand-alone models and can be externally coupled with water quality models such as WASP5 and CE-QUAL-ICM. Other hydrodynamic models are internally coupled, or connected, to the water quality and toxic simulation programs. The CE-QUAL-RIV1 and CE-QUAL-W2 models are examples of internally coupled formulation. Table 5 describes the key features of both the stand-alone hydrodynamic models and the internally coupled models. Models that are limited to steady-state (no variation in time) applications are included in the water quality modeling section. A review of the table shows that capabilities vary widely in terms of dimension. For river modeling, a 1-D formulation is usually sufficient, although for certain applications (e.g., sediment transport) 2-D horizontal models have been used. Modeling of lakes is typically limited to 2-D vertical (x/z) models except in rare cases, such as shallow, well-mixed lakes, where a 1-D representation is sufficient. Estuaries are most frequently simulated using fully 3-D hydrodynamic grids to account for the complex mixing and transport processes.

Water quality models. Water quality models can simulate the chemical and biological processes that occur within a waterbody system, based on external and internal inputs and reactions. For more detailed information on water quality modeling for nutrients and eutrophication, refer to USEPA, 1995. Eutrophication models include those which simulate biological inputs, nutrients, and algal growth in rivers, streams, lakes, reservoirs, and estuaries. Other receiving water models specialize in the simulation of toxic constituents and their transformation and degradation in waterbodies.

Water quality models can also be grouped by how they address changes over time. As mentioned above, some models employ a steady-state formulation for simulation purposes. Typical steady-state applications include use of design flow, or preselected critical conditions, for the assessment of steady-state water quality impacts. Steady-state formulations are the most commonly used and the easiest to implement. However, steady-state applications are limited when addressing time-variable inputs such as nonpoint source loads or examining waterbodies that experience short-term violations of acute criteria (e.g., storm or CSO events).

For more detailed assessments of time-varying conditions in receiving waters, water quality models can be linked with hydrodynamic models. As discussed earlier, hydrodynamic models are either internally or externally coupled to water quality models for dynamic simulations of receiving waters. The use of dynamic water quality models allows for a more detailed evaluation of time-varying inputs, such as nonpoint sources, and the examination of the short- and longer-term receiving water response. Fully dynamic applications require a significant level of effort in order to prepare data input files; set up, calibrate, and validate the model; and process output data. Dynamic models can also be applied to steady-state conditions. In some cases, because of their detailed algorithms and capabilities, dynamic models are used in steady-state applications for testing and analysis of constituent interactions.

Table 5. Evaluation of Capabilities—Hydrodynamic models

	Externally Coupled Models				Internally Coupled Models		
	RIVMOD	DYNHYD5	EFDC	CH3D-WES	CE-QUAL-RIV1	CE-QUAL-W2	HSPF
Waterbody Type							
Rivers/Streams	●	●	●	●	●	●	◐
Lakes/Reservoirs	○	○	●	●	○	●	○
Dimension	○	◒	●	●			
1-D	●	●	●	●	●	●	◐
2-D	-	-	●	●	-	●	-
3-D	-	-	●	●	-	-	-
Input Data Requirements							
Requirements	○	○	●	●	○	◒	◒
Calibration	●	●	●	●	●	●	◐
Grid generation/Interface	-	-	●	○	-	-	-
Output Data							
Format options	●	●	●	○	●	●	◐
Graphics	○	◒	○	○	○	○	○
Hydrologic Structure Simulation	●	○	●	●	●	●	◒
Expertise Required for Application	○	○	●	●	○	◒	◒
Documentation	●	●	●	●	●	●	◐

● High ◒ Medium ○ Low - Not Incorporated

> **Water quality models** can simulate the chemical and biological processes that occur within a waterbody system, based on external and internal inputs and reactions.

In addition to the physical/hydrologic essentials discussed above, the principal differentiating factors for characterizing water quality models is how they address the processes of advection, dispersion, and reaction. Advection is the primary transport mechanism in a downstream and/or lateral direction. Advective transport is often the dominant net transport mechanism, except in certain tidally mixed systems. Dispersive transport represents mixing (lateral and longitudinal) caused by local velocity gradients. Although dispersive transport is present to some extent in all bodies of water, it is typically minimal in rivers, lakes, and reservoirs. Dispersive transport can dominate, however, in tidally mixed systems. Reactions include the processes and transformation of constituents within a waterbody. For eutrophication models, temperature, oxygen, and nutrient cycling processes, and in some cases carbon cycling, phytoplankton, periphyton, and aquatic plants, are considered. For assessment of toxics, models can include transformation, speciation, and degradation of constituents. For both eutrophication and toxics, the interactions of constituents with the bottom sediments are of concern. In some cases users can define fluxes from the bottom sediments. Other models use sophisticated simulations of sediment diagenesis. Modelers continue to develop and link improved models of sediment diagenesis to water quality models (e.g., CE-QUAL-ICM).

Tables 6 and 7 present a summary of the key features of water quality models. Steady-state and dynamic models are grouped separately for review purposes. Short descriptions of each of the models discussed are presented in the following sections under the sub-headings of hydrodynamic models, steady-state water quality models, and dynamic water quality models. Fact sheets for the specific models are provided in Appendix B.

River Hydrodynamics Model (RIVMOD-H) (fact sheet, page B.31). RIVMOD-H is the hydrodynamic submodel of a dynamic sediment transport model (Hosseinipour et al., 1994). The model provides predictions of gradually or rapidly varying flow in water bodies which can be regarded as one-dimensional. RIVMOD-H is based on a model originally developed in the mid-1970s (Amein and Chu, 1975), which was modified to accept time-varying lateral inflows by Brown and Hosseinipour (1991). The governing flow equations are solved using a numerically efficient fully implicit scheme that allows the use of longer computational time steps. RIVMOD-H has been soft-linked to the WASP5 model to provide hydrodynamic flow computations as part of the LWMM modeling system (Dames and Moore, 1994). Warwick and Helm (1995) provide a comparison of the RIVMOD-H and DYNHYD5 models.

2.5.1 Hydrodynamic Models

Link-node tidal hydrodynamic model (DYNHYD5) (fact sheet, page B.13). DYNHYD5 is a one-dimensional model that uses the relatively simple link-node concept to represent a waterbody (Ambrose et al., 1987). The link-node representation is best applied to branching systems such as tidal rivers. The model solves the one-dimensional equations of continuity and momentum describing the movement of a long wave in a shallow water system. The model is distributed as a companion model to WASP5 and is typically applied externally to provide hydrodynamic flow computations, which are then input to WASP5. Most applications of DYNHYD5 will use a simulation time step on the order of 30 seconds to 5 minutes due to stability requirements. However, the hydrodynamic output file created by DYNHYD5 may be stored at any user-specified interval for use by a water quality simulation program. This interval may range from 1 to 24 hours, depending on the type of water quality simulation desired. If interest is focused on tide-induced transport, a 1- to 3-hour interval should be used. On the other hand, with long-term simulations, a time interval of 12 to 24 hours would be appropriate (Tetra Tech, 1995).

Environmental Fluid Dynamics Computer Code (EFDC) (fact sheet, page B.17). EFDC is a general-purpose three-dimensional hydrodynamic and salinity numerical model (Hamrick, 1992). The model may be applied to a wide range of boundary-layer-type environmental flows that can be regarded as vertically hydrostatic. The model code uses a finite-difference scheme to solve the equations of motion and transport, simulating density and topographically induced circulation, as well as tidal and wind-driven flows, and spatial and temporal distributions of salinity, temperature, and sediment concentration. In addition, the wetting and drying of shallow areas, hydraulic control structures, vegetation resistance for wetlands, and Lagrangian particle tracking may also be simulated by the model. EFDC has been integrated with a water quality model to develop a three-dimensional hydrodynamic-eutrophication model, HEM-3D (Park et al., 1995). The model was used to develop a three-dimensional hydrodynamic and salinity numerical model of the Indian River Lagoon/Turkey Creek, with calibration and validation for St. Johns river water management district, Palatka, Florida (Tetra Tech, 1994). The EFDC model was linked to WASP5 for application to the Norwalk Harbor estuary in Norwalk, Connecticut, for the purposes of developing a TMDL (Stoddard et al., 1995).

Curvilinear Hydrodynamics in Three-Dimensions-Waterways Experiment Station (CH3D-WES) (fact sheet being prepared, page B.7). CH3D-WES was developed as part of the Chesapeake Bay Model Package described by Cerco and Cole (1993). The model is derived from the CH3D model (Sheng, 1986) and uses a general curvilinear horizontal grid and a physical (Cartesian) vertical grid to provide computations of water surface, three-dimensional velocity field, salinity, and temperature. The governing equations are solved using a numerically efficient finite-difference scheme described by Johnson et al. (1991). The CH3D-WES includes consideration of the physical processes of tides, wind, freshwater inflows, turbulence, density effects (salinity and temperature), and the effect of the earth's rotation. The vertical turbulence algorithms included in the model provide improved representation of stratification and destratification in complex waterbodies such as the Chesapeake Bay. Johnson et al. (1993) describe the validation of CH3D-WES in an application to six data sets from the Chesapeake Bay.

Table 6. Evaluation of Capabilities—Steady-state water quality models.

	EPA SCREENING	EUTROMOD	PHOSMOD	BATHTUB	QUAL2E	EXAMSII	TOXMOD	SMPTOX4	TPM	DECAL
Water Body Type										
Rivers/Streams	●	-	-	-	●	●	-	●	-	-
Lakes/Reservoirs	●	●	●	●	○	-	●	-	-	-
Estuaries	●	-	-	-	◐	-	-	-	●	-
Coastal	-	-	-	-	-	-	-	-	-	●
Physical Processes										
Advection	●	-	-	●	●	●	-	●	●	●
Dispersion	●	-	-	●	●	●	-	●	●	●
Particle Fate	○	○	○	○	-	○	○	●	●	●
Eutrophication	●	●	●	●	●	-	-	-	●	-
Chemical Fate	●	-	-	○	○	●	●	●	○	●
Sediment-Water Interactions	○	○	◐	○	○	◐	◐	◐	●	◐
External Loading-Dynamic	●	●	●	●	●	●	●	●	●	●
Internally Calculated NPS Loading	-	●	-	-	-	-	-	-	-	-
User Interface	-	●	●	○	○	●	●	●	-	○
Documentation	●	●	●	●	●	●	●	●	●	●

● High ◐ Medium ○ Low - Not Incorporated

EPA Screening Procedures (fact sheet, page A.9). The EPA Screening Procedures are a compilation of simplified methodologies that allow preliminary assessment of conventional and toxic pollutants in rivers, impoundments, and estuaries (Mills et al., 1985). Additionally, methods are included to calculate initial dilution from a wastewater discharge. The compilation includes introductory material for each of the methodologies to provide orientation toward relevant theory, and to state limitations of the methodologies due to assumptions and simplifications. Conventional pollutants considered in the screening procedures are BOD-DO, temperature, coliform bacteria, nutrients, and sediment transport. The fate of toxics is assessed considering volatilization, sorption, and first-order degradation. The EPA Screening Procedures can be implemented using a hand-held calculator or spreadsheet program. Bowie et al. (1985) provide a comprehensive source of information on rate constants and coefficients that may be used in applying the screening procedures.

2.5.2 Steady-state water quality models

Watershed and Lake Modeling Software (EUTROMOD) (fact sheet, page B.19). EUTROMOD is a spreadsheet-based modeling procedure for eutrophication management developed at Duke University and distributed by the North American Lake Management Society (Reckhow, 1990). The steady-state modeling system allows for internal calculations of both nonpoint source loading and lake response. The system estimates nutrient loadings, various trophic state parameters, and trihalomethane concentrations in lake water. The computation algorithms used in EUTROMOD were developed based on statistical relationships and a continuously stirred tank reactor model. Model results include the most likely predicted phosphorus and nitrogen loading for the watershed and for each land use category. The model also determines the lake response to various pollution loading rates. The spreadsheet capabilities of the model allow graphical representations of the results and data export to other spreadsheet systems for statistical analyses. The model was used in conjunction with a GIS for establishing TMDLs to Wister Lake, Oklahoma (Hession et al., 1995).

Table 7. Evaluation of Capabilities—Dynamic Water Quality Models

	DYNTOX	WASP5	CE-QUAL-R1	CE-QUAL-W2	CE-QUAL-ICM	HSPF
Water Body Type						
Rivers/Streams	●	●	●	●	●	●
Lakes/Reservoirs	-	○	-	●	●	○
Estuaries	-	●	-	◒	●	-
Coastal	-	◒	-	○	●	-
Physical Processes						
Advection	●	●	●	●	●	●
Dispersion		●	●	●	●	-
Heat Balance	-	-	●	●	●	●
Particle Fate	-	◒	◒	◒	●	●
Eutrophication	-	●	●	●	●	●
Chemical Fate	○	●	○	○	○	●
Sediment-Water Interactions	-	◒	○	◒	●	○
External Loading-Dynamic	○	●	●	●	●	●
Internally Calculated NPS Loading	-	-	-	-	-	●
User Interface	●	○	-	-	-	○
Documentation	◒	●	◒	◒	◒	●

● High ◒ Medium ○ Low - Not Incorporated

Seasonal and Long-term Trends of Total Phosphorus and Oxygen in Stratified Lakes (PHOSMOD) (fact sheet, page B.25). PHOSMOD is a budget model that can predict the long-term response of a lake to changes in phosphorus loading (Chapra and Canale, 1991). In the model, the lake is treated as two layers: a water layer and a surface sediment layer. A total phosphorus budget for the water layer is developed with inputs from external loading and recycling from the sediments and considering losses due to flushing and settling. In the sediment layer budget, total phosphorus is gained by settling and lost by recycling and burial. The sediment-to-water recycling is dependent on the levels of sediment total phosphorus and hypolimnetic oxygen, with the concentration of the latter estimated with a semi-empirical model. Chapra and Canale (1991) present an application of the model and an analysis to demonstrate how the model predictions replicate in-lake changes not possible with simpler phosphorus budget models.

BATHTUB (fact sheet, page B.23). FLUX, PROFILE, and BATHTUB (Walker, 1986) are a collection of programs designed to assist in the data reduction and model implementation phases of eutrophication studies in lakes and reservoirs. FLUX is a tool for data reduction and preprocessing of tributary nutrient loadings from grab sampling and flow records. The program can assist in error detection and sampling program design. PROFILE provides displays of lake water quality data and assists in analysis of sampling information. Data analysis procedures include hypolimnetic oxygen depletion rates, spatial and temporal variability, and statistical summaries. BATHTUB allows the user to segment the lake into a hydraulic network. Nutrient balance and eutrophication models can be applied to the network to assess advection, dispersion, and nutrient sedimentation. Empirical relationships that have been calibrated and tested for reservoir applications are used to predict eutrophication-related water quality conditions. The segmented structure of BATHTUB allows its application to single reservoirs, partial reservoirs, networks of reservoirs, or collections of reservoirs, permitting regional comparative assessments of reservoir conditions, controlling factors, and model performance. Inputs and outputs can be expressed in probabilistic terms to account for limitations in input data and intrinsic model errors. The programs and models have been applied to U.S. Army Corps of Engineer reservoirs (Kennedy, 1995), as well as a number of other lakes and reservoirs. BATHTUB was recently cited as an effective tool for lake and reservoir water quality assessment and management, particularly where data are limited (Ernst et al., 1994).

Enhanced Stream Water Quality Model (QUAL2E) (fact sheet, page B.29). QUAL2E, originally developed in the early 1970s, is a one-dimensional water quality model that assumes steady-state flow but allows simulation of diurnal variations in temperature or algal photosynthesis and respiration (Brown and Barnwell, 1987). QUAL2E represents the stream as a system of reaches of variable length, each of which is subdivided into computational elements that have the same length in all reaches. Withdrawals, branches, and tributaries can be incorporated into the prototype representation of the stream system. The basic equation used in QUAL2E is the one-dimensional advection-dispersion mass transport equation. An implicit, backward difference scheme, averaged over time and space, is employed to solve the equation. Water quality constituents simulated include conservative substances, temperature, bacteria, BOD, DO, ammonia, nitrate and organic nitrogen, phosphate and organic phosphorus, and algae. QUAL2E includes components that allow quick implementation of uncertainty analysis using sensitivity analysis, first-order error analysis, or Monte Carlo simulation. The model has been widely used for stream wasteload allocations and discharge permit determinations in the United States and other countries. Paschal and Mueller (1991) used QUAL2E to evaluate the effects of wastewater effluent on the South Platte River from Chatfield reservoir through Denver, Colorado. Cubilo et al. (1992) applied QUAL2E to the major rivers of the *Comunidad de Madrid* in Spain. Little and Williams (1992) describe a nonlinear regression programming model for calibrating QUAL2E. Johnson and Mercer (1994) report a QUAL2E application to the Chicago waterway and Upper Illinois River waterway to predict DO and other constituents in the DO cycle in response to various water pollution controls. EPA's Office of Science and Technology (OST) has recently developed a Microsoft Windows-based interface for QUAL2E that facilitates data input and output evaluation.

Exposure Analysis Modeling System (EXAMSII) (fact sheet, page B.21). EXAMSII (Burns, 1990) is an interactive modeling system that uses the principle of mass balance and mathematical models of the kinetics and processes governing the transport and transformation of chemicals to provide predictions of their probable fate and persistence in aquatic ecosystems. EXAMSII is designed to evaluate the fate, exposure, and persistence of toxic chemicals in water systems where the concentrations of pollutants are at trace levels and the pollutant loading rates can be assumed to be at steady state. The hydrologic transport processes considered are advection and dispersion. The transformation processes included in the model are photolysis, hydrolysis, biotransformation, oxidation, and sorption with sediments and biota. Secondary daughter products and subsequent degradation of these products are also considered. The interactive nature of EXAMSII and the ability of the modeling system to store and easily modify previous inputs allows rapid and convenient analysis of chemical fate and transport in aquatic ecosystems.

TOXMOD (fact sheet, page B.35). TOXMOD is based on an extension of a modeling framework presented by Chapra (1991) to assess the impact of toxic organic compounds on lakes and impoundments. As in PHOSMOD, the receiving waterbody is idealized as a lumped system consisting of a well-mixed reactor (water layer) underlaid by a well-mixed sediment layer. A steady-state mass balance is developed for solids and the toxic. The toxic is partitioned into dissolved and particulate forms, with the dissolved form for both water and sediment layers further subdivided into a component associated with dissolved organic carbon. Particulates in the water layer are subdivided into abiotic and biotic suspended solids. Burial and resuspension are considered for both dissolved and particulate forms while diffusion acts selectively on the dissolved fraction. Chapra (1991) has used the modeling framework on which TOXMOD is based to develop a procedure for identifying priority pollutants that exhibit the weakest assimilative capacity for a range of lakes.

Simplified Method Program - Variable Complexity Stream Toxics Model (SMPTOX4) (fact sheet, page B.33). SMPTOX4 is a one-dimensional, steady-state model based on an EPA-recommended technique (USEPA, 1980) for calculating water column and streambed toxic substance concentrations caused by point source discharges into streams and rivers. Three levels of complexity are available within the model. At the simplest level, only total toxic pollutants can be predicted. The next level can be used to predict toxic water column concentrations, but interactions with bed sediments are not considered. The third level allows prediction of pollutant concentrations in dissolved and particulate phases for the water column and bed sediments, as well as the total suspended solids concentrations. Operating within a Windows environment, SMPTOX4 allows quick data input and easy access to routines for graphical output, sensitivity analysis, and uncertainty analysis. SMPTOX4 also contains a data base of chemical properties for many chemicals of concern.

Tidal Prism Model (TPM) (fact sheet, page B.37). TPM was originally developed as a tool for water quality management of small coastal basins (Kuo and Neilson, 1988). Physical transport processes are simulated in terms of the concept of tidal flushing. The numerical solution scheme implemented for solving the tidal flushing equations is well suited to application in small coastal basins, including those with a high degree of branching (Kuo and Park, 1994). The model allows consideration of shallow embayments connected to the primary branches in the basin. The basic assumptions in the model are that the tide rises and falls simultaneously throughout the waterbody and that the system is in hydrodynamic equilibrium. Kinetic formulations in TPM are similar to those in CE-QUAL-ICM (Cerco and Cole, 1993), and 23 state variables, including total active metal, fecal coliform bacteria, and temperature, can be simulated. TPM includes a sediment submodel, also based on the sediment process model in CE-QUAL-ICM, that considers the depositional flux of particulate organic matter, its diagenesis, and the resulting sediment flux. TPM has been applied to a number of tidal creeks and coastal embayments in Virginia (Kuo and Neilson, 1988).

Simplified Deposition Calculation for Organic Accumulation Near Marine Outfalls (DECAL) (fact sheet, page B.11). DECAL is a steady-state analytical model of sediment deposition for coastal areas impacted by outfalls (Farley, 1990). The model predicts metal and trace organic chemical accumulations in sediments near municipal ocean outfalls. DECAL considers coastal transport, particle dynamics, and organic carbon cycles. The model simulates the effects of coagulation and settling of effluent particles and natural organic material; however, bioturbation and sediment diagenesis of organic carbon are not included. Sediment-water exchange can be considered using a coefficient. When the coefficient is specified in units of reciprocal time, DECAL computes the flux of organic matter and a trace constituent to sediments. If the coefficient is specified in units of length per time, the accumulation of organic matter and trace constituent in bed sediments is computed. Short-term current speeds and directions and the components of the tidal ellipse, as well as long-term net advection currents and directions, have to be specified by the user. An application of DECAL to outfalls in Orange and Los Angeles counties in California showed model predictions agreed quite well with field observations (Farley, 1990).

Dynamic Toxics wasteload allocation model (DYNTOX) (fact sheet, page B.15). DYNTOX was developed for use in wasteload allocation of toxic substances (Limno-Tech, 1994). The fundamental analytical solution used in DYNTOX assumes a steady-state condition over the course of one day. The model provides a probabilistic framework for assessing toxic discharge impacts over a range of historical and future conditions. Three probabilistic simulation techniques can be used to calculate the frequency and severity of instream toxicity at different effluent discharge levels. In the continuous simulation approach, the model is run for a specified period of recorded history and the results are analyzed for frequency and duration. In the Monte Carlo method, inputs are described by probability distributions. Random input sets are then used to execute the model repeatedly and describe the model output in terms of a probability distribution. Both the continuous simulation and Monte Carlo methods produce probability distributions of calculated daily downstream concentrations from which the recurrence interval of any concentration of interest can be obtained. Probability distributions of running-averaged concentrations for any time period of interest can also be obtained. The lognormal analysis requires that all inputs be described by lognormal distributions, which allows computation of exceedance probabilities for the toxic concentration at the point of mixing through numerical integration.

2.5.3 Dynamic water quality models

Water Quality Analysis Simulation Program (WASP5) (fact sheet, page B.39). WASP5 is a general-purpose modeling system for assessing the fate and transport of conventional and toxic pollutants in surface waterbodies (Ambrose, 1987). WASP5 has a modular structure and allows the incorporation of specialized user-written routines into its computational structure. The model can be applied in one, two, or three dimensions and is designed for linkage with the link-node hydrodynamic model DYNHYD5 for dynamic simulation purposes. WASP5 has also been successfully linked with other hydrodynamic programs such as RIVMOD (Dames and Moore, 1994) and EFDC (Stoddard et al., 1995). WASP5 includes two submodels for water-quality/eutrophication and toxics, referred to as EUTRO5 and TOXI5, respectively. In EUTRO5, the transport and transformation of up to eight state variables in the water column and sediment bed can be simulated. These state variables include dissolved oxygen, carbonaceous BOD, phytoplankton carbon and chlorophyll *a*, ammonia, nitrate, organic nitrogen, organic phosphorus, and orthophosphate. In TOXI5 the transport and transformation of one to three chemicals and one to three types of particulate material can be simulated. A significant advantage of the WASP5 system is that the EUTRO5 and TOXI5 submodels can be used at variable levels of complexity by considering different processes, variables, and computations. WASP5 requires the user to input information on geometry, advective and dispersive flows (from hydrodynamic model or user), settling and resuspension rates, boundary conditions, external loadings (point and nonpoint source), and initial conditions. The waterbody is divided into a series of segments for simulation purposes. The WASP modeling system has been used in a wide range of regulatory and water quality management applications for rivers, lakes, and estuaries. Lang and Fontaine (1990) describe an application to predict the transport and fate of organic contaminants in Lake St. Clair, Michigan. Cheng et al. (1994) describe the development and application of a GIS-based modeling framework using a watershed loading model and WASP. Lu et al. (1994) used the model to simulate the transport and fate of DO, BOD and organic nitrogen in untreated wastewater discharges in Weeks Bay, Alabama. Lung and Larson (1995) used EUTRO5 to evaluate phosphorus loading reduction scenarios for the Upper Mississippi River and Lake Pepin. Cockrum and Warwick (1994) used WASP to characterize the impact of agricultural activities on instream water quality in a periphyton dominated stream. Stoddard et al. (1995) describe a fully three-dimensional application of EUTRO5 in conjunction with the EFDC hydrodynamic model to assess the effectiveness of total nitrogen removal options from a wastewater treatment plant.

Hydrodynamic and Water Quality Model for Streams (CE-QUAL-RIV1) (fact sheet, page B.3). CE-QUAL-RIV1 is a dynamic, one-dimensional (longitudinal) water quality model for unsteady flows in rivers and streams (Zimmerman and Dortch, 1989). The model has two submodels for hydrodynamics (RIV1H) and water quality (RIV1Q). Output from the hydrodynamic solution is used to drive the water quality model. Water quality constituents include temperature, dissolved oxygen, carbonaceous BOD, organic nitrogen, ammonia nitrogen, nitrate nitrogen, orthophosphate phosphorus, coliform bacteria, dissolved iron, and dissolved manganese. The effects of algae and macrophytes can also be included as external forcing functions specified by the user. CE-QUAL-RIV1 allows simulation of branched river systems with multiple hydraulic control structures such as run-of-the-river dams, waterway locks and dams, and reregulation dams. The model was developed to simulate the transient water quality conditions associated with unsteady flows that can occur on highly regulated rivers. Zimmerman and Dortch (1989) applied the model to provide examples of potential water quality impacts associated with operation alternatives for a regulation dam proposed for construction downstream from Buford Dam on the Chattahoochee River near Atlanta, Georgia. The RIV1Q component of CE-QUAL-RIV1 was used to develop statistical relationships to allow prediction of downstream water temperatures associated with different operational scenarios (Nestler et al., 1993a).

Two-dimensional, Laterally Averaged, Hydrodynamic and Water Quality Model (CE-QUAL-W2) (fact sheet, page B.5). CE-QUAL-W2 is a two-dimensional, laterally averaged hydrodynamic and water quality model (Cole and Buchak, 1994). CE-QUAL-W2 is best applied to stratified waterbodies like reservoirs and narrow estuaries where large variations in lateral velocities and constituents do not occur. The water quality and hydrodynamic routines are directly coupled; however, the water quality routines can be updated less frequently than the hydrodynamic time step, which can reduce the computation burden for complex systems. The model simulates the interaction of physical factors (such as flow and temperature regimes), chemical factors (such as nutrients), and algal interactions. The constituents are arranged in four levels of complexity, permitting flexibility in model application. The first level includes materials that are conservative and noninteractive, or do not affect other materials in the first level. The second level allows the user to simulate the interactive dynamics of oxygen-phytoplankton-nutrients. The third level allows simulation of pH and carbonate species, and the fourth level allows simulation of total iron. The model has been applied to rivers, lakes, reservoirs, and estuaries (Hall, 1987; Martin, 1988). Barnese and Bohannon (1994) report initial efforts to apply CE-QUAL-W2 to Taylorsville Lake in Kentucky.

Three-dimensional, Time-variable, Integrated-compartment Eutrophication Model (CE-QUAL-ICM) (fact sheet, page B.1). CE-QUAL-ICM was developed as the integrated-compartment eutrophication model component of the Chesapeake Bay model package (Cerco and Cole, 1993), which also includes a three-dimensional hydrodynamic component and a sediment-diagensis model. The model incorporates detailed algorithms for water quality kinetics. Interactions among the state variables are described in 80 partial differential equations that employ over 140 parameters (Cerco and Cole, 1993). The state variables can be categorized into a group and five cycles—the physical group and the carbon, nitrogen, phosphorus, silica, and dissolved oxygen (DO) cycles. An improved finite-difference formulation is used to solve the mass conservation equation for each grid cell and for each state variable. CE-QUAL-ICM was coupled with the three-dimensional hydrodynamic and benthic-sediment model components of the Chesapeake Bay model package to develop a state-of the-art 3-D model of the Chesapeake Bay (Cerco and Cole, 1993). The model was employed to simulate long-term trends in Chesapeake Bay eutrophication (Cerco, 1995). Mark et al. (1992) used CE-QUAL-ICM to assess the water quality impacts of a confined disposal facility in Green Bay, Wisconsin.

The Hydrological Simulation Program - FORTRAN (HSPF) (fact sheet, page A.15). HSPF is a comprehensive modeling system for simulation of watershed hydrology, point and nonpoint loadings, and receiving water quality for both conventional pollutants and toxicants (Bicknell et al., 1993). The receiving water component allows dynamic simulation of one-dimensional stream channels with several hydrodynamic routing options available. The eutrophication/water quality routines simulate BOD-DO interactions, temperature, and phytoplankton dynamics as affected by nutrients and organic material. The toxics routines combine organic chemical process kinetics with sediment balance algorithms to predict dissolved and sorbed chemical concentrations in the upper sediment bed and overlying water column. A data preprocessing and expert system have been developed to support model input file and meteorologic data file preparation (Lumb et al., 1990; Lumb and Kittle, 1993). Chen et al. (1995) described the development of a updated heat balance component for HSPF and initial model application for water balance and stream temperature simulation in Oregon. HSPF is being used by the Chesapeake Bay Program to model total watershed contributions of flow, sediment, nutrients, and associated constituents to the tidal region of the Bay (Donigian et al., 1990; Donigian and Patwardhan, 1992). Ball et al. (1993) describe an application of HSPF in Australia.

2.5.4 Mixing zone models

Mixing zone models are often described as "near-field" models; they assess limited areas of contaminant mixing in the vicinity of a wastewater discharger. Mixing zone models can be used in the development of discharger permits, and as part of this process can be applied during TMDL development. Although some of the more detailed and sophisticated water quality models can be configured to assess near-field impacts, several models that specialize in evaluating local impacts have been developed. Short descriptions of near field-models developed for coastal areas, rivers, and streams are provided below.

Cornell Mixing Zone Expert System (CORMIX) (fact sheet, page B.9). CORMIX is a series of models, embedded in an expert system shell, for the analysis, prediction, and design of aqueous toxic or conventional pollutant discharges into diverse waterbodies, with emphasis placed on the geometry and dilution characteristics of the initial mixing (near-field) zone. The model can be used to evaluate discharge compliance with regulatory constraints (Jones and Jirka, 1991). The

Mixing zone models assess limited areas of contaminant mixing in the vicinity of a wastewater discharger.

model can consider nonconservative pollutants with first-order decay and wind effects on plume mixing. Submodels within the CORMIX system allow analysis of submerged single-point discharges, submerged multiport diffuser discharges, and buoyant surface discharges. CORMIX conveys information to the user through qualitative descriptions and detailed quantitative numerical predictions.

PLUMES (fact sheet, page B.27). PLUMES is a model interface and manager for preparing common input and running two initial dilution (near-field) plume models (Baumgartner et al., 1994). Two far-field algorithms are automatically initiated beyond the zone of initial dilution. The near-field models are relatively sophisticated mathematical models for analyzing and predicting the initial dilution behavior of aquatic plumes, while the far-field algorithms are relatively simple implementations of far-field dispersion equations. PLUMES is applicable for discharges in marine and fresh water, with multiple outfalls types, configurations, and buoyant and dense plumes.

2.6 Integrated Modeling Systems

This section discusses some of the trends in watershed and receiving water model development and introduces a new generation of modeling systems that are just becoming available to watershed managers. Current trends include four types of system enhancements, which result in tools that are:

- Easier to use (often by the addition of Windows-based pre- and post-processors).
- Capable of linking models to each other (e.g., a loading model and a receiving water model).
- Capable of linking models to databases (e.g., GISs);
- Built from modules that allow the user the flexibility to choose a specialized analysis.

Although enhancements to model algorithms and methods continue and new versions of traditional models (e.g., HSPF, SWMM, QUAL2E) continue to be released, much of the recent research and development activity in watershed and receiving water modeling is centered on the way the modeler interacts with the system. Interfaces under development for models take advantage of new graphical user interfaces (GUI) and software to ease data input, output analysis, and calibration/validation procedures. New interface shells have been developed or are under development for some of the most widely used models, such as SWMM, QUAL2E, and HSPF by EPA, other federal agencies, private consultants, and universities. Most interface development efforts so far have focused on building shells, without modifying the original model code. Future development is likely to include newly coded models, taking full advantage of object-oriented coding procedures and other more recent software development trends.

The advent of GIS has already profoundly affected the modeling community. GIS provides excellent capabilities for data preparation for watershed and receiving water modeling applications. More recently, models are being tightly linked with GIS, allowing users to modify data and analyze resulting model output within the GIS. Cell-based models such as AGNPS and ANSWERS are well suited for linkage with GIS. Recent research includes the development of fully integrated, grid-based, distributed models. Limitations of the trend toward distributed models are the spatial variability and potentially high computational requirements (Zhang et al., 1995). Examples of distributed hydrologic models include Catchment Hydrology Distributed Model (CHDM) (Lopes, 1995), and r.hydro.CASC2D (Ogden and Saghafian, 1995). The newest hydrologic models, such as CASC2D, are fully linked with GIS, using a cell-based representation of the watershed system. Brigham Young University, in cooperation with the WES Hydraulics Laboratory, has developed a hydrologic modeling preprocessor, the Watershed Modeling System (WMS) (Nelson et al., 1995). WMS automatically delineates the dominant flow paths and calculates contributing areas (Nelson et al., 1995). Most fully distributed models currently include rainfall-runoff estimation and flow routing. In the future, such models might incorporate water quality simulation and pollutant transport as well. GIS is also used for data preparation and output display for receiving water models. For example, the University of Buffalo is currently developing a WASP/GIS linkage and interface. WES and Brigham Young University are developing FastTABS for two-dimensional analysis flow and sediment transport in rivers, streams, and estuaries (Holland, 1993).

Similar to GIS linkages, modeling systems are being developed that manage data systems and multiple models. Summarized below are examples of two such systems, the Watershed Screening and Targeting Tool (WSTT), and Better Assessment Science Integrating Point and Nonpoint Sources (BASINS). The objective of such systems is to provide the user with a fully integrated data, analysis, and modeling framework. Such systems allow managers to perform watershed assessment and TMDL-related characterizations and assessments, identify data needs, and prioritize and target resources.

The remainder of this section presents a sampling of efforts in these areas; many more integrated systems exist throughout the country at the local and state levels. Fact sheets have not been drafted for these models, and relevant contact information is included with each description.

Virginia Geographic Information System (PC-VirGIS). PC-VirGIS is a fully functional personal computer GIS, data analysis, and modeling system developed at the Information Support Systems Laboratory (ISSL), Biological Systems Engineering Department, Virginia Tech. The VirGIS database has approximately 20 layers of base and derived data covering 18 million acres in Virginia. Raster files are at a 33.3-meter cell size in the database, although cell size can be selected in PC-VirGIS. Vector files use a standard DLG-3 optional data structure. Models in the PC-VirGIS package can be accessed either from a menu interface or through a response file (command line information retrieved from a database file), and some models that can be accessed only through a response file. These models use the spatial information contained in the VirGIS database and apply hydrologic/water quality modeling procedures for:

- Total annual soil loss (from USLE) - cell loss rate determination
- Total annual stream nitrogen load determination
- Total annual stream phosphorus load determination
- Total annual stream sediment load (from USLE with delivery ratio) determination
- Cell sediment delivery ratio determination
- Spatial analysis models to rank stream pollutant loads

Modeling procedures for VirGIS under development and/or being field-tested include:

- Watershed Management System:
  - Nonpoint source simulation models for sediment and nutrients (total nitrogen and phosphorus) from chemical fertilizers and animal waste delivered to stream
  - Nonpoint-source-to stream entry point conversion
  - Instream routing
  - Simulation of stream biological status
  - Calculation of Critical Site Index based on water quality goals for the basin

  - Evaluation of alternative best management practice (BMP) strategies to meet water quality goals

- Groundwater vulnerability to pesticide contamination
- Groundwater recharge modeling
- Hydrologic/water quality models: Kinetic Runoff and Erosion Model (KINEROS), Finite Element Storm Hydrograph Model (FESHM), Penn State Runoff Quality Model (PSRM-QUAL), and Agricultural Nonpoint Source Pollution Model (AGNPS)

Results from PC-VirGIS can be displayed in map and tabular formats. This modeling system, although developed for Virginia, can be modified and applied elsewhere.

For more information, contact Vernon Shanholtz; MapTech, Inc.; Virginia Tech Corporate Research Center; 1872 Pratt Drive, Suite 1300-A; Blacksburg, VA 24060-6363, Ph (540) 231-8512, FAX (540) 231-3327.

GISPLM. GISPLM is a phosphorus loading model that was developed to address management issues in the Lake Champlain watershed (Artuso and Walker, 1997). Flows and phosphorus loads are evaluated using climatological data, watershed features that are accessed via a GIS, and other local data. BMPs are defined for up to 12 land use categories and estimates of load reduction efficiency, capital cost, and annual operating cost (based on literature values) are available for each BMP. The user can specify a target load reduction as a percentage of the load predicted with no controls and GISPLM will search for the spatial allocation of controls which achieves the reduction at minimum cost. Estimates of capital cost and operating costs are also generated, and individual control measures can be specifically included or excluded from the allocation process.

Surface runoff from pervious areas in GISPLM is predicted by HYDRO, a compiled Fortran program. Calculations are driven by daily precipitation and air temperature data, and algorithm and parameter estimates are taken from the GWLF model (see Section 2.3.2). LOADS, another compiled Fortran program, calculates flows and phosphorus loads based on runoff concentrations specified as a function of land use categories. LOADS produces an output file containing the total area, flow, load, impervious area, curve number, and surface runoff for each subwatershed in the study area.

The remaining calculations are performed within the GISPLM workbook (Quattro Pro version 7.0). Flows and loads from each source category (runoff, animal units, point sources) are totaled by model segment. Loads are adjusted to account for BMPs and loads and flows are totaled by segment and routed downstream to the mouth of the watershed. Empirical models (Vollenweider, 1976; Walker, 1987) are used to estimate the retention of phosphorus in lakes or impoundments optionally located at the downstream ends of segments.

Several graphical and tabular output formats that can be modified to suit project needs are provided in GISPLM. Model results can be displayed visually using *ArcView 3.0* software. Although GISPLM is configured specifically for application to the LaPlatte River watershed in Vermont and was developed generally for Northeastern watersheds, guidance for developing applications to other areas is provided. (Note: Peer review of the GISPLM model at the time of publication was not yet complete.)

For more information on the GISPLM model, contact Rick Hopkins, Vermont Department of Environmental Conservation, Water Quality, 103 South Main St, Waterbury, VT 05671-0408, Ph (802) 241-3770, FAX (802) 241-3287.

Watershed Screening/Targeting Tool (WSTT). WSTT, developed by EPA's Office of Wetlands, Oceans and Watersheds and EPA Region 4, is a screening and targeting tool intended to help watershed managers, EPA Regions, and state agencies evaluate and target watersheds based on specific environmental indicators. WSTT provides an interactive, user-friendly, two-step evaluation and targeting process. The first step allows for preliminary screening based on multiple criteria. Each criterion can be compared with a default or user-defined reference value. Data from EPA mainframe databases allow the user to compare reference values with land use and water quality observations from watersheds under consideration. The second level of targeting, comparative analysis, allows for a more detailed examination of watersheds using multiple objectives and criteria. This analysis also permits the user to include subjective weights and additional data in the targeting procedure.

An additional component of WSTT is the linkage to the Watershed Screening Model (WSM), which allows for estimation of point and nonpoint pollutant loads from the watershed. WSM predicts runoff, streamflow, erosion, sediment load, and nutrient loads for each cataloging unit modeled and presents results as graphs and tables to show seasonality and annual variability. WSTT can prepare watershed-specific (user-selected) input data files for use in the WSM simulation. WSTT also provides for direct access to WSM, where users can create or modify input files using a series of input screens. The addition of WSM to WSTT allows users to compare estimated loads as another option in the screening and targeting process.

WSTT is made up of 5 key components (1) databases; (2) watershed selection using maps or tables; (3) report generation (tables or graphics to screen, file, or printer); (4) targeting options (two types); and (5) data preparation for the WSM. Databases currently included are an accounting unit (AU)/catalog unit (CU) summary table; land use (National Resource Inventory (NRI) summary of acres per land use category); water quality (summarized by CU for 45 parameters); water quality station locations; water supplies (number, flow, location, type); point sources (number, flow, location, type); waterbodies (number, size); and WSM output.

System requirements for WSTT include an IBM-compatible PC, with a 386 or better processor, DOS version 3.3 or higher, a 3½-inch floppy drive, an EGA/VGA/SVGA monitor and adapter, and a hard disk with at least 7 MB of free space for program installation.

For additional information, contact the Watershed Branch (4503F), EPA Office of Wetlands, Oceans and Watersheds, 401 M Street, SW, Washington 20460, Ph (202) 260-7074, FAX (202) 260-1977 or laabs.chris@epamail.epa.gov.

Linked Watershed/Waterbody Model (LWWM). The LWWM, developed by Dames and Moore, Inc. and AScI Corporation for the Southwest Florida Water Management District (SWFWMD), is a linked model that can be used to rapidly evaluate and prioritize the effects of both point and nonpoint source loads on receiving waters. The LWWM analytically obtains GIS information from ARC/INFO coded output that is used to generate land use and soil type data by subbasin for the RUNOFF Block of EPA's Storm Water Management Model (SWMM). This part of the LWWM simulates storm events to predict runoff contaminant loads and water quantity for nonpoint sources. The time series of pollutant loads and the water quantity from SWMM are subsequently used as input for the River Hydrodynamics and Sediment Transport Model (RIVMOD), which calculates the longitudinal distributions of flows in a one-dimensional waterbody through time. Finally, EPA's Water Quality Analysis Simulation Program (WASP5) incorporates loads, flow distributions, and water quality data to simulate the movement and interaction of pollutants in water.

The information generated by the LWWM is accessible through interactive graphs and other interfaces. System requirements for LWWM include a high-speed personal computer (486/33 or higher), at least 40 MB of free disk space, and at least 4 MB of total random access memory (RAM).

LWWM is a public domain model; for additional information, contact Mike Holtcamp or Ray Kurz, SWFWMD, 7601 US Highway 301N, Tampa, FL 33637, (813) 985-7481 or michael-h%9217@etic66.dep.state.fl.us or download from the website: http://www.det.state.fl.us/swfwmd/.

Better Assessment Science Integrating Point and Nonpoint Sources (BASINS). BASINS is a multipurpose environmental analysis system developed by EPA's Office of Water to help regional, state, and local agencies perform watershed- and water quality-based studies. BASINS integrates data on water quality and quantity, land uses, and point and nonpoint source loadings, with supporting nonpoint and water quality models, providing the ability to perform comprehensive assessments of any watershed (at the cataloging unit level) in the continental United States. The system is distributed on CD-ROM and requires ArcView-2.1 software. BASINS has three major modules—screening and targeting, nonpoint source modeling to estimate loadings to receiving waters, and point-nonpoint integration.

The screening and targeting module helps the user characterize a watershed by examining river monitoring and status data that includes: drinking water supply sites, water quality monitoring station summaries, bacteria monitoring station summaries, USGS gaging stations, and Permit Compliance System (PCS) sites and computed loadings. The nonpoint source module helps the user estimate nonpoint source loadings of nutrients, sediment, bacteria, and toxics at a cataloging unit (USGS 8-digit) level anywhere in the country using data provided by the system. The model predicts loadings in mixed-land-use watersheds, including agricultural, forested, and urban areas. At the cataloging unit level, all data required for modeling are provided by the system.

The properties of the Nonpoint Source Model (NPSM) used in BASINS are: (1) Time step - variable or user-defined; (2) Spatial - initially, single watershed; future, subwatersheds; (3) Pollutants - nutrient species, sediment, bacteria, and toxics; (4) Urban - dust and dirt accumulation on impervious areas; (5) Rural - water balance using evapotranspiration and infiltration calculation; (6) Baseflow - baseflow recession curve, optional two-stage upper and lower zone; and, (7) Output - user-defined location and time step. The NPSM combines a Windows-based interface with EPA's Hydrologic Simulation Program-FORTRAN model, and is linked to ArcView.

Integration of nonpoint and point source loadings in BASINS is done by TOXI-ROUTE, a screening-level stream routing model that performs simple dilution calculations under mean and low flow conditions for entire watersheds. The model integrates the nonpoint source loadings described above with point source loadings, obtained from permit data derived from the PCS. For situations that require a modeling approach that is more detailed than the simple dilution used by TOXI-ROUTE, BASINS can use the nonpoint and point data with EPA's QUAL2E water quality model.

BASINS was released in September 1996 and EPA is planning on annually updating the system by adding new data, new databases, expanded state coverage, and enhanced modeling capabilities. For more information, contact Marjorie Coombs Wellman or Jerry LaVeck, EPA Office of Science and Technology (4305), Standards and Applied Science Division, 401 M Street, SW, Washington, DC 20460, Ph (202) 260-9821, FAX (202) 260-9830 or wellman.marjorie@epamail.epa.gov. (Jerry LaVeck: Ph (202) 260-7771 or laveck.jerry@epamail.epa.gov.)

Visit the BASINS website for information on new updates, answers to frequently asked questions, and additional documentation at http://www.epa.gov/ostwater/BASINS/

A limited number of BASINS version 1 CD-ROMS will be distributed free of charge upon request through the National Center for Environmental Publications and Information (NCEPI), P.O. Box 42419, Cincinnati, OH 45242. Tel.: (513) 489-8190. Fax: (513) 891-6685. Web Site: http://www.epa.gov/ncepihom/index.html. The package includes:

- User's Manual: Better Assessment Science Integrating Point and Nonpoint Sources. BASINS Version 1.0, May 1996 (EPA Document No.: EPA-823-R-96-001).
- A compact disk specific to one of 10 regions of interest within the conterminous US. The EPA regions are listed below with the corresponding document number for each cd.

1. EPA Region 1 (CT, ME, MA, NH, RI, VT);	EPA-823-C-96-001
2. EPA Region 2 (NJ, NY);	EPA-823-C-96-002
3. EPA Region 3 (DE, DC, MD, PA, VA, WV);	EPA-823-C-96-003
4. EPA Region 4 (AL, FL, GA, KY, MS, NC, SC, TN);	EPA-823-C-96-004
5. EPA Region 5 (IL, IN, MI, MN, OH, WI);	EPA-823-C-96-005
6. EPA Region 6 (AR, LA, NM, OK, TX);	EPA-823-C-96-006
7. EPA Region 7 (IA, KS, MO, NE);	EPA-823-C-96-007
8. EPA Region 8 (CO, MT, ND, SD, UT, WY);	EPA-823-C-96-008
9. EPA Region 9 (AZ, CA, NV);	EPA-823-C-96-009
10. EPA Region 10 (ID, OR, WA);	EPA-823-C-96-010

3 Ecological Assessment Techniques and Models

3.1 Introduction

This chapter presents a wide variety of ecological assessment techniques and models to help watershed managers address the Clean Water Act's challenge to restore and maintain the physical and *biological* quality of the Nation's waters. Ecological assessments are studies that examine or predict the status of a habitat, a biological population, or a biological community to provide an interpretation of a waterbody's ecological health. Ecological assessments can provide additional information and interpretation of watershed and waterbody conditions that can be helpful for developing TMDLs and other feasible and comprehensive watershed management solutions (Table 8).

Ecological assessments are studies that examine or predict the status of a habitat, a biological population, or a biological community to provide an interpretation of a waterbody's ecological health.

