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TMDL Model Evaluation and Research Needs

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Abstract

The report was submitted in fulfillment of contract number 68-C-04-007 by Tetra Tech, Inc., under the sponsorship of the United States Environmental Protection Agency. This review examines the modeling research needs to support environmental decision-making for the 303(d) requirements for development of total maximum daily loads (TMDLs) and related programs such as 319 Nonpoint Source Program activities, watershed management, stormwater permits, and National Pollutant Discharge Elimination System (NPDES) discharge evaluations. By examining the currently available models and considering the needs for TMDLs and related watershed programs, a comprehensive list of modeling research needs can be developed.

More than 65 currently available models were evaluated for their capabilities and applicability to TMDL development and related watershed management activities. Evaluation tables were developed to facilitate comparison of models and inventory the potential gaps in model capabilities, and fact sheets were developed for models to provide more detailed information on the capabilities of each model. Existing integrated models systems were also evaluated and compared, based on data processing, modeling tools, and model linkages supported. The review of available models demonstrates that many of the dominant pollutant types and waterbodies can be simulated using available technologies. However, many specific technical gaps remain, especially in linkages between air, surface water, groundwater and receiving water models.

The model reviews and emerging trends in technology were considered in developing a comprehensive list of research needs that encompass a variety of sources, processes, waterbodies, data, systems, and integration needs. This diversity of needs is consistent with the current development of TMDLs across the country. Initially, TMDL development focused on dominant source and pollutant types, but more recently, emphasis has shifted to completing TMDLs under a variety of site-specific conditions and supporting more detailed implementation planning. Because of the specialized and diverse characteristics of the needs, an equitable prioritization of specific needs cannot be defined. Key recommended research areas that could benefit multiple applications include: integrated best management practice (BMP) modeling systems, more physically based representation of watersheds, and support for linkage of watershed and receiving water models.

The review recommends that this diverse set of technical needs should be supported by new and more flexible modeling systems and tools. Development of integrated modeling systems can provide the commonly needed tools and support adoption of new solution techniques, source representation, and algorithms. Providing integrated system platforms, ideally Internet-based, can help minimize duplication of effort (shared on line data management, data display, shared resources), while maximizing resources for more fundamental development and research of key components. The use of Internet-based technologies has now emerged as a viable and practical medium for management of data, analysis techniques and tools to support TMDL and more generalized watershed analyses. Development of a standardized Internet-based framework could provide significant cost saving for the management and application of models. In addition, a standardized and open framework, with clearly defined linkage capabilities, could encourage research and continuous testing and update of new components.

Future development of models and the supporting infrastructure of data and guidance can support informed environmental decision-making, improve understanding of the physical systems in our world, and ultimately provide information to support the effective restoration and protection of the nation's waters.

Foreword

The U.S. Environmental Protection Agency (EPA) is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The National Risk Management Research Laboratory (NRMRL) is the Agency's center for investigation of technological and management approaches for preventing and reducing risks from pollution that threaten human health and the environment. The focus of the Laboratory's research program is on methods and their cost-effectiveness for prevention and control of pollution to air, land, water, and subsurface resources; protection of water quality in public water systems; remediation of contaminated sites, sediments and ground water; prevention and control of indoor air pollution; and restoration of ecosystems. NRMRL collaborates with both public and private sector partners to foster technologies that reduce the cost of compliance and to anticipate emerging problems. NRMRL's research provides solutions to environmental problems by: developing and promoting technologies that protect and improve the environment; advancing scientific and engineering information to support regulatory and policy decisions; and providing the technical support and information transfer to ensure implementation of environmental regulations and strategies at the national, state, and community levels.

This publication has been produced as part of the Laboratory's strategic long-term research plan. It is published and made available by EPA's Office of Research and Development to assist the user community and to link researchers with their clients.

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Acronyms and Abbreviations

ADEM	Alabama Department of Environmental Management
AGNPS	Agricultural Nonpoint Source Pollution Model
AGWA	Automated Geospatial Watershed Assessment
AnnAGNPS	Annualized Agricultural Nonpoint Source Pollution Model
ARS	Agricultural Research Service (USDA)
BASINS	Better Assessment Science Integrating Point and Nonpoint Sources
BMP	Best management practice
BOD	Biochemical oxygen demand
CAEDYM	Computational Aquatic Ecosystem Dynamics Model
CFR	Code of Federal Regulations
CH3D-IMS	Curvilinear-grid Hydrodynamics 3D-Integrated Modeling System
CH3D-SED	Curvilinear Hydrodynamics 3D-Sediment Transport
CONCEPTS	Conservational Channel Evolution and Pollutant Transport System
CREM	Council on Regulatory Environmental Modeling
CWA	Clean Water Act
DCIA	Directly connected impervious areas
DDT	Dichloro-Diphenyl-Trichloroethane
DEM	Digital elevation model
DIAS/IDLMAS	Dynamic Information Architecture System/Integrated Dynamic Landscape Analysis and Modeling System
DMR	Discharge monitoring report
DOC	Dissolved organic carbon
DWSM	Dynamic Watershed Simulation Model
ECOMSED	Estuary and Coastal Ocean Model with Sediment Transport
EDAS	Ecological Data Application System
EFDC	Environmental Fluid Dynamics Code
ELM	Everglades Landscape Model
EMC	Event mean concentration
EPA	U.S. Environmental Protection Agency
EPIC	Erosion Productivity Impact Calculator
FEMA	Federal Emergency Management Agency
FMS	Flexible Modeling System
GIS	Geographic information system
GISPLM	GIS-Based Phosphorus Loading Model
GLEAMS	Groundwater Loading Effects of Agricultural Management Systems
GLLVHT	Generalized, Longitudinal-Lateral-Vertical Hydrodynamic and Transport

GMS	Groundwater Modeling System
GSSHA	Gridded Surface Subsurface Hydrologic Analysis
GWLF	Generalized Watershed Loading Functions
HEC-6	Scour and Deposition in Rivers and Reservoirs
HEC-6T	Sedimentation in Stream Networks
HEC-HMS	Hydraulic Engineering Center-Hydrologic Modeling System
HEC-RAS	Hydrologic Engineering Center-River Analysis System
HSCTM-2D	Hydrodynamic, Sediment, and Contaminant Transport Model
HSPF	Hydrologic Simulation Program—FORTRAN
HUC	Hydrologic Unit Code
KINEROS2	Kinematic Runoff and Erosion Model, v2
LA	Load allocation
LEAM	Land-Use Evolution and Impact Assessment Model
LSPC	Loading Simulation Program in C++
MCM	Mercury Cycling Model
Mercury Loading Model	Watershed Characterization System—Mercury Loading Model
MGD	Million gallons per day
MINTEQA2	Metal Speciation Equilibrium Model for Surface and Ground Water
MMS	Modular Modeling System
MODIS	Moderate Resolution Imaging Spectroradiometer
MOS	Margin of safety
MRLC	Multi-Resolution Land Characteristics
MS4	Municipal separate storm sewer system
MUSLE	Modified Universal Soil Loss Equation
NEXRAD	Next Generation Weather Radar
NHD	National Hydrography Dataset
NPDES	National Pollutant Discharge Elimination System
P8-UCM	Program for Predicting Polluting Particle Passage through Pits, Puddles, and Ponds—Urban Catchment Model
PCB	Polychlorinated biphenyl
PCSWMM	Stormwater Management Model
PGC – BMP	Prince George's County Best Management Practice Module
ppb	Parts per billion
PRMS	Precipitation-Runoff Modeling System
QUAL2E	Enhanced Stream Water Quality Model
REMM	Riparian Ecosystem Management Model
RF3	Reach File, version 3
SCS	Soil Conservation Service
SED3D	Three-Dimensional Numerical Model of Hydrodynamics and Sediment Transport in Lakes and Estuaries
SLAMM	Source Loading and Management Model
SME	Spatial Modeling Environment
SNTEMP	Stream Network Temperature Model

SPARROW	SPAtially Referenced Regression On Watershed Attributes
SSTEMP	Stream Segment Temperature Model
STORM	Storage, Treatment, Overflow, Runoff Model
SWAT	Soil and Water Assessment Tool
SWMM	Storm Water Management Model
TMDL	Total maximum daily load
TN	Total nitrogen
TP	Total phosphorus
TSS	Total suspended solids
USACE	U.S. Army Corps of Engineers
USDA	U.S. Department of Agriculture
USFWS	U.S. Fish and Wildlife Service
USGS	U.S. Geological Survey
USLE	Universal Soil Loss Equation
WAMView	Watershed Assessment Model with an ArcView Interface
WARMF	Watershed Analysis Risk Management Framework
WASP	Water Quality Analysis Simulation Program
WEPP	Water Erosion Prediction Project
WinHSPF	Interactive Windows Interface to HSPF
WLA	Wasteload allocation
WMS	Watershed Modeling System
WQBEL	Water quality-based effluent limits
WRDB	Water Resources Database
WWTP	Wastewater treatment plant
XP-SWMM	Stormwater and Wastewater Management Model

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Chapter 1 Introduction

Models are used to answer questions, support decision-making, and assess alternatives. Models are used as a tool to describe and understand the dynamics of physical systems including watersheds and receiving waters such as lakes, rivers, estuaries, and coastal areas. Analysts use models to answer questions such as:

> *How do inputs from human sources and land management activities affect the conditions of our receiving waters?*
>
> *How should these inputs be changed to benefit the condition of our receiving waters?*

Exploration of these cause and effect relationships drives the need to develop and apply models. However, the development of models that can reliably represent watersheds and receiving waters is also a tremendous challenge. The analyst must consider how to represent the system with sufficient accuracy to have confidence in the result. Practical and technical constraints require that the representation of the system is consistent with available information, time, resources and scientific understanding. Each modeling application needs to address this challenge. Each modeling application must address the challenge of balancing the needs of the particular study at an appropriate level of accuracy and reliability.

Current environmental protection programs rely on modeling to evaluate and select various control strategies. Historically, models have been used to derive water quality-based effluent limits (WQBELs) for point source discharges. Large-scale national estuary program activities (e.g., Chesapeake Bay, Tampa Bay), which represent some of our most significant resources, have used models to determine allowable loading of nutrients and restoration needs. More recently, the Total Maximum Daily Load (TMDL) program has required the determination of loading allocations that will result in restoring waters designated as impaired on state 303(d) lists. In many cases, models are used during TMDL development to evaluate the relationship between load reduction and compliance with water quality standards. Models provide a "linkage" between loads and receiving water conditions. To address the TMDL development needs for a highly diverse group of impaired waters and pollutant sources, a wide range of model techniques is required. Although models are available and have been used successfully in environmental and water quality management since the 1970s, the diversity of the pollutants, sources, and receiving water conditions to be evaluated under the TMDL program have placed new challenges on the use of modeling to support environmental decision-making.

Watershed management planning also increasingly relies on modeling to develop restoration goals and identify load reduction needs. U.S. Environmental Protection Agency (EPA) released *Nonpoint Source Program and Grants Guidelines for States and Territories* (October 23, 2003) for grants appropriated by Congress in Fiscal Year 2004 and in subsequent years. The guidelines, available online at http://www.epa.gov/fedrgstr/EPA-WATER/2003/October/Day-23/w26755.htm, identify the following nine minimum elements that must be included in watershed plans funded by Section 319:

1. Causes and sources
2. Pollutant load reduction estimates
3. Management measures needed
4. Technical and financial assistance required to implement
5. Information and education activities
6. Implementation schedule

7. Interim measurable milestones

8. Indicators to evaluate progress toward load reductions and water quality standards

9. Monitoring program

Addressing these guidelines, especially elements 2 and 3, places increased emphasis on developing watershed plans that result in meeting water quality standards and demonstrate a linkage between pollutant sources and water quality.

The specific limitations of models for TMDL support and watershed management are not well documented. States and EPA continue to face new challenges as they address more complex waterbodies, impairments, and sources, for which there is limited experience. As models and supporting systems evolve, research should be targeted to those areas where our analysis capabilities need to be improved. As technology and various Internet-based applications and mapping systems continue to improve, new modeling systems (e.g., one or more linked models) and supporting analysis tools (e.g., data preparation, output display, optimization, uncertainty analysis) will clearly be needed.

This review will examine the modeling research needs to support environmental decision-making and programs such as 303(d)-related development of TMDLs, implementation of 319 Nonpoint Source Programs, watershed management, stormwater permits, and National Pollutant Discharge Elimination System (NPDES) discharge evaluations. By examining the currently available models and considering the needs for TMDLs and related watershed programs, a comprehensive list of modeling needs can be developed.

The first task of the review process was to identify and evaluate currently available model capabilities. The second task evaluates the ability of models to simulate the TMDL- and watershed-related load reduction needs and management related alternatives. The evaluation also considers model performance, simulation capabilities, level of effort, training, and user interfaces. Supporting this evaluation are case studies of two successful TMDL modeling applications for nutrients and mercury. Finally, the review provides recommendations for key areas of research to address the modeling needs and fill the gaps identified in the review of available models. The evaluation also considers the need for various software and supporting tools, including linkages between existing models, and further integration of new and emerging modeling resources to address multiple media (e.g., air, surface waters, groundwater).

This report is organized as follows:

- Chapter 2 discusses modeling needs for TMDL development, including programmatic and technical issues that affect model selection and application for TMDL development.
- Chapter 3 provides background on models, including what a model is, processes and levels of complexity represented in available models, and recent trends in model development.
- Chapter 4 discusses the types of models available and identifies the models included in this review.
- Chapter 5 evaluates the applicability of the reviewed models and integrated modeling systems to TMDL development and watershed management applications and provides an evaluation of their capabilities.
- Chapter 6 includes two case study applications: Case Study #1 – Development of Mercury TMDLs in Arivaca Lake and Peña Blanca Lake, Arizona; Case Study #2 – Linked Model Development for Nutrient TMDL in Cahaba River, Alabama
- Chapter 7 discusses modeling needs and recommendations for future research.
- Appendix includes detailed fact sheets on each of the models included in the review.

Chapter 2 Modeling Needs for TMDL Development

Section 303(d) of the Clean Water Act (CWA) and the EPA's Water Quality Planning and Management Regulations (40 Code of Federal Regulations [CFR] Part 130) require states to identify and list those waters within their boundaries that are water quality-limited, to prioritize them, and to develop TMDLs for the pollutants of concern. States develop and submit the 303(d) list that defines water quality-limited waters to EPA for review and approval. Water quality-limited waters are waterbodies that do not meet applicable water quality standards or are not expected to meet applicable standards after application of technology-based effluent limitations for point sources.

A TMDL is the allowable load of a specific pollutant that can be discharged into a waterbody and meet water quality standards. TMDLs consist of wasteload allocations (WLAs) for point sources, load allocations (LAs) for nonpoint sources, and a margin of safety (MOS). A TMDL is based on the relationship between pollutant sources and water quality and provides the scientific basis for a state to establish water quality-based controls to reduce pollutant loads from both point and nonpoint sources to restore and maintain the quality of the state's water resources. The load expressed is not necessarily a daily load but is expressed in the appropriate averaging period that protects water quality standards. TMDLs, once implemented should result in meeting the states' water quality standards.

Loading capacity. The greatest amount of loading that a water can receive without violating water quality standards. (40 CFR 130.2(f))

Load allocation (LA). The portion of a receiving water's loading capacity that is attributed either to one of its existing or future nonpoint sources of pollution or to natural background sources. (40 CFR 130.2(g))

Wasteload allocation (WLA). The portion of a receiving water's loading capacity that is allocated to one of its existing or future point sources of pollution. (40 CFR 130.2(h))

Total maximum daily load (TMDL). The sum of the individual WLAs for point sources and LAs for nonpoint sources and natural background. TMDLs can be expressed in terms of either mass per time, toxicity, or other appropriate measure. (40 CFR 130.2(i)) TMDLs must be calculated with seasonal variations and a margin of safety and must take into account critical conditions for stream flow, loading, and water quality parameters. (40 CRF 130(c)(1))

Margin of safety (MOS). TMDLs must be established with a margin of safety that takes into account any lack of knowledge concerning the relationship between effluent limitations and water quality. (40 CFR 130.7(c)) EPA guidance explains that the MOS may be implicit (i.e., incorporated into the TMDL through conservative assumptions in the analysis) or explicit (i.e., expressed in the TMDL as a portion of the loading capacity).

Across the country, thousands of waters are listed as impaired by a wide variety of pollutants. Based on most recent state 303(d) lists, there are approximately 34,000 impaired waters in the United States and more than 59,000 associated impairments (National Section 303(d) List Fact Sheet, http://www.epa.gov/owow/tmdl/, accessed August 1, 2005). Metals, pathogens, nutrients and sediment are the most common pollutants included on state lists, and the top 10 listed impairments account for over 75 percent of the total listings in the nation (Table 2-1). Since January 1, 1996, EPA has approved almost 15,000 TMDLs, accounting for approximately 25 percent of the nationwide listings.

Table 2-1. Top 10 303(d) List Impairments in the United States

General Impairment Name[1]	Number Reported	Percent Reported	Cumulative Percent
Metals	11,526	19.2	19.2
Pathogens	7,896	13.2	32.4
Nutrients	5,585	9.3	41.7
Sediment/siltation	5,045	8.4	50.1
Organic enrichment/low dissolved oxygen	4,406	7.3	57.4
Fish consumption advisories	3,178	5.3	62.7
pH	2,904	4.8	67.5
Other habitat alterations	2,389	4.0	71.5
Thermal modifications	2,200	3.7	75.2
Biological criteria	2,116	3.5	78.7

[1] "General impairment" categories may represent several associated pollutants or impairment listings. For example, the "metals" category includes 30 specific pollutants or related listings (e.g., iron, lead, contaminated sediments).

TMDL Modeling Requirements

Models are often used to support development of TMDLs—typically to estimate source loading and evaluate loading capacities that will meet water quality standards. The technical requirements of a TMDL stipulate that analysis should demonstrate that the allocation of point and nonpoint source loads would result in meeting water quality standards. The wording of the TMDL requirements also stipulates that WLA and LA must be separately defined. For modeling purposes, this requirements means that point and nonpoint sources must be evaluated as separate sources so that they can be simulated under various loading scenarios. Point sources are typically represented individually to accommodate TMDL regulations, which require "individual waste load allocations" for point sources. For wet weather or diffuse point sources (e.g., stormwater), the municipal boundaries may need to be addressed in the modeling analysis as well (USEPA 2002). For nonpoint sources, TMDL guidance identifies that allocation can be made to individual sources, categories or subcategories of sources. In cases of limited data, LAs can also be expressed as "gross allotments," allowing for larger scale grouping of nonpoint source.

In the development of a TMDL, load allocations might also be identified that affect sources upstream of a listed water depending on the transport properties of the pollutant. The need to look at sources upstream of the listed water necessitates a "watershed-based" approach to TMDLs. The contributions upstream of the listed water are all potentially part of the solution to the impairment. Although TMDLs are developed for specific listed waters and their associated watersheds, the TMDL analyses are sometimes developed in "bundles" to address groups of listed waters that are located within a larger collective watershed. This grouping of TMDL analyses can result in more efficient TMDL development and review.

EPA's 1991 guidance discusses the option of developing TMDLs using the "phased approach," often referred to as "adaptive management." Under the phased approach, TMDL development should be based on estimates that use available data and information, but monitoring for collection of new data would be required (USEPA 1991a). The phased approach provides for further pollution reduction without waiting for new data collection and analysis. The margin of safety developed for the TMDL under the phased approach should reflect the adequacy of data and the degree of uncertainty about the relationship between load allocations and receiving water quality (USEPA 1991a). The TMDL program does not dictate or require the use of any particular model or modeling procedures. NRC (2001) discusses the use of modeling in TMDL development, supporting the assertion that there is no recommended model for TMDLs but that any model chosen for TMDL development should meet a set of criteria related to the specific TMDL issues (e.g., water quality standards, data availability, cost).

TMDL Regulations and Guidance

Water Quality Planning And Management Regulations. Code of Federal Regulations, Title 40, Part 130. Regulations are available online at http://www.gpoaccess.gov/cfr/index.html.

USEPA. 2002. *The Twenty Needs Report: How Research Can Improve the TMDL Program*. EPA841-B-02-002. U.S. Environmental Protection Agency, Office of Water, Office of Wetlands, Oceans and Watersheds, Washington, DC. http://www.epa.gov/owow/tmdl/20needsreport_8-02.pdf

USEPA. 2002. *Establishing Total Maximum Daily Load (TMDL) Wasteload Allocations (WLAs) for Storm Water Sources and NPDES Permit Requirements Based on Those WLAs*. Memorandum from Robert H. Wayland, III, Director, Office of Wetlands, Oceans and Watersheds, and James A. Hanlon, Director, Office of Wastewater Management, U.S. Environmental Protection Agency, Washington, DC. November 22, 2002. http://www.epa.gov/npdes/pubs/final-wwtmdl.pdf

USEPA. 2001. *Protocol for Developing Pathogen TMDLs*. EPA 841-R-00-002. U.S. Environmental Protection Agency, Office of Water, Washington, DC. 132 pp. http://www.epa.gov/owow/tmdl/pathogen_all.pdf

USEPA. 1999. *Protocol for Developing Nutrient TMDLs*. EPA 841-B-99-007. U.S. Environmental Protection Agency, Office of Water, Washington, DC. 135 pp. http://www.epa.gov/owow/tmdl/nutrient/pdf/nutrient.pdf

USEPA. 1999. *Protocol for Developing Sediment TMDLs*. EPA 841-B-99-004. U.S. Environmental Protection Agency, Office of Water, Washington, DC. 132 pp. http://www.epa.gov/owow/tmdl/sediment/pdf/sediment.pdf

USEPA. 1997. *New Policies for Establishing and Implementing Total Maximum Daily Loads (TMDLs)*. Memorandum from Robert Perciasepe, Assistant Administrator, Office of Water, U.S. Environmental Protection Agency, Washington, DC. August 8, 1997. http://www.epa.gov/OWOW/tmdl/ratepace.html

USEPA. 1997. *Compendium of Tools for Watershed Assessment and TMDL Development*. EPA841-B-97-006. U.S. Environmental Protection Agency, Office of Water, Washington, DC.

USEPA. 1991. *Guidance for Water Quality-Based Decisions: The TMDL Process*. EPA 440/4-91-001. U.S. Environmental Protection Agency, Office of Water, Washington, DC. http://www.epa.gov/OWOW/tmdl/decisions/

EPA has provided guidance for major pollutant types that identify modeling and analysis needs and generalized approaches (USEPA 1999a; USEPA 1999b, USEPA 2001). Other modeling related guidance from USEPA mostly relates to the requirements for record keeping and documentation. All TMDL reports, models, and documentation are subject to public review and comment. Record keeping and documentation of all modeling code and software are recommended as part of the administrative records. The need for review by USEPA and open comment periods for stakeholders has resulted in a strong preference for public domain or open code modeling systems for application in TMDL development.

Administrative Records

While not a necessary part of the TMDL submittal, USEPA recommends preparation of an administrative record containing documents that support the establishment of and calculations/allocations in the TMDL. Components of the record should include all materials relied upon to develop and support the calculations/allocations in the TMDL, including any data, analyses, or references that were used, records of correspondence with stakeholders and USEPA, responses to public comments, and other supporting materials. This record is needed to facilitate public and/or USEPA review of the TMDL.

From: *Guidelines for Reviewing TMDLs Under Existing Regulations Issued in 1992*
http://www.epa.gov/owow/tmdl/guidance/final52002.html

Analysis Categories

Understanding the types of impairments that occur throughout the country can assist in identifying the types of models that are needed to investigate impairments, diagnose causes of impairment, and identify management solutions. The waterbody and general impairment types can be grouped into 10 dominant analysis categories (Figure 2-1). The grouping of analysis categories is based on defining the physical processes associated with the major waterbody types and the characteristics of impairments and associated pollutants. The physical processes of water movement characterize the major waterbody types including lakes, rivers, and tidal estuaries and coastal areas. Lakes and reservoirs are impounded waters, and the major processes are associated with relatively static water systems. Rivers are typically flowing systems characterized by velocity and volume of flow. Riverine studies normally focus on concentration of pollutants in flowing water. In tidal waters, analyses focus on the dominant processes related to tidal flux, salinity, and mixing. Similar to the physical conditions associated with waterbodies, pollutants can also be broadly grouped into nutrients, metals, pathogens, sediment and temperature. Nutrients are typically associated with eutrophication-related effects; metals and toxics are associated with sediment and water column criteria violations; elevated concentrations of sediment and deposition of fine-grained sediment are associated with fish habitat impairment; and in-stream temperature is a stressor associated with fish habitat.

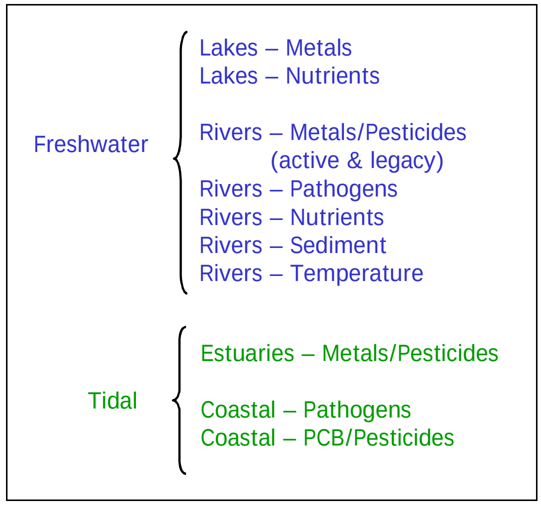

Figure 2-1. Ten major analysis categories.

These analysis categories illustrate the diversity of conditions that result in the selection of an appropriate analytical approach. Recent and current TMDL development efforts have resulted in the development of many TMDLs representative of the 10 major categories of frequently observed waterbody-impairment combinations. Examination of recent TMDLs and experience in the development of TMDLs were used to develop a general summary of the typical sequence of models or analysis techniques that have been used (Table 2-2; 10 major combinations, and 1 combination having two types of pesticides—active and legacy). This table is not intended to provide specific guidance on the selection of modeling approaches for TMDLs but to illustrate the typical sequences of approaches and the diversity of techniques employed. In addition, the table demonstrates how the selection of the appropriate modeling techniques is tightly linked to waterbody type and impairment. The table is organized according to the defining features of the analyses used in developing a TMDL.

- ***Impairment Conditions*** – TMDLs are a plan to meet water quality standards. An understanding of when and under what conditions impairment occurs is needed to determine the type of analysis needed.
- ***Delivery of Pollutants*** – Source loading can be delivered directly from discharges and from precipitation-driven processes. The type of impairment is often related to timing of pollutant delivery.
- ***Modeling Approach*** – The selected approach will include a combination of watershed loading and receiving water response models or other estimation techniques.
- ***Model Output Used to Calculate Loading Capacity*** – Output from the model(s) is processed to provide a representation of the loading capacity that meets the water quality standards.
- ***Typical Implementation*** – This feature qualitatively or quantitatively discusses the types of practices that could be used to achieve the loading target.
- ***Sample Case Studies*** – Case studies illustrate the types of approaches described in each column of the table.

Several observations relevant to modeling for TMDL development can be made from Table 2-2:

- TMDLs often require multiple models to address the watershed and receiving water components (see Category II, which includes Generalized Watershed Loading Functions [GWLF] and BATHTUB).
- Some pollutants are addressed through the use of statistical/analytical techniques that are not formal "models" or "modeling systems" (see Category VII).
- Although many models are available, the 11 categories presented can be addressed by using a relatively small set of models.
- Processing of model output is needed to specifically evaluate the TMDL's compliance with the water quality standard.
- The example models shown are typically public domain and/or EPA-supported models.
- Explicit modeling of best management practices (BMPs) is not typically included or required in a TMDL analysis.

However, examining the historical use of models for TMDL development is only a reflection of how the currently available models have been applied and does not explain the limitations in current models to address specific needs or local considerations. Many additional waterbodies will require TMDL development, and, in some areas, TMDLs will be revised to improve on previous analysis or reallocate source loading. If more efficient modeling systems or more robust, process-based models are developed, users are likely to adopt the new technology.

Table 2-2. Summary of Analysis Sequences for Analysis Categories

Category		I	II	III
		River – Pathogens	**Lake – Nutrients**	**River – Nutrients**
Impairment Conditions		Storm events or warm weather, dry season periods	Summer/dry season	Summer/dry season/year-round
Delivery of Pollutants		Storm event runoff or dry weather discharge, direct deposition	Stormwater runoff, dry weather inflows, point sources	Dry weather inflows (point source discharges, nonpoint sources, groundwater)
Modeling Approach	General Approach	Wet weather and dry weather pathogen analysis	Eutrophication analysis to identify nutrient loading thresholds to meet in-lake targets	Low- or high-flow analysis of nutrient loading thresholds to meet in-stream targets
Modeling Approach	Watershed Loading	Flow, concentration, and load estimation using HSPF	Load estimation using GWLF, AGNPS, AnnAGNPS, SWAT, SWMM, or HSPF	Load estimation based on tributary and point source low-flow monitoring
Modeling Approach	Receiving Water Response	In-stream response using HSPF (data collection consideration)	Lake response using BATHTUB. More detailed option using CE-QUAL-W2 or EFDC.	Stream response using mass balance, QUAL2E low-flow model, or WASP
Model Output Used to Calculate Loading Capacity		Number of exceedance days based on model output or monitoring data and comparison with reference watershed	Loading of nitrogen and phosphorus needed to meet lake target as simulated by lake model	Loading or concentration for critical low-flow or average summer, or high-flow periods
Typical Implementation		Targeted management of pathogen sources: stormwater, rural uses, septics	Targeted management of nutrient sources: stormwater, rural uses, open space uses, septics, point sources	Targeted dry or weather reductions from point sources, dry season nonpoint sources
Sample Case Studies		Santa Monica, CA http://www.swrcb.ca.gov/rwqcb4/html/meetings/tmdl/tmdl_ws_santa_monica.html	Lake Ontelaunee, PA http://www.epa.gov/reg3wapd/tmdl/pa_tmdl/Lake%20ontelauneeTMDL/index.htm	Wissahickon Creek, PA http://www.epa.gov/reg3wapd/tmdl/pdf/wissahickon_tmdl/index.htm

Table 2-2. Summary of Analysis Sequences for Analysis Categories (continued)

Category		IV River – Pesticides/Urban (Active Pesticide Sources)	V River – Pesticides/Legacy (No Current Pesticide Sources)	VI River/Estuary – Toxics
Impairment Conditions		Mixed. Associated with application dates and days when transport occurs	Mixed. Associated with disturbance or resuspension of historical deposits	Mixed
Delivery of Pollutants		Urban runoff, typically storm drains. Dry weather discharges including irrigation and dumping	Historic delivery. Resuspension due to storm events, aquatic life	Municipal and industrial wastewater, urban runoff, agricultural runoff, other sources
Modeling Approach	General Approach	Identification of reduction needed to meet water column toxicity-based targets	Identification of reduction needed to meet sediment, fish tissue, or water column water quality toxicity-based targets	Identification of reduction needed to meet sediment, fish tissue or water column toxicity-based targets
Modeling Approach	Watershed Loading	Source characterization	Tributary monitoring	Source characterization
Modeling Approach	Receiving Water Response	Allowable loading determination based on calculation from identified target at design flow or a range of flows	Allowable loading determination based on calculation from identified target at design flow or a range of flows	Allowable loading determination based on calculation from identified target at design flow or a range of flows
Model Output Used to Calculate Loading Capacity		Allowable load for design flow or annual period	Allowable load for design flow or annual period	Allowable load for design flow or annual period
Typical Implementation		Reduction or elimination of active pesticide sources	Removal or stabilization of deposits, long-term attenuation	Reduction or elimination of active toxic sources
Sample Case Studies		San Francisco Bay Area Urban Creeks Pesticide Toxicity/Diazinon TMDL, CA http://www.swrcb.ca.gov/rwqcb2/urbancrksdiazinontmdl.htm	Newport Bay, CA http://www.epa.gov/region09/water/tmdl/final.html	Newport Bay, CA http://www.epa.gov/region09/water/tmdl/final.html

Table 2-2. Summary of Analysis Sequences for Analysis Categories (continued)

Category	VII River – Sediment	VIII River – Temperature	IX River – Biological
Impairment Conditions	• Nonseasonal: estuary infilling, pool filling • Spring: spawning/incubation • All seasons: rearing • Winter: migration (turbidity-related)	Summer/dry-warm weather	Multiple/dry-wet season
Delivery of Pollutants	Storms and throughout the wet season over a wide range of flows	Summer heat input	Depends on pollutants/stressors associated with the impaired conditions
Modeling Approach – General Approach	• Long-term loading analysis based on sediment budget and reference approach. Sediment source analysis if full budget not possible • Turbidity/total suspended solids (TSS) events • Sedigraphs (combination of flow and turbidity/TSS data)	Temperature estimation based on flow, solar inputs, stream geometry, meteorologic conditions, vegetative shading, and other factors	Biological reference approach, load estimation for identified pollutants
Modeling Approach – Watershed Loading	• Load estimation using sediment budget or sediment source analysis • Estimation of inputs based on sediment yields and delivery from land use/erosion categories	Temperature estimation based on models of flow, travel time, solar/meteorologic conditions. Shade models do not address watersheds with dams or high levels of irrigation return flows, or cooling water discharges.	Load estimation of identified pollutant(s) contributing to biological impairment using GWLF or similar model
Modeling Approach – Receiving Water Response	• Load target determined from comparison with desired reference watershed • Rate of infilling • Geomorphic/habitat targets derived from literature	• SSTEMP or SNTEMP stream flow and temperature analysis, • QUAL2E stream flow and temperature analysis	Comparison of estimated watershed/source loads with loads in reference watershed
Model Output Used to Calculate Loading Capacity	• Average annual sediment load from dominant sources to meet reference conditions. • Identification of achievable reductions by source category	• Heat loading • Shade dominated streams Effective shade allocations (percent of stream shade)	Annual loading benchmarked to reference watershed
Typical Implementation	Targeted management of sediment sources for long-term restoration	Targeted management of vegetation and stream system, dam releases, irrigation withdrawals, or return flows	Targeted management of relevant pollutant sources
Sample Case Studies	Garcia River, CA http://www.epa.gov/region09/water/tmdl/final.html	North Fork Eel River, CA http://www.epa.gov/region09/water/tmdl/final.html	Cooks Creek, VA http://www.deq.state.va.us/tmdl/tmdlrpts.html

SNTEMP = Stream Network Temperature Model
SSTEMP = Stream Segment Temperature Model

Table 2-2. Summary of Analysis Sequences for Analysis Categories (continued)

Category		X Estuary – Nutrients	XI Coastal – Pathogen
Impairment Conditions		Die-off of macrophytes, floating maps, algal blooms	Spring runoff or winter and summer dry weather
Delivery of Pollutants		Annual/long-term nutrient loading from runoff, nutrients associated with sediment, groundwater	Runoff/wet weather sources or dry weather sources Direct deposition
Modeling Approach	General Approach	Long-term loading, nutrient cycling, and response of estuaries	Wet weather loading and response of estuaries
Modeling Approach	Watershed Loading	Load estimation using GWLF, HSPF, analyses of monitoring data, or similar model	Load estimation using HSPF or direct analysis of monitoring data
Modeling Approach	Receiving Water Response	Estuary response using Tidal Prism, WASP, EFDC, or similar model	Response using WASP, EFDC, or similar model Alternatively determine correlation of coastal impairment with tributary loading
Model Output Used to Calculate Loading Capacity		Annual loading based on meeting estuary target condition	Wet and dry weather exceedance frequencies and associated loading
Typical Implementation		Targeted management of nutrient and sediment sources: stormwater, rural uses, open space uses, septics, point sources, irrigation return flows, fertilizer management	Targeted management of pathogen sources: stormwater, rural uses, septics
Sample Case Studies		(Several available nationally)	Santa Monica, CA http://www.swrcb.ca.gov/rwqcb4/html/meetings/tmdl/tmdl_ws_santa_monica.html

Model Selection Considerations

When addressing any impairment, selecting the appropriate model is crucial in developing a feasible, defensible and equitable TMDLs and load allocations. The primary factor in determining the modeling approach for a TMDL, as demonstrated by the analytical categories, is the pollutant and associated endpoint that represents compliance with water quality standards. The TMDL endpoint is a numeric threshold that is equated with compliance with water quality standards. Some TMDL endpoints are derived directly from numeric water quality criteria and have a defined magnitude, duration, and frequency (e.g., zinc expressed as a concentration in µg/l, 4-day average, 1-in-3 year frequency of exceedence). Some endpoints are derived based on interpreting narrative criteria to derive a numeric endpoint. For example, a waterbody impaired by nuisance algal blooms could result in a TMDL that defines nutrient loads (total phosphorus [TP] and total nitrogen [TN]) that will result in meeting a summer chlorophyll *a* endpoint of 20 µg/l. Endpoints designed to address acute (short-term) impairments are typically based on instantaneous maximums or daily averages while chronic (long-term) problems (e.g., eutrophication, sediment loading and deposition) are represented by endpoints with longer durations (e.g., monthly average concentration, annual loading). The applicability of a model for a specific TMDL application is evaluated based on the ability to simulate at a time-scale and resolution appropriate for evaluation of the endpoint's magnitude, duration and frequency. For example, if an endpoint is based on a maximum daily concentration, a model that provides output of only monthly average concentration is not appropriate.

Other factors that guide model selection for TMDLs include defining the waterbody type, sources, necessary spatial resolution (e.g., gross watershed vs. subwatershed vs. site-scale) and special local features (e.g., surface-groundwater interactions) or land features (e.g., wetlands). If management solutions will be evaluated, model selection must consider the types of management techniques, spatial scale of the information, and degree of specificity required in the management alternatives analysis.

Water quality standards. Provisions of state or federal law which consist of a designated use or uses for the waters of the United States, water quality criteria for such waters based upon such uses. Water quality standards are to protect public health or welfare, enhance the quality of the water and serve the purposes of the Act (40 CFR 131.3(i))

Designated uses. Those uses specified in water quality standards for each waterbody or segment whether or not they are being attained (40 CFR 131.3(f))

Criteria. Elements of state water quality standards, expressed as constituent concentrations, levels, or narrative statements, representing a quality of water that supports a particular use. When criteria are met, water quality will generally protect the designated use (40 CFR 131.3(b))

Numeric Criteria. Numeric criteria or limits exist for many common pollutants, such as high concentrations of bacteria, suspended sediment, algae, dissolved metals, etc. An example of numeric criteria is "dissolved oxygen must be at least five milligrams per liter" (i.e., dissolved oxygen ≥ 5.0 mg/L). Numeric criteria are based on laboratory and other studies that test or otherwise examine pollutant impacts on live organisms from different species such as frogs, fish, and insect larvae.

Narrative Criteria. Non-numeric descriptions of desirable or undesirable water quality conditions. An example of narrative criteria might be that "all waters shall be free from sludge, floating debris, oil and scum, color and odor-producing materials, substances that are harmful to human, animal or aquatic life, and nutrients in concentrations that may cause algal blooms."

Chronic. Defines a stimulus that lingers or continues for a relatively long period of time, often one-tenth of the life span or more. Chronic should be considered a relative term depending on the life span of an organism. The measurement of a chronic effect can be reduced growth, reduced reproduction, etc., in addition to lethality (USEPA 1991b).

Acute. Refers to a stimulus severe enough to rapidly induce an effect; in aquatic toxicity tests, an effect observed in 96 hours or less is typically considered acute. When referring to aquatic toxicology or human health, an acute affect is not always measured in terms of lethality (USEPA 1991b).

Special processes or technical considerations that affect pollutant loading and impairment conditions and, therefore, TMDL development are of particular concern in the appropriate selection and application of models. Models that include more complex processes are typically more difficult to apply, require significantly more data for setup and testing, and might include untested algorithms. However, not all of the identified technical considerations may be crucial to include in a particular application—they may not have enough effect on the outcome of the results to merit selecting a more complex modeling approach to address them. The standard practice in modeling is to identify the dominant processes and identify the simplest models sufficient to meet the needs of the project.

In developing TMDLs, some key technical complexities or issues are often identified. Some have been addressed in simplified approaches or through the use of statistical or site-specific models. Many of these key technical considerations could be addressed through additional research and integration of new physically based modeling techniques and are discussed further in Chapter 6. Specific technical issues that have been encountered as considerations or limitations in TMDL development include the following:

- ***Sediment*** – Stream bank erosion and channel adjustments can be substantial sources of sediment in urban and rural areas and are difficult to characterize and quantify.
- ***Irrigation*** – Irrigation can significantly alter the natural hydrology of an area, and irrigation return flows are a significant source of pollutants in arid regions.
- ***Drainage*** – Drainage tile can affect the hydrologic response of the watershed and can provide discharges to rivers.
- ***High water table areas*** – In areas of high water tables, water fluctuations, and surface-groundwater interactions affect runoff and pollutant delivery. Wetland areas can retain water and affect water quality.
- ***Wetlands*** – Large areas of wetlands influence watershed hydrology, loading, and management options, and areas with wetting and drying can influence tidal areas (i.e., estuaries).
- ***Contaminated sediment*** – Contaminated sediment is subject to several processes that influence their interaction with the water column and aquatic biota, including accumulation, movement, burial, and

dredging. In many areas, contaminated sediments are the result of historical sources, limiting management options.

- ***Pesticides* –** Application of pesticides can result in water contamination through overspray or rainfall during or immediately after application. However, pesticide monitoring data are limited, and few tested simulations are available.

- ***Ecological impairments* –** Ecological or habitat related parameters/stressors are poorly understood or cannot be modeled directly.

- ***Best management practices*** – Data on existing management techniques are often not readily available, and techniques are difficult to represent accurately in models.

A number of issues that affect model selection and application for TMDL development are not related to the technical representation of the system. General issues related to the overall TMDL process and the use of models include:

- ***Data availability*** – Many TMDLs have limited local monitoring data available to support analysis, limiting the potential approach options as well as the confidence in modeling approaches (i.e., no data for calibration). TMDL guidance does not require data collection and supports the use of "available data and information" when possible (USEPA 1991a).

- ***Accuracy of models* –** TMDLs are developed with a wide range of approaches and models. Regardless of the approach, there are often concerns regarding oversimplifications, insufficient data or lack of confidence in complex models. No guidance is available that specifically recommends the level of accuracy expected for modeling studies.

- ***Water quality standards formulation*** – TMDLs often involve some degree of interpretation of applicable water quality standards. Standards may be narrative and may require a determination of a representative numeric value. Other examples include criteria that are not defined precisely (e.g., no frequency or duration) or situations where the parameter included in the standards is not suited to modeling (e.g., turbidity). Models may not be able to directly predict the endpoint associated with the water quality standard.

- ***Pollutant focus of TMDLs*** – TMDLs are developed to address specific impairments associated with a pollutant as identified on the 303(d) list (40 CFR 130.7(c)). Protection of designated uses, such as aquatic life support, may require an approach that addresses multiple stressors and the cumulative benefit on the impaired water. Some stressors, such as low flow or poor habitat, that affect aquatic life uses are not defined as pollutants under the CWA (§ 502(6)) and therefore do not require TMDLs. Watershed studies, which may or may not include a TMDL, may need to address broader ecological modeling or multiple stressor analyses.

Pollutant vs. Pollution

Pollutant. Dredged spoil, solid waste, incinerator residue, sewage, garbage, sewage sludge, munitions, chemical wastes, biological materials, radioactive materials, heat, wrecked or discarded equipment, rock, sand, cellar dirt and industrial, municipal, and agricultural waste discharged into water. (CWA § 502(6)).

Pollution. Generally, the presence of matter or energy whose nature, location, or quantity produces undesired environmental effects. In 40 CFR 130.2(c), pollution is defined as "The man-made or man-induced alteration of the chemical, physical, biological, and radiological integrity of water."

Chapter 3 What is a Model?

The term "model" describes the set of equations or algorithms that are used to simulate a physical system. In this report, "model" also refers to a variety of available software tools that automate the calculation of equations or groups of equations representing the system. To address a specific technical problem, an analyst may choose to apply an existing model, apply multiple models alone or in combination, modify an existing model, or develop a site-specific model. Each application of a model must be designed to meet the analytical needs of the specific system.

Model Complexity

Models are developed at various levels of complexity, depending on the application needs. The simplest models provide general predictions based on a limited set of environmental or physical factors. One example might be a loading rate model that provides an estimate of annual pollutant load as a simple function of land use type. These simplified approaches group physical processes and provide generalized estimates of response. Empirical equations, that build functional relationships based on long-term studies and statistical analysis, are typically used in simplified models (e.g., Universal Soil Loss Equation [USLE]). Simplified techniques, due to their inherent generalizations, are limited in applicability to the various pollutants and waterbodies addressed by TMDLs. On the other end of the spectrum are physically based models that seek to describe the fundamental processes that are associated with water, sediment, and pollutant movement, transport, transformation, and delivery. Physically based models describe fundamental processes, such as infiltration, through the use of scientifically based equations. The most sophisticated models will solve fundamental equations on a detailed spatial and temporal scale. Physically based models require additional data to estimate the various parameters used in the solution techniques. For example, infiltration calculations might require detailed information on precipitation, evaporation, slope, soil conductivity, soil profiles, and vegetated cover.

Additional Modeling Definitions

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

Lumped model. A model in which the physical characteristics for land units within a subwatershed unit are assumed to be homogeneous.

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

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

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.

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

The complexity of models is also a function of the spatial representation of the heterogeneity of the watershed or waterbody. The simplest watershed models group large areas by land use category. Similarly, a simplified lake model represents the lake as one large unit. More detailed watershed models will represent land areas as a network with grid cells that have defined land and soil features. Other watershed models compromise by using a hydrologically based network of subwatersheds and stream segments to represent the system. Within each subwatershed, the individual land use units are "lumped" based on similar characteristics (e.g., land use, soils, slope). This lumped approach simplifies the physical representation of the subwatershed and does not distinguish between small parcels and contiguous parcels of land areas within a subwatershed. Models are also distinguished by their temporal complexity – with simple models that use long timesteps (i.e., annual, seasonal) and detailed models that have timesteps of hours or minutes. Even the most detailed models are built using a combination of empirical and physically based techniques, with varying degrees of flexibility for users to select the spatial and temporal scale of the application.

Alternatives Analysis

Models can help evaluate and quantify the potential effects of alternative plans and operational schemes and help understand the relationships between natural systems and human influences on those systems. For TMDLs and watershed studies, models are particularly useful in evaluating the likely benefits and drawbacks associated with various loading alternatives and their effect on specific quantifiable endpoints that represent compliance with water quality standards. Central to the application of models is support for alternatives analysis. Modeling analyses can be used to test multiple scenarios, with various allocations to nonpoint and point sources (i.e., LA and WLAs). Among the scenarios, one or more may meet water quality standards; however, some distributions of loading may not be technically feasible or accepted by stakeholders. Using the model to develop an understanding of the magnitude of each source, its geographic location, and the sensitivity of the receiving water to changes in source loading supports the selection of feasible or preferred allocations. The allocation or alternatives analysis is typically performed based on the following discrete steps, as illustrated in Figure 3-1:

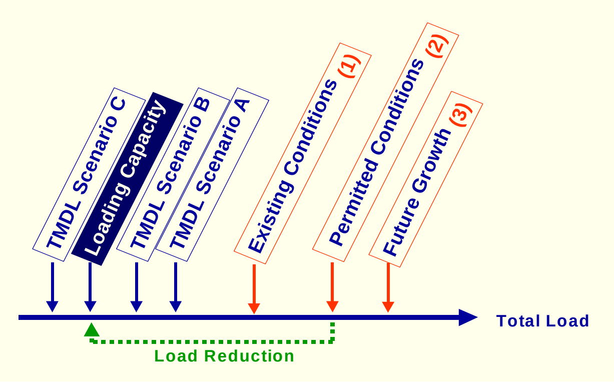

Figure 3-1. Steps for performing allocation analysis.

- ***Step 1: Application of the Model to Existing Conditions*** – This application represents the current condition (e.g., observed water quality, current loadings) and is compared to available monitoring data for model testing and calibration. Point sources are set at representative discharge concentrations, reflective of permit monitoring data. Representative concentrations may be lower or higher than permit limits.

- ***Step 2: Application of the Model to Existing Conditions with Point Sources at Permit Limits*** – This application establishes the baseline condition, which will be reduced to meet the allowable load. The point sources are set at permit limits for flow and pollutant concentration. If no permitted flow is available, the design flow or historic observed flow can be used. If the permit does not include a permit limit for the affected pollutant, then the observed concentration can be used.

- ***Step 3: Application of the Model to Future Conditions*** – When future growth is considered, it can be added to the nonpoint or point source loading contributions.

- ***Step 4: Develop and Test Allocation Scenarios*** – Working from the baseline condition (Step 2, or Step 3 if future growth is considered), sample allocation scenarios are applied with a variety of source reductions. These scenarios are shown as A, B, and C in Figure 3-1. The results of each scenario are compared with the applicable water quality standard, and scenarios are adjusted until water quality standards (or loading capacity) are achieved.

- ***Step 5: Select Final TMDL Scenario*** – Once the final TMDL scenario is selected, results are processed to provide the required TMDL elements.

Model Development

Models include suites of equations that represent key processes. Conventional wisdom indicates that the simplest model sufficient to answer management questions with confidence should be applied. Analysts will need to consider the level of complexity needed and appropriate for a given application. Additional complexity, in the form of more detailed simulation of physically based processes and higher spatial and temporal resolution, requires more experience, time, data, and resources to implement. However, the selected model will need to include sufficient description of processes to preserve sensitivity to evaluate management techniques or alternatives and the effects on the relevant performance measures. In other words, if the chosen TMDL model is not capable of quantifying the potential response of the selected endpoints to changes in source loads, that model is inadequate to the task.

The complexity of a model application can also be adjusted by configuring a specific modeling system. Typically, detailed modeling systems include the flexibility to select processes and define the appropriate spatial and temporal detail. For example, the Hydrological Simulation Program—FORTRAN (HSPF) provides the ability to use detailed descriptions of land runoff and erosion processes. But HSPF can also be applied without including explicit erosion processes. Simplified models are more limited by their original formulation and defining assumptions. For example, the GWLF model does not include simulation of in-stream processes, and no alternative formulations are offered. The user of a model makes numerous choices during model setup that define the complexity of a particular model application. The user defines spatial and temporal resolution, the specific processes simulated, and the level of detail of the analysis. For example, based on user setup selections, a model such as Stormwater Management Model (SWMM) can include pollutant simulation using a description of buildup and washoff of dust and dirt or a simpler approach, where a fixed concentration (e.g., event mean concentration [EMC]) is assigned to runoff. When applying the model to a specific watershed or waterbody, the user will also determine the spatial resolution of the model—how many land use categories, subwatersheds, and waterbody features to simulate. These decisions allow the user to change the level of complexity from a simplified approach to a more detailed analysis.

Integration of management practices will also affect the development of models for TMDL development and watershed assessments. Point sources that are discrete discharges, located at well-defined discharge points, typically will need to be represented individually to determine individual WLAs. Other management practices for wet-weather point sources, including combined sewer overflows, sanitary system overflows, and stormwater, and nonpoint sources can be represented in varying levels of detail depending on the pollutant type, watershed and waterbody conditions, and the level of detail of the management planning analysis. In most states, an implementation plan is not a required element of a TMDL, and detailed description of BMPs is not required. However, increasingly, TMDL practitioners are using models to demonstrate management techniques that can be used to achieve the needed load reductions. The 319 program guidelines also identify the need to evaluate load reductions and identify management measures needed to achieve the load reductions.

The spatial detail required for simulation of BMPs, especially stormwater and nonpoint source management techniques, place particular challenges on the development of practical and cost-effective model applications. Most applications use simplified estimates of BMP adoption and benefit to evaluate the potential for load reduction. Land use-based management might be represented by a general representation of a reduction in loading. For example, a change in crop practice could be estimated by percentage reduction in cropland loading expressed as a percentage of the total load. In detailed simulations, individual BMPs can be applied and their effects on water quality simulated. For example, in an urban watershed, specific stormwater management ponds can be simulated as a hydrologic unit and the trapping of runoff and pollutants simulated for each pond. Although simulation of individual BMPs can be achieved using existing modeling systems, the effort for data collection and modeling for watershed-wide applications is often too high. The selection and placement of the specific BMPs are typically addressed later, as part of a watershed implementation planning study. Often, implementation planning includes less rigorous modeling and focuses more on technical and budget-related specifics. In some studies, a "nested" model development process is used, where a small-scale, detailed evaluation of BMP performance is used as a basis for extrapolation to a larger watershed. Some studies use small-scale monitoring studies and literature values of BMP effectiveness to support watershed-wide estimates.

Integrated Modeling Systems and Linked Models

For watersheds with multiple land and water features, such as a land areas, rivers, canals, reservoirs, and estuaries, more than one model is often needed. In TMDL studies, representation of sources and receiving waters often requires two or more models. Modelers often connect or "link" models together to describe an entire system. The use of multiple models is necessary when multiple features of the system cannot be sufficiently described by one model. These linkages between models (either available modeling software systems or customized systems) can be static or dynamic. A static linkage takes output from one model and uses it as input to a second model. A dynamic linkage can be bi-directional, where information from each timestep transfers back and forth between the models and affects both simulations. Modelers often implement linkages through a simple file transfer system or a common database. Some models or modeling software systems provide software-enabled linkages so that all file exchange requirements are automatically performed as the models are applied.

Integrated modeling systems may also provide software that facilitates data exchange; uses common spatial and point data formats; and prepares input files. Often, shared tools support data management, Web-based data downloads, model setup, and post-processing. Some modeling systems are based on independent models with an open set of supporting tools. Other systems provide a unified system with a single interface that launches and manages several models concurrently.

Trends in Model Development

Models are needed to address the new questions that watershed managers ask that reflect the 21st century trends in policy and environmental decision-making. Many models are applied as part of larger scale watershed management studies that address multiple objectives, including TMDLs. Questions that models might be used to evaluate include:

- The implications of long-term changes in land use
- Competition among dischargers for limited assimilative capacity
- Conjunctive use of water resources for water supply, recreation, and aquatic life
- Management of harbors and shipping channels to maintain navigation and aquatic life support
- Planning for effective, targeted implementation of TMDLs
- Addressing multiple concurrent programs such as NPDES, TMDL, Endangered Species, Wetlands, and Source Water Protection
- Cost effectiveness of management alternatives
- Optimization techniques to help select alternatives that minimize cost and maximize benefit
- Implication of global climate changes on long-term changes in water quantity and quality

New technical challenges will be placed on modeling to support environmental decisions and emerging programmatic needs. This review will ultimately focus on identifying those specific areas where technical development is needed to support TMDL development and related programs. However, an initial review of existing trends in model use can help to develop a preliminary list of key technical needs.

- Less-familiar pollutant types will need to be analyzed. Many studies, especially for TMDLs and watershed and estuary restoration, have been performed to assess nutrients, dissolved oxygen, sediment, pathogens, and metals. But many more pollutant types will need to be addressed, including chloride, Dichloro-Diphenyl-Trichloroethane (DDT), polychlorinated biphenyls (PCBs), and mercury. Existing models and available supporting data are limited in the range of chemical processes and pollutants they can represent.
- The range of source types will need to be expanded. Typical modeling applications have focused on dominant, general source categories, such as “agriculture,” “urban,” “forest.” New studies will likely need to address more specific source types or source loading characteristics, such as agricultural specialty crops (e.g., strawberries), golf courses, or ski areas.
- Improved techniques are needed to address complex hydrologic conditions, such as high water tables with surface-to-groundwater interactions, pumped and managed systems, dams, decreasing baseflow due to groundwater pumping, or complex geology (e.g., karst).
- Competition for resources, management of airborne sources (i.e., mercury, nitrogen), and watershed-based management needs will increasingly require cross-media analyses (air-land-surface water-groundwater).

- Contaminated sediment problems and the need to examine restoration alternatives and dredging implications will require more detailed simulation of sediment transport and sediment chemistry.
- Evaluation of designated use support in waters of the United States and watershed management implications will require further analysis of aquatic life and terrestrial habitat (i.e., ecological models).
- An expanded focus on cost-effective implementation will drive technical development in modeling systems to include simulation of management practices, consider management cost, and include optimization techniques.
- Global climate change and rapid urbanization will require modeling of future conditions under changing land use and meteorological conditions, requiring more sophisticated land use and meteorologic projection techniques.
- As models are increasingly used to support decisions that result in significant financial investment for restoration and infrastructure, the defensibility and accuracy of models will be challenged. Techniques will be needed to support model testing, calibration support, verification, and uncertainty analysis.

Chapter 4 Available Models

This review initially focuses on models that are available today for simulation of watershed and receiving water conditions. The review emphasizes public domain models, although some selected private or proprietary models are included if they are published, provide significant technical benefit, or are typically used in TMDL development. Preparing the review categories considered prior model reviews including Kalin and Hantush (2003) and USEPA (1997) and online systems such as EPA's Council on Regulatory Environmental Modeling (CREM) Knowledge Base structure (http://cfpub.epa.gov/crem/knowledge_base/knowbase.cfm).

Most models focus on particular land-water features; some are dominantly receiving water models, while others are primarily oriented to calculating watershed loading. Both receiving water and watershed models can incorporate the ability to simulate management techniques. For this review, two major categories of models are recognized and used for evaluation and comparison:

- **Receiving water models (Hydrology, Water Quality).** This group of models emphasizes description of hydrology and water quality of water conveyance systems, including rivers, canals, reservoirs, lakes and estuaries. Some include bi-directional flow, pumps, and operations in freshwater systems. Others include evaluation of tidal systems and the influences of wind, waves, and tides on mixing. Water quality simulation involves representation of sediment and pollutant transport and transformation. Some models include ecological processes, such as vegetative growth, aquatic organisms and aquatic productivity. Not all receiving water models address water quality. Sometimes, water quality functions are provided by linking hydrologic and water quality models.
- **Watershed models.** This group of models emphasizes description of watershed hydrology and water quality, including runoff, erosion, and washoff of sediment and pollutants. Some models include surface-groundwater interactions and simplified groundwater transport. Some also include internally linked river transport and water quality processes and reservoirs.

Table 4-1 provides a summary of currently available models included in this review with contact information and support for watershed, receiving water, and other key features. Some models simulate BMP performance and treatment capabilities. Models continue to be expanded to address multiple categories of analysis, such as watershed models that include BMP analysis (e.g., SWMM), or receiving water models that include hydrology and water quality (e.g., Environmental Fluid Dynamics Code [EFDC]). Some models are identified as "system," to recognize that these systems support multiple models (e.g., the EPA TMDL Modeling Toolbox includes linkages between watershed models and receiving water models). Integrated systems are included in the list of models and include the multiple capabilities of their component models. This review uses the model categories for descriptive purposes but recognizes that available models may support both watershed and receiving water simulations.

Table 4-1. Summary of Available Models

Model Acronym	Full Model Name	Source	Receiving Water—Hydrodynamics	Receiving Water—Water Quality	Watershed	BMP	System	Statistical	Process-based
AGNPS	Agricultural Nonpoint Source Pollution Model	USDA-ARS	—	—	●	●	—	—	●
AGWA	Automated Geospatial Watershed Assessment	USDA-ARS	—	●	●	●	●	—	●
AnnAGNPS	Annualized Agricultural Nonpoint Source Pollution Model	USDA-ARS	—	—	●	●	—	—	●
AQUATOX	—	EPA	—	●	—	—	—	—	●
BASINS	Better Assessment Science Integrating Point and Nonpoint Sources	EPA	●	●	●	●	●	—	●
CAEDYM	Computational Aquatic Ecosystem Dynamics Model	University of Western Australia	●	●	—	—	—	—	●
CCHE1D	—	University of Mississippi	●	●	—	—	—	—	●
CE-QUAL-ICM/ TOXI	—	USACE	—	●	—	—	—	—	●
CE-QUAL-R1	—	USACE	●	●	—	—	—	—	●
CE-QUAL-RIV1	—	USACE	●	●	—	—	—	—	●
CE-QUAL-W2	—	USACE	●	●	—	—	—	—	●
CH3D-IMS	Curvilinear-grid Hydrodynamics 3D—Integrated Modeling System	University of Florida, Department of Civil and Coastal Engineering	●	●	—	—	—	—	●
CH3D-SED	Curvilinear Hydrodynamics 3D—Sediment Transport	USACE	●	●	—	—	—	—	●
DELFT3D	—	WL | Delft Hydraulics	●	●	—	—	—	—	●
DIAS/IDLMAS	Dynamic Information Architecture System/Integrated Dynamic Landscape Analysis and Modeling System	Argonne National Laboratory	—	—	●	●	●	—	●
DRAINMOD	—	North Carolina State University	—	—	●	●		—	●
DWSM	Dynamic Watershed Simulation Model	Illinois State Water Survey	—	●	●	●	—	—	●
ECOMSED	Estuary and Coastal Ocean Model with Sediment Transport	HydroQual, Inc.	●	●	—	—	—	—	●
EFDC	Environmental Fluid Dynamics Code	EPA and Tetra Tech, Inc.	●	●	—	—	—	—	●

Model Acronym	Full Model Name	Source	Receiving Water—Hydrodynamics	Receiving Water—Water Quality	Watershed	BMP	System	Statistical	Process-based
EPIC	Erosion Productivity Impact Calculator	Texas A&M University—Texas Agricultural Experiment Station	—	—		●	—	—	●
GISPLM	GIS-Based Phosphorus Loading Model	College of Charleston, Stone Environmental, and Dr. William Walker (for Vermont DEC)	—	—	●	●	—	—	●
GLEAMS	Groundwater Loading Effects of Agricultural Management Systems	USDA-ARS	—	—	—	●	—	—	●
GLLVHT	Generalized, Longitudinal-Lateral-Vertical Hydrodynamic and Transport	J.E. Edinger Associates, Inc.	●	●	—	—	—	—	●
GSSHA	Gridded Surface Subsurface Hydrologic Analysis	USACE	—	—	●	●	—	—	●
GWLF	Generalized Watershed Loading Functions	Cornell University	—	—	●	—	—	—	●
HEC-6	Scour and Deposition in Rivers and Reservoirs	USACE	●	●	—	—	—	—	●
HEC-6T	Sedimentation in Stream Networks	USACE	●	●	—	—	—	—	●
HEC-HMS	Hydraulic Engineering Center Hydrologic Modeling System	USACE	—	—	●	—	—	—	●
HEC-RAS	Hydrologic Engineering Center River Analysis System	USACE	●	—	—	—	—	—	●
HSCTM-2D	Hydrodynamic, Sediment, and Contaminant Transport Model	EPA	●	●	—	—	—	—	●
HSPF	Hydrologic Simulation Program—FORTRAN	EPA	—	●	●	●	—	—	●
KINEROS2	Kinematic Runoff and Erosion Model, v2	USDA-ARS	—	—	●	●	—	—	●
LSPC	Loading Simulation Program in C++	EPA and Tetra Tech, Inc.	—	●	●	●	—	—	●
MCM	Mercury Cycling Model	Tetra Tech, Inc	●	●	—	—	—	—	●
Mercury Loading Model	Watershed Characterization System—Mercury Loading Model	EPA	—	—	●	—	—	—	●
MIKE 11	—	Danish Hydraulic Institute	●	●	—	—	—	—	●
MIKE 21	—	Danish Hydraulic Institute	●	●	—	—	—	—	●
MIKE SHE[1]	—	Danish Hydraulic Institute	●	—	●	●	●	—	●

Model Acronym	Full Model Name	Source	Receiving Water—Hydrodynamics	Receiving Water—Water Quality	Watershed	BMP	System	Statistical	Process-based
MINTEQA2	Metal Speciation Equilibrium Model for Surface and Ground Water	EPA	—	●	—	—	—	—	●
MUSIC	Model for Urban Stormwater Improvement Conceptualization	Monash University, Cooperative Research Center for Catchment Hydrology	—	—	●	●	—	—	●
P8-UCM	Program for Predicting Polluting Particle Passage through Pits, Puddles, and Ponds—Urban Catchment Model	Dr. William Walker	—	—	●	●	—	—	●
PCSWMM	Stormwater Management Model	Computational Hydraulics Int.	—	●	●	●	—	—	●
PGC – BMP	Prince George's County Best Management Practice Module	Prince George's County, MD	—	—	—	●	—	—	●
QUAL2E	Enhanced Stream Water Quality Model	EPA	—	●	—	—	—	—	●
QUAL2K	—	Dr. Steven Chapra, EPA TMDL Toolbox	—	●	—	—	—	—	●
REMM	Riparian Ecosystem Management Model	USDA-ARS	—	—	—	●	—	—	●
RMA-11	—	Resource Modelling Associates	●	●	—	—	—	—	●
SED2D	—	USACE	●	●	—	—	—	—	●
SED3D	Three-Dimensional Numerical Model of Hydrodynamics and Sediment Transport in Lakes and Estuaries	EPA	●	●	—	—	—	—	●
SHETRAN	—	University of Newcastle (UK)	●	●	●	—	—	—	●
SLAMM	Source Loading and Management Model	University of Alabama	—	—	●	●	—	●	—
SPARROW	SPAtially Referenced Regression On Watershed Attributes	USGS	—	—	●	—	—	●	—
STORM	Storage, Treatment, Overflow, Runoff Model	USACE (Mainframe version), Dodson & Associates, Inc. (PC version)	—	—	●	●	—	●	●
SWAT	Soil and Water Assessment Tool	USDA-ARS	—	●	●	●	—	—	●
SWMM	Storm Water Management Model	EPA	—	●	●	●	—	—	●
Toolbox	TMDL Modeling Toolbox	EPA	●	●	●	●	●	—	●

Model Acronym	Full Model Name	Source	Receiving Water—Hydrodynamics	Receiving Water—Water Quality	Watershed	BMP	System	Statistical	Process-based
TOPMODEL	—	Lancaster University (UK), Institute of Environmental and Natural Sciences	—	—	●	—	—	—	●
WAMView	Watershed Assessment Model with an ArcView Interface	Soil and Water Engineering Technology, Inc. (SWET) and EPA	—	●	●	●	—	—	●
WARMF	Watershed Analysis Risk Management Framework	Systech Engineering, Inc.	—	●	●	●	—	—	●
WASP	Water Quality Analysis Simulation Program	EPA	●[2]	●	—	—	—	—	●
WEPP	Water Erosion Prediction Project	USDA-ARS	—	—	●	●	—	—	●
WinHSPF	Interactive Windows Interface to HSPF	EPA	—	●	●	●	—	—	●
WMS	Watershed Modeling System (Version 7.0)	Environmental Modeling Systems, Inc.	●	●	●	●	●	—	●
XP-SWMM	Stormwater and Wastewater Management Model	XP Software, Inc.	—	●	●	●	—	—	●

[1] When MIKE SHE is fully linked to MIKE 11, it can be characterized as a system and is able to simulate receiving water hydrodynamics
[2] Only when WASP is used together with DYNHYD–a hydrodynamic program for WASP
USDA-ARS = U.S. Department of Agriculture, Agricultural Research Service
USACE = U.S. Army Corps of Engineers
USGS = U.S. Geological Survey

Receiving water model simulation capabilities are examined in greater detail in Table 4-2. The type, complexity and water quality simulation capabilities are identified for each model. Model type is categorized as follows:

- **Steady State.** These models operate under a single nonvariable flow condition. Steady state models are typically used to evaluate a design flow.
- **Quasi-dynamic.** Quasi-dynamic models allow for limited variation, typically a variation in meteorologic conditions over the course of day, to examine variability.
- **Dynamic.** These models allow for variations in both flow and meteorologic conditions on a small timestep, typically shorter than daily.

Level of complexity in receiving water models is also evaluated based on spatial detail described as one, two or three dimensions. Most three-dimensional models also have the ability to be applied in one- or two-dimensional modes.

Descriptions of water quality capabilities are based on support for specific pollutants or parameters.

Watershed model capabilities are reviewed in Table 4-3. For watershed models, the evaluation is based on five separate factors: type, complexity, timestep, hydrology, and water quality. Types of watershed models are generally classified as landscape only, simulating only land-based processes, and comprehensive models, including land and conveyance systems (e.g., rivers, pipes). Complexity in watershed models is classified on three levels:

- **Export functions** are simplified rates that estimate loading based on a very limited set of factors (e.g., land use).
- **Loading functions** are empirically based estimates of load based on generalized meteorologic factors (e.g., precipitation, temperature).
- **Physically based** include more physically based representations of runoff, pollutant accumulation and washoff, and sediment detachment and transport. Most detailed models use a mixture of empirical and physically based algorithms.

Timestep, a defining characteristic of models, is often a factor in the comparison of model results to evaluate management alternatives. If a model is limited to simulation of individual events, it is noted next to the model name. If not specified, the model is capable of continuous simulation that provides an ongoing account of flow and load. The table identifies the smallest timestep supported by a model (e.g., hourly, daily). If larger output timesteps are needed, model output can be summarized from smaller timesteps. Hydrology evaluation criteria consider whether a model includes surface runoff only, or if surface and groundwater inputs are considered. Most comprehensive watershed models include a groundwater factor to account for baseflow contributions to streams and rivers. Finally, water quality capabilities are evaluated based on the pollutants or parameters simulated by the model. Depending on the level of complexity, the model may use various techniques to simulate the behavior of the individual pollutants.

Management practice simulation capabilities of watershed and receiving water models are evaluated in more detail in Table 4-4. Some models specialize in the representation of agricultural areas and include capabilities to evaluate various crops, crop rotations, tillage practices, and impoundments. Other models are primarily oriented to urban areas and typically include the ability to evaluate various structural solutions, such as detention ponds. The simulation of management practices is evaluated based on the scale, complexity, hydrology, and water quality. The final category identified the specific BMP types considered by the model. For BMP modeling assessment, model scale is defined as field, BMP, or generalized, as follows:

- **Field practices** refers to models that assess land use management for one or more single uniform land drainage area. These models are typically used in agricultural applications to examine crop rotation, tillage, or nutrient management practices on a small scale or as part of a larger watershed modeling simulation.
- **BMP** refers to models that can assess one or more individual BMPs and their influence on hydrology or water quality loading.
- **Generalized** identifies models that include a technique to estimate the effect of management as a gross or larger-scale effects, typically through the use of percentage reductions at the land use or subwatershed scale.

Hydrology evaluation describes the hydrologic processes of storage, overflow, infiltration and routing that typically describe BMPs. These hydrologic processes are fundamental to a more physically based description of the BMPs and are a basis for evaluation of related pollutant removal techniques. Water quality evaluation criteria consider the support for various pollutants. “Types of BMPs” provides a listing of the support for the major or most commonly encountered practices. “Vegetative practices” refers to BMPs that use vegetation as part of a system to slow runoff and help stormwater infiltrate the soil and settle particulates. Examples of vegetative practices include stream buffer zones, disturbed area stabilization (with mulch, sod, permanent vegetation, temporary vegetation), filter strips, and grass swales.

Each model included in the review is also described in a longer fact sheet (Appendix). The fact sheet includes a narrative discussion of essential features of each model and provides a comprehensive evaluation of the individual model software, tools, and supporting features. Each of the identified models was evaluated on key technical, practical, and software related capabilities. The evaluation format for the fact sheet is structured to support future use in a database format and facilitate comparison of models. The structure of the model fact sheets and definitions for each category are shown in Table 4-5.

Table 4-2. Summary of Receiving Water Simulation Capabilities

	Type			Level of Complexity			Water Quality							
Model	**Steady state**	**Quasi-dynamic**	**Dynamic**	**One-dimensional**	**Two-dimensional**	**Three-dimensional**	**User-defined**	**Sediment**	**Nutrients**	**Toxics**	**Metals**	**BOD**	**Dissolved oxygen**	**Bacteria**
AQUATOX	—	—	●	● (vert)	—	—	—	●	●	●	—	●	●	—
BASINS	—	●	●	●	—	—	●	●	●	●	●	●	●	●
CAEDYM	—	—	●	●	●	●	●	●	●	—	●	●	●	●
CCHE1D	—	—	●	●	—	—	—	●	—	—	—	—	—	—
CE-QUAL-ICM/TOXI	—	—	●	●	●	●	●		●	—	●	●	●	—
CE-QUAL-R1	—	—	●	●	—	—	—	●	●	—	●	●	●	●
CE-QUAL-RIV1	—	—	●	●	—	—	—	—	●	—	●	●	●	●
CE-QUAL-W2	—	—	●	—	●	—	—	—	●	—	—	●	●	●
CH3D-IMS	—	—	●	●	●	●	—	●	●	—	—	●	●	—
CH3D-SED	—	—	●	●	●	●	—	●	—	—	—	—	—	—
DELFT3D	—	—	●	●	●	●	●	●	●	●	●	●	●	●
DWSM	—	—	●	●	—	—	—	●	●	●	—	—	—	—
ECOMSED	—	—	●	●	●	●	—	●	—	—	—	—	—	—
EFDC	—	—	●	●	●	●	●	●	●	●	●	●	●	●
GISPLM	—	—	—	—	—	—	—	—	●	—	—	—	—	—
GLLVHT	—	—	●	—	—	●	—	●	●	—	—	●	—	●
GSSHA	—	—	●	—	●	—	—	●	—	—	—	—	—	—
HEC-6	—	—	●	●	—	—	—	●	—	—	—	—	—	—
HEC-6T	—	—	●	●	—	—	—	●	—	—	—	—	—	—
HEC-RAS	—	—	●	●	—	—	—	—	—	—	—	—	—	—

Model	Type: Steady state	Type: Quasi-dynamic	Type: Dynamic	Level of Complexity: One-dimensional	Level of Complexity: Two-dimensional	Level of Complexity: Three-dimensional	Water Quality: User-defined	Water Quality: Sediment	Water Quality: Nutrients	Water Quality: Toxics	Water Quality: Metals	Water Quality: BOD	Water Quality: Dissolved oxygen	Water Quality: Bacteria
HSCTM-2D	—	—	●	—	●	—	—	●	—	—	—	—	—	—
HSPF	—	—	●	●	—	—	●	●	●	●	●	●	●	●
LSPC	—	—	●	●	—	—	●	●	●	●	●	—	—	●
MCM	—	—	●	●	—	—	—	—	—	—	● (Hg)	—	—	—
MIKE 11	●	—	●	—	●	—	—	—	—	—	—	—	—	—
MIKE 21	—	—	●	—	●	—	—	●	●	●	●	●	●	●
MINTEQA2	●	—	—	—	—	—	—	—	—	—	●	—	—	—
PCSWMM	—	—	●	●	—	—	●	●	●	●	●	—	—	●
QUAL2E	—	●	—	●	—	—	●	—	●	—	—	●	●	●
QUAL2K	—	●	—	●	—	—	●	—	●	—	—	●	●	●
RMA-11	—	—	●	●	●	●	●	●	●	—	—	●	●	—
SED2D	—	—	●	—	●	—	—	●	—	—	—	—	—	—
SED3D	—	—	●	●	●	●	—	●	—	—	—	—	—	—
SHETRAN	—	—	●	●	—	—	—	●	—	—	—	—	—	—
SWAT	—	●	—	●	—	—	—	●	●	●	●	●	●	—
SWMM	—	—	●	●	—	—	●	●	●	●	●	—	—	●
Toolbox	—	●	●	●	●	●	●	●	●	●	●	●	●	●
WAMView	—	—	●	●	—	—	—	●	●	—	—	●	●	●
WARMF	—	—	●	●	●	—	—	●	●	●	●	●	●	●
WASP	—	—	●	●	●	●	●	●	●	●	●	●	●	—
WinHSPF	—	—	●	●	—	—	●	●	●	●	●	●	●	●
WMS	—	—	●	●	●	—	●	●	●	●	●	●	●	●
XP-SWMM	—	—	●	●	—	—	●	●	●	●	●	—	—	●

BOD = Biochemical oxygen demand

Table 4-3. Summary of Watershed Simulation Capabilities

Model	Type		Level of Complexity			Timestep				Hydrology		Water Quality						
	Grid-based	Stream routing included	Export coefficients	Loading functions	Physically based	Sub-daily	Daily	Monthly	Annual	Surface	Surface and groundwater	User-defined	Sediment	Nutrients	Toxics/pesticides	Metals	BOD	Bacteria
AGNPS (event based)	●	●	—	—	●	●	—	—	—	●	—	—	●	●	●	—	—	—
AnnAGNPS	—	●	—	—	●	—	●	—	—	●	—	—	●	●	●	—	—	—
BASINS	—	●	●	●	●	●	●	—	—	●	●	●	●	●	●	●	●	●
DIAS/IDLMAS	—	—	—	—	—	—	—	—	●	—	—	—	●	—	—	—	—	—
DRAINMOD	—	—	—	—	●	●	—	—	—	—	●	—	—	●	—	—	—	—
DWSM (event based)	—	●	—	—	●	●	—	—	—	●	—	—	●	●	●	—	—	—
EPIC	—	—	—	—	—	—	●	—	—	●	—	—	●	●	●	—	—	—
GISPLM	—	●	—	●	—	—	●	—	—	●	—	—	—	●	—	—	—	—
GLEAMS	—	—	—	—	—	—	●	—	—	●	—	—	●	●	●	—	—	—
GSSHA	●	●	—	—	●	●	—	—	—	—	●	—	●	—	—	—	—	—
GWLF	—	●	—	●	—	—	—	●	—	—	●	—	●	●	—	—	—	—
HSPF	—	●	—	—	●	●	—	—	—	—	●	●	●	●	●	●	●	●
HEC-HMS	—	●	—	—	●	●	—	—	—	●	—	—	—	—	—	—	—	—
KINEROS2 (event based)	—	●	—	—	●	●	—	—	—	●	—	—	●	—	—	—	—	—
LSPC	—	●	—	—	●	●	—	—	—	—	●	●	●	●	●	●	●	●
Mercury Loading Model	—	—	—	—	●	—	—	—	●	●	—	—	—	—	—	● (Hg)	—	—
MIKE SHE	—	●	—	—	●	●	—	—	—	—	●	—	—	—	—	—	—	—
MINTEQA2	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	●	—	—
MUSIC	—	—	—	—	●	●	—	—	—	●	—	●	—	—	—	—	—	—
P8-UCM	—	—	●	●	—	●	—	—	—	●	—	●	●	●	—	●	—	—

	Type		Level of Complexity			Timestep				Hydrology		Water Quality						
Model	**Grid-based**	**Stream routing included**	**Export coefficients**	**Loading functions**	**Physically based**	**Sub-daily**	**Daily**	**Monthly**	**Annual**	**Surface**	**Surface and groundwater**	**User-defined**	**Sediment**	**Nutrients**	**Toxics/pesticides**	**Metals**	**BOD**	**Bacteria**
PCSWMM	—	●	—	●	●	●	—	—	—	—	●	●	●	●	●	●	—	●
PGC – BMP	—	—	—	●	—	●	—	—	—	—	—	—	●	●	—	●	—	—
SHETRAN	—	●	—	—	●	●	●	—	—	—	●	—	●	—	—	—	—	—
SLAMM	—	—	—	—	—	●	—	—	—	●	—	—	●	●	—	●	—	—
SPARROW	—	●	—	—	—	—	—	—	●	●	—	—	●	●	●	—	—	—
STORM	—	—	●	—	●	●	—	—	—	●	—	—	●	●	—	—	—	●
SWAT	—	●	—	—	●	—	●	—	—	—	●	—	●	●	●	●	—	—
SWMM	—	●	—	—	●	●	—	—	—	—	●	●	●	●	●	●	●	●
Toolbox	—	●	—	—	●	●	—	—	—	—	●	●	●	●	●	●	●	●
TOPMODEL	—	—	—	—	●	●	●	—	—	—	●	—	—	—	—	—	—	—
WAMView	●	●	—	—	●	●	—	—	—	—	●	—	●	●	●	●	—	●
WARMF	—	●	—	—	●	—	●	—	—	—	●	—	●	●	●	●	●	●
WEPP	—	—	—	—	●	—	●	●	●	—	●	—	●	—	—	—	—	—
WinHSPF	—	●	—	—	●	●	—	—	—	—	●	●	●	●	●	●	●	●
WMS	—	●	—	—	●	●	—	—	—	—	●	●	●	●	●	●	●	●
XP-SWMM	—	●	—	—	●	●	—	—	—	—	●	●	●	●	●	●	●	●

Table 4-4. Summary of Management Practice Simulation Capabilities

Model	Type		Level of Complexity		Hydrology					Water Quality						Types of BMPs				
	Field practices	BMP	Generalized	Detailed	Storage	Overflow	Infiltration	Routing	User-defined	Sediment	Phosphorus	Nitrogen	Pesticides	Metals	Bacteria	Detention basin	Infiltration practices	Vegetative practices	Wetlands	Other structures
AGNPS	●	●	●	—	—	—	●	●	—	●	●	●	●	—	—	●	—	●	—	—
AnnAGNPS	●	●	●	—	—	—	●	●	—	●	●	●	●	—	—	●	—	●	—	—
AQUATOX	—	●	—	—	—	—	—	—	●	—	●	●	—	—	—	●	—	—	—	—
BASINS	●	●	●	●	—	—	—	—	—	●	●	●	●	—	—	●	—	●	—	●
DIAS/IDLMAS	—	●	●	—	—	—	—	—	—	●	—	—	—	—	—	—	—	—	—	—
DRAINMOD	●	—	—	●	●	●	●	—	—	—	—	●	—	—	—	—	—	—	●	—
DWSM	—	●	—	●	—	—	●	●	—	●	●	●	●	—	—	●	●	—	—	—
EPIC	●	—	—	●	●	●	●	—	—	●	●	●	●	—	—	●	●	—	●	—
GISPLM	—	●	●	—	—	—	—	—	—	—	●	—	—	—	—	—	—	—	—	—
GLEAMS	●	●	—	●	—	●	●	—	—	●	●	●	●	—	—	—	—	—	—	—
GSSHA	●	●	—	●	—	—	●	●	—	●	—	—	—	—	—	●	●		●	●
GWLF	●	—	●	—	—	—	—	—	—	●	●	●	—	—	—	—	—	●	—	—
HSPF	●	●	●	—	●	●	●	●	●	●	●	●	●	●	●	—	—	—	—	—
KINEROS2	●	—	—	●	—	—	●	●	—	●	—	—	—	—	—	●	—	●	—	●
LSPC	●	●	●	—	●	●	●	●	●	●	●	●	●	●	●	●	—	●	—	●
MUSIC	—	●	—	●	●	●	●	●	●	—	—	—	—	—	—	●	●	●	●	●
P8-UCM	—	●	—	●	●	●	●	—	●	●	●	●	—	●	—	●	●	●	—	●
PCSWMM	—	●	—	●	●	●	●	●	●	●	—	●	—	—	—	●	●	—	—	●
PGC – BMP	—	●	—	●	●	●	●	●	●	—	—	—	—	—	—	●	●	●	●	●
REMM	—	●	—	●	—	—	●	●	—	●	●	●	●	—	—	—	—	●	—	—
SLAMM	—	●	●	●	●	●	●	—	—	●	●	●	—	●	—	●	●	●	●	●
STORM	—	●	—	—	●	●	—	—	—	—	—	—	—	—	—	—	—	—	—	●

Model	Type		Level of Complexity		Hydrology					Water Quality						Types of BMPs				
	Field practices	BMP	Generalized	Detailed	Storage	Overflow	Infiltration	Routing	User-defined	Sediment	Phosphorus	Nitrogen	Pesticides	Metals	Bacteria	Detention basin	Infiltration practices	Vegetative practices	Wetlands	Other structures
SWAT	●	●	—	●	—	—	●	●	—	●	●	●	●	—	—	●	●	●	—	●
SWMM	—	●	—	●	●	●	●	●	●	●	—	●	—	—	—	●	●	—	—	—
Toolbox	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	—	●	—	●
WAMView	●	●	—	●	●	●	●	●	—	●	●	●	●	●	●	●	●	●	●	●
WARMF	—	●	—	●	—	—	—	—	—	●	●	●	—	●	●	—	—	—	●	●
WEPP	●	●	●	—	—	●	●	—	—	●	—	—	—	—	—	—	●	—	—	—
WinHSPF	●	●	●	—	—	—	—	—	●	●	●	●	●	●	●	—	—	—	—	—
WMS	●	●	●	●	—	—	●	●	●	●	●	●	●	●	●	●	●	—	●	●
XP-SWMM	—	●	—	●	●	●	●	●	●	●	—	●	—	—	—	●	●	—	—	●

Table 4-5. Overview of Models – Review Categories

Categories	Description
Contact Information	Includes: • Contact name • Affiliation • Address • Phone number • E-mail • Web site
Download Information	Includes location, contact, availability, and cost, if applicable, for downloading the model and related files on the Internet
Model Overview/Abstract	Provides a general summary of model purpose and capabilities
Model Features	Identifies the key model features characterizing the model type and simulation capabilities (e.g., lumped, nonpoint source)
Model Areas Supported	Grades the model's support for the following key features: • Watershed • Receiving water • Ecological • Air • Groundwater Each feature is graded as follows: • High—fully supported/physically based • Medium—some simplifying assumptions • Low—empirical representation • None—no support
Model Capabilities	Includes the following subcategories: *Conceptual basis*—summarizes of the general formulation of the model *Scientific detail*—discusses specific technical components and solution techniques used in the model *Model framework*—discusses the structure of the model
Scale	Includes the following subcategories: *Spatial scale*—identifies the smallest operational unit of the model (e.g., cell, watershed, size range) *Temporal scale*—identifies the model's timestep
Assumptions	Lists key operational or technical assumptions included in the model
Model Strengths	Lists key strengths (technical, operational, or systems/software-related) of the model
Model Limitations	Lists key limitations (technical, operational, or systems/software-related) of the model
Application History	Identifies past applications that demonstrate model utility and applicability and identifies documentation of model application
Model Evaluation	Summarizes any available formal testing of model, peer review, or other supporting documentation

Categories	Description
Model Inputs	Listing of key inputs and parameters (or categories of parameters) needed for model setup and application
Users' Guide	Identifies the availability of a user's manual and where to obtain it
Technical Hardware/Software Requirements	Listing of key computer and operational related information related to: • Computer hardware • Operating system • Programming language (code and interface)
Linkages Supported	Lists related or linked models or modeling systems
Related Systems	Lists other or alternate interfaces for the model
Sensitivity/Uncertainty/Calibration	Identifies supporting tools or measures of sensitivity/uncertainty and calibration components
Model Interface Capabilities	Lists model interface tools (e.g., pre- and post-processors, data display tools, data preparation tools)
References	Lists key references (selected recent or relevant articles)

Chapter 5 Applicability of Models

Although a variety of models is available, the assessment of modeling needs must also consider the applicability of models for TMDLs and watershed programs. In this chapter, the applicability of models is evaluated by matching model capabilities to a set of application criteria. Applicability considers the defining characteristics of project applications including pollutants, land and water characteristics, management alternatives, data, and user interfaces. The coverage provided by available models is discussed and key gaps identified. The ability of existing integrated modeling systems to address the application needs, through linkage of models and supporting utilities, is also discussed.

Application Criteria

The application criteria were designed to evaluate the capabilities of currently available models to support TMDL development and evaluation of implementation options. The application criteria match specific TMDL modeling needs with the modeling capabilities and processes described, the land and water features simulated, and the utilities that support model application. The application criteria were used to evaluate the capability of models to perform TMDL analyses, including training, level of effort, and user interface capabilities. In the previous chapter, the models were evaluated on their basic capabilities in watershed, receiving water, and BMP simulation. For this chapter, all available models were evaluated in each table, recognizing that each model could support multiple criteria. Integrated modeling systems (e.g., BASINS, Toolbox, and WMS) were evaluated on the capabilities of their component models.

A structured sequence of application criteria was used to evaluate capabilities for each of five major categories. The first application category, TMDL endpoints, considers the ability of models to predict the magnitude, frequency and duration of the typical endpoints (Table 5-1). Prediction of endpoints is essential for evaluating loading capacity in TMDLs and watershed simulation modeling. For example, a wide range of models—simple models that provide only annual loads or complex models that perform subhourly simulation—can evaluate annual phosphorus loading. Evaluation of a dissolved oxygen endpoint might require a model to evaluate hourly dissolved oxygen fluctuations.

The second application category was designed to identify the capabilities of models to address specific land and waterbody characteristics (Table 5-2). Some models are designed to address one or more waterbody types (e.g., lakes and rivers) while others are limited to a single waterbody type. The purpose of this category is to develop an inventory that characterizes the capabilities and scope of the available models. In practical application, as noted in Chapter 2, one or more models may be used in combination to address multiple land and water features present in an individual watershed.

Model Application Tables

TMDL Endpoints (Table 5-1). Considers the model's ability to simulate typical TMDL target pollutants and expressions (e.g., load vs. concentration). Characterizes the models depending on the timestep of the simulation for the target—steady state, storm event, annual, daily or hourly.

General Land and Water Features (Table 5-2). Rates models according to their ability to simulate general land uses and waterbody types.

Special Land Processes (Table 5-3). Rates models on their ability to simulate special land processes such as wetlands, hydrologic modification, urban BMPs and rural BMPs.

