WATERSHED-SCALE HYDROLOGIC AND NONPOINT-SOURCE POLLUTION MODELS: REVIEW OF MATHEMATICAL BASES

D. K. Borah, M. Bera

ABSTRACT. *A clear understanding of a model is important for its appropriate use. In this article, eleven watershed scale hydrologic and nonpoint-source pollution models are reviewed: AGNPS, AnnAGNPS, ANSWERS, ANSWERS-Continuous, CASC2D, DWSM, HSPF, KINEROS, MIKE SHE, PRMS, and SWAT. AnnAGNPS, ANSWERS-Continuous, HSPF, and SWAT are continuous simulation models useful for analyzing long-term effects of hydrological changes and watershed management practices, especially agricultural practices. AGNPS, ANSWERS, DWSM, and KINEROS are single rainfall event models useful for analyzing severe actual or design single-event storms and evaluating watershed management practices, especially structural practices. CASC2D, MIKE SHE, and PRMS have both long-term and single-event simulation capabilities. Mathematical bases, the most important and critical elements of these mathematical models, were identified and compiled. In this article, a comprehensive summary of the compilation is presented in tabular form. The flow-governing equations and their solution methods used in each of the eleven models are discussed. The compilation of the mathematical bases of these models would be useful to determine the problems, situations, or conditions for which the models are most suitable, the accuracies and uncertainties expected, their full potential uses and limitations, and directions for their enhancements or new developments. AGNPS, AnnAGNPS, DWSM, HSPF, MIKE SHE, and SWAT were found to have all the three major components (hydrology, sediment, and chemical) applicable to watershed-scale catchments. SWAT is a promising model for continuous simulations in predominantly agricultural watersheds, and HSPF is promising for mixed agricultural and urban watersheds. Among the single-event models, DWSM provides a balance between the simple but approximate and the computationally intensive models and, therefore, is a promising storm event model for agricultural watersheds.*

Keywords. *Agriculture, Agrochemical, Hydrology, Modeling, Nonpoint-source pollution, Sediment, Water quality, Watershed.*

Flooding, upland soil and streambank erosion, sedimentation, and contamination of water from agricultural chemicals are critical environmental, social, and economical problems in Illinois and other states of the U.S. and throughout the world. For example, damages from the 1993 flood in the upper Mississippi River were extensive, \$12 to \$16 billion, with unquantifiable impacts on the health and well-being of the U.S. Midwestern population (IFMRC, 1994). According to the Illinois Environmental Protection Agency's Clean Water Act Section 303(d) list (IEPA, 2002), there are currently 11,000 stream kilometers (km) and 55,440 inland lake hectares (ha) of waters in Illinois impaired by sediment and chemicals. More specifically, some drinking water supplies, such as Lake Decatur (Demissie et al., 1996), Pontiac (Keefer et al., 1996), and Georgetown (Mitchell et al., 2000), periodically exceed the drinking water standard of 10 mg/L of nitrate-nitrogen (nitrate-N) that was set to prevent incidence of methemoglobinemia (blue baby syndrome). These surface water sources receive water from primarily agricultural lands. Other drinking water sources, such as Lake Springfield, require expensive water treatments when they periodically exceed the 3 μg/L maximum concentration level (MCL) for atrazine, a commonly used herbicide (Luepke, 1996). Lake Decatur (Fitzpatrick et al., 1987), Lake Springfield (Fitzpatrick et al., 1985), and Peoria Lake (Demissie et al., 1988) in Illinois are examples of serious lake sedimentation reducing water supply capacity of the former two, filling the navigation channel of the latter, and adversely affecting recreational opportunities in all. Court Creek and its major tributaries above Dahinda, Illinois, have serious streambank erosion problems (Roseboom et al., 1982).

Understanding and evaluating the natural processes in a watershed leading to impairments and problems are continuing challenges for scientists and engineers. Mathematical models simulating these complex processes are useful analysis tools to understand the problems and to find solutions through land-use changes and best management practices (BMPs). The models can help in the development of total maximum daily load (TMDL) standards, required by the Clean Water Act, and evaluate and select from alternative land-use and BMP scenarios, implementation of which can help meeting the standards and reduce damaging effects of

Article was submitted for review in May 2003; approved for publication by the Soil & Water Division of ASAE in September 2003. Presented at the 2002 ASAE Annual Meeting as Paper No. 022091.

