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Evaluation of Sediment Transport Models and Comparative Application of Two Watershed Models

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Notice

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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.

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Lee A. Mulkey, Acting Director
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Abstract

Suspended solids and sediments are regarded as the two leading pollutants of nation's streams and waterbodies. They serve as carriers for various pesticides, radioactive materials and nutrients. Section 303(d) of the 1972 Clean Water Act requires states, territories, and authorized tribes to identify and list impaired waters every two years and to develop Total Maximum Daily Loads (TMDLs) for pollutants in these waters. Mathematical models are widely accepted, effective and powerful tools for TMDL development, and evaluating performances of Best Management Practices (BMP). The rapid pace of computer technology has been a milestone for mathematical models in hydrology, hydrodynamics and recently water quality. The high demand on computer models resulted in development of many models and placed a new burden on model users, that is model selection. The selection of the right model under certain constraints requires a comprehensive knowledge of the capabilities and features of available models. This report provides an overview and evaluation of sediment models and compares two distributed, watershed scale models by application to an experimental watershed. A probabilistic, risk-based mathematical optimization framework is presented and proposed as a strategy for solving the TMDL-BMP problem involving multiple stressors in feature endeavors. Future modeling efforts may benefit from exploring the use of system analysis approaches to obtain cost-effective, optimal load reductions using BMPs.

The report is comprised of two parts. The first part evaluates and summarizes some of the key features of the most widely cited watershed scale, hydrodynamic and water quality models with the emphasis on TMDLs and BMPs. Reviewed models were selected based on minimum criteria. Water quality models, specifically those that can simulate nutrients in the environment are also considered since transport and fate of sediments and nutrients are intimately related phenomena. Among the reviewed loading models SWAT and AGNPS offer the most BMP alternatives at agricultural watersheds. For urban areas SWMM, and for mixed land uses, i.e. rural and urban, HSPF are identified as the most suitable loading models. These models need to be used with hydrodynamic and water quality models for a complete TMDL analysis and BMP development. BASINS and MIKE-SHE are comprehensive watershed-water quality modeling systems, with varying degrees of complexity. WMS offers a tractable watershed-modeling platform if fully developed can be used for sediment TMDLs allocation. Available and potential model linkages between loading, hydrodynamic and water quality models are also discussed. It is observed that most physically based models are incapable for a complete BMP assessment. As a future need in modeling, enhancement of such models to simulate more BMPs is recommended along with development of more linkages between loading and hydrodynamic/water quality models.

The second part of the report evaluates, by application to an experimental watershed, two promising distributed watershed-scale sediment models in detail: KINEROS-2 and GSSHA. Sensitivity of KINEROS-2 to model parameters was evaluated within a probabilistic framework using Monte Carlo simulations to identify key model parameters for calibration. It was shown that the order of parameter sensitivities changes with the quantity of interest (peak flow, total sediment yield, etc.). The calibration/verification procedure performed over KINEROS-2 has shown that the Manning's roughness and soil erosion parameters show systematic seasonal variations. Both models were calibrated and verified and the results clearly highlight the challenges modelers face when applying complex, distributed watershed models. The results are discussed and compared. They highlight the importance for numerical application of different watershed models to gauged watersheds as means for models evaluation. Future efforts aiming at the evaluation of hydrologic and water quality models should migrate from qualitative analysis to actual comparative applications to real case studies.

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Acknowledgments

The U.S. Environmental Protection Agency through its Office of Research and Development funded the research described here through in-house efforts and in part by an appointment to the Postgraduate Research Program at the National Risk Management Research Laboratory administered by the Oak Ridge Institute for Science and Education through an interagency agreement between the U.S. Department of Energy and the U.S. Environmental Protection Agency. The report benefited from the constructive review comments of Dr. Zhonglong Zhang, Dr. Gokmen Tayfur and Dr. Rao S. Govindaraju.

1 Introduction

1.1 Overview

Suspended solid and sediment (SSAS) yield has important implications for water quality and water resources. The source of SSAS can be natural such as wind erosion, upland erosion (detachment by rainfall and rill erosion), stormwater runoff, and bank erosion, or man-driven such as wastewater discharge, tillage, mining, construction, silvicultural practices, etc. Sediments may serve as carriers for pesticides, radioactive materials and nutrients giving rise to water quality issues. Studies have shown that total suspended sediment concentrations are positively related to total phosphorus and nitrate concentrations. Nutrients, while essential for healthy aquatic systems, can have adverse effects at low concentrations by increasing algal and macrophtye production and decreasing average dissolved oxygen. Stream and waterbody water quality is important not only for protection of fish and aquatic life, but it is often used as an indicator of the environmental health of a watershed. Often, SSAS in surface waterbodies are contaminated by chemicals that tend to sorb to fine-grained organic as well as inorganic soil particles. The sources of such contamination can be from existing point or nonpoint sources (NPS) or from historical spills or discharges. When such contamination exceeds critical levels, they pose ecological and human health risks requiring appropriate remedial actions. Such remedial actions take the form of either isolating the contaminated sediments, reducing their exposure to other parts of the ecosystem, complete removal of the contaminated sediment, or some combination of the above. Estimates of SSAS yield are required for a wide spectrum of problems dealing with dams and reservoirs, fate and transport of pollutants in surface waters, design of stable channels, protection of fish and other aquatic life, watershed management and for environmental impact statements. Figures 1 and 2 show typical processes responsible for the transport and fate of particulate organic matter in waterbodies.

Oxidation of organic matter occurs in the water column and in the bottom sediments. The deposition of algal mass and particulate organic matter on bottom sediments and decomposition therein exert sediment oxygen demand (SOD) on the overlying water. Depletion of oxygen by oxidation of particulate organic matter in the water column and by SOD has undesirable environmental consequences, such as loss of fishery. Figure 3 links the flux of particulate organic matter delivered to the sediments to SOD and sediment fluxes across the sediment-water interface.

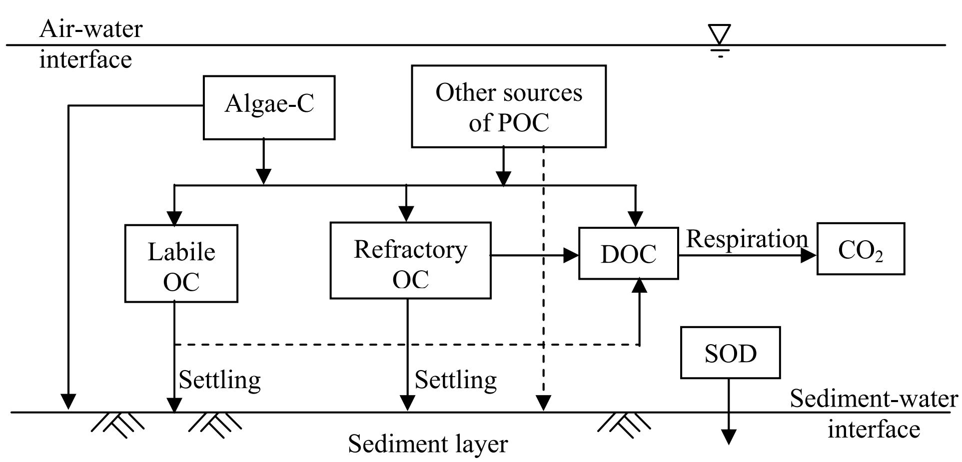


Figure 1. Carbon cycle.

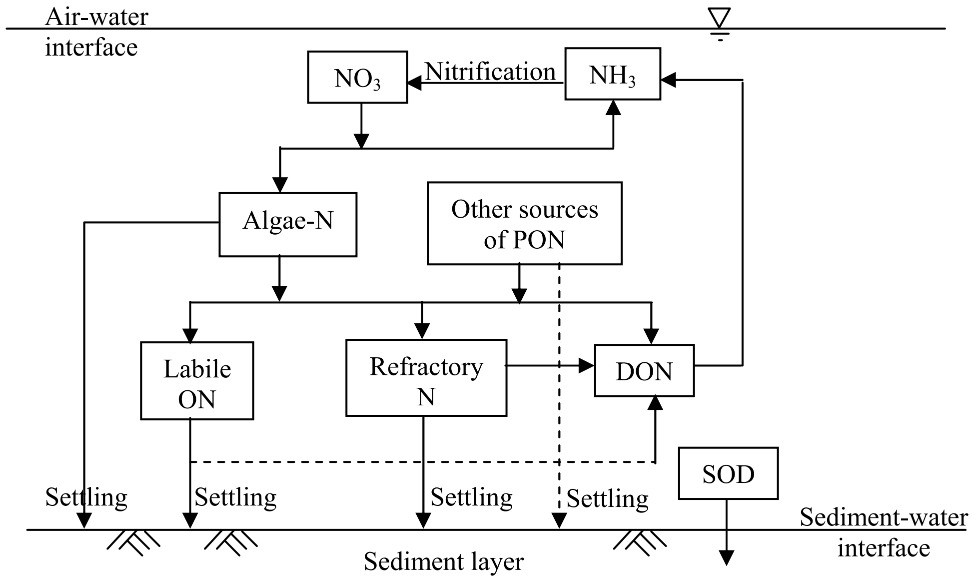


Figure 2. Nitrogen cycle.

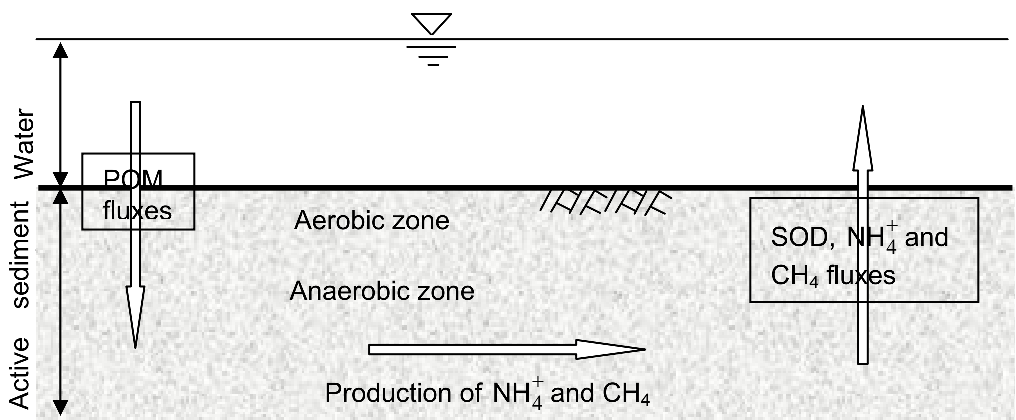


Figure 3. Simplified schematics of sediment water interactions.

The particulate organic matters (POM) carried by water settles and within the anaerobic region decomposes to yield dissolved CH_4. The methane is later diffused upward to the aerobic zone and gets oxidized generating SOD. Similarly, ammonification of organic N produces ammonium in the anaerobic zone which is later diffused to the aerobic zone where it is nitrified to produce NO_3^- resulting in SOD.

Changes in SSAS dynamics such as scour and erosion of channel bed and banks, deposition of fine particles, and resuspension of solids in the suspended sediment load of the water column, can have significant effects on the aquatic ecosystem health. Scouring and bank erosion may cause loss of habitat used for feeding, reproduction, and cover by fish, algae, birds etc. The consequences of deposition and resuspension are more obscure yet more significant (USEPA, 2002a). High suspended sediment concentrations increase the turbidity in waterbodies that can easily alter the environment for phytoplankton and other aquatic flora from nutrient limited conditions to light limited conditions which can eventually affect dissolved oxygen dynamics (Stanley 1994). The effects of high turbidity is more severe in the more tranquil waters of lakes, reservoirs and estuaries than streams and rivers due to accumulation of suspended solids in the water column from multiple sources (USEPA, 2002a).

In the 1998 analysis of the U.S. impairment patterns, SSAS was determined as the leading cause of impairments of rivers (USEPA, 2000). Further, in the same report sediment is listed as the third leading stressor in lakes, reservoirs and ponds, where nutrients and metals were ranked first and second among other stressors. In a recent report known as "The Twenty Needs Report", it is stated that currently over 40 % of our assessed waters do not meet the water quality standards set by states, territories and authorized tribes (USEPA, 2002b).

1.2 Total Maximum Daily Loading (TMDL)

Section 303(d) of the Clean Water Act and Water Quality Planning and Management Regulations (40 CFR Part 130) are directly relevant to the total maximum daily load (TMDL) program as they interpret the statutory requirements for states, territories and authorized tribes to list waterbodies that do not meet appropriate water quality standards. A TMDL is defined as the maximum amount of pollutant that a waterbody can receive and still meet the water quality standards. TMDLs include both the point source discharges and the nonpoint sources that arise from the watershed or the environs of the watercourse (Ward and Benaman, 1999). The Clean Water Act further requires development of TMDLs for all waters on the section 303(d) list by developing restoration scenarios. The ultimate goal of a TMDL development can be stated as removal of the waterbodies from the 303(d) list by attaining water quality standards. Eventually, the list of impaired waterbodies and established TMDLs by states, territories and authorized tribes must be approved by EPA.

Since its introduction, there has been a tremendous amount of activity around TMDL programs. This, in turn, brought many opinions on the program's scientific needs from different sources including National Research Council (NRC), The EPA regional TMDL coordinators, States and Tribes, professional associations such as the Water Environment Federation (WEF), non-governmental organizations and private industry, the Strategic Planning and Research Coordination (SPRC) research planners from EPA research and water offices, and others (USEPA, 2002b). The need to improve watershed and water quality modeling was among the recommended TMDL science needs in the "Twenty Needs Report" by the USEPA (2002b).

1.3 Mathematical Models

Models are extensively used by water resources planners, water quality managers, engineers and scientists to evaluate the effectiveness of various control strategies. Mathematical models can help us understand the important processes and interactions that affect the water quality of waterbodies. Further, they can be used in making decisions regarding pollution control strategies by evaluating their effectiveness on water quality improvement and performing cost-benefit analysis.

It's worth noting that Novotny and Olem (1994) provide a diagram that compares the reliabilities of models of NPS pollution. Based on that diagram, accuracy and reliability decrease with increased complexity and size of the modeled system. They list the hydrologic models simulating runoff from small, uniform and impervious surfaces as the most accurate, and water quality models for large watersheds as the least reliable. The order of reliabilities of NPS models decline as follows: Hydrology with impervious surface, hydrology, sediment, phosphates and metals, nitrogen and organic chemicals, and bacteria. The low uncertainty involved in the hydrologic and sediment transport models compared to other processes, such as fate and transport of nutrients, definitely explains the high confidence associated with them. In fact, this order of reliability becomes more discerning considering the fact that the physics used to describe each process also decreases with the same order.

The success in utilization of models in diverse fields has resulted in wide acceptance of models as an objective evaluation tool and as a result they are often given higher credibility than what they actually deserve. Models are only approximate representations of the complex natural processes and due to time and budget constraints involve many assumptions made by the model creator who develops the relationships and define the processes, and the model programmer who carries the model into computer platforms. Moreover, modelers usually simplify processes that are seemingly not as important as other processes. Yet, this simplification might not be valid for other applications due to uniqueness of the problem and counter-intuitive results may be produced (AWWA, 2001). Modeling also involves a profusion of uncertainty. Macintosh et al. (1994) defines two types of uncertainty: i) knowledge uncertainty and ii) stochastic uncertainty. The former is associated with measurement errors and inability of the model to accurately represent the physical, chemical and biological processes, and the latter arises from the random nature of natural systems like rainfall and natural heterogeneity. Any modeling application comprises both types of these uncertainties implying that modeling cannot be deemed as representing the absolute truth. Therefore, care must be taken when interpreting the results obtained through models. This clearly calls for the need for implementing risk management approaches to TMDL allocation using Best Management Practices (BMP), since model limitations, lack of perfect knowledge of physicochemical and biological processes, and inherent uncertainties preclude accurate, risk-free modeling approaches. We elaborated on this later as we provide a probabilistic optimization framework as a proposal for the solution of the BMP problem in general.

1.3.1 Brief History of Sediment Modeling

Singh and Woolhiser (2002) provide a historical perspective of hydrologic modeling, and discuss new developments and challenges in watershed models. In that paper they date the origin of mathematical modeling back to the rational method developed by Mulvany (1850) and an event model by Imbeau (1892) that relates the peak runoff rate to rainfall intensity. The work of Streeter and Phelps (1925) may be treated as the first effort in water quality modeling where the authors tried to address the relationship between dissolved oxygen in rivers and streams, and input from domestic wastewater. The works of Velz (1938) and O'Connor (1960, 1962) are among the other early attempts in water quality modeling. The earliest attempts in sediment modeling originated from relating soil loss from field plots to slope and steepness (Zingg, 1940). This work is extended by several researchers (Smith, 1941; Browning et al., 1947) which led to the development of the famous Universal Soil Loss Equation (USLE) (Wischmeier and Smith 1958; 1965; 1978). Early models were based on simple one-dimensional, steady-state conditions. Advances in the theory of flow and transport phenomena, and in computer technology elevated the art of sediment transport and water quality modeling as time constraint was not a factor anymore. Development of fully dynamic, steady state, and three-dimensional water quality models became feasible. The computational capability allowed the coupling of water quality models with watershed and hydrodynamic models. As a result, varieties of models have become available, and the choice of the right model became a challenge. Selecting the right model for a specific application depends on factors like type of the stressors considered, economic constraints such as time and labor, hardware, personal experience and preferences, hydrologic considerations, and scientific rigor and data availability.

In the following sections we classify sediment and nutrient water quality models and evaluate them based on selected criteria. We use previously published material (eg. Shoemaker et al., 1997; USEPA, 1999; Ward and Benaman, 1999; Tetratech, 2000; SAAESD, 2001; WERF 2001) and related web sites (eg. USGS-SMIC database: http:smig.usgs.gov/smic, Water Ways Experiment Station (WES) models: http://www.wes.army.mil/el/elmodels, Register of Ecological Models (REM) meta-database: http://eco.wiz.uni-kassel.de/ecobas.html) to synthesize necessary information. The goal of the evaluation process is to provide a list and summary of widely used sediment and nutrients models and their ability to simulate for BMPs.

1.4 Risk Management Watershed Modeling

The Twenty Needs Report (USEPA, 2002b) stresses improved ability to evaluate the effectiveness of Best Management Practices (BMP) to manage, among other stressors, suspended solids and sediments. BMPs reduce pollutant concentrations and loads in runoff by infiltration into the soil, physical infiltration by grass or other vegetation, adsorption on to soil and plants, bacterial decomposition, plant uptake, and sediment deposition (Komor, 1999). Varieties of BMPs are available to trap sediments and control nutrients at the watershed scale varying from structural such as wet and dry ponds, vegetative filter strips, riparian buffers, and wetlands to non-structural such as conservation tillage, and improved fertilizer and animal-waste management (Figure 4).

Models developed with BMP components are capable for allocating TMDLs in watersheds. The common practice in the use of models for TMDL allocation is to evaluate alternative BMP scenarios using simulations based on trial and error. There is no guarantee, however, that this approach can yield optimal results, as there is often frustratingly large number of feasible solutions. Even when combined with efficient techniques and enormous computational effort, the result may lead to a solution that is still far from the best possible. With increasingly powerful computers, an alternative approach is to implement a system analysis in which the BMP problem can be cast in terms of an objective function (e.g., cost of design and maintenance of BMPs) subject to TMDLs, physical, legal, technical, financial, and other constraints. In this case, the solution for the BMP selection problem involves the identification of several design and operating variables related to the ensemble of alternative BMPs. These variables are referred to as decision variables whose optimal values, which optimize the objective function (e.g., minimum cost), are to be determined (Louks et al., 1981). A few studies, however, exist in the literature which developed methodologies to identify the optimal BMP scenarios (eg. Udoyara et al., 1995; Mostaghimi et al., 1997; Zhen and Shaw, 2001; Srivastava et al., 2002). Most of these studies rely on coupling a water quality model with an optimization algorithm. Mathematically, the optimal solution for the BMP selection problem may be cast in this optimization framework

Objective Function:

$$\underset{\mathbf{x}}{\text{Min}} \quad \sum_{i=1}^{m} C_i(\mathbf{x}) \tag{1}$$

Subject to

$$g_j(\mathbf{x}) \le a_j, \qquad j = 1,2,\ldots,n \tag{2a}$$

$$g_j(\mathbf{x}) \ge b_j, \qquad j = n+1,n+2,\ldots,N \tag{2b}$$

where C_i is the cost corresponding to i^{th} BMP; $\mathbf{x}$ is the set of decision variables x_i associated with BMPs, both structural and nonstructural; m is the total number of BMPs (structural and non-structural), $g_j(\mathbf{x})$ is the model generated value; and a_j and b_j, respectively, are the upper or lower limits of the constraint j (e.g., TMDL of sediment); and N is the total number of constraints. Pollutants can have either lower or upper TMDL limits. For instance, sediment yield has an upper limit, whereas total dissolved oxygen has a lower limit.

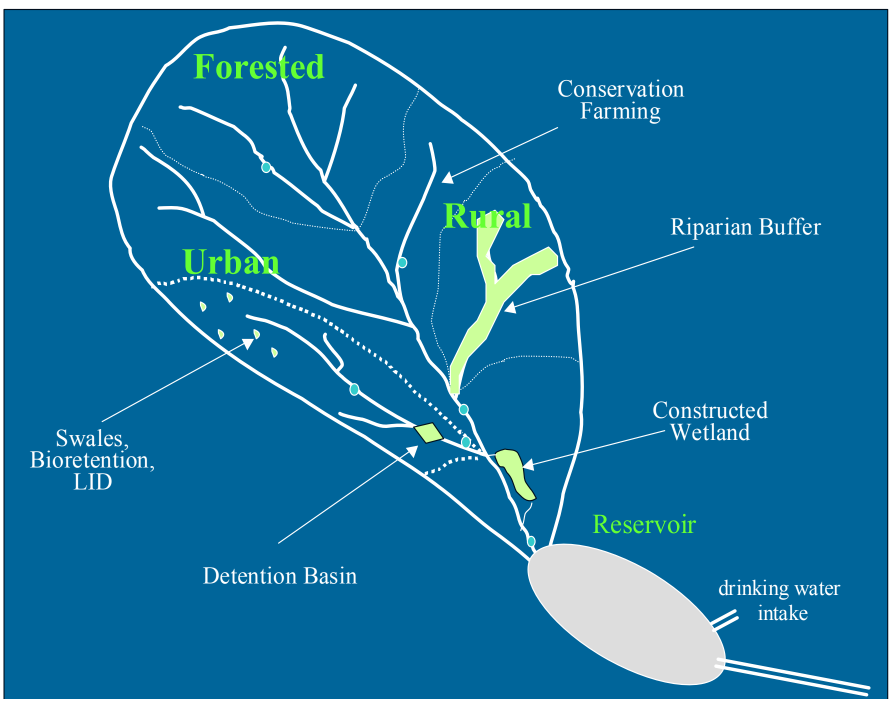


Figure 4. Simplified schematic of various BMPs at the watershed scale (adapted from USEPA 2002a).

Model limitations and technical, economic, social, and political uncertainties pose a formidable challenge to the application of suspended solids and sediment models, in fact, any other models, to risk management, especially at the watershed scale. The above optimization problem is rigid because it requires strict validation of the constraints (2a and 2b). A more realistic, risk-based approach is to acknowledge model imprecision, inherent uncertainties due to temporal variability and spatial heterogeneity, and lack of precise knowledge of TMDL targets. In light of the uncertainties, strict enforcement of the constraints (2a and 2b) may be redundant, perhaps too stringent of a requirement for realistic BMP planning problems. Instead, the approach should be a probabilistic one; that is, we acknowledge the uncertainties and accept the risk involved in violating a given constraint with a prespecified probability. The probability that each constraint would be violated constitutes an acceptable level of risk, whose value may be determined by water quality managers, regulatory agencies, and other stakeholders. Probabilistically, the above optimization model can be reformulated as follows

Objective Function:

$$\underset{\mathbf{x}}{\text{Min}} \sum_{i=1}^{m} C_i(\mathbf{x}) \tag{3}$$

Subject to

$$\Pr\{g_j(\mathbf{x}) \le A_j\} \ge \alpha_j, \qquad j = 1,2,\ldots,n \tag{4a}$$

$$\Pr\{g_j(\mathbf{x}) \ge B_j\} \ge \beta_j, \qquad j = n+1,n+2,\ldots,N \tag{4b}$$

where the model related function $g_j(x)$ is deterministic; and A_j and B_j are random variables whose distribution functions, respectively, $F_{Aj}(a_j)$ and $F_{Bj}(b_j)$ are known. This problem is also referred to as chance constrained optimization (Louks et al., 1981; Hantush and Mariño, 1989). The chance constraint (4a) requires that the function $g_j(\mathbf{x})$ be no greater than the random variable A_j with at least probability α_j. Conversely, the chance constraint (4b) requires that the function $g_j(\mathbf{x})$ be no less than the random variable B_j with at least probability β_j.

The risk involved in satisfying condition (4a) is $1-\alpha_j$, and for (4b) the risk is $1-\beta_j$. The deterministic equivalence of this chance-constrained problem can be shown to be

Objective Function:

$$\underset{\mathbf{x}}{\text{Min}} \sum_{i=1}^{m} C_i(\mathbf{x}) \tag{5}$$

Subject to

$$g_j(\mathbf{x}) \le F_{A_j}^{-1}(1-\alpha_j), \qquad j = 1,2,\ldots,n \tag{6a}$$

$$g_j(\mathbf{x}) \ge F_{B_j}^{-1}(\beta_j), \qquad j = n+1,n+2,\ldots,N \tag{6b}$$

where $F_{Aj}^{-1}(1-\alpha_j)$ is the $(1-\alpha_j)^{th}$ percentile of the distribution F_{Aj}; and $F_{Bj}^{-1}(\beta_j)$ is the β_j^{th} percentile of the distribution F_{Bj}. The schematic shown in Figure 5 depicts the flow of information between various elements in the probabilistic optimization framework. We emphasize that the constraint function $g_j(\mathbf{x})$ depends on the hydrological model under consideration.

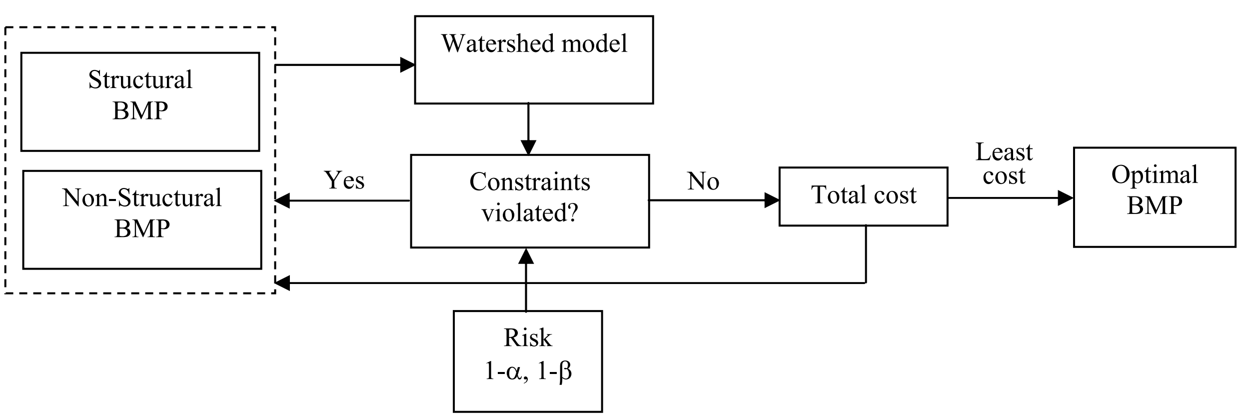


Figure 5. Flow of information during optimal BMP selection.

The above risk-based optimization approach may be suitable for problems involving multiple stressors (e.g., flow, sediments, dissolved oxygen, and nutrients), where multiple BMPs, both structural and nonstructural, can be implemented to achieve TMDL targets. To the best of the authors' knowledge no evidence exists in the literature which suggests that this approach has been implemented for the solution of the BMP selection problem. Future research may explore the use of probabilistic, constraint optimization for the management of pollutant loads reduction, because such an approach lends itself to risk-based management of stressors in watersheds.

2 Model Classifications

Hydrology constitutes the most important component of any water quality model. For a water quality model, flow distribution, both in time and space, is required. A model can have a hydrologic module and solve for the flow itself, or the flow distribution can be supplied externally as input through another hydrologic model. In either case, hydrologic models play a crucial role. Hydrologic models can be classified into various categories. For instance, they can be distinguished as empirical vs. physically based, deterministic vs. stochastic (randomness), lumped vs. distributed (spatial variation), steady state vs. dynamic (time variation), and linear vs. non-linear. Empirical models are usually based on statistical relationships obtained through regression analysis of observed data. The problem with empirical models is that they are usually suitable for conditions under which the relationships have been developed. In other words, such models become less reliable under the conditions outside the limit of the original environment and generally are not suitable for predictions under different conditions. Physically based models, in contrast to empirical models, are based on physical principles such as conservation of mass and momentum. The input parameters of physically based models can usually be obtained through field measurements. Deterministic models do not consider the randomness involved in the data and always produce the same result for a given input parameter set, whereas stochastic models reflect the uncertainty in the data and may produce different output from the same input parameter set. Chow et al. (1988) state this difference by calling deterministic models as forecasters and stochastic models as predictors. Lumped models usually consider the system as a black box and everything is spatially averaged over that single system. Distributed models, to some extent, take into account heterogeneities by dividing the system into smaller units, such as cascade of planes in case of a watershed. Such models assume that the model parameters and initial conditions are uniform within each unit. Steady state models do not consider the variation of flow with time, contrary to dynamic models. Linear models, such as the unit hydrograph theory, are based on two simple principles: principle of proportionality and principle of superposition. The former can be stated as; if f(x) is a solution of a system, then $c \cdot f(x)$ is also a solution of the same system with c being a constant. The latter principle implies that if $f_1(x)$ and $f_2(x)$ are both solutions of the same system, then $f_1(x) + f_2(x)$ is also a solution of the same system.

Based on how they function, suspended solids and sediments, and nutrients water quality models can be broadly categorized into three groups:

1. **Loading models**: Models in this group simulate field or watershed scale hydrologic processes and determine the generation and transportation of SSAS and nutrients from source in the upper lands to the receiving water. Loading models can be distinguished into agricultural, urban, or mixed categories based on land use.

2. **Receiving water models**: Again based on the functionality, receiving water models can be divided into two subclasses: hydrodynamic and water quality models. Hydrodynamic models solve for the hydraulics of water quality models including transport, deposition, circulation and the stratification processes. Water Quality models simulate the movement of SSAS in the water column and determine the fate and transport of nutrients, including eutrophication, in surface waters. Sediments and particulate organics are delivered to receiving models by loading models. Based on the waterbody (Figure 6) receiving water models can be further subdivided into three subcategories:
   a) Rivers and streams
   b) Lakes and reservoirs
   c) Estuaries

3- **Eutrophication/Ecological models**: These models are a subclass of receiving water models. They relate biomass production (algae, crops, riparian vegetation) to nutrient loading. Eutrophication models relate algal production and growth in the waterbody to nutrient loading and photosynthesis. They also include the sediment flux model. Refer to Figures 2 and 3 and Chapter 1 for more details. Figures 2 and 3 depict processes typically modeled in eutrophication models.

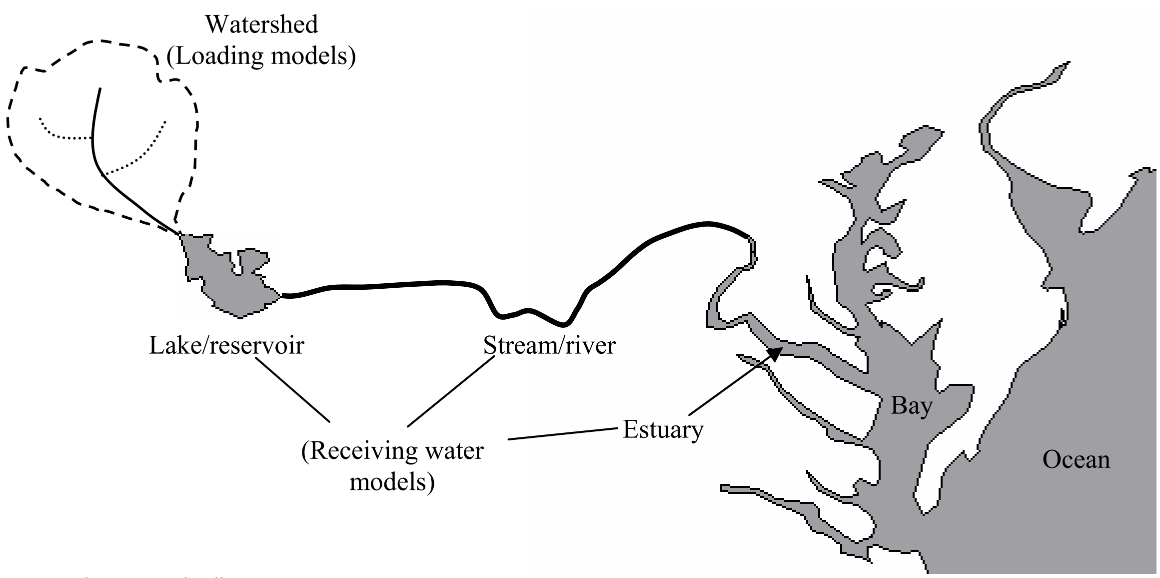


Figure 6. Various waterbodies.

The relationship between these groups of models is depicted in Figure 7. Models in each group can be stand alone or they may be coupled with other models. Often, hydrodynamic and pollutant models are integrated under the same modeling system. This is called direct or internal linkage. If not under the same system, the output of the hydrodynamic model such as water velocity, temperature, salinity, etc., may be fed externally into the pollutant model as input, called indirect or external linkage. A detailed discussion on this topic is given in WERF (2001).

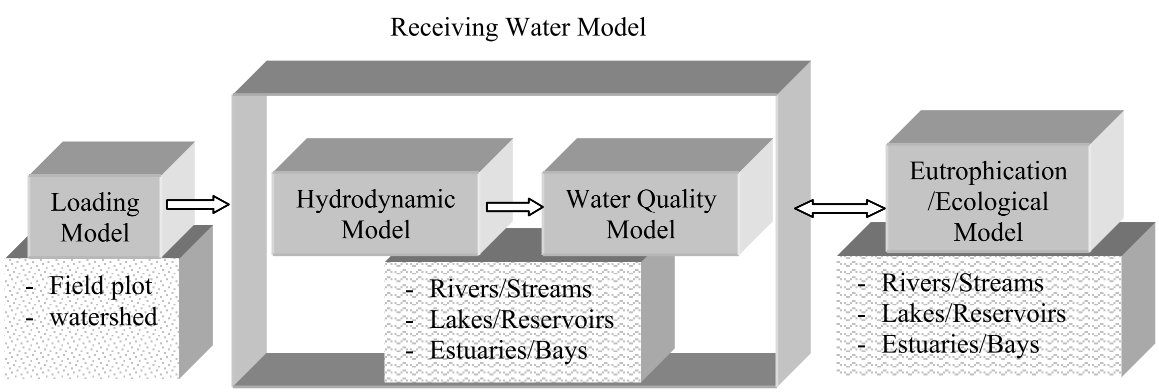


Figure 7. Relationship between different model groups.