Special Water Processes (Table 5-4). Rates models on their ability to simulate special processes occurring in receiving waterbodies such as air deposition, stream bank erosion, algae and fish.

Application Considerations (Table 5-5). Rates models on the following practical considerations affecting their application—experience required, time needed for application, data needs, support available, software tools and cost.

A uniform scoring system is defined in the "key" below each table.

Special application categories were also identified to highlight the land and water processes that are sometimes, but not always, needed in models (Table 5-3 and 5-4). The purpose of separating these application categories from the general categories is to highlight the differences between models and identify those that have incorporated specialized physically based algorithms that might be needed for specific applications. With these categories separated, the emerging capabilities are more clearly discernable.

The last application category examines the model interface and application considerations, including data needs, user interfaces, and availability of code (Table 5-5). These functional descriptions help evaluate model "usability" based on the data requirements and software systems. The criteria are generalized for each model, although complexity of a specific model application will vary depending on the number of endpoints, land uses, and processes simulated. This table evaluates models on their typical application complexity. In some cases, highly detailed models can also be applied very simply and cost-effectively by experienced users. For example, HSPF could be applied very simply and quickly to a small, homogeneous watershed. Simple models, however, have very little variation in the level of complexity. The design of these criteria recognizes that TMDLs are often highly constrained in data availability, application resources, and schedule. The considerations in model selection and application show a benefit in many cases for models that have low data requirements and are easy to apply. The criteria scores recognize these considerations by showing "solid dot" or high value for low data needs and "dashes" or low value for high data needs. Scores for user interfaces show solid dots for good software support.

Following Tables 5-1 through 5-5 is a discussion of the capabilities and limitations of the models based on the model review.

Table 5-1. TMDL Endpoints Supported

Model	TP load	TP concentration	TN load	TN concentration	Nitrate concentration	Ammonia concentration	TN : TP mass ratio	Dissolved oxygen	Chlorophyll *a*	Algal density (mg/m^2)	Net TSS load	TSS concentration	Sediment concentration	Sediment load	Sulfate concentration	Metals concentrations	Pesticides concentrations	Herbicides concentrations	Toxics concentrations[1]	Pathogen count (e.g., fecal coliform)	Temperature	Methylmercury tissue concentration	Metals sediment concentration	Mercury sediment concentration	Synthetic organic chemicals sediment concentration
AGNPS	○	○	○	○	—	—	—	○	—	—	—	○	○	○	—	—	○	○	—	—	—	—	—	—	—
AnnAGNPS	⊕	⊕	⊕	⊕	—	—	—	⊕	—	—	—	⊕	⊕	⊕	—	—	⊕	⊕	—	—	—	—	—	—	—
AQUATOX	—	—	—	—	⊕	⊕	—	⊕	⊕	⊕	—	⊕	⊕	⊕	—	—	⊕	⊕	⊕	—	—	—	—	—	⊕
BASINS	●	●	●	●	●	●	●	●	●	⊕	●	●	●	●	—	●	●	●	●	●	●	—	—	—	⊕
CAEDYM	●	●	●	●	●	●	●	●	●	●	—	●	●	—	—	—	—	—	—	●	—	—	—	—	—
CCHE1D	—	—	—	—	—	—	—	—	—	—	●	●	●	●	—	—	—	—	—	—	—	—	—	—	—
CE-QUAL-ICM/TOXI	●	●	●	●	●	●	●	●	●	●	●	●	●	●	—	●	●	●	●	—	●	—	●	●	●
CE-QUAL-R1	●	●	●	●	●	●	●	●	●	—	—	●	●	—	●	●	—	—	—	●	●	—	●	—	—
CE-QUAL-RIV1	●	●	●	●	●	●	●	●	●	—	—	—	—	—	—	●	—	—	—	—	●	—	—	—	—
CE-QUAL-W2	●	●	●	●	●	●	●	●	●	●	●	●	●	—	—	—	—	—	—	●	●	—	—	—	—
CH3D-IMS	●	●	●	●	●	●	●	●	●	—	●	●	●	●	—	—	—	—	—	—	●	—	—	—	—
CH3D-SED	—	—	—	—	—	—	—	—	—	—	●	●	●	●	—	—	—	—	—	—	—	—	—	—	—
DELFT3D	●	●	●	●	●	●	●	●	●	●	●	●	●	●	—	—	—	—	—	—	●	—	—	—	—
DIAS/IDLMAS	—	—	—	—	—	—	—	—	—	—	—	—	—	◑	—	—	—	—	—	—	—	—	—	—	—
DRAINMOD	—	—	—	—	●	●	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
DWSM	●	●	●	●	●	—	●	—	—	—	—	●	●	●	—	—	●	●	—	—	—	—	—	—	—
ECOMSED	—	—	—	—	—	—	—	—	—	—	—	●	●	—	—	—	—	—	—	—	●	—	—	—	—
EFDC	●	●	●	●	●	●	●	●	●	●	●	●	●	●	—	●	●	●	●	●	●	—	●	●	●
EPIC	⊕	⊕	⊕	⊕	⊕	⊕	⊕	—	—	—	—	—	—	⊕	—	—	⊕	⊕	—	—	—	—	—	—	—
GISPLM	⊕	⊕	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
GLLVHT	—	●	—	●	●	●	●	●	●	●	—	●	●	—	—	—	—	—	—	●	●	—	—	—	—
GSSHA	—	—	—	—	—	—	—	—	—	—	—	●	●	●	—	—	—	—	—	—	—	—	—	—	—

Model	TP load	TP concentration	TN load	TN concentration	Nitrate concentration	Ammonia concentration	TN : TP mass ratio	Dissolved oxygen	Chlorophyll *a*	Algal density (mg/m^2)	Net TSS load	TSS concentration	Sediment concentration	Sediment load	Sulfate concentration	Metals concentrations	Pesticides concentrations	Herbicides concentrations	Toxics concentrations[1]	Pathogen count (e.g., fecal coliform)	Temperature	Methylmercury tissue concentration	Metals sediment concentration	Mercury sediment concentration	Synthetic organic chemicals sediment concentration
GWLF[2]	⊕	⊕	⊕	⊕	—	—	⊕	—	—	—	—	—	⊕	⊕	—	—	—	—	—	—	—	—	—	—	—
HEC-6	—	—	—	—	—	—	—	—	—	—	●	●	●	●	—	—	—	—	—	—	—	—	—	—	—
HEC-6T	—	—	—	—	—	—	—	—	—	—	●	●	●	●	—	—	—	—	—	—	—	—	—	—	—
HEC-HMS	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
HEC-RAS	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
HSCTM-2D	—	—	—	—	—	—	—	—	—	—	●	●	●	●	—	—	—	—	—	—	—	—	—	—	—
HSPF	●	●	●	●	●	●	●	●	●	—	●	●	●	●	—	●	●	●	●	●	●	—	●	—	●
KINEROS2	—	—	—	—	—	—	—	—	—	—	●	●	●	●	—	—	—	—	—	—	—	—	—	—	—
LSPC	●	●	●	●	●	●	●	—	—	—	●	●	●	●	—	●	—	—	●	●	●	—	●	—	●
MCM	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	⊕	—	⊕	—
Mercury Loading Model	—	—	—	—	—	—	—	—	—	—	—	—	—	◑	—	—	—	—	—	—	—	—	—	◑	—
MIKE 11	●	●	●	●	●	●	●	●	●	●	●	●	●	●	—	●	—	—	—	●	●	—	●	●	●
MIKE 21	●	●	●	●	●	●	●	●	●	●	●	●	●	●	—	●	—	—	—	●	●	—	●	●	●
MIKE SHE	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
MINTEQA2	+	+	+	+	+	+	+	—	—	—	—	—	—	—	+	+	—	—	+	—	—	—	+	+	—
MUSIC	●	●	●	●	—	—	●	—	—	—	—	●	●	—	—	—	—	—	—	—	—	—	—	—	—
P8-UCM	●	●	●	●	—	—	—	—	—	—	●	●	●	—	—	—	—	—	—	—	—	—	—	—	—
PCSWMM	●	●	●	●	●	●	●	●	—	—	●	●	●	●	—	●	—	—	—	●	—	—	—	—	—
PGC – BMP	●	●	●	●	●	●	●	—	—	—	●	●	●	●	—	●	—	—	●	●	●	—	●	—	●
QUAL2E	+	+	+	+	+	+	+	+	+	—	—	—	—	—	—	—	—	—	—	+	+	—	—	—	—
QUAL2K	+	+	+	+	+	+	+	+	+	+	—	—	—	—	—	—	—	—	—	+	+	—	—	—	—
REMM	⊕	⊕	⊕	⊕	⊕	⊕	⊕	—	—	—	⊕	⊕	⊕	⊕	—	—	—	—	—	—	—	—	—	—	—

Model	TP load	TP concentration	TN load	TN concentration	Nitrate concentration	Ammonia concentration	TN : TP mass ratio	Dissolved oxygen	Chlorophyll *a*	Algal density (mg/m^2)	Net TSS load	TSS concentration	Sediment concentration	Sediment load	Sulfate concentration	Metals concentrations	Pesticides concentrations	Herbicides concentrations	Toxics concentrations[1]	Pathogen count (e.g., fecal coliform)	Temperature	Methylmercury tissue concentration	Metals sediment concentration	Mercury sediment concentration	Synthetic organic chemicals sediment concentration
RMA-11	●	●	●	●	●	●	●	●	●	●	●	●	●	●	—	—	—	—	—	●	●	—	—	—	—
SED2D	—	—	—	—	—	—	—	—	—	—	●	●	●	●	—	—	—	—	—	—	—	—	—	—	—
SED3D	—	—	—	—	—	—	—	—	—	—	●	●	●	●	—	—	—	—	—	—	—	—	—	—	—
SHETRAN	—	—	—	—	—	—	—	—	—	—	●	●	●	●	—	—	—	—	—	—	—	—	—	—	—
SLAMM	●	●	●	●	●	●	●	—	—	—	●	●	●	●	—	●	—	—	—	—	—	—	—	—	—
SPARROW	◑	◑	◑	◑	—	—	◑	—	—	—	—	—	—	◑	—	—	◑	◑	—	—	—	—	—	—	—
STORM	—	—	○	○	—	—	—	—	—	—	—	○	○	○	—	—	—	—	—	○	—	—	—	—	—
SWAT	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	—	—	⊕	⊕	⊕	—	⊕	⊕	⊕	—	⊕	⊕	—	—	—	—
SWMM	●	●	●	●	●	●	●	●	—	—	●	●	●	●	—	●	—	—	—	●	—	—	—	—	—
Toolbox	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	—	●	●	—
TOPMODEL	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
WAMView	●	●	●	●	●	●	●	—	—	—	●	●	●	●	—	●	●	●	●	●	—	—	—	—	—
WARMF	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	—	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	—	⊕	⊕	—	⊕	⊕	—
WASP	●	●	●	●	●	●	●	●	●	●	—	●	●	—	—	—	—	—	●	—	—	—	—	—	—
WEPP	—	—	—	—	—	—	—	—	—	—	—	—	⊕	⊕	—	—	—	—	—	—	—	—	—	—	—
WinHSPF	●	●	●	●	●	●	●	●	●	—	●	●	●	●	—	●	●	●	●	●	●	—	●	—	●
WMS	●	●	●	●	●	●	●	●	●	—	●	●	●	●	—	●	●	●	●	●	●	—	●	—	●
XP-SWMM	●	●	●	●	●	●	●	●	—	—	●	●	●	●	—	●	—	—	—	⊕	—	—	—	—	—

[1] Entries under this category indicate that models have the capacity to simulate user-defined toxic chemicals

[2] GWLF calculations are performed on a daily basis, but results are presented on a monthly basis.

Key:

- — Not supported
- + Steady State
- ○ Storm
- ◑ Annual
- ⊕ Daily
- ● Hourly (or less)

Table 5-2. General Land and Water Features Supported

Model	Urban	Rural	Agriculture	Forest	River	Lake	Reservoir/ impoundment	Estuary (tidal)	Coastal (tidal/shoreline)
AGNPS	—	●	●	—	—	—	—	—	—
AnnAGNPS	—	●	●	—	—	—	—	—	—
AQUATOX	—	—	—	—	○	◑	◑	—	—
BASINS	◑	●	●	●	●	◑	◑	—	—
CAEDYM	—	—	—	—	●	●	●	●	●
CCHE1D	○	○	○	○	●	—	—	—	—
CE-QUAL-ICM/TOXI	—	—	—	—	●	●	●	●	●
CE-QUAL-R1	—	—	—	—	—	○	○	—	—
CE-QUAL-RIV1	—	—	—	—	●	—	—	—	—
CE-QUAL-W2	—	—	—	—	●	●	●	●	●
CH3D-IMS	—	—	—	—	●	●	●	●	●
CH3D-SED	—	—	—	—	●	●	●	●	●
DELFT3D	—	—	—	—	●	●	●	●	●
DIAS/IDLMAS	—	◑	◑	●	—	—	—	—	—
DRAINMOD	—	●	●	●	—	—	●	—	—
DWSM	—	●	●	●	◑	—	○	—	—
ECOMSED	—	—	—	—	●	●	●	●	●
EFDC	—	—	—	—	●	●	●	●	●
EPIC	—	●	●	◑	—	—	—	—	—
GISPLM	○	◑	◑	◑	—	○	○	—	—
GLLVHT	—	—	—	—	●	●	●	●	●
GSSHA	○	●	●	●	●	◑	○	—	—
GWLF	◑	◑	◑	◑	○	—	—	—	—
HEC-6	—	—	—	—	●	—	—	—	—
HEC-6T	—	—	—	—	●	—	—	—	—
HEC-HMS	●	●	●	●	●	—	◑	—	—

Model	Urban	Rural	Agriculture	Forest	River	Lake	Reservoir/ impoundment	Estuary (tidal)	Coastal (tidal/shoreline)
HEC-RAS	—	—	—	—	●	—	—	—	—
HSCTM-2D	—	—	—	—	●	—	—	●	—
HSPF	◑	●	●	●	●	◑	◑	—	—
KINEROS2	○	●	●	◑	○	—	○	—	—
LSPC	◑	●	◑	●	●	●	●	—	—
MCM	—	—	—	—	—	●	●	—	—
Mercury Loading Model	○	◑	◑	◑	○	○	○	—	—
MIKE 11	—	—	—	—	●	—	●	—	—
MIKE 21	—	—	—	—	●	●	◑	●	●
MIKE SHE	●	●	●	●	●	—	●	—	—
MINTEQA2	—	—	—	—	—	—	—	—	—
MUSIC	●	—	—	—	—	—	—	—	—
P8-UCM	◑	○	○	○	○	—	◑	—	—
PCSWMM	●	◑	○	○	◑	○	◑	—	—
PGC – BMP	●	◑	◑	◑	—	—	○	—	—
QUAL2E	—	—	—	—	●	—	—	—	—
QUAL2K	—	—	—	—	●	—	—	—	—
REMM	—	—	●	●	—	—	—	—	—
RMA-11	—	—	—	—	●	●	●	●	●
SED2D	—	—	—	—	●	●	●	●	●
SED3D	—	—	—	—	●	●	●	●	●
SHETRAN	●	●	●	●	●	—	—	—	—
SLAMM	●	◑	—	○	—	—	—	—	—
SPARROW	◑	◑	◑	◑	◑	—	—	—	—
STORM	●	—	—	—	—	—	—	—	—
SWAT	◑	●	●	●	○	○	○	—	—
SWMM	●	◑	○	○	○	○	◑	—	—

Model	Urban	Rural	Agriculture	Forest	River	Lake	Reservoir/ impoundment	Estuary (tidal)	Coastal (tidal/shoreline)
Toolbox	●	●	●	●	●	●	●	●	●
TOPMODEL	—	●	●	●	○	—	—	—	—
WAMView	◑	●	●	●	◑	◑	◑	—	—
WARMF	●	●	●	●	○	●	●	—	—
WASP	—	—	—	—	●	●	●	●	●
WEPP	—	●	●	●	—	—	—	—	—
WinHSPF	◑	●	●	●	●	◑	◑	—	—
WMS	◑	●	●	●	●	◑	◑	—	—
XP-SWMM	●	◑	○	○	◑	◑	◑	—	—

Key:

– Not supported

○ Low–Simplified representation of features, significant limitations

◑ Medium–Moderate level of analysis, some limitations

● High–Detailed simulation of processes associated with land or water feature

Table 5-3. Special Land Features Supported

Model	Air deposition	Wetland	Land-to-land simulation[1]	Hydrologic modification	BMP siting/placement	Urban Land Management: Street sweeping	Nutrient control practices (fertilizer, pet waste mgmt.)	Stormwater structures (manhole, splitter)	Detention/retention ponds	Constructed wetland processes	Vegetative practices	Infiltration practices	Rural Land Management: Nutrient control practices (fertilizer, manure mgmt.)	Agricultural conservation practices (contouring, terracing, ow cropping)	Irrigation practices	Tile drains	Ponds	Vegetative practices
AGNPS	—	—	○	—	●	—	◑	—	◑	—	◑	—	●	●	—	○	◑	◑
AnnAGNPS	—	—	○	—	●	—	◑	—	◑	—	◑	—	●	●	○	○	◑	◑
AQUATOX	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	◑	—
BASINS	○	◑	◑	◑	○	○	○	—	○	○	○	—	●	●	—	—	◑	○
CAEDYM	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	●	—
CCHE1D	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
CE-QUAL-ICM/TOXI	○	○	—	—	—	—	—	—	—	—	—	—	—	—	—	—	●	—
CE-QUAL-R1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
CE-QUAL-RIV1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
CE-QUAL-W2	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	●	—
CH3D-IMS	○	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	●	—
CH3D-SED	○	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	●	—
DELFT3D	○	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	●	—
DIAS/IDLMAS	—	—	—	—	◑	—	—	—	—	—	—	—	—	—	—	—	—	—
DRAINMOD	—	◑	—	◑	—	—	—	—	—	—	—	—	●	—	●	●	●	—
DWSM	—	—	—	—	●	—	—	—	—	—	—	—	—	—	—	●	◑	◑
ECOMSED	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	●	—
EFDC	○	◑	—	◑	—	—	—	—	—	◑	○	○	—	—	—	—	●	○

						Urban Land Management							Rural Land Management					
Model	**Air deposition**	**Wetland**	**Land-to-land simulation[1]**	**Hydrologic modification**	**BMP siting/placement**	**Street sweeping**	**Nutrient control practices (fertilizer, pet waste mgmt.)**	**Stormwater structures (manhole, splitter)**	**Detention/retention ponds**	**Constructed wetland processes**	**Vegetative practices**	**Infiltration practices**	**Nutrient control practices (fertilizer, manure mgmt.)**	**Agricultural conservation practices (contouring, terracing, row cropping)**	**Irrigation practices**	**Tile drains**	**Ponds**	**Vegetative practices**
EPIC	—	—	—	—	—	—	—	—	—	—	—	—	●	●	●	●	○	○
GISPLM	—	—	—	—	◑	—	—	—	○	—	○	—	○	○	—	—	—	○
GLLVHT	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	●	—
GSSHA	—	◑	—	●	○	—	—	—	—	◑	—	—	—	◑	—	—	●	—
GWLF	—	—	—	—	—	○	—	—	—	—	○	—	○	○	—	—	—	○
HEC-6	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
HEC-6T	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
HEC-HMS	—	—	◑	◑	◑	—	—	—	—	◑	—	—	—	—	◑	—	—	—
HEC-RAS	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
HSCTM-2D	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
HSPF	○	◑	○	◑	○	—	○	—	○	—	○	○	●	●	—	—	◑	○
KINEROS2	—	—	—	◑	○	—	—	—	—	○	—	—	—	◑	—	—	◑	—
LSPC	—	◑	—	◑	○	—	○	—	○	—	○	○	◑	◑	—	—	◑	○
MCM	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Mercury Loading Model	—	○	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
MIKE 11	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
MIKE 21	○	—	—	◑	—	—	—	—	—	—	—	—	—	—	—	—	—	—
MIKE SHE	—	◑	●	●	○	—	—	○	—	○	○	○	—	○	○	—	—	—

Model	Air deposition	Wetland	Land-to-land simulation[1]	Hydrologic modification	BMP siting/placement	Urban Land Management: Street sweeping	Nutrient control practices (fertilizer, pet waste mgmt.)	Stormwater structures (manhole, splitter)	Detention/retention ponds	Constructed wetland processes	Vegetative practices	Infiltration practices	Rural Land Management: Nutrient control practices (fertilizer, manure mgmt.)	Agricultural conservation practices (contouring, terracing, row cropping)	Irrigation practices	Tile drains	Ponds	Vegetative practices
MINTEQA2	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
MUSIC	—	◑	—	—	—	—	—	—	●	—	●	●	—	—	—	—	◑	—
P8-UCM	—	○	—	—	◑	◑	○	○	◑	○	○	○	—	—	—	—	◑	—
PCSWMM	—	○	—	◑	◑	◑	○	◑	◑	○	○	—	○	○	—	—	◑	—
PGC – BMP	—	◑	—	●	●	—	—	—	—	◑	—	—	◑	—	—	—	●	—
QUAL2E	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
QUAL2K	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
REMM	—	—	—	—	—	—	—	—	—	—	●	—	—	—	—	—	—	●
RMA-11	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	●	—
SED2D	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
SED3D	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
SHETRAN	—	◑	●	●	○	—	○	○	—	○	○	○	○	○	○	—	—	—
SLAMM	—	○	—	○	○	○	○	○	○	○	○	○	—	—	—	—	◑	—
SPARROW	—	◑	—	—	—	—	—	—	—	—	—	—	○	○	—	—	—	—
STORM	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
SWAT	—	○	—	—	—	○	○	—	○	○	○	—	●	●	●	●	◑	◑
SWMM	—	○	—	◑	◑	◑	○	◑	◑	○	○	—	○	○	—	—	◑	—
Toolbox	○	●	●	◑	◑	○	◑	○	◑	●	◑	◑	◑	◑	◑	●	●	◑

Model	Air deposition	Wetland	Land-to-land simulation[1]	Hydrologic modification	BMP siting/placement	Urban Land Management: Street sweeping	Nutrient control practices (fertilizer, pet waste mgmt.)	Stormwater structures (manhole, splitter)	Detention/retention ponds	Constructed wetland processes	Vegetative practices	Infiltration practices	Rural Land Management: Nutrient control practices (fertilizer, manure mgmt.)	Agricultural conservation practices (contouring, terracing, row cropping)	Irrigation practices	Tile drains	Ponds	Vegetative practices
TOPMODEL	—	—	○	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
WAMView	○	●	●	◑	◑	○	◑	○	◑	●	◑	◑	◑	◑	◑	●	●	◑
WARMF	—	◑	—	—	—	—	—	—	—	—	—	—	●	—	—	—	●	—
WASP	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	●	—
WEPP	—	—	—	—	—	—	—	—	—	—	—	—	—	●	—	—	◑	—
WinHSPF	○	◑	○	◑	○	—	○	—	○	—	○	○	●	●	—	—	◑	○
WMS	○	◑	○	◑	○	—	○	—	○	—	○	○	●	●	—	—	◑	○
XP-SWMM	—	○	—	◑	◑	◑	○	◑	◑	○	○	—	○	○	—	—	◑	—

[1] Land-to-land simulation: Model capacity to transfer runoff, sediment, and nutrients from land to land instead of from land to streams or other receiving water.

Key:

– Not supported

○ Low–Simplified representation of features, significant limitations

◑ Medium–Moderate level of analysis, some limitations

● High–Detailed simulation of processes associated with land feature

Table 5-4. Special Water Features Supported

Model	Detailed operations (locks, pumps)	Near-field analysis (mixing zone)[1]	Air deposition	Surface/ groundwater interactions	Stream bank erosion	Sediment transport	Sediment diagenesis	Phytoplankton/ floating algae	Periphyton/ macrophytes	Planktonic and benthic algae	Fish
AGNPS	—	—	—	—	—	◑	—	—	—	—	—
AnnAGNPS	—	—	—	—	—	◑	—	—	—	—	—
AQUATOX	—	—	—	—	—	—	—	●	●	●	●
BASINS	◑	—	◑	◑	—	◑	—	●	●	●	●
CAEDYM	—	—	—	—	—	—	—	—	—	—	—
CCHE1D	—	—	—	—	◑	●	—	—	—	—	—
CE-QUAL-ICM/TOXI	—	—	◑	○	—	—	●	●	●	●	—
CE-QUAL-R1	—	—	—	—	—	—	—	—	—	—	—
CE-QUAL-RIV1	—	—	—	—	—	—	—	—	—	—	—
CE-QUAL-W2	●	—	○	—	—	—	—	●	●	●	—
CH3D-IMS	—	—	—	—	—	●	—	—	—	—	—
CH3D-SED	—	—	—	—	◑	●	—	—	—	—	—
DELFT3D	—	—	—	—	◑	●	—	—	—	—	—
DIAS/IDLMAS	—	—	—	—	—	—	—	—	—	—	—
DRAINMOD	—	—	—	●	—	—	—	—	—	—	—
DWSM	—	—	—	—	—	●	—	—	—	—	—
ECOMSED	—	—	—	—	—	—	—	—	—	—	—
EFDC	●	●	○	○	◑	●	●	●	●	●	◑
EPIC	—	—	—	○—	—	—	—	—	—	—	—
GISPLM	—	—	—	—	—	—	—	—	—	—	—
GLLVHT	—	—	—	—	—	—	—	—	—	—	—
GSSHA	—	—	—	●	—	◑	—	—	—	—	—
GWLF	—	—	—	—	—	—	—	—	—	—	—
HEC-6	—	—	—	—	◑	●	—	—	—	—	—

Model	Detailed operations (locks, pumps)	Near-field analysis (mixing zone)[1]	Air deposition	Surface/ groundwater interactions	Stream bank erosion	Sediment transport	Sediment diagenesis	Phytoplankton/ floating algae	Periphyton/ macrophytes	Planktonic and benthic algae	Fish
HEC-6T	—	—	—	—	◑	●	—	—	—	—	—
HEC-HMS	◑	—	—	—	—	—	—	—	—	—	—
HEC-RAS	—	—	—	—	—	—	—	—	—	—	—
HSCTM-2D	—	—	—	—	○	●	—	—	—	—	—
HSPF	◑	—	◑	◑	—	◑	—	—	—	○	—
KINEROS2	—	—	—	—	—	●	—	—	—	—	—
LSPC	◑	—	○	○	—	—	—	—	—	○	—
MCM	—	—	○	—	—	—	—	◑	◑	◑	◑
Mercury Loading Model	—	—	○	—	—	—	—	—	—	—	—
MIKE 11	◑	◑	—	—	—	◑	—	—	—	—	—
MIKE 21	◑	◑	○	—	◑	◑	—	◑	◑	◑	—
MIKE SHE	—	—	—	●	—	—	—	—	—	—	—
MINTEQA2	—	—	—	—	—	—	—	—	—	—	—
MUSIC	—	—	—	—	—	—	—	—	—	—	—
P8-UCM	—	—	—	—	—	—	—	—	—	—	—
PCSWMM	●	—	—	—	—	◑	—	—	—	—	—
PGC – BMP	○	—	—	—	—	—	—	—	—	—	—
QUAL2E	—	—	—	—	—	—	●	●	◑	◑	—
QUAL2K	—	—	—	—	—	—	●	●	◑	◑	—
REMM	—	—	○	◑	—	◑	—	—	—	—	—
RMA-11	—	—	—	—	—	—	—	—	—	—	—
SED2D	—	—	—	—	—	—	—	—	—	—	—
SED3D	—	—	—	—	—	—	—	—	—	—	—
SHETRAN	—	—	—	●	—	●	—	—	—	—	—

Model	**Detailed operations (locks, pumps)**	**Near-field analysis (mixing zone)[1]**	**Air deposition**	**Surface/ groundwater interactions**	**Stream bank erosion**	**Sediment transport**	**Sediment diagenesis**	**Phytoplankton/ floating algae**	**Periphyton/ macrophytes**	**Planktonic and benthic algae**	**Fish**
SLAMM	—	—	—	○	—	—	—	—	—	—	—
SPARROW	—	—	—	—	—	—	—	—	—	—	—
STORM	—	—	—	—	—	—	—	—	—	—	—
SWAT	—	—	—	◑	—	◑	—	—	—	—	—
SWMM	◑	—	—	—	—	◑	—	—	—	—	—
Toolbox	●	●	○	○	◑	●	●	●	●	●	—
TOPMODEL	—	—	—	◑	—	—	—	—	—	—	—
WAMView	◑	—	—	●	○	○	—	—	—	—	—
WARMF	○	—	◑	◑	—	—	—	—	—	—	—
WASP	—	—	○	—	—	—	●	●	●	◑	—
WEPP	—	—	—	—	—	—	—	—	—	—	—
WinHSPF	○	—	◑	◑	—	○	—	—	—	—	—
WMS	◑	—	◑	◑	—	◑	—	—	—	—	—
XP-SWMM	●	—	○	○	—	◑	—	—	—	—	—

[1] Near-field is the region of a receiving water where the initial jet characteristic of momentum flux, buoyancy flux, and outfall geometry influence the jet trajectory and mixing of an effluent discharge. This is a specialized feature included only in the most detailed receiving water models.

Key:

— Not supported

○ Low–Simplified representation of features, significant limitations

◑ Medium–Moderate level of analysis, some limitations

● High–Detailed simulation of processes associated with water feature

Table 5-5. Application Considerations

Model	Experience Required	Time Needed for Application	Data Needs	Support Available	Software Tools	Cost
AGNPS	◑	◑	◑	◑	◑	●
AnnAGNPS	◑	◑	◑	◑	◑	●
AQUATOX	◑	●	◑	◑	●	●
BASINS	○	○	○	●	●	●
CAEDYM	○	◑	○	◑	◑	◑
CCHE1D	—	○	○	●	◑	●
CE-QUAL-ICM/TOXI	—	—	○	◑	—	●
CE-QUAL-R1	●	●	●	○	○	◑
CE-QUAL-RIV1	—	○	◑	○	○	◑
CE-QUAL-W2	—	—	○	●	◑	●
CH3D-IMS	—	—	○	○	○	◑
CH3D-SED	—	—	○	○	○	◑
DELFT3D	—	—	○	◑	●	—
DIAS/IDLMAS	◑	●	◑	○	○	◑
DRAINMOD	◑	◑	◑	◑	◑	○
DWSM	◑	◑	●	○	○	●
ECOMSED	—	—	○	○	—	●
EFDC	—	—	○	●	●	●
EPIC	◑	◑	○	◑	◑	●
GISPLM	◑	●	●	○	●	●
GLLVHT	—	—	○	◑	◑	—
GSSHA	—	—	◑	○	●	—
GWLF	●	●	●	○	●	●
HEC-6	◑	◑	○	◑	●	●
HEC-6T	◑	◑	○	◑	●	○
HEC-HMS	◑	◑	○	◑	●	●

Model	Experience Required	Time Needed for Application	Data Needs	Support Available	Software Tools	Cost
HEC-RAS	◑	◑	○	◑	●	●
HSCTM-2D	—	—	○	○	○	●
HSPF	—	—	○	●	●	●
KINEROS2	○	◑	◑	○	●	●
LSPC	—	○	○	◑	●	●
MCM	○	●	◑	◑	◑	◑
Mercury Loading Model	●	●	◑	○	◑	●
MIKE 11	—	—	○	●	●	—
MIKE 21	—	—	○	●	●	—
MIKE SHE	—	—	○	●	●	—
MINTEQA2	◑	●	◑	○	○	●
MUSIC	◑	◑	◑	●	●	○
P8-UCM	●	●	●	○	○	●
PCSWMM	—	○	○	◑	●	—
PGC – BMP	◑	●	○	○	●	◑
QUAL2E	◑	●	◑	◑	○	●
QUAL2K	◑	●	◑	◑	◑	●
REMM	○	◑	○	○	—	●
RMA-11	—	—	○	◑	◑	—
SED2D	—	—	○	◑	◑	—
SED3D	—	—	○	◑	◑	●
SHETRAN	—	—	○	●	●	◑
SLAMM	○	◑	◑	◑	◑	○
SPARROW	◑	◑	●	●	◑	●
STORM	○	●	◑	○	—	●
SWAT	○	◑	◑	◑	●	●
SWMM	—	○	○	◑	○	●

Model	Experience Required	Time Needed for Application	Data Needs	Support Available	Software Tools	Cost
Toolbox	○	○	○	●	●	●
TOPMODEL	◑	◑	●	◑	●	●
WAMView	○	—	○	◑	●	◑
WARMF	○	○	◑	◑	◑	—
WASP	—	—	○	○	○	●
WEPP	◑	●	●	○	○	●
WinHSPF	—	○	○	●	●	●
WMS	—	○	○	◑	●	—
XP-SWMM	—	○	○	◑	●	—

Key:

Experience:
- – Substantial training or modeling expertise required (generally requires professional experience with advanced watershed and/or hydrodynamic and water quality models.)
- ○ Moderate training required (assuming some experience with basic watershed and/or water quality models)
- ◑ Limited training required (assuming some familiarity with basic environmental models)
- ● Little or no training required

Time Needed for Application:
- – > 6 months
- ○ > 3 months
- ◑ > 1 month
- ● < 1 month

Data Needs:
- ○ High
- ◑ Medium
- ● Low

Support Available:
- – None
- ○ Low
- ◑ Medium
- ● High

Software Tools:
- – None
- ○ Low
- ◑ Medium
- ● High

Cost:
- – Significant Cost (>$500)
- ○ Nominal Cost (<$500)
- ◑ Limited Distribution
- ● Public Domain

Capabilities and Limitations of Currently Available Models

The currently available models address many of the TMDL needs identified in Tables 5-1 through 5-5, at various levels of complexity and difficulty. Observations can be drawn from examination of each table to evaluate model capabilities and limitations for the development of TMDLs and waterbody restoration plans.

- **Endpoints supported (Table 5-1).** Of the more than 65 models reviewed, most of the models support some type of analysis of sediment and nutrients. Many models address related measures of eutrophication such as chlorophyll *a* and nutrient concentrations. Some models, in particular some of the more detailed models, support simulation of pathogens. However, significantly fewer models support evaluation of metals (20 models) and toxics (12 models). Contaminated sediment, herbicides and pesticides are the least frequently supported endpoints. Only a few highly specialized models support mercury simulation.

- **General Land and Water Features**. All waterbodies and general land use types are supported by models; however, most models specialize in one of the following: land/watershed system, freshwater rivers, lakes, and tidal areas. Many comprehensive watershed models (e.g., HSPF, LSPC, SWMM) include watersheds, rivers and simplified lakes. Simulation of tidal waters is addressed by specialized models (e.g., EFDC, CH3D, ECOM) that are limited to receiving water simulation. Development of watershed inputs for receiving water models is provided by linkage with watershed models or evaluation of monitoring data. Integrated modeling systems may include linked models that provide support for watersheds, rivers, lakes, and estuaries (e.g., EPA TMDL Toolbox). Support for linkage between watershed and receiving water models, especially tidal waters, is extremely limited.

- **Specialized Land Features**. Support for specialized land features is limited to a few models. The most commonly supported feature is simulation of impoundments such as ponds or reservoirs, often needed in the evaluation of stormwater management. However, although most receiving water models can simulate ponds, typically the models are too complex for practical application. More typically applied are simplified tools included in watershed models to assess stormwater management ponds (e.g., P8-UCM). Atmospheric deposition is an important consideration in large watershed or estuaries. The application criteria show that some watershed models assess dry and wet weather deposition but do not always consider a separate atmospheric deposition term. HPSF is one of the few available models with an explicit function to assessing atmospheric deposition of nutrients. Practices such as fertilizer and manure application are included in many agriculturally oriented watershed models (e.g., AnnAGNPS, SWAT). However, irrigation and tile drainage are less frequently included. Wetlands and BMPs that include constructed wetlands are also infrequently included in models. Similar to modeling of impoundments, wetland simulation, although possible using complex receiving water models, is not always practical for general application. For example, EFDC has the capability to evaluate wetland systems within the context of a larger simulation of a tidal waterbody. For urban areas, street sweeping is included only as a distinct practice in traditional urban models such as SWMM, SLAMM, and P8-UCM but not included in many other watershed models such as HSPF and GWLF.

- **Specialized Water Features.** Only the most detailed physically based models support multiple specialized water features. Few models address surface-groundwater interactions in detail. Few hydrodynamic models can address near-field mixing zone studies. Only rarely do models support calculation of stream bank erosion. More models address stream sediment transport at varying levels of complexity. Few models include sediment diagenesis, which can be an essential factor in the internal recycling of nutrients in lakes and estuaries. This feature is increasingly significant in performing long-term projections of restoration potential. Some support evaluation of multiple processes related to algal, periphyton, and macrophyte species. This is an important feature for many eutrophication-related TMDLs because simulation of aquatic vegetation is needed to determine allowable loading of nutrients. Of the reviewed models, ecological processes such as fish and food chain simulation are supported only by AQUATOX. Many of the three-dimensional models used for large-scale estuary applications integrate atmospheric deposition as a source (e.g., ECOM, EFDC, WASP). However, very few models incorporate irrigation and drainage processes, except agriculturally oriented systems (e.g., SWAT) or specialized drainage models (e.g., DRAINMOD).

- **Application Considerations**. Detailed models typically require a high level of experience, significant amounts of data, and time for setup and testing. Most of the models reviewed require experience and training to apply; application and interpretation of even the simplest models still require some experience in environmental analysis. The data requirements and time needed for application are typically associated with complexity. Some models have technical support available (e.g., list servers), while others have no formal network for support. Some of the propriety models provide technical support as part of the services included with purchase of the systems (e.g., XPSWMM, MIKE SHE). Levels of support vary and are typically more limited for research or public domain models. Many models include interfaces and software tools, such as post-processors, which can help to make application and interpretation of model results more efficient. Software tools often focus on the typical use of the model. Models that are actively used for watershed and TMDL development typically include specific software tools for calculating TMDL allocations (e.g., LSPC, WARMF). Integrated systems provide support for data, software, and analysis, although the complexity of the systems still requires training and experience for application (e.g., BASINS, TMDL Toolbox). Few models include tools for evaluation of model accuracy, support for calibration/validation, or sensitivity analysis. Cost of the models and systems varies from free distribution of public domain or open source code systems to significant costs (i.e., more than $1,000) for privately maintained and distributed models (e.g., MIKE SHE, XP-SWMM).

Of the dominant pollutants identified in TMDL listing across the country, many still have significant limitations in the availability and sensitivity of simulation techniques. Pathogens are simulated by few watershed models, and accuracy of source characterization is limited. Metals are also simulated by few watershed models with the major limitation being speciation of metals and pH-related processes. Nutrients are addressed relatively well by both watershed and receiving water models, building on a long history of eutrophication studies in lakes and estuaries. However, some of the more specific endpoints related to nutrients are not well described and require more development of ecological models. In addition, river models are less likely to include dynamic simulation of attached algae and dynamic calculation of the input of dissolved nutrients. Simulation of stream sediment, stream bank erosion, and channel formation is not supported by most watershed models. However, sediment-related aquatic life impairment comprises more than 8 percent of TMDL listings and is likely associated with additional listings for Biological Criteria.

The review of TMDL requirements and comparison with available models demonstrates that, although many of the technical needs are addressed, the capabilities are distributed among multiple models, techniques are not uniformly available, and selection of any single model is likely to result in limitations of simulation capabilities. The available models also reflect the genesis of their development—as agricultural or urban models, tidal modeling systems, or ecosystem models—that have been only partially adapted to TMDL and restoration plan development. The specialized land and water features, supported by few of the available models, include many of the technical considerations that are present in impaired waterbodies throughout the United States. The most promising aspect of model development for TMDL and restoration planning support is the integrated modeling systems discussed further in the following section.

Integrated Modeling Systems

In this section, the unique characteristics and system of supporting tools that comprise integrated systems are discussed further. In the previous sections, integrated modeling systems were reviewed for and categorized by the comprehensive capabilities of their component models. In this section, the applicability and capabilities of the integrated modeling systems are described and compared. These systems are evaluated for their capabilities in providing more comprehensive solutions of the need for simulation and development of management plans for TMDLs.

Integrated systems are compilations of data support tools and multiple models that provide a workspace or environment for executing multiple analytical steps. Integrated systems demonstrate a high level of support for TMDL needs, based on the application criteria examined in Tables 5-1 through 5-5. Integrated systems can satisfy multiple application criteria because they include the capabilities of multiple models, provide various software tools, and include data and analysis support. Much of the recent development of integrated systems for TMDL applications has focused on improving efficiency and consistency of modeling applications. Integrated systems typically provide linkages between data and models and include a set of tools to quickly and efficiently build, test, and apply models to support environmental decision-making. The development of integrated systems has generally focused on functionality and not on the fundamental research and development of new models and physically based processes.

In 1996, the first major release of an integrated modeling system in the public domain was the BASINS modeling system. BASINS provided a linkage between spatial and point data and a watershed model (HSPF) through the use of emerging geographic information system (GIS) technology. Bundled within the BASINS system was a series of tools that facilitated data analysis and development of model input files. Semi-automating various data analyses and facilitating spatial data processing significantly reduced the time and effort required for performing a basic watershed characterization and developing input files for HSPF. The linkage of GIS and modeling technology significantly advanced the ability of users to evaluate watershed systems including point and nonpoint sources under a variety of conditions. Since the original release, the BASINS system has continued to add models (e.g., SWAT, PLOAD, AQUATOX, KINEROS) and additional systems (e.g., AGWA) to improve the functionality of data download and management tools.

The TMDL Modeling Toolbox, sponsored by EPA Region 4 and EPA Office of Research and Development, Watershed and Water Quality Modeling Technical Support Center, provides a loosely linked system that is designed to facilitate TMDL development. In this framework, the models are developed and supported individually, but linkage is facilitated by data exchange tools and common data management and GIS interfaces. The Toolbox has emphasized support for linking watershed and receiving water models. Adding EFDC and WASP to the Toolbox supports the capability to evaluate watersheds, rivers, lakes, and estuaries. Additional specialized tools were added to address sediment and mercury impairments. WAMView provides an assessment tool for areas with high water tables. The recent addition of the Conservational Channel Evolution and Pollutant Transport System (CONCEPTS) provides a tool that can assess channel sediment and stream channel adjustments. The system also includes watershed report generation tools that facilitate characterization and a database system for managing and analyzing water monitoring data.

The WMS provides another format for an integrated modeling system, including various data management tools and watershed models. The WMS includes GIS, support tools, and watershed models. Most recently, WMS has added support for a grid-based model for hydrologic simulation (GSSHA) and HSPF for water quality modeling. This system, once tested, could provide more practical applicability for grid-based models for watershed simulation and TMDLs.

The three most commonly used and available integrated modeling systems are BASINS, the EPA TMDL Toolbox, and WMS (fact sheets are provided in the Appendix). The three systems are compared in more detail in Table 5-6, with particular focus on the included analytical tools and model linkages.

Examination of the recent history in development of the three major integrated systems discussed here shows a continuing expansion in three general areas—data analysis tools, available types and complexity of models, and linkages between models. Data analysis tools within integrated model systems include pre-processing tools to help understand watershed and waterbody conditions, perform diagnostic analysis of waterbody conditions or sources, and process data for use in model input files. Data analysis tools are also used in the evaluation and interpretation of model output datasets. Models are being added to integrated modeling systems to provide a variety of simple (e.g., PLOAD) and more detailed models addressing receiving waters (e.g., EFDC, WASP) or specific source types (e.g., SWAT for agricultural applications).

There is also increasing interest in developing systems that link models to each other and facilitate the linkage with GIS tools (to spatially locate linkage points) and provide file conversion and data management capabilities. For larger scale TMDL applications, multiple models are often needed to evaluate source loading and receiving water response (e.g., watershed and estuary models). For some TMDL applications, receiving water models are needed to compare predicted waterbody conditions to water quality standards. For example, to address dissolved oxygen impairment in an estuary, an estuary model might be used to simulate eutrophication processes and the sensitivity of dissolved oxygen concentrations to changes in nutrient loading, and a watershed model might be used to estimate the magnitude and sources of nutrient loading. Watershed model outputs in the form of discharge time series (i.e., daily or hourly flow and concentrations) provide input data at critical boundary points of the estuary model. Linkages between watershed and receiving water model are typically one-directional, because the data pass directly from one model to other, and the two models can be run separately. The watershed model output points are selected above the head of tide so that the flow is one-directional and is not controlled by the tidal fluctuations. Linkages between ground and surface water models are more complex, with typically bi-directional dynamic linkages. Surface and groundwater models both need to consider water table elevation and soil moisture content, and the two models may need to run concurrently with frequent data exchange to maintain continuity and assess water conservation. Examples of model-to-model linkages that are supported by the three integrated modeling systems discussed here include:

- Watershed to receiving water—LSPC to EFDC
- Receiving water hydrodynamic model to water quality model—EFDC to WASP
- Watershed model to water quality/ecological model—HSPF or SWAT to AQUATOX

Table 5-6. Capabilities of Integrated Modeling Systems

System	BASINS http://www.epa.gov/ost/basins/	EPA TMDL Toolbox http://www.epa.gov/athens/wwqtsc/ http://wcs.tetratech-ffx.com	WMS[1] http://www.ems-i.com/index.html
Datasets	• GIRAS land use • Soils • Digital Elevation Model (DEM) • Reach File, version 3 (RF3) and National Hydrography Dataset (NHD) • STORET water quality data summary • Permit Compliance System data • WDM weather data	• 303(d) listed waters • Multi-resolution Land Characteristics (MRLC) land use • Soils • DEM • RF3 and NHD • Agricultural Census • Population data • National Resources Inventory erosion data • STORET water quality data summary • Pesticide and fertilizer data • Monthly weather data summary	• DEM • Triangulated Irregular Network (TIN) • Land use • Soils • Watershed images • Hydrography • Precipitation • Stream stage
Analysis Tools	• Theme Manager • Import Tool • Data Download Tool • Grid Projector • GenScn • WDMUtil • AGWA • Manual Delineation Tool • Automatic Delineation Tool • PEST (parameter estimation/calibration) Predefined Delineation Tool • Land Use, Soil Classification, and Overlay • Land Use Reclassification • DEM Reclassification • Water Quality Observation Data Management • Lookup Tables	• WCS – characterization reports (including 12 physical reports, 4 water quality reports, and 5 loading reports) • WCS – manual delineation • WCS – automatic delineation • WCS – NHD download tool • LSPC data preprocessor • SWMM data preprocessor • NPSM data preprocessor • SNPP – WASP stream network preprocessor • WRDB – water resources data access and analysis • Watershed Sediment Loading Tool • Watershed Mercury Loading Tool • EFDC Grid Generator • EFDC Interface and Post-processor	• Map Module – defining watershed data and maps • GIS Module – manipulating spatial data • Terrain Data Module – processing terrain data • Drainage Module – watershed delineation • Hydrologic Modeling Interface • River Modeling Interface • Stochastic Simulations • Scatter Point Module – interpolate data from scattered points to grids • 2D Grid Module – surface visualization
Models	• PLOAD • WinHSPF • KINEROS • SWAT • QUAL2E • AQUATOX	• LSPC • PC-SWMM • EFDC • QUAL2K • WASP • WAMView • CONCEPTS	• HEC1 (HMS) • TR-20 • TR-55 • MODRAT • StormDrain • CE-QUAL-W2 • National Flood Frequency Program (NFF) • Rational Method • HSPF • HEC-RAS (steady flow analysis) • UNET (unsteady flow analysis) • BRI-STARS (flow and sediment transport analysis) • GSSHA
Model Linkages	• HSPF – AQUATOX • SWAT – AQUATOX	• LSPC – EFDC • EFDC – WASP	• HEC1 – HEC-RAS

[1]Distributed by Environmental Modeling Systems, Inc. (EMS-I, http://www.ems-i.com/index.html). Similar to WMS, EMS-I also distributes a groundwater modeling system (GMS) and a surface water modeling system (SMS).

These types of linkages provide the capability to assess the complex waterbodies that often require consideration in TMDLs. Numerous other linkages are performed in practice but are not yet supported by a specific modeling system. For example, HSPF has been linked with MODFLOW to address groundwater-surface water interactions. In TMDL applications, linkages are often essential for identifying the allowable loading capacity and determining the source loading components.

The newest trends in model integration are toward Web-based or partially Web-based systems that use the Internet to extract, manage, and manipulate data. Integral to Web-based data systems is the adoption of uniform data storage and management standards and formats. Other research has emphasized building universal and flexible systems that can be used to build model linkages. However, practical application of many of the emerging systems is not yet demonstrated. Selected emerging systems include:

- **Modular Modeling System (MMS).** MMS provides a framework for linking modules to provide a comprehensive modeling system that can be used to develop and test physical process algorithms (http://www.brr.cr.usgs.gov/projects/SW_precip_runoff/mms/). The individual modules can be new code or created as executable objects from existing models. However, MMS places strict requirements on the structure of source code that comprises the modules. Application of the system requires experience in modeling and software development.

- **Flexible Modeling System (FMS).** FMS (http://www.gfdl.noaa.gov/~fms/) is designed for the construction of climate models, and is oriented to facilitating parallel and vector solution techniques. Modules or kernels are developed for high-performance solutions that are linked together based on the FMS structure specifications. Independent groups of researchers can collaborate by evaluating different subsystems concurrently. The system includes specific standards and a shared software environment.

- **Spatial Modeling Environment (SME).** SME (Maxwell and Costanza 1994; Maxwell and Costanza 1997; Maxwell 1999; http://giee.uvm.edu/SME3) provides an environment for linking models and solving analysis with parallel supercomputers. The modeling environment is graphically based and draws from a generic object database. The environment facilitates sharing modules and reusing components in new configurations. Early applications of the system for ecological and nutrient modeling include Patuxent River, Buzzards Bay, and the Everglades Landscape Model (ELM). One application of the SME is the Land-Use Evolution and Impact Assessment Model (LEAM) that provides an approach for simulating the evolution of urban systems by using the Cellular Automata approach combined with the open architecture tools (http://www.rehearsal.uiuc.edu/projects/leam/).

Chapter 6 Case Studies

This chapter includes case studies of two TMDL applications for mercury and nutrient impairments, respectively. Case studies are included to provide an illustration of how models are applied for the purposes of developing TMDLs. These case studies were selected as demonstrations of the typical techniques used in recent years in developing TMDLs for two of the most critical pollutant types, mercury and nutrients. Each study had particular complexities that required the use of models to support the analysis and involved the use multiple models.

Selection of the case studies considered the type of pollutants, the use of multiple models, and the availability of the final report and supporting documents. Each TMDL considered in the case studies is also complete and approved by the state and appropriate EPA region.

The first case study discusses the development of mercury TMDLs in Arivaca Lake and Peña Blanca Lake, Arizona. A combination of watershed loading model, spreadsheet analyses, and mercury lake cycling model is used to describe various sources of mercury loading, in lake processes, and bioaccumulation of mercury in fish.

The second case study summarizes the TMDL development for nutrients in the Cahaba River, Alabama. This case study demonstrates the use of multiple models to address elevated nutrient concentrations during low flow that cause excessive periphyton (attached algae) growth in the Cahaba River. A combination of watershed hydrology modeling, spreadsheet analyses, and river modeling are used to examine the relationship between various low-flow sources and resulting algal growth.

Each case study provides a description of the steps in the TMDL development process, with a clear emphasis on the development of the modeling aspects.

- Background and Problem Identification, including watershed characteristics, listing information and water quality standards and TMDL targets
- Sources
- Model Selection
- Model Setup
- Model Evaluation
- Model Application

Development of Mercury TMDLs in Arivaca Lake and Peña Blanca Lake, Arizona

Background and Problem Identification

Watershed Characteristics

Arivaca Lake and Peña Blanca Lake are impoundments in rural southern Arizona in the Santa Cruz watershed (hydrologic unit code [HUC] 15050304) near the Mexican border. Arivaca, impounded in 1970, has a full-pool surface area of 89 acres, a volume of 1,037 acre-feet, and a maximum depth of 25 feet. Peña Blanca, impounded in

1958, has a full-pool surface area of 49 acres, a volume of 1071 acre-feet, and a maximum depth of 60 feet. Both lakes establish strong summer stratification, which typically breaks down in October.

The region has a semi-arid climate, with abundant rainfall only in July and August. Most of the remainder of the annual precipitation occurs in the winter months. The watersheds are predominantly evergreen forest and shrub and brush rangeland, and tributary inflow to both lakes is intermittent. Both lakes are managed as recreational fisheries.

Listing Information

Both Arivaca and Peña Blanca lakes were placed on Arizona's 303(d) list following detection of elevated levels of mercury in fish tissue and issuance of Fish Consumption Advisories. The criterion used by Arizona to establish Fish Consumption Advisories is an average concentration in target species of greater than 1 mg/kg wet weight (ppm). In Peña Blanca Lake, average concentrations in yearly samples of largemouth bass collected from 1994 to 1997 ranged from 1.31 to 1.53 mg/kg mercury, with individual fish samples ranging up to 2.02 mg/kg. Similar concentrations have been observed in Arivaca Lake, with largemouth bass averages ranging from 1.03 to 1.5 mg/kg. The two lakes were determined not to support their designated uses of fish consumption.

TMDL Targets

The applicable numeric targets for the Arivaca and Peña Blanca TMDLs are the Arizona water quality standard of 0.2 µg/l total mercury in the water column and the Fish Consumption Guideline criterion of 1 mg/kg total mercury concentration in fish tissue. Water column mercury concentrations have not been found in excess of the ambient water quality standard; however, fish tissue concentrations have consistently exceeded the guideline value. Fish in the lakes accumulate unacceptable tissue concentrations of mercury even though the ambient water quality standard appears to be met. The most binding regulatory criterion is the fish tissue concentration criterion of 1 mg/kg total mercury, which is selected as the primary numeric target for calculating the TMDL.

Mercury bioaccumulates in the food chain. Within a lake fish community, top predators usually have higher mercury concentrations than forage fish, and tissue concentrations generally increase with age class. Top predators are often target species for sport fishermen, and Arizona's Fish Consumption Guideline is based on average concentrations in a sample of sport fish. Therefore, the criterion should not be applied to the extreme case of the most-contaminated age class of fish within a target species; instead, the criterion is most applicable to an average-age top predator. Within Arivaca Lake and Peña Blanca Lake, the top predator sport fish is the largemouth bass. A site-specific spreadsheet model was developed to evaluate lake water quality model output and predict mercury concentrations in fish tissue for each age class at each trophic level. Average mercury concentrations in fish tissue of target species are assumed to be approximated by average concentration in 5-year-old largemouth bass. In the May 1995 sampling of Peña Blanca Lake, the average mercury tissue concentration in largemouth bass (1.31 mg/kg) was slightly lower than the average concentration in 5-year-old largemouth bass (1.35 mg/kg), and the average concentrations in all other sampled species were lower than that in largemouth bass. Therefore, the selected target for the TMDL analysis is an average tissue concentration in 5-year-old largemouth bass of 1.0 mg/kg or less.

Source Assessment

There are no permitted point source discharges and no known sources of mercury-containing effluent in the Arivaca or Peña Blanca watersheds. External sources of mercury load to the lake include natural background load from the watershed, nonpoint loading from past mining activities, and atmospheric deposition.

Watershed Background Load

The watershed background load of mercury derives from mercury in the parent rock and from the net effects of atmospheric deposition of mercury on the watershed. Because no near-field significant sources of mercury deposition were identified, mercury from atmospheric deposition onto the watershed is treated as part of a general watershed background load in this analysis. Atmospheric deposition of mercury occurs throughout the world, and mercury enters these watersheds through both wet deposition (precipitation) and dry deposition. As described below, atmospheric deposition is estimated to contribute more than 12 micrograms of mercury per square meter per year ($\mu g/m^2/yr$). The direct atmospheric loading to the lake is greater than the total estimated load of mercury from the watershed to the lake; however, portions of the atmospheric mercury deposition do not enter the lake because they are recycled to the atmosphere or sequestered within the watershed.

Mercury is also present within the parent rock formations of the Peña Blanca and Arivaca watersheds. Cinnabar (HgS), the primary naturally occurring ore of mercury, typically consists of 86.2 percent mercury and 13.8 percent sulfide. Cinnabar occurs as impregnations and vein fillings in near-surface environments from solutions associated with volcanic activity and hot springs. Cinnabar also may occur in placer-type concentrations produced from the erosion of mercury-bearing rocks. In the Peña Blanca watershed, cinnabar has been reported to occur as traces in irregular and lensing fissure veins in association with argentiferous galena, pyrite, marcasite, and chalcopyrite.

The net contributions of both atmospheric deposition and weathering of native rock were assessed by measuring concentrations in sediment of tributaries to Arivaca Lake and Peña Blanca Lake. Based on these data, as well as three background sediment samples from just outside the Arivaca Lake watershed (in areas expected to be relatively uncontaminated by anthropogenic sources of mercury), most of the sediment samples from the Arivaca and Peña Blanca watersheds may be considered at or near background mercury levels. In the Peña Blanca watershed, sediment mercury concentrations were below 100 parts per billion (ppb), except for samples at and just downstream of an old gold mine tailings pile found during reconnaissance. The sample just below the tailings pile showed an extremely elevated concentration of 555,000 ppb. In the Arivaca watershed, sediment mercury concentrations were below 150 ppb, except for samples at and just downstream of the Ruby Dump site, in the southern end of the watershed. Samples within Ruby Dump had mercury levels as high as 1467 ppb.

Nonpoint Loading from Past Mining Activity

The mining of precious metals such as gold and silver was common in the Parajitto mining area surrounding Peña Blanca Lake. It was also common in the area surrounding Arivaca Lake, but apparently not within the Arivaca watershed itself.

Before the introduction of cyanidation technology at the beginning of the 20th century, mercury-amalgamation of precious metal ores it was a common practice throughout the western United States, using mercury to amalgamate gold ore in ball mills. Ball mill process mercury is likely to be of greater concern for environmental impact because the residue is more likely to contain soluble species of mercury than low-solubility cinnabar outcrops. Studies of the highly contaminated Carson River area in Nevada demonstrate that the dominant form of mercury present in amalgamation-process tailings is still elemental mercury, approximately a century after peak mining activity, while stream sediments in the tailings area were dominated by elemental and exchangeable forms of mercury. Significant conversion to relatively insoluble cinnabar occurs only when these materials are transported to more anoxic, reducing environments with concentrations of labile sulfur in excess of 0.1 percent by weight. Thus, the mercury contained in ball mill tailings is likely to be more mobile and more bioavailable than the mercury contained in cinnabar in the watershed soils and tailings residue from hard rock mines (which were not processed by mercury amalgamation).

One ball mill site has been identified in the Peña Blanca watershed, associated with the St. Patrick Mine and with a tailings pile adjoining an intermittent stream bed. In June 1999, 30 samples were collected from the tailings pile, mill site, and adjacent streambed site. Samples from outside of the tailings pile generally revealed low levels of contamination (from nondetectable up to 15 mg/kg). Seven samples collected from the tailings pile gave higher results, ranging from 63 to 460 mg/kg total mercury. These results confirm that the tailings pile is a mercury hot spot.

Reconnaissance efforts in the Arivaca watershed have not located any obvious ball mill sites within the watershed. Although the possibility cannot be ruled out, the likelihood of finding previously unknown additional mill sites or tailings piles in the Arivaca drainage is low. No detectable mercury was found at two known mine shaft sites in the watershed. However, somewhat elevated levels of mercury were found within the old Ruby Dump, in the southern end of the watershed. Ruby Dump is located in the southern portion of Arivaca watershed, at the very upstream end of Cedar Canyon Wash. The dump apparently served the town of Ruby and the Montana Mine. This former mining town is located about 1 mile southwest of the dump site, outside the Arivaca watershed.

Atmospheric Deposition

The third component of mercury loading is direct atmospheric deposition to the lake surface. Atmospheric deposition is often separated into near-field, or local sources, and far-field sources. Elevated near-field deposition is often found downwind of coal-fired power plants, smelters, and lime kilns. A variety of potential near-field sources was evaluated in the United States and Mexico. Based on the lack of major nearby sources, particularly sources along the axis of the prevailing wind, near-field atmospheric deposition of mercury attributable to individual emitters is not believed to be a major component of mercury loading to the Arivaca and Peña Blanca watersheds.

Long-range atmospheric deposition is a major source of mercury in many parts of the country. A study of trace metal contamination of reservoirs in New Mexico indicated that perhaps 80 percent of mercury found in surface waters was coming from atmospheric deposition. In other remote areas (e.g., in Wisconsin, Sweden, and Canada), atmospheric deposition has been identified as the primary (or possibly only) contributor of mercury to waterbodies.

Wet deposition of mercury has been measured by the Mercury Deposition Network in its first year of operation (February 1995-February 1996), the Mercury Deposition Network found a volume-weighted average concentration of 10.25 ng/L total mercury in precipitation at 17 stations located mainly in the upper Midwest, Northeast, and Atlantic seaboard (http://nadp.nrel.colostate.edu/ NADP/mdn/mdn.html). Volume-weighted average concentration of mercury did vary by station, ranging from 3.62 ng/L at Acadia National Park, Maine, to 13.56 ng/L at Bondville, Illinois. Average weekly wet deposition at the 17 stations ranged from 63 ng/m^2 to 280 ng/m^2.

Only limited monitoring of atmospheric deposition of mercury is available in the Southwest and none in Arizona. Dry deposition were measured in the Peña Blanca watersheds (Caballo data), but the monitoring location is about 150 miles closer to the subject lakes than the Peña Blanca lakes. Lack of geographically closer monitoring introduces considerable uncertainty; however, as shown below, direct atmospheric deposition appears to account for only a small portion of the total mercury load to the lake. Even if the direct atmospheric loading rate is underestimated by a significant amount, it would have only a minor effect on the predicted lake response. The Caballo data therefore were selected to characterize mercury wet deposition to the lake surfaces. The short period of record available was extrapolated to provide estimates across the period of simulation. Two approaches were considered to make this extrapolation: development of a relationship between mercury concentration and rainfall volume, and calculation of average deposition rates. The first approach is based on the observation that mercury wet deposition concentrations are typically inversely related to rainfall volume. There is considerable scatter in this relationship in the Caballo data, particularly at low precipitation volumes. Given this scatter and the short period of record available, the concentration approach was rejected. Instead, it was assumed that cumulative deposition mass was a more robust estimator than concentration. To make maximum use of the available data, the series of all possible running 12-month sums were calculated and then averaged, yielding an average annual deposition rate of 4.125 µg/m^2-yr (79 ng/m^2-wk). This annual sum was then apportioned to months based on the observed deposition pattern from May 1997 through April 1998.

The Caballo station does not measure dry deposition. Although there are few direct measurements to support well-characterized estimates, dry deposition of mercury often is assumed to be approximately equal to wet deposition (e.g., Lindberg et al., 1991), as is reported in the Peña Blanca Lake. Because the climate at Arivaca and Peña Blanca is wetter than at Caballo, the distribution of wet and dry deposition is likely to be different. Total mercury deposition at Arivaca/Peña Blanca is assumed to equal that estimated for Caballo, New Mexico, but Arivaca/Peña Blanca are estimated to receive greater wet deposition and less dry deposition than Caballo because more of the particulate mercury and reactive gaseous mercury that contribute to dry deposition will be scavenged at a site with higher rainfall.

Model Selection

The TMDLs needed to be completed on a short time line established in a consent decree and with limited resources. This condition required focusing efforts on those aspects of the problem that were most important to the decision process. Of the many physical and chemical processes linking mercury sources to bioaccumulation in fish, some were, of necessity, addressed through simple scoping models, while for other components, highly sophisticated methods were used. Focusing the modeling effort was a key factor in successful completion of the TMDLs and depended on two factors: use of a cross-sectional comparison (using a reference lake) and collection of a high-quality dataset.

The Mercury Cycle

Development of the risk hypothesis, and therefore selection of appropriate modeling approaches, requires an understanding of how mercury cycles in the environment. Mercury chemistry in the environment is quite complex. Mercury has the properties of a metal (including great persistence due to its inability to be broken down) but also has some properties of a hydrophobic organic chemical due to its ability to be methylated via a bacterial process. Methylmercury, easily taken up by organisms, tends to bioaccumulate; it is very effectively transferred through the food web, magnifying at each trophic level. This transfer can result in high levels of mercury in organisms high on the food chain, despite nearly immeasurable quantities of mercury in the water column. In fish, mercury is not usually found in levels high enough to cause the fish to exhibit signs of toxicity, but wildlife that habitually eat contaminated fish are at risk of accumulating mercury at toxic levels, and the mercury in sport fish can present a potential health risk to humans.

Mercury and methylmercury form strong complexes with organic substances (including humic acids) and strongly sorb onto soils and sediments. Once sorbed to organic matter, mercury can be ingested by invertebrates, thus entering the food chain. Some of the sorbed mercury will settle to the lake bottom; if buried deeply enough, mercury in bottom sediments will become unavailable to the lake mercury cycle. Burial in bottom sediments can be an important route of removing mercury from the aquatic environment.

Methylation and demethylation play an important role in determining how mercury will accumulate through the food web. Hg(II) is methylated by a biological process that appears to involve sulfate-reducing bacteria. Rates of biological methylation of mercury can be affected by a number of factors. Methylation can occur in water, sediment, and soil solution under anaerobic conditions and, to a lesser extent, under aerobic conditions. In lakes, methylation occurs mainly at the sediment-water interface and at the oxic-anoxic boundary within the water column. The rate of methylation is affected by the concentration of available Hg(II), microbial concentration, pH, temperature, redox potential, and the presence of other chemical processes. Demethylation of mercury is also mediated by bacteria.

Note that both Hg(II) and methylmercury (MeHg) sorb to algae and detritus, but only methylmercury is assumed to be passed up to the next trophic level (inorganic mercury is relatively easily egested). Invertebrates eat both algae and detritus, thereby accumulating sorbed MeHg. Fish eat the invertebrates and either grow into larger fish (which have been shown to have higher body burdens of mercury) or are eaten by larger fish. At each trophic level, a bioaccumulation factor must be assumed to represent the magnification of mercury concentration that occurs up the food chain.

Typically, almost all of the mercury found in fish (more than 95 percent) is in methylmercury form. Studies have shown that fish body burdens of mercury increase with increasing size or age of the fish, with no signs of leveling off.

Although it is important to identify sources of mercury to the lake, there may be fluxes of mercury within the lake that would continue nearly unabated for some time, even if all sources of mercury to the lake were eliminated. In other words, compartments within the lake probably currently store a significant amount of mercury, and this mercury can continue to cycle through the system even without an ongoing outside source of mercury. The most important store of mercury within the lake is likely to be the bed sediment. Mercury in the bed sediment may cause exposure to biota by being:

- Resuspended into the water column, where it is ingested or it adsorbs to organisms that are later ingested.
- Methylated by bacteria. The methylmercury tends to attach to organic matter, which may be ingested by invertebrates and thereby introduced to the lake food web. Methylmercury poses the real threat to biota due to its strong tendency to accumulate in biota and magnify up the food chain.

Data Collection

Unfortunately, much of the historic database on environmental mercury concentrations is suspect, due to high detection limits and potential contamination due to lack of ultra-clean sampling and analysis techniques. Further, while methylmercury concentrations are key to predicting bioaccumulation, the methylated component is rarely measured.

To develop a defensible TMDL linkage analysis, high-quality data were needed to describe mercury distribution and movement in the waterbodies and their watersheds, but time and resources for data collection were limited. During two sampling events representing stratified and unstratified lake conditions, data were collected using ultra-clean techniques on mercury species in biota, mercury species and general chemistry in the water column and sediments of both lakes. Sampling of inflow was not possible, given the highly intermittent nature of runoff. Watershed sampling therefore focused on evaluating mercury concentrations and sediment characteristics in the beds of the intermittent stream networks feeding each lake. Another important aspect of data collection was detailed field reconnaissance. While there are no permitted point sources or active mines in either watershed, the field reconnaissance, together with evidence from stream sediments, identified an important mercury source area in old ball-mill tailings in the Peña Blanca watershed.

Summer stratified surface water concentrations in both lakes were low (about 4 ng/l total mercury in Peña Blanca and 8 ng/l in Arivaca), but increased with depth, reaching 20 to 40 ng/l near the sediment. Methylmercury concentrations below the hypolimnion were 4 ng/l in Peña Blanca and 14 ng/l in Arivaca. Higher concentrations were found in lake sediment, ranging up to 470 ppb in Peña Blanca and 192 ppb in Arivaca. Surveys of watershed sediments revealed higher concentrations. Within Peña Blanca watershed, concentrations ranged up 554,937 ppb dry weight and in Arivaca watershed up to 1,222 ppb dry weight; however, most samples were less than 100 ppb. Background concentrations collected in an area just outside the Arivaca watershed believed to be relatively uncontaminated by anthropogenic sources ranged from 12 to 197 ppb mercury, consistent with other studies of background mercury levels in soils. Thus, both watersheds appear to be largely in the range of background measurements, with isolated mercury hot spots.

Cross-Sectional/Reference Site Approach

The complex nature of mercury cycling in the environment can introduce considerable uncertainty into linkage analysis modeling. From examination of a single waterbody, it is difficult to determine the relative contributions of gross mercury loading, internal mercury cycling, and rates of mercury methylation and food chain accumulation to observed body burdens in fish.

Additional constraints on the analysis can be developed by examining several lakes within the same region simultaneously (cross-sectional approach). Explaining the differences in mercury load, cycling, and bioaccumulation among several lakes provides a robust basis on which to develop the conceptual model. Therefore, the linkage analysis for Arivaca Lake was developed simultaneously with analyses for Peña Blanca Lake and Patagonia Lake. Patagonia Lake is within the same region, yet it has acceptable fish tissue mercury concentrations. Patagonia thus serves as an unimpaired reference site for the cross-sectional analysis. The basic physical characteristics of the three lakes and their watersheds are compared in Table 6-1.

All three lakes lack known point source discharges of mercury and have a fairly similar distribution of rural rangeland and forest land uses. The Patagonia watershed has far more historical gold mining operations (but also a much larger watershed area), but it is not known how many (if any) of the Patagonia mines are associated with mercury-contaminated ball mill sites. EPA has not detected elevated sediment mercury in the Patagonia watershed. Physically, Patagonia differs from Peña Blanca and Arivaca because it has a much larger volume, a larger contributing watershed, and a shorter hydraulic residence time. Patagonia is also the deepest of the three lakes.

EPA collected data from all three lakes and their watersheds in July 1998, providing a valuable basis for cross-sectional comparison. All three lakes were strongly stratified with anoxic hypolimnia at the time of sampling.

Table 6-1. Cross-Sectional Comparison of Studied Lakes

Characteristic	Peña Blanca Lake	Arivaca Lake	Patagonia Lake
Surface area (acres)	49	90	200
Volume at full pool (acre-feet)	1071	1050	11000
Average depth (ft)	21.8	11.7	29.1
Maximum depth (ft)	60	25	86
Estimated hydraulic residence time (yrs), 1985-98 average	0.36	0.33	0.16
Watershed area (acres)	8820.6	12696.4	145904
Rangeland (acres)	845.9	5761.3	55509.7
Evergreen Forest (acres)	7906.7	6421.1	88503.8
Cropland and Pasture (acres)	0	420.3	1204.2
Urban and Residential (acres)	33.2	26.5	408.2
Water (acres)	34.8	67.3	278.1
Producing mines identified in MILS	4 inactive	none	88 inactive 6 active
Mines producing gold	2 inactive	none	51 inactive 1 active

Note: “Active” mines include those on temporary shutdown as of the 1995 MIL. Prospects are omitted from the tabulation.

At the time of the July sampling, all three lakes had similar total mercury concentrations in the sediment but very different concentrations in the water column. Lake sediment concentrations in Peña Blanca were somewhat elevated relative to Arivaca and Patagonia. All three lakes showed significant amounts of methylmercury in sediment, but Patagonia, unlike Arivaca and Peña Blanca, did not have much methylmercury in the water column. This condition seems to explain why fish have unacceptable levels of mercury contamination in Arivaca and Peña Blanca but not in Patagonia.

The July data emphasize that there may be little correlation between the total mercury mass stored in lake sediments and mercury concentration in fish. Sediment concentrations in Patagonia Lake of both total mercury and methylmercury were higher than those observed in Arivaca, yet Patagonia Lake has acceptable fish tissue concentrations while Arivaca does not. Sediment concentrations of total mercury in Peña Blanca were three times those in Arivaca, but total mercury concentrations in the water column were about twice as high in Arivaca as in Peña Blanca. These observations—indicating that total mercury concentrations in sediment are not linearly related to fish body burden—suggest that the linkage analysis requires a model that can describe the relationship between external mercury load and methylmercury generation.

Why are mercury levels in the water column higher in Arivaca and Peña Blanca than in Patagonia, despite rather similar sediment concentrations? Strong clues emerge from the water column chemistry results from the July sampling. As shown in Table 6-2, sulfate is strongly elevated in the hypolimnion of Patagonia relative to the other lakes, while alkalinity and pH are also elevated, and dissolved organic carbon (DOC) is somewhat depressed.

These observations suggest that relatively high sulfate concentrations (under alkaline conditions) promote precipitation of cinnabar in Patagonia, thus reducing water column concentrations. Differences in sediment chemistry might also play an important role. The sediment of Patagonia Lake has a stronger reducing environment and lower organic carbon content than the other two lakes. Finally, Patagonia is the deepest lake, which might reduce growth of algae and photosynthetic bacteria at the sediment interface.

Table 6-2. Comparison of Summer Hypolimnetic Water Chemistry between Studied Lakes

Parameter	Patagonia	Arivaca	Peña Blanca
Sulfate (mg/L)	185	0.2	7
Alkalinity (mg/L)	156	91	86
pH	7.5	6.6	7
DOC (mg/L)	7	24	10
Total Hg (ng/L)	2	38	20
MeHg (ng/L)	0.8	14.3	3.9
Total Hg in sediment (µg/kg)	148	129	360
MeHg in sediment (µg/kg)	0.45	0.30	0.95

Risk Hypotheses

In sum, the key differences among the lakes appear to be in water chemistry and in consequent effects on mercury speciation and cycling, rather than in gross total mercury load (as indicated by sediment concentration). Prior to model development, this understanding was summarized in the following risk hypothesis:

1. Mercury concentrations in fish are driven by summer methylmercury concentrations in the epilimnion.
2. Summer methylmercury concentrations in the epilimnion are driven by mixing from methylmercury concentrations in the hypoxic zone just below the thermocline.
3. Methylmercury concentrations below the thermocline are determined primarily by water chemistry and its effect on mercury methylation in the anoxic portion of the water column and cycling between the water and sediment, and secondarily by mercury concentration in the sediment or gross mercury loads.
4. Total mercury concentration in the sediments is driven by watershed loads but reflects accumulation over relatively long periods of time and changes slowly.

For each lake, the linkage analysis components described in the following sections are designed to provide a quantitative investigation of this risk hypothesis. The linkage tools are separated into several general components. The first two components address the watershed, and the third and fourth address the lake itself. First is a watershed hydrologic and sediment loading model, which represents the movement of water and sediment from the watershed to the lake. This model supports the second component, an analysis of watershed loading of mercury to the reservoir. A lake hydrologic model is the third component. Finally, a model of lake mercury cycling and bioaccumulation is used to address the cycling of mercury in the lake among and between abiotic and biotic components. When combined, these components are the TMDL linkage analysis.

Model Setup

Watershed Hydrologic and Sediment Loading Model

An analysis of watershed loading could be conducted at many different levels of complexity, ranging from simple export coefficients to a dynamic model of watershed loads. Data are not available, however, to parameterize or calibrate a detailed representation of flow and sediment delivery within the watersheds. Therefore, a relatively simple, scoping-level analysis of watershed mercury load, based on an annual mass balance of water and sediment loading from the watershed, is used for the TMDL. Uncertainty introduced in the analysis by use of a simplified and uncalibrated watershed loading model must be addressed in the Margin of Safety.

Watershed-scale loading of water and sediment was simulated using the GWLF model (Haith et al. 1992). The complexity of this model falls between that of detailed simulation models, which attempt a mechanistic, time-dependent representation of pollutant load generation and transport, and simple export coefficient models, which do not represent temporal variability. GWLF provides a mechanistic, simplified simulation of precipitation-driven runoff and sediment delivery, yet is intended to be applicable without calibration. Solids load, runoff, and groundwater seepage can then be used to estimate particulate and dissolved-phase pollutant delivery to a stream, based on pollutant concentrations in soil, runoff, and groundwater.

GWLF simulates runoff and streamflow by a water-balance method, based on measurements of daily precipitation and average temperature. Precipitation is partitioned into direct runoff and infiltration using a form of the SCS Curve Number method. The Curve Number determines the amount of precipitation that runs off directly, adjusted for antecedent soil moisture based on total precipitation in the preceding 5 days. A separate Curve Number is specified for each land use by hydrologic soil grouping. Infiltrated water is first assigned to unsaturated zone storage, where it may be lost through evapotranspiration. When storage in the unsaturated zone exceeds soil water capacity, the excess percolates to the shallow saturated zone. This zone is treated as a linear reservoir that discharges to the stream or loses moisture to deep seepage, at a rate described by the product of the zone's moisture storage and a constant rate coefficient.

Stream flow may derive from surface runoff during precipitation events or from groundwater pathways. The amount of water available to the shallow groundwater zone is strongly affected by evapotranspiration, which GWLF estimates from available moisture in the unsaturated zone, potential evapotranspiration, and a cover coefficient. Potential evapotranspiration is estimated from a relationship to mean daily temperature and the number of daylight hours. In the arid Southwest, evapotranspiration often exceeds moisture supply, so stream runoff occurs sporadically in response to precipitation exceeding infiltration capacity. All the streams feeding Arivaca Lake are classified by USGS as intermittent and lack a consistent base flow component.

Monthly sediment delivery from each land use is computed from erosion and the transport capacity of runoff, and total erosion is based on the Universal Soil Loss Equation (Wischmeier and Smith 1978), with a modified rainfall erosivity coefficient that accounts for the precipitation energy available to detach soil particles (Haith and Merrill 1987). Thus, erosion can occur with precipitation but no surface runoff to the stream; delivery of sediment, however, depends on surface runoff volume. Sediment available for delivery is accumulated over a year, although excess sediment supply is not assumed to carry over from one year to the next.

GWLF application requires information on land use, land cover, soil, and parameters that govern runoff, erosion, and nutrient load generation.

Watershed Mercury Loading Model

Estimates of watershed mercury loading are based on the sediment loading estimates generated by GWLF through application of a sediment potency factor. A background loading estimate was first calculated, then combined with estimates of loads from individual hot spots.

The majority of the EPA sediment samples showed no clear spatial patterns in sediment mercury concentrations, with the exception of the "hot spot" areas identified at Ruby Dump and the St. Patrick Mine tailings pile. Therefore, background loading was calculated using the central tendency of sediment concentrations from all samples excluding the hot spots. The background sediment mercury concentrations were assumed to be distributed lognormally, as is typical for environmental concentration samples, and an estimate of the arithmetic mean was calculated from the observed geometric mean and coefficient of variation. Applying this assumption to the GWLF estimates of sediment transport yields an estimated rate of mercury loading from watershed background of 178.9 g/yr. This load is ultimately derived from a combination of atmospheric deposition on the land, naturally occurring mercury in rocks underlying the watershed, and dispersed human activities.

Loading from the Ruby Dump and St. Patrick mine area are calculated separately but are also based on the GWLF estimate of sediment load generated per hectare of rangeland (the land use surrounding the hot spots), as reduced by the sediment delivery ratio for the watershed.

Based on assumptions regarding hot spot size and sediment load multipliers, less than 1 percent of the watershed mercury load to Arivaca Lake appears to originate from Ruby Dump, which is the only identified hot spot in the watershed. Given the uncertainties in estimation of erosion rates and the incomplete status of the USFS characterization of the St. Patrick Mine ball mill tailings, the assessment of mercury loading from this area should be judged to be only a rough, order of magnitude estimate. The estimate suggests, however, that this source plays a significant role in mercury loading to Peña Blanca Lake. Given the assumptions used to estimate loads, approximately 69 percent of the watershed mercury load to Peña Blanca appears to originate from the tailings pile and contaminated downstream sediments. This large percentage is a result of the high average concentration reported for the tailings (287,000 ppb) relative to the average mercury concentration in sediments in the remainder of the watershed (48 ppb).

Direct Atmospheric Deposition to Lake

The direct deposition of mercury from the atmosphere onto the lake surfaces was calculated by multiplying the estimated atmospheric deposition rates times the lake surface area. Although Patagonia Lake has a higher total annual mercury load, the load per volume of inflow is much lower than those in the two impaired lakes. Atmospheric deposition directly to the lake surface does not appear to be a major source of total mercury load, as it is estimated to account for only about 1 percent of the total annual load to the lakes. Atmospheric deposition to the watershed could, however, constitute a significant portion of the net loading from the watershed.

Lake Hydrologic Model

No monitoring data for inflow, water stage, or outflow are available for Arivaca Lake or Peña Blanca Lake. The lake levels are not actively managed, and releases occur only when storage capacity is exceeded. Therefore, lake hydrology was represented by a simple monthly water balance, using the following assumptions:

- Inflow from the watershed is given by monthly predictions from the GWLF model application.
- Direct precipitation on the lake surface is estimated from local observed monthly precipitation depth times the lake surface area at the beginning of the month.
- Evaporation from the lake surface is estimated from pan evaporation data and a pan coefficient of 0.7. This estimate represents the ratio between mean annual lake surface evaporation and average annual evaporation from Class A evaporation pans for this area of southern Arizona, and is within the range recommended by Dunne and Leopold (1978).
- Net gain from or loss to groundwater seepage through the lake bed is assumed to be zero, lacking any evidence to the contrary.
- Potential storage at the end of the month is calculated as the sum of initial storage plus inflow plus direct precipitation minus evaporation.
- The stage-area-discharge curve is used to estimate the surface area and elevation of the lake surface corresponding to the potential storage at the end of the month. If the lake surface elevation is computed to be higher than the spillway elevation, the excess volume is assumed to spill downstream.
- Actual storage at the end of the month is the smaller of potential storage and full-pool storage.

- Surface area and elevation of the lake surface at the end of the month are updated to reflect actual storage.

Lake Mercury Cycling and Bioaccumulation Model

Cycling and bioaccumulation of mercury within the lake was simulated using the Dynamic Mercury Cycling Model (D-MCM; Tetra Tech 1999). D-MCM is a Windows 95/NT™-based simulation model that predicts the cycling and fate of the major forms of mercury in lakes, including methylmercury, Hg(II), and elemental mercury. D-MCM is a time-dependent mechanistic model, designed to consider the most important physical, chemical and biological factors affecting fish mercury concentrations in lakes. It can be used to develop and test hypotheses, scope field studies, improve understanding of cause and effect relationships, predict responses to changes in loading, and support design and evaluation of mitigation options.

The major processes in D-MCM include inflows and outflows (surface and groundwater), adsorption/desorption, particulate settling, resuspension and burial, atmospheric deposition, air/water gaseous exchange, industrial mercury sources, in-situ transformations (e.g., methylation, demethylation, MeHg photodegradation, Hg(II) reduction), mercury kinetics in plankton, and bioenergetics related to methylmercury fluxes in fish.

Model compartments include the water column, sediments, and a food web that includes three fish populations. Mercury concentrations in the atmosphere are input as boundary conditions to calculate fluxes across the air/water interface (gaseous exchange, wet deposition, dry deposition). Similarly, watershed loadings of Hg(II) and methylmercury are input directly as time-series data. The user provides for hydrologic inputs (surface and groundwater flowrates) and associated mercury concentrations, which are combined to determine the watershed mercury loads.

The food web consists of six trophic levels—phytoplankton, zooplankton, benthos, nonpiscivorous fish, omnivorous fish, and piscivorous fish. Fish mercury concentrations tend to increase with age, and thus are followed in each year class. Bioenergetics equations for individual fish (Hewitt and Johnson 1992) have been adapted to simulate year classes and entire populations.

Input parameters for conducting the simulations for all three lakes in this study can be broadly separated into five categories:

- Hydrologic dynamics and lake physical characteristics (morphometry, stratification)
- External loading rates of Hg (atmospheric, nonpoint source, and point source)
- Thermodynamic and kinetic rate constants
- Water, and sediment chemistry
- Biotic data

Model Evaluation

Sensitivity Analysis on Hotspot Sediment Load Multipliers

Watershed mercury loading from the known mercury hot spots (Ruby Dump and the St. Patrick mine ball mill site) was calculated separately from the general sediment-associated watershed mercury loading, as discussed previously. For both hot spots, sediment load per hectare from the hot spot is assumed to be four times greater than that for normal rangeland. For the Ruby Dump site, this multiplier is intended to reflect the lack of vegetation at the site; for the ball mill site, it reflects the fine consistency of tailings. This sediment load multiplier factor may be thought of in terms of the USLE equation (RE*K*LS*C*P), which predicts sediment loss. The K factor for rangeland in the watershed was set to 0.08, based on data in the STATSGO soil coverage. This K factor represents a sandy soil. The consistency of the mine tailings, however, has been compared to that of talcum powder. A typical K factor for very fine sand with low organic content is 0.42, which is 5.2 times the K factor for rangeland soil (and would therefore increase sediment loading estimates by 5.2 times). This factor is compensated somewhat by the fact that sediment at the ball mill site is likely to be a mixture of native sandy soil and the finer tailings, and by lower slopes at the ball mill site than the average for rangeland soils in the watershed (because the site is located at the bottom of the canyon).

For both sites, a simple sensitivity analysis was carried out on the sediment load multiplier to estimate its effect on overall load estimates. In the case of the Ruby Dump site, doubling the load multiplier has very little effect on the overall estimated load (Table 6-3). The sediment load multiplier is a more important parameter in the Peña Blanca watershed (Table 6-4), however, because the ball mill site appears to be the dominant contributor of mercury loading to the lake.

Table 6-3. Sensitivity Analysis on the Ruby Dump Sediment Load Multiplier

Sediment Load Multiplier	Percent of Load Attributed to Ruby Dump
1	0.1%
2	0.2%
4	0.4%
8	0.7%

Table 6-4. Sensitivity Analysis on the Ball Mill Site Sediment Load Multiplier

Sediment Load Multiplier	Percent of Load Attributed to St. Patrick Ball Mill Tailings
2	54.7%
4	70.7%
8	82.8%

Mercury Cycling Model

As stated previously, it was necessary to focus the modeling efforts, applying the most sophisticated modeling approaches to the processes that seem most important in driving fish mercury concentrations (i.e., cycling and accumulation of mercury within the lake). Therefore, though other modeling components (e.g., the GWLF watershed model) remained uncalibrated, more effort was expended on the D-MCM component, including examining known areas of scientific uncertainty in the model, modifying the model to better represent the lakes in this study, and calibrating the model to the three lakes used in the cross-sectional approach.

Scientific Knowledge Gaps in D-MCM

The current version of D-MCM has updated mercury kinetics and an enhanced bioenergetics treatment of the food web. The predictive capability of D-MCM is evolving but is currently limited by some scientific knowledge gaps, including:

- The true rates and governing factors for methylation and Hg(II) reduction
- Factors governing methylmercury uptake at the base of the food web
- The effects of anoxia and sulfur cycling

For example, there is evidence that anoxia and sulfides can affect mercury cycling and influence water column mercury concentrations in lakes (e.g., Benoit et al. 1999, Gilmour et al. 1998, Watras et al 1995, Driscoll et al. 1994), but the underlying mechanisms and controlling factors have not been quantified.

Another important assumption in the current version of D-MCM is that all of the Hg(II) on particles is readily exchangeable. This results in longer predicted response times for lakes to adjust to changing conditions or mercury loads than likely would occur. It is quite plausible that a significant fraction of Hg(II) on particles is strongly bound, reducing the amount of Hg(II) available for mercury cycling and the time required for fish mercury concentrations to adjust to changes in mercury loadings. The magnitude of this error potentially can be quite large for oligotrophic lakes with very low sedimentation rates and very long particulate mercury residence times in the surficial sediments. For systems that have very high sedimentation rates such as many reservoirs, the practical consequence of this assumption could be small.

Modifying D-MCM for this Modeling Application

Because strong anoxia in the hypolimnion is a prominent feature during summer stratification for the Arizona lakes simulated in this study, D-MCM was modified to explicitly allow significant methylation to occur in the hypolimnion. In previous applications of D-MCM, the occurrence of methylation has been restricted to primarily within surficial sediments. That the locus of methylation likely includes or is even largely within the hypolimnion (at least for Arivaca and Peña Blanca lakes) is supported by (1) the detection of significant, very high methylmercury concentrations in the hypolimnia of Arivaca and Peña Blanca lakes and (2) almost complete losses of sulfate in Arivaca Lake in the hypolimnion resulting from sulfate reduction. An input was added to the model to specify the rate constant for hypolimnetic methylation, distinct from sediment methylation.