The authors are **Deva K. Borah, ASAE Member Engineer,** Research Hydrologic Engineer, and **Maitreyee Bera,** Supportive Scientist, Illinois State Water Survey, Champaign, Illinois. **Corresponding author:** Deva K. Borah, Illinois State Water Survey, 2204 Griffith Drive, Champaign, IL 61820; phone: 217-244-8856; fax: 217-333-2304; e-mail: borah@uiuc.edu.

storm water runoff on water bodies and the landscape. Developing reliable watershed simulation models and validating them on real-world watersheds with measured and monitored data are also challenging. The unique hydrology in many of the agricultural watersheds in the Midwest, associated with flat terrain and the presence of extensive tile drainage, causes more challenges in modeling and searching for the most suitable model.

Some of the commonly used watershed-scale hydrologic and nonpoint-source pollution models include: Agricultural NonPoint Source pollution model or AGNPS (Young et al., 1987), Annualized Agricultural NonPoint Source model or AnnAGNPS (Bingner and Theurer, 2001), Areal Nonpoint Source Watershed Environment Response Simulation or ANSWERS (Beasley et al., 1980), ANSWERS-Continuous (Bouraoui et al., 2002), CASCade of planes in 2-Dimensions or CASC2D (Ogden and Julien, 2002), Dynamic Watershed Simulation Model or DWSM (Borah et al., 2002b), Hydrological Simulation Program - Fortran or HSPF (Bicknell et al., 1993), KINematic runoff and EROSion model or KINEROS (Woolhiser et al., 1990), the European Hydrological System model or MIKE SHE (Refsgaard and Storm, 1995), Precipitation-Runoff Modeling System or PRMS (Leavesley et al., 1983), and Soil and Water Assessment Tool or SWAT (Arnold et al., 1998). References to and descriptions of more models may be found in Singh (1995) and Singh and Frevert (2002a, 2002b). The current study deals with watershed-scale models only, and therefore, the field-scale models are not mentioned and discussed here.

Some of the models are based on simple empirical relations having robust algorithms, and the others use physically based governing equations having computationally intensive numerical solutions. The simple models are sometime incapable of giving desirable detailed results, and the detailed models are inefficient and could be prohibitive for large watersheds. Therefore, finding an appropriate model for an application and for a certain watershed is quite a challenging task. For certain applications, it is desirable to have a balance or compromise between the simple, approximate models and the detailed, computationally intensive models. Most of the commonly used models were formulated in the 1970s and 1980s, and since the early 1990s, most modeling research has focused on development of graphical user interfaces (GUI) and integration with geographic information systems (GIS) and remote sensing data. While enormous progress has been made in developing and refining interfaces, greater efforts are now needed to focus on model formulations and development of state-of-the-art models for watershed evaluation (Chen, 2001; CWM, 1999).

The main focus of this study is to take a closer look at the commonly used watershed-scale hydrologic and nonpoint-source pollution models and find their mathematical strengths and applicability to the various kinds of watersheds and problems. All the eleven models cited above were reviewed. AnnAGNPS, ANSWERS-Continuous, HSPF, and SWAT are continuous simulation models and are useful for analyzing long-term effects of hydrological changes and watershed management practices, especially agricultural practices. AGNPS, ANSWERS, DWSM, and KINEROS are single rainfall event models useful for analyzing severe actual or design single-event storms and evaluating watershed management practices, especially structural practices. CASC2D, MIKE SHE, and PRMS have both long-term and single-event simulation capabilities. The mathematical bases of different components of these models, the most important and critical elements of these mathematical models, were identified and compiled. Summary of the compilation is presented in tabular form. These compilation tables and brief discussions were presented earlier (Borah, 2002). Here in addition, the flow-governing equations and their solution methods used in each of the eleven models are discussed. Flow routing is a basic and critical component of hydrologic models as well as nonpoint-source pollution models. Performance and wide applicability of a model depends greatly on this key component. The compilation of the mathematical bases of these models would be useful to determine the problems, situations, or conditions for which the models are most suitable, the accuracies and uncertainties expected, their full potential uses and limitations, and directions for their enhancements or new developments. Based on these compilations, promising nonpoint-source pollution models are identified. Reviews of applications of the promising models are currently in progress (Borah and Bera, 2003a, 2003b, 2003c).