Numerous techniques have been developed by many agencies and organizations to perform environmental and ecological assessment studies (Atkinson, 1985; Schuytema, 1982). This chapter focuses on those techniques which have potential applicability to watershed management and the TMDL process. To facilitate selection

Table 8. Ways in Which Ecological Assessments Can Support the Five Steps in the Water Quality-Based Approach

1. Identification of Water Quality-Limited Waters That Require TMDLs
   - *Determine waters that are not meeting designated uses, or are threatened, stressed, or impaired, by assessing numbers and diversity of aquatic biota.*
   - *Enable states to meet reporting requirements for listing waters that need TMDLs.*
2. Priority Ranking and Targeting Listed Waters
   - *Interpret ecological assessment data to determine the relative vulnerability of waterbodies to specific stressors.*
   - *Assist in characterizing the magnitude and significance of impairments.*
   - *Combine with water quality evaluations to assist in determining certain explicative cause-effect relationships needed for restoration alternatives.*
3. TMDL Development
   - *Provide the data necessary for selection of a TMDL endpoint, and aid in developing TMDLs for nonchemical stressors that have been identified through ecological assessments.*
   - *Indicate the type and geographic extent of stressors that should be controlled to improve habitat and overall ecological integrity.*
4. Implementation of Control Actions
   - *Provide data for selecting and siting required controls, including habitat restoration.*
5. Assessment of Water Quality-Based Control Actions
   - *Act as a component of an integrated monitoring approach to measure system response to control of stressors following implementation of management actions.*
   - *Provide information over time about the ecological integrity of a waterbody and indicate whether decisions are achieving the biological endpoints specified by a TMDL.*

of an appropriate technique, the chapter first discusses different ways of conducting assessments and then describes each ecological assessment technique in one of two categories: habitat assessments and species/community assessments. This distinction has been made to underscore the importance of considering both living resources and the physical, biological, and chemical surroundings on which they depend. Assessing the habitat and the species or community, and their relationships, provides additional information to watershed managers useful in characterizing problems and determining restoration solutions.

Summaries of the capabilities of the techniques and models reviewed in the chapter are presented in Tables 9 and 10. Fact sheets that outline each technique are also provided in Appendix C.

3.2 Approaches to ecological assessments

Three general approaches exist for performing ecological assessments: comparative analyses, index/classification procedures, and ecological modeling techniques. As discussed in this chapter, these techniques are not mutually exclusive, and frequently overlap or can be used in combination to provide a comprehensive assessment methodology. Several ecological techniques are usually needed to address the stressors on a watershed.

3.2.1 Comparative analyses

Comparative analyses are a broad-based category of assessments that rely on field measurements, monitoring data, and statistical analysis as a basis for determining the status of a habitat or species/community. The main objectives of comparative analyses are to (1) identify the type and location of impairments, (2) characterize both the absolute and relative magnitude of impairments, (3) generate criteria for prioritizing and ranking waterbodies, and (4) track and evaluate the benefit of a control action.

When performing a comparative analysis, data are collected for waterbodies on a specific spatial and temporal scale and are then compared to one of the following:

(1) similar, unaffected sites (i.e., paired site analysis);

(2) composited reference (i.e., unimpaired or minimally impaired) site conditions; or

(3) historical data from the same site characterizing the "before impairment" or "control implementation" condition. For screening-level techniques (e.g., reconnaissance bioassessment), best professional judgment can also be used in place of a comparative site to assess the collected data.

Paired-site approaches involve the use of control and treatment sites for the detection of changes in biological condition. They are useful for the detection of ecological effects from changes in water quality and quantity, habitat quality, or land use features. A key element of the approach, as the name implies, is the simultaneous monitoring of (1) sites that are not affected by the changes for which the monitoring is being conducted (control sites) and (2) separate sites that are impaired or affected by a "treatment" (treatment sites), for example, implementation of best management practices (BMPs). Many of the techniques described in this chapter can be applied using the paired approach.

Composited reference site assessment techniques form an approach in which data are compared to "reference" biological communities or habitats (reference conditions), which represent biological communities and habitats in unimpaired or minimally impaired waterbodies in the ecological region (or subregion) of interest. A reference condition is derived from numerous reference sites within an ecoregion during an index period (Gibson et al., 1994). EPA's *Biological Criteria: Technical Guidance for*

Table 9. Evaluation of Model/Technique Capabilities—Habitat Assessment Techniques

Criteria		HEP/ HSI	HES	WET II	HGM	Visual-based Habitat Assessment	QHEI	Rosgen's Stream Classification	IFIM (PHABSIM/ TSLIB)	SNTEMP/ SSTEMP	MNSTREM
Aquatic habitat assessment		◐	◐	-	-	●	●	◐	●	○	○
Terrestrial habitat assessment		●	●	-	-	-	-	-	-	-	-
Wetland habitat assessment		-	-	●	●	-	-	-	-	-	-
Assessment Technique	Computer modeling	●	●	●	-	-	-	-	●	●	●
	Data analysis	◐	◐	◐	●	○	○	●	●	●	●
Input data	Requirements (Level of effort)	●	●	●	●	○	○	● ◐ ○	●	● ◐ ○	●
	Calibration (Reference conditons)	-*	-*	●	●	●	●	-	-	-	○
Output data	Habitat quality/ integrity	●	●	●	●	○	○	◐	●	◐	◐
	Habitat quantity	●	●	-	-	-	-	◐	●	-	-
Documentation		●	●	●	●	◐	◐	◐	●	●	●

● High   ◐ Medium   ○ Low   - Not incorporated   * - If used in appropriate region

Streams and Small Rivers (1994) also describes the process for classifying and selecting reference sites.

Because of the difficulties in reducing ecological data into a single meaningful number, many comparative analysis techniques rely on aggregating ecological/ monitoring data into metrics and deriving a representative index, based on which comparisons can be easily made.

3.2.2 Index/classification methods

Index and classification methods are techniques based on comparative analyses, but they go a step further by analyzing and aggregating data into a numerical index (or indices) that describes the overall integrity of a habitat or community. This index (or indices) can then be compared to reference sites or can be used in a "before and after" comparison. For example, the Index of Biological Integrity (IBI) is a technique that uses 12 metrics (describing species composition, trophic composition, and fish abundance and conditions) to assess attributes that are assumed to correlate with the ecological health of a waterbody. Individually, each metric provides information about a specific attribute of the sampling site, and consequently on the type and magnitude of impairment. When examined together, metrics characterize the underlying biological integrity of a site.

Table 10. Evaluation of Model/Technique Capabilities—Species/Biological Community Assessment Techniques

Criteria		RBP I	RBP II	RBP III	RBP IV	RBP V (IBI)	ICI	IWB	PVA	FGETS
Single species assessment	Bioaccumulation	-	-	-	-	-	-	-	-	●
	Population modeling	-	-	-	-	-	-	-	●	-
Multiple species/ community assessment	Benthic macro-invertebrates	●	●	●	-	-	●	-	-	-
	Fish	-	-	-	●	●	-	●	-	-
Assessment technique	Computer modeling	-	-	-	-	-	-	-	●	●
	Data analysis	○	◒	●	◒	●	◒	◒	-	-
Input data	Requirements (Level of effort)	○	◒	●	◒	●	◒	◒	●	●
	Calibration (Reference conditons)	-	●	●	-	●	●	●	-	-
Output data	Species/ Community Integrity	○	◒	●	●	●	◒	◒	◒	-
	Species/ Community abundance	-	-	-	-	-	-	-	-	●
Documentation		●	●	●	●	●	◒	◒	●	◒

● High ◒ Medium ○ Low - Not incorporated

Classification techniques, such as the Rosgen method, reduce several measurable indicators into various categories. Analysis of these categories provides an indication of the presence of an impairment and also assists in defining the need for and selection of restoration programs.

3.2.3 Ecological models

In cases where biotic data are lacking, where obtaining such data is cost-prohibitive, or where predictions of future conditions are needed, ecological models can provide a means to characterize existing conditions, predict potential impacts from a proposed action, and identify potential sources of impairments.

Ecological modeling is a wide-ranging, relatively new scientific field that focuses on quantifying the relationships between the biotic and abiotic components of an ecosystem. It can include, for example, simulations of population and community dynamics, oxygen balance estimation, fate and transport of toxics and their impact on a biological community (e.g., ecotoxicological models), and eutrophication modeling (Jorgensen, 1995). Because Section 2.5 of this document (receiving water models) discusses approaches for simulating biochemical interactions (e.g., dissolved oxygen) and algal growth (e.g., eutrophication), further use of the term "ecological model" in this document is limited to those methods which focus explicitly on how species and biological communities are affected by exposure to stressors (both from direct contact and through habitat modification).

Abiotic and biotic relationships in ecological models are typically simulated using mathematical algorithms describing either statistical relationships or mechanistic processes. Statistical models, such as regression or principal components analysis, derive generalizations about ecological conditions using experimental and/or observational data (Suter, 1993). Mechanistic models, on the other hand, attempt to quantitatively describe a phenomenon by its underlying causal mechanisms, often by integrating complex sets of spatial and temporal data and reproducing the principal component and relationship in the model (Suter, 1993).

Because of the complexity inherent in ecosystem processes that affect aquatic species and communities, a few predictive (and generally statistically based) models exist that have demonstrated applicability to TMDL development and watershed management. On the other hand, most of the mechanistic modeling efforts that incorporate interspecific, intraspecific, and abiotic (e.g., chemical and physical) interactions, while considering temporal and spatial heterogeneity in these factors, have been pursued at the research level and require large amounts of data and novel analytical techniques (e.g., STAC, 1993; Turner et al., 1995). Nevertheless, continuing advancements in knowledge about ecosystems, the need for more quantitative data to better manage natural resources, and increased accessibility to sophisticated computing and programming equipment will continue to lead to improvements in developing mechanistic models that more easily and realistically represent ecosystems, and that can eventually be applied at a practical level.

One area of model development currently being explored is in large-scale, holistic ecosystem modeling. The approach used in the Chesapeake Bay, for example, links a variety of submodels that describe important processes and interactions in the bay (STAC, 1993). Included in the modeling system are:

- Ecosystem process models that determine the flow of nutrients and organic materials.
- Water quality models that consider both loading and receiving water processes.

- Spatially explicit fish bioenergetic models that identify habitats with the highest potential for growth.
- Individual-based fishery dynamics models that describe population dynamics.
- Ecosystem regression models that identify strong relationships is systems.
- Ecosystem network analysis models that allow examination of indirect connections between species in an ecosystem.
- Landscape spatial models that incorporate space as well as time to quantitatively predict and describe landscape phenomena through the use of GISs.

Habitat assessments are used to define existing conditions and/or to examine the impact of a given stress or environmental change on terrestial and aquatic communities.

Advances in ecological risk assessment methods also offer promise for TMDL development and watershed management (e.g., Barnthouse, 1992; USEPA, 1994e). Ecological risk assessments (i.e., assessments that use data to estimate the probability that some undesired ecological event will occur) have typically involved extrapolating results of laboratory toxicity tests to estimate the effects on aquatic ecosystems (Bartell et al., 1992). Existing models, such as the EPA-supported Comparative Toxicology Models, EXAMS, and FGETS, examine either the fate (movement and transformation) or effects (direct effect on biota) of toxics through aquatic ecosystems. New modeling approaches in ecological risk assessment are focusing on:

- Integrating fate and effects models, where physical and chemical processes that influence the exposure concentration of the toxic chemicals are explicitly included with simulations of the effects of stress on biota (Bartell et al., 1992). AQUATOX, being jointly developed by EPA's Office of Science and Technology and the Office of Pollution Prevention and Toxics, is one such model.
- Incorporating spatial data via GISs into ecological risk assessment frameworks (e.g., Clifford et al., 1995).
- Applying the ecological risk assessment methodology to cases that consider stressors other than toxics. For example, Brody et al. (1993) use the methodology to assess the probability of ecological risk as it relates to changes in hydrology and subsequent changes in wildlife habitat to a watershed in Louisiana.

3.3 Habitat assessment techniques

Habitat quality is a critical determinant of ecological integrity (Plafkin et al., 1989), and the condition of physical habitat has a direct effect on the condition of biological communities. Habitat assessments for aquatic ecosystems typically evaluate habitat structure, which influences the overall health of the water resource. Physical parameters, such as the substrate, channel morphology, water quality, bank structure, and riparian vegetation, are often used to assess or predict the condition of the waterbody. Other factors, such as structural heterogeneity of microhabitats, temporal persistence, and an energy base consistent with the water resource type, size, and region, are also used to assess a waterbody's integrity.

Habitat assessment techniques are used to define existing conditions and/or to examine the impact of a given stress or environmental change on terrestrial and aquatic communities. The existing status of a community can be determined through evaluation of variables such as habitat type; species abundance and distribution; level of disturbance; connectedness to corridors, confluences, or greenways; and percent of surrounding development or exposure to pollutants. Once the habitat has been assessed, changes to it can be measured or modeled, and subsequently evaluated.

Habitat Evaluation Procedure/Habitat Suitability Indices (fact sheet, page C.3). The Habitat Evaluation Procedure (HEP) is a species-based index method designed by the U.S. Fish and Wildlife Service and used to document the quality and quantity of available habitat for selected aquatic and terrestrial wildlife species (USFWS, 1980; Wakely and O'Neil, 1988). HEP provides information for two general types of habitat comparisons: (1) the relative value of different areas at the same point in time and (2) the relative value of the same area at future points in time. By combining the two types of comparisons, the impact of proposed or anticipated land or water use changes on habitat can be quantified.

HEP analysis begins with three basic steps:

(1) Defining the study area

(2) Delineating cover types

(3) Selecting evaluation species

The study area should include sites where direct or indirect biological changes are expected to occur as a result of a proposed action. The concept of cover types used in HEP is analogous to habitat types, which include deciduous forest, coniferous forest, grassland, residential woodland, and medium-sized warmwater stream. Evaluation species (i.e., indicator species) are used in HEP to quantify habitat units (HUs), and a typical HEP study incorporates four to six species. The analysis is structured around the calculation of HUs for each evaluation species in the study area before and after a proposed action. The number of HUs is defined as the product of the Habitat Suitability Index (HSI, a measure of habitat quality) and the total area of available habitat (habitat quantity).

For stream assessments, HEP provides a method that correlates physical habitat characteristics to fishery resources. The technique is a useful fisheries management tool because it identifies the physical habitat features that reduce the biological integrity of the waterbody. The habitat features typically evaluated include temperature, turbidity, velocity, depth, cover, pool and riffle sizes, riparian vegetation, bank stability, and siltation. The habitat parameters are correlated to fish species based on an evaluation of their importance to the life cycle of the species.

Habitat Suitability Indices (HSIs) are modeled components of HEPs developed to provide an understanding of habitat requirements for species by identifying the key habitat variables and the range and optimum for each variable. Using mathematical models, HSIs provide an index between 0 and 1 indicating habitat quality (0 - unsuitable, 1 - optimal). HSIs characterize species-habitat relationships and are helpful in identifying the physical habitat conditions that are vital to a given species, as well as identifying the ranges and optimal conditions necessary for species survival and propagation. For fish, habitat requirements are evaluated for four life stages: spawning/embryo, larvae/fry, juvenile, and adult. The applicability of each species-specific HSI is designated according to season, minimum habitat area, and verification level (i.e., expert review and evaluation, and whether model design is based on literature or field tests).

Three software programs have been developed by the U.S. Fish and Wildlife Service to assist with application of the HEP (Mangus, 1990). The HEP Accounting Program computes the values needed to use the HEP procedures (USFWS, 1980) and can evaluate up to 25 species, 15 planning alternatives, and 15 management plans. Inputs include the areas of usable habitat for each species and HSIs for each species over time for each management alternative. The Habitat Management Evaluation Method System (HMEM) software allows a user to investigate and compare the cost-effectiveness of different management alternatives to achieve desired HUs for a selected species. HSI modeling system software can be used to compute an HSI value for selected species from field measurements of habitat variables. The software allows a user to examine intermediate values for each species model and evaluate model response to specific habitat variables with a response surface analysis; it can also perform sensitivity analysis. The software has a library of over 200 models for aquatic and terrestrial species. HSI software also transfers habitat models to HMEM, where the user specifies the constraints for each management activity. Following compilation of species and management models, strategies are ranked according to their cost-effectiveness (i.e., lowest management cost and highest HUs).

Habitat Evaluation System (fact sheet, page C.5). The Habitat Evaluation System (HES) is a community-based index evaluation technique originally developed by the U.S. Army Corps of Engineers to evaluate water resource projects in the lower Mississippi Valley area (U.S. Army Corps of Engineers, 1976). A modified version (U.S. Army Corps of Engineers, 1980) is commonly used today and can be applied to assess the impacts of development projects for two aquatic habitats (streams and lakes) and four terrestrial habitats (wooded swamps, upland forests, bottomland hardwood forests, and open lands). HES can also be used to estimate the terrestrial wildlife value of aquatic habitats.

HES assumes that presence, abundance, and diversity of animal populations in a habitat are determined by biotic and abiotic factors that can be readily quantified. HES determines the quality of a particular habitat type through the use of functional curves that relate habitat quality and carrying capacity to these factors. HES uses general habitat characteristics that indicate quality for aquatic and terrestrial wildlife communities as a whole.

Six steps are involved in an HES:

(1) Obtaining habitat type and land use acreage.

(2) Deriving Habitat Quality Index (HQI) scores.

(3) Deriving Habitat Unit Values (HUVs) (4) Projecting HUVs for future with- and without-project conditions.

(5) Using HUVs to assess impacts of project alternatives.

(6) Determining mitigation requirements, if any.

The first step in the HES is delineating the acreage of each habitat type in the project area for existing conditions, future without-project conditions, and future with-project conditions. The second step consists of deriving HQI scores for each land use category or habitat type. Data are obtained on several key variables (e.g., species associations, benthic diversity, sinuosity index, total dissolved solids, land use type) for each habitat type from field measurements, literature, and historical information. Each variable measured is then converted to an HQI score (between 0 and 1) using functional curves developed for that variable and habitat. The third step combines the habitat type or land use size data (acreage) and the associated HQI scores to compute an HUV for the habitat. Next, HUVs over the life of the project are projected based on estimated changes in land use or habitat size. Estimated changes can be developed using engineering and related planning studies.

Step 5 consists of calculating total and/or annualized HUVs for each habitat type for the with- and without-project scenarios. The impacts from each alternative can be estimated by subtracting the with-project HUV from the without-project HUV. Total impacts from a project can then be determined by summing the impacts for all affected habitats, allowing trade-off analyses and comparisons between plans. For complex projects with several habitat types, computer software is available for HES steps 1 through 5 (U.S. Army Corps of Engineers, 1980). Inputs to this software are the data for land use or habitat size and HQI scores. Finally, HES can be used to determine the amount and type of mitigation necessary to compensate any possible adverse impacts from a project.

Wetland Evaluation Technique (fact sheet, page C.25). The Wetland Evaluation Technique version 2.0 (WET II) is a community-based index evaluation approach that can provide a broad overview of potential project impacts on several wetland habitat functions (Adamus et al., 1987). WET II evaluates functions and values in terms of social significance, effectiveness, and opportunity. A project team implements WET II by identifying the physical, chemical, and biological characteristics of a wetland through the use of predictor species or characteristics within a habitat representative of the study area. A series of questions are asked for each predictor to more precisely define its relationship to the habitat and determine the social significance of the wetland area. The predictors are then evaluated for each function's effectiveness and opportunity based on interpretation keys that define the relationship between predictor and wetland function or value; the evaluation ratings are high, moderate, or low. Similar ratings are also used for significance. The ratings are then combined to give a final rating of functional significance.

This method was designed primarily for conducting an initial, rapid evaluation of wetland functions and values. However, WET II can be applied in a variety of other situations or circumstances including (1) comparison of different wetlands in terms of their functions and values; (2) selection of priorities for wetland acquisition or more detailed, site-specific research; (3) selection of priority wetlands for advanced identification; (4) identification of options for conditioning of permits; (5) determination of the effects of preproject and post-project activities on wetland functions and values; and (6) comparison of created or restored wetlands with reference, or preimpact, wetlands during mitigation.

Hydrogeomorphic Assessment (HGM) (fact sheet, page C.7). HGM is a hydrogeomorphic classification and assessment methodology for determining the integrity of physical, chemical, and biological functions of wetlands as they compare to reference conditions (Brinson, 1993). Absent in the methodology is the use of predictor species, which significantly reduces the time and effort required to conduct an assessment. Instead, the method focuses on identifying wetland groups that exhibit a relatively narrow range of variation in the properties that fundamentally influence how wetlands function. The HGM method relies on the use of reference wetlands, which represent a collection of sites of a specific wetland class that can be used for developing the upper and lower boundaries of functioning within the class. The steps in the assessment approach are:

(1) Classify wetlands according to HGM properties.

(2) Make connections between the properties of each wetland class and the ecological functions that they perform based on logic and research results.

(3) Develop functional profiles for each wetland class.

(4) Choose reference wetlands that represent the range of both natural and human-imposed stresses and disturbances.

(5) Design the assessment method using indicators calibrated to reference wetlands.

The HGM classification uses principles of hydrogeomorphology to separate wetlands into functional classes at a gross level, and it serves as the organizing principle for the development of an assessment method. Because the classification is hierarchical and modular, it can be easily modified for different geographic regions or scales. To establish the relationship between fundamental properties and functions of a wetland (step 2), extensive data sets are not needed. With the establishment of reference wetlands (steps 3 and 4), in which functions have already been evaluated, the site being evaluated is compared to the reference group of the same class. This avoids the need to establish an arbitrary scale for ranking; the scale is defined by the variation within the reference population itself.

The connections established between hydrogeomorphic properties and functions can then be summarized in "functional profiles" for wetlands that have been assessed. A functional profile is a body of descriptive information that characterizes a functional wetland class or a single wetland (the reference wetland). At a minimum, one must develop a profile on a small reference population as a basis for the scaling of functions within a class (step 4), but the profile must also provide the basis for comparison between the reference population and a new site undergoing assessment. Step 4, determining where a wetland falls along the scale of function, requires a method for estimating or quantifying the properties of the wetland that determine how it functions. This step is still in the development process.

The final step in the HGM is the development of the assessment method. The assessment tasks include, but are not limited to, (1) acquiring maps (topographic, National Wetland Inventory, land use, etc.), soil surveys, aerial photographs, hydrologic data (discharge, water levels), water quality data, and land use of the watershed; (2) becoming acquainted with the site by walking the boundary and several traverses; (3) filling out field sheets related to developing a profile of the site (water source, hydrodynamics, vegetation cover, soil type); (4) assessing whether indicators of functioning are present; and (5) developing narrative that describes the rank of the wetland relative to the reference wetland population.

Visual-based Habitat Assessment (fact sheet, page C.23). The habitat assessment procedure, an index-based methodology originally developed for the Rapid Bioassessment Protocols (RBPs) (Plafkin et al., 1989), were based on *Stream Classification Guidelines for Wisconsin* (Ball, 1983) and *Methods of Evaluating Stream, Riparian, and Biotic Conditions* (Platts et al., 1983). The habitat assessment parameters were later modified to include additional assessment parameters for high-gradient streams, as well as new, more appropriate parameters for low-gradient streams (Barbour and Stribling, 1991). Additional modifications have since been made based on evaluations of observer bias and include an increase in parameter objectivity, the use of different parameters for different targeted biological assemblages, and a nonweighted point-scoring framework (Barbour et al., 1995).

The habitat assessment procedures use 10 parameters to characterize the integrity of habitat conditions. The parameters characterize substrate, instream cover, channel morphology, and riparian and bank structure and stability on a site-specific basis. Each parameter is assigned a numerical score within a gradient of optimal (20) to poor (0), based on visual inspection or a minimal amount of measurement. The approach incorporates the assumptions that there is a continuum of conditions for each parameter within each stream type, and that the continuum is easily recognized by experienced biologists. The continuum for each parameter is divided into four parts that represent optimal, suboptimal, marginal, and poor habitat quality. The scoring range within each part allows for a judgment of differential conditions (e.g., high, middle, low) and for better resolution among varying conditions. The final score for the site is calculated by summing the scores for each parameter. Although significant variability exists between streams, some generalizations among stream types can be made based on gradient. Higher-gradient streams of the montane and piedmont regions are assessed using the "riffle/run prevalence" parameters, and the "glide/pool prevalence" parameters are used for the valley/plains and coastal plains streams.

This final habitat assessment score is compared to the score established for regionally expected reference conditions. The judgment criteria for the site are optimal, suboptimal, marginal, and poor. The judgment criteria are defined as follows: *optimal*—meets natural expectations; *suboptimal*—less than desirable, but satisfies expectations in most areas; *marginal*—moderate level of degradation, severe degradation at intermittent areas; *poor*—characteristics of parameters substantially altered, severe degradation.

Qualitative Habitat Evaluation Index (fact sheet, page C.23). The Qualitative Habitat Evaluation Index (QHEI) provides an empirical, quantified evaluation of the general lotic macrohabitat characteristics important to fish communities (Rankins, 1991). The index is a composite of the quantitative values for six physical habitat characteristics obtained from visual estimates. Ohio EPA relates these characteristics to tiered aquatic life uses assigned to warmwater streams in Ohio.

The QHEI is based on a composite of six habitat variables: substrate, instream cover, riparian characteristics, channel characteristics, pool and riffle quality, and gradient and drainage area. Visual estimates of several components for each habitat variable are assigned scores based on observed or predicted relationships with fish species diversity and/or measures of community integrity. The characteristics of each habitat variable are related to tiered aquatic life uses for warmwater streams (i.e., exceptional warmwater habitat, warmwater habitat, modified warmwater habitat, and limited resource water). To accommodate widespread application, the index considers covariate habitat quality factors at the ecoregion, reach, and subbasin levels. On a 200- to 500-meter stream segment, the QHEI can be completed in less than 1 hour.

In Ohio, the QHEI was significantly correlated to the Index of Biotic Integrity (IBI) (Rankins, 1991), demonstrating the strong influence of habitat quality on fish communities. The correlation varied with differences in stream size and ecoregion, suggesting the influence of factors other than site-specific habitat quality. Fish communities in streams with relatively intact habitat throughout the drainage can compensate for short reaches of poor habitat; however, stream basins with extensively degraded habitat will not support sensitive fish species and fish community structure will be drastically altered.

Rosgen's Stream Classification (fact sheet, page C.19). The Rosgen approach for stream classification and restoration uses morphological stream characteristics to organize streams into relatively homogenous stream types (Rosgen, 1994). This classification method was developed for use as a tool to predict a stream's behavior based on its geomorphologic condition, to extrapolate data from one stream for use on another with similar characteristics, and to provide a consistent frame of reference when comparing one stream to another (Rosgen and Fittante, 1986). The criteria used to organize streams into types represent measured variables that govern channel morphology and determine the stream's dominant features.

There are four hierarchical levels of classification based on the desired levels of resolution and project objectives (Rosgen, 1994). Level I is used to provide a broad morphological characterization by integrating landform and fluvial features of valley morphology with channel relief, pattern, shape, and dimension (Rosgen, 1994). The influences of climate, depositional history, and life zones or ecotones (desert shrub, alpine, etc.) on channel morphology are also considered at Level I.

Level II delineates streams into major, broad categories (A through G) that provide a more detailed level of interpretation and extrapolation than Level I. Stream types are separated based on discrete channel patterns, entrenchment ratios, width/depth ratios, sinuosity, dominant channel-material particle sizes, and slope ranges, which results in a total of 42 major stream types.

Level III provides a very detailed description of the existing stream conditions, as well as specific information for predicting responses to outside influences. This is accomplished by integrating information on riparian vegetation, depositional patterns, meander patterns, confinement features, fish habitat indices, flow regime, river size category, debris occurrence, channel stability index, and bank erodibility.

Level IV provides reach-specific information on channel processes and involves direct measurement/observation of sediment transport, bank erosion rates, aggradation/degradation processes, and stream geometry. The Level IV classification also uses biological data such as fish biomass, aquatic macroinvertebrates, and riparian vegetation evaluations.

Applications for the classification system include the ability to evaluate sensitivity to disturbance and to predict stream behavior as a result of changes in the watershed; the assessment of impacts; the ability to design stable, self-maintaining channels in restoration work; the ability to determine flow resistance; and the selection of appropriate fish habitat improvement structures. At the highest classification level (Level IV), the Rosgen system can be used to provide sediment, hydraulic, and biological information related to specific stream types. It can also evaluate the effectiveness of mitigation and impact assessments by stream type.

Instream Flow Incremental Methodology (IFIM) (fact sheet, page C.11). IFIM is a conceptual framework that consists of a collection of analytical procedures, indices, and computer models used to assess riverine habitats (Bovee, 1982, 1986; Gordon et al., 1992). Developed by the U.S. Fish and Wildlife Service, National Ecology Research Center, Aquatic Systems Branch, IFIM attempts to determine the effects of any of a number of hydraulic modifications on aquatic habitat through a complete process consisting of the application of seven steps (Gordon et al., 1992):

(1) Describe the state of the river system in key variables.

(2) Develop functions that describe the habitat preferences of identified species.

(3) Develop functions that integrate the macro- and microhabitat availability of the system.

(4) Incrementally change one or more variables (e.g., discharge or channel morphology) to reflect a management option, and determine the available habitat for this new system.

(5) Determine alternatives or other actions to avoid or correct adverse impacts from the previous step.

(6) Repeat steps 3 and 4 to develop a range of management options.

(7) Evaluate alternatives and perform selection.

IFIM considers changes to both microhabitat (the distribution of structural and hydraulic features that form the living space for an organism) and macrohabitat (channel characteristics, temperature, and water quality) (Gordon et al., 1992). Included as components of IFIM are the Physical Habitat Simulation System and the Time Series Library, both of which are used to develop habitat preference and availability functions.

Physical Habitat Simulation System. (PHABSIM). PHABSIM is a collection of computer programs that form the key microhabitat simulation component of IFIM (used in steps 2, 3, and 4). PHABSIM relies on the assumption that aquatic species will react to hydraulic changes in a stream by selecting the most favorable conditions (Gordon et al., 1992). To measure this, PHABSIM produces habitat-discharge relationships that estimate how suitable habitats for aquatic species change with discharge by describing local physical niches using depth, velocity, and stream channel characteristics. PHABSIM has two components: hydraulic simulation (in which the user selects from three types of calculations to calculate water-surface elevations and velocities) and habitat simulation (in which the user selects from three types of models to compute the amount of physical habitat available for a particular species).

The final habitat-discharge relationships produced by PHABSIM show the change in Weighted Usable Area (WUA) with discharge (Gordon et al., 1992). The WUA is an indicator of physical habitat suitability for a certain life stage of a certain species for a given stream reach. Physical habitat (depth, velocity, cover, and substrate) is assessed for a stream reach for a given discharge and then combined with habitat suitability curves to determine the WUA for that discharge. By calculating WUAs for numerous discharges, the method describes the relative habitat suitability of a stream under different flow conditions. Since changes in habitat resulting from changes in streamflow can be quantified, PHABSIM can provide answers to "what if" water management questions.

PHABSIM uses a combination of standard, one-dimensional, steady-flow, open-channel hydraulic models and habitat models to describe WUAs under a variety of channel configurations and flow management conditions. Use of simulation models allows physical habitats to be described for unmeasured discharges. This approach allows cost savings in collecting field data because each flow does not have to be measured, and it allows practitioners to describe flow conditions that would be too dangerous to measure.

Time Series Library (TSLIB). TSLIB uses a set of programs to create monthly or daily habitat time series and habitat-duration curves using the habitat-discharge relationships produced by PHABSIM (Gordon et al., 1992). The programs can calculate basic statistics for monthly data, generate flow-duration habitat curves for designated months, and create monthly or annual habitat time series for four to seven life stages of selected species.

MNSTREM Stream Temperature Model (fact sheet, page C.13). MNSTREM is a dynamic stream water temperature simulation model developed for the simulation of water temperatures in the experimental streams of the U.S. EPA/Monticello Ecological Research Station (Gulliver, 1977; Stefan et al., 1980). It has been applied to assess the impacts of instream flow requirements upon water temperature in the Central Platte River, Nebraska (Sinokrot et al., 1996) and other streams ranging in size from the Mississippi River to a 50 cfs stream. MSTREM solves the one-dimensional heat advection-dispersion equation and incorporates heat exchange with the atmosphere. MSTREM has been found to predict hourly stream temperatures with standard errors of only 0.2 and 0.3°C when accurate weather paramaters and stream morphology data are available. MNSTREM was extended to include streambed heat flux in the heat budget, side stream inflow, and groundwater inflow by Sinokrot and Stefan (1994).

Data requirements for MNSTREM include location, weather data, and stream data. Location data consist of latitude and altidude. Weather data include air temperature, relative humidity, solar radiation, wind velocity, cloud cover, and air pressure. Stream data are total length of river reach, cross-sectional area and surface width as a function of discharge, upstream water temperature as a boundary condition, observed water temperature (hourly) for calibration, daily stream flow rate, groundwate inflow/outflow, and streambed data (temperature profile in the sediment data (temperature profile in the sediment).

Stream Network/Segment Temperature Model (SNTEMP/SSTEMP) (fact sheet, page C.21). SNTEMP and SSTEMP are computer models that estimate how the temperature of a stream changes with altered conditions of flow, riparian shade, and meteorological conditions (Theurer et al., 1984). SNTEMP is a more complicated program that can simulate a stream network with multiple tributaries for multiple time periods. SSTEMP is a simplified version of SNTEMP that can assess only a single stream for a single time period.

Both programs require input parameters that describe the stream geometry, hydrology, and meteorology to simulate minimum, mean, and maximum daily water temperature. SNTEMP and SSTEMP assume that water in the system is instantaneously and thoroughly mixed at all times, that all stream geometry (e.g., slope, shade, friction coefficient) is characterized by mean conditions, that distribution of lateral inflow is uniformly apportioned throughout the segment length, and that solar radiation and other meteorological and hydrological parameters are 24-hour means. The programs also handle the special case of a dam with steady-state release at the upstream end of the segment. The companion programs SHADE and SOLAR can be used in tandem with SNTEMP/SSTEMP to calculate percent shade, solar radiation, and day length. PHABSIM can also be used to calculate the width-flow function. Incorporation of macrohabitat temperature suitability as described in the Instream Flow Incremental Methodology (see Bovee, 1982) is a logical next step for factoring temperature consequences of altered streamflow into management decisions. SNTEMP and SSTEMP are typically used in deciding whether regulatory requirements are being met for fisheries in rivers and streams.

Riverine Community Habitat Assessment and Restoration Concept (RCHARC). RCHARC is a simulation model developed recently at the U.S. Army Corps of Engineers Waterways Experiment Station that relates aquatic habitat quality to hydraulic diversity based on a "comparison standard" reach approach (Nestler et al., 1993a,b). The comparison standard river system (CSRS) used represents the ideal or target habitat for an aquatic community as defined by channel morphology and flow frequency (Peters et al., 1995). RCHARC assumes that for a given discharge, a distribution of flow depths and velocities exists that represents habitat of varying quality; changes in the frequency and distribution of these depths and velocities will therefore change the composition of the aquatic community (Peters et al., 1995). RCHARC integrates field observations, survey data, and the U.S. Army Corps of Engineers' HEC-2 computer model (which calculates water surface elevations and velocities) to generate three-dimensional bivariate plots of velocity, depth, and percent occurrence of species for each stream segment. Habitat similarity between comparison reaches is determined by assessing the velocity-depth distributions for a range of discharges. Such comparisons offer great promise in planning restoration activities. The RCHARC model is still being validated; a Beta test for RCHARC was recently completed in Rapid Creek in South Dakota (Peters et al., 1995). No fact sheet or model evaluation has been included because of its developmental stage.

3.4 Species/biological community assessment techniques

> **Biological communities** integrate the effects of different pollutant stressors, such as excess nutrients, toxic chemicals, increased temperature, and excessive sediment loading, and thus provide an overall measure of the aggregate impact of the stressors.

This section includes techniques for evaluating the status of a species, population, or biological community in a waterbody, or examining or predicting the effects of changing water quality conditions on a species, population, or biological community. The central purpose of assessing biological condition is to determine how well a waterbody supports aquatic life. Biological communities integrate the effects of different pollutant stressors, such as excess nutrients, toxic chemicals, increased temperature, and excessive sediment loading, and thus provide an overall measure of the aggregate impact of the stressors. Although biological communities respond to changes in water quality more slowly than water quality actually changes, they respond to stresses of various degrees over time.

Tools that use biological surveys and other direct measurements of biota in surface waters often compare them to reference conditions to evaluate the overall health of an aquatic species or community. These assessments commonly use benthic macroinvertebrates and fish, as well as assemblages of plankton, macrophytes, and periphyton, as indicators of the condition of biological communities. Comparisons of macroinvertebrates or fish communities can be made between those characterizing the reference condition and those found at monitored sites to determine how closely they resemble one another. It is important to note that many of these techniques can be modified to accommodate local situations, and frequently states or local governments adapt the techniques to establish regional or statewide biological assessment programs.

Screening-level or Reconnaissance Bioassessment (fact sheet, page C.17). The simplest bioassessment approach that can be used to obtain useful information about the status of an aquatic community and condition of a site is a screening-level, or reconnaissance, bioassessment (Plafkin et al., 1989; USEPA, 1994c). This type of survey can be done inexpensively and with few resources. If the screening-level bioassessment is conducted by a trained and experienced biologist with a knowledge of aquatic ecology, taxonomy, and field sampling techniques, the results will have the greatest validity. Since a screening-level bioassessment is done without the benefit of comparison to unimpaired sites, a judgment of biological condition is made based solely on the presence or absence of indicator taxa, dominance of nuisance or sensitive taxa in the sampled habitats, or evenness of taxonomic distribution. A trained biologist will be able to determine whether the biota at a site are moderately or severely impaired using this approach, but subsequent sampling is often necessary to confirm any findings. The most useful application of this approach is for problem identification or screening and for setting pollution abatement priorities. Examples of reconnaissance techniques are the Rapid Bioassessment Protocols (RBPs) I and IV (Plafkin et al. 1989; USEPA, 1994c). A summary of all five RBPs is also provided in Table 11. RBP-type methods for fish and invertebrates have been adapted for use by many states and federal agencies and are in use across the country (Southerland and Stribling, 1995).

RBP I. RBP I is a screening assessment involving the systematic documentation of visual observations by a trained professional (Plafkin et al., 1989). The first element of RBP I is a habitat assessment that consists of inspection of the instream habitat for the amount of embeddedness; type of bottom substrate; depth; flow velocity; presence of scoured areas or areas of sediment deposition; relative abundance of different habitat types (pools, riffles, runs); presence of woody debris, aquatic vegetation, riparian vegetation, and bank erosion; and proximity of altered land uses. Biological sampling for this type of bioassessment involves macroinvertebrate collection, from which calculations of relative abundance and number of orders/families represented are made. Calculations of basic community structure can also be made if specimen identifications are sufficiently detailed to allow determination of the functional feeding group the organisms occupy.

RBP IV. The purpose of RBP IV is to serve as a screening tool by maximizing existing knowledge of fish communities through the use of a questionnaire and general habitat and water quality data (Plafkin et al., 1989). The questionnaire surveys local, state, and university fish biologists to obtain information such as historical trends, and incidents of tainting and fish tissue contamination. This technique provides a quick and inexpensive assessment of a large number of waterbodies. Development of a questionnaire is flexible, but the questionnaire should provide information including the integrity of the fish community, frequency of occurrence of limiting factors and causes, frequency of occurrence of particular fish community conditions throughout time and space, effects of waterbody type and size on these conditions, likelihood of improvement/degradation, and the major limiting factor (Plafkin et al., 1989).

Questionnaires are often disseminated more easily and receive a better response if sent in electronic form.

Multimetric Approaches for Biological Assessment (fact sheets, pages C.9 and C. 17). Accurate assessment of biological condition requires a method that integrates biotic responses through an examination of patterns and processes from the organism level to the ecosystem level (Karr et al., 1986). Multimetric approaches define an array of measures, or metrics, that individually provide information on community structure, taxonomic composition, individual condition, and biological processes. Numerous biological metrics have been tested in various regions of the country, primarily for fish and benthos. Summaries of those used have recently been presented (Barbour et al., 1995; Gibson et al., 1994). Those presented here are some of the more common approaches and include the Rapid Bioassessment Protocols (RBPs) II, III, and V (also known as the Index of Biotic Integrity) (Karr, 1981; Plafkin et al., 1989); the Invertebrate Community Index or ICI (DeShon, 1995); and the Index of Well-Being (Gammon, 1980; Hughes and Gammon, 1987).

The raw data collected during these biological surveys consist entirely of taxonomic identifications and numbers of individuals within each taxon. The level of identification—whether to family, genus, or species—depends on the method being used. For instance, RBP II involves identification to the family level, whereas RBP III involves identification to the lowest practical level, generally genus or species. These data are used to calculate or enumerate a variety of values, or metrics. Each reflects a different characteristic of community structure and has a different range of sensitivity to pollution stress (Plafkin et al., 1989). Appropriately developed metrics can be used to draw conclusions about different aspects of the biological condition at a site, and measurements of multiple metrics in a biological assessment will yield a more accurate representation of the overall biological condition at a site. Gray (1989) stated that the three best-documented biological responses to environmental stressors are a reduction in species richness, a change in species composition to dominance by opportunistic species, and a reduction in the mean body size of organisms. Though the last type of biological response (change in mean body size) might be well-documented, it is rarely used in the more common bioassessment protocols because the level of effort for an accurate interpretation can be prohibitive.

RBP II. RPB II provides a more detailed methodology than RBP I for characterizing benthic macroinvertebrate communities (Plafkin et al., 1989). RBP II characterizes the severity of an impairment into one of three categories (none, moderate, severe), gives a generic indication of impairment cause, and ranks and prioritizes streams for further assessment. This protocol uses systematic collection and analyses of benthic data to detect sites of intermediate impairment and prioritize sites for more intensive assessment. RBP II uses an integrated assessment of metrics that measure components of family-level community structure.

In addition to the standard RBP habitat and water quality data collection (i.e., characterizing and rating substrate/instream cover, channel morphology, and riparian/bank structure; measuring conventional water quality parameters; and examining physical characteristics), RBP II specifies examination of riffle/run community, sampling of coarse particulate organic matter, identification of a 100-organism subsample in the field to family or order level, and analysis of coarse particulate organic matter and functional feeding group of riffle/run in the field. The metrics that are developed with the collected data are taxa richness, Family Biotic Index, ratio of scrapers/filtering collectors, ratio of EPT (Ephemeroptera, Plecoptera, and Trichoptera) and chironomid abundances, percent contribution of dominant family, EPT index, community similarity index, and ratio of shredders/total. Plafkin et al. (1989) describe collection procedures and the computation of each metric in further detail. Each metric is given a score when compared to that of a reference condition, and all metrics are summed to determine the overall biological condition. In cases where final scores border on established ranges, additional data such as those from water quality, habitat, and physical assessments can aid in the final evaluation of biological condition.

RBP III. RBP III is the most rigorous bioassessment technique for characterizing the health of a benthic invertebrate community (Plafkin et al., 1989). This technique involves systematic field collection of data similar to that of RBP II, but also includes subsequent laboratory analysis to detect more subtle degrees of waterbody impairment. Use of RBP III allows determination of the severity of an impairment into one of four categories (no, slight, moderate, severe); it gives a generic indication of its cause; establishes a basis for trend monitoring; and prioritizes streams for further assessment.

In addition to the standard RBP habitat and water quality data collection (see RBP II), RBP III focuses on the sampling of benthic macroinvertebrates plus cursory field observation of periphyton, macrophyton, slime, and fish communities. The metrics developed from data collection include taxa richness, Hilsenhoff Biotic Index, ratio of scrapers/filtering collectors, ratio of EPT and chironomid abundances, percent contribution of dominant taxon, EPT index, community similarity index, and ratio of shredders/total. Similar to RBP II, each metric is given a score when compared to that of a reference condition, and all metrics are summed to determine the overall biological condition. In cases where final scores border on established ranges, additional data such as those from water quality, habitat, and physical assessments can aid in the final evaluation of biological condition.

Invertebrate Community Index (ICI). The ICI was developed by the Ohio Environmental Protection Agency as a principal measure of overall macroinvertebrate community health (DeShon, 1995). The ICI is a single value calculated by summing 10 structural and compositional community metrics, each of which is attributed a score of 0, 2, 4, or 6 points based on watershed area and comparisons with scores developed from ecoregional reference sites. The 10 metrics collected in the development of the ICI are total number of taxa, number of mayfly taxa, number of caddisfly taxa, number of dipteran taxa, percent mayfly composition, percent caddisfly composition, percent tribe tanytarsini midge composition, percent other dipteran and noninsect composition, percent tolerant organisms, and number of qualitative EPT taxa.

Table 11. Five Tiers of the Rapid Bioassessment Protocols

Level or Tier	Organism Group	Relative Level of Effort	Level of Taxonomy/ Where Performed	Level of Expertise Required
I	benthic invertebrates	low; 1-2 hr per site (no standardized sampling)	order, family/field	one highly trained biologist
II	benthic invertebrates	intermediate; 1.5-2.5 hr per site (all taxonomy performed in field)	family/field	one highly trained biologist and one technician
III	benthic invertebrates	most rigorous; 3-5 hr per site (2-3 hr of total are for lab taxonomy)	genus or species/ laboratory	one highly trained biologist and one technician
IV	fish	low; 1-3 hr per site (no field work involved)	not applicable	one highly trained biologist
V	fish	most rigorous; 2-7 hr per site (1-2 hr per site are for data analysis)	species/ field	one highly trained biologist and 1-2 technicians

Source: Plafkin et al., 1989.

Structural and compositional metrics, rather than functional metrics, were chosen because of their historic use and ease of derivation and interpretation (DeShon, 1995). The metrics chosen do, however, incorporate into the scoring scheme functionally based differences between macroinvertebrates over a range of stream conditions. As with other multimetric approaches, the strength of the ICI is its ability to compare the biological integrity of a stream with reference conditions (DeShon, 1995). With changes to collection methodologies, metric selection, and reference conditions to account for geographic setting and ecoregions other than those in Ohio, the ICI approach can be used successfully to assess the condition of macroinvertebrate communities throughout the country.

RBP V/Index of Biotic Integrity (IBI). RBP V, which is also known as the IBI, is a broadly based index that is firmly grounded in fisheries community ecology and is used to measure the biological integrity of a waterbody. When tied to ecological systems, the term "biological integrity" has been defined as the ability to support and maintain a balanced, integrated, adaptive community of organisms having a species composition, diversity, and functional organization comparable to that of the natural habitat of the region (Karr and Dudley, 1981). Systems with biotic integrity can withstand or rapidly recover from most perturbations imposed by natural environmental processes and can survive many of the major disruptions induced by humans. Biotic integrity is possessed by aquatic ecosystems in which composition, structure, and function have not been adversely impaired by human activities.

The IBI was designed to include a range of attributes of fish assemblages. Its 12 metrics fall into 3 broad categories: species composition, trophic composition, and fish abundance and conditions (Karr, 1981). These metrics assess attributes that are assumed to correlate with biotic integrity. Individually, each metric provides information about a specific attribute of the sampling site. Together, they characterize the underlying biotic integrity of that site. The values of the 12 metrics, however, are functions of the underlying biotic integrity; biotic integrity is not a function of the metrics. The metrics developed by Karr et al. (1986) applied to warmwater fish assemblages most commonly found in midwestern streams. They are not suitable for the fish assemblages that inhabit coldwater and montane streams. Chandler and Maret (1991) developed 20 metrics for coldwater, salmonid-dominated streams such as those found in the western and northwestern United States. Applying Principal Component Analysis and Multiple Discriminant Analysis to field data collected from Idaho streams, Robinson and Minshall (1992) narrowed the list down to six important metrics.

At a given site, data are obtained for each of these metrics and evaluated in light of what might be expected at an unimpacted or relatively unimpacted site located in a similar geographical region on a stream of comparable size. A numerical rating is then assigned to each metric based on whether its evaluation deviates strongly from, deviates somewhat from, or approximates expectations. The sum of the 12 ratings, in turn, yields an overall site score. The strength of the IBI is its ability to integrate information from individual, population, community, zoogeographic, and ecosystem levels into a single ecologically based index of the quality of a water resource. A recent review further discusses application of the IBI (Simon and Lyons, 1995).