Calibration of D-MCM

D-MCM was calibrated to the three study lakes by compiling and inputting data specific to each lake on:

- Hydrology and lake physical characteristics (morphometry, stratification)
- External loading rates of mercury (from the atmosphere, watershed, and Ruby Dump)
- Thermodynamic and kinetic rate constants
- Water and sediment chemistry
- Biotic data

Data specific to each of the three lakes were input into the model first, followed by data derived from calibrations for other lakes where site-specific data were lacking for Arivaca and Peña Blanca lakes. For instance, thermodynamic and kinetic rate constants specific to the lakes are not available and were obtained from previous calibrations of D-MCM to lakes in other regions.

Calibration proceeded by running the model with a daily timestep for 10 years and adjusting the model so that concentrations of mercury in largemouth bass matched observed averages for each lake. Because the hydrology of these lakes is so dynamic and "flashy," more weight was placed on matching largemouth bass Hg concentrations than on trying to match predicted and observed water chemistry data precisely. This decision was based on the following:

- Limited water chemistry data that indicate that chemistry in these systems varies rapidly.
- Hydrologic budgets that show that the hydraulic residence time of all three lakes is relatively short (less than 0.4 year).

- The lack of truly local atmospheric loading data adequate for resolving and validating short-term dynamics in any of the lakes.
- The fact that mercury concentrations in older cohorts of largemouth bass reflect dietary intake throughout their life history and are rather insensitive to short-term variations in water column chemistry and Hg loading dynamics.

The calibrations used the same kinetic (rate constant) assumptions for all three lakes letting only differences in loading, hydrology, and chemistry dictate differences in response. The following paragraphs give a brief overview of how the input data were assembled and input to the model.

Calibration of the model assumed that there were no good *a priori* reasons to use differing rate or thermodynamic constants for each lake to account for differing mercury behavior. Initial application to Arivaca and Peña Blanca resulted in large overestimates of the amount of mercury predicted in fish. The particle-Hg(II) partition coefficients were adjusted for particles in the sediment and water column to yield stronger particulate binding, thus reducing the dissolved pool available for methylation. Higher partition coefficients are appropriate for the epilimnion because the hypolimnion becomes seasonally anoxic, which can reduce the ability of inorganic particles to sorb trace elements. To further improve the model calibration, focus was placed on one feature of the model known to be potentially inadequate—the ability of the model to predict the amount of labile Hg truly available for desorption. Previous simulations with D-MCM have illustrated that, although initial sorption of Hg to particles may be well characterized by conventional sorption models such as the Freundlich and Langmuir isotherms, desorption of "aged" Hg bound to particles may not follow the same models. In others, some Hg may become irreversibly bound after adsorption has initially occurred, and the amount of mercury ultimately available for desorption is less than the initial sorption models would predict. The final model calibration assumed that watershed background mercury loads were 62 percent available for desorption, while loads derived from ball mill tailings at Peña Blanca Lake and from Ruby Dump at Arivaca Lake were wholly available. This approach yielded a good match to observations of mercury concentrations in water and in fish (Table 6-5).

A comparison of model-predicted internal fluxes in the three lakes shows that the key difference between Patagonia versus Peña Blanca and Arivaca lakes is the rate of hypolimnetic methylation of mercury.

Table 6-5. D-MCM Calibration for Peña Blanca, Arivaca, and Patagonia Lakes

Lake	Parameter Type	Methyl Hg (ng/L)	$Hg(II)_{total}$ (ng/L)	5-year Bass Hg (mg/kg wet)
Peña Blanca	Observed	3.92	11.38	1.42
	Predicted	0.00 – 4.26	0.00 – 17.69	1.40
Arivaca	Observed	14.3	1.46 – 8.3	1.18
	Predicted	0.00 – 12.07	0.00 – 6.28	1.18
Patagonia	Observed	0.78	1.14	0.14
	Predicted	0.00 – 0.12	0.00 – 11.38	0.05

Model Application

The application of the linkage models provides an estimate of the loading capacity of the two lakes, or the rate of external mercury loading consistent with achieving the numeric targets. The TMDL represents the sum of all individual allocations of portions of the waterbody's loading capacity. Allocations are made to point sources (wasteload allocations) and nonpoint sources or natural background (load allocations). In many cases, it is appropriate to hold in reserve a portion of the loading capacity to provide a MOS, as provided for in the TMDL regulation.

After calibration, the model was used to identify the loading capacity and load reductions necessary to meet the numeric target in 5-year-old largemouth bass. The response of mercury in 5-year-old largemouth bass to changes in external loads is nearly linear for these lakes (after a period of several years' adjustment). This is because sediment burial rates are high and sediment recycling is low, with the majority of the methyl mercury that enters the food chain being created in the anoxic portion of the water column. The numeric target of 1 mg/kg in 5-year-old largemouth bass is predicted to be met with a 37 percent reduction in total watershed mercury loads to Peña Blanca Lake and a 16 percent reduction in total watershed mercury loads to Arivaca Lake.

Because there are no permitted point sources in the watersheds, there are no wasteload allocations in the TMDL. Load allocations represent assignment of a portion of the TMDL to nonpoint sources.

The current knowledge of mercury sources in the watershed and transport to the lake requires use of a "gross allotment" approach to the watershed as a whole, rather than assigning individual load allocations to specific tracts or land areas within the watershed. Loading from geologic sources also has not been separated from the net effects of atmospheric deposition onto the watershed. Information is currently available to separate sources for load allocations into three components: (1) direct atmospheric deposition onto the lake surface, (2) loading from watershed hotspots, and (3) generalized background watershed loading, including mercury derived from parent rock and soil material, small amounts of residual mercury from past mining operations, and the net contribution of atmospheric deposition onto the watershed land surface.

The allocations are summarized in Table 6-6. It is assumed that the direct atmospheric deposition load was essentially uncontrollable at these lakes and is therefore not reduced. For Peña Blanca, loading attributed to the St. Patrick Mine hotspot is considerable and is already proposed to be addressed by a removal action; therefore, load reductions are focused on that site. For Arivaca, watershed background is most important, and load reductions must be achieved there. The allocations are developed as annual average loads and address fish tissue concentrations associated with bioaccumulation of mercury. Because methyl mercury accumulates in tissue, concentrations in tissue of fish integrate exposure over a number of years; therefore, annual mercury loading is more important for the attainment of uses than daily loads.

Table 6-6. TMDL Allocations for Peña Blanca and Arivaca Lakes

	Peña Blanca Lake			**Arivaca Lake**		
Allocations	**Allocation (g-Hg/yr)**	**Existing Load (g-Hg/yr)**	**Needed Reduction**	**Allocation (g-Hg/yr)**	**Existing Load (g-Hg/yr)**	**Needed Reduction**
Atmospheric Deposition	2.3	2.3	0.0	4.2	4.2	0.0
Hotspot Loads	18.6	133.0	114.4	0.7	0.7	0.0
Watershed Background	58.6	58.6	0.0	111.2	178.9	67.7
Total	79.5	193.9	114.4	116.1	183.8	67.7
Unallocated	65.2	—	—	38.7	—	—
Loading Capacity	144.7	—	—	154.8	—	—

Development of a Nutrient TMDL in the Cahaba River, Alabama

Background and Problem Identification

Watershed Characteristics

The Cahaba River watershed (HUC 03150202) in central Alabama encompasses much of the Birmingham metropolitan area (Figure 6-1). The Cahaba River, a tributary of the Alabama River, has three segments listed for impairment by nutrients on the Alabama Department of Environmental Management (ADEM) 2002 §303(d) list. Historically, nutrient impacts have been documented as nuisance blooms and persistent growth of periphyton. The purpose of the modeling effort by Tetra Tech was to evaluate in-stream nutrient dynamics and predict the effectiveness of source reductions based on allocations to point and nonpoint sources of TP. This modeling case study describes: (1) nutrient TMDL numeric criteria development and interpretation (35 µg/L growing-season median at specific points), (2) watershed and receiving model design and application, and (3) interpretation of modeling results to determine TMDL load allocations. The Cahaba River Nutrient TMDLs were proposed as a cooperative effort between ADEM and EPA Region 4 (ADEM 2004b).

Listing Information

ADEM listed one of the segments for nutrient impairment in 1996, but the remaining two segments listed for nutrients were added to ADEM's 1998 303(d) list by EPA Region 4, based on consultation with the U.S. Fish and Wildlife Service (USFWS) regarding combined nutrient and siltation impacts to overall habitat degradation. USFWS, in addition to other agencies such as EPA Region 4, ADEM, and the Geological Survey of Alabama, attributed excessive periphyton growth in the Cahaba River as the cause of associated impacts to the aquatic life use, including impacts to threatened and endangered species of mussels, fishes, and snails.

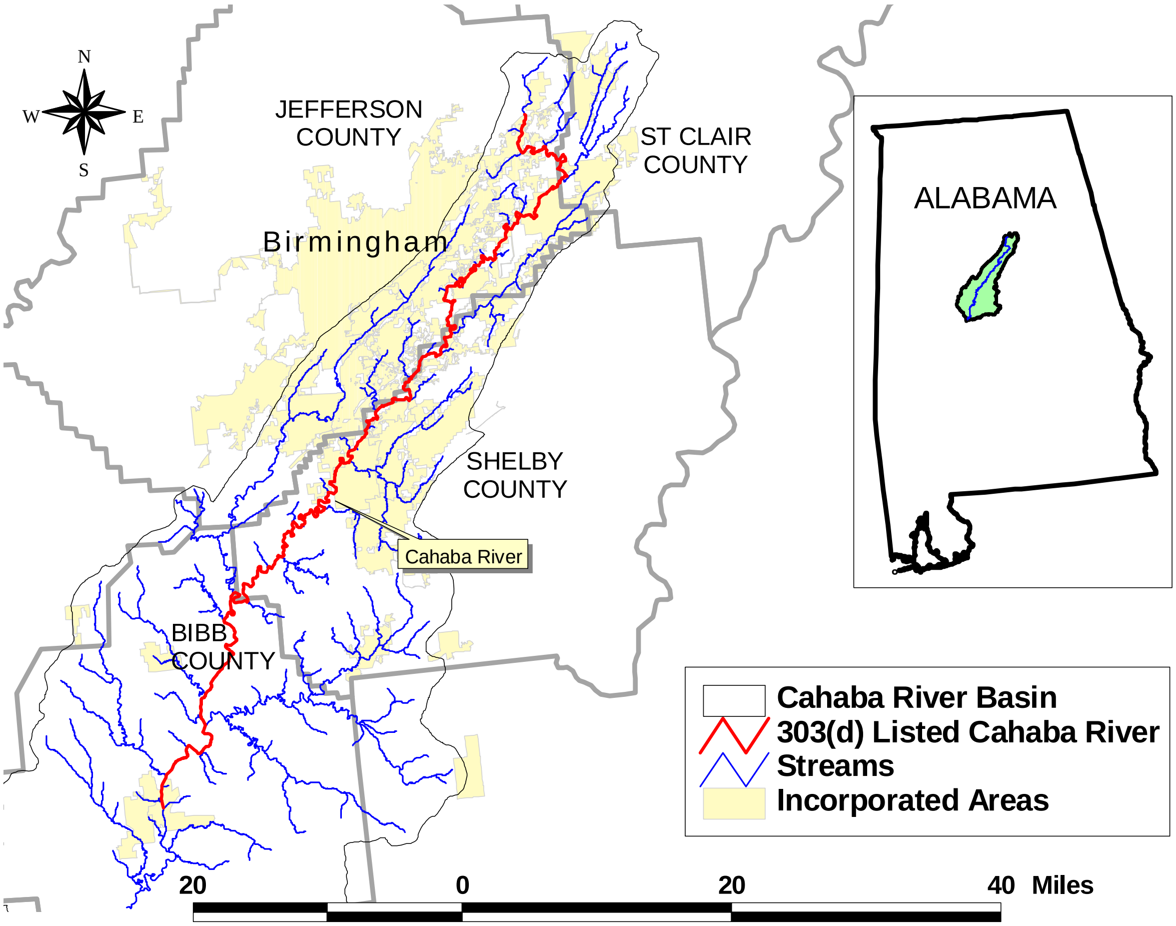

Figure 6-1. Location of Upper Cahaba River watershed, Alabama.

Water Quality Standards and TMDL Targets

The state of Alabama has narrative rather than numeric criteria for nutrients, which this requires determination of a numeric target prior to determining TMDLs. In other words, allowable pollutant loads must be determined to meet numeric TMDL target(s) established by interpretation of the narrative criteria. Early in TMDL development for the Cahaba River, EPA Region 4 and ADEM undertook a cooperative effort to determine appropriate nutrient targets to protect the aquatic life designated use as well as threatened and endangered species viability. These efforts included literature reviews, consultation with national experts, and an ecoregion-based reference-stream evaluation of ambient total phosphorus.

After evaluating periphyton growth-limiting nutrient thresholds in the literature, ADEM decided to focus on determining ambient water-column total phosphorus concentrations during the growing season that would limit periphyton growth and preserve habitat viability. ADEM decided to use an ecoregion reference-stream approach to determine the appropriate TP target. The ecoregion reference approach is recommended by EPA (USEPA 2000) in the absence of sufficient data to support a strictly effects-based target. In a reference-stream approach, ambient nutrient levels in comparable least-affected streams are evaluated to determine ambient nutrient levels that protect aquatic habitat and that prevent excessive periphyton growth.

The 303(d)-listed portion of the Cahaba River system is in the southeast portion of the Ridge and Valley province (Ecoregion 67), as shown in Figure 6-2. Six sites located on “least-impacted” reference streams were assessed for a few years of monthly ambient water-column nutrient data. ADEM previously established the reference reaches and their associated watersheds using various methods to characterize their condition and determine if they were good candidates. Such methods include watershed surveys, land use coverage, inventorying point and nonpoint sources, conducting field reconnaissance, and ultimately collecting chemical, physical and biological data to ensure their condition and verify the streams are of high quality and fully meet designated uses. A summary of nutrient data at these sites is listed in Table 6-7.

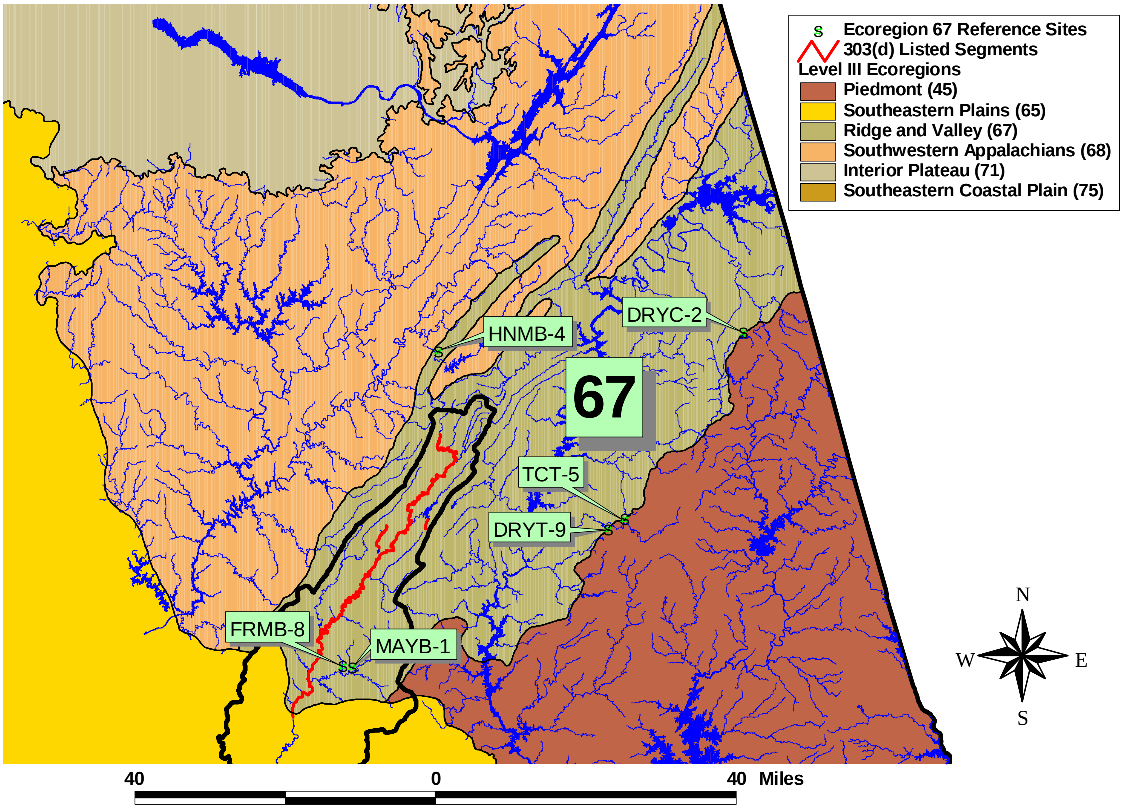

Figure 6-2. Locations of sites utilized for ecoregion reference-stream analysis.

Table 6-7. Summary of Median Nutrient Concentrations for April-October at the ADEM Reference Stations in Ecoregion 67

Station	Samples	11-digit HUC	Median TP (µg/L)	Median TN (µg/L)	Stream Name	Basin
DRYC-2	7	03150106240	24	295	Dry Cr (Calhoun Co.)	Coosa
DRYT-9	6	03150106330	32	203	Dry Cr (Talladega Co.)	Coosa
FRMB-8	13	03150202090	26	228	Fourmile Cr (Bibb Co.)	Cahaba
HNMB-4	11	03160111070	28	273	Hendrick Mill Branch	Black Warrior
MAYB-1	20	03150202080	21	173	Mayberry Cr	Cahaba
TCT-5	13	03150106330	19	167	Talladega Cr	Coosa

The nutrient target was determined to be the 75th percentile TP of all data collected at these sites within the growing season (April–October). This target was calculated to be 35-µg/L median TP during the growing season (ADEM 2004a).

Source Assessment

Nutrient loading causing excessive periphyton growth was found to be a result of both point sources and urban nonpoint source runoff from municipal separate storm sewer systems (MS4s). The drainage area contributing to the 105 river miles of 303(d)-listed segments in the upper Cahaba River is approximately 1,027 square miles, including a dozen NPDES-permitted municipal wastewater treatment plants (WWTPs) with discharges greater than 1.0 million gallons per day (MGD), as shown in Figure 6-3. In the study period 1999–2001, these WWTPs operated advanced secondary treatment processes with little or no implementation of nutrient removal. In drought periods, wastewater can comprise up to 60 percent of the total streamflow at certain locations, exacerbating eutrophic conditions in critical periods. Natural streamflow in the river is further modified in low-flow periods by a reservoir on a tributary, the Little Cahaba River, and a major (~80 MGD) drinking water withdrawal in the mainstem river. Available data for the TMDL included biweekly nutrient samples collected by local municipalities for three years at various locations, in addition to a few USGS streamflow gages and ADEM long-term trend data.

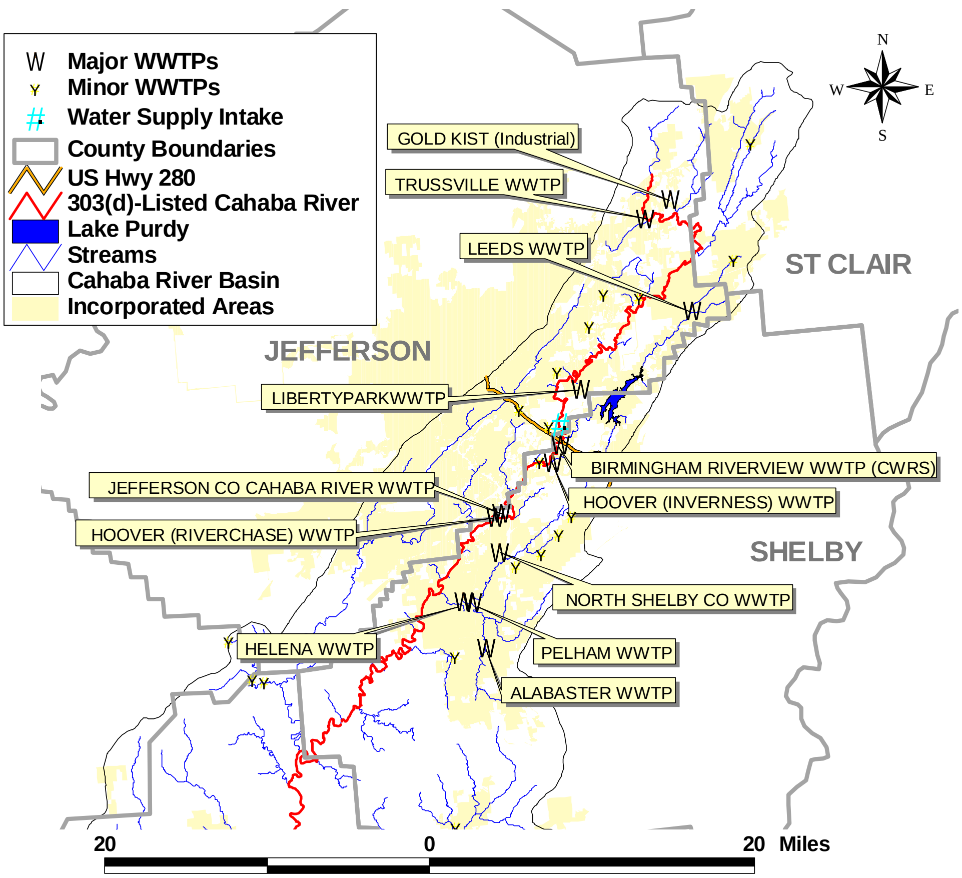

Figure 6-3. Locations of major (≥1.0 MGD) NPDES-permitted point source discharges in the Upper Cahaba River watershed

Data analysis to support the water quality modeling effort, specifically prediction of in-stream TP concentrations, required compilation of extensive NPDES discharge monitoring reports (DMRs) for the major (≥1.0 MGD) WWTPs and estimated discharge and nutrient loading for the minor WWTPs.

Nonpoint Source Data Analysis

Nonpoint source TP loads to the Cahaba River were determined by evaluation of in-stream data collected at locations not influenced by point sources. These nonpoint source evaluation sites and contributing watershed areas are shown in the land use map in Figure 6-4.

Characteristic nonpoint source TP concentrations for each land use category were derived by the simple correlation of median TP with MRLC land use classification (urban, forest, and other). Descriptions of each site are listed in Table 6-8.

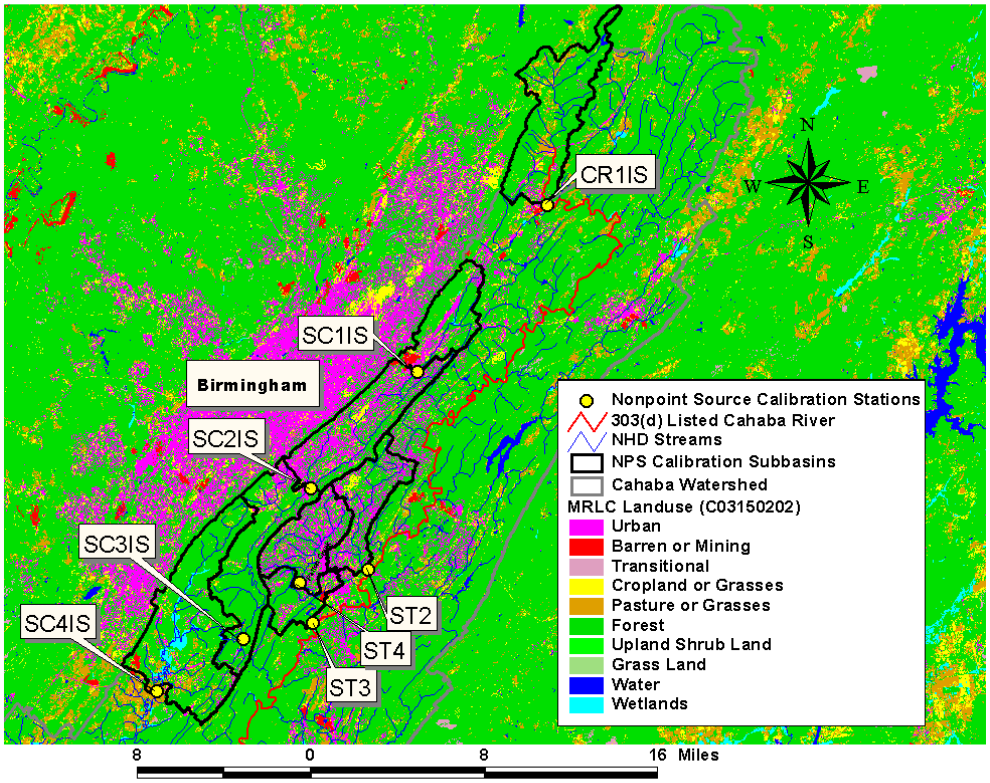

Figure 6-4. Water quality sampling sites used to assess nonpoint source concentrations of TP and other nutrients.

Table 6-8. Sites Within the Cahaba River Watershed Not Impacted by Point Sources

Station ID	Location	Percent Forest	Percent Other	Percent Urban	Median TP (µg/L)
CR1IS	Cahaba River at Hwy 11 Civitan Park—Trussville	82	14	3.7	50
SC1IS	Shades Cr at Elder St near Eastwood Mall in Birmingham	67	11	21.5	70
SC2IS	Shades Cr at Columbiana Rd—Lakeshore Drive Junction	57	10	32.9	70
SC3IS	Shades Cr at Hwy 150 Galleria area—Hoover	67	9	24.5	66
SC4IS	Shades Cr at Dickey Springs Rd (02423630) nr Greenwood	71	12	16.6	75
ST2	Little Shades Creek above Cahaba River	56	9	34.5	160
ST3	Patton Creek above Cahaba River	55	9	35.5	130
ST4	Patton Creek at Patton Church Rd.	47	8	44.3	145

The correlations of TP/percent urban and TP/(urban, forest, other) are shown in Figure 6-5. Estimated concentrations for 100 percent urban land use (~285 µg/L TP) determined by this correlation corresponded very closely with evaluated MS4/stormwater data (Pitt et al., 2004). Further validation of general application of this correlation is that estimated forest concentrations (zero percent urban area) are virtually identical to evaluated medians of reference stream (least-impacted watershed) data at ~25 µg/L TP (ADEM 2004a). Based on the correlation, nonpoint source concentrations of TP could be empirically applied to tributary streamflows based on each tributary watershed's land use composition of urban, forest, and other land use percent areas.

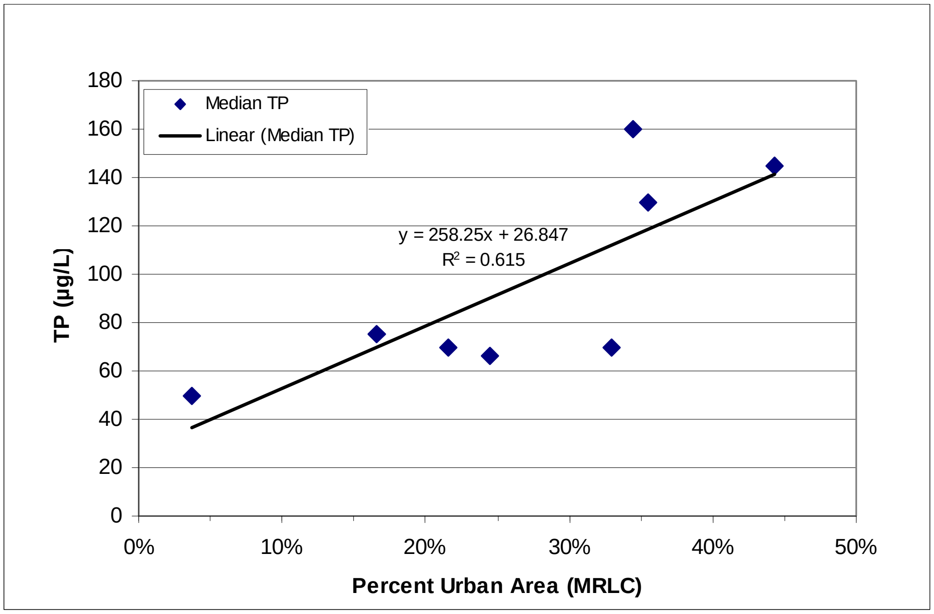

Figure 6-5. Nonpoint source concentrations of TP as a function of percent urban area.

Based on the correlation, it was possible to make the estimates of "existing" TP concentrations by land use as follows: Urban, 285 µg/L; Forest, 25 µg/L; Other, 60 µg/L. (The "Other" category was assumed to be between Urban and Forest, and the best fit was chosen; the value chosen for "Other" had minimal effect on overall results).

Although it was important to evaluate nonpoint source tributary concentrations of TP, it was obvious from assessment of in-stream data that sources of TP were dominated by municipal point sources, because high TP measurements, often in excess of 1 mg/L, corresponded to drought periods of low streamflow and virtually no urban stormwater runoff. At the time the point and nonpoint source water quality data compilation was complete, it became apparent that simple mixing of high-TP point source effluent with low-TP streamflow was the dominant process controlling concentrations of TP in critical locations of the river immediately upstream of reaches where periphyton growth was of greatest concern.

Model Selection

The modeling system applied to evaluate nutrient TMDLs for the Cahaba River system includes: (1) the LSPC, which is an enhanced watershed model based on HSPF algorithms (Bicknell et al. 1996) and including a Windows-based GIS interface; (2) EPDRIV1, a one-dimensional unsteady-flow hydrodynamic model based on CE-QUAL-RIV1; and (3) a custom-developed Spreadsheet Model which combines results from both simulation models to interpret scenarios for management options. Load allocations and wasteload allocations necessary to meet the nutrient target were determined using the Spreadsheet Model, so that the target would be met as a growing season median at three critical locations.

At the beginning of the effort to model pollutant dynamics in the Cahaba River, because no single model could be expected to adequately predict hydrology and nutrient fate and transport in such a complex system, it was determined that at least two models would be required—a watershed model to simulate hydrologic response (i.e.

runoff as a function of precipitation, geomorphology, and land use) and a receiving water model that would account for both hydrodynamic transport and water quality kinetics (i.e., eutrophication).

Development of a comprehensive modeling system to assess the Cahaba system required consideration of urban and rural hydrology, in addition to nutrient fate and transport in the mainstem river. LSPC was selected as the hydrologic model for tributaries and the overall watershed, and EPDRIV1 was chosen to assess the mainstem river receiving water (hydrodynamic transport and water quality). Design of the system was such that tributary and subbasin hydrology was determined by using the LSPC model based on precipitation records, geomorphology, and land use classification. Although LSPC features the capability to predict water quality constituent concentrations in runoff, nutrient concentrations from runoff and tributaries were determined instead by empirical estimates described in the evaluation of nonpoint sources above.

Overall, the watershed and receiving water models accurately represented nutrient dynamics in the Cahaba River, but it was necessary to simplify the issue in order to evaluate existing conditions and propose TMDL allocations. To combine the dynamic elements of watershed hydrology, urban nonpoint source and background phosphorus loading, and predict in-stream mixing and dilution of major point source inputs, a mass-balance spreadsheet model ("Cahaba Spreadsheet Model") was created with Microsoft Excel, using and combining information from USGS streamflow gages, daily LSPC model-predicted hydrology, land use classification and associated TP concentrations, river geometry, EPDRIV1 dynamically predicted stream velocity, and historical WWTP data from NPDES DMRs. In this way, the Cahaba Spreadsheet Model is essentially a postprocessor for the dynamic model results for tributary steamflow and transport, but also incorporates empirical and raw data for upstream flow, tributary TP, point source flow and point source TP.

Model Setup

Watershed Hydrologic Model

Configuration of LSPC was supported with the ArcView application known as the Watershed Characterization System (which uses datasets specific to states within EPA Region 4) and the WCS-to-LSPC autoconfiguration tool, which automatically delineates watershed subbasins guided by streamlined user input, overlays and tabulates land use areas, and calculates reach lengths and slopes based on DEM and NHD data.

WCS was used to automatically delineate 300 subbasins within the watershed. Using the WCS-to-LSPC tool, land use areas for each MRLC classification were tabulated for each subbasin and converted to the LSPC database format, which uses Microsoft Access. A pictorial example of land use areas within subbasin boundaries for a few headwaters subbasins is shown in Figure 6-6.

More than 300 subbasins were delineated, and each was assigned to one of a dozen hourly and daily precipitation stations featuring complete records for three years (1999–2001). Average subbasin size for the LSPC watershed model is approximately 3 mi^2. The model was run for a three-year period corresponding to available precipitation data at all of the sites, although some had to be patched with adjacent stations for short periods, and, in some cases, daily rainfall was disaggregated to hourly totals. Locations of the 12 precipitation stations are illustrated in Figure 6-7.

LSPC model output for daily streamflow at 88 subbasins corresponding to tributary subbasins were passed to the EPDRIV1 mainstem hydrodynamic model. Both daily streamflow and monthly median tributary flows were incorporated into the Cahaba Spreadsheet Model. An example of the LSPC model interface is shown in Figure 6-8.

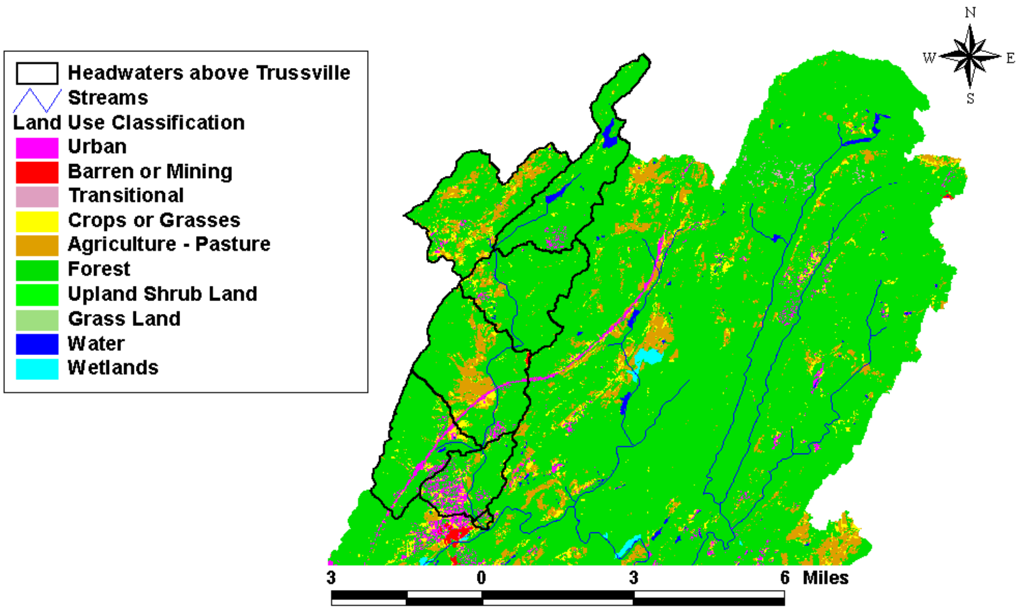

Figure 6-6. MRLC land use aggregation calculated by LSPC subbasin delineation.

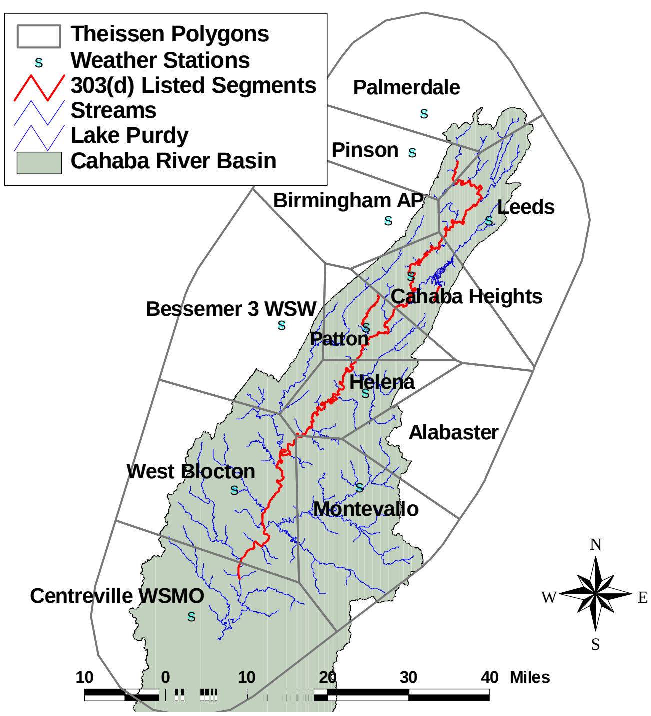

Figure 6-7. Precipitation sites with 3 years of hourly or daily data used in the LSPC watershed model.

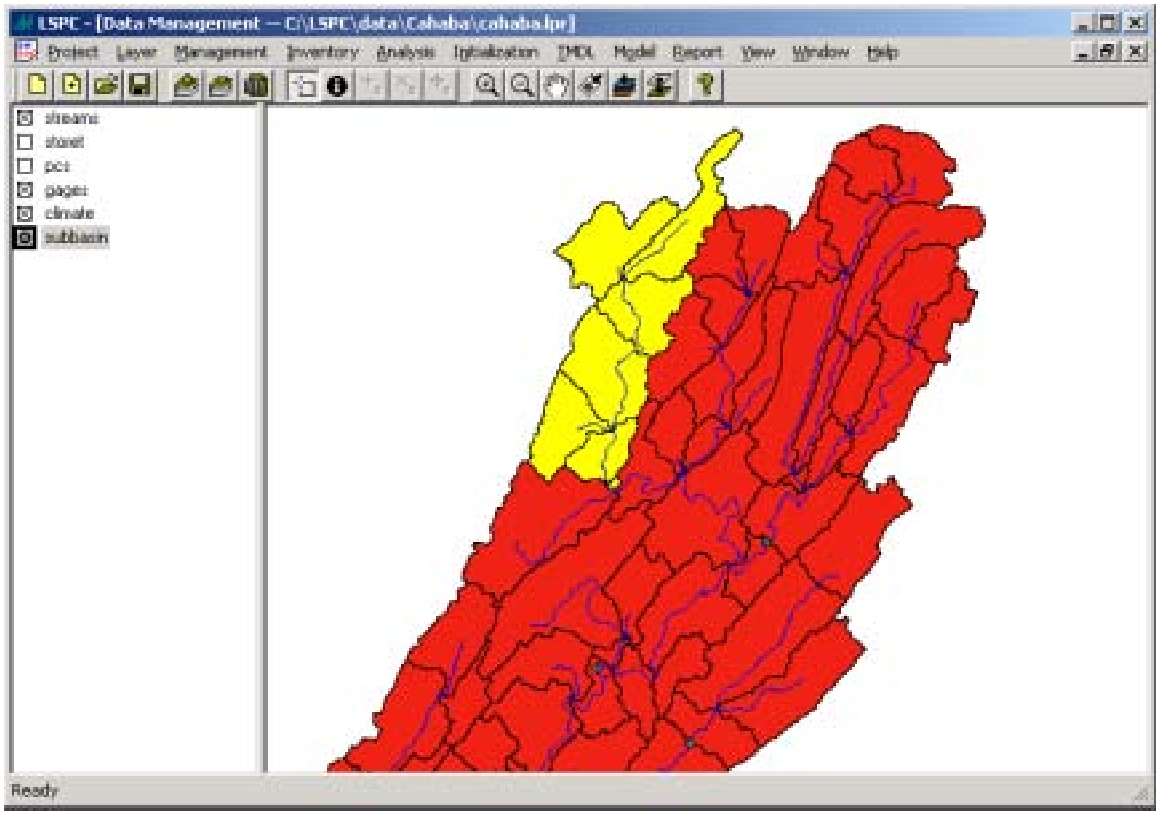

Figure 6-8. Example of LSPC GIS interface for selecting headwater subbasins.

Mainstem Hydrodynamic Model

In-stream hydraulics and transport in the mainstem Cahaba River were calculated using the EPDRIV1 model, the Cahaba application of which was originally configured by Jefferson County Environmental Services Division in conjunction with a SWMM watershed model (now superseded by the LSPC watershed model). For TMDL development, the EPDRIV1 model's extent was expanded upstream and downstream to encompass 303(d) listed segments of the Cahaba River, using additional cross-section surveys from Federal Emergency Management Agency (FEMA) flood studies for a total of 160 cross sections and 105 river miles. A minimum flow was instituted at times of zero flow in the headwaters to allow the model to run. Examples of model cross sections are shown in Figure 6-9.

Output tributary streamflow predictions from LSPC were linked to the EPDRIV1 input fileset at 88 cross-sections via a custom post-processing routine (LSPCRIV1) written in FORTRAN. Due to hydraulic modification at the drinking water withdrawal and operation of the Lake Purdy reservoir, streamflow was corrected mid-river to correspond with the USGS streamflow record at a nearby location, and calibrated at downstream locations based on calculated hydrodynamic transport and additional LSPC-derived inflows.

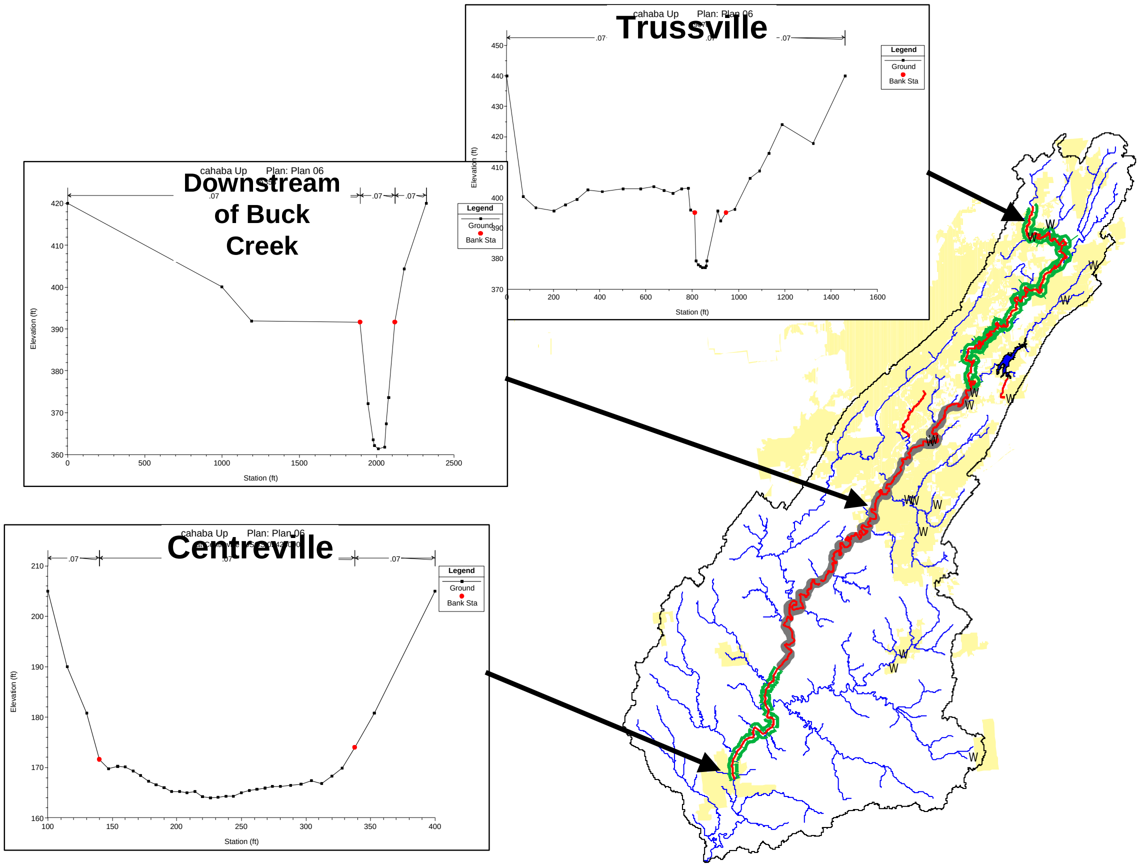

Figure 6-9. Examples of EPDRIV1 cross-sections derived from FEMA survey data.

Mass-Balance Spreadsheet Model

The Cahaba Spreadsheet Model estimates monthly median TP concentrations at 160 points along the Cahaba River (corresponding to EPDRIV1 cross sections) from Trussville to Centreville, for each month in the study period 1999–2001 and based on historical and projected point source loads, historical flows, and estimated nonpoint source loads. The transport scheme was simplistic in nature, accounting for TP loss from the system by simple first-order decay based on time of travel (cf.. SPARROW work of Smith et al. 1997). The decay parameter was chosen to be 0.25 day^{-1} by best fit to measured in-stream data.

Inputs for the Cahaba Spreadsheet Model included the following combination of data sources:

- River geometry (segment length) from EPDRIV1 cross-section input
- USGS monthly median streamflow at Trussville (upstream boundary) and Caldwell Mill (below US 280 dam)
- Predicted monthly median streamflow at 88 tributary points from LSPC watershed model
- Estimated empirical nonpoint source nutrient concentrations based on percent urban land use for all 88 tributary subwatersheds
- Reported and estimated monthly WWTP effluent discharge and nutrient concentrations from DMR reports, as available
- Predicted monthly median in-stream velocities from EPDRIV1 simulation output

A schematic of the basic process of combining these data in the Cahaba Spreadsheet Model is shown in Figure 6-10.

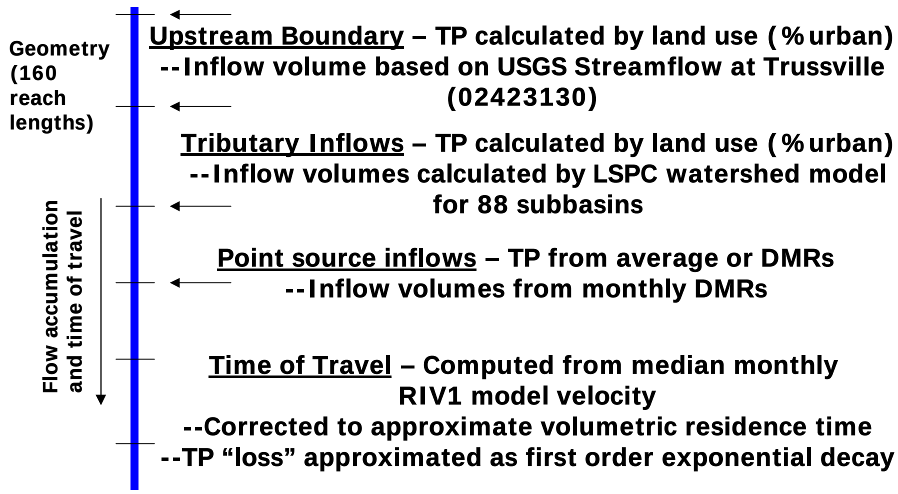

Figure 6-10. Schematic of the functional relationship of data inputs in the Cahaba Spreadsheet Model.

Calculations of in-stream TP are performed on a monthly timestep, the smallest timestep on which point source nutrient data are available. Because the nutrient target was established as a growing-season median, the monthly results from the Spreadsheet Model have been aggregated to examine in-stream TP concentrations for three years of growing seasons.

Model Evaluation

Watershed and Mainstem Streamflow

Streamflow predictions from LSPC were calibrated to USGS streamflow in multiple locations, including the upper Cahaba River headwaters and tributaries such as Shades Creek. An example of hydrologic predictions in a tributary of the Cahaba River is shown in Figure 6-11.

Hydraulic transport results were calibrated in EPDRIV1 using friction factors and with particular attention to the hydrologic discontinuity at the US 280 dam, water withdrawal, and controlled discharge from Lake Purdy. Ultimately, the EPDRIV1 model average velocities were evaluated to derive daily time of travel between cross-sections, which was transferred to the Cahaba Spreadsheet Model.

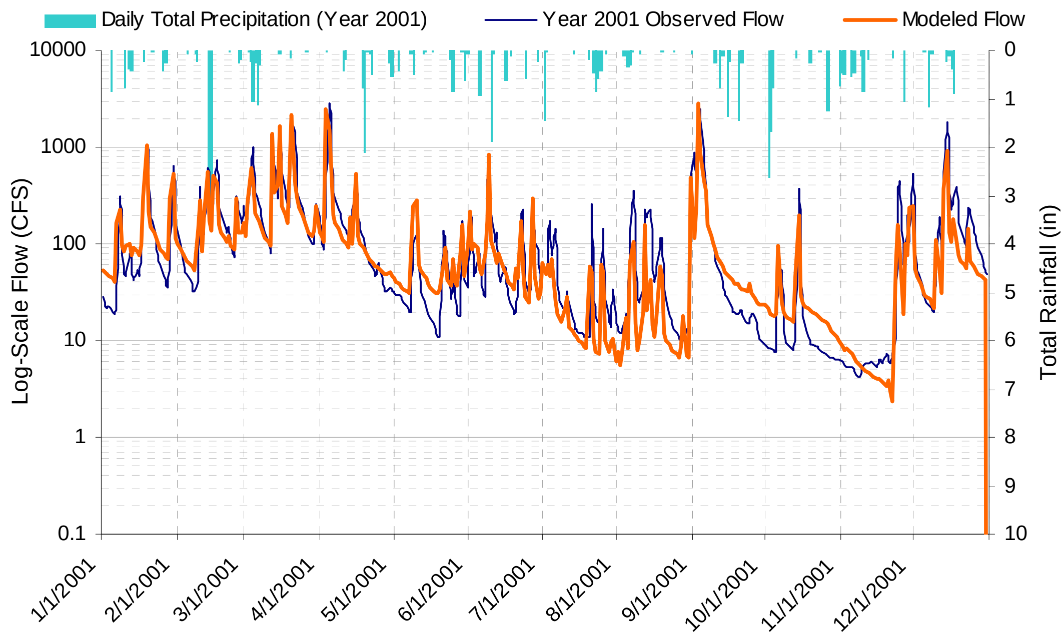

Figure 6-11. Example of hydrologic model calibration: model and observed streamflow.

Spreadsheet Model: Mass Balance for Flow and Total Phosphorus

Mass balance for flow in the Cahaba Spreadsheet Model was established by combining flows from USGS daily streamflow data at the upstream boundary and below the US280 dam, 88 watershed tributary daily inflows to the mainstem, and 9 major and 22 minor point sources on a monthly basis. Monthly median combined flows, used because long-term water quality analysis ultimately was performed monthly, compare favorably to USGS data, as shown in Figure 6-12.

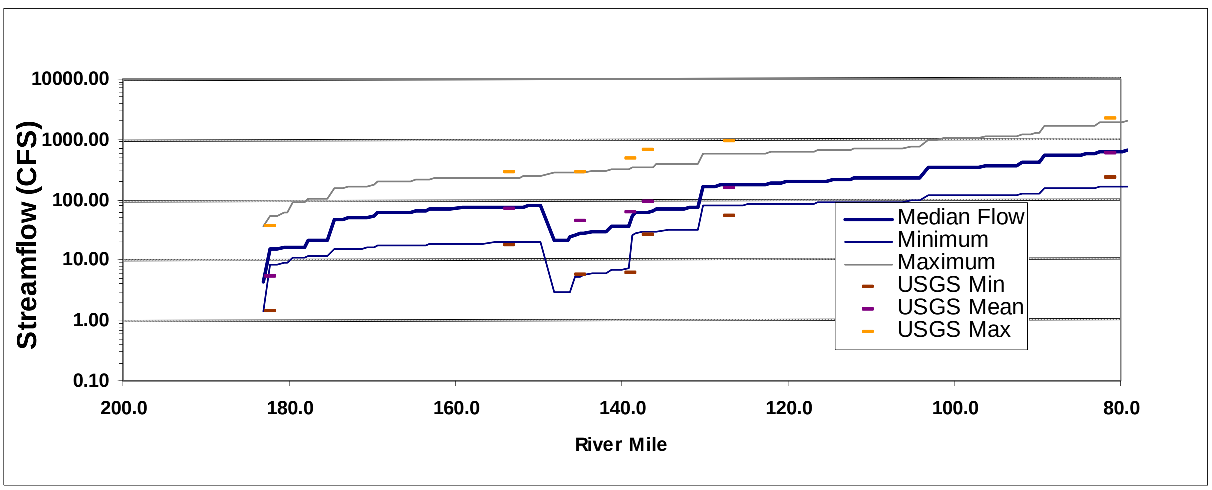

Figure 6-12. Example of monthly streamflow predictions compared to USGS data at seven sites.

Mass balance for total phosphorus was calculated by mixing upstream cross-section TP concentrations with tributary and point source TP concentrations (where applicable) and their associated monthly median streamflow values. Losses during downstream transport were estimated by a first-order exponential loss factor based on EPDRIV1 time of travel. An example of predicted longitudinal TP concentrations (in this case, monthly median concentrations) is shown in Figure 6-13. Data from grab samples from random times during a given month were not expected to precisely match the monthly median of daily model results, but the results are very similar and trends are identical (primarily dominated by longitudinal locations of major point sources and tributaries).

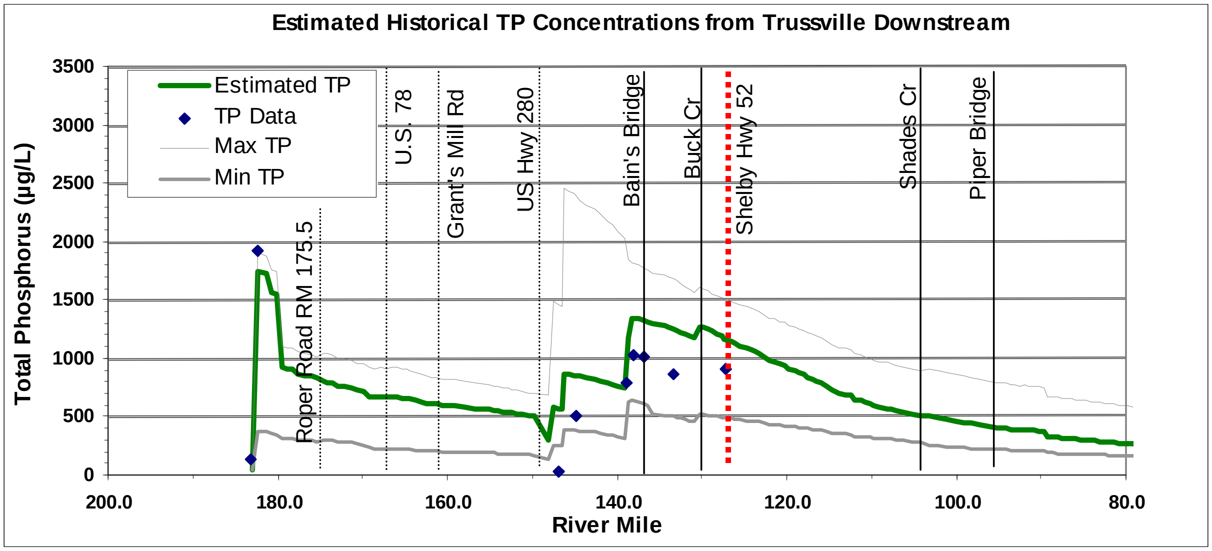

Figure 6-13. Estimated monthly median TP concentrations in the Cahaba River in September 1999, from Trussville (upstream at left) to Centreville (downstream at right). Gray lines indicate maximum and minimum monthly predicted TP concentrations based on streamflow variation.

Model Application

Spatial Interpretation of Nutrient Target

Once the integrated results of the Spreadsheet Model made it possible to evaluate long-term (growing-season) TP conditions to compare to the ecoregion reference stream target of 35 µg/L TP, it was still necessary to determine the spatial applicability of the target. ADEM determined that evaluating TP concentrations at three sites (rather than every reach of the river) would be sufficient to prevent periphyton growth at levels that would potentially affect aquatic life uses. These sites were determined to be upstream of critical sites where periphyton had been confirmed to be a major problem. At the critical sites, it was apparent that the greatest periphyton growth effects observed had been due to not only historically high TP levels but also geomorphological conditions: wider and shallower reaches, more sun exposure, and higher availability of substrate. Based on these observations, the spreadsheet model was used to evaluate growing-season TP conditions at three sites upstream of critical periphyton reaches. The selection of three sites also simplifies ADEM's future workload of follow-up monitoring for comparison of in-stream ambient conditions to the TMDL target. The three sites selected for TMDL evaluation are illustrated in Figure 6-14.

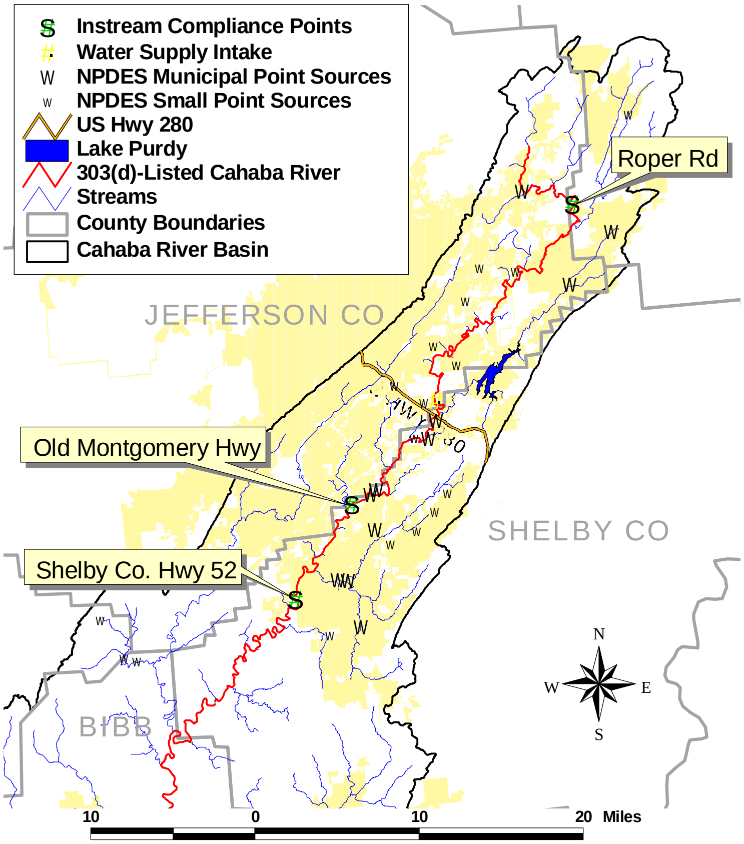

Figure 6-14. Cahaba River nutrient TMDL evaluation points upstream of critical reaches.

TMDL Results: Determining Wasteload Allocations and Load Allocations

Based on the three critical years (1999–2001), the TMDLs were determined as the necessary load allocations and wasteload allocations to achieve the growing-season median water quality target of 35 µg/L (April–October) at the three designated critical locations along the river. Point source TP concentrations at maximum permitted flow were reduced such that the target was not exceeded at the three evaluation sites for the average of the three (1999–2001) growing-season median values. In addition, nonpoint source concentrations were reduced from urban land areas by 65 percent in the final scenario. A longitudinal perspective of growing-season median TP concentrations, the final TMDL scenario is shown in Figure B-15.

ADEM and EPA determined the Cahaba River Nutrient TMDLs to be achieved in three phases of implementation over 15 years. Wasteload Allocations and Load Allocations necessary to meet the three phases of the TMDL are shown in Table 6-9.

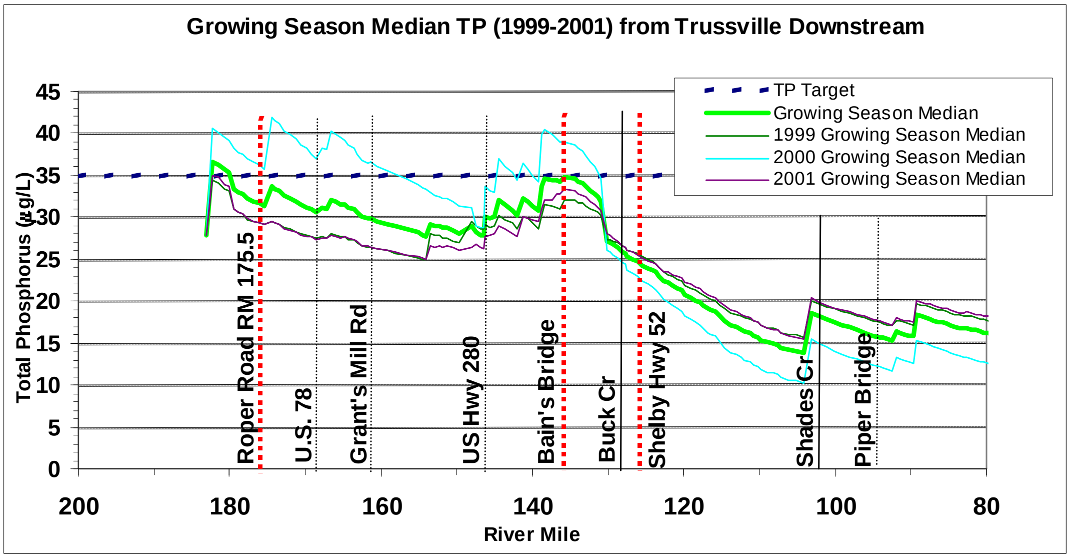

Figure 6-15. TMDL scenario, growing-season median TP for 1999–2001 and three=year average

Table 6-9. TMDL Summary for Cahaba River Phased TP Reductions

Reduction Phase	Growing Season (April-October) Wasteload Concentration (µg/L TP)	Nonpoint Source Load Allocation and MS4 Wasteload Allocation by MRLC Land Use Classification (µg/L TP)	Continuous Point Source Percent Reduction from 1999-2001 loads	LA and MS4 WLA Percent Reduction by MRLC Land Use Classification
Phase 1 (Initial Reductions 2005-2010)	400 major WWTPs (≥1.0 MGD design) / 2000 minor WWTPs[1] (<1.0 MGD design)[2]	285 urban/MS4 25 forest 60 other	36%	0% urban/MS4 0% forest 0% other
Phase 2 (Intermediate Reductions 2010-2015)	200 major WWTPs (≥1.0 MGD design) / 500 minor WWTPs (<1.0 MGD design)[1]	214 urban/MS4 25 forest 60 other	62%	25% urban/MS4 0% forest 0% other
Phase 3 Final Reductions (2015-2020)	43 major WWTPs (≥1.0 MGD design) / 300 minor WWTPs (<1.0 MGD design)[1]	100 urban/ MS4 25 forest 60 other	81%	65% urban / MS4 0% forest 0% other

[1]Minor WWTPs with a current permit limit less than that proposed will keep their current limit.
[2]Margaret WWTP (0.5 MGD), due to its headwaters location, is required to meet the following: Phase 1–1000 µg/L; Phase 2–250 µg/L; Phase 3–150 µg/L.

MS4 and urban nonpoint source loads (considered identically as land use-based sources in this analysis) were determined by the empirical method using percent urban, forest, and other land uses described above. Urban loads were derived from empirical data and fraction of USGS MRLC land use classification designated as urban types (high-intensity residential, low-intensity residential, and high-intensity commercial/industrial/transportation). MS4 loads included in the WLA are defined as urban area loads within designated NPDES MS4 boundaries, but urban area loads outside of MS4 areas are defined as part of the LA, in order to be consistent with EPA guidelines. No reductions are required from forested areas or "other" land use classifications. Reductions in loading from MS4 and urban areas are required beginning in Phase 2 because marginal benefits of such reductions would be negligible in Phase 1. Continuous point sources (WWTPs) dominate in the low-flow summer period; therefore, only WWTPs are required to make a reduction in Phase 1.

Table 6-10 shows existing and predicted in-stream growing season (April–October) median total phosphorus concentrations for the three phases of implementation at the three critical evaluation points on the Cahaba River.

Table 6-10. Existing and Predicted Instream Growing Season Median TP in the Cahaba River

Evaluation Site	Existing Condition (1999-2001)	Phase 1 (Initial Reductions 2005-2009)	Phase 2 (Intermediate Reductions 2010-2014)	Phase 3 (Final Reductions 2005-2010)
	1999-2000 Instream Growing Season Median Conditions[1] (µg/L TP)	Predicted Instream Growing Season Median Conditions[1] (µg/L TP)	Predicted Instream Growing Season Median Conditions[1] (µg/L TP)	Predicted Instream Growing Season Median Conditions[1] (µg/L TP)
Cahaba River at Roper Rd.	1,140[2]	124	67	31
Cahaba River at Old Montgomery Hwy	895	247	126	35
Cahaba River at Shelby Co. Hwy 52	560	156	82	25

[1]Instream conditions are evaluated as median value of growing season April-October.
[2]Downstream of Trussville site existing conditions shown due to lack of data at Roper Rd.

The Cahaba Spreadsheet Model, using and simplifying results from the dynamic watershed model LSPC and mainstem river model EPDRIV1, has proven extremely useful as a management tool to judge at a screening level the results of proposed management actions (i.e., NPDES point source wasteload allocations for nutrient TMDLs). Although the watershed system exhibits extremely dynamic hydrology and water quality conditions, at the high concentrations of TP caused by primarily WWTP effluent in low-flow critical conditions, consideration of the dominant process of mixing and dilution has proven sufficient to evaluate the system for management alternatives, namely a 3-tier phased implementation schedule of nutrient TMDLs (ADEM 2004b). Furthermore, the system of linking models together to take advantage of the strengths of each can be extended in a modular fashion. For example, output of LSPC and EPDRIV1 has been used to drive an experimental application of WASP6 simulating periphyton conditions in the Cahaba River, and the water quality module of EPDRIV1 can be used if necessary in the future, although its data requirements are more extensive than those of the Cahaba Spreadsheet Model.

Chapter 7 Research Needs

The research needs for supporting modeling for TMDL development are as varied as the watersheds and water impairments throughout the United States. Examining research needs for modeling must address many issues, including the interface between users and models; the fundamental science and physically based processes employed by models; and the supporting framework of reference data, training and application guidance. This section builds on the previous model evaluations and case studies to identify key recommendations for model capabilities, supporting tools and systems.

Methodology for Identifying Research Needs

In Chapters 1 and 2, the needs for TMDL modeling were discussed and some of the critical limitations in existing models identified. Chapter 3 focused on the general types and formulation of models. In Chapter 4, the available models were identified and described. In Chapter 5 the models' capabilities to meet specific TMDL analysis needs were discussed. Applicability of models was evaluated across multiple performance criteria, including hydrology, sediment, water quality simulation, BMP simulation, and user interface and supporting tools. Examination of the model review tables also highlighted areas where models can provide detailed and comprehensive representation (e.g., eutrophication processes). In addition, integrated modeling systems were discussed and the current availability of modeling linkages and supporting tools reviewed. Chapter 6 demonstrated the use of multiple linked models in the evaluation of TMDLs for mercury and nutrients. The review and case studies demonstrated some of the current strengths and limitations of modeling systems. A variety of supporting tools were needed in the analysis and the case studies showed a diversity of approaches used. Depending on the pollutant type and critical conditions the emphasis of the modeling varied. The case studies indicated that continued work is needed in supporting the various linkages and expanding the science of nutrient/algae and mercury simulation.

Dominant Trends in Application Needs

- Integration of water systems. Many traditional models specialize in individual waterbody types such as lakes, rivers, or estuaries. Watershed-based studies may require a comprehensive assessment on a larger scale and the ability to evaluate multiple management alternatives. Increasingly, modeling studies need to address the linked behavior of multiple surface waterbodies or multimedia, including rivers and lakes, estuaries, and coastal regions. In other applications, considerations of interactions between air, surface, and groundwater need to be evaluated.
- Model Complexity. The typical perception of scientific progress is a trend to develop increasingly detailed physical representations of systems. This trend is demonstrated by the use of physically based models, models that include solutions of fundamental equations, and 3-dimensional representations of waterbodies. However, in TMDL and watershed-based applications, there is an equally strong need to employ simplified solution techniques. Users are searching for reasonable simplifications, practical solutions, and easily applied tools. The need for simple techniques is driven by data, time, and resource constraints.
- Management Planning. TMDLs and related watershed-based programs (e.g., NPDES stormwater, 319 NPS plans) are moving toward implementation planning and assessment. Implementation planning requires analysis of BMP performance, management alternatives, and consideration of cost. Implementation planning might include examination of multiple solutions and selection of preferred approaches based on a broader assessment of efficiency, cost and social-political considerations.

To identify specific recommendations for future development, the modeling needs were evaluated in the context of TMDL requirements and watershed applications, current trends, and evolving model application needs. In addition, the needs analysis recognizes that future model development efforts can exploit emerging technology in computer hardware and software, Internet access, and current research. Historically, several leaps in modeling interfaces and user support tools occurred with the emergence of GIS technology. The convergence of disparate technologies and science continue to provide an opportunity for innovation and significant expansion of the capabilities of models and applicability of more detailed, physically based simulation techniques.

Modeling systems or interface development has always been closely linked to the availability of new computing technology. Early advances in modeling were closely linked to the availability of personal computers (1980s) and later the emergence of GIS (1990s). Technological advances continue to provide opportunities to facilitate model application. Creative adoption of new technologies can profoundly change the ways that users work with data and models in the future. New technologies also can influence collaboration during model development and review and interpretation of model results. Key recent and potentially relevant technological advances include:

- Significant increases in computing speed and parallel processing capabilities can support more complex and computationally intensive applications.
- Reduction in cost and increase in size of data storage devices allow users to store and process much larger datasets efficiently.
- The proliferation of broadband access can facilitate data access, remote data storage, and on-line analysis capabilities (e.g., databases, mapping, searches). Broadband can affect all stages of model development and application.
- Research and development of "grid-based" computing technologies and "middleware" can provide techniques for Internet-based data exchange, data management, and distributed computing techniques.
- Visualization software is now more widely available and affordable. Broader availability of visualization software encourages use of dynamic displays and interpretative tools for modeling results.
- Remote sensing systems and software are available and can more reliably provide spatially heterogeneous land cover, stream quality, soil moisture, and precipitation information.

The following sections provide specific recommendations developed by combining an understanding of the needs with the availability of modeling tools and the emerging technological trends. Some recommendations for supporting tools and guidance are also identified. Application of models also relies on the availability of appropriate guidance, reference documents, and supporting information. Specific needs for model support are identified as well. The recommendations provided below are organized in the following major areas:

- Model capabilities
- Data
- Model defensibility
- Systems development/supporting tools
- Integrated modeling systems

Model Capabilities

Currently available models support assessment of a range of sources and waterbody types. Described below are recommendations for enhancing and broadening the capabilities of models to encompass specific source behavior, provide more sensitivity to management changes, and improve resolution of results. These changes could be implemented by enhancing existing modeling systems or through development of new models or supplemental components. Where appropriate, enhancements or updates for specific models are recommended. The recommendations are grouped according to sources (e.g., irrigation, septic systems) and functional groups, including hydrology, sediment, nutrients, pathogens, ecological simulation, and evaluation of management practices.

This section discusses model capabilities for the following topics:

- Sources
- Hydrology
- Sediment Loading
- Mercury
- Pathogens
- Management Practice Simulation
- Hydrodynamics
- Sediment Transport
- Nutrients/Eutrophication
- Ecological/Habitat

Sources

Development of a TMDL allocation includes the distribution of the load among sources. Sources are often grouped in categories and subcategories such as agricultural and urban areas. Source groupings may vary in detail and type, depending on the regional dominance of source types and the desire of the TMDL developers to explore source behavior and management options. In some applications, dominance of a particular source type or the dynamic nature of source behavior (e.g., time variable management or change) will require new modeling approaches or more refined, detailed model development. Listed below are the major research needs that have been identified for improving representation of source behavior in models.

- **Variable Land Use and Cover**. Existing watershed models should be enhanced through improved spatial data interfaces or new models developed to better simulate time-variable land uses or changes in land use management activities over time. Currently, watershed models are applied based on a fixed or static land use coverage. Future or alternate land use configuration is represented by using a separate, static land use coverage. Remote sensing technology could provide a more dynamic representation of historic land use conditions. Land use planners also simulate projections of land use conversion over time. A system that can integrate land use simulation and watershed modeling in one framework could be used to dynamically incorporate land use conditions and the effects on watershed loading. Variable land use and cover representation can improve the accuracy of predicted conditions compared to historic flow and water quality measurements. This type of dynamic land use change could be especially important for western watersheds where timber harvesting and fires can dramatically change conditions in a matter of years. Similarly, areas experiencing rapid urban growth could be modeled more accurately through implementation of a variable land use schema. The LEAM provides an approach for simulating the evolution of urban systems by using the Cellular Automata approach combined with the open architecture tools of STELLA and SME (http://www.rehearsal.uiuc.edu/projects/leam/). LEAM simulates land use transformation and effects on multiple metrics, including water quality. Potential linkage of this technology with more detailed representations of water quality processes will benefit TMDL evaluations of dynamic land use conditions.

- **Tile Drainage**. Existing watershed models (e.g., GWLF, HSPF/LSPC) should be enhanced to better simulate the hydrologic and water quality effects of tile drainage. Many areas of the country include extensively drained areas that affect the hydrologic response of the system. Models that include capabilities for representation of drainage and examples of their application are needed.

- **Irrigation.** Irrigation practices have a significant effect on the water balance, runoff, and water quality of watersheds. Irrigation transfers water from surface and groundwater sources and increases water available for evapotranspiration. Better tools for assessing effects of irrigation on water quantity and quality could be built into existing watershed models. Significant modeling work has been done to simulate irrigation for agronomic purposes. For example, watershed models such as HSPF and GWLF do not explicitly incorporate irrigation practices.

- **Roads.** Paved roads provide significant impervious coverage, and unpaved roads are often major sources of sediment. Existing models can be used to represent a variety of surfaces through use of pervious and impervious land use coverages, but a more systematic approach (similar to WEPP) could be incorporated in frequently used watershed models (e.g., SWMM, HSPF, SWAT) to enhance their ability to accurately account for loadings from different types of roads.

- **Septic Systems**. Septic systems are a potential source of nutrients and pathogens in many rural and suburban areas. Watershed models do not typically include a standard approach for representation of septic systems. Potential septic system loading is often estimated as a function of failure rate and provided as a direct input (i.e., discharge) to watershed models. Septic system loading is typically a function of location (proximity to waterbodies), failure rate, and water table elevation. Currently available watershed models should be enhanced to simulate nutrient and pathogen loads from septic systems.

- **Coalbed Methane**. In western states (e.g., Wyoming), coalbed methane extraction has resulted in the discharge of waters with elevated concentrations of sodium and total dissolved solids. The water has limited suitability for domestic and animal consumption—its high saline and sodium content make it unsuitable for agriculture—and it has the potential to damage wildlife habitat and surface water supplies. These issues have been the central focus of TMDL development efforts in the Tongue River, Powder River, and Rosebud Creek watersheds in southeastern Montana and northeastern Wyoming (http://www.deq.state.mt.us/wqinfo/TMDL/TonguePowderRosebudTMDL.asp). Currently, the effect of coalbed methane is simulated using simple mass balance approaches or with continuous watershed modeling that addresses only direct discharges. Both of these approaches simplify the in-stream kinetics, however, and do not address the potentially significant affects on groundwater from leaking containment ponds. Modeling could be improved by better integrating detailed groundwater models with existing watershed models, as well as obtaining additional data on the fate and transport of discharge water that is pumped to containment ponds.

Hydrology

Hydrology in watershed models is well understood, and various levels of simulation are available in numerous models (e.g., GWLF, SWAT, HSPF, SWMM, GSSHA). Depending on the specific application, annual, seasonal, daily, hourly or smaller timesteps can be used, and simulation can include sensitivity to rainfall intensity. Many models include various formulations for representation of snow accumulation and melting processes as well. However, improvements could still be made in the application and understanding of existing models, the structural formulation of hydrologic systems (e.g., representation of land surface), and surface-groundwater interactions. In addition to the traditional hydrology modeling systems, there has been a growing trend toward developing physically based distributed watershed models over the past decade. These models are necessary because decision makers are asking questions that require a more refined examination of the spatial heterogeneity of watershed systems. Distributed models have the potential to examine changes in management techniques, provide sensitivity to fine variations in location and changes in slope or regrading, and represent a diversity of soils and land use characteristics. Distributed models can predict at spatial scales smaller than what can be modeled with lumped parameter models. A distributed model's primary advantage is its physically realistic representation of hydrological and pollutant transport processes, instead of the generalizations used by lumped models. Key limitations are the availability of spatially distributed soils and management information, lack of water quality simulation capabilities, and the processing time required for analysis. Recent advances in remote sensing, availability of spatially detailed data, and computer processing capabilities continue to support the application of distributed models. The distributed models will remain an essential part of research designed to understand watershed system processes.

The following are the primary research needs regarding model simulation of hydrology:

- **Models Based on the Soil Conservation Service (SCS) Curve Number Equation.** Guidance should be reviewed, tested, and developed on where the use of the simplified SCS Curve Number approach is adequate for continuous hydrologic simulation. The Curve Number approach is used in models such as GWLF and SWAT (one option) that are employed in many TMDLs; however, the Curve Number (developed for event volume estimation) can provide biased and inappropriate estimates of hydrograph components in certain soils and landscapes. The use of Green and Ampt or other alternative infiltration-based approach should be provided as an alternative, similar to the optional formulation provided in SWAT.

- **Spatially Distributed Meteorologic Data**. The Next Generation Weather Radar (NEXRAD) system, operated by the U.S. Departments of Defense, Commerce, and Transportation, provides data and processing software for weather observations throughout the United States. This system operates approximately 159 Weather Surveillance Radar - 1988 Doppler (WSR-88D) stations throughout the United States and select international sites, with data available through the National Climatic Data Center. Through the transmission and reception of electomagnetic signals, the system provides improved spatial and temporal resolution of rainfall estimates over traditional rain gage networks. This increased spatial precision of rainfall estimates may improve hydrologic simulation capabilities. To fully use the NEXRAD data for input, watershed models must include similar capabilities in simulating spatial variability. Grid-based watershed models can provide more of a one-to-one linkage to spatially variable meterological data for input. For lumped parameter models spatial data would need to be distributed by subwatershed. Because the datasets involved are extremely large, techniques are needed to process and input data into either watershed-based or grid cell-based watershed modeling systems. The NEXRAD system has functioned since 1988, but the number of stations and length of historic records for each station vary. Stations are continually added to the system, but many of them are limited to more recent years. As a result, use of NEXRAD data for model configuration also limits the period of simulation. Model calibration may require simualtion of longer periods for analysis of model performance based on statistical methods. Also, the use of NEXRAD data can confine simulation to recent years that do not indicate long-term or critical conditions necessary for analysis of the TMDL. Therefore, rainfall gage networks are often selected over NEXRAD data for calibration and validation of models. This limitation will diminish as more data are collected over time.

- Meteorologic models can also be used to develop grid cell-based estimates of time variable meteorologic inputs (http://www.waterboards.ca.gov/lahontan/TMDL/Tahoe/Tahoe_Index.htm). Ultimately, input of time varying and spatially detailed meteorologic information can support more accurate calibration and application of watershed models, particularly in the prediction of hydrology. Hydrology is particularly sensitive to variations in the spatial distribution of precipitation and temperature.

- **Grid-Based Models**. Most traditional watershed models are built on a lumped parameter network of subwatershed units and stream reaches. The hydrologic connectivity between these components is used to route runoff through the system. This type of configuration is appropriate for the prediction of downstream hydrographs and is particularly well suited to systems that have a well-defined hydrologic network. Some limitations of this formulation are the necessary "lumping" of heterogeneous spatial information (e.g., soils, slopes, land use) into virtual land units within each subwatershed. Grid cell-based models have potential applicability in areas with more complex or low gradient hydrologic systems, areas with highly heterogeneous soils or land use practices, and areas with surface-to-groundwater interactions (i.e., high water tables). Development and testing of grid cell-based models, and improvement in the development of input data and computational efficiency, are needed to bring this class of models into practical application. Linkage of the hydrologic processes to water quality simulation is needed to provide the water quality analysis needed for TMDLs.

- **Surface-Groundwater Models**. Currently, watershed-scale simulation is largely confined to conceptual and pseudo-distributed surface water models that are poorly linked to subsurface models or have highly simplified representation of subsurface storage and transport. Traditional watershed models have used groundwater components to calculate stream baseflow. The groundwater simulation was not oriented to addressing dynamic water tables, changes in baseflow due to groundwater withdrawals, or more dynamic interactions between surface and groundwater systems. As the realization increases that groundwater and surface water are closely interconnected and need to be thought of as one hydrologic system, studies of their conjunctive use and management are also increasing. If one or the other system is modeled independently, a technique must be found to represent changes in the other system in the model, but such techniques usually have serious limitations related to reconciling the scale and averaging across the interface. A more accurate approach is to model the systems as a single integrated system. This approach can account for process changes in both the groundwater and surface water systems and their mutual interaction as such changes occur. Presently, there are watershed and groundwater models that solve various components of the hydrologic cycle. However, there is no single model that solves the entire hydrologic cycle in satisfactory detail. Nor are there any models that include dynamic transport and fate of distributed pollutants in both surface and subsurface regimes.

  In many areas with low gradients, hydro-modification, and high water tables, the surface and groundwater systems are tightly and dynamically linked. Evaluation of management and source loading implications, in these cases, requires consideration of groundwater and surface water interactions. For example, in many areas of Florida, the management of water quality in canal systems requires concurrent and linked evaluation of water table elevation, groundwater quality, canal and lock operations, evapotranspiration, and rainfall-runoff processes. Although a number of detailed watershed hydrologic models and groundwater models are available, they are not dynamically linked. Some applications have used a linkage between HSPF using variable water table options and the USGS's MODFLOW. Few models are designed with this capability, and the currently available models are proprietary (e.g., MIKE SHE). Continued research and testing of linked surface and groundwater models for areas with high water tables and complex hydrology are a significant need. Enhancement, linkage, or new development of public domain or open source models are also encouraged.

Among the numerical methods for solving hydrology and transport equations, the finite difference method seems to be more popular for the ease of implementation and its relative simplicity. However, the finite element method has potential for addressing more complex geometries and should be further investigated for addressing hydrologic simulation.

In general, watershed hydrologic modeling research must continue to modify and improve existing algorithms to more accurately account for physical processes, especially as affected by altered hydrology, sediment erosion, interaction with groundwater, and watershed restoration alternatives, such as BMPs and constructed or restored wetlands. Watershed modeling's future is very strongly linked to investigating interactions between runoff processes and chemical and biological processes, which are crucial for water quality predictions (sediments, nutrients, contaminants, etc.). One solution is to develop a hybrid hydrologic model, in which an adaptive selection of kinematic, diffusive, or dynamic wave approaches can be made over all ranges of slopes in a watershed. The hydrologic models must be linked to dynamic contaminant transport in the overland planes, transport in the rivers, vertical transport in the unsaturated zone, and multidimensional transport in the saturated aquifer zone.

Sediment Loading

Watershed models have been extensively used to estimate overland flow or runoff sediment loads to surface waterbodies. For example, HSPF and LSPC essentially predict a sediment mass loading time function corresponding to the flow hydrograph for each subwatershed or watershed unit. For pervious surfaces, the empirical formulations incorporating gross watershed characteristics, such as land use, slope and antecedent conditions, are used to predict the mass loading, but for impervious surfaces, a particle buildup and washoff approach is used. Other models, such as SWMM, SWAT, and GWLF, use formulations based on various versions of the USLE to generate sediment loading as a function of soil, slope, and precipitation characteristics. Some models specialize in sediment loading and include more detailed spatial heterogeneity such as KINEROS, GSSHA, and WEPP.

Linking or transferring the sediment mass loading time function from the watershed to the receiving water model generally requires user definitions of how the total sediment mass loading is distributed among sediment type classes simulated in the receiving water model. Both the empirical approach for total loading and the necessity of user intervention to define the sediment type distribution for linking with the receiving water model pose limitations on predictive ability. Similar to many other modeling needs, improvement in sediment calculations is needed across the interface between watersheds and receiving waters, including dynamic changes in head-cutting of channels, rill erosion, stream bank erosion, and riparian zones. Most often, the calibration process for linked watershed-receiving water sediment modeling requires that the watershed component be interactively calibrated with the receiving water model, with the watershed loading as a primary calibration parameter for the receiving water models. Because the physics of sediment transport on impervious surfaces and saturated pervious surfaces in the watershed are the same as those in stream channels, there is considerable opportunity to improve the ability of watershed models to predict both the total mass and size distribution of sediment loads by the incorporation of a higher level of physics with more quantitative information regarding soil types.

Research needs vary depending on the application type. For large multipurpose applications, often including multiple endpoints, enhancement of traditionally used watershed models is needed. For more specialized applications focusing on sediment management, enhancement or development of sediment modeling systems is the focus. The following are major research needs for simulation of sediment loading:

- **Enhancement of HSPF/LSPC Sediment Simulation**. HSPF/LSPC have been used extensively for TMDL development, including many applications where sediment and sediment-associated pollutants are a concern. Improvement of the sediment simulation capabilities in these particular models would be of great benefit to many large-scale watershed and TMDL studies. Use of kinematic and diffusive wave theory incorporating vegetation resistance slope variations in a watershed unit would improve estimates of flow stress responsible for surface erosion. Likewise, a better quantification of soil properties would allow the differing processes responsible for cohesive and noncohesive resuspension to be represented. These two improvements would contribute significantly to the ability of a watershed model to predict sediment loading by sediment type. HSPF/LSPC would also benefit from an alternative formulation that would allow use of USLE-type erosion algorithms (rather than the Negev model). This would facilitate the derivation of parameter values directly from USDA soils databases.

- **Refine SWAT Modified Universal Soil Loss Equation (MUSLE)**. Review, validation, and refinement of SWAT MUSLE implementation are needed. The code appears to contain a units error for MUSLE, and the implementation for Hydrologic Response Units containing impervious land can be improved.

- **Update SWMM Sediment Simulation**. SWMM is also a commonly applied watershed model that would benefit from an improved sediment simulation capability. This improvement would enhance the ability of SWMM to be used in mixed land use watersheds. The current SWMM system uses the original USLE formulation parameterized based on land unit characteristics. SWMM's current approach could be updated to the more recent formulation of MUSLE with the ability to set land unit-specific parameters. Additional improvements could be achieved by allowing for seasonal or year-to-year variations in settings.

- **Overland Sediment Transport.** Models for describing sediment transport in shallow overland flow need improvement. Currently used equations were developed for channel flow conditions, which differ significantly from shallow, overland flow conditions.

- **Distributed or grid-based modeling systems.** Additional research, development, and applications of grid-based hydrologic and sediment modeling systems are needed. These models show promise for detailed spatially heterogeneous applications, can link more effectively with receiving waters and riparian areas, and can be used to evaluate a variety of spatially detailed management techniques. Further research is needed to demonstrate their efficacy and demonstrate their use in TMDLs.

Pathogens

Pathogen sources, transport and behavior in water (e.g., growth and decay) are represented in general forms in several models including HSPF, LSPC, and SWAT. Pathogen predictions, in particular fecal coliforms and *E. coli*, are extremely variable and unreliable. Localized sources (e.g., wildlife) can significantly effect pathogen modeling results. New genetic identification techniques have been used to identify specific sources present in discrete samples; however, analysis of discrete and limited samples is insufficient to describe the dynamic loading of pathogens from multiple sources. A complicating factor is the use of new indicator organisms for pathogen presence including *E. coli* and enterococci. For example, Georgia's Environmental Protection Department recently added *E. coli* in upland streams and enterococci in coastal waters to the existing fecal coliform bacteria criteria. New indicators have additional limitations resulting from the lack of data, historic records, and modeling experience. Several specific recommendations below suggest enhancements or alternatives to current modeling techniques.

- **Statistical Modeling of Pathogens**. Guidance and additional techniques for modeling pathogens using statistical techniques are needed. Building statistical models that associate sources or localized loading potentials could help support evaluation of management alternatives. Simple spreadsheet tools could be developed to facilitate analysis.

- **Guidance**. Examples, guidance and applications of modeling *E. coli* and enterococci should be developed. An expanded dataset and compilation of available source loading and die-off characteristics would assist in parameterizing models. Increased data collection will assist in developing calibrated applications.

- **Genetic Tracer Analysis**. Genetic source typing can provide a discrete representation of the sources present at a particular location. Guidance and examples are needed on how to link genetic source typing information with dynamic modeling applications.

- **Growth and Die-off Rates**. Models typically represent bacteria behavior by using a first-order decay term. However, in many systems, bacteria appear to die-off or regrow depending on environmental conditions.

Development of second-order equations or functional relationships that more accurately represent bacteria growth and die-off rates would significantly improve modeling accuracy. The regrowth potential is of particular concern in coastal areas with shellfish beds and beaches.

- **Shellfish Areas.** In tidally influenced areas, often located in the vicinity of shellfish beds and beaches, specialized modeling techniques are needed to evaluate loading and associated pathogen counts. The ability to comply with water quality standards for pathogens in tidal areas strongly correlate to the tidal circulation and configuration of the shoreline. Areas with poor flushing potential are particularly prone to high pathogen counts, in some cases due to highly localized sources. Some options proposed for simulation of these tidal areas include linkage of watershed models such as HSPF and LSPC to the Tidal Prism Model. Other techniques have included simplified loading estimates using monitoring data or genetic tracer information in combination with receiving water models such as the Tidal Prism Model. Additional research is needed to better characterize sources and develop protocols for linking monitoring with models.