WATERSHED-SCALE MODEL DESCRIPTIONS

Sources and brief backgrounds of the eleven models reviewed in this study are given below. Model components or capabilities, temporal scale, watershed representation, procedures to compute rainfall excess or water balance on overland planes, overland runoff, subsurface flow, channel runoff, reservoir flow, overland sediment, channel sediment, reservoir sediment, chemicals, and BMP evaluations in each of these models are summarized in table 1 for the continuous simulation models and in table 2 for the single-event models.

AGNPS, the Agricultural NonPoint Source pollution model (Young et al., 1987, 1989), was developed at the USDA-ARS North Central Soil Conservation Research Laboratory in Morris, Minnesota. It is an event-based model simulating runoff, sediment, and transport of nitrogen (N), phosphorous (P), and chemical oxygen demand (COD) resulting from single rainfall events. Version 4.03 of the model (Young et al., 1994) was widely distributed. The model is currently undergoing extensive revisions and upgrading at the USDA-ARS National Sedimentation Laboratory (NSL) in Oxford, Mississippi, and one of its upgrades is AnnAGNPS, the Annualized Agricultural NonPoint Source model (Bingner and Theurer, 2001), for continuous simulations of hydrology, soil erosion, and transport of sediment, nutrients, and pesticides. It is designed to analyze the impact on the environment of nonpoint-source pollutants from predominantly agricultural watersheds.

ANSWERS, Areal Nonpoint Source Watershed Environment Response Simulation (Beasley et al., 1980), was developed at Purdue University in West Lafayette, Indiana, and uses a distributed parameter concept to model the spatially varying processes of runoff, infiltration, subsurface drainage, and erosion for single-event storms. The model has two major components: hydrology and upland erosion responses. The conceptual basis for the hydrologic model was taken from Huggins and Monke (1966) and for the erosion simulation from Foster and Meyer (1972). Similar to AnnAGNPS, ANSWERS-Continuous (Bouraoui and Dilla-

Table 1. Summary of watershed-scale hydrologic and nonpoint-source pollution models: continuous models.