Index of Well-Being. The Index of Well-being (Gammon, 1980; Hughes and Gammon, 1987) incorporates measures of species abundance and diversity estimates in approximately equal fashion, thereby representing the quality of fish assemblages more realistically than a single measure of abundance or diversity.

The measures of abundance include the number and biomass of individuals, and the Shannon-Weaver diversity index is calculated for number of individuals and biomass.

The sensitivity of the index can be increased for degraded environments by a minor modification, resulting in a modified IWB. The computational formula remains the same; however, any of 13 highly tolerant species, exotics, and hybrids are deleted from the number and biomass components of the IWB. The tolerant and exotic species are included in the two calculations for the Shannon-Weaver diversity index. The modification is designed to eliminate the undesired effect caused by the high abundance of tolerant species, while retaining the desired influence of the diversity indices.

The IWB is most frequently used in concert with the IBI and the Invertebrate Community Index (ICI) to identify impact type (e.g., complex toxic) based on biological response signatures (Yoder, 1991). This combination of ecological measures of community structure and function has been used for assigning causes of and sources to aquatic life use impairments in Ohio streams and rivers.

Population Viability Analysis (fact sheet, page C.15). Population viability analyses (PVAs) model the effects of demographic, genetic, or environmental variability on population stability to examine how expected time to extinction changes with the environment, population structure, or behavior. An important innovation of this risk assessment method is the consideration of uncertainty due to unknown or unpredictable events. Uncertainty is incorporated by modeling variation in population parameters and estimating probabilities of extinction over specified periods of time instead of using a single estimate for an unspecified time. PVAs have been used mostly in a generalized sense to determine how a population will respond to environmental changes, rather than specifically to assess risk from alternative management scenarios. However, the method is potentially applicable to specific cases involving land development.

The accurate projection of population growth requires a knowledge of the age structure of the population and the survival and fecundity of individuals of each age. This is often achieved using a life table (or matrix) approach in which the demographic parameters include annual rates of survival, growth or change among defined life history stages, and fecundity. Life tables set out the fecundities and probabilities of survival for each age class of individuals in a population and use an "accounting" formulation to calculate future population size on the basis of current size and rates of growth, death, and birth.

Food and Gill Exchange of Toxic Substances (FGETS) (fact sheet, page C.1). The Food and Gill Exchange of Toxic Substances (FGETS) program is a FORTRAN simulation model that predicts temporal dynamics of a fish's whole-body concentration (ìg chemical/(g live weight fish)) of nonionic, nonmetabolized organic chemicals that are bioaccumulated from water and food (Barber et al., 1988, 1991). FGETS also calculates the time to reach the chemical's lethal activity by assuming that the chemical elicits its pharmacological response through a narcotic mode of action.

FGETS can be used to analyze the bioaccumulation of organic chemicals under laboratory or field conditions, and its predictions have been shown to agree well with both types of data. For laboratory applications, FGETS can be used to model either constant flow or static exposures. For field assessments, FGETS can be used to simulate the chemical bioaccumulation in multiple fish species that are exposed to either constant or time-varying water concentrations and that feed on either single or multiple food resources. For such assessments, FGETS can be configured to predict the dietary accumulation of chemicals in fish that feed on multiple fish species, plankton/drift organisms, and benthos. The relative contributions of these food items can be specified as a function of either the fish's age or size.

FGETS considers both the biological attributes of the fish and the physicochemical properties of the chemical that determine diffusive exchange across gill membranes and intestinal mucosa. Important biological characteristics addressed by the model are the fish's gill and intestinal morphometry, the body weight of the fish, and the fractional aqueous, lipid, and structural organic composition. Relevant physicochemical properties are the chemical's aqueous diffusivity, the molar volume, and the n-octanol/water partition coefficient, which is used as a surrogate to quantify chemical partitioning to the fish's lipid and structural organic fractions. FGETS is parameterized for a particular fish species by means of morphological, physiological, and trophic databases that delineate the fish's gill morphometry, feeding and metabolic demands, and body composition. Presently, joint water and food exposure is parameterized for salmonids, centrarchids, cyprinids, percids, and ictalurids.

AQUATOX. AQUATOX is an ecosystem fate and effects model authored by Dr. Richard A. Parks that is being developed by EPA's Office of Science and Technology. Upon completion, the model will predict the ecological effects of chemical (nutrient and toxic) loadings from their point of entry to the top of the aquatic food chain by estimating the amount of toxicant per unit biomass over time. AQUATOX, which will run in a Microsoft Windows-95 format, accounts for many ecological processes, including nutrient effects (e.g., growth, algae biomass, and nutrient recycling), acute toxicity and subsequent effects on trophic structure, feeding and predation rates, bioaccumulation, and chemical conversions (e.g., nitrification, volatilization, and hydrolysis). Potential applications of AQUATOX are the evaluation of different management scenarios, testing relative risks of several stressors, and factoring biological componenets into water quality modeling. Because AQUATOX is currently undergoing testing and verification (and is not available for distribution), no fact sheet or analysis of capabilities has been included in this compendium.

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4 Model Selection

Model Selection Criteria (as adapted from Nix, 1990)

1. **Hardware Availability.** With the evolution of the ever more powerful personal computer, this factor becomes less constraining but still must be considered given today's technology.
2. **Availability of trained personnel.** Water resource models are becoming more user friendly and are thus easier to use by the lay-person. However, the expertise of an experienced water resources or environmental engineer is invaluable for developing model parameters and critically evaluating model results.
3. **Long-term commitment to the model.** If a number of future projects will require the use of a particular model, it may be advantageous to use this particular model for a current project even when the model is less than optimal for the current application. Sometimes it may be more beneficial to invest heavily in one model than to switch models from project to project.
4. **In-house model experience.** Experience with a particular model is often available in-house. In this case, the fact that no "warm-up period" is necessary in learning a new model may out weigh the costs of using a less than optimal model.
5. **Acceptance and support of the model.** If a model is not widely used, it becomes more difficult to establish credibility and to interpret its results.
6. **Commitment to modeling as a tool.** The various interest groups involved in a project study must be willing to accept model results if the model is to be useful in implementing policy decisions.

Although mathematical simulation models and assessment techniques are becoming more integrated at the various levels of watershed and water quality analysis, selecting the model or set of models that best matches project objectives is still a complex task since more models are becoming available to users. Models and assessment techniques reviewed in the previous chapters cover a wide range of functions and can be applied, either directly or with minimum modification, to support a majority of decisions associated with watershed planning and management issues.

As the federal government and state and local agencies progress in resolving the programmatic issues associated with watershed characterization and management, there is an increasing need for analytical tools to support the decision-making process. This increased need is further amplified by the adoption of a holistic and watershed-based approach to resource management. This broader, ecologically based approach involves integrated analyses of multiple stressors by incorporating the physical, biological, and chemical components of a watershed system. The success of the watershed approach resides in the ability to consider multiple spatial scales, from upland terrestrial habitats to downstream receiving waterbodies, and to consider the time-varying and dynamic loading conditions. Watershed management decisions require the consideration of existing conditions, as well as the projection of anticipated future changes in various components of a watershed. The most challenging tasks of understanding the cause-effect relationships within a watershed include selecting the most appropriate mix of assessment tools, developing the most cost-effective procedures to use these tools, and generating the needed information to support the decisions made using the tools.

Selection of a watershed or water quality model or a combination of models is an important decision, not only because of the time and resources a modeling effort involves, but also because of the technical expertise required to maintain a model. Before selecting a model or set of models, watershed managers should determine both the need for modeling and the commitment of their program in using mathematical models to support management decisions. The success of adopting a model or set of models usually requires a firm commitment to provide the human and financial resources necessary to apply and contribute to further enhancement and development of the model(s). Nix (1990) compares the selection and use of a maladapted model to using no model at all. Such maladapted models can produce misleading results and lead to further complications and controversial decisions. Nix (1990) also advises that it is desirable to select a model that meets the most application requirements and has demonstrated applications and continuous support from the developer and user communities. Even if the model is not ideal, Nix (1990) recommends that the user allow for the development of in-house expertise, rather than switching models from application to application.

The first section of this chapter provides a brief description of considerations that outline the preliminary steps in selecting a model. Such considerations will assist users in characterizing the intended use of the model(s). Well-defined objectives can help users select the appropriate model, and design the model application. The remaining sections of this chapters provide comparative tables useful in selecting watershed loading models, receiving water response models, and ecological assessment techniques.

4.1 Preliminary Model Selection Considerations

Following is a list of considerations that can support the development of a framework for reviewing and selecting the appropriate model or assessment technique to meet project needs:

A single model might not be enough. Previous chapters of this document presented an extensive review of modeling and technical tools available to environmental managers to address multiple and often conflicting objectives and associated technical and economic constraints. Because most of these tools were developed in isolation to address a specific objective, they do not offer the completeness necessary to cover all management decisions. Individually, they do not explain the complex interrelationships governing all watershed stressors and the economic and environmental implications. One of the major dilemmas facing today's watershed manager is not only "which model to use," but also "how many models or techniques should be used" to allow for an integrated analysis and to support the conceptual design of an "integrated watershed protection approach." As the number and sources of stressors increase, a single model might not be able to represent all the watershed components and pathways of interest. A combination of tools working together within a structured framework to capture the spatial and temporal variability of each stressor and the interaction among these stressors and the resulting impact may be needed.

A single model can be applied at various levels of detail. Throughout this document, model and assessment techniques have been grouped from simple to complex classes. Nevertheless, more sophisticated models (e.g., SWMM, HSPF) can be applied at various levels of detail. In many cases, it is advantageous to adopt a more detailed model to address various scientific and engineering applications than to continuously switch models from one phase of a project to another or from one project to another (Nix, 1990). As indicated in the previous chapters, no one model is ideal, and although most simple and mid-range models can provide valuable information for screening- and planning- level decisions, they are of a little use for advanced phases in the development of TMDLs or siting and designing of management plans.

Model Selection and Project Steps: TMDL Example

Project Step	Level of Detail
Identify impairments	No to low level
Priority ranking	Low to medium
TMDL development	Medium to high
Implementation	High (design)
Assess effectiveness	Medium to high

Models/techniques should be matched with the project phase. Most watershed or water quality management studies are performed in several phases, ranging from the screening and planning level to more detailed analysis and design of management measures. For example, the TMDL process in some cases employs a phased approach. In the preliminary phases of a project, screening-level tools are usually sufficient to support management decisions associated with prioritization and ranking. During this phase, the model results are typically used for relative comparisons. As projects move to advanced phases dealing with TMDL development or the design of management measures to meet certain water quality or ecological goals, a higher degree of accuracy is required of the model prediction results. During these advanced phases, model selection and configuration need to be defensible, additional data and monitoring is required, and the results must be verified.

Characterize Management Decisions

Types of anticipated use
- Compliance and permitting
- Continuous management of a resource(s)
- Watershed development considering management of point and nonpoint sources
- "One-shot" modeling effort

Impact and significance of decisions
- Ecological impact
- Human health impact
- Economic impact

Level of defensibility
- Level of accuracy of model results
- Calibration and verification needed

Characterize management decisions. One major element that should be considered in selecting a model(s) is the intended use of that model and the type and importance of the decisions to be made based on model results. In many cases a detailed analysis of implications of the project decisions and their required level of defensibility will dictate not only the selection of a given model(s), but most importantly the way the model should be configured and applied.

When adopting the watershed approach and accepting the use of mathematical models and assessment techniques to support management decisions, it is the watershed manager's responsibility to ensure that the selected model and the way it is applied meet the minimum validity and accuracy required for a successful application. A cost-effective approach can be taken by committing to use one or a limited set of models, to provide sufficient human and financial resources, and to contribute to the scientific and practical growth of the model through active participation within the developer's and users' group supporting the model.

Characterize Ecological Components to be Addressed by a Model

Prepare check lists
- Known impacted environments
- Suspected stressors

Identify potential interrelationships
- Stressor vs. type of impact

Identify impact pathways

Define a list of pertinent processes to model

Define the spatial and temporal resolution needed to model selected processes

Characterize ecological components to be addressed by a model. Mathematical models are developed based on a set of algorithms representing environmental processes and pathways. The most detailed model available might not include all the required processes needed to simulate a given multiple-stressor problem; the idea is to find a model that best fits the problem at hand and provides the flexibility for further enhancement and development. A simple way of generating selection criteria to assist in finding a model that best fits the short- and long-term decision-making needs is to develop a series of checklists based on available problem statements characterization studies and current understanding of watershed stressors. Such a checklist will include an inventory of known impacted environments and suspected stressors. This approach allows for determining interrelationships between the stressors, impacts, and corresponding pathways, and also permits identifying and ranking impact processes (e.g., agricultural nonpoint source loading) that should be represented in a selected model. Furthermore, the analysis of such processes and review of available literature and past studies will allow the model user to define the minimum spatial and temporal resolution necessary to represent each process within the desirable accuracy.

Define anticipated types of management alternatives to be modeled/assessed. The objectives of most watershed and water quality projects consist of developing potential management and restoration alternatives. The strength of the selected model or assessment technique provides the ability to evaluate such management and restoration plans and therefore display the environmental and economic trade-off between plans. One set of selection criteria that should be considered in evaluating models is the ability to simulate the anticipated management practices for the project.

4.2 Model Calibration and Validation

The results of loadings, receiving water, and ecological simulations are more meaningful when they are accompanied by some sort of confirmatory analysis. The capability of any model to accurately depict water quality conditions is directly related to the accuracy of input data and the level of expertise required to operate the model. It is also largely dependent on the amount of data available. Detailed models lacking the required verification calibration and validation are limited in accuracy.

Verification involves checking the governing equations of a model to determine if they have been accurately entered. Calibration involves minimization of deviation between measured field conditions and model output by adjusting parameters of the model (Jewell et al., 1978). Data required for this step are a set of known input

Verification: Checking the equations within a model to ensure they have been accurately entered.

Calibration: Testing and tuning of a model to a set of field data not used in the model validation step or in the development of the model; also includes minimization of deviations between measured filed conditions and output of a model by selecting appropriate model coefficients.

Validation: Subsequent testing of a pre-calibrated model to additional field data, usually under different external conditions, to further examine the model's ability to predict future conditions.

values along with corresponding field observation results. The results of the sensitivity analysis provide information as to which parameters have the greatest effect on output. For the best results, CSO models should be calibrated during storm events as opposed to dry flow periods (Water Pollution Control Federation, 1989).

Validation involves the use of a second set of independent information to check the model calibration. The data used for validation should consist of field measurements of the same type as the data output from the model. Specific features such as mean values, variability, extreme values, or all predicted values may be of interest to the modeler and require testing (Reckhow and Chapra, 1983). Models are tested based on the levels of their predictions, whether descriptive or predictive. More accuracy is required of a model designed for absolute versus relative predictions. If the model is calibrated properly, the model predictions will be acceptably close to the field observations.

In many cases, observed data for model calibration and validation might be insufficient or unavailable. Model selection must be based on an assessment of the available data. Screening-level applications might be possible with limited input data. As noted by Donigian and Rao (1988), most models are more accurate when applied in a relative rather than an absolute manner. Model output data concerning the relative contribution of a watershed to overall pollutant loads is more reliable than an absolute prediction of the impacts of one control alternative viewed alone. When examining model output from watershed-pollution sources, it is important to note three factors that can influence the model output and produce unreasonable data. First, suspect data can result from calibration or validation data that are insufficient or inappropriately applied. Second, any given model, including detailed models, might not represent enough detail to adequately describe existing conditions and generate reliable output. Finally, modelers should remember that all models have limitations and the selected model might not be capable of simulating desired conditions. Model results must therefore be interpreted within the limitations of their testing and their range of application. Inadequate model calibration and validation can result in spurious model results, particularly when used for absolute predictions. Data limitations might require that model results be used only for relative comparisons.

Modeling Management Alternatives

Define the type of anticipated management practices

- Types of stressors (pollutant, runoff, temperature, imperviousness, etc.)
- Nonstructural practices
- Structural practices

Define the level of simulation needed

- Compare management plan
- Generate design criteria to meet specific goals

Based on a review of project needs and objectives, and the considerations discussed above, the user can select the appropriate tools for watershed assessment or TMDL development. In the following sections, each category of modeling is discussed, and some of the considerations for selection of a specific model within each category are reviewed.

4.3 Watershed Loading Models

Most watershed loading models include three components: a hydrology component, which estimates the quantity of runoff and streamflow generated from the watershed or subwatersheds; an erosion and sediment component, which drives the amount of sediment delivered to a receiving waterbody; and a quality component, which computes the pollutant loadings. The basic simulation functions used in each model to generate pollutant loadings are presented in Tables 12, 13, and 14. These tables also present the type of pollutant handled by each model and the corresponding computation time steps.

As shown in Tables 12 through 14, most models are based on similar mathematical formulations. The curve number equation (CNE) developed by the USDA-SCS is widely used for simulating runoff and stream flows (e.g., SITEMAP, GWLF, P8-UCM, AGNPS, STORM, SWRRBQ), and the Universal Soil Loss Equation (USLE) is commonly used for determining erosion and sediment yield from rural areas or watersheds (e.g., EPA screening procedures, Water Screen, Watershed, SLOSS-PHOSPH,

Table 12. A Descriptive List of Model Components - Simple Methods

Model	Main Land Use	Hydrology	Erosion/ Sediment	Pollutant Load	Pollutants	Time Scale
EPA Screening Procedures	Mixed watershed	N/A	USLE-MUSLE	Loading functions, potency factors	Wide range[1]	Mean annual
The Simple Method	Urban	Runoff coefficient	N/A	Mean concentration	NURP data: TSS, P, metals, O&G	Variable (annual, monthly, event)
Regression Method	Urban	N/A	N/A	Regression equations	TSS, N, P, COD, metals	Storm event
SLOSS/PHOSP	Rural	N/A	USLE	Loading functions	P	Annual
Watershed	Mixed watershed	N/A	USLE	Unit area loadings	Wide range	Annual
FHWA	Highways	Runoff coefficient, observed data	N/A	Median concentration	TSS, N, P, organics, metals	Storm event
WMM	Mixed watershed	Runoff coefficient	N/A	Event mean concentration	N, P, lead, zinc	Annual

[1]Depends on available pollutant parameters and default data.

N = nitrogen O&G = oil and gas P = phosphorus TSS = total suspended solids COD = chemical oxygen demand

65

Storm event simulation: The use of a model to simulate the response to a single storm event.

Continuous simulation: The use of a model to simulate the response of a catchment to a series of storm events and the hydrological processes that occur between them.

GWLF, AGNPS, STORM, SWRRBQ). Pollutant loadings from rural areas are often calculated based on loading functions or potency factors (e.g., EPA screening procedures, Water Screen, AGNPS, SWRRBQ, HSPF). For urban areas, unit area loading rates (e.g., GWLF) or buildup and wash-off functions (e.g., STORM, SWMM) are widely used. The advantage of the CNE- and USLE-based models is that detailed default parameters are available for a wide variety of soil conditions and agricultural management techniques. The differences among models using similar simulation functions reside in the degree of spatial discretization they use, the number of processes for which they account, and the computational time steps they use.

Many of the simple methods do not take hydrologic processes into account when simulating pollutant loads. When dealing with urbanized areas, simple methods usually generate runoff based on empirical or statistical relationships between runoff coefficients and the degree of imperviousness (e.g., the Simple Method, FHWA, and WMM). It is, however, difficult to extrapolate such relationships to rural and agricultural areas.

Detailed models use more complex formulations for simulating runoff and sediment yield. The hydrology component generally involves a set of deterministic equations to represent the elements of the water balance equation (e.g., infiltration, evapotranspiration, groundwater recharge and/or seepage, depression storage). These models also use a physical description of the erosion and sediment yield mechanisms (e.g., soil detachment, transport, and deposition). Predictions of pollutant wash-off are usually made based on exponential decay functions (e.g., SWMM) with hourly time steps. Default values for parameters are pollutant- and site-specific and therefore might not be readily available, making calibration difficult and time-consuming. In most cases, additional laboratory testing and field measurement might be required.

Table 13. A Descriptive List of Model Components - Mid-Range Models

Model	Main Land Use	Hydrology	Erosion/ Sediment	Pollutant Load	Pollutants	Time Scale
SITEMAP	Mixed watershed	SCS curve number	N/A	Runoff concentration	N, P	Storm event, Continuous
GWLF	Mixed watershed	SCS curve number	Modified USLE	Unit loading rates	N, P	Storm event, Continuous
P8-UCM	Urban	SCS curve number (modified), TR 20	N/A	Nonlinear accumulation	TSS, N, P, metals	Storm event, Continuous
Auto-QI	Urban	Water balance	N/A	Accumulation and wash-off	Wide Range	Storm event, Continuous
AGNPS	Agriculture	SCS curve number	Modified USLE	Potency factors	N, P	Storm event
SLAMM	Urban watershed	Small storm-based coefficient	N/A	Nonlinear accumulation and wash-off	N, P, COD bacteria, metals	Storm event, Continuous

[1]Depends on available pollutant parameters and default values.

N = nitrogen P = phosphorus TSS = total suspended solids COD = chemical oxygen demand

Table 14. A Descriptive List of Model Components - Detailed Models

Model	Main Land Use	Hydrology	Erosion/ Sediment	Pollutant Load	Pollutants	Time Scale
STORM	Urban	Runoff coefficient - SCS curve numbers - Unit hydrograph	USLE	Buildup/wash-off functions	P, N, COD, metals	Continuous
ANSWERS	Agriculture	Distributed storage model	Detachment transport equations	Potency factors (correlation with sediment)	N/A	Storm event
DR3M-QUAL	Urban	Surface storage balance kinematic wave method	Related to runoff volume and peak	Buildup/wash-off functions	TSS, N, P, organics, metals	Continuous
SWRRBWQ/ SWAT	Agriculture	SCS curve number	Modified USLE	Loading functions	N, P, COD, metals, bacteria	Continuous
SWMM	Urban	Nonlinear reservoir	Modified USLE	Buildup/wash-off functions	Wide range[1]	Storm event, continuous
HSPF	Mixed watershed	Water balance of land surface and soil processes	Detachment/ wash-off equations	Loading/wash-off functions and sub-surface concentrations	Wide range[1]	Storm event, continuous

[1]Depends on available pollutant parameters and default values.

N = nitrogen P = phosphorus TSS = total suspended solids COD = chemical oxygen demand

The type and amount of input data required for operation, calibration, and verification of the model and the output results should be considered in the model selection process. Depending on the type of formulations the model uses, input data can range from simple watershed characteristics to hourly meteorological parameters, pollutant transformation kinetic coefficients, and field onitoring data. Tables 15, 16, and 17 present a brief summary of input and output information for each of the models reviewed.

Novotny and Chesters (1981) have developed three sets of input parameters that might be required for a typical modeling application (Table 18). Interpretation of the type and amount of data required, along with information contained in the preceding tables, can be used to evaluate the time and resources required to apply a given model for a given situation or project. For a detailed listing of input requirements, refer directly to the model documentation.

Watershed loading models are usually developed to target a specific setting, characterized primarily by land use or land activity. Few models are developed to evaluate watersheds with mixed land uses. Among the detailed models, HSPF appears to be the most versatile for watersheds with complex land use/land cover. SWMM, STORM, and DR3M-QUAL are designed primarily for urban areas, while ANSWERS and SWRRB are primarily agricultural models. Among the mid-range models, SITEMAP and GWLF are the two models that account for both rural and urban watersheds. The GWLF model offers the possibility of generating long-term time series of pollutant loadings at various time steps, allowing analysis of seasonal and interannual variabilities. GWLF also allows evaluation of watershed response to changes in land use patterns and point and nonpoint source loadings. Urban models such as P8-UCM and

Table 15. Input and Output Data - Simple Methods

Models	Main Input Data	Output Information
EPA Screening Procedures	Watershed and land use data Loading factors (default values)	Mean annual sediment and pollutant loads
The Simple Method	Annual rainfall data Land use and imperviousness data Pollutant mean concentration BMP removal efficiencies	Runoff volume and pollutant concentration/load, storm or annual
Regression	Mean annual rainfall Mean minimum January temperature Drainage areas and land use Percent imperviousness	Mean annual storm event load and confidence interval
SLOSS/ PHOSPH	Rainfall erosivity factor Soil, crop, topography, and land use data	Mean annual loads of sediment and phosphorus
Watershed	Rainfall erosivity factor Land use and soil parameters Unit loading rates BMP cost information	Mean annual pollutant loads; BMP cost-effectiveness
FHWA	Site and receiving water data Flow and storm event concentrations	Statistics on storm runoff and concentrations; impacts on receiving water
WMM	Land use and soil data Annual precipitation and evaporation Inputs from baseflow and precipitation Event mean concentrations in runoff Reservoir, lake, or stream hydraulic characteristics Removal efficiencies of proposed BMPs	Annual urban and rural pollutant loads from point and nonpoint sources, including septic tanks; load reductions from combined effects of multiple BMPs; in-lake nutrient concentrations as related to trophic state; concentrations of metals

Table 16. Input and Output - Mid-Range Models

Models	Main Input Data	Output Information
SITEMAP	Meteorologic and hydrologic data, hourly or daily (maximum one year) Watershed and channel parameters Point sources and pollutant parameters (e.g., decay)	Runoff and nutrient loadings Pollution load allocations
GWLF	Meteorologic and hydrologic data, daily Land use and soil data parameters Nutrient loading rates	Monthly and annual time series of runoff, sediment, and nutrients
P8-UCM	Meteorologic and hydrologic data, hourly storm or storm sequence Land use and soil parameters BMP information	Daily runoff and pollutant loads BMP removal efficiencies
Auto-QI	Hourly/daily rainfall Watershed and land use data BMP removal rates	Continuous or storm event simulation of runoff and selected pollutants
AGNPS	Watershed, land use, management, and soil data Rainfall data, topography BMP removal data	Storm runoff volume and peak flow Sediment, nutrient, and COD concentrations
SLAMM	Hourly rainfall data Pollution source characteristics, areas, soil type, imperviousness, and traffic Structure characteristics	Pollutant load by source area BMP evaluation and cost estimates

SLAMM were mainly designed for evaluating management practices to control urban stormwater runoff. Simple methods use generic empirical relationships that can be used in both rural and urban settings provided site-specific or default values are available.

Model applications may be classified as screening, intermediate, or detailed depending on the focus and objectives of the application. Simple methods are most frequently used for screening applications; however, mid-range and detailed models allow for a wider range of applications. Screening applications are generally performed at the preplanning level, with specific objectives such as comparisons of the relative contribution of point and nonpoint sources using a relatively limited set of available information. Screening analyses can consider a broad range of land use types and sources and can be performed at various stages of project development (e.g., planning, evaluation of alternatives, preliminary design). At the planning level, screening applications can be directed toward scoping the project objective and identifying general areas where controls or additional sampling might be required.

Intermediate applications provide a more detailed description of the geographic variables that contribute to nonpoint pollution, in addition to consideration of multiple point sources. Intermediate applications can assist in the identification of specific point and nonpoint source activities and in preliminary selection of pollution control options incorporating a higher degree of spatial variation within land uses.

As it becomes necessary to accurately distinguish differences in pollutant characteristics from multiple-source areas, pollutant behavior is considered in more detail and a more mechanistic description of pollutant generation, transformation, and removal by various control practices is required. Detailed applications are, therefore, necessary to

Table 17. Input and Output Data - Detailed Models

Models	Main Input Data	Output Information
STORM	Hourly rainfall data Buildup and wash-off parameters Runoff coefficient and soil type	Event-based runoff and pollutant loads Storage and treatment utilization and number of overflows Hourly hydrographs and pollutographs
ANSWERS	Hourly rainfall data Watershed, land use, and soil data BMP design data	Predicts storm runoff (volume and peak flow) Sediment detachment and transport Analysis of relative effectiveness of agricultural BMPs
DR3M-QUAL	Meteorologic and hydrologic data Watershed characteristics related to runoff Channel dimensions and kinematic wave parameters Characteristics of storage basins Buildup and wash-off coefficients	Continuous series of runoff and pollutant yield at any location in the drainage system Summaries for storm events Hydrographs and pollutographs
SWRRBWQ/ SWAT	Meteorologic and hydrologic data Watershed and receiving waterbody parameters Land use and soil data Pond and reservoir data	Continuous water and sediment yield Peak discharge Water quality concentrations and loads
SWMM	Meteorologic and hydrologic data Land use distribution and characteristics Accumulation and wash-off parameters Decay coefficients	Continuous and event-based runoff and pollutant loads Transport through streams and reservoirs Analysis of control strategies
HSPF	Meteorologic and hydrologic data Land use distribution and characteristics Loading factors and wash-off parameters Receiving water characteristics Decay coefficients	Time series for runoff and pollutant loadings Analysis of impacts on receiving water Analysis of controls

provide either storm-based or continuous simulation of water and water quality processes and to assist in developing design criteria for achieving project objectives.

The potential range of applications of watershed models in planning, evaluation of management measures, and analysis of impacts on the quality of receiving waters is illustrated in Tables 19, 20, and 21. The tables show that the majority of the models can be used for screening-level applications. The simple methods, in particular, provide only an order-of-magnitude estimate on an annual basis and therefore are limited to screening applications at the planning level. Some of the mid-range models (e.g., GWLF, SITEMAP, and AGNPS) incorporate point and nonpoint source pollution routines and are also good candidates for screening activities. SLAMM, P8-UCM, and SIMPTM are primarily urban runoff models, and their application to evaluation of urban stormwater control practices and strategies might be useful at an intermediate level. SWMM, HSPF, DR3M, STORM, and SWRRB stand out from the others as models capable of providing a detailed indication of the contribution of pollutants from various point and nonpoint sources. Their simulation capabilities allow for evaluation of control strategies and development of design criteria.

Application of detailed models such as HSPF and SWMM for screening purposes, using estimated default values for a number of parameters, can reduce time and input requirements. However, representative default values for many of the detailed models

Table 18. Input Data Needs for Watershed Models

1. System Parameters Watershed size Subdivision of the watershed into homogenous subareas Imperviousness of each subarea Slopes Fraction of impervious areas directly connected to a channel Maximum surface storage (depression plus interception storage) Soil characteristics including texture, permeability, erodibility, and composition Crop and vegetative cover Curb density or street gutter length Sewer system or natural drainage characteristics
2. State Variables Ambient temperature Reaction rate coefficients Adsorption/desorption coefficients Growth stage of crops Daily accumulation rates of litter Traffic density and speed Potency factors for pollutants (pollutant strength on sediment) Solar radiation (for some models)
3. Input Variables Precipitation Atmospheric fallout Evaporation rates

Source: After Novotny and Chester, 1981.

Table 19. Range of Application of Watershed Models—Simple Methods.

Simple Methods	Watershed Analysis			Control Analysis		Receiving Water Quality
	Screening	Intermediate	Detailed	Planning	Design	
EPA Screening	●	-	-	-	-	○
The Simple Method	●	-	-	○	-	-
Regression	●	-	-	-	-	-
SLOSS/PHOSPH	○	-	-	-	-	-
Watershed	●	-	-	○	-	-
FWHA	●	-	-	○	-	○
WMM	●	○	-	◒	-	◒

● High ◒ Medium ○ Low - Not Available

Table 20. Range of Application of Watershed Models—Mid-Range Models

Mid-Range Methods	Watershed Analysis			Control Analysis		Receiving Water Quality
	Screening	Intermediate	Detailed	Planning	Design	
SITEMAP	●	○	○	◒	-	○
GWLF	●	◒	○	-	-	-
P8-UCM	●	◒	◒	○	●	-
Auto-QI	●	●	○	◒	○	○
AGNPS	●	●	○	●	○	○
SLAMM	●	◒	◒	●	◒	○

● High ◒ Medium ○ Low - Not Incorporated

Table 21. Range of Application of Watershed Models—Detailed Models

Detailed Methods	Watershed Analysis			Control Analysis		Receiving Water Quality
	Screening	Intermediate	Detailed	Planning	Design	
STORM	●	●	○	●	○	○
ANSWERS	●	●	◒	●	○	○
DR3M-QVAL	◒	●	●	●	◒	◒
SWRRBQ/SWAT	◒	●	●	●	◒	◒
SWMM	◒	●	●	●	◒	-
HSPF	◒	●	●	●	◒	●

● High ◒ Medium ○ Low - Not Incorporated

are difficult to obtain. In addition, their accuracy as screening tools might be jeopardized by replacing mechanistic equations with their simplified forms and including inappropriate default values. Urban stormwater runoff models, such as SWMM, HSPF, SLAMM, P8-UCM, and DR3M-QUAL, are capable of providing design criteria for a number of structural practices. Models with such capabilities, however, are data-intensive and require trained profession-als to operate the model, select appropriate default values, and interpret the results.

4.4 Receiving Water Models

The major considerations in the selection of one or more models to simulate a receiving waterbody's response to various pollutant loading scenarios are (1) the waterbody type; (2) whether flow rates are to be represented as steady or unsteady; (3) the various hydrodynamic, water quality, toxics, and sediment processes that need to be modeled; and (4) data available for model parameterization, calibration, and verification. The key components of hydrodynamic, steady-state water quality, and dynamic water quality models are shown in Tables 22, 23, and 24, respectively.

Unsteady flow rates can be simulated by a separate hydrodynamic model (RIVMOD-H, DYNHYD5, EFDC, CH3D-WES) and input to a water quality model in a external linkage. Some models such as CE-QUAL-RIV1 and CE-QUAL-W2 allow for internal hydrodynamic simulation. Selection of hydrodynamic models depends on the waterbody types and circulation processes that affect water quality conditions. For rivers

Table 22. A Descriptive List of Model Components - Hydrodynamic Models

Model	Dimension	Horizontal Coordinate System	Vertical Coordinate System	Vertical Mixing	Solution Technique
Externally Coupled					
RIVMOD-H	1-D	N/A	N/A	N/A	Implicit
DYNHYD5	1-D	Link Node	N/A	N/A	Explicit Runge-Kutta
EFDC	1-D, 2-D (x/y, x/z), 3-D	Cartesian, orthogonal boundary fitted, laterally averaged	Staircase Cartesian, sigma transformation to local bathymetry	Turbulence closure	Implicit
CH3D-WES	1-D, 2-D (x/y, x/z), 3-D	Cartesian, orthogonal boundary fitted, laterally averaged	Staircase Cartesian	Turbulence closure	Implicit
Internally Coupled					
CE-QUAL-RIV1	1-D	N/A	N/A	N/A	Implicit (RIV1H)
CE-QUAL-W2	1-D, 2-D (x/z)	Cartesian, laterally averaged	Staircase Cartesian	Wind shear	Implicit
HSPF	1-D	N/A	N/A	N/A	Implicit

that are laterally and vertically well-mixed, a one-dimensional representation is generally sufficient. The one-dimensional formulation captures the longitudinal transport processes that dominate in most river systems. Both RIVMOD-H and CE-QUAL-RIV1 share the same one-dimensional formulation. DYNHYD5 is also applied to river systems, although the model experiences numerical stability problems in high-gradient streams. In lakes, where vertical stratification and mixing dominate, a two-dimensional formulation is normally preferred. Mixing is often influenced by temperature and most hydrodynamic models applied to lakes consider heat balance. CE-QUAL-W2 is an example of a model that specializes in modeling vertically stratified systems (x/z). Three-dimensional models such as EFDC can also be collapsed for a two-dimensional representation. Full three-dimensional simulations are typically reserved for estuarine and near coastal systems. Estuaries experience complex circulation patterns due to tidal influences, freshwater inflows, wind-induced mixing, temperature and salinity gradients, and physical geometry. Three-dimensional models, such as EFDC and CH3D-WES, simulate many of these key features. In some cases estuaries are simulated as one- (DYNHYD5/WASP5, TPM), or two-dimensional systems in order to simplify the analysis process.

Some of the simple and easy-to-use models employ empirically based solution techniques to assess eutrophication processes. Models such as EUTROMOD, PHOSMOD, EPA Screening Methods, and BATHTUB evaluate loading and lake/reservoir response based on these empirically based statistical relationships. These models do not explicitly describe each process (e.g., algal growth), resulting in low input data requirements and limited calibration requirements. Drawbacks of such models include limitations in application areas and accuracy. For example, EUTROMOD was developed for lakes in North Carolina and has limitations for application in other regions. PHOSMOD enhances the simplified empirical framework with consideration

Table 23. A Descriptive List of Model Components - Steady-State Water Quality Model

Model	Waterbody Type	Parameters Simulated	Processes Simulated	
			Physical	Chemical/Biological
EPA Screening Methods	River, lake/ reservoir, estuary, coastal	Waterbody nitrogen, phosphorus, chlorophyll , or chemical concentrations	Dilution, advection, dispersion	First-order decay empirical relationships between nutrient loading and eutrophication indices
EUTROMOD	Lake/reservoir		Dilution	Empirical relationships between nutrient loading and eutrophication indices
PHOSMOD	Lake/reservoir	DO, phosphorus	Dilution	Empirical relationships between phosphorus loading and eutrophication indices
BATHTUB	Lake/reservoir	DO, nitrogen, phosphorus, chlorophyll	Dilution	Empirical relationships between nutrient loading and eutrophication indices
QUAL2E	Rivers, (well-mixed/ shallow lakes or estuaries)	DO, CBOD, temperature, organic N, ammonia, nitrite, nitrate, organic P, dissolved phosphorous, phytoplankton, fecal coliform, arbitrary nonconservative substances, three conservative substances	Dilution, advection, dispersion, heat balance	First-order decay, DO-BOD cycle, nutrient-algal cycle
EXAMSII	Rivers	Conservative and nonconservative substances	Dilution, advection, dispersion	First-order decay, process kinetics, daughter products, exposure assessment
TOXMOD	Lake/reservoir	Conservative and nonconservative substances	Dilution, advection, dispersion	First-order decay, sediment burial and release
SYMPTOX4	River/reservoir	Conservative and nonconservative substances	Dilution, advection, dispersion	First-order decay, sediment exchange
TPM	Estuaries	DO, CBOD, NBOD, temperature, ammonium, nitrate, nitrite, organic nitrogen, total phosphate, organic phosphorus, salinity, inorganic suspended solids, dissolved labile, and refractory particulate organic carbon, dissolved silica, particulate biogenic silica, fecal coliform, total active metal	Dilution, advection, dispersion, heat balance, particle fate	First-order decay, DO-BOD cycle, nutrient-algal cycle, carbon cycle, silica cycle, benthic algae, sediment digenesis
DECAL	Coastal	Sediment, conservative and nonconservative substances	Dilution, advection, dispersion, particle fate	First-order decay

of the benthic flux component for long-term assessments of lake/reservoir concentrations.

Water quality processes considered in a model help to define the ability of that model to simulate the fate and transport of pollutants and the eutrophication process. Models typically consider dissolved oxygen (DO) and biochemical oxygen demand (BOD) relationships, and in some cases CBOD. Temperature, salinity, and bacteria can also be modeled explicitly. Eutrophication models consider the nitrogen and phospho-

Table 24. A Descriptive List of Model Components - Dynamic Water Quality Models

Model	Waterbody Type	Parameters Simulated	Processes Simulated	
			Physical	Chemical/Biological
DYNTOX	River	Conservative and nonconservative substances	Dilution, advection	First-order decay
WASP5	Estuary, river, (well mixed/ shallow lake)	DO, CBOD, NBOD, ammonium, nitrate, nitrite, organic nitrogen, total phosphate, organic phosphorus, inorganic suspended solids, fecal coliform, conservative and nonconservative substances	Dilution, advection, dispersion, reaeration	First-order decay, process kinetics, daughter products, hydrolysis, oxidation, volatilization, photolysis, equilibrium adsorption. Settling, DO-CBOD, nutrient-algal cycle
CE-QUAL-RIV1	Rivers	DO, CBOD, temperature, ammonia, nitrate, algae, coliform, phosphate, organic nitrogen	Dilution, advection, dispersion, heat balance	First-order decay, DO-CBOD, nutrient-algal cycle
CE-QUAL-W2	Lakes	DO, CBOD, NBOD, temperature, ammonium, nitrate, nitrite, organic nitrogen, total phosphate, organic phosphorus, salinity, inorganic suspended solids, dissolved, labile, and refractory particulate organic carbon, dissolved silica, particulate biogenic silica, fecal coliform, total active metal	Dilution, advection, dispersion, heat balance	First-order decay, DO-CBOD, nutrient-algal cycle, carbon cycle
CE-QUAL-ICM	Estuaries, rivers, lakes, coastal	DO, CBOD, NBOD, temperature, ammonium, nitrate, nitrite, organic nitrogen, total phosphate, organic phosphorus, salinity, inorganic suspended solids, dissolved, labile, and refractory particulate organic carbon, dissolved silica, particulate biogenic silica, fecal coliform, total active metal	Dilution, advection, dispersion, heat balance, particle fate, sediment digenesis	First-order decay, DO-BOD, nutrient-algal cycle, carbon cycle, silica cycle, zooplankton, sediment diagenesis
HSPF	River, (well-mixed/shallow lakes)	DO, BOD, nutrients, pesticide, sediment, organic chemicals, and temperature	Dilution, advection, heat balance, particle fate, cohesive/ noncohesive sediment transport	First-order decay, process kinetics, daughter products, hydrolysis, oxidation, volatilization, photolysis, benthic demand, respiration, nutrient-algal cycle

rus cycles to model phytoplankton. Zooplankton and benthic algae are also modeled in some cases. Some of the most comprehensive models include the silica cycle and carbon cycle. A key consideration for model selection is the capability of the model to simulate sediment oxygen demand (SOD) and fluxes of nutrients from the bottom sediments (e.g., CE-QUAL-ICM, TPM). Some allow the user to specify constant flux rates, while others include explicit simulation of sediment diagenesis (e.g., CE-QUAL-ICM, TPM).

Among the steady-state models that specialize in eutrophication, only QUAL2E and TPM provide detailed simulation of water quality processes. QUAL2E considers DO-

BOD and algal growth cycles, with limited consideration of sediment functions. Although TPM is considered a steady-state model for estuarine assessment, it incorporates the same sophisticated water quality processes as CE-QUAL-ICM, such as carbon and silica cycles and sediment diagenesis.

When the receiving waterbody's response over time is of interest, the CE-QUAL series of dynamic models developed by the Corps of Engineers represent the most comprehensive water quality models available. CE-QUAL-RIV1 provides a more simplified assessment of eutrophication processes and is best suited to application in well-mixed streams and rivers where a one-dimensional representation is appropriate. CE-QUAL-W2 can be applied to waterbodies where a two-dimensional representation is required, such as stratified lakes. It also includes simulation of algal, carbon, and silica cycles. CE-QUAL-ICM represents the state of the art in public domain water quality models. It includes comprehensive assessment of DO, algal cycles (three species), carbon and silica cycles, and sediment diagenesis.

WASP5 has been widely applied to estuarine and river assessment. It includes both water quality and toxics modeling, offering a wide range of flexibility. The model considers comprehensive DO and algal processes, but does not include the carbon and silica cycles or a full sediment diagenesis model. A pore water flux approach is included for sediment analysis; however, flux rates are more typically defined by the user. WASP5 can be used in full three-dimensional simulations by linking with an appropriate hydrodynamic model such as EFDC or CH3D-WES. For many applications, the forcing functions and state variables included in WASP5 are more than sufficient, although a comprehensive monitoring data set is still required for full calibration and validation. Although CE-QUAL-ICM has expanded functionality, the expertise and data requirements for it are considerably higher than those of WASP5 for a complete application.

Chemical and sediment processes considered define a model's capability to simulate the fate and transport of toxics. Most models consider first-order degradation; some consider process kinetics, in which degradation rates are predicted from various environmental functions. Some models have the ability to track daughter products resulting from degradation. Equilibrium linear sorption, generally characterized by a partition coefficient, is considered by most models that specialize in toxics. Models that simulate sediment processes generally employ a mass balance approach with deposition, resuspension, and burial rates input by the user. However, some models can simulate deposition and resuspension rates for noncohesive and, less frequently, cohesive sediment. HSPF is one of the few models that consider cohesive and noncohesive sediment transport. For most models, such as WASP5, sediment transport fluxes are input by the user.

SMPTOX4 and EXAMSII represent rivers as simplified systems, using steady-state transport processes and first-order decay for modeling toxics. User interfaces result in models that are more easily used but less predictive. DYNTOX uses a probabilistic framework to assess the impact of toxic discharges over a range of historical and future conditions, thereby allowing an analysis of the frequency and duration of exposure above specified limits. Although technically a steady-state solution of first-order decay and mixing, DYNTOX offers both continuous simulation and Monte Carlo options. More detailed dynamic- and process-based toxics evaluation is offered by WASP5's TOXIWASP module and HSPF.

Tables 25, 26, and 27 review the input and output data requirements and tables 28, 29, and 30 review the range of applicability for the receiving water models discussed. Clearly, the three-dimensional formulations require the most rigorous data collection efforts. Data input file preparation can be laborious for three-dimensional grid systems. Some packages, such as EFDC, include grid generation software to facilitate

Table 25. Input and Output Data - Hydrodynamic Models

Model	Main Input Data	Output Information
Externally Coupled		
RIVMOD-H	River geometry and boundary conditions, inflows, withdrawals, meteorologic data	Water surface elevations, velocities, and temperatures
DYNHYD5	Waterbody geometry and boundary conditions, inflows, withdrawals, meteorologic data	Water surface elevations, velocities
EFDC	River geometry, bathymetry, geometric data, grid system, and boundary conditions, inflows, withdrawals, meteorologic data	Water surface elevations, velocity magnitude and orientation, temperature, salinity, and conservative tracer
CH3D-WES	River geometry, bathymetry, geometric data, grid system, and boundary conditions, inflows, withdrawals, meteorologic data	Water surface elevations, velocity magnitude and orientation, temperature
Internally Coupled		
CE-QUAL-RIV1	River geometry and boundary conditions, inflows, withdrawals, meteorologic data	Water surface elevations, velocities, and temperatures
CE-QUAL-W2	Waterbody geometry, bathymetry, and boundary conditions, inflows, withdrawals, meteorologic data	Water surface elevations, velocities longitudinal and vertical, and temperature
HSPF	River geometry and boundary conditions, inflows, withdrawals, meteorologic data	Water surface elevations, velocities, and temperatures

input file preparation. Water quality data gathering and input file creation can range from the minimal (EUTROMOD, PHOSMOD) to extreme (CE-QUAL-ICM) for full application. In some cases, extensive data-gathering efforts are needed to compile data for calibration and validation of detailed modeling efforts (e.g., WASP5, CE-QUAL-W2, CE-QUAL-ICM, HSPF).

The input data requirements range widely depending on the type and level of application for the receiving water model. Simple empirically based models are generally limited to screening or mid-range applications. QUAL2E incorporates more flexibility and can be applied in a more rigorous fashion with full calibration and validation. Even more detailed water quality models can initially be applied in a minimal fashion, using only a subset of the available state variables. This allows the model to be set up with available data and enhanced and broadened as information becomes available. WASP5 and CE-QUAL-W2 models are examples of techniques that can be used at various levels of detail. Some models, such as HSPF and CE-QUAL-RIV1, can be used to examine river operations or structural controls. Similarly, CE-QUAL-W2 can be used to evaluate reservoir operations and their effect on water quality.

Models that specialize in toxics and point source discharge assessments have been used successfully in the development of permit limits and TMDLs. Although simple, models such as DYNTOX and SYMTOX4 can be appropriate when the waterbody under consideration meets the underlying assumptions of the model. DECAL is a specialized model used in coastal areas for assessing the impacts of proposed ocean outfalls.