3 Model Evaluation Criteria

3.1 Screening Criteria

Transport and fate of sediments and nutrients are intimately related phenomena, because suspended solids and sediments (SSAS) include particulate organic matter and serve as carriers for highly adsorbed phosphor. We therefore consider in our evaluation water quality models, specifically those that can simulate nutrients in the environment. These models are evaluated based on various criteria listed in the next section. A vast number of hydrologic and water quality models is available ranging from heavily used ones to models with no users at all. We limit the focus of this evaluation to models related to SSAS and nutrients. The following minimum criteria are used:

1. Capability of modeling SSAS
2. Good model documentation and model support
3. Proven record of application with sufficient history

The first criterion limits the focus of this report to SSAS models. Those models that do not simulate SSAS were excluded. The second minimum requirement is strong model support and a well-documented manual. Modelers should be able to access the corresponding user manual and, preferably get technical assistance. The last constraint in the initial screening is the acceptability of the model. The history of successful applications is a measure of acceptability of a model.

3.2 Evaluation Criteria

The models passing the initial screening are further appraised in detail based on the following criteria

1. Level of analysis: screening or management
2. Rigor of processes i.e. level of sophistication
3. Spatial and time scale
4. Ease of use: preprocessing, post processing (GIS-GUI)
5. Hardware/software requirements
6. Data requirements
7. Linkage capabilities, adaptability
8. Model availability and cost
9. BMP evaluation, BMP costs

Screening models are relatively simple models and usually do not require much modeling expertise. They don't account for spatial or temporal variability. They are mostly useful for a preliminary evaluation and can be used for deciding whether a more thorough evaluation of the problem is required or not. Default values usually suffice for screening models and hence an extensive calibration/verification procedure is not justified. They are usually preferred in the absence of data. On the other hand, planning and management models are much more complex than screening models. If the scope of a water quality problem is identified, more complex management models can provide a comprehensive, more detailed analysis. They are preferred over screening models to answer 'what if' scenarios. Though not necessarily, most of them can handle spatial and temporal variability.

Rigor of processes refers to the soundness behind the theory used to develop the model. As described under model classification section, physically based models do rely on the physical laws and empirical models are usually derived from observed data by regression techniques. Although subject to argument, the general consensus is that physically based models are superior to empirical models, at least during the planning phase. For instance, Woolhiser (1996) cautioned against overselling models. By referring to physically based models, he states that "...*we should be able to estimate the parameters a priori or measure them in the field, yet such estimates have a great deal of uncertainty. Further, it is more difficult to calibrate physically based models because they are overparameterized*". There is no fully physically based sediment transport model. Wherever applicable, the accuracy and stability of numerical solution schemes used in the models form another basis for evaluating model robustness.

Another norm used during the assessment of models is the spatial and temporal scales. Field scale models run over a single overland plane. Watershed models require both overland flow planes and channels. On the other hand, the detail of representation of channels may vary from small to large watershed models as channels dominate flow in large watersheds, whereas in small watersheds hydrology is still governed by overland flow. Models also differ in terms of temporal scales. Some models only provide annual averages. For instance the USLE formulation is based on annual sediment yield. Some models are event based requiring very small time steps, sometime on the order of seconds. Large time steps, commonly a day, usually suffice for continuous models, but not always. For example, when the full Richards' Equation option is employed in the GSSHA model, the required time step is well less than a minute if the size of the grid meshes is small (less than 30 m).

The required effort in using a model depends on several factors. The first, and perhaps the most important factor, is the complexity involved in the model. The availability of a Graphical User Interface (GUI) can drastically reduce the input effort from a modeler's perspective. GUIs can help the user both in pre- and post-processing stages. Most models nowadays offer GIS (Geographical Information Systems) interfaces which help extraction of model parameters from digital maps such as DEMs (Digital Elevation Models), soil maps, land use maps, etc. They can also be utilized in interpreting model results visually.

While computer cost has dropped drastically in the last decade, the hardware requirement may still be an issue for the user. For instance, some models only run on a UNIX platform which is generally available only in universities and research institutes. This puts a severe limitation on number of potential users. Some models heavily rely on computer power as they solve for full partial differential equations using numerical techniques, disregarding simplifications. This necessitates computers with fast processors (CPU) and large memories (RAM). Simple screening models can run on almost any computer.

The amount and type of required data might play a significant role in model selection. In case measured data is not available, often input data can be gathered from literature for physically based models. On the other hand, it is hard to make initial guesses for empirical models and an exhaustive calibration/verification effort may be required.

Model linkage is important for a comprehensive watershed analysis, especially for the evaluation of alternative BMP scenarios. For instance, a water quality model which runs only on UNIX platform can only be linked to models designed for UNIX platforms. Similarly, the output data of a loading model must be compatible with the input requirements of a hydrodynamic model. The same is true between a hydrodynamic model and a water quality model. If the outputs of the supplier model do not involve all the inputs of the receiving model then they can not be linked. Examples of successful model linkages are given in the Tetra Tech 2000 report which summarizes sediment-contaminant transport models. For example, it is reported that the water quality model CE-QUAL-ICM/TOXI is designed to be linked to hydrodynamic model CH3D-WES. Further EFDC can be linked to CE-QUAL-ICM and WASP5.

Model availability is a significant criterion in model selection. Some models (most EPA and USDA models) are available free to public, yet some proven models such as MIKE-SHE require purchase of a license which may not be affordable for some users.

Last but probably the most desired feature of the listed models within the context of this report is the capability of simulating BMPs. Since this report focuses on review of models for risk management purposes, having a BMP component is a preference.

4 Model Selection and Comparisons

4.1 Model Selection

Models or systems of models selected for review after the initial screening are listed in Table 1. Some models are included in the list because of their promising futures despite short application histories. Some models appear multiple times in the table, since they have more than one component such as hydrodynamic and water quality (eg. MIKE-11 falls into all categories). Some of the models listed below are only Graphical User Interfaces (GUIs) which integrate various models under the same umbrella and provide the linkages between them. BASINS and WMS are such modeling systems.

Table 1. Models selected for review after initial screening.

	Receiving	
Loading	Hydrodynamic	Water Quality (sediment/nutrient)
AGNPS, AGWA, ANN-AGNPS, ANSWERS, ANSWERS-2000*, BASINS, EPIC, DWSM*, GLEAMS, GSSHA, GWLF, HSPF, KINEROS-2, MIKE-11, MIKE-SHE, OPUS, PRMS, REMM*, SWAT, SWMM, VFSMOD*, WEPP, WMS(HSPF,GSSHA)	CE-QUAL-RIV1, CE-QUAL-W2, CH3D-WES, DELFT3D, DYNHYD5, EFDC, MIKE-11, MIKE-21, MIKE-3	CE-QUAL-ICM, CE-QUAL-ICM/TOXI, CE-QUAL-R1, CE-QUAL-RIV1, CE-QUAL-W2, CH3D-SED, DELFT3D, EFDC, HSPF, MIKE-11, MIKE-21, MIKE-3, QUAL2E, WASP5

* Models having insufficient application history but are very promising

Features of each model are summarized in a tabular format in Tables 2, 3 and 4. These tables provide a summary of each model's attributes. SC in the tables, under the platform category, refers to availability of the source code which can be compiled on any platform and used accordingly. Model linkages in Table 2 are divided into two categories i) Linked: means such a link already exists, and ii) Potential: means either work is under progress for model linkages or the models are compatible and can be linked in future. Description of each model's features and capabilities are given in the Appendix. It should be noted that model summaries are based on model manuals and other available literature (eg. Shoemaker et al., 1997; USEPA 1999; Ward and Benaman, 1999; Tetratech 2000; WERF 2001, SAAESD 2001).

4.2 Evaluation and BMPs Capabilities

Table 2 lists capability of models to simulate BMP features. Among the models reviewed the USDA's AGNPS model appears to offer the most comprehensive BMP simulation capability (agricultural practices, ponds, grassed waterways, irrigation, tile drainage, vegetative filter strips and riparian buffers) to the user. Tillage effects, soil consolidation, residue decomposition etc. are considered within the Revised Universal Soil Loss Equation (RUSLE). The impoundment module uses a modified sediment deposition algorithm. It is modified to reflect the simplifications associated with small impoundments with restricted pressurized outflow and/or some permanent pool storage. These simplifications are i) constant transport discharge equal to a constant outflow; ii) zero sediment transport capacity for all sediment sizes; and iii) dilution of the incoming water-sediment mixture by the permanent pool storage. AGNPS is suited for agricultural watersheds. Its major drawback, however, is its semi-empiricism. It can be used for both event and continuous simulations. Numerous applications of AGNPS are found in literature, perhaps due to its ability to model various BMPs.

SWAT is another widely accepted continuous simulation model suitable for large agricultural watersheds (>100 km^2), however it is also semi-empirical. It has the ability of simulating surface flow, subsurface flow, sediment, and nutrients in addition to various BMPs (agricultural practices, ponds, tile drains). Management practices are handled within the Modified Universal Soil Loss Equation (MUSLE). SCS curve numbers can also be varied throughout the year to taker into account variations in the management conditions. SWAT divides the watershed into Hydrologic Response Units (HRU) that has uniform properties. Edge-of filter strips may be defined in an HRU. The filter strip trapping efficiency for sediment is calculated empirically as a function of the width of the filter strip. When calculating sediment movement through a water body, SWAT assumes the system is completely mixed. Settling occurs only when the sediment concentration in the water body exceeds the equilibrium sediment concentration specified by the user. The sediment concentration at the end of a day is determined based on an exponential decay function. SWAT also simulates the buildup and washoff mechanisms similar to SWMM model. SWAT has its own GIS interface and currently integrated into USEPA's BASINs and USDA's AGWA modeling systems. SWAT is also linked to the water quality model QUAL2E.

The WEPP model probably has the most mechanistic sediment transport conception, but it has received little application outside the National Soil Erosion Research Laboratory staff. It can simulate various BMPs including agricultural practices (e.g. tillage, contouring, irrigation, drainage, crop rotation, etc.), ponds, terraces, culverts, filter fences and check dams. Soil erosion is represented in two ways for WEPP overland flow profile applications: i) soil particle detachment by raindrop impact and transport by sheet flow on interrill areas (interrill delivery rate), and ii) soil particle detachment, transport and deposition by concentrated flow in rill areas (rill erosion). Effect of different agricultural management practices is reflected with soil detachment parameters. Deposition of sediments in impoundments is calculated by assuming complete mixing and later adjusted to account for stratification, non-homogeneous concentrations and the impoundment shape. It is applicable to very small watersheds. SWAT, AGNPS and WEPP are all available free to public.

The DHI's MIKE-SHE watershed model is physically based, comprehensive with a history of applications in peer reviewed journals. MIKE-SHE includes virtually all of the processes in the land phase of the hydrologic cycle with several BMP options including wetlands, nutrient and pesticide management, etc. MIKE-SHE can be used in combination with MIKE-11 for river hydraulics. This modeling package, however, is proprietary.

For urban areas, the most complete loading model is the widely used SWMM model. Modelers can simulate all aspects of the urban hydrologic and quality cycles, including rainfall, snowmelt, surface and subsurface runoff, flow routing through the drainage network, storage and treatment. SWMM is structured in the form of blocks. Infiltration can be computed by Green-Ampt or Horton's equations. Kinematic wave routing is used in the transport block. For hydraulic flow routing complete Saint Venants' equations are used. Detention basin simulations and street cleaning are the available BMP alternatives. Using SWMM requires high expertise. SWMM outputs can be directed to the USEPA's WASP6 receiving water model.

For large watersheds comprised of both urban and rural areas HSPF is the most suitable model to address the sediment and nutrient TMDL problems. The BMP components of HSPF can be listed as: nutrient and pesticide management, urbanization and ponds. HSPF employs the same algorithms for sediment transport in reservoirs as rivers/streams. Deposition or scour of cohesive sediment is calculated based on the bed shear stress. Whenever shear stress is less than the user-supplied critical shear stress for deposition, deposition occurs; whenever shear stress is greater than the user-supplied critical shear stress for scour, scouring of cohesive bed sediments occurs. The rate of deposition is given by simplified Krone's equation (1962) which is a function of settling velocity (user defined), current sediment concentration, shear stress and critical shear stress. Like SWMM, HSPF is freely available to the public.

GLEAMS can be utilized for simple screening analysis over field scale agricultural areas where different agricultural practices, irrigation and ponds can be simulated as alternative BMPs. Hydrology, erosion/sediment yield, pesticide transport and nutrients are the four major components of GLEAMS. USLE formulation is implemented for computation of erosion. It is publicly available.

The KINEROS-2 model is suitable for event based studies over small watersheds. It is one of the two models in the AGWA modeling system. Model performances reported in the literature (see model detail in appendix) are impressive. Different agricultural practices, detention basins and culverts can be listed as the BMP options available in KINEROS-2. Effect of different agricultural management practices on the sediment transport is reflected by splash and hydraulic erosion parameters. Pond sedimentation in KINEROS-2 is similar to that for tank sedimentation Particle fall velocities and flow-through velocities are used to find the trajectories that intersect the reservoir bottom. Particle fall velocities are calculated for each particle size class. Suspended and slowly falling particles are subject to molecular diffusion and dispersion. With the addition of an evapotranspiration component, it can be used for continuous time simulations.

GSSHA is another promising model. Its flow component is fully physically based and has a proven applications trackrecord (see references given in model details in the appendix), whereas the sediment component is semi-empirical. On the other hand, the sediment component is currently being reformulated based on physics based sediment transport concepts. In its current version, the sediment transport formulation is based on the USLE soil parameters. Thus, agricultural management practices can be listed as the GSSHA's BMPs. US Army Waterways Experiment Station (WES) supports the model and it is incorporated into the WMS modeling system.

Most of the agricultural areas with low slopes especially in the Midwest contain tile drains. In addition to SWAT and AGNPS, the newly developed DWSM model presents a promising future for development of BMPs in tile-drained watersheds. It is a physically based and event model capable of simulating surface and subsurface flows, sediments and agrochemicals in tiled-drained agricultural watersheds. Detention basins, alternative ground covers and tile drains can be listed as its BMP component. The source code is in FORTRAN and is freely available.

REMM and VFSMOD are two field scale models being able to route flow and sediment through riparian buffers and vegetative filter strips, respectively. REMM is suitable for long-term simulations and VFSMOD is event based. REMM simulates movement and storage of water within riparian buffer systems by a process-based, two-dimensional water balance operating on a daily time step. Sediment transport is simulated both in channels and overland flow areas, but channel erosion or detachment is not simulated. Because of the roughness of the riparian buffers, it is assumed that sediment transport is primarily of suspended particles. Upland loadings are assumed to be provided as input to the REMM. Overland flow erosion is based on the USLE equation. Five classes of sediment are considered: sand, large aggregate, small aggregate, silt and clay. Sediment load computations are performed for each of these classes. Steady state continuity equation is used to compute the sediment at the downslope edge. VFSMOD considers that during a rainfall/runoff event, field runoff reaches the upstream edge of the filter with time dependent flow rate and sediment load. The vegetation produces a sudden increase in hydraulic resistance that slows the flow, lowers its transport capacity and produces deposition of the coarse material (particle diameter dp >0.0037 cm) carried mostly as bed load transport. The trapped bedload forms a trapezoidal shape. Suspended load zone follows this zone. The calculation procedure utilizes a modified Manning's open channel flow equation, continuity equation, and Einstein's sediment bed load transport function. The sediment trapping algorithm for the suspended load zone follows Tollner et al. (1976) equation based on a probabilistic approach to turbulent diffusion for non-submerged flow. REMM and VFSMOD can be linked to appropriate watershed models to analyze sediment transport and potential trapping through riparian buffers or vegetative filter strips in detail. REMM is already being linked to ANNAGNPS and has the potential to be linked to SWAT. VFSMOD can potentially be linked to KINEROS-2. The receiving water models CE-QUAL-RIV1, CE-QUAL-W2, DELFT3D, EFDC, MIKE-21 and MIKE-3 have both hydrodynamic and water quality components, and they can be run as standalone programs if they are linked to a loading model. Within these models DELFT3D and MIKE models are proprietary.

In spite of its one-dimensional, steady-state flow component, QUAL2E is a widely used water quality model for streams and rivers. Although it is not suited for sediment transport, it simulates for particulate organic matter; therefore, can be linked to watershed loading models to evaluate the impact of BMPs on transport and fate of nutrients in surface waterbodies. QUAL2E is relatively simple and easy to use. This model is integrated into the USEPA's BASINS's system where it is coupled with a watershed model which provides flow data to QUAL2E. A linkage between QUAL2E and SWAT is also available. CE-QUAL-W2, a 2-D model, has a complete eutrophication module which is suitable for deep lakes and reservoirs. If linked to a loading model, CE-QUAL-W2 can be used to assess impacts of various BMP scenarios on the state of eutrophication in surface waterbodies.

For large, complex waterbodies where 3-D consideration is important, EFDC or WASP6 can be used for sediment and nutrient analysis. Momentum and conservation equations form the basis of governing hydrodynamic equations of EFDC. The sediment routine used in EFDC is relatively unsophisticated. Both cohesive and non-cohesive sediments can be simulated. User is given the option to select number of sediment size classes. Problems that have been studied using WASP6 include biochemical oxygen demand, dissolved oxygen dynamics, nutrients/eutrophication, bacterial contamination, and toxic chemical movement. The WASP6 system consists of two stand-alone computer programs, DYNHYD5 and WASP6 that can be run in conjunction or separately. WASP has been linked to the hydrodynamic models DYNHYD5, EFDC and CH3-WES. The SWMM outputs can be directed to the WASP6 as well.

The HSPF model is a full-scale simulation model that can be applied to large watersheds containing both urban and rural areas, streams, rivers, lakes and reservoirs to assess the effects of land-use change, reservoir operations, point or nonpoint source treatment alternatives, flow diversions, etc. It has been widely used for TMDL studies and watershed planning. However, it is a very complex model requiring high level of knowledge of watershed processes. The source code written in F-77 is freely available and can be compiled and used on any platform. It is also part of the USEPA's BASINS modeling system and has been incorporated into the WMS modeling environment. MIKE-11 is another full-scale and complex simulation model capable of simulating, among others, sediment transport in estuaries, rivers, and other inland waters. It has a module for automated model calibration that uses the state of the art global optimization routine called the Shuffled Complex Evolution (SCE). MIKE-11 has a fully integrated interface in the ArcView GIS that facilitates input data preparation and output visualization. The inclusion of MIKE-11 by The US Federal Emergency Management Agency (FEMA) on their list of hydraulic models accepted for use in the National Flood Insurance Programme (NFIP) shows its credibility. Like other DHI products, license purchase is necessary.

USEPA's BASINS is a complete modeling system which has loading (SWAT and HSPF), and stream and river water quality (QUAL2E and HSPF) models. The system provides the linkages between these models within an ArcView environment to simulate for sediments and nutrients. EPA is also working on expanding BASINS to include the 3-D water quality model EFDC. WMS is another modeling system which incorporates HSPF and GSSHA models at this stage. WMS is an effective and easy to apply modeling system for runoff and sediment yield analysis. AGWA is a GIS-based hydrologic modeling tool. It is an ArcView 3.X extension within which spatially-distributed data are collected and used to prepare model input files and evaluate model results for SWAT and KINEROS models. For event-based studies over small watersheds ($<100\ km^2$) KINEROS is recommended and for long-term, continuous-time simulations over large watersheds ($>100\ km^2$) SWAT is utilized.

The information given thusfar can be used to select group of candidate models based on qualitative comparisons. To further decide on the optimal model a more quantitative comparison might be necessary. In the following two chapters such an exercise is presented. Two distributed, hydrologic and sediment transport models, the Kinematic Erosion Model (KINEROS) and GSSHA, are applied to an experimental watershed. We conduct sensitivity analysis, calibrate and verify both models, and evaluate their performances. Both models are commonly used and are promising with many applications in peer reviewed literature. GSSHA is supported by Waterways Experiment Station and is embedded into the WMS modeling system. KINEROS is developed by USDA scientists and is one of the two models under the AGWA modeling system which is supported by both USDA and USEPA.

Table 2. Loading Model Features.

	Field-F Agricultural watershed-A Urban watershed-U	Level of Analysis Screening-S Detailed-D	Rigor Empirical-E Semi-Empr.-S Phys. Based-P	Spatial Scale Lumped-L Distributed-D	Temporal Scale Event-E Continuous-C	Level of Effort Low-L Medium-M High-H	Platform[x]	Availability
AGNPS/AnnAGNPS	A	S, D	E	D	E, C	M-H	WIN/SC, AV	Public
AGWA (KINEROS-2)	A, U	S, D	P	D	E	M-H	WIN, AV	Public
AGWA (SWAT)	A	S, D	S	D	C	M	WIN, AV	Public
ANSWERS	A	S, D	P	D	E	M-H	DOS/SC	Public
ANSWERS-2000*	A	S, D	P	D	C	M-H	WIN, AV	Public
BASINS (HSPF)	A, U	S, D	P	D	C	M-H	WIN, AV	Public
BASINS (SWAT)	A	S, D	S	D	C	M-H	WIN, AV	Public
DWSM*	A	S, D	P	D	E	M	SC	Public
EPIC	F	S, D	E	L	C	M	DOS/UNIX	Public
GLEAMS	F	S, D	E	L	C	M	DOS/SC	Public
GSSHA**	A, U	D	P	D	E, C	H	DOS	Proprietary
GWLF	A	S	E	L	C	M	WIN, AV	Public
HSPF	A, U	S, D	P	D	C	M-H	DOS	Public
KINEROS	A, U	S, D	P	D	E	M-H	DOS/WIN/SC	Public
MIKE-11	A	S	P	L	E, C	H	WIN, AV	Proprietary
MIKE-SHE	A	D	P	D	E, C	H	WIN, AV	Proprietary
OPUS	F	D	P	D	C	M	DOS	Public
PRMS	A	S, D	P	D	E, C	M-H	DOS/UNIX/SC	Public
REMM*	F	S, D	S	L	C	M	WIN	Public
SWAT	A	S, D	S	D	C	M	WIN, AV	Public
SWMM	U	S, D	P	D	E, C	H	DOS/SC	Public
VFSMOD*	F	D	P	D	E	M	DOS/WIN/SC	Public
WEPP	A	S, D	P	D	E, C	M	WIIN/DOS	Public
WMS (HSPF)	A, U	S, D	P	D	C	M-H	WIN	Proprietary
WMS (GSSHA)	A, U	D	S	D	E, C	M-H	WIN	Proprietary

* Models having insufficient application history but are very promising
[x] SC = Source Code, AV =ArcView, AI = ArcInfo, WIN = WINDOWS

** Flow is physically based, sediment transport is semi empirical

Table 2. Loading Model Features (continued).

	Linkage		
	Linked	Potential	BMP
AGNPS/AnnAGNPS		REMM	Agricultural practices, ponds, grassed waterways, tile drainage, vegetative filter strips, riparian buffers
AGWA	KINEROS, SWAT		See SWAT and KINEROS-2
ANSWERS			Agricultural management, ponds, grassed waterways, tile drainage
ANSWER2-2000			Agricultural management, ponds, grassed waterways, tile drainage
BASINS	SWAT, HSPF, QUAL2E	EFDC	See SWAT and HSPF
DWSM			Detention basins, alternative ground covers, tile drains
EPIC	GLEAMS		Agricultural practices
GLEAMS	EPIC		Agricultural practices, ponds, irrigation
GSSHA	WMS		Agricultural practices
GWLF			Agricultural practices, septic systems, manured areas
HSPF	BASINS,WMS	CE-QUAL-W2	Nutrient and pesticide management, ponds, urbanization
KINEROS-2	AGWA	VFSMOD	Agricultural practices, detention basins, culverts
MIKE-11	MIKE-SHE		
MIKE-SHE	MIKE-11		Agricultural and forest practices, wetlands, nutrient and pesticide management, irrigation, drainage
OPUS			Terraces, contours, furrows, grassed buffer-strips or waterway, and farm ponds
PRMS			
REMM		AGNPS, SWAT	Agricultural practices, riparian buffers
VFSMOD		KINEROS-2	Vegetative filter strips
SWAT	AGWA, QUAL2E, BASIN	REMM	Agricultural practices, ponds, tile drains
SWMM		WASP	Detention basins, street cleaning
WEPP			Agricultural practices, ponds, terraces, culverts, filter fences, check dams
WMS	HSPF, GSSHA		See HSPF and SWAT

* Agricultural practices may include: tillage, irrigation, drainage, nutrient and pesticide management, crop management, crop rotation, grazing etc.

Table 3. Hydrodynamic Model Features.

	Dimension	Waterbody Stream-S River-R Lake/Res.-LR Estuary-E Coastal-C	Level of Analysis Screening-S Detailed-D	Rigor Empirical-E Phys. Based-P	Steady-S Unsteady-U	Level of Effort Low-L Medium-M High-H	Platform (SC=Source Code available) & GIS	Availability	Water Quality Model Linkage
CE-QUAL-RIV1	1-D	S, R	S, D	P	U	M-H	SC	Public	
CE-QUAL-W2	2-D	S, R, LR, E	S, D	P	U	H	SC	Public	
CH3D-WES	3-D	S, R, E, C	S, D	P	U	H	UNIX	Public	CE-QUAL-ICM, WASP5
DELFT3D	3-D	S, R, LR, E, C	S, D	P	U	M-H	WIN	Proprietary	
DYNHYD5	1-D	S, R, E	S, D	P	U	M	DOS/WIN	Public	WASP6
EFDC	3-D	S, R, LR, E, C	S, D	P	U	M-H	SC	Public	WASP6, CE-QUAL-ICM
MIKE-11	1-D	S, R, E	S, D	P	U	M-H	WIN, AV	Proprietary	
MIKE-21	2-D	R, LR, E, C	S, D	P	U	M-H	WIN	Proprietary	
MIKE-3	3-D	R, LR, E, C	S, D	P	U	M-H	WIN	Proprietary	

Table 4. Water Quality (Sediment/Nutrients) Model Features.

	Dimension	Waterbody Stream-S River-R Lake/Res.-LR Estuary-E Coastal-C	Level of Analysis Screening-S Detailed-D	Rigor Empirical-E Phys. Based-P	Steady/ Unsteady	Level of Effort Low-L Medium-M High-H	Platform (SC=Source Code available) & GIS	Availability	Hydrodynamic Model Linkage
CE-QUAL-ICM	3-D	S, R, LR, E, C	S, D	P	U	M-H	DOS/SC	Public	EFDC, CH3D-WES
CE-QUAL-ICM/TOXI	3-D	S, R, LR, E, C	S, D	P	U	H	DOS/SC	Public	EFDC, CH3D-WES
CE-QUAL-R1	1-D	LR	S, D	P	U	M	DOS/WIN/SC	Public	
CE-QUAL-RIV1	1-D	S, R	S, D	P	U	M-H	SC	Public	
CE-QUAL-W2	2-D	S, R, LR, E	S, D	P	U	H	WIN/SC	Public	
CH3D-SED	3-D	S, R, E, C	S, D	P	U	M-H	UNIX	Public	
DELFT3D	3-D	S, R, LR, E, C	S, D	P	U	M-H	WIN	Proprietary	
EFDC	3-D	S, R, LR, E, C	S, D	P	U	M-H	DOS/SC	Public	WASP5, CE-QUAL-ICM
HSPF	1-D	S, R, LR	S, D	P	U	M	DOS/WIN	Proprietary	BASINS, WMS
MIKE-11	1-D	S, R	S, D	P	U	M-H	WIN, AV	Proprietary	
MIKE-21	2-D	S, R, LR, E, C	S, D	P	U	M-H	WIN	Proprietary	
MIKE-3	3-D	S, R, LR, E, C	S, D	P	U	M-H	WIN	Proprietary	
QUAL2E	1-D	S, R	S, D	P	U	L-M	DOS/WIN/SC	Public	BASINS, SWAT
WASP6	3-D	S, R, LR, E, C	S, D	P	U	M-H	DOS/WIN	Public	CH3D-WES, DYNHYD5, EFDC, RIVMOD, SWMM

5 Modeling of Sediment Yield in a Small Agricultural Watershed with KINEROS-2

Distributed models are favored over lumped ones for detailed TMDL developments and BMP implementations. The availability of high power computers has relaxed the burden of long simulation times. Among the distributed models, the physically-based ones are generally preferred over empirical ones, since model parameters have physical meaning and can be measured in the field. When measurements are not available, model parameters can be still be deduced from published data in literature based on topography, soil and land use maps. Where flow is concerned, to our knowledge three models seem to be the most physically based with proven history, and separate themselves from others: GSSHA (Downer and Ogden 2002), KINEROS-2 (Smith et al. 1995) and MIKE-SHE (Refsgaard and Storm 1995).

Calibration is a very time demanding process and is a prerequisite before using complex models with many parameters. Most physically based and distributed models require enormous amount of input data. Although some parameters play crucial roles, some have minimal effect on model results. Therefore, it is a common practice to perform sensitivity analysis before calibrating model parameters. In doing so, the number of parameters to be calibrated can be reduced drastically and only most sensitive parameters are calibrated while average values can be used for the rest of the parameters. The sensitivity of KINEROS-2 to various input parameters was evaluated in this section through Monte Carlo (MC) simulations. Based on the sensitivity analysis, the model parameters were calibrated and then validated over several events. In the following chapter we examine and compare KINEROS-2 and GSSHA for their performances on modeling flow and sediment movement.

5.1 Model Background:

KINEROS-2 is a distributed, event-oriented, physically based model describing the processes of surface runoff and erosion from small agricultural and urban watersheds (Woolhiser et al., 1990). The watershed is represented by cascade of planes and channels, in which flow and sediments are routed from one plane to the other and, ultimately, to the channels. The elements (planes or channels) allow rainfall, infiltration, runoff, and erosion parameters to vary spatially. This model may be used to determine the effects of various artificial features such as urban development, small detention reservoirs, or lined channels on flood hydrographs and sediment yield.

When rainfall rate approaches the infiltration capacity, Hortonian overland flow begins. KINEROS-2 assumes one-dimensional flow in each plane and solves the kinematic wave approximation of the overland and channel flow equations using finite differences. The flow rate is related to the channel flow cross-sectional area or overland flow depth through Chezy and Manning flow resistance relationships. In these relationships the channel or bed slope approximates the friction slope.

Sediment transport equation is described by the following mass balance equation:

$$\frac{\partial}{\partial t}(AC) + \frac{\partial}{\partial x}(QC) - e(x,t) = q_s(x,t) \tag{7}$$

in which C is the volumetric sediment concentration [L^3/L^3]; A is the channel cross section area [L^2]; for overland flow it is equal to the flow depth h for a unit flow width [L]; Q is the is the channel discharge [L^3/T]; for overland flow it is equal to the discharge per unit width [L^2/T]; e is sediment erosion rate [L^2/T] given below; and q_s is the rate of lateral sediment inflow for channels [$L^3/T/L$]. In KINEROS-2 Sediment erosion/deposition rate e is composed of rainfall splash erosion rate g_s and hydraulic erosion rate g_h:

$$e = g_s + g_h \tag{8}$$

Rainfall splash erosion is given by (Woolhiser et al., 1990)

$$\begin{aligned} g_s &= c_f \; e^{-c_h h} \; r\, q; \qquad q > 0 \\ &= 0; \qquad\qquad\qquad q < 0 \end{aligned} \tag{9}$$

in which c_f is a positive constant [T]; h is flow depth [L]; c_h is damping coefficient for splash erosion [L^{-1}]; r is rainfall rate [L/T]; q is excess rainfall (rainfall rate minus interception minus infiltration) [L/T]. The exponential term represents the reduction in splash erosion caused by increasing depth of water (Smith et al. 1995). In channel flow, this term is usually equal to zero: the accumulating water depth absorbs nearly all the imparted energy by the raindrops. The hydraulic erosion represents the rate of exchange of sediment between the flowing water and the soil over which it flows. Such interplay between shear force of water on the loose soil or channel bed and the tendency of the soil particles to settle under the force of gravity may be described by this first-order rate expression:

$$g_h = c_g (C^* - C) A \tag{10}$$

where C^* is the volumetric concentration at equilibrium transport capacity [L^3/L^3]; c_g is a transfer rate coefficient [T^{-1}]. For sheet flow A = h. This relationship assumes that if C exceeds equilibrium saturation, C^*, deposition occurs. c_g is usually very high for fine, noncohesive material, and very low for cohesive material. Several expressions for C^* are available from literature (see, e.g., Woolhiser et al. 1990). In our analysis, we used Engelund and Hansen (1967) formula.

Successful applications of KINEROS-2 and its older version KINEROS to gaged watersheds has been reported in the literature (Osborn and Simanton 1990, Goodrich et al. 1994, Smith et al. 1999, Ziegler et al. 2001, Kalin et al. 2003, and Kalin and Hantush 2003 etc.).

5.2 Data and Model Parameters

A small USDA experimental watershed (W-2) located near Treynor, Iowa having an area of 83 acres was employed in this study (Figure 8). Measurements of runoff and sediment load are available. There are two rain gauges (115 and 116) around the watershed. W-2 has a rolling topography defined by gently sloping ridges, steep side slopes, and alluvial valleys with incised channels that normally end at an active gully head, typical of the deep loess soil in MLRA 107. Slopes usually change from 2 to 4 percent on the ridges and valleys and 12 to 16 percent on the side slopes. An average slope of about 8.4 percent is estimated, using first-order soil survey maps. The major soil types are well drained Typic Hapludolls, Typic Udorthents, and Cumulic Hapludolls (Marshall-Monona-Ida and Napier series), classified as fine-silty, mixed, mesics. The surface soils consist of silt loam (SL) and silty clay loam (SCL) textures that are very prone to erosion, requiring suitable conservation practices to prevent soil loss. Corn has been grown continuously on W-2 since 1964.

5.3 Sensitivity Analysis and MC Simulations

Sensitivity of KINEROS-2 was performed over the parameters listed in Table 5. In the table K_s is saturated conductivity, λ is pore size distribution index, Ψ_b is bubbling pressure, G is net capillary drive, ϕ is porosity, S_i is initial saturation, n_{ch} and n_p are channel and plane Manning's roughness, respectively, I is the interception depth, CAN is canopy percentage, c_g is the transfer rate coefficient, c_f is rainsplash coefficient and d_{50} is the mean particle diameter. One thousand random values were generated for each parameter. The ranges of parameters from which the random numbers were generated are shown in Table 5 for two soil types (SL and SCL). KINEROS manual (Woolhiser et al., 1990) suggests values and puts limits for c_g and c_f. During calibration, however, we found values outside the margins. In a similar study, Smith et al. (1999) estimated even larger values for these two parameters during the calibration of Catsop Catchment. After confirming with one of the model developers (C. Unkrich, personal communication) it was decided not to limit ourselves to the values given in the manual. The random values for the parameters K_s, λ, Ψ_b and ϕ were generated from log-normal distributions using IMSL routine, where the corresponding mean and standard deviations are given respectively in parentheses in Table 5. The parameter Ψ_b is not required by KINEROS-2 but used here to generate random G values as described below. The rest of the parameters were generated from uniform distributions.