Description/ Criteria	AnnAGNPS	ANSWERS-Continuous	HSPF	MIKE SHE	SWAT
Model components/ capabilities	Hydrology, transport of sediment, nutrients, and pesticides resulting from snowmelt, precipitation and irrigation, source accounting capability, and user interactive programs including TOPAGNPS generating cells and stream network from DEM.	Daily water balance, infiltration, runoff and surface water routing, drainage, river routing, ET, sediment detachment, sediment transport, nitrogen and phosphorous transformations, nutrient losses through uptake, runoff, and sediment.	Runoff and water quality constituents on pervious and impervious land areas, movement of water and constituents in stream channels and mixed reservoirs, and part of the USEPA BASINS modeling system with user interface and ArcViewGIS platform.	Interception-ET, overland and channel flow, unsaturated zone, saturated zone, snowmelt, exchange between aquifer and rivers, advection and dispersion of solutes, geochemical processes, crop growth and nitrogen processes in the root zone, soil erosion, dual porosity, irrigation, and user interface with pre- and post-processing, GIS, and UNIRAS for graphical presentation.	Hydrology, weather, sedimentation, soil temperature, crop growth, nutrients, pesticides, agricultural management, channel and reservoir routing, water transfer, and part of the USEPA BASINS modeling system with user interface and ArcViewGIS platform.
Temporal scale	Long term; daily or sub-daily steps.	Long term; dual time steps: daily for dry days and 30 seconds for days with precipitation.	Long term; variable constant steps (hourly).	Long term and storm event; variable steps depending numerical stability.	Long term; daily steps.
Watershed representation	Homogeneous land areas (cells), reaches, and impoundments.	Square grids with uniform hydrologic characteristics, some having companion channel elements; 1-D simulations.	Pervious and impervious land areas, stream channels, and mixed reservoirs; 1-D simulations.	2-D rectangular/square overland grids, 1-D channels, 1-D unsaturated and 3-D saturated flow layers.	Sub-basins grouped based on climate, hydrologic response units (lumped areas with same cover, soil, and management), ponds, groundwater, and main channel.
Rainfall excess on overland/ water balance	Water balance for constant sub-daily time steps and two soil layers (8-in. tillage depth and user-supplied second layer).	Daily water balance, rainfall excess using interception, Green-Ampt infiltration equation, and surface storage coefficients.	Water budget considering interception, ET, and infiltration with empirically based areal distribution.	Interception and ET loss and vertical flow solving Richards equation using implicit numerical method.	Daily water budget; precipitation, runoff, ET, percolation, and return flow from subsurface and groundwater flow.
Runoff on overland	Runoff curve number generating daily runoff following SWRRB and EPIC procedures and SCS TR-55 method for peak flow.	Manning and continuity equations (temporarily variable and spatially uniform) solved by explicit numerical scheme.	Empirical outflow depth to detention storage relation and flow using Chezy-Manning equation.	2-D diffusive wave equations solved by an implicit finite-difference scheme.	Runoff volume using curve number and flow peak using modified Rational formula or SCS TR-55 method.
Subsurface flow	Lateral subsurface flow using Darcy's equation or tile drain flow using Hooghoudt's equation and parallel drain approximation.	Subsurface flow defined by tile drainage coefficient and groundwater or interflow release fraction; unsaturated zone drainage determined using Darcy's gravity flow.	Interflow outflow, percolation, and groundwater outflow using empirical relations.	3-D groundwater flow equations solved using a numerical finite-difference scheme and simulated river-groundwater exchange.	Lateral subsurface flow using kinematic storage model (Sloan et al., 1983), and groundwater flow using empirical relations.
Runoff in channel	Assuming trapezoidal and compound cross-sections, Manning's equation is numerically solved for hydraulic parameters and TR-55 for peak flow.	Manning and continuity equations (temporarily variable and spatially uniform) solved by explicit numerical scheme.	All inflows assumed to enter one upstream point, and outflow is a function of reach volume or user-supplied demand.	1-D diffusive wave equations solved by an implicit finite-difference scheme.	Routing based on variable storage coefficient method and flow using Manning's equation adjusted for transmission losses, evaporation, diversions, and return flow.

ha, 1996; Bouraoui et al., 2002) emerged from ANSWERS as a continuous model at the Virginia Polytechnic Institute and State University in Blacksburg, Virginia. The model was expanded with upland nutrient transport and losses based on GLEAMS (Leonard et al., 1987), EPIC (Williams et al., 1984), and others.

CASC2D, CASCade of planes in 2-Dimensions, initially developed at Colorado State University in Fort Collins, Colorado (Julien and Saghafian, 1991; Julien et al., 1995), and further modified at the University of Connecticut in Storrs, Connecticut (Ogden, 1998; Ogden and Julien, 2002), is a physically based model. It simulates water and sediment in two-dimensional overland grids and one-dimensional

Table 1. Summary of watershed-scale hydrologic and nonpoint-source pollution models: continuous models (continued).