Nutrient Loading Simulation

Watershed models are used to develop estimates of nutrient loading to receiving waters. For watershed management or nutrient TMDL development, the simulation might need to provide sensitivity to changes in land use practices such as fertilizer application, tillage, and land cover management. Several existing models provide the ability to track nutrient applications, crop uptake, and nutrient processes in soils. However these capabilities are traditionally available only in agriculturally oriented models, such as SWAT. Nutrient loading is also an issue in mixed land use or urbanizing areas. Comprehensive approaches are needed to evaluate changes in land use and the management of nutrients in urban areas. In addition, because atmospheric deposition is a significant source of nitrogen, models should provide the ability to track atmospheric sources. The following areas of research or enhancement of existing models are recommended:

- **Mixed land use watersheds.** Although algorithms are available to track accumulation, uptake, and washoff of nutrients from land areas, these techniques are not uniformly available for mixed land use watersheds. One of the nutrient loading-related research needs includes providing and facilitating nutrient simulation in mixed land use watersheds.

- **Urban Area Nutrient Simulation.** Urban areas can be significant sources of nutrients from fertilizer application and pet waste and atmospheric deposition. Most urban models have limited representation of the accumulation and transport of nutrients. Improving the simulation of nutrients in urban areas could facilitate the exploration of management alternatives and the benefits of various education, street sweeping, and infiltration or impoundment practices.

- **Atmospheric Deposition.** Most watershed models estimate nutrient availability through pollutant buildup and washoff (e.g., SWMM), concentrations in runoff and soils (e.g., GWLF), or more detailed application, transformation, and washoff (e.g., SWAT). Most models do not include atmospheric deposition as a discrete source. For large-scale simulation of the Chesapeake Bay, HSPF includes a discrete term for atmospheric deposition. The ability to separate atmospheric nutrients as a source is recommended for nutrient budget development and alternatives analysis.

- **Nutrient Transport Simulation.** Simulation of nutrients should consider the linkage to various pathways through overland flow, infiltration to groundwater, or across riparian buffers. There is also a need to improve the simulation of nitrogen and phosphorus transformation in overland flow. Development of improved nitrogen accounting models to allow better simulations of nitrogen transformations and availability of various nitrogen species in surface-groundwater systems is needed as well. In addition, current models could be improved by adding or facilitating the simulation of nutrient capture and transformation in riparian areas (i.e., filter strips, riparian zones).

Mercury

Mercury simulation continues to challenge modelers due the complex chemical processes and atmospheric source loading. Many model applications are limited by field data to characterize toxic and mercury contamination levels in the sediment bed, which generally are significant sources of water column contamination. Field collection of such data is often beyond the resources of many model applications. Also, nonpoint sources and nonpermitted point sources of contamination are difficult to determine. Improved model parameter estimation procedures offer promise in estimating bed contamination levels and source locations and magnitude for data limited applications. EPA has supported the development of simplified modeling systems (e.g., Mercury Tool in the TMDL Toolbox), and continued enhancement of this system is ongoing. The most detailed modeling techniques are not in the public domain. Detailed models are considerably more data intensive and difficult to apply. The mercury case study in Chapter 6 reinforces the need to continue research and development in mercury modeling, including continued improvement in detailed models, development of rates for mercury methylation, model testing, and linkages between models. Specific recommendations for improving mercury modeling include:

- **Detailed Mercury Models**. A public domain or open code version of the MCM model should be made available, and a user interface and modeling techniques to facilitate the application of the system to decision-making should be provided. The more detailed description of chemical processes should be included in a wider distribution of modeling systems.
- **Fire Mobilization**. Further research is needed in the role of fire in mobilization and transport of mercury from the watershed. Recent TMDL development in New Mexico suggests this is a significant factor in the watershed mercury budget in the arid West.
- **Mercury Methylation**. Improved methods are needed to estimate rates of mercury methylation in the stream network (riparian wetlands, hyporheic zone, etc.). Research is needed to improve simulation of mercury methylation in the water column (e.g., at metalimnion boundary) rather than bedded sediment, which may be a dominant process in some turbid western lakes.
- **Model Testing**. New evaluation and testing of mercury transport models on detailed, radio-label studies (e.g., METAALICUS) could assist in verifying models. To further refine models, the development and statistical analysis of large cross-sectional databases are needed for correlation between mercury methylation rates and other environmental variables and for correlation between methyl mercury concentrations and biotic accumulation rates. Many assumptions are built into various models, but further refinement and validation are needed.
- **Organic Mercury Compounds.** Model capabilities need to be improved to simulate other organic mercury compounds (e.g., mercuric acetate) derived from anthropogenic sources.
- **Model Linkages**. Model linkages and examples of integrated atmospheric, watershed and waterbody models for mercury are recommended. Support is also needed to develop and link air models to watershed models.
- **Mercury Snowpack Modeling**. Evaluation of storage, transformation, and release of atmospheric mercury in snowpack is needed for simulation in cold climate regions.

Other Pollutants and Toxics

Other pollutants and toxics addressed by models can include: PCBs, DDT, Dioxin, other pesticides, and heavy metals (i.e., copper, zinc, selenium). Chlorides, although naturally occurring, can be a significant pollutant if accumulated in toxic amounts. Various toxics, such as PCBs, DDT, and dioxin, are rarely included in watershed loading models due to lack of active sources and limited data characterizing their availability, sources, or behavior. Some actively used pesticides (e.g., atrazine) could be modeled as toxics; however, even these materials are rarely modeled on a larger scale because specific data on application rates, decay, and transport behavior are limited. Some models have the flexibility to be parameterized to include soil adsorbed and dissolved concentrations of a variety of pollutants and toxics, so simulation is possible when needed. Generally required are better techniques for evaluation of sources, setup and parameterization of models, and examples for application techniques. More information on rates, constants, and modeling techniques is needed. One frequently observed need in TMDL modeling relates to problems associated with irrigated areas and chloride and selenium accumulations.

Chloride and Selenium

Areas of the country affected by irrigation and drainage practices may have elevated concentrations of chlorides and selenium. These elevated concentrations have resulted in water quality impairments and the need to assess management alternatives. Modeling of these conditions is rather complex and can require a combination of surface and groundwater simulation, examination of irrigation and crop management practices, and leaching of pollutants from soils. The first major limitation of these studies is the lack of reliable, public domain systems for simulation of surface groundwater interactions. Ultimately, more robust hydrologic models should include the chemical processes and accounting for the transport of pollutants (e.g., chloride, selenium, and others) through multiple pathways.

Management Practice Simulation

Management practices can include a combination of landscape management activities (e.g., fertilizer application), impervious area reduction or control, and various structural management techniques (e.g., detention ponds). Point source controls can include reduction or removal of discharges under various treatment technologies. Nontraditional point sources can include urban areas under stormwater programs. Stormwater management, including both structural and nonstructural management techniques, is needed to achieve water quality improvements under stormwater program initiatives or for impaired areas to meet TMDL requirements. Implementation of TMDL allocations will typically require a combination of point and nonpoint source control practices.

For TMDL development, models are applied to represent various levels of point and nonpoint source control sufficient to meet water quality improvements or load allocations. Models of receiving waters (rivers, lakes, and estuaries) can typically evaluate impoundments (e.g., ponds, reservoirs). Many models do not explicitly include representation of management practices. For TMDLs, detailed implementation planning is not required, and the limitations of management simulations are not an initial concern. River, lake and estuary models typically accept input information on discharges from point sources or upstream tributaries (including point and nonpoint sources). As discussed previously, many models represent load reduction alternatives through a generalized percent reduction from individual sources and point source dischargers. However, a more detailed analysis of management options requires models that support simulation of practices (or groups of practices), evaluate the implications of BMP location, and allow for examination of management alternatives. As more TMDL studies result in implementation, the use of models for management planning and alternatives analysis is increasing. Evaluating management alternatives and considering financial investments will need more sophisticated BMP modeling systems.

- **Large Scale Watershed Allocation Strategies**. Continued development of tools that support large-scale TMDL allocations at the subwatershed/source scale is needed. For example, the LSPC system includes techniques for sequential allocations to multiple subwatersheds and sources and has been successfully applied in systems with thousands of subwatersheds. Additional tools that provide optimization or cost-related analysis and various alterative allocation techniques could facilitate development of cost-effective and user-supported allocations.

- **Comprehensive BMP Simulation Systems.** For implementation planning, modeling systems are needed that seamlessly provide support for watershed loading analysis, subwatershed and source level allocations, and BMP placement and analysis. The majority of traditional BMPs (e.g., detention ponds, infiltration techniques, conservation tillage) can be modeled by one or more systems. However, the practical application of these techniques on a large-scale watershed-based application is limited. Most models that include BMPs are not easily applied and require significant expertise in setup and adjustment of the various BMP components, resulting in uneven levels of detail and incomplete application for management planning. New comprehensive systems are needed, or existing watershed models should be enhanced to provide the capability.

- **BMP Simulation Techniques.** Multiple techniques are available to simulate individual BMPs. Most rely on a combination of infiltration, deposition/settling, and first-order decay. For example, SWMM includes techniques for the simulation of detention ponds that incorporate these techniques. Agricultural models include representation of land practices such as conservation tillage and crop rotations. Continued research is needed into the transformation and transport of pollutants in BMPs. In particular, most BMP simulation techniques provide limited representation of nutrient transformation. A more physically based approach could improve understanding of the nutrient removal potential and the movement of dissolved and adsorbed forms through one or more BMPs.

- **Riparian Areas**. Riparian zones and stream buffers filter runoff and remove sediment and pollutants. Riparian zones also provide shading with potential reduction of in-stream temperatures and improved aquatic habitat. Typical watershed models have limited capabilities for simulation of the benefits of riparian zones on water quality. The HSPF model has the capability of simulating land-to-land transfer, which can be used for limited riparian area simulations. Specialized models such as REMM can be used to evaluate individual riparian areas, but research is needed to provide practical techniques that can be used to represent the benefits of riparian zones on a watershed scale.

- **Bioretention Simulation Techniques**. Bioretention and infiltration practices are increasingly used in watershed retrofit or new development applications. Bioretention is a commonly used practice in the application of Low Impact Development procedures or in areas where small-scale and distributed management techniques are employed. Several models include techniques for simulation of infiltration-type practices; however, more detailed simulation of evapotranspiration as a function of land cover types and nutrient/chemical processes are needed. Techniques or monitoring data are needed to evaluate the efficacy of small-scale bioretention practices on watershed scale.

- **Economic Analysis of Management Strategies**. TMDL allocations are typically selected to provide an equitable distribution of the load reduction that results in meeting water quality standards. Improved techniques are needed for evaluating the economics of allocation strategies and tradeoffs between management techniques. Improved economic analysis tools could result in lower cost allocations and more efficient use of resources. Analysis tools could include cost models, databases of management practice cost, or optimization tools. Research is ongoing to develop optimization tools that support placement and selection of BMPs and allow users to select water quantity, quality, and cost-related objectives for optimization (Lai et al. 2003).

- **Demonstration of Management Success**. As more TMDLs are implemented, it will be important to document and demonstrate the reduction of loads and progress or achievement of meeting water quality standards. To demonstrate progress, monitoring of the baseline conditions is needed with follow-up on management practice adoption and continued monitoring of the watershed.

- **Management Practice Information**. Datasets that compile information on location, type, and characteristics of structural and nonstructural management practices should be developed and maintained. For traditional point sources, such as industrial discharges, states and EPA maintain detailed databases of permit numbers, location, and discharge monitoring records. However, for nonpoint source and stormwater BMPs, the estimation of load reduction opportunities is often limited by a lack of consistent information on management practices. If information is available that includes the areas served by BMPs, models or simplified accounting techniques can be used to evaluate potential progress made toward load reduction targets and the potential for additional management.

Hydrodynamics

Hydrodynamic modeling of surface water systems is very mature. Model physics is well established, and three-dimensional model applications are now the norm for coastal, estuary, lake, and reservoir applications. The major challenge in hydrodynamic modeling tends to be model run time, as grid resolutions become finer and model simulation periods increase. Key recommendations include:

- Models and systems that support parallelization of hydrodynamic model codes are essential to address demands of finer spatial resolution and extended simulation periods.
- Additional software is needed to facilitate model input data preparation and display and animation of output data. Although propriety systems have been developed, a broader distribution and support of public domain systems are needed. The EPA TMDL Toolbox includes a public domain EFDC interface. Continued development of user support tools is needed.

Sediment Transport

Sediment transport remains the major unsolved problem in hydraulic engineering and environmental fluid dynamics. With respect to clean and contaminated sediment TMDL development and contaminated sediment remediation studies at Superfund sites, predicting the source of in-stream sediment and associated sorbed contaminants and their ultimate fate remains a particularly difficult problem. Sediment sources include erosion or resuspension of the in-stream sediment bed, bank erosion including mass failure during high flow events, and sediment delivered via overland flow from adjacent watersheds. Recommendations for improving source loading capabilities were discussed above. Key recommendations for improving sediment transport capabilities are provided below.

- **Laboratory and Field Research.** For resuspension and erosion of in-stream beds, fairly reliable experimentally derived relationships are available to parameterize resuspension under homogeneous bed conditions where either cohesive or noncohesive sediment classes dominate a system. Garcia and Parker (1991) provided a critical evaluation of the predictive ability of widely used formulations for noncohesive sediment resuspension, and their findings remain valid today—15 years later. Recent formulations for the resuspension of cohesive sediment are exemplified by the work of Sanford and Maa (2001) and Lick and McNeil (2001). However, most natural surface water systems are characterized by heterogeneous sediment bed mixtures. For example, relationships for noncohesive sediment resuspension typically fail to be predictive when the cohesive fraction approaches 10 percent. Because laboratory results necessary to parameterize resuspension of heterogeneous sediment mixtures are extremely limited—Gailani, et al. (2001) being a notable exception—recourse must be made to expensive site-specific field resuspension studies, which are well beyond the budget for many sediment modeling applications. Laboratory and field research as well as accompanying theoretical studies are needed to develop heterogeneous bed resuspension formulation for use in surface water models.
- **Stream Bank Erosion – Simple Methods**. Bank erosion is a significant source of sediment in some stream systems and can be a source identified for load reduction in TMDLs. Techniques are needed to evaluate the potential source as a function of local physical and hydrologic conditions. Existing watershed models should be updated to include a stream bank erosion source to help account for the sediment sources during calibration and for evaluation of allocation alternatives. In addition, information or techniques that relate management actions (i.e., reduced imperviousness, riparian buffers) to the potential reduction of stream bank and channel erosion are needed to demonstrate potential restoration.
- **Laterally Averaged Bank Erosion Techniques**. Bank erosion is likely the primary source of excessive in-stream sediment levels and contributes to event-driven redistribution of contamination. Several sediment transport models incorporating mass failure erosion of cohesive sediment banks have been developed using the bank stability approaches (Darby and Thorne 1996b). They include the model reported by Darby and Thorne (1996a) and the USDA-ARS CONCEPTS model (Langendoen 2000), both based on one-dimensional longitudinal hydrodynamic and sediment transport. The CONCEPTS model incorporates a piecewise description of the channel bed perimeter with the steeper side portions of the perimeter representing the banks. Although appropriate for many applications, the averaged cross-sectional approach is a simplification of bank erosion and overbank processes. Providing a more efficient approach for application of CONCEPTS would assist in broader application of the technique. CONCEPTS has been applied with AGNPS and is included in the EPA TMDL Toolbox. Developing a linkage between watershed models (LSPC, HSPF) and the CONCEPTS model would provide additional utility and more opportunities for application.

- **Multidimensional Sediment Transport**. Multidimensional evaluation of cohesive and noncohesive sediment transport is needed. This formulation can be used to evaluate contaminated sediment transport in complex river systems. Continued development of solution techniques, sample applications, and supporting software is needed. Further research is recommended to test and validate physically based bank erosion formulations, such as those in the EFDC model, and to provide procedures for their application to data limited sites.

- **Turbidity**. The ability to predict turbidity (an optical property) from inorganic sediment, algae, and DOC concentrations should be improved and tested.

Nutrients and Eutrophication

Nutrient cycling and eutrophication dynamics in natural waters is fairly well understood. The major challenge in nutrient and eutrophication modeling is calibration or estimation of kinetic coefficients and quantifying uncertainty in model predictions. Optimization is a possible technique to address this challenge and is discussed further in Model Defensibility. In addition, selected areas of research and improvement can broaden the applicability of models to various algal species and eutrophication processes. Evaluation of nutrient processes in the hyporheic zone, active areas at the interface between receiving waters and riparian or stream beds, could expand applicability of models. For the Cahaba nutrient case study the Toolbox provided many of the needed tools for building the modeling applications, assessing the various nutrient concentrations and evaluating the algal response. However, the ability to model benthic algal and periphyton is still limited and relatively untested. Specific areas for additional research in nutrient and eutrophication techniques include:

- **Benthic Algae.** Benthic algae can be a significant source of impairment in streams. Some limited modeling of benthic algal response in streams has been developed (e.g., QUAL2K), and users have customized CE-QUAL-W2 and WASP to estimate benthic algal growth. However, simpler, empirical methods would be useful additional tools for analysis of streams. To date, these simple methods do not adequately account for effects of scour, which appear to be a dominant control in many streams. Biggs' New Zealand work showed that including "days of accrual" as a measure of scour frequency significantly improved ability to predict benthic algal density from nutrient concentrations; however, the work in this wet climate does not appear directly transferable to Mediterranean-type hydrologic regimes (Biggs 1988).

- **Macrophyte**. Macrophyte processes and hydrodynamics interaction simulation technology are needed for riverine and lake systems. The ability to simulate macrophyte growth and submerged aquatic vegetation as a function of nutrient loads is needed for many TMDLs. A more rigorous and predictive formulation should be developed to account for the interactions between macrophytes and hydrodynamics. By predicting not only the mass of macrophyte growth but also the height and volume, the effect of macrophytes on dissolved oxygen, pH, and water circulation patterns can be evaluated.

- **Evolution of Macrophyte/Periphyton**. One potential technique to evaluating long-term growth of macrophyte and periphyton is to use the Cellular Automata technology with traditional hydrodynamic and water quality modeling technology to simulate evolution of macrophyte and periphyton over multiple years (Marsili-Libelli and Giusti 2004). This technology could be extended to simulate aquatic habitat variations over time.

- **Buoyancy-compensating Algae**. The ability to simulate buoyancy-compensating algae (primarily cyanophytes) in lakes, integrated with hydrodynamic simulation, could assist in better simulation and calibration of local conditions. Some algae move according to light and local conditions. This process can affect accuracy of the vertical layers in the simulation model.

- **Bacterial-Nutrient-Algae Interactions.** Bacteria can be associated with algal processes. Storage and regrowth of bacteria can also be linked to algal processes. Additional research and development of simulation algorithms are needed to support linked evaluation of bacteria and nutrients.

- **Wetland and Riparian Zone Processes**. Enhanced procedures are needed to address the water quality processes that occur at the interfaces between wetland and riparian zones and receiving waters. Because of the extensive interactions between these systems multimedia modeling capabilities are needed. For example, EFDC includes capabilities for addressing wetting and drying of tidal wetland areas. Further enhancement of these capabilities and the exchange of nutrients could be beneficial, especially for studies that include preservation or enhancement of riparian areas.

- **Nutrient and Eutrophication Endpoints and Targets**. Closely related to modeling of nutrient and eutrophication processes is the derivation of the specific indicators or thresholds used to evaluate compliance with water quality standards. Some TMDLs are directly keyed to a numeric dissolved oxygen standard. However, in many rivers and streams, the numeric measures of eutrophication effects are not well defined. Additional research is needed to develop locally derived effects-based targets for sediment, nitrogen, and phosphorus.

- **Monitoring to Support Periphyton and Macrophyte Modeling**. As new modeling techniques are developed for periphyton and macrophytes, additional guidance is needed on monitoring techniques, field procedures, laboratory analysis techniques, and input parameter development.

Ecological/Habitat

Ecological modeling can provide simulation of conditions that relate to key indicators of designated use support. For example, an ecological model could predict fish propagation as a function of habitat conditions. Ecological models can be used to evaluate response of aquatic life to elevated concentrations of toxics or the effects of bioaccumulative substances. Other systems can evaluate response to habitat conditions, including shading, temperature, and sediment, on fish. Application of ecological models may go beyond typical TMDL development needs and address potential changes in water quality criteria or direct interpretation of designated uses or narrative criteria. Key areas where new or enhanced ecological modeling techniques are needed include:

- **Impervious Areas Impacts on Habitat**. The ability to link changes in storm hydrographs to changes in habitat quality and benthic biota response is needed. Impervious areas and associated hydrologic effects are widely believed to be associated with aquatic health impairments. However, the response to changes in imperviousness is not easily related to specific, measurable endpoints representative of aquatic health.

- **Dissolved Oxygen Criteria**. Evaluation of water quality criteria for dissolved oxygen may require the assessment of the effect of low dissolved oxygen on fish. Improved ecological modeling tools could support the development of site-specific criteria, where appropriate.

- **Bioaccumulation of Toxics**. In areas with contaminated sediment or excess loading of bioaccumulative toxics, additional modeling tools could be used to evaluate bioaccumulation rates. Food chain models can be used to evaluate bioaccumulation under various loading scenarios.

- **Habitat.** Techniques are needed to simulate the effects of stream channel habitat indicators on the aquatic habit, including stream shading, fine sediment substrates, and flow frequencies. Traditional approaches use a weight of evidence process and statistical analysis to evaluate the response of aquatic life to a variety of habitat indicators. Modeling systems could provide enhanced multimedia analysis techniques to integrate the various habitat indicators, predict response to land use changes, and evaluate the potential effects on aquatic life.

Data

Modeling and environmental analysis requires data to apply models. Sufficient data are needed to verify that models are performing appropriately and build confidence in model predictions. Typical data needs include spatial coverages (e.g., soils, topography, land cover), water quality monitoring, point source discharges, management activities or structures, and land use practices. Current state and local data collection studies need to continue to support the development of comprehensive and long-term monitoring records. As watershed model sophistication increases, the demand for more frequent and higher resolution data will also increase to setup, calibrate, and validate models. The challenges faced in watershed modeling have reflected the need to deal with spatial variability while considering the linkages among climatology, hydrology, biology, and geochemistry. The more physically based models require significant information on meteorology and chemistry. Some of the most important advances in watershed modeling during the past decade have involved approaches that employ GIS and remotely sensed data. The availability of GIS coverages and remotely sensed data has stimulated model development and facilitated the representation of landscape heterogeneity. Continuous improvements in the ability to process very large distributed sources of remotely sensed and space-based hydrologic and climatic data, combined with advanced data assimilation algorithms, should lead to benefits in both watershed modeling and TMDL studies. With the use of remote sensing, radar, and satellite technology, the ability to observe data over large and inaccessible areas and to map these areas spatially is vastly improved, making it possible to develop truly distributed models. Identified below are some of the key areas where new research can facilitate data collection and improve the quality and comprehensiveness of data.

- **Remote Sensing**. Remote sensing provides a technique for developing spatial heterogeneous information. Key areas where remote sensing might improve data gathering include Moderate Resolution Imaging Spectroradiometer (MODIS) satellite data to evaluate algae and turbidity in larger fresh waterbodies, techniques to reconcile satellite-based land cover and parcel-based land use information, estimation of directly connected impervious areas (DCIA), and estimation of soil moisture content. Remote sensing shows promise for developing detailed representation of soil moisture content that can affect infiltration and runoff calculations. NEXRAD data can provide more spatially detailed precipitation data. Spatially detailed information could significantly benefit development and application of distributed (grid-based) hydrologic models.

- **Specialized Monitoring Guidance**. Guidance is needed on how to collect data for complex environments such as SOD, sediment nutrient fluxes, reaeration, photosynthesis and respiration, mixing zones, diurnal dissolved oxygen, periphyton and macrophytes.

- **Geomorphic Evaluations**. Guidance is needed on how best to perform geomorphic assessments to determine sediment impairment, evaluate sources and causes, and provide insights into management techniques. Methods are needed to collect data that can support stream sediment transport and in-stream sediment evaluations.

- **Implementation Monitoring**. Guidance is needed on monitoring approaches for measuring water quality conditions in large watersheds and evaluating the performance of management practices. Guidance should include targeted and probability-based sampling and management practice tracking techniques.

- **Testing Data**. Data are needed to verify models at multiple scales. Many watershed models use individual land units as the fundamental simulation unit. Existing models were developed and tested initially on small-scale test plots. The USLE was developed based on an extensive national network for test plots. Historically test plot data have been collected to support modeling of forest and agricultural lands. However, similar datasets are not available for suburban residential lands, which comprise significant land areas considered in many TMDLs. This information can be used to build a library of loading rates and EMCs. Additional data gathering is needed to describe the national variability in loading from urban and suburban land areas. An approach is needed to improve access to existing and ongoing monitoring data and standardize data collection approaches.

Model Defensibility

Model defensibility has generally involved two components—the defensibility of the model code or computer program and the defensibility of the model application. Defensibility of the model computer program, termed generic defensibility, is generally inferred from previous model applications, peer reviews, and the general acceptability of the model with respect to regulatory agencies. Although these things are certainly an important component of generic defensibility, they provide no guarantee that the model computer program is verified.

Verification is here defined as determining if the model program or code is error-free and makes no judgment as to whether the physical and biogeochemical process upon which the numerical algorithms in the program are based are correct. Errors have been found and will continue to be found in widely accepted surface water modeling systems.

The emerging discipline of computational science and engineering has developed robust methodologies for verifying computer models (Roache 1998; Knupp and Salari 2002) and these methodologies should be applied to major surface water modeling systems. Generic model verification addresses issues associated with the correctness and acceptability of the physical and biogeochemical process representation upon which a model is based and the accuracy and robustness of the numerical algorithms used in the model code. Additional guidance is needed on verification of computer models, and fundamental testing of publicly applied models should be encouraged and documented.

The defensibility of each model application is evaluated and documented through a process of model calibration and validation. The model setup requires parameter estimation as part of calibration and can include additional sensitivity and uncertainty analyses. Calibration is the adjustment of model parameters to achieve an acceptable level of agreement between model application predictions and prototype observations. Validation is the independent evaluation of model performance without further adjustment of model parameters. A major concern in the demonstration of model defensibility is the lack of consistent techniques, measures, and procedures. Both watershed and receiving water modeling studies include ample examples of calibration and validation but the measures are not consistent, and the "goodness of fit" required for various studies is not defined. In addition, the use and accuracy of models for predictive simulations of future conditions are not well defined. Key considerations in using models for alternatives and forecasts need to be identified and addressed in more specific guidance. Guidance is needed to support consistent and robust approaches for evaluating model defensibility. Specific recommendations include the following:

- **Model Performance Criteria**. Various model developers and reviewers have suggested model performance criteria for hydrologic and water quality simulation of watershed and receiving waters. Standardized statistical tests and application procedures are needed to provide a common context for the evaluation of model performance. Compilation of a set of typical model performance criteria and measures would help standardize model evaluations and documentation and provide additional confidence in model predictions by stakeholders and federal, state, and local agencies.

- **Model Calibration and Validation Guidance**. Additional guidance is needed on model calibration techniques and approaches. Guidance can help to standardize approaches, statistical techniques, and appropriate techniques for rivers, estuaries, and lakes. Guidance should define techniques performing uncertainty analysis that put "error bars" on model predictions. New guidance could build on the initial development of generalized modeling guidance provided by CREM (USEPA 2003).

- **Optimization Techniques for Model Testing.** Optimization can provide a framework for evaluating model calibration, parameters, and measures of sensitivity and uncertainty. A general class of optimization-based parameter estimation procedures, including generalized software packages, is available but has found limited use in surface water modeling with respect to both nutrients and toxics. Research to develop and make available a number of optimization-based calibration and parameter estimation systems compatible with surface water modeling systems is essential. Uncertainty analysis using existing methods, including Monte Carlo and Latin-Hypercube, is rarely used due to the intensity of efforts required, or, when they are used, only limited-duration model simulations are conducted. A new class of highly efficient stochastic response surface methods offers significant advantages for uncertainty analysis and can be incorporated in a streamlined manner with optimization-based model calibration. One approach is to express the level of agreement as an objective function, such as the weighted space-time squared difference between model predictions, and observations, at multiple locations and times, with respect to a set of model parameters. The classical minimization methods require estimation of the gradients of the objective function sequentially as the minimum condition is approached. These gradients in turn define the sensitivity of the model's ability to predict prototype observations with respect to model parameters over a range of parameter sets. Thus, the optimization approach to model calibration accumulates a significant amount of information on sensitivity.

The primary obstacle to employing an optimization-based model calibration-sensitivity analysis approach is obtaining a sufficient number of estimations of the objective function gradients in model parameter space. The gradient estimation approach includes brute-force parameter perturbation, tangent-linear sensitivity, and variational adjoint methods. The later two are extremely promising but have received relatively little attention in surface water modeling. Given probability distributions of model parameters, the probability distributions of the response surface can be determined with significantly fewer model simulations than are necessary for Monte Carlo or Latin-Hypercube uncertainty analysis. It is highly recommended that further research be directed to this potentially powerful approach that combines model calibration, parameter estimation, sensitivity analysis, and uncertainty analysis in a unified and potentially efficient manner.

Systems Development and Supporting Tools

Development and application of models requires trained and experienced modelers. The development of shared resources, datasets, and guidance is essential to promoting the knowledge among the user community. Listed below are the major recommendations for guidance and tools to support the modeling community. Specific technical guidance is also recommended in the capabilities sections included earlier.

- **Linkage Tools.** Standards and software tools for model interlinkages and data transfer need to be developed and improved. Key linkages that should be supported include watershed models to receiving water models, such as: GSSHA/HSPF/LSPC/SWMM to EFDC/WASP or CE-QUAL type models.
- **Universal Database Systems.** Universal databases that include water quantity, quality, biological, physical habitat, fish, and geomorphic data should be provided to support model development, test, calibration, and validation. One option is to link Water Resources Database (WRDB) in the EPA TMDL Toolbox with the Ecological Data Application System (EDAS).
- **Rates and Constants Manual Update.** Databases and guidance are needed on key parameters and datasets used for initial setup and parameter selection for models. The "rates and constants" manual (Bowie et al. 1985) has provided modelers with an excellent reference document. An updated system could include an on-line searchable database and documentation. Significant experience and data gathering has been performed during the past 20 years. Compilation of this new information would be a great service to the modeling community.
- **Application Library**. Model applications either completed or under development can provide a useful repository of knowledge and experience. A library of completed applications, provided on-line, could link to project reports, model input files, parameters used, and documentation of model updates. This library could link to available on-line reviews of models, such as CREM (http://cfpub.epa.gov/crem/)
- **Modeling Guidance.** Additional guidance is needed on available models, model selection, calibration, application techniques, and allocation procedures, including optimization. Model guidance could be delivered through on-line materials, case studies, on-line or workshop training courses, and interim technical notes.
- **Training.** Additional training is needed in watershed and receiving water modeling fundamentals, watershed modeling techniques, and the application of multiple linked modeling systems.

Integrated Modeling Systems

Flexible and adaptable integrated modeling systems are needed that can address the many technical, data, and systems recommendations identified above. These integrated systems, if developed with a universal format and data exchange structure, could share information and modeling modules to achieve a variety of modeling needs. However, in the current development of systems, there are still a multitude of standards, unique data structures and formats, and disparate systems. EPA's BASINS and Toolbox systems share information and utilities; however, the linkage between the various systems is not yet complete.

Encouraging open architecture and modular modeling systems could facilitate the future development and integration of models. The EPA TMDL Toolbox (http://www.epa.gov/athens/wwqtsc/Toolbox-overview.pdf) is designed with an open architecture that could lead to the integration of the individual model components into a variety of modeling systems. Adoption of the most flexible modeling systems, such as Precipitation-Runoff Modeling System (PRMS) and MMS, will require continued development, demonstration applications, and more rapid application timeframes. Training a broader audience in the development and application of modeling using these tools will be needed before they will be widely adopted.

The continuous improvement in the science and the description of the physical processes is inconsistently distributed and adopted by modeling systems. By providing on-line or desktop access to modular modeling components, new algorithms can more easily be shared among applications. For example, by building on a hydrodynamic modeling framework, an unstructured set of modules can be developed to simulate any number of species of phytoplankton, zooplankton, macrophytes, or higher-level organisms, including fish. With a flexible set of modules, models can be applied at various levels of complexity to address water quality problems and ecological system analysis without the need for users to modify the code.

Modular modeling systems provide an opportunity to address many of the specific recommendations for expanding technical capabilities of models. If a unified framework is developed, new models or algorithms can share data management, post-processors, and analytical tools. In an Internet environment, the maintenance of systems and user support techniques can be more centralized and potentially more efficient.

More aggressive development of Internet-based modeling systems is highly recommended. Internet-based systems are fully possible with emerging software for GIS, visualization, and data management now widely available and suitable for practical use. The maintenance and application of Internet-based software can significantly reduce the distribution and management of software systems. Internet-based systems reduce the need to address compatibility with multiple desktop software and hardware specifications. The systems can be used without requirements for desktop proprietary software for GIS or database management. Software updates can be provided seamlessly through a single copy, and model runtimes can be reduced by the use of parallel processing techniques.

Future systems can provide on-line access to stakeholders to evaluate alternatives and interactively examine assumptions. The development of on-line modeling systems has another significant potential benefit in providing public access, transparency of technical analysis and assumptions, and interactive interfaces for community decision-making. An on-line system can provide a dynamic representation of alternatives where users can select criteria and see alternative predictions of results (e.g., pollutant loading, measures of ecological conditions). For TMDLs, systems that allow users to evaluate the load allocation alternatives or implications of various user-defined choices can encourage more involved and proactive comment and agreement with selection of preferred allocations. One example of an on-line user interface is an evaluation of land use patterns and growth developed by the Illinois LEAM group (http://www.rehearsal.uiuc.edu/projects/leam/KaneFinal/Model6.html) for the Kane County, Illinois, project. This example is specific to land use planning activities but provides an example of a format and approach that could be used with water quality modeling approaches. These more transparent and inclusive modeling approaches can significantly expand the acceptance of models by the community at large.

Conclusions

An understanding of current trends in technology and research can help increase an understanding of how modeling might evolve and how to support the next generation of modeling systems. However, anticipating trends is a "crystal ball" exercise, and sometimes adoption of technology can take surprising turns. This review concludes that, although significant progress has been made in model development, major areas of research are still needed to expand the capabilities, defensibility, and application of models. Research has an opportunity to capitalize on the emergence of new data management and processing technologies (e.g., GIS, graphic user interfaces, data collection techniques (e.g., remote sensing), and the burst in enhanced performance of modern-day computers and Internet communications.

The research needs identified are diverse and consistent with TMDL and management needs that encompass a wide range of sources, pollutants, and processes. The diversity of the needs is indicative of the current status of the

TMDL program and environmental management applications. Over the past 10 years, development of analytical tools has emphasized simulation of dominant pollutants (i.e., nutrients, sediment, metal, pathogens). More recently, the emphasis has shifted to addressing a more diverse group of listed waters and areas with specialized problems. Although some of these concerns may affect only a small group of waters, the analytical needs are still relevant. Continued model development should encourage building linkages and multimedia models that address air, surface water, and groundwater interfaces more accurately. Linkage of meteorlogic, atmospheric, and watershed models can support the evaluation of potential long-term climate changes. Multimedia-linked models encourage a holistic and integrated approach to water quality management that can result in improved decision-making. Grid-based models show particular promise as a framework for linking multiple media in a more physically based approach. As development of TMDLs continues, the most significant emerging need is the evaluation of management options and selection and determination of optimal solutions. Ultimately, more comprehensive systems are needed that can evaluate management options and solutions at multiple scales.

New and more flexible modeling systems and tools could support a diverse set of technical needs. Common databases and GIS systems can support multiple solution techniques at various scale and levels of complexity. Technical innovation can be encouraged by providing integrated systems and work environments that are flexible and modular. These integrated systems can provide the commonly needed tools and support integration of new solution techniques, source representation, and algorithms. In particular for BMP simulation, a flexible modeling environmental that can incorporate new solution techniques will be beneficial. Providing integrated system platforms can help minimize duplication of effort (shared on-line data management, data display, shared resources), while maximizing resources for more fundamental development and research of key components.

The vision of a consistent, Web-based framework so far has proved elusive and difficult to implement. However, continued rapid expansion of broadband accesses and Internet-based GIS and data management technology make this vision more realistic. The use of Internet-based technologies has emerged as a viable and practical medium for management of data, analysis techniques and tools to support TMDL and more generalized watershed analyses. Development of a standardized Internet-based framework could provide significant cost saving for the management and application of models. In addition, a standardized and open framework, with clearly defined linkage capabilities, could encourage research and continual testing and update of new components.

Guidance and consistent metrics and methods for assessing defensibility of models and model predictions are critical needs to support the reliable application of models and maintain user confidence in applications. Continued emphasis on high-quality data collection and guidance on data collection methods that can support parameter estimation and testing are also critical needs.

Future development of models and the supporting infrastructure of data and guidance will improve our ability to support informed environmental decision-making, help improve understanding of the physical systems in our world, and ultimately provide information to support the effective restoration and protection of the nation’s waters.

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Appendix A. Model Fact Sheets

Mercury Loading Model: Watershed Characterization System—Mercury Loading Model

MIKE 11

MIKE 21

MIKE SHE

MINTEQA2: Metal Speciation Equilibrium Model for Surface and Groundwater

MUSIC: Model for Urban Stormwater Improvement Conceptualization

P8-UCM: Program for Predicting Polluting Particle Passage through Pits, Puddles, and Ponds—Urban Catchment Model

PCSWMM: Storm Water Management Model

PGC – BMP Module: Prince George's County Best Management Practice Module

QUAL2E: Enhanced Stream Water Quality Model

QUAL2K

REMM: Riparian Ecosystem Management Model

RMA-11

SED2D

SED3D: Three-Dimensional Numerical Model of Hydrodynamics and Sediment Transport in Lakes and Estuaries

SHETRAN

SLAMM: Source Loading and Management Model

SPARROW: SPAtially Referenced Regression on Watershed Attributes

STORM: Storage, Treatment, Overflow, Runoff Model

SWAT: Soil and Water Assessment Tool

SWMM: Storm Water Management Model

TMDL Modeling Toolbox

TOPMODEL

WAMView: Watershed Assessment Model with an Arc View Interface

WARMF: Watershed Analysis Risk Management Framework

WASP: Water Quality Analysis Simulation Program

WEPP: Water Erosion Prediction Project

WinHSPF: An Interactive Windows Interface to HSPF

WMS: Watershed Modeling System

XP-SWMM: Stormwater and Wastewater Management Model

Appendix: Model Fact Sheets

AGNPS: Agricultural Nonpoint Source Pollution

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Download Information

Availability: Nonproprietary
Required to register prior to download, http://www.ars.usda.gov/Research/docs.htm?docid=5199
Cost: N/A

Model Overview/Abstract

AGNPS is a storm event model developed by the USDA Agricultural Research Service to estimate the pollution loads from agricultural watersheds and to assess the effects of different management programs. AGNPS is capable of simulating surface water runoff, nutrients, sediments, chemical oxygen demand, and pesticides from point and nonpoint sources of agricultural pollution. The different point sources include feedlots, wastewater treatment plants, gully erosion, and stream bank erosion. As a distributed model, AGNPS represents the spatial distribution of watershed properties with a square-grid cells system. GIS interfaces in GRASS or TOPAZ are available to create the model inputs. The model can be used to evaluate best management practices (BMPs).

Model Features

- Distributed, single-event model
- Point and nonpoint sources

Model Areas Supported

Watershed	High or medium
Receiving Water	None
Ecological	None
Air	None
Groundwater	Medium

Model Capabilities

Conceptual Basis

AGNPS calculates surface runoff for each grid cell separately. The surface runoff calculated in each grid cell is then routed through the watershed based on flow directions from one grid cell to the next grid cell until it reaches the drainage outlet.

Scientific Detail

AGNPS is a distributed parameter model developed by USDA, Agricultural Research Service (ARS) scientists and engineers. It predicts soil erosion and nutrient transport/loadings from agricultural watersheds for real or hypothetical storms; i.e., it's an event-based model. Its distributed model design derives from subdividing a watershed to be simulated into a grid of square elemental areas, assumed to have uniform physical characteristics, and then applying three lumped parameter models to each element:

- Erosion modeling is based on the USLE applied on a storm basis; thus, it uses an EI-index but for single storm events.
- Its hydrology is based on the Soil Conservation Service Curve Number technique, and it uses the Smith algorithm for calculate peak flow rate.
- AGNPS uses another ARS-developed model named CREAMS to predict nutrient/pesticide and soil particle size generation, transport and interaction. For sediment discharge, AGNPS uses the steady state continuity equation, and it uses the Bagnold equation for sediment transport capacity calculation.

Outflows from one element become inputs to adjacent ones. Thus, AGNPS integrates lumped model predictions for each element's behavior into a distributed watershed simulation.

Each AGNPS elemental area, typically about 100 m square, requires 22 parameters (coefficients) to describe its antecedent conditions, physical characteristics (e.g., soil type and slope steepness), management practices and rainfall. To predict NPS pollution, the USLE, SCS Curve Number hydrology and CREAMS relationships are computed for each element as a function of time. Nineteen output parameters are computed, as a function of time, for each watershed element.

AGNPS-GRASS developers recommend its use on watersheds up to 20,000 ha. (80 mi^2) in size.

Model Framework

Subwatershed or cell-based distributed modeling framework. Modules are linked to calculate hydrology, erosion, and nutrients loadings cell by cell. GIS interface is used to facilitate the cell-by-cell watershed characterization.

Scale

Spatial Scale

- One-dimensional, cell or subwatershed overland
- One-dimensional channel network

Temporal Scale

- Event

Assumptions

- Channels are assumed to have a triangular shape.
- Sediment eroded by rill and sheet erosion is assumed to be completely transported to stream without any deposition in the fields.
- Surface runoff is assumed to flow through a 1 cm soil surface layer.
- Chemicals on the soil surface are assumed to be uniformly mixed with the surface layer.
- Infiltration first must pass through the surface layer.
- The initial abstraction (Ia) is the first increment of rainfall prior to surface runoff.

Model Strengths

- A distributed model

- Capable of evaluating the effects of many BMPs, such as agricultural practices, ponds, grassed waterways, irrigation, tile drainage, vegetative filter strips, and riparian buffers

Model Limitations

- Used only to simulate single event
- An empirical model
- Channels are assumed to have a triangular shape

Application History

AGNPS has been widely used for watershed studies (Hession et al., 1989; Engel et al., 1993; Mitchell et al., 1993; Srinivasan and Engel, 1994) but mostly to evaluate land use change scenarios. Grunwald and Norton (1999) applied AGNPS to two small watersheds in Germany to predict runoff and sediment yield and found that the application of the model to unmonitored watersheds resulted in considerable under- and over prediction of surface runoff and sediment yield. Other applications of AGNPS include Grunwald and Norton, (1999, 2000), Grunwald and Frede (1999), and Chaubey et al. (1999).

Model Evaluation

SCS has conducted some model evaluation studies, which are available on the AGNPS Web site. A limited number of studies used measured data to validate the AGNPS model. In a study by Srinivasan and Engel (1994) comparing 13 measured and simulated rainfall-runoff events, the simulated runoff volume was found to be underestimated for all events.

Model Inputs

- Watershed delineation, cell (subwatershed) boundaries, land slope, slope direction, and reach information—can be generated by TOPAZ, TOPAGNPS and AGFLOW
- Daily precipitation, maximum and minimum temperature, dew point temperature, sky cover, and wind speed—can be generated by the climate data generator, GEM
- Management information, land characteristics, crop characteristics, field operation data, chemical operation data, feedlots, and soil information—can be imported from RUSLE or NRCS sources
- If impoundment is present, then, elevation-storage power curve coefficient and exponent; elevation discharge coefficient and exponent; permanent pool stage; runoff event water volume; and incoming mass of sediment by particle size and its associated fall velocity

Users' Guide

Available online: http://sedlab.olemiss.edu/AGNPS.html

Technical Hardware/Software Requirements

Computer hardware:

- PC

Operating system:

- PC-DOS program that works on Windows 95/98

Programming language:

- Borland C

Runtime estimates:

- Minutes

Linkages Supported

- NRCS GIS-support computer model HU/WQ to prepare input

Related Systems

AnnAGNPS

Sensitivity/Uncertainty/Calibration

Not available

Model Interface Capabilities

- GIS interfaces available for creating the model inputs in TOPAZ, GRASS, and Arc/Info

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AGWA: Automated Geospatial Watershed Assessment

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Download Information

Availability: Nonproprietary
http://www.tucson.ars.ag.gov/agwa/
Cost: None

Model Overview/Abstract

The USDA-ARS Southwest Watershed Research Center, in cooperation with the EPA Landscape Ecology Branch, has developed the Automated Geospatial Watershed Assessment tool (AGWA) to facilitate using spatially distributed data to prepare model input files and evaluate model results. AGWA uses widely available standardized spatial datasets that can be obtained via the Internet. The data are used to develop input parameter files for Kinematic Runoff and Erosion Model (KINEROS2) and Soil and Water Assessment Tool (SWAT), two watershed runoff and erosion simulation models that operate at different spatial and temporal scales. AGWA automates the process of transforming digital data into simulation model results and provides a visualization tool to help the user interpret results. The utility of AGWA in joint hydrologic and ecological investigations has been demonstrated on such diverse landscapes as southeastern Arizona, southern Nevada, central Colorado, and upstate New York.

Model Features

- User-friendly interface for generating model input using spatial data
- Flexibility in use from an event-oriented model for small watershed (>100 km^2) to a continuous daily timestep model for large complex watershed (>100 km^2)
- Can be used to evaluate the impacts of land-use changes
- Available as an ArcView application or as an integrated part for BASINS version 3.1

Model Areas Supported

Watershed	High
Receiving Water	Low
Ecological	Low
Air	None
Groundwater	Low

Model Capabilities

Conceptual Basis

AGWA is a GIS-based system that integrates two watershed runoff and erosion models: an event-oriented model—KINEROS—and a continuous daily timestep model—SWAT.

Scientific Detail

A fundamental assumption of AGWA is that the user has previously compiled the necessary GIS data layers, all of which are easily obtained for the conterminous United States. The AGWA extension for ArcView adds the "AGWA Tools" menu to the View window and must be run from an active view. Preprocessing of the DEM to ensure hydrologic connectivity within the study area is required, and tools are provided in AGWA to aid in this task. Once the user has compiled all relevant GIS data and initiated an AGWA session, the program is designed to lead the user in steps through the transformation of GIS data into simulation results. The AGWA Tools menu is designed to reflect the order of tasks necessary to conduct a watershed assessment, which is divided into five major steps: (1) location identification and watershed delineation; (2) watershed subdivision; (3) land cover and soils parameterization; (4) preparation of parameter and rainfall input files; and (5) model execution and visualization and comparison of results.

Step 1: The user first creates a watershed outline, which is a grid based on the accumulated flow to the designated outlet (pour point) of the study area. If a GIS coverage of the outlet location exists (such as would be the case for a runoff gauging station), it can be used to designate the drainage outlet. Alternatively, the user has the option of using a mouse to click on the watershed outlet. If internal gauging stations exist as a separate GIS coverage, AGWA will use them as internal drainage pour points and generate output at each of the stations. This option is particularly useful for calibration and validation of model results.

Step 2: A polygon shapefile is built from the watershed outline grid created in step 1. The user specifies the threshold of contributing area for the establishment of stream channels, and the watershed is divided into model elements required by the model of choice. From this point onward, tasks are specific to the model that will be used (KINEROS2 or SWAT), but the same general process is followed, independent of model choice.

Step 3: The watershed created in Step 2 is intersected with soil and land cover data, and parameters necessary for the hydrologic model runs are determined through a series of GIS analyses and look-up tables. The hydrologic parameters are added to the polygon and stream channel tables to facilitate the generation of input parameter files. At this point, the user can manually alter parameters for each model element if additional information is available to guide the estimation of those values.

Step 4: Rainfall input files are built at this stage. For SWAT, the user must provide daily rainfall values for rainfall gages within and near the watershed. If multiple gages are present, AGWA will build a Thiessen polygon map and create an area-weighted rainfall file. For KINEROS2, users can select from a series of predefined rainfall events dependent on the geographic location, choose to build their own rainfall file through an AGWA module, or use NOAA Atlas II return period rainfall depth grids distributed with AGWA. Precipitation files may be created for uniform (single gage) or distributed (multiple gage) rainfall data.

Step 5: After Step 4, all necessary input data have been prepared: The watershed has been subdivided into model elements; hydrologic parameters have been determined for each element; and rainfall files have been created. The user can proceed to run the hydrologic model of choice. AGWA will automatically import the model results and add them to the polygon and stream map tables for display. A separate module controls the visualization of model results. The user can toggle among viewing various model outputs for both upland and channel elements, enabling the problem areas to be identified visually. If multiple land cover scenes exist, the user can parameterize either or both of the two models and attach the results to a given watershed. Results can then be compared on either an absolute or percent-change basis for each model element (Miller et al., 2002a). Model results can also be overlaid with other digital data layers to further prioritize management activities.

Model Framework

- SWAT
    - Hydrologic response unit, subwatershed, and watershed
    - Simple one-dimensional stream and well-mixed reservoir/lake model
- KINEROS
    - Fields/planes and channels
- AGWA is based on ArcView GIS interface to process input data for the finest spatial unit of its component models

Scale

Spatial Scale

- KINEROS: Fields and watershed with channel network.
- SWAT: Watershed with channel network, hydrological response unit, or single cell

Temporal Scale

- Different models in the AGWA have different temporal scales. KINEROS uses a variable timestep (normally in minutes) to simulate a single storm event, and SWAT uses a daily timestep and can simulate a watershed over 100 years

Assumptions

- Users previously have compiled the necessary GIS data layers, all of which can be obtained for the conterminous United States.
- Users are familiar with GIS software
- Assumptions of the component models. See fact sheets for KINEROS and SWAT

Model Strengths

- Includes user-friendly interface to generate model input
- Includes more than one watershed model from which to choose
- Includes a visualization tool to display and interpret modeling results
- Can simulate watershed in different spatial (small to large watersheds) and temporal (event-based to continuous daily) scales

Model Limitations

- Requires a large set of GIS data, making it difficult to setup the model for locations outside of the United States
- Requires proprietary software: ArcView 3.x and the Spatial Analyst for grid operation
- May require training to use the advanced modeling options

Application History

The individual models within the model suite, such as KINEROS2 and SWAT have been used extensively for watershed studies.

There are several primary intended uses of AGWA. For example, AGWA can be used in a research environment as a hydrologic modeling tool. Without a rigorous training set for calibration and validation, AGWA is well suited for watershed assessment using hydrologic response as a metric of change. If multiple land cover scenes are available, a relative assessment of the effects of land cover change on hydrologic response as a function of time may be accomplished following Miller et al. (2002a).

Preliminary research during the development of AGWA was presented by Hernandez et al. (2000). In their study, they showed that simulated runoff response is sensitive to land cover change in both the SWAT and KINEROS2 models and showed how the assumptions inherent in the look-up tables determine the direction and magnitude of change.

Recent research by Miller, et al. (2002a) illustrated the use of AGWA in coordinated ecological and hydrologic assessment. The authors analyzed of the ecological changes since the early 1970s within the Upper San Pedro River Basin in southeastern Arizona and the Cannonsville Watershed in the Catskill/Delaware region of New York.

Model Evaluation

See application history and Miller et al. (2002b).

Model Inputs

KINEROS

- Overland flow element:
  - Plane geometry (length, width, and slope), Manning's n, Chezy conveyance factor
  - Canopy cover, interception depth, average micro topographic relief, average micro topographic spacing
  - Infiltration related parameters: saturated hydraulic conductivity (Ks), initial degree of soil saturation, coefficient of variation of Ks, mean capillary drive, porosity, pore size distribution index, volumetric rock fraction, thickness of soil layers (up to two layers)
  - Rain splash coefficient, soil cohesion coefficient, and particle class fractions.
- Channel element
  - Type (simple or compound), base flow discharge
  - Channel geometry (length, width, bed slope, and bank slopes), Manning's n, and Chezy conveyance factor
  - Infiltration related parameters (same as specified in overland flow element)
  - Cohesion coefficient of bed material
- Pond element
  - Initial storage volume
  - Volume, surface area, and discharge rating table
  - Seepage rate
- Rainfall File
- External flow file (optional)

SWAT

- Land uses (MRLC and others)
- Soil (STATSGO and others)
- Topography (30 x 30 m^2 DEM or other resolutions)
- Subwatersheds (derived from manual or auto delineation tools in BASINS 3.0)
- Point Source (PCS or other database)
- Climate data (daily temperature, precipitation, solar radiation, and wind speed)
- Crop and management databases
- USGS flow data (for calibration)
- Long-term watershed quality data (for model calibration)

Users' Guide

Available online: http://www.tucson.ars.ag.gov/agwa/

Technical Hardware/Software Requirements

Computer hardware:

- IBM-PC

Operating system:

- Windows XP/2000/NT/98

Programming language:

- AGWA is in ArcView Avenue.
- AGWA requires ArcView 3.1 or later and Spatial Analyst version 1.1.
- Models SWAT and KINEROS are in FORTRAN.

Runtime estimates:

- Minutes to less than an hour

Linkages Supported

AGWA is also available as an integrated part of BASINS 3.1.

Related Systems

- Migration to ArcGIS is currently being developed.
- DotAGWA, a Web-based interface for AGWA, is also under development.
- Better Assessment Science Integrating Point and Nonpoint Sources (BASINS), version 3.1

Sensitivity/Uncertainty/Calibration

The SWAT interface allows basic model calibration and sensitivity analysis (27 key parameters). No tools were developed for uncertainty analysis.

In numerous modeling studies, the KINEROS model has been applied on the USDA-ARS Walnut Gulch Experimental Watershed. Goodrich et al. (1994) investigated the sensitivity of runoff production to the pattern of antecedent moisture condition at the small watershed scale (6.31 km^2). They suggested that a simple basin average of initial moisture content will normally prove adequate and that, again, knowledge of the rainfall patterns is far more important. Michaud and Sorooshian (1994) compared three different models at the scale of the whole watershed, a lumped curve number model, a simple distributed curve number model, and the more complex distributed KINEROS model. The modeled events were 24 severe thunderstorms with a rain gage density of one per 20 km^2. Their results suggested that none of the models could adequately predict peak discharge and runoff volumes but that the distributed models did somewhat better in predicting time to runoff initiation and time to peak.

Goodrich et al. (1997) used data from the entire Walnut Gulch watershed to investigate the effects of storm area and watershed scales on runoff coefficients. They concluded that, unlike humid areas, there is a tendency for runoff response to become more nonlinear with increasing watershed scale in this type of semi-arid watershed, as a result of the loss of water into the bed of ephemeral channels and the decreasing relative size of rainstorm coverage with watershed area for any individual event.

Model Interface Capabilities

- Customized ArcView 3.x interface with the capacity to automate the model input creation

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AnnAGNPS: Annualized Agricultural Nonpoint Source Pollution Model

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Download Information

Availability: Nonproprietary
(required to register prior to download)
Cost: N/A

Model Overview/Abstract

AnnAGNPS is a continuous simulation watershed-scale program developed based on the single-event model AGNPS. AnnAGNPS simulates quantities of surface water, sediment, nutrients, and pesticides leaving the land areas and their subsequent travel through the watershed. Runoff quantities are based on runoff curve numbers while sediment is determined by using the Revised Universal Soil Loss Equation (RUSLE). Special components are included to handle concentrated sources of nutrients (feedlots and point sources), concentrated sediment sources (gullies), and added water (irrigation). Output is expressed on an event basis for selected stream reaches and as source accounting (contribution to outlet) from land or reach components over the simulation period. The model can be used to evaluate best management practices (BMPs).

Model Features

- Distributed, continuous simulation
- Point and nonpoint sources
- Source accounting

Model Areas Supported

Watershed	High or medium
Receiving Water	None
Ecological	None
Air	None
Groundwater	Medium

Model Capabilities

Conceptual Basis

AnnAGNPS divides the watershed into homogenous drainage areas, which are then integrated together by simulated rivers and streams, routing the runoff and pollutants from each area downstream. The hydrology of the model is based on simple water balance approach.

Scientific Detail
The model uses the SCS curve number technique to calculate the daily runoff and RUSLE 1.05 technology to calculate daily sheet and rill erosion. The Hydro-geomorphic Universal Soil Loss Equation (HUSLE) is used for the calculation of the sediment delivery ratio (yield from erosion divided by the amount delivered to the stream). The instantaneous peak discharge of the runoff hydrograph is calculated using TR-55, which is then used to calculate the time of concentration, Tc. The key processes and their details are given below:

- Climate – Climate data are generated using GEM and Complete_Climate
- Hydrology – Daily soil moisture balance
- Runoff – SCS curve number
- Potential evapotranspiration – Penman equation
- Subsurface flow – lateral subsurface flow using Darcy's equation or tile drain flow
- Rill and sheet erosion – RUSLE
- Sediment delivery – HUSLE
- Chemical routing – dissolved or adsorbed by mass balance approach

Model Framework
- Subwatershed or cell-based approach
- Simple one-dimensional channel routing
- GIS interface is used for watershed characterization and model parameterization

Scale

Spatial Scale
- One-dimensional grid or subwatershed overland
- One-dimensional channel network

Temporal Scale
- Daily

Assumptions
The climate generation module assumes that daily precipitation is independent of any precipitation on either the day before or day after. The RUSLE K and C factors are assumed to not vary significantly day-to-day and thus the minimum timestep of 15 days used in RUSLE is assumed to be appropriate.

Model Strengths
AnnAGNPS is a distributed parameter, watershed scale model that is used for continuous simulations. AnnAGNPS can be used to study the effect of BMPs (agricultural practices, ponds, grassed waterways, irrigation, tile drainage, vegetative filter strips and riparian buffers).

Model Limitations
All runoff and associated sediment, nutrient, and pesticide loads for a single day are routed to the watershed outlet before the next day simulation. There is no tracking of nutrients and pesticides attached to sediment deposited in stream reaches from one day to the next. Point sources are limited to constant loading rates (water and nutrients) for the entire simulation period. Spatially variable rainfall is not allowed.

Application History

There have been few application studies of the model other than the model evaluation studies discussed in the next section. Srivastava et al. (2002) conducted a study using AnnAGNPS and genetic algorithm of optimization of best management practices. Baginska et al. (2003) applied AnnAGNPS and PEST model to predict nutrient export from a small catchment in Australia and found that the accuracy of predictions was moderate.

Model Evaluation

In a model evaluation study, Yuan et al. (2001) found out that the model-predicted monthly sediment yield was in close agreement ($R^2 = 0.7$) with the actual observed sediment yield, but the short-term individual event predictions were not acceptable. In another study, Yuan et al. (2003) found out that AnnAGNPS predictions of monthly loadings were poor though statistically not significantly different from observed values.

Model Inputs

- Watershed delineation, cell (subwatershed) boundaries, land slope, slope direction, and reach information – generated by TOPAGNPS and AGFLOW
- Daily precipitation, maximum and minimum temperature, dew point temperature, sky cover, and wind speed – can be generated by the climate data generator, GEM
- Management information, land characteristics, crop characteristics, field operation data, chemical operation data, feedlots, and soil information – can be imported from RUSLE or NRCS sources
- If impoundment is present, then elevation-storage power curve coefficient and exponent; elevation discharge coefficient and exponent; permanent pool stage; runoff event water volume; and incoming mass of sediment by particle size and its associated fall velocity

Users' Guide

Available online: http://sedlab.olemiss.edu/AGNPS.html

Technical Hardware/Software Requirements

Computer hardware:

- PC

Operating system:

- Windows 98/NT/2000 and XP

Programming language:

- ANSI FORTRAN 95

Runtime estimates:

- Minutes

Linkages Supported

Different tools or models that are linked to AnnAGNPS include TOPAZ for watershed delineation, Stream Network Temperature Model (SNTEMP), Sediment Intrusion & Dissolved Oxygen Model (SIDO), Conservation Channel Evolution and Pollutant Transport System Model (CONCEPTS), and Stream Network Watershed Scale Model (CCHE1D). NRCS plans to revise HU/WQ to work with AnnAGNPS.

Related Systems

AGNPS is the predecessor of AnnAGNPS.

Sensitivity/Uncertainty/Calibration

Not available

Model Interface Capabilities

- Window GUI for editing input
- GIS interface in ArcView and ArcGIS for preprocessing input data

References

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AQUATOX

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http://www.epa.gov/waterscience/models/aquatox/about.html

Download Information

Availability: Nonproprietary
Cost: N/A

Model Overview/Abstract

AQUATOX simulates multiple environmental stressors (including nutrients, organic loadings and chemicals, and temperature) and their effects on the algal, macrophyte, invertebrate, and fish communities. Therefore, AQUATOX can help identify and understand the cause and effect relationships between chemical water quality, the physical environment, and aquatic life. AQUATOX can represent a variety of aquatic ecosystems spatially, including vertically stratified lakes, reservoirs and ponds, and rivers and streams.

Model Features

- Evaluates which of several stressors is causing observed biological impairment
- Predicts effects of pesticides and other toxic substances on aquatic life
- Evaluates potential ecosystem responses to invasive species
- Explores how changes in land use or agricultural practices in a watershed might affect aquatic life, by using the new linkage to BASINS
- Compares differences in biological responses to control alternatives
- Develops targets for nutrients in lakes and reservoirs with nuisance algal blooms
- Estimates time to recovery of fish or invertebrate communities after reducing pollutant loads
- Calculates bioaccumulation factors for organic toxic chemicals
- Estimates how long before tissue levels of toxic organics in fish will return to safe levels following removal of contaminated sediments
- Has a large increase in the number of biotic state variables, with two representatives for each taxonomic group or ecologic guild
- Macrophyte category includes bryophytes
- Includes a multi-age fish category with up to 15 age classes for age-dependent bioaccumulation and limited population modeling
- Simulates maximum of 20 toxicants, with the capability for modeling daughter products due to biotransformations
- Disaggregates stream habitats into riffle, run, and pool
- Includes mechanistic current- and stress-induced sloughing, light extinction, and accumulation of detritus in periphyton
- Includes macrophyte breakage due to currents

- Computes chlorophyll *a* for periphyton and bryophytes, as well as for phytoplankton
- Enters and tracks fish biomass in g/m^2
- Includes entrainment and washout of animals, including fish, during high flow
- Has options of computing respiration and maximum consumption in fish as functions of mean individual weight, using allometric parameters from the Wisconsin Bioenergetics Model
- Includes density-dependent respiration in fish
- Fish spawning can occur on user specified dates as an alternative to temperature-cued spawning
- Includes detailed elimination of toxicants from biota
- Includes settling and erosional velocities for inorganic sediments as user-supplied parameters
- Includes uncertainty analysis that covers all parameters and loadings
- Provides biotic risk graphs as an alternative means of portraying probabilistic results
- Outputs limitation factors for photosynthesis along with the biotic rates
- Extends BASINS, providing linkages to GIS data, and HSPF and SWAT simulations

Model Areas Supported

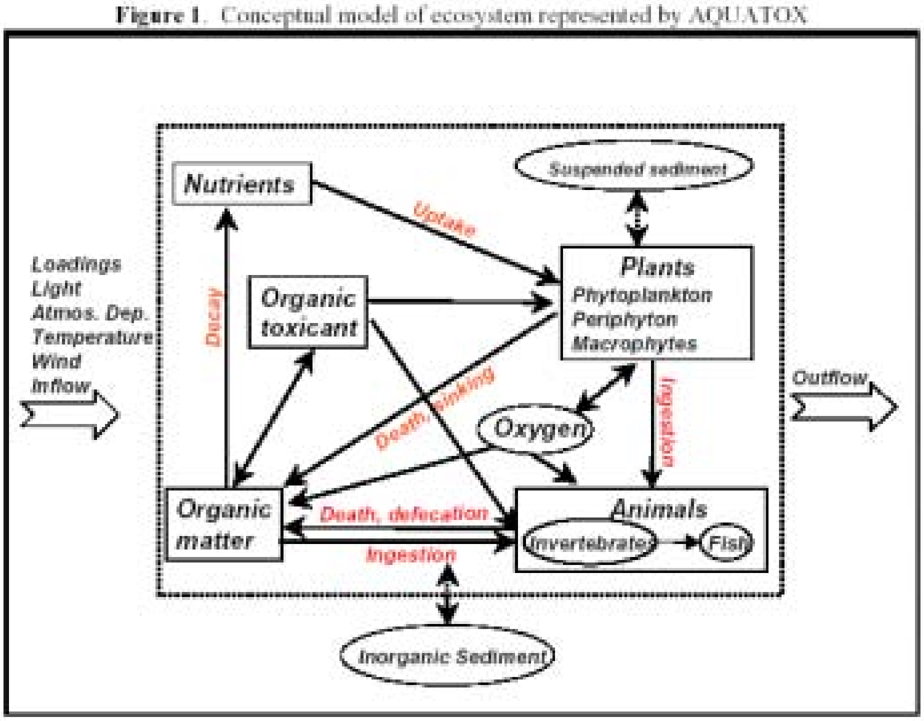
Watershed	None
Receiving Water	Medium
Ecological	High
Air	None
Groundwater	None

Model Capabilities

Conceptual Basis

AQUATOX predicts the fate of various pollutants, such as nutrients and organic toxicants, and their effects on the ecosystem, including fish, invertebrates, and aquatic plants (Figure 1). It simultaneously computes important chemical and biological processes over time. AQUATOX can predict not only the fate of chemicals in aquatic ecosystems but also their direct and indirect effects on the resident organisms.

Figure 1. Conceptual model of ecosystem represented by AQUATOX



Scientific Detail

AQUATOX uses differential equations to represent changing values of state variables, normally with a reporting timestep of one day. AQUATOX uses fourth- and fifth-order Runge-Kutta integration routines with adaptive step size to solve the differential equations. The routine uses the fifth-order solution to determine the error associated with the fourth-order solution; it decreases the step size (often to 15 minutes or less) when rapid changes occur and increases the step size when there are slow changes, such as in winter. However, the step size is constrained to a maximum of one day so that daily pollutant loadings are always detected. The reporting step, on the other hand, can be as long as 99 days or as short as 0.1 day; the results are integrated to obtain the desired reporting time period.

The process equations contain another class of input variables—the parameters or coefficients that allow the user to specify key process characteristics. For example, the maximum consumption rate is a critical parameter characterizing various consumers. AQUATOX is a mechanistic model with many parameters; however, default values are available so that the analyst has to be concerned with only those parameters necessary for a specific risk analysis, such as characterization of a new chemical.

The system being modeled is characterized by site constants, such as mean and maximum depths. At present, one can model small lakes, reservoirs, streams, small rivers, and ponds—and even enclosures and tanks.

Model Framework

It uses a waterbody ecosystem compartment framework to describe interactions between biotic and abiotic system components.

The fate portion of the model, which applies especially to organic toxicants, includes partitioning among organisms, suspended and sedimented detritus, suspended and sedimented inorganic sediments, and water; volatilization; hydrolysis; photolysis; ionization; and microbial degradation. The effects portion of the model includes chronic and acute toxicity to the various organisms modeled; and indirect effects such as release of grazing and predation pressure, increase in detritus and recycling of nutrients from killed organisms, dissolved oxygen sag due to increased decomposition, and loss of food base for animals.

Scale

Spatial Scale

- One-dimensional stream
- Two-box for reservoir, lake, and pond

Temporal Scale

- Daily

Assumptions

Aquatic system is considered to be a well-mixed condition. The model uses a two-box (epilimnion and hypolimnion) approach for the lake.

Model Strengths

AQUATOX is an ecosystem model that predicts the fate of nutrients and organic chemicals in water bodies as well as their direct and indirect effects on the resident organisms. Most water quality models predict only concentrations of pollutants in water; they do not project effects of pollutants on organisms.

Model Limitations

AQUATOX represents the aquatic ecosystem by simulating the changing concentrations (in mg/L or g/m^3) of organisms, nutrients, chemicals, and sediments in a unit volume of water. It differs from population models, which represent the changes in numbers of individuals modeling individual species at risk and modeling fishing pressure and other age- or size-specific aspects.

Application History
Validation studies using AQUATOX:

- Nutrient analysis on Onondaga Lake, New York (http://www.epa.gov/waterscience/models/aquatox/validation/onondaga.pdf)
- Nutrient analysis of the Coralville Reservoir, Iowa (http://www.epa.gov/waterscience/models/aquatox/validation/coralville.pdf)
- Bioaccumulation of PCBs in Lake Ontario (http://www.epa.gov/waterscience/models/aquatox/validation/ontario.pdf)
- Simulation of periphyton in Walker Branch, Tennessee (http://www.epa.gov/waterscience/models/aquatox/periphytonvalid.pdf)

Model Evaluation
The model and documentation have undergone successful peer review by an external panel convened by the U.S. Environmental Protection Agency.

Model Inputs
- Loadings to the waterbody
- General site characteristics
- Chemical characteristics of any organic toxicant
- Biological characteristics of the plants and animals.

AQUATOX comes bundled with data libraries that provide default data. These data libraries are of particular importance for the biological data, which are probably the most difficult for a user to obtain.

Users' Guide
Available online: http://www.epa.gov/waterscience/models/aquatox/users/user.pdf

Technical Hardware/Software Requirements

Computer hardware:
- PC

Operating system:
- Graphical User Interface

Programming language:
- Object-oriented Pascal using the Delphi programming system for Windows

Runtime estimates:
- Seconds to minutes

Linkages Supported
BASINS

Related Systems
None

Sensitivity/Uncertainty/Calibration

AQUATOX provides probabilistic modeling capability to consider the implications of uncertainty in the modeling analyses by allowing the user to specify the types of distributions and key statistics for any and all input variables. Quantitative uncertainty analysis is based on a Monte Carlo simulation.

Model Interface Capabilities

- Pre- and postprocessors
- Data display tools

References

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Park, R. A., and J. S. Clough. 2004. *Aquatox (Release 2): Modeling Environmental Fate and Ecological Effects in Aquatic Ecosystems Volume 2: Technical Documentation*. U.S. Environmental Protection Agency, Office of Water, Washington, DC.

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BASINS: Better Assessment Science Integrating point and Nonpoint Sources

Contact Information

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Download Information

Availability: Nonproprietary
http://www.epa.gov/waterscience/basins/index.html
Cost: N/A

Model Overview/Abstract

BASINS was developed by the EPA's Office of Water to support environmental and ecological studies in a watershed context. BASINS, a multipurpose environmental analysis system designed for use by regional, state, and local agencies in performing watershed and water quality-based studies, was originally introduced in 1996 with subsequent releases in 1998 and 2001. BASINS works with a geographic information system (GIS) framework and consists of: (1) national databases (2) assessment tools (3) a watershed delineation tool (4) classification utilities (5) characterization reports (6) watershed loading and transport models, HSPF and Soil and Water Assessment Tool, (SWAT); (7) a simplified GIS-based model, PLOAD, that estimates annual average nonpoint loads; (8) the Automated Geospatial Watershed Assessment (AGWA) tool, a GIS-based hydrologic modeling tool; and (9) model calibration tool, Parameter Estimation (PEST) tool. The system provides a user-friendly interface to conduct simple watershed-level screening analysis or detailed water quality modeling studies. The interface also helps the user to easily create the input files for various models.

Model Features

- User-friendly interface
- Flexibility in use from the simple watershed-level screening analysis to detailed water quality modeling
- Easy access to required GIS data layers for locations within the United States
- Linkage between GIS and the selected popular watershed and water quality models

Model Areas Supported

Watershed	High
Receiving Water	High
Ecological	Medium
Air	None
Groundwater	Medium

Model Capabilities

Conceptual Basis

BASINS is a GIS-based system that integrates a suite of watershed and water quality models with different approaches.

Scientific Detail

BASINS is a freely available multipurpose ArcView desktop environmental analysis system for use by regional, state, and local agencies in performing watershed and water quality-based studies. Many states and local agencies are moving toward a focused, watershed-based approach. The BASINS system is configured to support environmental and ecological studies in a watershed context. The system is designed to be flexible but support a variety of scales using tools that range from simple to sophisticated.

BASINS also was conceived as a system for supporting the development of total maximum daily loads (TMDLs), as defined in Section 303(d) of the Federal Clean Water Act. A TMDL is the sum of the allowable loads of a particular pollutant from all contributing point and nonpoint sources. The calculation must include a margin of safety (MOS) to ensure that the waterbody can be used for the purposes the state has designated (i.e., drinking water, fishing, swimming, etc.). Developing TMDLs requires a watershed-based point and nonpoint source analysis for a variety of pollutants. It also lets the modeler test different best management options for the impaired waterbody.

Traditional approaches to watershed-based assessments typically involve many separate steps for preparing data, summarizing information, developing maps and tables, and applying and interpreting models. BASINS makes watershed and water quality studies easier by bringing key data and analytical components together on a user's desktop. Using the now-familiar Windows environment, an analyst can quickly access national environmental data, apply some assessment and analysis tools, run several calculations and processes through hundreds of nonpoint source loadings, and obtain results in the form of maps, charts, graphs, and reports from a choice of water quality models in a matter of minutes.

Model Framework

BASINS consists of a GIS-based framework that links to environmental databases, characterization tools, and watershed models that simulate watershed and subwatershed processes with 1-D streams.

- BASINS is based on the ArcView GIS interface.
- BASINS includes many ArcView modular extensions
- BASINS integrates environmental data and watershed and water quality models into a coherent system for assisting in TMDL development and solving environmental problems.

The following components are new in BASINS 3.x:

- Extensions with an Extension Manager
- Web-based online help

Scale

Spatial Scale

- Watershed scale
- One-dimensional waterbody

Temporal Scale

- Different models in the BASINS suite have different temporal scales—HSPF: user-defined timestep, typically hourly, continuous simulation from days to years; SWAT: daily timestep, continuous simulation for months to years; PLOAD: Export coefficient model, annual; and KINEROS: single-storm event, part of AGWA, variable timestep typically in minutes

Assumptions

- Uses a lumped approach for the hydrologic response unit

Model Strengths

- Includes a large dataset for the nation
- Includes more than one watershed or water quality model from which to choose
- Has associated automatic downloading of data from Internet
- Has good customer support and e-mail listing service

Model Limitations

- Requires a large set of GIS data, making it difficult to setup the model for locations outside of the United States
- Requires proprietary software: ArcView 3.x, and the Spatial Analyst for grid operation
- May require training to use the advanced modeling options

Application History

Previous versions of BASINS have been applied to many TMDL studies across the United States. The individual models within the model suit like SWAT and HSPF have been used extensively for watershed and water quality studies.

Model Evaluation

BASINS system and most of its components have been used for many TMDL developments. There are many peer-reviewed publications available for the system and individual models.

Model Inputs

The BASINS system requires many GIS data layers with specific attributes combined with them. For locations within the United States, all the essential datasets can be downloaded from EPA's Web site based on 8-digit watershed or HUC in the lower 48 states, Alaska, Hawaii, and Puerto Rico with the U.S. Virgin Islands. The input requirements for individual watershed and water quality models available in the system vary among the models. For example, the HSPF model requires hourly precipitation depths, while SWAT requires only daily precipitation depths.

Users' Guide

Available online: http://www.epa.gov/waterscience/basins/bsnsdocs.html

Technical Hardware/Software Requirements

Computer hardware:

- PC

Operating system:

- Windows XP/2000/NT/98

Programming language:

- BASINS system and PLOAD are developed in ArcView 3.X.
- Models including HSPF, SWAT, and KINEROS are in FORTRAN

Runtime estimates:

- Minutes

Linkages Supported

BASINS system is a suite of tools and models linked together.

Models

- Updated the Hydrological Simulation Program-Fortran (HSPF) to version 12 and created a Windows interface for the HSPF model (WinHSPF) to replace the NonPoint Source Model (NPSM) in the previous versions of BASINS.
- The Automated Geospatial Watershed Assessment (AGWA) tool features the USDA-ARS models KINEROS and SWAT.
- The Kinematic Runoff and Erosion Model (KINEROS)
- Soil and Water Assessment Tool (SWAT), developed by the USDA Agriculture Research Service. BASINS uses the updated SWAT2000 model.
- A model called PLOAD, developed by CH2M-Hill, which uses export coefficients to estimate watershed loading. Rosgen's Bank Erosion Hazard Index has been incorporated into PLOAD as PLOAD-BEHI
- AQUATOX receives and automatically formats output from HPSF or SWAT in order to integrate watershed analysis with the likely effects on the aquatic biota in receiving waters.

Related Systems

Watershed Characterization System (WCS) (http://wcs.tetratech-ffx.com), TMDL Modeling Toolbox (http://www.epa.gov/athens/wwqtsc/html/tools.html)

Sensitivity/Uncertainty/Calibration

The new Parameter Estimation (PEST) tool in WinHSPF automates the model calibration process and allows users to quantify the uncertainty associated with specific model predictions. This tool can also be used for uncertainty analysis, such as Monte Carlo Analysis.

Model Interface Capabilities

- Customized ArcView 3.x interface with individual extensions organized in the following categories: Assess, Data, Delineate, Models, Reports, and Utilities
- A scenario generator, GenScn, developed by USGS, that allows users to manage, visualize, analyze, and compare results from WinHSPF or SWAT simulations
- A Web data extraction tool that dynamically downloads GIS data and databases from the BASINS Web site and a variety of other sources
- A tool that automatically checks all components of the BASINS application and the last update
- Automatic watershed delineation tools based on DEM GRID
- Updated manual delineation tools based on ArcView’s dynamic segmentation process
- A GRID projector, which requires Spatial Analyst extension
- An FTP process for downloading NHD layers from USGS and importing, then projecting them directly into a BASINS project window
- A tool to archive and restore BASINS projects

References

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CAEDYM: Computational Aquatic Ecosystem Dynamics Model

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Download Information

Availability: Nonproprietary
www.cwr.uwa.edu.au/~ttfadmin/model/caedym
Cost: N/A

Model Overview/Abstract

The Computational Aquatic Ecosystem Dynamics Model (CAEDYM) is a comprehensive aquatic ecological model that is based on the nutrient-phytoplankton-zooplankton food chain relationship. The state variables of CAEDYM include carbon, oxygen, silica, inorganic particulate, and other biological factors. CAEDYM can be linked with several hydrodynamic models, such as DYRESM and ELCOM, to describe one-, two-, and three-dimensional processes of primary production, secondary production, nutrient and metal cycling, and oxygen dynamics and the movement of sediment.

Model Features

- Phytoplankton: up to seven groups
- Dissolved oxygen, biochemical oxygen demand ("fast" and "slow")
- Nutrients (NH_4, NO_3, PO_4, TP, TN and internal phytoplankton N, P and C)
- Suspended solids: two groups
- Zooplankton: up to five groups
- Fish: up to nine groups including jellyfish and seagrasses/macrophytes
- Macroalgae
- Macroinvertebrates (bivalves, polychaetes and crustacean grazers)
- pH
- Metals: iron, manganese and aluminum

Model Areas Supported

Watershed	None
Receiving Water	Medium
Ecological	High
Air	None
Groundwater	None

Model Capabilities

Conceptual Basis
The waterbody is conceptualized as a network of grid points (finite difference).

Scientific Detail
CAEDYM is a detailed aquatic ecological model that simulates the nutrients, phytoplankton, zooplankton, fish, and benthic habitat. The model requires external hydrodynamic models to provide temperature, salinity, and transport driving forces. CAEDYM usually runs at the same timestep as the hydrodynamic models. The state variables include dissolved oxygen, inorganic nutrients, dissolved organic nutrients, particulate organic nutrients, and inorganic suspended solids in both the water column and sediment layer. The water column variables also include pH, color, one group of bacteria, seven groups of algae, five groups of zooplankton, one group of jellyfish, five groups of fish, one group of pathogen, four groups of macroalgae, one group of seagrass, and three groups of invertebrates.

Model Framework
- One-dimensional vertical
- One-dimensional longitudinal
- Two-dimensional longitudinal-vertical
- Three-dimensional
- Reservoir, lake, estuary, river, floodplain

Scale

Spatial Scale
- One-, two-, or three-dimensional

Temporal Scale
- User-defined timestep

Assumptions
Aquatic ecological dynamics can be described with the ordinary differential equations.

Model Strengths
- Detailed aquatic ecology, strong ecological modeling capability
- Flexible structure

Model Limitations
- No sediment diagenesis

Application History
CAEDYM is used in 59 countries around the world.

Model Evaluation
Not available

Model Inputs
- Initial concentrations of state variables

- Inflows and concentrations in inflows and over forcing regions
- Parameter values
- Other data may be required by the hydrodynamic driver (DYRESM or ELCOM), e.g., meteorological forcing data

Users' Guide

Computational Aquatic Ecosystem Dynamics Model CAEDYM v2.1 Science Manual
Computational Aquatic Ecosystem Dynamics Model CAEDYM v2.1 User Manual
Available online: http://www.cwr.uwa.edu.au/~ttfadmin/model/caedym/

Technical Hardware/Software Requirements

Computer hardware:

- PC

Operating system:

- Windows 95/98/NT, Linux, DEC Unix

Programming language:

- FORTRAN 95

Runtime estimates:

- Minutes to hours

Linkages Supported

CAEDYM can be linked with the following hydrodynamic models:

- DYRESM (one-dimensional vertical for deep lakes and reservoirs)
- DYRISM (Quasi-two-dimensional Lagrangian for rivers and floodplains)
- ELCOM-2D (two-dimensional laterally averaged for narrow lakes and reservoirs)
- ELCOM (three-dimensional for any waterbody)

Related Systems

CE-QUAL-R1, EFDC, CE-QUAL-ICM, WASP/EUTRO, CE-QUAL-RIV1, CE-QUAL-W2

Sensitivity/Uncertainty/Calibration

Not available

Model Interface Capabilities

- Graphic Interface written with Java

References

Hipsey, M.R., J.R. Romero, J.P. Antenucci, and D.P. Hamilton. 2004. *Computational Aquatic Ecosystem Dynamics Model CAEDYM v2*. (Computer program manual). Centre for Water Research, The University of Western Australia.

Romero, J.R., M.R. Hipsey, J.P. Antenucci, and D.P. Hamilton. 2004. *Computational Aquatic Ecosystem Dynamics Model CAEDYM v2.1*. (Science manual). Centre for Water Research, The University of Western Australia

CCHE1D

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Download Information

Availability: Nonproprietary (for beta testing program)
Cost: N/A

Model Overview/Abstract

The CCHE1D model is a general one-dimensional model that simulates unsteady flows and sedimentation processes in channel networks, including bed aggradation and degradation, bed material composition (hydraulic sorting and armoring), bank erosion, and the resulting channel morphologic changes.

CCHE1D uses a watershed-based approach that provides straightforward integration with existing watershed processes (rainfall-runoff and field erosion) models to produce estimations of sediment loads and morphological changes in channel networks. CCHE1D has a GIS-based graphical interface that provides support for automated spatial analysis, channel network digitizing, digital mapping, and visualization of modeling results.

Model Features

- Unsteady, one-dimensional channel network flow simulation
- Nonequilibrium, nonuniform sediment transport and channel morphology modeling
- ArcView-based graphical user interface (GUI)
- Channel network and subwatershed extraction
- Channel networks digitizing
- Mesh generation
- Data management
- Interface to watershed modeling programs.

Model Areas Supported

Watershed	Medium
Receiving Water	Medium
Ecological	None
Air	None
Groundwater	None

Model Capabilities

Conceptual Basis
The river channels are conceptualized as a one-dimensional channel network.

Scientific Detail
The governing equations for the one-dimensional flow are the St. Venant equations, which describe the conservation of mass and momentum in the channel network. Preissmann's implicit scheme is applied to solve the governing equations numerically. The sediment transport component simulates the nonequilibrium transport of nonuniform sediment with bed load, suspended load, and wash load. The Preissmann's implicit scheme is also applied to solve the governing equation of sediment transport. Several empirical equations such as the sediment transport capacity, bed-material porosity, mixing layer thickness, and settling velocities of sediment particles are used to simulate the sediment transport.

Model Framework
- Horizontal one-dimension model
- Channel network

Scale

Spatial Scale
- One-dimensional channel network

Temporal Scale
- User-defined timestep, typically minutes.

Assumptions
- Laterally and vertically averaged

Model Strengths
The model is able to simulate unsteady flow, including hydraulic structures, and various sediment processes, including bed aggradation and degradation, bed material composition (hydraulic sorting and armoring), bank erosion, and the resulting channel morphologic changes. The model also provides interfaces and preprocessing tools for preparing input data.

Model Limitations
- Only a single outlet is allowed in the dendritic channel networks.
- Flow must be primarily subcritical in all reaches. Local supercritical and transcritical flows without hydraulic jumps in isolated cross sections are handled through the hybrid dynamic/diffusive wave model.
- Tidal flow conditions are not tested.
- The model cannot be applied to dam-break flows.

Application History
Applications examples: East Fork River, Wyoming; Danjiangkou Reservoir, China; Goodwin Creek Watershed, Mississippi

Model Evaluation
Application and test of CCHE1D can be found in various technical reports, journals, and conference papers from http://www.ncche.olemiss.edu/cche1d/cche1d_publications.html.

Model Inputs

- Geometric data, including cross section, reach length, channel roughness, and channel junctions
- Inflow and outflow
- Sediment properties, inflow sediment data, bed material data, bank material data
- Hydraulic structure data, including bridge crossing, culverts, drop structures, and measuring flumes
- Watershed data

Users' Guide

Available online: http://www.ncche.olemiss.edu/cche1d/cche1d_documents.html

Technical Hardware/Software Requirements

Computer hardware:

- PC-Intel or compatible

Operating system:

- Windows95 or newer

Programming language:

- FORTRAN, C, and Avenue

Runtime estimates:

-

Linkages Supported

- Linked to TOPAZ for spatial analysis
- Linked to AGNPS and SWAT for watershed processes

Related Systems

None

Sensitivity/Uncertainty/Calibration

Not available

Model Interface Capabilities

- ArcView3.x as the GUI

References

Wu, W.M, D.A. Vieira, 2002, One-Dimensional Channel Network Model CCHE1D version 3.0, Technical Manual, University of Mississippi, University, MS

Vieira, D.A., W.M Wu. 2002. *Users Manual for One-Dimensional Channel Network Model CCHE1D version 3*.0, (Computer program manual). University of Mississippi, University, MS

CE-QUAL-ICM/TOXI

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http://www.wes.army.mil/el/elmodels

Download Information

Availability: Nonproprietary
Cost: N/A

Model Overview/Abstract

The CE-QUAL-ICM water quality model was initially developed as one component of a model package employed to study eutrophication processes in Chesapeake Bay. The ICM/TOXI model is the toxic chemical model and has routines from EPA's WASP (Water Quality Analysis Simulation Program).

Model Features

- Water quality modeling
- Toxics model
- Eutrophication
- Sediment diagenesis model

Model Areas Supported

Watershed	None
Receiving Water	High
Ecological	Low
Air	None
Groundwater	None

Model Capabilities

Conceptual Basis

There are two distinctly different development pathways to ICM: a eutrophication model (ICM) and an organic chemical model (ICM/TOXI). The model employs an unstructured grid system, which facilitates linkage to a variety of hydrodynamic models.

Scientific Detail

- ICM stands for "integrated compartment model," which is analogous to the finite-volume numerical method. The model computes constituent concentrations resulting from transport and transformations in well-mixed cells that can be arranged in arbitrary one-, two-, or three-dimensional configurations. Thus, the model employs an unstructured grid system.
- The release version of the eutrophication model computes 22 state variables, including physical properties; multiple forms of algae, carbon, nitrogen, phosphorus, and silica; and dissolved oxygen. Recently, two size classes of zooplankton, two benthos compartments (deposit feeders and filter feeders), submerged aquatic vegetation (roots and shoots biomass), epiphytes, and benthic algae were added, although this version of the code is not generally released to the public.
- Each state variable may be individually activated or deactivated.
- One significant feature of ICM, eutrophication version, is a diagenetic sediment submodel. The sub-model interactively predicts sediment-water oxygen and nutrient fluxes. Alternatively, these fluxes may be specified based on observations.
- The ICM/TOXI model resulted from incorporating the toxic chemical routines from EPA's WASP (Water Quality Analysis Simulation Program) model into the transport code for ICM, incorporating a more detailed benthic sediment model, and enhancing linkages to sediment transport models.
- ICM/TOXI includes physical processes, such as sorption to DOC and three solid classes, volatilization, and sedimentation. It also includes chemical processes such as ionization, hydrolysis, photolysis, oxidation, and biodegradation.
- ICM/TOXI can simulate temperature, salinity, three solids classes, and three chemicals (total chemical for organic chemicals and trace metals). Each species can exist in five phases (water, DOC-sorbed, and sorbed to three solids types) via local equilibrium partitioning.

Model Framework

The model consists of a main program, an INCLUDE file, and subroutines. Both the main program and subroutines perform read and write operations on numerous input and output files. The model does not compute hydrodynamics. Flows, diffusion coefficients, and volumes must be specified externally and read into the model. Hydrodynamics may be specified in binary or ASCII format and may be obtained from a hydrodynamics model such as the CH3D-WES or EFDC.