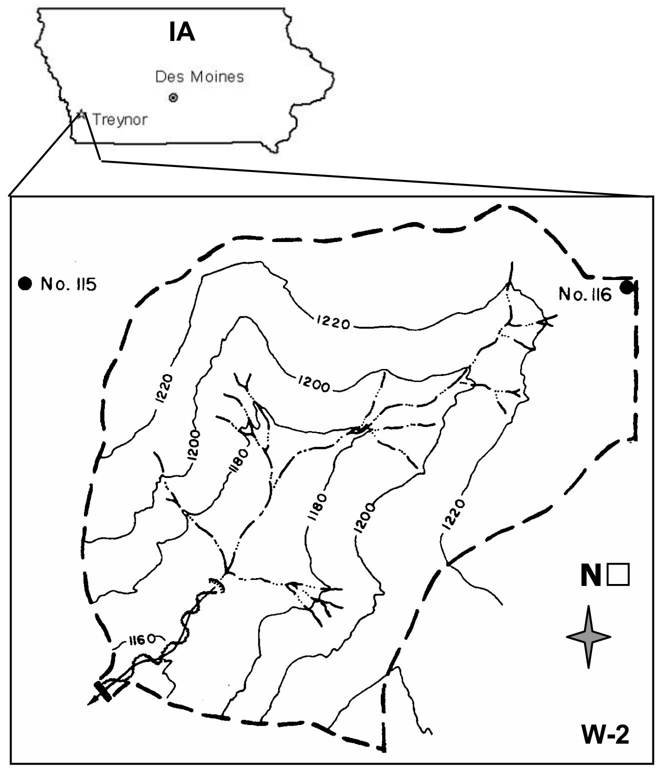


Figure 8. Schematic of W-2 watershed.

Table 5. Input parameters of KINEROS-2.

	K_s (mm/hr) [a]	λ [b]	Ψ_b (cm) [c]	G (cm) [d]	ϕ [b]	S_i [b]	n_{ch} [e]
SL	log(4.5,12.3)	log(0.23,0.13)	log(51,59)	0.2-694	log(0.50,0.08)	0.03-0.97	0.01-1
SCL	log(0.7,1.9)	log(0.18,0.14)	log(70,74)	0.7-7380	log(0.47,0.05)	0.08-0.92	

	n_p [e]	I [e]	CAN [e]	c_g [e]	c_f [e]	d_{50} (μm) [b]
SL	0.01-1	0-3	0-1.0	0.01-1.00	100-1000	3-50
SCL				0.01-1.00	100-1000	

[a] US EPA/600/R-93/046, 1993. PRIZM-2 Users Manual for Release 2.0
[b] KINEROS Manual (Woolhiser et al., 1990)
[c] Rawls et al., 1982
[d] From $G=\Psi_b(2+3\lambda/(1+3\lambda)$
[e] Randomly decided

The net capillary drive parameter, G is defined as

$$G = \int_{-\infty}^{0} [K(\psi)/K_s]\, d\psi \tag{11}$$

Using the Brooks-Corey soil characteristic relation for unsaturated conductivity $K(\psi) = K_s\, (\psi_b/\psi)^{2+3\lambda}$ leads to the simple expression

$$G = \psi_b \frac{2+3\lambda}{1+3\lambda} \tag{12}$$

Rawls et al. (1982) indicated that ψ_b and λ are log-normally distributed; they provided the arithmetic and geometric mean values with the corresponding standard deviations for both parameters, for different texture class. Over the reported range of values for λ, we have this approximation (Hantush and Kalin, 2003)

$$\ln G \sim N(\mu_{\ln G}, \sigma^2_{\ln \psi_b}), \tag{13}$$

and

$$\mu_{\ln G} \approx \mu_{\ln \psi_b} + \ln\left[(2+3\bar{\lambda})/(1+3\bar{\lambda})\right] \tag{14}$$

Thus, G is **lognormally** distributed, with the mean of lnG (i.e., geometric mean) given by (14) and variance of lnG ≈ $\sigma^2_{\ln \psi_b}$, which is the variance of $\ln\psi_b$. $\bar{\lambda}$ is the geometric mean of λ. Rawls et al. (1982) provide values of $\sigma^2_{\ln \psi_b}$ and $\bar{\lambda}$ for different soil textures. Table 6 (Hantush and Kalin, 2003) provides the arithmetic mean and standard deviations of G for different soil textures obtained from the lognormal approximation and by performing 10000 Monte Carlo simulations, using the statistics of the lognormally distributed ψ_b and λ (Rawls et al. 1982). It is striking that the suggested G values in the KINEROS-2 manual are much smaller than the values shown in Table 6.

Table 6. Summary statistics of G (cm) parameter for various soil types.

	Arithmetic				Geometric (MC)	
	mean		std.			
Soil Texture	theoretical	MC	theoretical	MC	mean	std.
Sand	39	40	118	156	9.9	5.3
Loamy sand	41	44	131	156	12.3	4.8
Sandy loam	64	62	186	153	22.1	4.3
Loam	105	112	475	493	17.9	6.9
Silt loam	158	156	563	544	33.5	5.8
Sandy clay	181	180	864	800	44.1	5.0
Clay loam	129	129	364	309	42.3	4.5
Silty clay loam	195	183	601	561	55.0	4.9
Sandy clay	219	224	909	937	48.6	5.9
Silty clay	209	204	666	583	59.0	4.9
Clay	242	232	770	689	64.1	5.0

Figure 9 plots the theoretical arithmetic mean (analytical) and standard deviation versus those obtained by MC simulations. The comparison shows that the l**ognormal** approximation of G is valid over different soil textures.

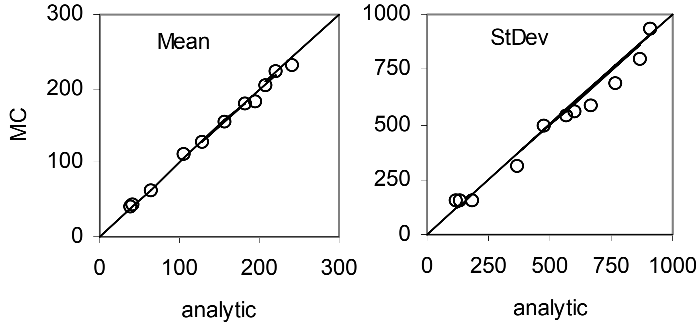


Figure 9. MC versus theoretical mean and std. of G.

A rainfall event was randomly selected. It occurred on 6/13/1983 with a total rainfall depth of 48 mm (Figure 10). MC simulations are performed with this event for each parameter by running KINEROS-2 (Kalin and Hantush, 2003). Peak flow (q_p), cumulative flow (q_t), time to peak flow (t_{pf}), peak sediment discharge (q_{sp}), total sediment yield (q_{st}) and time to peak sediment discharge (t_{ps}) values were recorded. Figures 11 and 12 show results from the MC simulations. Since our focus is on sediment, only results related to sediment are shown. The vertical axis in each figure shows the exceedance probabilities (1-CDF). Results for less sensitive parameters are not shown. A sudden drop from 1 to 0 in the exceedance probability implies no variation of the model output with respect to the particular parameter uncertainty, whereas the more gradual the transition from 1 to 0, the more sensitive the model output to the parameter. Only parameters shown in Figure 12 are directly affecting sediment transport. In other words, parameters shown in Figure 11 determine the shape of the hydrograph and since sediment discharge is a function of flow, they indirectly affect sedimentograph. MC simulations were performed for an additional, smaller event (8/26/81) with a total rainfall depth of 17 mm for c_f and c_g (Figure 10). The secondary axes in Figure 12 correspond to this event. From Figure 11 it is clear that the order of sensitivity is K_s, n_p, G, λ (with ψ_b fixed at its geometric mean), S_i and n_c when peak sediment discharge, q_{sp}, is concerned. When total sediment yield, q_{st}, is concerned K_s is by far the most sensitive parameter followed by G, S_i, n_p, and λ. Time to peak sediment discharge, t_{ps}, is most sensitive to n_{ch} and n_p. K_s and G are the next most sensitive parameters. Although λ affects model output only through the G parameter, allowing ψ_b to vary randomly, but independently, with λ explains the more gradual transition from 1 to zero of the probability exceedance curve for G than that for λ, indicating a greater uncertainty of the model output with respect to the former. Order of sensitivities may differ depending on the size and the nature of the rainfall event and quantity of interest. For instance, interception depth may play a significant role during small events. However, the general picture is the same. The model sensitivity to c_f and c_g are again event dependent as shown in Figure 12. It is more sensitive to c_g than c_f during large events. This mode of sensitivity is reversed for smaller events, where rain splash erosion dominates model output uncertainty (Kalin and Hantush, 2003). The time to peak sediment discharge, t_{ps}, is insensitive to c_f and c_g. During calibration, since flow parameters have to be calibrated first, Manning's roughness should be estimated initially to match hydrograph timings. Next, K_s, G and S_i should be calibrated to adjust the volume of hydrographs. The parameter S_i depends on the antecedent moisture condition and should be adjusted for each event.

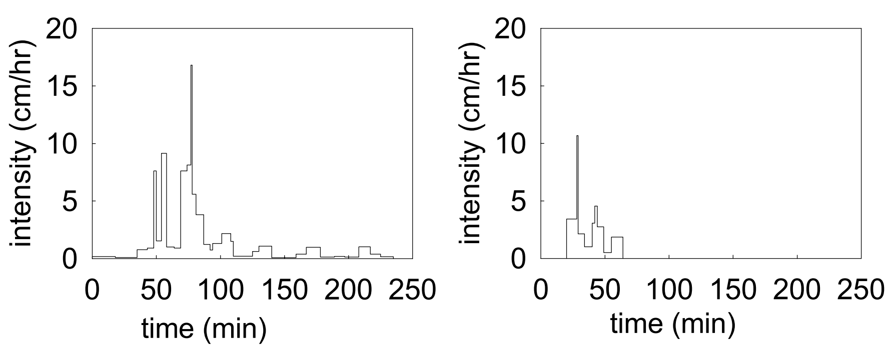


Figure 10. Rainfall events at 6/13/83 (left) and 8/26/81 (right).

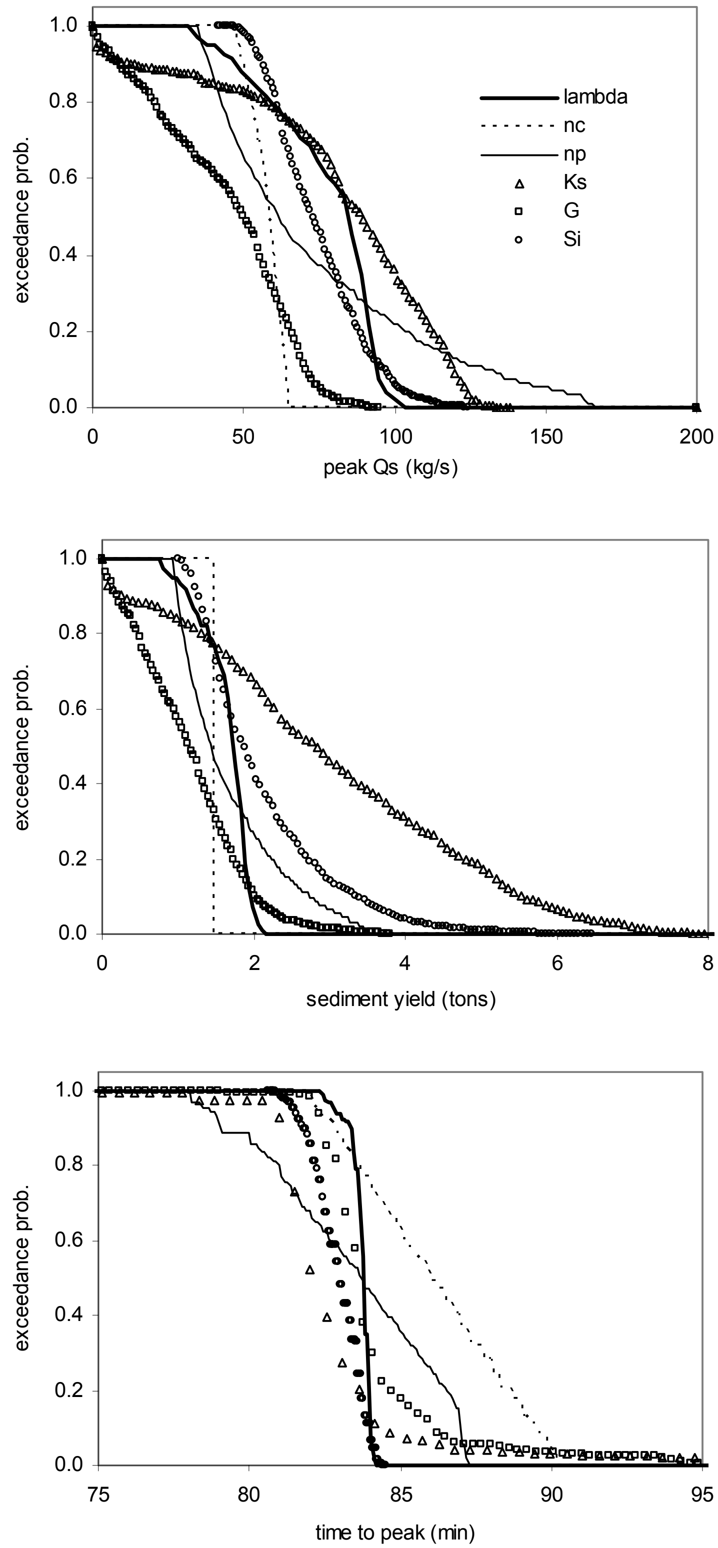
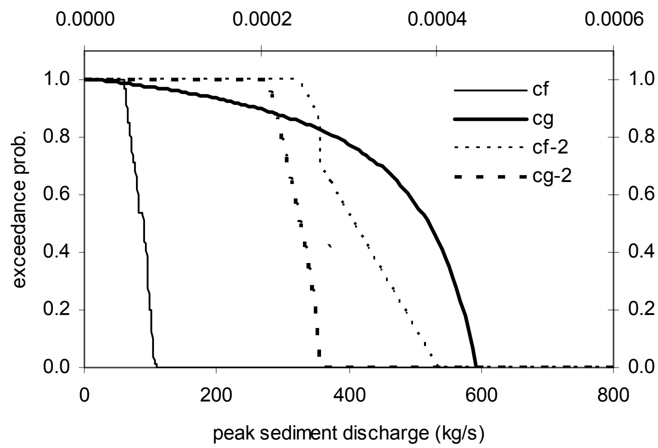


Figure 11. Probability of exceedance of peak sediment discharge (kg/s), total sediment yield (tons), and time to peak sediment discharge (min) for some selected parameters.



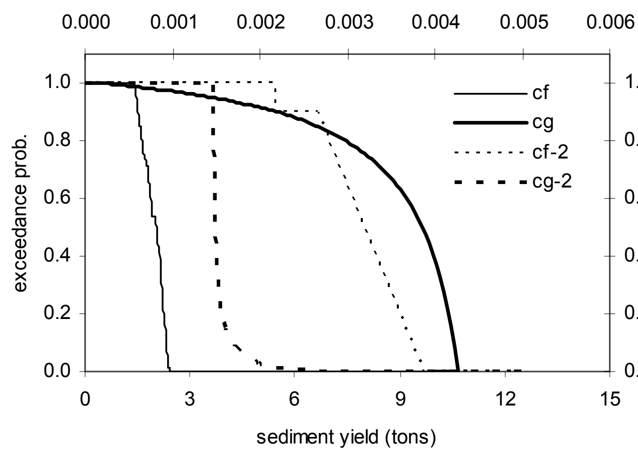


Figure 12. Probability of exceedance of peak sediment discharge (kg/s) and total sediment yield (tons) for c_f and c_g parameters. Secondary axes are for c_f-2 and c_g-2 (second event).

The antecedent moisture condition has a significant effect on the sensitivity results. For instance, Figure 13 shows the effect of initial saturation (S_i) on the sensitivity of peak sediment discharge and sediment yield to K_s. It is clear that both the peak sediment discharge and sediment yield become more sensitive to K_s as the antecedent moisture condition becomes dryer. A small perturbation in K_s results in significant differences as indicated by the large coefficient of variations (COV) of peak sediment discharge and sediment yield. COV is a measure of deviation from the mean and is computed by dividing standard deviation to the mean. This signifies that, under dry conditions, model is sensitive to more parameters and calibration is more difficult.

5.4 Model Calibration, Validation

Three events for model calibration and 4 events for model validation were selected. Calibrations were performed manually by comparing computed and observed hydrographs and sedimentographs (Kalin and Hantush, 2003). Average values were used for G (20,35 cm), λ (0.6,0.6), Φ (0.50,0.47) and d_{50} (7 μm). First values in parenthesis are for silt loam (SL) and second values are for silty clay loam (SCL). Table 7 shows calibrated parameters. The first three events are for calibration and the rest is for validation purposes. At the end of each row the Nash-Sutcliffe statistics are given for both flow and sediment. The sensitivity results indicate that peak sediment discharge and sediment yield are very sensitive to plane roughness (n_p), but almost insensitive to channel roughness (n_c). Time to peak sediment discharge is equally sensitive to n_c and n_p. Therefore, we calibrated for n_p and used the same value for n_c. This simplifies calibration as well. Considering the agricultural nature of W-2, n_p and n_c are allowed to vary by time of the year due to growing crops. It is assumed lowest at the beginning and largest at the end of the growing season. S_i was allowed to vary from event to event. S_i values were calibrated by taking precipitation fallen during the previous five days into account. Since KINEROS-2 does not model evapotranspiration losses, these losses were incorporated into the interception depth I, which was also allowed to vary by event and seasonally. The soil erosion parameters c_g and c_f are known to vary from event to event due to sediment availability (Ziegler et al, 2001) and seasonally due to tillage practices, freeze-thaw processes and change in vegetation (Smith et al., 1999). Therefore, they were allowed to decay exponentially from highest values at beginning of the growing season to lowest at the end of the growing season. They were highest in 5/30/1982 and lowest in 8/26/1981. Negligible differences in K_s values were observed during calibration.

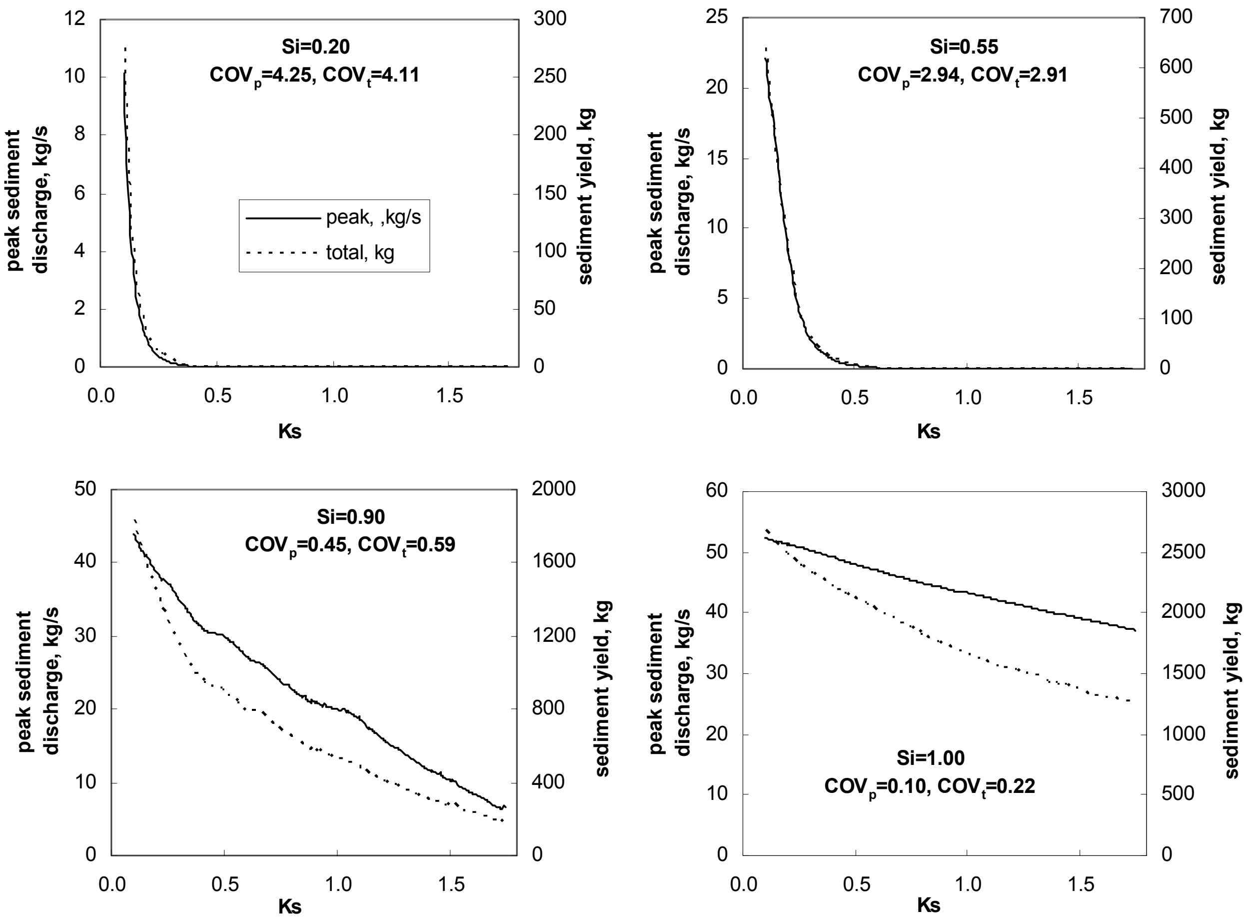


Figure 13. Effect of antecedent moisture condition on K_s sensitivity. S_i is initial saturation, COV_p and COV_t are the coefficient of variations of peak sediment discharge and sediment yield, respectively.

Table 7. Parameter set following calibration.

	n	Ks_{SL} (mm/hr)	Ks_{SCL} (mm/hr)	Inter (mm)	Si_{SCL}	Si_{SL}	c_g	c_f	$Nash_{flow}$	$Nash_{sed}$
5/30/1982	0.04	6	1.5	0.0	0.86	0.90	0.250	200		
6/13/1983	0.055	6.5	1.8	2.0	0.27	0.44	0.150	160		
8/26/1981	0.08	7	2.0	1.0	0.60	0.84	0.050	100		
6/12/1980	0.055	6.5	1.8	2.0	0.27	0.44	0.150	160	0.92	0.83
7/8/1981	0.08	16	5.0	3.5	0.20	0.24	0.080	130	0.99	0.91
8/1/1981	0.02	13	3.0	4.0	0.20	0.24	0.015	100	0.87	0.84
8/29/1975	0.09	9	2.5	2.5	0.20	0.34	0.010	90	0.96	0.93

Two different strategies can be followed for model validation purposes. The first technique is based on employing the parameters, estimated with calibration, at the validation stage and comparing the performances of predicted and observed hydrographs/sedimentographs. In the second method, parameters are recalibrated so as to have good matches between observed and predicted model outputs. Then, recalibrated parameters are compared to the expected values obtained through calibration. In this study we utilized the latter method. Parameters estimated using the validation events are, in general, in good agreement with calibrated parameters (Table 7). There are acceptable amount of variations in K_s values considering the nature of K_s which has very high coefficient of variations in most soils (eg. 2.73 for SL). The only unexpected result is with the n value of the event 8/1/1981. A value of 0.02 is estimated in contrast to an expected value of 0.08 to accommodate the early response observed in measured data. Based on rainfall records, the soil is expected to be very dry prior to this event. Therefore S_i is kept minimum, and since it is the month of August, I can not be zero. Possible explanations might be i) potential measurement errors, or ii) even at this small scale spatial variation of rainfall may play an important role. The computed and observed sedimentographs are shown in Figure 14.

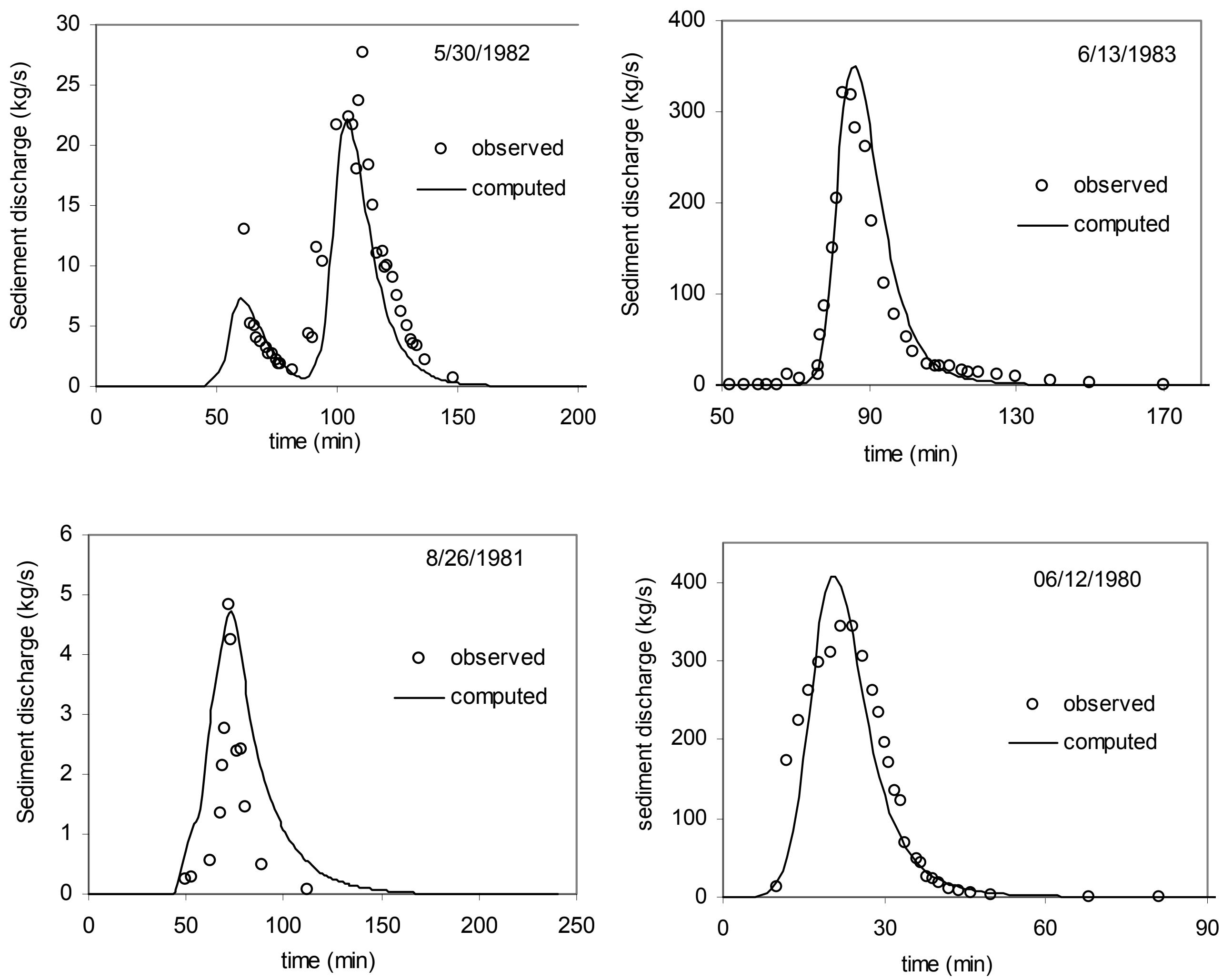


Figure 14. Computed and observed sedimentographs for selected events.

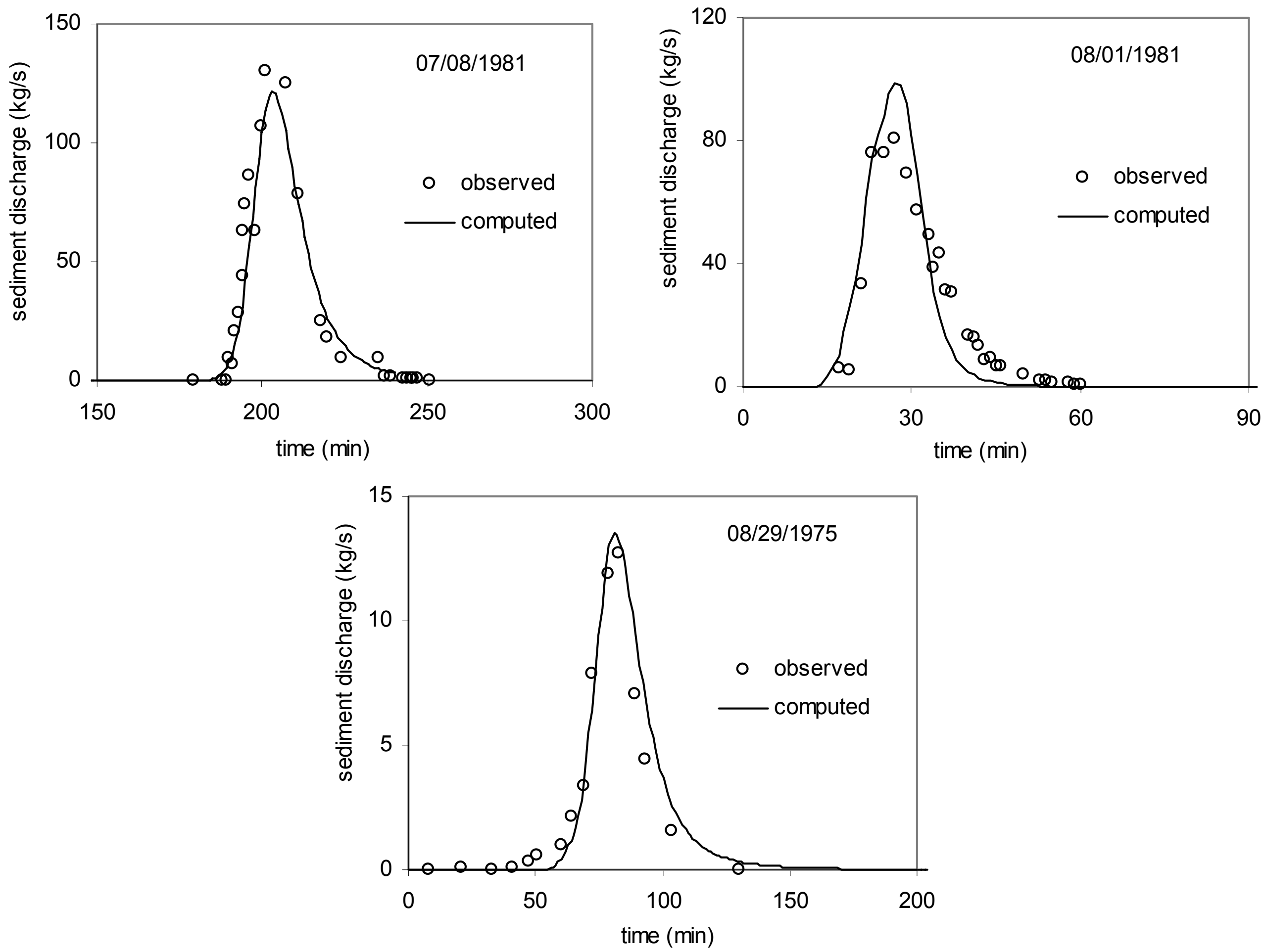


Figure 14 (continued). Computed and observed sedimentographs for selected events.

5.5 Discussion:

The calibration and validation exercise performed over the W-2 watershed with KINEROS-2 show that channel roughness, n_c, plane roughness, n_p, and soil erodibilities c_g and c_f, show seasonal variations. This is due to the agricultural nature of W-2. During calibration it is recommended that n_p and n_c be calibrated first to adjust hydrograph timings. Average values suggested in the literature can be used for n_c, as the sensitivity results indicate that KINEROS-2 is more sensitive to n_p than n_c when peak sediment discharge and sediment yield are concerned. The time to peak sediment discharge is almost equally sensitive to both parameters. The saturated hydraulic conductivity, K_s and effective capillary drive parameter, G can be calibrated next by focusing more on K_s to match the flow volumes. The soil erosion parameters c_g and c_f can be calibrated next, to adjust the computed sediment yield to the observed.

Beven (1989) states that calibration to match a single event is not difficult where a loss function and a routing function are all that is needed. However, the calibrated data set has to be verified over additional events. The difficulty lies under the estimation of initial soil moisture content which depends primarily on prior rainfall events. Like all physically-based models, KINEROS-2 requires the initial estimation of soil moisture which is usually not available. Figure 13 shows how important the selection of the initial soil moisture content is in the KINEROS-2 model. The best way to overcome the effect of the initial soil moisture is performing continuous simulations where none of the critical processes are ignored in the water balance and soil moisture is redistributed between the storms, i.e. during rainfall hiatus. Although KINEROS-2 considers soil moisture redistribution, it ignores evapotranspiration. Therefore it is not suitable for continuous simulations since a true water balance is not possible. In the next section the GSSHA model having both event and continuous simulation capabilities is investigated. The flow and sediment results are compared to

KINEROS-2 by running the event module of GSSHA with the same events employed in KINEROS-2 simulations. Later, long-term, continuous-time simulations are performed over the same watershed with GSSHA and results are discussed.

6 Comparison of KINEROS-2 with GSSHA

In this chapter KINEROS-2 and GSSHA (Downer and Ogden, 2002) models are compared quantitatively based on their performances on modeling flow and sediment movement. Each model has a different watershed conceptualization (Figures 15 and 16). GSSHA divides the watershed into cells, and flow and sediments are routed through these cells in a cascading fashion. Conversely, KINEROS-2 divides the watershed into sub-watersheds or transects and channel segments having uniform properties. GSSHA may require much longer simulation times depending on what is simulated. KINEROS-2, on the other hand, entails relatively less data and effort. Simulations were performed with each model over the W-2 watershed. Both models were calibrated using the same events and the differences in estimated parameters were discussed. Both models have resulted in different calibration parameters. The differences in model behaviors are discussed. Model descriptions and features are given in the previous sections. For full model descriptions users can refer to the references given.

6.1 Model Features

Features of KINEROS-2 model, with emphasis on the sediment component, was described in the previous chapter. Here, the properties of the GSSHA model are presented with the focus on the sediment formulation.

GSSHA is a reformulation and enhancement of the hydrologic model CASC2-D (Ogden and Julien, 2002). However, the sediment components are exactly the same. GSSHA can perform single event and continuous time simulations. Watershed is divided into cells and water and sediment is routed from one cell to another in two principle dimensions. It uses one and two-dimensional diffusive wave flow routing at channels and overland planes, respectively. Although only Hortonian flows were modeled by employing Green-Ampt (G-A) infiltration model in the initial versions, GSSHA considers other runoff generating mechanisms such as lateral saturated groundwater flow, exfiltration, stream/groundwater interaction etc. GSSHA offers three options for computation of infiltration: G-A, G-A with redistribution (Ogden and Saghafian 1997) and the full Richards' equation.