Description/ Criteria	AnnAGNPS	ANSWERS-Continuous	HSPF	MIKE SHE	SWAT
Flow in reservoir	Average outflow during runoff event is calculated based on permanent pool storage and stage, runoff volume, and coefficients derived from elevation-storage relation.	Not simulated.	Same as channel.	No information.	Water balance and user-provided outflow (measured or targeted).
Overland sediment	Uses RUSLE to generate sheet and rill erosion daily or user-defined runoff event, HUSLE for delivery ratio, and sediment deposition based on size distribution and particle fall velocity.	Raindrop detachment using rainfall intensity and USLE factors, flow erosion using unit-width flow and USLE factors, and transport and deposition of sediment sizes using modified Yalin's equation.	Rainfall splash detachment and wash off of the detached sediment based on transport capacity as function of water storage and outflow plus scour from flow using power relation with water storage and flow.	No information.	Sediment yield based on Modified Universal Soil Loss Equation (MUSLE) expressed in terms of runoff volume, peak flow, and USLE factors.
Channel sediment	Modified Einstein equation for sediment transport and Bagnold equation to determine transport capacity of flow.	Not simulated.	Non-cohesive (sand) sediment transport using user-defined relation with flow velocity or Toffaleti or Colby method, and cohesive (silt, clay) sediment transport based on critical shear stress and settling velocity.	No information.	Bagnold's stream power concept for bed degradation and sediment transport, degradation adjusted with USLE soil erodibility and cover factors, and deposition based on particle fall velocity.
Reservoir sediment	Sediment deposition based on constant detention discharge, zero transport capacity, and dilution with pool water.	Not simulated.	Same as channel.	No information.	Outflow using simple continuity based on volumes and concentrations of inflow, outflow, and storage.
Chemical simulation	Soil moisture, nutrients, and pesticides in each cell are tracked using NRCS soil databases and crop information, and reach routing includes fate and transport of nitrogen, phosphorous, and individual pesticides, and organic carbon.	Nitrogen and phosphorous transport and transformations through mineralization, ammonification, nitrification, and denitrification, and losses through uptake, runoff, and sediment.	Soil and water temperatures, dissolved oxygen, carbon dioxide, nitrate, ammonia, organic N, phosphate, organic P, pesticides in dissolved, adsorbed, and crystallized forms, and tracer chemicals chloride or bromide to calibrate solute movement through soil profiles.	Dissolved conservative solutes in surface, soil, and ground waters by solving numerically the advection-dispersion equation for the respective regimes.	Nitrate-N based on water volume and average concentration, runoff P based on partitioning factor, daily organic N and sediment adsorbed P losses using loading functions, crop N and P use from supply and demand, and pesticides based on plant leaf-area-index, application efficiency, wash off fraction, organic carbon adsorption coefficient, and exponential decay according to half lives.
BMP evaluation	Agricultural management.	Impact of watershed management practices on runoff and sediment losses.	Nutrient and pesticide management.	No information.	Agricultural management: tillage, irrigation, fertilization, pesticide applications, and grazing.

channels and has both single-event and long-term continuous simulation capabilities. Similarly, MIKE SHE (Refsgaard and Storm, 1995), based on SHE, the European Hydrological System (Abbott et al., 1986a, 1986b), is a comprehensive, distributed, and physically based model simulating water, sediment, and water quality parameters in two-dimensional overland grids, one-dimensional channels, and one-dimensional unsaturated and three-dimensional saturated flow layers. It also has both continuous long-term and single-event simulation capabilities. The model was developed by a European consortium of three organizations: the U.K. Institute of Hydrology, the French consulting firm SOGREAH, and the Danish Hydraulic Institute.

DWSM, the Dynamic Watershed Simulation Model (Borah et al., 2002b), was put together at the Illinois State Water Survey (ISWS) in Champaign, Illinois, based on research conducted over many years at several institutions (Borah et al., 1980; Borah et al., 1981; Borah, 1989a, 1989b; Ashraf and Borah, 1992; Borah et al., 1999; Borah et al., 2000, 2002c). DWSM simulates distributed surface and subsurface storm water runoff, propagation of flood waves, upland soil and streambed erosion, sediment transport, and

Table 2. Summary of watershed-scale hydrologic and nonpoint-source pollution models: single-event models.