Scale

Spatial Scale

- One-, two-, or three-dimensional

Temporal Scale

- User-defined timestep. The timestep may be varied through the auto-stepping option or at discrete, user-specified intervals.

Assumptions

The model assumes that the dynamics of each physical, chemical, and biological component can be described by the principle of conservation of mass.

Model Strengths

- The model has a predictive diagenetic sediment submodel that interactively predicts sediment-water oxygen and nutrient fluxes.
- The ICM/TOXI model has toxic chemical routines, which further enhance linkage with sediment transport models.

Model Limitations

- The model does not compute hydrodynamics. Flows, diffusion coefficients, and volumes must be specified externally and read into the model.
- The user must provide processors, which prepare input files and process output for interpretation and presentation.

Application History

The ICM eutrophication model has been applied to a variety of sites, including Chesapeake Bay, Inland Bays of Delaware, New York Bight, Newark Bay, New York–New Jersey Harbors and Estuaries, Lower Green Bay, Los Angeles–Long Beach Harbors, Cache River wetland, San Juan Bay and Estuaries, Florida Bay, and Lower St. Johns River (on–going).

The WASP toxic chemical model on which ICM/TOXI is based has been applied to a wide variety of sites. CE-QUAL-ICM also has been linked to the CH3D-WES and EFDC hydrodynamic models.

Model Evaluation

Not available

Model Inputs

- Initial conditions
- Time sequences of boundary conditions (inputs from watershed sources and discharges)
- Reservoir geometry
- Physical coefficients
- Biological and chemical reaction rates
- Time sequences of meteorological data used to compute temperature.

Users' Guide

Available online: http://www.wes.army.mil/el/elpubs/pdf/trel95-15.pdf

Technical Hardware/Software Requirements

Computer hardware:

- PC

Operating system:

- PC-DOS. Operates on a variety of platforms, including 486 PC, Silicon Graphics and Hewlett Packard workstations, and Cray Y-MP and C-90 mainframes

Programming language:

- FORTRAN 77

Runtime estimates:

- Minutes to hours

Linkages Supported

CH3D-WES, EFDC

Related Systems

Surface Water Modeling System (SMS)

Sensitivity/Uncertainty/Calibration

Highly accurate for simulation of reservoir systems with adequate monitoring data and application experience.

Model Interface Capabilities

Not available

References

Creco, C.F. 1995. Simulation of trends in Chesapeake Bay Eutrophication. Journal of Environmental Engineering. 121(4):298-310.

Cerco, C.F., and T. Cole. 1993. Three-dimensional eutrophication model of Chesapeake Bay. Journal of Environmental Engineering. (119):1006-1025.

Cerco, C.F., and T. Cole. 1994. *Three-dimensional eutrophication model of Chesapeake Bay*. Technical Report EL-94-4. US Army Corps of Engineers Water Experiment Station, Vicksburg, MS.

Cerco, C.F., and T. Cole. 1995. *User's Guide to the CE-QUAL-ICM Three-dimensional eutrophication model, release version 1.0*. Technical Report EL-95-15. US Army Corps of Engineers Water Experiment Station, Vicksburg, MS.

DiToro, D.M., and J.F. Fitzpatrick (Hydroqual, Inc.). 1993. *Chesapeake Bay sediment flux model*. Contact Report EL-93-2. Prepared for EPA Chesapeake Bay Program, US. Army Engineers District, Baltimore, MD, and US. Army Engineer Waterways Exp. Station by Hydroqual, Inc.

Mark, D., B. Bunch, and N. Scheffner. 1992. Combined hydrodynamic and water quality modeling of Lower Green Bay. Miscellaneous Paper W-92-3. In *Proceedings of Water Quality ’92 9th Seminar*, Environmental Laboratory, *Army Engineers Waterways Experiment Station*, Vicksburg, MS, pp 226-233.

CE-QUAL-R1

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Download Information

Availability: Nonproprietary download currently for U.S. Army Corps of Engineers use only
Cost: N/A

Model Overview/Abstract

CE-QUAL-R1 is a water quality model that describes the time-variable vertical distribution of 27 water quality variables in reservoirs. In addition, 11 variables associated in the sediment can be modeled. CE-QUAL-R1 is spatially one-dimensional and horizontally averaged; temperature and concentration gradients are computed only in the vertical direction. The reservoir is conceptualized as a vertical sequence of horizontal layers in which thermal energy and materials are uniformly distributed in each layer. The mathematical structure of the model is based on horizontal layers whose thickness depends on the balance of inflowing and outflowing waters. Variable layer thicknesses permit accurate mass balancing during periods of inflow and outflow.

Model Features

- Temperature
- Dissolved oxygen
- Nutrients
- Metals
- Algaes
- Macrophytes
- Fish
- pH, alkalinity
- Coliforms

Model Areas Supported

Watershed	None
Receiving Water	Medium
Ecological	Medium
Air	None
Groundwater	None

Model Capabilities

Conceptual Basis

In CE-QUAL-R1, the reservoir is conceptualized as a vertical sequence of horizontal layers in which thermal energy and materials are uniformly distributed in each layer.

Scientific Detail

The mathematical structure is based on a set of differential equations that express conservation of mass and energy in each horizontal layer. Solution of these equations provides material or energy concentrations as functions of time and depth. The thermal analysis portion of CE-QUAL-R1 is provided as an independent model (CETHERM-R1) to simplify simulation of water budgets and temperature profiles. CETHERM-R1 includes the variables of temperature, suspended solids, and total dissolved solids. The algorithms representing physical processes are the same as in CE-QUAL-R1. The flux model calculates and lists the rates of change for all biological processes, which should aid the user in correctly predicting variable concentrations.

Model Framework

- One-dimensional vertical waterbody
- Deep reservoirs

Scale

Spatial Scale

- One-dimensional vertical

Temporal Scale

- User-defined timestep, typically seconds

Assumptions

- Laterally and longitudinally averaged reservoir layers
- Well-mixed in each layer

Model Strengths

The model is capable of simulating physical, chemical, and biological factors, including radiation and heat transfer; conservative substance routing; suspended solids routing and settling; dissolved oxygen through aeration, photosynthesis, respiration, and organic decomposition; carbon, nitrogen, and phosphorus cycles; dynamics and trophic relationships of phytoplankton and macrophytes; coliform bacteria mortality; and accumulation, dispersion, and reoxidation of manganese, iron, and sulfide when anaerobic conditions prevail.

Model Limitations

Limitations include the one-dimensional representation of reservoirs that limits simulation to a vertical series of well-mixed horizontal layers. This assumption cannot predict longitudinal and lateral variations in water quality and requires the assumption of instantaneous dispersion of all inflow quantities and constituents throughout the horizontal layers. The model assumes that the dynamics of each physical, chemical, and biological component can be described by the principle of conservation of mass. Because the equations are not solved in closed form, minor errors concerning the conservation of mass can occur. The dynamic calculation of nutrient flux from bottom sediments is not included.

Application History

Application example: Eau Galle Reservoir, Wisconsin

Model Evaluation
Not available

Model Inputs
- Initial conditions
- Time sequences of boundary conditions (inputs from watershed sources and discharges)
- Reservoir geometry
- Physical coefficients
- Biological and chemical reaction rates
- Time sequences of hydrometeorological conditions

Users' Guide
Available online: http://www.wes.army.mil/el/elmodels/pdf/ire82-1/ire82-1.pdf

Technical Hardware/Software Requirements

Computer hardware:
- PC

Operating system:
- PC-DOS

Programming language:
- FORTRAN

Runtime estimates:
- Minutes to hours

Linkages Supported
None

Related Systems
None

Sensitivity/Uncertainty/Calibration
Not available

Model Interface Capabilities
- WESWIN is an interactive Windows package to execute CE-QUAL-R1.
- WESPLOT is for post-processing the modeling results.

References
U.S. Army Corps of Engineers, South Florida Water Management District and Kimley-Horn and Associates, Inc. 2003. *Comprehensive Everglade Restoration Plan, G.1. - Water Quality Modeling, G.1.1. - Reservoir Phosphorus Uptake Model - Interim Report*. U.S. Army Corps of Engineers, South Florida Water Management District.

Environmental Laboratory. 1990. *A dynamic one-dimensional (longitudinal) water quality model for streams: User's manual*. CE-QUAL-R1. U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, MS.

Nestler, J.M., Lt. Scheider, 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 Corps of Engineers Waterways Experiment Station, Vicksburg, MS.

Zimmerman, M.J., and M.S. Dortch. 1989. Modeling water quality of a regulated stream below a peaking hydropower dam. Regulated Rivers: Research and Management. 4: 235-247.

CE-QUAL-RIV1

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http://www.wes.army.mil/el/elmodels/riv1info.html

Download Information

Availability: Nonproprietary download currently for U.S. Army Corps of Engineers use only
Cost: N/A

Model Overview/Abstract

CE-QUAL-RIV1 is a coupled one-dimensional hydrodynamic and water quality model for river systems. The model consists of two parts, a hydrodynamic code (RIV1H) and a water quality code (RIV1Q). RIV1H is applied first to predict flows, depths, velocities, water surface elevations, and other hydraulic characteristics. RIV1Q uses the RIV1H output file to drive the transport of the water quality variables. RIV1Q can predict variations in each of 12 state variables—temperature, carbonaceous biochemical oxygen demand (CBOD), organic nitrogen, ammonia nitrogen, nitrate + nitrite nitrogen, dissolved oxygen, organic phosphorus, dissolved phosphates, algae, dissolved iron, dissolved manganese, and coliform bacteria. In addition, the impacts of macrophytes can be simulated.

Model Features

- One-dimensional unsteady flow
- Nutrients, dissolved oxygen dynamics, eutrophication, metals, and bacteria

Model Areas Supported

Watershed	None
Receiving Water	High
Ecological	Medium
Air	None
Groundwater	None

Model Capabilities

Conceptual Basis

In CE-QUAL-RIV1, the river is conceptualized as a series of horizontal grids in one-dimension.

Scientific Detail
The governing equations for CE-QUAL-RIV1 consist of continuity equation, momentum equation, and constituent fate and transport equation. The Preissmann's implicit scheme is applied to solve the governing equations for flow. The advection of the constituent transport is solved using a fourth-order explicit scheme. The diffusion of the constituent transport is solved using an implicit scheme. The source/sink and reaction of water quality variables are solved separately.

Model Framework
- One-dimensional horizontal model
- River

Scale

Spatial Scale
- One-dimensional horizontal

Temporal Scale
- User-defined timestep
- Time-variable simulation of flow and water quality variables

Assumptions
- No lateral circulation
- Hydrostatic assumption
- No lateral variation of water quality variables

Model Strengths
- Provides a high-order accuracy advection scheme to deal with various flow conditions
- Is capable of simulating physical, chemical, and biological processes in rivers

Model Limitations
- Cannot model a one-dimensional tidal system
- Does not include a sediment diagenesis component

Application History
Application example: water temperature and dissolved oxygen simulation of Youghiogheny River, Pennsylvania

Model Evaluation
Not available

Model Inputs
- Initial conditions
- Boundary conditions
- Segmentation of river network
- Physical and biological parameters

Users' Guide
Available online: http://www.wes.army.mil/el/elmodels/pdf/el952/el-95-2.pdf

Technical Hardware/Software Requirements

Computer hardware:

- PC

Operating system:

- PC-DOS, Windows

Programming language:

- FORTRAN

Runtime estimates:

- Minutes to hours

Linkages Supported

None

Related Systems

EFDC1D, DYNHYD5/WASP5

Sensitivity/Uncertainty/Calibration

Not available

Model Interface Capabilities

Not available

References

Environmental Laboratory. *CE-QUAL-RIV1: a dynamic, one-dimensional (longitudinal) water quality model for streams*. (Computer program manual). U.S. Army Corps of Engineers.

CE-QUAL-W2

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http://www.cee.pdx.edu/w2/

Download Information

Availability: Nonproprietary
Cost: N/A

Model Overview/Abstract

CE-QUAL-W2 is a two-dimensional, longitudinal/vertical, laterally averaged, finite-difference hydrodynamic and water quality model. Because the model assumes lateral homogeneity, it is best suited for relatively long, narrow waterbodies exhibiting longitudinal and vertical water quality gradients. The model can be applied to rivers, lakes, reservoirs, and estuaries. Branched networks can be modeled.

The model accommodates variable grid spacing (segment lengths and layer thicknesses) so that greater resolution in the grid can be specified where needed. The model equations are based on the hydrostatic approximation (negligible vertical accelerations). Eddy coefficients are used to model turbulence. The hydrodynamic timestep is calculated internally as the maximum allowable timestep that ensures numerical stability. A third-order accurate (QUICKEST) advection scheme reduces numerical diffusion.

The water quality portion of the model includes the major processes of eutrophication kinetics and a single algal compartment. The bottom sediment compartment stores settled particles, releases nutrients to the water column, and exerts sediment oxygen demand based on user-supplied fluxes; a full sediment diagenesis model is under development.

Model Features

- Reservoir and river hydrodynamics and transport

- Temperature simulation
- Water quality modeling
- Eutrophication

Model Areas Supported

Watershed	None
Receiving water	High
Ecological	Low
Air	None
Groundwater	None

Model Capabilities

Conceptual Basis

In CE-QUAL-W2, the river or reservoir is conceptualized as a laterally averaged two-dimensional model having horizontal segments and vertical layers.

Scientific Detail

The mathematical structure is based on a set of differential equations that express conservation of mass and energy in each horizontal layer. Solution of these equations provides material or energy concentrations as functions of time and depth. Some of the key model features are given below:

- Variable layer heights and segment lengths between waterbodies; surface layer can extend through multiple layers
- Ability to model multiple waterbodies in the same computational grid, including multiple reservoirs, steeply sloping riverine sections between reservoirs, and estuaries
- Momentum transfer between branches
- Additional reaeration algorithms for rivers
- Additional vertical turbulence algorithms for rivers
- Numerical algorithms for pipe, weir, spillway, and pump flow
- Internal weir algorithm for submerged or skimmer weirs
- The effect of hydraulic structures on gas transfer and total dissolved gas transport
- Algorithm to calculate the maximum allowable timestep and adjust the timestep to ensure hydrodynamic stability requirements were not violated (autostepping)
- A selective withdrawal algorithm that calculates a withdrawal zone based on outflow, outlet geometry, and upstream density gradients
- Higher-order transport scheme (QUICKEST) that reduces numerical diffusion. Leonard's ULTIMATE algorithm, which eliminates over/undershooting in the transport solution scheme, has been added. The QUICKEST can be used alone or in conjunction with the ULTIMATE scheme, where oscillations due to over/undershoots are encountered.
- Step function or linear interpolation of inputs
- Ice-cover algorithm
- Internal calculation of equilibrium temperatures and coefficients of surface heat exchange or a term-by-term accounting of surface heat exchange
- Generalized time-varying data input subroutine with input data accepted at any frequency
- Sediment/water heat exchange
- Any number of user-defined arbitrary constituents defined by a decay rate, settling rate, and temperature rate multiplier that can include conservative tracers, coliform bacteria, water age, and contaminants
- An implicit solution for the effects of vertical eddy viscosity in the horizontal momentum equation
- Momentum transfer between branches
- Any number of user-defined phytoplankton, epiphyton, CBOB, and inorganic solids groups
- Dissolved and particulate biogenic silica

- Derived constituents, such as total DOC, organic nitrogen, and organic phosphorus, that are not state variables
- Ability to output kinetic fluxes

Model Framework

The model predicts water surface elevations, velocities, and temperatures. Temperature is included in the hydrodynamic calculations because of its effect on water density. The water quality algorithms incorporate 21 constituents in addition to temperature, including nutrient/phytoplankton/dissolved oxygen interactions during anoxic conditions. Any combination of constituents can be simulated. The effects of salinity or total dissolved solids/salinity on density and thus on hydrodynamics are included only if they are simulated in the water quality module. The water quality algorithm is modular, allowing constituents to be easily added as subroutines. The model can be applied to estuaries, rivers, or portions of a waterbody by specifying upstream or downstream head boundary conditions. The branching algorithm allows application to geometrically complex waterbodies such as dendritic reservoirs or estuaries. Variable segment lengths and layer thicknesses can be used, allowing specification of higher resolution where needed. Water quality can be updated less frequently than hydrodynamics, thus reducing computational requirements. However, water quality kinetics are not decoupled from the hydrodynamics (i.e., separate, standalone code for hydrodynamics and water quality where output from the hydrodynamic model is stored on disk and then used to specify advective fluxes for the water quality computations).

Scale

Spatial Scale

- Two-dimensional in the horizontal and vertical direction, with any number of waterbodies having any number of branches
- Previous applications have used a horizontal grid spacing of 100 to 10,000 m and a vertical grid spacing of 0.2 to 5 m

Temporal Scale

- User-defined timestep

Assumptions

- Dynamics of each physical, chemical, and biological component can be described by the principle of conservation of mass.
- Waterbody is laterally averaged.

Model Strengths

- Can model hydrodynamics and water quality for entire river basin with dams, river, and lakes, with a variety of hydraulic structures.
- A higher-order transport scheme (QUICKEST) that reduces numerical diffusion is included.

Model Limitations

- Well-mixed in lateral direction.
- Hydrostatic assumption for vertical momentum equation.
- Considerable technical expertise in hydrodynamics and eutrophication/water quality processes is required to apply the model.
- Simplistic sediment oxygen demand; the model does not have a sediment diagenisis compartment.
- No zooplankton or macrophyte.
- No toxics.
- Pre-processor of the model only helps in creating the main control file and bathymetry visualization and editing. No bathymetry grid generator or data display/preparation or post-processing capabilities.

Application History
The model has been successfully applied to more than 100 waterbodies. Apart from the example applications provided in the user's manual, a partial list of CE-QUAL-W2 applications can be found at http://www.ce.pdx.edu/w2/w2app.htm.

Model Evaluation
Unknown

Model Inputs
- Initial conditions
- Time sequences of boundary conditions (inputs from watershed sources and discharges)
- Reservoir geometry
- Physical coefficients
- Biological and chemical reaction rates
- Time sequences of hydrometeorological conditions

Users' Guide
User documentation can be downloaded along with the model: http://www.ce.pdx.edu/w2 or http://www.wes.army.mil/el/elmodels/index.html

Technical Hardware/Software Requirements

Computer hardware:
- PC

Operating system:
- PC-DOS/Windows or UNIX environment

Programming language:
- FORTRAN90

Runtime estimates:
- Minutes to hours

Linkages Supported
HSPF

Related Systems
Watershed Modeling System (WMS)

Sensitivity/Uncertainty/Calibration
Not available

Model Interface Capabilities
- Graphical pre-processor

References

Cole, T.M., and S. A. Wells. 2000. *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.

Cole, T.M., and S. A. Wells. 2003. *CE-QUAL-W2: A two-dimensional, laterally averaged, Hydrodynamic and Water Quality Model, Version 3.1*. Instruction Report EL-03-1. US Army Engineering and Research Development Center, Vicksburg, MS.

CH3D-IMS: Curvilinear-grid Hydrodynamics 3D—Integrated Modeling System

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Download Information

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Cost: Contact Dr. Y. Peter Sheng at pete@coastal.ufl.edu

Model Overview/Abstract

CH3D-IMS is an integrated modeling system based on a CH3D model framework. It models circulation, wave, sediment transport, water quality, light attenuation, and seagrass on curvilinear grids. The circulation is solved using CH3D. Wave is modeled using SWAN framework. Four additional modules: CH3D-SED3D, CH3D-WQ3D, CH3D-LA, and CH3D-SAV are used for calculating the sediment transport, water quality, light attenuation, and seagrass.

Model Features

- Three-dimensional hydrodynamics
- Cohesive and noncohesive sediment transport
- Nitrogen, phosphorus, phytoplankton, zooplankton, and dissolved oxygen
- Light attenuation and seagrass kinetics

Model Areas Supported

Watershed	None
Receiving Water	High
Ecological	High
Air	None
Groundwater	None

Model Capabilities

Conceptual Basis

The waterbody is conceptualized as a series of grid points on a curvilinear orthogonal coordinate system.

Scientific Detail

The details of the circulation model are presented in the fact sheet of CH3D. The governing equations for sediment transport and water quality are solved on a nonorthogonal curvilinear coordinate on the horizontal plane. In the vertical direction, both the σ-coordinate and z-coordinate are provided. Sediment transport and water quality are solved using the same timestep as the hydrodynamic calculation. The sediment transport processes include advection, turbulent mixing, settling/flocculation, deposition, and resuspension. Wave-current interaction inside the bottom boundary layer also is considered. For water quality simulation, the nitrogen cycling models dissolved, particulate, organic, and inorganic nitrogen species; the phosphorus cycling models dissolved, particulate, organic, and inorganic phosphorus species. In addition, dissolved oxygen, phytoplankton, and zooplankton are modeled. The seagrass module calculates the growth and decay of seagrass biomass due to light, nutrient, temperature, and salinity.

Model Framework

- Three-dimensional model
- River, lake, reservoir, estuary, ocean

Scale

Spatial Scale

- One-dimensional, two-dimensional, and three-dimensional

Temporal Scale

- User-defined timestep

Assumptions

- Hydrostatic assumption
- Boussinesq approximation
- Reynold’s stress assumption

Model Strengths

- Capable of modeling one-dimensional, two-dimensional, and three-dimensional hydrodynamics, sediment transport, and eutrophication in various waterbodies with complex bathymetry.
- Boundary-fit curvilinear coordinate can represent the waterbody boundaries accurately.
- The σ and z coordinates in the vertical direction provides flexible options for modeling waterbodies with different bathymetry.

Model Limitations

- Not a public modeling system.
- No source code available.
- No user’s manual.

Application History

The model has been applied in Chesapeake Bay, James River, Lake Okeechobee, Sarasota Bay, Tampa Bay, Indian River Lagoon, Florida Bay, St. Johns River, Biscayne Bay, Charlotte Harbor, Gulf of Mexico, and Pinellas County and offshore.

Model Evaluation

The model has been evaluated in many journal and conference papers.

Model Inputs

- Initial conditions
- Time sequences of boundary conditions (inputs from watershed sources and discharges)
- Reservoir geometry

- Physical coefficients
- Biological and chemical reaction rates
- Time sequences of hydrometeorological conditions

Users' Guide
Not available

Technical Hardware/Software Requirements

Computer hardware:
- VAX, SGI, SUN, DEC, IBM, IBM-PC

Operating system:
- PC-DOS, UNIX, WINDOWS, Linux

Programming language:
- FORTRAN

Runtime estimates:
- Minutes to hours

Linkages Supported
None

Related Systems
POM, EFDC, ECOMSED, GLLVHT

Sensitivity/Uncertainty/Calibration
Not available

Model Interface Capabilities
- ArcView-based GUI for grid generation, pre- and post- processing

References
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Sheng, Y.P. 1994. Modeling Hydrodynamics and Water Quality Dynamics in Shallow Waters. *In Proceedings of the International Symposium on Ecology and Engineering*, Taman Negara, Malaysia, November, 1994.

CH3D-SED (& CH3D-WES): Curvilinear Hydrodynamics in Three Dimensions

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Download Information

Availability: Available only to Department of Defense Agencies
Cost: N/A

Model Overview/Abstract

CH3D-SED is the newly developed mobile bed version of CH3D-WES, which was developed for the Chesapeake Bay Program. The USACE is using it to investigate sedimentation on bendways, crossings, and distributaries on the lower Mississippi and Atchafalaya rivers. These applications address dredging, channel evolution, and channel training structure evaluations. CH3D-SED functions as a hydrodynamic (through the incorporation of CH3D-WES) and sediment transport model. Physical processes affecting 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. CH3D-SED can be applied to rivers, lakes, reservoirs, estuaries, or coastal waters.

Model Features

- Hydrodynamic
- Sediment transport
- Linkage to CE-QUAL-IC water quality model

Model Areas Supported

Watershed	None
Receiving Water	High
Ecological	None
Air	None
Groundwater	None

Model Capabilities

Conceptual Basis

The CH3D-SED hydrodynamic and sediment transport model is based on an extension of the stretched vertical coordinate version of the CH3D-SED by Spasojevic and Holly (1997) to include cohesive sediment transport. The model is capable of two- or three-dimensional operation and employs standard formulations for settling, deposition, and resuspension.

CH3D-WES makes hydrodynamic computations on a curvilinear or boundary-fitted platform 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 on the assumption of local equilibrium of turbulence is employed.

A boundary-fitted, nonorthogonal, finite-difference approximation in the horizontal plane and a sigma-stretched approximation in the vertical direction are used for the approximations of the governing equations.

Scientific Detail

The hydrodynamic model solves the depth-averaged Reynolds approximation of the momentum equation for velocity and the depth-averaged conservation of mass equation for water surface elevation. The three-dimensional velocity field is determined by computing the deviation from the depth-averaged velocity by solving the conservation of mass equation in conjunction with a k-e closure for vertical momentum diffusion.

Sedimentation computations are based on a two-dimensional solution of the conservation of mass equation for the channel bed, and three-dimensional advection-diffusion equation for suspended sediment transport. The sediment transport algorithms independently account for the movement of sediment as either bed load or suspended load, as well as the exchange of sediment between these two modes of transport. The model is also generalized for application to mixed-grain-size sediments, with appropriate bed material sorting and armoring routines. The formulation to a user-specified multiple-grain-size distribution uniquely allows the simulation of erosion, entrainment, transport, and deposition of contaminated sediments on the bed and in the water column. A contaminated sediment associated with a given grain size can be independently accounted for by applying a small dimensional perturbation from the reference grain size. This perturbation has negligible effects on sediment mobility characteristics. Because each grain size specification is independently tracked, however, tracking of zones of contaminated bed material is possible.

Model Framework

- Curvilinear Finite Difference Numerical Formulations for Hydrodynamic and Sediment Transport

Scale

Spatial Scale

- Three-dimensional

Temporal Scale

- Dynamic

Assumptions

- Based on accepted formulations of the three-dimensional, hydrostatic, hydrodynamic equations and conservative transport equation.

Model Strengths

- Strong capabilities for hydrodynamics and sediment transport.

Model Limitations

- Considerable technical expertise in hydrodynamics is required to use the model effectively.

Application History

CH3D-SED was applied to investigate maintenance dredging quantities for channel alignment studies on the lower Atchafalaya River (Hall 1996). The model successfully reproduced existing sediment deposition quantities and locations, and it was instrumental in the decision made by the local sponsor to maintain the existing channel alignment.

The 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 on 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.

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.

Model Evaluation

Johnson et al. (1993) validated the model by applying it to six datasets. The first three datasets 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.

Model Inputs

- 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 at one or more locations.
- All input data, including initial conditions, bathymetry, boundary, and computational control data are input from fixed files.

Users’ Guide

Not available

Technical Hardware/Software Requirements

Computer hardware:

- Unix workstation or super computer.

Operating system:

- Unix

Programming language:

- FORTRAN

Run time estimates:

- Compute intensive

- Run time is highly dependent on computer hardware, model domain spatial resolution, the period of prototype conditions simulated and other options such as whether the model is simulation only hydrodynamic or hydrodynamics and the fate and transport of dissolved and suspended material. Under this wide range of variability, simulations could require minutes to weeks.

Linkages Supported
CE-QUAL-ICM

Related Systems
Surface Water Modeling System (SMS)

Sensitivity/Uncertainty/Calibration
Not available

Model Interface Capabilities
- US Army Corps of Engineers Surface Water Modeling System (SMS)

References

Cerco, C.F. and T. Cole. 1993. Three-Dimensional Eutrophication Model of Chesapeake Bay. Journal of Environmental Engineering. 119(6):1006-1025.

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DELFT3D

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Download Information

Availability: Proprietary
Cost: Varies by user type (academic, governmental, private)
Delft3D may be purchased as an integrated package or in individual modules. The GUI will be part of any initial purchase. WL | Delft Hydraulics will take care of the set-up and calibration of the model applications for clients.

Model Overview/Abstract

Delft3D models two- and three-dimensional flow and transport for tidal and riverine problems. Delft3D is an integrated modeling environment for hydrodynamics, waves, sediment transport, morphology, water quality, and ecology. Relevant applications include

- Prediction of nearshore currents and waves
- Prediction of small scale morphology
- Estimation of bathymetry
- Prediction of large-scale morphology based on historical observations
- Prediction of short- and long-term effects of structures
- Prediction of the effects of dike or dam breaches

The model can be applied to rivers, lakes, reservoirs, estuaries, and coastal waters. Deft3D can be applied to evaluate

- Hydrodynamics—salt intrusion; river flow simulations; fresh water river discharges in bays; thermal stratification in lakes, seas and reservoirs; cooling water intakes and waste water outlets; transport of dissolved material and pollutants; tide and wind driven flows (i.e., storm surges); stratified and density driven flows; and wave driven flows
- Sediment transport—transport of cohesive and non-cohesive sediments, e.g., spreading of dredged materials to study sediment/erosion pattern.
- Contaminant transport— evaluation of over 140 substances including contaminants in 2 sediment layers.

Model Features

- Hydrodynamics
- Waves
- Sediment transport
- Morphology
- Water quality
- Particle tracking for water quality

- Ecology

Model Areas Supported

Watershed	None
Receiving Water	High
Ecological	None
Air	None
Groundwater	None

Model Capabilities

Conceptual Basis

Scientific Detail

Delft3D includes the following modules:

- Hydrodynamics module (Delft3D-FLOW)
- Wave module (Delft3D-WAVE)
- Water quality module (Delft3D-WAQ)
- Particle tracking module (Delft3D-PART)
- Ecological module (Delft3D-ECO)
- Sediment transport module (Delft3D-SED)
- Morphdynamic module (Delft3D-MOR)

Hydrodynamic

The FLOW module of Delft3D is a multi-dimensional (two- or three-dimensional) hydrodynamic (and transport) simulation program that calculates non-steady flow and transport phenomena resulting from tidal and meteorological forcing on a curvilinear, boundary-fitted grid. Features of the FLOW module include

- Coriolis force
- Advection-diffusion solver included to compute, for example, density gradients (due to nonuniform temperature and salinity concentration distributions)
- Inclusion of pressure gradients terms in the momentum equation (density driven flows)
- Turbulence model to account for the vertical turbulent viscosity and diffusivity based on the eddy viscosity concept.
- Shear stresses exerted by the turbulent flow on the bottom based on a quadratic Chézy or Manning's formula
- Wind stresses on the water surface modeled by a quadratic friction law
- Simulation of the thermal discharge, effluent discharge, and the intake of cooling water at any location and any depth in the computational field (advective-diffusion module)
- Facility to calculate drogue tracks
- Simulation of drying and flooding of intertidal flats (moving boundaries) for both two-dimensional and three-dimensional cases

Sediment Transport

The SED module can be applied in all geographic regions where Delft3D is used. The module is generally used to calculate the short-term transport of sediment and sand. In particular the SED is used when the effect of changes in bottom topography on flow conditions can be neglected. For long-term development of the bottom topography or coastal morphology, a separate morphological module with coupling capabilities with the FLOW and WAVE modules can be applied. The following discusses the standard features of the SED module.

Sedimentation

- Effects of "hindered settling" (i.e., decrease in sedimentation velocity at very high suspended solids concentration) can be included
- Each of the particulate fractions are treated independently (i.e., sand and silt)
- Bottom shear stresses take into account currents, waves, and effects of shipping and fisheries

Re-suspension

- The re-suspension flux is limited based on the available amount of sediment in a sediment layer for the variable layer option. The re-suspension is unlimited if the fixed layer option is used
- Re-suspension flux is zero if the water depth becomes too small
- The effect of short waves (on the sediment transport) can only be taken into account as wind effects

Burial

- Sediment can be transferred downward from one sediment layer to an underlying layer in a process known as "burial"

Upward sediment transport ("Digging")

- Sediment can be transferred upward to one sediment layer from an underlying layer in a process known as digging

Contaminant Transport

The WAQ module of DLFT3D is a general water quality program capable of describing a wide range of water quality processes. The water quality processes may be described by arbitrary linear or nonlinear functions of the selected state variables and model parameters. Typical types of applications are

- Exchange of substances with the atmosphere (oxygen, volatile organic substances, temperature)
- Adsorption and desorption of contaminant substances (heavy metals, organic micropollutants) and ortho-phosporous
- Deposition of particles and adsorbed substances to the bed
- Re-suspension of particles and adsorbed substances from the bed

Model Framework

- Three-dimensional curvilinear-orthogonal finite difference

Scale

Spatial Scale

- Three-dimensional

Temporal Scale

- Dynamic

Assumptions

- Based on accepted formulations of the three-dimensional hydrostatic hydrodynamic equations and conservative transport equation

Model Strengths

- Strong capabilities for hydrodynamics

Model Limitations

- Considerable technical expertise in hydrodynamics is required to use the model effectively

Application History

Delft3D has been used for storm surge and flood forecasting in India and typhoon surge modeling in Vietnam. Delft3D has also been used to model other estuarine and riverine systems, such as Victoria Harbor in Hong Kong.

The DELFT3D hydrographic model was used for large-scale hydrodynamics and connected mass transport in Lake Malawi/Nyasa/Niassa.

DELFT3D was also used to support the project, Sustainable Development of the Laguna de Bay Environment.

Model Evaluation

Although there are no specific evaluation studies available, as a policy, new versions are released only after an internal, 6 month test and application period to ensure stable and validated products.

Model Inputs

- 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 at one or more locations
- All input data, including initial conditions, bathymetry, boundary, and computational control data are input from fixed files

Users' Guide

- Must be purchased with model

Technical Hardware/Software Requirements

Computer hardware:

- PC and Unix Workstations

Operating system:

- UNIX workstations (HP, SGI and Sun) or Windows/Intel platform (Windows 95, 98 and NT4)

Programming language:

- FORTRAN

Runtime estimates:

- Computation intensive
- Run time is highly dependent on computer hardware, model domain, spatial resolution, the period of prototype conditions simulated, and other options, such as whether the model is simulation-only hydrodynamic or hydrodynamics and the fate and transport of dissolved and suspended material. Under this wide range of variability, simulations could require minutes to weeks

Linkages Supported

None

Related Systems
None

Sensitivity/Uncertainty/Calibration
Not available

Model Interface Capabilities
- Visualization: Delft-GPP
- Grid generator: Delft-RGFGRID
- Bathymetry generator: Delft-QUICKIN

References
Not available

DIAS/IDLAMS: Dynamic Information Architecture System/Integrated Dynamic Landscape Modeling and Analysis System

Contact Information

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http://www.dis.anl.gov/idlams/index.html

Download Information

Availability: Nonproprietary
Need to contact the author. A Java version of DIAS is available for customization.
Cost: DIAS is licensed but free for government agencies.

Model Overview/Abstract

Argonne's Integrated Dynamic Landscape Analysis and Modeling System (IDLAMS) integrates data, environmental models, land-use planning, and decision support technologies through a GIS-based framework (GIS-IDLAMS). The IDLAMS prototype is populated with models appropriate for use by military land managers and decision makers at Fort Riley, Kansas, and can be used to

- Simulate "what-if" scenarios for predicting future ecological conditions under a given land management plan
- Incorporate trade-off analyses when comparing different land management alternatives
- Identify and resolve land-use issues and determine cost-effective solutions to long-term land stewardship problems

Recently, IDLAMS has evolved to take advantage of a flexible, dynamic, and cost-effective object-oriented approach. This new framework, called OO-IDLAMS, is built on Argonne's DIAS, a generic, object-oriented architecture that supports distributed, dynamic representation of interlinked processes.

OO-IDLAMS provides environmental managers and decision makers with a strategic, adaptive approach to integrated natural resources planning and ecosystem management. The OO-IDLAMS framework

- Brings together disparate data and software for integrated natural resource planning and ecosystem management in a flexible and adaptive way
- Provides the ability to reflect the dynamics of living ecosystems, land uses, and land management activities
- Reduces the cost of simulation modeling by using and reusing existing data, models, and system components with minimal reworking
- Allows for a comprehensive regional, landscape, or ecosystem approach

Model Features

GIS-IDLAMS

- Vegetation dynamics simulation
- Wildlife habitat suitability modeling
- Erosion calculated using Revised Universal Soil Loss Equation (RUSLE)
- Trade-off analyses for land management alternatives

OO-IDLAMS

- Object-oriented architecture, military land management, integrated natural resource planning, adaptive ecosystem management, run-time model interoperability, code reuse, environmental decision support
- Vegetation dynamics simulation
- Henslow's Sparrow habitat model
- Human activities simulation for military training, burning, and planting

Model Areas Supported

Watershed	Medium
Receiving Water	None
Ecological	High, Medium
Air	None
Groundwater	None

Model Capabilities

Conceptual Basis

Uses GIS or object-oriented DIAS to integrate natural resource planning, ecosystem management, and simulation models and to support environmental decision making processes.

Scientific Detail

Four major models were developed and integrated for the GIS-IDLAMS prototype: (1) a vegetation dynamics model, (2) a set of wildlife habitat suitability models, (3) an erosion model, and (4) a scenario evaluation module.

Vegetation Dynamics Model

The Vegetation Dynamics Model is the core model for IDLAMS because the output from this model is the input for all other connected IDLAMS models. The Vegetation Dynamics Model is a spatially explicit model that incorporates vegetation changes due to (1) natural succession, (2) land use impacts, and (3) land management actions.

Wildlife Models

The Wildlife Models are five submodels that represent individual wildlife species and are based on U.S. Fish and Wildlife Service Habitat Suitability Indices (HSIs). Each submodel requires that the user input either a vegetation/landcover map representing the current condition or a simulated landcover map generated by the Vegetation Dynamics Model. In some submodels, additional input maps may be required.

Erosion Model

IDLAMS currently integrates RUSLE to generate an erosion status map for each current condition or simulated vegetation/landcover map input by the user. RUSLE also requires other spatial data representing various factors affecting erosion.

Scenario Evaluation Module
IDLAMS uses a value-based decision-analysis process to link the ecological models with the management needs and user requirements of the resource manager. This module is then used to perform trade-off analyses for land management alternatives, on the basis of the results from the spatially explicit modeling, and to rank the alternatives according to how well they meet the specified objectives.

In OO-IDLAMS, because the objective of the research was to demonstrate the advantages of this new object-oriented architecture approach rather than to totally rebuild the old IDLAMS, the OO-IDLAMS prototype integrates only a subset of the original IDLAMS. Models in the new OO-IDLAMS include the Vegetation Dynamics Model and the Henslow's Sparrow Habitat Model. In addition, to demonstrate improved modularity and flexibility of OO-IDLAMS and fully utilize the object-oriented capabilities of DIAS, the Military Training and Land Management components, previously coded within the original Vegetation Dynamics Model, were broken out into three Course of Action (COA) objects. A DIAS COA object is essentially a flowchart of individual steps constituting a specific plan or action and is used in DIAS to model procedural or sequential processes. OO-IDLAMS employs an object-oriented GIS module and provides real-time spatially oriented displays of an object's positions and/or parameters.

Model Framework
GIS-IDLAMS uses GIS software as the model integration framework. OO-IDLAMS is built on an object-oriented architecture called the DIAS. DIAS supports distributed, dynamic representation of interlinked environmental processes and behaviors at variable scales (spatial and temporal) of resolution and aggregation. For integrated environmental modeling, the main components of a DIAS simulation are (1) software objects (entity objects) that represent real-world entities such as atmosphere, fish, or groundwater; and (2) simulation models or other applications that express the dynamic behaviors of the real-world entities (e.g., surface exchange, reproductive cycles, and fate and transport). In DIAS simulations, external models or applications participate in a simulation through a formalized registration process that "wraps" each model or application for use in DIAS. This "wrapping" procedure requires a formal registration procedure that enables the DIAS entity objects to implement external models to address behaviors. An important feature of DIAS is that the "wrapped" models and applications run in their native languages rather than requiring translation to a common or standard system language.

Scale

Spatial Scale
- One-dimensional, grid and subwatershed overland

Temporal Scale
- Depends on models integrated in the system

Assumptions
The model assumes that vegetation dynamics caused by natural and human forces immediately affect the wildlife habitats. The model also assumes that the main erosion type in the study area is sheet and rill erosion that can be described by RUSLE.

Model Strengths
Argonne's flexible object-oriented approach to model integration overcomes several limitations of a GIS-based integration framework. GIS-based systems are static in nature and do not lend themselves well to dynamic intermodel processing. Furthermore, integration of new environmental models or data formats into a GIS-based framework can require time-consuming and expensive reworking of the system.

OO-IDLAMS can execute external applications in their native languages (e.g., FORTRAN and C) and allows them to dynamically interact with each other indirectly via real-world ecosystem objects that package attribute information together with behavior (how the object acts and reacts). Because external applications do not interact directly with one another, OO-IDLAMS provides a robust environment that easily accommodates adding and removing applications. The OO-IDLAMS prototype includes an object-oriented GIS (GeoViewer), but in addition, external GIS software applications can be integrated to provide further spatial analysis functions.

OO-IDLAMS provides a graphical user interface for selecting appropriate applications and for easy input of data and parameters. The OO-IDLAMS prototype integration framework runs under both UNIX (Solaris) and Windows NT platforms.

Model Limitations

Although DIAS provides an excellent framework for the integration of multiple models (even models at different spatial and temporal scales), it does not solve the more basic ecological and environmental research issues related to model integration. These issues include, but are not limited to (1) the ecological implications of multiple-scale modeling and simulation and (2) the impacts of data aggregation and disaggregations. However, DIAS can be used as an excellent workbench from which to explore and investigate these issues. In addition, further development of the DIAS architecture should include the application of uncertainty analysis functionality to models within the DIAS suite and a multidisciplinary/multiagency approach to object design and development.

Technically, DIAS has the following additional limitations:

- Programming languages (C++, SmallTalk, Java, etc.) must be used for a DIAS model integration
- Substantial skills are needed for full technical utilization of the system (customization).

Application History

Object-Oriented Integrated Dynamic Landscape Analysis and Modeling System (OO-IDLAMS) is one example of the application of DIAS, other examples include

Healthcare Management Simulator – This DIAS application was developed to simulate all major aspects of healthcare delivery – clinical/physiological, procedural, logistical, and financial – at a level of detail appropriate to the need.

Integrated Ocean Software Architecture – This application of DIAS is an object-based virtual maritime environment within which existing models are employed to simulate the transition of wind-generated waves in the deep water, to waves in the near shore environment, then to surf height and currents. The application allows for the use of several different model combinations according to the complexity of the shoreline and near-shore sea bottoms.

Model Evaluation

Reviewed by Cooperative Research Centre for Catchment Hydrology, Australia
http://science.csumb.edu/~fwatson/publications/B2Report%20001201.pdf

Model Inputs

- Landcover map
- Successional timestep map
- Area impacted by training
- Area impacted by burning
- Area impacted by planting
- Number of maneuver impact miles
- RUSLE parameter values (GIS- IDLAMS)

Users' Guide

Not available, need to contact the authors

Technical Hardware/Software Requirements

Computer hardware:

- PC or SUN workstation

Operating system:

- UNIX (Solaris) or Windows NT platforms

Programming language:

- SmallTalk, C, Java, and FORTRAN

Runtime estimates:

- Not available, depends on models integrated in the system

Linkages Supported

None

Related Systems

DIAS

Sensitivity/Uncertainty/Calibration

Not available

Model Interface Capabilities

- Windows interface with menus and tool buttons
- Map displaying capacity

References

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DRAINMOD: A Hydrological Model for Poorly Drained Soils

Contact Information

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Availability: Proprietary
http://www.bae.ncsu.edu/soil_water/drainmod
Cost (if applicable): $250

Model Overview/Abstract

DRAINMOD is a hydrological model developed at North Carolina State University (NCSU) by Dr. Wayne Skaggs at the Department of Biological and Agricultural Engineering. The model was initially developed in 1980 for analyzing field-scale watershed management scenarios for poorly drained soils, but in the last 2 decades it has been updated and used on both field- and watershed-scale watershed management sites. The model has been updated several times to extend its capabilities. The latest version, DRAINMOD Version 5.1, has the original DRAINMOD hydrology model with the addition of DRAINMOD-N (nitrogen submodel) and DRAINMOD-S (salinity submodel) into a Windows-based program. The DRAINMOD hydrology model simulates the hydrology of poorly drained, high water table soils on an hourly or daily basis for long periods of weather data. Hourly rainfall is used to compute the infiltration using a modified Green-Ampt approach and remaining excess rainfall is considered runoff. The water balance is made using a one-dimensional vertical column, which is further used as inputs to the one-dimensional nitrogen fate and transport module. In addition to organizing the hydrology, nitrogen, and salinity components of DRAINMOD, the graphical user interface allows easy preparation of input datasets, running simulations, and displaying model outputs.

Model Features

- Field and watershed-scale analysis
- Simulates the hydrology of poorly drained, high water table soils
- Simulates nitrogen and salinity transport
- Models the performance of water table management systems
- The graphical user interface

Model Areas Supported

Watershed	Medium to High
Receiving Water	None
Ecological	None
Air	Low
Groundwater	Low

Model Capabilities

Conceptual Basis

DRAINMOD is based on one-dimensional water balance in the soil profile and uses long duration weather data to simulate the performance of drainage systems. The model was developed specifically for shallow water table, poorly drained soils. The model avoids the complex numerical methods by using approximate methods to quantify the hydrologic components, including subsurface drainage, subirrigation, infiltration, evapotranspiration (ET), and surface runoff. For example, subsurface drainage is computed using the Houghoudt equation, which assumes an elliptical water table shape. The change in water table depth is based on the assumption that the soil water profile above the water table is drained to equilibrium with the water table.

Hourly rainfall is used to compute infiltration using a modified Green-Ampt method. Excess rainfall fills surface storage and any remaining rainfall is considered runoff. Evapotranspiration is computed from potential evapotranspiration as limited by soil water availability. Actual evapotranspiration is the amount that can be supplied from the water table plus the amount available from the unsaturated zone.

DRAINMOD version 5.1 is also linked to a one-dimensional nitrogen cycling model (Breve et al., 1997a and b). The model uses the water balances and fluxes from hydrology as inputs to a one-dimensional advective-dispersive-reactive equation for nitrogen fate and transport. The model uses nitrate as the main pool for the simplification of the nitrogen cycle. The nitrogen balance considers fertilizer dissolution, mineralization of organic nitrogen, denitrification, and plant uptake using first order rate equations.

Scientific Detail

The major process of the model is a water balance for the soil profile. The water balance for a time increment of Δt is expressed as,

$$\Delta V = D + ET + DS - F$$

Where ΔV is the change in the volume (cm), D is lateral drainage (cm) from the section, ET is evapotranspiration (cm), DS is deep seepage (cm), and F is infiltration (cm) entering the section during time interval Δt. All of the right-hand side terms are computed in terms of the water table elevation, soil water content, soil properties, site and drainage system parameters, and atmospheric conditions.

The amount of runoff and storage on the surface is computed from a water balance at the soil surface for each time increment as,

$$P = F + \Delta S + RO$$

Where P is the precipitation (cm), F is infiltration (cm), ΔS is the change in volume of water stored on the surface (cm), and RO is runoff (cm) during time interval Δt.

Model Framework

- Version 5.1 includes a user interface written in Visual Basic 6.0 and combines the different versions of DRAINMOD (Hydrology, Nitrogen, and Salinity). Following are the model components:
    - Precipitation (hourly data)
    - Infiltration (the Green-Ampt equation)
    - Surface drainage (the average depth of depression storage)
    - Subsurface drainage (the rate of subsurface water movement into drain ditches)
    - Subirrigation (lateral flow)
    - Evapotranspiration
    - Soil water distribution
    - Rooting depth

Scale

Spatial Scale

- Watershed and field level

Temporal Scale

- Hourly and daily

Assumptions

- Assumes an elliptical water table shape
- Assumes subsurface drains are parallel
- Drains the soil water profile above the water table to equilibrium with the water table

Model Strengths

- Simulates surface and subsurface water flows in response to water management systems in soils with high water tables
- Compares and evaluates the effectiveness of the design over a range of weather scenarios

Model Limitations

- Supports only parallel subsurface drains
- Should not be applied to situations that are widely different than conditions for which it was developed, without further testing

Application History

DRAINMOD reference report (Skaggs, 1980) presented these four sets of model application examples:

1. Combination surface-subsurface drainage systems
2. Subirrigation and controlled drainage
3. Irrigation of waste water on drained lands
4. Effect of root depth on the number and frequency of dry days

In addition to hydrology of DRAINMOD, the nitrogen and salinity portions of the model have been tested by Breve et al. (1997b), Kandil et al. (1995), and Merz and Skaggs (1998). Other field testing is currently ongoing for these versions of the model.

Model Evaluation

The reliability of DRAINMOD has been tested for a wide range of soil, crop, and weather conditions. Results of tests in North Carolina (Skaggs, 1982), Ohio (Skaggs et al., 1981), Louisiana (Fouss et al., 1987), and Virginia (McMahan et al., 1988) indicate that the model can be used to reliably predict water table elevations and drain flow rates.

Model Inputs

- Soil property inputs
- Hydraulic conductivity
- Soil water characteristics
- Drainage volume – water table depth relationship
- Upward flux
- Green-Ampt equation parameters
- Crop input data

- Drainage system parameter
- Surface drainage
- Effective drain radius

Users' Guide
Available online: http://www.bae.ncsu.edu/soil_water/drainmod/index.htm

Technical Hardware/Software Requirements

Computer hardware:
- PC

Operating system:
- Microsoft Windows 95/98/2000/NT/XP.

Programming language:
- Visual Basic and FORTRAN

Runtime estimates:
- Minutes to less than 1 hour

Linkages Supported
The original DRAINMOD hydrology model has been modified to include submodels on the fate and transport of nitrogen in the soil and salinity. Following are the models developed at the Biological and Agricultural Engineering Department at NCSU.

- DRAINLOB: DRAINMOD-based field-scale forest hydrologic model
- DRAINMOD-S: DRAINMOD-based field-scale model for predicting salinity on arid/semi-arid lands
- DRAINMOD-N: DRAINMOD-based field-scale model for predicting Nitrogen from agricultural lands
- WATGIS: A GIS-based lumped parameter watershed-scale hydrology and water quality model. DRAINMOD and DRAINMOD-N models coupled with a delivery ratio routine to route drainage water and nutrients to the watershed outlet
- DRAINMOD-GIS: A GIS-based lumped parameter watershed-scale hydrology and water quality model. DRAINMOD/DRAINMOD-N models coupled with a simplified water and nutrient fate and transport submodels
- DRAINMOD-W: A watershed-scale model based on DRAINMOD and DRAINMOD-N field-scale submodels with a finite difference canal routing model and a finite element solute transport submodel

Related Systems
DRAINMOD supports several numerical models as listed in *Linkage Supported* section.

Sensitivity/Uncertainty/Calibration
The results for the sensitivity analyses conducted for different soils and water management systems of North Carolina are presented in DRAINMOD reference report (Skaggs, 1980). This report indicated that hydraulic conductivity (K) is a very sensitive parameter in this model. Similarly, SEW-30 (Sum of Excess Water for water table depths greater than 30 cm) was more sensitive to errors in K and PET than to any of the other input parameters.

The number of dry days (days in which actual ET is less than PET) were less dependent on K than either working days (a day is counted as a working day if the drained or water free pore space is greater than a threshold value) or

SEW-30 for all cases evaluated. Dry days were also reported to be quite sensitive to errors in the water content at the lower limit (wilting point).

Model Interface Capabilities

- A graphical user interface for assisting the user in developing input datasets
- Options to enable the user to analyze the model results graphically
- No GIS interface available for the latest version of the model, but watershed and drainage basin scale versions are currently under development, which utilize ARC Info and ARCView to assist in model setup and analysis of results

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DWSM – Dynamic Watershed Simulation Model

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Download Information

Availability: Non-Proprietary
Cost: Free

Model Overview/Abstract

Developed by the Illinois State Water Survey, the DWSM (Borah et al., 2002; Borah and Bera, 2003) uses physically based governing equations to simulate surface and subsurface storm water runoff, propagation of flood waves, soil erosion, and entrainment and transport of sediment and agricultural chemicals in agricultural watersheds during severe rainfall events. The model has three major components: (1) DWSM-Hydrology (Hydro) simulating watershed hydrology, (2) DWSM-Sediment (Sed) simulating soil erosion and sediment transport, and (3) DWSM-Agricultural chemical (Agchem) simulating agricultural chemical (nutrients and pesticides) transport. Each component has routing schemes developed using approximate analytical solutions of the physically based equations preserving the dynamic behaviors of water, sediment, and the accompanying chemical movements within a watershed.

Model Features

- Agricultural watershed, nonpoint sources
- Distributed, single event model
- Spatially varying rainfall inputs
- Individual hyetograph for each overland
- Rainfall excess, surface and subsurface overland flow
- Surface erosion and sediment transport
- Agrochemical mixing and transport
- Channel erosion and deposition and routing of flow, sediment, and agrochemical and flow routing through reservoirs
- Detention basins, alternative ground covers, and tile drains

Model Areas Supported

Watershed	Medium
Receiving Water	Low
Ecological	None
Air	None
Groundwater	None

Model Capabilities

Conceptual Basis

The watershed is divided into subwatersheds, specifically, into one-dimensional overland elements, channel segments, and reservoir units. An overland element is represented as a rectangular area with the same area as in the field, width equal to the adjacent (receiving) channel length, length equal to area divided by the width, and representative slope, soil, cover, and roughness based on physical observations of these characteristics in the element. A channel segment is represented with a straight channel having the same length as in the field and having a representative cross-sectional shape, slope, and roughness based on physical observations and measurements. A reservoir unit is represented with a stage-storage-discharge relation (table) developed based on topographic data and discharge calculations using outlet measurements and established relations.

Scientific Detail

The DWSM-Hydro: Hydrologic Simulations

The overland elements are the primary sources of runoff in which rainfall turns into surface runoff after losing first to interception at canopies and ground covers, then to infiltration through the ground surface and depression storage above it. The rainfall available for surface runoff is the rainfall excess. A portion of the infiltrated water flows laterally towards downstream as subsurface flow sometimes in accelerated mode in the presence of tile drains. Two overland elements contribute surface and subsurface flows into one channel segment laterally from each side of the channel. The excess rainfall is routed over the overland elements beginning at their upstream edges (ridges), at which flows are zeros, to their downstream edges, coinciding with the receiving channel banks. Similarly, subsurface water from infiltration is routed through the soil matrix underneath the overland elements beginning at their upstream edges (ridges), at which flows are assumed zeros, to their downstream edges, coinciding with the receiving channel banks. Currently, the tile drain flows from overland elements having tile drains are lumped with the subsurface flow through the soil matrix using an effective lateral saturated hydraulic conductivity concept. The channel segments carry the receiving waters from overland elements and upstream channel segments towards the downstream side of the watershed and ultimately to the watershed outlet. During its journey, the runoff water may be intercepted by reservoirs, which release it again to downstream channels at reduced rates after temporary storage.

The DWSM-Sed: Soil Erosion and Sediment Transport Simulations

Similar to the hydrologic component, soil erosion and sediment transport are simulated along with water through the overland elements and stream segments. The eroded soil or sediment is divided into number of particle size groups. Agricultural watersheds having extensive aggregates, the sediment is divided into five size groups: sand, silt, clay, small aggregate, and large aggregate. Each size group is dealt individually during the simulation of each of the processes, and total response, in the form of sediment concentration and discharge is obtained by integrating the responses from all the size groups.

The model computes soil erosion due to raindrop impact. The eroded (detached) soil is added to an existing detached (loose) soil depth from where entrainment to runoff takes place with sufficient velocity and shear (capacity). Erosion due to flow shear stress and deposition depends on sediment transport capacity of the flow and the sediment load (amount of sediment already carried by the flow). Sediment transport capacity is computed using established formulas. If the capacity is higher than the sediment load, erosion takes place and the flow picks up more materials from the bed. If the loose soil volume at the bed is sufficient, sediment entrainment takes place from the detached soil depth. Otherwise, the flow erodes additional soil from the parent bed material. If the sediment transport capacity is lower than the sediment load, the flow is in a deposition mode and the potential rate of deposition is equal to the difference of the two. The actual rate of deposition is computed by taking into account particle fall velocities. Deposited sediment is added to the loose soil volume. If the sediment transport capacity and the sediment load are equal, an equilibrium condition is assumed where there is neither erosion nor deposition. All the above processes are interrelated and must satisfy locally the conservation of sediment mass principle expressed by the sediment continuity equation. The continuity equation is solved to keep track of erosion, deposition, and sediment discharges along the flow segments.

The DWSM-Agchem: Agricultural Chemical Transport Simulations
The agricultural chemical transport component of DWSM involves simulations of mixing of nutrients and pesticides and transport of these chemicals with surface runoff in dissolved form, and with sediment in adsorbed form in each of the flow segments. Similar to the hydrologic and soil erosion-sediment transport components, these processes are simulated along with water and sediment through the overland elements and stream or channel segments.

The model assumes equilibrium between dissolved and adsorbed phases of the chemicals, governed by a linear adsorption isotherm. The soil profile is divided into small homogeneous soil increments. The model routes infiltrating rainwater and solutes through the soil increments and computes resulting water contents and chemical concentrations. When runoff begins, exchange of chemicals from a mixing soil layer of the soil profile, containing the chemicals in dissolved form, with surface runoff are simulated using the concept of non-uniform mixing of runoff with the mixing soil layer. Exchange of chemicals in adsorbed forms with the eroded and deposited sediments is computed based on preference factors of the individual size groups. The entrained chemicals are routed along slope lengths in dissolved form with surface runoff and in adsorbed form with the transported sediment using solutions of the continuity (mass conservation) equations.

Model Framework
The watershed is divided into subwatersheds, specifically, into one-dimensional overland elements, channel segments, and reservoir units. Overland elements are spatially distributed. Modules are linked to calculate hydrology, erosion and sediment transport, and agricultural chemical transport.

Scale

Spatial Scale
- Watersheds of sizes ranging from few acres to several hundred square kilometers are divided into hydrologic units defined by topographical or natural boundaries and further divided into overland, channel, and reservoir segments.

Temporal Scale
- Several days of storm events divided into constant time intervals ranging from few minutes to few hours

Assumptions
- Uses kinematic wave equation assuming that all the acceleration and pressure gradient terms in the momentum equation can be ignored
- Assumes equilibrium between dissolved and adsorbed phases of the chemicals, governed by a linear adsorption isotherm.
- Assumes all sediment are trapped in reservoir and no downstream discharge

Model Strengths
- Is a distributed model (overland elements)
- Detailed and physically-based model yet relatively efficient, provides a balance between the simple (lumped) and complicated (computationally intensive) models
- Suitable for flat Midwestern watersheds with extensive tile-drained lands
- Is capable of evaluating the effects of some BMPs, such as detention basins, alternative ground covers, and tile drains

Model Limitations
- Only used to simulate single event
- Only for agricultural watersheds
- One-dimensional channel simulation (no ecological processes)

Application History

The DWSM-Hydro was applied and tested on the Upper Sangamon River basin draining a 2,400-km2 agricultural watershed to Lake Decatur in Illinois (Borah et al., 1999, 2000). Lake Decatur is a public water supply reservoir for the City of Decatur having a history of high nitrate nitrogen (nitrate-N) concentration, periodically exceeding 10 milligrams per liter (mg/L), and violating state and national drinking water standards. The lake also has a high sedimentation rate that is gradually reducing its water supply capacity. The goal is to use the model to evaluate the benefits of applying alternative land use and BMPs in reducing soil erosion, and sediment and agricultural chemical discharges into the lake and help solve the water quality and sedimentation problems.

The DWSM-Hydro & Sed were applied and tested (calibrated and validated) on the Big Ditch watershed using data monitored during 1998 spring and early summer storm events (Borah et al., 1999; Borah et al., 2001). Big Ditch is a tributary to the Upper Sangamon River draining 100-km2 agricultural lands. In this application, scaling effects on model parameters and water and sediment discharges resulting from watershed divisions with alternative subdivision sizes were investigated. The DWSM-Agchem was also applied and tested on the Big Ditch watershed (Xia et al., 2001) and preliminary results indicated that the model needed improvements in simulating agricultural chemicals, especially nitrate-N.

The DWSM-Hydro was applied to the Court Creek watershed in Illinois (Borah and Bera, 2000a,b). This 251-km^2 watershed is part of the Illinois multi-agency Pilot Watershed and Conservation Reserve Enhancement Programs. The DWSM-Hydro was calibrated and validated using storm data monitored and reported earlier by the ISWS (Roseboom et al., 1982, 1986). The model was then run for design storms and high, moderate, and low runoff potential areas of the watershed were identified and ranked. The committee is currently using these results to plan their initial restoration programs within the watershed. It has been realized that the design storms with Soil Conservation Service's (SCS) rainfall distributions generated unrealistically high flows for BMP design purposes. Therefore, rankings of overland elements and channel segments have been revised using a historical storm occurred in the springtime. Rankings are based on unit-width peak flows and unit-width sediment yields for the overland elements and on peak flows and sediment yields for the channel segments.

Model Evaluation

The model developers has conducted many studies to evaluate the model (see Model Application History)

Model Inputs

- Physical data representing the watershed, initial moisture, soil and agricultural chemicals and meteorological data representing the rainfall events

Users' Guide

Contact the authors for documentation

Technical Hardware/Software Requirements

Computer hardware:

- PC

Operating system:

- PC-DOS or Windows system with FORTRAN complier

Programming language:
- FORTRAN

Runtime estimates:
- > Minutes

Linkages Supported
None

Related Systems
None

Sensitivity/Uncertainty/Calibration
Sensitive to runoff curve number, saturated hydraulic conductivity, Manning's roughness coefficient, flow detachment coefficient, chemical partition coefficient, chemical mixing parameter, sediment particle size distribution, and rainfall intensities and their temporal distributions

Calibration parameters include runoff curve number or saturated hydrological conductivity, Manning’s roughness coefficient, flow detachment coefficient, chemical partition coefficient, and chemical mixing parameter

Model Interface Capabilities
Not available.

References

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ECOMSED: Estuary and Coastal Ocean Model with Sediment Transport

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Download Information

Availability: Nonproprietary Version Available
Register to download files: http://www.hydroqual.com/ehst_ecomsed.html
Cost: N/A

Model Overview/Abstract

ECOMSED is a three-dimensional hydrodynamic and sediment transport model. The hydrodynamic module solves the conservation of mass and momentum equations with a 2.5-level turbulent closure scheme on a curvilinear orthogonal grid in horizontal plane and σ-coordinate in the vertical direction. Water circulation, salinity, and temperature are obtained from the hydrodynamic module. The sediment transport module computes the sediment settling and resuspension processes for both cohesive and noncohesive sediments under the impact of waves and currents. The hydrodynamic component is same as the ECOM3D/POM model.

Model Features

- Three-dimensional hydrodynamics
- Cohesive and noncohesive sediment transport
- Sediment-bound and dissolved tracer transport
- Wind-waves-generated shear stress

Model Areas Supported

Watershed	None
Receiving Water	High
Ecological	None
Air	None
Groundwater	None

Model Capabilities

Conceptual Basis

The waterbody is conceptualized as a series of grid points on a curvilinear orthogonal coordinate system.

Scientific Detail

The governing equations of the hydrodynamic component in ECOMSED are the continuity equation, Reynold's equations, heat and salinity transport equations on curvilinear-orthogonal grid on the horizontal plane and σ-coordinate in the vertical direction. It uses a 2.5-level turbulence closure scheme that solves the transport of turbulent kinetic energy and turbulent macroscale. The governing equation of sediment transport is an advection-dispersion equation that uses the hydrodynamic results. The hydrodynamic governing equations are solved using a mode-splitting technique. The external mode that contains fast moving gravity wave is solved with small timesteps to ensure stability, whereas the internal mode uses large timesteps to save the computation time. Finite difference of the differential equation is applied on a staggered C grid in space, and the three-time-level leap-frog scheme is applied for the timestepping. Three schemes, including central difference, upwind difference, and the multidimensional positive definite advection scheme are provided in the model to solve the advection term in the transport equations. The sediment transport component uses the same grid, structure, and computational framework as the hydrodynamic component to simulate the settling, deposition, and resuspension of both cohesive and noncohesive sediments. The Grant-Madson wave-current model is incorporated in ECOMSED to account for wind-wave-generated shear stress.

Model Framework

- Three-dimensional model
- River, lake, reservoir, estuary, ocean

Scale

Spatial Scale

- One-, two-, and three-dimensional

Temporal Scale

- User-defined timestep

Assumptions

- Hydrostatic assumption
- Boussinesq approximation
- Reynold’s stress assumption

Model Strengths

- ECOMSED is capable of modeling one-, two-, and three-dimensional hydrodynamics in various water bodies with complex bathymetry.
- The boundary-fit curvilinear coordinate can represent the waterbody boundaries accurately with fewer grids than Cartesian coordinate.
- The vertical σ-coordinate represents the bathymetry without assuming rectangular bottom boundary.

Model Limitations

- The vertical σ-coordinate may cause significant pressure gradient error at areas with sharp bottom elevation change.
- Timestep and grid size need to be chosen carefully to balance the computation time and model resolution and ensure model stability.

Application History

ECOMSED has been applied to Chesapeake Bay, New York Bight, Delaware Bay, Delaware River, Gulf Stream Region, Massachusetts Bay, Georges Bank, the Oregon Continential Shelf, New York Harbor, and Onondaga Lake.

Model Evaluation

The hydrodynamic component of ECOMSED is based on Princeton Ocean Model, which has been tested and applied by various users. The theory and model testing history can be found in journal and conference papers.

Model Inputs

- Initial conditions
- Bathymetry and waterbody boundaries
- Physical coefficients
- Water surface elevations or flow rate at open boundary
- Time sequences of hydrometeorological conditions

Users' Guide

Available online (after registering): http://www.hydroqual.com/ehst_ecomsed.html

Technical Hardware/Software Requirements

Computer hardware:

- PC, workstation, and mainframe

Operating system:

- PC-DOS, Unix, Windows

Programming language:

- FORTRAN

Runtime estimates:

- Minutes to hours

Linkages Supported

Linked with HydroQual's RCA model.

Related Systems

POM, EFDC, CH3D, GLLVHT

Sensitivity/Uncertainty/Calibration

Not available

Model Interface Capabilities

Input file in text format.

References

HydroQual, Inc. 2002. *A Primer for ECOMSED version 1.3.* (Computer program manual). HydroQal, Inc., Mahwah, NJ.

EFDC: Environmental Fluid Dynamics Code

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Download Information

Availability: Nonproprietary
Cost: N/A

Model Overview/Abstract

The EFDC model is single-source-code three-dimensional modeling system having hydrodynamic, water quality-eutrophication, sediment transport, and toxic contaminant transport components transparently linked together. The model can execute in a fully coupled mode, simultaneously simulating hydrodynamics and sediment and contaminant transport, or in a transport-only mode, using saved hydrodynamic transport information. The EFDC model uses a finite difference spatial representation and is capable of reduced dimension execution in one-dimensional network and two-dimensional (horizontal or vertical plane) modes. Water column transport includes three-dimensional advection and vertical and horizontal turbulent diffusion. Shear dispersion may be included for two-dimensional horizontal applications. A water quality-eutrophication model, functionally equivalent to CE-QUAL-IC, is also incorporated into EFDC (Hamrick and Wu, 1997; Park, et al., 1995). The model can be applied to rivers, lakes, reservoirs, estuaries, wetlands, and coastal regions.

Model Features

- General purpose three-dimensional hydrodynamic and transport model
- 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

Model Areas Supported

Watershed	Low
Receiving Water	High
Ecological	High
Air	None
Groundwater	Low

Model Capabilities

Conceptual Basis

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 in 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 noncohesive 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 21-state-variable water quality model is based on the CE-QUAL-ICM reaction kinetic. A 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.

Scientific Detail

The EFDC model framework includes methods for computing hydrodynamics, mixing zone dilution, eutrophication, sediment transport, and toxic contaminant transport.

Mixing Zone

A Lagrangian buoyant jet near-field dilution and mixing-zone model is embedded within the far field solution allowing representation of the local distribution of contaminated sediment near point sources.

Hydrodynamic

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.

Sediment Transport

The sediment transport component simulates a user specified number of size classes of cohesive and noncohesive sediment. Sediment settling is represented by concentration and ambient-flow-turbulence-dependent formulations to represent hindered settling of noncohesive sediment and approximately represent aggregation and disaggregation of cohesive sediment. Water column-bed sediment and sorbed contaminant exchange is represented by deposition and erosion fluxes. For noncohesive sediment, the net flux is represented as dependent on the bed stress, the near bottom and bed surface sediment concentration, and the critical Shield’s parameter. For cohesive sediment, deposition and erosion fluxes are dependent on the bed stress, critical deposition and erosion stresses, and the shear strength of the bed. The sediment bed is represented by a time varying number of layers. Sediment in each layer is characterized by mass per unit area, void ratio, and shear strength. The void ratio, of the layers is specified or determined by a bed consolidation model with shear strength being determined as a function of void ratio.

Contaminant Transport

Vertical transport of sediment and sorbed contaminants between bed layers is implicitly represented by sediment particle displacement in response to layer thickness variations dynamically determined by the consolidation model. Transport of dissolved contaminants between the water column and bed and between bed layers includes pore water advection, dynamically determined by the bed consolidation model and pore water diffusion. An arbitrary number of toxic contaminants can be simultaneously transported. The simple contaminant processes option includes constant coefficient equilibrium partitioning, volatilization, and lumped first-order decay with unique coefficients for the water column and sediment bed. The complex contaminant processes option allows for solids-concentration-dependent partitioning and specification of ambient-environment-dependent volatilization, hydrolysis, photolysis, oxidation, and biodegradation reactions specific to the contaminants being simulated.

Ecosystem
The model is based on the CE-QUAL-ICM and incorporates a predictive sediment process or diagenesis model (DiToro and Fitzpatrick, 1993). The eutrophication model is directly coupled to the hydrodynamic model and is capable of two and three-dimensional spatial resolution. Water column state variables include up to three algae classes represented in carbon equivalent units, ammonia, nitrite-nitrate, organic nitrogen, orthophosphate or inorganic phosphorous, organic phosphorus, organic carbon, chemical oxygen demand, dissolved oxygen, available and unavailable silica, and total active metal, which is used as a sorption site. Organic carbon, nitrogen, and phosphorous are subdivided into three classes: dissolved, labile particulate, and refractory particulate. Model variables in the sediment bed include particulate organic carbon, nitrogen, and phosphorous, each in three reaction rate classes; particulate and available silica; sulfide or methane; ammonia; nitrate; inorganic phosphorus; bed-water column fluxes of ammonia, nitrate, inorganic phosphorous and silica; sediment oxygen demand; and release of chemical oxygen demand. The model's formulation allows direct determination of organic carbon levels in the water column and sediment bed.

Model Framework

- Three-dimensional curvilinear-orthogonal finite difference

Scale

Spatial Scale

- Three-dimensional

Temporal Scale

- Dynamic

Assumptions

- Based on accepted formulations of the three-dimensional hydrostatic hydrodynamic equations and conservative transport equation

Model Strengths

- Completely integrated three-dimensional hydrodynamics, water quality/eutrophication, and sediment-contaminant transport

Model Limitations

- Requires considerable technical expertise in hydrodynamics to use the model effectively
- Requires expertise in eutrophication processes to use the water quality component

Application History

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 in Taiwan. The model has also been used to simulate large-scale wetlands flow and transport in the Everglades. The EFDC model has been applied extensively for circulation, discharge dilution, and water quality/eutrophication studies (Hamrick, 1992b; Tetra Tech, 1994, 1995, 1998). The model has also been applied for estuarine-cohesive sediment transport simulation (Yang, 1996), and coastal noncohesive sediment transport (Zarillo and Surak, 1995), and heavy metals and organic contaminant transport (Schock and Hamrick, 1998).

Model Evaluation

- Not available

Model Inputs

- Open boundary water surface elevation
- Wind and atmospheric thermodynamic conditions
- Open boundary salinity and temperature
- Volumetric inflows
- 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

Users' Guide

- Contact the developer at john.hamrick@tetratech-ffx.com.

Technical Hardware/Software Requirements

Computer hardware:

- PC, MacIntosh, Unix workstation, Super computer

Operating system:

- Windows, Mac OS, Unix, Linux

Programming language:

- FORTRAN

Runtime estimates:

- Can be computation intensive but is highly optimized and has faster documented runtime than similar software systems
- Runtime is highly dependent on computer hardware, model domain spatial resolution, the period of prototype conditions simulated, and other options, such as whether the model is simulation-only hydrodynamic or hydrodynamics and the fate and transport of dissolved and suspended material; under this wide range of variability, simulations could require minutes to weeks

Linkages Supported

- Linkages to WASP, CE-QUAL-ICM, RCA, and a generic output for food chain and risk assessment model

Related Systems

GridEFDC, EFDCexplorer, EFDCview, EPA TMDL Toolbox

Sensitivity/Uncertainty/Calibration

Not available

Model Interface Capabilities

- Public domain GUI including EFDCexplorer and EFDCview

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EPIC: Erosion Productivity Impact Calculator

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Download Information

Availability: Nonproprietary
Cost: N/A

Model Overview/Abstract

EPIC assesses the effects of soil erosion on productivity and predicts the effects of management decisions on soil, water, nutrient, and pesticide movements and their combined impact on soil loss, water quality, and crop yields for areas with homogeneous soils and management.

Model Features

- Simulates erosion effects on water quality
- Crop management tool that examines sediment, nutrient, and pesticide transport processes

Model Areas Supported

Watershed	Medium
Receiving Water	None
Ecological	None
Air	None
Groundwater	None

Model Capabilities

Conceptual Basis

EPIC is a field-scale model that was developed to assess the effects of soil erosion on agricultural productivity and water quality. It is used to examine farming practices and implementation activities.

EPIC has also been used widely for the study of global climate change. The USDA and Texas Agricultural Experimental Station (Texas A&M) jointly developed this version of the model called Environmental Policy Integrated Climate (EPIC).

Scientific Detail

EPIC is a continuous simulation model that has been used to examine long-term effects of various components of soil erosion on crop production (Williams et al., 1983). EPIC is a public domain model that has been used to examine the effects of soil erosion on crop production in over 60 different countries in Asia, South America, and Europe. The model is used to examine soil erosion, economic factors, hydrologic patterns, weather effects, nutrients, plant growth dynamics, and crop management. The major components in EPIC are weather simulation, hydrology, erosion-sedimentation, nutrient cycling, pesticide fate, plant growth, soil temperature, tillage, economics, and plant environment control.

The model requires input from GIS layers. These include soil series and weather data, although the model can generate the necessary weather parameters. The model also requires management information that can be input from a text file. Currently, there are many management files that exist for EPIC, and an effort is underway to catalog these files and provide them to users. The model provides output on crop yields, economics of fertilizer use, and crop values.

In the calculations for surface runoff, runoff volume is estimated by using a modification of the Soil Conservation Service (SCS) curve number technique. There are two options for estimating the peak runoff rate—the modified Rational formula and the SCS TR-55 method. The EPIC percolation component uses a storage routing technique to simulate flow through soil layers. When soil water content exceeds field capacity, the water flows through the soil layer. The reduction in soil water is simulated by a derived routing equation. Lateral subsurface flow is calculated simultaneously with percolation. The evapotranspiration is calculated in four ways, using the following equations:

- Hargreaves and Samani
- Penman
- Priestley-Taylor
- Penman-Monteith

The water table height is simulated without direct linkage to other soil water processes in the root zone to allow for offsite water effects. EPIC drives the water table up and down between input values of maximum and minimum depths from the surface.

The EPIC precipitation model developed by Nicks is a first-order Markov chain model. Temperature and radiation are simulated in EPIC by using a model developed by Richardson. The EPIC wind erosion model, WECS (Wind Erosion Continuous Simulation), is used to calculate wind characteristics, including erosion due to the wind. The relative humidity model simulates daily average relative humidity from the monthly average by using a triangular distribution.

To simulate rainfall/runoff erosion, EPIC used six equations—the USLE, the Onstad-Foster modification of the USLE, the MUSLE, two recently developed variations of MUSLE, and a MUSLE structure that accepts input coefficients. The six equations are identical except for their energy components. Contaminants, such as nitrogen and phosphorus, are used in the EPIC model. EPIC simulates the following processes involving contamination:

- Nitrate losses
- Contaminant transport due to soil water evaporation
- Organic nitrogen transport due to sediment

- Denitrification
- Mineralization
- Immobilization
- Nitrification
- Volatilization
- Soluble phosphorus loss in surface runoff
- Mineral phosphorus cycling

For climate change studies, the EPIC model appears to be the most complete model available for evapotranspiration cover design. The most noteworthy example is the MINK (Missouri-Iowa-Nebraska-Kansas) study (Rosenberg and Crosson, 1991). This study examined the effects of elevated CO_2 (EPIC had to be modified to incorporate sensitivity to CO_2) and temperature on crop yields, soil erosion, and economics in this four state region. The MINK study also provides general insights about the use of models for global change research.

Model Framework

- Field-scale, erosion based

Scale

Spatial Scale

- One-dimensional, agricultural field/farm scale

Temporal Scale

- Daily timestep, long-term simulations (1–4,000 years)

Assumptions

The model assumes that the dynamics of each physical, chemical, and biological component can be described by the principle of conservation of mass.

Model Strengths

- Has been used extensively to examine the effects of soil erosion and agricultural processes.
- Describes the phosphorus cycle and differentiates between all forms of phosphorus.
- Can be used to simulate the fate of agricultural pesticides.

Model Limitations

- Cannot represent watershed subsurface flow.
- Does not simulate sediment routing in detail.
- No mention of how the model deals with tile drains.

Application History

See available literature.

Model Evaluation

EPIC has been used extensively in the United State and abroad to predict soil erosion and effects, along with the potential costs associated with various management activities. See References for more information.

A soil loss model comparison was conducted by Bhuyan et al. 2002, which included evaluations of EPIC, ANSWERS, and WEPP. Although the results from all three models were within the range of observed values in the case study, WEPP soil loss predictions were the most accurate. However, WEPP cannot be used to examine water quality effects.

Model Inputs

- Daily timestep—long term simulations (1–4,000 years)
- Soil, weather, tillage, and crop parameter data supplied with model
- Soil profile can be divided into ten layers
- Homogeneous areas up to large fields
- Weather generation is optional

Users' Guide

Available online: http://www.wiz.uni-kassel.de/model_db/mdb/epic.html

Technical Hardware/Software Requirements

Computer hardware:

- PC

Operating system:

- PC-DOS, UNIX

Programming language:

- FORTRAN version 5125

Runtime estimates:

- Minutes (1 sec./simulation year)

Linkages Supported

Unknown

Related Systems

APEX – small watershed scale agricultural model

Sensitivity/Uncertainty/Calibration

See references. No specific tools available.

Model Interface Capabilities

- Spatial-EPIC is a recently developed GIS-based application for EPIC

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GISPLM: GIS-Based Phosphorus Loading Model

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Download Information

Availability: Nonproprietary
http://wwwalker.net/gisplm/index.htm
Cost: N/A

Model Overview/Abstract

GISPLM uses a spreadsheet interface to develop cost-effective strategies to reduce phosphorus loads from watersheds. The watershed is defined as a number of *subwatersheds or segments* linked in a branched network. Flows and phosphorus loads are evaluated using watershed features extracted from GIS, climatologic data, and other local data. Phosphorus sources include runoff, farm animal populations, and point discharges. All calculations are controlled from a Quattro Pro (version 7.0) workbook. The workbook also provides access to all input and output screens. The workbook executes simulations by calling two FORTRAN programs, HYDRO and LOADS, which predict surface runoff, stream flows, and phosphorus loads for each subwatershed. Flows and loads from each source category (runoff, animal units, point sources) are totaled by model segment (subwatershed). Loads and flows totaled by segment are routed downstream to the mouth of the watershed. Empirical models are used to estimate the retention of phosphorus in lakes or impoundments optionally located at the downstream ends of segments. The user defines load control options for each source category. Nonpoint source controls (BMPs) are defined for up to 12 land use categories. Point source controls for up to 3 treatment levels are defined based on effluent phosphorus concentration and flow-dependent costs. The user specifies a target load reduction as a percentage of the load predicted with no controls. GISPLM searches for the spatial allocation of controls, which achieves the target reduction with minimum cost. Model results can be displayed spatially using ArcView 3.0 software.

Model Features

- Spreadsheet interface (Quattro Pro)
- Calculates surface runoff for each subwatershed
- Calculates phosphorus load through surface runoff for each subwatershed
- Flows and loads can be summarized from upstream subwatersheds to downstream outlet
- Simple empirical calculation for phosphorus retention in lakes and impoundments
- Capacity to define nonpoint source BMPs for up to 12 land use categories
- Capacity to define 3 treatment levels for point sources
- Calculates minimum treatment cost for a targeted reduction of phosphorus for the entire watershed (optimization)

Model Areas Supported

Watershed	Medium
Receiving Water	Low
Ecological	None
Air	None
Groundwater	Very Low

Model Capabilities

Conceptual Basis

In GISPLM, a watershed is divided into many small subwatersheds to capture the spatial heterogeneity. Runoff and phosphorus load are calculated for each subwatershed. Flow and loads can be summarized from the upstream subwatersheds to the downstream outlet. Best management practices are specified for each source in each subwatershed.

Scientific Detail

GISPLM is tool for developing cost-effective strategies to reduce phosphorus loads from watersheds. The watershed is defined as a number of subwatersheds or segments linked in a branched network. Flows and phosphorus loads are evaluated using watershed features extracted from GIS, climatologic data, and other local data. Phosphorus sources include runoff, farm animal populations, and point discharges. All calculations are controlled from the Menu page of the GISPLM.WB3 workbook. The Menu also provides access to all input and output screens.

HYDRO, a compiled FORTRAN program, predicts surface runoff from pervious areas for a user-defined date interval. Calculations of daily runoff resulting from rainfall and snowmelt are driven by daily precipitation and air temperature data. The algorithm and parameter estimates are taken from Generalized Watershed Loading Functions or GWLF model (Haith et al., 1992). HYDRO generates a table relating unit area surface runoff from pervious areas to SCS Runoff Curve Number. This table is later accessed by LOADS and the GISPLM workbook.

LOADS, another compiled FORTRAN program, calculates flows and phosphorus loads. The model reads watershed data extracted from GIS databases and creates an index based on segment (subwatershed) number, model land use code, and existing BMP code. LOADS calculates the total flow and load for each value of the index, accounting for differences in soil group, soil origin, slope, and stream proximity. Runoff concentrations are specified as a function of land use categories based on literature review. LOADS produces an output file containing the total area, flow, load, impervious area, curve number, and surface runoff for each index. This file is subsequently accessed by GISPLM workbook for subsequent processing.

The remaining calculations are performed within the GISPLM workbook. Flows and loads from each source category (runoff, animal units and point sources) are totaled by model segment. Loads are adjusted to account for existing phosphorus controls. 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.

The user defines load control options for each source category. Nonpoint-source controls (BMPs) are defined for up to 12 land use categories. Estimates of load reduction efficiency, capital cost, and annual operating cost are specified for each BMP. Point-source controls for up to 3 treatment levels are defined based on effluent phosphorus concentration and flow-dependent costs.

The user specifies a target load reduction as a percentage of the load predicted with no controls. GISPLM searches for the spatial allocation of controls, which achieves the target reduction with minimum cost. Total annualized costs are minimized. Estimates of capital and operating costs are also generated. Allocations can be constrained to provide equal distribution of effort across source categories. Individual control measures can be specifically included or excluded.

Several graphical and tabular output formats are provided. These can be easily customized and manipulated within the workbook to suit project needs. Model results can be displayed spatially using ArcView 3.0 software.

GISPLM is configured for application to the 137 km^2 LaPlatte River watershed in Vermont. Guidance for developing applications to other watersheds is provided.

Model Framework

- Watersheds are subdivided into subwatersheds with mixed land uses
- Land use, surface hydrology, and optional lakes or impoundments at the outlet of each subwatershed

Scale

Spatial Scale

- One-dimensional, subwatersheds

Temporal Scale

- Daily timestep

Assumptions

- Is a distributed model by land use but ignores the spatial location within a land use in a subwatershed
- Summarizes downstream flow and loads simply by adding the outputs from the upstream subwatersheds
- Describes BMP controls by their effectiveness and cost

Model Strengths

- Is a simple model
- Requires low level of expertise
- Can be quickly applied to evaluate phosphorus reductions due to lakes, impoundments, and BMP implementations
- Performs optimization on the total BMP cost for the entire watershed, given a load reduction target

Model Limitations

- Simulates only phosphorus
- Does not simulate sediment and sediment phosphorus
- Results in weak simulation of nutrient fluxes because a constant concentration is used
- Includes highly simplified flow routing
- Highly simplifies groundwater inflow
- Bases BMP simulations on a single reduction effectiveness value

Application History

GISPLM was applied to the 137-km^2 LaPlatte River watershed in Vermont. Guidance for developing applications to other watersheds is provided in the users' manual.

Model Evaluation

Unknown

Model Inputs

- Daily weather data (mean temperature and precipitation)

- Farm animal population data
- GIS data, including watershed boundaries, land use, soils (hydrologic group and slope class), streams, and BMP locations and types
- Runoff phosphorus concentrations by land uses
- Point source flow and concentrations
- BMP cost and efficiency

Users' Guide

Available online (as part of installation package): http://wwwalker.net/gisplm

Technical Hardware/Software Requirements

Computer hardware:
- PC

Operating system:
- WINDOWS (95 or NT)

Programming language:
- Quattro Pro Macros and FORTRAN

Runtime estimates:
- Minutes

Linkages Supported

None

Related Systems

GWLF

Sensitivity/Uncertainty/Calibration

The users' manual provides simple guidance on model calibration.

Model Interface Capabilities

- Controls all calculations from a menu page of a spreadsheet workbook (GISPLM.WB3, Quattro Pro). The workbook also provides access to all input and output screens.
- Can display model results spatially, using ArcView 3.0 software.

References

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Walker, W.W. 1987. Phosphorus Removal by Urban Runoff Detention Basin. In *Lake and Reservoir Management Volume 3*, North American Lake Management Society, pp. 314-238.

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Vermont DEC & New York DEC. 1994. *A Phosphorus Budget, Model, and Load Reduction Strategy for Lake Champlain, Lake Champlain Diagnostic-Feasibility Study*. Final Report.

GLEAMS: Groundwater Loading Effects of Agricultural Management Systems

Contact Information

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Download Information

Availability: Nonproprietary
http://sacs.cpes.peachnet.edu/sewrl/Gleams/gleams_y2k_update.htm
Cost: N/A

Model Overview/Abstract

Groundwater Loading Effects of Agricultural Management Systems (GLEAMS) is an extension of Chemicals, Runoff, and Erosion from Agricultural Management Systems (CREAMS) model. GLEAMS, a continuous simulation, field-scale model assumes that a field has homogeneous land use, soils, and precipitation. The four major components of the model are hydrology, erosion/sediment yield, pesticide transport, and nutrients. It also estimates surface runoff and sediment losses from the field. GLEAMS can be used to evaluate the impact of farm-level management practices on potential pesticide and nutrient leaching within, through, and below the root zone. GLEAMS can provide estimates of the impact management systems, such as planting dates, cropping systems, irrigation scheduling, and tillage operations, have on the potential for chemical movement. GLEAMS can also be useful in long-term simulations for pesticide screening of soil/management. The model tracks movement of pesticides with percolated water, runoff, and sediment. Upward movement of pesticides and plant uptake are simulated with evaporation and transpiration. Degradation into metabolites is also simulated for compounds that have potentially toxic bi-products. Erosion in overland flow areas is estimated using a modified Universal Soil Loss Equation. Erosion in chemicals and deposition in temporary impoundments such as tile outlet terraces are used to determine sediment yield at the edge of the field.

Model Features

- Edge of field simulation model

Model Areas Supported

Watershed	Low
Receiving Water	None
Ecological	Medium
Air	None
Groundwater	Medium

Model Capabilities

Conceptual Basis
GLEAMS is a physically based field-scale model.

Scientific Detail
The hydrology component of GLEAMS uses a mass balance approach and represents the principal hydrologic processes of infiltration, runoff, water application by irrigation, evapotranspiration, and soil water movement within and through the root zone. Runoff calculation is based on the modified Soil Conservation Service (SCS) curve number method. Percolation is calculated using storage-routing technique. Plant evapotranspiration is calculated using either Priestley-Taylor or Penman-Monteith method. Erosion is calculated as detachment and transport processes using USLE elements. The nutrient component of GLEAMS simulates the nitrogen and phosphorous cycles. The pesticide component of the model calculates the daily decay based on the pesticide half-life. Based on the partition coefficient, a portion of the pesticide is lost into runoff solution and the other part into the soil phase.

Model Framework
- Edge-of-field and bottom-of-root zone simulations of water, nutrients and pesticides
- Mainly used to simulate management systems in agricultural land

Scale

Spatial Scale
- One-dimensional field-scale

Temporal Scale
- Daily

Assumptions
- Uses a lumped parameter approach
- Assumes a spatially homogenous agricultural field

Model Strengths
- Is a simple model with few input requirements

Model Limitations
- Is limited to an agricultural field of very small size
- Is not suited for bigger watersheds
- Is not suited for urban land uses

Application History
GLEAMS is developed as an improvement over CREAMS model. Both models have sufficient application history. http://sacs.cpes.peachnet.edu/sewrl/Gleams/glmspub.htm.