Modified Kilinc and Richardson equation (Julien 1995) is used to compute sediment transport capacity at plane cells. The potential sediment transport rate is computed in x and y directions as

$$q_{si} = 25500 q_i^{1.664} S_{fi}^{1.664} \frac{K \cdot C \cdot P}{0.15} \qquad (15)$$

where q_s is sediment unit discharge (ton/m/s), q is unit flow discharge (m^2/s), S_f is friction slope, and K (soil erodibility factor), C (cropping factor) and P (conservation factor) are the USLE (Universal Soil Lois Equation) soil parameters. The index i represents the two principal directions, x and y, therefore sediment transport capacity is computed in both directions.

Each cell can either be eroded or aggraded depending on the sediment in suspension and potential sediment rates. This determination is made for three particle sizes: silt, clay and sand. If sediments in suspension are unable to satisfy the potential transport rate, erosion occurs. If the potential transport rate is unable to transport the sediment already in suspension, deposition occurs. A trap efficiency measure is used to determine how much material is deposited (Johnson et al., 2000).

$$TE_j = 1 - e^{\frac{\Delta x w_j}{uy}} \qquad (16)$$

where TE_j is the trap efficiency for the j^{th} particle size ranging from 0 to 1, Δx is the grid cell size (m), w_j is the fall velocity of the j^{th} particle size (m/s), u is the overland flow velocity (m/s) and y is the overland flow depth (m). The use of trapping efficiency allows deposition of larger particles before the smaller ones.

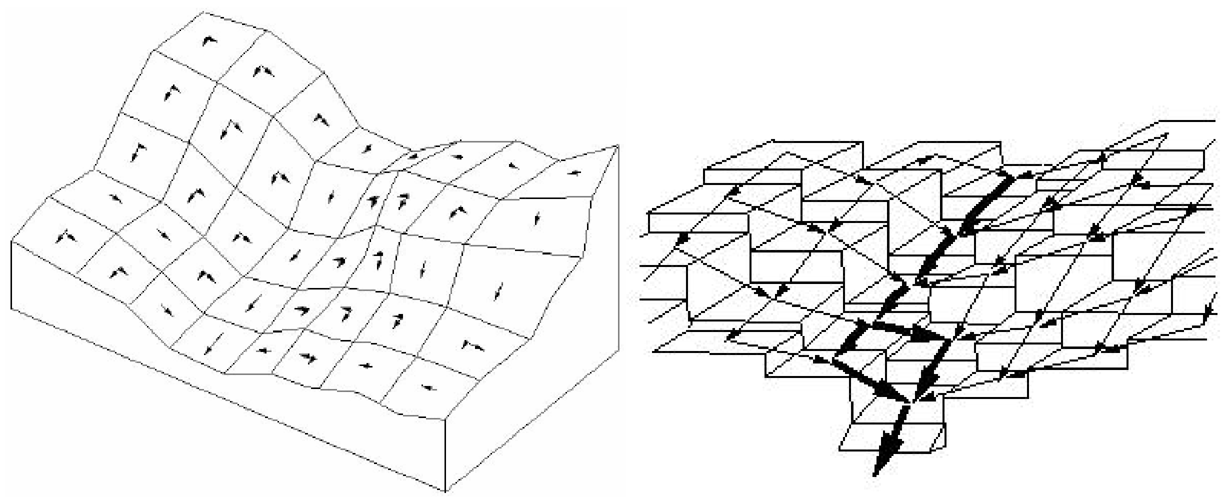


Figure 15. Watershed conceptualization in GSSHA.

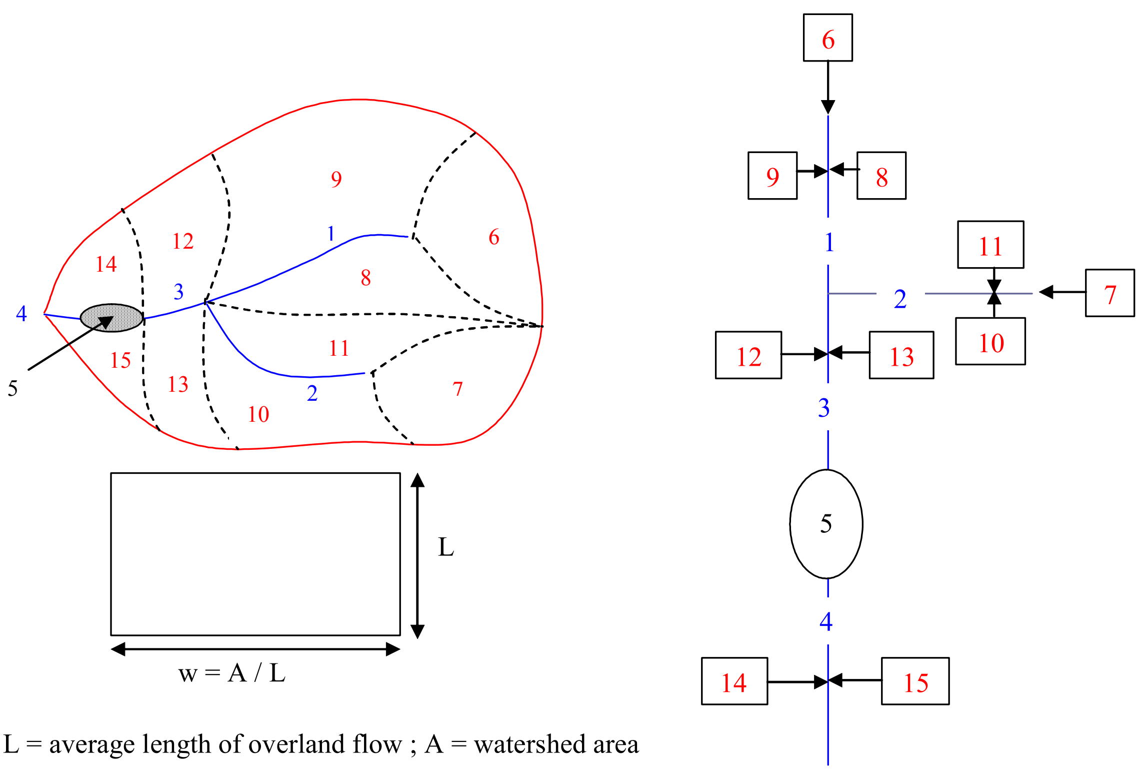


Figure 16. Watershed conceptualization in KINEROS-2.

Yangs' unit stream power method (1973) is used for routing sand size particles in stream channels. This routing formulation is limited to trapezoidal channels. Silt and clay particles are assumed to be always in suspension and therefore transported as wash load. More details on theory and equations used can be found in Downer and Ogden (2002).

Many applications of the GSSHA model and its predecessor CASC2D can be found in peer reviewed literature (eg. Johnson et al. 2000; Molnar and Julien, 2000; Senarath et al., 2000; Ogden and Heilig, 2001; Downer and Ogden, 2003a; Downer and Ogden, 2003b).]

The watershed conceptualization employed in GSSHA seems more realistic than the realization used in KINEROS-2. The use of diffusive wave approximation to the full Saint Venant equations in GSSHA is an improvement over the kinematic wave approach utilized in KINEROS-2. KINEROS-2 is limited to Hortonian flow and is not suitable for long-term simulations because it lacks evapotranspiration (ET) component which is important for the mass balance of the water cycle. On the other hand, GSSHA can handle various runoff generating mechanisms. In general, the flow component of GSSHA can be expected to perform better than the flow component of KINEROS-2 since it involves less simplification. Contrary to flow, the sediment formulation of GSSHA is not as strong. KINEROS-2 has a better sediment transport formulation. GSSHA's sediment component is based on semi-empirical relationships, whereas KINEROS-2 employs a more physically based-approach.

6.2 Approach

KINEROS-2 was already calibrated for W-2 watershed in the previous section using 3 rainfall events. The fixed parameters are net capillary drive, G(20,35 cm), pore size distribution index, λ(0.6,0.6), porosity, ϕ(0.50,0.47), and median particle size diameter, d_{50}(7 μm). The two values given in parentheses represent different soil types, silt loam (SL) and silty clay loam (SCL), respectively. Table 8 lists the parameter sets used after calibration of KINEROS-2. In the table, n is Manning's roughness, K_s is saturated hydraulic conductivity, I is interception depth, S_i is initial saturation, c_g is soil cohesion coefficient and c_f is rain splash coefficient. The sensitivity results in chapter 5 indicated that peak sediment discharge and sediment yield are very sensitive to plane roughness (n_p), but almost insensitive to channel roughness (n_c). Time to peak sediment discharge is equally sensitive to n_c and n_p. Therefore, we calibrated for n_p and used the same value for n_c. Since corn has been grown on W-2, the parameters n_c, n_p, c_g and c_f were allowed to vary with season where c_g and c_f were assumed to decay exponentially with the growing season. This assumption was justified over 4 independent verification events (see previous section).

Table 8. Parameter sets used in KINEROS-2.

event	n	K_s (mm/hr)	I (mm)	S_i	C_g	C_f
6/13/1983	0.055	(6.5,1.8)	2	(0.27,0.44)	0.15	160
5/30/1982	0.04	(6.0,1.5)	0	(0.86,0.90)	0.25	200
8/26/1981	0.08	(7.0,2.0)	1	(0.60,0.84)	0.05	100

6.2.1 Flow Simulations

GSSHA was run with the above events. KINEROS-2 values were directly substituted for parameters common to both models i.e. λ, ϕ, n, I and S_i. Other parameters were adjusted accordingly. The infiltration scheme in GSSHA is the Green-Ampt (G-A) model, whereas KINEROS-2 uses Smith-Parlange infiltration model, which is a generalization of the former. G-A capillary head (Ψ_f) needs to be provided in GSSHA. We approximated Ψ_f as equal to G in KINEROS-2. We used the K_s values given in Table 8 for the G-A hydraulic conductivity ($K_{G\text{-}A}$). Figure 17 shows the comparison of the simulation results for flow with two models. It is clear that both models perform differently when similar parameter sets are used as inputs. The most striking observation is that, in all cases GSSHA generates later responses and lower peak flows than KINEROS-2. For instance, the difference in time to peaks for the event 8/26/81 is around 25 minutes which is very significant considering the fact that the base time is around 150 minutes. Similarly, the peak flow generated by KINEROS-2 is about 45 % larger than the peak flow generated by GSHHA. One possible rationale to this might be the different watershed conceptualizations involved in each model. Flow routing in GSSHA is only in x-y directions (Figure 15). In other words, flow from a cell is allowed only in the four principal directions. Diagonal neighboring cells can not be receivers which well might be the reality. This results in overestimation of the travel lengths of water particles which might be up to 41 %. On the other hand, the travel paths used to compute the average travel lengths of each element in KINEROS-2 were determined based on the D-8 methodology using the TOPAZ algorithm (Garbrecht and Martz 1999) which allows flow in 8 directions. Considering the fact that flow in the study watershed is mostly diagonal, the overestimation of travel lengths by GSSHA resulted in longer travel time leading to more resistance to flow, and consequently lower and retarded peaks.

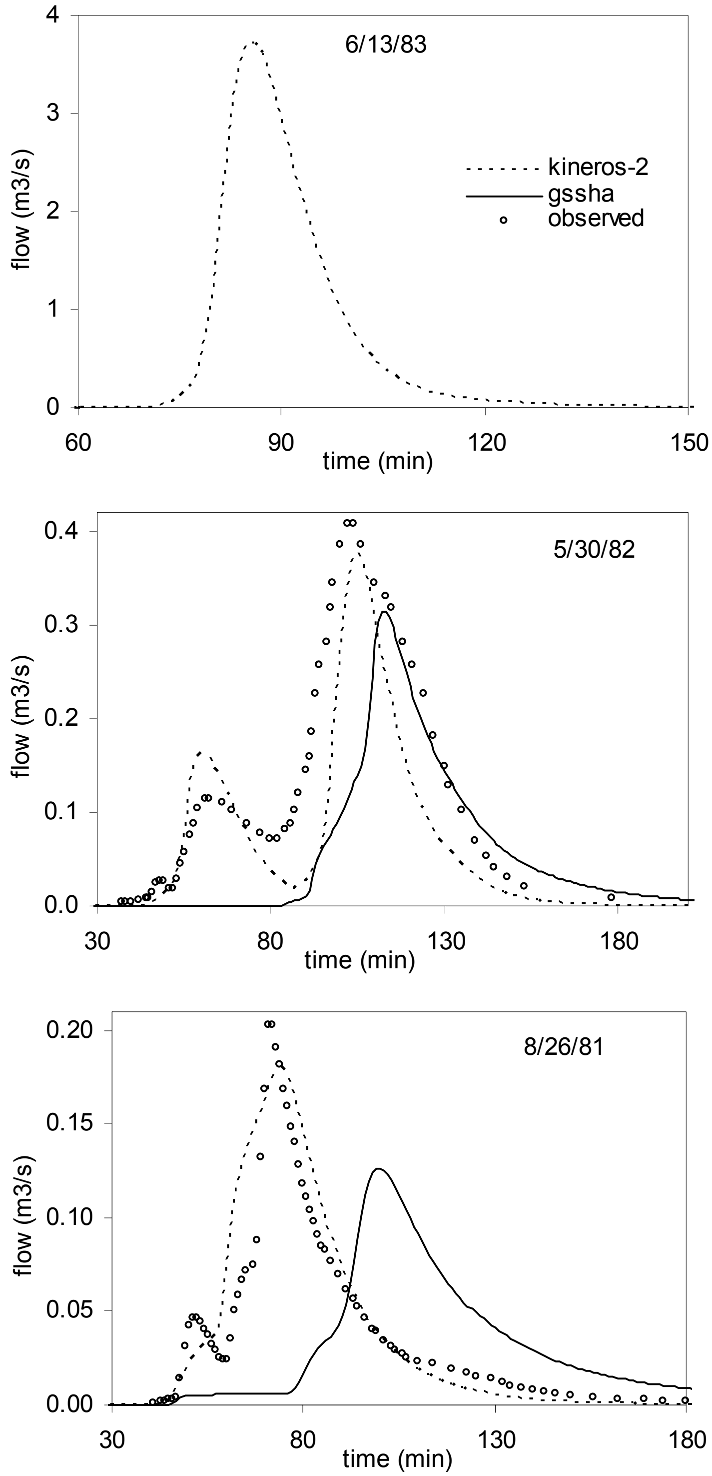


Figure 17. Comparison of hydrographs generated with GSSHA (straight lines) and KINEROS-2 (dashed lines) based on KINEROS-2 calibrated parameters. Observed data is shown as hollow circles (Kalin and Hantush, 2003).

Total flows at the watershed outlet for observed data and KINEROS-2 and GSSHA simulations are shown in Table 9. The differences between the flow volumes of KINEROS-2 and GSSHA do not seem to be significant. With this set of parameters KINEROS-2 seems to simulate events having multi-modal shapes, such as the one in 5/30/82, better than GSSHA. In fact GSSHA completely misses the first and second humps in 5/30/82 (at 48 and 61 minutes, respectively) as opposed to KINEROS-2. KINEROS-2, to some extent, performs better than GSSHA in simulating the small hump seen on the observed data of 8/26/81.

Table 9. Total flows in m^3 at the watershed outlet from observed data, and KINEROS-2 and GSSHA simulations with KINEROS-2 calibrated parameters.

	6/13/83	5/30/82	8/26/81
OBSERVED	3801	1042	317
KINEROS-2	3435	679	335
GSSHA	3509	602	318

It is important to keep in mind that all these observations are based on simulations with the parameters calibrated for KINEROS-2. Therefore, we recalibrated the GSSHA parameters for the same events. This time each event was calibrated individually and parameters were compared to KINEROS-2 calibrated parameters. We accept that we did not follow the traditional model calibration/verification methodology. However, we need to mention that the aim of this study is basically a comparison of the two models rather than a model calibration effort. Keeping this in mind, we kept I, S_i and the overland plane roughness (n_p) same and recalibrated channel roughness (n_c) and K_{G-A}. Figure 18 shows the hydrographs after calibration. For the event 6/13/83 both model performs equally. For 5/30/82 GSSHA is still underestimating the first and second humps (at 48 min and 61 min, respectively). Although KINEROS-2 could not simulate the first hump (the smallest hump in the figure) GSSHA was able to generate all the humps. Finally, when we look at the last event we see that GSSHA almost perfectly reproduces the observed hydrograph shape while KINEROS-2 does a poorer job of simulating the first peak.

The recalibrated parameters for GSSHA are summarized in Table 10. In the table C is the USLE cropping management factor which will be discussed later. The value of n_c had to be decreased dramatically for each event which is clearly expected from Figure 17 as GSSHA generated later responses in each case. One remarkable observation is that n_c values are very close to each other which confirms the comments of Larry Kramer (personal communication) who has extensive experience on Treynor watersheds. He stated that channels are covered with bromegrass and they are cultivated such a way that channel roughness can be assumed invariable year around. K_{G-A} values are very close to KINEROS-2 K_s values. Rawls and Brakensiek (1983) recommends K_{G-A}=K_s/2 based on Bouwer's (1966) findings.

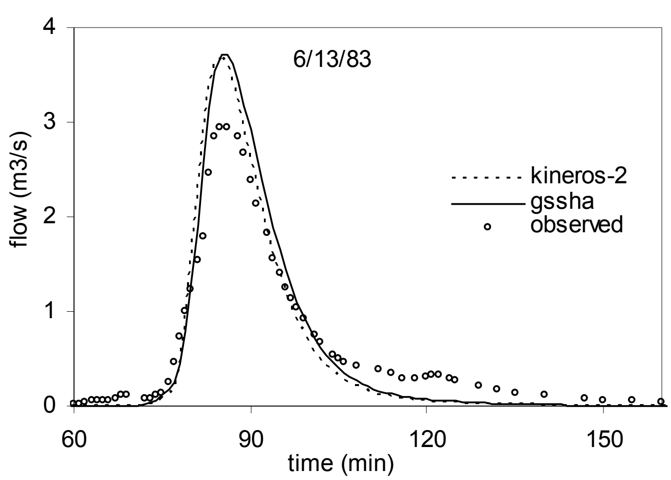


Figure 18. Comparison of hydrographs generated with GSSHA (straight lines) and KINEROS-2 (dashed lines). GSSHA is recalibrated. Observed data is shown as hollow circles (Kalin and Hantush, 2003).

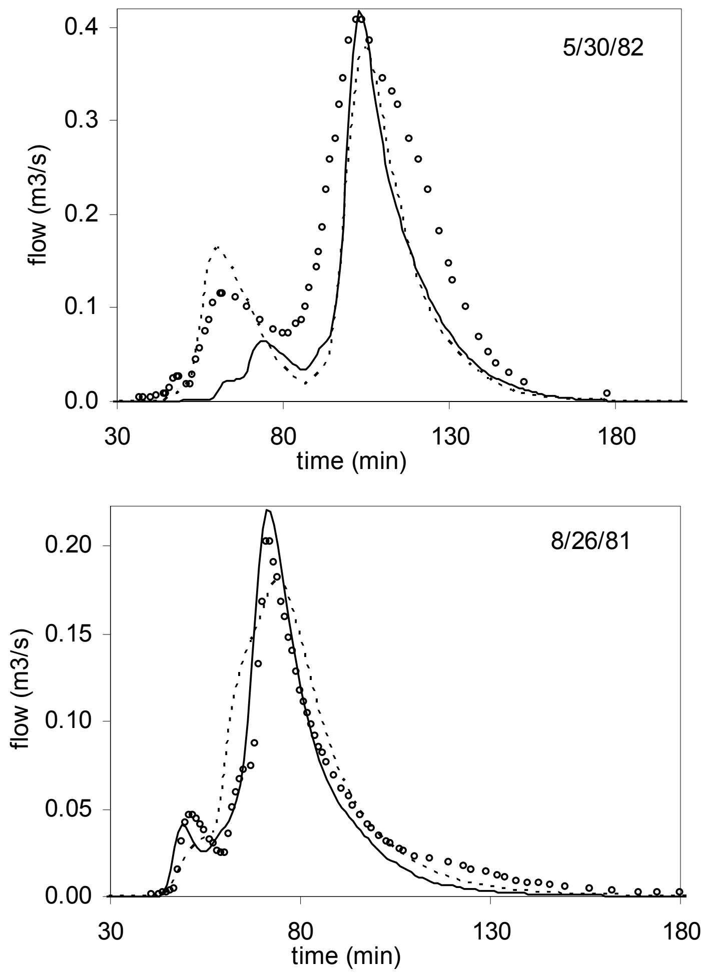


Figure 18 (continued). Comparison of hydrographs generated with GSSHA (straight lines) and KINEROS-2 (dashed lines). GSSHA is recalibrated. Observed data is shown as hollow circles (Kalin and Hantush, 2003).

Table 10. Calibrated parameters with GSSHA.

event	n_c	$K_{G\text{-}A}$ (mm/hr)	C
6/13/1983	0.025	(7.7,2.0)	0.042
5/30/1982	0.020	(6.0,1.5)	0.150
8/26/1981	0.025	(6.5,1.8)	0.050

6.2.2 Erosion Simulations

GSSHA requires silt and sand percentages for sediment computations. The default values used in the GSSHA model for D_{50} are 0.25 mm for sand, 0.016 mm for silt and 0.003 mm for clay. Based on these values compositions of each soil class were determined as sand % (25,10) and silt % (61,56) so that the overall average D_{50} is 7 mm, which is the value used in KINEROS-2. Again, the values in the parentheses are for silty loam (SL) and silty clay loam (SCL), respectively. The sediment routine in GSSHA is empirical and based on the USLE concept that requires three parameters: K (soil erodibility factor), C (cropping management factor) and P (conservation practice factor). It is not practical to infer estimates of these parameters from the KINEROS-2 soil parameters; i.e., c_g and c_f. Therefore, by keeping KP product constant C was calibrated for each event, since it is only the product of K, C, and P that matters. The values of K and P are (0.37,0.48) and (0.01,0.01), correspondingly. The estimated C values are listed in Table 10.

The pattern observed in KINEROS-2 is that erodibility decreases with the growing season, but is not observed between the C values here. The C values obtained for the event 8/26/1981 is unexpectedly high, even higher than the value of 6/13/83. Figure 19compares the sedimentographs obtained by KINEROS-2 and GSSHA. The general observation is that GSSHA generates narrower sedimentographs than KINEROS-2 generates. This may be attributed to the fact that unlike the physically based sediment component in KINEROS-2, GSSHA utilizes empirical relationships for sediment transport. Further, this cannot be attributed to flow, since such a behavior is not reflected in Figure 19.

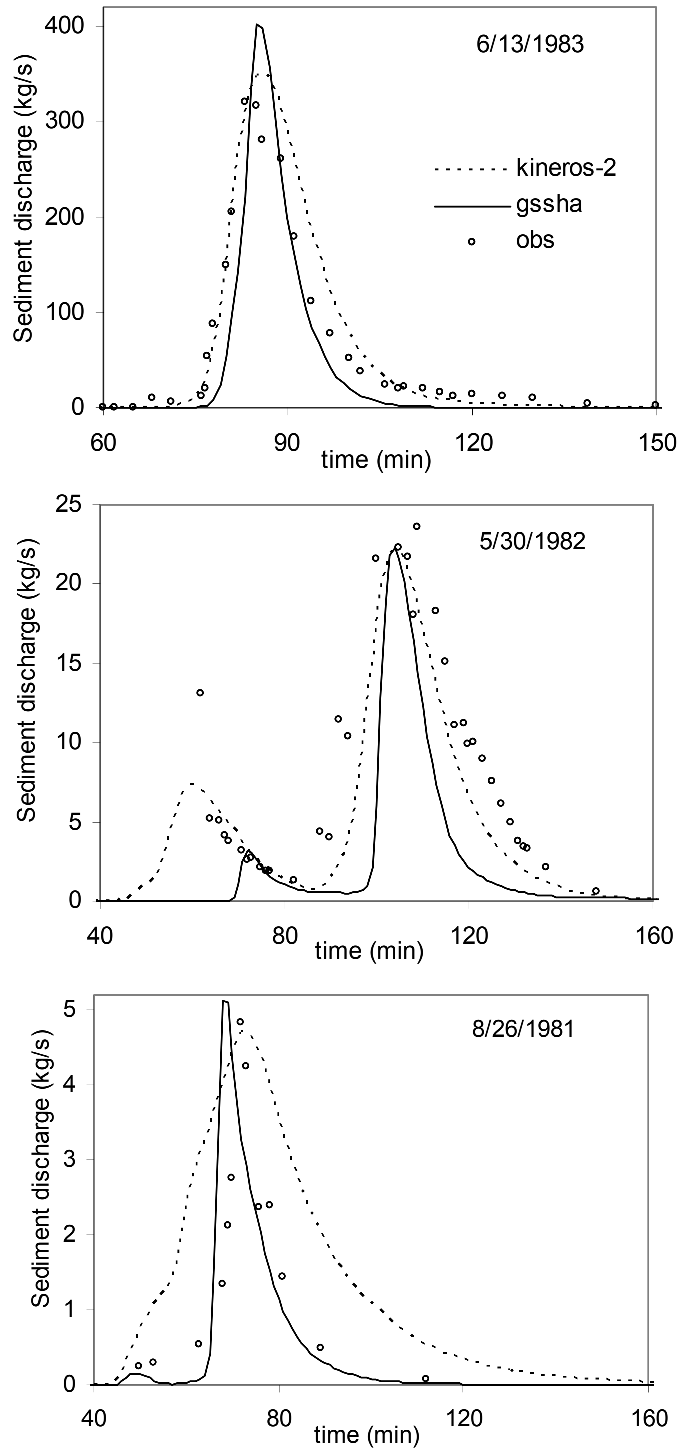


Figure 19. Comparison of sedimentographs generated with GSSHA (straight lines) and KINEROS-2 (dashed lines). Observed data is shown as hollow circles (Kalin and Hantush, 2003).

It is interesting to note that the erosion parameters, c_f and c_g, found after calibration for KINEROS-2 are well above the recommended values given in Woolhiser et al. (1990) and the calibrated C parameters for GSSHA are well below the literature values. This implies that when literature values are used GSSHA overestimates erosion compared to KINEROS-2. Slope is an important factor in both models' erosion formulation. The smaller the computational element, which is the grid size for GSSHA and the average length of overland flow planes in KINEROS-2, the greater the erosion. This occurs because, as the element size increases the tendency of smoothing the topography increases, and this results in loss of areas with steep slopes meaning reduction in erosion. KINEROS-2 uses far less elements than GSSHA, thus leading to loss of local slope information in the former. This probably elucidates the difference in estimates of soil erosion. A detailed discussion on this topic can be found in Rosalia (2002).

6.3 Long-Term Simulations with GSSHA

Here we investigate the long term simulation capabilities of the GSSHA model over the W-2 watershed. In order to perform long-term simulations in GSSHA, in addition to rainfall data, hydrometeorological data are required for the entire period of the simulation. The required data are hourly values of barometric pressure, relative humidity, total sky cover, wind speed, dry bulb temperature, direct radiation and global radiation. These data can be supplied in three different formats to GSSHA: WES, SAMSON and NOAA/NCDC surface airways format. WES is the simplest and the preferred format, while the last one is the least recommended. SAMSON data is used in this study which can be purchased from National Climatic Data Center (NCDC) in a CD-ROM. The closest station to the W-2 watershed was in Omaha, NE.

GSSHA offers two options for infiltration calculations during long-term simulations: Richards' equation (RE) (Richards, 1931) and Green-Ampt with redistribution (GAR) (Ogden and Saghafian, 1997) which is basically simplification of RE. In Hortonian basins GAR method produces comparable results to RE (Downer and Ogden, 2003a). However, when Hortonian flow is not the dominant stream flow generating mechanism, GAR may produce erroneous results, and RE should be used (Downer and Ogden, 2003a). Since W-2 is a Hortonian watershed we used GAR to simulate a period from 5/17/1984 to 6/17/1984.

The precipitation data used in this long-term simulation is shown in Figure 20. The last rainfall event before 5/17/84 is on 5/6/84. Therefore, we assumed dry initial condition with initial moisture content of 0.1 for both soil types (SL and SCL). In fact, we considered the first 7 days of the simulation as warm up period and thus disregarded the results in that period to reduce the effect of initial moisture content.

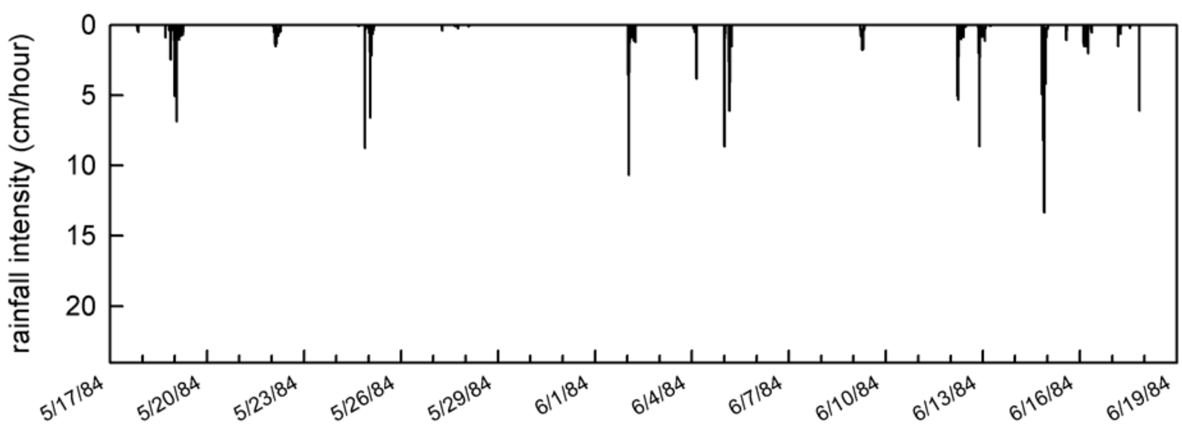


Figure 20. Rainfall histogram used in the long-term simulations of GSSHA.

The parameters used in the simulation and their values are shown in Table 11. In the table $K_{G\text{-}A}$ corresponds to G-A hydraulic conductivity, Θ_r is residual water content, Θ_w is wilting point water content, Θ_i is initial water content, and Ψ_f is wetting front capillary pressure head. Other parameters are as defined before. The values listed in the table are selected in a way that they are close to the values listed in Tables 9 and 10 for the event 5/30/82, since 5/30 seasonally falls in the middle of the simulation period (5/17–6/17). The only significant difference is in the $K_{G\text{-}A}$ values. We recalibrated $K_{G\text{-}A}$ values for the first two events occurring on 5/25/84 and 6/2/84 (5/19 and 5/25 are discarded as they are in the warm up period). These calibrated $K_{G\text{-}A}$ values are smaller than the values given in Table 10. In single-event calibrations, the initial moisture content has to be estimated more realistically. Any overestimation of initial water content results in overestimation of hydraulic conductivity and vice versa. In continuous long-term simulations, however, effect of initial water content is more considerable at earlier stages, and decays with time. Therefore, obtaining different $K_{G\text{-}A}$ values within tolerable ranges from event and continuous simulations is reasonable.

Table 11. Parameter values used in GSSHA long-term simulations.

	n_p	n_c	K (mm/hr)	Φ	Θ_r	Θ_w	Θ_i	Ψ_f (cm)	λ	I (mm)	K	C	P	sand %	silt %
SL	0.04	0.02	3.5	0.486	0.015	0.133	0.10	20	0.23	1.0	0.48	0.15	0.01	25	61
SCL			1.0	0.432	0.040	0.208	0.10	35	0.18		0.37			10	56

Nine different events are recorded between the periods 5/25/85 and 6/17/82 in W-2. Figure 21 shows the hydrographs of the first seven events. Last two events occurring on 6/16/84 and 6/17/84 are not shown in the graph since GSSHA estimated no flow during those two events, although significant flows are observed in both events (peak discharge is 0.39 m^3/s on 6/16/84, and 0.42 m^3/s on 6/17/84). Events on 6/4/84 and 6/5/84 are shown on the same graph (Figure 21). First two events are the calibration events where only G-A hydraulic conductivity ($K_{G\text{-}A}$) was calibrated. Rest are validation events. Estimated and observed flow hydrographs from calibration and validation events conform well as can be seen in Figure 21. Interestingly, validation events produce even better results than calibration events. As mentioned earlier, GSSHA did not generate runoff for the events happening on 6/16/04 and 6/17/04. Simulations were performed with the RE option, by adjusting the parameters accordingly (results not shown) to explore if this might be linked to the infiltration routine used. GSSHA was still unable to generate any flow during the last two events. The observed flows in both events are smaller than the observed flows of the other events. Thus, either GSSHA has difficulty in generating small events, or there is an anomaly in the rainfall data during that time interval, such as inappropriate representation of the rainfall pattern due to spatial variation.

Figure 22 shows the observed and GSSHA generated sedimentographs. Sediment data was not available for 6/2/84. The overall performance is poor. However, in 6/12/84 and 6/14 the falling limbs are well represented.

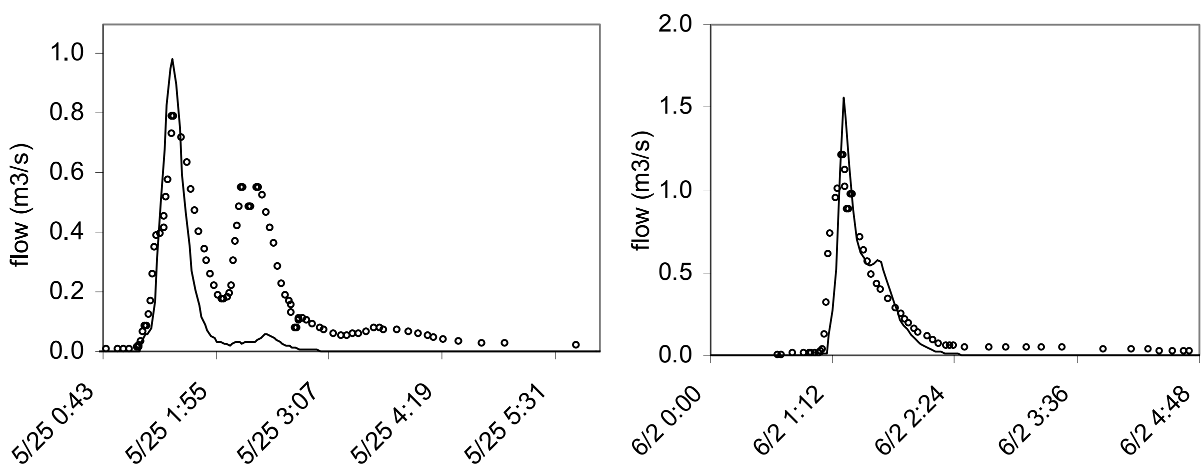


Figure 21. Observed (hollow circles) and simulated (straight line) hydrographs from the long-term simulations of GSSHA.