Description/ Criteria	AGNPS	ANSWERS	CASC2D	DWSM	KINEROS	PRMS Storm Mode
Model components/ capabilities	Hydrology, soil erosion, and transport of sediment, nitrogen, phosphorous, and chemical oxygen demand from nonpoint and point sources, and user interface for data input and analysis of results.	Runoff, infiltration, subsurface drainage, soil erosion, and overland sediment transport.	Spatially varying rainfall inputs including radar estimates, rainfall excess and 2-D flow routing on cascading overland grids, continuous soil moisture accounting, diffusive wave or full-dynamic channel routing, upland erosion, sediment transport in channels, and part of U.S. Army Corps of Engineers' Watershed Modeling System with graphical user interface and GIS data processing.	Spatially varying rainfall inputs; individual hyetograph for each overland, rainfall excess, surface and subsurface overland flow, surface erosion and sediment transport, agrochemical mixing and transport, channel erosion and deposition and routing of flow, sediment, and agrochemical and flow routing through reservoirs.	Distributed rainfall inputs; each catchment element assigned to a rain gauge from a maximum of 20, rainfall excess, overland flow, channel routing, surface erosion and sediment transport, channel erosion and sediment transport, flow and sediment routing through detention structures.	Hydrology and surface runoff, channel flow, channel reservoir flow, soil erosion, overland sediment transport, and linkage to USGS data-management program ANNIE for formatting input data and analyzing simulated results.
Temporal scale	Storm event; one step is the storm duration.	Storm event; variable constant steps depending numerical stability.	Long term and storm event; variable steps depending numerical stability.	Storm event; variable constant steps.	Storm event; variable constant steps depending numerical stability.	Storm event; variable constant steps depending numerical stability.
Watershed representation	Uniform square areas (cells), some containing channels.	Square grids with uniform hydrologic characteristics, some having companion channel elements; 1-D simulations.	2-D square overland grids and 1-D channels.	Overland, channel, and reservoir segments defined by topographic-based natural boundaries; 1-D simulations.	Runoff surfaces or planes, channels or conduits, and ponds or detention storage; 1-D simulations.	Flow planes, channel segments, and channel reservoirs; 1-D simulations.
Rainfall excess on overland	Runoff curve number method.	Surface detention with empirical relations and infiltration with modified Holton-Overton relation.	Interception and ET loss, infiltration using Green-Ampt method, and overland flow retention.	Two options: simple runoff curve number procedure for computing time varying rainfall intensities, or extensive interception and Smith-Parlange infiltration procedure.	Interception loss and extensive infiltration procedure by Smith and Parlange.	Interception and infiltration using an empirically based areal distribution of point infiltration (Green-Ampt equation), similar to HSPF.
Runoff on overland	Runoff volume using runoff curve number, and flow peak using an empirical relation similar to Rational formula or SCS TR-55 method.	Manning and continuity equations (temporarily variable and spatially uniform) solved using an explicit numerical scheme.	2-D diffusive wave equations solved by explicit finite-difference scheme.	Kinematic wave equations solved using analytical and an approximate shock-fitting solutions.	Kinematic wave equations solved by an implicit numerical scheme.	Kinematic wave equations solved using a numerical scheme.

agrochemical transport in agricultural and rural watersheds during single rainfall events. Similarly, KINEROS, the KINematic runoff and EROSion model (Woolhiser et al., 1990; Smith et al., 1995), which evolved during the 1960s to the 1980s at the USDA-ARS in Fort Collins, Colorado, is a distributed rainfall-runoff and soil erosion-sediment transport model for single rainfall events.

HSPF, the Hydrological Simulation Program - Fortran (Donigian et al., 1995), first publicly released in 1980, was put together by a group of consultants (Johanson et al., 1980) under contract with the U.S. Environmental Protection Agency (USEPA). It is a continuous watershed simulation model that produces a time history of water quantity and quality at any point in a watershed. HSPF is an extension of several previously developed models: the Stanford Watershed Model (SWM) (Crawford and Linsley, 1966), the Hydrologic Simulation Program (HSP) including HSP Quality (Hydrocomp, 1977), the Agricultural Runoff Management (ARM) model (Donigian and Davis, 1978), and the Nonpoint Source Runoff (NPS) model (Donigian and Crawford, 1979). HSPF uses many of the software tools developed by the U.S. Geological Survey (USGS) for providing interactive capabilities on model input, data storage, input-output analyses, and calibration. Several versions of the model have been released: Version 8 was released in 1984 (Johanson et al., 1984), and Version 10 was released in 1993 (Bicknell et al., 1993). HSPF has been promoted and marketed by the above consultants worldwide. Its major application in the U.S. is the Chesapeake Bay basin model (Donigian et al. 1986). HSPF has been incorporated as a nonpoint-source model (NPSM) into the USEPA's Better Assessment Science Integrating Point and Nonpoint Sources (BASINS), which was developed by Tetra Tech, Inc. (Lahlou et al., 1998), under contract with the USEPA. The main

Table 2. Summary of watershed-scale hydrologic and nonpoint-source pollution models: single-event models (continued).