Table 26. Input and Output Data - Steady-State Water Quality Model

Model	Main Input Data	Output Information
EPA Screening Methods	Climate, waterbody morphometry, external loadings	Waterbody nitrogen, phosphorus, chlorophylla, or chemical concentrations
EUTROMOD	Climate, lake morphometry, watershed characteristics (land use)	Lake DO, nitrogen, phosphorus, and chlorophylla concentrations
PHOSMOD	Climate, lake morphometry, external loadings, benthic flux	Lake DO, phosphorus, and chlorophylla concentrations
BATHTUB	Climate, lake morphometry, external loadings	Lake DO, nitrogen, phosphorus, and chlorophylla concentrations
QUAL2E	Climate, river geometry, stream network, flow, boundary conditions, 26 physical, chemical, and biological properties for each reach, inflows/ withdrawals	DO, CBOD, nitrogen, phosphorus, conservative and nonconservative constituent concentrations
EXAMSII	Stream geometry, flow, chemical loadings, total pollutant and suspended solids concentrations, physical/chemical coefficients	Chemical exposure, fate and persistence
TOXMOD	Lake morphometry, initial conditions, external loadings, benthic flux	Conservative and nonconservative substance concentrations
SYMPTOX4	Stream geometry, flow, total pollutant and suspended solids concentrations, physical/chemical coefficients and rates	Conservative and nonconservative substance concentrations in total, dissolved and particulate forms, in the water column and bed sediments. Suspended solids concentration in water column.
TPM	Climate, geometric data, boundary conditions, up to 140 parameters for full simulation of water quality kinetics	DO, CBOD, NBOD, temperature, ammonium, nitrate, nitrite, organic nitrogen, total phosphate, organic phosphorus, salinity, inorganic suspended solids, dissolved, labile, and refractory particulate organic carbon, dissolved silica, particulate biogenic silica, fecal coliform, total active metal
DECAL	Coastal geometry, tidal oscillations, loadings, initial and boundary conditions	Contour plots of suspended particle concentrations in lower water layers. Daily averaged deposition rates of organic material.

4.5 Ecological Assessment Techniques and Models

As with loading and receiving water model selection, the selection of an ecological assessment technique (or set of techniques) is driven by a number of factors:

- Goals (e.g., an assessment of existing conditions, the prioritization of stream restoration projects, or the prediction of future conditions following land use change).
- Objectives (e.g., determine/predict the type of habitat, its quality and/or quantity, and the integrity of resident species/community).
- Level of detail necessary to accomplish the goals (e.g., screening-level, intermediate, or detailed).
- Availability of data (including reference conditions).

Table 27. Input and Output Data - Dynamic Water Quality Model

Model	Main Input Data	Output Information
DYNTOX	River geometry, flow (continuous records or statistical summaries), external loadings, boundary conditions	Conservative and nonconservative substance concentrations, plots of return period for water quality violations below each discharge
WASP5	Waterbody geometry, climate, waterbody segmentation, flow (or input from hydrodynamic model), boundary conditions, initial conditions, benthic flux, external loadings, spatially variable and time-variable functions, rate constants	DO, CBOD, NBOD, ammonium, nitrate, nitrite, organic nitrogen, total phosphate, organic phosphorus, inorganic suspended solids, fecal coliform, conservative and nonconservative substance concentrations for each segment and user-defined time interval
CE-QUAL-RIV1	River geometry, climate, river segmentation, upstream boundary conditions, initial conditions, external loadings, benthic flux, spatially variable and time-variable functions, rate constants	DO, CBOD, temperature, ammonia, nitrate, algae, coliform, phosphate, organic nitrogen concentrations for each segment and user-defined time interval
CE-QUAL-W2	Lake geometry, climate, waterbody segmentation, boundary conditions, initial conditions, external loadings or withdrawals, benthic flux, spatially variable and time-variable functions, rate constants	DO, CBOD, NBOD, temperature, ammonium, nitrate, nitrite, organic nitrogen, total phosphate, organic phosphorus, salinity, inorganic suspended solids, dissolved, labile, and refractory particulate organic carbon, dissolved silica, particulate biogenic silica, fecal coliform, total active metal concentrations for each segment and user-defined time interval
CE-QUAL-ICM	Waterbody geometry, climate, grid, flow (or input from hydrodynamic model), boundary conditions, initial conditions, external loadings, spatially variable and time-variable functions, rate constants	DO, CBOD, NBOD, temperature, ammonium, nitrate, nitrite, organic nitrogen, total phosphate, organic phosphorus, salinity, inorganic suspended solids, dissolved, labile, and refractory particulate organic carbon, dissolved silica, particulate biogenic silica, fecal coliform, total active metal concentrations for each segment and user-defined time interval
HSPF	River, well-mixed/shallow lakes	DO, CBOD, nutrients, pesticide, sediment, and organic chemical concentrations for each segment and user-defined time interval

Table 28. Range of Application—Hydrodynamic Models.

	Hydrodynamic Analysis			Water Supply-Control Analysis Operations/Management	
	Screening	Intermediate	Detailed	Planning	Design
Externally Coupled					
RIVMOD-H	●	◒	○	●	◒
DYNHYD5	●	●	○	○	-
EFDC	○	◒	●	●	◒
CH3D-WES	○	◒	●	●	◒
Internally Coupled					
CE-QUAL-RIV1	●	◒	○	◒	○
CE-QUAL-W2	○	●	●	●	●
HSPF	◒	●	◒	◒	◒

● High   ◒ Medium   ○ Low   - Not Incorporated

Table 29. Range of Application—Steady-State Water Quality Models.

Model	Screening	Intermediate	Detailed	Management Planning and Analysis
EPA Screening Methods	●	○	-	○
EUTROMOD	●	◒	-	◒
PHOSMOD	●	◒	-	◒
BATHTUB	●	◒	-	◒
QUAL2E	●	●	◒	●
EXAMSII	●	●	-	◒
TOXMOD	●	◒	-	◒
SMPTOX3	●	◒	◒	●
TPM	●	●	◒	●
DECAL	●	●	◒	●

● High ◒ Medium ○ Low - Not Incorporated

Table 30. Range of Application—Dynamic Water Quality Models

	Water Quality Analysis			Management Planning and Analysis
Model	Screening	Int.	Detailed	
DYNTOX	●	○		○
WASP5	○	●	○	●
CE-QUAL-RIV1	●	●	●	●
CE-QUAL-W2	○	●	●	●
CE-QUAL-ICM		◒	●	●
HSPF	○	◒	●	●

● High ◒ Medium ○ Low - Not Incorporated

- Applicability of use with other ecological assessments, as well as loadings and receiving water models.
- Level of expertise required (many techniques require professional biologists to collect and analyze data).
- Cost.

This section addresses ecological assessment technique selection for those techniques discussed in Chapter 3. Data in the tables included in this section can assist with the evaluation and selection of appropriate techniques for watershed assessment and TMDL development. Tables 31 and 32 provide a descriptive list of technique components, including biota/habitat type assessed and methodology. Tables 33 and 34 present a brief summary of input and output information for each of the techniques reviewed. The potential range of applications of ecological assessment techniques and models is illustrated in Tables 35 and 36.

Because of the inherent connection between a species or community and its habitat, the techniques presented are often best used in combination with each other, as well as with loading and receiving water models, to provide a holistic depiction of an aquatic ecosystem. Frequently, habitat assessment techniques are combined with

Table 31. A Descriptive List of Model/Technique Components - Habitat Assessment Techniques

Technique/ Model	Habitat Type Assessed	Habitat Parameter	Habitat Level Assessed	Methodology
HEP/HSI	Terrestrial/ aquatic	Quantity and quality	Single or multiple species	Modeling of habitat quantity and quality using key parameters collected from field; can simulate effects of future development/conditions
HES	Terrestrial/ aquatic	Quantity and quality	Community	Modeling of habitat quantity and quality using abiotic and biotic field-collected data; can simulate effects of future development/conditions
WET II	Wetland	Quality	Single or multiple species	Collection and analysis of physical, chemical, and biological predictors to assess wetland functions
HGM	Wetland	Quality	Community	Data collection and classification; development and comparison to reference conditions
Visual-based Habitat Assessment	Aquatic	Quality	Community	Multimetric collection and analysis; comparison to reference conditions
QHEI	Aquatic	Quality	Community	Multimetric collection and analysis; comparison to reference conditions
Rosgen's Stream Classificatio	Aquatic	Quantity and quality	N/A	Collection and analysis of morphological stream data; classification to predict stream behavior
IFIM (PHABSIM/ TSLIB)	Aquatic	Quantity and quality	Single or multiple species	Modeling of aquatic habitat quantity and quality using key parameters collected from field; can simulate effects of future development/conditions
SNTEMP/ SSTEMP	Aquatic	Quality	N/A	Modeling of stream temperature using stream geometric, hydrologic, and meteorologic data

species or community assessments to provide additional data or analyses necessary for decision making. Also, different tools of the same assessment type can be applied through time. For example, a watershed manager might initially conduct a screening-level assessment for benthic invertebrate communities (e.g., RBP I) and then, based on results showing an impairment, perform a more detailed assessment (e.g., RBP III) to characterize that impairment and establish monitoring trends. Rosgen's stream classification might also be used concurrently to explore opportunities for stream restoration.

Generalized assessment of existing habitat condition can be achieved using a variety of techniques. Screening-level techniques, such as visual-based habitat assessment, QHEI, and the habitat assessment components of RBPs, are approaches based on minimal field data collection and analysis to determine the status of aquatic habitat integrity. These techniques are most helpful for watershed managers who want to know whether impairments exist in a waterbody and how to prioritize watersheds for more detailed assessments in the future.

Consideration of the effects of a proposed project or other future conditions on general aquatic habitat can best be achieved using the HEP, HES, and IFIM procedures.

Table 32. A Descriptive List of Model/Technique Components - Species/ Biological Community Assessment Techniques

Technique/ Model	Biota Assessed	Data Source	Methodology
RBP I	Benthic macroinvertebrates	Field	Visual only
RBP II	Benthic macroinvertebrates	Field	Analysis of eight metrics in the field; comparison to reference conditions
RBP III	Benthic macroinvertebrates	Field	Analysis of eight metrics in the field and laboratory; comparison to reference conditions
RBP IV	Fish	Questionnaire	Analysis of questionnaire data
RBP V (IBI)	Fish	Field	Analysis of 12 metrics in the field; comparison to reference conditions
ICI	Benthic macroinvertebrates	Field	Analysis of 10 metrics in the field; comparison to reference conditions
IWB	Fish	Field	Analysis of species abundance and diversity in the field; comparison to reference conditions
PVA	Any	Field/literature	Modeling of wildlife population stability using data describing birth, death, and growth rates
FGETS	Any	Field/literature	Modeling of fish bioaccumulation of chemicals based on biological attributes and physicochemical properties

These techniques can be applied to a variety of situations, and require significant data, calibration, and analysis. Although of little value to TMDL development, the HES and HEP techniques are also capable of assessing changes in the quantity and quality of terrestrial habitat.

Rosgen's stream classification and SNTEMP/SSTEMP are methodologies that provide information about specific components of aquatic habitats. Rosgen's stream classification can be used to predict changes in stream morphology from watershed changes, and to design stable channels as part of restoration efforts. The SNTEMP/SSTEMP models can estimate stream temperature changes (that can be linked to fish health) following changes in climate, stream hydrology, and riparian conditions.

WET II and HGM are highly specialized techniques that focus on wetland assessment and do not have relevance beyond that habitat type. Both methods use physical, chemical, and biological data to understand wetland functions; WET II can be used to compare wetlands or assess the effects of a proposed project; HGM focuses on determining the functional integrity of a wetland as it compares to other comparable (reference) wetlands.

Species/biological community assessment techniques generally assess aquatic resource integrity by focusing on either benthic invertebrate or fish communities. Again, a combination of these methods can provide a more detailed understanding of the waterbody.

RBP I (benthic invertebrates) and RBP IV (fish) are screening-level protocols that use easilycollected data to establish whether a waterbody is impaired, to give a general indication of the impairment, and to identify whether further assessment is needed. RBP II and ICI (both for benthic invertebrates) and IWB (for fish) are intermediate-level techniques that use field-collected data to perform multimetric analysis and compare results with reference conditions for that ecological region. Using more

Table 33. Input and Output - Habitat Assessment Techniques

Technique/ Model	Output Information	Main Input Data
HEP/HSI	A quantitative assessment of the quality and quantity of available habitat for selected wildlife species in terms of proposed or anticipated land use changes, and the cost-effectiveness of different management alternatives to achieve desired HUs for a selected species.	Data to be collected include delineation of cover types (e.g., deciduous forest, coniferous forest, grassland, residential woodland) within the project area; size (acreage) of existing habitat for each evaluation species; selection of evaluation species; Habitat Suitability Index (HSI) reflecting current habitat conditions for each evaluation species; future habitat conditions for each evaluation species. HSI data collection includes (1) species-specific habitat use information such as general information (e.g., geographic distribution); age, growth, and food requirements; water quality, depth, and flow; species-specific habitat requirements; reproductive information; (2) species-specific life history information for each life stage (spawning/ embryo, fry, juvenile, and adult); (3) suitability indices for each habitat variable.
HES	A quantitative assessment of the quality and quantity of available habitat for entire wildlife communities in terms of proposed or anticipated land use changes.	Baseline data on habitat types and land uses in the project area. Size (acreage) of each habitat type and land use for existing and future conditions. Measurements of key variables (e.g., percent understory, number of large trees, number of mast trees, species associations, number of snags) identified for each habitat and land use type for existing conditions. Projected measurements of same key variables for future conditions.
WET II	A "broad-brush," quantitative assessment of potential project impacts on several wetland habitat functions.	Baseline data (e.g., water source, hydrodynamics, surface roughness, vegetation cover, soil type) characterizing the following wetland functions and values: groundwater discharge, groundwater recharge, sediment stabilization, flood flow alteration, sediment retention, toxicant retention, nutrient transformation, production export, wildlife diversity, aquatic diversity, recreation, uniqueness/heritage.
HGM	A quantitative assessment of the functioning of wetlands that uses the concepts of hydrogeomorphic classification, functional capacity, reference domain, and reference wetlands.	Baseline data to develop a reference set of wetlands representing the range of conditions that exist in a wetland ecosystem and its landscape in a reference domain. Baseline data on the condition of assessment wetland variables (e.g., surface and subsurface water storage, nutrient cycling, retention of particulates, organic matter export, spatial structure of habitat, distribution and abundance of invertebrates and vertebrates, plant community characteristics, etc.) measured directly or indirectly using indicators to develop a relationship between variable conditions in the assessment wetland and functional capacity of the reference set.
Visual-based Habitat Assessment	A quantitative assessment, based on qualitative information, of aquatic habitat quality in wadable streams and rivers.	Data to be collected include instream cover (fish)(riffle/run only), bottom substrate/available cover (glide/pool only), epifaunal substrate (riffle/run only), pool substrate chacterization (glide/pool only), embeddedness (riffle/run only), pool variability (glide/pool only), channel alteration, sediment deposition, frequency of riffles (riffle/run only), channel sinuosity (glide/pool only), channel flow status, bank vegetative protection, bank stability, riparian vegetative zone width.

Table 33. Input and Output - Habitat Assessment Techniques (continued)

Technique/ Model	Output Information	Main Input Data
QHEI	A quantitative assessment based on qualitative information. Developed to help distinguish the influence of habitat effects on fish communities in midwestern streams.	Data to be collected include substrate (type, origin, and quality), instream cover (type and amount), channel morphology (sinuosity, development, channelization, stability, modifications/other), riparian zone and bank erosion (riparian width, floodplain quality, and bank erosion), glide/pool and riffle/run quality (max. depth, morphology, current velocity, riffle/run depth, riffle/run substrate, and riffle/run embeddedness), gradient, drainage area, percent pool, percent glide, percent riffle, percent run.
Rosgen's Stream Classification	A quantified classification system that can be used to predict stream behavior and to apply interpretive information. Interpretations can be used to evaluate a stream's sensitivity to disturbance, recovery potential, sediment supply, vegetation controlling influence, and streambank erosion potential.	Data to be collected depend on the level of classification: Level 1: landform, lithology, soils, climate, depositional history, basin relief, valley morphology, river, profile morphology, general river pattern. Level 2: channel pattern, sinuosity (usually expressed as Schumm's ratio), gradient or slope, entrenchment or entrenchment ratio (width of floodplain: the bankfull width of channel surface), channel bed material, width/depth ratio. Level 3: riparian vegetation, depositional patterns, meander patterns, confinement features, fish habitat indices, flow regime, river size category, debris occurrence, channel stability index, bank erodibility.
IFIM (PHABSIM/ TSLIB)	A quantitative assessment (usually in graphical form) of the changes in a given species' habitat with changes in hydrologic regime.	Detailed data collection is required for both physical (e.g., depth, velocity, stream channel characteristics, riparian cover) and biological (e.g., life history and habitat preference information for the species of concern) characteristics of the stream.
SNTEMP/ SSTEMP	Minimum, mean, and maximum daily water temperature for a stream segment.	20 input parameters are required that describe the stream geometry (e.g., segment length, elevation, roughness, shading), hydrology (e.g., segment inflow and outflow, dam locations), and meteorology (e.g., air temperature, relative humidity, solar radiation).

detailed data and analysis, these intermediate techniques provide impairment identification, the ability to rank sites for control action, and the ability to prioritize sites for further assessment. RBP III (benthic invertebrates) and RBP V/IBI (fish) are detailed methodologies that require significant field (and laboratory for RBP III) analysis to develop multiple metrics and compare results with reference conditions. Detailed techniques provide impairment identification, bases for trend monitoring, the ability to rank sites for control action, and the ability to prioritize sites for further assessment based on more detailed data and analysis.

Although their applicability to TMDLs might be peripheral, PVA and FGETS can provide interesting analyses that model the response of biota to changes in environmental conditions. PVA is used to assess population stability with changes in demographic, genetic, and environmental variability. FGETS models the bioaccumulation of chemicals in fish and could be used in tandem with receiving water analyses to determine the risk of chemical presence to aquatic biota. Both techniques are relatively sophisticated and require significant data collection and analysis.

Table 34. Input and Output - Species/Biological Community Assessment Techniques

Technique/Model		Output Information	Main Input Data
Screening-level approaches	RBP I	Based on a macroinvertebrate community assessment, RBP I determines whether an impairment exists in a stream (or whether further investigation is needed) and gives a generic indication of impairment cause (e.g., habitat, organic enrichment, toxicity).	Characterize and rate substrate/instream cover, channel morphology, and riparian/bank structure; measure conventional water quality parameters; examine physical characteristics; determine relative abundance of benthic macroinvertebrates.
	RBP IV	Based on a fish community assessment, RBP IV determines whether an impairment exists in a stream (or whether further investigation is needed) and gives a generic indication of impairment cause.	Characterize and rate substrate/instream cover, channel morphology, and riparian/bank structure; measure conventional water quality parameters; examine physical characteristics; questionnaire survey regarding fish communities; survey ecoregional reference reaches and randomly selected streams.
Multimetric approaches	RBP II	Based on benthic macroinvertebrate collection and analysis, RBP II characterizes the severity of an impairment into one of three categories, gives a generic indication of its cause, and ranks and prioritizes streams of further assessment.	Characterize and rate substrate/instream cover, channel morphology, and riparian/bank structure; measure conventional water quality parameters; examine physical characteristics; examine riffle/run community and sample coarse particulate organic matter; 100-organism subsample identified in field to family or order level; functional feeding group analysis of riffle/run and coarse particulate organic matter in the field. Data describing reference conditions are also necessary.
	RBP III	Based on benthic macroinvertebrate collection and analysis, RBP III characterizes the severity of an impairment into one of four categories, gives a generic indication of its cause, establishes a basis for trend monitoring, and prioritizes streams for further assessment.	Characterize and rate substrate/instream cover, channel morphology, and riparian/bank structure; measure conventional water quality parameters; examine physical characteristics; examine riffle/run community and sample coarse particulate organic matter; collect riffle/run benthos, collect coarse particulate organic matter sample; determine shredder abundance; perform riffle/run analysis in laboratory, identify 100-organism subsample to species level and perform functional feeding group analysis. Data describing reference conditions are also necessary.
	ICI	ICI provides a quantitative measure of overall macroinvertebrate community condition.	Data necessary for development of the ICI include total number of taxa, number of mayfly taxa, number of caddisfly taxa, number of dipteran taxa, percent mayfly composition, percent caddisfly composition, percent tribe tanytarsini midge composition, percent other dipteran and noninsect composition, percent tolerant organisms, and number of qualitative EPT taxa. Data for reference conditions are also necessary.

Table 34. Input and Output - Species/Biological Community Assessment Techniques (continued)

Technique/Model		Output Information	Main Input Data
Multimetric approaches (continued)	RBP V (IBI)	Based on fish collection and analysis, RBP V computes a quantitative index that incorporates individual, population, community, zoogeographic, and ecosystem-level information to evaluate biological integrity as one of five classes; it also gives a generic indication of impairment cause, establishes a basis for trend monitoring, and ranks and prioritizes streams for further assessment.	Data to be collected include substrate/instream cover, channel morphology, and riparian/bank structure; conventional water quality parameters; physical characteristics; major habitats and cover types; total number of native fish species; number and identity of darter species; number and identity of sunfish species; number and identity of sucker species; number and identity of intolerant species; proportion of individuals as tolerant species; proportion of individuals as omnivores; proportion of individuals as insectivorous cyprinids; proportion of individuals as piscivores (top carnivores); number of individuals in sample; proportion of individuals as hybrids; proportion of individuals with disease, tumors, fin damage, and skeletal anomalies. Data describing reference conditions are also necessary.
	IWB	The IWB provides a quantitative measure of the quality of a fish assemblage.	Data to be collected include number of individuals/kilometer; biomass of individuals/kilometer; Shannon-Weaver diversity index (number of individuals in sample and number of individuals of species in the sample). Data describing reference conditions are also necessary.
Population Viability Analysis (PVA)		PVAs supply a quantified analysis of the stability of a specified population following a change in environment, population structure, or behavior.	Data required include the age structure of the population being studied, and the survival and fecundity of each age.
FGETS		FG ETS predicts the temporal dynamics of a fish's whole-body concentration of nonioonic, nonmetabolized, organic chemicals that are bioaccumulated from water and food.	Data required include morphological, physiological, and trophic parameters that describe the gill morphometry, feeding and metabolic demands, and body composition for the species in questions; and relevant physicochemical parameters that describe partitioning to the fish's lipid and structural organic fractions for a specific chemical.

Table 35. Range of Application—Habitat Assesment Techniques and Models.

Technique/ Model	Habitat Assessment		
	Terrestrial	Aquatic	Wetland
HEP/HSI	●	◒	-
HES	●	●	-
WET II	-	-	●
HGM	-	-	●
Visual-based Habitat Assessment	-	○	-
QHEI	-	○	-
Rosgen's Stream Classification	-	◒	-
IFIM (PHABSIM/TSLIB)	-	●	-
SNTEMP/SSTEMP	-	◒	-

Level of complexity addressed: ● High ◒ Medium ○ Low - Not Applicable

Table 36. Range of Application—Species/Biological Community Assessment Techniques and Models.

Technique/ Model	Assessment Type		
	Benthic community	Fish community	Single-species (Bioaccumulation and population modeling)
RBP I	○	-	-
RBP II	◒	-	-
RBP III	●	-	-
RBP IV	-	○	-
RBP V (IBI)	-	●	-
ICI	◒	-	-
IWB	-	◒	-
PVA	-	-	●
FGETS	-	-	●

Level of complexity addressed: ● High ◒ Medium ○ Low - Not Applicable

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Glossary

Acute toxicity: A chemical stimulus severe enough to rapidly induce an effect; in aquatic toxicity tests, an effect observed within 96 hours or less is considered acute. When referring to aquatic toxicology or human health, an acute effect is not always measured in terms of lethality.

Adsorption-desorption: Adsorption is the process by which nutrients such as inorganic phosphorus adhere to particles via a loose chemical bond with the surface of clay particles. Desorption is the process by which inorganic nutrients are released from the surface of particles back into solution.

Advection: Bulk transport of the mass of discrete chemical or biological constituents by fluid flow within a receiving water. Advection describes the mass transport due to the velocity, or flow, of the waterbody.

Aerobic: Environmental conditions characterized by the presence of dissolved oxygen; used to describe biological or chemical processes that occur in the presence of oxygen.

Algae: Any organisms of a group of chiefly aquatic microscopic nonvascular plants; most algae have chlorophyll as the primary pigment for carbon fixation. As primary producers, algae serve as the base of the aquatic food web, providing food for zooplankton and fish resources. An overabundance of algae in natural waters is known as eutrophication.

Algal bloom: Rapidly occurring growth and accumulation of algae within a body of water, which usually results from excessive nutrient loading and/or a sluggish circulation regime with a long residence time. Persistent and frequent blooms can result in low oxygen conditions.

Algal growth: Algal growth is related to temperature, available light, and the available abundance of inorganic nutrients (N, P, Si). Algal species groups (e.g., diatoms, greens, etc.) are typically characterized by different maximum growth rates.

Algal respiration: Process of endogenous respiration of algae in which organic carbon biomass is oxidized to carbon dioxide.

Algal settling: Phytoplankton cells (algae) are lost from the water column by physical sedimentation of the cell particles. Algal biomass lost from the water column is then incorporated as sediment organic matter and undergoes bacterial and biochemical reactions releasing nutrients and consuming dissolved oxygen.

Ambient water quality: Natural concentration of water quality constituents prior to mixing of either point or nonpoint source load of contaminants. Reference ambient concentration is used to indicate the concentration of a chemical that will not cause adverse impact to human health.

Ammonia: Inorganic form of nitrogen; product of hydrolysis of organic nitrogen and denitrification. Ammonia is preferentially used by phytoplankton over nitrate for uptake of inorganic nitrogen.

Ammonia toxicity: Under specific conditions of temperature and pH, the un-ionized component of ammonia can be toxic to aquatic life. The un-ionized component of ammonia increases with pH and temperature.

Anaerobic: Environmental condition characterized by zero oxygen levels. Describes biological and chemical processes that occur in the absence of oxygen.

Analytical model: Exact mathematical solution of the differential equation formulation of the transport, diffusion, and reactive terms of a water quality model. Analytical solutions of models are often used to check the magnitude of the system response computed using numerical model approximations.

Anoxic: Aquatic environmental conditions containing zero or little dissolved oxygen. See also anaerobic.

Anthropogenic: Relating to or resulting from the influence of human activities on nature.

Aquatic ecosystem: Complex of biotic and abiotic components of natural waters. The aquatic ecosystem is an ecological unit that includes the physical characteristics (such as flow or velocity and depth), the biological community of the water column and benthos, and the chemical characteristics such as dissolved solids, dissolved oxygen, and nutrients. Both living and nonliving components of the aquatic ecosystem interact and influence the properties and status of each component.

Assimilative capacity: The amount of contaminant load (expressed as mass per unit time) that can be discharged to a specific stream or river without exceeding water quality standards or criteria. Assimilative capacity is used to define the ability of a water body to naturally absorb and use waste matter and organic materials without impairing water quality or harming aquatic life.

Attached algae: Photosynthetic organisms that remain in a stationary location by attachment to hard rocky substrate. Attached algae, usually present in shallow hard-bottom environments, can significantly influence nutrient uptake and diurnal oxygen variability.

Autotroph: An organism that derives cell carbon from carbon dioxide. The conversion of carbon dioxide to organic cell tissue is a reductive process that requires a net input of energy. The energy needed for cell synthesis is provided by either light or chemical oxidation. Autotrophs that use light, phototrophs, include photosynthetic algae and bacteria. Autotrophs that use chemical energy, chemotrophs, include nitrifying bacteria.

Background levels: The chemical, physical, and biological conditions that would result from natural geomorphological processes such as weathering and dissolution.

Bacterial decomposition: Breakdown by oxidation, or decay, of organic matter by heterotrophic bacteria. Bacteria use the organic carbon in organic matter as the energy source for cell synthesis.

Baseflow: That part of the runoff contribution that originates from springs or wells.

Benthic: Relating to or occurring at the bottom of an aquatic ecosystem.

Benthic ammonia flux: The decay of organic matter within the sediments of a natural water results in the release of ammonia nitrogen from the interstitial water of sediments to the overlying water column. Benthic release, or regeneration, of ammonia is an essential component of the nitrogen cycle.

Benthic denitrification: Under anaerobic, or low-oxygen, conditions denitrifying bacteria synthesize cellular material by reducing nitrate to ammonia and nitrogen gas. Denitrification is a component of the overall nitrogen cycle and has been shown to account for a significant portion of the "new" nitrogen loading to freshwater and estuarine ecosystems.

Benthic nitrification: Under aerobic conditions, nitrifying bacteria synthesize cellular material by oxidizing ammonia to nitrite and nitrate. Benthic nitrification is a component of the overall nitrogen cycle and has been shown to account for a significant portion of the nitrogen budget of shallow freshwater and estuarine ecosystems.

Benthic organisms: Organisms living in, or on, bottom substrates in aquatic ecosystems.

Benthic photosynthesis: Synthesis of cellular carbon by algae attached to the bottom of a natural water system. Benthic photosynthesis typically is limited to shallow waters because of the availability of light at the bottom.

Best management practices (BMPs): Methods, measures, or practices that are determined to be reasonable and cost-effective means for a landowner to meet certain, generally nonpoint source, pollution control needs. BMPs include structural and nonstructural controls and operation and maintenance procedures.

Biochemical oxygen demand (BOD): The amount of oxygen per unit volume of water required to bacterially or chemically oxidize (stabilize) the oxidizable matter in water. Biochemical oxygen demand measurements are usually conducted over specific time intervals (5, 10, 20, 30 days). The term BOD generally refers to the standard 5-day BOD test.

Biological nutrient removal (BNR): A waste treatment method that employs natural biological processes to reduce the quantity of nitrogen and phosphorus discharged to natural waters. Treatment processes employ the movement of primary effluent through aerobic, anoxic/anaerobic zones to facilitate bacterially mediated processes of nitrification and denitrification.

Biomass: The amount, or weight, of a species, or group of biological organisms, within a specific volume or area of an ecosystem.

Boundary conditions: Values or functions representing the state of a system at its boundary limits.

Calibration: Testing and tuning of a model to a set of field data not used in the development of the model; also includes minimization of deviations between measured field conditions and output of a model by selecting appropriate model coefficients.

Carbonaceous: Pertaining to or containing carbon derived from plant and animal residues

Catchment: The area producing the runoff passing a particular channel or stream location.

Channel: A natural stream that conveys water; a ditch or channel excavated for the flow of water.

Channel improvement: The improvement of the flow characteristics of a channel by clearing, excavation, realignment, lining, or other means in order to increase its capacity. Sometimes used to connote channel stabilization.

Channel stabilization: Erosion prevention and stabilization of velocity distribution in a channel using jetties, drops, revetments, vegetation, and other measures.

Chloride: An atom of chlorine in solution, bearing a single negative charge.

Chlorophyll: A group of green photosynthetic pigments that occur primarily in the chloroplast of plant cells. The amount of chlorophyll *a*, a specific pigment, is frequently used as a measure of algal biomass in natural waters.

Chronic toxicity: Toxicity impact that lingers or continues for a relatively long period of time, often one-tenth of the life span or more. Chronic effects could include mortality, reduced growth, or reduced reproduction.

Coliform bacteria: A group of bacteria that normally live within the intestines of mammals, including humans. Coliform bacteria are used as an indicator of the presence of sewage in natural waters.

Combined sewer overflows (CSOs): A combined sewer carries both wastewater and stormwater runoff. CSOs discharged to receiving water can result in contamination problems that may prevent the attainment of water quality standards.

Complete mixing: No significant difference in concentration of a pollutant exists across the transect of the waterbody.

Concentration: Amount of a substance or material in a given unit volume of solution. Usually measured in milligrams per liter (mg/L) or parts per million (ppm).

Conservative substance: Substance that does not undergo any chemical or biological transformation or degradation in a given ecosystem.

Contamination: Act of polluting or making impure; any indication of chemical, sediment, or biological impurities.

Continuous simulation: The use of a model to simulate the response of a watershed to a series of storm events and the hydrological processes that occur between them.

Conventional pollutants: As specified under the Clean Water Act, conventional contaminants include suspended solids, coliform bacteria, biochemical oxygen demand, pH, and oil and grease.

Cross-sectional area: Wet area of a waterbody normal to the longitudinal component of the flow.

Decay: Gradual decrease in the amount of a given substance in a given system due to various sink processes including chemical and biological transformation, dissipation to other environmental media, or deposition into storage areas.

Decomposition: Metabolic breakdown of organic materials; the by-product formation releases energy and simple organics and inorganic compounds. (see also Respiration)

Denitrification: The decomposition of ammonia compounds, nitrites, and nitrates (by bacteria) that results in the eventual release of nitrogen gas into the atmosphere.

Design stream flow: The stream flow used to conduct water quality modeling.

Designated use: Uses specified in water quality standards for each waterbody or segment regardless of actual attainment.

Detritus: Any loose material produced directly from disintegration processes. Organic detritus consists of material resulting from the decomposition of dead organic remains.

Diagenesis: Production of sediment fluxes as a result of the flux of particulate organic carbon in the sediment and its decomposition. The diagenesis reaction can be thought of as producing oxygen equivalents released by various reduced species.

Dilution: Addition of less concentrated liquid (water) that results in a decrease in the original concentration.

Discharge Monitoring Report (DMR): Report of effluent characteristics submitted by a municipal or industrial facility that has been granted an NPDES discharge permit.

Discharge permit (NPDES): A permit issued by the U.S. EPA or a state regulatory agency that sets specific limits on the type and amount of pollutants that a municipality or industry can discharge to a receiving water; it also includes a compliance schedule for achieving those limits. The permit process was established under the National Pollutant Discharge Elimination System (NPDES), under provisions of the Federal Clean Water Act.

Dispersion: The spreading of chemical or biological constituents, including pollutants, in various directions from a point source, at varying velocities depending on the differential in-stream flow characteristics.

Dissolved oxygen (DO): The amount of oxygen that is dissolved in water. It also refers to a measure of the amount of oxygen available for biochemical activity in a waterbody, and as indicator of the quality of that water.

Dissolved oxygen sag: Longitudinal variation of dissolved oxygen representing the oxygen depletion and recovery following a waste load discharge into a receiving water.

Distributed model: A model in which the physical heterogeneities of a watershed are included.

Diurnal: Actions or processes that have a period or a cycle of approximately one tidal-day or are completed within a 24-hour period and which recur every 24 hours.

Domestic wastewater: Wastewater discharged from residences and from commercial, institutional, and similar facilities; also called sanitary wastewater.

Drainage basin: A part of the land area enclosed by a topographic divide from which direct surface runoff from precipitation normally drains by gravity into a receiving water. Also referred to as a watershed, river basin, or hydrologic unit.

Dye study: Use of conservative substances to assess the physical behavior of a natural system in response to a given stimulus.

Dynamic model: A mathematical formulation describing the physical behavior of a system or a process and its temporal variability.

Dynamic simulation: Modeling of the behavior of physical, chemical, and/or biological phenomena and their variation over time.

Ecosystem: An interactive system that includes the organisms of a natural community association together with their abiotic physical, chemical, and geochemical environment.

Effluent: Municipal sewage or industrial liquid waste (untreated, partially treated, or completely treated) that flows out of a treatment plant, septic system, pipe, or other conduit.

Effluent plume: Delineates the extent of contamination in a given medium as a result of effluent discharges (or spills). Usually shows the concentration gradient within the delineated areas or plume.

Epiphyte: A plant growing on another plant; more generally, any organism growing attached to a plant.

Estuary: Brackish-water area influenced by the tides where the mouth of the river meets the sea.

Estuarine number: Nondimensional parameter accounting for decay, tidal dispersion, and advection velocity. Used for classification of tidal rivers and estuarine systems.

Eutrophication: Enrichment of an aquatic ecosystem with nutrients (nitrates, phosphates) that accelerate biological productivity (growth of algae and weeds) and an undesirable accumulation of algal biomass.

Eutrophication model: Mathematical formulation that describes the advection, dispersion, and biological, chemical, and geochemical reactions that influence the growth and accumulation of algae in aquatic ecosystems. Models of eutrophication typically include one or more species groups of algae, inorganic and organic nutrients (N, P), organic carbon, and dissolved oxygen.

Extinction coefficient: Measure for the reduction (absorption) of light intensity within a water column.

Factor of safety: Coefficient used to account for uncertainties in representing, simulating, or designing a system.

Fate of pollutants: Physical, chemical, and biological transformation in the nature and changes of the amount of a pollutant in an environmental system. Transformation processes are pollutant-specific. However, they have comparable kinetics so that different formulations for each pollutant are not required.

Fecal coliform bacteria: Bacteria that are present in the intestines or feces of warm-blooded animals. They are often used as indicators of the sanitary quality of water. See Coliform bacteria.

Field-scale: Taking place at the sub-basin or smaller level. Field scale modeling usually refers to geographic areas composed of one land use (e.g., a cornfield).

First-order kinetics: Describes a reaction in which the rate of transformation of a pollutant is proportional to the amount of that pollutant in the environmental system.

Flocculation: The process by which suspended colloidal or very fine particles are assembled into larger masses or flocules that eventually settle out of suspension.

Flux: Movement and transport of mass of any water quality constituent over a given period of time. Units of mass flux are mass per unit time.

Forcing functions: External empirical formulation used to provide input describing a number of processes. Typical forcing functions include parameters such as temperature, point and tributary sources, solar radiation, and waste loads and flow.

Geochemical: Refers to chemical reactions related to earth materials such as soil, rocks, and water.

Geographic information system (GIS): Computer programs that link features commonly seen on maps (such as roads, town boundaries, waterbodies) with related information not usually presented on maps, such as the type of road surface, population, type of vegetation, land use, or water quality information. A GIS is a unique information system in which individual observations can be spatially referenced to each other.

Gradient: The rate of decrease (or increase) of one quantity with respect to another; for example, the rate of decrease of temperature with depth in a lake.

Groundwater: Phreatic water or subsurface water in the zone of saturation. Groundwater inflow describes the rate and amount of movement of water from a saturated formation.

Half-saturation constant: Nutrient concentration at which the growth rate is half the maximum rate. Half-saturation constants define the nutrient uptake characteristics of different phytoplankton species. Low half-saturation constants indicate the ability of the algal group to thrive under nutrient-depleted conditions.

Heterotroph: An organism that uses organic carbon for the formation of cell tissue. Bacteria are examples of heterotrophs.

Hydraulics: The physical science and technology of the static and dynamic behavior of fluids.

Hydrodynamic model: Mathematical formulation used in describing circulation, transport, and deposition processes in receiving water.

Hydrograph: A graph showing variation in stage (depth) or discharge of water in a stream over a period of time.

Hydrologic cycle: The circuit of water movement from the atmosphere to the earth and return to the atmosphere through various stages or processes, such as precipitation, interception, runoff, infiltration, storage, evaporation, and transpiration.

Hydrology: The science dealing with the properties, distribution, and circulation of water.

Hydrolysis: Reactions that occur between chemicals and water molecules resulting in the cleaving of a molecular bond and the formation of new bonds with components of the water molecule.

In situ: In place; in situ measurements consist of measurements of components or processes in a full-scale system or a field rather than in a laboratory.

Initial conditions: The state of a system prior to the introduction of an induced stimulus. Conditions at the start-up of system simulations.

Initial mixing zone: Region immediately downstream of an outfall where effluent dilution processes occur. Because of the combined effects of the effluent buoyancy, ambient stratification, and current, the prediction of initial dilution can be complicated.

Interstitial water: Water contained in the interstices, which are the pore spaces or voids in soils and rocks.

Kinetic processes: Description of the rate and mode of change in the transformation or degradation of a substance in an ecosystem.

Light saturation: Optimal light level for algae and macrophyte growth and photosynthesis.

Loading, load, loading rate: The total amount of material (pollutants) entering the system from one source or multiple sources; measured as a rate in weight per unit time.

Load allocation (LA): The portion of a receiving water's total maximum daily load that is attributed either to one of its existing or future nonpoint sources of pollution or to natural background sources.

Long stream: A receiving water in which nutrients are in excess of growth-limiting conditions, and where the travel time allows growth and physical accumulation of algal biomass.

Longitudinal dispersion: The spreading of chemical or biological constituents, including pollutants, downstream from a point source at varying velocities due to the differential in-stream flow characteristics.

Low-flow (7Q10): The 7-day average low flow occurring once in 10 years. This probability-based statistic is used in determining stream design flow conditions and evaluating the water quality impact of effluent discharge limits.

Lumped model: A model in which the physical characteristics of a watershed are assumed to be homogeneous.

Macrophyte: Large, vascular, rooted aquatic plant.

Margin of safety (MOS): A required component of the TMDL that accounts for the uncertainty about the relationship between the pollutant load and the quality of the receiving waterbody. This uncertainty can be caused by insufficient or poor-quality data or a lack of knowledge about the water resource and pollution effects.

Mass balance: An equation that accounts for the flux of mass going into a defined area and the flux of mass leaving the defined area. The flux in must equal the flux out.

Mathematical model: A system of mathematical expressions that describe the spatial and temporal distribution of water quality constituents resulting from fluid transport and the one, or more, individual processes and interactions within some prototype aquatic ecosystem. A mathematical water quality model is used as the basis for TMDL evaluations.

Mechanistic model: A model that attempts to quantitatively describe a phenomenon by its underlying casual mechanisms.

Mineralization: The transformation of organic matter into a mineral or an inorganic compound.

Mixing characteristics: Refers to the tendency for natural waters to blend; i.e., for dissolved and particulate substances to disperse into adjacent waters.

Monte Carlo simulation: A stochastic modeling technique that involves the random selection of sets of input data for use in repetitive model runs. Probability distributions of receiving water quality concentrations are generated as the output of a Monte Carlo simulation.

N/P ratio: The ratio of nitrogen to phosphorus in an aquatic system. The ratio is used as an indicator of the nutrient limiting conditions for algal growth; also used as an indicator for the analysis of trophic levels of receiving waters.

Natural waters: Flowing water within a physical system that has developed without human intervention, in which natural processes continue to take place.

Nitrate (NO_3) and nitrite (NO_2): Oxidized nitrogen species. Nitrate is the form of nitrogen preferred by aquatic plants.

Nitrification: The oxidation of ammonium salts to nitrites (via *Nitrosomonas* bacteria) and the further oxidation of nitrite to nitrate (via *Nitrobacter* bacteria).

Nitrogenous biochemical oxygen demand (NBOD): The oxygen demand associated with the oxidation of nitrate.

Nonconservative substance: Substance that undergoes chemical or biological transformation in a given environment.

Nonpoint source pollution: Pollution that is not released through pipes but rather originates from multiple sources over a relatively large area. Nonpoint sources can be divided into source activities related to either land or water use including failing septic tanks, improper animal-keeping practices, agricultural and forestry practices, and urban and rural runoff.

Numerical model: Model that approximates a solution of governing partial differential equations which describe a natural process. The approximation uses a numerical discretization of the space and time components of the system or process.

Nutrient: A primary element necessary for the growth of living organisms. Carbon dioxide, nitrogen, and phosphorus, for example, are nutrients required for phytoplankton growth.

Nutrient limitation: Deficit of nutrient (e.g., nitrogen and phosphorus) required by microorganisms in order to metabolize organic substrates.

One-dimensional (1-D) model: A mathematical model defined along one spatial coordinate of a natural water system. Typically, 1-D models are used to describe the longitudinal variation of water quality constituents along the downstream direction of a stream or river. In writing the model, it is assumed that the cross-channel (lateral) and vertical variability is relatively homogenous and can, therefore, be averaged over those spatial coordinates.

Organic matter: The organic fraction that includes plant and animal residue at various stages of decomposition, cells and tissues of soil organisms, and substances synthesized by the soil population. Commonly determined as the amount of organic material contained in a soil or water sample.

Organic nitrogen: Form of nitrogen bound to an organic compound.

Orthophosphate ($O\_PO_4\_P$): Form of phosphate available for biological metabolism without further breakdown.

Outfall: Point where water flows from a conduit, stream, or drain.

Oxidation: The chemical union of oxygen with metals or organic compounds accompanied by a removal of hydrogen or another atom. It is an important factor for soil formation and permits the release of energy from cellular fuels.

Oxygen demand: Measure of the dissolved oxygen used by a system (microorganisms) in the oxidation of organic matter. See also Biochemical oxygen demand.

Oxygen depletion: Deficit of dissolved oxygen in a water system due to oxidation of organic matter.

Oxygen saturation: Natural or artificial reaeration or oxygenation of a water system (water sample) to bring the level of dissolved oxygen to saturation. Oxygen saturation is greatly influenced by temperature and other water characteristics.

Partition coefficients: Chemicals in solution are partitioned into dissolved and particulate adsorbed phases based on their corresponding sediment-to-water partitioning coefficient.

Peak runoff: The highest value of the stage or discharge attained by a flood or storm event; also referred to as flood peak or peak discharge.

Periphyton: Attached benthic algae.

Photoperiod: Time period of the seasonal response by organisms to change in the length of the daylight period; for example, flowering, germination of seeds, reproduction, migration, and diapause are frequently under photoperiod control.

Photosynthesis: The biochemical synthesis of carbohydrate-based organic compounds from water and carbon dioxide using light energy in the presence of chlorophyll. Photosynthesis occurs in all plants, including aquatic organisms such as algae and macrophytes.

Phyla: Species groups of the same family of organisms. Phyla of phytoplankton include diatoms, blue-green algae, dinoflagellates, and green algae.

Phytoplankton: A group of generally unicellular microscopic plants characterized by passive drifting within the water column. See Algae.

Plankton: A group of generally microscopic plants and animals passively floating, drifting, or swimming weakly. Plankton include phytoplankton (plants) and zooplankton (animals).

Point source: Pollutant loads discharged at a specific location from pipes, outfalls, and conveyance channels from either municipal wastewater treatment plants or industrial waste treatment facilities. Point sources can also include pollutant loads contributed by tributaries to the main receiving water stream or river.

Pollutant: A contaminant in a concentration or amount that adversely alters the physical, chemical, or biological properties of a natural environment. The term includes pathogens, toxic metals, carcinogens, oxygen-demanding substances, or other harmful substances. Examples of pollutant sources include dredged spoil, solid waste, incinerator residue, sewage, garbage, sewage sludge, munitions, chemical waste, biological material, radioactive materials, heat, wrecked or discharged equipment, sediment, cellar dirt, hydrocarbons, oil, and municipal, industrial, and agricultural waste discharged into surface water or groundwater.

Postaudit: A subsequent examination and verification of model predictive performance following implementation of an environmental control program.

Pretreatment: The treatment of wastewater or runoff to remove or reduce contaminants prior to discharge into another treatment system or a receiving water.

Primary productivity: A measure of the rate at which new organic matter is formed and accumulated through photosynthesis and chemosynthesis activity of producer organisms (chiefly, green plants). The rate of primary production is estimated by measuring the amount of oxygen released (oxygen method) or the amount of carbon assimilated by the plant (carbon method).

Primary treatment plant: Wastewater treatment process where solids are removed from raw sewage primarily by physical settling. The process typically removes about 25-35 percent of solids and related organic matter (BOD5).

Priority pollutant: Substance listed by the U.S. EPA under the Federal Clean Water Act as a harmful substance that has priority for regulatory controls. The list includes metals (13), inorganic compounds (2), and a broad range of naturally occurring or artificial organic compounds (111).

Publicly owned treatment works (POTW): Municipal wastewater treatment plant owned and operated by a public governmental entity such as a town or city.

Raw sewage: Untreated municipal sewage.

Reaction rate coefficient: Coefficient describing the rate of transformation of a substance in an environmental medium characterized by a set of physical, chemical, and biological conditions such as temperature and dissolved oxygen level.

Reaeration: The net flux of oxygen occurring from the atmosphere to a body of water with a free surface.

Receiving waters: Creeks, streams, rivers, lakes, estuaries, groundwater formations, or other bodies of water into which surface water and/or treated or untreated waste is discharged, either naturally or in constructed systems.

Refractory organics: A broad lumping of anthropogenic organic chemicals that resist chemical or bacterial decomposition, including many pesticides, herbicides, household and industrial cleaners and solvents, photofinishing chemicals, and dry-cleaning fluids.

Reserve capacity: Pollutant loading rate set aside in determining stream waste load and load allocations accounting for uncertainty and future growth.

Residence time: Length of time that a pollutant remains within a section of a stream or river. The residence time is determined by the streamflow and the volume of the river reach or the average stream velocity and the length of the river reach.

Respiration: Biochemical process by means of which cellular fuels are oxidized with the aid of oxygen to permit the release of the energy required to sustain life; during respiration oxygen is consumed and carbon dioxide is released.

Roughness coefficient: A factor in velocity and discharge formulas representing the effects of channel roughness on energy losses in flowing water. Manning's "n" is a commonly used roughness coefficient.

Scour: To abrade and wear away. Used to describe the weathering away of a terrace or diversion channel or streambed. The clearing and digging action of flowing water, especially the downward erosion by stream water in sweeping away mud and silt on the outside of a meander or during flood events.