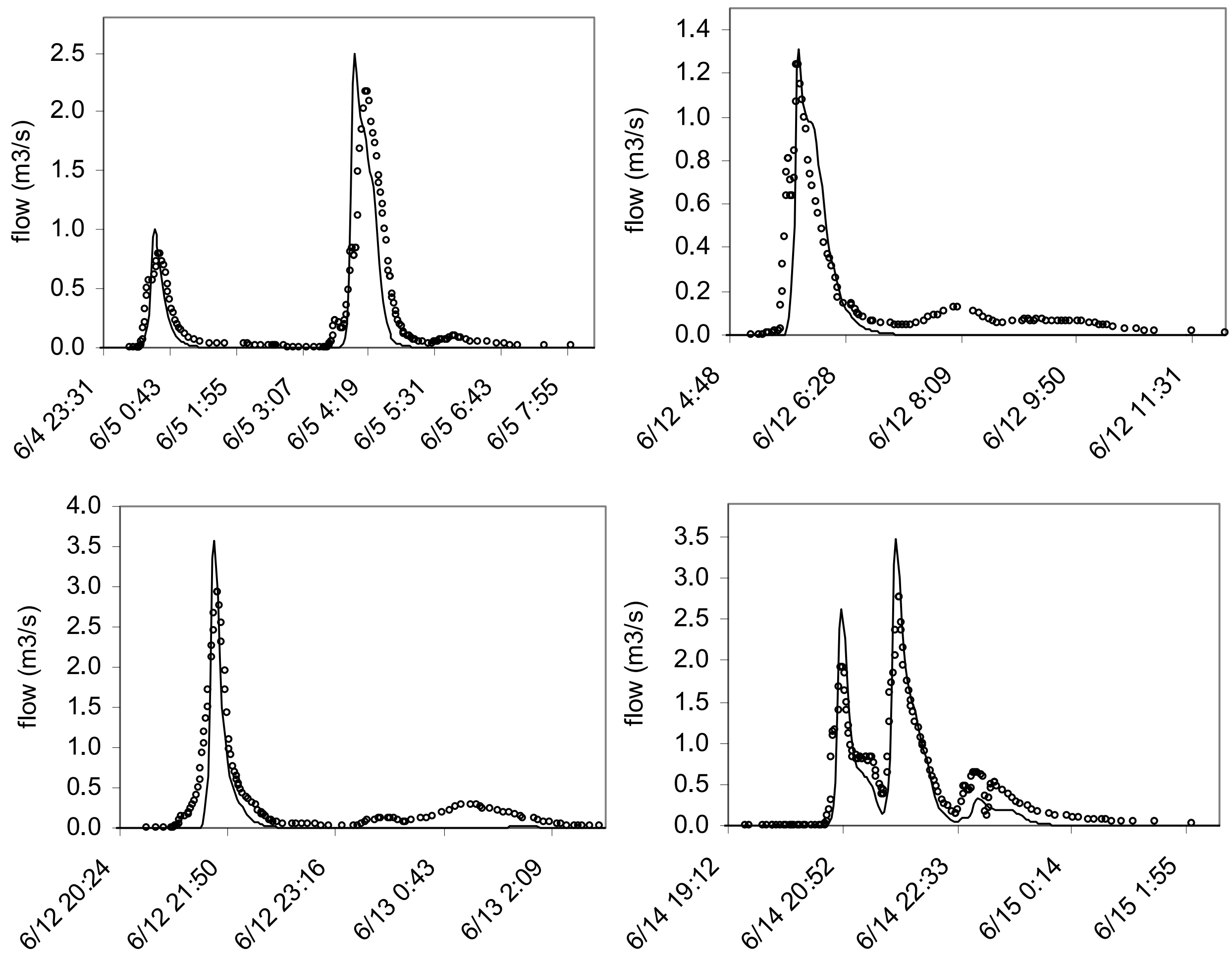


Figure 21 (continued). Observed (hollow circles) and simulated (straight line) hydrographs from the long-term simulations of GSSHA.

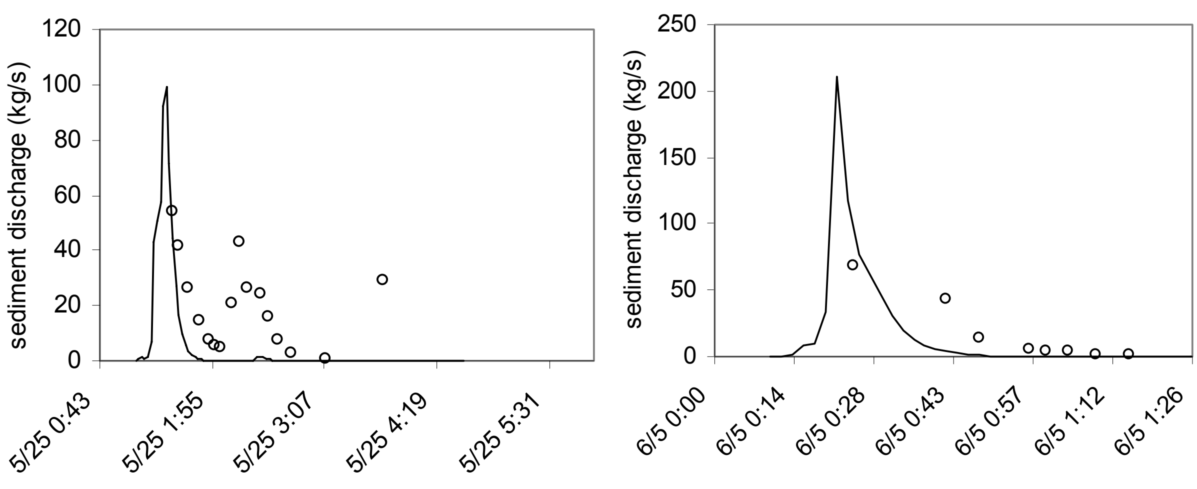


Figure 22. Observed (hollow circles) and computed (straight line) sedimentographs from the long-term simulations of GSSHA.

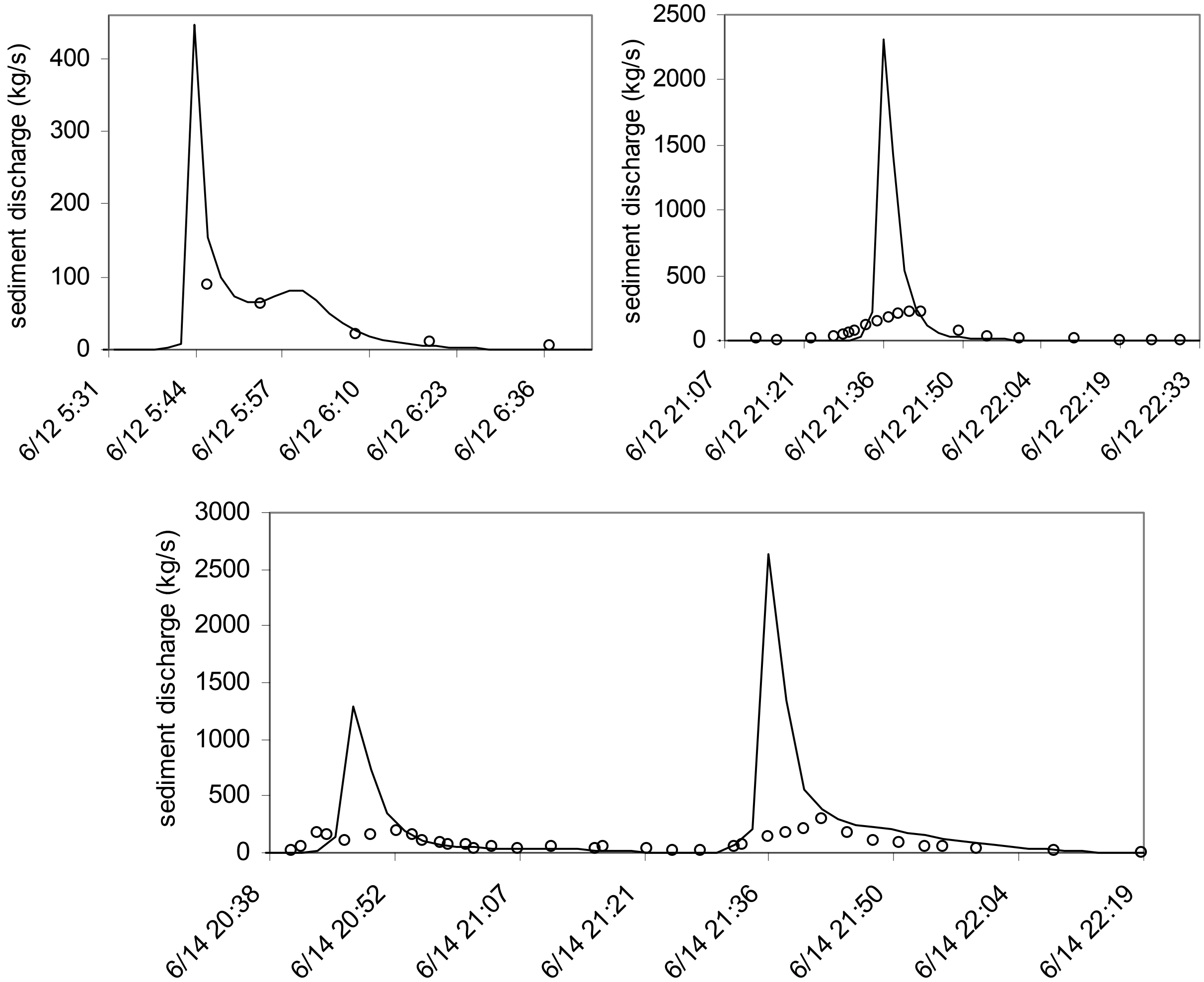


Figure 22 (continued). Observed (hollow circles) and computed (straight line) sedimentographs from the long-term simulations of GSSHA.

6.4 Discussion

It is known that in numerical solutions involving finite difference schemes, as the grid size decreases the required time interval should also decrease. In fact, this is reflected in the Courant Condition as a stability criteria which can be stated as $U<\Delta x/\Delta t$ where U is velocity, and Δt and Δx are time and space increments, respectively (Chapra 1997). The grid size used for W-2 in GSSHA simulations was 10 m. This is an unusually small grid size for such simulations. In fact, 5 m horizontal resolution DEM data is also available for this area, but because of the interaction between Δt and Δx we decided to use 10 m. Using coarser grid size than 10 m would lead to inaccurate representation of the watershed since it is only 83 acres. In a review of several watershed scale hydrologic and non-point source pollution models, Borah (2002) refers to a study on CASC2D, the older version of GSSHA, where Molnar and Julien (2000) found that for a 150 m grid size the required time step was about 5 seconds. This number decreased to 1 second when the grid size was reduced to 30 m. The smallest time interval allowed by GSSHA is 1 second which is the value used in our simulations. This might have introduced additional uncertainty.

One of the deficiencies of GSSHA is that erosion in channels is not transport limited. GSSHA can generate sediment which has a volume larger than what the flow can carry. This is physically impossible; however, because of the empirical nature of GSSHA sediment component, there is nothing in the GSSHA formulation to prevent this from happening once sediment reaches the channels (Downer, personal communication). When we initially used the literature values for C, K, and P parameters, we observed this effect. Eventually we had to decrease these parameters dramatically to get more realistic results. This suggests that the sediment routine in KINEROS-2 is more robust than the routine used in GSSHA. In fact, there is a contract between US Army Corps of Engineers' Engineering Research and Development Center and University of Connecticut to completely reformulate the sediment routine of GSSHA (Downer and Ogden, personal communications). It would be interesting to redo this whole exercise once that project is completed.

Long-term, continuous simulations performed over W-2 with GSSHA using the Green-Ampt with redistribution (GAR) infiltration option produced hydrographs comparable to observed data except for two events which are at the end of the simulation period. GSSHA was unable to generate runoff during those two events, though observed data indicate considerable flow. The performance of sediment results was poor. In some events, however, the falling limbs of the sedimentographs were well represented.

7 Summary and Conclusions

As required by the 1972 Clean Water Act, states, territories, and authorized tribes are required to develop TMDLs for sediments which is the leading stressor of nation's streams. Water quality managers and stakeholders are increasingly relying on hydrologic and water quality models as cost-effective tools for preliminary and detailed watershed planning, including TMDL development and BMP performance evaluations. BMPs are important parts of risk management studies since they are used to reduce pollutant loading and achieve TMDL targets. A large amount of models are available for users to select from. The process of selecting the right model given the needs is not an easy one, entailing familiarity with the available models. Several studies exist in the literature assessing models and summarizing their features and capabilities, all based on different perspectives. This report presented an evaluation of the most widely used suspended solids and sediment transport models and related nutrients water quality models. The report addressed the capability of the models to simulate for BMPs, both structural and nonstructural. A probabilistic, risk-based mathematical optimization framework was presented and was proposed as a strategy for solving the TMDL-BMP problem involving multiple stressors. Although, the framework was presented in general mathematical formulation it may guide future model applications to the management of sediment and nutrients in complex watersheds. Future modeling efforts should be directed toward applying system analysis approaches to solve the BMP problem in an optimal fashion.

The models evaluated in this report had a proven track record of applications and documentation, and were cited in numerous reports. However, some of the models that have a less visible track record and applications may be promising. Models were selected after an initial phase of screening, based on their suspended solid or sediment modeling capability, strong model documentation and/or support, and proven record of application with sufficient history. Relatively new and promising models were also added to the list for future considerations. The latter models have short history and some are still in the beta versions, but have been cited in peer reviewed publications. Models were reviewed under two basic categories: loading or watershed models, and receiving water models. Features of each model were summarized in a tabular form. Detailed description of the model features was included in the Appendix.

Among the loading models that have capabilities to simulate sediment and nutrient load reductions by management practices were AGNPS (ANNAGNPS for continuous time simulations) and SWAT. Both models are widely used in agricultural watersheds. The latter has its own GIS interface and currently integrated into USEPA's BASINs and USDA's AGWA modeling systems. It is also linked to the water quality model, QUAL2E. For urban areas, the most comprehensive sediment loading model is the widely used SWMM model. An urban watershed-receiving waterbody modeling system can be formulated by linking SWMM to the USEPA's WASP. The latter has a eutrophication component. For large watersheds comprised of both urban and rural areas HSPF is the most suitable model to address the sediment and nutrient TMDL problems. HSPF can be run under BASINS and WMS modeling systems. The DHI's MIKE-SHE watershed model is probably the most physically based, comprehensive "modeling system", especially in agricultural watersheds, with a history of applications in peer reviewed journals. It is equipped with several BMP simulations capabilities including wetlands, nutrient and pesticide management. This modeling package, however, is proprietary. USEPA's BASINS is another complete modeling system and has been applied for TMDLs. It has loading (SWAT and HSPF), and stream and river water quality (QUAL2E and HSPF) models. EPA is also working on expanding BASINS to include 3-D hydrodynamic and water quality model EFDC. It not only simulates for sediments, but also simulates transport and fate of many other pollutants. However, it is less physically based than MIKE-SHE. The system provides the linkages between these models within an ArcView environment. The WMS is a watershed modeling system into which the GSSHA and HSPF models have been integrated. It is an effective, user-friendly package for simulating sediment yield from watersheds. If linked to QUAL2E and WASP, it has the potential to be a formidable watershed analysis tool for suspended solids, sediments, and nutrients.

In conclusion SWAT and ANNAGNPS are suitable for sediment and nutrient BMP simulations analysis in agricultural areas. SWIMM is preferable for development of sediment TMDLs and BMP strategies in urban areas, and HSPF is the recommended model for large watersheds with mixed land use containing both rural and urban areas. To our knowledge MIKE-SHE and BASINS are the only comprehensive modeling systems for TMDL allocation and sediment and nutrients load reduction assessment of BMPs. If fully developed for water quality and eutrophication, WMS can be a promising, user-friendly watershed modeling system capable of a complete sediment TMDL analysis.

Unless extra, often time consuming, effort is made, current watershed and water quality models can not be used for comprehensive sediment TMDL allocation and reductions. Future efforts should focus on state-of-the-science in terms of processes improvement, and on the state-of-the-art by further developing efficient, user-friendly modeling frameworks. A suggested enhancement would be developing more model linkages. Widely used receiving water quality models either have their own hydrodynamic components, or are linked to other hydrodynamic models. However, there appears to be a big gap between loading models and hydrodynamic models. Developing modular modeling frameworks that provide selective linkages between loading models and hydrodynamic models, or complete modeling systems is worthwhile. Most mechanistic models that are based on sound physical principles lack comprehensive BMP components due to the fact that the original objectives during model developments were not geared toward TMDL development and assessment of BMPs. Enhancement of such physically based models with additional BMP capabilities would benefit TMDL developments and evaluation of diverse BMP options. Further, most BMP models rely on empirical relationships and are functional only at the local field scale. Future efforts should focus on developing process-oriented, mechanistic models for both structural and nonstructural management practices, and should develop techniques to take processes at the local management scale and scale them up to the watershed scale. For instance, REMM and VFSMOD can be linked to loading models to simulate sediment transport in riparian buffers and vegetative filter strips, respectively.

The second part of the report addressed numerical evaluation of two physically based runoff and sediment transport models, KINEROS-2 and GSSHA. The purpose of the second part was demonstration of a strategy for quantitative model comparison. The models were applied to an USDA experimental, agricultural watershed. Both models are promising, distributed hydrologic loading models. KINEROS-2 is suitable for small agricultural watersheds (<100 km^2) and is one of the two models in the newly developed AGWA modeling system which is supported by both USEPA and USDA. It is suitable for event-based simulations since it does not have a complete soil moisture accounting component. The sediment component is physically based and has a track record of successful applications in literature (see model summary). The sensitivity analysis performed over KINEROS-2 with Monte Carlo showed that among the flow parameters the most sensitive parameters in descending order are K_s, n_p, G, λ, S_i and n_c when peak sediment discharge is concerned. For total sediment yield, K_s is by far the most sensitive parameter followed by G, S_i, n_p, and λ. Time to peak sediment discharge is most sensitive to n_{ch} and n_p. The soil erosion parameters c_g and c_f have mixed effects. For large storms c_g is the dominant parameter, whereas results are more affected by c_f in smaller events. Model is sensitive to more parameters as the antecedent moisture condition get dryer. KINEROS-2 was calibrated for 3 events and the calibrated parameters were verified for 4 events. The overall model performance was good. Results indicated that the Manning's roughness and soil erosion parameters show seasonal variations. In future applications, it is recommended that Manning's roughness should be estimated initially to match hydrograph timings. Next, K_s, G and S_i should be calibrated to adjust the volume of hydrographs. The parameter S_i depends on the antecedent moisture condition and should be adjusted for each event.

Both models, KINEROS-2 and GSSHA were calibrated and verified. The results indicated that the flow component of the latter over performed the former. Conversely KINEROS-2 was more robust in simulating erosion and sediment transport. GSSHA, however, has both event-based and continuous simulation capabilities, whereas KINEROS-2 is essentially event based. At this stage both models lack nutrient components, and their capability to simulate for BMPs is limited. Future efforts concerned with watershed model evaluation may benefit from migrating from qualitative analysis to quantitative evaluation using real watershed data. The limits and merits of models can only be identified through numerical evaluation on selected watersheds.

8 References

AWWA. 2001. Water Resource Planning Manual (M50). Edited by W.O. Maddaus, American Water Works Association, AWWA, Denver, CO.

Beven, K.J. 1989. Changing ideas in hydrology – the case of the physically-based models. Journal of Hydrology, 105:157-172.

Borah, D.K. 2002. Watershed scale non-point source pollution models: mathematical bases. 2002 ASAE Annual International Meeting/CIGR World Congress, Chicago, IL. Paper no. 022091.

Bouwer, H. 1966. Rapid field measurement of air entry value and hydraulic conductivity of soil as significant parameters in flow system analysis. Water Resources Research, 2:729-738.

Browning, G.M., C.L. Parish, and J.A. Glass. 1947. A Method for Determining the Use and Limitation of Rotation and Conservation Practices in Control of Soil Erosion in Iowa. *Soil Science Society of America Proceedings*. 23:246-249.

Chapra, S.C. 1997. Surface-Water Quality Modeling. McGraw-Hilll, Inc.

Chow, V.T., D.R. Maidment, L.W. Mays. 1988. Applied Hydrology. McGraw-Hill, Inc.

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, Engineering Research and Development Center, Vicksburg, MS.

Downer, C.W., and F.L. Ogden. 2003a. Prediction of runoff and soil moistures at the watershed scale: effects of model complexity and parameter assignment. Water Resources Research, 39(3):1.1–1.13

Downer, C.W., and F.L. Ogden. 2003b. Appropriate vertical discretization of Richards' equation for two-dimensional watershed-scale modeling. Hydrological Processes, in press.

Engelund, F., and E. Hansen. 1967. A monograph on sediment transport in alluvial streams. Teknisk Vorlag, Copenhagen.

Garbrecht, J., and L.W. Martz. 1999. An automated digital landscape analysis tool for topographic evaluation, drainage identification, watershed segmentation, and sub-catchment parameterization. Rep.# GRL 99-1, Grazinglands Research Laboratory, USDA, Agricultural Research Service, El Reno, OK.

Goodrich, D.C., T.J. Schmugge, T.J. Jackson, C.L. Unkrich, T.O. Keefer, R. Parry, L.B. Bach, and S.A. Amer. 1994. Runoff simulation sensitivity to remotely sensed initial soil water content. Water Resources Research, 30:1393-1405.

Hantush, M. M., and L. Kalin. 2003. Modeling uncertainty of runoff and sediment yield using a distributed hydrologic model. Proceedings of the First Interagency Conference on Research in the Watersheds, Benson, AZ, 27-30 October.

Hantush, M. M. and M. A. Mariño. 1989. Chance-constrained model for management of a stream-aquifer system. *J Water Resour. Plan. Manag*, ASCE, 115(3), 259-277.

Imbeau, M.E. 1892. La Durance: Regime, Crues et Inundations. *Ann. Ponts Chaussees, Mem. Doc. Ser.*, 3(I):5-18 (in French).

Johnson, B.E., P.Y. Julien, D.K. Molnar, and C.C. Watson. 2000. The two dimensional upland erosion model CASC2D-SED. Journal of American Water Resources Association, 36:31-42.

Julien, P.Y. 1995. Erosion and sedimentation. Press Syndicate of the University of Cambridge, New York, NY.

Kalin, L., and M.M. Hantush. 2003. Probabilistic modeling of sediment yield in a small agricultural watershed using Kineros-2. In Conference Proceedings, AWRA Specialty Conference, Kansas City, MO, May 2003.

Kalin, L., and M.M. Hantush. 2003. Assessment of two physically-based watershed models based on their performances of simulating water and sediment movement", In Conference Proceedings, 1st Interagency Conference on Research in the Watersheds (ICRW), Benson, AZ, 27-30 October 2003.

Kalin, L., R.S. Govindaraju, and M.M. Hantush. 2003. Effect of geomorphologic resolution on runoff hydrograph and sedimentograph. J. Hydrol. 276: 89-111.

Komor, S.C. 1999. Water Chemistry in a Nutrient and Sediment Control System near Owasco, New York. *Water Resources Impact*, 1(6):19-21.
Krone, R.B. 1962. Flume studies of the transport of sediment in estuarial shoaling processes. Hydraulic Engineering Laboratory and Sanitary Engineering Research Laboratory, University of California, Berkeley, CA.
Louks, D. P., J. Stedinger, and D. A. Haith. 1981. *Water Resource Systems Planning and Analysis*. Prentice-Hall, New Jersey.
Macintosh, D.L., G.W. Suter, and F.O. Hoffman. 1994. Uses of Probabilistic Exposure Models in Ecological Risk Assessments of Contaminated Sites, *Risk Analysis*, 14(4):405-419.
Molnar, D.K., and P.Y. Julien. 2000. Grid size effects on surface water modeling. Journal of Hydrologic Engineering 5:8-16.
Mostaghimi, S., S.W. Park, R.A. Cooke, and S.Y. Wang. 1997. Assessment of Management Alternatives on a Small Agricultural Watershed. *Water Research*, 31(8):1867-1878.
Mulvany, T.J. 1850. On the Use of Self-Registering Rain and Flood Gauges. *Proc. Int. Civ. Eng*., 4(2):1-8.
Novotny, V., and H. Olem. 1994. Water Quality: Prevention, Identification, and Management of Diffuse Pollution. Van Nostrand, Reinhold, New York, NY.
O'Connor, D.J. 1960. Oxygen Balance of an Estuary. *Journal of Sanitation Engineering Division*, 86(3):35-55.
O'Connor, D.J. 1962. Organic Pollution of New York Harbor: Theoretical Considerations. *Journal of Water Pollution Control*, 34(9):905-919.
Ogden, F.L., and A. Heilig, 2001, Two-dimensional watershed-scale erosion modeling with CASC2D. In: Landscape Erosion and Evolution Modeling, (R.S. Harmon and W.W. Doe III, eds.), Kluwer Academic Publishers, New York, ISBN 0-306-4618-6, 535 pp.
Ogden, F.L., and P.Y. Julien. 2002. CASC2D: A two-dimensional, physically-based, hortonian, hydrologic model. In: Mathematical Models of Small Watershed Hydrology and Applications, V. J. Singh and D. Freverts, eds., Water Resources Publications, Littleton, CO, ISBN 1-887201-35-1, 972 pp.
Ogden, F.L., and B. Saghafian. 1997. Green and Ampt infiltration with redistribution. Journal of Irrigation and Drainage Engineering, 123:386-393.
Osborn, H.B., and J.R. Simanton. 1990. Hydrologic modeling of a treated rangeland watershed. Journal of Range Management 43:474-481.
Rawls, W.J., D.L. Brakensiek, and K.E. Saxton. 1982. Estimation of soil water properties. Trans. ASAE 25:1316-1320.
Rawls, W.J., D.L. Brakensiek. 1983. Green-Ampt infiltration parameters from soils data. Journal of Hydraulic Engineering, 109(1):62-70.
Refsgaard, J.C., and B. Storm. 1995. MIKE-SHE. Singh, V.J. (Ed), Computer Models of Watershed Hydrology, 809-846, Water Resources Pub., Highlands Ranch, CO.
Richards, L.A. 1931. Capillary conduction of liquids in porous mediums, Physics, 1:318-333.
Rosalia, R.S. 2002. GIS-based upland erosion modeling, geovisualization and grid size effects on erosion simulations with CASC2D-SED. Ph.D. Thesis, Colorado State University, Fort Collins, CO.
SAAESD 2001. Agricultural non-point source water quality models: their use and application. Southern Cooperative Series Bulletin #398, edited by J.E. Parsons et al., ISBN: 1-58161-398-9.
Senarath, S.U.S., Ogden, F.L., Downer, C.W., and H.O. Sharif. 2000. On the calibration and verification of two-dimensional, distributed, Hortonian, continuous watershed models. Water Resources Research, 36:1495-1510.
Shoemaker, L., M. Lahlou, M. Bryer, D. Kumar, and K. Kratt. 1997. Compendium of tools for watershed assessment and TMDL development. Report EPA841-B-97-006, Office of Water, U.S. Environmental Protection Agency, Washington, D.C.
Singh, V.J., and D.A. Woolhiser. 2002. Mathematical Modeling of Watershed Hydrology. *Journal of Hydrologic Engineering*, 7(4):270-292.
Smith, D.D. 1941. Interpretation of Soil Conservation Data for Field Use. *Agricultural Engineering*, 22:173-175.
Smith, R.E., D.C. Goodrich, and J.N. Quinton. 1995. Dynamic, Distributed Simulation of Watershed Erosion: the KINEROS2 and EUROSEM Models. Journal of Soil and Water Conservation 50(5):517-520.
Smith, R.E., D.C. Goodrich, and C.L. Unkrich. 1999. Simulation of Selected Events on the Catsop Catchment by KINEROS2: A Report for the GCTE Conference on Catchment Scale Erosion Models. Catena 37:457-475.
Srivastava, P., J.M. Hamlett, P.D. Robillard, and R.L. Day. 2002. Watershed optimization of best management practices using AnnAGNPS and a genetic algorithm. *Water Resources Research*, 38(3):1-13.
Stanley, D.W. 1994. Regulation of Primary Production and Hypoxia in the Pamlico River Estuary, NC, by Factors Other Than Nutrients: Implications for Management Strategies to Control Eutrophication. Program and Abstracts, IAGLR, Buffalo, NY.
Streeter, H.W., and E.B. Phelps. 1925. A Study of the Pollution and Natural Purification of the Ohio River. III: Factors Concerned in the Phenomena of Oxidation and Reareation, Bull. No. 146. US. Public Health Service.

Tetra Tech Inc., 2000. Overview of Sediment-Contaminant Transport and Fate Models for Use in Making Site-Specific Contaminated Sediment Remedial Action Decisions. Prepared for US. EPA OERR, Tetra Tech Inc., Fairfax, Va.

Tollner, E.W., B.J. Barfield, C. Vachirakornwatana, and C.T. Haan. 1977. Sediment deposition patterns in simulated grass filters. Transactions of ASAE. 20(5):940-944.

Udoyara, S.T., J. Robert, and H.H. Liao. 1995. Impact of Landscape Feature and Feature Placement on Agricultural Non-Point-Source Pollution Control. *Journal of Water Resources Planning and Management*, 121(6):463-469.

U.S. EPA. 1999. Selection of Eutrophication Models for Total Maximum Daily Loads Analyses Based on Regulatory Environmental Modeling Guidelines. NERL, US. EPA.

U.S. EPA. 2000. The Quality of Our Nation's Waters. A Summary of the National Water Quality Inventory: 1998 Report to Congress. Office of Water, Washington, D.C. 841-S-00-001.

U.S. EPA. 2002a. Risk Management Research Plan for Suspended Solids and Sediments. EPA600-R-02-002, Office of Research and Development, Cincinnati, OH. (91 pp).

U.S. EPA. 2002b. The Twenty Needs Report: How Research Can Improve the TMDL Program. EPA841-B-02-002, Office of Water, Washington, D.C. (43 pp).

Velz, C.J. 1938. Deoxygenation and Reoxygenation. *ASCE Transactions*, 560-572.

Ward, G.H., and J. Benaman. 1999. Models for TMDL Application in Texas Watercourses: Screening and Model Review. Report submitted to Texas Natural Resource Conservation Commission, Austin, TX. Online report CRWR-99-7.

WERF. 2001. Water Quality Models: A survey and Assessment. Edited by J. Fitzpatrick, J. Imhoff, E. Burgess, and R. Brashear. Water Environment Research Foundation, Project 99-WSM-5, Alexandria, VA.

Wischmeier, W.H., and D.D. Smith. 1958. Rainfall Energy and Its Relation to Soil Loss. *American Geophysical Union Transactions*. 39: 285-291.

Wischmeier, W.H., and D.D. Smith. 1965. Predicting Rainfall-Erosion Losses from Cropland East of Rocky Mountains: Guide for Selection of Practices for Soil and Water Conservation. *USDA Agricultural Handbook*, No 282.

Wischmeier, W.H., and D.D. Smith. 1978. Predicting Rainfall Erosion Losses: A Guide to Conservation Planning. *USDA Agricultural Handbook*, No 537.

Woolhiser, D.A. 1996. Search for physically based runoff model – A hydrologic El Dorado? *Journal of Hydraulic Engineering*. 3:122-129.

Woolhiser, D.A., R.E. Smith, and D.C. Goodrich. 1990. KINEROS-A kinematic runoff and erosion model: Documentation and user manual, USDA-ARS, ARS-77, 130 pp.

Yang, C.T. 1973. Incipient motion and sediment transport. Journal of Hydraulic Division, ASCE, 99, No. HY10:1679-1704.

Zhen, J.X., and L.Y. Shaw. 2001. Development of a Best Management Practice (BMP) Placement Strategy at the Watershed Scale. *In* Proceedings of the 2001 Wetland Engineering and River Restoration Conference, Aug 27-31, 2001, Reno, NV.

Ziegler, A.D., T.W. Giambelluca, and R.A. Sutherland. 2001. Erosion Prediction on Unpaved Mountain Roads in Northern Thailand: Validation of Dynamic Erodibility Modeling Using KINEROS2. *Hydrological Processes* 15:337-358.

Zingg, A.W. 1940. Degree and Length of Land Slope as It Affects Soil Loss in Runoff. *Agricultural Engineering*, 21:59-64.

Appendix: Model Summaries

The model summaries provided here are mostly from model web sites (if available), model manuals and other sited literatures. The URLs of the model web sites are given at the end of each summary, if exists.

8.1 Loading Models

***AGNPS (AGricultural NonPoint Source pollution model) & AnnAGNPS (Annualized AGNPS)*:** AGNPS, supported by USDA-ARS-NRCS, was a single event model initially. The current version refers to system of modeling components and is geared toward continuous simulations (daily time steps) of sediment and nutrient transport from agricultural watersheds. The set of computer programs consist of: i) input generation & editing as well as associated databases, ii) the "annualized" science & technology pollutant loading model for agricultural-related watersheds (AnnAGNPS), iii) output reformatting & analysis, and iv) the integration of more comprehensive routines (CCHE1D) for the stream network processes, v) a stream corridor model (CONCEPTS), vi) an instream water temperature model (SNTEMP), and vii) several related salmonid models (SIDO, Fry Emergence, Salmonid Total Life Stage, & Salmonid Economics). Not all of the models are electronically linked but there are paths of common input/output that, with the use of standard text editors, can be linked. The input programs include: i) a GIS-assisted computer program (TOPAZ with an interface to AGNPS) to develop terrain-following cells with all the needed hydrologic & hydraulic parameters that can be calculated from readily available DEM's, ii) an input editor to initialize, complete, and/or revise the input data, and iii) an AGNPS-to-AnnAGNPS converter for the input data sets of the old single-event versions of AGNPS (4.03 & 5.00). Watershed is divided into cells to reflect landscape spatial heterogeneity. Several BMPs can be modeled including ponds, vegetative filter strips, riparian buffers and different management practices. AGNPS can be classified as an empirical model. Runoff generation is based on unit hydrograph theory with total runoff being computed from SCS curve number and peak discharge from TR-55. Sediment mobilized is calculated from RUSLE and sediment delivery is based on HUSLE. The latest version of AnnAGNPS includes tile drainage, multiple climate file capabilities and enhanced lateral subsurface flow options. The basic model outputs are runoff volume, peak runoff rate, sediment yield, sediment concentration, sediment particle size distribution, upland erosion, amount of deposition (%), enrichment ratios by particle size, delivery ratios by particle size, nitrogen, phosphorus, and chemical oxygen demand. Efforts are going on to integrate REMM (Riparian Ecosystem Management Model) to AGNPS system.
BMPs: Agricultural practices, ponds, grassed waterways, tile drainage, vegetative filter strips, riparian buffers.
URL: http://www.sedlab.olemiss.edu/agnps.html

Application and Model References:

Bingner, R., C. Murphree, and C. Mutchler. 1989: Comparison of sediment yield models on watershed in Mississippi. Trans. ASAE, 32(2):529-534.

Bingner, R. L., and F. D. Theurer. 2001. AGNPS 98: A Suite of water quality models for watershed use. In Proceedings of the Sediment: Monitoring, Modeling, and Managing, 7th Federal Interagency Sedimentation Conference, Reno, NV, 25-29 March 2001. p. VII-1 - VII-8.

Fisher, P., R. Abrahart, and W. Herbinger. 1997. The sensitivity of two distributed non-point source pollution models to the spatial arrangement of the landscape. Hydrological Processes, 11(3):241-252.

McCool, D.K., M.T. Walter, and L.G. King. 1995. Runoff index values for frozen soil areas of the Pacific Northwest. Journal of Soil and Water Conservation, 50(5):466-469.

Srivastava, P., J.M. Hamlett, P.D. Robillard, and R.L. Day. 2002. Watershed optimization of best management practices using AnnAGNPS and a genetic algorithm. Water Resources Research, 38(3):1-13.