Model Evaluation
Many peer-reviewed publications are available for GLEAMS. Few studies are conducted to evaluate the accuracy of GLEAMS and to compare with similar models like EPIC and WEPP.
http://sacs.cpes.peachnet.edu/sewrl/Gleams/glmspub.htm.

Model Inputs

The inputs are provided separately for hydrology, erosion, pesticides, and nutrient components of the model. The input requirements of the hydrology model include

- Daily precipitation
- Mean monthly minimum and maximum temperatures or mean daily temperature
- Mean monthly solar radiation
- Mean monthly wind movement and dew point temperature, if Penman-Monteith method is chosen for evapotranspiration calculation
- Soil composition

The input requirements of the erosion component include

- Overland flow profile (length and slope)
- Soil properties (erodibility and horizon depths)
- Overland flow channel rating-curve properties

The pesticide component's input requirements include

- Crop rotation information
- Water solubility and partitioning coefficient of pesticide
- Half-life, initial concentration, and fraction available for washoff for foliage and soil
- Crop uptake coefficient

The nutrient component's input requirements include

- Crop rotation information
- Initial soil concentration and concentrations of nutrients in rainfall and irrigation water
- Fertilizer application rate
- Crop uptake coefficient

Users' Guide

Available online:
http://www.cpes.peachnet.edu/sewrl/Gleams/gleams_y2k_update.htm#GLEAMS%20V3.0%20Revisions

Technical Hardware/Software Requirements

Computer hardware:

- IBM-PC

Operating system:

- PC-DOS

Programming language:

- FORTRAN

Runtime estimates:

- Minutes

Linkages Supported

None

Related Systems

CREAMS is the predecessor of GLEAMS.

Sensitivity/Uncertainty/Calibration

Not available

Model Interface Capabilities

- ArcView GIS interface (see Tucker et al. 1996 and http://www3.bae.ncsu.edu/Regional-Bulletins/Modeling-Bulletin/asae_2227-draft-extra.html)

References

Knisel, W.G., and F.M. Davis. 2000. *GLEAMS: Groundwater Loading Effects of Agricultural Management Systems. Version 3.0*. Publication No. SEWRL-WGK/FMD-050199. U.S. Department of Agriculture, Agricultural Research Service, Southeast Watershed Research Laboratory, Tifton, GA. 191 pp.

Leonard, R. A., W. G. Knisel, and D. A. Still. 1987. GLEAMS: Groundwater loading effects of agricultural management systems. Trans. ASAE. 30(5):1403-1418.

Tucker, M. G., D. L. Thomas, and D. D. Bosch. 1996. *GLEAMS and REMM GIS-based model system: results and sensitivity of hydrologic components.* ASAE Technical Paper No. 96-2022. ASAE, St. Joseph, MI.

More publications: http://sacs.cpes.peachnet.edu/sewrl/Gleams/glmspub.htm

GLLVHT: Generalized, Longitudinal-Lateral-Vertical Hydrodynamics and Transport

Contact Information

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http://www.jeeai.com/Softwares-GEMSS.htm

Download Information

Availability: Proprietary
Cost: Unknown

Model Overview/Abstract

GLLVHT is a three-dimensional numerical model that provides solutions for rivers, lakes, estuaries, and coastal waters. GLLVHT has five modules—hydrodynamics, water quality, sediment transport, particle tracking, and oil-spill simulation. The hydrodynamics module provides the transport information for all the other modules. The water quality module is a modified version of EUTRO5. The sediment transport module simulates the processes of settling, flocculation, deposition, erosion/resuspension, bed load, armoring, bed structure, slump failure, and bed deformation.

Model Features

- Hydrodynamic, temperature, and salinity
- Tracer simulation
- Suspended solids and sediment transport
- Nutrients, dissolved oxygen, and phytoplankton
- Coliform/bacteria
- Toxic organics and metals

Model Areas Supported

Watershed	None
Receiving Water	High
Ecological	Medium
Air	None
Groundwater	None

Model Capabilities

Conceptual Basis

The waterbody is conceptualized as a series of grid points on a quasi-curvilinear coordinate system.

Scientific Detail

The governing equations of the hydrodynamic module are developed from the horizontal momentum balance, continuity, constituent transport, and the equation of state. The hydrostatic assumption is applied to simply the vertical momentum balance. A zero equation turbulence scheme is utilized to close the governing equations. The velocities and water surface elevations are obtained by solving the governing equations with a semi-implicit numerical scheme. Transport equations are solved with an explicit scheme. A high-order difference of space is applied for solving the transport. The transport of water quality variables and sediments are solved using the same numerical scheme for temperature and salinity. Other processes, such as the kinetic reactions of water quality and sediment settling and erosion, are considered as the source and sink terms in the governing equations.

Model Framework

- Three-dimensional
- River, lake, reservoir, estuary, and ocean

Scale

Spatial Scale

- One-, two-, and three-dimensional

Temporal Scale

- Variable timestep

Assumptions

- Hydrostatic assumption, Boussinesq approximation

Model Strengths

- Coupled hydrodynamic and transport model
- High-order accuracy transport scheme similar to ULTIMATE scheme

Model Limitations

- Zero equation turbulence closure scheme (Prandtl mixing length)
- Vertical Z grid (not able to follow the bathymetry)
- No sediment diagenesis
- Single phytoplankton group

Application History

Examples of application include modeling various processes such as intake entrainment; jet discharge; biochemical oxygen demand; plume; and cooling water discharge into rivers, lakes, reservoirs, estuaries, and coastal waters, such as Humboldt River, Nevada; Grand Lake, New Brunswick; Nechako Reservoir, British Columbia; Delaware Estuary, Delaware; and San Diego Bay, California.

Model Evaluation

The theory and model development are published in several peer review journal papers.

Model Inputs

- Initial conditions
- Bathymetry and waterbody boundaries

- Physical coefficients
- Water surface elevations or flow rate at open boundary (boundary conditions)
- Time sequences of hydrometeorological conditions
- Load of water quality variables

Users' Guide
GLLVHT Model, Technical Information and User's Guide

Technical Hardware/Software Requirements

Computer hardware:
- PC

Operating system:
Microsoft Windows 95/98/2000, XP, or Microsoft Windows NT 4.0

Programming language:
- FORTRAN 90

Runtime estimates:
- Minutes to hours

Linkages Supported
EUTRO, CE-QUAL-ICM, JEEAI's GITF

Related Systems
EFDC, ECOMSED, WASP/EUTRO, CE-QUAL-ICM

Sensitivity/Uncertainty/Calibration
Not available. No specific supporting tools included.

Model Interface Capabilities
- GEMSS provides pre-processing and post-processing functions

References
J.E.Edinger Associate, Inc. *GLLVHT Model, Technical Information and User's Guide.* J.E.Edinger Associate, Inc., Wayne, PA .

GSSHA: Gridded Surface Subsurface Hydrologic Analysis

Contact Information

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Download Information

Availability:
GSSHA is included in WMS 2D Hydrology Package and can be purchased from EMS-I. Demonstration version is free for download from the EMS-I website: http://www.ems-i.com/home.html
Cost: $2400 for WMS 7 2D Hydrology Package (includes Map/Data/Drain/Grid/GSSHA)
$1000 for GSSHA Model + 2D Grid Package (requires Map, Data, Drainage)

Model Overview/Abstract

GSSHA is a reformulation and enhancement of CASC2D developed by the Hydrologic Systems Branch of the U.S. Army Corps of Engineers' Coastal and Hydraulics Laboratory (Downer et al., 2002). GSSHA retains the functionality of CASC2D, but adds non-Hortonian runoff as well as many other features. Other improvements in GSSHA that go beyond CASC2D include Richard's equation infiltration, lakes, wetlands, detention basins, improved computational routines, full-dynamic wave channel routing with tidal influence, hydraulic structures with rule curves, rating curves, scheduled releases, and improved erosion and sediment transport routines. CASC2D development was initiated in 1989 at the Center for Excellence in Geosciences at Colorado State University funded by the U.S. Army Research Office (ARO). GSSHA is also one of the surface-water hydrologic models supported by the Watershed Modeling System (WMS).

GSSHA is a fully unsteady, physically based, distributed-parameter, square-grid, two-dimensional, hydrologic model for simulating the response of a watershed subject to rainfall (Ogden, 2001) on an event or a continuous basis. Major processes simulated include continuous soil-moisture accounting, precipitation distribution, snow accumulation and melting; rainfall interception, infiltration, evapotranspiration, surface water retention, overland flow routing, channel flow routing, unsaturated zone two-dimensional lateral flow, saturated zone groundwater flow; overland sediment erosion, transport, and deposition; and sediment channel routing. GSSHA allows the user to select a grid size (typically 30–200 m) that appropriately describes the spatial variability in all watershed characteristics. The physically based distributed model is superior in simulation of runoff process at small scales within the watershed. As a spatially distributed model, GSSHA offers the capability of determining the value of any hydrologic variable at any grid point in the watershed at the expense of requiring significantly more input than traditional approaches. GSSHA can accept spatially varied hydrologic parameter input or rainfall input; however, because of the extensive amount of data, data uncertainty may result in a non-unique calibration.

Model Features

- Grid-based hydrologic model
- Precipitation distribution and snow accumulation and melting
- Rainfall interception, infiltration, evapotranspiration, surface water retention, overland flow routing, channel flow routing, unsaturated zone two-dimensional lateral flow, saturated zone groundwater flow
- Overland sediment erosion, transport, and deposition
- Sediment channel routing
- Lakes, wetlands, and detention basins simulation
- Hydraulic structures with rule curves, rating curves, and scheduled releases

Model Areas Supported

Watershed	High
Receiving Water	Medium
Ecological	None
Air	None
Groundwater	Medium

Model Capabilities

Conceptual Basis

The watershed is divided into a uniform finite difference grid. Processes that occur before, during, and after a rainfall event are calculated for each grid, routed through the flow direction, and integrated to produce the watershed output.

Scientific Detail

GSSHA is physically based and solves the equations of conservation of mass and energy to determine the timing and path of runoff in the watershed. GSSHA applies Green and Ampt, with or without a redistribution method, and optional Richard's equation for infiltration simulation; an explicit finite-difference, two-dimensional, diffusive-wave method for overland flow routing; and options of explicit one-dimensional, diffusive-wave, or implicit dynamic-wave channel routing. Snowmelt is simulated based on energy balance. GSSHA applies bucket model or Richard's equation for computing soil moisture in the vadose zone; Deardoff or Penman-Monteith with seasonal canopy resistance method for evapotranspiration; and Darcy's Law for stream/groundwater interaction and exfiltration. The empirical Kilinc and Richardson soil erosion model, as modified by Julien (1995), is applied in GSSHA to determine the sediment transport from one overland flow grid cell to the next. GSSHA employs Yang (1973) method to routing sand-size sediment in stream channels. Silt and clay size sediment is assumed to be transported with flow; therefore, deposition or erosion of silt and clay within the channels is neglected (Ogden, 1998). A physically based nutrient module has been incorporated into the GSSHA and can simulate N and P transformation based on the SWAT nitrogen and phosphorus cycle kinetics.

Model Framework

- Grid-based

Scale

Spatial Scale

- Two-dimensional grid overland
- One-dimensional channel network

Temporal Scale

- Variable timestep (seconds to minutes)

Assumptions

- Sediment discharge by means of overland flow is related to flow rate, soil erodibility, and surface condition
- Deposition or erosion of silt and clay within the channels is negligible

Model Strengths

- Fully unsteady physically based distributed watershed model at a user-specified resolution
- Offers fully dynamic hydraulic channel routing
- Uses diffusive wave method to route overland flow
- Performs continuous simulation using variable timestep

Model Limitations

- Splash overland erosion is not considered
- Requires extensive input data preparation and calibration

Application History

It has been mainly used by the U.S. Army Corps of Engineers (USACE). CASC2D was recently applied to study the extreme flood on the Rapidan River, Virginia, on June 27, 1995 (Smith et al., 1996), for the purpose of examining geomorphological changes. CASC2D was also used by the USACE to evaluate the extreme urban flood event in Trenton, New Jersey (Stock, C.A., B.S. Thesis, Princeton University, May 1997) for the purpose of recommending stormwater management improvements. CASC2D is currently being applied to evaluate the impact of radar-rainfall estimation errors in a study funded by ARO and in an NSF-sponsored study of the devastating flood that severely impacted Fort Collins, Colorado, on June 28, 1997.

Model Evaluation

Studies have been conducted on GSSHA’s predecessor, CASC2D. Recent experiences with CASC2D have shown that in regions of infiltration-excess (Hortonian) runoff production, CASC2D is quite accurate at predicting runoff, even at internal locations within the watershed (Johnson et al., 1993, Ogden et al., 1998). The continuous simulation capability of CASC2D has been found to be particularly good for reducing the uncertainty in estimating initial soil-moisture conditions and for improving calibration uniqueness (Ogden and Senarath 1997, Ogden et al., 1998). CASC2D has also proven to be valuable for studying extreme runoff events. The overland erosion/sediment transport capabilities of CASC2D were evaluated in detail by Johnson (1997). In upland areas, the method was shown to calculate sediment yield well within the acceptable range of -50% to +200%. Compared with actual field observations of annual sediment yield, CASC2D predictions were generally within 20% of observed values.

Model Inputs

- Rainfall (intensity, duration, and start time)
- Grid setup (grid size, number of rows and columns, and outlet grid row and column)
- For each grid (infiltration parameters, retention-interception parameters, soil properties, and canopy parameters)
- For each channel (cross-section information, slope, Manning’s n, and initial and boundary conditions)

Users' Guide

Available online (as part of the WMS document package): http://www.ems-i.com/home.html

Technical Hardware/Software Requirements

Computer hardware:

- PC

Operating system:

- PC-DOS and Windows

Programming language:

- C

Runtime estimates:

- Minutes to hours

Linkages Supported

- WMS 2D Hydrology Package

Related Systems

WMS, CASC2D

Sensitivity/Uncertainty/Calibration

GHHSA provides an automated calibration procedure using the shuffled complex evolution (SCE) method.

Model Interface Capabilities

- The WMS system provides full input data preparation and output display capabilities.
- The GRASS GIS, developed by the U.S. Army Construction Engineering Research Laboratories, can be used in the preparation of CASC2D datasets.

References

Downer, C. W., and F. L. Ogden. 2002. *GSSHA-User's Manual, Gridded Surface Subsurface Hydrologic Analysis Version 1.43 for WMS 6.1*. ERDC Technical Report, Engineer Research and Development Center, Vicksburg, Mississippi.

Downer, C.W., and F.L. Ogden. 2004. GSSHA: A model for simulating diverse streamflow generating processes. J. Hydrol. Engrg. 9(3):161-174.

Downer, C.W., and F.L. Ogden. 2004. Appropriate Vertical Discretization of Richards' Equation for Two-Dimensional Watershed-Scale Modelling. *Hydrological Processes*. 18:1-22.

Downer, C.W., and F.L. Ogden. 2004. Prediction of runoff and soil moistures at the watershed scale: Effects of model complexity and parameter assignment. *Water Resour. Res.* 39(3).

Julien, P.Y., B. Saghafian, and F.L. Ogden. 1995. Raster-based Hydrological Modeling of Spatially-varied Surface Runoff. Water Resources Bulletin. 31(3):523-536.

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Smith, J.A., M.L. Baeck, and M. Steiner. 1996. Catastrophic rainfall from and upslope thunderstorm in the central Appalachians: The Rapidan storm of June 27, 1995. Water Resources Research. 32(10):3099-3113.

Stock, C.A. 1997. B.S. Thesis, Princeton University, Princeton, New Jersey.

Yang, C.T. 1973. Incipient motion and sediment transport. Journal Hydraulics. 99(HY10):1679-1704.

GWLF: Generalized Watershed Loading Functions

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Download Information

Availability: Nonproprietary
The original version of the model has been used for 15 years and can be obtained from Dr. Haith at Cornell University.
A Windows interface is available at http://www.vims.edu/bio/vimsida/basinsim.html (Dai et al., 2000).
Penn State University developed an ArcView interface for GWLF (http://www.avgwlf.psu.edu/) and compiled data for the entire State of Pennsylvania (Evans et al., 2002).
Cost: N/A

Model Overview/Abstract

GWLF is used for the simulation of mixed land use watersheds to evaluate the effect of land use practices on downstream loads of sediment and nutrients (N, P). Typically used to evaluate long-term loadings, GWLF was developed at Cornell University as “a compromise between the empiricism of export coefficients and the complexity of chemical simulation models” (Haith and Shoemaker, 1987). As a loading function model, it simulates runoff and sediment delivery using the curve number (CN) and Universal Soil Loss Equation (USLE), combined with average nutrient concentration, based on land use. Because of the lack of detail in predictions and stream routing, the outputs are only given monthly, although they are calculated on a daily basis.

More recently, an in-stream routing and sediment transport component has been added and linked to BasinSim GWLF model with a generic ArcView interface that is able to utilize the national land use and soil GIS data. The new component employs the algorithms in the Annualized Agricultural Nonpoint Source Model (AnnAGNPS) to simulate sediment transport. The ArcView interface automatically prepares the input files for GWLF and generates stream network that links multiple subwatersheds in a study area. Sediment transport is simulated using three particle size classes (clay, silt, and sand). The Muskingum-Cunge method is used for flow routing. The GWLF output is interpolated for small timesteps (daily or subdaily) to meet the requirement of the in-stream modeling component. The new enhanced GWLF modeling system (the generic ArcView interface, BasinSim GWLF, and the in-stream routing/transport module) is currently being applied to West Virginia TMDL projects (Tetra Tech, Inc., Fairfax, Virginia).

Model Features

- Calculation of water, sediment, and total and dissolved nitrogen and phosphorus from a watershed with mixed land uses
- Low input data requirements

Model Areas Supported

Watershed	Medium
Receiving Water	None (original version), Low (Tetra Tech version)

Ecological	None
Air	None
Groundwater	Low

Model Capabilities

Conceptual Basis

GWLF was developed as "a compromise between the empiricism of export coefficients and the complexity of chemical simulation models" (Haith and Shoemaker, 1987). As a loading function model, it simulates runoff and sediment delivery using very simple, yet widely acceptable, algorithms, combined with average nutrient concentration, based on land use.

Scientific Detail

Runoff is calculated by means of the SCS curve number equation. USLE is applied to simulate erosion. Rural nutrients are estimated based on empirical concentrations of each land use, which are based on both dissolved concentration in runoff and solid concentration in sediment. Urban nutrient loads are computed by exponential accumulation and washoff 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.

Model Framework

- Watershed with mixed land uses
- Land use, surface hydrology, unsaturated soil zone, shallow saturated zone, and deep saturated zone

Scale

Spatial Scale

- One-dimensional, subwatershed overland

Temporal Scale

- Daily input
- Monthly output

Assumptions

- It is a distributed model by land use but ignores the spatial location within a land use in a subwatershed
- A unit (watershed or subwatershed) is divided into surface, unsaturated zone, and saturated zone
- Pollutant parameters values are based on data of a particular study area

Model Strengths

- It is a simple model
- It requires low level of expertise
- It can be quickly applied to evaluate potential loadings with some recognition of seasonal variability

Model Limitations

- Simplifications in stream transport and water quality simulation
- Simulation of peak nutrient fluxes is weak because a constant concentration is used
- Highly simplified flow routing
- Groundwater inflow represented using a user-defined recession coefficient

- Stormwater storage and treatment are not considered

Application History

GWLF has been used in studies and TMDL development nationally. It is suitable for application to generalized watershed loading, source assessment, and seasonal and interannual variability. It has been extensively used in northeast and mid-Atlantic regions. It has been adopted by Pennsylvania as state system for TMDL development and agricultural land management.

Model Evaluation

GWLF validations have been published in a number of peer-reviewed studies, including Haith and Shoemaker (1987), Howarth et al. (1991), Swaney et al. (1996), Lee et al. (2000), and Schneiderman et al. (2002), who made several modifications to the model. The algorithms on which the model is based are widely used and accepted. The model is in the public domain and the source code is available through Cornell University.

Model Inputs

- Climate: daily precipitation and temperature data and runoff source areas
- Transport parameters: runoff curve numbers, soil loss factor, evapotranspiration cover coefficient, 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
- Septic System: per capita nutrient load, system effluent, nutrient losses due to plant uptake, and people served by septic system
- Point source discharge and concentration

Users' Guide

Complete documentation is readily available (contact Dr. Haith for a hardcopy). The manual (Haith et al., 1992) is available as part of the BasinSim manual (Dai et al., 2000) at http://www.vims.edu/bio/vimsida/basinsim.html.

Technical Hardware/Software Requirements

Computer hardware:

- PC

Operating system:

- PC-DOS, Windows

Programming language:

- BASIC, Visual BASIC

Runtime estimates:

- Seconds to minutes

Linkages Supported

Tetra Tech has developed an ArcGIS interface and a stream network transport model for BasinSim (GWLF) for Windows

Related Systems

BasinSim for Windows (http://www.vims.edu/bio/models/basinsim.html), AVGWLF (http://www.avgwlf.psu.edu/)

Sensitivity/Uncertainty/Calibration

The BasinSim interface provides a plotting tool for users to compare the simulated monthly watershed flow, sediment, and nutrients loadings with observed data.

Model Interface Capabilities

- DOS version: Option menu and graphic and text output
- Windows version: Standard Windows features
- ArcGIS interface: Penn State AVGWLF; Tetra Tech ArcView for BasinSim

References

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.

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HEC-6: Scour and Deposition in Rivers and Reservoirs

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http://www.hec.usace.army.mil/software/legacysoftware/hec6/hec6.htm

Download Information

Availability: Nonproprietary
Cost: N/A

HEC-6 was developed for the U.S. Army Corps of Engineers, but the model program files, executables, and documentation are available for free download by the public at the website above. However, the Hydrologic Engineering Center (HEC) of the U.S. Army Corps of Engineers will not provide user support to non-Corps users. In addition, public distribution of the model source code is generally discouraged by HEC.

Proprietary versions of HEC-6 are also available through venders that provide model distribution and user support for a fee. A list of venders is included at the HEC website. Some proprietary versions of HEC-6 include enhanced simulation capabilities that expand on limitations of HEC-6 and provide more user friendliness. For example, the proprietary HEC-6T (MBH Software, Inc., 2002) provides additional plotting and hydraulic simulation capabilities not available in the HEC-6 version downloadable from HEC.

Model Overview/Abstract

HEC-6 is a one-dimensional open channel flow model capable of simulating changes of river profile due to scour and/or sediment deposition. Based upon flow records, a water surface profile is calculated that provides an energy slope, velocity, and depth at each cross-section. These predictions are used to estimate potential sediment transport rates at each section, which are considered with volume of flow and sediment yield from upstream sources to determine the scour and deposition. Changes in bed elevation, which impacts channel geometry and subsequent sediment transport potential, are also computed for each section. HEC-6 can be used to simulate both channel and reservoir sediment deposition and can include analysis of impacts of dredging.

Model Features

- Water surface and energy profile simulation
- Sediment scour and deposition modeling
- Sediment transport modeling
- River geometry simulation

Model Areas Supported

Watershed	None
Receiving Water	High
Ecological	None
Air	None

Groundwater None

Model Capabilities

Conceptual basis
Capability to analyze networks of streams, reservoirs, automatic channel dredging, various levee and encroachment options, and several options for computation of sediment transport rates.

Scientific detail
HEC-6 (HEC, 1991a) simulates sediment bed and suspended load transport as a function of Einstein's Bed-Load Function (1950) that assumes an alluvial stream with consistent sediment material between the streambed and that moving in the stream. Based on characteristics of the stream hydraulics and the sediment material (e.g., grain size distribution), the rate of sediment transport is calculated.

A one-dimensional energy equation (USACE, 1959) is used to compute water surface profiles for characterization of stream hydraulics. Flow conveyance limits, levee hydraulic assumptions, and hydraulic energy and resulting water surface elevation are simulated in a manner similar to HEC-2 (HEC, 1991b). HEC-6 can be operated in a "fixed bed" mode that is similar to a HEC-2 application for simulation of water surface elevation only.

Sediment transport rates can be estimated by HEC-6 for grain sizes up to 2048 mm. Different methods for sediment transport are used by HEC-6 based on grain size and user specification. Sediment transport potential is based only on hydraulic and sediment material characteristics. Boundary conditions for sediment loading at the river main stem, tributaries, or inflow/outflow points can be specified to change with time.

Model Framework
The model can represent a river or reservoir system consisting of a main stem, tributaries, and local inflow/outflow points in a one-dimensional mode. Inflowing sediment loads are related to water discharge by sediment-discharge curves for the upstream boundaries.

Scale

Spatial Scale
- Operation unit one-dimensional

Temporal Scale
- Variable timesteps—Short timesteps must be taken during flood events when large amounts of sediment are moving and the hydrograph is rapidly changing. Longer timesteps are used during low flow periods.
- This is discussed in further detail in the document *Guidelines for the Calibration and Application of Computer Program HEC-6* available at http://www.hec.usace.army.mil/software/legacysoftware/hec6/td13-documentation.htm

Assumptions
- Bed material transport algorithms assume that equilibrium conditions are reached within each timestep.
- The cross section is subdivided into two parts representative of a movable and immovable bed based on limits of the wetted perimeter and other considerations.
- The entire wetted part of the cross section is normally moved uniformly up or down; however, an option is available to adjust the bed elevation in horizontal layers when deposition occurs.
- Irregularities of the streambed are not simulated, but Manning's n values can be specified as functions of discharge that can be assumed to indirectly account for effects of bed forms.

Model Strengths

- Simulates the sediment passing through each cross section and the volume of sediment deposited or scoured at each section.
- Can be used for simulating changing sediment and hydraulic conditions
- Can be used for simulation and design of channel or reservoir dredging

Model Limitations

- Does not include capabilities for simulating the development of meanders or lateral distribution of sediment load across a cross section.
- Does not simulate density and secondary currents.
- Designed to analyze long-term scour and/or deposition. Single flood event analyses must be performed with caution.
- Sediment transport in diverging streams is not possible
- Flow around islands (i.e., closed loops) cannot be directly accommodated
- Only one junction or local inflow point is allowed between any two cross sections.

Application History

See available references.

Model Evaluation

Results of model testing and evaluation are reported extensively by HEC (1986, 1990a, 1990b, and 1991a).

Model Inputs

- Stream cross-sectional geometry and longitudinal elevation information
- Sediment particle characteristics
- Time series data of boundary inflows and sediment loading assumptions

Users' Guide

HEC-6, Scour and Deposition in Rivers and Reservoirs, User's Manual (HEC, 1991a). Available online: http://www.hec.usace.army.mil/software/legacysoftware/hec6/hec6-documentation.htm.

Technical Hardware/Software Requirements

Computer hardware:

The minimum hardware requirements include

- 570 KB of RAM
- 20 MB of free disk space

Operating system:

PC-DOS. Two editions of the HEC-6 program are distributed in the HEC-6 package: "overlayed" and "extended memory." While the basic programs are the same, the extended memory version runs faster and provides for up to 500 cross sections in a 10-stream network, whereas the overlayed version only allows 150 sections. The overlayed version operates within the DOS 640K limit (570Kb RAM). The extended memory version requires a 386 (or better) computer with 2–4MB extended memory and a math co-processor.

Programming language:

FORTRAN

Runtime estimates:
Minutes to hours

Linkages Supported
HEC-DSS

Related Systems
HEC-6T, HEC-2

Sensitivity/Uncertainty/Calibration
HEC (1991a) provides a description of the sensitivity of simulated bed profile changes to various input data uncertainties. A qualitative assessment of the sensitivity of model results to field data (geometry, sediment and hydrology) is presented in the manual. HEC (1991a) also reports results of analyses of sensitivity to cross sections, movable bed limits, roughness, bed material gradation, inflowing load, flow record, rating curve, and temperature. Additional results of model sensitivity analyses to bed roughness is reported by HEC (1992). Apart from sensitivity, HEC (1986 and 1991a), USACE (1992), and Gee (1984) provide detailed descriptions and guidance in calibration and selection of hydraulic and sediment modeling parameters.

Model Interface Capabilities
HEC-DSS (HEC, 1990c) can be used for managing and displaying time series data when simulating for long time periods.

References
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HEC-HMS: Hydraulic Engineering Center Hydrologic Modeling System

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Download Information

Availability: Nonproprietary
Cost: N/A

HEC-HMS was developed for the U.S. Army Corps of Engineers, but the model program files, executables, and documentation are available for free download by the public at the website above. However, the Hydrologic Engineering Center (HEC) of the U.S. Army Corps of Engineers will not provide user support to non-Corps users. In addition, public distribution of the model source code is generally discouraged by HEC.

Model Overview/Abstract

The Hydrologic Engineering Center (HEC) of the U.S. Army Corps of Engineers released the Hydrologic Modeling System (HEC-HMS) (HEC, 2001a) for rainfall-runoff simulation as a successor to HEC-1 (HEC, 1998). This model includes many of the watershed runoff and routing computation methods of HEC-1 but also includes many additional capabilities, including continuous hydrograph simulation over longer periods of time, distributed runoff computation using a grid cell representation of the watershed, a GUI, integrated hydrograph analysis tools, data storage and management tools, and graphics and reporting packages. HEC (2001b) reports specific differences between HEC-HMS and HEC-1.

HEC-HMS is specifically designed for simulation of rainfall-runoff processes of networking watershed systems. The modeling system includes many modernized and expanded algorithms from previous HEC models, including HEC-1, HEC-1F (HEC, 1989), PRECIP (HEC, 1989), and HEC-IFH (HEC, 1992).

Model Features

Modeling components

- Losses
- Runoff transform
- Open-channel routing
- Analysis of meteorologic data
- Rainfall-runoff simulation
- Parameter estimation
- Reservoir system simulations

User interface includes

- File management

- Data entry and editing
- Basin mapping for model configuration and data input and access
- Tabular and graphical display of input and output data

Model Areas Supported

Watershed	Low
Receiving Water	Low
Ecological	None
Air	None
Groundwater	Low

Model Capabilities

Conceptual basis

HEC-HMS is designed to simulate the rainfall-runoff processes of networked watershed systems. This model serves as the successor to HEC-1, providing a user interface and improvements and additional capabilities for distributed modeling and continuous simulation. It is designed to be applicable in a wide range of geographic areas for solving the widest possible range of problems.

Scientific detail

The physical representation of watersheds or basins and rivers is configured in the model based on representation of general hydrologic elements, including subbasins, reaches, junctions, reservoirs, diversions, sources, and sinks. The system encompasses losses, runoff transform, open-channel routing, analysis of meteorological data, rainfall-runoff simulation, and parameter estimation. A wide array of options is available to simulate losses, including initial and constant rates, the SCS curve number method, and the Green-Ampt method. Runoff transform methods include the Clark, Snyder, and SCS unit hydrograph techniques. User-specified unit hydrograph ordinates can also be used. Open-channel routing methods include the lag method, Muskingum method, the modified Puls method, the kinematic wave method, and the Muskingum-Cunge method. Meteorological data analysis can also be performed in the model for precipitation and evapotranspiration and includes various historical and synthetic methods (HEC, 2001).

Model Framework

Each model run combines a basin model, meteorologic model, and control specifications with run options to obtain results. The system connectivity and physical data describing the watershed are stored in the basin model. The precipitation and evapotranspiration data necessary to simulate watershed processes are stored in the meteorologic model (HEC, 2001).

Scale

Spatial Scale

- One-dimensional

Temporal Scale

- User-defined

Assumptions

Multiple assumptions are made that reduce the watershed to three separate processes—loss, transform, and baseflow. The number of assumptions is controlled by the hydrologic methods selected by the user for simulation. HEC (2000) reports specific assumptions for each method and algorithm used in HEC-HMS.

Model Strengths

- Simplified methods of hydrologic simulation encourage reduced number of parameters for model calibration.
- Capable of modeling common types of hydraulic control structures with appropriate on and off features.
- Includes a GUI with pre- and post-processing capabilities.

Model Limitations

- Cannot simulate water quality processes
- Relatively difficult to use in conjunction with other water quality models
- Cannot simulate groundwater levels

Application History

Multiple example model applications are reported by HEC (2001a and 2002). Many algorithms from HEC-1, HEC-1F, PRECIP, and HEC-IFH have been modernized and combined with new algorithms to form a comprehensive library of simulation routines in HEC-HMS.

Model Evaluation

See available references.

Model Inputs

- Initial conditions and attributes
- Inputs from watershed sources and discharges
- Element data
- Physical coefficients
- Time sequences of hydrometeorological conditions

Users' Guide

Hydrologic Modeling System, HEC-HMS: User's Manual (HEC, 2001a). Available online:
http://www.hec.usace.army.mil/software/hec-hms/documentation/hms_user.pdf

Technical Hardware/Software Requirements

Computer hardware:

The minimum hardware requirements for a Microsoft Windows installation includes

- Intel 80486 compatible processor
- 16-MB memory to run the program individually
- 15-MB available hard-disk space
- 15-inch VGA monitor
- Microsoft compatible mouse

The minimum hardware requirements for a Unix installation includes

- 64-MB memory to run the program individually
- SuperSPARC processor
- 28-MB available hard-disk space
- 10-MB available hard-disk space per user
- 17-inch color monitor

Operating system:

- Microsoft Windows 2000, 98, and 95

- Microsoft Windows NT 4.0
- Unix 2.5 or higher

Programming language:
FORTRAN

Runtime estimates:
Available intervals range from 1 minute to 24 hours

Linkages Supported
HEC-DSS

Related Systems
HEC-1, HEC-1F, PRECIP, HEC-IFH, HEC-RAS, HEC-DSS

Sensitivity/Uncertainty/Calibration
Not available

Model Interface Capabilities
The program features a completely integrated work environment including a database, data entry utilities, computation engine, and results reporting tools. A GUI is also included.

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U.S. Army Corps of Engineers, Hydrologic Engineering Center (HEC). 2001b. *Hydrologic Modeling System, HEC-HMS: Differences Between HEC-HMS and HEC-1*. CPD-74B. U.S. Army Corps of Engineers, Hydrologic Engineering Center, Davis, CA. Available at http://www.hec.usace.army.mil/software/hec-hms/documentation/hms_differences.pdf.

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HEC-RAS: Hydrologic Engineering Centers River Analysis System

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Download Information

Availability: Nonproprietary
Cost: N/A

HEC-RAS was developed for the U.S. Army Corps of Engineers, but the model program files, executables, and documentation are available for free download by the public at the website above. However, the Hydrologic Engineering Center (HEC) of the U.S. Army Corps of Engineers will not provide user support to non-Corps users. In addition, public distribution of the model source code is generally discouraged by HEC.

Model Overview/Abstract

The Hydrologic Engineering Center (HEC) of the U.S. Army Corps of Engineers released the River Analysis System (HEC-RAS) (HEC, 2002a and 2002b) for one-dimensional steady and unsteady flow simulation and sediment transport/moveable boundary conditions. HEC-RAS is designed to perform one-dimensional hydraulic calculations for a full network of natural and constructed channels. The model expands on methods from previous models for steady and unsteady flow simulation, including HEC-2 (HEC, 1991) and UNET (Barkau, 1992; HEC, 1997) and provides additional capabilities for simulation of bridge scour.

Model Features

Hydraulic analysis components

- Steady flow water surface profiles
- Unsteady flow simulation
- Sediment transport/moveable boundary computations

User interface includes

- File management
- Data entry and editing
- Hydraulic analyses
- Tabular and graphical display of input and output data
- Reporting facilities

Model Areas Supported

Watershed	None
Receiving Water	Low
Ecological	None

Air	None
Groundwater	None

Model Capabilities

Conceptual basis

HEC-RAS is an integrated system composed of a GUI, separate hydraulic analysis components, data storage and management capabilities, graphics, and reporting facilities. The system ultimately contains three one-dimensional hydraulic analysis components for (1) steady flow water surface profile computations, (2) unsteady flow simulation, and (3) moveable boundary sediment transport computations. All three components use a common geometric data representation and common geometric and hydraulic computation routines. In addition, the system contains several hydraulic design features that can be invoked once the basic water surface profiles are computed.

Scientific detail

The steady flow component is capable of modeling subcritical, supercritical, and mixed flow regime water surface profiles. The basic computational procedure is based on the solution of a one-dimensional energy equation. Energy losses are evaluated by friction and contraction/expansion. The momentum equation is utilized in situations where the water surface profile is rapidly varied.

The model can perform mixed flow regime calculations in the unsteady flow computations module, based on methods adapted from UNET (Barkau, 1992; HEC, 1997). For HEC-RAS, the hydraulic calculations for cross sections and hydraulic structures (e.g., bridges and culverts) that were developed for steady flow simulation were incorporated in the unsteady flow module.

The sediment transport/movable boundary computations are based on methods reported by the Federal Highway Administration (1995 and 1996). This module includes one-dimension calculation of sediment transport potential based on grain size distribution and results of the hydraulic model. The current version of HEC-RAS (Version 3.1) is limited to short-term analyses of scour at piers and abutments. However, the current version does not include long-term analysis of aggregation and degradation.

Model Framework

Model supports the following analyses:

- River flow simulation
- Floodway encroachment analysis
- Bridge scour simulation
- Channel hydraulic design

Scale

Spatial Scale

- One-dimensional

Temporal Scale

- User-defined

Assumptions

Key assumptions in model development are definition of channel geometry and flow path for model configuration. Cross-sectional assumptions include consideration of effective and ineffective flow areas, longitudinal slope, overflow of floodplains, and considerations to channel roughness. Inherent assumptions of the model based on theoretical formulations and requirements for model parameterization are reported by HEC (2002a and 2002b).

Additional assumptions are related to inflows required for modeling analyses, which are determined outside of model development or based on analysis of flow records or results of separate watershed models.

Model Strengths

- Capable of modeling common types of hydraulic control structures with appropriate on and off features.
- Has a GUI with pre- and post-processing capabilities.

Model Limitations

- Cannot simulate water quality processes and relatively difficult to use in conjunction with other water quality models.
- Cannot simulate groundwater levels.

Application History

Multiple example model applications are reported by HEC (2002c).

Model Evaluation

See available references.

Model Inputs

- Channel geometric data and assumptions for channel roughness
- Flow data and boundary conditions

Users Guide

HEC-RAS, River Analysis System User's Manual (HEC, 2002b).
Available online: http://www.hec.usace.army.mil/software/hec-ras/hecras-document.html

Technical Hardware/Software Requirements

Computer hardware:

The minimum hardware requirements for a Microsoft Windows installation includes

- Intel-based PC or compatible machine with Pentium processor or higher
- 40-MB available hard disk space
- 32-MB of RAM if using Windows 95, 98, ME or 64-MB of RAM using Windows NT, 2000, or XP
- Color video display

Operating system:

- Microsoft Windows XP, 2000, 98, 95, or later editions
- Microsoft Windows NT 4.0

Programming language:

FORTRAN

Runtime estimates:

Available intervals range from 1 minute to 24 hours

Linkages Supported
HEC-DSS

Related Systems
HEC-2, UNET, HEC-HMS, HEC-DSS

Sensitivity/Uncertainty/Calibration
Not available

Model Interface Capabilities
- Pre- and post-processors
- Data display tools
- Data preparation tools

References
Barkau, R.L. 1992. *One-Dimensional Unsteady Flow Through a Full Network of Open Channels.* (Computer Program). UNET, St. Louis, MO.

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HSCTM-2D: Hydrodynamic, Sediment, and Contaminant Transport Model

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ftp://ftp.epa.gov/epa_ceam/wwwhtml/ceamhome.htm

Download Information

Availability: Nonproprietary
http://www.epa.gov/ceampubl/swater/hsctm2d/index.htm
Cost: N/A

Model Overview/Abstract

HSCTM-2D is a single model that incorporates internally linked hydrodynamic, sediment transport and contaminant transport and fate simulation components. HSCTM-2D (Hayter et al., 1998) uses a two-dimensional finite element formulation and incorporates the RMA2 hydrodynamic model (King, 1990) and the CSTM-H sediment transport model (Hayter and Mehta, 1986) extended to include sorptive contaminants. Horizontal water column transport includes advection and shear dispersion. The model can be applied rivers, lakes, estuaries, and coastal waters.

Model Features

- Hydrodynamics
- Sediment transport
- Contaminant transport

Model Areas Supported

Watershed	None
Receiving Water	High
Ecological	None
Air	None
Groundwater	None

Model Capabilities

Conceptual Basis

HSCTM2D is a finite element modeling system for simulating two-dimensional, vertically integrated, surface water flow (typically riverine or estuarine hydrodynamics), sediment transport, and contaminant transport. The modeling system consists of two modules, one for hydrodynamic modeling (HYDRO2D) and the other for sediment and contaminant transport modeling (CS2D). One example problem is included. The HSCTM2D modeling system may be used to simulate both short-term (less than 1 year) and long-term scour and/or sedimentation rates and contaminant transport and fate in vertically well mixed bodies of water.

Scientific Detail

The hydrodynamic module HYDRO2D simulates two-dimensional, depth-averaged flow of surface waters. The governing equations, eqs. 3.1, 3.7, and 3.8, are solved by the Galerkin method of weighted residuals using the finite element method, as described in Section 4. The depth-averaged velocities in the two horizontal directions and the flow depth are computed at each node. In addition, continuity can be checked across multiple cross sections. The effects of bottom, internal, and surface shear stresses and the Coriolis force are simulated in HYDRO2D. Bottom and surface stresses are due to friction; internal stresses are the results of turbulence. The module can simulate both steady state and dynamic flows.

The cohesive sediment transport model CS2D is a time varying, two-dimensional finite element model that is capable of predicting the horizontal and temporal variations in the depth-averaged suspended cohesive sediment concentrations and bed surface elevations in an estuary, coastal waterway, or river (Hayter and Mehta, 1986). In addition, it can be used to predict the steady state or unsteady transport of any conservative or nonconservative constituent if the reaction rates are known. CS2D simulates the advection and dispersion of suspended constituents, aggregation, and deposition to and erosion from the bed of cohesive sediments. Hayter (1983) describes a series of experiments that were used to partially validate the model.

Model Framework

- Depth average finite element

Scale

Spatial Scale

- Two-dimensional in horizontal

Temporal Scale

- Dynamic

Assumptions

- Based on accepted formulations of the two-dimensional, depth-averaged hydrodynamic equations and conservative transport equation

Model Strengths

- Strong capabilities for hydrodynamics and sediment transport in vertically mixed waterbodies

Model Limitations

- Two-dimensional, vertically averaged homogeneous flow
- Will not accurately simulate supercritical flow
- Based on a streamwise bottom slope that is mild and not steeper than (01:10)

Application History

The model has been applied to the Maurice River and Union Lake in New Jersey (Hayter and Gu, 1998).

Model Evaluation

None

Model Inputs

For HYDRO2D

- Program operation data
- Grid geometry data
- Initial conditions data
- Boundary conditions data

For CS2D:

- Program operation data
- Grid geometry data
- Nodal velocities and salinities
- Initial conditions
- Boundary conditions
- Parameters describing the erosional and depositional behavior of the cohesive sediment as well as the structure of the bed and contaminant partition coefficients and decay rates.

Users' Guide

Available online http://www.epa.gov/ceampubl/swater/hsctm2d/USERMANU.PDF

Technical Hardware/Software Requirements

Computer hardware:

- PC and UNIX workstations

Operating system:

- Windows or UNIX

Programming language:

- FORTRAN

Runtime estimates:

- Compute intensive with slower run times than similar two-dimensional finite difference models
- Run time is highly dependent on computer hardware, model domain spatial resolution, the period of prototype conditions simulated, and other options, such as whether the model is simulation-only hydrodynamic or hydrodynamics and the fate and transport of dissolved and suspended material. Under this wide range of variability, simulations could require minutes to weeks.

Linkages Supported

None

Related Systems

None

Sensitivity/Uncertainty/Calibration

No sensitivity, uncertainty, or calibration capabilities directly incorporated into model

Model Interface Capabilities

None

References

Hayter, E.J., and A.J. Mehta. 1982. *Modeling of Estuarial Fine Sediment Transport for Tracking Pollutant Movement*. UFL/COEL-82/009. Coastal and Oceanographic Engineering Department, University of Florida, Gainesville, Florida.

Hayter, E. J., and A. J. Mehta. 1986. Modelling cohesive sediment transport in estuarial waters. Appl. Math. Modelling. 10:294-303.

Hayter, E.J., M. Bergs, R. Gu, S. McCutcheon, S. J. Smith, and H. J. Whiteley. 1998. *HSCTM-2D, a finite element model for depth-averaged hydrodynamics, sediment and contaminant transport*. Technical Report. U. S. EPA Environmental Research Laboratory, Athens, Georgia.

Hayter, E.J., and R. Gu. 1998. Prediction of contaminated sediment transport in the Maurice River-Union Lake, New Jersey. Paper presented at 5th International Conference on Cohesive Sediment Dynamics, May, 1998, Seoul, Korea.

HSCTM-2D: Hydrodynamic, Sediment, and Contaminant Transport Model

Contact Information

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Athens, GA 30605-2700
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ftp://ftp.epa.gov/epa_ceam/wwwhtml/ceamhome.htm

Download Information

Availability: Nonproprietary
http://www.epa.gov/ceampubl/swater/hsctm2d/index.htm
Cost: N/A

Model Overview/Abstract

HSCTM-2D is a single model that incorporates internally linked hydrodynamic, sediment transport and contaminant transport and fate simulation components. HSCTM-2D (Hayter et al., 1998) uses a two-dimensional finite element formulation and incorporates the RMA2 hydrodynamic model (King, 1990) and the CSTM-H sediment transport model (Hayter and Mehta, 1986) extended to include sorptive contaminants. Horizontal water column transport includes advection and shear dispersion. The model can be applied rivers, lakes, estuaries, and coastal waters.

Model Features

- Hydrodynamics
- Sediment transport
- Contaminant transport

Model Areas Supported

Watershed	None
Receiving Water	High
Ecological	None
Air	None
Groundwater	None

Model Capabilities

Conceptual Basis

HSCTM2D is a finite element modeling system for simulating two-dimensional, vertically integrated, surface water flow (typically riverine or estuarine hydrodynamics), sediment transport, and contaminant transport. The modeling system consists of two modules, one for hydrodynamic modeling (HYDRO2D) and the other for sediment and contaminant transport modeling (CS2D). One example problem is included. The HSCTM2D modeling system may be used to simulate both short-term (less than 1 year) and long-term scour and/or sedimentation rates and contaminant transport and fate in vertically well mixed bodies of water.

HSPF: Hydrologic Simulation Program FORTRAN

Contact Information

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Washington, DC 20460
basins@epa.gov
http://www.epa.gov/ost/ftp/basins/system/BASINS3/gww.htm

AQUA TERRA
http://www.aquaterra.com/

Download Information

Availability: Nonproprietary
Cost: N/A

Model Overview/Abstract

HSPF is a comprehensive package for simulating watershed hydrology and water quality for a wide range of conventional and toxic organic pollutants. With its predecessors dating back to the 1960s, HSPF is the culminating evolution of the Stanford Watershed Model (SWM), watershed-scale Agricultural Runoff Model (ARM), and Nonpoint Source Loading Model (NPS) into an integrated basin-scale model that combines watershed processes with in-stream fate and transport in one-dimensional stream channels. HSPF simulates watershed hydrology, land and soil contaminant runoff, and sediment-chemical interactions. The model can generate time series results of any of the simulated processes. Overland sediment may be divided into three types of sediment (sand, silt, and clay) for in-stream fate and transport. Pollutants interact with suspended and bed sediment through soil-water partitioning. The most recent release is HSPF Version 12, which is distributed as part of the EPA BASINS (Better Assessment Science Integrating Point and Nonpoint Sources) system.

Model Features

- Detailed watershed simulation model
- Watershed hydrology
- Runoff/sediment/pollutant generation and transport
- One-dimensional stream hydrology and transport
- Pesticide fate and transport simulation

Model Areas Supported

Watershed	High
Receiving Water	Medium
Ecological	None
Air	None
Groundwater	Low

Model Capabilities

Conceptual Basis

In HSPF, a subwatershed is typically conceptualized as a group of various land uses all routed to a representative stream segment. Several small subwatersheds and representative streams may be networked together to represent a larger watershed drainage area. Various modules are available and may be readily activated to simulate various processes, both on land and in-stream.

Scientific Detail

Land processes for pervious and impervious areas are simulated through water budget, sediment generation and transport, and water quality constituents' generation and transport. Hydrology is modeled as water balance of soil (or storage) in different layers as described by the SWM methodology. Interception, infiltration, evapotranspiration, interflow, groundwater loss, and overland flow processes are considered and are generally represented by empirical equations. Sediment production is based on detachment and/or scour from a soil matrix and transport by overland flow in pervious areas, whereas solids buildup and washoff is simulated for impervious areas. It includes agricultural components for land-based nutrient and pesticide processes and a special actions block for simulating management activities. HSPF also simulates the in-stream fate and transport of a wide variety of pollutants, such as nutrients, sediments, tracers, dissolved oxygen/biochemical oxygen demand, temperature, bacteria, and user-defined constituents.

Model Framework

- Hydrologic response unit, subwatershed, and watershed
- Simple one-dimensional stream and well-mixed reservoir/lake model

Scale

Spatial Scale

- One-dimensional, lumped parameters on a land use or subwatershed basis

Temporal Scale

- User-defined timestep, typically hourly

Assumptions

- Land simulation component is a distributed model by land use but ignores the spatial variation within a land use in a subwatershed.
- For overland flow, model assumes one-directional kinematic-wave flow.
- Model also assumes subwatershed and streams as series of reservoirs while routing flows.
- The receiving waterbody assumes complete mixing along the width and depth.

Model Strengths

- One the few watershed models capable of simulating land processes and receiving water processes simultaneously.
- Capable of simulating both peak flow and low flows.
- Simulates at a variety of timesteps, including subhourly to 1 minute, hourly or daily.
- Simulates the hydraulics of complex natural and man-made drainage networks
- Includes capabilities to address a variable water table.
- Simulates results for many locations along a reservoir or tributary.
- Includes user-defined model output options by defining the external targets block.
- Can be setup as simple or complex, depending on application, requirements, and data availability.

Model Limitations

- Relies on many empirical relationships to represent physical processes.
- Lumps simulation processes for each land use type at the subwatershed level (i.e., does not consider the spatial location of one land parcel relative to another in the watershed). The model approaches a distributed model when smaller subwatersheds are used; however, this may result in increased model complexity and simulation time.
- Requires extensive calibration.
- Requires a high level of expertise for application.
- Is limited to well-mixed rivers and reservoirs and one-directional flow.

Application History

The modeling concept had its debut in the early 1960s as the Stanford Watershed Model. During the 1970s, water quality processes were added. A FORTRAN version was developed in the late 1970s, incorporating several related models and software engineering design and development concepts funded by EPA's research laboratory in Athens, GA. In the 1980s, pre- and post-processing software, algorithm enhancements, and use of the USGS binary Watershed Data Management (WDM) system were developed jointly by the USGS and EPA. Since 1980, all model code changes have been maintained by Aqua Terra Consultants, under contract with EPA and USGS. During the mid to late 1990s, Tetra Tech, Inc., under contract with EPA developed the BASINS system and NPSM, resulting in the first Windows-based interface for the HSPF model. The current supported model release is Version 12, distributed with BASINS 3.0 as the WinHSPF model and interface. HSPF is a proven and tested continuous simulation watershed model. It is one of the models recommended by the EPA for complex TMDL studies. The HSPF model has been widely used and its application has been documented throughout its development cycle.

Model Evaluation

HSPF has been widely reviewed and applied throughout its long recent history (Hicks, 1985; Ross et al., 1997; and Tsihrintzis et al., 1996). One of the largest applications of the model was to the Chesapeake Bay Watershed, as part of the EPA's Chesapeake Bay Program's management initiative (Donigian, 1990, 1992). Tsihrintzis et al. (1994, 1995) applied HSPF in a GIS shell (using ARC/INFO) to evaluate the impact of agricultural activities, specifically transport of sediments, nutrients, and pesticides, on streams and groundwater in Southern Florida. An extensive HSPF bibliography has been compiled to document model development and application and is available online at http://hspf.com/hspfbib.html.

Model Inputs

- Continuous meteorological time series records including (at a minimum)
    - Rainfall
    - Potential evapotranspiration

  For SNOW simulation, additional required meteorological time series include
    - Temperature
    - Wind speed
    - Solar radiation
    - Dewpoint temperature

  For additional simulation options, other required meteorological time series may include
    - Pan evaporation
    - Cloud cover
- Soils data (auxiliary dataset to guide hydrologic calibration), pollutant buildup and washoff, stream dimensions or rating curves, and point-source loading inputs
- A large number of parameters need to be specified (some default values are available)

Users' Guide

- For model documentation, underlying theory, and parameterization, the HSPF users' manual is a recommended source (Bicknell et al., 2001).
- A browseable Windows help file version of the manual is available at http://hspf.com/pub/hspf/HSPF.chm.

Technical Hardware/Software Requirements

Computer hardware:
- PC

Operating system:
- DOS or Windows Operating System

Programming language:
- FORTRAN

Runtime estimates:
- Seconds to minutes or hours, depending on spatial/temporal resolution and computer performance

Linkages Supported
CE-QUAL-W2

Related Systems
WinHSPF, an interface to HSPF, is a key component of Better Assessment Science Integrating point and Nonpoint Sources (BASINS) Version 3.0. BASINS 3.0 was developed for the U.S. Environmental Protection Agency's Office of Water to respond to the continued needs of various agencies to perform watershed and water quality assessments, integrating point and nonpoint sources.

LSPC, another interface to HSPF, is available through the EPA Modeling Toolbox (http://www.epa.gov/athens/wwqtsc/index.html).

Sensitivity/Uncertainty/Calibration
HSPFParm is a free HSPF parameter database distributed with EPA's BASINS System. The software is installed independent of the BASINS system. It provides regionalized model parameters for published applications across the United States. It serves as a good starting point for parameter selection during model setup and calibration.

The Expert System for calibration of HSPF (HSPEXP) is an interactive program that evaluates modeled versus observed time series using over 35 rules and some 80 conditions (Lumb, 1994). It uses Artificial Intelligence techniques, incorporating expert advice, based on statistics and evaluation results, to recommend which parameters should be adjusted.

The Parameter Estimation software package (PEST) is a model calibration aid that can be run in conjunction with HSPF (Doherty, 2003). The objective function's goal is to minimize the least squares of the difference between modeled and observed flow by varying model parameters over a range that the user defines. PEST then iterates through a series of HSPF model runs, changing selected parameters and rerunning the model, until the objective is satisfied.

Model Interface Capabilities
Using the HSPF Model requires at least two files: the User Control Input File (UCI) for parameters and control specifications and a WDM file for time series. When run by itself, the UCI text file serves as the interface for the HSPF model.

The WinHSPF interface, first distributed with BASINS 3.0, provides an interactive interface to HSPF in a Windows environment. WinHSPF may be used for creating a new HSPF input sequence or for modifying an existing HSPF input sequence. The program HSPF may be run from within WinHSPF. Input sequences may be modified and saved under another name, thus creating simulation scenarios.

References

Bicknell, B.R., J.C. Imhoff, J.L. Kittle, Jr., T.H. Jobes, and A. S. Donigian, Jr. 2001. *HYDROLOGICAL SIMULATION PROGRAM - FORTRAN, Version 12, User's Manual*. (Computer program manual). AQUA TERRA Consultants.

Doherty, John, and John M. Johnston. 2003. Methodologies for calibration and predictive analysis of a watershed model. J. American Water Resources Association. 39(2):251-265.

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Donigian, A.S., Patwardhan, A.S., and R.M. Jacobson. 1996. Watershed Modeling of Pollutant Contributions and Water Quality in the Le Sueur Basin of Southern Minnesota. *In Proceedings of Watershed 96*, Baltimore, MD, June 8-12, 1996.

Hicks, C.N. 1985. *Continuous Simulation of Surface and Subsurface Flows in Cypress Creek Basin, Florida, Using Hydrological Simulation Program - FORTRAN (HSPF).* Water Resources Research Center, University of Florida, Gainesville, FL.

Lumb, A.M., McCammon, R.B., and Kittle, J.L., Jr. 1994. *Users manual for an expert system (HSPEXP) for calibration of the Hydrologic Simulation Program—FORTRAN*. U.S. Geological Survey Water-Resources Investigations Report 94-4168. U.S. Geological Survey.

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.

Ross, M.A., P.D. Tara, J.S. Geurink, and M.T. Stewart. 1997. *FIPR Hydrologic Model: Users Manual and Technical Documentation*. Prepared for Florida Institute of Phosphate Research, Bartow, FL, and Southwest Florida Water Management District, Brooksville, FL by University of South Florida, Tampa, FL.

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. Lewis Publishers, Boca Raton, FL. pp. 175-187.

Tsihrintzis, V.A., H.R. Fuentes and R. Gadipudi. 1996. Modeling Prevention Alternatives for Nonpoint Source Pollution at a Wellfield in Florida. Water Resources Bulletin, Journal of the American Water Resources Association (AWRA). 32(2):317-331.

Tsihrintzis, V., H. Fuentes, and R. Gadipudi. 1995. Modeling prevention alternatives for nonpoint source pollution at a wellfield in Florida. Water Resources Bulletin. 32(2):317-331.

Tsihrintzis, V., H. Fuentes, and R. Gadipudi. 1994. Interfacing GIS and water quality models for agricultural areas. Hydraulic Engineering '94, ed. G. Cotroneo and R. Rumer, ASCE,1, pp 252-256.

KINEROS2: Kinematic Runoff and Erosion Model v2

Contact Information

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Agricultural Research Service
Southwest Watershed Research Center
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Tucson, Arizona 85719
(520) 670-6381
http://www.tucson.ars.ag.gov/kineros/

Download Information

Availability: Nonproprietary
Cost: N/A

Model Overview/Abstract

KINEROS2 is the upgrade from an earlier version called KINEROS (Woolhiser, et al., 1990). The model is an event-oriented, physically based model that describes the processes of interception, infiltration, surface runoff, and erosion from small agricultural and urban watersheds (USDA, 2003). The model represents a watershed by an abstraction into a tree-like network sequence of planes and channels and solves the partial differential equations describing overland flow, channel flow, erosion, and sediment transport by using finite-difference techniques. Spatial variation of rainfall, infiltration, runoff, and erosion parameters can be accommodated. The model allows pipe flow and pond elements as well as infiltrating surfaces and includes a partially paved element to use in urban area simulation. KINEROS can be used to determine the effects of various artificial features, such as urban developments, small detention reservoirs, or lined channels, on flood hydrographs and sediment yield. This model is suitable for small agricultural and disturbed urban watersheds.

Model Features

- Overland flow and channel flow
- Erosion and sediment transport

Model Areas Supported

Watershed	High
Receiving Water	Low
Ecological	None
Air	None
Groundwater	None

Model Capabilities

Conceptual Basis

KINEROS2 represents a watershed as a cascade of planes and sequence of channels. Multigage rainfall input is distributed by assigning rain gages to overland flow planes.

Scientific Detail

KINEROS uses one-dimensional kinematic equations to simulate flow over rectangular planes and through trapezoidal open channels, circular conduits, and small detention ponds. Runoff is routed with an implicit finite difference solution of the kinematic wave equation. The infiltration algorithm is dynamic, physically based, and interacting with both rainfall and surface water in transit. The infiltration capacity is simulated as a function of infiltrated depth and allows estimation of the soil redistribution behavior by using the pore size distribution index. Further, as an option, the effect of spatial variation in soil hydraulic conductivity can be simulated by assuming a normal distribution and a user-defined coefficient of variation. Channel transmission losses are also included in the model. For overland surfaces, erosion consists of two major components—erosion by splash of rainfall on bare soil and hydraulic erosion (or deposition) due to the interplay between the shearing force of water on the loose soil bed and the tendency of soil particle to settle under the force of gravity. The splash erosion is approximated as a function of the rainfall rate square and a reduction factor representing the ponding water depth. The hydraulic erosion is simulated by applying a modified Engelund and Hansen equation to calculate the shallow flow transport capacity. Erosion and flow equations are solved numerically at each timestep and for each particle size. A four-point finite-difference scheme is used.

Model Framework

- Fields/planes and channels

Scale

Spatial Scale

- One-dimensional, fields, subwatershed overland
- One-dimensional, channel network

Temporal Scale

- Variable timestep (normally in minutes)

Assumptions

- For overland flow and channel flow routing, it is assumed that backwater and diffusive wave attenuation is negligible
- Normal distribution of the soil hydraulic conductivity

Model Strengths

- Contains a physically based infiltration model that allows estimation of the soil redistribution behavior and considers heterogeneity
- Simulates both splash erosion and hydraulic erosion
- Can represent rainfall spatial variability by assigning different rainfall data to difference elements

Model Limitations

- As an event-based model, does not treat long periods of soil water redistribution, plant growth, and other interstorm changes
- Does not contain subsurface component
- Simulates sediment only

Application History

USDA-ARS illustrated the application of KINEROS to simulate runoff from a 6.3 km^2 semiarid experimental watershed near Tombstone, Arizona.

Ziegler applied KINEROS2 to modeling erosion on unpaved roads, the results of which are available at http://www.age.uiuc.edu/s&w/hawaii/Ap30.htm.

Model Evaluation

The model application done by USDA-ARS-SWRC for an experimental watershed near Tombstone, Arizona, showed that KINEROS2 could reasonably predict the overall trend of the outflow hydrograph.

The work by Ziegler showed that

> "KINEROS2 can be parameterized to simulate reasonably total discharge, sediment transport, and sediment concentration on small-scale road plots, for a range of slopes, during simulated rainfall events. KINEROS2, however, did not accurately predict time-dependent changes in sediment output and concentration. In particular, early flush peaks and the temporal decay in sediment output were not predicted, owing to the inability of KINEROS2 to model removal of a surface sediment layer of finite depth." (Abstract is available at http://www.age.uiuc.edu/s&w/hawaii/Ap30.htm.)

Model Inputs

- Overland flow element
  - Plane geometry (length, width, and slope), Manning's n, Chezy conveyance factor
  - Canopy cover, interception depth, average micro topographic relief, average micro topographic spacing
  - Infiltration-related parameters including saturated hydraulic conductivity (Ks), initial degree of soil saturation, coefficient of variation of Ks, mean capillary drive, porosity, pore size distribution index, volumetric rock fraction, thickness of soil layers (up to 2 layers)
  - Rain splash coefficient, soil cohesion coefficient, and particle class fractions
- Channel element
  - Type (simple or compound) and base flow discharge
  - Channel geometry (length, width, bed slope, and bank slopes), Manning's n, Chezy conveyance factor
  - Infiltration-related parameters (same as specified in overland flow element)
  - Cohesion coefficient of bed material.
- Pond element
  - Initial storage volume
  - Volume, surface area, and discharge rating table
  - Seepage rate
- Rainfall file
- External flow file (optional)

Users' Guide

Available online: http://www.tucson.ars.ag.gov/kineros/

Technical Hardware/Software Requirements

Computer hardware:

- PC

Operating system:

- PC-DOS

Programming language:

- FORTRAN 77/90

Runtime estimates:

- Seconds to minutes

Linkages Supported

None

Related Systems

BASINS

Sensitivity/Uncertainty/Calibration

Not available

Model Interface Capabilities

- ArcView extension to facilitate input data preparation

References

USDA-ARS-Southwest Watershed Research Center. *KINEROS2 Documentation*. http://www.tucson.ars.ag.gov/kineros/Docs/Doc.htmlTechnical Manual

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LSPC: Loading Simulation Program in C++

Contact Information

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Download Information

Availability: Nonproprietary
http://www.epa.gov/athens/wwqtsc/html/lspc.html
Cost: N/A

Model Overview/Abstract

The Loading Simulation Program in C++ (LSPC) is a watershed modeling system that includes streamlined Hydrologic Simulation Program FORTRAN (HSPF) algorithms for simulating hydrology, sediment, and general water quality on land as well as a simplified stream transport model. It is a EPA-accepted TMDL modeling application, developed by Tetra Tech, Inc., partially under contract with EPA. A key advantage of LSPC is that it has no inherent limitations in terms of modeling size or model operations and has been applied to large, complex watersheds. In addition, the Microsoft Visual C++ programming architecture allows for seamless integration with modern-day, widely available software such as Microsoft Access and Excel.

Model Features

- Watershed modeling
- Hydrologic simulation and hydraulic transport
- Overland and in-stream sediment simulation
- Temperature simulation

Model Areas Supported

Watershed	High
Receiving Water	Medium
Ecological	None
Air	Medium
Groundwater	Medium

Model Capabilities

Conceptual Basis

In LSPC, a subwatershed is typically conceptualized as a group of various land uses all routed to a representative stream segment. Several small subwatersheds and representative streams may be networked together to represent a larger watershed drainage area. Various modules are available and may be readily activated to simulate various land and stream processes.

Scientific Detail

Land processes for pervious and impervious areas are simulated through water budget, sediment generation and transport, and water quality constituents' generation and transport. Hydrology is modeled as water balance of soil (or storage) in different layers as described by the Stanford Watershed Model (SWM) methodology. Interception, infiltration, evapotranspiration, interflow, groundwater loss, and overland flow processes are considered and are generally represented by empirical equations. Sediment production is based on detachment and/or scour from a soil matrix and transport by overland flow in pervious areas, whereas solids buildup and washoff is simulated for impervious areas. For water quality, buildup and washoff of a quality constituent on a land surface, baseflow-associated pollutant concentrations, sediment-associated pollutant load, and soil temperature and heat transfer to water are available.

For in-stream simulation, the model simulates radiation and heat transfer, conservative substance routing, suspended solids routing and settling, and general first-order pollutant loss, which is applicable for simulating a wide range of conservative substances, such as fecal coliform bacteria, total nitrogen and phosphorus, and total metals. The hydraulic compartment, which determines the advection terms for all of the other components, is based on a time-interval budget of water volume between inflow from the above reach, user-specified outflows, and discharge to the next downstream reach.

Model Framework

- Watershed hydrologic, sediment, and water quality
- Time series climate-driven, overland, subsurface, and in-stream simulation

Scale

Spatial Scale

- Lumped parameters at a land use subwatershed scale
- One-dimensional in-stream fate and transport
- Capable of simulating many subwatersheds (100+) over large drainage areas (8-digit HUCs)

Temporal Scale

- User-defined timestep, typically hourly

Assumptions

- Land simulation component is a distributed model by land use but ignores the spatial variation within a land use in a subwatershed.
- For overland flow, model assumes one-directional kinematic-wave flow.
- Model also assumes subwatershed and streams as series of reservoirs while routing flows.
- Model assumes complete mixing along the width and depth of the receiving waterbody.

Model Strengths

LSPC is one the few watershed models that is capable of simulating land processes and receiving water processes simultaneously. It is capable of simulating both peak flow and low flows and a variety of timesteps, including sub-hourly to one minute, hourly or daily. The model simulates the hydraulics of complex natural and man-made drainage networks and includes capabilities to address variable water table. A key strength of LSPC model output is that the model automatically aggregates results and manages the output at a subwatershed or reach-segment level. The model can be setup as simple or complex, depending on the application requirement and data availability. The design of the modeling system and supporting databases is particularly well suited for efficient application to large, complex watersheds. Data management tools support the evaluation of loading and management within multiple watersheds simultaneously.

Model Limitations

The model relies on many empirical relations to represent physical processes. For land simulation, processes are lumped for each land use type at the subwatershed level; therefore, the model does not consider the spatial location of one land parcel relative to another in the watershed. The model approaches a distributed model when smaller subwatersheds are used; however, this may result in increased model size and simulation time. For in-stream simulation, it is limited to well mixed rivers and reservoirs and one-directional flow. It requires extensive calibration. It generally requires a high level of expertise for application.

Application History

LSPC is the key watershed modeling component of the TMDL Toolbox. TMDL's model applications have been successfully developed using LSPC in Alabama, Mississippi, South Carolina, Georgia, California, Kentucky, Tennessee, West Virginia, Virginia, Maryland, Arizona, Ohio, Montana, Puerto Rico, and U.S. Virgin Islands. Several recent watershed TMDLs have been done using LSPC. Two are listed as follows:

- Published Tennessee TMDL documents may be accessed at the following web address: http://www.state.tn.us/environment/wpc/tmdl/approved.php
- Published Alabama TMDL documents may be accessed at the following web address: http://www.epa.gov/region4/water/tmdl/alabama/index.htm

Model Evaluation

HSPF, on which LSPC is based, has been widely reviewed and applied throughout its history (Hicks, 1985; Ross, et al., 1997; and Tsihrintzis, et al., 1996). Tsihrintzis, et al., (1994, 1995) applied HSPF in a GIS shell (using ARC/INFO) to evaluate the impact of agricultural activities, specifically transport of sediments, nutrients, and pesticides, on streams and groundwater in Southern Florida. The underlying HSPF algorithms used in the LSPC model have been widely used and the applications have been documented over more than 20 years.

Model Inputs

- Continuous meteorological time series records including (at a minimum)
    - Rainfall
    - Potential evapotranspiration

  For SNOW simulation, additional required meteorological time series include
    - Temperature
    - Wind speed
    - Solar radiation
    - Dewpoint temperature
- Soils data (auxiliary dataset to guide hydrologic calibration), pollutant buildup and washoff, stream dimensions or rating curves, and point-source loading inputs
- A large number of parameters need to be specified (some default values are available)

Users' Guide

- An LSPC Users' Manual (Tetra Tech, 2002) is available through EPA's Watershed and Water Quality Modeling Technical Support Center.
- For model documentation, underlying theory, and parameterization, the HSPF users' manual is a recommended source (Bicknell, et al., 2001).

- A browseable Windows help file version of the manual is available at http://hspf.com/pub/hspf/HSPF.chm.

Technical Hardware/Software Requirements

Computer hardware:
- PC (Pentium III or higher recommended, but not required)

Operating system:
- Windows 98 or later

Programming language:
- C++

Runtime estimates:
- Seconds to minutes or hours, depending on spatial/temporal resolution

Linkages Supported
EFDC, WASP, CE-QUAL-W2, EPD-Riv1

Related Systems
HSPF, WinHSPF

Sensitivity/Uncertainty/Calibration
LSPC includes a data analysis component that may be used to quickly compare model output against observed data in time series form, as monthly summaries, or on a one-to-one graph. LSPC model output is especially tailored for spreadsheet use; consequently, many users prefer to develop independent spreadsheet analysis, summarization, calibration, and plotting applications, which are readily linked to LSPC model output.

HSPFParm is a free HSPF parameter database distributed with EPA's BASINS System. The software is installed independent of the BASINS system. It provides regionalized model parameters for published applications across the United States. It serves as a good starting point for parameter selection during model setup and calibration.

The Parameter Estimation software package (PEST) is a model calibration aid that can be run in conjunction with HSPF (Doherty, 2003). Although PEST is not currently linked with LSPC, it is a generalized calibration system that can potentially be linked to any model. Since parameter values and definitions in HSPF and LSPC are interchangeable, results from a small-scaled HSPF PEST run can be used to calibrate LSPC. The objective function's goal is to minimize the least squares of the difference between modeled and observed flow by varying model parameters over a range that the user defines. PEST then iterates through a series of model runs until the objective is satisfied.

Model Interface Capabilities
When launched from within the EPA Watershed Characterization System (WCS), LSPC has an extension for automatically setting up the model using GIS information. The LSPC model interface has two components: (1) a stand alone GIS component, and (2) a model parameter management component. The LSPC Map Objects GIS interface, which is compatible with ArcView shapefiles, acts as the control center for managing and launching watershed model scenarios. The stand alone interface communicates with shapefiles and the underlying Access database. Therefore, once a watershed system is created, it is easily transferable to users who may not have ArcView or MS Access. The LSPC model parameter management component can be used either independently on previously saved model setup files or in conjunction with the GIS component to setup model scenarios on the fly.

LSPC also includes a suite of additional tools, including data management tools for editing watershed data, data inventory tools for reporting and summarizing model inputs and outputs, and data analysis tools for both visualizing and summarizing model inputs or outputs and observed data. The model includes a TMDL calculation that allows the user to specify source-specific allocations and generate corresponding model results for TMDL analysis.

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Mercury Loading Model: Watershed Characterization System—Mercury Loading Model

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http://wcs.tetratech-ffx.com/System/index.htm

Download Information

Availability: Nonproprietary
http://wcs.tetratech-ffx.com/System/index.htm
Cost: N/A

Model Overview/Abstract

Watershed-scale Mercury Loading Model is an ArcView 3.x grid-based modeling extension of the Watershed Characterization System (WCS). The complexity of this loading function model falls between that of a detailed simulation model, which attempts a mechanistic, time-dependent representation of pollutant load generation and transport, and simple export coefficient models, which do not represent temporal variability. The WCS provides simulation of precipitation-driven runoff and sediment delivery at a grid-based landscape. Solids load from runoff is used to estimate pollutant delivery to the receiving waterbody from the watershed. This estimate is based on mercury concentrations in wet and dry deposition and processed by soils in the watershed and ultimately delivered to the receiving waterbody by runoff, erosion, and direct deposition. The main driving force for the WCS mercury model is the input of the appropriate wet and dry deposition rates or maps for mercury as well as the climate condition of a watershed.

Model Features

- ArcView GIS grid-based watershed mercury loading calculation
- Estimates total annual average mercury load from different sources of a watershed
- Model results are summarized in maps and tables that can be incorporated into a WCS automatic report

Model Areas Supported

Watershed	Medium
Receiving Water	None
Ecological	None
Air	Low
Groundwater	None

Model Capabilities

Conceptual Basis

The WCS Mercury Loading model is based on a soil-mercury mass balance model, IEM v2.05, developed by EPA's Office of Health and Environmental Assessment and Environmental Research Lab, Athens, Georgia. The soil-mercury mass balance model was expanded to account for the spatial heterogeneity of a watershed landscape using ArcView GIS and grid-processing technology.

Scientific Detail

The WCS Mercury Loading model uses three major algorithms to calculate watershed mercury load:

1. Erosion and sediment transport algorithm for the calculation of mercury load from sediment. The algorithm implemented in the model is the same as that used in the sediment budget model described in the previous section. USLE is used to calculate the erosion potential, and an area-based sediment delivery ratio equation is used as the default formula to calculate the sediment delivery.

2. Hydrology algorithm for the calculation of mercury load from surface runoff. Monthly rainfall is used to calculate the average rainfall amount for rainfall events. The number of rain days is first compiled from selected weather stations in EPA Region 4. Rainfall/event is then derived by dividing monthly rainfall by monthly number of rain days. Rainfall/event is used to calculate the runoff using the curve number method developed by USDA-NRCS. The hydrology algorithm also includes the computation of other components of the water balance processes, including evapotranspiration and infiltration.

3. Chemistry algorithm for the calculation of mercury concentration in soil (particle phase and water phase). U.S. national mercury deposition maps were used for atmospheric mercury input. Atmospheric input deposits mercury directly on water surfaces, impervious land surfaces, and pervious land surfaces. For the pervious land surface, mercury concentration in soils is calculated using the steps outlined in *Mercury Study Report to Congress* (USEPA, 1997). The equation for the calculation of the soil mercury concentration can be written as:

$$C_s = (C_0 * e^{k\text{-}ks_{total} * T}) + (D + W) * (1 - e^{-ks_{total} * T}) * 10^5 / (z_d * BD * ks_{total})$$

where C_s = soil mercury concentration at equilibrium (ng/g or ppb); C_0 = initial (pre-industrial) soil mercury concentration (ng/g); k = soil mercury mineralization rate (yr^{-1}); ks_{total} = soil mercury loss rate (yr^{-1}) from leaching, runoff, and erosion; z_d = watershed soil incorporation depth or mixing depth (cm); BD = soil bulk density (g/cm^3); T = deposition period (yr^{-1}); D = annual dry deposition rate ($g\ m^{-2}\ yr^{-1}$); and W = annual wet deposition rate ($g\ m^{-2}\ yr^{-1}$). Based on atmospheric deposition rate and soil mercury concentration, mercury load from sediment, runoff, and impervious surface, direct deposition on water can be calculated for the selected subwatersheds in a WCS modeling project. The total watershed mercury load can be written as

$$Load_{total} = L_{erosion} + L_{runoff} + L_{impervious\ runoff} + L_{water} + L_{point\ source}$$

where L stands for mercury load.

The final results from the WCS mercury loading model are mercury loading tables and maps. All the loading tables and maps, as well as results of loading comparison between the different subwatersheds, can be exported to a Microsoft Word document using the automated reporting function.

Model Framework

- WCS Mercury Loading Model calculates sediment load, runoff, atmospheric deposition, and mercury concentration in watershed soils using grid-based data (e.g., land use and elevation). The model summarizes mercury load from various sources in each subwatershed of the study area.

Scale

Spatial Scale
- One-dimensional, subwatershed, grid

Temporal Scale
- Annual and long-term average

Assumptions
- Soil concentrations within a deposition grid are uniform within the grid and can be estimated by the following key parameters: dry and wet contaminant deposition rates, a set of soil transformation rates, a soil bulk density, and a soil mixing depth.
- The partition of mercury components among soil water and soil particle phases can be described by partition coefficient.
- The mercury gas phase in soil is insignificant in the total mercury mass balance, and the mercury reduction loss is equal to the volatilization loss.
- The total runoff of an area is a simple sum of the runoff of each grid, and there is no mercury loss when it is transported from a source cell to the watershed outlet through the runoff.
- The sediment transport can be described using an area-based delivery ratio formula.

Model Strengths
- ArcView 3.x based, calculates soil mercury concentrations and loading potential grid-by-grid
- Model is easy to setup and use
- Generates mercury load map showing contributions of different sources
- Generates maps and results table in an automatic report

Model Limitations
- Calculates only total mercury annual average load
- Lacks detailed algorithm for wetlands and forests
- Lacks mercury stream transport algorithm
- Lacks mercury input from soil parent material and mercury load calculation through shallow groundwater

Application History
The WCS Mercury Loading model was used to develop mercury TMDLs for the Middle and Lower Savannah River basins and many other areas in EPA Region 4 (http://www.epa.gov/region4/water/tmdl/general.htm).

Model Evaluation
Model has been tested and evaluated against the original IEM-2M spreadsheet watershed model. The model was also published in the Water Environment Federation Specialty Conference in 2002. The model has been applied to many TMDLs in EPA Region 4 since 2000.

Model Inputs
- Mercury atmospheric deposition rate or map
- Monthly average precipitation and temperature
- Mercury point sources
- Land use/cover map
- Soil map
- Digital elevation model
- Stream reach files

Users' Guide

Available online: http://wcs.tetratech-ffx.com/Documentation/index.htm

Technical Hardware/Software Requirements

Computer hardware:

- PC

Operating system:

- Microsoft Windows, requires ArcView 3.x and ArcView Spatial Analyst extension

Programming language:

- ArcView 3.x and Avenue script

Runtime estimates:

- Minutes to less than 1 hour

Linkages Supported

Output can be used with WASP (requires some manual processing)

Related Systems

Watershed Characterization System or WCS (http://wcs.tetratech-ffx.com)
BASINS (http://www.epa.gov/ostwater/BASINS/)

Sensitivity/Uncertainty/Calibration

Not available. For a calibration example, see "Total Maximum Daily Load (TMDL) for Total Mercury in Fish Tissue Residue in the Middle & Lower Savannah River Watershed" (USEPA Region 4, 2001).

Model Interface Capabilities

- ArcView 3.x as the user interface
- WCS system provides manual and auto delineation tools for watershed delineation
- WCS web site has core input datasets available for EPA Region 4, the data can be downloaded by USGS 8-digit hydrologic units in Region 4

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MIKE 11

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Download Information
Availability: Proprietary
Demo versions available online only.
Cost (if applicable): $3000

Model Overview/Abstract
MIKE 11 is a general river modeling system developed by DHI. MIKE 11 is the most advanced and comprehensive of its type today, and it is presently used by more than 1500 users around the world. MIKE 11 has become industry standard in many countries, including Australia, New Zealand, and Bangladesh and in many European countries. MIKE 11 contains modules for run-off simulations, hydrodynamics, flood forecasting, transport and dilution of dissolved substances, sediment transport, and river morphology as well as various water quality processes. MIKE 11 has an interface to GIS allowing for preparation of model input and presentation of model output in a GIS environment.

Model Features
A modular engineering tool for modeling conditions in rivers, lakes and reservoirs, irrigation canals, and other inland water systems. It is designed for

- Flood risk analysis and mapping
- Design of flood alleviation systems
- Real-time flood forecasting
- Real-time water quality forecasting and pollutant tracking
- Hydraulic analysis and design of structures, including bridges
- Drainage and irrigation studies
- Optimization of river and reservoir operations
- Dam break analysis
- Water quality issues
- Integrated groundwater and surface water analysis

Model Areas Supported

Watershed	Low
Receiving Water	High
Ecological	None
Air	None
Groundwater	Low

Model Capabilities

Conceptual Basis

The hydrodynamic module (HD), which is the core of MIKE 11, contains an implicit, finite difference computation of unsteady flows in rivers and estuaries. The formulations can be applied to branched and looped networks and quasi two-dimensional flow simulation on flood plains. The computational scheme is applicable to vertically homogeneous flow conditions ranging from steep river flows to tidally influenced estuaries. Both subcritical and supercritical flow can be described by means of a numerical scheme, which adapts according to the local flow conditions.

The complete nonlinear equations of open channel flow (Saint-Venant) can be solved numerically between all grid points at specified time intervals for given boundary conditions. In addition to this fully dynamic description, a choice of other flow descriptions is available:

- High-order, fully dynamic
- Diffusive wave
- Kinematic wave
- Quasi-steady state
- Kinematic routing (Muskingum, Muskingum-Cunge)

Within the standard HD module, advanced computational formulations enable flow over a variety of structures to be simulated:

- Broad-crested weirs
- Culverts
- Bridges
- Pumps
- Regulating structures
- Control structures
- Dam-break structures
- User-defined structures
- Tabulated structures

The HD module is available in a number of different sizes, which can be upgraded at any time.

Furthermore, a number of add-on modules are available, which ensures that the system can be tailored to suit the exact requirements.

Scientific Detail

The MIKE 11 hydrodynamic module (HD) uses an implicit, finite difference scheme for the computation of unsteady flows in rivers and estuaries. The module can describe subcritical as well as supercritical flow conditions through a numerical scheme that adapts according to the local flow conditions (in time and space). Advanced computational modules are included for description of flow over hydraulic structures, including possibilities to describe structure operation. The formulations can be applied to looped networks and quasi two-dimensional flow simulation on flood plains. The computational scheme is applicable for vertically homogeneous flow conditions extending from steep river flows to tidal influenced estuaries. The system has been used in numerous engineering studies around the world.

Model Framework

MIKE 11 consists of a hydrodynamic core module and a number of add-on modules, each simulating certain phenomena in a river system.

The modular structure offers great flexibility, because

- Each module can be operated separately
- Data transfer between modules is automatic
- Complex physical processes can be coupled (e.g., river morphology, sediment re-suspension and water quality)
- Updating or expansion of existing installations or models with new modules is simple

Scale

Spatial Scale

- One-dimensional model

Temporal Scale

- User-defined, variable timestep

Assumptions

The hydrodynamic module solves the complete nonlinear St. Venant equations for open-channel flow. It also includes a quasi-steady state solver for rapid calculation of long-term simulations. The model automatically adapts to subcritical and supercritical flow and can simulate a wide variety of flow structures, including weirs, culverts, bridges and user-defined structures. It also allows the flexible operation of flood control and reservoir structures (e.g., gates and pumps).

Model Strengths

Some of the strengths for the MIKE 11 model include

- MIKE 11 has an interface to GIS allowing for preparation of model input and presentation of model output in a GIS environment
- Easily links up to other MIKE models

Model Limitations

Some of the limitations for the MIKE 11 model include

- Need to purchase multiple modules to take full advantage of the system
- Significant data needed to setup

Application History

Everglades Agricultural Area (CERP). The project was highly demanding on local knowledge and required countless educated assumptions to be made with respect to agricultural and reservoir interactions.

Others: http://www.dhisoftware.com/MIKE11/News/MIKE_11_Applications.htm

Model Evaluation

http://www.dhisoftware.com/MIKE11/News/MIKE_11_Papers.htm

Model Inputs

- Graphical data input/editing
- Simultaneous input/editing of various data types
- Copy and paste facility for direct import (export) from, e.g., spreadsheet programs
- Fully integrated tabular and graphical windows
- Importing of river network and topography data from ASCII text files

- User-defined layout of all graphical views (colors, font settings, lines, marker types, etc.)

Users' Guide
Available online: http://www.dhisoftware.com

Technical Hardware/Software Requirements

Computer hardware:
- 128 Mb DRAM
- 1 Gb hard drive space
- Pentium 200 Mhz minimum

Operating system:
- MS Windows 98/2000/NT/XP

Programming language:
- None

Runtime estimates:
- Depends on CPU

Linkages Supported
Other MIKE models by DHI.

Related Systems
DHI series of MIKE models, built on the MIKE Zero interface.

Sensitivity/Uncertainty/Calibration
Built in Auto Calibration tool (http://www.dhisoftware.com/Generic_tools/index.htm)

Model Interface Capabilities
MIKE 11 is operated through an efficient Windows-based interactive Graphical User Interface including both graphical and tabular editing of data. The use of generic editors makes learning easy and efficient. Hence, the time from learning to production is short.

The advanced graphical facilities enable visual data checking and presentation of the information stored in data files and time series databases. The same graphical environment is used for data control, analysis, and presentation of results. The graphical presentation includes river network plan plots, cross-sectional plots, pre-selection of longitudinal profiles, time series plots, comparison of measured/simulated and simulated/simulated time series, animation of flows and water levels on both plans and profiles, control of plotting parameters, etc.

References
DHI Software. *Mike 11 References*. http://www.dhisoftware.com/MIKE11/News/MIKE_11_Papers.htm

MIKE 21

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Download Information

Availability: Proprietary
Demo versions available online only.
Cost (if applicable): $3000

Model Overview/Abstract

MIKE 21 is a professional engineering software package containing a comprehensive modeling system for two-dimensional free-surface flows. MIKE 21 is applicable to the simulation of hydraulic and related phenomena in lakes, estuaries, bays, coastal areas, and seas where stratification can be neglected.

MIKE 21 provides the design engineer with a unique and flexible modeling environment, using techniques that have set the standard in 2D modeling.

It is provided with a modern user-friendly interface facilitating the application of the system. A wide range of support software for use in data preparation, analysis of simulation results, and graphical presentation is included.

MIKE 21 is the result of more than 20 years of continuous development and is tuned through the experience gained from thousands of applications worldwide. DHI continues to use MIKE 21 in its own studies, thus giving a valuable symbiosis between development and application.

Model Features

MIKE 21 HD simulates water level and flow variations in river channels; on river floodplains (both urban and rural); and in lakes, estuaries and coastal areas in response to various forcing functions. The water levels and flows are resolved using a rectangular nested grid or tin or finite volume grid covering the area of interest, using the river channel and floodplain topography, bed resistance coefficients, and hydrographic boundary conditions.

MIKE 21 HD solves the vertically integrated, fully dynamic equations of continuity and conservation of momentum in two horizontal directions using implicit finite difference methods. The following effects are included in the equations:

- Convective and cross momentum
- Momentum dispersion
- Floodplain flooding and drying
- Evaporation
- Wind shear stress
- Supercritical flow

- Hydraulic structures

MIKE 21 HD forms the basis for calculations in additional MIKE 21 modules, describing advection dispersion, water quality, and sediment transport.

Model Areas Supported

Watershed	Low
Receiving Water	High
Ecological	None
Air	None
Groundwater	Low

Model Capabilities

MIKE 21 HD simulates water level and flow variations in river channels, on river floodplains (both urban and rural), and in lakes, estuaries, and coastal areas in response to various forcing functions. The water levels and flows are resolved using a rectangular nested grid or tin or finite volume grid covering the area of interest, using the river channel and floodplain topography, bed resistance coefficients, and hydrographic boundary conditions.

MIKE 21 HD solves the vertically integrated, fully dynamic equations of continuity and conservation of momentum in two horizontal directions, using implicit finite difference methods. The following effects are included in the equations:

- Convective and cross momentum
- Momentum dispersion
- Floodplain flooding and drying
- Evaporation
- Wind shear stress
- Supercritical flow
- Hydraulic structures

MIKE 21 HD forms the basis for calculations in additional MIKE 21 modules describing advection dispersion, water quality, and sediment transport.

Scale

Spatial Scale

In MIKE 21 HD, the floodplain and channel topography are described by a rectangular grid. The grid size is specified by the user and should be based on the level of topographical detail to be represented. MIKE 21 HD can be used to simulate two-dimensional flooding over a wide, flat, spatial range from small-scale urban situations, with channels only meters wide, to broad-scale river floodplains of several kilometers' width.