Secchi depth: A measure of the light penetration into a water column. Light penetration is influenced by turbidity.

Secondary treatment: A waste treatment process in which oxygen-demanding organic materials (BOD) are removed by bacterial oxidation of the waste to carbon dioxide and water. Bacterial synthesis of wastewater is enhanced by injection of oxygen.

Sediment: Particulate organic and inorganic matter that accumulates in a loose, unconsolidated form on the bottom of natural waters.

Sediment oxygen demand (SOD): The oxygen demand required for the aerobic and anaerobic decomposition of organic bottom solids. The oxygen consumed in aerobic decomposition represents another dissolved oxygen sink for the waterbody.

Sedimentation: Process of deposition of waterborne or windborne sediment or other material; also refers to the infilling of bottom substrate in a waterbody by sediment (siltation).

Short stream: A receiving water where nutrients are in excess of growth-limiting conditions and where the time of travel within the stream reach is not sufficient to allow growth and physical accumulation of algal biomass.

Simulation: The use of mathematical models to approximate the observed behavior of a natural water system in response to a specific known set of input and forcing conditions. Models that have been validated, or verified, are then used to predict the response of a natural water system to changes in the input or forcing conditions.

Sorption: The adherence of ions or molecules in a gas or liquid to the surface of a solid particle with which they are in contact.

Spatial segmentation: A numerical discretization of the spatial component of a system into one or more dimensions; forms the basis for application of numerical simulation models.

Steady-state model: Mathematical model of fate and transport that uses constant values of input variables to predict constant values of receiving water quality concentrations.

Stoichiometric ratio: Mass-balance-based ratio for nutrients, organic carbon, and algae (e.g., nitrogen-to-carbon ratio).

STORET: U.S. Environmental Protection Agency (EPA) national mainframe data base for storage and retrieval (STORET) of water quality data. STORET includes physical, chemical, and biological data measured in waterbodies throughout the United States.

Storm runoff: Rainfall that does not evaporate or infiltrate the ground because of impervious land surfaces or a soil infiltration rate lower than rainfall intensity, but instead flows onto adjacent land or waterbodies or is routed into a drain or sewer system.

Stratification (of waterbody): Formation of water layers, each with specific physical, chemical, and biological characteristics. As the density of water decreases due to surface heating, a stable situation develops with lighter water overlying heavier and denser water.

Streamflow: Discharge that occurs in a natural channel. Although the term "discharge" can be applied to the flow of a canal, the word "streamflow" uniquely describes the discharge in a surface stream course. The term "streamflow" is more general than "runoff" because streamflow can be applied to discharge regardless of whether it is affected by diversion or regulation.

Substrate: Bottom sediment material in a natural water system.

Surface waters: Water that is present above the substrate or soil surface. Usually refers to natural waterbodies such as rivers, lakes and impoundments, and estuaries.

Suspended solids or load: Organic and inorganic particles (sediment) suspended in and carried by a fluid (water). The suspension is governed by the upward components of turbulence, currents, or colloidal suspension.

Temperature coefficient: Rate of increase in an activity or process over a 10 °C increase in temperature. Also referred to as the Q10.

Tertiary treatment: Waste treatment processes designed to remove or alter the forms of nitrogen or phosphorus compounds contained in domestic sewage.

Three-dimensional (3-D) model: Mathematical model defined along three spatial coordinates (length, width, and depth) where the water quality constituents are considered to vary over all three spatial coordinates.

Total Kjeldahl nitrogen (TKN): The total of organic and ammonia nitrogen in a sample, determined by the Kjeldahl method.

Total maximum daily load (TMDL): The sum of the individual wasteload allocations, load allocations, and a margin of safety (MOS) required to achieve water quality standards. The MOS accounts for scientific uncertainty about whether the TMDL reflects the actual loading capacity of the waterbody.

Total coliform bacteria: A particular group of bacteria that are used as indicators of possible sewage pollution. They are characterized as aerobic or facultative anaerobic, gram-negative, nonspore-forming, rod-shaped bacteria that ferment lactose with gas formation within 48 hours at 35 °C. See also Fecal coliform bacteria.

Toxic substances: Those chemical substances, such as pesticides, plastics, heavy metals, detergents, solvents, or any other materials, which are poisonous, carcinogenic, or otherwise directly harmful to human health and the environment.

Toxicant: A poisonous agent that kills or injures animal or plant life.

Transit time: In nutrient cycles, average time that a substance remains in a particular form; ratio of biomass to productivity.

Transport of pollutants (in water): Transport of pollutants in water involves two main processes: (1) advection, resulting from the flow of water, and (2) diffusion, or transport due to turbulence in the water.

Travel time: Time period required by a particle to cross a transport route such as a watershed, river system, or stream reach.

Tributary: A lower order stream compared to a receiving waterbody. "Tributary to" indicates the largest stream into which the reported stream or tributary flows.

Trickling filter: A wastewater treatment process consisting of a bed of highly permeable medium to which microorganisms are attached and through which wastewater is percolated or trickled.

Turbidity: Measure of the amount of suspended material in water.

Turbulent flow: A flow characterized by irregular, random-velocity fluctuations.

Turbulence: A type of flow in which any particle may move in any direction with respect to any other particle and in a regular or fixed path. Turbulent water is agitated by cross current and eddies. Turbulent velocity is that velocity above which turbulent flow will always exist and below which the flow may be either turbulent or laminar.

Two-dimensional (2-D) model: Mathematical model defined along two spatial coordinates where the water quality constituents are considered averaged over the third remaining spatial coordinate. Examples of 2-D models include descriptions of the variability of water quality properties along (a) the length and width of a river that incorporates vertical averaging or (b) the length and depth of a river that incorporates lateral averaging across the width of the waterbody.

Ultimate biochemical oxygen demand (UBOD or BODu): Long-term oxygen demand required to completely stabilize organic carbon in wastewater or natural waters.

Uncertainty factors: Factors used in the adjustment of toxicity data to account for unknown variations. Where toxicity is measured on only one test species, other species may exhibit more sensitivity to that effluent. An uncertainty factor would adjust measured toxicity upward and downward to cover the sensitivity range of other, potentially more or less sensitive species.

Unstratified: Indicates a vertically uniform or well-mixed condition in a water body. See also Stratification.

Validation (of a model): Subsequent testing of a precalibrated model to additional field data, usually under different external conditions, to further examine the model's ability to predict future conditions. Same as verification.

Verification (of a model): Subsequent testing of a precalibrated model to additional field data, usually under different external conditions, to further examine the model's ability to predict future conditions. Same as validation.

Volatilization: Process by which chemical compounds are vaporized (evaporated) at given temperature and pressure conditions by gas transfer reactions. Volatile compounds have a tendency to partition into the gas phase.

Waste load allocation (WLA): The portion of a receiving water's total maximum daily load that is allocated to one of its existing or future point sources of pollution.

Wastewater: Usually refers to effluent from a sewage treatment plant. See also Domestic wastewater.

Wastewater treatment: Chemical, biological, and mechanical procedures applied to an industrial or municipal discharge or to any other sources of contaminated water to remove, reduce, or neutralize contaminants.

Water quality: The biological, chemical, and physical conditions of a waterbody; a measure of the ability of a waterbody to support beneficial uses.

Water quality criteria (WQC): Water quality criteria comprise numeric and narrative criteria. Numeric criteria are scientifically derived ambient concentrations developed by EPA or states for various pollutants of concern to protect human health and aquatic life. Narrative criteria are statements that describe the desired water quality goal.

Water quality standard (WQS): A law or regulation that consists of the beneficial designated use or uses of a waterbody, the numeric and narrative water quality criteria that are necessary to protect the use or uses of that particular waterbody, and an antidegradation statement.

Watershed: The area of land from which rainfall (and/or snowmelt) drains into a stream or other waterbody. Watersheds are also sometimes referred to as drainage basins. Ridges of higher ground generally form the boundaries between watersheds.

At these boundaries, rain falling on one side flows toward the low point of one watershed, while rain falling on the other side of the boundary flows toward the low point of a different watershed.

Watershed-scale: Taking place at the watershed level, as opposed to modeling at smaller geographic areas (such as fields or sub-basins).

Wind mixing: A physical process that occurs when wind over a free water surface influences the atmospheric reaeration rate.

Zero-order kinetics: The rate of transformation or degradation of a substance; the reaction rate of change isindependent of the concentrations in solution.

Zooplankton: Minute animals (protozoans, crustaceans, fish embryos, insect larvae) that live in a waterbody and are moved aimlessly by water currents and wave action.

Appendix A:

Watershed-Scale Loading Models—Fact Sheets

AGNPS: Agricultural Nonpoint Source Pollution Model

1. Distributor:

The source code and appropriate documentation of the latest version (5.0) is available to the general public at the following Internet anonymous FTP site: ftp.mrsars.usda.gov.

For information about the content of this FTP site and instructions on downloading, execute the following commands at the FTP prompt: "open ftp.mrsars.usda.gov" <ENTER> "anonymous" <ENTER> "your E-mail address" <ENTER>, "cdpub/ars/agnps" <ENTER>, "bin" <ENTER>, "Get about.txt" <ENTER>. Please see notes in updating version below.

2. Type of Modeling:

- Simulation of pollutant loads from agricultural watersheds
- Storm-event simulation
- Single, continuous, multiple, and diffuse source/release
- Distributed modeling using a grid system with square elements
- Screening, intermediate, and detailed applications
- Evaluation of best management practices (BMPs).

3. Model Components:

- Rainfall/runoff assessment
- Water quality analysis (emphasis on nutrients and sediments)
- Point source inputs available (feedlots, springs, wastewater treatment plant discharge, stream bank, and gully erosion)
- Source accounting, which allows pollutants to be tracked as they move through the watershed.
- Linkage to GIS possible

4. Method/Techniques:

AGNPS can be used to evaluate nonpoint source pollution from agricultural watersheds. The model allows comparison of the effects of implementing various conservation alternatives within the watershed. Cropping systems, fertilizer application rates, point source loads, nutrient contributions from feedlots, and the effect of terraced fields can be modeled. Any 24-hour duration precipitation amount can be simulated using NRCS rainfall types I, Ia, II, or III, with peak discharges determined using NRCS TR-55 methodology. The Universal Soil Loss Equation (USLE), adjusted for slope shape, predicts local sediment yield within the originating cell. An estimate of gully erosion occurring in a cell can be input by the user. Sediment and runoff routing through impoundment terrace systems can also be simulated. Some versions are linked to GIS with automatic generation of terrain parameters (Panuska et al., 1991).

5. Applications:

- Erosion, sediment, and chemical transport
- Surface water flow routing

6. Number of Pollutants:

Sediment, nutrients, pesticides, and chemical oxygen demand (COD)

7. Limitations:

- Only a single event version is currently available, although a continuous simulation version that includes snowmelt and frozen soil components should be released soon.
- Lacks nutrient transformation and instream processes.
- Needs further field testing for pollutant transport component.
- No simulation of subsurface soil processes.

A 2

- Rainfall intensity is not considered in the runoff analysis.

8. Experience:

The AGNPS model is widely applied to rural watersheds, commonly using a GIS framework. Prato et al. (1989) describe an application to provide an economic assessment of soil erosion and water quality in Idaho. Panuska et al. (1991) integrated two terrain-enhancing programs into AGNPS to automate data input. Vieux and Needham (1993) describe a GIS-based analysis of the sensitivity of AGNPS predictions to grid-cell size. Engel et al. (1993) present GRASS-based tools to assist with the preparation of model inputs and visualization and analysis of model results. Needham and Young (1993) describe the development of a continuous version of AGNPS. Tim and Jolly (1994) used AGNPS with ARC/INFO to evaluate the effectiveness of several alternative management strategies in reducing sediment pollution in a 417-ha watershed in southern Iowa.

9. Updating Version:

Ann AGNPS 1.0 (a continuous simulation version of AGNPS; under the leadership of the USDA-ARS National Sedimentation Lab in Oxford, Mississippi.)

For more information, contact Fred Theuer (301) 504-8642. The model should be available for public release in June of 1997.

10. Input Data Requirements:

- Topography and soil characteristics
- Meteorologic data
- Land use data (cropping history and nutrient applications)
- Point source data
- Global geomorphic parameter input capability is permitted for hydraulic channel geometry and/or stream length

11. Simulation Output:

- Hydrology output: storm runoff volume and peak rate
- Sediment output: sediment yield, concentration, particle size distribution, upland erosion, amount of deposition
- Chemical output: pollutant concentration and load

12. References Available:

Engel, B.A., R. Srinivasan, and C. Rewerts. 1993. Modeling erosion and surface water quality. In *Geographic Information Systems: Proceedings of the Seventh Annual GRASS Users Conference*, Lakewood, CO, March 16-19, 1992. National Park Service Technical Report NPS/NRGISD/NRTR-93/13.

Needham, S.E., and R.A. Young. 1993. ANN-AGNPS: A continuous simulation watershed model. In *Proceedings of the Federal Interagency Workshop on Hydrologic Modeling Demands for the 90's*, Fort Collins, CO, June 6-9, 1993. U.S. Geological Survey Water Resources Investigation Report 93-4018.

Panuska, J.C., I.D. Moore, and L.A. Kramer. 1991. Terrain analysis: Integration into the agricultural nonpoint source (AGNPS) pollution model. *Journal of Soil and Water Conservation* 46(1):59-64.

Prato, T., H. Shi, R. Rhew, and M. Brusven. 1989. Soil erosion and nonpoint-source pollution control in an Idaho watershed. *Journal of Soil and Water Conservation* 44(4):323-328.

Tim, U.S., and R. Jolly. 1994. Evaluating agricultural nonpoint-source pollution using integrated geographic information systems and hydrologic/water quality model. *Journal of Environmental Quality* 23:25-35.

Vieux, B.E., and S. Needham. 1993. Nonpoint-pollution model sensitivity to grid-cell size. *Journal of Water Resources Planning and Management* 119(2):141-157.

Young, R.A., C.A. Onstad, D.D. Bosch, and W.P. Anderson. 1986. *Agricultural Nonpoint Source Pollution Model: A watershed analysis tool.* Agriculture Research Service, U.S. Department of Agriculture, Morris, MN.

Young, R.A., C.A. Onstad, D.D. Bosch, and W.P. Anderson. 1989. AGNPS: A nonpoint-source pollution model for evaluating agriculture watersheds. *Journal of Soil and Water Conservation* 44:168-173.

ANSWERS: Areal Nonpoint Source Watershed Environment Response Simulation

1. Distributor:

Dr. David Beasley
Department of Agricultural Engineering
North Carolina State University
Raleigh, NC
(919) 515-2694

2. Type of Modeling:

- Simulation of agricultural watersheds with emphasis on erosion and sediment yield
- Distributed simulation using a grid system
- Storm event simulation
- Single and diffuse source/release
- Screening and intermediate applications
- Evaluation of BMPs

3. Model Components:

- Rainfall/runoff assessment
- Overland flow and channel flow
- Loading of nutrients and pesticides
- Erosion, sediment transport, and deposition

4. Method/Techniques:

This model simulates the effects of land use, management, and conservation practices on the quality and quantity of water in a watershed. The hydrology component is based on surface and subsurface water movement relationships using a modified form of the Holton infiltration model. Erosion processes are predicted by an event-based particle detachment and transport model. The quality component was added to the model to compute pollutant loadings based on correlation relationships between concentration, sediment yield, and runoff volume. Improvements to the pollutant loading and transformation routines have been incorporated by Dillaha et al. (1988). A continuous version of the model is under development (Bouraoui et al., 1993).

5. Applications:

- Hydrologic and erosion response of agriculture land and construction sites
- Movement of water in overland, subsurface, and channel flow phases
- Identification of critical areas for erosion and sedimentation control
- Siting and evaluation of BMPs

6. Number of Pollutants:

Sediment and nutrients (phosphorus and nitrogen)

7. Limitations:

- Mainframe computer required for large watershed simulation.
- Complexity of input data file.
- Snowmelt processes and pesticide modeling are not included.
- No chemical transformation of nitrogen and phosphorus.
- Small time steps are necessary for finite difference algorithms and restrict the simulation to a single event.
- Requires small element grid; assumes homogeneous condition within each element.

8. Experience:

Applied successfully in Indiana on agricultural watersheds and construction sites for best management practice (BMP) evaluation. Evaluated the relative importance of point and nonpoint source contributions to Saginaw Bay. De Roo et al. (1992) report a Monte Carlo simulation based procedure to evaluate the effects of spatial variations in the values of the infiltration parameter on the results of the ANSWERS model.

9. Updating Version:

N/A

10. Input Data Requirements:

Detailed description of the watershed topography, drainage network, soils, and land use (available from USDA-SCS soil surveys, land use, and cropping surveys)

11. Simulation Output:

- Alternative erosion control management practices on an element basis or entire watersheds (flow and sediment)
- Limited graphical representation of output results

12. References Available:

Beasley, D.B. 1986. Distributed parameter hydrologic and water quality modeling. In *Agricultural Nonpoint Source Pollution: Model Selection and Application*, ed. A. Giorgini and F. Zingales, pp. 345-362.

Beasley, D.B., and L.F. Huggins. 1981. *ANSWERS User's Manual.* EPA905/ 9-82-001. U.S. Environmental Protection Agency, Region 5, Chicago, IL.

Bouraoui, F., T.A. Dillaha, and S. Mostaghimi. 1993. *ANSWERS 2000: Watershed model for sediment and nutrient transport.* ASAE Paper No. 93-2079. American Society of Agricultural Engineers, St. Joseph, MI.

De Roo, A. P. J., L. Hazelhoff, and G. B. M. Heuvelink. 1992. Estimating the effects of spatial variability of infiltration of a distributed runoff and soil erosion model using Monte Carlo methods. *Hydrological Processes* 6:127-143.

Dillaha, T.A., C.D. Heatwole, M.R. Bennett, S. Mostaghimi, V.O. Shanholtz, and B.B. Ross. 1988. *Water quality modeling for nonpoint source pollution control planning: Nutrient transport.* Report No. SW-88-02. Virginia Polytechnic Institute and State University, Dept. of Agricultural Engineering.

Freedmann, P.L., and D.W. Dilks. 1991. Model capabilities - A user focus. In *EPA Workshop on the Water Quality-based Approach for Point Source and Nonpoint Source Controls,* June 1991, pp. 26-28. EPA 503/9-92-001.

Automated Q-ILLUAS (AUTO-QI)

1. Distributor:

Robert A. Sinclair
Illinois State Water Survey
2204 Griffith Drive
Champaign, IL 61820-7495
Cost: $50
(217) 333-4952

2. Type of Modeling:

- Urban stormwater processes
- Storm event simulation of runoff and continuous soil moisture simulation
- Nonpoint source pollutant loading and event mean concentration simulation (EMC)
- Screening and intermediate applications
- Evaluation of BMPs

3. Model Components:

- Rainfall/runoff assessment from pervious and impervious areas
- Pollutant loadings and EMC analysis
- Simulation of BMPs, separate or overlapping
- Linkage to geographic information system (GIS)

4. Method/Techniques:

AUTO-QI is based on continuous simulation of soil moisture. Runoff volumes are adjusted for soil moisture, pervious and impervious depression storage, interception, and infiltration based on Horton infiltration curves. Exponential pollutant accumulation and wash-off functions are used to determine the pollutant loads. The impacts of a series of pollutant reduction practices are simulated based on user-supplied removal efficiencies. The model handles nine different kinds of land use-soil combinations.

5. Applications:

- Simulation of runoff volumes, pollutant loads, and event mean concentrations for a watershed with different land use types
- Comparison of pollutant levels with and without BMPs and with various fertilizer application rates

6. Number of Pollutants:

Several pollutants including nitrogen, phosphorus, chemical oxygen demand (COD), metals, and bacteria (at least four at once)

7. Limitations:

- Does not include any kind of hydraulic or hydrologic routing.
- Does not calculate pollutant removal efficiencies; removal efficiencies must be supplied by the user.
- Lacks nutrient transformation and instream processes.
- Tested in the State of Illinois only
- No simulation of subsurface soil processes.

8. Experience:

- Simulation of urban pollutant loads for suspended solids, phosphorus, and lead from the greater Lake Calumet area after calibration on Boneyard Creek in Champaign, Illinois (Terstriep et al., 1990).
- Preliminary water quality simulation for Waukegan City for fecal coliforms, nitrogen, phosphorus, BOD, suspended solids, lead, chromium, and zinc. Based on past calibration and literature values (Cardona et al., 1995).

9. Updating Version:

October 1990

10. Input Data Requirements:

- Daily and hourly rainfall data
- Monthly evaporation and evapotranspiration values
- BMP removal efficiencies
- Soil infiltration parameters
- Land use parameters and soil types for each subcatchment
- Buildup and wash-off characteristics of each pollutant
- For GIS interface: land use, soil, basin and subbasin coverages

11. Simulation Output:

- A summary for the watershed by event is created for rainfall, total runoff, total runoff duration, maximum rainfall and runoff events, and maximum event duration
- Average event mean concentrations and loadings for each pollutant constituent
- Output ASCII files are created containing detailed information of runoff per land use for each storm event
- Output ASCII files are created containing detailed information about wash-off data for each constituent and each storm event.

12. References Available:

Cardona, M.E., J. Stillman, and R.A. Sinclair. 1975. *Waukegan Stormwater Quality Simulation: Application of AUTO-QI modeling.* Prepared for the U.S. Environmental Protection Agency by the Illinois State Water Survey.

Terstriep, M.L., M.T. Lee, E.P. Mills, A.V. Greene, and M.R. Rahman. 1990. *Simulation of urban runoff and pollutant loading from the Greater Lake Calumet area.* Prepared for the U.S. Environmental Protection Agency, Region 5, Water Division, Watershed Management Unit, Chicago, IL, by the Illinois State Water Survey.

DR3M-QUAL: Multi-Event Urban Runoff Quality Model

1. Distributor:

Kathleen M. Flynn
415 National Center
Mail stop 437
U.S. Geological Survey
Reston, VA 20192
(703) 648-5313
E-mail: h20.softeusgs.gov
http://water.usgs.gov/software/

2. Type of Modeling:

- Urban stormwater pollutant loads
- Continuous simulation
- Continuous, intermittent, and diffuse source/release
- Intermediate and detailed applications

3. Model Components:

- Rainfall/runoff assessment
- Water quality analysis

4. Method/Techniques:

DR3M is a watershed model for routing storm runoff through a branched system of pipes and/or natural channels using rainfall as input. The model provides detailed simulation of storm runoff periods selected by the user and a daily soil moisture accounting between storms. Kinematic wave theory is used for routing flows over contributing overland-flow areas and through the channel network. Storm hydrographs may be saved for input to DR3M-QUAL.

DR3M-QUAL is a model for simulating the quality of surface runoff from urban watersheds. The model simulates impervious areas, pervious area, and precipitation contributions to runoff quality as well as the effects of street sweeping and/or detention storage. Variations of runoff quality are simulated for user-specified storm runoff periods. Between these storms, a daily accounting of the accumulation and wash-off of water quality constituents on effective impervious areas is maintained. Input to the model includes the storm hydrographs, usually from DR3M.

Empirical equations use relationships between sediment yield and runoff volume and peak to simulate erosion. The erosion parameters are selected based on the USLE. The transport process is modeled assuming plug flow and using a Lagrangian scheme. Calibration is required for accurate quality predictions. However, default values may be used for screening-level analysis.

5. Applications:

- Rainfall/runoff assessment
- Surface water quality analysis

6. Number of Pollutants:

- Sediment, nitrogen, and phosphorus, metals, and organics

7. Limitations:

- No interaction among quality parameters
- Weak sediment transport simulation

8. Experience:

The program has been extensively reviewed within the USGS and applied to several urban modeling studies (Brabets, 1986; Guay, 1990; Lindner-Lunsford and Ellis, 1987) .

9. Updating Version and System requirements:

Version II (1982). DR3M has been successfully installed and run on a number of different computer platforms. An update to DR3M uses a watershed data management file for the input and output time series.

DR3M-QUAL may require some modifications to be PC-compatible.

10. Input Data Requirements:

- Daily rainfall, daily evaporation, and storm event rainfall at a constant time step
- Subcatchment data: area, imperviousness, length, slope, roughness, and infiltration parameters
- Trapezoidal or circular channel dimensions and kinematic wave parameters
- Stage-area-discharge relationships for storage basins
- Water quality parameters, including buildup and wash-off coefficients

13. Simulation Output:

- Time series of runoff hydrographs and quality pollutographs (concentration or load vs. time) at any location in the drainage system
- Summaries for storm events
- Graphical output of water quality and quantity analysis

14. References Available:

Alley, W.M., and P.E. Smith. 1982. *Distributed Routing Rainfall-Runoff Model - Version II.* Open File Report 82-344. U.S. Geological Survey, Reston, VA.

Alley, W.M., and P.E. Smith. 1982. *Multi-event Urban Runoff Quality Model.* Open File Report 82-764, U.S. Geological Survey. Reston, VA.

Brabets, T. P. 1986. *Quantity and quality of urban runoff from the Chester Creek Basin, Anchorage, Alaska.* Water Resources Investigations Report 86-4312. U.S. Geological Survey, Denver, CO.

Guay. J. R. 1990. Simulation of urban runoff and river water quality in the San Joaquin River near Fresno, California. In *Symposium Proceedings on Urban Hydrology*, American Water Resources Association, Denver, CO, November 4-8, 1990, pp. 177-182.

Lindner-Lunsford, J.B., and S.R. Ellis. 1987. *Comparison of conceptually based and regression rainfall-runoff models, Denver Metropolitan Area, Colorado, and potential applications in urban areas.* Water Resources Investigations Report 87-4104. U.S. Geological Survey, Denver, CO.

EPA Screening Procedures

1. Distributor:

NTIS PB 86122496
National Technical Information Services
5285 Port Royal Road
Springfield, VA 22161
(703) 487-4650

Please refer to document number PB86122496 (EPA/600/6-85/002a).

Complete title is "Water Quality Assessment: A Screening Procedure for Toxic and Conventional Pollutants in Surface and Groundwater - Part 1."

2. Type of Modeling:

- Not a computer program, consists of a series of equations/techniques
- Screening application
- Assessment of point and nonpoint source loadings, including salt loads in irrigation return flows and dry/wet atmospheric deposition loads
- Impact of point and nonpoint sources for conventional and toxic pollutants in rivers, impoundments, and estuaries

3. Model Components:

- Prediction of sediment, nutrient, and pesticide losses.
- Receiving water impacts consider BOD-DO interactions, temperature, coliform bacteria, nutrients, sediment transport. Toxicant processes considered are volatilization, sorption, and first-order degradation.

4. Method/Techniques:

Agricultural nonpoint loads are based on the Universal Soil Loss Equation (USLE), SCS runoff curve number procedure, and loading functions using enrichment ratios. Urban nonpoint loads are estimated using the buildup-wash-off concept. Receiving water analyses are carried out using simplified water quality kinetics, sediment-toxicant interactions, and a mass balance approach that assumes steady-state conditions.

5. Applications:

Loading functions have been incorporated into several hydrologic models to estimate pollutant loadings. Several of the simplified procedures for receiving water impacts have also been incorporated into water quality/ eutrophication and toxicant models.

6. Number of Pollutants:

Nitrogen, phosphorus, sediment, heavy metals, pesticides, organics, salinity, BOD-DO interactions, coliform bacteria

7. Limitations:

- Accuracy is limited when default parameters are substituted for site-specific data.
- Neglects seasonal variation in predicting annual loadings.
- Considers only steady-state conditions for receiving water analyses and greatly simplifies water quality kinetics and toxicant processes.

8. Experience:

EPA Screening Procedures have been applied (Donigian and Huber, 1991) to the Sandusky River in northern Ohio and the Patuxent, Ware, Chester, and Occoquan basins in the Chesapeake Bay region (Davis et al., 1981; Dean et al., 1981). Bowie et al. (1985) provide a comprehensive source of information on rate constants and coefficients that may be used in applying the screening procedures.

9. Updating Version:

N/A

10. Input Data Requirements:

- USLE parameters, SCS runoff curve number, enrichment ratios
- Geometric/morphometric data to define receiving waterbody, and rate constants/coefficients for various water quality and toxicant processes

11. Simulation Output:

- Annual pollutant loads (may be adopted for computation of seasonal or storm event loadings)
- Prediction of steady-state response of receiving waterbody to point and nonpoint source loadings for conventional and toxic pollutants

12. References Available:

Bowie, G.L., W.B. Mills, D.B. Porcella, C.L. Campbell, R.R. Pagenkopf, G.L. Rupp, K.M. Johnson, P.W.H. Chan, and S.A. Gherini. 1985. *Rates, constants, and kinetic formulations in surface water quality modeling.* 2nd ed. Prepared for the U.S. Environmental Protection Agency.

Davis, M.J., M.K. Snyder, and J.W. Nebgen. 1981. *River basin validation of the water quality assessment methodology for screening nondesignated 208 areas - Volume I: Nonpoint source load estimation.* U.S. Environmental Protection Agency, Athens, GA.

Dean, J.D., B. Hudson, and W.B. Mills. 1981. *River basin validation of the MRI nonpoint calculator and Tetra Tech's nondesignated 208 screening methodologies, Vol. II. Chesapeake-Sandusky nondesignated 208 screening methodology demonstration.* U.S. Environmental Protection Agency, Athens, Georgia.

Donigian, A. S., and W. C. Huber. 1991. *Modeling of nonpoint source water quality in urban and non-urban areas.* EPA/600/3-91/039. U.S. Environmental Protection Agency.

Mills W.B., B.B. Borcella, M.J. Ungs, S.A. Gherini, K.V. Summers, Mok Lingsung, G.L. Rupp, G.L. Bowie, and D.A. Haith. 1985. *Water quality assessment: A screening procedure for toxic and conventional pollutants in surface and ground water, Parts 1 and 2.* EPA/600/6-85/002a,b. U.S. Environmental Protection Agency, Environmental Research Laboratory, Athens, GA.

FHWA: The Federal Highway Administration Model

1. Distributor:

Office of Engineering and Highway Operations R&D
Federal Highway Administration
6300 Georgetown Pike
McLean, VA 22101

2. Type of Modeling:

- Statistical
- Screening application

3. Model Components:

- Computation of water quality impact from site data for either lakes or streams
- Simple evaluation of controls

4. Method/Techniques:

Pollutant loadings and the variability of loadings are estimated from runoff volume distributions and event mean concentrations for the median runoff event at a site. Rainfall is converted to runoff using a runoff coefficient calculated from the percent imperviousness. Runoff velocity is estimated from runoff intensity. Mean runoff concentrations are calculated from site median pollutant concentrations, coefficient of variation for event mean concentrations (EMCs), and the mean EMC as:

$$MCR = TCR \cdot \sqrt{(1+CVCR^2)}$$

where:

MCR = mean EMC for site (mg/L).
TCR = site median pollutant concentration (mg/L)
CVCR = coefficient of variation of EMCs

Mean event mass loading is computed as:

$$M(Mass) = MCR \cdot MVR \cdot (62.45.10^{-6})$$

where:

M(Mass) = mean pollutant mass loading (pounds per event)
MCR = mean runoff concentration (mg/L)
MVR = mean storm event runoff volume (cf)

Annual loads are calculated by multiplying by the number of storms per year. Pollutant buildup is based on traffic volumes and surrounding area characteristics.

5. Applications:

- Evaluation of lake and stream impacts of highway stormwater discharges
- Uncertainty analysis of runoff and pollutant concentrations, or loads
- Highway stormwater runoff management

6. Number of Pollutants:

Heavy metals (copper, lead, and zinc), nitrogen, and phosphorus.

7. Limitations:

- Assesses seasonal variability in a limited manner as expressed in the probability distributions of the output.
- Limited in its evaluation of controls.
- Does not consider the soluble fraction of pollutants or the precipitation and settling of phosphorus in lakes.

8. Experience:

The FHWA model has been used by the Federal Highway Administration to evaluate the impacts of stormwater runoff from highways and their surrounding drainage areas.

9. Updating Version:

N/A

10. Input Data Requirements:

- Hourly rainfall data to be transformed into mean and coefficient of variation
- Drainage and paved areas, average rainfall volumes, intensities, and durations
- Coefficients of variation are required for all average rainfall characteristics
- Traffic volumes for the surrounding area are required
- Runoff concentrations (average and coefficient of variations) for each pollutant

11. Simulation Output:

- Mean and variance of in-stream or lake concentrations
- Mean and variance of pollutant loadings and concentrations in runoff

12. References Available:

Driscoll, E.D., P.E. Shelley, and E.W. Strecker. 1990. *Pollutant loadings and impacts from highway stormwater runoff, Volume I: Design procedure.* Prepared for the Office of Engineering and Highway Operations R&D, Federal Highway Administration.

Driscoll, E.D., P.E. Shelley and E.W. Strecker. 1990. *Pollutant loadings and impacts from highway stormwater runoff, Volume II: Users guide for interactive computer implementation of design procedure*. Prepared for the Office of Engineering and Highway Operations R&D, Federal Highway Administration.

GWLF: Generalized Watershed Loading Functions

Department of Agricultural and Biological Engineering
Cornell University
Ithaca, NY 14853
(607) 255-2802

2. Type of Modeling:

- Pollutant loads from urban and agricultural watersheds, including septic systems
- Continuous simulation using daily time step
- Point and nonpoint sources
- Screening to intermediate application
- Evaluation of effects of land use changes

3. Model Components:

- Rainfall/runoff assessment
- Surface water/groundwater quality analysis

4. Method/Techniques:

This model is based on simple runoff, sediment, and groundwater relationships combined with empirical chemical parameters. It evaluates streamflow, nutrients, soil erosion, and sediment yield values from complex watersheds. Runoff is calculated by means of the SCS curve number equation. The Universal Soil Loss Equation (USLE) is applied to simulate erosion. Urban nutrient loads are computed by exponential accumulation and wash-off functions. Nutrient loads from septic systems are calculated by estimating the per capita daily load from each type of septic system considered and the number of people in the watershed served by each type.

Groundwater runoff and discharge are obtained from a lumped-parameter watershed water balance for both shallow saturated and unsaturated zones. Daily water balances are calculated for unsaturated and shallow saturated zones.

The model does not require water quality data for calibration.

5. Applications:

Relatively large watersheds with multiple land uses and point sources

6. Number of Pollutants:

Total and dissolved nutrients (nitrogen and phosphorus) and sediment

7. Limitations:

- Simulation of peak nutrient fluxes is weak.
- Stormwater storage and treatment are not considered.

8. Experience:

GWLF was validated for an 85,000-hectare watershed from the West Branch Delaware River Basin in New York using a 3-year period of record

9. Updating Version and System Requirements:

Version 2.00 (1992). PC-compatible.

10. Input Data Requirements:

- Daily precipitation and temperature data and runoff source areas
- Transport parameters: runoff curve numbers, soil loss factor, evapotranspiration cover coefficient, erosion product, groundwater recession and seepage coefficients, and sediment delivery ratio

  Chemical parameters: urban nutrient accumulation rates, dissolved nutrient concentrations in runoff, and solid-phase nutrient concentrations in sediment

- For septic systems, estimates of the per capita nutrient load in septic system effluent and per capita nutrient losses due to plant uptake, as well the number of people served by each type of septic system considered
- Point sources

11. Simulation Output:

- Monthly precipitation, evapotranspiration, groundwater discharge to streamflow, watershed runoff, streamflow, watershed erosion and sediment yield, and total nitrogen and phosphorus loads in streamflow.
- Annual erosion from each land use, nitrogen and phosphorus loads from each land use and in streamflow, and annual loads from septic systems.

12. References Available:

Delwiche, L.L.D., and D.A. Haith. 1983. Loading functions for predicting nutrient losses from complex watersheds. *Water Resources Bulletin* 19(6):951-959.

Haith, D.A. 1985. An event-based procedure for estimating monthly sediment yields. *Transactions of the American Society of Agricultural Engineers* 28(6):1916-1920.

Haith, D.A., and L.L. Shoemaker. 1987. Generalized watershed loading functions for stream flow nutrients. *Water Resources Bulletin* 23(3):471-478.

Haith, D.A. 1990. Mathematical models of nonpoint-source pollution. *Cornell Quarterly* 25(1):26.

Haith, D.A., R. Mandel, and R. S. Wu. 1992. *GWLF - Generalized Watershed Loading Functions, Version 2.0 - User's manual.* Department of Agricultural Engineering, Cornell University, Ithaca, NY.

HSPF: Hydrological Simulation Program - FORTRAN

1. Distributor:

Model Distribution Coordinator
Center for Exposure Assessment Modeling (CEAM)
USEPA
960 College Station Road
Athens, GA 30605-2700
(706) 355-8400
Models are available for FTP from:
ftp://ftp.epa.gov/epa_ceam/wwwhtml/software.htm

2. Type of Modeling:

- Pollutant load and water quality in complex watersheds
- Continuous and storm event simulation
- Single, continuous, intermittent, multiple, and diffuse source/release
- Screening, intermediate, and detailed applications
- BMP evaluation and design criteria

3. Model Components:

- Watershed hydrology assessment
- Surface water quality analysis (conventional and toxic organic pollutants)
- Soil/groundwater contaminant runoff processes with instream hydraulic and sediment-chemical interactions (saturated and unsaturated zones)
- Pollutant decay and transformation

4. Method/Techniques:

This model calculates surface and subsurface pollutant transport from complex watersheds to receiving waters. Hydrolysis, oxidation, photolysis, biodegradation, volatilization, and sorption are used to describe the transfer and reaction processes. First-order kinetic processes are employed to model sorption. Water quality is simulated by a lumped-parameter model. Three sediment types (sand, silt, and clay) and a single organic chemical, as well as transformation products of that chemical, can be simulated. Currently, potency factors are used for all pervious areas, but enhancements are under way to use detailed agrichemical modules to better represent the impacts of agricultural BMPs. Calibration is required for model application. Because of the modular approach, detail of application can be varied depending on data availability and modeling needs.

5. Applications:

- Surface and subsurface pollutant transport to receiving water with subsequent simulation of instream transport and transformations
- Watershed hydrology and water quality for both conventional and toxic organic pollutants
- Evaluation of BMPs and development of design criteria

6. Number of Pollutants:

Seven pollutants: three sediment components (sand, silt, and clay), one pesticide or other toxic pollutant (user-specified), BOD, ammonia or nitrate, and orthophosphate

7. Limitations:

- The techniques used in the Stanford Watershed Model (SWM) are assumed to be appropriate for the area being modeled.
- Limited to well-mixed rivers and reservoirs.
- Extensive water quality sampling data required for calibration or verification.
- Highly trained staff required for model application.

8. Experience:

HSPF is being used by the Chesapeake Bay Program to model total watershed contributions of flow, sediment, nutrients, and associated constituents to the tidal region of the Bay (Donigian et al., 1990; Donigian and Patwardhan, 1992). Moore et al. (1992) describe an application to model BMP effects on a Tennessee watershed. Scheckenberger and Kennedy (1994) discuss how HSPF may be used in subwatershed planning. Ball et al. (1993) describe an application of HSPF in Australia. Lumb et al. (1990) describe an interactive program for data management and analysis that can be effectively used with HSPF. Lumb and Kittle (1993) have presented an expert system that can be used for calibration and application of HSPF.

9. Updating Version:

Version 10.11 (1995)

10. Input Data Requirements:

- Continuous rainfall records
- Continuous records of evapotranspiration, temperature, and solar intensity
- A large number of parameters need to be specified (some default values are available)

11. Simulation Output:

- Time series of the runoff flow rate, sediment load, and nutrient and pesticide concentrations
- Time series of water quantity and quality at any point in a watershed
- Frequency and duration analysis routine

12. References Available:

Ball, J. E., M. J. White, G. de R. Innes, and L. Chen. 1993. Application of HSPF on the Upper Nepean Catchment. In *Proceedings of Hydrology and Water Resources Symposium*, Newcastle, New South Wales, Australia, June 30-July 2, 1993, pp. 343-348.

Bicknell, B. R., J. C. Imhoff, J. L. Kittle, A. S. Donigian, and R. C. Johanson. 1993. *Hydrological Simulation Program - FORTRAN (HSPF): User's manual for release 10.0.* EPA 600/3-84-066. Environmental Research Laboratory, U.S. Environmental Protection Agency, Athens, GA.

Donigian, A.S., Jr., B.R. Bicknell, L.C. Linker, J. Hannawald, C. Chang, and R. Reynolds. 1990. *Chesapeake Bay Program Watershed Model application to calculate bay nutrient loadings: Preliminary Phase I findings and recommendations.* Prepared for the U. S. Chesapeake Bay Program, Annapolis, MD, by AQUA TERRA Consultants.

Donigian, A.S., Jr., and A.S. Patwardhan. 1992. Modeling nutrient loadings from croplands in the Chesapeake Bay Watershed. In *Proceedings of Water Resources sessions at Water Forum '92*, Baltimore, MD, August 2-6, 1992, pp. 817-822.

Donigian, A.S., Jr., B.R. Bicknell, and J.C. Imhoff. 1994. Hydrological Simulation Program - FORTRAN (HSPF). Chapter 12 in *Computer models of watershed hydrology*, ed. V.P. Singh. Water Resources Publications, Littleton, CO.

Lumb, A.M., J.L. Kittle, and K.M. Flynn. 1990. *Users manual for ANNIE, A computer program for interactive hydrologic analyses and data management.* Water Resources Investigations Report 89-4080. U. S. Geological Survey, Reston, VA.

Lumb, A.M., and J.L. Kittle. 1993. Expert System for calibration and application of watershed models. In *Proceedings of the Federal Interagency Workshop on Hydrologic Modeling Demands for the 90's*, Fort Collins, CO, June 6-9, 1993. U.S. Geological Survey Water Resources Investigation Report 93-4018.

Moore, L.W., C.Y. Chew, R.H. Smith, and S. Sahoo. 1992. Modeling of Best Management Practices on North Reelfoot Creek, Tennessee. *Water Environment Research* 64(3):241-247.

Scheckenberger, R.B., and A.S. Kennedy. 1994. The use of HSPF in subwatershed planning. In *Current practices in modelling the management of stormwater impacts*, ed. W. James, pp. 175-187. Lewis Publishers, Boca Raton, FL.

P8-UCM: Urban Catchment Model

1. Distributor:

Richard Ribb
Narragansett Bay Project
291 Promenade Street
Providence, RI 02908-5767
(401) 277-4700, ext. 7271

2. Type of Modeling:

- Urban watersheds
- Storm event/sequence simulation
- Surface water quality analysis
- Evaluation of BMPs and development of design criteria
- Single, continuous, and diffuse source/release
- Screening application

3. Model Components:

- Stormwater runoff assessment
- Surface water quality analysis
- Routing through structural controls

4. Method/Techniques:

The P8 program predicts the generation and transport of stormwater runoff pollutants in small urban catchments. It consists mainly of methods derived from other tested urban runoff models (i.e., SWMM, HSPF, D3RM, TR-20). Runoff from impervious areas is calculated directly from rainfall once depression storage is exceeded. Particle build-up and wash-off processes are obtained using equations derived primarily from the SWMM program. The SCS curve number equation is used to predict runoff from pervious areas, and water balance used to calculate percolation. Baseflow is simulated by a linear reservoir. Without calibration, use of model results should be limited to relative comparisons.

5. Applications:

- Development/Comparison of stormwater management plans
- Watershed-scale land use planning
- Site planning and evaluation for compliance
- Effectiveness of sedimentation ponds and constructed wetlands
- Selecting and sizing BMPs

6. Number of Pollutants:

Total suspended solids (TSS), total phosphorus, total Kjeldahl nitrogen, lead, copper, zinc, and hydrocarbons

7. Limitations:

- No snowfall, snowmelt, or erosion is calculated.
- Effects of variations in vegetation type/cover on evapotranspiration are not considered.
- Watershed lag is not simulated.

8. Experience:

- Computation of total suspended solids (TSS) removal efficiency of various BMPs for compliance with state NPS plans for Rhode Island
- Evaluation of stormwater strategies for New York city's wastewater treatment facilities.
- To meet requirements of NPDES municipal stormwater permit for the city of St. Paul, Minnesota
- Watershed planning for New York City's water supply system

9. Updating Version:

Version 1.1 (1990)

10. Input Data Requirements:

- Device (hydraulic) parameters for pond, basin, buffer, pipe, splitter, and aquifer
- Watershed parameters: areas, impervious fraction and depression storage, street-sweeping frequency, SCS runoff curve number for pervious portion
- Particle parameters: accumulation/ wash-off parameters, runoff concentrations, street-sweeper efficiencies, settling velocities, decay rates, filtration efficiencies
- Water quality component parameters: pollutant concentrations
- Air temperatures required for stream baseflow computations

11. Simulation Output:

- Water and mass balances, removal efficiencies, mean inflow/outflow concentrations, and statistical summaries by device and component
- Comparison of flow, loads, and concentration across devices
- Peak elevation and outflow ranges for each device
- Sediment accumulation rates by device
- Violation frequencies for event mean concentrations

12. References Available:

Palmstrom, N., and W.W. Walker, Jr. 1990. *P8 Urban Catchment Model: User's guide, program documentation, and evaluation of existing models, design concepts and Hunt-Potowomut data inventory*. The Narragansett Bay Project Report No. NBP-90-50.

Walker, W.W., 1990. *Urban Catchment Model Program Documentation, Version 1.1*. Prepared for IEP, Inc., Northborough, MA and Narragansett Bay Project, Providence, RI.

Sediment and Phosphorus Prediction (SLOSS, PHOSPH)

1. Name of Distributor:

N/A (see references below)

2. Type of Modeling:

- Sediment yield and phosphorus loading from a watershed
- Annual prediction (may be adapted to storm events)
- The prediction equations have been incorporated into the PC-VirGIS system(Yagow et al., 1992).
- Screening application

3. Model Components:

- Two simple models for sediment and phosphorus

4. Method/Techniques:

SLOSS uses the Universal Soil Loss Equation (USLE) to predict erosion and a delivery ratio employed to predict watershed sediment yield:

$$A_s = \sum_{i=1}^{n} K_i \; x \; LS_i \; x \; C_i \; x \; P_i$$

$$DR_i = exp[-(b_i \; Sf_i \; Lf_i)]$$

where:

A_s = soil loss per unit of watershed
K_i = soil erodibility factor
LS_i = topographic factor
C_i = land use/land cover management factor
P_i = support practice factor
n = the maximum number of cells
DR_i = delivery ratio
b_i = land cover factor
Sf_i = slope function; and
Lf_i = length of the flow path between cell i and the channel outlet

Phosphorus loading is calculated as the product of the average phosphorus content of the surface soil and a phosphorus enrichment ratio.

$$TP_s = \sum_{i=1}^{n} Pc_i \; x(L_s)_i \; x(ER_p)_i$$

where

Tp_s = total sediment-associated phosphorus delivered to the stream outlet
Pc_i = average phosphorus content of the surface soil layer for soil in cell i
L_s = sediment yield for each cell
ER_p = phosphorus enrichment ratio

5. Applications:

- Identify critical areas of pollutant production in watersheds
- Predict annual soil loss and phosphorus yields

6. Number of Pollutants:

- SLOSS predicts erosion and sediment yield
- PHOSPH predicts phosphorus loading

7. Limitations:

- Does not address seasonal variation.
- Considers sediment and phosphorus only.
- Most suited to application in a GIS framework.

8. Experience:

Applied to Nomini Creek watershed in Westmoreland County, Virginia (USEPA, 1992).

9. Updating Version:

N/A

10. Input Data Requirements:

- Parameters for the USLE (soil erodibility, cropping and management factors, topography, and rainfall erosivity factor) and channel parameters

- Phosphorus concentration in soil, phosphorus enrichment ratio

11. Simulation Output:

- Mean annual loads of sediment and phosphorus

12. References Available:

Shanholtz, V. O., C. J. Desai, N. Zhang, J. W. Kleene, and C. D. Metz. 1990. *Hydrologic/ water quality modeling in a GIS environment.* Paper No. 90-3033. ASAE Summer Meeting, Columbus, OH. American Society of Agricultural Engineers, St. Joseph, MI.

USEPA, 1992. *TMDL Case Study #4: Nomini Creek Watershed.* TMDL Case Study Series. EPA841-F-93-004. U.S. Environmental Protection Agency, Office of Water, Washington, DC.