Yuan, Y., Dabney, S., and Bingner, R. L. 2002. Cost/benefit analysis of agricultural BMPs for sediment reduction in the Mississippi Delta. Journal of Soil and Water Conservation 57(5): 259-267.

Wu, T., J. Hall, and J. Bonta. 1993. Evaluation of Runoff and Erosion Models. Journal of Irrigation and Drainage Engineering, 119(2):364-382.

Zhen, J.X., and L.Y. Shaw. 2001. Development of a best management practice (BMP) placement strategy at the watershed scale. In Proc. Wetlands Engineering and River Restoration Conference, August 27-31, 2001, Reno, Nevada.

AGWA (Automated Geospatial Watershed Assessment): This is a GIS interface developed by The USDA-ARS Southwest Watershed Research Center, in cooperation with the U.S. EPA Office of Research and Development to facilitate the data preparation efforts of two USDA models: SWAT for large watersheds and term simulations, and KINEROS-2 for small watersheds (<100 km^2) for event based studies (see corresponding model descriptions below for details on SWAT and KINEROS-2). AGWA is designed as a tool for performing relative assessment (change analysis) resulting from land cover/use change. Areas identified through large-scale assessment with SWAT as being most susceptible to change can be evaluated in more detail at smaller scales with KINEROS-2. Data used in AGWA include Digital Elevation Models (DEMs), land cover grids, soils data, and precipitation data. It is built on ArcView version 3.X and the interface is similar to USEPA's BASINS. There are five major tasks: i) watershed delineation, ii) land cover and soils parameterization, iii) writing a precipitation file for model input, iv) writing parameter files and running the chosen model, and v) viewing results. To use AGWA, ARcView version 3.1 or later of ArcView and version 1.1 of the Spatial Analyst extension is required.
URL: http://www.tucson.ars.ag.gov/agwa

***ANSWERS (Areal Nonpoint Source Watershed Environment Response Simulation) & ANSWERS-2000*:** ANSWERS is an event based, distributed parameter, physically-based, watershed scale, upland planning model developed for evaluating the effectiveness of agricultural and urban BMPs in reducing sediment and nutrient delivery to streams in surface runoff and leaching of nitrogen through the root zone. The model is intended for use by planners on ungaged watersheds where data for model calibration is not available. It divides the area into uniform grid squares (less than 1 hectare), where all properties are assumed homogeneous. ANSWERS-2000 is the continuous version of the model. Both versions simulate interception; surface retention/detention; infiltration; percolation; sediment detachment and transport of mixed particle size classes in rills, interrill areas, and channels. The continuous version, in addition, simulates crop growth, evapotranspiration, soil moisture redistribution, plant uptake of nutrients; N and P dynamics in the soil; nitrate leaching; and losses of nitrate, ammonium, total Kjeldahl nitrogen, and P in surface runoff. Event based version uses Holton model to simulate infiltration, whereas Green-Ampt model is employed in the continuous version. A GIS interface of the event version with GRASS is available. The continuous version has an ArcView based user interface, QUESTIONS, that facilitates data file creation and manipulation. Model documentation and user support is very limited for the continuous version. The model is currently only suitable for use by expert modelers with a good knowledge of upland hydrology and agriculture. The current version of the model makes heavy use of relationships derived from the WEPP and EPIC models.
BMPs: Agricultural practices, ponds, grassed waterways, tile drainage.
URL: http://dillaha.bse.vt.edu/answers/index.htm

Application and Model References:

Beasley, D.B., L.F.Huggins, and E.J. Monke. 1980. ANSWERS: A model for watershed planning. Trans. of the ASAE 23(4):938-944.

Beasley, D.B., and L.F. Huggins. 1991. ANSWERS Users Manual, 2nd Ed. Agricultural Engr. Dept., Coastal Plain Experiment Station, Univ. of Georgia, Tifton, GA.

Bouraoui, F., and T. A. Dillaha. 1996. ANSWERS-2000: Runoff and sediment transport model. Journal of Environmental Engineering, ASCE 122(6):493-502.

Bouraoui, F., and T.A. Dillaha. 2000. ANSWERS-2000: Nonpoint source nutrient transport model. J. of Environmental Engineering, ASCE 126(11):1045-1055.

Bouraoui, F., G. Vachaud, R. Haverkamp and B. Normand. 1997. A distributed physical approach for surface-subsurface water transport modeling in agricultural watersheds. J. of Hydrology 203:79-92.

Fisher, P., R. Abrahart, and W. Herbinger. 1997. The sensitivity of two distributed non-point source pollution models to the spatial arrangement of the landscape. Hydrological Processes, 11(3):241-252.

Montas, H.J., C.A. Madramootoo. 1991. Using ANSWERS model to predict runoff and soil loss in Southwestern Quebec. Transactions of the ASAE 34(4):1752-1762.
Srinivasan, R, and J. Arnold. 1994. Integration of a basin-scale water quality model with GIS. Water Resources Bulletin, 30(3):453-462.
Storm, D. E., T. A. Dillaha, S. Mostaghimi, and V. O. Shanholtz. 1988. Modeling phosphorus transport in surface runoff. Transactions of the ASAE 31(1):117-127.

***BASINS (Better Assessment Science Integrating point and Nonpoint Sources)*:** BASINS is a multipurpose environmental analysis system for use by regional, state, and local agencies in performing watershed and water quality based studies. The heart of BASINS is its suite of interrelated components essential for performing watershed and water quality analysis. These components are grouped into several categories:

- Nationally derived environmental and GIS databases (the 48 continuous states and the District of Columbia)
- Assessment tools (TARGET, ASSESS, and DATA MINING) for evaluating water quality and point source loadings at a large or small scales
- Utilities including local data import and management of local water quality observation data
- Two watershed delineation tools
- Utilities for classifying elevation (DEM), land use, soils, and water quality data
- An in-stream water quality model (QUAL2E)
- A simplified GIS based nonpoint source annual loading model (PLOAD)
- Two watershed loading and transport models (HSPF and SWAT)
- A postprocessor (GenScn) of model data and scenario generator to visualize, analyze, and compare results from HSPF and SWAT
- Many mapping, graphing, and reporting formats for documentation.

BASINS' databases and assessment tools are directly integrated within an ArcView GIS environment. The simulation models run in a Windows environment, using data input files generated in ArcView. EPA is working on expanding BASINS system to include three dimensional water quality model EFDC.
URL: http://www.epa.gov/OST/BASINS

*****DWSM (Dynamic Watershed Simulation Model)*:** DWSM was developed at the Illinois State Water Survey. It simulates surface and subsurface flow, upland soil erosion, sediment transport, and agrochemical transport in agricultural and rural watersheds. It is a one dimensional, event based model. Rainfall excess at overland flow planes can be computed in two ways: i) Curve number method, ii) Smith-Parlange infiltration model. Kinematic Wave equations are solved using analytical and an approximate shock fitting solutions to compute runoff over planes and channels. Flows in reservoirs are based modified pulse method. Subsurface flow is a combination of interflow, tile drain flow and base flow. Soil erosion is based on raindrop detachment and hydraulic erosion. Scour and deposition of user defined particle sizes is computed based on sediment transport capacity. Approximate analytic solution of temporal and spatially varying continuity equation is employed. All sediments entering the reservoirs are assumed trapped. Nutrients and pesticides are simulated in dissolved and adsorbed phases with water and sediment respectively. The watershed is divided into overland planes, channel segments, and reservoir units. 18 applications of the model or its components are available in the literature. All these applications are performed by the model developers.
BMPs: Detention basins, alternative ground covers, tile drainage.

Application and Model References:

Borah, D.K. and M. Bera. 2003. Watershed scale hydrologic and nonpoint source pollution models: review of mathematical bases. Transactions of the ASAE. Uner review.
Borah, D.K, R.Xia, and M. Bera. 2002. DWSM-A Dynamic Watershed Simulation Model. Chapter 5 in Mathematical Models of Small Watershed Hydrology and Applications, 113-166. Singh and D.K. Frevert eds. Water Resources Publications, LLC, Highlands Ranch, CO.
Borah, D.K, R.Xia, and M. Bera. 2002. Watershed model to study hydrology, sediment, and agricultural chemicals in rural watersheds. In Surface Water Hydrology Vol-1, 343-358. V.P Singh, M. Al-Rashed, and M.M. Sherif eds. A.A. Balkema Publishers, Lisse/Abingdon/Exton (PA)/Tokyo.

EPIC (Erosion-Productivity Impact Calculator)**:** EPIC was developed to assess the effect of soil erosion on soil productivity. EPIC is a continuous simulation model that can be used to determine the effect of management strategies on agricultural production and soil and water resources. The drainage area considered by EPIC is generally a field-sized area, up to 100 ha (weather, soils, and management systems are assumed to be homogeneous). 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. Recently, most of the EPIC model development has been focused on problems involving water quality and global climate/CO_2 change. Example additions include the GLEAMS (Leonard et al., 1987) pesticide fate component, nitrification and volatilization submodels, a new more physically based wind erosion component, optional SCS technology for estimating peak runoff rates, newly developed sediment yield equations, and mechanisms for simulating CO_2 effects on crop growth and water use. These and other less significant developments extend EPIC's capabilities to deal with a wide variety of agricultural management problems. Example applications include:

- 1985 RCA analysis
- 1988 drought assessment
- soil loss tolerance tool
- Australian sugarcane model (AUSCANE)
- pine tree growth simulator
- global climate change analysis (effect of CO_2, temperature, and precipitation change on runoff and crop yield)
- farm level planning
- five-nation EEC assessment of environmental/agricultural policy alternatives
- Argentine assessment of erosion/ productivity
- USDA-Water Quality Demonstration Project Evaluation
- N leaching index national analysis.

BMPs: Agricultural practices.
URL: http://www.brc.tamus.edu/epic

Application and Model References:

Benson, V.W., K.N. Potter, H.C. Bogusch, D. Goss, and J.R. Williams. 1992. Nitrogen leaching sensitivity to evapotranspiration and soil water storage estimates in EPIC. J. Soil and Water cons. 47(4):334-337.

Leonard, R.A., W.G. Knisel, and D.A. Still. 1987. GLEAMS: Groundwater loading effects on agricultural management systems. Trans. ASAE 30(5):1403-1428.

Vijay, P. S., J.R. Williams. 1995. The EPIC model. Computer Models of Watershed Hydrology, chapter 25. Water Resources Publications, Highlands Ranch, Colorado.

Williams, J. 1995. The EPIC model. Chap. 25, Computer models of watershed hydrology (V.P. Singh, ed.), pp. 909-1000. Highlands Ranch, CO: Water Resources Publications.

Williams, J.R., J.R. Kiniry, and V.W. Benson. 1991. Water quality sensitivity to EPIC crop growth parameters. ASAE Paper No. 91-2075.

Williams, J.R., C.A. Jones, and P.T. Dyke. 1990. The EPIC model. Chapter 2, pp. 3-92. In: A.N. Sharpley and J.R. Williams (eds.) EPIC-Erosion/Productivity Impact Calculator: 1. Model Documentation. USDA Tech. Bull. No. 1768.

Williams, J.R., P.T. Dyke, W.W. Fuchs, V.W. Benson, O.W. Rice, and E.D. Taylor. 1990. EPIC Erosion/Productivity Impact Calculator: 2. User Manual. In : A.N. Sharpley and J.R. Williams (eds.) USDA Tech. Bull. No. 1768.

GLEAMS (Groundwater Loading Effects of Agricultural Management Systems)**:** GLEAMS is a continuous simulation, field scale model, which was developed as an extension of the Chemicals, Runoff and Erosion from Agricultural Management Systems (CREAMS) model. GLEAMS assumes that a field has homogeneous land use, soils, and precipitation. It consists of four major components: hydrology, erosion/sediment yield, pesticide transport, and nutrients. GLEAMS was developed to evaluate the impact of management practices on potential pesticide and nutrient leaching within, through, and below the root zone. It also estimates surface runoff and sediment losses from the field. GLEAMS was not developed as an absolute predictor of pollutant loading. It is a tool for comparative analysis of complex pesticide chemistry, soil properties, and climate. 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. Application rates, methods, and timing can be altered to account for these systems and to reduce the possibility of root zone leaching. The model also accounts for varying soils and weather in determining leaching potential. GLEAMS can also be useful in 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 products. Flow is determined by SCS curve number method. Erosion in overland flow areas is estimated using modified USLE. 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.
BMPs: Agricultural practices, ponds.
URL: http://arsserv0.tamu.edu/nrsu/glmsfact.htm, http://www.cpes.peachnet.edu/sewrl/Gleams/gleams_y2k_update.htm

Application and Model References:

Knisel, W.G., and J.R. Williams. 1995. Hydrology components of CREAMS and GLEAMS models. In: V. J. Singh (Ed.) Computer Models of Watershed Hydrology. Chapter 28. pp. 1069-1114.

Knisel, W.G., and E. Turtola. 1999. GLEAMS model application on a heavy clay soil in Finland. Agricultural Water Management, 43(3):285-309.

Leonard, R.A., W.G. Knisel, and F.M. Davis. 1995. Modeling pesticide fate with GLEAMS. Eur. J. Agron. 4(4):485-490.

Morari, F., and W.G. Knisel. 1997. Modifications of the GLEAMS model for crack flow. Trans., Amer. Soc. of Agric. Engrs., 40(5):1337-1348.

Michael, J.L., M.C. Smith, W.G. Knisel, D.G. Neary, W.P. Fowler, and D.J. Turton. 1996. Using a hydrologic model to determine the most environmentally safe windows for herbicide application. New Zealand J. of Forestry Science, 26:288-297.

Shirmohammadi, A., B. Ulen, L.F. Bergstrom, and W.G. Knisel. 1998. Simulation of nitrogen and phosphorus leaching in a structured soil using GLEAMS and a new submodel, "PARTLE". Trans. Amer. Soc. Of Agric. Engrs., 41(2):353-360.

Sugiharto, T; T. McIntosh, R. Uhrig, and J. Lardinois. 1994. Modeling alternatives to reduce dairy farm and watershed nonpoint source pollution. Journal of Environmental Quality, 23(1):18-24.

***GSSHA (Gridded Surface Subsurface Hydrologic Analysis)*:** This is a reformulation and enhancement of CASC2D (Downer and Ogden 2002). The CASC2D model was initiated at Colorado State University by Pierre Julien as a two dimensional overland flow routing model. In its final form, it is a distributed-parameter, physically-based watershed model. Both single event and continuous simulations are possible. The US Army Waterways Experiment Station considered this model as very promising and therefore fully incorporated this model into WMS (Watershed Modeling System). Watershed is divided into cells and water and sediment is routed from one cell to another. It uses one and two-dimensional diffusive wave flow routing at channels and overland planes, respectively. Although only Hortonian flows were modeled by employing Green-Ampt (G-A) infiltration model in the initial versions, GSSHA considers other runoff generating mechanisms such as lateral saturated groundwater flow, exfiltration, stream/groundwater interaction etc. GSSHA offers two options for simulations: G-A with redistribution (Ogden and Saghafian 1997) and the full Richards' equation. The latter requires tremendous amount of simulation time and is very sensitive to time step and horizontal and vertical cell sizes. Modified Kilinc and Richardson equation (Julien 1995) is used to compute sediment transport capacity at plane cells. A trap efficiency measure is used to determine how much material is transported from the outgoing cell. Details on theory and equations used can be found in Julien et al. 1995, Johnson et al. 2000, and Downer and Ogden 2002. GSSHA is currently available under the WMS suite of models which significantly reduces burden on input preparation.
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BMPs: Agricultural practices.

Application and Model 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, Engineering Research and Development Center, Vicksburg, MS.
Downer, C.W., and F.L. Ogden. 2003. Prediction of runoff and soil moisture at the watershed scale: effects of model complexity and parameter assignment. Water Resources Research, 39(3):1045.
Julien, P.Y. 1995. Erosion and Sedimentation, Press Syndicate of the University of Cambridge, New York, N.Y.
Julien, P.Y., B. Saghafian, and F.L. Ogden. 1995. Raster-based hydrologic modeling of spatially-varied surface runoff. Water Resources Bulletin 31:523-536.
Johnson, B.E., P.Y. Julien, D.K. Molnar, and C.C. Watson. 2000. The two-dimensional upland erosion model CASC2D-SED. Journal of American Water Resources Association 36:31-41.
Ogden, F.L., and A. Heilig, 2001, Two-dimensional watershed-scale erosion modeling with CASC2D, in Landscape Erosion and Evolution Modeling, (R.S. Harmon and W.W. Doe III, eds.), Kluwer Academic Publishers, New York, ISBN 0-306-4618-6, 535 pp.
Senarath, S., F.L. Ogden, C.W. Downer, and H.O. Sharif. 2000. On the calibration and verification of two-dimensional, distributed, Hortonian, continuous watershed models. Water Resources Research, 36(6):1495-1510.

***GWLF (Generalized Watershed Loading Functions)*: ** GWLF model was developed by Haith and Shoemaker (1987). The GWLF model provides the ability to simulate runoff, sediment, and nutrient (N and P) loadings from a watershed given variable-size source areas (i.e., agricultural, forested, and developed land). It also has algorithms for calculating septic system loads, and allows for the inclusion of point source discharge data. It is a continuous simulation model which uses daily time steps for weather data and water balance calculations. Monthly calculations are made for sediment and nutrient loads, based on the daily water balance accumulated to monthly values. GWLF is considered to be a combined distributed/lumped parameter watershed model. For surface loading, it is distributed in the sense that it allows multiple land use/cover scenarios, but each area is assumed to be homogenous in regard to various attributes considered by the model. Additionally, the model does not spatially distribute the source areas, but simply aggregates the loads from each area into a watershed total; in other words there is no spatial routing. For sub-surface loading, the model acts as a lumped parameter model using a water balance approach. No distinctly separate areas are considered for sub-surface flow contributions. Daily water balances are computed for an unsaturated zone as well as a saturated sub-surface zone, where infiltration is simply computed as the difference between precipitation and snowmelt minus surface runoff plus evapotranspiration. With respect to the major processes simulated, GWLF models surface runoff using the SCS-CN approach with daily weather (temperature and precipitation) inputs. Erosion and sediment yield are estimated using monthly erosion calculations based on the USLE algorithm (with monthly rainfall-runoff coefficients) and a monthly composite of KLSCP values for each source area (i.e., land cover/soil type combination). A sediment delivery ratio based on watershed size and a transport capacity based on average daily runoff are then applied to the calculated erosion to determine sediment yield for each source area. Surface nutrient losses are determined by applying dissolved N and P coefficients to surface runoff and a sediment coefficient to the yield portion for each agricultural source area. Point source discharges can also contribute to dissolved losses and are specified in terms of kilograms per month. Manured areas, as well as septic systems, can also be considered. Urban nutrient inputs are all assumed to be solid-phase, and the model uses an exponential accumulation and washoff function for these loadings. Sub-surface losses are calculated using dissolved N and P coefficients for shallow groundwater contributions to stream nutrient loads, and the sub-surface sub-model only considers a single, lumped-parameter contributing area. Evapotranspiration is determined using daily weather data and a cover factor dependent upon land use/cover type. Finally, a water balance is performed daily using supplied or computed precipitation, snowmelt, initial unsaturated zone storage, maximum available zone storage, and evapotranspiration values. An ArcView interface of the model is available called AVGWLF.
BMPs: Agricultural practices, septic systems, manured areas.
URL: http://www.avgwlf.psu.edu/AVGWLFmanual.htm#GWLFModel

Application and Model References:
Haith, D.A. and L.L. Shoemaker. 1987. Generalized Watershed Loading Functions for Stream Flow Nutrients. Water Resources Bulletin, 23(3):471-478.
Haith, D.R., R. Mandel, and R.S. Wu, 1992. GWLF: Generalized Watershed Loading Functions User's Manual, Vers. 2.0. Cornell University, Ithaca, NY.
Howarth, R., J. Fruci, and D. Sherman. 1991. Inputs of sediment and carbon to an estuarine ecosystem: influence of land use. Ecological applications 1:27-39.
Swaney, D.P., D. Sherman, and R.W. Howarth. 1996. Modeling water, sediment and organic carbon discharges in the Hudson-Mohawk basin: Coupling to terrestrial sources. Estuaries, 19(4):833-847.

***HSPF (Hydrological Simulation Program)*:** HSPF simulates for extended periods of time the hydrologic, and associated water quality, processes on pervious and impervious land surfaces and in streams and well-mixed impoundments. It is supported by both USEPA and USGS. It is incorporated into the BASINS and WMS modeling systems. The model contains hundreds of process algorithms developed from theory, laboratory experiments, and empirical relations from instrumented watersheds. There are three basic modules: PERLND and IMPLND watershed loading models with former for pervious surfaces and latter for impervious surfaces. RCHRES is a one-dimensional stream model serving as the receiving water model. It is based on the Stanford Watershed Model, ARM (Agricultural Runoff Management) and NPS (NonPoint Source) models. It uses simple storage based equations for flow routing. Flows in streams are one-dimensional. It is one of the few comprehensive models of watershed hydrology and water quality that allows the integrated simulation of land and soil contaminant runoff processes with in-stream hydraulic and sediment-chemical interactions. HSPF uses continuous rainfall and other meteorologic records to compute streamflow hydrographs and pollutographs. HSPF simulates interception soil moisture, surface runoff, interflow, baseflow, snowpack depth and water content, snowmelt, evapotranspiration, ground-water recharge, dissolved oxygen, biochemical oxygen demand (BOD), temperature, pesticides, conservatives, fecal coliforms, sediment detachment and transport, sediment routing by particle size, channel routing, reservoir routing, constituent routing, pH, ammonia, nitrite-nitrate, organic nitrogen, orthophosphate, organic phosphorus, phytoplankton, and zooplankton. Program can simulate one or many pervious or impervious unit areas discharging to one or many river reaches or reservoirs. Frequency-duration analysis can be done for any time series. Any time step from 1 minute to 1 day that divides equally into 1 day can be used. Any period from a few minutes to hundreds of years may be simulated. HSPF is generally used to assess the effects of land-use change, reservoir operations, point or nonpoint source treatment alternatives, flow diversions, etc. Programs, available separately, support data preprocessing and postprocessing for statistical and graphical analysis of data saved to the Watershed Data Management (WDM) file. The major application of HSPF is the Chesapeake Bay Project.
BMPs: Nutrient and pesticide management, ponds.
URL: http://water.usgs.gov/software/hspf.html

Application and Model References:

Bicknell, B.R., J.C. Imhoff, J.L. Kittle, A.S. Donigian, and R.C. Johanson. 1997. Hydrological Simulation Program - FORTRAN. User's Manual for Release 11. EPA/600/R-97/080. U.S. EPA Environmental Research Laboratory, Athens, GA.

Chen, Y.D., D.J. Norton, and J.P. Craig. 1996. Enhancement and Application of HSPF for Stream Temperature Simulation in Upper Grande Ronde Watershed, Oregon. Published in Proceedings. Watershed '96. US Environmental Protection Agency. June 8-12.

Donigian, A.S., Jr., B.R. Bicknell, and J.C. Imhoff. 1995. Hydrologic Simulation Program -FORTRAN (HSPF). Chapter 12 in Computer Models of Watershed Hydrology, V.P. Singh, Ed., Water Resources Publications, Littleton, CO.

Donigian, A.S., J.C. Imhoff, B.R. Bicknell and J.L. Kittle. 1984. Application Guide for Hydrological Simulation Program - FORTRAN (HSPF). EPA- 600/3-84-065. Office of Research and Development, U.S. Environmental Protection Agency, Athens, GA.

Donigian, A.S., B.R. Bicknell, A.S. Patwardhan, L.C. Linker, C.H. Chang, and R. Reynolds. 1994. Chesapeake Bay Program - Watershed Model Application to Calculate Bay Nutrient Loadings: Final Findings and Recommendations (FINAL REPORT). Prepared for U.S. EPA Chesapeake Bay Program, Annapolis, Maryland.

Fontaine, T., and V. Jacomino. 1997. Sensitivity analysis of simulated contaminated sediment transport. J. Amer. Water Res. Assn., 33(2):313-326.

Jacomino, VMF; Fields, DE. 1997. A critical approach to the calibration of a watershed model. Journal of the American Water Resources Association, 33(1):143-154.

Laroche, A., J. Gallichand, R. Lagace, and A. Pesant. 1996. Simulating atrazine transport with HSPF in an agricultural watershed. J. Envir. Engr., 122 (7):622-630.

***KINEROS-2 (KINematic EROSion model)*:** This is the improved version of KINEROS (Woolhiser et al., 1990). It is event based since it lacks a true soil moisture redistribution formulation for long rainfall hiatus and more importantly it does not consider evapotranspiration (ET) losses. This model is primarily useful for predicting surface runoff and erosion over small agricultural and urban watersheds. Smith et al. 1995 suggest watershed size smaller than 1000 ha for best results. Runoff is calculated based on the Hortonian approach using a modified version of Smith- Parlange (Smith and Parlange 1978) infiltration model. KINEROS-2 requires the watershed divided into homogeneous overland flow planes and channel segments, and routs water movement over these elements in a cascading fashion. Mass balance and the kinematic wave approximations to the Saint Venant equations are solved with implicit finite difference numerical scheme in a 1-D framework. KINEROS-2 accounts for erosion resulting from raindrop energy and by flowing water separately. A mass balance equation is solved to describe sediment dynamics at any point along a surface flow path. Erosion is based on maximum transport capacity determined by Engelund-Hansen equation (1967). The rate of sediment transfer between soil and water is defined with a first order uptake rate. KINEROS-2 can be used under the

AGWA system which provides a GIS interface for data preparation and visualization of results. A detailed description of the model and the equations used can be found in Smith et al. 1995 and at the official URL of the model: http://www.tucson.ars.ag.gov/kineros.
BMPs: Agricultural practices, detention basins, culverts.

Application and Model References:

Kalin, L., R.S. Govindaraju, M.M. Hantush. 2003. Effect of geomorphologic resolution on runoff hydrograph and sedimentograph. J. Hydrol., 276:89-111.

Kalin, L., and M.M. Hantush. 2003. Modeling of sediment yield in a small agricultural watershed with KINEROS-2. In J. D. Williams and D. W. Koplin, ed., American Water Resources Association 2003 Spring Specialty Conference on Agricultural Hydrology & Water Quality, Kansas City, MO, CD-ROM.

Lane, L.J., D.A. Woolhiser, and V. Yevjevich. 1975. Influence of simplifications in watershed geometry in simulation of surface runoff. Hydrology paper No. 81, Colorado State University, Fort Collins, CO. 27 pp.

Smith, R.E., D.C. Goodrich, D.A. Woolhiser and C.L. Unkrich. 1995. A kinematic runoff and erosion model. Singh, V.J. (Ed), Computer Models of Watershed Hydrology, 697-732, Water Resources Pub., Highlands Ranch, CO.

Smith, R.E., and J.Y. Parlange. 1978. A parameter-efficient hydrologic infiltration model. Water Resources Research, 14:553-538.

Woolhiser, D.A., R.E. Smith, and D.C. Goodrich. 1990. KINEROS-A kinematic runoff and erosion model: Documentation and user manual. USDA-ARS, ARS-77.

Zevenbergen, L.W., and M.R. Peterson. 1988. Evaluation and testing of storm event hydrologic models. Proc. ASCE Nat. Conf. On Hydraulic Engr., Colorado Springs, CO, Aug. 6-12., p. 467472.

Ziegler, A.D., T.W. Giambelluca, and R.A. Sutherland. 2001. Erosion prediction on unpaved mountain roads in northern Thailand: Validation of dynamic erodibility modeling using KINEROS2. Hydrological Processes, 15:337-358.

***MIKE-11*:** MIKE-11 is a software tool for the simulation of hydrology, hydraulics, water quality and sediment transport in estuaries, rivers, irrigation systems and other inland waters. It is based on an integrated modular structure with a variety of basic modules and add-on modules, each simulating certain phenomena in river systems. Each module can be operated separately and data transfer between modules is automatic. Coupling of physical processes (e.g. river morphology, sediment re-suspension, and water quality) are facilitated. MIKE-11 includes basic modules for:

- Rainfall-runoff (RR): This module contains three different models that can be used to estimate catchment runoff: i) NAM is a lumped, conceptual rainfall-runoff model simulating overland flow, interflow and baseflow as a function of the moisture content in four mutually interrelated storages: snow storage, surface storage, root zone storage, and groundwater storage. In addition NAM allows treatment of man-made interventions in the hydrological cycle such as irrigation and groundwater pumping, ii) The present UHM module simulates the runoff from single storm events by the use of the unit hydrograph technique and constitutes an alternative to the NAM model for flood simulation in areas where no stream flow records are available or where unit hydrograph techniques have already been well established. The module calculates simultaneously the runoff from several catchments and includes facilities for presentation and extraction of the results. The output from the module can be used as lateral inflow to the advanced hydrodynamic module in MIKE-11, iii) SMAP: A monthly soil moisture accounting model. The RR module can either be applied independently or used to represent one or more contributing catchments that generate lateral inflows to a river network. In this manner it is possible to treat a single catchment or a large river basin containing numerous catchments and a complex network of rivers and channels within the same modeling framework. An auto-calibration tool is available for the NAM module which uses a global optimization routine called the Shuffled Complex Evolution (SCE) algorithm.
- Hydrodynamics (HD): The HD module 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 non-linear 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: i) high-order, fully dynamic, ii) diffusive wave, iii) kinematic wave, and iv) quasi-steady state. Within the standard HD module advanced computational formulations enable flow over a variety of structures to be simulated: broad-crested weirs, culverts, regulating structures, control structures, dam-break structures, user-defined structures, and tabulated structures.
- Advection-dispersion and cohesive sediments (AD): The AD module is based on the one-dimensional equation of conservation of mass of a dissolved or suspended material (e.g., salt or cohesive sediments). The behavior of

conservative materials which decay linearly can be simulated. The module requires output from the hydrodynamic module, in space and time, of discharge and water level, cross-sectional area and hydraulic radius. The module includes a description of the erosion and deposition of cohesive sediment. Erosion and deposition are modeled as source/sink terms in the advection-dispersion equation. Whereas the erosion rate depends on the local hydraulic conditions, the deposition rate depends also on the concentration of suspended sediment. It is also possible to simulate non-cohesive sediments with the AD module. Here the transport of the suspended sediment is described with the advection-dispersion equation, and the erosion and deposition terms are described by conventional sediment transport formulations.

- Water quality (WQ): WQ is coupled to the advection-dispersion (AD) module and simulates the reaction processes of multi-compound systems including the degradation of organic matter, the photosynthesis and respiration of plants, nitrification and the exchange of oxygen with the atmosphere. The mass balance for the parameters involved are calculated for all grid points at all time steps using a rational extrapolation method in an integrated two-step procedure with the AD module. A number of modules have been developed describing BOD-DO relationships, nitrification, the influence of bed vegetation on water quality, sedimentation and re-suspension, and oxygen consumption from reduced chemicals. Two add-on modules are available for the WQ-module: Water Quality Heavy Metals module (WQHM), and the Eutrophication module (EU).
- Non-cohesive sediment transport: The non-cohesive sediment transport module (ST) can be used to study the sediment transport and morphological conditions in rivers. The features include: i) five models for the calculation of sediment transport capacity: Engelund-Hansen, Ackers-White, Engelund-Fredsøe, van Rijn and Smart Jeaggi, ii) sediment description by an average particle size and standard deviation of the grain size distribution, iii) explicit (no feedback with HD) or morphological (with feedback via sediment continuity and bed resistance) models, and iv) output of sediment transport rates, bed level changes, resistance numbers and dune dimensions.

An ArcView interface of the model is available which facilitates input data preparation and output visualization. The US Federal Emergency Management Agency (FEMA) has recently approved and included MIKE-11 on their list of hydraulic models accepted for use in the National Flood Insurance Programme (NFIP).
URL: http://www.dhisoftware.com/mike11

Application and Model References:
Please visit http://www.dhi.dk/ContactUs/Library for all DHI compendium of technical papers and publications.

***MIKE-SHE*: ** MIKE-SHE is a distributed, physically based, dynamic modeling tool that can simulate the entire land phase of the hydrologic cycle. It has the capability of handling both single events and continuous simulations. Watershed is divided into square grid cells. Overland flow routing is based on 2-D diffusive wave equations whereas options vary for channel flow from simple Muskingum routing to the Higher Order Dynamic Wave formulation of the Saint-Venant equations. Ground water flow is solved with 3-D full Richards' equation. Stream-ground water interactions are considered. In general, depending on the size of the watershed, simulations can be computationally very intensive. Typical MIKE-SHE applications are:

- 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

ArcView interface is available. Most of the applications find in literature belong to the model developers.
BMPs: Agricultural practices, wetlands, nutrient and pesticide management.
URL: http://www.dhisoftware.com/mikeshe

Application and Model References:
Abbott, M.., J. Bathurst, P.Cunge, P. O'Connel, and J. Rasmussen. 1986. An introduction to the European Hydrologic System-Systeme-Hydroloque European, SHE, 1: History and Philosophy of a physically-based distributed modeling system. Journal of Hydrology (87):45-59.

Abbott, M.., J. Bathurst, P.Cunge, P. O'Connel, and J. Rasmussen. 1986. An introduction to the European Hydrologic System-Systeme-Hydroloque European, SHE, 2: Structure of a physically-based distributed modeling system. Journal of Hydrology 87: 61-77.

Abbot, M., and Refsgaard (eds.). 1996. Distributed Hydrologic Modeling. Kluwer Academic Publishers, Dodrecht.

Gustafsson, L.G., S. Winberg, A. Refsgaard. 1997. Towards a distributed physically based model description of the urban aquatic environment. Water Science & Technology, 36:8-9.

Jayatilaka, C., B. Storm, and L. Mudgway. 1998. Simulation of water flow on irrigation bay scale with MIKE-SHE. J. Hydrology, 208(1-2):108-130.

Refsgaard, J.C.. 1997. Paramterization, calibration and validation of distributed hydrological models, Journal of Hydroloigy, 198(1-4):69-97.

Refsgaard, J.C., and J. Knudsen. 1996. Operational validation and intercomparison of different types of hydrologic models, Water Resources Research, 32(7):2189-2202.

Refsgaard, J., and B. Storm. 1995. Mike She. Chap 23, Computer Models of Watershed Hydrology, V. Singh, Ed., 809-846. Highland Ranch, CO, Water Resources Publications.

Xevi, E, K. Christiaens, A. Espino, W. Sewnandan, D. Mallants, H. Sorensen, J. Feyen. 1997. Calibration, validation and sensitivity analysis of the MIKE-SHE model using the Neuenkirchen catchment as case study. Water Resources Management, 11(3):219-242.

Also visit http://www.dhi.dk/ContactUs/Library for additional all DHI compendium of technical papers and publications.