Temporal Scale

The temporal scale of MIKE 21 HD is characterized by its flexibility and is based on the boundary time series defined by the user. MIKE 21 HD has the flexibility to run short-scale, event-based time series or time series covering months or years of flow simulation. Boundary time series are entered into a database by the user, who also defines the length and timestep of the series.

Assumptions

MIKE 21 HD solves the vertically integrated, fully dynamic equations of continuity and conservation of momentum in two horizontal directions. Model parameters for MIKE 21 are

- Bed resistance
- Momentum dispersion (eddy) coefficients
- Wind friction factor (optional)

Model Strengths

Some of the strengths for the MIKE 21 model include

- MIKE 21 has an interface to GIS allowing for preparation of model input and presentation of model output in a GIS environment.
- Easily links up to other MIKE models.

Model Limitations

Some of the limitations for the MIKE 21 model include

- Need to purchase multiple modules to take full advantage of the system.
- Significant data needed to setup.

Application History

MIKE 21 HD has been utilized in a wide range of flooding-related studies worldwide including:

- Flood studies
- Floodplain management studies
- Flood protection studies, especially where a detailed description of the impact on flood flow patterns is required
- Dam break studies
- Urban flooding

Some of today's flood modeling systems offers a combination of a one-dimensional river hydraulics model and a two-dimensional surface water model. Combining such models provides a highly efficient modeling framework as benefits of both models can be applied where most appropriate. The modeler can apply detailed modeling and obtain accuracy where needed without sacrificing computational or model construction time.

MIKE FLOOD is a dynamically linked one-dimensional and two-dimensional flood-modeling package. The new tool is assembled from components taken from two of the most widely applied flood modeling packages - MIKE 11 and MIKE 21. MIKE FLOOD is FEMA-approved.

MIKE FLOOD provides a seamless coupling between river and floodplain, between the sea and inland waterways/bays/lagoons. Long river reaches may be dynamically linked to the adjacent floodplain, enabling accurate representation of complex lateral flood plain flooding and drainage. MIKE FLOOD offers extensive capabilities for accurately representing dams, levees, bridges, road crossings, culverts, and operational structures. GIS is used to process input data and for flood plain mapping.

Model Evaluation

A search of the Internet and recent publications did not yield any information for the MIKE 21 model evaluation.

Model Inputs

- Basic model parameters
    - Model grid size and extent
    - Timestep and length of simulation
    - Type of output required and its frequency

- River channel and floodplain topography
- Calibration factors
    - Bed resistance coefficients
    - Momentum dispersion coefficients
    - Wind friction factor (optional)
- Boundary conditions
    - Water levels or flow magnitudes
    - Flow direction

MIKE 21 HD utilizes the powerful and flexible MIKE Zero graphical interface for the input and pre- and post-processing of data.

Users' Guide

MIKE 21 HD is supported by thorough online-help system and user manual and technical reference documentation.

In addition, DHI offers a comprehensive system of technical support through its dedicated Software Support Center. 24-hour assistance from DHI's technical staff can be obtained through the Software Support Center via telephone hotline, fax, or the Internet. As a part of License Service Agreements, DHI software users are updated regularly with software developments via newsletters and Internet broadcasts.

Technical Hardware/Software Requirements

Computer hardware:

- 128 Mb DRAM
- 1 Gb hard drive space
- Pentium 200 Mhz minimum

Operating system:

- MS Windows 98/2000/NT/XP

Programming language:

- None

Runtime estimates:

- Depends on CPU

Linkages Supported

Other MIKE models by DHI.

Related Systems

DHI series of MIKE models, built on the MIKE Zero interface.

Sensitivity/Uncertainty/Calibration

Parameter Estimation/Model Calibration

MIKE 21 HD has three calibration parameters, namely bed resistance factor, momentum dispersion (eddy) coefficient, and wind friction factor (optional). Calibration of the model can be achieved easily by adjustment of these factors. In practice, the calibration of a model depends more on the accuracy of the available data (e.g., topography and boundary time series definition) than the model parameters. Model calibration parameters are chosen by the user. Instruction and guidelines for parameter selection are provided in the model documentation and online help. Further information on parameter selection is available from a wide choice of published references and case studies.

Model Testing and Verification
MIKE 21 HD has been extensively tested on a wide range of coastal and flood projects worldwide and has a proven record of accomplishment within the wider consulting community. A list of applications and case studies is available on the DHI web site or by contacting DHI directly.

Model Sensitivity
The sensitivity of MIKE 21 HD to calibration parameters is largely case-dependent (e.g., in areas where the floodplain topography is uniform and the flood slope gentle, little sensitivity to parameters is observed). However, on floodplains with rapidly varying topographies or steep floodwater slopes, model outputs may be more sensitive to the parameter values chosen.

Model Reliability
MIKE 21 HD has a reliability proven over many years on numerous projects worldwide. When properly calibrated, MIKE 21 HD can predict flood levels to within 0.05m and flood flows and velocities to within 10 percent of observed data.

Model Interface Capabilities
MIKE 21 is operated through an efficient Windows-based interactive Graphical User Interface including both graphical and tabular editing of data. The use of generic editors makes learning easy and efficient. Hence, the time from learning to production is short.

The advanced graphical facilities enable visual data checking and presentation of the information stored in data files and time series databases. The same graphical environment is used for data control, analysis, and presentation of results. The graphical presentation includes river network plan plots, cross-sectional plots, preselection of longitudinal profiles, time series plots, comparison of measured/simulated and simulated/simulated time series, animation of flows and water levels on both plans and profiles, control of plotting parameters, etc.

References
DHI Software. 2004. *Coastal and Inland Waters in 2D.* http://www.dhisoftware.com/MIKE21/

MIKE SHE

Contact Information

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www.dhigroup.com
Demo versions available online only.

Download Information

Availability: Proprietary
Cost (if applicable): $3000

Model Overview/Abstract

The MIKE SHE code is a powerful, physically based, distributed parameter, fully integrated code for three-dimensional simulation of hydrologic systems. It has been successfully applied at multiple scales, using spatially distributed and continuous climate data to simulate a broad range of integrated hydrologic, hydraulic, and transport problems in humid as well as in more arid areas. (See http://typhoon.mines.edu/software/igwmcsoft/mikeshe.htm.)

Model Features

MIKE SHE can be used for the analysis, planning, and management of a wide range of water resources and environmental problems related to surface water and groundwater, such as

- Surface water impact from groundwater withdrawal
- Conjunctive use of groundwater and surface water
- Wetland management and restoration
- River basin management and planning
- Environmental impact assessments
- Aquifer vulnerability mapping with dynamic recharge and surface water boundaries
- Groundwater management
- Floodplain studies
- Impact studies for changes in land use and climate
- Impact studies of agricultural practices including irrigation, drainage, and nutrient and pesticide management with DAISY

Model Areas Supported

Watershed	Medium
Receiving Water	High
Ecological	Low
Air	None
Groundwater	High

Model Capabilities

Conceptual Basis

- Can simulate all the major processes in the land phase of the hydrologic cycle
- Is applicable on spatial scales ranging from single soil profiles (for infiltration studies) to regional watershed studies
- Includes both simple and advanced process descriptions to maximize computational efficiency
- Has a flexible modular structure that allows users to include only the necessary processes
- Easily links regional and local scale models
- Can be linked to ESRI's ArcView for advanced GIS applications
- Includes alternate process descriptions for different applications
- Links to original data rather than importing the data
- Allows you to update your original data, and your model is automatically updated
- Includes a dynamic data tree that gives you a precise overview of all your data
- Has automatic data and model verification routines
- Includes sophisticated output tools, including animations
- Manipulating time varying data
- Model calibration
- Water and mass balance analysis

Scientific Detail

The MIKE SHE code couples several partial differential equations that describe flow in the saturated and unsaturated zones with overland and channel flow. Different numerical solution schemes are then used to solve the different partial differential equations for each process. A solution to the system of equations associated with each process is found iteratively by use of different numerical solvers.

Model Framework

Internally coupled groundwater and surface water model.

Scale

Spatial Scale

- Grid-based model.

Temporal Scale

- User-defined, variable timestep.

Assumptions

Several assumptions are associated with use of the specific partial differential equations. The significant assumptions that have direct implications to the application of the MIKE SHE code to the RFETS SWWB model include the following.

Unsaturated Zone

The main assumption is that flow is one-dimensional and vertical. In some cases, for example, beneath ephemeral streams, or near buildings/paved areas, or below trenches, flow in the unsaturated zone may actually have local areas where flow is horizontal, causing this vertical-flow assumption to be violated. However, it is currently believed that these local areas will not significantly affect the interpretation of site-wide conditions.

Other Unsaturated Zone processes not simulated in MIKE SHE Zone include the following:

- Hysteresis

- Air entrapment
- Vapor transport
- Freezing and thawing of soils

Although, locally these processes exert strong influences on unsaturated zone flow, their effects will likely be much less pronounced on the site-wide model dynamics and mass balance than other factors (e.g., precipitation intensity and distribution, saturated hydraulic conductivities, and hydrostratigraphic structure).

Saturated Zone

Properties are uniform within a single grid cell. In reality, porous media properties likely vary by orders of magnitude within each grid cell. On average, however, these local scale variations are not expected to control the site-wide flow dynamics or mass balance, and it is reasonable to assume that properties can be averaged. Comparisons of model simulations with observed sitewide data will help to confirm this assumption.

Overland Flow

The kinematic wave approximation is used in MIKE SHE to simulate overland flow. This simplification to the full Saint Venant flow equations does not permit detailed simulation of backwater effects; however, given the anticipated grid resolution of the sitewide model, the assumption is reasonable. Specific hydrologic processes, such as rill-flow, are not considered in this code, but at the scale considered for application these processes are not likely to be strong controls of flow.
See http://www.dhisoftware.com/mikeshe/Reviews/External_Evaluations/RFETS_2-20-01.PDF.

Model Strengths

Some of the strengths for the MIKE SHE model include

- MIKE SHE has an interface to GIS allowing for preparation of model input and presentation of model output in a GIS environment
- Easily links up to other MIKE models

Model Limitations

Some of the limitations for the MIKE SHE model include

- Need to purchase multiple modules to take full advantage of the system
- Significant data needed to setup

Application History

The model has limited verification. See http://www.dhisoftware.com/mikeshe/Reviews/ for more information.

Model Evaluation

See http://www.dhisoftware.com/mikeshe/Reviews/index.htm.

Model Inputs

MIKE SHE includes all of the processes in the land phase of the hydrologic cycle:

- Precipitation (rain or snow)
- Evapotranspiration, including canopy interception
- Overland sheet flow
- Channel flow
- Unsaturated sub-surface flow
- Saturated groundwater flow

Within each of these, MIKE SHE offers several different approaches ranging from simple, lumped, and conceptual approaches to advanced, distributed, and physically based approaches. Simple and advanced approaches may be combined, which leads to an unparalleled flexibility that truly enables you to tailor the model to the hydrological problem rather than the opposite. Changing from a simple to a more advanced approach, or vice versa, is seamless and utilizes, to the extent possible, the existing data.
See http://www.sfwmd.gov/org/exo/cwmp/mikeshe/finalreport.html#_Toc455045031.

Users' Guide

Available online: http://www.dhisoftware.com

Technical Hardware/Software Requirements

Computer hardware:

- 128 Mb DRAM
- 1 Gb hard drive space
- Pentium 200 Mhz minimum

Operating system:

- MS Windows 98/2000/NT/XP

Programming language:

- None

Runtime estimates:

- Depends on CPU

Linkages Supported

Other MIKE models by DHI.

Related Systems

DHI series of MIKE models, built on the MIKE Zero interface.

Sensitivity/Uncertainty/Calibration

Built in Auto Calibration tool (http://www.dhisoftware.com/Generic_tools/index.htm).

Model Interface Capabilities

- **Dynamic navigation tree** – gives you a complete overview of your model while hiding irrelevant items
- **Logical, dynamic dialogs** – allows you to concentrate on the required data, because subdialogs contain only relevant parameters
- **Top-down/Left-right model design** – leads you through the model development in a natural manner
- **Automatic data checking** – saves you time trying to decipher obscure run-time errors
- **Online documentation** – Comprehensive, context sensitive online documentation allows you to find answers quickly

The MIKE SHE user interface has been designed to make it easy for you to move from your conceptual model to your results and back again.

- **Stores the <u>link</u> to your original data** – not the original data itself, which gives you unprecedented flexibility, for example, you can
  - Run multiple models from the same dataset
  - Update your data and update all your models automatically
  - Run rapid sensitivity analyses on your model domain, grid spacing, layer specifications, etc.
  - Use your favorite editor for managing your data
- **GIS integration** – the seamless link to ArcView shape files for all distributed parameters and overlays saves you time and effort
- **Geo-objects for natural, object-oriented model design** – input your natural geologic formations (including lenses!) and let MIKE SHE take care of the conversion to the numerical grid
- **Link models together** – easily link local-scale models to regional-scale models or multiple regional models together to include interactions between watersheds

See http://www.dhisoftware.com/mikeshe/Interface/index.htm.

References

DHI Software. *Mike SHE External Reviews.* http://www.dhisoftware.com/mikeshe/Reviews/index.htm

MINTEQA2: Metal Speciation Equilibrium Model for Surface and Groundwater

Contact Information

U.S. Environmental Protection Agency
Office of Research and Development
National Exposure Research Laboratory
Center for Environmental Assessment Modeling
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ceam@epamail.epa.gov
http://www.epa.gov/ceampubl/mmedia/minteq/index.htm

Download Information

Availability: Nonproprietary
Cost: N/A

Model Overview/Abstract

MINTEQA2, a geochemical equilibrium speciation model for dilute aqueous systems, is an update of MINTEQ, which was developed by combining the fundamental mathematical structure of MINEQL with the thermodynamic data base of WATEQ3. MINTEQA2 is an equilibrium speciation model that can be used to calculate the equilibrium composition of dilute aqueous solutions in the laboratory or in natural aqueous systems. The model is useful for calculating the equilibrium mass distribution among dissolved species, adsorbed species, and multiple solid phases under a variety of conditions, including a gas phase with constant partial pressures. A comprehensive database is included that is adequate for solving a broad range of problems without need for additional user-supplied equilibrium constants. The model employs a predefined set of components that includes free ions, such as Na+, and neutral and charged complexes (e.g., H4SiO4, Cr(OH)2+). The database of reactions is written in terms of these components as reactants. An ancillary program, PRODEFA2, serves as an interactive preprocessor to help produce the required MINTEQA2 input files.

Model Features

- The equilibrium mass distribution among dissolved species, adsorbed species, and multiple solid phases under a variety of conditions, including a gas phase with constant partial pressures

Model Areas Supported

Watershed	None
Receiving Water	High for metals chemistry
Ecological	None
Air	None
Groundwater	None

Model Capabilities

Conceptual Basis

MINTEQA2 calculates the equilibrium composition of dilute aqueous solutions in the laboratory or in natural aqueous systems.

Scientific Detail

To solve the chemical equilibrium problem, MINTEQA2 uses an initial guess for the activity of each component to calculate the concentration of each species according to mass action expressions written in terms of component activities. The total mass of each component is then calculated from the concentrations of every species containing that component. The calculated total mass for each component is then compared with the known input total mass for each component. If the calculated total mass and the known input total mass for any component differ by more than a pre-set tolerance level, a new estimate of the component activity is made, and the entire procedure is repeated (Newton-Raphson approximation method). After equilibrating the aqueous phase, MINTEQA2 computes the saturation index (SI) for each possible solid with respect to the solution. The solid with the most positive SI is allowed to precipitate by depleting the dissolved concentrations of those components comprising the solid in accordance with the known stoichiometry of each component. The reverse process occurs if an existing solid is found to be undersaturated with respect to the solution. In either case, it is necessary to re-equilibrate the solution after mass has been added to or depleted from the aqueous phase. Thus, the aqueous solution is re-equilibrated just as before except with one less degree of freedom, if precipitation has occurred, or one more, if dissolution has occurred. The entire computational loop of iterating to equilibrium, checking for precipitation or dissolution, and shifting mass from the aqueous to the solid phase or vice versa is repeated until equilibrium is achieved and there are no oversaturated possible solids and no undersaturated existing solids. The model calculates simultaneous solutions of nonlinear mass action expressions and linear mass balance relationships.

Model Framework

- Dilute aqueous solutions in the laboratory or in natural aqueous systems

Scale

Spatial Scale

None

Temporal Scale

None

Assumptions

- Chemical reactions are based on equilibrium concept

Model Strengths

- Capable of simulating detailed chemical speciation simulations, including dissolved species, adsorbed species, and multiple solid phases under a variety of conditions

Model Limitations

- Does not include time series calculation capability

Application History

MINTEQA2 has been used for numerous applications to groundwater and surface water by USGS, EPA, and academic institutions.

Model Evaluation

The model has been internally peer reviewed by EPA Science Advisory Board (SAB) and ERD-Athens internal review panels. Model has been externally peer reviewed via publications in the technical literature.

Model Inputs

- Total concentrations

Users' Guide

Available online: http://www.epa.gov/ceampubl/mmedia/minteq/index.htm

Technical Hardware/Software Requirements

Computer hardware:

- PC

Operating system:

- PC-DOS

Programming language:

- FORTRAN

Runtime estimates:

- Seconds

Linkages Supported

None

Related Systems

PHREEQ

Sensitivity/Uncertainty/Calibration

Not available

Model Interface Capabilities

Not available

References

Benjamin, M.M. and J.O. Leckie. 1981. Multiple-Site Adsorption of Cd, Cu, Zn, and Pb on Amorphous Iron Oxyhydroxide. J. Coll. Inter. Sci. 79:209-221.

Davies, C.W. 1962. *Ion Association*. Butterworths Pub., Washington, DC.

Davis, J.A., R.O. James and J.O. Leckie. 1978. Surface Ionization and Complexation at the Oxide/Water Interface: I. Computation of Electrical Double Layer Properties in Simple Electrolytes. J. Coll. Inter. Sci. 63:480-499.

Davis, J.A. and J.O. Leckie. 1978. Surface Ionization and Complexation at the Oxide/Water Interface: II. Surface Properties of Amorphous Iron Oxyhydroxide and Adsorption of Metal Ions. J. Coll. Inter. Sci. 67:90-107.

Dzombak, D.A. 1986. Toward a Uniform Model for the Sorption of Inorganic Ions on Hydrous Oxides. Ph.D. diss., Massachusetts Institute of Technology, Cambridge Massachusetts.

Felmy, A.R., D.C. Girvin, and E.A. Jenne. 1984. *MINTEQ--A Computer Program for Calculating Aqueous Geochemical Equilibria*. EPA-600/3-84-O32. U.S. Environmental Protection Agency, Athens, GA..

MUSIC: Model for Urban Stormwater Improvement Conceptualization

Contact Information

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http://www.toolkit.net.au/music

Download Information

Availability: Proprietary
Cost: $330 for new user

Model Overview/Abstract

The Model for Urban Stormwater Improvement Conceptualization (MUSIC) was developed by the Cooperative Research Center (CRC) for Catchment Hydrology in Australia. MUSIC is designed to simulate urban stormwater systems operating at a range of temporal and spatial scales: catchments from 0.01 km^2 to 100 km^2 and modeling timesteps ranging from 6 minutes to 24 hours to match the catchment's scale. MUSIC provides a user-friendly interface, to allow complex stormwater management scenarios to be quickly and efficiently created, and the results to be viewed using a range of graphical and tabular formats. The stormwater control devices that can be simulated in MUSIC include ponds, bioretention, infiltration buffer strips, sedimentation basins, pollutant traps, wetlands, and swales. Major algorithms applied in BMP simulation are Continuously Stirred Tank Reactors (CSTRs) in series model and first-order decay (k-C* model).

Model Features

- Urban stormwater treatment conceptual design tool

Model Areas Supported

Watershed	Medium (urban)
Receiving Water	Low
Ecological	None
Air	None
Groundwater	Low

Model Capabilities

Conceptual Basis

The algorithm adopted to generate urban runoff is based on a simplified mass balance model that was developed by Chiew et al. (1997). For simulation of BMPs, the Plus Method for reservoir routing is used to simulate the movement of water through the treatment system, and a first-order kinetic model combined with the Continuously Stirred Tank Reactors (CSTRs) model to simulate the removal of pollutants within the treatment system.

Scientific Detail

The simplified rainfall-runoff model (Chiew et al., 1997) is a mass balance model, which involves potential ET, impervious storage, soil moisture storage, and a groundwater component.

For stormwater treatment process simulation, assume that the pollutant removal is a first-order decay process toward an equilibrium value. This behavior is described by the first-order kinetic (k-C*) model, in which C* is the background concentration, and k is the decay rate constant. In addition, the number of CSTRs is used to reflect the shape factor on pollutant removal effectiveness. The concentration attenuation simulated by the k-C* model is computed separately at each timestep for each CSTR.

Model Framework

A catchment (the entire catchment being simulated) is made up of a number of nodes, joined together by drainage links. The catchment may contain a number of subcatchments, which are called source nodes. Three types of source nodes represent three default land uses: urban, agricultural and forested. these source nodes differ only in their default baseflow and stormflow pollutant concentrations. Users therefore can create source nodes to simulate any type of land use (e.g. road runoff), using their own water quality data. A catchment contains only one receiving node, which represents the receiving waterway (e.g. River, lake, bay). A catchment may also have a number of junction nodes, which simply act as confluences. They have no effect on flow or water quality; they simply join multiple upstream nodes into one. Treatment nodes are used to represent stormwater treatment measures.

Scale

Spatial Scale

- Catchment, 0.01 km^2 to 100 km^2

Temporal Scale

- 6 minutes to 24 hours

Assumptions

- Physical process (sedimentation) is the predominant pollutant removal mechanism during the event and is described by the order kinetics (k-C*) model
- Constant seepage rate for infiltration processes

Model Strengths

- Includes an intuitive and user-friendly interface
- Capable of simulating various type of BMPs
- Suitable for evaluation of urban stormwater treatment conceptual design

Model Limitations

- The first-order kinetics (k-C*) modeling approach adopted in the USTM strictly applies only during event operation. The parameter k lumps together the influence of a number of predominantly physical factors on the removal of stormwater pollutants. While the assumption of a predominance of physical removal processes during storm event operation is reasonable for particulate (inorganic) contaminants, other factors associated with chemical and biological processes can also be significant. These factors are currently not accounted for in the determination of k. The background concentration C* is assumed to be a constant at present and therefore does not reflect the influence of hydraulic loading, flow velocity, and other factors on water quality of stormwater runoff.
- The treatment device infiltration process is simulated by applying a constant seepage rate.

- Default empirical parameters values provided in the model were derived from monitoring data collected in Australia, and it is strongly recommended that the model be calibrated before it is applied.

Application History
The model has been applied mainly in Australia.

Model Evaluation
Not available

Model Inputs
- Climate data (MUSIC comes with Bureau of Meteorology-formatted climate files for 30 reference cities widely distributed throughout Australia.)
- Catchment characteristics (area, land use, impervious area, etc)
- Conceptual designs of stormwater treatment measures (type, size, etc)

Users' Guide
Available online: http://www.toolkit.net.au/music

Technical Hardware/Software Requirements

Computer hardware:
- Intel-based PC with CD-ROM drive
- Pentium III 750Mhz (preferably 1GHz)
- 256Mb RAM (preferably 512 Mb)
- 5Gb of free hard drive space (preferably 10Gb)
- Monitor capable of 800 x 600 pixels (preferably 1024 x 768) @ 8-bit (256) colors (preferably 16-bit)

Operating system:
- Microsoft Windows 2000/XP

Programming language:
- Unknown

Runtime estimates:
- Minutes to hours

Linkages Supported
None

Related Systems
None

Sensitivity/Uncertainty/Calibration
Displays the observed value with modeled time series to facilitate calibration process.

Model Interface Capabilities

- Graphical user interface for node/link network construction and data input, viewing, and editing
- Post-processor displays time series graphs, tables of statistics, cumulative frequency graphs, and file export

References

Chiew, F.H.S. & McMahon, T. A. 1997. Modelling Daily Runoff and Pollutant Load from Urban Catchments. Water – Journal of the Australian Water Association. 24:16-17.

Wong, T. H. F., Duncan, H. P., Fletcher, T. D., Jenkins, G. A., & Coleman, J. R. 2001. A unified approach to modelling urban stormwater treatment. Paper presented at the Second South Pacific Stormwater Conference, June 27-29, 2001, Auckland, New Zealand.

Wong, T.H.F. 2000. Improving Urban Stormwater Quality – From Theory to Implementation. Water – Journal of the Australian Water Association. 27(6):28-31.

P8-UCM: Program for Predicting Polluting Particle Passage through Pits, Puddles, and Ponds—Urban Catchment Model

Contact Information

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Download Information

Availability: Nonproprietary
http://wwwalker.net/p8/
Cost: N/A

Model Overview/Abstract

P8 is a model for predicting the generation and transport of stormwater pollutants in urban watersheds. Continuous water balance and mass balance calculations are performed on a user-defined system consisting of watersheds, devices (runoff storage/treatment areas, BMPs), particle classes, and water quality components. Simulations are driven by continuous hourly rainfall and daily air temperature time series data. The model simulates pollutant transport and removal in a variety of treatment devices (BMPs), including swales, buffer strips, detention ponds (dry, wet, and extended), flow splitters, and infiltration basins (offline and online), pipes, and aquifers. Water quality components include total suspended solids (TSS) (five size fractions), total phosphorus (TP), total Kjeldahl nitrogen (TKN), copper, lead, zinc, and hydrocarbons.

Model Features

- Urban watershed hydrology
- Urban pollutants
- Stormwater BMPs

Model Areas Supported

Watershed	Medium
Receiving Water	Low
Ecological	None
Air	None
Groundwater	Low

Model Capabilities

Conceptual Basis

In P8-UCM, continuous water balance and mass balance calculations are performed on a user-defined system consisting of watersheds (pervious and impervious areas are separately considered), devices (runoff storage/treatment areas, BMPs), particle classes, and water quality components.

Scientific Detail

Runoff from pervious areas is computed using the Soil Conservation Service's (SCS) curve number technique. Antecedent moisture conditions are adjusted, based on 5-day antecedent precipitation and season. Percolation from pervious areas is estimated by water balance at the surface (percolation = precipitation – runoff – evapotranspiration). Evapotranspiration is computed from air temperature and season using Hamon's method. Runoff from impervious areas starts after the cumulative storm rainfall exceeds the specified depression storage. Both rainfall and snowmelt are considered in runoff estimations. Particle concentrations in runoff from pervious areas are computed using a method similar to the sediment rating curve included in EPA's Stormwater Management Model (SWMM). Particle loads from impervious areas are computed using either or both of two techniques: (1) particle accumulation and washoff and/or (2) fixed runoff concentration. The first method is used in default particle datasets. An exponential washoff relationship similar to that employed in SWMM is used to simulate particle buildup and washoff from impervious surfaces.

Receiving water processes are limited to devices, ponds, infiltration basins, and shallow channels. Storage area or volume and outflow relations represent flow in ponds. Shallow channel flow is estimated by Manning equation. Settling and transport of sediments are simulated in the model.

Model Framework

- Watershed model
- Shallow channels, ponds, infiltration basins, and storage devices

Scale

Spatial Scale

- Subwatersheds

Temporal Scale

- Hourly

Assumptions

- A watershed is divided into a lumped pervious area and a lumped impervious area.
- SCS Curve Number approach is appropriate for estimating surface runoff.
- All the pollutants entering the waterbodies are sediment-adsorbed.

Model Strengths

- A simple model that requires moderate effort to setup, calibrate, and validate
- Simulates urban stormwater BMPs and wetlands

Model Limitations

- SCS Curve Number approach at hourly timestep requires substantial calibration
- Limited capability in flow and pollutant routing
- Limited capability in groundwater process and groundwater and surface water interaction

Application History

P8 is widely applied in the Northeast and Midwest regions of the United States, especially to size stormwater BMPs in urban watersheds.

Model Evaluation

P8 documentation presents model evaluation in various applications.

Model Inputs

- Climate data: hourly precipitation and daily air temperature
- 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/washoff parameters, runoff concentrations, street-sweeper efficiencies, settling velocities, decay rates, filtration efficiencies
- Water quality component parameters: pollutant concentrations

Users' Guide

Available online: http://www.wwwalker.net/p8/p8v1doc.pdf

Technical Hardware/Software Requirements

Computer hardware:

- PC

Operating system:

- PC-DOS

Programming language:

- FORTRAN

Runtime estimates:

- Minutes to less than an hour

Linkages Supported

None

Related Systems

None

Sensitivity/Uncertainty/Calibration

Built in capability for calibration and sensitivity analysis

Model Interface Capabilities

- DOS User Interface
- P8CONV – a preprocessor to develop precipitation input file

References

Palmstrom, N. & W. Walker. 1990. *The P8 Urban Catchment Model for Evaluating Nonpoint Source Controls at the Local Level, Enhancing States' Lake Management Programs.* U.S. Environmental Protection Agency, Washington, DC.

U.S. Environmental Protection Agency (USEPA). 1992. *Compendium of Watershed-Scale Models for TMDL Development.* EPA841-R-92-002. U.S. Environmental Protection Agency, Office of Water, Washington, DC.

HDR Inc. 1992. *Evaluation of Storm Water Computer Models*. Prepared for City of Minneapolis by HDR Inc.

U.S. Environmental Protection Agency (USEPA). 1997. *Compendium of Tools for Watershed Assessment & TMDL Development*. EPA841-B-97-006. U.S. Environmental Protection Agency, Office of Water, Washington, DC.

Walker, W. 1990. *P8 Urban Catchment Model Program Documentation Version 1.1*. (Computer program). IEP, Inc., Northboroug, MA and Narragansett Bay Project, Providence, RI.

PCSWMM: Storm Water Management Model

Contact Information

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http://www.computationalhydraulics.com/

Download Information

Availability: Proprietary
http://www.computationalhydraulics.com/Software/PCSWMM/index.html
Cost: $599.95

Model Overview/Abstract

PCSWMM 2003 has a menu-driven interface for running the EPA's Stormwater Management Model (SWMM) and providing hydro/pollutographs and animated hydraulic gradelines. It is suitable for projects ranging from small BMP installations to continuous hydrology, hydraulics and quality simulation of major and minor drainage systems. It also provides GIS links to the EPA's SWMM core processes.

PCSWMM 2003 is flexible to be used with any of the following versions of the SWMM engine: WMM4.4h, SWMM4.3 and later SWMM4.31, 4.40 and 4.4gu releases. PCSWMM fully supports all modules of SWMM, including the Rain, Temperature, Runoff, Transport, Extran, Storage/Treatment, Combine, and Statistics modules.

Model Features

- Watershed hydrology and water quality
- Stream transport
- Urban stormwater systems and pipes

Model Areas Supported

Watershed	High
Receiving Water	Medium
Ecological	None
Air	None
Groundwater	Low

Model Capabilities

Conceptual Basis

The basic spatial unit for SWMM is the subcatchment, into which the modeled watershed is subdivided. Several small subwatersheds and representative streams may be networked together to represent a larger watershed drainage area. The SWMM-RUNOFF and SWMM-TRANSPORT modules can be used to simulate various processes, both on land and in-stream.

Scientific Detail

Infiltration is calculated using the Horton or Green-Ampt methods, at the user's choice. A version of Manning's equation is used to estimate flow rate from the subcatchment area based on a conceptual model of the subcatchment as a "nonlinear reservoir." The lumped storage scheme is applied for soil and groundwater modeling. For impervious areas, a linear formulation is used to compute daily and 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.

Transport block has kinematic wave routing of flow and quality, base flow generation, and infiltration capabilities, and it routes flow through user-defined system ranges from natural channel to concrete pipes. The EXTRAN block carries out a numerical solution of the complete St. Venant equations for the urban drainageways and conduits, by modeling the network as a link-node system (cf., DYNHYD). SWMM can directly be interfaced with EPA's WASP receiving water quality model.

Model Framework

- Subwatersheds and watershed
- One-dimensional mass balance flow and pollutant routing

Scale

Spatial Scale

- Subwatershed. Flexible size
- One-dimensional channel/pipe system

Temporal Scale

- User-defined timestep, typically hourly

Assumptions

- The model performs best in urbanized areas with impervious drainage, although it has been widely used elsewhere.
- Model parameters for quantity and quality simulations are developed such that the model will be calibrated to enhance its capability.
- Water table elevation is assumed to be fixed value.
- All the pollutants entering the waterbodies are sediment-adsorbed.

Model Strengths

- Unlimited model size
- Flexible input file editor
- Easy to setup SWMM runs
- Hot-swapping SWMM engines
- User friendly
- Sensitivity, calibration, and error analysis tools
- Full support of all SWMM modules and procedures

Model Limitations

- Not a public domain product
- Lack of subsurface quality routing
- No interaction of quality processes
- Limited kinetics (a first-order decay rate can be specified for each pollutant in the Transport Block)
- Difficulty in simulation of wetlands quality processes

- Rudimentary scour-deposition routine in the Transport Block

Application History

SWMM is applied to urban hydrologic quantity and 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 of 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.

Model Evaluation

It is widely applied in Florida, but the applications are limited primarily to urban areas, stormwater studies, and event based applications.

Model Inputs

- Data requirements for hydrologic simulation include area, imperviousness, slope, roughness, width, depression storage, and infiltration parameters. Land use data are used to determine ground cover type for each model subarea.
- Depending on the options set for the loading calculations, additional parameters are necessary (e.g., buildup coefficients would be needed for the dry weather buildup simulation).
- Additional data are necessary if the user intends to model subsurface drainage and interflow.
- Depending on the stormwater system, dimensions, slope, roughness coefficients, elevations, storage, etc., are required.
- Continuous records of evapotranspiration, temperature, and solar intensity

Users' Guide

Available online: http://www.computationalhydraulics.com/Publications/Books/r219.html
Cost: $85

Technical Hardware/Software Requirements

Computer hardware:

- PC with 50MB available hard-drive space and preferably 256MB RAM

Operating system:

- Microsoft Windows

Programming language:

- FORTRAN (model) and Visual Basic (interface)

Runtime estimates:

- Minutes to less than an hour

Linkages Supported

EPA's Stormwater Management Model (SWMM)

Related Systems

PCSWMM provides a SWMM environment for model development, display and analysis. GIS component of PCSWMM is completely rewritten with innovative model creation and output visualization tools.

Sensitivity/Uncertainty/Calibration

The Genetic Algorithm Calibration tool is provided in PCSWMM for the complete calibration of SWMM Runoff, Transport, Extran and/or Storage Treatment modules. It significantly reduces the effort required for calibration and design optimization. This tool helps in model development and verification.

Model Interface Capabilities

- User-friendly model interface
- Graphical dialog boxes
- Data input is through wizard-style interface technology
- Data entry and model output in graphical form
- Animated hydraulic grade lines and multiple observed vs. computed plots provide visualizations of model results
- Background layer support for ArcView, AutoCAD, MapInfo, TIFF, JPEG, and BMP

References

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Warwick, J. J., and P. Tadepalli. 1991. Efficacy of SWMM application. Journal of Water Resources Planning and Management. 117(3):352-366.

PGC - BMP Module: Prince George's County Best Management Practice Module

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Download Information

Availability: Nonproprietary
Cost: N/A

Model Overview/Abstract

Prince George's County, working with Tetra Tech, Inc., developed a best management practice (BMP) evaluation module to assist in assessing the effectiveness of low-impact development (LID) technology. This module uses simplified process-based algorithms to simulate BMP control of modeled flow and water quality time series generated from runoff models such as the HSPF. These unit-process algorithms include weir and orifice control structures, storm swale characteristics, flow and pollutant transport, flow routing and networking, infiltration and saturation, evapotranspiration, and a general loss/decay representation for a pollutant. The module offers the user the flexibility to design retention style or open-channel BMPs, define flow routing through a BMP or BMP network, simulate IMPs such as reduced or discontinued imperviousness through flow networking, and compare BMP controls against some defined benchmark such as a simulated pre-development condition. Because the underlying algorithms are based on physical processes, BMP effectiveness can be evaluated and estimated over a wide range of storm conditions, BMP designs, and flow routing configurations. Such a tool provides a quantitative medium for assessing and designing TMDL allocation scenarios and evaluating the effectiveness of a proposed management approach.

Model Features

- Retention-style BMP simulation
- Open-channel BMP simulation
- Soil media storage, infiltration, and filtration
- Time series input and output simulation
- Linked water quality, with generalized first-order pollutant loss and filtration loss

Model Areas Supported

Watershed	Medium
Receiving Water	Medium
Ecological	Low
Air	None
Groundwater	Low

Model Capabilities

Conceptual Basis

The BMP module requires unit-area time series of runoff from different land uses, typically generated by a related watershed model of the area. It offers the flexibility to schematically represent the site's land parcel distribution and flow routing (from land segment to BMP or BMP to BMP). Each BMP represents an evaluation point, where the effect of the BMP or BMP network is assessed. An analysis spreadsheet allows the user to compare the developed condition with and without BMPs to the pre-developed condition (typically represented as an equal-area forest site). Analysis includes long-term volume and loads, storm-by-storm hydrograph and pollutograph comparison, and multi-storm trend analysis for peak flow, volume control, and pollutant load reduction.

Scientific Detail

An external model that is capable of generating hourly time series of flow and pollutant load is used to generate the required runoff inputs for the BMP Module. Examples of such models include HSPF, LSPC, and SWMM. The primary function of the BMP Module is to provide detailed simulation of processes within BMPs. The BMP Module presents two main categories for BMPs: Class A, retention/detention structures, and Class B, open-channel structures. Between these two categories, the actual BMP unit processes may be combined interchangeably to represent a wide range of BMPs. These BMP unit processes include (or are influenced by) evapotranspiration, infiltration, orifice outflow, under-drain outflow, weir-controlled overflow or spillway, BMP bottom slope, bottom roughness, soil media filtration of pollutant using under-drain outflow, and general first-order loss or decay of pollutant. Computational methods include standard rectangular or triangular weir equations, orifice equations, Manning's Equation coupled with the continuity equation, and the Holtan-Lopez infiltration model. This infiltration model is built on the premise that infiltration is proportional to the capacity of the soil to store water, giving it an advantage over other methods (e.g. Horton's equation, Green-Amp equation) in that it is physically based and describes the infiltration and recovery capacity during low-flow or dry periods (Haan et al., 1994). This equation was developed on the premise that soil moisture storage, surface-connected porosity, and the effects of root paths are the dominant factors influencing infiltration capacity (Maidment, 1993).

Model Framework

- Modeled runoff inputs are land use-specific unit-area time series
- One-dimensional mass balance flow and pollutant routing (land-to-BMP or BMP-to-BMP)
- Combinations of BMP unit process used to simulate activity within a management structure
- Assumes complete mixing within BMP compartments

Scale

Spatial Scale

- Site-level or small watershed-scale analysis

Temporal Scale

- Hourly input and output time series

Assumptions

Simulated time series components can be spatially distributed and scaled by area; however, unit characteristics remain constant within each unique land use type. Flow routing and simulation order are performed on a top-down basis. Complete mixing is assumed within the surface storage volume of the BMP. Infiltrating or outflow water exits at the current concentration of the completely mixed surface storage volume. The module assumes one-directional flow from land to BMP or BMP to BMP.

Model Strengths

The BMP Module interface allows the user to design the schematic site layout and represent flow diversions and alterations by the placement of BMP structures. BMP scenarios such as reduced imperviousness can be represented as a change in land use parcels. The BMP Module offers a great deal of detail in how a BMP can be physically represented and simulates both hydrologic and generalized water quality activity within the BMP. It uses process-based algorithms to represent BMP unit processes. The result is a time history of both influent and effluent flow and pollutant levels on an hourly basis. A Visual Basic Applications (VBA)-enhanced Excel analysis spreadsheet automatically queries and summarizes model results and produces a set of BMP performance measures for analysis between multiple scenarios.

Model Limitations

Because the model currently supports hourly time series, the model assumptions are most valid with BMPs that have residence times of at least an hour. Runoff characteristics must be predetermined within an external watershed model; therefore, factors like land slope and its influence on influent runoff to BMPs cannot be changed from within the BMP Module.

Application History

Conceptualization and design of the BMP Module began in late 1999 to early 2000. The Module has been under internal testing, development, and enhancement during its relatively short recent history. Applications include both proposed retrofit and development sites in Prince Georges County, Maryland. Examples include a commercial site example from a Maryland state design manual, some proposed LID integrated site plans, and individual BMP types in the LID Design Manual (Prince George's County, 1999). BMP Module application has been limited to screening-level and planning purposes. The module has never been used for BMP design purposes.

Model Evaluation

A validation/confirmation exercise was performed using the BMP Module and laboratory data that documented measured performance of a set of bioretention basins (Davis, 2001). The BMP Module was configured and loaded consistent with the reported data to test the module's predictive capability. The results showed good agreement between modeled and observed BMP performance.

Model Inputs

- Continuous hourly runoff unit-area time series model output by land parcel type
- Relevant BMP design and dimensional information

Users' Guide

A guide is available from Prince George's County (Tetra Tech, 2003).

Technical Hardware/Software Requirements

Computer hardware:

- IBM-compatible PC

Operating system:

- Windows 98 or later

Programming language:

- Module interface: C++, Analysis Tool: Visual Basic Applications in Microsoft Excel

Runtime estimates:

- Seconds to minutes, depending on spatial/temporal resolution and computer performance

Linkages Supported

- Input format is closely compatible with HSPF, LSPC, or SWMM time series outputs
- Output format links to Excel Analysis Tool

Related Systems

The related systems listed below contain BMP simulation capability:

- Public domain models: SWMM, P8, VFSMOD
- Proprietary models: MUSIC, LIFE

Sensitivity/Uncertainty/Calibration

- Runoff inputs must be calibrated externally within the context of the relevant runoff generation model.
- BMP Module specifications include BMP size and/or geometry.
- Calibration parameters are associated with the infiltration method.
- The model is primarily designed to represent the *relative* change or impact of a BMP for comparison between scenarios. Actual validation/confirmation of the model using data requires detailed BMP influent and effluent monitoring.

Model Interface Capabilities

- User-friendly model interface.
- Data input allows user to build library of predefined BMPs.
- Drag-and-drop interface allows users to build complex networks of land, and single or multiple BMPs in series.
- Postprocessing tools provide a graphic summary of multiple evaluation criteria.

References

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Tetra Tech, Inc. 2003. *Low–Impact Development Management Practices Evaluation Computer Module – User’s Guide*. Prepared for Prince George’s County by Tetra Tech, Inc., Fairfax, VA.

QUAL2E: Enhanced Stream Water Quality Model

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Download Information
Availability: Nonproprietary
http://www.epa.gov/docs/QUAL2E_WINDOWS/
http://www.epa.gov/ceampubl/swater/index.htm
Cost: N/A

Model Overview/Abstract
The QUAL2E model simulates nutrient dynamics, algal production, and dissolved oxygen with the impact of benthic and carbonaceous demand in streams. Fifteen water quality variables are modeled in QUAL2E. The model solves the time-variable water quality variable under steady, nonuniform flow. It can be applied to steady state and diurnal time-variable situations.

Model Features
- Dissolved oxygen and oxygen demand
- Nutrients
- Tracer
- Algal dynamics
- Bacteria

Model Areas Supported

Watershed	None
Receiving Water	Medium
Ecological	Medium
Air	None
Groundwater	None

Model Capabilities

Conceptual Basis
Rivers are conceptualized as a collection of reaches. Within each reach, the hydrogeometric properties are assumed to be same. The reaches are further divided into a series of control volumes of the same length.

Scientific Detail

The governing equations of QUAL2E are the advection-dispersion-reaction equations with external sources and sinks. A flow balance is assumed, and steady, nonuniform flow is used to solve the advection. QUAL2E assumes that the channel has a trapezoidal cross section. An empirical function is applied to obtain the dispersion coefficient. The governing equations are solved with an implicit scheme in time and a backward difference in space.

Model Framework

- One-dimensional model
- Rivers, streams, channel network

Scale

Spatial Scale

- One-dimensional horizontal, nonuniform flow

Temporal Scale

- Steady state

Assumptions

- Steady, nonuniform flow
- Trapezoidal cross section channel
- Flow balance

Model Strengths

- A simple model with comprehensive nutrient, algal, and dissolved oxygen dynamics
- Easy to use, easy to understand
- Complete documentation
- Sensitivity analysis with QUAL2E-UNCAS

Model Limitations

- One-dimensional channel that cannot handle tidal impact
- Equal-length elements
- Steady flow (not able to model variable flow condition)
- Specified sediment oxygen demand (SOD); no sediment diagenesis

Application History

QUAL2E has been widely applied in the United States and around the world, including Chile, Italy, Spain, Slovenia, India, and South Africa.

Model Evaluation

QUAL2E has been widely tested. Materials related to QUAL2E can be found in textbooks, journal papers, and technical reports. An example is the evaluation of QUAL2E written by Francois Birgand, available at http://www3.bae.ncsu.edu/Regional-Bulletins/Modeling-Bulletin/qual2e.html.

Model Inputs

- Reach identification and river mile/kilometer data
- Computational elements flag field data

- Hydraulic data
- Biochemical oxygen demand and dissolved oxygen rate constants
- Initial conditions
- Incremental inflow
- Headwater sources
- Point source or withdrawal

Users' Guide

Available online: http://smig.usgs.gov/cgi-bin/SMIC/model_home_pages/model_home?selection=qual2e.

Technical Hardware/Software Requirements

Computer hardware:

- PC

Operating system:

- PC-DOS, Windows

Programming language:

- FORTRAN

Runtime estimates:

- Minutes

Linkages Supported

BASINS

Related Systems

QUAL2K, DYNHYD5/WASP5, CE-QUAL-RIV1

Sensitivity/Uncertainty/Calibration

QUAL2E-UNCAS conducts uncertainty analysis

Model Interface Capabilities

- DOS version: QUAL2E reads text-based input file
- Latest QUAL2E Windows version provides Windows interface

References

Barnwell, T. O. and Brown, L. C. 1987. *The Enhanced Stream Water Quality Models QUAL2E and QUAL2E-UNCAS: Documentation and User Manual*. EPA/600/3-87/007. U.S. Environmental Protection Agency, Washington, DC.

Manual for Windows Interface available separately as: U.S. Environmental Protection Agency (USEPA). 1995. *QUAL2E Windows Interface Users Guide*. EPA/823/B/95/003. U.S. Environmental Protection Agency, Washington, DC.

Chapra, S.C. 1997. *Surface Water Quality Modeling*. McGRAW-HILL, Inc. New York

QUAL2K

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http://www.epa.gov/ATHENS/wwqtsc/html/qual2k.html

Download Information

Availability: Nonproprietary
http://www.epa.gov/ATHENS/wwqtsc/html/qual2k.html
Cost: N/A

Model Overview/Abstract

The QUAL2K model simulates nutrient dynamics, algal production, and dissolved oxygen with the impact of benthic and carbonaceous demand in streams. QUAL2K is similar to QUAL2E but QUAL2K is enhanced with two species of CBOD and internal sediment processes. In addition, QUAL2K models pH and alkalinity. The pathogen die-off is modeled as a function of temperature, light intensity, and settling. The model solves the time-variable water quality variable under steady, nonuniform flow. QUAL2K can be applied to model steady state and dinurnal time-variable situations.

Model Features

- Dissolved oxygen and oxygen demand
- Nutrients
- Tracer
- Algal dynamics
- Bacteria
- pH, alkalinity

Model Areas Supported

Watershed	None
Receiving Water	Medium
Ecological	Medium
Air	None
Groundwater	None

Model Capabilities

Conceptual Basis

Rivers are conceptualized as a collection of reaches. Within each reach, the hydrogeometric properties are assumed to be same. The reaches are further divided into a series of control volumes of the same length.

Scientific Detail
The governing equations of QUAL2K model are the advection-dispersion-reaction equations with external sources and sinks. A flow balance is assumed, and steady, nonuniform flow is used to solve the advection. QUAL2K assumes that the channel has a trapezoidal cross section. An empirical function is applied to obtain the dispersion coefficient. The governing equations are solved with an implicit scheme in time and a backward difference in space.

Model Framework
Structural description of the model, internal linkages, such as one-dimensional model, internally coupled watershed and one-dimensional stream models…

Narrow rivers and streams

Scale

Spatial Scale
- One-dimensional

Temporal Scale
- Steady state

Assumptions
- Steady, nonuniform flow
- Trapezoidal cross section channel
- Flow balance

Model Strengths
- A simple model with comprehensive nutrient, algal, and dissolved oxygen dynamics
- Easy to use, easy to understand
- Internal sediment processes
- Complete documentation

Model Limitations
- One-dimensional channel cannot handle tidal impact
- Equal length elements
- Steady flow; not able to model variable flow condition

Application History
Application examples include the Wind River temperature TMDL in Washington State and biochemical oxygen demand simulation in the Hanjiang River, China.

Model Evaluation
Not available

Model Inputs
- Reach identification and river mile/kilometer data
- Computational elements flag field data

- Hydraulic data
- Biochemical oxygen demand and dissolved oxygen rate constants
- Initial conditions
- Incremental inflow
- Headwater sources
- Point source or withdrawal

Users' Guide

Available online: http://www.epa.gov/ATHENS/wwqtsc/html/qual2k.html

Technical Hardware/Software Requirements

Computer hardware:

- PC

Operating system:

- Windows ME/2000/XP with MS Office 2000 or Higher

Programming language:

- Excel VBA

Runtime estimates:

- Minutes to hours

Linkages Supported

None

Related Systems

QUAL2E, CE-QUAL-RIV1, DYNHYD5/WASP5

Sensitivity/Uncertainty/Calibration

Not available

Model Interface Capabilities

- Microsoft Excel interface

References

Chapra, S.C. and Pelletier, G.J. 2003. *QUAL2K: A Modeling Framework for Simulating River and Stream Water Quality: Documentation and Users Manual*. Civil and Environmental Engineering Department, Tufts University, Medford, MA.

REMM: Riparian Ecosystem Management Model

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Download Information

Availability: Nonproprietary
Cost: N/A

As of July 2004, REMM 1.0 is under testing. The testing version can be downloaded at http://sacs.cpes.peachnet.edu/remmwww/remm/users.htm

Model Overview/Abstract

REMM has been developed as a tool that can help quantify the water quality benefits of riparian buffers. REMM simulates the movement of surface and subsurface water; sediment transport and deposition; nutrient transport, sequestration, and cycling; and vegetative growth in riparian forest systems on a daily timestep. In REMM, the riparian system is considered to consist of three zones between the field and the waterbody. Each zone includes litter and three soil layers, as well as a plant community that can have six plant types in two canopy levels. REMM can be used to quantify nitrogen and phosphorus trapping in the riparian buffer zone, determine buffer effectiveness, investigate the long-term fate of nutrients in buffer zones, evaluate the influence of vegetation type on buffer effectiveness, and determine the impacts of harvesting on buffer effectiveness. As of July 2004, REMM is still under development and has been continuously updated. A user interface is being built to assist input and output data management. The strength of REMM is its capability to simulate subsurface compartments and comprehensive nutrient cycling. Because of the model's complexity, application requires extensive data.

Model Features

- Surface and subsurface water movement
- Sediment and nutrients transport
- Nutrients cycling
- Vegetative growth

Model Areas Supported

Watershed	High
Receiving Water	None
Ecological	Medium (Vegetative: High)
Air	None
Groundwater	Medium

Model Capabilities

Conceptual Basis

In REMM, the riparian system consists of three zones between the field (drainage area) and the receiving waterbody. Each zone includes litter and three soil layers that terminate at the bottom of the plant root system and a plant community that can include six plant types in two canopy levels. Surface hydrology, erosion, vertical and horizontal subsurface flows, carbon and nutrient dynamics, and plant growth that occur in each zone are modeled on a daily timestep.

Scientific Detail

Movement and storage of water within riparian buffer systems is simulated by a process-based, two-dimensional water balance on a daily basis. Infiltration is estimated using the explicit form of modified Green-Ampt equation. Surface runoff is assumed to be generated when the sum of rainfall and upslope runoff depth exceeds the infiltration capacity, also when the top soil layer is saturated and cannot accept any additional water. REMM also includes subsurface drainage in both the vertical and lateral directions. Vertical subsurface drainage is simulated as gravitational drainage between horizons and as deep groundwater seepage from the lower layer. The upward evapotransporation flux is simulated in REMM using Darcy Buckingham equation given by Skaggs in the presence of a shallow water table. In the absence of a shallow water table, evapotransporation loss is limited to the soil layer wilting point moisture content. A simple routing scheme is used to distribute the incoming upland runoff down the riparian slope based on its depth and flow velocity.

Overland soil erosion is simulated using USLE. Sediment routing is performed using equations applied in the AGNPS model.

Carbon dynamics are simulated using the Century model, which divides carbon in the soil and residue (litter) layers into different pools. Soil nitrogen is modeled in organic forms associated with soil carbon, residue carbon, and dissolved carbon and in inorganic forms as ammonium and nitrate. Nitrification, denitrification, and immobilization of nitrogen from plant residues are simulated. REMM simulates soil phosphorous in both organic and inorganic forms. Partitioning of phosphorous into dissolved and adsorbed fractions is computed using the Langmuir isotherm. Soil temperature is simulated in REMM using an empirical approach for the soil surface and a heat flux approach for the subsurface soil. Vegetation can be represented in REMM using up to 12 plant types in two canopies. A thorough model simulating the photosynthesis, respiration, growth, and development of the vegetation is applied in REMM. Consumption of water and nutrients are related to the increase in biomass of various vegetation types.

Model Framework

- Vegetative buffer system
- Three buffer zones
- Litter and three soil layers
- Plant community (up to six plant types in two canopy levels)

Scale

Spatial Scale

- Field/hill slope

Temporal Scale

- Daily timestep

Assumptions

The model assumes that the dynamics of each physical, chemical and biological component can be described by the principal of conservation of mass.

Model Strengths

- Capability for simulating subsurface compartment
- Comprehensive nutrients cycling.

Model Limitations

- Extensive data requirement
- Employs a simplified method to distribute the incoming upland runoff down the riparian slope based on its depth and flow velocity, which limits the accuracy of flow routing and, hence, infiltration calculation

Application History

REMM is still in the development stage, with a testing version released. Testing is being performed using data from riparian buffer sites located on Gibbs Farm in Tifton, Georgia.

Model Evaluation

Testing is being performed using data from riparian buffer sites located on Gibbs Farm in Tifton, Georgia.

Model Inputs

- Daily weather data
    - daily precipitation amount (mm)
    - duration of precipitation (hr)
    - ratio of time to rainfall peak/rainfall duration
    - ratio of max. rainfall intensity/average rainfall intensity
    - max. daily temperature (deg C)
    - min. daily temperature (deg C)
    - daily solar radiation (langleys/day)
    - wind velocity (m/s)
    - wind direction (deg from north)
    - dew point temperature (deg C)
- Daily field input data
    - surface runoff depth (mm/ha)
    - subsurface depth (mm/ha)
    - sediment loading (kg/ha)
    - sediment–clay fraction
    - sediment–silt fraction
    - sediment–small aggregate fraction
    - sediment–large aggregate fraction
    - sediment–sand fraction
    - carbon-humus-active-surface runoff (kg/ha)
    - CN-ratio–surface runoff
    - CP-ratio–surface runoff
    - carbon-humus-active-suburface flow (kg/ha)
    - CN-ratio subsurface flow
    - CP-ratio subsurface flow
    - carbon-humus-active-sediment (kg/ha)
    - CN-ratio sediment
    - CP-ratio sediment
    - ammonium–surface runoff (kg/ha)
    - ammonium–subsurface flow (kg/ha)
    - ammonium–sediment (kg/ha)
    - nitrate–surface runoff (kg/ha)
    - nitrate–subsurface flow (kg/ha)
    - phosphorus–surface runoff (kg/ha)

  - phosphorus–subsurface flow (kg/ha)
  - phosphorus–sediment (kg/ha)
  - rainfall–carbon-humus-active (kg/mm-ha)
  - rainfall–CN ratio
  - rainfall–CP ratio
  - rainfall–nitrate (kg/mm-ha)
  - rainfall–ammonium (kg/mm-ha)
  - rainfall–phosphorus (kg/mm-ha)

- Zone parameters:
  - field surface drainage area (ha)
  - field subsurface drainage area (ha)
  - field length (m)
  - stream depth (m)
  - latitude of location
  - zone length (m)
  - zone width (m)
  - zone slope (%)
  - seepage from aquiclude (mm/day)
  - number of surface channels

- Litter layer parameters:
  - layer depth (cm)
  - evaporation factor
  - evaporation constant
  - litter transmission factor
  - litter moisture (mm)
  - litter humus moisture holding capacity by weight (%)
  - litter residue moisture holding capacity weight (%)
  - litter bulk density (g/cm^3)
  - litter $CaCo_3$ (g/kg)
  - litter P group
  - litter base saturation (%)
  - ammonium adsorption coefficients
  - ammonium absorption coefficients
  - litter pH
  - litter C structural pool (kg/ha)
  - litter C metabolic pool (kg/ha)
  - litter C active pool (kg/ha)
  - litter C slow pool (kg/ha)
  - litter C passive pool (kg/ha)
  - litter C lignin (kg/ha)
  - litter ammonium pool (kg/ha)
  - litter nitrate pool (kg/ha)
  - litter N structural pool (kg/ha)
  - litter N metabolic pool (kg/ha)
  - litter N active pool (kg/ha)
  - litter N slow pool (kg/ha)
  - litter N passive pool (kg/ha)
  - litter P structural pool (kg/ha)
  - litter P metabolic pool (kg/ha)
  - litter P active pool (kg/ha)
  - litter P slow pool (kg/ha)
  - litter P passive pool (kg/ha)
  - litter P labile inorganic pool (kg/ha)
  - litter P active inorganic pool (kg/ha)

- litter P stable inorganic pool (kg/ha)
- Soil layer parameters (repeat for 3 soil layers):
  - rock density (g/cm^3)
  - rock fraction (g/g)
  - pore size distribution index
  - bubbling pressure head (cm)
  - soil layer depth (cm)
  - wilting point (cm/cm)
  - field capacity (cm/cm)
  - porosity (cm/cm)
  - initial moisture content (cm/cm)
  - saturated conductivity (cm/hr)
  - sand content (%)
  - silt content (%)
  - clay content (%)
  - bulk density (g/(cm)3)
  - $CaCO_3$ content
  - base saturation
  - initial carbon structural pool (kg/ha)
  - initial carbon metabolic pool (kg/ha)
  - initial carbon active pool (kg/ha)
  - initial carbon slow pool (kg/ha)
  - initial carbon passive pool (kg/ha)
  - initial carbon lignin pool (kg/ha)
  - initial nitrogen ammonium pool (kg/ha)
  - initial nitrogen nitrate pool (kg/ha)
  - initial nitrogen structural pool (kg/ha)
  - initial nitrogen metabolic pool (kg/ha)
  - initial nitrogen active pool (kg/ha)
  - initial nitrogen slow pool (kg/ha)
  - initial nitrogen passive pool (kg/ha)
  - initial phosphorus structural pool (kg/ha)
  - initial phosphorus metabolic pool (kg/ha)
  - initial phosphorus active pool (kg/ha)
  - initial phosphorus slow pool (kg/ha)
  - initial phosphorus passive pool (kg/ha)
  - initial inorganic phosphorus labile pool (kg/ha)
  - initial inorganic phosphorus active pool (kg/ha)
  - initial inorganic phosphorus stable pool (kg/ha)

Users' Guide

Available online: http://sacs.cpes.peachnet.edu/remmwww/remm/documents/Userguide.pdf
Hard copy of technical document is available upon request.

Technical Hardware/Software Requirements

Computer hardware:

- PC

Operating system:

- Windows

Programming language:

- C++

Runtime estimates:

- Seconds to minutes

Linkages Supported

None

Related Systems

None

Sensitivity/Uncertainty/Calibration

Not available

Model Interface Capabilities

- A user interface is under development

References

U.S. Department of Agriculture, Agricultural Research Service (USDA-ARS). *Riparian Ecosystem Management Model: User's manual*. USDA-ARS Southeast Watershed Research Laboratory. Tifton, GA. <http://sacs.cpes.peachnet.edu/remmwww/remm/remmoldwww/default.htm>.

Altier, L.S., R. Lowrance, R.G. Williams, S. P. Inamdar, D. D. Bosch, J. M. Sheridan, R. K. Hubbard, and D. L. Thomas. 2002. *Riparian Ecosystem Management Model – Simulator for Ecological Processes in Riparian Zones*. Report 46. U.S. Department of Agriculture, Agricultural Research Service, Conservation Research.

Lowrance, R., L.S. Altier, R.G. Williams, S.P. Inamdar, D.D. Bosch, J.M. Sheridian, D.L. Thomas and R.K. Hubbard. 1998. The Riparian Ecosystem Management Model: Simulator for ecological processes in riparian zones. In *Proceedings of the First Federal Interagency Hydrologic Modeling Conference*, Las Vegas, NV, April 1998, pp. 1.81-1.88.

Inamdar, S.P., J.M. Sheridan, R.G. Williams, D.D. Bosch, R. Lowrance, L.S. Altier, D.L. Thomas. 1998. The Riparian Ecosystem Management Model: Evaluation of the hydrology component. In *Proceedings of the First Federal Interagency Hydrologic Modeling Conference*, Las Vegas, NV, April 1998, pp. 7.17-7.24.

Bosch, D.D., R.G. Williams, S.P. Inamdar, J.M. Sheridan, and R. Lowrance. 1998. Erosion and sediment transport through riparian forest buffers. In *Proceedings of the First Federal Interagency Hydrologic Modeling Conference*, Las Vegas, NV, April 1998, pp. 3.31-3.38.

Inamdar, S.P., L.S. Altier, R. Lowrance, R.G. Williams, R. Hubbard. 1998. The Riparian Ecosystem Management Model: Nutrient Dynamics. In *Proceedings of the First Federal Interagency Hydrologic Modeling Conference*, Las Vegas, NV, April 1998, pp. 1.73-1.80.

L.S. Altier, R.G. Williams, R. Lowrance, and S.P. Inamdar. 1998. The Riparian Ecosystem Management Model: Plant growth component. In *Proceedings of the First Federal Interagency Hydrologic Modeling Conference*, Las Vegas, NV, April 1998, pp. 1.33-1.40.

Williams, R.G., R. Lowrance, L.S. Altier, and S.P. Inamdar. 1998. The Riparian Ecosystem Management Model: A demonstration. In *Proceedings of the First Federal Interagency Hydrologic Modeling Conference*, Las Vegas, NV, April 1998, pp. 8.133-8.138.

RMA-11

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Download Information

Availability: Proprietary
Cost:

RMA-11 (One-dimensional/Two-dimensional)	$1250
RMA-11 (One-dimensional/Two-dimensional/Three-dimensional)	$2500
RMA-2 (One-dimensional/Two-dimensional hydrodynamics)	$1500
RMAGEN (Pre-processor graphics)	$750
RMAPLT (Post-process graphics)	$750

Model Overview/Abstract

RMA-11 is a finite element water quality model for simulation of one-, two-, or three-dimensional estuaries, bays, lakes, and rivers. It is also capable of simulating one- and two-dimensional approximations to systems. It is designed to accept velocity and depth input from the results of the two-dimensional hydrodynamic model or the three-dimensional stratified flow model. The input hydrodynamic data are used in the solution of the advection-diffusion constituent transport equations. The model operates independently of the timesteps in the hydrodynamic model, and the input data are automatically interpolated.

Model Features

- Finite element water quality model.
- Constituents that may be included in the simulation are
    - Temperature with a full atmospheric heat budget at the water surface
    - Biological oxygen demand/dissolved oxygen
    - The nitrogen cycle
    - The phosphorous cycle
    - Algae growth and decay
    - Cohesive suspended sediment
    - Non-cohesive suspended sediment such as sand
    - Salinity
    - Coliform

Model Areas Supported

Watershed	None
Receiving Water	High
Ecological	None

Air	None
Groundwater	None

Model Capabilities

Conceptual Basis

RMA-11 represents the latest in the RMA model development series. The capabilities of all the earlier models, in particular RMA4Q, have been systematically incorporated into the latest version. In addition, the advection-diffusion-settling capabilities have been expanded to permit fully three-dimensional simulation. This model is capable of one-, two-, three-dimensional approximations in any combination. It also has a bed model capable of tracking the evolution of cohesive or noncohesive sediments.

Scientific Detail

The two- and three-dimensional advection diffusion equations are simulated for conservative and decaying constituents. The equations are solved by the finite element method. The prototype system is represented by a network of triangles and quadrilaterals/cubes and prisms that may have curved sides if desired. Within each element, the model uses quadratic approximations for water quality constituents. A fully implicit solution scheme is used for solution of time dependent problems. The primary features of RMA-11 are as follows:

- RMA11 shares many of the same capabilities of the RMA-2/RMA-10 hydrodynamics models, including irregular boundary configurations, variable element size, one-dimensional elements, and the wetting and drying of shallow portions of the modeled region.
- RMA11 may be executed in steady state or dynamic mode. The velocities supplied may be constant or interpolated from an input file (this may be RMA-2 or RMA-10 output).
- Source pollutant loads may be input to the system either at discrete points, over elements, or as fixed boundary values.
- In formulating the element equations, the element coordinate system is realigned with the local flow direction. This permits the longitudinal and transverse diffusion terms to be separated, with the net effect being to limit excessive constituent dispersion in the direction transverse to flow.
- For increased computational efficiency, up to fifteen constituents may be modeled at one time, each with separately defined loading, decay, and initial conditions.
- The model may be used to simulate temperature with a full heat exchange with the atmosphere, nitrogen and phosphorous nutrient cycles, biochemical oxygen demand/dissolved oxygen, algae, cohesive or noncohesive suspended sediments, and other nonconservative constituents.
- A multilayer bed model for the cohesive sediment transport constituent keeps track of thickness and consolidation of each layer.

Model Framework

RMA-11 is a finite element water quality model for simulation of one-, two-, or three-dimensional estuaries, bays, lakes, and rivers.

Scale

Spatial Scale

- Operation unit one-, two-, or three-dimensional

Temporal Scale

- User-defined timestep

Assumptions

- Represents the waterbody in a finite element model

Model Strengths

- Simulates temperature with a full heat exchange with the atmosphere, nitrogen and phosphorous nutrient cycles, biochemical oxygen demand/dissolved oxygen, algae, cohesive or noncohesive suspended sediments, and other nonconservative constituents
- Has a pre-and post-processor (RMAGEN and RMAPLT)

Model Limitations

- Uses finite element solution.

Application History

It has recently been used by Australian Water and Coastal Studies for studies of sand transport and power station effluents in Lake Macquarie and bacteria and nutrient loadings and dispersion in Salt Pan Creek, Sydney. It has also been used for the waters surrounding Hong Kong and is currently being used for a study of Moreton Bay near Brisbane.

The models have been applied in numerous coastal systems, estuaries, and rivers around the world. Resource Management Associates (RMA) in California has made numerous outfall location studies in San Francisco Bay, including studies for East Bay Municipal Utility District, City of San Francisco, and Tri Valley Waste Management District. The U.S. Army Corps of Engineers has used the models extensively in its sedimentation studies for coastal estuary systems. Examples include the Columbia River in Oregon and the Atchafalaya Estuary in Louisiana. RMA-4, along with earlier version of RMA-2, was selected by Brigham Young University for inclusion in its commercially marketed FASTTABS (now known as SMS) system.

Model Evaluation

See literature.

Model Inputs

- Initial conditions
- Time sequences of boundary conditions (inputs from watershed sources and discharges)
- Geometry of waterbody
- Physical coefficients
- Biological and chemical reaction rates

Users' Guide

Available with purchase of model

Technical Hardware/Software Requirements

Computer hardware:

- PC-DOS or UNIX

Operating system:

- PC-DOS or UNIX

Programming language:

- FORTRAN

- Used on IBM PCs, UNIX workstations, Dec VAX systems, and Cray super computers. Source and executable versions of the models are available for the finite element models.

Runtime estimates:
- Minutes to hours

Linkages Supported
RMA-2 and RMA-10

Related Systems
RMA-1, RMAGEN, RMA11PR, RMA4QPR, RMAPLT, RMA-2, RMA-10, CONVRM4 and CONVRM4Q

Sensitivity/Uncertainty/Calibration
Not available

Model Interface Capabilities
- RMA-1 and RMAGEN are pre-processor programs used to aid construction and display of finite element networks.
- RMA-2 simulation results generate current vectors and stage for input into RMA-11.
- RMAPLT is a graphical postprocessor program for development of (1) velocity vector plots, (2) contour plots of constituent concentration, water surface elevation, or velocity magnitude, and (3) time histories of these parameters for selected locations.

References
King, I. P. 1998. *RMA-11 - A Three Dimensional Finite Element Model For Water Quality in Estuaries and Streams.* Department of Civil and Environmental Engineering, University of California, Davis, CA.

SED2D

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http://chl.wes.army.mil/software/tabs

Download Information

Availability: Proprietary
Cost: Contact distributor

Organizations other than the U.S. Corps of Engineers can obtain the model from the vendors listed below; however, WES cannot provide support nor offer guarantees of suitability to users outside the Corps of Engineers.

- Resource Management Associates (RMA), 4171 Suisun Valley Rd, Suite C, Suisun, CA (USA) 94585. Phone 707-864-2950
- Brigham Young University (BYU), Engineering Computer Graphics Laboratory, 368B CB, Provo, UT (USA) 84602. Phone 801-378-2812. A company named BOSS Corporation handles their distribution (1-800-488-4775).

Model Overview/Abstract

SED2D, formerly STUDH, is a two-dimensional numerical model for depth-averaged transport of cohesive or a representative grain size of noncohesive sediments and their deposition, erosion, and formation of bed deposits.

Model Features

- Sediment transport
- Deposition
- Erosion

Model Areas Supported

Watershed	None
Receiving Water	High
Ecological	None
Air	None
Groundwater	None

Model Capabilities

Conceptual Basis
SED2D provides a high level of sophistication in its representation of cohesive sediment bed dynamics and water column exchange. The SED2D model can execute simultaneously with or externally linked with the RMA-2 model.

Scientific Detail
The derivation of the basic finite element formulation is presented in Ariathurai (1974) and Ariathurai, MacArthur, and Krone (1977) and is summarized below. The model does four major computations:

1. Convection-Diffusion Governing Equation
2. Bed Shear Stress Calculation
3. The Bed Source/Sink Term
4. The Bed Strata Discretization

The model simulates cohesive and noncohesive sediment transport. Horizontal water column transport includes advection and shear dispersion. Cohesive sediment transport is represented by a single size class with concentration-dependent settling to approximately account for flocculation or aggregation and disaggregation. Water column-bed sediment and sorbed contaminant exchange includes bottom-stress dependent-deposition and bottom stress and bed-shear-strength-dependent erosion or resuspension. Cohesive bed erosion by mass erosion and surface erosion processes are represented. Cohesive sediment beds are represented by a time-varying number of layers that increase and decrease in number during periods of deposition and resuspension, respectively. Although the model does not include a mathematically formulated consolidation simulation, the thickness, void ratio, density, and shear strength of the layers vary with time since deposition, through the use of experimentally determined relationships. Vertical advection of sediment and sorbed material in the bed is implicitly represented by the dynamic bed layering process.

Model Framework
SED2D WES requires that hydrodynamic data be externally supplied, usually by a numerical hydrodynamic model. The TABS-MD modeling system has been designed to satisfy this and other needs for a comprehensive modeling package. TABS-MD consists of RMA-2 WES, a general-purpose program for hydrodynamic modeling, in addition to SED2D WES. The graphical user interface, SMS, and a number of utility programs are used to develop input, translate data, analyze output, and provide graphical output from the models.

Scale

Spatial Scale
- Two-dimensional operation unit

Temporal Scale
- User-defined timestep

Assumptions
- The model considers a single, effective grain size during each simulation.
- An implicit assumption of the SED2D WES model is that the changes in the bed elevation due to erosion and/or deposition do not significantly affect the flow field.
- The sediment transport model formulation assumes that the input geometric mesh and the resulting hydrodynamic solution from RMA-2 are of adequate resolution, accuracy, and quality to allow for an accurate and reasonable solution to the governing sediment transport equation to be solved.

Model Strengths
- The model simulates cohesive and noncohesive sediment transport.

- It is useful for both deposition and erosion studies and, to a limited extent, for stream width studies.
- It has the ability to compute sediment loadings and bed elevation changes.

Model Limitations

- Both clay and sand may be analyzed, but the model considers a single, effective grain size during each simulation. Therefore, a separate model run is required for each effective grain size.
- Fall velocity must be prescribed along with the water surface elevations, x-velocity, y-velocity, diffusion coefficients bed density, critical shear stresses for erosion, erosion rate constants, and critical shear stress for deposition.
- The program does not compute water surface elevations or velocities; these data must be provided from an external calculation of the flow field. For most problems, a numerical model for hydrodynamic computations, RMA-2 WES, is used to generate the water surface elevations and velocities.
- In addition, the sediment transport model formulation assumes that the input geometric mesh and the resulting hydrodynamic solution from RMA-2 are of adequate resolution, accuracy, and quality to allow for an accurate and reasonable solution to the governing sediment transport equation to be solved. In such a case, then the mathematical solution from SED2D will potentially have severe oscillations with negative concentrations.

Application History

Refer to References

Model Evaluation

See publications.

Model Inputs

- Initial conditions
- Time sequences of boundary conditions
- Geometry mesh
- Physical coefficients

Users' Guide

Available online: http://chl.erdc.usace.army.mil/CHL.aspx?p=s&a=ARTICLES;483

Technical Hardware/Software Requirements

Computer hardware:

- PC

Operating system:

- PC-DOS

Programming language:

- FORTRAN

Runtime estimates:

- Minutes to hours

Linkages Supported
RMA-2, FastTABS

Related Systems
SED3D

Sensitivity/Uncertainty/Calibration
Not available

Model Interface Capabilities
- A computer program (developed at the U.S. Army Corps of Engineers' Waterways Experiment Station [WES] and Brigham Young University [BYU]), called FastTABS, provides a graphical, point and click means for performing pre- and post-processing for surface water numerical models and can be used to process data for SED2D.

References
Hayter, E.J., M.A. Bergs, R. Gu, S.C. McCutcheon, and S. J. Smith. 1996. *SED2D, A Finite Element Model for Cohesive Sediment Transport*. Prepared for U. S. Environmental Protection Agency by Clemson University, Clemson, SC.

Ackers, P., and W. R. White. l973. Sediment Transport: New approach and analysis. *Journal of the Hydraulics Division, American Society of Civil Engineers*. no. HYll.

Ariathurai, R. l974. A Finite Element Model for Sediment Transport in Estuaries. Ph. D. thesis, University of California, Davis.

Ariathurai, R., R.C. MacArthur, and R.B. Krone. l977. *Mathematical Model of Estuarial Sediment Transport.* Technical Report D-77-12. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Krone, R.B. l962. *Flume Studies of the Transport of Sediment in Estuarial Shoaling Processes, Final Report*. Hydraulic Engineering Laboratory and Sanitary Engineering Research Laboratory, University of California, Berkeley.

McAnally, W.H., and W.A. Thoma,. l980. S*hear Stress Computations in a Numerical Model for Estuarine Sediment Transport*. Memorandum for Record, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Swart, D.H. l976. *Coastal Sediment Transport, Computation of Longshore Transport*. Report 968, Part l. Delft Hydraulics Laboratory, The Netherlands.

White, W.R., H. Milli, and A.D. Crabbe. l975. *Sediment Transport Theories: An Appraisal of Available Methods*. Report Int. ll9. Hydraulics Research Station, Wallingford, England. vols. 1-2.

SED3D: Three-Dimensional Numerical Model of Hydrodynamics and Sediment Transport in Lakes and Estuaries

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http://www.epa.gov/ceampubl/swater/sed3d/

Download Information

Availability: Nonproprietary
Cost: N/A

Model Overview/Abstract

SED3D simulates the flow and sediment transport in lakes, estuaries, harbors, and costal waters. SED3D is a dynamic modeling system that can be used to simulate the flow and sediment transport in various waterbodies under the forcing of winds, tides, freshwater inflows, and density gradients with the influence of the Coriolis acceleration, complex bathymetry, and shoreline geometry.

Model Features

- Hydrodynamics
- Sediment
- Transport
- Lakes
- Estuaries
- Harbors
- Coastal waters
- Three-dimensional

Model Areas Supported

Watershed	None
Receiving Water	High
Ecological	Low
Air	None
Groundwater	None

Model Capabilities

Conceptual Basis
SED3D simulates the flow and sediment transport in lakes, estuaries, harbors, and costal waters. SED3D is a dynamic modeling system that can be used to simulate the flow and sediment transport in various waterbodies under the forcing of winds, tides, freshwater inflows, and density gradients with the influence of the Coriolis acceleration, complex bathymetry, and shoreline geometry.

Scientific Detail
Given proper boundary and initial conditions, the model can compute the time-dependent, three-dimensional velocity components (u,v,w), temperature (T), salinity (S), and suspended sediment concentration (c) in the Cartesian and vertically stretched grid system (x,y,s). The model contains a free surface, as opposed to a rigid-lid, with proper boundary conditions for velocity, temperature, salinity, and sediment. A simplified second-order closure model of turbulent transport is used to compute the vertical eddy viscosity and diffusivity contained in the model equations.

Model Framework
SED3D can be run in a three-dimensional mode, a two-dimensional vertically integrated ‘x-y’ mode, or a two-dimensional ‘x-z’ mode.

Scale

Spatial Scale
- Three-dimensional operation unit

Temporal Scale
- User-defined timestep

Assumptions
To be determined

Model Strengths
- Can simulate the flow and sediment transport in lakes, estuaries, harbors, and coastal waters.
- Provides a three dimensional numerical grid and a quasi-second-order closure scheme and sediment transport capabilities.

Model Limitations
- The SED3D model and its associated files are designed for Digital Equipment Corporation (DEC) installation, compilation, link edit, and execution. This model has not been successfully compiled, linked, or executed at the EPA CEAM using a DOS-based FORTRAN development tool
- Complicated

Application History
To be determined

Model Evaluation
To be determined

Model Inputs
- Initial conditions
- Time sequences of boundary conditions
- Reservoir geometry
- Physical coefficients
- Time sequences of hydrometeorological conditions

Users' Guide
Document must be requested from contact:

Sheng, Y.P., D.E. Eliason, X.J. Chen, and J.-K. Choi. 1991 A Three-Dimensional Numerical Model of Hydrodynamics and Sediment Transport in Lakes and Estuaries: Theory, Model Development and Documentation. U.S. Environmental Protection Agency, Athens GA.

Technical Hardware/Software Requirements

Computer hardware:
- DEC VAX 6310

Operating system:
- DEC VAX VMS version 5.3-1

Programming language:
- DEC VAX FORTRAN version 5.5-98
- VAX VMS/DCL LINK version V05-05

Runtime estimates:
- Minutes to hours or longer depending on the complexity of the system

Linkages Supported
None

Related Systems
None

Sensitivity/Uncertainty/Calibration
Not available

Model Interface Capabilities
Not available

References

Sheng, Y.P., D.E. Eliason, X.-J. Chen, and J.-K. Choi. 1991. *A Three-Dimensional Numerical Model of Hydrodynamics and Sediment Transport in Lakes and Estuaries: Theory, Model Development and Documentation.* U.S. Environmental Protection Agency, Athens GA.

SHETRAN

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http://www.ncl.ac.uk/wrgi/wrsrl/rbms/rbms.html#SHETRAN

Download Information

This information could not be obtained from either an Internet or recent publication search.

Model Overview/Abstract

The SHETRAN system was developed by the Water Resources Systems Research Laboratory (WRSRL), is based on the SHE (Systeme Hydrologique Europeen), and was developed by international collaboration between groups in the United Kingdom, Denmark, and France. SHETRAN is a three-dimensional, coupled surface/subsurface, physically-based, spatially-distributed, finite-difference model for coupled water flow, multifraction sediment transport and multiple, reactive solute transport in river basins. It gives a detailed description in time and space of the flow and transport in the basin, which can be visualized using animated graphical computer displays. This makes it a powerful tool for use in studying the environmental impacts of land erosion, pollution, and the effects of changes in land use and climate and in studying surface water and groundwater resources and management. SHETRAN is currently being integrated in a decision-support system to maximize its usefulness in environmental impact management.

Model Features

The main difference between SHETRAN and existing physically based, spatially distributed, river basin modeling systems lies in its comprehensive nature and its capabilities for modeling subsurface flow and transport. The subsurface is treated as a variably saturated heterogeneous porous medium and fully three-dimensional flow and transport can be simulated for combinations of confined, unconfined, and perched systems. The “unsaturated zone” is modeled as an integral part of the subsurface, and subsurface flow and transport are coupled directly to surface flow and transport. So, for example, it is possible to model flow and transport in “deep” groundwater, while at the same time modeling flow and transport in complex near-surface regions, which respond rapidly to rainfall and strongly affect recharge and surface runoff.

SHETRAN represents physical processes using physical laws applied on a three-dimensional finite-difference mesh. The mesh follows the topography of the basin, and the parameters of the physical laws vary from point to point on the mesh, thus allowing the representation of the spatial heterogeneity of the physical properties of the rocks, soils, and vegetation cover, etc. SHETRAN can be used for basins of less than 1 km^2 to 2500 km^2 in area and typically uses a mesh with 20,000 finite-difference cells, stacked 50 deep, to model hourly flow and transport for periods of up to a few decades. Stream channels are simulated as a network of links, each link running along the edge of a finite-difference cell. The results from SHETRAN simulations can be viewed and analyzed using the SHEGRAPH dedicated graphics package.

Model Areas Supported

Watershed	Medium
Receiving Water	High
Ecological	Low
Air	None
Groundwater	High

Model Capabilities

The main difference between SHETRAN and existing physically based, spatially distributed, river basin modeling systems lies in its comprehensive nature and its capabilities for modeling subsurface flow and transport. The subsurface is treated as a variably-saturated heterogeneous porous medium and fully three-dimensional flow and transport can be simulated for combinations of confined, unconfined, and perched systems. The "unsaturated zone" is modeled as an integral part of the subsurface, and subsurface flow and transport are coupled directly to surface flow and transport. So, for example, it is possible to model flow and transport in "deep" groundwater, while at the same time modeling flow and transport in complex near-surface regions, which respond rapidly to rainfall and strongly affect recharge and surface runoff.

Scale

Spatial Scale

- Physically based, spatially distributed

Temporal Scale

- User-defined, variable timestep.

Assumptions

Represents physical processes using physical laws applied on a three-dimensional finite-difference mesh. The mesh follows the topography of the basin, and the parameters of the physical laws vary from point to point on the mesh, thus allowing the representation of the spatial heterogeneity of the physical properties of the rocks, soils, and vegetation cover, etc. Can be used for basins 1 km^2 to 2500 km^2 in area, and typically uses a mesh with 20,000 finite-difference cells, stacked 50 deep, to model hourly flow and transport for periods of up to a few decades. Simulates stream channels as a network of links, each link running along the edge of a finite-difference cell.

Model Strengths and Limitations

This information could not be obtained from either an Internet or recent publication search.

Model Limitations

This information could not be obtained from either an Internet or recent publication search.

Application History

Examples of SHETRAN validation and application studies include

- Validation for water flow and the effect of fire on erosion, Rimbaud basin, France.
- Validation for nitrate transport, Slapton Wood basin, United Kingdom.
- Validation for flow and conservative and nonconservative solute transport through complex Quaternary deposits, Cumbria, United Kingdom.
- Validation for flow and solute transport in a perched system at Hazelrigg, Lancaster, United Kingdom.
- Validation for erosion at Draix badlands gully basins, France.
- Validation of snowmelt modeling, Upper Sheep Creek, Idaho, USA.

- Study of climate change impacts for Mediterranean desertification: Cobres (Portugal), Mula (Spain), and Agri (Italy) basins.
- Impact assessment for radionuclide transport in the near surface and surface regions following releases from a deep underground repository for radioactive wastes, United Kingdom.

Model Evaluation
This information could not be obtained from either an Internet or recent publication search.

Model Inputs
This information could not be obtained from either an Internet or recent publication search.

Users' Guide
This information could not be obtained from either an Internet or recent publication search.

Technical Hardware/Software Requirements

Computer hardware:
This information could not be obtained from either an Internet or recent publication search.

Operating system:
This information could not be obtained from either an Internet or recent publication search.

Programming language:
This information could not be obtained from either an Internet or recent publication search.

Runtime estimates:
This information could not be obtained from either an Internet or recent publication search.

Linkages Supported
This information could not be obtained from either an Internet or recent publication search.

Related Systems
This information could not be obtained from either an Internet or recent publication search.

Sensitivity/Uncertainty/Calibration
This information could not be obtained from either an Internet or recent publication search.

Model Interface Capabilities
SHETRAN models results can be viewed and analyzed using the SHEGRAPH dedicated graphics package.

References
Water Resources Group, Dept. of Civil Engineering, University of Newcastle, Tyne, UK. <http://www.ncl.ac.uk/wrgi>.

Water Resource Systems Research Laboratory (WRSRL), Dept. of Civil Engineering at the University of Newcastle, Tyne, UK. <http://www.ncl.ac.uk/wrgi/wrsrl>.

SLAMM: Source Loading and Management Model

Contact Information

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Download Information

Availability: Proprietary, http://www.winslamm.com/
Cost: $200

Model Overview/Abstract

SLAMM was originally developed to better understand the relationships between sources of urban pollutants and runoff quality (Pitt, 1993). SLAMM is strongly based on field observations, with minimal reliance on pure theoretical processes that have not been adequately documented or confirmed in the field. The EPA's Nationwide Urban Runoff Program (NURP) has contributed significantly to the development of empirical relationships used in SLAMM. SLAMM now also includes a wide variety of source area and outfall control practices (e.g., infiltration practices, wet detention ponds, porous pavement, street cleaning, catch basin cleaning, and grass swales). Beginning with version 5, SLAMM is Windows-based and thus is called WinSLAMM.

The model performs continuous mass balances for particulate and dissolved pollutants and for 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 is calculated for both impervious and pervious areas. Triangular hydrographs, parameterized by a statistical approach, are used to simulate flow. Exponential buildup and washoff, as well as wind removal functions, are used in computing runoff pollutant loadings. Water and sediment from various source areas are tracked as they are routed through treatment devices. SLAMM is mostly used as a planning tool to better understand sources of urban runoff pollutants and the effectiveness of their control.

SLAMM is capable of considering many stormwater controls (affecting source areas, drainage systems, and outfalls) for a long series of rainfall events. The program considers how particulates filter or settle out in control devices. Particulate removal is calculated based on the structural design characteristics. 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. Another of its abilities is to accurately describe a drainage area in sufficient detail for water quality investigations but without requiring a great deal of superfluous information that field studies have shown to be of little value in accurately predicting discharge results. SLAMM also applies stochastic analysis procedures to more accurately represent actual uncertainty in model input parameters to better predict the actual range of outfall conditions (especially pollutant concentrations). Like all stormwater models, SLAMM needs to be accurately calibrated and then tested (verified) as part of any local stormwater management effort.

Model Features

- Urban stormwater runoff and water quality empirical simulation model: initial abstraction, infiltration, and pollutant buildup and washoff
- Stormwater treatment devices (BMPs) simulation

Model Areas Supported

Watershed	Medium
Receiving Water	None
Ecological	None
Air	None
Groundwater	None

Model Capabilities

Conceptual Basis

SLAMM represents the urban catchment by unconnected areas, connected areas, and drainage system. Unconnected areas drain to adjacent pervious areas before the runoff enters drainage system. Connected areas directly drain to drainage system. The drainage system consists of curbs, gutters, swale ditches, treatment devices, manholes, and sewerage. SLAMM routes stormwater runoff and pollutants from unconnected source areas to the drainage system directly, or to adjacent connected or pervious areas, which drain to the drainage system.

Scientific Detail

The model performs continuous mass balances for particulate and dissolved pollutants and for runoff volumes. Runoff is calculated by a method developed by Pitt (1987) for small-storm hydrology, which empirically determines the initial losses and infiltration loss based on experiment data. Runoff is based on rainfall minus initial abstraction, and infiltration is calculated for both impervious and pervious areas. Triangular hydrographs, parameterized by a statistical approach, are used to simulate flow. Exponential buildup and washoff and wind removal functions, are used in computing runoff pollutant loadings. The characteristics of the source areas are used to determine pollutant loads in solid and dissolved phases based on an empirical method derived using available field observations. The pollutant removal effectiveness of treatment devices are estimated, also based on empirical equations derived from field data. SLAMM also applies stochastic analysis procedures to more accurately represent uncertainty in model input parameters to better predict the range of outfall conditions (especially pollutant concentrations). SLAMM applies Monte Carlo sampling procedures to consider the uncertainties in model input values

Model Framework

- Urban areas (impervious, pervious)
- Stormwater treatment devices

Scale

Spatial Scale

- Site
- Catchment

Temporal Scale

- Variable timestep (hourly or sub-hourly)

Assumptions

- Triangular runoff hydrograph
- Exponential pollutant buildup and washoff

Model Strengths

- Better representation of small storms
- Treatment devices (BMPs) simulation capabilities
- Suitable for site-scale evaluation of urban runoff pollutants and the effectiveness of their control without requiring a great deal of information
- Uncertainty analysis capability

Model Limitations

- Does not have channel routing capability; limited use at the watershed scale
- Does not simulate base flow
- Is strongly based on a statistical approach that uses the current available field observations; is not a process-based model

Application History

SLAMM is mostly used as a planning tool to better understand sources of urban runoff pollutants and the effectiveness of their control. Early users of SLAMM include the Ontario Ministry of the Environment's Toronto Area Watershed Management Strategy (TAWMS) study and the Wisconsin Department of Natural Resources' Priority Watershed Program.