Yagow, E.R., V.O. Shanholtz, and J.M. Flagg. 1992. *Agricultural NPS model applications with a PC-based GIS.* Paper No. 92-2013. ASAE Summer Meeting, Charlotte, NC. American Society of Agricultural Engineers, St. Joseph, MI.

The Simple Method

1. Distributor:

Metropolitan Washington Council of Governments (MW-COG)
777 North Capitol Street, Suite 300
Washington, DC 20002
(202) 962-3200

2. Type of Modeling:

- Not a computer program
- Pollutant concentration from urban drainage areas
- Diffuse source
- Storm-based computations
- Screening application

3. Model Components:

- Pollutant export in storm runoff
- Sediment event mean concentration estimates
- Threshold exceedance frequencies

4. Method/Techniques:

The Simple Method uses the following expression as its governing equation:

$$L_i = P \cdot P_j \cdot R_v \cdot C \cdot A \cdot \frac{2.72}{12}$$

where:
L_i = pollutant loading (lb/year)
P = average annual rainfall (inches)
P_j = unitless correction factor to account for storms that produce no runoff
R_v = runoff coefficient (dimensionless)
C = flow-weighted mean pollutant concentration (mg/L)
A = area of development (acres)

Runoff is estimated using runoff coefficients for the fraction of rainfall converted to runoff. The portion of storms that do not produce runoff are accounted for by a correction factor determined based on analysis of site-specific or regional precipitation pattern (p = 0.9 for Washington, DC, area). Runoff coefficients are determined based on the following equation:

$$R_v = 0.05 + 0.009 \cdot PI$$

where:
PI = percent imperviousness

Pollutant concentrations in runoff depend on the land use/land activity and can be obtained from sampling programs such as the NURP program. Sediment event mean concentrations are calculated as a function of the surface area of the drainage basin. It is assumed that the channels in urban watersheds are a major source of sediment and thus larger watersheds will have higher event mean concentrations. Factors such as the channel stability, storage, and stream velocity are taken into account in the event mean concentration determination.

5. Applications:

- Estimate increased pollutant loading from an uncontrolled development site
- Estimate expected extreme concentration that occurs over a specified interval of time

6. Number of Pollutants:

Phosphorus, nitrogen, COD, BOD, metals, including zinc, copper, and lead

7. Limitations:

- Limited to watersheds where data are available or must assume national NURP values.
- Intended for recently stabilized suburban watersheds.
- Limited to small watersheds (less than 1 square mile).

- Application limited to relative comparisons.

8. Experience:

The Simple Method is used to evaluate development plans in the metropolitan Washington, DC, area. The Simple Method has also been used by municipalities in preparation of NPDES stormwater permits.

9. Updating Version:

N/A

10. Input Data Requirements:

- Characteristics of pollution sources
- Flow and concentrations of point sources
- Areas served by urban land uses such as storm sewers, combined sewers, and unsewered areas along with their corresponding unit area loads for the pollutant of concern
- Areas and unit area loads for grass and woodland areas
- Parameters for the USLE for croplands
- Pollutant delivery ratios and pollutant reduction efficiency ratio
- Treatment schemes and associated costs

11. Simulation Output:

- Total annual loads and load reductions achieved by controls for the site or watershed
- Program costs and cost per unit load removed

12. References Available:

Northern Virginia Planning District Commission. 1981. *Comparison of nonpoint pollution loadings from suburban and downtown central business districts.* Northern Virginia Planning District Commission, Annandale, VA.

Northern Virginia Planning District Commission. 1990. *Analysis of the recommended guidance calculation procedure for the Chesapeake Bay Preservation Act.* Draft report, Northern Virginia Planning District Commission, Annandale, VA.

Schueler, T.R. 1987. *Controlling urban runoff: A practical manual for planning and designing urban BMPs.* Document No. 87703, Metropolitan Washington Council of Governments, Washington, DC.

USGS Regression Method

SITEMAP: Stormwater Intercept and Treatment Evaluation Model for Analysis and Planning

1. Distributor:

Dr. Jack Douglas Smith
Omicron Associates
12264 NW Barnes Road, Suite 180
Portland, OR 97229
(503) 644-5526

2. Type of Modeling:

- Nonpoint source runoff and pollutant loadings analysis
- Continuous simulation
- Small watershed or drainage area
- Management practices analysis
- Control strategy screening

3. Model Components:

- Runoff and pollutant loadings
- SCS runoff hydrology
- Diversions through wet detention and wetland system controls
- Soil moisture
- Irrigation and drainage
- Snowfall and snowmelt
- Operates in Lotus 1-2-3 spreadsheet

4. Method/Techniques:

SITEMAP is a spreadsheet-based program that operates within the Lotus 1-2-3 graphical interface programming environment. SITEMAP is a dynamic simulation program that computes, tabulates, and displays daily runoff, pollutant loadings, infiltration, soil moisture, irrigation water demand, evapotranspiration, drainage to groundwater, daily outflows, and water and residual pollutant levels in retention basins or wetland systems (natural or engineered). Nitrogen and phosphorus are typically modeled pollutants.

5. Applications:

- Nonpoint source runoff and pollutant loadings, including performance of nonpoint source control systems
- Assessment of land use changes and land management practices
- Irrigation and groundwater recharge

6. Number of Pollutants:

Any two during a single simulation

7. Limitations:

Operates in Lotus 1-2-3 version 2.01, with IMPRESS add-in, or version 2.2, with WYSIWYG graphical interface; is not supported for versions 3.0 or later.

8. Experience:

Applied as a component of the full watershed model NPSMAP in the Tualatin River basin for Oregon Department of Environmental Quality and in the Fairview Creek watershed for the Metropolitan Service District (Metro) in Portland, Oregon.

9. Updating Version:

Version 1.1 (1993)

10. Input Data Requirements:

- Land use category
- Hydrologic soil group (SCS classification)
- SCS runoff curve number
- Soil moisture parameters
- Pollutant suspensions, washoff parameters
- Wetland system or retention basin dimensions
- Weather records (daily or event) including rainfall, snowfall, temperature, and evapotranspiration

11. Simulation Output:

- Daily record of all computation results in spreadsheet format
- User-specified graphic displays
- User-specified graphic displays
- User-specified statistical summaries
- Complete Lotus graphics display, printing, file management

12. References Available:

Omicron Associates. 1990. *Nonpoint Pollution Source Model for Analysis and Planning (NPSMAP) - Users manual,* Oregon Department of Environmental Quality, Portland, OR. (See Technical Reference Sections 10.1 @NPSCOMP, 10.2 @SOILM, 10.4 @WETLAND.)

SLAMM: Source Loading and Management Model

1. Distributor:

Through workshops taught by:
Dr. Robert Pitt
Department of Civil and Environmental Engineering
The University of Alabama at Birmingham
1150 Tenth Avenue South, Room 257
Birmingham, AL 35204-4401
(205) 934-8430

SLAMM is distributed as part of graduate stormwater management classes at the University of Alabama at Birmingham and as part of stormwater workshops that have been conducted in many locations. Attendees receive program training and a copy of the computer-executable code. For information concerning additional stormwater workshops featuring SLAMM, contact:

Mr. David Eckhoff
Division of Special Studies
University of Alabama at Birmingham
917 11th Street South
Birmingham, AL 35294-4480
(205) 934-3870

Mr. Pat Eagan
Engineering Professional Development
University of Wisconsin - Madison
432 North Lake Street
Madison, WI

2. Type of Modeling:

- Continuous and diffuse source/ release
- Continuous series of storm events (up to 350)
- Screening application
- Evaluation of controls and pollutant sources.

3. Model Components:

- Rainfall/runoff assessment
- Water quality analysis

4. Method/Techniques:

This program can identify pollutant sources and evaluate the effects of a number of different stormwater control practices on runoff. SLAMM performs continuous mass balances for particulate and dissolved pollutants and runoff volumes. Runoff is calculated by a method developed by Pitt (1987) for small storm hydrology. Runoff is based on rainfall minus initial abstraction and infiltration and is calculated for both pervious and impervious areas. Triangular hydrographs, parameterized by a statistical approach are used to simulate flow. Exponential buildup and rain wash-off and wind removal functions are used for pollutant loadings. Water and sediment from various source areas is tracked by source area as it is routed through various treatment devices. The program considers how particulates filter or settle out in control devices. Particulate removal is calculated based on the design characteristics of the basin or other removal device. Storage and overflow of devices is also considered. At the outfall locations, the characteristics of the source areas are used to determine pollutant loads in solid and dissolved phases. Loads from various source areas are summed.

5. Applications:

- Evaluates multiple control strategies such as wet detention basins, porous pavement, infiltration devices, street cleaning, catchment cleaning, grass swales, roof runoff disconnections, and paved parking lot disconnections, individually or in combination
- Planning tool for urban runoff quality and quantity assessments
- Applicable to the study of stormwater pollutant control from a wide variety of rainfall regions

6. Number of Pollutants:

Particulate and dissolved pollutants (depending on the calibration information), such as particulate and filterable forms of residue, phosphorus, phosphate, total Kjeldahl nitrogen, chemical oxygen demand (COD), fecal coliform bacteria, aluminum, copper, lead, and zinc

7. Limitations:

- Does not evaluate snowmelt and baseflow conditions.
- Evaluates runoff characteristics at the source area within the watershed and at the discharge outfall but does not consider instream processes that remove or transform pollutants.
- Does not develop or evaluate specific hydraulic designs, except for grass swales and detention ponds.
- Does not model erosion from pervious areas or construction sites.

8. Experience:

SLAMM has been used in conjunction with receiving water quality models (HSPF) to examine the ultimate effects on urban runoff from Toronto for the Ontario Ministry of the Environment. SLAMM was also used to evaluate control options for controlling urban runoff in Madison, Wisconsin, using GIS information. The State of Wisconsin uses SLAMM as part of its Priority Watershed Program. It was used in Portland, Oregon, for a study evaluating CSOs.

9. Updating Version:

Current version is 6.3

10. Input Data Requirements:

- Rainfall start and end dates (and times) and rainfall depths
- Areas of each source type and effective SCS soil type
- Building and traffic density
- Pavement texture, roof pitch, and presence of alleys
- Land use
- Pond shape, size, and type of outlet structures of wet detention basins or percolation ponds
- Soil infiltration rates for infiltration devices

11. Simulation Output:

- Source area and outfall flow volume estimates for each rainfall event and land use
- Source area and outfall particulate residue mass discharge and concentration estimates for each rainfall event and land use
- Relative source area runoff volume and particulate residue mass contribution estimates for each rainfall event
- Mass discharge, concentration, and relative contribution estimates for each pollutant selected
- Cost estimates of stormwater control practices, graphical summaries, baseflow predictions, and snowmelt predictions are under development.

12. References

Pitt, R. 1986. The incorporation of urban runoff controls in Wisconsin's Priority Watershed Program. In *Advanced Topics in Urban Runoff Research*. American Society of Civil Engineers.

Pitt, R. 1987. Small storm urban flow and particulate washoff contributions to outfall discharges. Ph.D. dissertation, Civil and Environmental Engineering Department, University of Wisconsin, Madison, WI.

Pitt, R. 1993. Source loading and management model (SLAMM). Presented at the National Conference on Urban Runoff Management, March 30-April 2, Chicago, IL.

Thum, P.G., S.R. Pickett, B.J. Niemann, Jr., and S.J. Ventura. 1990. LIS/GIS: Integrating nonpoint pollutant assessment with land development planning. *Wisconsin Land Information Newsletter* 5(2):1-12.

Ventura, S.J., and K.H. Kim. 1993. Modeling urban nonpoint source pollution with a geographical information system. *Water Resources Bulletin* 29(2):189-198.

STORM: Storage, Treatment, Overflow, Runoff Model

1. Distributor:

Mainframe version:
U.S. Army Corps of Engineers
Hydrologic Engineering Center (HEC)
609 Second Street
Davis, CA 95616

Enhanced PC version (ProStorm) with pre- and post-processors:
Dodson & Associates, Inc.
5629 FM 1960 West, Suite 314
Houston, TX 77069-4216
(281) 440-3787

2. Type of Modeling:

- Urban runoff processes
- Continuous simulation (hourly time steps)
- Continuous and diffuse source/ release
- Screening application

3. Model Components:

- Rainfall/runoff assessment
- Water quality analysis
- Statistical and sensitivity analysis

4. Method/Techniques:

This is a quasidynamic program. A modified rational formula is used for hydrology simulation. Rainfall/runoff depth and volumes are computed by means of an area-weighted runoff coefficient and the SCS curve number equation, respectively. The Universal Soil Loss Equation (USLE) is applied to simulate erosion. Water quality is simulated by linear buildup and first-order exponential wash-off coefficients. Calibration is advisable, but relative comparisons can be evaluated without calibration.

5. Applications:

- Storm and combined sewer overflows including dry-weather flow
- Surface water quantity and quality routing with storage/ treatment option
- Urban areas assessments

6. Number of Pollutants:

Six prespecified pollutants: suspended solids, settleable solids, BOD, total coliforms, ortho-phosphate, and total nitrogen

7. Limitations:

- Little flexibility in parameters to calibrate to observed hydrographs.
- Lacks microcomputer version.
- Requires a large amount of input data.

8. Experience:

STORM was extensively used in the late 1970s and early 1980s. The model was applied to the San Francisco master drainage plan for abatement of combined sewer overflows. STORM continues to be used to assess runoff and management practices in urban areas.

9. Updating Version and System requirements:

Version 1.0 (1977) for mainframe systems. PC version (ProStorm) also available.

10. Input Data Requirements:

- SCS curve number, buildup and wash-off parameters
- Runoff coefficient and soil type

11. Simulation Output:

- Storm event summaries (runoff volume, concentrations, and loads)
- Summaries of storage and treatment, utilization, total overflow loads and concentrations

  Hourly hydrographs and pollutographs (concentration vs. time)
- Statistical summaries on annual and total simulation period basis (percentage of runoff passing through storage and the number of overflows)

12. References Available:

Abbott, J. 1977. *Guidelines for calibration and application of STORM.* Training Document No. 8. U.S. Army Corps of Engineers, Hydrologic Engineering Center. Davis, CA.

Abbott, J. 1978. *Testing of several runoff models on an urban watershed.* Technical Memorandum No. 34. ASCE Urban Water Resources Research Program, ASCE, New York, NY.

Donigian, A.S., Jr., and W.C. Huber. 1991. *Modeling of nonpoint source water quality in urban and non-urban areas.* EPA/600/3-91/039. U.S. Environmental Protection Agency, Environmental Research Laboratory, Athens, Georgia.

Hydrologic Engineering Center. 1977. *Storage, Treatment, Overflow, Runoff Model, STORM, User's manual.* Generalized Computer Program 723-S8-L7520. U.S. Army Corps of Engineers, Davis, CA.

Najarian, T.O., T.T. Griffin, and V.K. Gunawardana. 1986. Development impacts on water quality: A case study. *Journal of Water Resources Planning and Management, ASCE,* 112(1):20-35.

Pantalion, J., A. Scharlach, and G. Oswald. 1995. Water quality master planning in an urban watershed. In *Watershed Management: Planning for the 21st Century*, proceedings of the ASCE's First International Conference of Water Resources Engineering, San Antonio, TX, August 14-16, 1995, pp. 330-339.

Shubinski, R.P., A.J. Knepp, and C.R. Bristol. 1977. *Computer program documentation for the continuous storm runoff model SEM-STORM.* Report to the Southeast Michigan Council of Governments, Detroit, MI.

SWMM: Storm Water Management Model

1. Name of Distributor:

Model Distribution Coordinator
Center for Exposure Assessment Modeling (CEAM), USEPA
960 College Station Road
Athens, GA 30605-2700
(706) 355-8400
Models are available for FTP from:
ftp://ftp.epa.gov/epa_ceam/wwwhtml/software.htm

Windows SWMM is available: Includes windows menus for SWMM input and some post processing. Contact:

Gerald D. LaVeck
Environmental Protection Agency
Office of Science & Technology (4305)
401 M Street, SW
Washington, DC 20460
(202) 260-7771
or go to:
http://www.epa.gov/ost/Tools

SWMM manuals and programs may also be obtained from:

Dr. Wayne C. Huber
Dept. of Civil Engineering
Oregon State University
202 Apperson Hall
Corvallis, OR 97331-2302
Phone (541) 737-4934
Fax: (541) 737-3052

Dr. William James
CHI, 36 Stuart St.
Guelph, Ontario N1E 4S5
Phone: (519) 767-0197
Fax: (519) 767-2770
Web: www.chi.on.ca/
[Contact for prices.]

The executable program, Fortran code and documentation files are also available on the internet via anonymous FTP at OSU at: engr.orst.edu, path: /pub/swmm/pc and at the Web site: www.orst.edu/dept/ccee/swmm.htm

2. Type of Modeling:

- Urban stormwater processes
- Continuous and storm event simulation with variable and user-specified time steps (wet and dry weather periods)
- Single, continuous, intermittent, multiple, and diffuse source/release
- Screening, intermediate, and detailed planning applications
- Evaluation of BMPs and development of design criteria

3. Model Components:

- Rainfall/runoff assessment
- Water quality analysis
- Point source inputs available

4. Method/Techniques:

This model simulates overland water quantity and quality produced by storms in urban watersheds. Several modules or blocks are included to model a wide range of quality and quantity watershed processes. A distributed parameter sub-model (RUNOFF) describes runoff based on the concept of surface storage balance. The rainfall/runoff simulation is accomplished by the nonlinear reservoir approach. The lumped storage scheme is applied for soil/groundwater modeling. For impervious areas, a linear formulation is used to compute daily/hourly increases in particle accumulation. For pervious areas, a modified Universal Soil Loss Equation (USLE) determines sediment load. The concept of potency factors is applied to simulate pollutants other than sediment.

5. Applications:

- Urban stormwater and combined systems
- Surface water routing
- Urban watershed analysis, including baseflow contributions

6. Number of Pollutants:

Limited to 10 pollutants, including sediment

7. Limitations:

- Lack of subsurface quality routing
- No interaction of quality processes (apart from adsorption)
- Weak scour-deposition routines

8. Experience:

Applied to urban hydrologic quantity/ quality problems in scores of U.S. cities as well as extensively in Canada, Europe, and Australia. The model has been used for very complex hydraulic analysis for combined sewer overflow mitigation, as well as for many stormwater management planning studies and pollution abatement projects, and there are many instances of successful calibration and verification (Huber, 1992). Warwick and Tadepalli (1991) describe calibration and verification of SWMM on a 10-square-mile urbanized watershed in Dallas, Texas. Tsihrintzis et al. (1995) describe SWMM applications to four watersheds in South Florida representing high- and low-density residential, commercial, and highway land uses. Ovbiebo and She (1995) describe an application of SWMM in a subbasin of the Duwamish River, Washington.

9. Updating Version, System Requirements:

Version 4.30 (1994)

10. Input Data Requirements:

- Rainfall hyetographs, antecedent conditions, land use, and topography
- Dry-weather flow and soil characteristics
- Gutters/pipes - hydraulic inputs
- Pollutant accumulation and wash-off parameters
- Hydraulics and kinetic parameters

11. Simulation Output:

- Time series of flow, stage, and constituent concentration at any point in watershed
- Seasonal and annual summaries

12. References Available:

Donigian, A.S., Jr., and W.C. Huber. 1991. *Modeling of nonpoint source water quality in urban and non-urban areas*. EPA/600/3-91/039. U.S. Environmental Protection Agency, Environmental Research Laboratory, Athens, GA.

Huber, W.C., and R.E. Dickinson. 1988. *Storm Water Management Model Version 4, User's manual*. EPA 600/ 3-88/ 001a (NTIS PB88-236641/ AS). U.S. Environmental Protection Agency, Athens, GA.

Huber, W. C. 1992. Experience with the US. EPA SWMM Model for analysis and solution of urban drainage problems. *Proceedings, Inundaciones Y Redes De Drenaje Urbano*, ed. J. Dolz, M. Gomez, and J. P. Martin, eds., Colegio de Ingenieros de Caminos, Canales Y Puertos, Universitat Politecnica de Catalunya, Barcelona, Spain, pp. 199-220.

Ovbiebo, T., and N. She. 1995. Urban runoff quality and quantity modeling in a subbasin of the Duwamish River using XP-SWMM. *Watershed Management: Planning for the 21st Century*, American Society of Civil Engineers, San Antonio, TX, August 14-16, 1995, pp.320-329.

Tshihrintzis, V. A., R. Hamid, and H. R. Fuentes. 1995. Calibration and verification of watershed quality model SWMM in subtropical urban areas. In *Proceedings of the First International Conference - Water Resources Engineering*. American Society of Civil Engineers, San Antonio, TX, August 14-16, 1995, pp 373-377.

Warwick, J. J., and P. Tadepalli. 1991. Efficacy of SWMM application. *Journal of Water Resources Planning and Management* 117(3):352-366.

SWRRBWQ: Simulator for Water Resources in Rural Basins - Water Quality

1. Name of Distributor:

Jeff Arnold or Nancy Sammons
USDA-ARS
808 E. Blackland Rd.
Temple, TX 76502
(817) 770-6502 or (817) 770-1308
arnold@brcsun0.tamn.edu
sammons@brcsun0.tamn.edu

The SWRRBWQ Windows interface is available on the Internet at:
http://www.epa.gov/ost/tools
For more information contact:
Jerry LaVeck
USEPA (4305)
401 M Street, SW
Washington, DC. 20460
(202) 260-7771
laveck.jerry@epamail.epa.gov

2. Type of Modeling:

- Hydrologic and related processes in large, complex rural basins
- Diffuse source/release
- Screening, intermediate, and detailed applications

3. Model Components:

- Rainfall/runoff assessment
- Surface water quality analysis
- Below-root-zone leaching losses

4. Method/Techniques:

SWRRBWQ is a comprehensive, continuous simulation model covering aspects of the hydrologic cycle, pond and reservoir storage, sedimentation, crop growth, nutrient yield, and pesticide fate. A basin can be divided into a maximum of 10 subbasins to account for differences in soils, land use, crops, topography, vegetation, or weather. The model partitions nitrate loss between runoff, lateral subsurface flow, percolation, and crop uptake. Runoff volume is estimated using a modification of the SCS curve number method for continuous models, and peak runoff rate predictions are based on a modification of the rational formula. Sediment yield is calculated using several procedures including the Hydrogeomorphic Universal Soil Loss Equation (HUSLE). Nutrient, pesticide, and sediment yields at the basin outlet are determined after accounting for channel transmission losses and deposition. SWRRBWQ allows for simultaneous computation on each subbasin and routes the water, sediment, and chemicals from the subbasin outlets to the basin outlet. It also has a lake water quality component that tracks the fate of pesticides and phosphorus from their initial application on the land to their final deposition in a lake. Calibration is not specifically required but is desirable.

5. Applications:

- Usefulness of ponds or reservoirs to trap sediment at the subbasin or the watershed outlet can be determined.
- Effects of farm-level management systems, such as crop rotations, tillage, planting date, irrigation scheduling, and fertilizer and pesticide application rates and timing.

6. Number of Pollutants:

Sediment, nitrogen, phosphorus, and pesticides

7. Limitations:

- A maximum of 10 subareas per analysis is allowed.
- Organic waste applications cannot be modeled.
- As nutrients and pesticides flow from each subbasin to the basin outlet, no degradation occurs.
- Hydraulic residence time is not considered by the lake water quality module.

8. Experience:

The model was tested on 11 large watersheds. The testing results showed that SWRRBWQ can simulate water and sediment yield under a wide range of soils, climate, land use, topography, and management systems.

9. Updating Version:

SWRRBWQ is no longer under active development; however, the technology is being incorporated in the Soil and Water Assessment Tool (SWAT) as part of the Hydrologic Unit Model for the United States (HUMUS) project at Temple, Texas (Arnold et al., 1993; Srinivasan and Arnold, 1994).

10. Input Data Requirements:

- Meteorological data (daily precipitation and solar radiation)
- Soils, land use, and fertilizer and pesticide application

11. Simulation Output:

- Daily runoff volume and peak rate, sediment yield, evapotranspiration, percolation, return flow, and pesticide concentration in both runoff and sediment
- Nutrient concentrations/loads

12. References Available:

Arnold, J.G., B.A. Engel, and R. Srinivasan. 1993. A continuous time, grid cell watershed model. In *Proceedings of Application of Advanced Information Technologies for the Management of Natural Resources*, sponsored by ASAE, June 17-19, 1993, Spokane, WA.

Arnold, J.G., J.R. Williams, A.D. Nicks, and N.B. Sammons. 1989. *SWRRB, a basin scale simulation model for soil and water resources management.* Texas A&M Press.

Arnold, J.G., and J.R. Williams. 1987. Validation of SWRRB - simulator for water resources in rural basins. *Journal of Water Resources Planning and Management* 113(2):243-256.

Srinivasan, R., and J.G. Arnold. 1994. Integration of a basin-scale water quality model with GIS. *Water Resources Bulletin* 30(3):453-462.

Williams, J.R., A.D. Nicks, and J.G. Arnold. 1985. Simulator for water resources in rural basins. *Journal of Hydraulic Engineering, ASCE* 111(6):970-986.

USGS Regression Method

1. Name of Distributor:

Gary D. Tasker
U.S. Geological Survey
430 National Center
Reston, VA 22092
(703) 648-5892

2. Type of Modeling:

- Not a computer program
- Pollutant concentration from urbanized watersheds
- Statistical approach
- Annual, seasonal, or storm event mean pollutant loads
- Screening applications

3. Model Components:

- Regression equations for mean storm event pollutant load estimation
- Confidence interval around the mean

4. Method/Techniques:

Regression equations were developed from historical records of storm loads for 10 pollutants at 76 gaging stations in 20 states. Ten explanatory parameters were used to reflect possible site variability associated with pollutant processes. The nonuniformity of the variance required a generalized least squares analysis. The general form of the regression model is as follows:

$$W = 10^{\left[a + b\sqrt{DA} + cIA + dMAR + eMJT + fX_2\right]} B$$

where:

W = the mean load, in pounds, associated with a runoff event
DA = drainage area in square miles
IA = impervious area, in percent of DA
MAR = mean annual rainfall, inches
MJT = mean minimum January temperature, in degrees Fahrenheit
X_2 = land-use indicator variable
BCF = bias correction factor

The regression coefficients (a, b, c, d, e, and f) for different pollutants may be obtained from Gary and Tasker (1988). The mean annual pollutant load can be calculated by multiplying W by the mean annual number of storm events.

5. Applications:

- Estimation of average mean annual storm event loads when data are severely limited
- Comparing different locations

6. Number of Pollutants:

Chemical oxygen demand, suspended solids, dissolved solids, total nitrogen, total ammonia-nitrogen (NH3-N), total phosphorus, dissolved phosphorus, total copper, total lead, and total zinc.

7. Limitations:

- Valid only for areas for which regression coefficients are provided, i.e., regional transferability is limited.
- Valid only within the range of observed values of pollutant loads and explanatory variables.
- Tends to underestimate the contributions of snowmelt or extreme events.
- Does not address causation.
- Applies only to small watersheds.

8. Experience:

Used by cities and counties to estimate pollutant loadings from storm-sewer outfalls as part of the NPDES permit application process.

9. Updating Version:

N/A

10. Input Data Requirements:

- Drainage areas
- Percent imperviousness
- Mean annual rainfall
- Land use indicator
- Mean minimum January temperature
- Mean annual number of storm events

11. Simulation Output:

- Average annual storm event load and confidence interval

12. References Available:

Tasker, G.D., and N.E. Driver. 1988. Nationwide regression models for predicting urban runoff water quality at unmonitored sites. *Water Resources Bulletin* 24(5):1091-1101.

Tasker, G.D., E.J. Gilroy, and M.E. Jennings. 1990. Estimation of mean urban stormwater loads at unmonitored sites by regression. In *Symposium Proceedings on Urban Hydrology*, American Water Resources Association, Denver, CO, November 4-8, 1990, pp. 127-138.

Sediment and Phosphorus Prediction (SLOSS, PHOSPH)

Watershed

1. Distributor:

John F. Walker
U.S. Geological Survey
6417 Normandy Lane
Madison, WI 53719-1133
(608) 274-3535

2. Type of Modeling:

- Various multiple point sources plus continuous and diffuse source/release
- Screening application

3. Model Components:

- Program is divided into seven worksheets. The first summarizes basic watershed characteristics. The next three worksheets estimate pollutant loads from point sources and cropland and noncropland agricultural land uses for controlled and uncontrolled conditions. Sources are totaled for controlled and uncontrolled conditions by worksheet 5.
- Program costs and cost-effectiveness per unit load reduction are also calculated.

4. Method/Techniques:

Separate methods are used to calculate urban, rural non-cropland, and rural cropland loads. Urban loads are calculated from point estimates of flow and concentration, rural non-cropland loads are estimated on a unit area basis, and rural cropland loads are based on the Universal Soil Loss Equation (USLE). The rainfall factor (R) in the USLE is unspecified for use as a calibration parameter. Delivery ratios and trapping efficiencies for tributary wetlands are used to convert eroded sediment to sediment delivered. These values are also calibrated. The model uses the sorting features of the EXCEL spreadsheet program for the Macintosh computer to rank the most cost-effective alternatives.

5. Applications:

- Phosphorus loading from point sources, CSOs, septic tanks, rural cropland, and non-cropland rural sources was estimated for Delavan Lake watershed in Wisconsin.
- Evaluation of the trade-offs between control of point and nonpoint sources.

6. Number of Pollutants:

Used for only one at a time, e.g., phosphorus

7. Limitations:

- Cannot assess seasonal variability.
- Can assess only a limited number of land management control practices.
- Requires calibration to determine the rainfall factor and the sediment delivery ratio.
- Can assess only contaminants associated with soils and sediments.

8. Experience:

Watershed was applied to the study of point and nonpoint sources in the Delavan Lake watershed in Wisconsin. It was determined that runoff controls would be insufficient to meet water quality standards. Instead of focusing controls for phosphorus on nonpoint sources, the study recommended several in-lake controls.

9. Updating Version:

N/A

10. Input Data Requirements:

- Sources of pollution along with their respective position and point of entry to the basin
- Flows and concentrations of point sources

Areas served by urban land uses such as storm sewers, combined sewers, and unsewered areas along with their corresponding unit area loads for the pollutant of concern

Areas and unit area loads for grass and woodland areas

Parameters for the USLE for croplands

Pollutant delivery ratios and pollutant reduction efficiency ratio

Treatment schemes and associated costs

11. Simulation Output:

- Total annual loads and load reductions achieved by controls for the site or watershed
- Program costs and cost per unit load removed

12. References Available:

Monteith, T.J., R.A. Sullivan, T.M. Heidtke, and W.C. Sonzogni. 1981. *Watershed handbook: A management technique for choosing among point and nonpoint control strategies.* Prepared for the U.S. Environmental Protection Agency, Region 5, Chicago, IL.

Walker, J.F., S.A. Pickard, and W.C. Sonzogni. 1989. Spreadsheet watershed modeling for nonpoint-source pollution management in a Wisconsin basin. *Water Resources Bulletin* 25(1):139-147.

WMM: Watershed Management Model

1. Distributor:

Prepared by Camp, Dresser & McKee Inc. for:
Stormwater and Nonpoint Source Section
Florida Department of Environmental Regulation
Twin Towers Office Building
2600 Blair Stone Road
Tallahassee, Florida 32301-8241
(904) 488-0782

2. Type of Modeling:

- Watershed stormwater pollutant loads
- Multiple diffuse source release
- Annual time steps
- Screening application

3. Model Components:

- Computation of annual nutrient and metal loads to reservoirs
- Computation of in-lake or in-stream water quality from pollutant loads
- Load reduction estimates for site or regional BMP implementation
- Uptake and removal in stream courses
- Estimates of annual pollutant loads from baseflow
- Comparison with point sources
- Failing septic tank loads
- Chlorophyll *a* and nutrient concentrations in downstream lakes and reservoirs

4. Method/Techniques:

Runoff coefficients are used for rural areas; for urban areas runoff is based on a linear function of the percent imperviousness. Loading of nutrients and metals is based on event mean concentrations measured locally or from NURP data. Baseflow is estimated from flow records and concentrations. There is a choice of three lake water quality routines that output mean annual concentrations of chlorophyll *a*. (The model can be adapted to predict seasonal loads or chlorophyll *a* concentrations provided that seasonal event mean concentration data are available.) Simple calculations are included for in-stream transport and transformation based on travel time. The program can assess the relative contributions of point and nonpoint sources. Resultant water quality is predicted with a version of the Vollenweider eutrophication model, adapted to lakes in the southeastern United States. Removal of metals associated with sediments in reservoirs is estimated from the sediment-trapping efficiency of the reservoir.

5. Applications:

Estimates the annual nonpoint source loads, including baseflow and precipitation inputs, for management planning.

6. Number of Pollutants:

Total phosphorus, total nitrogen, lead, and zinc

7. Limitations:

- Accuracy is limited when default parameters are substituted for site-specific data.
- Neglects seasonal variation.
- Does not predict sediment yields.
- Does not evaluate control practices except through assumption of a constant removal fraction.
- Does not consider loadings associated with snowmelt events.
- Can assess only relative impacts of land use categories or controls.

8. Experience:

The model has been applied to between 10 and 15 watersheds. It has been used as part of a wasteload allocation study for Lake Tohopekaliga and for Jacksonville, Florida, watershed's Master Plan. It has been applied in Norfolk County, Virginia, and to a Watershed Management Plan for North Carolina.

9. Updating Version:

Under development

10. Input Data Requirements:

- Land use and soil types
- Average annual precipitation, evaporation, and evapotranspiration
- Nutrient concentrations in precipitation
- Annual baseflow and baseflow pollutant concentrations
- Event mean concentrations in runoff
- Reservoir, lake, or stream hydraulic characteristics
- Removal efficiencies of proposed BMPs

11. Simulation Output:

- Annual pollutant loads from point and nonpoint sources, including both agricultural and urban land use
- Relative magnitude of inputs from point sources and septic tanks
- Load reductions from combined effects of multiple BMPs
- In-lake nutrient concentrations as related to trophic state; also, concentrations of metals are evaluated for the reservoir
- Standard statistics and bar graphs of results

12. References Available:

Camp, Dresser and McKee (CDM). 1992. *Watershed Management Model user's manual, Version 2.0.* Prepared for the Florida Department of Environmental Regulation, Tallahassee, FL.

Pantalion, J., A. Scharlach, and G. Oswald. 1995. Water quality master planning in an urban watershed. In *Watershed Management: Planning for the 21st Century.* Proceedings of the ASCE's First International Conference of Water Resources Engineering, San Antonio, TX, August 14-16, 1995, pp. 330-339.

Appendix B:

Receiving Water Models—Fact Sheets

CE-QUAL-ICM: A Three-Dimensional Time-Variable Integrated-Compartment Eutrophication Model

1. Distributor:

Water Quality and Contaminant
Modeling Branch
Environmental Laboratory
U.S. Army Engineer Waterways
Experiment Station
3909 Halls Ferry Road
Vicksburg, MS 39180
(601) 634-3785

2. Type of Modeling/Application:

- May be applied to most waterbodies in 1-, 2-, or 3-D
- Unsteady flow
- Predicts time-varying concentrations of water quality constituents
- Advective and dispersive transport
- Considers sediment diagenesis benthic exchange
- Finite difference

3. Model Processes:

- Temperature
- Salinity
- DO-carbon balance
- Nitrogen cycle
- Phosphorus cycle
- Silicon cycle
- Phytoplankton (up to 3 species)
- Zooplankton
- Bacteria
- First-order decay
- Sediment process rates may be input or simulated using the diagenesis sub-model

4. Method/Techniques:

CE-QUAL-ICM incorporates detailed algorithms for water quality kinetics. Interactions among state variables are described in 80 partial-differential equations that employ over 140 parameters (Cerco and Cole, 1993). An improved finite-difference method is used to solve the mass conservation equation for each cell in the computational grid and for each state variable. The state variables can be categorized into six groups and cycles—the physical group, and the carbon, nitrogen, phosphorus, silica, and dissolved oxygen (DO) cycles.

5. Limitations:

Although the model has full capabilities to simulate state-of-the-art water quality kinetics, it is potentially limited by available data for calibration and verification. In addition, the model may require significant technical expertise in aquatic biology and chemistry to be used appropriately.

6. Experience:

Used in conjunction with a hydrodynamic model and a benthic-sediment model to develop a state-of-the-art 3-D model of the Chesapeake Bay. The model was employed to simulate long-term trends in Chesapeake Bay eutrophication (Cerco, 1995). Mark et al. (1992) used CE-QUAL-ICM to assess the water quality impacts of a confined disposal facility in Green Bay, Wisconsin.

7. Updating Version and System Requirements:

Model is currently under active development, and the capability to simulate toxicants is planned. PC-compatible. The model is computationally intensive for large waterbodies particularly when all processes are simulated.

8. Input Data Requirements:

Geometric data to define the finite difference representation of the waterbody have to be defined, and approximately 140 are parameters needed to specify kinetic interactions. Initial and boundary conditions have to be specified.

9. Outputs:

Temperature, salinity, inorganic suspended solids, diatoms, blue-green algae and other phytoplankton, dissolved, labile, and refractory components of particulate organic carbon, organic nitrogen, and organic phosphorus ammonium, nitrite and nitrate, total phosphate, dissolved oxygen, chemical oxygen demand, dissolved silica, particulate biogenic silica.

10. References Available:

Cerco, C.F., and T. Cole. 1995. *User's Guide to the CE-QUAL-ICM.* Release Version 1.0. Technical Report EL-95-1, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Cerco, C.F., and T. Cole. 1993. Three-dimensional eutrophication model of the Chesapeake Bay. *Journal of Environmental Engineering* 119(6):1006-1025.

Cerco, C.F. 1995. Simulation of long-term trends in Chesapeake Bay Eutrophication. *Journal of Environmental Engineering* 121(4): 298-310.

Mark, D. J., B.W. Bunch, and N.W. Scheffner. 1992. Combined Hydrodynamic and water quality modeling of Lower Green Bay. In *Water Quality '92: Proceedings of the 9th Seminar.* U.S. Army Engineers Waterways Experiment Station, San Antonio, TX, March 16-20, 1992 p. 226-233.

CE-QUAL-RIV1: Hydrodynamic and Water Quality Model for Streams

1. Distributor:

Water Quality and Contaminant
Modeling Branch
Environmental Laboratory
U.S. Army Engineer Waterways
Experiment Station
3909 Halls Ferry Road
Vicksburg, MS 39180
(601) 634-3670

2. Type of Modeling/Application:

- Rivers and estuaries
- Far-field
- One-dimensional, branching
- Unsteady flow
- Predicts time-varying concentrations of water quality constituents
- Advective and dispersive transport
- Finite difference

3. Model Processes:

- Temperature
- Salinity
- DO-BOD
- Nitrogen cycle
- Phosphorus cycle
- Phytoplankton in water column
- Benthic algae and macrophytes
- Bacteria
- First-order decay

4. Method/Techniques:

CE-QUAL-RIV1 was developed to simulate transient water quality conditions associated with highly unsteady flows that can occur in regulated rivers. The model consists of two codes: RIV1H, a stand-alone hydraulic routing code, and RIV1Q, a water quality code that uses output from RIV1H to provide dynamic water quality simulation.

An implicit, finite-difference method is used to solve the continuity and momentum equations in RIV1H, with cross-sectional area and discharge as dependent variables. RIV1H allows the simulation of dynamically coupled, branched river systems with multiple control structures. In RIV1Q, an explicit, finite-difference method is used to solve the constituent advective transport and reaction equations and calculate dynamic changes in the concentrations of water quality variables.

5. Limitations:

- Only applicable to situations where flow is predominantly one-dimensional.
- The program may exhibit numerical instability under certain conditions.

6. Experience:

Applied to provide examples of potential water quality impacts associated with operations alternatives for a regulation dam proposed for construction downstream from Buford Dam on the Chattahoochee River near Atlanta, Georgia (Zimmerman and Dortch, 1989).

The RIV1Q component of CE-QUAL-RIV1 was used to develop statistical relationships to allow prediction of downstream water temperatures associated with different operational scenarios (Nestler et al., 1993).

7. Updating Version and System Requirements:

Last updated in 1990. PC-compatible.

8. Input Data Requirements:

RIV1H requires river geometry and boundary conditions to perform hydraulic calculations. Geometric data include locations of control structures, streambed elevations, river cross sections, and distances between nodes.

Manning's coefficients are used to describe channel roughness. Boundary conditions include initial flow rates and stages, lateral inflows or withdrawals, and boundary conditions defined by discharge, stage, or a stage-discharge rating curve.

RIV1Q requires initial instream and inflow boundary water quality concentrations, meteorologic data for temperature computations, and rate coefficients.

9. Outputs:

Dissolved oxygen, carbonaceous biochemical oxygen demand, temperature, organic nitrogen, ammonia nitrogen, nitrate nitrogen, orthophosphate, dissolved iron, dissolved manganese, coliform bacteria.

10. References Available:

Environmental Laboratory. 1990. *CE-QUAL-RIV1: A dynamic, one-dimensional (longitudinal) water quality model for streams: User's manual, instruction report.* U.S. Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Nestler, J.M., L.T. Schneider, and B.R. Hall. 1993. *Development of a simplified approach for assessing the effects of water release temperatures on tailwater habitat downstream of Fort Peck, Garrison, and Fort Randall Dams.* Technical Report EL-93-23. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Zimmerman, M.J., and M.S. Dortch. 1989. Modeling water quality of a reregulated stream below a peaking hydropower dam. *Regulated Rivers: Research and Management* 4:235-247.

CE-QUAL-W2: A Two-Dimensional, Laterally Averaged, Hydrodynamic and Water Quality Model

1. Distributor:

Water Quality and Contaminant
Modeling Branch
Environmental Laboratory
U.S. Army Engineer Waterways
Experiment Station
3909 Halls Ferry Road
Vicksburg, MS 39180
(601) 634-3785

2. Type of Modeling/Application:

- May be applied to most water bodies in 1-D or laterally averaged 2-D (X/Z)
- Unsteady flow
- Predicts time-varying concentrations of water quality constituents
- Advective and dispersive transport
- Finite difference

3. Model Processes:

- Temperature
- Salinity
- DO-carbon balance
- Nitrogen cycle
- Phosphorus cycle
- Silicon cycle
- Phytoplankton
- Bacteria
- First-order decay

4. Method/Techniques:

CE-QUAL-W2 is a two-dimensional, longitudinal/vertical, hydrodynamic and water quality model. The hydrodynamic and water quality routines are directly coupled; however, the water quality routines can be updated less frequently than the hydrodynamic time step, which can reduce the computational burden for complex systems.

The water quality routines incorporate 21 constituents in addition to temperature and include constituent interactions during anoxic conditions. The constituents are arranged in four levels of complexity, permitting flexibility in model application. The water quality component is modular, allowing constituents to be easily added as additional subroutines.

5. Limitations:

- Because the model assumes lateral homogeneity, it is best suited for relatively long and narrow waterbodies exhibiting strong longitudinal and vertical water quality gradients; it may be inappropriate for large waterbodies.
- Only one algal compartment is included, and algal succession cannot be modeled.
- No zooplankton or macrophytes are modeled.
- Simplified sediment oxygen demand component based on first-order decay.

6. Experience:

The model has been applied to rivers, lakes, reservoirs, and estuaries (Adams et al., 1993; Hall, 1987; Martin, 1988). Barnese and Bohannon (1994) report initial efforts to apply CE-QUAL-W2 to Taylorsville Lake in Kentucky.

7. Updating Version and System Requirements:

Version 2.0 (1994). PC-compatible.

8. Input Data Requirements:

Geometric data are required to define the finite difference representation of the waterbody. Initial and boundary conditions have to be specified. Required hydraulic parameters include horizontal and vertical dispersion coefficients for momentum and temperature/constituents and the Chezy coefficient, used to calculate boundary friction. Simulation of water quality kinetics requires the specification of approximately 60 coefficients. Finally, data are required to provide boundary conditions and assess model performance during calibration.

9. Outputs:

The hydrodynamic component of the model predicts water surface elevations, velocities, and temperatures. Water quality constituents that may be modeled include a conservative tracer, inorganic suspended solids, coliform bacteria, total dissolved solids, labile and refractory dissolved organic matter, algae, dissolved oxygen, ammonia-nitrogen, nitrate-nitrogen, phosphorus, total inorganic carbon, pH, carbonate, and total iron.

10. References Available:

Adams, R.W., E.L. Thackston, R.E. Speece, D.J. Wilson, and R. Cardozo. 1993. *Effect of Nashville's combined sewer overflows on the water quality of Cumberland River*. Technical Report No. 42. Environmental and Water Resources Engineering, Vanderbilt University, Nashville, TN.

Barnese, L.E., and J.A. Bohannon. 1994. The distribution of nutrients and phytoplankton in Taylorsville Lake -
A model study. In *Symposium Proceedings on Responses to Changing Multiple-Use Demands: New Directions for Water Resources Planning and Management.* American Water Resources Association, Nashville, TN, April 17-20, 1994, pp. 33-35.

Cole, R.W., and E.M. Buchak. 1995. *CE-QUAL-W2: A two-dimensional, laterally averaged, hydrodynamic and water quality model.* Version 2.0. Instructional Report EL-95-1, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Hall, R.W. 1987. *Application of CE-QUAL-W2 to the Savannah River Estuary.* Technical Report EL-87-4. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Martin, J.L. 1988. Application of two-dimensional water quality model. *Journal of Environmental Engineering* 114(2):317-336.

CH3D-WES: Curvilinear Hydrodynamics in Three-Dimensions - Waterways Experiment Station

1. Distributor

Water Quality and Contaminant Modeling Branch
Environmental Laboratory
U.S. Army Engineer Waterways Experiment Station
3909 Halls Ferry Road
Vicksburg, MS 39180-6199
(601) 634-3785

2. Type of Modeling/Application:

- Hydrodynamic model developed for the Chesapeake Bay Program.
- Physical processes impacting circulation and vertical mixing that can be modeled include tides, wind, density effects (salinity and temperature), freshwater inflows, turbulence, and the effect of the Earth's rotation.

3. Model Processes:

CH3D-WES makes hydrodynamic computations on a curvilinear or boundary-fitted planform grid. Deep navigation channels and irregular shorelines can be modeled because of the boundary-fitted coordinates feature of the model. Vertical turbulence is predicted by the model and is crucial to a successful simulation of stratification, destratification, and anoxia. A second-order model based upon the assumption of local equilibrium of turbulence is employed.

4. Method/Techniques:

Capabilities of CH3D are illustrated by its application to the Chesapeake Bay. The numerical grid employed in the Chesapeake Bay model has 734 active horizontal cells and a maximum of 15 vertical layers, resulting in 3,992 computational cells. Grid resolution is 1.52 m vertical and approximately 10 km longitudinal and 3 km lateral. The x, y coordinates of the grid are transformed into the ,ç-curvilinear coordinates to allow for better handling of the complex horizontal geometries. Velocity is also transformed so that its components are perpendicular to the ,ç-coordinate lines, thus allowing boundary conditions to be prescribed on a boundary-fitted grid in the same manner as a Cartesian grid. Major tributaries are modeled three-dimensionally in the lower reach of the bay and two-dimensionally with constant width in the upper reach.

5. Limitations:

- Considerable technical expertise in hydrodynamics is required to use the model effectively.

6. Experience:

Johnson et al. (1993) validated the model by applying it to six data sets. The first three data sets contained approximately one month's worth of data each and represented a dry summer condition, a spring runoff, and a fall wind-mixing event. The last three applications were yearlong simulations for 1984 (a wet year), 1985 (a dry year), and 1986 (an average year). Results demonstrate that the model is a good representation of the hydrodynamics of the Chesapeake Bay and its major tributaries.

Cerco et al. (1993) used CH3D-WES in conjunction with CE-QUAL-ICM to predict water column and sediment processes that affect water quality in the Chesapeake Bay. Data from 1984-1986 were used and the linked modeling approach was successful in predicting the spring algal bloom, onset and breakup of summer anoxia, and coupling of organic particle deposition with sediment-water nutrient and oxygen fluxes.

7. Updating Version and System Requirements:

- Model requires a Unix Workstation or Super Computer.