OPUS**:** Opus is a continuous field-scale (unit area) root-zone model, developed as a research and management tool to assist in agricultural nonpoint source pollution control. Hydrology, erosion, nutrient, pesticide, and crop growth components are included. Runoff/infiltration is partitioned using either a daily hydrology option (curve number) or infiltration equation using break-point rainfall. Unsaturated flow is modeled with Richards' equation. Evapotranspiration is computed from air temperature, solar radiation, soil-water, and crop stage. The crop growth component considers radiation, nutrients, temperature, and water availability. Carbon, nitrogen, and phosphorus processes are represented in the soil-water-plant dynamics. Pesticides are modeled assuming equilibrium or kinetic adsorption, first-order decay, and advective transport. If daily runoff option is used erosion is estimated based on the Modified Universal Loss Equation (MUSLE). A more detailed, spatially and temporally distributed approach that considers particle size classes is used with the infiltration equation. OPUS considers variation in vertical direction (soil column), but assumes uniform soil, crop and climate characteristics. Fields with divided flow, and features such as terraces, contours, furrows, grassed buffer-strips or waterway, and farm ponds can be simulated. Model documentation is published, and the model is distributed free. Model and the manual is available through the National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161

BMPS: terraces, contours, furrows, grassed buffer-strips or waterway, and farm ponds.

Application and Model References:

Arenstein, D.J., S.R. Workman, and S.E. Nokes. 1995. Calibration and validation of the Opus model at the Ohio Management Systems Evaluation Area. Paper 95-2403. St. Joseph, Mich.: ASAE.

Ferreira, V.A., and R.E. Smith. 1992. Opus, an integrated simulation model for transport of nonpoint source pollutants at the field scale: Volume II, User Manual. ARS-98. Washington: USDA Agricultural Research Service. 200 pp.

Heatwole, C.D., S. Zacharias, and N. Persaud. 1997. Comparison of Opus and GLEAMS in simulating spatial variability of pesticide movement in a field soil. In: Application of GIS, Remote Sensing, Geostatistics, and Solute Transport Modeling. Washington: Amer. Geophysical Union.

Ma, Q.L., R.D. Wauchope, J.E. Hook, A.W. Johnson, C.C. Truman, C.C. Dowler, G.J. Gascho, J.G. Davis, H.R. Summer, and L.D. Chandler. 1998. GLEAMS, Opus, and PRZM-2 model predicted versus measured runoff from a coastal plain loamy sand. Transactions of the ASAE 41(1):77-88.

Pierson, F.B., G.N. Flerchinger, and J.R. Wight. 1992. Simulating near-surface soil temperature and water on sagebrush rangelands: A comparison of models. Transactions of the ASAE 35(5):1449-1455.

Ramanarayanan, T.S., G.J. Sabbagh, M.R. Reyes, R.L. Bengston, D.E. Storm, and J.L. Fouss. 1994. Performance of transport models in predicting nitrate runoff from high water table areas. Paper 94-2152. St. Joseph, Mich.: ASAE. 13 pp.

Santos, D.V., R.E. Smith, P.L. Sousa, and L.S. Pereira. 1996. Calibration and validation of model Opus for water and nitrate simulation. In: R.Ragab, D.E. El-Quosy, B. van Den Boek, and L.S. Pereira, eds, Crop Water Environment Models, proceedings of the Cairo Workshop, ICID, Cairo. pp. 17-28.

Santos, D.V., P.L. Sousa, and R.E. Smith. 1997. Model simulation of water and nitrate movement in a level-basin under fertigation treatments. Agricultural Water Management 32:293-306.

Smith, R.E. 1992. Opus, an integrated simulation model for transport of nonpoint source pollutants at the field scale: Volume I, Documentation. ARS-98. Washington: USDA Agricultural Research Service. 120 pp.
Smith, R.E. 1993a. Simulation of crop water balance with Opus. In: L.S. Pereira, B.J. van denBroek, P.Kabat, and R.G. Allen, editors, Crop-Water-Simulation Models in Practice. Selected papers, 15th ICID Congress, The Hague, pp.215-227.
Smith, R.E. 1993b. Simulation experiments on the role of soil hydraulic characteristics in Agro-Ecosystems. Modeling of Geo-Biosphere Processes 2(1/4):1-14.
Smith, R.E. 1995. Opus simulation of a wheat/sugarbeet plot near Neuenkirchen, Germany. Ecological Modeling 81:121-132.
Smith, R.E., and B. Diekkruger. 1992. Field-scale soil water flow in heterogeneous soils, I, Modeling statistical soil variation and large-scale constituent relations. Modeling of Geo-Biosphere Processes 1:205-227.
Smith, R.E., and V.A. Ferreira. 1989. Comparative evaluation of unsaturated flow methods in selected USDA simulation models. In: H.J. Morel-Seytoux (ed), Unsaturated Flow in Hydrologic Modeling Theory and Practice. Kluwer Academic Publishers. pp.391-412.
Zacharias, S. and C.D. Heatwole. 1993. Predicting tillage treatment effects on pesticide transport: A validation study. Paper 93-2592. St. Joseph, Mich.: ASAE.
Zacharias, S., and C.D. Heatwole. 1996. A stochastic framework for incorporating spatial variability in NPS models. Paper 96-2028. St. Joseph, Mich.: ASAE.
Zacharias, S., and C.D. Heatwole. 1997. Stochastic simulation of root zone water and solute movement in an agricultural field. Paper 97-2001. St. Joseph, Mich.: ASAE.

PRMS (Precipitation-Runoff Modeling System)**:** PRMS is a distributed watershed model that simulates precipitation- and snowmelt-driven movement of water through the basin via overland flow, interflow, and baseflow. Watershed response can be simulated at a daily time step or more frequently over the course of a storm. Kinematic routing of the unidirectional flow and the transport of sediments through a receiving network of well-mixed channel reaches can be simulated when the model is in "storm mode". Simulation of the energy balance in the snowpack and the water balance is based on many theoretically- and empirically-developed relations. The resulting model is comprehensive and flexible, but also very complex and requires a large number of parameters. The model contains procedures for parameter optimization and sensitivity analyses. A Unix-based GUI is available through the modeling framework MMS. Watershed is divided into subunits based on such basin characteristics as slope, aspect, elevation, vegetation type, soil type, land use, and precipitation distribution. Two levels of partitioning are available. The first divides the basin into homogeneous response units (HRU) based on the basin characteristics. Water and energy balances are computed daily for each HRU. The sum of the responses of all HRU's, weighted on a unit-area basis, produces the daily system response and streamflow for a basin. A second level of partitioning is available for storm hydrograph simulation. The watershed is conceptualized as a series of interconnected flow planes and channel segments. Surface runoff is routed over the flow planes into the channel segments; channel flow is routed through the watershed channel system. An HRU can be considered the equivalent of a flow plane or it can be delineated into a number of flow planes. The source of code of RPMS is available to public. It is written in Fortran 77, and therefore can be considered platform independent.
URL: http://smig.usgs.gov/cgi-bin/SMIC/model_home_pages/model_home?selection=prms
http://water.usgs.gov/software/prms.html

Application and Model References:

Carey, W.P., and A. Simon. 1984. Physical basis and potential estimation techniques for soil erosion parameters in the Precipitation-Runoff Modeling System (PRMS). U.S. Geological Survey Water-Resources Investigations Report 82-4218, 32 p.
Cary, L.E. 1984. Application of the U.S. Geological Survey's Precipitation-Runoff Modeling System to the Prairie Dog Creek basin, Southeastern Montana. U.S. Geological Survey Water-Resources Investigations Report 84-4178, 98 p.
Kidd, R.E., and C.R. Bossong. 1987. Application of the precipitation-runoff model in the Warrior Coal Field, Alabama. U.S. Geological Survey Water-Supply Paper 2036, 42 p.
Kuhn, G. 1989. Application of the U.S. Geological Survey's Precipitation-Runoff Modeling System to Williams Draw and Bush Draw basins, Jackson County, Colorado. U.S. Geological Survey Water-Resources Investigations Report 88-4013, 38 p.
Norris, J.M., and R.S. Parker. 1985. Calibration procedure for a daily flow model of small watersheds with snowmelt runoff in the Green River coal region of Colorado. U.S. Geological Survey Water-Resources Investigations Report 83-4263, 32 p.
Parker, R.S., and J.M. Norris. 1989. Simulation of streamflow in small drainage basins in the southern Yampa River Basin, Colorado. U.S. Geological Survey Water-Resources Investigations Report 88-4071, 47 p.
Puente, C., and J.T. Atkins. 1989. Simulation of rainfall-runoff response in mined and unmined watersheds in coal areas of West Virginia. U.S. Geological Survey Water-Supply Paper 2298, 48 p.

Scott, A.G. 1984. Analysis of characteristics of simulated flows from small surface-mined and undisturbed Appalachian watersheds in the Tug Fork basin of Kentucky, Virginia, and West Virginia. U.S. Geological Survey Water-Resources Investigations Report 84-4151, 169 p.

[*] ***REMM (Riparian Ecosytem Management Model)*****:**
REMM is a tool for estimating the nonpoint source pollution control by field-scale riparian ecosystems. It can be used to simulate hydrology, nutrient dynamics and plant growth for land areas between the edge of fields and a waterbody. Management options such as vegetation type, size of the buffer zone, and biomass harvesting can also be simulated. A riparian buffer system is divided into three zones i) Zone 1 is permanent woody vegetation immediately adjacent to the stream bank., ii) Zone 2 is managed forest occupying a strip upslope from zone 1, iii) Zone 3 is an herbaceous strip upslope from zone 2. The primary purposes of zone 3 are to remove sediment from surface runoff and to convert channelized flow to sheet flow. The primary function of zone 2 is to block transport of sediment and chemicals from upland areas into the adjacent wetland or aquatic system. The purpose of Zone 1 is to maintain the integrity of the stream bank and a favorable habitat for aquatic organisms. Movement and storage of water within riparian buffer systems is simulated by a process-based, two-dimensional water balance operating on a daily time step. Surface runoff is assumed to be generated by infiltration excess and saturation excess. Infiltration is estimated using an explicit form of modified Green-Ampt equation. A very simple surface runoff routing scheme is used which is based on the time of concentration concept. Only incoming runoff is routed. Runoff generated within the riparian area by infiltration excess and saturation excess is not subject to routing. Upward flux from a shallow water table is computed using Dary-Buckingam equation. Sediment transport is simulated both in channels and overland flow areas, but channel erosion or detachment is not simulated. Channel shapes are assumed triangular. Lateral subsurface movement is modeled with Darcy's equation. Because of the roughness of the riparian buffers, it is assumed that sediment transport is primarily of suspended particles. Upland loadings are assumed to be provided as input to the REMM. Overland flow erosion is based on the USLE equation. Five classes of sediment are considered: sand, large aggregate, small aggregate, silt and clay. Sediment load computations are performed for each of these classes. Steady state continuity equation is used to compute the sediment at the downslope edge.
BMPs: Agricultural practices, riparian buffers
URL: http://sacs.cpes.peachnet.edu/remmwww

Application and Model References:
Altier, L.S., R.G. Williams, R. Lowrance, and S.P. Inamdar. 1998. The Riparian Ecosystem Management Model: Plant growth component. Proceedings of the First Federal Interagency Hydrologic Modeling Conference, Las Vegas, NV, April 1998, Pgs: 1.33-1.40.
Bosch, D.D., R.G. Williams, S.P. Inamdar, J.M. Sheridan, and R. Lowrance. 1998. Erosion and sediment transport through riparian forest buffers. Proceedings of the First Federal Interagency Hydrologic Modeling Conference, Las Vegas, NV, April 1998, Pgs: 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. Proceedings of the First Federal Interagency Hydrologic Modeling Conference, Las Vegas, NV, April 1998, Pgs: 1.73-1.80.
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. Proceedings of the First Federal Interagency Hydrologic Modeling Conference, Las Vegas, NV, April 1998, Pgs: 7.17-7.24.
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. Proceedings of the First Federal Interagency Hydrologic Modeling Conference, Las Vegas, NV, April 1998, Pgs: 1.81-1.88.
Williams, R.G., R. Lowrance, L.S. Altier, and S.P. Inamdar. 1998. The Riparian Ecosystem Management Model: A demonstration. Proceedings of the First Federal Interagency Hydrologic Modeling Conference, Las Vegas, NV, April 1998, Pgs: 8.133-8.138.

SWAT (Soil Water Assessment Tool)**:** SWAT is a conceptual, continuous time model and is more suitable for large river basins. The SWAT model emerged from the models SWRBB, CREAMS, GLEAMS, EPIC and ROTO. It operates on daily time step. The watershed is divided into sub-basins and each sub-basin is further partitioned into Hydrologic Response Units (HRU) having uniform topographic, soil and land use properties. Input information for each subbasin is grouped or organized into the following categories: weather or climate; unique areas of land cover, soil, and management within the subbasin (hydrologic response units or HRUs); ponds/reservoirs; groundwater; and the main channel, or reach, draining the subbasin. In SWAT water balance is the driving force behind everything that happens in the watershed. Simulated hydrologic processes are surface runoff with SCS curve number or Green-Ampt infiltration, lateral subsurface flow, groundwater flow, evapotranspiration, snowmelt, transmission losses from streams and water storage and losses from ponds. Flow is routed through the channel using a variable storage coefficient method. Sediment yield is computed from MUSLE for each sub-basin. The transport of sediment in the channel is controlled by the simultaneous operation of two processes, deposition and degradation. Deposition in the channel is based on sediment particle fall velocity calculated with Stoke's Law. Stream power is used to predict degradation in the routing reaches. An ArcView interface is available which enables extraction of input parameters easily, and visualization of results. SWAT is integrated into the USEPA's BASINS and USDA's AGWA systems. It is also linked to the river and stream water quality model QUAL2E. Some applications of SWAT and projects in which the model has been used are summarized on http://www.brc.tamus.edu/swat/swatapp.html

BMPs: Agricultural practices, ponds, tile drains.

URL: http://www.brc.tamus.edu/swat

Application and Model References:

Arnold, J.G. and P.M. Allen. 1992. A Comprehensive surface-groundwater flow model. J. Hydrol. 142:47-69.

Arnold, J.G. and P.M. Allen. 1999. Automated Methods for Estimating Baseflow and Groundwater Recharge from Streamflow Records. JAWRA, 34(2):411-424.

Arnold, J.G., R. Srinivasin, R.S. Muttiah, and J. R. Williams. 1998. Large Area Hydrologic Modeling and Assessment: Part I. Model Development. JAWRA 34(1):73-89.

Arnold, J.G., R. Srinivasan, R.S. Muttiah, and P.M. Allen. 1999. Continental Scale Simulation of the Hydrologic Balance. JAWRA 35(5):1037-1051.

Arnold, J.G., Williams, J.R., and Maidment D.A. 1992. Continuous-Time Water and Sediment-Routing Model for Large Basins. Journal of Hydraulic Engineering, Vol 121. No. 2., February, 1995, ASCE. Pgs. 171-183.

Srinivasan, R. and J.G. Arnold. 1994. Integration of a Basin-Scale Water Quality Model with GIS. Water Resources Bulletin. Vol. 30, No. 3., June 1994. Pgs. 453-462.

Srinivasan, R., J.G. Arnold, R.S. Muttiah, and P.T. Dyke. 1995. Plant and Hydrologic Simulation for the Conterminous U.S. Using SWAT and GIS. Hyd Sci &Tech, Vol. 11, No 1-4, Amer. Inst of Hyd., Pg 160-168.

SWMM (Storm Water Management Model)**:** SWMM is a comprehensive computer model for analysis of quantity and quality problems associated with urban runoff. Both single-event and continuous simulation can be performed on catchments having storm sewers, or combined sewers and natural drainage, for prediction of flows, stages and pollutant concentrations. It is structured in the form of blocks. The principal computational blocks include the Runoff Block for generation of runoff and quality constituents from rainfall (plus simple routing of flow and quality), the Transport Block for kinematic wave routing and for additional dry-weather flow and quality routing, the Storage/Treatment Block for reservoir routing and simulation of treatment and storage quality processes, and the Extended Transport or Extran Block for hydraulic routing of flow (no quality routing) using the complete Saint-Venant equations. Using SWMM, the modeler can simulate all aspects of the urban hydrologic and quality cycles, including rainfall, snowmelt, surface and subsurface runoff, flow routing through the drainage network, storage and treatment. The Rain Block is used for processing of hourly and 15-minute precipitation time series for input to continuous simulation. Although the historical basis of the model was for analysis of urban runoff quality problems, the model often is used just for hydrologic and hydraulic analysis. The model is designed for use by engineers and scientists experienced in urban hydrological and water quality processes. An engineering background is necessary to appreciate most methods being used and to verify that the model results are reasonable. SWMM Version 4 is microcomputer based (DOS-compatible), although the Fortran code may be compiled on any machine. For hydrologic simulation in the Runoff Block, data requirements include area, imperviousness, slope, roughness, width (a shape factor), depression storage, and infiltration parameters for either the Horton or Green-Ampt equations for up to 100 subcatchments. (Number of subcatchments, pipes, etc. is variable depending on the compilation). Flow routing can be performed in the Runoff, Transport and Extran Blocks, in increasing order of sophistication. Extran can also simulate dynamic boundary conditions, e.g., tides. Quality processes are initiated in the Runoff Block and include options for constant concentration, regression of load vs. flow, and buildup washoff, with the latter requiring the most data. Additional options include street cleaning, erosion, and quality contributions from precipitation, catchbasins, adsorption, and base flow. EPA Nationwide Urban Runoff Program data are often used as starting values for quality computations. SWMM interfacing requirements are clearly defined. E.g., output may be directed to the EPA WASP receiving water model. Basic SWMM output consists of hydrographs and pollutographs (concentration vs. time) at any desired location in the drainage system. Depths and velocities are also available as are summary statistics on surcharging, volumes, continuity and other quantity parameters. Additional quality output includes loads, source identification, continuity, residuals (e.g., sludge), and other parameters. GIS linkage is available. The model performs best in urbanized areas with impervious drainage, although it has been widely used elsewhere. Technical limitations include lack of subsurface quality routing (a constant concentration is used), no interaction of quality processes (apart from adsorption), difficulty in simulation of wetlands quality processes (except as can be represented as storage processes), and a weak scour deposition routine in the Transport Block. The biggest impediment to model usage is the

user interface, with its lack of menus and graphical output. The model is still run in a batch mode (the user constructs an input file with an editor), unless third-party software is used for pre- and post-processing. It has been used in scores of U.S. cities as well as extensively in Canada, Europe, Australia and elsewhere. Source code, executable version and the models manuals can be downloaded freely from
URL: http://www.cee.odu.edu/model/swmm.php
BMPs: Detention basins, street cleaning.

Application and Model References:

Curtis, T.G., and W.C. Huber. 1993. SWMM AML - An ARC/INFO Processor for the Storm Water Management Model (SWMM). Proc. 1993 Runoff Quantity and Quality Modeling Conference, Reno, NV, (NTIS, in press), U.S. EPA, Athens, GA, 30605.

Donigian, A.S., Jr. and W.C. Huber. 1991. Modeling of Nonpoint Source Water Quality in Urban and Non-Urban Areas. EPA/600/3-91/039, U.S. EPA, Athens, GA, 30605.

Huber, W.C. 1986. Deterministic Modeling of Urban Runoff Quality. In: H.C.Torno et. al. (eds.) Urban Runoff Pollution, Proceedings of the NATO Advanced Research Workshop on Urban Runoff Pollution, Montpellier, France. Springer-Verlag, New York, Series G: Ecological Sciences, 10:167-242.

Huber, W.C. 1992. Experience with the U.S. EPA SWMM Model for Analysis and Solution of Urban Drainage Problems. Proceedings, Inundaciones Y Redes De Drenaje Urbano, J. Dolz, M. Gomez, and J.P. Martin, eds., Colegio de Ingenieros de Caminos, Canales Y Puertos, Universitat Politecnica de Catalunya, Barcelona, Spain, p.199-220.

Huber, W.C. and R.E. Dickinson. 1988. Storm Water Management Model, Version 4, User's Manual. EPA/600/3-88/001a (NTIS PB88-236641/AS), U.S. EPA, Athens, GA, 30605.

Huber, W.C., Heaney, J.P. and B.A. Cunningham. 1985. Storm Water Management Model (SWMM) Bibliography. EPA/600/3-85/077 (NTIS PB86-136041/AS), U.S. EPA, Athens, GA, September 1985.

Huber, W.C., Zollo, A.F., Tarbox, T.W. and J.P. Heaney. 1991. Integration of the SWMM Runoff Block with ARC/INFO and AutoCAD: A Case Study. Final Report to Foster-Wheeler Enviresponse, Inc. and U.S. EPA, Edison, NJ, Contract VN1-320-420000, from Dept. of Environmental Engineering Sciences, University of Florida, Gainesville.

Martin, J.L. 1993. Modification of the Storm Water Management Model's (SWMM's) Transport Submodel for Creation of a Hydrodynamic Linkage to the Water Analysis Simulation Program (WASP). Report to Camp, Dresser and McKee, Inc. by AScI Corp., Athens, GA, 30605.

Roesner, L.A., Aldrich, J.A. and R.E. Dickinson. 1988. Storm Water Management Model, Version 4, User's Manual: Extran Addendum. EPA/600/3-88/001b (NTIS PB88-236658/AS), U.S. EPA, Athens, GA, 30605.

[*] ***VFSMOD (Vegetative Filter Strips hydrology and sediment transport MODel)*****:** VFSMOD is a field scale, mechanistic, storm-based model designed to route the incoming hydrograph and sedimentograph from an adjacent field through a vegetative filter strip (VFS) and to calculate the outflow, infiltration and sediment trapping efficiency. The model handles time dependent hyetographs, space distributed filter parameters (vegetation roughness or density, slope, infiltration characteristics) and different particle size of the incoming sediment. Any combination of unsteady storm and incoming hydrograph types can be used. VFSMOD consists of a series of modules simulating the behavior of water and sediment in the surface of the VFS: i) Green-Ampt infiltration module: a module for calculating the water balance in the soil surface; ii) kinematic wave overland flow module: a 1-D module for calculating flow depth and rates on the infiltrating soil surface; iii) sediment filtration module: a module for simulating transport and deposition of the incoming sediment along the VFS. The model can be used to describe transport at the field scale (or field edge) if flow and transport is mainly in the form of sheet flow (Hortonian) and the 1-D path represents average conditions (field effective values) across the VFS. A windows version of the model called VFSMOD-W has recently been developed. The model is provided free of charge as an educational and research tool. The model and documentation can be downloaded from the internet. No formal training is available. Limited support is available from the authors. Through the web site, the user can send feedback and questions to the authors.
URL: http://www3.bae.ncsu.edu/vfsmod/
BMPs: Vegetative filter strips.

Application and Model References:

Muñoz-Carpena, R., J. E. Parsons and J. W. Gilliam. 1993b. Numerical approach to the overland flow process in vegetative filter strips. Transactions of ASAE. 36(3):761-770.

Muñoz-Carpena, R., J. E. Parsons and J. W. Gilliam. 1999. Modeling hydrology and sediment transport in vegetative filter strips and riparian areas. J. of Hydrology 214(1-4):111-129.

Muñoz-Carpena, R. and J. E. Parsons. 1999. Evaluation of VFSMOD, a vegetative filter strip hydrology and sediment filtration model. 1999 ASAE/CSAE-SCGR Annual International Meeting, Toronto, Ontario, Canada. July 18-22, 1999. ASAE Paper No. 992152.

Parsons, J.E. and R. Muñoz-Carpena. 2001. Impact of uncertainty on the design of vegetative filter strips. ASAE Annual International Meeting, Sacramento, California. July 29-Aug. 1, 2001. ASAE Paper No. 012214.

WEPP (Water Erosion Prediction Project)**:** The Water Erosion Prediction Project (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) is applicable to hillslope erosion processes (sheet and rill erosion), as well as simulation of the hydrologic and erosion processes on small watersheds (<640 Acres). Processes considered in hillslope profile model applications include rill and interrill erosion, sediment transport and deposition, infiltration, soil consolidation, residue and canopy effects on soil detachment and infiltration, surface sealing, rill hydraulics, surface runoff, plant growth, residue decomposition, percolation, evaporation, transpiration, snow melt, frozen soil effects on infiltration and erodibility, climate, tillage effects on soil properties, effects of soil random roughness, and contour effects including potential overtopping of contour ridges. The model accommodates the spatial and temporal variability in topography, surface roughness, soil properties, crops, and land use conditions on hillslopes. In watershed applications, the model allows linkage of hillslope profiles to channels and impoundments. Water and sediment from one or more hillslopes can be routed through a small field scale watershed. Almost all of the parameter updating for hillslopes is duplicated for channels. The model simulates channel detachment, sediment transport and deposition. Impoundments such as farm ponds, terraces, culverts, filter fences and check dams can be simulated to remove sediment from the flow. The procedures do not consider classical gully erosion. Also, model application is limited to areas where the hydrology is dominated by Hortonian overland flow. The infiltration component of the hillslope model is based on a modified Green-Ampt equation. Overland flow routing procedures include both an analytical solution to the kinematic wave equations and an approximate method. Soil erosion is represented in two ways for WEPP overland flow profile applications: i) soil particle detachment by raindrop impact and transport by sheet flow on interrill areas (interrill delivery rate), and ii) soil particle detachment, transport and deposition by concentrated flow in rill areas (rill erosion). Flow depth and hydraulic shear stress along the channel are computed by regression equations based on a numerical solution of the steady-state spatially-varied flow equation. Detachment, transport, and deposition of sediment are calculated by a steady-state solution to the sediment continuity equation. Impoundment component outputs include: i) peak outflow rate and volume leaving the impoundment; ii) peak sediment concentration and the total sediment yield leaving the impoundment for the five particle size classes; and iii) the median particle size diameter of the sediment leaving the impoundment for the five particle size classes. WEPP has a weather generator (CLIGEN) which generates mean daily precipitation, daily maximum and minimum temperature, mean daily solar radiation, and mean daily wind direction and speed using two-sate Markov Chain model.
BMPs: Agricultural practices, ponds, terraces, culverts, filter fences, check dams.
URL: http://topsoil.nserl.purdue.edu/nserlweb/weppmain/wepp.html

Application and Model References:

Cochrane, T.A. and D.C. Flanagan. 1999. Assessing water erosion in small watersheds using WEPP with GIS and digital elevation models: J. Soil and Wat. Conserv., 54(4):678-685.

Elliot, W.J., W. Qiong and A.V. Elliot. 1993. Application of the WEPP model to surface mine reclamation. Paper presented at Challenge of Integrating Diverse Perspectives in Reclamation, 10th National Meeting. Spokane, WA: Am. Soc. Surface Mine Reclam.

Flanagan, D.C and S.J. Livingston (eds.). 1995. *USDA-Water Erosion Prediction Project: WEPP User Summary*. NSERL Report No. 11. USDA-ARS National Soil Erosion Research Laboratory, West Lafayette, Indiana.

Flanagan, D.C. and M.A. Nearing (eds.). 1995. *USDA-Water Erosion Prediction Project: Hillslope Profile and Watershed Model Documentation.* NSERL Report No. 10, USDA-ARS National Soil Erosion Research Laboratory, West Lafayette, Indiana.

Flanagan, D.C. and M.A. Nearing. 2000. Sediment particle sorting on hillslope profiles in the WEPP model: Trans. Am. Soc. Agric. Eng., 43(3):573-583.

Nearing, M.A., L.A. Deer-Ascough, and J.M. Laflen. 1990. Sensitivity analysis of the WEPP hillslope profile erosion model. Trans. Am. Soc. Agric. Eng. 33(3):839-849.

Nearing, M.A., G.R. Foster, L.J. Lane, and S.C. Finkner. 1989. A process-based soil erosion model for USDA-Water Erosion Prediction Project (WEPP) technology. Trans. Am. Soc. of Agric. Eng. 32(5):1587-1593.

Nearing, M.A. and A.D. Nicks.1998. Evaluation of the Water Erosion Prediction Project (WEPP) model for hillslopes: in Modelling Soil Erosion by Water (J. Boardman and D.T. Favis-Mortlock, eds.), Springer-Verlag NATO-ASI Series I-55, Berlin: 45-56.

Savabi, M.R., D.C. Flanagan, B. Hebel, B.A. Engel. 1995. Application of WEPP and GIS-GRASS to a Small Watershed in Indiana. Journal of Soil and Water Conservation 50(5):477-483.

***WMS (Watershed Modeling System)*:** The WMS software provides a comprehensive environment for hydrologic analysis of watershed systems. Developed in cooperation with the Waterways Experiment Station (WES), WMS provides graphical tools for use in the delineation of watersheds and flood plains. Hydrologic models may be set up and viewed in a user-friendly graphical environment. The WMS software package is divided logically into six well-integrated, task-oriented modules. These modules are: Triangulated Irregular Networks (TINs), DEMs, Tree, Grid, Scatter Point, and Map (GIS). The WMS software package provides an interface to HEC-1, TR-20, Rational Method, National Flood Frequency (NFF), GSSHA, and HSPF. The interface to last two models is still a beta version. WMS can be operated under UNIX or WINDOWS operating systems.
URL: http://chl.wes.army.mil/software/wms, http://www.ems-i.com/WMS/wms.html

8.2 Receiving Water Models:

CE-QUAL-ICM & CE-QUAL-ICM/TOXI: 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. Subsequent to employment in the Bay study, the model code was generalized and minor corrections and improvements were installed. 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 model computes and reports concentrations, mass transport, kinetics transformations, and mass balances. Features to aid debugging include the ability to activate or deactivate model features, diagnostic output, and volumetric and mass balances. Computations can be restarted following interruption due to computer failure or similar circumstances. CE-QUAL-ICM is coded in ANSI Standard FORTRAN F77. The model operates on a variety of platforms including 486 PC, Silicon Graphics, and Hewlett Packard workstations. A multi-processor version is available but not generally released. The user must provide processors that prepare input files and process output for presentation. The model does not compute hydrodynamics. Flows, diffusion coefficients, and volumes must be specified externally and read into the model. For simple configurations, flows may be entered through an ASCII input file. For more advanced applications, hydrodynamics are usually obtained from a hydrodynamics model such as the CH3D-WES model. The unstructured, finite volume structure of the model was selected to facilitate linkage to a variety of hydrodynamic models. There are two distinctly different development pathways to ICM: a eutrophication model (ICM), and an organic chemical model (ICM/TOXI). 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 sub-model. The sub-model interactively predicts sediment-water oxygen and nutrient fluxes. Alternatively, these fluxes may be specified based on observations. The 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 ICM/TOXI model resulted from incorporating the toxic chemical routines from EPA's WASP (Water 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; and 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. WASP toxic chemical model upon which ICM/TOXI is based has been applied to a wide variety of sites. CE-QUAL-ICM also has been linked to EFDC hydrodynamic model.
URL: http://www.wes.army.mil/el/elmodels

Application and Model 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. 1993. Chesapeake Bay sediment flux model. Prepare by Hydroqual, Inc. for US. EPA Chesapeake Bay Program, US. Army Engineers District, Baltimore, MD, and US. Army Engineer Waterways Exp. Station. Contact Report EL-93-2, 200 pp.

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

***CE-QUAL-R1*:** CE-QUAL-R1 is spatially one dimensional and horizontally averaged reservoir water quality model. Temperature and concentration gradients are computed only in the vertical direction. The reservoir is conceptualized as a vertical sequence of horizontal layers where thermal energy and materials are uniformly distributed in each layer. The mathematical structure of the model is based on horizontal layers whose thicknesses depend on the balance of inflowing and outflowing waters. Variable layer thicknesses permit accurate mass balancing during periods of inflow and outflow. The distribution of inflowing waters among the horizontal layers is based on density differences. Simulations of surface flows, interflows, and underflows are possible. Similarly, outflowing waters are withdrawn from layers after considering layer densities, discharge rates, and outlet configuration. Reservoir outflows may take place according to a specified schedule of port releases. Alternately, specification of total release and desired release temperatures can be made. In this case, the model will select port flows. In addition, both continuous (normal) and scheduled operations can be simulated. Continuous operation refers to normally uninterrupted port and weir outflows. Scheduled operation refers to fluctuating generation outflows or pumpback inflows. Vertical transport of thermal energy and materials occurs through entrainment and turbulent diffusion. Entrainment is a transport process that sharpens gradients and determines the depth of the upper mixed region and the onset of stratification. It is calculated from the turbulent kinetic energy influx generated by wind shear and convective mixing. Turbulent diffusion is a transport process that reduces gradients and is calculated using a turbulent diffusion coefficient that is dependent on wind speed, inflow and outflow magnitudes, and density stratification. The interaction of numerous biological and chemical factors is a major attribute of CE-QUAL-R1. The model simulates interactions of physical factors (such as flow and temperature), chemical factors (such as nutrients), and biological assemblages in both aerobic and anaerobic environments. It can perform stochastic simulations using Monte Carlo methods. Statistical data describing biological and chemical coefficients are used to provide probabilistic estimates of key output variables. The thermal analysis portion of CE-QUAL-R1 is provided as an independent model (CE-THERM-R1) to simplify simulation of water budgets and temperature profiles. CE-THERM-R1 includes the variables of temperature, suspended solids, and total dissolved solids. Algorithms representing physical processes are the same as in CE-QUAL-R1. A number of utilities are also provided with CE-QUAL-R1. These include preprocessors, which are aids in assembling a usable data set, two graphic utilities, statistics for comparing measured and predicted data, and a flux model. The flux model calculates and lists the rates of change for all biological processes, which should aid the users of CE-QUAL-R1 to correctly predict variable concentrations. An interactive windows package (WESWIN) is available which enables the execution of CE-QUAL-R1 and the utilities associated with it. This interface also has a plotting program which makes model calibration easier by letting the user view the model results immediately.
URL: http://www.wes.army.mil/el/elmodels

Application and Model References:

Chen, R. L., Brannon, J. M., and Gunnison, D. 1984. Anaerobic and aerobic rate coefficients for use in CE-QUAL-R1. Miscellaneous Paper E-84-5, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS. NTIS No. AD A145 499.

Collins, C. D., and Wlosinski, J. H. 1983. Coefficients for use in the U.S. Army Corps of Engineers reservoir model, CE-QUAL-R1. Technical Report E-83-15, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS. NTIS No. AD A135 733.

Environmental Laboratory. 1986. CE-QUAL-R1: A Numerical One- Dimensional Model of Reservoir Water Quality; User's Manual. Instruction Report E-82-1 (Revised Edition), US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

U.S. Army Engineer Waterways Experiment Station. 1982. CE-QUAL-R1: A numerical one-dimensional model of reservoir water quality; User's manual. Instruction Report E-82-1, Vicksburg, MS. NTIS No. AD A116 538.

U.S. Army Engineer Waterways Experiment Station. 1995. CE-QUAL-R1: A numerical one-dimensional model of reservoir water quality; User's manual. Instruction Report E-82-1, Vicksburg, MS.

Wlosinski, J. H. 1984. Evaluation techniques for CE-QUAL-R1: A one-dimensional reservoir quality model. Miscellaneous Paper E-84-1, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS. NTIS No. AD A140 766.

Wlosinski, J. H., and Collins, C. D. 1985. Confirmation of the water quality model CE-QUAL-R1 using Data from Eau Galle Reservoir, Wisconsin. Technical Report E-85-11, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS. NTIS No. AD A164 226.