Model Evaluation

The SLAMM hydrology simulation component was verified by Pitt using field data from three sites in Wisconsin and one site in Michigan.

Model Inputs

- Rainfall depth
- Site characteristics (area, land use type, surface condition, soil type, and infiltration rate)
- Drainage system characteristics (type of drainage system, density, underlying soil type, and infiltration rate)
- Treatment devices (type, size, outlet structure, underlying soil type, and infiltration rate; if applicable, street cleaning date and/or frequency, and wet pond natural seepage and evaporation rate)

Users' Guide

Available online: http://unix.eng.ua.edu/~rpitt/SLAMMDETPOND/WinSlamm/MainWINSLAMM_book.html

Technical Hardware/Software Requirements

Computer hardware:

- PC

Operating system:

- DOS and Windows

Programming language:

- VB

Runtime estimates:

- Seconds to minutes

Linkages Supported

The WinSLAMM-SWMM Interface Program has been developed to allow WinSLAMM to provide the runoff and pollutant loads from input to SWMM TRANSPORT or EXTRAN blocks.

Related Systems

WinSLAMM

Sensitivity/Uncertainty/Calibration

SLAMM applies Monte Carlo sampling procedures to consider the uncertainties in model input values and enable the model output to be expressed in probabilistic terms.

Model Interface Capabilities

- A Windows-based interface to facilitate data input
- Output is summarized in a series of user selectable tables

References

Pitt, R., and J. Voorhees. 2000. *The Source Loading and Management Model (SLAMM), a Water Quality Management Planning Model for Urban Stormwater Runoff*. University of Alabama, Department of Civil and Environmental Engineering, Tuscaloosa, AL.

Pitt, R. 1987. *Small Storm Urban Flow and Particulate Washoff Contributions to Outfall Discharges.* Ph.D. diss., 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.

SPARROW: SPAtially Referenced Regression On Watershed Attributes

Contact Information

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REGIONAL SPARROW
Chesapeake Bay (Maryland District)

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Preston, Steve	410-267-9875 (spreston@usgs.gov)

New England (New Hampshire District)

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Robinson, Keith	603-226-7809 (kwrobins@usgs.gov)

North Carolina Coastal (North Carolina District)

McMahon, Gerard	919-571-4068 (gmcmahon@.usgs.gov)

Download Information

Availability: Nonproprietary
Cost: N/A

Model Overview/Abstract

SPARROW relates in-stream water quality measurements to spatially referenced characteristics of watersheds, including contaminant sources and factors influencing terrestrial and stream transport. The model empirically estimates the origin and fate of contaminants in streams and quantifies uncertainties in these estimates based on model coefficient error and unexplained variability in the observed data.

Model Features

- Empirically based method
- Riverine pollutant loading rates prediction
- Contaminants modeled: sediment, nutrients, etc.
- Datasets used: Reach File (RF1 or version), USGS's National Land Cover Dataset (NLCD), STATSGO, and other spatial datasets

Model Areas Supported

Watershed	Medium
Receiving Water	Low
Ecological	None
Air	Low (Model supports inclusion of atmospheric deposition loads)
Groundwater	None

Model Capabilities

Conceptual Basis

The SPARROW model uses spatially referenced regressions of contaminant transport on watershed attributes to support regional water quality assessment goals, including descriptions of spatial and temporal patterns in water quality and identification of the factors and processes that influence those conditions. The method is designed to reduce the problems of data interpretation caused by sparse sampling, network bias, and basin heterogeneity.

Scientific Detail

SPARROW uses statistical methods to calibrate a simple, structural model of riverine water quality, one that imposes mass balance in accounting for changes in contaminant flux. Regression equations relate measured transport rates in streams to spatially referenced descriptors of pollution sources and land surface and stream channel characteristics. Spatial referencing of land-based and water-based variables is accomplished via superposition of a set of contiguous land surface polygons on a digitized network of stream reaches that define surface water flow paths for the region of interest. The primary spatial reference frame for the model is the RF1 reach network: all point sources and landscape features are referenced to a particular RF1 reach.

Water quality measurements are obtained from monitoring stations located in a subset of the stream reaches. Water quality predictors in the model are developed as a function of both reach and land surface attributes and include quantities describing contaminant sources (point and nonpoint) as well as factors associated with rates of material transport through the watershed (such as soil permeability and stream velocity). Predictor formulae describe the transport of contaminant mass from specific sources to the downstream end of a specific reach. Loss of contaminant mass occurs during both overland and in-stream transport. The model can also take into account pollutant loads contributed by atmospheric deposition.

SPARROW was first used to estimate the distribution of nutrients in streams and rivers of the U.S. and subsequently shown to describe land and stream processes affecting the delivery of nutrients (Smith, et al., 1997; Alexander, et al., 2000; Preston and Brakebill 1999).

Model Framework

- Empirical, regression-based
- Uses national datasets, wide applicability

Scale

Spatial Scale

- Large watersheds

Temporal Scale

- Annual
- User-defined modeling period

Assumptions
The model is based on an empirical regression approach using mass balance calculations. Regression equations relate measured transport rates in streams to spatially referenced descriptors of pollution sources and land surface and stream channel characteristics.

Model Strengths
The model is capable of simulating a variety of pollutants at different spatial scales using national level datasets, including RF1 (stream reach file), NLCD (USGS land use/land cover), and STATSGO (NRCS soils data). The model can be used to model large- and small-scale systems with flexibility in the datasets and level of detail incorporated. The model is readily available from USGS and has been applied in several case studies.

Model Limitations
The model is limited to broadly estimating pollutant loads and fate/transport characteristics. Stream processes and model output are based on statistical relationships that were developed using national and regional water quality datasets.

Application History
The model has been primarily used to estimate nutrient and sediment loads at various spatial scales. Refer to the USGS SPARROW website for case studies.

Model Evaluation
Refer to USGS website - http://water.usgs.gov/nawqa/sparrow/

Model Inputs
- Initial conditions
- Time sequences of boundary conditions (inputs from watershed sources and discharges)
- Stream reach file reference (e.g., RF1)
- Physical coefficients
- Biological and chemical reaction rates
- Land use, soils, and other spatial datasets

Users' Guide
Not readily available on website. Website provides several journal articles and contacts:
http://water.usgs.gov/nawqa/sparrow/

Technical Hardware/Software Requirements

Computer hardware:
- PC

Operating system:
- PC-DOS

Programming language:
- SAS

Runtime estimates:

- Minutes

Linkages Supported

None

Related Systems

None

Sensitivity/Uncertainty/Calibration

In calibrating the model, measured rates of contaminant transport are regressed on predicted transport rates at the locations of the monitoring stations, giving rise to a set of estimated linear and nonlinear coefficients from the predictor formulae.

Once calibrated, the model is used to estimate contaminant transport and concentration in all stream reaches. A variety of regional characterizations of water quality conditions are then possible based on statistical summarization of reach-level estimates. The application of bootstrap techniques allows estimation of the uncertainty of model coefficients and predictions.

Model Interface Capabilities

None

References

Refer to USGS website for complete list - http://water.usgs.gov/nawqa/sparrow/

Smith, R.A., G.E. Schwarz, and R.B. Alexander. 1997. *Regional Interpretation of Water-quality Monitoring Data*. Water Resources Research, 33(12): 2781-2798.

Alexander, R.B., R.A. Smith, M.J. Focazio, and M.A. Horn. 1999. *Source-Area Characteristics of Large Public Surface-Water Supplies in the Conterminous United States: An Information Resource for Source-Water Assessment*. Open-File Report 99-248. U.S. Geological Survey, Reston, VA.

Preston, S.D. and J.W. Brakebill. 1999. *Application of Spatially Referenced Regression Modeling for the Evaluation of Total Nitrogen Loading in the Chesapeake Bay Watershed*. Report 99-4054. U.S. Geological Survey Water Resources Investigations, Baltimore, MD.

STORM: Storage, Treatment, Overflow, Runoff Model

Contact Information

Mainframe version:
U.S. Army Corps of Engineers
Hydrologic Engineering Center (HEC)
609 Second Street
Davis, CA 95616

PC Version (ProStorm):
Dodson & Associates, Inc.
5629 FM 1960 West, Suite 314
Houston, Texas 77069
1-800-235-8069 or 281-440-3787

Download Information

Availability: Nonproprietary
Cost: N/A

No downloads available.

Model Overview/Abstract

The STORM model was developed by Water Resources Engineers, Inc., in 1973 under a contract with the U.S. Army Corps of Engineers' Hydrologic Engineering Center (HEC). STORM is designed to model urban watersheds and is capable of calculating loads and concentrations of water quality parameters, such as suspended and settleable solids, biochemical oxygen demand, total nitrogen, orthophosphate, and total coliform. STORM is also capable of calculating land surface erosion. STORM is used to aid in sizing of storage and treatment facilities to control the quantity and quality of stormwater runoff and land surface erosion. A continuous simulation model, STORM requires hourly precipitation data to model the seven stormwater elements, such as rainfall/snowmelt, runoff, dry weather flow, pollutant accumulation and washoff, land surface erosion, treatment rates, and detention reservoir storage. Dust and dirt and the associated pollutants are washed off from the watershed by the rainfall. The runoff is routed to the treatment-storage facilities and the effect of treatment is calculated. Runoff in excess of treatment plant capacity is stored and treated later except for the quantity in excess of storage, which is waste untreated and becomes overflow directly into the receiving waters.

Model Features

- Urban watershed model

Model Areas Supported

Watershed	High
Receiving Water	None
Ecological	None
Air	None
Groundwater	None

Model Capabilities

Conceptual Basis
STORM is a quasi-dynamic model that uses modified rational formula for hydrology simulation. Erosion is simulated using USLE, and water quality is simulated by linear buildup and washoff coefficients.

Scientific Detail
The runoff of water is computed by one of three methods—coefficient method, the SCS Curve Number technique, or a combination of the two.

The model computes a soil moisture balance at the beginning of each time increment by the following equation:

$$S_t = S_{t-1} - IN \times \Delta t + A \times EV \times \Delta t + B \times MP \times \Delta t$$

where $A = 0.7((SM - S_{t-1}) / SM)^v$

$$B = ((SM - S_{t-1}) / SM)^p$$

where, S is the soil moisture capacity for storage of water (in), IN is the maximum infiltration rate from initial abstractions (in/hr), EV is the pan evaporation rate (in/hr), MP is the maximum soil percolation rate (in/hr), SM is the maximum soil moisture capacity for storage of water (in), t is the time, Δt is time increment (1 hr), v is the exponent regulating evapotranspiration, and p is the exponent regulating percolation.

Dry weather flow in the combined sewer systems is computed by specifying either the total waste water flow and infiltration flow (mgd), domestic, commercial, industrial, and infiltration flow separately or the coefficients required to compute the individual flows based on population and areas of commercial and industrial land.

The STORM model calculates the pollutant loadings based on either dust and dirt method or the daily pollutant accumulation method. The dust and dirt method calculates pollutants as fractions of the dust and dirt for each land use. The amount of the dust and dirt is calculated based on accumulation rate specified in terms of pounds per 100 feet of gutter length per day for each land use. The factors such as the intensity of rainfall, the rate of runoff, the accumulation of dust and dirt on the watershed, and the frequency and efficiency of street sweeping operations affects the amount of pollutants entering the storm drains and the treatment facilities or the receiving waters.

Dry weather pollutant loading in the combined sewer systems is computed similarly to the flow calculation during the same period by specifying either the total waste water flow and infiltration flow (mgd), domestic, commercial, industrial, and infiltration flow separately or the coefficients required to compute the individual flows based on population and areas of commercial and industrial land.

Model Framework
The model simulates runoff, erosion, and pollutant loading from urban watersheds, and routes through the treatment storage facilities and discharges the excess runoff into receiving waters.

Scale

Spatial Scale
- Watershed scale

Temporal Scale
- Hourly

Assumptions

- Pollutants accumulated over the land between the consecutive rainfall events will be washed off during a rainfall event

Model Strengths

- Capable of calculating loads and concentration of many pollutants
- Simulates land surface erosion
- Can aid in sizing of storage and treatment facilities

Model Limitations

- Little flexibility in parameters to calibrate to observed hydrographs
- Requires a large amount of data

Application History

The STORM model 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.

Model Evaluation

To be determined

Model Inputs

- Runoff coefficients
- SCS parameters
- Hourly precipitation

Users' Guide

Available upon request from U.S. Army Corps of Engineers

Technical Hardware/Software Requirements

Computer hardware:

- PC and Mainframe

Operating system:

- Windows and Mainframe

Programming language:

- FORTRAN

Runtime estimates:

- Minutes

Linkages Supported

None

Related Systems
None

Sensitivity/Uncertainty/Calibration
Not available

Model Interface Capabilities
- ProStorm

References
Donigian, A.S., Jr., and W. C. Huber. 1991. *Modeling of Nonpoint Source Water Quality in Urban and Non-urban Area*. EPA/600/3-91/039. U.S. Environmental Protection Agency, Environmental Research Laboratory, Athens, GA.

U.S. Army Corps of Engineers, Hydrologic Engineering Center (USACE-HEC). 1977. *Storage, Treatment, Overflow, Runoff Model, STORM, Generalised Computer Program 723-58-L77520*. USACE-HEC. Davis, California.

Shoemaker, L., M. Lahlou, M. Bryer, D. Kumar, and K. Kratt. 1997. *Compendium of Tools for Watershed Assessment and TMDL Development*. EPA 841/B/97/006. U.S. Environmental Protection Agency, Office of Water, Washington, D.C.

SWAT: Soil and Water Assessment Tool

Contact Information

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http://www.brc.tamus.edu/swat/index.html

Download Information

Availability: Nonproprietary, http://www.brc.tamus.edu/swat/swat2000.html
Cost: N/A

Model Overview/Abstract

SWAT is a river basin, or watershed, scale model developed by Dr. Jeff Arnold for the USDA Agricultural Research Service (ARS). SWAT was developed to predict the impact of land management practices on water, sediment, and agricultural chemical yields in large complex watersheds with varying soils, land use, and management conditions over long periods of time. The model is physically based and computationally efficient; it uses readily available inputs and allows users to study long-term impacts. SWAT is a continuous time model (i.e., a long-term yield model). The model is not designed to simulate detailed, single-event flood routing.

Model Features

- Watershed hydrology, sediment, and water quality model
- Pesticide fate and transport simulation
- Channel erosion simulation
- Rural and agricultural management practices including detailed agricultural land planting, tillage, irrigation, fertilization, grazing, and harvesting procedures

Model Areas Supported

Watershed	High
Receiving Water	Medium
Ecological	Low
Air	None
Groundwater	Low

Model Capabilities

Conceptual Basis

SWAT divides a watershed into subwatersheds. Each subwatershed is connected through a stream channel and further divided in to Hydrologic Response Unit (HRU). HRU is a unique combination of a soil and a vegetation type in a subwatershed, and SWAT simulates hydrology, vegetation growth, and management practices at the HRU level.

Water, nutrients, sediment, and other pollutants from each HRU are summarized in each subwatershed and then routed through the stream network to the watershed outlet.

Scientific Detail

The following is a list of key processes and algorithms used in SWAT:

- Climate: Weather generator or user's input
- Hydrology: Canopy interception, runoff (SCS CN) infiltration (Green-Ampt), and evapotranspiration (Penman-Monteith, Priestley-Taylor, or Hargreaves) flow
- Land cover/plant growth: Water and nutrient uptake, crop and plant growth database
- Erosion: MUSLE using peak runoff rate
- Nutrients: Nitrogen and phosphorus cycles
- Agricultural practices: Planting, tillage, irrigation, fertilization, pesticide management, grazing, and harvesting. SWAT also has auto-fertilization and auto-irrigation as management options that are useful for many agricultural areas
- For urban areas, SWAT employs buildup and washoff approach similar to approaches used in SWMM
- SWAT uses two methods to simulate water routing in stream network: Variable storage routing method (flow continuity equation) and Muskingum routing method (wedge and prism storage)
- Sediment transport: Stream sediment transport power is related to the stream flow rate. Model calculates the maximum sediment that can be transported, compares the maximum sediment concentration to the actual sediment concentration, and extra sediment is deposited. If the actual sediment is less than the maximum, settled sediment will be re-suspended and enter the water
- SWAT simulates in-stream biological and nutrient processes, including algal growth, death, and settling and oxygen in water, aeration and photosynthesis, and changes in water temperature
- Temporal and spatial scale: Daily; watershed or flexible size
- SWAT simulates sediment settling and mass balance, pesticide transport and fate (reservoirs only), nutrient (N and P) settling and lake chlorophyll *a* production (empirical) processes in ponds, wetlands, reservoirs, and potholes.

Model Framework

- Hydrologic response unit, subwatershed, and watershed
- Simple one-dimensional stream and well mixed reservoir/lake model

Scale

Spatial Scale

- 1D, cell or subwatershed

Temporal Scale

- Daily

Assumptions

- SCS CN approach (Green-Ampt approach for infiltration was also implemented but requires hourly data) and MUSLE are appropriate for the area being modeled
- Flows in streams and reservoirs are one-dimensional

Model Strengths

- Physically based
- Great documentation
- Uses readily available inputs facilitated by the GIS interface (BASINS)

- Detailed crop growth model and databases
- Good land management modules and databases
- Suitable for study watersheds from small to very large sizes

Model Limitations

- Not for simulating sub-daily events such as a single storm event and diurnal changes of dissolved oxygen in a waterbody
- Only for simulating conservative metal species from the point source input
- Only route one pesticide each time through the stream network
- Cannot specify actual areas to apply fertilizers
- Assumes one-dimensional well mixed streams and reservoirs
- A large watershed can be divided into hundreds of HRUs resulting in many hundreds of input files, which are difficult to manage and modify without a solid interface
- The current version does not have a good model post-processor

Application History

This model has been applied widely to study hydrology, nonpoint source pollution, and TMDLs since early 1990s. See the reference list for details.

Model Evaluation

Many peer-review research papers have evaluated the model and model applications (see references)

Model Inputs

- Land uses (MRLC and others)
- Soil (STATSGO and others)
- Topography (30 x 30 m^2 DEM or other resolutions)
- Subwatersheds (derived from manual or auto delineation tools in BASINS 3.0)
- Point source (PCS or other database)
- Climate data (daily temperature, precipitation, solar radiation, and wind speed)
- Crop and management databases
- USGS flow data (for calibration)
- Long-term watershed quality data (for model calibration)
- BASINS provides substantial input data and pre-processing to develop and run SWAT model

Users' Guide

The SWAT2000 Theoretical Documentation reviews all processes simulated with the model.
The SWAT2000 User's Manual provides definitions for all input variables.
Available online: http://www.brc.tamus.edu/swat/swatdoc.html

Technical Hardware/Software Requirements

Computer hardware:

- PC

Operating system:

- PC-DOS, Microsoft Windows

Programming language:

- FORTRAN (model) and ArcView Avenue (interface)

Runtime estimates:

- Minutes to less than an hour

Linkages Supported

BASINS

Related Systems

SWAT incorporates features of several ARS models and is a direct outgrowth of the SWRRB model (Simulator for Water Resources in Rural Basins). Specific models that contributed significantly to the development of SWAT were CREAMS (Chemicals, Runoff, and Erosion from Agricultural Management Systems), GLEAMS (Groundwater Loading Effects on Agricultural Management Systems), and EPIC 4 (Erosion-Productivity Impact Calculator).

Sensitivity/Uncertainty/Calibration

The calibration tool in the BASINS 3.0 interface allows basic model calibration and sensitivity analysis (27 key parameters). No tools were developed for uncertainty analysis.

Model Interface Capabilities

- Non-GIS DOS interface (Util)
- ArcView interface—AVSWAT
- BASINS 3.0 ArcView GIS interface (includes input editing and output viewing utilities and a simple calibration tool)

References

Neitsch S.L., J.G. Arnold, J.R. Kiniry, and J.R. Williams. 2001. *Soil and Water Assessment Tool User's Manual, Version 2000*. U.S. Department of Agriculture, Agricultural Research Service, Temple, TX. <http://www.epa.gov/waterscience/basins/basinsv3.htm>.

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SWMM: Storm Water Management Model

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Download Information

Availability: Nonproprietary
SWMM 4.4: http://ccee.oregonstate.edu/swmm
SWMM 5 (available for beta testing): http://www.epa.gov/ednnrmrl/swmm/index.htm
Cost: N/A

Model Overview/Abstract

SWMM is a dynamic rainfall-runoff simulation model developed by EPA. It is applied primarily to urban areas and for single-event or long-term (continuous) simulation using various timesteps (Huber and Dickinson, 1988). It was developed for the analysis of surface runoff and flow routing through complex urban sewer systems. The latest official version of SWMM is 4.4h, which is recommended for all users. EPA SWMM5 is a completely revised and updated release of SWMM. The first beta test version SWMM5 was released in June 2003. However, SWMM5 is still under development, with additional functions being incorporated and released over time. In SWMM, flow routing is performed for surface and sub-surface conveyance and groundwater systems, including the options of nonlinear reservoir channel routing and fully dynamic hydraulic flow routing. In the fully dynamic hydraulic flow routing option, SWMM simulates backwater, surcharging, pressure flow, and looped connections. SWMM has a variety of options for quality simulation, including traditional buildup and washoff formulation as well as rating curves and regression techniques. Universal Soil Loss Equation (USLE) is included to simulate soil erosion. SWMM incorporates first order decay and particle settling mechanism in pollutant transport simulations and includes an option of simple scour-deposition routine. Storage, treatment, and other BMPs can also be simulated.

Model Features

- Watershed hydrology and water quality
- Stream/conduit transport

- Urban stormwater and sewage systems

Model Areas Supported

Watershed	High
Receiving Water	Medium
Ecological	None
Air	None
Groundwater	Low

Model Capabilities

Conceptual Basis

The basic spatial unit for SWMM is the subcatchment into which the modeled watershed is subdivided. Multiple small subwatersheds and representative streams may be networked together to represent a larger watershed drainage area.

Scientific Detail

Infiltration is calculated using the Horton or Green-Ampt methods, at the user's choice. A version of Manning's equation is used to estimate flow rate from the subcatchment area based on a conceptual model of the subcatchment as a "nonlinear reservoir." 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 USLE determines sediment load. The concept of potency factors is applied to simulate pollutants other than sediment.

The Transport block has kinematic wave routing of flow and quality, base flow generation, and infiltration capabilities and it routes flow through user-defined system ranges from natural channel to concrete pipes. The EXTRAN block carries out a numerical solution of the complete St. Venant equations for urban drainageways and conduits, by modeling the network as a link-node system. SWMM can be directly interfaced with EPA's WASP receiving water quality model.

Model Framework

- Subwatersheds and watershed
- Channel/pipe network
- One-dimensional flow and pollutant routing

Scale

Spatial Scale

- Subwatershed of flexible size

Temporal Scale

- User-defined timestep, typically minutes to hourly

Assumptions

- The model performs best in urbanized areas with impervious drainage, although it has been widely used elsewhere.
- Model parameters for quantity and quality simulations are developed such that the model will be calibrated to enhance its capability.
- Water table elevation is assumed to be fixed.
- All the pollutants entering the waterbodies are sediment adsorbed.

Model Strengths

- Fully dynamic hydraulic routing
- Hydraulic structure (manhole, weir, orifice, etc.) simulation
- Overland flow routing between pervious and impervious areas within a subcatchment (latest version)
- Various options for quality simulation, including buildup and washoff, rating curves, and regression techniques

Model Limitations

- Only considers settling and first-order decay in in-stream pollutant routing and transformation
- Weak groundwater simulation capability

Application History

SWMM has been applied to urban hydrologic quantity/quality problems in scores of U.S. cities as well as extensively in Canada, Europe, and Australia (Donigian and Huber, 1991; Huber, 1992). 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 (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.

Model Evaluation

The applications are primarily limited to urban areas.

Model Inputs

- Data requirements for hydrologic simulation include area, imperviousness, slope, roughness, width, depression storage, and infiltration parameters. Land use data are used to determine ground cover type for each model subarea.
- Depending on what options are set for the loading calculations, additional parameters are necessary (e.g., buildup coefficients would be needed for the dry weather buildup simulation).
- Additional data are necessary if the user intends to model subsurface drainage and interflow.
- Depending on the stormwater system, dimensions, slope, roughness coefficients, elevations, and storage are required.
- Continuous records of evapotranspiration, temperature, and solar intensity are required.

Users' Guide

- Huber, W.C. and R.E. Dickinson. 1988 *Storm Water Management Model User's Manual, Version 4*. EPA/600/3-88/001a (NTIS PB88-236641/AS). U.S. Environmental Protection Agency, Athens, GA, pp.595
- Roesner, L.A., J.A. Aldrich and R.E. Dickinson. 1988. *Storm Water Management Model User's Manual, Version 4: Addendum I, EXTRAN*. EPA/600/3-88/001b (NTIS PB88236658/AS). U.S. Environmental Protection Agency, Athens, GA. pp.203
- A revised and more readable User's Guide from William James at CHI can be purchased at http://www.computationalhydraulics.com/Publications/Books/r219.html

Cost: $85

Technical Hardware/Software Requirements

Computer hardware:
- PC

Operating system:
- DOS and Windows

Programming language:
- FORTRAN (v4.4 and previous versions)
- C (v5)

Runtime estimates:
- Minutes

Linkages Supported
- SWMM can directly be interfaced with EPA's WASP receiving water quality model.

Related Systems
PCSWMM, XP-SWMM, MIKE-SWMM

Sensitivity/Uncertainty/Calibration
SWMM 4.4 includes a STATISTICS module, which performs simple statistical analyses on both quantity and quality parameters.

Model Interface Capabilities
- SWMM 5 includes a Graphical User Interface for input data preparation and output data display

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TMDL Modeling Toolbox

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Download Information

Availability: Nonproprietary, http://www.epa.gov/athens/wwqtsc/index.html
Cost: N/A

Model Overview/Abstract

The TMDL Modeling Toolbox is a collection of models, modeling tools, and databases that have been utilized over the past decade in the development of Total Maximum Daily Loads (TMDLs). The Toolbox takes these proven technologies and provides the capability to more readily apply the models, analyze the results, and integrate watershed loading models with receiving water applications. The design of the Toolbox is such that each of the models is a stand-alone application. The toolbox provides an exchange of information between the models through common linkages. Because of the modular design of the Toolbox, additional models can be added easily to integrate with the other tools. In addition, the Toolbox provides the capability to visualize model results, a linkage to GIS and non-geographic databases (including monitoring data for calibration), and the functionality to perform data assessments.

Model Features

The Toolbox allows for the stead state dynamic simulation of mass transport and water quality processes in all types of surface water environments, including overland flow, small creeks, rivers, lakes, estuaries, coastal embayments, and offshore areas.

Model Areas Supported

Watershed	High
Receiving Water	High
Ecological	None
Air	Medium
Groundwater	Medium

Model Capabilities

Conceptual Basis
The Toolbox is designed to address a broad range of waterbody types and pollutants. EPA actively supports the components of the TMDL Modeling Toolbox. EPA is committed to enhancing and improving components of the Toolbox to meet the technical demands of the TMDL program and watershed protection. This will ensure defensibility when TMDLs are faced with legal challenges. Additionally, knowledge gained through the TMDL development experience and modeling with the Toolbox in one region of the country can be distributed readily throughout the others regions.

Scientific Detail
The Toolbox contains assessment tools, watershed models, and receiving water models including the following:

Assessment Tools: (http://wcs.tetratech-ffx.com)
- Water Resources Database (WRDB)
- Watershed Characterization System (WCS)
- WCS Sediment Tool
- WCS Mercury Tool
- WCS LSPC Tool

Watershed Models:
- Loading Simulation Program in C++ (LSPC)
- Watershed Assessment Model (WAMView)
- Storm Water Management Model (SWMM)

Receiving Water Models:
- A Dynamic One-Dimensional Model of Hydrodynamics and Water Quality (EPDRiv1)
- Stream Water Quality Model (QUAL2K)
- CONservational Channel Evolution and Pollutant Transport System (CONCEPTS)
- Environmental Fluid Dynamics Code (EFDC)
- Water Quality Analysis Simulation Program (WASP)

Model Framework
- Watershed hydrologic, sediment, and water quality
- Time series overland, subsurface, and in-stream simulation

Scale

Spatial Scale
- Watershed or Flexible size
- Lumped parameters at a land use-subwatershed basis

Temporal Scale
- Variety of timesteps, including hourly or daily depending on the model.

Assumptions
Each model and modeling tool in the TMDL Modeling Toolbox has its own assumptions based on the physical/chemical processes modeled.

Model Strengths

- Has standardized tools and models used by EPA, states, and consultants.
- Includes models with proven track records.
- Provides an exchange of information between the models through common linkages.
- Includes a flexible design for adding new models to integrate with the existing tools.
- Is in the public domain.

Model Limitations

- Requires a high level of expertise for each application.
- Each model and modeling tool has own limitation.

Application History

The Toolbox models and databases have been used both independently and collectively to develop defensible TMDLs for a wide array of issues including pathogens, sediment, nutrients, dissolved oxygen, metals, temperature, and toxicants. The WCS Sediment Tool has been applied to sediment-impaired waters throughout the southeast. Mercury TMDLs were developed in Georgia using a combination of the WCS Mercury Tool and WASP. LSPC has been used in Alabama for pathogen TMDLs; Georgia, Tennessee, Kentucky, and Alabama for nutrient and/or dissolved oxygen TMDLs; and Alabama, West Virginia, and Arizona for metals TMDLs. EFDC has been used widely throughout the country to support TMDL development—Washington, California, Oklahoma, Florida, Mississippi, Alabama, North Carolina, West Virginia, Delaware, Pennsylvania, and Massachusetts.

Model Evaluation

Toolbox model linkages have been successful in a number of situations, most notably for TMDL development using EFDC and WASP in the Neuse Estuary, North Carolina; Cape Fear River, North Carolina; and Fenholloway River Estuary, Florida; and TMDL development using LSPC, EFDC, and WASP for Mobile Bay, Alabama; Flint Creek, Alabama; Coosa Lakes, Alabama; Lake Allatoona, Georgia; and Alabama River, Alabama.

Model Inputs

The Toolbox provides an exchange of information between the models through common linkages. Each model has its own specific input data requirement. In general, model inputs include

- Continuous meteorological time series records
- Soils data (auxiliary dataset to guide hydrologic calibration)
- Pollutant buildup and washoff
- Stream dimensions or rating curves
- Point source loading inputs
- A large number of specified calibration parameters

Users' Guide

Documentation is available online at http://www.epa.gov/athens/wwqtsc

Technical Hardware/Software Requirements

Computer hardware:

- IBM Compatible PC (Pentium III or higher recommended, but not required)

Operating system:

- Microsoft Windows 98/NT/2000/XP

Programming language:

- Different tools use different programming platforms

Runtime estimates:

- Minutes to less than an hour and daily depending on the model.

Linkages Supported

- Loading Simulation Program in C++ (LSPC)
- Watershed Assessment Model (WAMView)
- Storm Water Management Model (SWMM)
- A Dynamic One-Dimensional Model of Hydrodynamics and Water Quality (EPDRiv1)
- Stream Water Quality Model (QUAL2K)
- CONservational Channel Evolution and Pollutant Transport System (CONCEPTS)
- Environmental Fluid Dynamics Code (EFDC)
- Water Quality Analysis Simulation Program (WASP)

Related Systems

The TMDL Modeling Toolbox supports several numerical models as listed in the *Linkage Supported* section.

Sensitivity/Uncertainty/Calibration

The TMDL Modeling Toolbox supports several numerical models such as LSPC, which includes a data analysis component that may be used to quickly compare model output against observed data in time series form, as monthly summaries, or on a one-to-one graph. LSPC model output is specially tailored for spreadsheet use; consequently, many users prefer to develop independent spreadsheet analysis, summarization, calibration, and plotting applications, which are readily linked to LSPC model output.

Model Interface Capabilities

The Model Visualization Enhancement Module (MOVEM), a graphical post processor, provides an efficient method for reviewing model predictions and comparing them with field data for calibration. MOVEM has the ability to display results from all of the WASP models as well as EFDC, DYNHYD, and EPD-RIV1. MOVEM allows the modeler to displays the results in two graphical formats:

- Spatial Grid – a two dimensional rendition of the model network is displayed in a window where the model network is color shaded based upon the predicted concentration.
- x/y Plots – generates an x/y line plot of predicted and/or observed model results in a window.

There is no limit on the number of x/y plots, spatial grids, or even model result files the user can utilize in a session. Separate windows are created for each spatial grid or x/y plot created by the user.

References

Tetra Tech, Inc. and U.S. Environmental Protection Agency (USEPA). 2002. *The Loading Simulation Program in C++ (LSPC) Watershed Modeling System—Users' Manual.*

WAMView User's Manual. Soil and Water Engineering Technology, Inc.

Wool, T.A, R.B. Ambrose, J.L. Martin, and E.A. Comer. Water Quality Analysis Simulation Program (WASP) Version 6.0 Draft: User's Manual.

TOPMODEL

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Download Information

Availability: Nonproprietary, (http://www.es.lancs.ac.uk/hfdg/TOPMODEL.html)
Cost: None for non-commercial uses.

Contact the author for other uses.

Model Overview/Abstract

TOPMODEL is a physically based, distributed watershed model that simulates hydrologic fluxes of water (infiltration-excess overland flow, saturation overland flow, infiltration, exfiltration, subsurface flow, evapotranspiration, and channel routing) through a watershed. The model simulates explicit groundwater/surface-water interactions by predicting the movement of the water table, which determines where saturated land-surface areas develop and have the potential to produce saturation overland flow.

Model Features

- Rainfall-runoff modeling in single or multiple subwatersheds.
- The Windows version of the model allows Monte Carlo runs with parameter sets chosen from specified parameter ranges.
- The Windows version of the model displays simulated hydrograph time series—the topographic index derived from the elevation data—and map of saturated area in a watershed.

Model Areas Supported

Watershed	Medium
Receiving Water	Low
Ecological	None
Air	None
Groundwater	Medium

Model Capabilities

Conceptual Basis

TOPMODEL is a rainfall-runoff model that bases its distributed predictions on an analysis of watershed topography. The model predicts saturation excess and infiltration excess surface runoff and subsurface stormflow. Since the first article was published about the model in 1979 (Beven and Kirkby, 1979) there have been many different versions.

The idea has always been that the model should be simple enough to be modified by the user so that the predictions conform as far as possible to the user's perceptions of how a watershed works.

Scientific Detail

TOPMODEL is defined as a variable contributing area conceptual model in which the dynamics of surface and subsurface saturated areas is estimated on the basis of storage discharge relationships established from a simplified steady state theory for downslope saturated zone flows. The theory assumes that the local hydraulic gradient is equal to the local surface slope and implies that all points with the same value of the topographic index, $a/\tan B$ will respond in a hydrologically similar way. This index is derived from the basin topography, where a is the drained area per unit contour length and $\tan B$ is the slope of the ground surface at the location. Thus the model need make calculations only for representative values of the index. The results may then be mapped back into space by knowledge of the pattern of the index derived from a topographic analysis.

The soil profile is defined by a set of stores. The upper one is the root zone storage, where rainfall infiltrates until the field capacity is reached. When forest canopies appear, an additional interception and surface storage may be necessary. In this store, evapotranspiration is assumed to take place at the potential rate to decrease at a linear rate when the root zone becomes depleted.

Once the field capacity is exceeded, a second store starts filling until the water content reaches saturation. The gravity drainage store links the unsaturated and saturated zones, according to a linear function that includes a time delay parameter for vertical routing through the unsaturated zone. An alternative approach based on the Darcian flux at the base of the unsaturated zone may be considered.

When the deficit in the gravity drainage store or the water table depth equals 0 the saturation condition is reached and the rainfall produces direct surface runoff. Hence the main goal of TOPMODEL is the computation of the storage deficit or the water table depth at any location for every timestep. The theory relates mean watershed storage deficit to local storage deficits using the local value of a function of the topographic index. In the original version of TOPMODEL the soil hydraulic conductivity, or by extension the soil transmissivity, is assumed to decay following a negative exponential law. In this case, the expression that estimates the value of the local storage deficit or the water table depth is given in terms of the topographic index $\ln(a/\tan B)$. Other forms of soil hydraulic conductivity decay functions lead to different index functions. When distributed values of soil transmissivity ($T0$) are known a soil-topographic index may be considered, $\ln(a/T0 \tan B)$.

The topographic index derivation was obtained by manual analysis of contour maps and hillslope streamtubes in the early versions of the model. The current version of the model provides a program to derive its distribution from a regular raster grid of elevations for any watershed or subwatershed using the multiple direction flow algorithm and the channel initiation threshold for positioning river headwaters.

To compute runoff according to the infiltration excess mechanism TOPMODEL uses the exponential Green-Ampt model. If infiltration excess does occur it does so over the whole area of the subwatershed (although alternatively a statistical distribution of hydraulic conductivity values in the watershed can be assumed). A parameter for controlling the fraction of watershed area that generates runoff by infiltration excess was considered recently by a few studies to compute runoff using the Philip’ two term-equation.

Subwatershed discharges are routed to the watershed outlet using a linear routing algorithm with constant velocity both in the main channel and in the internal subwatershed.

Model Framework

- Watershed and subwatersheds
- Watershed surface are divided into surface zone, root zone, and saturated zone.
- Channel networks

Scale

Spatial Scale
- Grid or subwatersheds

Temporal Scale
- Variable, from 1 to 24 hours

Assumptions
- The hydraulic gradient of subsurface flow is equal to the land-surface slope.
- The actual lateral discharge is proportional to the specific watershed area (drainage area per unit length of contour line).
- The redistribution of water within the subsurface can be approximated by a series of consecutive steady states.
- The soil profile at each point has a finite capacity to transport water laterally downslope.

Model Strengths
- It is a simple distributed watershed model and results can be visualized in a spatial context.
- It requires few watershed parameters and low level of expertise.
- It has been studied extensively.
- The model code is available for modification.

Model Limitations
- TOPMODEL only simulates watershed hydrology, although studies have been conducted to modify it to simulate water quality dynamics.
- TOPMODEL can be applied most accurately to watersheds that do not suffer from excessively long dry periods and have shallow homogeneous soils and moderate topography.
- Model results are sensitive to grid size, and grid size <=50 m is recommended.

Application History
TOPMODEL has a long history of application. See an extensive list of publications at http://www.es.lancs.ac.uk/hfdg/TOPMODEL/new-bibliog.html.

Model Evaluation
The model has been validated with rainfall-discharge data (e.g. Beven et al. 1984, Hornberger et al. 1985, Robson et al. 1993, Obled et al. 1994, Wolock 1995) and several studies have examined its applicability to water quality problems (Wolock et al. 1990, Robson et al. 1992).

Model Inputs
- Project file: Text description of application and input file names and paths.
- Catchment (watershed) data file: Watershed and subwatershed topographic index—ln(a/tan B) distributions and the following parameters:
    - The mean soil surface transmissivity
    - A transmissivity profile decay coefficient
    - A root zone storage capacity
    - An unsaturated zone time delay
    - A main channel routing velocity and internal subwatershed routing velocity

To use the infiltration excess mechanism, a hydraulic conductivity (or distribution), a wetting front suction and the initial near surface water content should be added.

The initialization of each run requires an initial stream discharge and the root zone deficit.

- Hydrological input data file: rainfall, potential evapotranspiration, and observed discharge time series in m/h
- Topographic index map data file: the topographic index map may be prepared from a raster digital elevation file using the DTM-ANALYSIS program. This file includes number of pixels in X direction, number of pixels in Y direction, grid size, and topographic index values for each pair of X and Y.

Users' Guide

Available online: http://www.es.lancs.ac.uk/hfdg/TOPMODEL.html

Technical Hardware/Software Requirements

Computer hardware:

- PC

Operating system:

- PC-DOS, PC-WINDOWS

Programming language:

- FORTRAN, Visual Basic

Runtime estimates:

- Minutes

Linkages Supported

Links to GLUE (Generalized Likelihood Uncertainty Estimation) program for sensitivity/uncertainty/calibration analyses.

Related Systems

TOPMODEL is integrated in GRASS GIS version 5. TOPSIMPL, another Windows version of the model written by Georges-Marie Saulnier can be downloaded directly from the main TOPMODEL site http://www.es.lancs.ac.uk/hfdg/TOPMODEL.html.

Sensitivity/Uncertainty/Calibration

The Windows version of TOPMODEL allows the sensitivity analysis of the objective functions to changes of one or more of the parameters to be explored. An initial run of the model is made with the current values of the parameters. Then each chosen parameter is varied across its range, keeping the values of the other parameters constant. The results are displayed as graphs.

TOPMODEL's Monte-Carlo simulation output can be exported for further sensitivity and uncertainty analyses on the model results using the GLUE (Generalized Likelihood Uncertainty Estimation) program.

TOPMODEL calibration procedures are relatively simple because it uses very few parameters in the model formulas. The model is very sensitive to changes of the soil hydraulic conductivity decay parameter, the soil transmissivity at saturation, the root zone storage capacity, and the channel routing velocity in larger watersheds. The calibrated values of parameters are also related to the grid size used in the digital terrain analysis. The timestep and the grid size also have been shown to influence TOPMODEL simulations.

Model Interface Capabilities

There are three options available in the program interface:

- The Hydrograph Prediction Option: This option allows the model to be run and hydrographs displayed. If a Topographic Index Map File is available, then a map button is displayed that allows the display of predicted simulation, either as a summary over all timesteps or animated.
- The Sensitivity Analysis Option: This screen allows the sensitivity of the objective functions to changes of one or more of the parameters to be explored.
- The Monte Carlo Analysis Option: In this option a large number of runs of the model can be made using uniform random samples of the parameters chosen for inclusion in the analysis. Check boxes can be used to choose the variables and objective functions to be saved for each run. The results file produced will be compatible with the GLUE analysis software package.

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WAMView: Watershed Assessment Model with an ArcView Interface

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Download Information

Availability: Proprietary.
Cost: N/A

The source code is not available. The executable code can be downloaded from http://www.swet.com with a registration.

Model Overview/Abstract

WAMView allows engineers and planners to assess the water quality of surface and groundwater based on land use, soils and weather stations.

Model Features

- Overland attenuation
- Stream routing and various water control structures

Model Areas Supported

Watershed	High
Receiving Water	None
Ecological	Low
Air	None
Groundwater	Low

Model Capabilities

Conceptual Basis

In WAMView, the watershed is conceptualized as a series of cells/grids with different land use, soil, and land slope. The streams are conceptualized as a series of reaches with computed geometries based on upstream drainage areas, which may be redefined by the user.

Scientific Detail

The watershed runoff model BUCSHELL generates grid-based runoff based on land use, soil, topography, and rainfall with two built-in watershed model GLEAMS and EAAMOD. GLEAMS is applied to upland while EAAMOD is applied to the area with a shallow groundwater table.

The stream routing algorithm BLASROUTE is developed based on Manning's equation without a momentum component. A looping technique is implemented in the stream routing algorithm, and various flow structure configurations and operation schedules are implemented. It is noted that BLASROUTE employs first order attenuation from cells to reaches, depression and wetlands.

Model Framework

- Grid-based watershed
- One-dimensional stream routing

Scale

Spatial Scale

- Grid-based watershed; typical grid size 100m x 100m
- Typical reach/stream length 1000m to 10000m

Temporal Scale

- User-defined timestep: typically, a day

Assumptions

- Transport of water and constituent is dependent on flow distances, gradients, and type of conveyance system.
- All input data such as land use, soil, hydrology coverages, and land use management activities are accurate.
- Rainfall data from individual stations are representative of rainfall across the entire basin.
- A reservoir routing technique without a momentum component is representative of low gradient streams.
- Phosphorous and nitrogen process models within the submodels are representative of actual transport processes.

Model Strengths

- Capable of simulating the water quality of surface and groundwater based on land use, soil and weather.
- Capable of simulating various BMP scenarios.
- Provides a higher resolution of results than models that rely on polygon coverages.
- Works well for wetlands.
- Capable of routing attenuated runoff into a complex reach network with flow structures in the latest version.

Model Limitations

- Does not include a momentum component in the stream routing algorithm.
- May predict flow inaccurately when applied to streams with steep slopes.
- Considers limited chemistry constituents.
- Includes groundwater component empirically, not fully integrated into the system.

Application History

Past applications of WAMView include:

- St. Johns River Watershed Assessment Project
- Suwannee River Watershed Assessment Project
- Lower St. Johns River Mainstem Subbasins Hydrologic/Water Quality Modeling
- Hydrologic Water Quality Assessment for Myakka River Basin
- North Palm Beach County Basin Pollutant Loading and Abatement Analysis

Model Evaluation

Model evaluation was done through various projects in which the model was calibrated and then validated to a different time period. The two watershed models used in WAMView are GLEAMS (modified slightly by SWET) and EAAMOD (developed by SWET for areas with a shallow groundwater table). They were tested and evaluated in the past. (See EAAMOD -- Everglades Agricultural Area Model at http://www.swet.com/.)

Model Inputs

- Time sequences of boundary conditions—outflow with chemistry constituents of interest (if tidal outflow exits), point sources flow with chemistry constituent of interest
- Basin polygon coverage, topography coverage, land use coverage, soil coverage, reach coverage, rain station coverage, and utility coverage if any
- Time sequences of rainfall data for each station and other weather data, including monthly maximum and minimum temperature, monthly average dew point temperature, wind speed and solar radiation
- Water control structure configurations and operation schedules, if any

Users' Guide

Available with the download of the executable code: http://www.swet.com. The guide is too simple.

Technical Hardware/Software Requirements

Computer hardware:

- Minimum 100 Mb hard disk space
- Minimum 64 Mb RAM
- Minimum 200 MHZ co-processor
- Minimum 600 x 800 screen resolution

Operating system:

- Windows 95/98/ME/NT/2000/XP
- ArcView 3.2a with Spatial Analyst 1.1 (or 2.0)

Programming language:

- FORTRAN for BUCSHELL and BLASROUTE
- AVENUE for pre- and post-processor in a customized ArcView

Runtime estimates:

- Hours to a day

Linkages Supported

None

Related Systems

None

Sensitivity/Uncertainty/Calibration

Not available.

Model Interface Capabilities

The model interface is a customized ArcView interface with good pre- and post-processors. The pre-processor can process GIS coverage data and create some model input files, and the post-processor can display simulated results in GIS view and layout windows.

References

WAMView User's Manual. Soil and Water Engineering Technology, Inc.

Jacobson, B.M., A.B. Bottcher, N.B. Pickering, and J. G. Hiscock. 1998. Unique routing algorithm for watershed assessment model. *American Society of Agricultural Engineers Paper* No. 98-2237. American Society of Agricultural Engineers, St. Joseph, MI.

Bottcher, A.B., J.G. Hiscock, N.B. Pickering, and B.M. Jacobson. 1998. WAM: Watershed Assessment Model for Agricultural and Urban Landscapes. Presented at the 7th International Conference on Computers in Agriculture. October 26-30, 1998, Orlando, FL.

WARMF: Watershed Analysis Risk Management Framework

Contact Information

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Download Information

Availability: Proprietary
Cost: Depending on projects (Systech conducts an initial model setup)

Model Overview/Abstract

WARMF was developed by Systech Engineering under sponsorship from Electric Power Research Institute (EPRI) as a decision support system to support the watershed approach. It was designed to take stakeholders through a series of steps to develop and evaluate water quality management alternatives for a river basin. WARMF also provides a procedure to calculate the total maximum daily load (TMDL) of pollutants. All necessary databases, simulation models, and graphical software are integrated into a Windows Graphical User Interface (GUI).

Model Features

- Calculates TMDLs using a bottom-up approach. TMDLs are determined for multiple control points and different allocations of point and nonpoint loads.
- Links catchments, river segments, and lakes to form a watershed model.
- Uses data commonly available from National Climatic Data Center, EPA, USGS, Natural Resources Conservation Services, state and other local agencies, and private data purveyors.
- Uses meteorological data to dynamically simulate runoff and nonpoint source loads from land.
- Predicts daily hydrology and water quality of rivers and lakes.
- Simulates flow, pH, temperature, dissolved oxygen, ammonia, nitrate, phosphate, suspended sediment, coliform bacteria, major cations and anions, three algal species, and periphyton.
- Simulate metals such as iron, zinc, manganese, and copper.
- Displays spatial distributions of point and nonpoint loading using GIS map format.
- Displays water quality status in terms of suitability for fish habitat, swimming, water supply, and other uses.
- Accounts for the source controls of atmospheric deposition, nonpoint and point source loads.
- Evaluates cost sharing schemes for pollution trading between point and nonpoint dischargers.

Model Areas Supported

Watershed	High
Receiving Water	Medium
Ecological	None
Air	Low
Groundwater	Medium

Model Capabilities

Conceptual Basis

WARMF is organized into five linked modules—Engineering, Data, Knowledge, Consensus, and TMDL. The Engineering module is the dynamic, simulation model that drives WARMF. The Data module provides time series input data (meteorological, point source) and calibration data. The Knowledge module is a utility to store documents for the watershed. The Consensus and TMDL modules provide road maps to engage stakeholders in building consensus on a watershed management or TMDL plan.

Scientific Detail

The computing engine is taken from the Integrated Lake-Watershed Acidification Study (ILWAS) model. The ILWAS model divides a watershed into catchments, stream segments, and lake layers. The hydrologic module simulates the processes of canopy interception, snow pack accumulation and snow melt, infiltration through soil layers, evapotranspiration from soil, ex-filtration of groundwater to stream segments, kinematic wave routing of stream flows, and flow routing of the terminal reservoir. The chemistry module performs mass balance and chemical equilibrium calculations to account for the processes of dry deposition to the canopy, nitrification of ammonia on the canopy, ion leaching from sap to the canopy surface, washoff by throughfall, ion leaching by snowmelt, and the soil processes (e.g. litter fall, litter breakdown, litter decay, nitrification, denitrification, cation exchange, anion adsorption, weathering, and nutrient uptake). Algorithms for sediment erosion and pollutant transport from farm lands and other land uses were adapted from ANSWERS and the Universal Soil Loss Equation (USLE). The pollutant accumulation and washoff from urban areas was adapted from the Storm Water Management Model (SWMM).

Model Framework

- Watershed (up to five soil layers)
- One-dimensional stream segments
- Lake layers (option to select CE-QUAL-W2)

Scale

Spatial Scale

- Watershed
- One-dimensional stream
- Lake layers

Temporal Scale

- Daily

Assumptions

- The catchment is idealized by a series of compartments (canopy, snow pack, and soil layers).
- Each compartment is considered as a continuously stirred tank reactor (CSTR) for flow routing and mass balance calculation.
- Stream hydrology is based on conservation of mass.
- The model represents the stream segment as a CSTR.

Model Strengths

- For lakes and reservoirs, it has an option of one-dimensional horizontally mixed and vertically stratified or two-dimensional vertically stratified.

Model Limitations

- The user needs to contract Systech to setup and calibrate the model.
- In the TMDL module, percent reductions can be specified for either point or nonpoint source and WARMF will calculate the other. However, as the TMDL module runs through its iterations, it will reduce all upstream sources equally. For example, if multiple point sources exist within a subwatershed or upstream, all nonpoint sources are reduced equally; the model can not account for individual source contributions.

Application History

WARMF has been applied to various watersheds in the United States and the Techi Watershed of Taiwan.

Model Evaluation

WARMF is being tested on the Catawba River (Duke Energy), Cheat River (AEP and Allegheny Power), Chartiers Creek (Pennsylvania power companies), and Oostanaula Creek (TVA) basins. In addition, WARMF is being tested in cooperation with government agencies and other stakeholders in the Truckee River (California/Nevada) and Blue River (Colorado) watersheds.

Model Inputs

- Meteorological data
- Point source loading information
- Atmospheric deposition loads
- Fertilizer application
- Subbasin shape file
- Land use shape file
- Reach Network shape file

Users' Guide

Documentation reports (e.g., User's Guide to WARMF, Documentation of Graphical User Interface) are available to WARMF users and all reports are available for purchase from Electric Power Research Institute (EPRI).

Technical Hardware/Software Requirements

Computer hardware:

- PC

Operating system:

- Graphical User Interface

Programming language:

- Computational code: FORTRAN

Runtime estimates:

- Minutes to hours

Linkages Supported

None

Related Systems

None

Sensitivity/Uncertainty/Calibration

An uncertainty analysis can be performed to evaluate the chance of failure for a management plan.

Model Interface Capabilities

- Pre- and post-processors
- Data display tools

References

Chen, C.W., J. Herr and W. Tsai. 2003. *Enhancement of WARMF to Track Mercury Species in a River Basin from Atmospheric Depositions to Fish Tissues*. Publication No.1005470. Electric Power Research Institute, Palo Alto, CA.

Chen, C.W., J. Herr, and L. Weintraub. 2001. *Watershed Analysis Risk Management Framework (WARMF): Update One – A Decision Support System for Watershed Analysis and Total Maximum Daily Load Calculation, Allocation and Implementation.* Publication No.1005181. Electric Power Research Institute, Palo Alto, CA.

Chen, C., J. Herr, and L. Weintraub. 2000. *Watershed Analysis Risk Management Framework (WARMF) User's Guide: Documentation of Graphical User Interface.* Report TR1000729. Electric Power Research Institute, Palo Alto, CA.

Chen, C. W., J. Herr, and L. Ziemelis. 1998. *Watershed Analysis Risk Management Framework - A Decision Support System for Watershed Approach and TMDL Calculation.* Documentation Report TR110709. Electric Power Research Institute, Palo Alto, CA.

Chen, C.W., L. Weintraub, L. Olmsted, and R.A. Goldstein. Decision framework for sediment control in muddy creek watershed. *Journal of the American Water Resources Association*.

Chen, C.W., J. Herr, and L. Weintraub. 2004. Decision support system for stakeholder involvement. *Journal of Environmental Engineering, American Society of Civil Engineers*. 130(6):714-721.

Chen, C.W., J. Doherty, and J.M. Johnston. 2003 Methodologies for calibration and predictive analysis of a watershed model. *Journal of the American Water Resources Association*.

Herr, J., C.W. Chen, R.A. Goldstein, R. Herd, and J.M. Brown. 2003. Modeling acid mine drainage on a watershed scale for TMDL calculations. *Journal of the American Water Resources Association*. 39(2).

Chen, C.W., L.H.Z. Weintraub, J. Herr, and R.A. Goldstein. 2000. Impacts of a thermal power plant on the phosphorus TMDL of a reservoir. *Environmental Science and Policy*. 3:217-223.

Chen, C. W., J. Herr, L. Ziemelis, R. A. Goldstein, and L. Olmsted. 1999. Decision support system for total maximum daily load. *Journal of Environmental Engineering, American Society of Civil Engineers.* 125(7):653-659.

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Chen, C.W., D. Leva, and A. Olivieri. 1996. Modeling the fate of copper discharged to San Francisco Bay. *Journal of Environmental Engineering*, *American Society of Civil Engineers*. 122(10).

Chen, C.W., W.T. Tsai, and L.E. Gomez. 1994. *Modeling Responses of Ponderosa Pine to Interacting Stresses Ozone and Drought Forest Science*. 40(2):267-288.

WASP: Water Quality Analysis Simulation Program

Contact Information

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Download Information

Availability: Nonproprietary
Version 5.1: http://www.epa.gov/ceampubl/swater/wasp/index.htm
Version 6.2: http://www.epa.gov/athens/wwqtsc/html/wasp.html
Cost: N/A

Model Overview/Abstract

WASP is a generalized modeling framework based on the finite-volume concept for quantifying fate and transport of water quality variables in surface waters. The three components of the model are WASP for mass transport; EUTRO for dissolved oxygen, nutrients, and algal kinetic; and TOXI for toxic substances. WASP is capable of analyzing time-variable or steady state, one-, two-, or three-dimensional water quality problems. WASP5 is a DOS application and WASP6 is a Windows application. WASP model has been widely applied to investigate dissolved oxygen, bacteria, eutrophication, suspended solids, and toxic substance problems.

Model Features

- Tracer transport
- Eutrophication
- Dissolved oxygen
- Nutrients
- Toxic
- Sediment transport

Model Areas Supported

Watershed	None
Receiving Water	High
Ecological	Medium
Air	None
Groundwater	None

Model Capabilities

Conceptual Basis
The waterbodies are conceptualized as well-mixed control volume, and the law of conservation of mass is applied to each control volume.

Scientific Detail
The governing equations for the WASP model are the advection-dispersion-reaction equations for the water quality variables. The WASP module provides the advection and dispersion solution and the EUTRO and TOXI modules provide the reaction solutions of dissolved oxygen, nutrients, and algae. A one-step Euler solution technique is applied for the time difference. The advection terms in the governing equations are solved with UPWIND difference in space. The water quality variables can be turned on/off depending on modeling requirements.

Model Framework
- One-, two-, or three-dimensional
- Any type of waterbody

Scale

Spatial Scale
- One-, two-, or three-dimensional

Temporal Scale
- User-defined timestep

Assumptions
- Completely mixing control volume

Model Strengths
- WASP model is a very flexible modeling framework and can simulate water quality in one-, two-, or three-dimensional space.
- The control volume structure promises the conservation of mass. WASP provides the transport computation framework and can be incorporated with EUTRO to simulate eutrophication, nutrient, and dissolved oxygen. It also can be incorporated with TOXI to model metals, toxics, and sediment transport.

Model Limitations
- Requires external hydrodynamic model to provide flow file for solving advection. The file size might be very large in several gigabytes for long-term simulation.
- User specified dispersion coefficient and temperature.
- First-order UPWIND difference in space may cause significant numerical diffusion.
- Over-simplified sediment flux calculation.
- No periphyton or macroalgae.
- Sediment transport processes are not related to shear stress.

Application History
A significant amount of WASP applications can be found in technical reports, journal and conference papers. Examples of application include modeling eutrophication of Tampa Bay, Neuse River, the Great Lakes, and Potomac Estuary; and examining phosphorus loading to Lake Okeechobee, PCB pollution of the Great Lakes, and kepone pollution of the James River Estuary.

Model Evaluation
WASP model is widely cited in peer reviewed journal papers.

Model Inputs
- Initial conditions
- Point and nonpoint sources inputs
- Flow file
- Vertical mixing coefficients
- Open boundary conditions
- Biological and chemical reaction rates

Users' Guide
WASP5:
- The Water Quality Analysis Simulation Program, WASP5, Part A: Model Documentation.
- The Water Quality Analysis Simulation Program, WASP5, Part B: The WASP5 Input Data Set
- Available in model download file: http://www.epa.gov/ceampubl/swater/wasp/index.htm

WASP6:
- Water Quality Analysis Simulation Program (WASP) Version 6.0, Draft: User's Manual
- Available online: http://www.epa.gov/athens/wwqtsc/html/wasp.html:

Technical Hardware/Software Requirements

Computer hardware:
- PC

Operating system:
- PC-DOS, Windows

Programming language:
- FORTRAN (WASP5),

Runtime estimates:
- Minutes to hours

Linkages Supported
DYNHYD5 provides the flow information to WASP5. Other models that provides flow file include RIVMOD, EFDC, and SWMM.

Related Systems
QUAL2E, QUAL2K, CE-QUAL-RIV1, CE-QUAL-W2, CW-QUAL-ICM, CAEDYM

Sensitivity/Uncertainty/Calibration
Not available

Model Interface Capabilities

- WASP6 provides a Windows interface including pre-processor and post-processor

References

Ambrose, R.B., T.A. Wool, and J.L. Martin. 1993a. *The Water Quality Analysis Simulation Program, WASP5, Part A: Model Documentation*. U.S. Environmental Protection Agency, Center for Exposure Assessment Modeling, Athens, GA.

Ambrose, R.B., T.A. Wool, and J.L. Martin. 1993b. *The Water Quality Analysis Simulation Program, WASP5, Part B: The WASP5 Input Dataset*. U.S. Environmental Protection Agency, Center for Exposure Assessment Modeling, Athens, GA.

Wool, T.A, R.B. Ambrose, J.L. Martin, and E.A. Comer. *Water Quality Analysis Simulation Program (WASP) Version 6.0 Draft: User's Manual*

WEPP: Water Erosion Prediction Project

Contact Information

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Download Information

Availability: Nonproprietary
Download site: http://topsoil.nserl.purdue.edu/nserlweb/weppmain/wepp.html
Download instructions/limitations: Registration optional
Cost: N/A

Model Overview/Abstract

The WEPP model is a process-based, distributed parameter, continuous simulation, erosion prediction model for use on personal computers running Windows 95/98/NT/2000/XP. The current model version (v2002.700) available for download is applicable to hillslope erosion processes (sheet and rill erosion) as well as simulation of the hydrologic and erosion processes on small watersheds. The WEPP model (version 2002.700), WEPP Windows interface (March 2004), CLIGEN climate generators (versions 4.3 and 5.2), documentation, and example data are included in the download package.

Model Features

- Process-oriented
- Continuous simulation
- Erosion prediction
- Applicable to small watersheds (field-sized); can simulate small profiles (USLE types) up to large fields.
- Mimics the natural processes that are important in soil erosion. Everyday it updates the soil and crop conditions that affect soil erosion. When rainfall occurs, the plant and soil characteristics are used to determine if surface runoff will occur. If predicted, then the program will compute estimated sheet and rill detachment and deposition and channel detachment and deposition.

Model Areas Supported

Watershed	Medium (sediment only)
Receiving Water	Low (channels)
Ecological	None
Air	None
Groundwater	None

Model Capabilities

Conceptual Basis

Conceptually WEPP is similar to CREAMS, SWRRB, and EPIC, but formulations are more process-based, rather than statistical relations. The model is based on stochastic weather generations, infiltration theory, hydrology, soil physics, plant science, hydraulics, and erosion mechanics.

Scientific Detail

The WEPP model includes components for weather generation, frozen soils, snow accumulation and melt, irrigation, infiltration, overland flow hydraulics, water balance, plant growth, residue decomposition, soil disturbance by tillage, consolidation, and erosion and deposition.

- Weather generator – precipitation by two-state Markov chain model; daily maximum and minimum temperatures and solar radiation from normal distributions; and wind speed and direction based on the historical distributions
- Winter processes – soil frost by fundamental heat theory and snow melt by generalized snow melt equation
- Irrigation – stationary sprinkler systems with four irrigation-scheduling options—(1) no irrigation, (2) depletion-level scheduling, (3) fixed-date scheduling, and (4) a combination of the second and third options
- Infiltration – Green-Ampt Mein-Larson infiltration equation
- Evapotransipration – Penman equation
- Hillslope erosion and deposition – RUSLE for hillslope version; deterministic equations based on infiltration theory, soil physics, and erosion mechanics, for other versions; and detachment, transport, and deposition based on steady state solution to the sediment continuity equation
- Flow depth and hydraulic shear stress – steady state, spatially varied flow equations
- Impoundment component – runoff and sediment routed through several types of impoundment structures, including farm ponds, culverts, filter fences, and check dams.

Model Framework

- Single watershed composed of a network of hillslopes and channels.

Scale

Spatial Scale

- Hillslope or small watershed

Temporal Scale

- Daily, monthly or annual

Assumptions

- Sediment delivery rate is assumed to be proportional to the product of rainfall intensity and interrill runoff rate.
- Broad sheet flow on an idealized surface is assumed for overland flow routing and hydrograph development.
- Steady state conditions are assumed at the peak runoff rate for erosion calculations.
- Heat flow in a frozen or unfrozen soil or soil-snow system is unidirectional.

Model Strengths

- WEPP is capable of estimating the spatial and temporal distributions of soil loss.

- Since the model contains processed based hydrology, water balance, plant growth, and residue decomposition components, the model has wider range of applications compared to other erosion prediction models.

Model Limitations

- The model is not suitable for large watersheds. It is appropriate only for hillslope profiles of tens of meters and small watersheds up to hundreds of meters.

Application History

Application of WEPP other than by the developers is very limited. Kincaid (2002) used WEPP to predict runoff and erosion under sprinkler irrigation and found that the model can be used as an irrigation and management tool to help prevent runoff from sprinkler irrigation.

Model Evaluation

Though there are a lot of publications available evaluating the applicability of the model. Most of them are publications by members of the development team and are not peer reviewed. There are also few peer-reviewed publications available. Tiwari et al. (2000) conducted a study to evaluate WEPP and also to compare the results with the predictions by USLE and RUSLE. Bjorneberg et al. (1999) evaluated the model under furrow irrigated conditions and found that the model could not be used without modifications. Reyes et al. (2004) conducted a study to compare the runoff volume predictions of GLEAMS, EPIC and WEPP and the soil loss predictions of GLEAMS, RUSLE, EPIC and WEPP. They found that the WEPP consistently under-predicted the soil loss.

Model Inputs

The WEPP model includes a number of conceptual components, which are used to predict and calculate estimates of soil detachment and deposition. The different input requirements for these components include:

- Climate–rainfall parameters, temperature, solar radiation, wind
- Winter–freeze-thaw, snow accumulation, snow melting
- Irrigation–stationary sprinkler, furrow
- Hydrology–infiltration, depressional storage, runoff
- Water balance–evapotranspiration, percolation, drainage
- Soils–types and properties
- Crop growth–cropland, rangeland, forestland
- Residue management and decomposition
- Tillage impacts on infiltration and erodibility
- Erosion–interrill, rill, channel
- Deposition–rills, channels, and impoundments
- Sediment delivery, particle sorting and enrichment

Users' Guide

Available online: http://topsoil.nserl.purdue.edu/nserlweb/weppmain/wepp.html

Technical Hardware/Software Requirements

Computer hardware:

- PC

Operating system:

- Windows 95/98/NT/2000/XP

Programming language:

- FORTRAN 77

Runtime estimates:

- Minutes

Linkages Supported

None

Related Systems

CREAMS, SWRRB and EPIC

Sensitivity/Uncertainty/Calibration

Not available

Model Interface Capabilities

- Windows-based GUI interface for input creation
- GIS interface for WEPP (GeoWEPP)

References

Blorneberg, D. L., T. J. Trout, R. E. Sojka, and J. K. Aase. 1999. Evaluating WEPP-predicted infiltration, runoff, and soil erosion for furrow irrigation. *Transactions of the American Society of Agricultural Engineers.* 42(6): 1733-1741.

Cochrane, T. A., and D. C. Flanagan. 2003. Representative hillslope methods for applying the WEPP model with DEMs and GIS. *Transactions of the American Society of Agricultural Engineers.* 46(4): 1041-1049.

Flanagan, D. C., and M. A. Nearing, eds. 1995. *USDA-water Erosion Prediction Project: Technical documentation.* NSERL Report No. 10. U.S. Department of Agriculture-Agricultural Research Service- National Soil Erosion Research Lab, West Lafayette, ID.

Kincaid, D. C. 2002. The WEPP model for runoff and erosion prediction under sprinkler irrigation. *Transactions of the American Society of Agricultural Engineers.* 45(1): 67-72.

Reyes, M. R., C. W. Raczkowski, G. A. Gayle, and G. B. Reddy. 2004. Comparing the soil loss predictions of GLEAMS, RUSLE, EPIC, and WEPP. *Transactions of the American Society of Agricultural Engineers.* 47(2): 489-493.

Tiwari, A. K., L. M. Risse, and M. A. Nearing. 2000. Evaluation of WEPP and its comparison with USLE and RUSLE. *Transactions of the American Society of Agricultural Engineers.* 43(5): 1129-1135.

Ward, George H., Jr. and Jennifer Benaman. 1999. *Models for TMDL Application in Texas Watercourses: Screening and Model Review.* Online Report CRWR-99-7. Center for Research in Water Resources, University of Texas, Austin.

WinHSPF: An Interactive Windows Interface to HSPF

Contact Information

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AQUA TERRA
http://www.aquaterra.com/

Download Information

Availability: Nonproprietary
http://www.epa.gov/ost/ftp/basins/system/BASINS3/gww.htm
Cost: N/A

Model Overview/Abstract

WinHSPF was designed as an interactive Windows interface to Hydrologic Simulation Program FORTRAN (HSPF). It is a fully-integrated component of the BASINS system but can be run stand-alone. WinHSPF can be used to build User Control Input (UCI) files from GIS data, especially data from the EPA's BASINS system. After the UCI file is built, WinHSPF can be used to view and modify the model representation of a watershed. The FORTRAN program HSPF can be run from within WinHSPF. Modifying a given UCI file and saving as another name creates multiple simulation scenarios. Within the BASINS system, WinHSPF is intended to be used in conjunction with the interactive program known as "GENeration and analysis of model simulation SCeNarios," or GenScn. GenScn allows the user to analyze results of model simulation scenarios and compare scenarios. This system architecture allows the user to choose the system environment that best suits his or her needs.

Model Features

- Detailed watershed simulation model
- Watershed hydrology
- Runoff/Sediment/Pollutant generation and transport
- One-dimensional stream hydrology and transport
- Pesticide fate and transport simulation

Model Areas Supported

Watershed	High
Receiving Water	Medium
Ecological	None
Air	None
Groundwater	Low

Model Capabilities

Conceptual Basis

HSPF was the primary watershed model adopted into the original BASINS system. HSPF simulates the complete watershed hydrology precipitation, interception, evapotranspiration, runoff, interflow, groundwater flow, and groundwater loss to deep aquifers. A continuous simulation model driven by meteorological time series data, HSPF also simulates the fate and transport of a wide variety of pollutants, such as nutrients, sediments, tracers, dissolved oxygen/biochemical oxygen demand, temperature, bacteria, and user-defined constituents. It simulates pollutant accumulation and reactions on pervious and impervious land segments, runoff and pollutant discharge loads to stream segments, in-stream reactions, flow, and pollutant routing through river reach networks.

The BASINS WinHSPF Windows interface replaces the former Nonpoint Source Model (NPSM) interface included in the original versions of BASINS. WinHSPF provides complete access to HSPF's functionality and user input data files. The model estimates land use (rural and urban mixtures) specific nonpoint source loadings for selected pollutants at an 8-digit HUC or subwatershed scale. The model uses GIS landscape data such as land use distribution and elevation data together with the watershed and drainage stream network characteristics to automatically prepare many of the input data it requires. WinHSPF is a continuous simulation model driven by meteorological events and used to analyze water quality impacts from multiple point and nonpoint pollutant sources. It can be used for single or multiple hydrological connected watersheds and is designed for evaluating alternative pollution control scenarios.

A user also can simulate point source contributions in WinHSPF. Data from EPA's Permit Compliance System (PCS) are provided. This is a simplified implementation in that only a single value of flow from the facility and pollutant concentration (based on NPDES permit limits) can be specified.

Scientific Detail

Land processes for pervious and impervious areas are simulated through water budget, sediment generation and transport, and water quality constituents' generation and transport. Hydrology is modeled as water balance of soil (or storage) in different layers as described by the Stanford Watershed Model (SWM) methodology. Interception, infiltration, evapotranspiration, interflow, groundwater loss and overland flow processes are considered and are generally represented by empirical equations. Sediment production is based on detachment or scour from a soil matrix and transport by overland flow in pervious areas, while solids buildup and washoff are simulated for impervious areas. It includes agricultural components for land-based nutrient and pesticide processes and a special actions block for simulating management activities. HSPF also simulates the in-stream fate and transport of a wide variety of pollutants such as nutrients, sediments, tracers, dissolved oxygen/biochemical oxygen demand, temperature, bacteria, and user-defined constituents.

Model Framework

- Hydrologic response unit, subwatershed, and watershed
- Simple one-dimensional stream and well-mixed reservoir/lake model
- WinHSPF interface uses an object-oriented data structure to link to the HSPF model

Scale

Spatial Scale

- Lumped parameters at a land use-subwatershed basis
- Subwatershed—variable size up to internal operations limit

Temporal Scale

- User-defined timestep, typically hourly

Assumptions

- It is a distributed model by land use but ignores the spatial variation within a land use in a subwatershed.

- The receiving waterbody is well mixed along the width and depth. Assumes one-directional flow.

Model Strengths

- One of the few watershed models capable of simulating land processes and receiving water processes simultaneously.
- Capable of simulating both peak flow and low flow.
- Simulates at a variety of timesteps, including sub-hourly to one minute, hourly or daily.
- Simulates the hydraulics of complex natural and man-made drainage networks.
- Includes capabilities to address a variable water table.
- Simulate results for many locations along a reservoir or tributary.
- Includes user-defined model output options by defining the external targets block.
- Can be setup as simple or complex, depending on application, requirement, and data availability.

Model Limitations

- Relies on many empirical relations to represent physical process.
- Lumps simulation processes for each land use type at the subwatershed level (i.e., does not consider the spatial location of one land parcel relative to another in the watershed). The model approaches a distributed model when smaller subwatersheds are used; however, this may result in increased model size and simulation time.
- Requires extensive calibration.
- Requires a high level of expertise for application.
- Is limited to well-mixed rivers and reservoirs and one-directional flow.

Application History

The underlying HSPF model is a proven, tested continuous simulation watershed model. It is one of the models recommended by the EPA for complex TMDL studies. The HSPF model has been used widely and the applications have been documented for more than 20 years.

Model Evaluation

The WinHSPF interface has an application history dating to the recent release of BASINS 3.0. However, the underlying HSPF model has been widely reviewed and applied throughout its history (Hicks, 1985, Ross et al., 1997, and Tsihrintzis et al., 1996). One of the largest applications of the model was to the Chesapeake Bay Watershed, as part of the Chesapeake Bay Program's management initiative (Donigian, 1990, 1992). Tsihrintzis et al. (1994, 1995) applied HSPF in a GIS shell (using ARC/INFO) to evaluate the impact of agricultural activities, specifically the transport of sediments, nutrients, and pesticides, on streams and groundwater in southern Florida. An extensive HSPF bibliography has been compiled to document model development and application, and is Available online: http://hspf.com/hspfbib.html.

Model Inputs

- Continuous meteorological time series records including (at a minimum):
    - Rainfall
    - Potential evapotranspiration

For snow simulation, additional required meteorological time series include:

- Temperature
- Wind speed
- Solar Radiation
- Dewpoint Temperature

For additional simulation options, other required meteorological time series may include:

- Pan Evaporation
- Cloud Cover

- Soils data (auxiliary dataset to guide hydrologic calibration), pollutant buildup and washoff, stream dimensions or rating curves, point-source loading inputs
- A large number of parameters need to be specified (some default values are available).

Users' Guide

- WinHSPF Users' Manual is available online: http://www.epa.gov/waterscience/basins/bsnsdocs.html#win
- For model documentation, underlying theory, and parameterization the HSPF users' manual is a recommended source (Bicknell et al, 2001).
- A browsable Windows help file version of the manual is available at http://hspf.com/pub/hspf/HSPF.chm.

Technical Hardware/Software Requirements

Computer hardware:

- PC with Windows Operation System

Operating system:

- Microsoft Windows

Programming language:

- FORTRAN (model) and Visual Basic (interface)

Runtime estimates:

- Minutes to less than an hour

Linkages Supported

None

Related Systems

WinHSPF, an interface to the Hydrological Simulation Program-FORTRAN (HSPF), is a key component of Better Assessment Science Integrating Point and Nonpoint Sources (BASINS) Version 3.0. BASINS 3.0 is being developed for the EPA's Office of Water to respond to the continued needs of various agencies to perform watershed and water quality assessments integrating point and nonpoint sources.

Sensitivity/Uncertainty/Calibration

WinHSPF assists the user in building the necessary datasets and making the necessary modifications to the input sequence for hydrologic calibration using the U.S. Geological Survey's Expert System for the Calibration of HSPF (HSPEXP).

Model Interface Capabilities

WinHSPF provides an interactive interface to HSPF in a Windows environment. WinHSPF may be used for creating a new HSPF input sequence or for modifying an existing HSPF input sequence. The program HSPF may be run from within WinHSPF. Input sequences may be modified and saved under another name to create simulation scenarios.

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WMS: Watershed Modeling System

Contact Information

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South Jordan, UT 84095-4612
(801) 302-1400
info@ems-i.com

U.S. Army Corps of Engineers
Engineer Research and Development Center
Coastal and Hydraulics Lab
Hydrological Systems Branch
Vicksburg, MS 39180

Download Information

Availability: Proprietary
http://www.ems-i.com/WMS/wms.html
A limited public domain version also is available at this link:
http://www.ems-i.com/WMS/WMS_Freeware/wms_freeware.html
Cost: Complete Package ($4,600)

Model Overview/Abstract

WMS is a comprehensive graphical modeling environment for all phases of watershed hydrology and hydraulics. It was developed by the Environmental Modeling Research Laboratory of Brigham Young University in cooperation with the U.S. Army Corps of Engineers Waterways Experiment Station. WMS consists of tools that automate modeling processes such as automated basin delineation, geometric parameter calculations, and GIS overlay computations (CN, rainfall depth, roughness coefficients, etc.). WMS 7 supports hydrologic modeling with HEC-1 (HEC-HMS), TR-20, TR-55, Rational Method, NFF, MODRAT, and HSPF. It also supports hydraulic models such as HEC-RAS and CE-QUAL-W2. WMS is designed to be modular, enabling the user to select only those modules and hydrologic modeling capabilities that are required. Additional WMS modules can be added at any time. To facilitate data transfer between ArcView GIS and WMS, an extension called WMSHydro has been developed. This extension creates a WMS/ArcView "super file" which is a collection of ArcView shapefiles and ASCII grid files. The super file can be exported either from WMS or this extension. This super file also can be imported into WMS or ArcView as themes (coverages) and grids.

Model Features

WMS is structured into eight modules. Only one module is active at any given time.

- Terrain Data: Used for basin delineation with Triangulated Irregular Networks (TINs).
- Drainage: Used for basin delineation with gridded Digital Elevation Models (DEMs).
- Map: Used to create data layers from GIS objects (drainage, soil, land use, etc.)
- Hydrologic Modeling: Contains interfaces to hydrologic models.
- River: Contains tools for creating one-dimensional hydraulic models.
- GIS: Used to open shape file data and convert them to feature objects.
- 2D Grid: Used for finite difference models (currently research models only).

- 2D Scatter Point: Contains two-dimensional scatter point interpolation tools.

Model Areas Supported

Watershed	High
Receiving Water	High
Ecological	None
Air	None
Groundwater	Medium

Model Capabilities

Conceptual Basis

In WMS, a subwatershed is delineated based on DEM (grid) or TIN. Several small subwatersheds and representative streams may be networked together to represent a larger watershed drainage area. Various hydrological and hydraulic models are supported by WMS and can be used through WMS to simulate the various land and stream processes.

Scientific Detail

WMS supports several numerical models to compute peak flow, hydrographs, and water quality. Each model is supported through the Hydrologic Modeling Module with a completely integrated interface for parameter input, model run, and output display. The models available for use with WMS are:

- HEC-1 (HMS): HEC-1 is the most commonly used lumped parameter model and was developed by the U.S. Army Corp of Engineers' (USACE) Hydrologic Engineering Center. HEC-1 simulates the surface runoff from a single precipitation event.
- TR-20: TR-20 is designed to compute surface runoff from natural or synthetic rainstorm events and was developed by the U.S. Department of Agriculture's Natural Resource Conservation Service (NRCS).
- TR-55: TR-55 was developed by the NRCS as a simplified method to compute storm runoff in small, urbanized watersheds.
- MODRAT: MODRAT is the specialized Modified Rational Method program used by the Los Angeles County, California, to compute surface runoff.
- StormDrain: The StormDrain model does complete storm sewer network analysis for steady state or transient flow conditions. It is based on the HYDRAIN analysis code from the Federal Highway Administration (FHWA).
- CE-QUAL-W2: CE-QUAL-W2 is a two-dimensional (profile) hydraulic model used for water quality analysis in rivers and reservoirs where vertical variation analysis is required.
- National Flood Frequency (NFF): The NFF program evaluates regional regression equations for estimating flood peak discharges. It is developed by the U.S. Geological Survey (USGS) in cooperation with FHWA and Federal Emergency Management Agency (FEMA).
- Rational Method: The Rational Method is one of the simplest and best-known methods of hydrology. It computes peak discharge from an area based on rainfall intensity and a runoff coefficient.
- Hydrological Simulation Program-FORTRAN (HSPF): HSPF simulates hydrologic and water-quality processes on land surfaces, streams, and impoundments. It is commonly used in the development of TMDLs.
- HEC-RAS: HEC-RAS is a one-dimensional hydraulic model for computing water surface profiles for steady state or gradually varied flow.
- GSSHA: GSSHA is a distributed (two-dimensional) hydrologic model developed for analysis of surface runoff, channel hydraulics, and groundwater interaction. Water quality and sediment transport also are supported. It was developed by the USACE Engineer Research and Development Center (ERDC).

Model Framework

- Watershed hydrologic, sediment, and water quality

- Time series overland, subsurface, and in-stream simulation

Scale

Spatial Scale

- Watershed or subwatershed—flexible size
- Lumped parameters at a land use-subwatershed basis

Temporal Scale

- Variety of timesteps, including hourly or daily

Assumptions

- It is a distributed model by land use but ignores the spatial variation within a land use in a subwatershed.

Model Strengths

- It is more robust in TIN triangulation and processing.
- It provides tools to extract the significant elevation points from DEMs.
- TINs or DEMs contours can be exported as feature lines and then to shape files.
- It supports several hydrological and hydraulic models through WMS interfaces.

Model Limitations

- The model relies on many empirical relations to represent physical process.
- It requires a high level of expertise for application.
- There is a limited public domain version and the full package is expensive.

Application History

WMS provides the interface linkage to various popular and tested models such as HSPF, which is a continuous simulation watershed model. HSPF is one of the models recommended by the EPA for complex TMDL studies. The HSPF model has been used widely and the applications have been documented for more than 20 years.

Model Evaluation

HSPF has been widely reviewed and applied throughout its long history (Hicks, 1985, Ross et al., 1997, and Tsihrintzis et al., 1996). One of the largest applications of the model was to the Chesapeake Bay Watershed, as part of the EPA's Chesapeake Bay Program's management initiative (Donigian, 1990, 1992). An extensive HSPF bibliography has been compiled to document model development and application, and is available online at http://hspf.com/hspfbib.html.

Model Inputs

Some of the most common coverage types used in WMS include:

- Drainage
- Storm Drain
- 1D-Hyd Centerline
- 1D-Hyd Cross Section
- Area Property
- NFF Region
- Soil Type
- Land Use

- Time Computation

A large number of parameters need to be specified for the specific model through the graphical user interface.

Users' Guide

WMS documentation is available online:
http://www.ems-i.com/WMS/WMS_Downloads/wms_downloads.html
WMS online help is available at these links:
http://www.ems-i.com/wms70help/WMSHELP.htm
http://www.bossintl.com/online_help/wms/source/introduction/introduction.htm

Technical Hardware/Software Requirements

Computer hardware:

- 500MhZ processor
- 128 MB RAM
- 100 MB disk space

Operating system:

- Microsoft Windows NT/Me/2000/XP

Programming language:

- Visual Basic with ArcObjects and OpenGL Technology

Runtime estimates:

- Minutes to less than an hour

Linkages Supported

- HEC-1 (HEC-HMS)
- TR-20
- TR-55
- MODRAT
- StormDrain
- CE-QUAL-W2
- National Flood Frequency Program (NFF)
- Rational Method
- Hydrologic Simulation Program - FORTRAN (HSPF)
- HEC-RAS
- GSSHA (Gridded Surface Subsurface Hydrologic Analysis)

Related Systems

WMS supports several numerical models as listed in *Linkages Supported* section.

Sensitivity/Uncertainty/Calibration

The Hydrologic Modeling Module of WMS contains the tools for computing complex hydrologic parameters by using digital terrain or GIS data needed for input to a model. It serves as a good starting point for model setup and calibration.

Model Interface Capabilities

WMS provides GIS style tools and functionality that make it easy to build models and view results. All modeling parameters are entered through interactive graphics and easy-to-use dialog boxes. The system reads and writes native model input/output files through graphical user interface.

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Tsihrintzis, V.A., H.R. Fuentes and R. Gadipudi. 1996. Modeling prevention alternatives for nonpoint source pollution at a wellfield in Florida. *Water Resources Bulletin, Journal of the American Water Resources Association*, 32(2):317-331.

XP-SWMM: Stormwater and Wastewater Management Model

Contact Information

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Portland, OR, 97213
(888) 554-5022
info@xpsoftware.com

Download Information

Availability: Proprietary
http://www.xpsoftware.com/products/xpswmm.htm
Cost: XP-SWMM2000 is sold as a link/node model; the cost of the software is proportionate to the size of the project, for which it will be used.

Model Overview/Abstract

XP-SWMM is an enhanced version of SWMM coupled with the XP interface. The graphical EXPERT environment (XP) is a friendly, graphics-based environment that encompasses data entry, run-time graphics, and post-processing of results in graphical form. Drainage networks are drawn either on the screen over real-world topographical backgrounds or imported from a database. It has the ability to handle systems comprising pipes and open channels, rivers, loops, bifurcations, pumps, weirs, and ponds.

Model Features

- Watershed hydrology and water quality
- Stream transport
- Urban stormwater systems and pipes.

Model Areas Supported

Watershed	High
Receiving Water	Medium
Ecological	None
Air	None
Groundwater	Low

Model Capabilities

Conceptual Basis

The SWMM 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.

Scientific Detail

In addition to EPA SWMM's Non-linear Runoff Routing, XP-SWMM has 10 additional ways to estimate surface runoff:

1. SCS Unit Hydrographs using a Curve Number with curvilinear unit hydrographs
2. SCS Unit Hydrographs using a Curve Number with triangular unit hydrographs
3. Kinematic Wave
4. Snyder Unit Hydrograph
5. Snyder (Alameda) Unit Hydrograph
6. Nash Unit Hydrograph
7. Santa Barbara Urban Hydrograph
8. Laurenson's Non-linear Runoff Routing (RAFTS)
9. Rational Method
10. Colorado Urban Hydrograph Procedure (CUHP)

The model has more capabilities in infiltration, sub-surface flow, and groundwater flow than that of EPA SWMM. In addition to SWMM capabilities, pollutant routing is available for all modules, including the Hydraulics layer. More than 30 types of conduits can be input into the model.

Model Framework

- One-dimensional mass balance flow and pollutant routing

Scale

Spatial Scale

- Watershed or subwatershed—flexible size

Temporal Scale

- Variety of timesteps, including hourly or daily

Assumptions

- The model performs best in urbanized areas with impervious drainage, although it has been widely used elsewhere.
- Model parameters for quantity and quality simulations are developed such that the model will be calibrated to enhance its capability.
- All the pollutants entering the waterbodies are sediment adsorbed.

Model Strengths

- Completely interactive analysis engine, allowing the user to change parameters mid-run, pause or terminate a run, and to graph results on the fly.
- Dynamic memory allocation.

Model Limitations

- Not a public domain product.
- Lack of subsurface quality routing
- No interaction of quality processes
- Limited kinetics (A first order decay rate can be specified for each pollutant in the Transport Block.)
- Difficulty in simulation of wetlands quality processes
- Rudimentary scour-deposition routine in the Transport Block

Application History
SWMM has been 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 (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.

Model Evaluation
[SWMM or XP-SWMM] is widely applied in Florida, but the applications are primarily limited to urban areas and event-based applications.

Model Inputs
- Data requirements for hydrology depend on the user’s choice. Land use data are used to determine ground cover type for each model subarea.
- Depending on what options are set for the loading calculations additional parameters are necessary (e.g., buildup coefficients would be needed for the dry weather buildup simulation).
- Additional data are necessary if the user intends to model snowmelt, subsurface drainage, and interflow.
- Depending on the stormwater system, dimensions, slopes, roughness coefficients, elevations, and storage are required.

Users’ Guide
Available online: http://www.xpsoftware.com/products/xpswmm.htm

Technical Hardware/Software Requirements

Computer hardware:
- 200 Mb of available disk space
- 128 Mb of RAM

Operating system:
- Microsoft Windows

Programming language:
- FORTRAN (model) and Visual Basic (interface)

Runtime estimates:
- Minutes to less than an hour

Linkages Supported
EPA SWMM model

Related Systems
XP-SWMM can optionally run EPA SWMM model.

Sensitivity/Uncertainty/Calibration

SWMM has a high level of accuracy with careful calibration and sufficient data.

Model Interface Capabilities

- XP-SWMM has intuitive graphical dialog boxes.
- Data input is subject to expert system filtering and checking.
- Storage and retrieval of typical infrastructure attributes such as pipe depths and locations is made easy through the user-friendly model interface.
- Data entry and model output is in graphical form.
- XP-SWMM uses an object oriented Graphical Expert Environment in which the user can create the drainage network interactively on the screen using a mouse and toolbar icons.

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