8. Input Data Requirements:

Basic inputs required are time-varying water-surface elevations, salinity, and temperature conditions at the ocean entrance and at freshwater inflows at the head of all tributaries. Time-varying wind and surface heat exchange data must also be prescribed at one or more locations. All input data, including initial conditions, bathymetry, boundary, and computational control data are input from fixed files.

9. Outputs:

The CH3D-WES model can be used to predict system response to water levels, flow velocities, salinities, temperatures, and the three-dimensional velocity field. Predictions can be made for each cell of the grid at a specified time interval.

10. References available:

Cerco, C.F. and T. Cole. 1993. Three-Dimensional Eutrophication Model of Chesapeake Bay. *Journal of Environmental Engineering*. 119(6):1006-1025.

Johnson, B.H., K. W. Kim, R.E. Heath, B.B. Hsieh, and H.L. Butler. 1993. Validation of Three-Dimensional Hydrodynamic Model of Chesapeake Bay. *Journal of Hydraulic Engineering*. 119(1):2-20.

Johnson, B.H., R.E. Heath, B.B. Hsieh, K.W. Kim, H.L. Butler. 1991. *User's Guide for a Three-Dimensional Numerical Hydrodynamic, Salinity, and Temperature Model of Chesapeake Bay*. Department of the Army, Waterways Experiment Station, Corps of Engineers, Vicksburg, MS.

CORMIX: Cornell Mixing Zone Expert System

1. Distributor:

Model Distribution Coordinator
Center for Exposure Assessment Modeling (CEAM)
USEPA
960 College Station Road
Athens, GA 30605-2700
(706) 546-8400
Models are available for FTP from:
ftp://ftp.epa.gov/epa_ceam/wwwhtml/ceamhome.htm

2. Type of Modeling/Application:

- May be applied to most waterbodies.
- Near-field and far-field hydrodynamic mixing processes
- Single Port, Multiport, and Surface Discharges
- Includes effects of plume boundary interaction
- Can be applied to tidal environments

3. Model Processes:

- Computation of physical parameters and length scales to allow hydrodynamic classification of the given discharge/ambient situation into one of many possible generic flow configurations.
- Detailed numerical prediction of effluent plume characteristics.

4. Method/Techniques:

CORMIX predicts plume geometry and dilution characteristics within a receiving water's initial mixing zone and allows an analysis of toxic or conventional pollutant discharges into diverse waterbodies. The model is able to consider nonconservative pollutants with first-order decay and wind effects on thermal plume mixing.

Submodels within the CORMIX system can be used to predict the geometry and dilution characteristics of effluent flow from different discharging systems. The first submodel considers a submerged single-port diffuser of arbitrary density discharging into a waterbody that may have ambient stratification of different types. The second submodel applies to commonly used types of submerged multiport diffuser discharges under the same general effluent and ambient conditions as the first submodel. The third submodel considers buoyant surface discharges that result when an effluent enters a larger waterbody laterally through a canal, channel, or near-surface pipe.

As the name implies, CORMIX is embedded in an expert system shell that greatly facilitates data input, provides range checking for inputs, and allows convenient output analysis.

5. Limitations:

- All CORMIX submodels assume steady-state ambient and discharge conditions.
- CORMIX gives limited quasi-steady state predictions in unsteady tidal environments

6. Experience:

The CORMIX system has been extensively verified by the developers and independent users through comparison of simulation results to available field and laboratory data on mixing processes, and has undergone extensive peer review. The system has been used for a wide range of applications, ranging from a single submerged pipe discharging into a small stream with rapid cross-sectional mixing to complicated multiport diffuser installations in deep, stratified coastal waters.

7. Updating Version and System Requirements:

Version 3.2 (1996). PC MS-DOS compatible.

8. Input Data Requirements:

All inputs are entered interactively and include complete specification of the site or case, ambient conditions, discharge characteristics, level of output detail, and regulatory definitions.

9. Outputs:

The output consists of qualitative descriptions and detailed quantitative numerical predictions. Qualitative information includes physical information and insight into the reasoning employed by the system and flow class descriptions. The post-processor CORGRAPH is included to give 2-D sketch graphics of resulting plumes. The FFLOCATR post-processor can be used to compare field dye test data to plume predictions when detailed ambient cross-section data is available. Quantitative output provides details on the effluent plume trajectory and mixing and regulatory compliance.

10. References available:

Akar, P.J. and G.H. Jirka. 1991. *CORMIX2: An Expert System for Mixing Zone Analysis of Conventional and Toxic Multiport Diffuser Discharges*. EPA/600/3-91/073. U.S. Environmental Protection Agency, Center for Exposure Assessment Modeling, Athens, GA.

Doneker, R.L. and G.H. Jirka. 1990. *CORMIX1: An Expert System for Mixing Zone Analysis of Conventional and Toxic Single Port Aquatic Discharges*. EPA/600/3-90/012. U.S. Environmental Protection Agency, Center for Exposure Assessment Modeling, Athens, GA.

Jirka, G.H. and P.J. Akar. 1991. Hydrodynamic classification of submerged multiport diffuser discharges. *Journal of Hydraulic Engineering* 117(9):1113-1128.

Jirka, G.H., and R.L. Doneker. 1991. Hydrodynamic classification of submerged single port discharges. *Journal of Hydraulic Engineering* 117(9):1095-1112.

Jirka, G.H., R.L. Doneker, and S.W. Hinton. 1996. *User's Manual for CORMIX: A Hydrodynamic Mixing Zone Model and Decision Support System for Pollutant Discharges Into Surface Waters*. To be published by USEPA, Office of Water, Office of Science and Technology, 1996. Available at http://ese.ogi.edu.

Jones, G.R. and G.H. Jirka. 1991. *CORMIX3: An expert system for the analysis and prediction of buoyant surface discharges*. Technical report. DeFrees Hydraulics Laboratory, School of Civil and Environmental Engineering, Cornell University, Ithaca, NY.

DECAL: A Simplified Deposition Calculation for Organic Accumulation Near Marine Outfalls

1. Distributor:

Marine Pollution Control Branch
Oceans and Coastal Protection Division
Office of Coastal Protection
USEPA
401 M Street, SW
Washington, DC 20460
(202) 260-8448

2. Type of Modeling/Application:

- Coastal waterbodies
- Two-dimensional, depth-averaged
- Steady, point source loadings
- Steady, tidally driven flow
- Analytical, steady-state predictions
- Advective and dispersive transport

3. Model Processes:

- Particle deposition and accumulation of organic material in sediments employing a second-order rate law
- Metal and trace organic chemical accumulations in sediments
- Carbon fixation by phytoplankton
- First-order decay of organic material in water column and sediment

4. Method/Techniques:

In DECAL, the removal of organic material from the water column is assumed to occur primarily within the time scale of one to several days. Transport, particle dynamics, and organic carbon cycling are described by averaging over a daily period to account for tidal oscillations. The user can specify long-term net drift.

The water column consists of a well-mixed surface and lower layer, separated by a pycnocline region. The daily-averaged discharge of effluent is distributed over an extended spatial domain by tidal oscillations. Particle deposition rates are determined from coagulation and settling kinetics and are described by a second-order dependency on mass concentration. Carbon fixation by phytoplankton is expressed by measured productivity rates. Decomposition of organic material in the water column and sediments is described by first-order decay.

5. Limitations:

- Plume entrainment, tidal oscillations, and mixing in the surface and lower waters are assumed to be instantaneous.
- Diffusion through the pycnocline and horizontal dispersion are not considered significant over travel distances larger than about 15 miles.
- The distribution of daily-averaged sewage discharge is assumed to be uniformly distributed over the tidal-excursion ellipse.

6. Experience:

Applied to Orange County and Los Angeles County outfalls using calibrated modeling coefficients (Farley, 1990).

7. Updating Version and System Requirements:

Last updated in 1987. PC-compatible.

8. Input Data Requirements:

Wasteflow characteristics (flow rates and effluent solids concentrations), outfall diffuser location and geometry, background oceanographic information (total water column depth, height of the lower layer, and rate of phytoplankton primary production), short-term tidal oscillations, and long-term nontidal flows.

9. Output

Output from DECAL is given as sets of contour plots for suspended particle concentrations in the lower water layer, for the daily-averaged deposition rates of organic material, or for organic accumulation of particles in sediments.

10. References Available:

Farley, K.J. 1990. Predicting organic accumulation in sediments near marine outfalls. *Journal of Environmental Engineering* 116(1): 144-165.

Tetra Tech. 1987. *A simplified deposition calculation (DECAL) for organic accumulation near marine outfalls. Final report.* Prepared for Marine Operations Division, Office of Marine and Estuarine Protection, USEPA, Washington DC, by Tetra Tech, Inc.

DYNHYD5: Link-Node Tidal Hydrodynamic Model

1. Distributor:

Model Distribution Coordinator
Center for Exposure Assessment
Modeling (CEAM)
USEPA
960 College Station Road
Athens, GA 30605-2700
(706) 355-8400

2. Type of Modeling/Application:

- Well-mixed unstratified rivers and estuaries (one-dimensional)
- Variable tidal cycles, wind, and unsteady inflows

3. Model Processes:

DYNHYD5 solves the one-dimensional equations of continuity and momentum for a branching or channel-junction (link-node) computational network. Most applications of DYNHYD5 will use a simulation time step on the order of 30 seconds to 5 minutes due to stability requirements. However, the hydrodynamic output file created by DYNHYD5 may be stored at any user-specified interval for use by a water quality simulation program. This interval may range from 1 to 24 hours, depending on the type of water quality simulation desired. If interest focuses on tide-induced transport, a 1- to 3-hour interval should be used. On the other hand, with long-term simulations, a time interval of 12 to 24 hours would be appropriate.

4. Method/Techniques:

DYNHYD5 solves one-dimensional equations describing the propagation of a long wave through a shallow water, using an explicit two-step Runge-Kutta procedure. The continuity equation, based on the conservation of volume, is used to predict water heights (heads) and volumes. The equation of motion, based on the conservation of momentum, predicts water velocities and flows, and includes terms accounting for local inertia, convective inertia, gravitational acceleration, frictional resistance, and wind stress along the channel axis.

5. Limitations:

- Applicable only to situations where flow is predominantly well-mixed vertically and laterally (one-dimensional).
- Assumes channels can be adequately represented by a constant top width with a variable hydraulic depth.
- Assumes wave length is significantly greater than the depth, and bottom slopes are moderate.
- Difficult to apply to small rivers or streams with steep hydraulic grades.

6. Experience:

The model is distributed as part of the comprehensive WASP5 modeling system and is typically applied externally to provide hydrodynamic flow computations, which are then input to the WASP5 water quality model. Various versions of DYNHYD have been applied to several rivers and estuaries as part of wasteload allocation and eutrophication studies. There are many examples of successful calibration and validation. Warwick and Heim (1995) provide a comparison of the performance of DYNHYD and RIVMOD models.

7. Updating Version and System Requirements:

Released with WASP Version 5.10 (1993). PC-compatible. Pre- and post- processors are supplied with the model.

8. Input Data Requirements:

Data requirements include a description of the physical geometry and the forcing functions. For junction elements, initial surface elevation, surface area, and bottom elevation must be given. For channel elements, length, width, hydraulic radius, channel orientation, initial velocity, and Manning's roughness coefficient are required. Seaward boundary elevations can be described by an average repetitive tidal function or by specifying the high and low tidal heights versus time for multiple tidal cycles.

9. Outputs:

The model reports time-variable channel flows and velocities, as well as junction volumes and depths throughout the computational network at user-specified print intervals.

10. References Available:

Ambrose, R.B., T.A. Wool, and J.L. Martin. 1993. *The water quality analysis simulation program, WASP5 version 5.10. Part A: Model Documentation.* U.S. Environmental Protection Agency, Office of Research and Development, Environmental Research Laboratory, Athens, GA.

Warwick, J.J., and K.J. Heim. 1995. Hydrodynamic modeling of the Carson River and Lahontan Reservoir, Nevada. *Water Resources Bulletin* 31(1):67-77.

DYNTOX: Dynamic Toxics Model

1. Distributor:

Ibrahima B. Goodwin
Office of Water
Office of Science and Technology
USEPA
401 M Street, SW
Washington, DC 20460
(202) 260-1308

2. Type of Modeling/Application:

- One-dimensional rivers and streams
- Steady-state predictions
- Explicitly accounts for duration and frequency of loadings using a probabilistic framework

3. Model Processes:

- Effluent mixing with upstream flow, including consideration of incomplete lateral mixing at discharge point
- First-order decay

4. Method/Techniques:

The fundamental analytical solution in DYNTOX assumes a steady-state condition over the course of a day. The model allows the use of three probabilistic simulation techniques to calculate the frequency and severity of instream toxicity at different effluent discharge levels. The three procedures considered are continuous simulation, Monte Carlo simulation, and lognormal analysis.

In the continuous simulation approach, the model is run for a specified period of recorded history and the results are analyzed for frequency and duration.

In the Monte Carlo method, inputs are described by probability distributions. Random input sets are then used to repeatedly execute the model and describe the model output in terms of a probability distribution. Both the continuous simulation and Monte Carlo methods produce probability distributions of calculated daily downstream concentrations from which the recurrence interval of any concentration of interest can be obtained. Probability distributions of running averaged concentrations for any time period of interest can also be obtained.

The lognormal analysis requires all inputs to be described by lognormal distributions, which allows computation of exceedance probabilities for the toxic concentration at the point of mixing through numerical integration.

5. Limitations:

- Simulates only steady-state conditions
- Dispersion is assumed to be negligible in the longitudinal direction
- Does not consider daughter products or processes.
- Kinetic reactions are restricted to first-order loss of total pollutant
- The lognormal analysis is limited to one effluent discharge without decay

6. Experience:

The framework on which the DYNTOX model is based was applied to modeling stream toxics in the Flint River, Michigan (USEPA, 1984).

7. Updating Version and System Requirements:

Version 2.0 (1994). PC-compatible.

8. Input Data Requirements:

Upstream boundary data describing flow and concentration in the river upstream of the discharges, water quality standards, time of travel between outfalls, and effluent data. Drainage area ratios can be specified for each reach of the system under study to account for nonpoint sources of water entering the stream. Depending on the simulation method used, additional model parameters upstream and effluent data specific to the method are required. The continuous simulation and Monte Carlo methods require a first-order decay rate.

9. Outputs:

DYNTOX provides tabular and graphic outputs indicating the return period (in years) of water quality standard violations below each discharge and the percent of time that predicted receiving water quality falls in different concentration ranges, as well as the return period for selected concentrations.

10. References Available:

Limno-Tech, Inc. 1994. *Dynamic Toxics Wasteload Allocation Model (DYNTOX). Version 2.0. Users manual.* Limno-Tech, Inc., Ann Arbor, MI.

USEPA. 1984. *Technical guidance manual for performing waste load allocations - Book II, Streams and rivers, Chapter 3, Toxic substances.* U.S. Environmental Protection Agency, Office of Water Regulations and Standards, Monitoring and Data Support Division, Washington, DC.

EFDC: Environmental Fluid Dynamics Computer Code

1. Distributor

John M. Hamrick
Tetra Tech, Inc.
10306 Eaton Place, Suite 340
Fairfax, VA 22030
703-385-6000
ham@visi.net

or

Virginia Institute of Marine Science
School of Marine Science
The College of William and Mary
Gloucester Point, VA 23052
(804) 642-7000

2. Type of Modeling/Application:

- General purpose three-dimensional hydrodynamic and transport model applicable to rivers, lakes, reservoirs, estuaries, wetlands, and coastal regions.
- Model simulates tidal, density, and wind driven flow; salinity; temperature; and sediment transport.
- Two built in, fully coupled water quality/eutrophication submodels are included in the code, as well as a toxicant transport and fate model.

3. Model Processes:

The EFDC model solves the vertically hydrostatic, free-surface, variable-density, turbulent-averaged equations of motion and transport equations for turbulence intensity and length scale, salinity, and temperature in a stretched, vertical coordinate system, and horizontal coordinate systems that may be Cartesian or curvilinear-orthogonal. Equations describing the transport of suspended sediment, toxic contaminants, and water quality state variables are also solved. Multiple size classes of cohesive and non-cohesive sediments and associated deposition and resuspension processes and bed geomechanics are simulated. Toxics are transported in both the water and sediment phases in the water column and bed. The built in 20 state variable water quality model is based on the CE-QUAL-ICM reaction kinetic. The 10 state variable reduced water quality model is functionally equivalent to WASP5. Other model features include: drying and wetting, hydraulic structure representation, vegetation resistance, and Lagrangian particle tracking. The model also accepts radiation stress fields from wave refraction-diffraction models, which allows simulation of longshore currents and sediment transport.

4. Method/Techniques:

EFDC uses a finite difference scheme with three time levels and an internal-external mode splitting procedure to achieve separation of the internal shear or baroclinic mode from the external free-surface gravity wave or barotropic mode. An implicit external mode solution is used with simultaneous computation of a two-dimensional surface elevation field by a multicolor successive overrelaxation procedure. The external solution is completed by calculation of the depth-integrated barotropic velocities using the new surface elevation field. Various options can be used for advective transport in EFDC. These include the "centered in time and space" scheme, and the "forward in time and upwind in space" scheme.

5. Limitations:

- Considerable technical expertise in hydrodynamics is required to use the model effectively.
- Expertise in eutrophication processes is required to use the water quality component.

6. Experience:

The EFDC model has been used for modeling studies in the estuaries of the Chesapeake Bay System, the Indian River Lagoon and Lake Okeechobee in Florida, the Peconic Bay System in New York, Stephens Passage in Alaska, and Nan Wan Bay, Taiwan. The model has also been used to simulate large scale wetlands flow and transport in the Everglades.

7. Updating Version and System Requirements:

The universal FORTRAN source code is maintained compatible with DEC, IBM, HP, SGI and SUN Unix workstations and Cray Supercomputers as well as PC-compatibles and Power Macintoshs. Microsoft, Lahey and Absoft compilier are supported on PC, with Language Systems and Absoft compilier supported on Macintoshes.

8. Input Data Requirements:

Input data to drive the model include open boundary water surface elevation, wind and atmospheric thermodynamic conditions, open boundary salinity and temperature, volumetric inflows and inflowing concentrations of sediment and water quality state variables. Input file templates are included with the source code and the user's manual to aid in input data preparation.

9. Outputs:

The model outputs include water surface elevation, horizontal velocities, salinity, temperature, sediment concentration, and toxicant concentration. Water quality concentrations can also be predicted in a variety of formats suitable for time series analysis and plotting, horizontal and vertical plane vector and contour plotting, and three-dimensional slice and volumetric visualization. Post processing software is available to convert generic output files for use by a numbers of scientific visualization applications.

10. References available:

Hamrick, J.M. 1992. *A three-dimensional environmental fluid dynamics computer code: theoretical and computational aspects.* SRAMSOE #317, The College of William and Mary, Gloucester Point, VA.

Hamrick, J. M. 1992. Estuarine environmental impact assessment using a three-dimensional circulation and transport model. In *Estuarine and Coastal Modeling, Proceedings of the 2nd International Conference*, ed. M. L. Spaulding et al., pp. 292-303. American Society of Civil Engineers, New York.

Hamrick, J. M. 1996. *A User's Manual for the Environmental Fluid Dynamics Computer Code (EFDC)*. The College of William and Mary, Virginia Institute of Marine Science, Special Report 331, 234 pp.

Hamrick, J. M., and T. S. Wu. 1996. Computational design and optimization of the EFDC/HEM3D surface water hydrodynamic and eutrophication models. In *Computational Methods for Next Generation Environmental Models*, ed. G. Delich, Society of Industrial and Applied Mathematics, Philadelphia. In press.

Park, K., A. Y. Kuo, J. Shen, and J. M. Hamrick. 1995. *A three-dimensional hydrodynamic-eutrophication model (HEM3D): description of water quality and sediment processes submodels*. The College of William and Mary, Virginia Institute of Marine Science, Gloucester Point, VA.. Special Report 327, 113 pp.

Tetra Tech. 1994. *User's guide for the three-dimensional EFDC hydrodynamic and salinity model of Indian River Lagoon and Turkey Creek*. Final report. Tetra Tech, Inc., Fairfax, VA.

EUTROMOD: Watershed and Lake Modeling Procedure

1. Distributor

North American Lake Management Society (NALMS)
PO Box 5443
Madison, WI 53705
(608) 233-2836

2. Type of Modeling/Application:

- Provides guidance and information for managing eutrophication in lakes and reservoirs
- Collection of spreadsheet-based nutrient loading and lake response models
- Predicts lakewide, growing season average conditions as a function of annual nutrient loadings
- Allows for uncertainty analysis by providing estimates of model error and hydrologic variability.

3. Model Processes:

- Annual watershed point and nonpoint source loadings
- Nonlinear regression equations from multi-lake regional data sets in the United States used to predict lake response

4. Method/Techniques:

EUTROMOD is a spreadsheet-based watershed and lake modeling procedure for eutrophication management, with an emphasis on uncertainty analysis. The model estimates nutrient loading, various trophic state parameters, and trihalomethane concentration in the lake using data pertaining to land use, pollutant concentrations, and lake characteristics. EUTROMOD uses several algorithms based on statistical relationships and a continuously stirred tank reactor (CSTR) model. The model was developed using empirical data from the USEPA's national eutrophication survey, with trophic state models used to relate phosphorus and nitrogen loading to in-lake nutrient concentrations. The phosphorus and nitrogen concentrations were then related to maximum chlorophyll level, Secchi disk depth, dominant algal species, hypolimnetic dissolved oxygen status, and trihalomethane concentration. EUTROMOD allows for uncertainty analysis by considering the error in regression equations employed, and using an annual mean precipitation and coefficient of variation to account for hydrologic variability.

5. Limitations:

- Specific to watersheds in the southeastern United States.
- Provides only predictions of growing season average conditions.

6. Experience:

Used in conjunction with a GIS for establishing total maximum daily loads to Wister Lake, Oklahoma (Hession et al., 1995).

7. Updating Version and System Requirements:

Last updated in 1990. PC-compatible.

8. Input Data Requirements:

Data required for simulating basin loadings and lake response include information about climate, watershed characteristics, and lake morphometry. Climate parameters include precipitation and lake evaporation estimates. Several parameters are needed to describe the watershed in terms of land use, soils, and topography. Lake morphometry is described using surface area and mean depth.

9. Outputs:

The output from EUTROMOD consists of predicted phosphorus and nitrogen loads by category, and lake responses. The lake responses include total phosphorus and nitrogen concentrations in the lake influent averaged for all inputs and land uses, total P and N concentrations in the lake, chlorophyll *a* concentration, Secchi disk depth, the probability that the blue-green algae dominate the algae population and that the hypolimnion remains oxic, trihalomethane concentrations.

10. References Available:

Hession, W.C., D.E. Storm, S.L. Burks, M.D. Smolen, R. Lakshminarayanan, and C.T. Haan. 1995. Using EUTROMOD with a GIS for establishing total maximum daily loads to Wister Lake, Oklahoma. In *Impact of animal waste on the land-water interface*, 53-60. Lewis Publishers. In press.

Reckhow, K.H. 1990. *EUTROMOD spreadsheet program - a regional modeling scheme for nutrient runoff and lake trophic state modeling*. School of Forestry and Environmental Studies, Duke University, Durham, NC.

EXAMS II: Exposure Analysis Modeling System

1. Distributor:

Model Distribution Coordinator
Center for Exposure Assessment Modeling (CEAM)
USEPA
960 College Station Road
Athens, GA 30605-2700
(706) 355-8400
Models are available for FTP from:
ftp://ftp.epa.gov/epa_ceam/wwwhtml/ceamhome.htm

2. Type of Modeling/Application:

- Streams/Rivers and lakes/reservoirs in one, two, or three dimensions
- Steady flow
- Steady-state/Quasidynamic predictions
- Advective and dispersive transport
- Considers benthic exchange
- Inputs may be steady or variable

3. Model Processes:

- First-order decay, daughter products
- Process kinetics
- Equilibrium sorption
- Pore water advection
- Local sediment mixing

4. Method/Techniques:

EXAMSII is an interactive modeling system that uses the principle of mass balance and mathematical models of the kinetics and processes governing the transport and transformation of chemicals to provide predictions of their probable fate and persistence in aquatic ecosystems. The hydrologic transport processes considered are advection and dispersion. The transformation processes included in the model are photolysis, hydrolysis, biotransformation, oxidation, and sorption with sediments and biota. Secondary daughter products and subsequent degradation of these products are also considered.

EXAMSII includes separate mathematical models of the kinetics of the physical, chemical, and biological processes governing transport and transformations of chemicals. An advantage in using the model is its ability to accept standard water quality parameters, chemical data, and system characteristics for which information is readily available.

5. Limitations:

- Designed to evaluate consequences of long-term, primarily time-averaged chemical loadings, thus transient effects cannot be analyzed.
- Chemicals are assumed not to radically change the environmental variables that drive their transformations.
- Sorption isotherms are assumed to be linear, and biotransformation kinetics are assumed to be second-order rather than Michaelis-Menton-Monod.

6. Experience:

EXAMSII has been used in a wide range of regulatory applications for the USEPA. The model has been validated and reviewed by independent experts (Mulkey et al., 1986; Schnoor et al., 1987).

7. Updating Version and Systems Requirements:

Version 2.941 (1995). PC-compatible. The model includes pre- and post- processing systems.

8. Input Data Requirements:

Basic inputs include system geometry and hydrology specification, a set of chemical loadings on each sector of the ecosystem, and parameters that define the strength of the advective and dispersive transport pathways.

Although EXAMSII allows for the entry of extensive environmental data, the program can be run with a much-reduced data set when the chemistry of a compound of interest precludes some of the transformation processes. Chemical parameters include molecular weight, solubility, and ionization constants of the compound. Sediment-sorption/biosorption, volatilization, photolysis, hydrolysis, oxidation, and biotransformation processes may also be specified.

9. Outputs:

The output includes summary tables of input data and predictions of chemical exposure, fate, and persistence. The exposure summary includes expected (long-term chronic, 96-hour acute, 21-day chronic) environmental concentrations due to a specified pattern of chemical loadings. The fate summary gives the distribution of chemicals in the system and the relative dominance of each transport and transformation process. Plots of longitudinal and vertical concentration profiles can be obtained.

10. References Available:

Burns, L.A. 1990. *Exposure analysis modeling system: User's guide for EXAMSII Version 2.94.* EPA/600/3-89/084. U.S. Environmental Protection Agency, Athens, GA.

Mulkey, L.A., R.B. Ambrose, and T.O. Barnwell. 1986. Aquatic fate and transport modeling techniques for predicting environmental exposure to organic pesticides and other toxicants: A comparative study. In *Urban runoff pollution.* Springer-Verlag, New York, NY.

Schnoor, J.L., C. Sato, D. McKetchnie, and D. Sahoo. 1987. *Processes, coefficients, and models for simulating toxic organics and heavy metals in surface waters.* EPA/600/3-87/015. U.S. Environmental Protection Agency, Athens, GA.

FLUX, PROFILE, and BATHTUB: Methods for the Description and Prediction of Eutrophication-Related Processes in Lakes and Reservoirs

1. Distributor:

Dr. Robert Kennedy
Ecosystem Processes and Effects Branch
Environmental Laboratory
U.S. Army Engineer Waterways Experiment Station
3909 Halls Ferry Road
Vicksburg, MS 39180
(601) 634-3659

Software and user documentation available through the Internet. For notices of availability, contact:
http://limnos.wes.army.mil
For additional information, contact:
kennedy@limnos.wes.army.mil

2. Type of Modeling/Application:

- Lakes and reservoirs
- Mass loading computation
- In-lake data description/assessment
- Nutrient and water balance computation
- Models of eutrophication-related responses
- Steady-state, empirical models
- Assessment and evaluation of selected management alternatives

3. Model Processes:

- Nutrient and water balances in a segmented hydraulic network
- Nutrient sedimentation
- Algal (chlorophyll) response to flushing, light, and nutrient concentration
- Hypolimnetic oxygen depletion

4. Method/Techniques:

FLUX - Provides an estimation of tributary mass discharges (loadings) from sample concentration data and continuous (e.g., daily) flow records. Five estimation methods are available and potential errors in estimates are quantified.

PROFILE - Facilitates analysis and reduction of in-lake water quality data. Algorithms are included for calculation of hypolimnetic oxygen depletion rates and estimation of area-weighted, surface-layer mean concentrations of nutrients and other eutrophication response variables.

BATHTUB - Applies a series of empirical eutrophication models to morphologically complex lakes and reservoirs. The program performs steady-state water and nutrient balance calculations in a spatially segmented hydraulic network that accounts for advective and diffusive transport, and nutrient sedimentation. Eutrophication-related water quality conditions (total phosphorus, total nitrogen, chlorophyll *a*, transparency, and hypolimnetic oxygen depletion) are predicted using empirical relationships derived from assessment of reservoir data (Walker, 1985, 1986).

5. Limitations:

Applications of BATHTUB are limited to steady-state evaluation of relationships between nutrient loading, transparency and hydrology, and eutrophication responses. Short-term responses and effects related to structural modifications or responses to variables other than nutrients cannot be explicitly evaluated.

6. Experience:

The programs and models have been applied to U.S. Army Corps of Engineer reservoirs (Kennedy, 1995), as well as a number of other lakes and reservoirs. BATHTUB was recently cited as an effective tool for lake and reservoir water quality assessment and management, particularly where data are limited (Ernst et al., 1994).

7. Updating Version and System Requirements:

The current version is being updated (see Section 2.2). PC-compatible.

8. Input Data Requirements:

BATHTUB requires information describing watershed characteristics, water and nutrient loads, lake or reservoir morphology, and lake or reservoir water quality.

9. Outputs:

FLUX - Graphic and tabular displays allow users to evaluate input data and calculate results.

PROFILE - Graphic and tabular displays allow users to evaluate and summarize lake or reservoir water quality data.

BATHTUB - Model outputs include tabular and/or graphic displays of segment hydraulics, water and nutrient balances, predictions of nutrient concentrations, transparency, chlorophyll *a* concentrations, and oxygen depletion. Statistics relating observed and predicted values are provided.

10. References Available:

Ernst, M.R., W. Frossard, and J.L. Mancini. 1994. Two eutrophication models make the grade. *Water Environment and Technology*, November, 15-16.

Kennedy, R.H., 1995. *Application of the BATHTUB Model to selected south eastern reservoirs.* Technical Report EL-95-14, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Walker, W.W., 1985. *Empirical methods for predicting eutrophication in impoundments; Report 3, Phase III: Model Refinements*. Technical Report E-81-9, U. S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Walker, W. W., 1986. *Empirical methods for predicting eutrophication in Impoundments; Report 4, Phase II: Applications Manual.* Technical Report E-81-9. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

PHOSMOD: Seasonal and Long-Term Trends of Total Phosphorus and Oxygen in Stratified Lakes

1. Distributor:

North American Lake Management Society (NALMS)
PO Box 5443
Madison, WI 53705
(608) 233-2836

2. Type of Modeling/Application:

- Modeling framework designed to assess the impact of phosphorus loading on stratified lakes
- Allows rapid generation and analysis of phosphorus loading scenarios

3. Model Processes:

- Lake stratification into two segments: the water layer and a surface sediment layer
- Computes total phosphorus and hypolimnetic oxygen concentrations, taking sediment-water interactions into account

4. Method/Techniques:

PHOSMOD uses a modeling framework described by Chapra and Canale (1991) for assessing the impact of phosphorus loading on stratified lakes. A total phosphorus budget for the water layer is developed with inputs from external loading and recycling from the sediments and considering losses due to flushing and settling. In the sediment layer, total phosphorus is gained by settling and lost by recycling and burial. The sediment to water recycling is dependent on the levels of sediment total phosphorus and hypolimnetic oxygen, with the concentration of the latter estimated with a semi-empirical model.

5. Limitations:

- Steady-state analyses.
- Developed to assess long-term trends only.

6. Experience:

Chapra and Canale (1991) present an application of the model to Shagawa Lake in Michigan and demonstrate how its predictions replicate in-lake changes not possible with simpler phosphorus budget models.

7. Updating Version and System Requirements:

Version 1.0 (1991). PC-compatible. Pre- and post-processor provided.

8. Input Data Requirements:

Lake stratification periods and morphometry; initial lake total phosphorus, sediment parameters, initial hypolimnetic DO concentrations; settling and burial rates for sediments; time series of flow and inflow phosphorus concentrations; print and calculation times. Observed data, if available, may also be input for display with outputs.

9. Outputs:

Tabular and graphical output of lake total phosphorus; percentage of total phosphorus in sediment; hypolimnetic DO concentrations; days of anoxia at specified print intervals.

10. References Available:

Chapra, S., and R.P. Canale. 1991. Long-term phenomenological model of phosphorus and oxygen for stratified lakes. *Water Research* 25(6):707-715.

Chapra, S. 1991. *PHOSMOD 1.0 - Software to model seasonal and long-term trends of total phosphorus and oxygen in stratified lakes.* CADWES Working Paper No. 14, The University of Colorado, Boulder, CO.

PLUMES: Dilution Models for Effluent Discharges

1. Distributor:

Model Distribution Coordinator
Center for Exposure Assessment
Modeling (CEAM)
USEPA
960 College Station Road
Athens, GA 30605-2700
(706) 355-8400
Models are available for FTP from:
ftp://ftp.epa.gov/epa_ceam/wwwhtml/
ceamhome.htm

2. Type of Modeling/Application:

- May be applied to most deep waterbodies.
- Near-field hydrodynamic mixing processes
- Point source buoyant or submerged discharges
- Single or multiple inputs

3. Model Processes:

- Consists of two initial dilution models (RSB and UM) with two far-field algorithms automatically initiated beyond the initial dilution zone.
- Incorporates the flow classification scheme of the CORMIX modeling system and provides recommendations for model usage under a range of mixing conditions.

4. Method/Techniques:

PLUMES incorporates two relatively sophisticated initial dilution models (RSB and UM) and two relatively simple far-field algorithms.

RSB is based on experimental studies on multiport diffusers in stratified currents. UM is the latest in a series of models first developed for atmospheric and freshwater applications and later for marine applications. Outstanding UM features are the Lagrangian formulation and the projected area entrainment (PAE) hypothesis, which is a statement of forced entrainment—the rate at which mass is incorporated into the plume in the presence of current. The Lagrangian formulation offers comparative simplicity that is useful in developing PAEs.

The far-field algorithms are relatively simple implementations of dispersion equations applied to nearshore coastal waters, and confined channels.

5. Limitations:

- RSB is a an empirical model developed from experimental studies under stable ambient stratification, and it may have limited application in situations where ambient layers are unstratified or unstable.
- The PAE hypothesis, which was developed for plumes discharged to open, unbounded environments, free from interference, is assumed to be valid in UM.
- The farfield algorithms in PLUMES are relatively simplistic compared to the initial dilution models.

6. Experience:

The PLUMES modeling system is recommended for use in designing outfall diffusers.

7. Updating Version and System Requirements:

Version 3.0 (1994). PC-compatible.

8. Input Data Requirements:

Port geometry, spacing, and total flow. Plume diameter and depth, effluent salinity and temperature. Ambient conditions in receiving water and far-field distance.

9. Outputs:

CORMIX flow classification, pollutant concentration and dilution ratios at various points in the plume.

10. References Available:

Baumgartner, D.J., W.E. Frick, and P.J.W. Roberts. 1994. *Dilution models for effluent discharges*. 3rd ed. EPA/600/R-93/139. U.S. Environmental Protection Agency, Newport, OR.

QUAL2E: The Enhanced Stream Water Quality Model

1. Distributor:

Model Distribution Coordinator
Center for Exposure Assessment Modeling (CEAM)
USEPA
960 College Station Road
Athens, GA 30605-2700
(706) 355-8400
Models are available for FTP from:
ftp://ftp.epa.gov/epa_ceam/wwwhtml/software.htm

Windows QUAL2E is also available. Contact
Gerald D. LaVeck
Environmental Protection Agency
Office of Science and Technology (4305)
401 M Street, SW
Washington, DC 20460
(202) 260-7771

or go to http://www.epa.gov/ost/tools

Documentation for QUAL2E is also available at http://www.epa.gov/ord/webpubs/qual2e/.

2. Type of Modeling/Application:

- Water quality/Eutrophication
- Far-field
- Stream/River
- 1-D, branching
- Steady flow
- Steady-state/Quasidynamic (diurnal variations in meteorological inputs)
- Advective/Dispersive transport
- Finite difference

3. Model Processes:

- Temperature
- Salinity
- BOD-DO
- Nitrogen cycle
- Phosphorus cycle
- Chlorophyll *a* (is modeled as the indicator of planktonic algae biomass; benthic algae is not considered)
- Conservative constituent
- Nonconservative constituent
- First-order kinetics of constituents
- Uncertainty analysis

4. Method/Techniques:

The QUAL2E model permits simulation of several water quality constituents in a branching stream system using an implicit backward-difference, finite-difference solution to the one-dimensional advective-dispersive equation. The stream is conceptually represented as a system of reaches of variable length, each of which is subdivided into computational elements that have the same length in all reaches. A mass and heat balance is applied for every element. Mass may be gained or lost from elements by transport processes, external sources and sinks, or internal sources and sinks. The UNCAS component allows quick implementation of uncertainty analysis using sensitivity analysis, first-order error analysis, or Monte Carlo simulation.

5. Limitations:

- Considers only steady flow.
- Only time-varying forcing functions are the climatologic variables that primarily affect diurnal temperature and dissolved oxygen.

6. Experience:

The QUAL series of models has a two-decade history in water quality management and wasteload allocation studies. Paschal and Mueller (1991) used QUAL2E to evaluate the effects of wastewater effluent on the South Platte River from Chatfield reservoir through Denver, Colorado. Cubilo et al. (1992) applied QUAL2E to the major rivers of the Comunidad de Madrid in Spain. Little and Williams (1992) describe a nonlinear regression programming model for calibrating QUAL2E. Johnson and Mercer (1994) report a QUAL2E application to the Chicago waterway and Upper Illinois River waterway to predict DO and other constituents in the DO cycle in response to various water pollution controls.

7. Updating Version and System Requirements:

Version 3.21 (1995). PC-compatible. A Windows-based pre- and post-processor is available from EPA's Office of Science and Technology.

8. Input Data Requirements:

The stream is represented by a network of headwaters, reaches, and junctions. Twenty-six physical, chemical, and biological properties have to be specified for a reach.

9. Outputs:

Dissolved oxygen, biochemical oxygen demand, temperature, chlorophyll *a*, ammonia-N, nitrite-N, nitrate-N, organic N, organic P, dissolved P, coliforms, arbitrary nonconservative constituents, three conservative constituents.

10. References Available:

Brown, L.C., and T.O. Barnwell. 1987. *The enhanced stream water quality model QUAL2E and QUAL2E-UNCAS: Documentation and user manual.* EPA-600/3-87/007. U.S. Environmental Protection Agency, Athens, GA.

Cubilo, F., B. Rodriguez, and T.O. Barnwell, Jr. 1992. A system for control of river water quality for the community of Madrid using QUAL2E. *Water Science and Technology* 26(7/8):1867-1873.

Johnson, C.R., and G. Mercer. 1994. Modeling the water quality processes of the Chicago waterway. In *Proceedings of the National Symposium on Water Quality,* American Water Resources Association, Chicago, IL, November 6-10, 1994, p. 315.

Little, K.W., and R.E. Williams. 1992. Least-squares calibration of QUAL2E. *Water Environment Research* 64(2):179-185.

Paschal, J. E., Jr., and D. K. Mueller. 1991. *Simulation of water quality and the effects of wastewater effluent on the South Platte River from Chatfield Reservoir through Denver, Colorado.* Water-Resources Investigations Report 91-4016. U.S. Geological Survey, Denver, CO.

RIVMOD-H: River Hydrodynamics Model

1. Distributor:

RIVMOD-H can be requested with the WASP5 modeling package from:

Model Distribution Coordinator
Center for Exposure Assessment Modeling (CEAM)
USEPA
960 College Station Road
Athens, GA 30605-2700
(706) 355-8400
Ftp from: Ftp://ftp.epa.gov/epa_ceam/wwwhtml/ceamhome.htm

2. Type of Modeling/Application:

- Applicable to rivers, streams, tidal estuaries, reservoirs, and other waterbodies where the one-dimensional assumption is appropriate
- Considers time-varying lateral inflows

3. Model Processes:

RIVMOD-H solves the one-dimensional equations of unsteady flow using a fully implicit finite difference method. The model can be used for flow routing only or can be linked with a water quality modeling package.

4. Method/Techniques:

RIVMOD-H solves the governing flow equations using a numerically efficient fully implicit scheme that overcomes the restriction of the Courant gravity wave criterion, permitting the use of longer time steps (in comparison with explicit schemes). The numerical solution scheme is very flexible and allows the specification of a weighting factor for fully explicit, fully implicit, or any other combination of implicit-explicit solutions. The model has the capability of handling flow or head as boundary conditions. The specification of head as a boundary condition allows the use of the model where an open boundary is required (e.g., an estuary or a river flowing into a lake). The model has been soft-linked to the WASP5 and SWMM models as part of the LWWM modeling system (Dames and Moore, 1994).

5. Limitations:

- May be inappropriate in situations where large lateral or vertical gradients exist.
- Neglects the effect of eddy diffusivity.
- Assumes hydrostatic pressure distribution is valid at every point in the channel, and that the water surface slope is small.

6. Experience:

The model has been applied on several rivers in the United States and abroad (Hosseinipour et al., 1994). Warwick and Heim (1995) provide a comparison of the performance of DYNHYD and RIVMOD-H.

7. Updating Version and System Requirements:

Released with the LWWM modeling system (Dames and Moore, 1994). PC-compatible.

8. Input Data Requirements:

Data requirements for RIVMOD-H include channel morphometry, bed elevations, and initial and boundary conditions. If cross-sectional topography data are available, separate software can be used to generate exponential rating functions for cross-sectional area and wetted perimeter as a function of depth. The model then uses these relationships to automatically calculate the area and wetted perimeter as the water depth changes. This feature allows the model to use natural cross sections, and therefore simulation results should be closer to the natural behavior of the stream.

9. Outputs:

Time-variable water surface elevations or stages and discharges for unsteady flows at specified cross-sections and time intervals.

10. References Available:

Dames and Moore. 1994. *User's Manual - Linked Watershed/Waterbody Model.* Prepared for the Southwest Florida Water Management District. Dames and Moore, Tampa, FL.

Hosseinipour, E.Z., R.B. Ambrose, Jr., J.L. Martin, and T. Wu. 1994. RIVMOD-H - A One-Dimensional hydrodynamic model - Model Theory and User's Manual. In *User's manual - Linked Watershed/Waterbody Model.* Dames and Moore, Tampa, FL.

Warwick, J.J., and K.J. Heim. 1995. Hydrodynamic modeling of the Carson River and Lahontan Reservoir, Nevada. *Water Resources Bulletin* 31(1):67-77.

SMPTOX4: Simplified Method Program - Variable-Complexity Stream Toxics Model

1. Distributor:

Model Distribution Coordinator
Center for Exposure Assessment
Modeling (CEAM)
USEPA
960 College Station Road
Athens, GA 30605-2700
(706) 355-8400
Models are available for FTP from:
ftp://ftp.epa.gov/epa_ceam/wwwhtml/
software.htm

2. Type of Modeling/Application:

- Streams/Rivers in one dimension
- Steady flow
- Steady-state predictions
- Advective and dispersive transport
- Considers benthic exchange
- Capability to simultaneously model multiple chemicals

3. Model Processes:

- First-order decay
- Equilibrium sorption
- Sediment processes may be input

4. Method/Techniques:

SMPTOX4 is a steady-state, one-dimensional analytical model for predicting suspended solids, and dissolved and particulate toxicant concentrations in the water column and streambed resulting from point source discharges into streams and rivers, based on an EPA-recommended technique (USEPA, 1980). Three levels of complexity are available within the model. At the simplest level, only total toxic pollutants can be predicted. The next level can be used to predict toxic water column concentrations but interactions with bed sediments are not considered. The third level allows prediction of pollutant concentrations in dissolved and particulate phases for the water column and bed sediments, as well as the total suspended solids concentrations. Operating within a Windows environment, SMPTOX4 allows quick data input and easy access to graphical output, sensitivity analysis, and uncertainty analysis. SMPTOX4 also contains a database of chemical properties for many chemicals of concern.

5. Limitations:

- Steady-state predictions only.
- Nonpoint source loadings cannot be simulated.
- Does not consider daughter products or process.
- Process kinetics are not simulated.

6. Experience:

The users manual presents an example application using data from investigations on the Flint River, Michigan, in EPA's guidance manual for stream toxics modeling (USEPA, 1984).

7. Updating Version and System Requirements:

Version 2.01(1993). PC-compatible.

8. Input Data Requirements:

Flow, total pollutant and suspended solids concentrations, geomorphic parameters, physical/chemical coefficients and rates. Observed pollutant concentrations may be input for use during model calibration.

9. Outputs:

Model calculations for total, dissolved, and particulate concentrations for the toxicant in the water column and bed sediments, and suspended solids concentration in the water column at incremental river miles throughout the length of the stream.

10. References Available:

Limno-Tech, Inc. 1993. *Simplified method program - Variable complexity stream toxics model (SMPTOX3) Version 2.01. Users manual.* Limno-Tech, Inc., Ann Arbor, MI.

USEPA. 1980. *Simplified analytical method for determining NPDES effluent limitations for POTWs discharging into low-flow streams*. U.S. Environmental Protection Agency, Office of Water Regulations and Standards, Monitoring and Data Support Division, Washington, DC.

USEPA. 1984. *Technical guidance manual for performing waste load allocations - Book II, Streams and rivers, Chapter 3, Toxic substances*. U.S. Environmental Protection Agency, Office of Water Regulations and Standards, Monitoring and Data Support Division, Washington, DC.

TOXMOD: Long-Term Trends of Toxic Organics in Lakes

1. Distributor:

North American Lake Management Society (NALMS)
P.O. Box 5443
Madison, WI 53705
(608) 233-2836

2. Type of Modeling/Application:

- Modeling framework designed to assess the impact of toxic organic compounds on lakes and impoundments
- Allows rapid generation and analysis of scenarios

3. Model Processes:

- Lake idealized as a well-mixed reactor (water layer) underlain by a well-mixed sediment layer
- Computes sediment and water concentration of toxicant

4. Method/Techniques:

TOXMOD is based on an extension of a modeling framework presented by Chapra (1991) to assess the impact of toxic organic compounds on lakes and impoundments. A steady-state mass balance is developed for solids and toxics. Toxics are partitioned into dissolved and particulate forms, with the dissolved form for both water and sediment layers further subdivided into a component associated with dissolved organic carbon. Particulates in the water layer are subdivided into abiotic and biotic suspended solids.

Burial and resuspension are considered for both dissolved and particulate forms while diffusion acts selectively on the dissolved fraction.

5. Limitations:

- Steady-state analyses.
- Developed to assess long-term trends only.

6. Experience:

Chapra (1991) has used the modeling framework on which TOXMOD is based to develop a procedure for identifying priority pollutants that exhibit the weakest assimilative capacity for a range of lakes.

7. Updating Version and System Requirements:

Version 1.0 (1991). PC-compatible. Pre- and post-processor provided.

8. Input Data Requirements:

Lake depth and surface area; sediment thickness and area; solids mass balance data, including settling and burial rates for sediments; dissolved organic carbon concentrations; sorption and volatilization coefficients and decay rates of toxicant; initial toxicant concentration; time series of flow and inflow toxicant concentrations; print and calculation intervals. Observed data, if available, can also be input for display with outputs.

9. Outputs:

Tabular and graphical output of sediment and water toxicant concentration at specified print intervals.

10. References Available:

Chapra, S. 1991. Toxicant-loading concept for organic contaminants in Lakes. *Journal of Environmental Engineering* 117(5):656-677.

Chapra, S. 1991. *TOXMOD 1.0 - Software to model long-term trends of toxic organics in lakes*. CADWES Working Paper No. 13, The University of Colorado, Boulder, CO.