CE-QUAL-RIV1**:** CE-QUAL-RIV1 is a one-dimensional hydrodynamic and water quality model, meaning that the model resolves longitudinal variations in hydraulic and quality characteristics and is applicable where lateral and vertical variations are small. CE-QUAL-RIV1 consists of two parts, a hydrodynamic code (RIV1H) and a water quality code (RIV1Q). The hydrodynamic code is applied first to predict water transport and its results are written to a file, which is then read by the quality model. It can be used to predict one-dimensional hydraulic and water quality variations in streams and rivers with highly unsteady flows, although it can also be used for prediction under steady flow conditions. RIV1H predicts flows, depths, velocities, water surface elevations, and other hydraulic characteristics. The hydrodynamic model solves the St. Venant equations as the governing flow equations using the widely accepted four-point implicit finite difference numerical scheme. 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. Numerical accuracy for the advection of sharp gradients is preserved in the water quality code through the use of the explicit two-point, fourth-order accurate, Holly-Preissman scheme.
URL: http://www.wes.army.mil/el/elmodels

Application and Model References:

Curtis, L. T., J.M. Nestler, and J.L. Martin. 1987. Comparative effects on trout habitat of hydropower modification with and without reregulation in the Cumberland River below Wolf Creek Dam, Kentucky. Miscellaneous Paper EL-87-2, U.S. *Army Engineer Waterways Experiment Station*, Vicksburg, MS. NTIS No. AD A179 787.

Environmental Laboratory. 1985. CE-QUAL-RIV1: A Dynamic, One-Dimensional (Longitudinal) Water Quality Model for Streams. User's Manual," Instruction Report EL-95-2, U.S. *Army Engineer Waterways Experiment Station*, Vicksburg, MS.

Martin, J. L. 1986. Water quality study of proposed reregulation dam downstream of Wolf Creek Dam, Cumberland River, Kentucky. Miscellaneous Paper EL-86-4, U.S. *Army Engineer Waterways Experiment Station*, Vicksburg, MS. NTIS No. AD A167 132.

Martin, J. L., T. Curtis, and J.M. Nestler. 1986. Effects of flow alterations on trout habitat in the Cumberland River below Wolf Creek Dam, Kentucky. Miscellaneous Paper EL-86-11, U.S. *Army Engineer Waterways Experiment Station*, Vicksburg, MS. NTIS No. AD A176 481.

Martin, J.L., and L. Owoputi. 1997. Water Quality Model Application to Youghiogheny Lake and River, Pennsylvania. Presented at the 17th International Symposium on Lake and Reservoir Management, Decemer 2-5, Houston, Texas.

Nestler, J. M., J.A. Gore, L.T. Curtis, and J.L. Martin. 1988. Predicted effects of hydropower uprate on trout habitat in the Cumberland River, downstream of Wolf Creek Dam, Kentucky. Miscellaneous Paper EL-88-10, U.S. *Army Engineer Waterways Experiment Station*, Vicksburg, MS. NTIS No. AD A200 562.

Owoputi, L., and J.L. Martin. 1998. Water Quality Model Application to Stonewall Jackson Lake and River, Pennsylvania. Presented at the 18th International Symposium on Lake and Reservoir Management, November 10-13, Banff, Alberta.

Schreiner, S. 1997. A Temperature Simulation Model of the Youghiogheny River From Deep Creek Station To Sang Run. Report PPRP-DC1, Maryland Power Plant Research Program, Annapolis, Maryland.

Zimmerman, M. J., and Dortch, M. S. 1988. Water quality modeling study of proposed reregulation dam downstream from Buford Dam, Chattahoochee River, Georgia. Technical Report EL-88-14, U.S. *Army Engineer Waterways Experiment Station*, Vicksburg, MS. NTIS No. AD A200 039.

CE-QUAL-W2**:** CE-QUAL-W2 is a two-dimensional, longitudinal/vertical, hydrodynamic and water quality model developed by the Waterways Experiment Station (WES). Because the model assumes lateral homogeneity, it is best suited for relatively long and narrow waterbodies exhibiting longitudinal and vertical water quality gradients. The model has been applied to rivers, lakes, reservoirs, and estuaries. Application of CE-QUAL-W2 is complicated and very time consuming. The WES website offers "A word of caution to the first time user". The model predicts water surface elevations, velocities, and temperatures. Temperature is included in the hydrodynamic calculations because of its effect on water density. Water quality. The water quality algorithms incorporate 21 constituents in addition to temperature including nutrient/phytoplankton/dissolved oxygen (DO) interactions during anoxic conditions. Any combination of constituents can be simulated. The effects of salinity or total dissolved solids/salinity on density and thus 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 additional 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). Storage

requirements for hydrodynamic output to drive the water quality model are prohibitive for anything except very small grids. Additionally, reduction in computer time is minimal when hydrodynamic data used to drive water quality are input every time step. The WERF 2001 reports over 200 applications of CE-QUAL-W2 to rivers, lakes, reservoirs, and estuaries in the U.S. and throughout the world.
URL: http://www.wes.army.mil/el/elmodels

Application and Model References:

Adams, W., E. Thackston,and R. Speece. 1997. Modeling CSO impacts from Nashville using EPA's demonstration approach. J. Environ. Engr, 123 (2), pp. 126-133.

Cole, T.M. 1994. The future role of sophisticated models in reservoir management. Lake and Reservoir Management, 9 (2):64.

Cole, T.M., and Buchak, E.M. 1995. CE-QUAL-W2: A two-dimensional, laterally averaged, hydrodynamic and water quality model, version 2.0. Instruction Report EL- 95-1, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Easley, E., L. Barness-Walz, P. Neichter, and J. Bohannon. 1994. Evaluation of water quality in Taylorsville Lake, Kentucky, using the CE-QUAL-W2 model. Lake and Reservoir Management, 9(2):71-72.

Guenduez, O, S. Soyupak, and C. Yurteri. 1998. Development of water quality management strategies for the proposed Isikli Reservoir. Reservoir Management and Water Supply - An Integrated System (P. Delojs, J. Edzwald, C. O'Melia, and G. Oskam, eds), Water Science & Technology, 37(2).

Harrison, J., and K. Anderson. 1997. Brownlee Reservoir water quality model response to nutrient and algae inflow concentration. Draft report to Idaho Power. HDR/CH2M-Hill Project Team.

Hayes, B., G. Hauser, and M. Eiffe. 1994. Two-dimensional water quality modeling of Douglas Reservoir. Lake and Reservoir Management, 9(2):80.

Kingery, D., and J. Harrison. 1997. Brownlee Reservoir: water quality model development. Draft report to Idaho Power. HDR/CH2M-Hill Project Team.

Shiao, M., P. Craig, B. Hayes, and J. Parsly. 1994. Learning reservoir water quality dynamics with computer animation. Lake and Reservoir Management, 9(2):114.

***CH3D-SED & CH3-WES*:** CH3D-SED is the newly developed mobile bed version of CH3D-WES which is a three dimensional hydrodynamic model developed for the Chesapeake Bay Program. It is applicable to rivers, streams, estuaries and coastal zones. The physical processes modeled are tides, wind, density effects (salinity and temperature) freshwater inflows, turbulence and the effect of the earth's rotation. A boundary fitted, non-orthogonal, 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. 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-ε closure for vertical momentum diffusion. Sedimentation computations are based on a two dimensional solution of the conservation of mass 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 will have negligible effects on sediment mobility characteristics. Since each grain size specification is independently tracked, however, tracking of zones of contaminated bed material is possible. Model requires substantial expertise for efficient usage. It is publicly available but not well documented.
URL: http://chl.wes.army.mil/software/ch3d

Application and Model References:

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

Chapman, R.S., B.H. Johnson, and S.R. Vemulakonda. 1996. User's Guide for the Sigma Stretched Version of CH3D-WES. Technical Report HL-96-21, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Engel, J. J., R.H. Hotchkiss, and B.R. Hall. 1995. Three Dimensional Sediment Transport Modeling Using CH3D Computer Model. Proceedings of the First International Water Resources Engineering Conference. William H. Espey Jr. and Phil G. Combs, ed., American Society of Civil Engineers, New York, 628-632.

Hall, B.R. 1996. Quantifying Sedimentation Using a Three Dimensional Sedimentation Model. Water Quality '96, Proceedings of the 11th Seminar, Corps of Engineers Committee on Water Quality, Seattle, WA, 88-93.

Johnson, B.H., R.E. Heath, B.B. Hsieh, K.W. Kim, and H.L. Butler. 1991. User's Guide for a Three-Dimensional Numerical Hydrodynamic, Salinity, and Temperature Model of Chesapeake Bay. Department of the Army, Waterways Experiment Station, Corps of Engineers, Vicksburg, MS.

Johnson, B.H., K.W. Kim, R.E., B.B. Hsieh, and H.L. Butler. 1993. Validation of Three- Dimensional Hydrodynamic Model of Chesapeake Bay. Journal of Hydraulic Engineering. 119(1):2-20.

Spasojevic, M., and F.M. Holly. 1994. Three-Dimensional Numerical Simulation of Mobile-Bed Hydrodynamics. Contract Report HL-94-2, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

DELFT3D**:** Delft3D is a 2D/3D integrated modeling environment for hydrodynamics, waves, sediment transport, morphology, water quality, particle tracking for water quality, and ecology. The FLOW module of Delft3D is a multi-dimensional calculates non-steady flow and transport phenomena resulting from tidal and meteorological forcing on a curvilinear, boundary fitted grid. The areas of applications are: 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. The sediment module (SED) of Delft3D can be applied to model the transport of cohesive and non-cohesive sediments, e.g. spreading of dredged materials, to study sediment/erosion patterns. Sedimentation takes place when the bottom shear stress drops below a critical value. The model treats each of the particulate fractions independently (i.e. sand and silt). 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. Sediment can be transferred downward from one sediment layer to an underlying layer in a process known as 'burial'. Sediment can be transferred upward to one sediment layer from an underlying layer in a process known as 'digging'. The water quality (WAQ) module can include any combination of constituents and is not limited to the number and complexity of the processes. For many water quality problems, the process formulations have been standardized in the form of a library. The water quality processes may be described by linear or non-linear functions of the selected state variables and model parameters. Typical applications of WAQ are biochemical reactions like the decay of BOD and nitrification, growth of algae (primary production) and nutrient cycling, 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, mortality of bacteria, and predation (e.g. zooplankton on phytoplankton). The PART module of DELFT3D simulates transport processes and simple chemical reactions by means of a particle tracking method using the flow data from the FLOW module. The tracks are followed in three dimensions over time, whereby a dynamic concentration distribution is obtained through averaging of separate particle tracks. DELFT3D requires huge amount of resources. According to the model web site the minimal and recommended resources are as follows:

	Minimal	**Preferred**
Processor	Pentium 166 MHz	Pentium 4 1 GHz or more
Internal memory	64 MB	512 MB or more
Free disk space	2 GB	10 GB

URL: http://www.wldelft.nl/soft/d3d/index.html

Application and Model References:

Bent E.J., L. Postma, A. Roelfzema, and R.J.H. Stive. 1991. Hydrodynamic and dispersion modeling of Swansey Bay, IK, Enivronmental Hydraulics, 1:865-870.

Gerritsen, H., A.C. Baart, and J.G. Boon. 1997. NOMADS: North Sea Model Advection Dispersion Study : experiment 3: instantaneous releases : intercomparison of 2D and 3D model results. WL, research Z2084, January 1997.

Salden, R.M., J.M. de Kok, J.G. Boon, and H. Gerritsen. 1996. NOMADS: NOrth sea Model Advection-Dispersion Study : the Dutch contribution to the simulations. WL report Z 0854/Z 0995/T 1643. (Rijkswaterstaat, RIKZ, report 96.010).

Vatvani, D., and M. Montazeri. 1989. Performance of some high accurate semi Langrangian numerical schemes for the scalar advection equation, Dt. Hydrogr. Zeitung, 42, H.3-6, Semi-Langrangian numerical Schemes, pp 279-305.
Vos, R.J., A.G. Dekker, S.W.M. Peters, G.A. van Rossum, and L.J. Hooijkaas. 1998. RESTWAQ 2, part II : comparison of remote sensing data, model results and in-situ data for the southern Frisian lakes (1998). BCRS report no. 98-08b), i.s.m. WL, IvM-VU, NIOZ, KNMI, K&M en waterschap Friesland. - ISBN 90-5411-255-7.
Vos, R.J. 1995. Restwaq : applications of remote sensing to water quality modeling : data assessment and development of methodology. WL report T1083/T1479, maart 1995, i.o.v. Rijkswaterstaat, Meetkundige Dienst.
Vos, R.J., and M. Schuttelaar. 1995. RESTWAQ : data assessment, data-model integration and application to the Southern North Sea. BCRS report no. 95-19, December 1995. ISBN 90-5411-168-2
Vos, R.J., E.J. de Goede, and R.E. Uittenbogaard. 1999. Validation of a 3D temperature model for the North Sea with in-situ data and remote sensing data. WL report Z 2506, February 1999. I.o.v. Rijkswaterstaat, RIKZ.

DYNHYD5**:** The DYNHYD5 model is a USEPA supported simple hydrodynamic model that simulates variable tidal cycles, wind, and unsteady inflows. It produces an output file that can be linked with WASP5 to supply the flows and volumes to the water quality model. It can simulate velocity, volume, and water depth in rivers and streams, estuaries and costal waters, and reservoirs and lakes. The WASP hydrodynamics model DYNHYD is an enhancement of the Potomac Estuary hydrodynamic model which was a component of the Dynamic Estuary Model. DYNHYD solves the one-dimensional equations of continuity and momentum for a branching or channel-junction (link-node), computational network. Driven by variable upstream flows and downstream heads, simulations typically proceed at one- to five-minute intervals. The resulting unsteady hydrodynamics are averaged over larger time intervals and stored for later use by the water quality program. The hydrodynamic model solves one-dimensional equations describing the propagation of a long wave through a shallow water system while conserving both momentum (energy) and volume (mass). The equation of motion, based on the conservation of momentum, predicts water velocities and flows. The equation of continuity, based on the conservation of volume, predicts water heights (heads) and volumes. This approach assumes that flow is predominantly one-dimensional, Coriolis and other accelerations normal to the direction of flow are negligible, channels can be adequately represented by a constant top width with a variable hydraulic depth, i.e., rectangular, the wave length is significantly greater than the depth, and bottom slopes are moderate. Although no strict criteria are available for the latter two assumptions, most natural flow conditions in large rivers and estuaries would be acceptable. Dam-break situations could not be simulated with DYNHYD nor could small mountain streams. Both DOS and Windows versions are available.
URL: http://www.epa.gov/ceampubl/swater/wasp/index.htm, http://www.cee.odu.edu/model/wasp.php, http://www.scisoftware.com/products/wasp_overview/wasp_overview.html

Application and Model References:
Ambrose, R., T.A. Wool, and J.L. Martin. 1993. The Dynamic Estuary Model Hydrodynamics Program, DYNHYD5: Model Documentation and User Manual. Environmental Research Laboratory. USEPA. Athens, GA.
Cusimano, R.F. 1995. Snohomish River Estuary Dry Season, TMDL Study - Phase I: Water Quality Model Calibration. Washington State Department of Ecology, Watershed Assessment Section, Olympia, Washington. 56 p.
Cusimano, R.F. 1997. Snohomish River Estuary Dry Season, TMDL Study - Phase II: Water Quality Model Confirmation and Pollutant Loading Capacity Recommendations.
Roesch, S.E., L.J. Clark, and M.M. Bray. 1979. User's Manual for the Dynamic (Potomac) Estuary Model. U.S. Environmental Protection Agency, Annapolis, MD. EPA-903/97-001.
Warwick, J.J., and K.J. Heim. 1995. Hydrodynamic Modeling of the Carson River and Lohontan Reservoir, Nevada. Water Resources Bulletin 31(1):67-77.

EFDC (Environmental Fluid Dynamics Code)**:** EFDC is a three dimensional hydrodynamic and transport model, but it can be used for two, even one-dimensional problems, though not recommended. It is applicable to estuaries, costal ocean, lakes, and reservoirs. Momentum and conservation equations form the basis of governing hydrodynamic equations. A Mellor-Yamada level 2.5 turbulence closure scheme is employed to compute vertical mixing coefficients. The model is based on the curvilinear-orthogonal horizontal grid with a sigma stretched (or topography following) vertical coordinate system. Effects of wind waves on bottom stresses can be simulated. Vegetation resistance can be simulated in submerged and emergent vegetated environments. Wetting and drying computational cells can be simulated allowing modeling of wetlands and estuaries with shallow marshes. The sediment routine used in EFDC is relatively unsophisticated. Both cohesive and non-cohesive sediments can be simulated. User is given the option to select number of sediment size classes. The model does not consider the effect of armoring which is shown to be a very important process in estuarine waterbodies. A simplistic rather obsolete heat exchange budget model is utilized. EFDC has the internal capability to simulate the transport and transformation of an arbitrary number of dissolved and suspended constituents. Transformation kinetics are specified by a user-specified subroutine. The model is written is Fortran-77 meaning that it can be used on any platform after proper calibration. However its usage requires very high level of expertise. Indirect linkages between EFDC and WASP5 and CE-QUAL-ICM water quality models are possible, as EFDC has the ability to generate outputs files already in the format for input to these water quality models. Works is going on to include EFDC to the USEPA's BASINS system. There is no web site dedicated to EFDC for providing information. Model source code and manual can be obtained by contacting:

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Application and Model References:

Hamrick, J.M. 1992. A three-dimensional environmental fluid dynamics computer code:theoretical and computational aspects. SRAMSOE #317, The College of William and Mary, Gloucester Point, VA.

Hamrick, J.M. 1992. Estuarine environmental impact assessment using a three-dimensional circulation and transport model. In Estuarine and Coastal Modeling, Proceedings of the 2nd International Conference, ed. M.L. Spaulding, et al., pp. 292-303. American Society of Civil Engineers, New York.

Hamrick, J.M. 1996. A User's Manual for the Environmental Fluid Dynamics Computer Code (EFDC). The College of William and Mary, Virginia Institute of Marine Science, Special Report 331, 234 pp.

Hamrick, J.M., and T.S. Wu. 1996. Computational design and optimization of the EFDC/HEM3D surface water hydrodynamic and eutrophication models. In Computational Methods of Next Generation Environmental Models, ed. G. Delich, Society of Industrial and Applied Mathematics, Philadelphia.

Park, K., A.Y. Kuo, J. Shen, and J.M. Hamrick. 1995. A three-dimensional hydrodynamic-eutrophication model (HEM3D): description of water quality and sediment processes submodels. The College of William and Mary, Virginia Institute of Marine Science, Gloucester Point, VA. Special Report 327, 113 pp.

Tetra Tech. 1994. User's guide for the three-dimensional EFDC hydrodynamic and salinity model of Indian River Lagoon and Turkey Creek. Final Report. Tetra Tech, Inc., Fairfax, VA.

***HSPF*:** See loading models.

***MIKE-11*:** See loading models.

***MIKE-21*:** MIKE-21 is supported and distributed by the DHI Software. It contains a comprehensive modeling system for 2D free-surface flows and is applicable to the simulation of hydraulic and related phenomena in lakes, estuaries, bays, coastal areas and seas where stratification can be neglected. 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 compiled as a true 32-bit application implying that it can only be executed under Windows 95/98 or Windows NT. MIKE-21 is constructed in a modular manner around the four main application areas:

- Coastal hydraulics and oceanography: Includes two modules: the Hydrodynamic Module (HD)and the Nested Grid Hydrodynamic Module (NHD). The HD Module (MIKE-21 HD) is the basic module in the MIKE-21 package. It provides the hydrodynamic basis for the computations performed in the modules for Sediment Processes and Environmental Hydraulics. The HD Module simulates the water level variations and flows in response to a variety of forcing functions in lakes, estuaries and coastal areas. The water levels and flows are resolved on a rectangular grid covering the area of interest when provided with the bathymetry, bed resistance coefficients, wind field, hydrographic boundary conditions, etc. The system solves the full time-dependent non-linear equations of continuity and conservation of momentum. The solution is obtained using an implicit ADI finite difference scheme of second-order accuracy. The outcome of a simulation is the water level and fluxes (velocities) in the computational domain.
- Environmental hydraulics: The group of environmental modules include Advection-Dispersion Module (AD) plus three process modules: Water Quality Module (WQ), Eutrophication Module (EU), Heavy Metal Module (ME) and Spill Analysis Module (SA). All these environmental modules are also available as nested grid versions: NAD, NWQ, NEU, NME, and NSA. All modules use output from the HD (or NHD) Module, and the AD (or NAD) Module is used automatically by the three process modules. The AD Module simulates the spreading of dissolved substances subject to

advection and dispersion processes, eg: salt, heat, coliform bacteria, xenobiotic compounds etc. Linear decay and heat dissipation to the atmosphere are included. The WQ Module used for advanced water quality studies considers the following determinants: dissolved oxygen (DO), organic matter (BOD), ammonia, nitrate, and phosphorus. EU Module simulates carbon and nutrient cycling, growth of phytoplankton and zooplankton, oxygen balance, and benthic vegetation. The state variables included in the ME modules are dissolved metal in water, adsorbed metal in water, suspended sediment, dissolved metal in the bed porewater, and metal adsorbed on sediment in the bed sediment layer thickness. The Spill Analysis Module of MIKE-21 simulates the spreading and weathering of suspended substance in an aquatic environment under the influence of the fluid transport and the associated dispersion processes.

- Sediment processes: MIKE-21 comprises three types of sediment transport models. Sand Transport Module (ST), Mud Transport Module (MT), and Particle Module (PA). ST is used to determine the sediment transport rates due to the effect of current only, or a combination of current and waves in areas with a sandy bottom. MT describes the erosion, transport and deposition of cohesive sediments (mud, silt or clay) under the action of waves and currents. The model also takes into account the consolidation of the bed. The model can be used to determine the siltation of cohesive materials in harbors, lagoons or coastal areas and to determine the fate of dredged spoils. PA describes the transport and fate of solutes or suspended matter. The model can be used to determine the fate of suspended matter that is discharged or accidentally spilled in lakes, estuaries, coastal areas or the open sea. Settling and decay processes are included.
- Waves: A range of wave modules are included in MIKE-21, each with their particular area of application. The models can be divided basically into two groups: models based on wave action concept (OSW and NSW), and models based on the momentum concept (BW, EMS and PMS). Interested reader's can find details of this module at the URL below.

The US Federal Emergency Management Agency (FEMA) has approved three modules of MIKE-21 for National Flood Insurance Program (NFIP) usage. The three modules, which are hydrodynamic module (HD/NHD), near-shore spectral wind-wave module (NSW) and offshore spectral wind-wave module (OSW), have been accepted for coastal storm surge, coastal wave height, and coastal wave effect usage.
URL: http://www.dhisoftware.com/mike21

Application and Model References:

Gierlevsen, T., M. Hebsgaard, and J. Kirkegaard. 2001. Wave Disturbance Modeling in the Port of Sines, Portugal– with special emphasis on long period oscillations. Presented at the International Conference on Port and Maritime R&D and Technology, Singapore, 29-31 October 2001.

Hansen, H.K., P. Sloth, O.R. Sørensen, and J. Fuchs. 2000. Combined numerical and physical modelling of seiching in exposed new marina. In Proceedings of 27th International Coastal Engineering Conference, 16-21 July 2000, Sydney, Australia.

Johnson, H.K., C.M. Appendini, M. Soldati, B. Elfrink, P. Sørensen. 2001. Numerical modeling of morphological changes due to shoreface nourishment. In: Proc of the 4th Conference on Coastal Dynamics, ASCE, pp.878-887. Lund, Sweden, June 2001.

McCowan, A.D., E.B. Rasmussen, and P. Berg. 2001. Improving the Performance of a Two-dimensional Hydraulic Model for Floodplain Applications. Presented at the 6th Conference on Hydraulics in Civil Engineering, I.E. Aust., 28-30 November 2001, Hobart.

Also visit http://www.dhi.dk/ContactUs/Library for additional all DHI compendium of technical papers and publications.

***MIKE-3*:** Yet another DHI product, MIKE-3, is applicable for simulations of hydrodynamics, water quality and sediment transport in all waterbodies where 3D effects are important. MIKE-3 is compatible with MIKE-21 and other DHI Software products. MIKE-3 simulates unsteady flow taking into account density variations, bathymetry and external forcing such as meteorology, tidal elevations, currents and other hydrographic conditions. MIKE-3 is designed in a modular structure with the three main components:

- Estuarine and coastal hydraulics and oceanography: The hydrodynamic module (HD) is the core of the MIKE-3 modeling system. It provides the hydrodynamic basis for computations performed in other modules (water quality, eutrophication etc). MIKE-3 HD solves the time-dependent conservation equations of mass and momentum in three dimensions, the so-called Reynolds-averaged Navier-Stokes equations, where the flow is decomposed into mean quantities and turbulent fluctuations. The flow field and pressure variation are computed in response to a variety of forcing functions, when provided with the bathymetry, bed resistance, wind field, hydrographic boundary conditions, etc. The closure problem is solved in the turbulence module through the Boussinesq eddy viscosity concept relating the Reynold stresses to the mean velocity field. To handle density variations, the equations for conservation of salinity and temperature are included and solved in the transport equation module. An equation of state (the UNESCO formulation) constitutes the relation between the density and the variations in salinity and temperature. Thus, the turbulence module and the transport equation module are integrated components of the hydrodynamic module, and the suite of those three constitutes the HD module. The hydrodynamic phenomena included in the equations are tidal propagation, effects of stratification, turbulent (shear) diffusion and dispersion, Coriolis forces, barometric pressure gradients, wind stress, variable bathymetry and bed resistance, flooding and drying of intertidal areas, hydrodynamic effects of rivers and outfalls, sources and sinks (both mass and momentum), and heat exchange with the atmosphere including evaporation and precipitation.

- Environmental hydraulics: The group of environmental modules includes the advection-dispersion module (AD), and two process modules: the water quality module (WQ) and the eutrophication module (EU). All environmental modules are similar to those used in the MIKE-11 and MIKE-21 packages. The WQ Module used for advanced water quality studies considers, dissolved oxygen (DO), organic matter (BOD), ammonia, nitrate, and phosphorus. The simulated physical, chemical and biological processes include carbon and nutrient cycling, growth of phytoplankton and zooplankton, oxygen balance, and benthic vegetation.
- Sediment processes: MIKE-3 includes two types of sediment transport modules: the mud transport module (MT) and the particle module (PA). The modules for sediment processes are also similar to those used in MIKE-11 and MIKE-21.

All facilities necessary for data preparation and analysis are contained in MIKE-3 or under the common MIKE Zero shell. The compatibility between MIKE-3 and MIKE-21 implies that many of the facilities are common in the two model packages. All input to MIKE-3 is handled through a dialogue-based user interface. The output from MIKE-3 can be either time series of points, lines, 2D maps or full 3D matrices. This output may be further processed, analyzed, printed and presented graphically as appropriate.
URL: http://www.dhisoftware.com/mike3

Application and Model References:

Reference Manual and Scientific Documentation are provided for each module within the MIKE-3 package along with an on-line help system. The URL http://www.dhi.dk/ContactUs/Library lists all DHI compendium of technical papers and publications.

***QUAL2E*:** The Enhanced Stream Water Quality Model (QUAL2E) is in public domain and is supported and distributed by USEPA. It is included in the EPA's BASINS system. QUAL2E is applicable to well mixed dendritic streams. It is basically one-dimensional and operates as a steady state model. It can simulate up to 15 water constituents including dissolved oxygen, biochemical oxygen demand, temperature, algae, organic nitrogen, ammonia, nitrite, nitrate, organic Phosphorous, and dissolved phosphorous. Advection, dispersion, dilution, constituent reactions and interactions, and sources and sinks are all considered within the model. Analyzing the impact of waste loads on the stream quality, effects of diurnal variations in meteorological data on water quality (mainly dissolved oxygen and temperature) and diurnal oxygen variations due to algal growth are some potential areas of use of QUAL2E. QUAL2E does not have a hydrodynamic component, therefore data pertinent to flow must be provided by the user. QUAL2E has been one of the most heavily used water quality models in the United States. Most of its applications were addressing dissolved oxygen problems. QUAL2EU is an enhancement to QUAL2E which allows users to perform uncertainty analysis. It offers three uncertainty options to the user: sensitivity analysis, first order error analysis, and Monte Carlo simulations. The windows version of QUAL2E greatly facilitates the input preparation. It provides screens to prepare input, run the model and visualize the model results. It also offers a help screen. The windows version comes with three examples with data sets included to demonstrate the usage of the model. This version including model manual can be downloaded from
http://www.epa.gov/waterscience/QUAL2E_WINDOWS/index.html.
The DOS version can be downloaded from
http://www.epa.gov/ceampubl/swater/qual2eu/index.htm

Application and Model References:

Brown, L.C. and T.O. Barnwell, Jr., 1987. The Enhanced Stream Water Quality Models QUAL2E and QUAL2E-UNCAS: Documentation and User's Manual. (EPA 600/3-87-007). NTIS Accession Number:PB87 202 156.

Cubilo, F., B. Rodriguez, and T.O. Barnwell, Jr.. 1992. A system for control of river water quality for the community of Madrid using Qual2E. Water Science and Technology 26(7/8):1867-1873.

Johnson, C.R., and G. Mercer. 1994. Modeling the water quality processes of the Chicago waterway. In Proceedings of the National Symposium on Water Quality, American Water Resources Association, Chicago, IL, November 6-10, 1994, p. 315.

Little, K.W. and R.E. Williams. 1992. Least squares calibration of QUAL2E. Water Environment Research 64(2):79-185.

Macaitis, B. and C. Johnson. 1993. Water quality model of the Chicago waterway. Proceedings of the 20th Anniversary Conference on Water Management in the '90s, ASCE, pp 189-192.

Melching, C. and T. Chang. 1996. Simulation of water quality for Salt Creek in northeastern Illinois. USGS Open-File Report: 96-318.

Paschal, J.E., Jr., and D.K. Mueller. 1991. Simulation of water quality and the effects of wastewater effluent on the South Platte River from Chatfield Reservoir through Denver, Colorado. Water-Resources Investigations Report 91-4016. U.S. Geological Survey, Denver, CO.

Pelletier, G. 1997. Colville River Water Quality: Pollutant Loading Capacity and Recommendations for Total Maximum Daily Loads. Report Number: 96-349, Washington State Department of Ecology. (Also available at: http://www.ecy.wa.gov/pubs/96349.pdf)

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.

WASP6 (Water quality Analysis Simulation Program)**:** WASP6 is an enhanced Windows version of the USEPA Water Quality Analysis Simulation Program (WASP). WASP6 has been developed to aid modelers in the implementation of WASP. WASP6 has features including a pre-processor, a rapid data processor, and a graphical post-processor that enable the modeler to run WASP more quickly and easily and evaluate model results both numerically and graphically. With WASP6, model execution can be performed up to ten times faster than the previous USEPA DOS version of WASP. Nonetheless, WASP6 uses the same algorithms to solve water quality problems as those used in the DOS version of WASP. The WASP6 modeling system, supported and distributed by EPA's CEAM, is a generalized modeling framework for contaminant fate and transport in surface waters. Based on flexible compartment modeling, WASP6 can be applied in one, two, or three dimensions. Problems that have been studied using WASP6 include biochemical oxygen demand, dissolved oxygen dynamics, nutrients/eutrophication, bacterial contamination, and toxic chemical movement. The WASP6 system consists of two stand-alone computer programs, DYNHYD5 and WASP6 that can be run in conjunction or separately. WASP6 is supplied with two kinetic submodels to simulate two of the major classes of water quality problems: conventional pollution (involving dissolved oxygen, biochemical oxygen demand, nutrients and eutrophication) and toxic pollution (involving organic chemicals, metals, and sediment). The linkage of either submodel with the WASP6 program gives the models EUTRO and TOXI, respectively. The hydrodynamic data can be supplied in three different ways to WASP: i) user can provide steady state flow data in a file, ii) DYNHYD5 output can be used or iii) another hydrodynamic model can be linked. The Eutrophication Model (EUTRO) combines a kinetic structure adapted from the Potomac Eutrophication Model with the WASP6 transport structure. This model predicts dissolved oxygen, carbonaceous biochemical oxygen demand, phytoplankton, carbon, chlorophyll-a, ammonia, nitrate, organic nitrogen, and orthophosphate in bed and overlying waters. The Toxic Chemical Model (TOXI) combines a kinetic structure adapted from the Exposure Analysis Modeling System (EXAMS) with the WASP6 transport structure and simple sediment balance algorithms. TOXI predicts dissolved and sorbed chemical concentrations in the bed and overlying waters. Sediment modeling is based on simple mass balance. The WASP6 package also includes three other programs: PREDYN, W5DSPLY and PLOT. PREDYN is an interactive preprocessor program for DYNHYD5. W5DSPLY is a tabular post processor program for TOXI, EUTRO and DYNHYD5. PLOT is a graphical post processor for TOXI, EUTRO and DYNHYD. WASP6 is one of the well-established models and numerous applications are available. There are several other hydrodynamic models that have been linked with WASP6: DYNHYD5, RIVMOD, EFDC and SWMM's transport module.

URL: http://www.epa.gov/ceampubl/swater/wasp/index.htm, http://www.cee.odu.edu/model/wasp.php, http://www.scisoftware.com/products/wasp_overview/wasp_overview.html

Application and Model References:

Cheng, C. J.E. Atkinson, and J.V. DePinto. 1994. A coupled GIS-water quality modeling study. In Proceedings of the 1994 Hydraulic Engineering Conference, ASCE, Buffalo, NY, 1994, pp. 247251.

Cockrum, D.K., and J.J. Warwick. 1994. Assessing the impact of agricultural activities on water quality in a periphytondominated stream using the Water Quality Analysis Program (WASP). In Proceedings of the Symposium on the Effects of Human Induced Changes on Hydrologic Systems, AWRA, Jackson Hole, WY, June 26-29, 1994, p. 1157.

Hajda, P., and V. Novotny. 1996. Modelling Impact of Urban and Upstream Nonpoint Sources on Eutrophication of the Milwaukee River. *Wat. Sci. Tech.* 44:153-158.

Minei, V., and W. Dawydiak. 1995. Controlling nitrogen inputs into the Peconic Estuary system. *2nd Annual Marine & Estuarine Shallow Water Science and Management Conf.*, USEPA, p. 32.

Lang, G.A., and T.D. Fontaine. 1990. Modeling the fate and transport of organic contaminants in Lake St. Clair. Journal of Great Lakes Research 16(2):216-232.

Lu, Z., G.C. April, D.C. Raney, and W.W. Schroeder. 1994. DO, BOD, and organic nitrogen transport in Weeks Bay, Alabama. In Proceedings of the National Symposium on Water Quality, American Water Resources Association, Chicago, IL, November 6-10, 1994, pp.

Lung, W., and C.E. Larson.1995. Water quality modeling of the upper Mississippi River and Lake Pepin. Journal of Environmental Engineering 121(10):691-699.

Tetra Tech. 1995. Hydrodynamic and water quality mathematical modeling study of Norwalk harbor, Connecticut. Final report. Tetra Tech, Inc., Fairfax, VA.

Thomann, R.V., and J.J. Fitzpatrick. 1982. Calibration and Verification of a Mathematical Model of the Eutrophication of the Patomac estuary. Prepared for Department of Environmental Services, Government of the District of Columbia, Washington, D.C.

Zhou, J., 1998. Water quality modeling of reservoir using WASP. *Proceedings of the 1998 International Water Resources Engineering Conference*, Part 2, ASCE, pp 1458-1463.