TPM: Tidal Prism Model

1. Distributor:

Albert Y. Kuo
Virginia Institute of Marine Science
School of Marine Science
The College of William and Mary
Gloucester Point, VA 23062
(804) 642-7212

2. Type of Modeling/Application:

- Primarily applicable to small coastal basins and tidal creeks
- May be applied to marinas where tidal forces are predominant with oscillating flow (e.g., an estuary or a tidal river)
- Steady-state model capable of simulating up to 23 water quality variables

3. Model Processes:

- Simulates physical transport processes in terms of the concept of tidal flushing
- Relatively detailed kinetic model that allows a more complete description of the eutrophication process
- Includes a sediment process model that considers the depositional flux of particulate organic matter, its diagenesis, and the resulting sediment flux

4. Method/Techniques:

TPM predicts the longitudinal distribution of conservative and nonconservative substances at slack-before-ebb (high slackwater). The model is best applied to an elongated embayment or tidal creek, where the creek is branched and/or freshwater discharge is negligibly small. The basic assumptions in the model are that the tide rises and falls simultaneously throughout the waterbody and that the system is in hydrodynamic equilibrium. Kinetic processes included in TPM are based on the formulations used in CE-QUAL-ICM (Cerco and Cole, 1994). Twenty-three state variables are considered including total active metal, fecal coliform bacteria, and temperature. The sediment process model in TPM has 16 water-quality-related model state variables and fluxes. Benthic sediments are represented as two layers in the sediment model. The lower layer is permanently anoxic, while the upper layer may be oxic or anoxic depending on dissolved oxygen concentration in the overlying water.

5. Limitations:

- The waterbody being simulated must be in hydrodynamic equilibrium.
- Only applicable to waterbodies where tidal forces are predominant with oscillating flow; the model therefore is not applicable to marinas located on a sound or an open sea.

6. Experience:

The model has been applied to a number of tidal creeks and coastal embayments in Virginia (Kuo and Neilson, 1988).

7. Updating Version and System Requirements:

Latest version released in September 1994. PC-compatible.

8. Input Data Requirements:

Two basic types of input data are required—geometric and physical. Geometric data define the system being simulated, including the returning ratio, initial concentration, and boundary conditions. Physical data include water temperature, reaction rates, point and nonpoint sources, and initial and boundary conditions for water quality parameters modeled.

9. Outputs:

Temperature, salinity, inorganic suspended solids, diatoms, blue-green algae and other phytoplankton, dissolved, labile, and refractory particulate organic carbon, organic nitrogen, and organic phosphorus ammonium, nitrite and nitrate, total phosphate, dissolved oxygen, chemical oxygen demand, dissolved silica, particulate biogenic silica, total active metal, and fecal coliform bacteria.

10. References available:

Cerco, C.F., and T. Cole. 1993. Three-dimensional eutrophication model of the Chesapeake Bay. *Journal of Environmental Engineering* 119(6):1006-1025.

Kuo, A.Y., and B.J. Neilson. 1988. A modified tidal prism model for water quality in small coastal embayments. *Water Science Technology* 20(6/7):133-142.

Kuo, A.Y., and K. Park. 1994. *A PC-based tidal Prism water quality model for small coastal basins and tidal creeks.* SRAMSOE No. 324. The College of William and Mary, Gloucester Point, VA.

WASP5: Water Quality Analysis Simulation Program

1. Distributor:

Model Distribution Coordinator
Center for Exposure Assessment
Modeling (CEAM)
USEPA
960 College Station Road
Athens, GA 30605-2700
(706) 355-8400
Models are available for FTP from:
ftp://ftp.epa.gov/epa_ceam/wwwhtml/
ceamhome.htm

2. Type of Modeling/Application:

- May be applied to most waterbodies in one, two, or three dimensions
- Can be linked with simulated hydrodynamics
- Predicts time-varying concentrations of water quality constituents
- Advective and dispersive transport
- Considers benthic exchange
- Finite difference

3. Model Processes:

- Temperature
- Salinity
- Bacteria
- DO-BOD
- Nitrogen cycle
- Phosphorus cycle
- Phytoplankton
- First-order decay, daughter products
- Process kinetics
- Equilibrium sorption
- Net resuspension/deposition

4. Method/Techniques:

WASP5 is a general-purpose modeling system for assessing the fate and transport of conventional and toxic pollutants in surface waterbodies.The model simulates time-varying processes of advection and dispersion, considering point and diffuse mass loading, and boundary exchange.

WASP5 includes two submodels for water quality/eutrophication and toxics, referred to as EUTRO5 and TOXI5, respectively. In EUTRO5, the transport and transformation of up to eight state variables in the water column and sediment bed may be simulated. In TOXI5, the transport and transformation of one to three chemicals and one to three types of particulate material can be simulated.

5. Limitations:

- There is a potential for instability or numerical dispersion in the user-specified computational network.
- If chemical concentrations in the waterbody are much higher than tra level, the assumptions of linear partitioning and transformation in TOXI5 begin to break down.
- Zooplankton dynamics are not simulated in EUTRO5 although their effect may be described by user-specified forcing functions that vary in space and time.
- Intermediate-level method for computation of sediment oxygen demand and benthic nutrient fluxes.

6. Experience:

Used in a wide range of regulatory and water quality management applications for rivers, lakes, and estuaries. Lang and Fontaine (1990) describe an application to predict the transport and fate of organic contaminants in Lake St. Clair, Michigan. Cheng et al. (1994) describe the development and application of a GIS-based modeling framework using a watershed loading model and WASP. Lu et al. (1994) used the model to simulate the transport and fate of DO, BOD, and organic nitrogen in untreated wastewater discharges in Weeks Bay, Alabama. Lung and Larson

(1995) used EUTRO5 to evaluate phosphorus loading reduction scenarios for the Upper Mississippi River and Lake Pepin. Cockrum and Warwick (1995) used WASP to characterize the impact of agricultural activities on instream water quality in a periphyton-dominated stream. Tetra Tech (1995) describes a full three-dimensional application of EUTRO5 in conjunction with the EFDC hydrodynamic model to assess the effectiveness of options for total nitrogen removal from a wastewater treatment plant.

7. Updating Version and System Requirements:

Version 5.10 (1993). PC-compatible. Pre- and post-processors are available from the distributor.

8. Input Data Requirements:

The body of water to be simulated must be divided into a series of completely mixed computational segments. Loads, boundary concentrations, and initial concentrations must be specified for each state variable. Forcing functions must be specified for time and spatially variable parameters.

In TOXI5, up to 12 spatially variable environmental variables, such as pH and light extinction, may be specified as needed. In addition, up to 17 time-variable functions may be used to study diurnal or seasonal effects on pollutant behavior. In EUTRO5, up to 16 spatially variable environmental parameters, 60 rate constants, and 14 time-variable functions can be specified.

9. Outputs:

TOXI5 provides time-variable chemical concentrations for every segment at the specified output time interval. Chemical concentrations are reported for the dissolved and sorbed phases, and as neutral and ionic concentrations.

EUTRO5 reports a set of state variable concentrations, forcing functions, and process rates for every segment at the specified output time interval. Variable concentrations include dissolved oxygen, carbonaceous biochemical oxygen demand (BOD), ultimate BOD, phytoplankton carbon and chlorophyll *a*, total nitrogen, ammonia, nitrate, organic nitrogen, total inorganic nitrogen, organic phosphorus, and inorganic phosphorus.

10. References Available:

Ambrose, R.B., T.A. Wool, and J.L. Martin. 1993. *The water quality analysis simulation program, WASP5 version 5.10. Part A: Model documentation.* U.S. Environmental Protection Agency, Office of Research and Development, Environmental Research Laboratory, Athens, GA.

Cheng, C., J.F. Atkinson, and J.V. DePinto. 1994. A coupled GIS-water quality modeling study. In *Proceedings of the 1994 Hydraulic Engineering Conference*, American Society of Civil Engineers, Buffalo, NY, 1994, pp. 247-251.

Cockrum, D.K., and J.J. Warwick. 1994. Assessing the impact of agricultural activities on water quality in a periphyton-dominated stream using the Water Quality Analysis Program (WASP). In *Proceedings of the Symposium on the Effects of Human-Induced Changes on Hydrologic Systems*, American Water Resources Association, Jackson Hole, WY, June 26-29, 1994, p. 1157.

Lang, G.A., and T.D. Fontaine. 1990. Modeling the fate and transport of organic contaminants in Lake St. Clair. *Journal of Great Lakes Research* 16(2):216-232

Lu, Z., G.C. April, D.C. Raney, and W.W. Schroeder. 1994. DO, BOD, and organic nitrogen transport in Weeks Bay, Alabama. In *Proceedings of the National Symposium on Water Quality,* American Water Resources Association, Chicago, IL, November 6-10, 1994, pp. 191-200.

Lung, W., and C.E. Larson. 1995. Water quality modeling of the upper Mississippi River and Lake Pepin. *Journal of Environmental Engineering* 121(10):691-699.

Tetra Tech. 1995. *Hydrodynamic and water quality mathematical modeling study of Norwalk Harbor, Connecticut: Final report.* Tetra Tech, Inc., Fairfax, VA.

Appendix C:

Ecological Assessment Techniques and Models—Fact Sheets

FGETS: Food and Gill Exchange of Toxic Substances

1. Distributor:

Model Distribution Coordinator
Center for Exposure Assessment Modeling (CEAM)
USEPA
960 College Station Road
Athens, GA 30605-2700
(706) 355-8400

2. Type of Modeling/Technique:

Fish bioaccumulation simulation modeling for laboratory conditions (constant flow or static exposures) or for field assessments (for multiple fish species that are exposed to constant or time-varying water concentrations and that feed on either single or multiple food resources).

3. Methods:

FGETS considers both the biological attributes of the fish and the physicochemical properties of the chemical that determine diffusive exchange across gill membranes and intestinal mucosa. The model is based on a set of diffusion and forced convection partial differential equations, coupled to a process-based fish growth formulation. Chemical exchange rates are estimated using fundamental principles of passive diffusion and thermodynamics rather than phenomenological toxicokinetic data.

4. Applications:

FGETS provides regulators and practitioners with an objective, process-based assessment of residue-based, toxicological responses and dietary exposures for fish assemblages.

5. Experience:

Used extensively for ecotoxicology studies.

6. Updating Version and System Requirements:

Version 3.0.18 was released in September 1994. FGETS operates on IBM PCs and compatibles in DOS.

7. Input Data Requirements:

Morphological, physiological, and trophic parameters that describe the gill morphometry, feeding and metabolic demands, and body composition for the species in question; and relevant physicochemical parameters that describe partitioning to the fish's lipid and structural organic fractions for a specific chemical.

8. Outputs:

- Temporal dynamics of a fish's whole-body concentration (ìg chemical/(g live weight fish)) of nonionic, nonmetabolized organic chemicals that are bioaccumulated from water and food.
- Calculation of the time to reach the chemical's lethal activity by assuming that the chemical elicits its pharmacological response through a narcotic mode of action.

9. References Available:

Barber, M.C., L.A. Suarez, and R.R. Lassiter. 1988. Modeling bioconcentration of nonpolar organic pollutants by fish. *Environmental Toxicology and Chemistry* 7: 545-558.

Barber, M.C., L.A. Suarez, and R.R. Lassiter. 1991. Modeling bioaccumulation organic pollutants in fish with an application to PCBs in the Great Lakes salmonids. *Canadian Journal of Fisheries and Aquatic Sciences* 48:318-337.

HEP/HSI: Habitat Evaluation Procedures/ Habitat Suitability Indices

1. Distributor:

U.S. Fish and Wildlife Service
National Ecology Research Center
2627 Redwing Road
Fort Collins, CO 80526
(303) 226-9421
BBS: (303) 226-9365 (N/8/1)
Internet: http://www.fws.gov

2. Type of Modeling/Application:

A species-based evaluation method that determines the quality and quantity of available habitat for selected aquatic and terrestrial wildlife species, and measures the impact of proposed or anticipated land or water use changes on that habitat.

3. Model Components:

Three software programs have been developed to assist with the HEP:

- HEP Accounting Program computes the values needed to use the HEP procedures.
- Habitat Management Evaluation Method System (HMEM) software allows a user to investigate and compare the cost-effectiveness of different management alternatives to achieve desired HUs for a selected species.
- HSI modeling system software is used to compute an HSI value for selected species from field measurements of habitat variables.

4. Method/Techniques:

HEP analysis begins with three basic steps: (1) defining the study area, (2) Delineating cover types, and (3) selecting evaluation species.

Evaluation species (i.e., indicator species) are used in HEP to quantify habitat units (HUs); a typical HEP study incorporates four to six species. The analysis is structured around the calculation of HUs for each evaluation species in the study area. The number of HUs is defined as the product of the Habitat Suitability Index (HSI, a measure of habitat quality) and the total area of available habitat (habitat quantity).

HUs are then used to make comparisons of (1) the relative value of different areas at the same point in time and/or (2) the relative value of the same area at future points in time.

5. Applications:

- Quantitative assessment of habitat conditions for wildlife species Comparison of the impacts of project alternatives on wildlife resources

6. Experience:

Used extensively by the U.S. Fish and Wildlife Service, the U.S. Army Corps of Engineers, and the U.S. Bureau of Reclamation.

7. System Requirements:

All three software programs operate on IBM PCs and compatibles in DOS.

8. Input Data Requirements:

Data to be collected include delineation of cover types (e.g., deciduous forest, coniferous forest, grassland, residential woodland) within the project area; size (acreage) of existing habitat for each evaluation species; selection of evaluation species; Habitat Suitability Index (HSI) reflecting current habitat conditions for each evaluation species; future habitat conditions for each evaluation species.

HSI data collection includes
(1) species-specific habitat use information such as general information (e.g., geographic distribution); age, growth, and food requirements; water quality, depth, and flow; species-specific habitat requirements; reproductive information; (2) species-specific life history information for each life stage,

C.4

(i.e., spawning/embryo, fry, juvenile, and adult); (3) suitability indices for each habitat variable.

9. Outputs:

- A quantitative assessment of the quality and quantity of available habitat for selected wildlife species in terms of proposed or anticipated land use changes
- The cost-effectiveness of different management alternatives to achieve desired HUs for a selected species

10. References Available:

USFWS. 1980. *Habitat Evaluation Procedures (HEP)*. ESM 102. U.S. Department of the Interior, U.S. Fish and Wildlife Service, Division of Ecological Services, Washington, DC.

USFWS. 1981. *Standards for the Development of Habitat Suitability Index Models.* ESM 103. U.S. Department of the Interior, U.S. Fish and Wildlife Service, Division of Ecological Services, Washington, DC.

Wakely, J.S., and L.J. O'Neil. 1988. *Techniques to increase efficiency and reduce effort in applications of the Habitat Evaluation Procedures (HEP).* Technical Report EL-88-13. U.S. Army Engineers Waterways Experiment Station, Vicksburg, MS.

HES: Habitat Evaluation System

1. Distributor:

U.S. Army Engineer Waterways
Experiment Station
3909 Halls Ferry Road
Vicksburg, MS 39180
(601) 634-5276

2. Type of Modeling/Application:

A community-based evaluation technique used to assess the impacts of development projects for two aquatic habitats (streams and lakes) and five terrestrial habitat evaluations (wooded swamps, upland forests, bottomland hardwood forests, open lands, and terrestrial wildlife value of aquatic habitats).

3. Method/Techniques:

HES assumes that presence, abundance, and diversity of animal populations in a habitat are determined by biotic and abiotic factors that can be readily quantified. HES determines the quality of a particular habitat type through the use of functional curves that relate habitat quality and carrying capacity to these factors. HES uses general habitat characteristics that indicate quality for aquatic and terrestrial wildlife communities as a whole.

Six steps are involved in an HES:
(1) obtaining habitat type and land use acreage; (2) deriving Habitat Quality Index (HQI) scores; (3) deriving Habitat Unit Values (HUVs); (4) projecting HUVs for future with- and without-project conditions; (5) using HUVs to assess impacts of project alternatives; (6) determining mitigation requirements, if any.

For complex projects with several habitat types, computer software is available for making HES computations for steps 1-5. Inputs to this software are the data for land use or habitat size and HQI scores.

4. Applications:

- Evaluating the effects of projects on the quantity and quality of wildlife habitats in the Lower Mississippi Valley Region of the United States.
- Aiding in the selection between project alternatives.

5. Experience:

HES has been used in major ecosystems in the Lower Mississippi Valley Region. With revisions to curves, weights, and other variables, it can be applied to many other areas of the United States.

6. Updating Version and System Requirements:

N/A

7. Input Data Requirements:

- Baseline data on habitat types and land uses in the project area
- Size (acreage) of each habitat type and land use for existing and future conditions
- Measurements of key variables (e.g., percent understory, number of large trees, number of mast trees, species associations, number of snags) identified for each habitat and land use type for existing conditions
- Projected measurements of same key variables for future conditions

9. Outputs:

A quantitative assessment of the quality and quantity of available habitat for entire wildlife communities in terms of proposed or anticipated land use changes

C.6

10. References Available:

U.S. Army Corps of Engineers. 1976. *A tentative Habitat Evaluation System (HES) for water resources planning*. Lower Mississippi Valley Division, Vicksburg, MS.

U.S. Army Corps of Engineers. 1980. *A Habitat Evaluation System for water resources planning*. Lower Mississippi Valley Division, Vicksburg, MS.

HGM: Hydrogeomorphic Assessment

1. Contact:

Daniel Smith
U.S. Army Engineer Waterways
Experiment Station
3909 Halls Ferry Road
Vicksburg, MS 39180
(601) 634-2718

2. Type of Modeling/Application:

HGM (currently under development) is a hydrogeomorphic classification and assessment methodology for determining the integrity of physical, chemical, and biological functions of wetlands as they compare to reference conditions.

3. Method/Techniques:

HGM focuses on identifying wetland groups that exhibit a relatively narrow range of variation in the properties that fundamentally influence how wetlands function. The HGM method relies on the use of reference wetlands, which represent a collection of sites of a specific wetland class that can be used for developing the upper and lower boundaries of functioning within the class. The steps in the assessment approach are (1) classify wetlands according to HGM properties, (2) make connections between the properties of each wetland class and the ecological functions that they perform based on logic and research results, (3) develop functional profiles for each wetland class, (4) choose reference wetlands that represent the range of both natural and human-imposed stresses and disturbances, and (5) design the assessment method using indicators calibrated to reference wetlands.

4. Applications:

Once completed, HGM will be able to assess the degree to which a wetland performs expected physical, chemical, and biological functions.

5. Experience:

Once completed, HGM will be used by the U.S. Army Corps of Engineers and other agencies to evaluate the quality of wetlands within a context of reference conditions.

6. Updating Version and System Requirements:

N/A

7. Input Data Requirements:

- Baseline data to develop a reference set of wetlands representing the range of conditions that exist in a wetland ecosystem and its landscape in a reference domain
- Baseline data on the condition of assessment wetland variables (e.g., surface and subsurface water storage, nutrient cycling, retention of particulates, organic matter export, spatial structure of habitat, distribution and abundance of invertebrates and vertebrates, plant community characteristics, etc.) measured directly or indirectly using indicators to develop a relationship between variable conditions in the assessment wetland and functional capacity of the reference set

8. Outputs:

A quantitative assessment of the functioning of wetlands that uses the concepts of hydrogeomorphic classification, functional capacity, reference domain, and reference wetlands.

9. References Available:

Brinson, M.M. 1993. *A hydrogeomorphic classification for wetlands.* Wetlands Research Program Technical Report WRP-DE-4. U.S. Army Engineers Waterways Experiment Station, Vicksburg, MS.

C 8

ICI and IWB: Invertebrate Community Index and Index of Well-Being

1. Distributor:

N/A - see references

2. Type of Modeling/Technique:

Two biological indices that are usually used in tandem with the RBP V (IBI) (see fact sheet, p. C.17) to provide a measure of the integrity of aquatic invertebrate communities (ICI) and fish communities (IWB) based on field-collected data.

3. Method/Techniques:

The ICI is a single value calculated by summing 10 structural and compositional community metrics describing invertebrate communities. Each metric is attributed a score of 0, 2, 4, or 6 points based on watershed area and comparisons with scores developed from ecoregional reference sites. Each metric also incorporates into the scoring scheme functionally based differences between macroinvertebrates over a range of stream conditions. The sum of all 10 metric provides an overall ranking for the waterbody.

IWB incorporates measures of fish species abundance and diversity estimates in the computational formula as follows:

$$IWB = 0.5\ lnN + 0.5\ lnB + H'_N + H'_B$$

where:
N = number of individuals caught per kilometer
B = biomass of individuals caught per kilometer
H' = Shannon-Weaver diversity index

$$H' = -\sum_{i=1}^{S} \frac{n_i}{N} \log_e \frac{n_i}{N}$$

where:
N = number of individuals in the sample
= biomass of sample
n_i = number of individuals of species i in the sample
= biomass of species i in the sample

4. Applications:

By assessing the biological condition of a waterbody, ICI and IWB can be used to determine whether a waterbody is impaired, to provide information for ranking sites and prioritization for further assessment, and to establish a basis for trend monitoring.

5. Experience:

The ICI and IWB have been used extensively in the state of Ohio (where they were developed) for assigning causes of and sources to aquatic life use impairments in Ohio streams and rivers. With changes to collection methodologies, metric selection, and reference conditions to account for geographic setting and ecoregions other than those in Ohio, the ICI and IWB approaches can be used successfully to assess the condition of macroinvertebrate communities throughout the country.

6. Updating Version and System Requirements:

N/A

7. Input Data Requirements:

Data necessary for development of the ICI include total number of taxa, number of mayfly taxa, number of caddisfly taxa, number of dipteran taxa, percent mayfly composition, percent caddisfly composition, percent tribe tanytarsini midge composition, percent other dipteran and noninsect composition, percent tolerant organisms, and number of qualitative EPT taxa. Data for reference conditions are also necessary.

Data to be collected for the IWB include number of individuals/kilometer; biomass of individuals/kilometer; Shannon-Weaver diversity index (number of individuals in sample and number of individuals of species i in the sample). Data describing reference conditions are also necessary.

8. Outputs:

- ICI provides a quantitative measure of overall macroinvertebrate community condition.
- IWB provides a quantitative measure of the quality of a fish assemblage.

9. References Available:

DeShon, J.E. 1995. Development and application of the Invertebrate Community Index, In *Biological assessment and criteria: Tools for water resource planning and decision making,* ed. W.S. Davis and T.P. Simon, pp. 217-229. Lewis Publishers, Boca Raton, FL.

Gammon, J.R. 1980. The use of community parameters derived from electrofishing catches of river fish as indicators of environmental quality. In *Seminar on water quality management tradeoffs.* EPA-905/9-80-009. U.S. Environmental Protection Agency, Washington, DC.

Hughes, R.M., and J.R. Gammon. 1987. Longitudinal changes in fish assemblages and water quality in the Willamette River, Oregon. *Transactions of the American Fisheries Society,* 116(2):196-209.

Ohio EPA. 1987. *Biological criteria for the protection of aquatic life.* Vol I-III. Ohio Environmental Protection Agency, Division of Water Quality Monitoring and Assessment, Surface Water Section, Columbus, OH.

Yoder, C.O. 1991. The integrated biosurvey as a tool for evaluation of aquatic life use attainment and impairment in Ohio surface waters. In USEPA, *Biological criteria: Research and regulation. Proceedings of a symposium.* EPA-440/5-91-005. U.S. Environmental Protection Agency, Office of Water, Washington, DC.

IFIM: The Instream Flow Incremental Methodology

1. Distributor:

Riverine and Wetlands Ecosystem Branch
National Biological Service
4512 McMurray Avenue
Fort Collins, CO 80525-3400
(303) 226-9337

2. Type of Modeling/Technique:

A conceptual framework that consists of a collection of analytical procedures and computer models used to assess riverine habitats.

3. Model Components:

- Physical Habitat Simulation System (PHABSIM)
- Time-Series Library (TSLIB)

4. Methods:

IFIM attempts to determine the effects of any of a number of hydraulic modifications on aquatic habitat through a complete process that steps through the description of the river system and available habitat and incrementally changes one or more variables describing the system to reflect a management option, and determining the available habitat for this new system. Each option is then evaluated and a management strategy is selected.

IFIM considers changes to both microhabitat (the distribution of structural and hydraulic features that form the living space for an organism) and macrohabitat (channel characteristics, temperature, and water quality).

PHABSIM is a collection of computer programs that form the key microhabitat simulation component of IFIM. Relying on the assumption that aquatic species will react to hydraulic changes in a stream by selecting the most favorable conditions, PHABSIM uses a combination of standard, one-dimensional, steady-flow, open-channel hydraulic models and habitat models to describe the Weighted Usable Area (a measure of habitat) under a variety of channel configurations and flow management conditions.

TSLIB uses a set of computer programs to create monthly or daily habitat time-series and habitat-duration curves using the habitat-discharge relationships produced by PHABSIM. It can calculate basic statistics for monthly data, generate flow-duration habitat curves for designated months, and create monthly or annual habitat time series for four to seven life stages of selected species.

5. Applications:

IFIM, and its components, can be applied as guidelines to solve problems regarding the hydraulic disturbance of a riverine ecosystem.

6. Experience:

Used extensively by the U.S. Fish and Wildlife Service and state fisheries management agencies.

7. System Requirements:

PHABSIM and TSLIB operate on IBM PCs and compatibles in DOS and are written in FORTRAN.

8. Input Data Requirements:

Detailed data are required for both physical characteristics (e.g., depth, velocity, stream channel characteristics, riparian cover) and biological characteristics (e.g., life history and habitat preference information for the species of concern) of the stream.

9. Outputs:

Quantitative assessment (usually in graphical form) of the changes in a given species' habitat with changes in hydrologic regime

10. References Available:

Bovee, K. D. 1982. *A guide to stream habitat analysis using the Instream Flow Incremental Methodology.* Instream Flow Information Paper 12. FWS/OBS-82/26. U.S. Department of the Interior, U.S. Fish and Wildlife Service, Office of Biological Services.

Bovee, K.D. 1986. *Development and evaluation of habitat suitability criteria for use in the Instream Flow Incremental Methodology.* Instream Flow Information Paper 21. U.S. Fish and Wildlife Service Biological Report 86.

Milhous, R.T., M.A. Updike, and D.M. Schneider. 1989. *Physical Habitat Simulation System reference manual—Version II.* Instream Flow Information, Paper No. 26. Biological Report 89(16). U.S. Fish and Wildlife Service, National Ecology Research Center, Fort Collins, CO.

MNSTREM: Minnesota Stream Temperature Model

1. Distributor:

St. Anthony Falls Laboratory
University of Minnesota
Mississippi River at Third Avenue, SE
Minneapolis, MN 55414

2. Type of Modeling/Application:

MNSTREM is a computer model that simulates dynamic stream temperatures averaged over one to six hours. Water temperature is assumed to be laterally uniform, but they can be highly unsteady, with strong longitudinal gradients.

3. Method/Techniques:

MNSTREM solves the unsteady, one-dimensional advection-dispersion equation with non-linear source terms for water temperature. The control volume technique is used, with source/sink inputs across the water surface from evaporation, conduction, long wave radiation, and solar radiation; and sediment-water heat flux from conduction. Groundwater flow and tributaries can also be incorporated as inputs to the system. The primary coefficients that can be calibrated are in the wind function (relating wind velocity to surface shear), a shading coefficient (the fraction of the water surface that is shaded), and Manning's n value (frictional resistance of the river bottom).

4. Applications:

MNSTREM can be used any time that dynamic water temperatures are to be simulated for a stream. It has been developed for maximum accuracy with minimum calibration, and therefore requires substantial input data. Its best use is for situations where maximum and minimum temperatures are important to the simulation. It has been used to predict hourly temperatures in the U.S. EPA Monticello Experimental Streams (standard errors of between 0.2 and 0.3 degrees C without calibration), numerous streams in the upper Midwest USA (standard errors of approximately 1 degree C with calibration), and in the central Platte River (standard errors of approximately 1.5 degrees C) where diel variations were as high as 18 degrees C.

5. Experience:

MNSTREM is used primarily when models that predict average daily temperature are not suitable. All applications, to date, have been performed by individuals at the St. Anthony Falls Laboratory or by alumni of the Laboratory.

6. System Requirements:

MNSTREM is written in FORTRAN and runs on PCS.

7. Input Data Requirements:

Initial conditions: water temperature, Manning's n values, cross-sectional area and surface width at various locations along the reach to be simulated. Groundwater temperature and discharge, and tributary discharge, if relatively constant, can also be input with initial conditions.

Boundary conditions over time: upstream temperature, discharge, solar radiation, relative humidity, wind velocity, air temperature, and cloud cover.

Other data: calendar day, latitude, altitude, and for calibration, water temperature.

8. Outputs:

Stream water temperature averaged over one to six hour time periods, the standard error for any comparison with measured data, and heat inputs from solar radiation, long wave radiation evaporation and conduction.

9. References available:

Gulliver, J.S. 1977. *Analysis of Surface Heat Exchange and Longitudinal Dispersion in a Narrow Open Field Channel with Application to Water Temperature Prediction.* M.S. Thesis, University of Minnesota, Minneapolis, MN. 187 p.

Sinokrot, B.A. and H.G. Stefan. 1992. *Deterministic Modeling of Stream Water Temperatures: Development and Applications to Climate Change Effects on Fish Habitat*. Project Report 337. St. Anthony Falls Laboratory. University of Minnesota, Minneapolis, MN.

Sinokrot, B.A. and H.G. Stefan. 1993. Stream Temperature Dynamics: Measurements and modeling. *Water Resources Research*. 29(7): 2299-2312.

Sinokrot, B.A. and H.G. Stefan. 1994. Stream water-temperature sensitivity to weather and bed parameters. *J. of Hydraulics Engineering*. 120(6): 722-736.

Sinokrot, B.A, R. Gu, and J.S. Gulliver. 1996. *Impacts of In-Stream Flow Requirements Upon Water Temperature in the Central Platte River.* Project Report 381. Prepared for U.S. Environmental Protection Agency, Region VIII. University of Minnesota. St. Anthony Falls Laboratory.

Stefan, H.G., J. Gulliver, M.G. Hahn, and A.Y. Fu. 1980. *Water Temperature Dynamics in Experimental Field Channels: Analysis and Modeling.* Project Report 193. St. Anthony Falls Laboratory. University of Minnesota, Minneapolis, MN.

Sinokrot, B., and H.G. Stefan. 1994. Stream water-temperature sensitivity to weather and bed parameters. *J. Hydraulic Engineering*. 120(6): 722-736.

PVA: Population Viability Analyses

1. Distributor:

A commercially available form of a PVA is RAMAS, available from:

Applied Biomathematics, Inc.
100 North Country Road
Setauket, NY 11733-1345
(800) 735-4350
fax (516) 751-3435

2. Type of Modeling/Technique:

Population dynamics modeling for aquatic or terrestrial populations that examines how expected time to extinction changes with the effects of demographic, genetic, or environmental variability on population stability.

3. Methods:

The accurate projection of population growth requires a knowledge of the age structure of the population and the survival and fecundity of individuals of each age. This is often achieved using a life table (or matrix) approach in which the demographic parameters include annual rates of survival, growth or change among defined life history stages, and fecundity. Life tables set out the fecundities and probabilities of survival for each age class of individuals in a population and use an "accounting" formulation to calculate future population size on the basis of current size and rates of growth, death, and birth. PVAs also incorporate uncertainty due to unknown or unpredictable events by modeling variation in population parameters and estimating probabilities of extinction over specified periods of time, instead of using a single estimate for an unspecified time.

4. Applications:

PVAs can provide risk assessors and other scientists with simulations of the impact of a stressor (that has been translated into demographic parameters) to examine how expected time to extinction changes with the environment, population structure, or behavior. PVAs have been used mostly in a generalized sense to determine how a population will respond to environmental changes, rather than specifically to assess risk from alternative management scenarios.

5. Experience:

Used extensively for ecological risk analysis and wildlife population research.

6. System Requirements:

RAMAS operates on IBM PC- and compatibles in DOS.

7. Input Data Requirements:

Age structure of the population being studied; survival and fecundity of each age or life stage.

8. Outputs:

PVAs supply a quantified analysis of the stability of a specified population following a change in environment, population structure, or behavior.

9. References Available:

Begon, M., and M. Mortimer. 1986. *Population ecology: A unified study of animals and plants.* Blackwell Scientific Publications, London.

RBPs: Rapid Bioassessment Protocols

1. Distributor:

N/A - see references

2. Type of Modeling/Application:

A set of five protocols that offer techniques of varying complexity to characterize the biological integrity of streams and rivers.

3. Model Components:

RBP I: A screening-level protocol involving the systematic documentation of visual observations by a trained professional focusing on benthic macroinvertebrate communities.

RBP II: A mid-level protocol involving integrated assessment of metrics that measure components of family-level community structure in the field for benthic macroinvertebrate communities.

RBP III: A detailed protocol involving systematic field collection of data for macroinvertebrate communities and metric computation similar to that of RBP II, but also includes subsequent laboratory analysis to permit detection of more subtle degrees of waterbody impairment.

RBP IV: A screening-level protocol involving the use of a questionnaire to maximize existing knowledge of fish communities.

RBP V (also known as the Index of Biotic Integrity or IBI): A detailed protocol involving the collection of data to compute 12 metrics describing the biological integrity of fish communities.

4. Methods/Techniques:

All five RBPs use the collection and analysis of biological, physical, and chemical data to assess the biological integrity of streams or rivers.

For RBPs I and IV, a screening approach is used to obtain information about the status of an aquatic community and condition of a site. These protocols are done without the benefit of comparison to unimpaired sites; therefore, the judgment of biological condition is made by a professional based solely on the presence or absence of indicator taxa, dominance of nuisance or sensitive taxa in the sampled habitats, or evenness of taxonomic distribution.

For RBPs III, IV, and V (IBI), multimetric approaches are used that define an array of measures, or metrics, that individually provide information on community structure, taxonomic composition, individual condition, and biological processes. Each metric is given a score based on the collected data and that of reference conditions (unimpaired or minimally impaired conditions). All metrics are summed and compared to reference conditions to determine the overall biological condition.

5. Applications:

RBPs can be used to determine whether biological impairments exist in a stream or river, to provide information for ranking sites and prioritization for further assessment, and to establish a basis for trend monitoring.

6. Experience:

RBPs, and modifications to them by local, state, and regional organizations, have been used successfully in a variety of watershed management applications.

7. Updating Version and System Requirements:

N/A

8. Input Data Requirements:

For all five protocols, habitat assessment and water quality data are necessary to characterize and rate substrate/instream cover, channel morphology, and riparian/bank structure; measure conventional water quality parameters; and examine physical characteristics. For biological assessment:

RBP I: Determine relative abundance of benthic macroinvertebrates.

RBP II: Examine riffle/run community and sample coarse particulate organic matter; identify 100-organism subsample identified in field to family or order level; perform functional feeding group analysis of riffle/run and coarse particulate organic matter in the field. Data describing reference conditions are also necessary.

RBP III: Examine riffle/run community and sample coarse particulate organic matter; collect riffle/run benthos, collect coarse particulate organic matter sample; determine shredder abundance; perform riffle/run analysis in laboratory, identify 100-organism subsample to species level and perform functional feeding group analysis. Data describing reference conditions are also necessary.

RBP IV: Questionnaire survey regarding fish communities; survey ecoregional reference reaches and randomly selected streams.

RBP V: Major habitats and cover types; total number of native fish species; number and identity of darter species; number and identity of sunfish species; number and identity of sucker species; number and identity of intolerant species; proportion of individuals as tolerant species; proportion of individuals as omnivores; proportion of individuals as insectivorous cyprinids; proportion of individuals as piscivores (top carnivores); number of individuals in sample; proportion of individuals as hybrids; proportion of individuals with disease, tumors, fin damage, and skeletal anomalies. Data describing reference conditions are also necessary.

9. Outputs:

RBP I: Determination of whether impairment exists; indication of generic cause (habitat, organic enrichment, toxicity).

RBP II: Characterization of biological conditions as impairment (none, moderate, severe); indication of generic cause.

RBP III: Evaluation of site impairment (none, slight, moderate, severe); indication of generic cause.

RBP IV: Determination of whether impairment exists; indication of generic cause.

RBP V (IBI): Evaluation of biological integrity as excellent, good, fair, poor, very poor; indication of generic cause of impairment.

10. References Available:

Karr, J.R. 1981. Assessment of biotic integrity using fish communities. *Fisheries* 6(6):21-27.

Karr, J.R., K.D. Fausch, P.L. Angermeier, P.R. Yant, and I.J. Schlosser. 1986. *Assessing biological integrity in running waters a method and its rationale.* Illinois Natural History Survey Special Publication 5.

Plafkin, J.L., M.T. Barbour, K.D. Porter, S.K. Gross, and R.M. Hughes. 1989. *Rapid bioassessment protocols for use in streams and rivers: Benthic macroinvertebrates and fish.* EPA 440/4-89/001. U.S. Environmental Protection Agency, Office of Water, Washington, DC.

Simon, T.P., and J. Lyons. 1995. Application of the Index of Biotic Integrity to evaluate water resource integrity in freshwater ecosystems. In *Biological assessment and criteria: Tools for water resource planning and decision making,* ed., W.S. Davis and T.P. Simon, pp. 245-262. Lewis Publishers, Boca Raton, FL.

Southerland, M., and J.B. Stribling. 1995. Status of biological criteria development and implementation. Chapter 7 in *Biological criteria tools for water resources planning and decision making,* ed. W.D. Davis and T. Simon, pp. 79-94. Lewis Publishers, Boca Raton, FL.

Rosgen's Stream Classification

1. Distributor:

N/A - see references

2. Type of Modeling/Technique:

A classification method that uses morphological stream characteristics to organize streams into relatively homogenous stream types to predict a stream's behavior based on its appearance, to extrapolate data from one stream for use on another with similar characteristics, and to provide a consistent frame of reference when comparing one stream to another.

3. Method/Techniques:

There are three levels of classification based on the desired level of resolution and project objectives. Level 1 is used to provide a broad morphological characterization by integrating landform and fluvial features of valley morphology with channel relief, pattern, shape, and dimension. Level 2 delineates streams into major, broad categories (A through G) that provide a more detailed level of interpretation and extrapolation than Level 1. Stream types are separated based on discreet channel patterns, entrenchment ratios, width/depth ratios, sinuosity, dominant channel-material particle sizes, and slope ranges, which results in a total of 42 major stream types. Level 3 provides a very detailed description of the existing stream conditions, as well as specific information for predicting responses to outside influences. This is accomplished by integrating information on riparian vegetation, depositional patterns, meander patterns, confinement features, fish habitat indices, flow regime, river size category, debris occurrence, channel stability index, and bank erodibility.

4. Application:

- Evaluate sensitivity to disturbance and to predict stream behavior as a result of changes in the watershed
- Assess impacts to stream morphology
- Design stable, self-maintaining channels in restoration work
- Determine flow resistance
- Selection of appropriate fish habitat improvement structures

5. Experience:

This classification system (and modified versions of it) have been applied successfully to various streams throughout the United States.

6. Updating Version and System Requirements:

N/A

7. Input Data Requirements:

Data to be collected depend on the level of classification:

Level 1: landform, lithology, soils, climate, depositional history, basin relief, valley morphology, river, profile morphology, general river pattern.

Level 2: channel pattern, sinuosity (usually expressed as Schumm's ratio), gradient or slope, entrenchment or entrenchment ratio (width of flood plain:the bankfull width of channel surface), channel bed material, width/depth ratio.

Level 3: riparian vegetation, depositional patterns, meander patterns, confinement features, fish habitat indices, flow regime, river size category, debris occurrence, channel stability index, bank erodibility.

8. Outputs:

A quantified classification system that can be used to predict stream behavior and to apply interpretive information. Interpretations can be used to evaluate a stream's sensitivity to disturbance, recovery potential, sediment supply, vegetation controlling influence, and streambank erosion potential.

9. References Available:

Rosgen, D.L. 1994. A classification of natural rivers. *Catena* 22:169-199.

Rosgen, D.L., and B.L. Fittante. 1986. Fish habitat structures: A selection guide using stream classification. In *5th Trout Stream Habitat Improvement Workshop,* Lock Haven University, Lock Haven, PA. Penn. Fish Comm. Publics., Harrisburg, PA.

SNTEMP/SSTEMP: Stream Network/Stream Segment Temperature Models

1. Distributor:

Riverine and Wetlands Ecosystem Branch
National Biological Service
4512 McMurray Avenue
Fort Collins, CO 80525-3400
(303) 226-9319

2. Type of Modeling/Application:

Computer models that simulate mean daily water temperature for a stream segment for a single time period (SSTEMP) or for a stream network with multiple tributaries for multiple time periods (SNTEMP). Minimum and maximum water temperatures can also be estimated from equations utilizing the stream characteristics.

3. Method/Techniques:

SNTEMP and SSTEMP are computer models that estimate how the temperature of a stream changes with altered conditions of flow, riparian shade, and meteorologic conditions. They calculate the heat flux components for the stream segment and then transport that heat downstream. Both models assume that (1) water in the system is instantaneously and thoroughly mixed at all times; (2) all stream geometry (e.g., slope, shade, friction coefficient) is characterized by mean conditions; (3) distribution of lateral inflow is uniformly apportioned throughout the segment length; and (4) solar radiation and the other meteorological and hydrological parameters are 24-hour means.

The programs also handle the special case of a dam with steady-state release at the upstream end of the segment. The companion programs SHADE and SOLAR can be used in tandem with SNTEMP/SSTEMP to calculate percent shade, solar radiation, and day length.

4. Applications:

SNTEMP and SSTEMP are typically used in deciding whether regulatory requirements are being met for fisheries in rivers and streams. IFIM (see page C.11) is a logical next step for factoring temperature consequences of altered streamflow into management decisions.

5. Experience:

Used extensively by the U.S. Fish and Wildlife Service and state fisheries management agencies.

6. System Requirements:

SNTEMP and SSTEMP operate on IBM PCs and compatibles in DOS, and are written in FORTRAN.

7. Input Data Requirements:

Twenty input parameters are required that describe the stream geometry (e.g., segment length, elevation, roughness, shading), hydrology (e.g., segment inflow and outflow, dam locations) and meteorology (e.g., air temperature, relative humidity, solar radiation).

8. Outputs:

- Minimum, mean, and maximum daily water temperature for a single stream segment and time period (SSTEMP) or for a stream network with multiple tributaries for multiple time periods (SNTEMP).
- Other outputs include the intermediate parameters average width, average depth and slope, and heat flux components (atmospheric, convection, conduction, evaporation, friction, solar radiation, vegetative radiation, and water's back radiation).

9. References Available:

Theurer, F.D., and K.A. Voos. 1982. IFG's instream water temperature model validation. In *Conference on Water and Energy: Technical and policy issues,* ASCE proceedings of the Hydraulics Conference, Pittsburgh, PA, and Fort Collins, CO, May 23-26 and June 23-27, 1982, pp. 315-318.

Theurer, F.D., K.A. Voos, and W.J. Miller. 1984. *Instream Water Temperature Model.* Instream Flow Information paper 16. Cooperative Instream Flow and Aquatic System Group, U.S. Fish and Wildlife Service, Fort Collins, CO.

Visual-Based Habitat Assessments

1. Distributor:

N/A - see references

2. Type of Modeling/Application:

A variety of data collection procedures (e.g., the Qualitative Habitat Evaluation Index) that characterize the integrity of aquatic habitats.

3. Method/Techniques:

These techniques are based on field-collected data that characterize aquatic habitat through parameters such as substrate, instream cover, riparian characteristics, channel characteristics, pool and riffle quality, and gradient to and drainage area.

Each parameter is assigned a numerical score within a gradient of optimal to poor, based on visual inspection or a minimal amount of measurement. The scoring range within each part allows for a judgment of differential conditions (e.g., high, middle, low) and for better resolution among varying conditions. The final score for the site is calculated by summing the scores for each parameter. This final habitat assessment score is compared to the score established for regionally expected reference conditions.

4. Applications:

- Quick and cost-effective estimation of aquatic habitat quality that can be used for determining whether impairments exist and prioritizing streams for more detailed assessment.

5. Experience:

Visual-based techniques are used by watershed managers throughout the United States.

6. Updating Version and System Requirements:

N/A

7. Input Data Requirements:

Variable with technique, but generally include:

- Substrate (type, origin, and quality)
- Instream cover (type and amount)
- Channel morphology (sinuosity, flow status, development, channelization, stability, modifications/other)
- Riparian zone and bank erosion (riparian width, floodplain quality, and bank erosion)
- Glide/pool and riffle/run quality (max. depth, morphology, current velocity, riffle/run depth, riffle/run substrate, and riffle/run embeddedness)
- Gradient
- Drainage area
- Percent pool/glide/riffle/run

8. Outputs:

A quantitative assessment, based on qualitative information, of aquatic habitat quality wadable streams and rivers.

9. References Available:

Ball, J. 1983. Stream classification guidelines for Wisconsin. Wisconsin Dept. Nat. Res. Tech. Bull. In *Water quality standards handbook*. U.S. Environmental Protection Agency, Office of Water Regulations and Standards, Washington, DC.

Barbour, M.T., and J.B. Stribling. 1991. Use of habitat assessment in evaluating the biological integrity of stream communities. EPA/440/5-91-005. In *Biological criteria: Research and regulation. Proceedings of a Symposium*. U.S. Environmental Protection Agency, Office of Water, Washington, DC, pp. 25-38.

Plafkin, J.L., M.T. Barbour, K.D. Porter, S.K. Gross, and R.M. Hughes. 1989. *Rapid bioassessment protocols for use in streams and rivers: Benthic macroinvertebrates and fish.* EPA 440/4-89/001. U.S. Environmental Protection Agency, Office of Water, Washington, DC.

Platts, W.S., W.F. Megahan, and G.W. Minshall. 1983. *Methods for evaluating stream, riparian, and biotic conditions.* Gen. Tech. Rep. INT-138. U.S. Department of Agriculture, U.S. Forest Service, Ogden, UT.

Rankins, E.T. 1991. Use of the Qualitative Habitat Evaluation Index for use attainability studies in streams and rivers in Ohio. In: *Biological Criteria: Research and Regulation - Proceedings of a Symposium.* EPA-440/5-91-005.

WET II: Wetland Evaluation Technique, version 2.0

1. Contact:

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U.S. Army Engineer Waterways
Experiment Station
3909 Halls Ferry Road
Vicksburg, MS 39180
(601) 634-2718

WETWorks software
R.P. Novitzki and Assoc., Inc.
4853 NW Bruno Place
Corvallis, OR 97330
(800) 758-0057

2. Type of Modeling/Application:

WET II is a community-based habitat evaluation approach that can provide a broad overview of potential project impacts on several wetland habitat functions. Computerized versions (WET from the U.S. Army Corps and WETWorks, a commercial Windows version of WET) are also available to apply the evaluation techniques.

3. Method/Techniques:

WET II evaluates functions and values in terms of social significance, effectiveness, and opportunity. A project team implements WET II by identifying the physical, chemical, and biological characteristics of a wetland through the use of predictor species or characteristics within a habitat representative of the study area. The predictors are evaluated for each function's effectiveness and opportunity based on interpretation keys that define the relationship between predictor and wetland function or value; the evaluation ratings are high, moderate, or low. Ratings for each predictor are combined to give a final rating of functional significance.

4. Applications:

WET II was designed primarily for conducting an initial, rapid evaluation of wetland functions and values by the U.S. Army Corps of Engineers. However, WET II can be applied for other situations, such as prioritizing wetlands for more detailed, site-specific research, or determining the effects of pre-project and post-project activities on wetland functions and values.

5. Experience:

WET II has been used by the U.S. Army Corps of Engineers and other agencies to evaluate many of their water resources projects.

6. Updating Version and System Requirements:

N/A

7. Input Data Requirements:

Baseline data (e.g., water source, hydrodynamics, surface roughness, vegetation cover, soil type) characterizing the following wetland functions and values: groundwater discharge, groundwater recharge, sediment stabilization, flood flow alteration, sediment retention, toxicant retention, nutrient transformation, production export, wildlife diversity, aquatic diversity, recreation, uniqueness/heritage

8. Outputs:

A "broad-brush," quantitative assessment of potential project impacts on several wetland habitat functions

9. References Available:

Adamus, P.R., E.J. Clairain, Jr., R.D. Smith, and R.E. Young. 1987. *Wetland evaluation technique.* U.S. Army Engineers Waterways Experiment Station, Vicksburg, MS.