Description/ Criteria	AGNPS	ANSWERS	CASC2D	DWSM	KINEROS	PRMS Storm Mode
Subsurface flow	Not simulated.	Water moving from a control zone to tile drainage and groundwater release or interflow depending on infiltration rate, total porosity, and field capacity.	Not simulated.	Combined interflow, tile drain flow, and base flow using Sloan et al. (1983) kinematic storage equation and spatially uniform and temporarily varying continuity equation.	Not simulated.	No subsurface simulation in the storm mode.
Runoff in channel	Included in the overland cells.	Same as overland.	Two options: 1-D diffusive wave equations solved by explicit finite-difference method mostly for headwater channels, or implicit finite-difference solution of the 1-D full dynamic equations for limited subcritical flows.	Same as overland.	Same as overland.	Same as overland.
Flow in reservoir	Flow routing through impoundments associated with terrace systems having pipe outlets.	Not simulated.	Not simulated.	Modified-Puls method; solving analytically the temporarily varying and spatially uniform continuity equation.	Finite difference solution of the temporarily varying and spatially uniform continuity equation.	Modified-Puls method; solving the temporarily varying and spatially uniform continuity equation.
Overland sediment	Soil erosion using USLE and routing of clay, silt, sand, and small and large aggregates through cells based on steady-state continuity, effective transport capacity from a modification of the Bagnold stream power equation, fall velocity, and Manning's equation.	Raindrop detachment using USLE factors and flow erosion and transport of four sizes (0.01 to 0.30 mm) using modified Yalin's equation and an explicit numerical solution of the steady-state continuity equation.	Soil erosion and sediment deposition are computed using modified Kilinc-Richardson equation with USLE factors and conservation of mass.	Raindrop detachment and sediment transport, scour, and deposition of user-specified particle size groups based on sediment transport capacity and approximate analytical solution of temporarily and spatially varying continuity equation.	Raindrop detachment and sediment transport, scour, and deposition of one particle size based on sediment transport capacity and explicit numerical solution of temporarily and spatially varying continuity equation.	Raindrop detachment based on rainfall intensity, overland flow detachment based on transport capacity, and routing based on sediment continuity.
Channel sediment	Included in overland cells.	Assumed negligible and not simulated.	Sand-size total sediment load is computed using Yang's unit stream power method.	Streambed scour/deposition and sediment transport of the same size groups based on sediment transport capacity and approximate analytical solution of temporarily and spatially varying continuity equation.	Streambed scour/deposition and sediment transport of the same sediment size based on sediment transport capacity and explicit numerical solution of temporarily and spatially varying continuity equation.	Sediment delivered from flow planes is transported as conservative substance without detachment and deposition.

purpose of BASINS is to analyze for and develop TMDL standards and guidelines nationwide.

PRMS, the Precipitation-Runoff Modeling System (Leavesley et al., 1983, Leavesley and Stannard, 1995), developed at the USGS in Lakewood, Colorado, is a modular design, distributed-parameter, physical-process watershed model that was developed to evaluate the effects of various combinations of precipitation, climate, and land use on watershed response. Watershed response to normal and extreme rainfall and snowmelt can be simulated to evaluate changes in water-balance relations, flow regimes, flood peaks and volumes, soil-water relations, sediment yields, and groundwater recharge. PRMS has been coupled with USGS's data management program ANNIE (Lumb et al., 1990) and the U.S. Weather Service's Extended Streamflow Prediction (ESP) program (Day, 1985) to produce a watershed-modeling and data-management system for hydrologic simulation and data analysis. PRMS has both long-term

Table 2. Summary of watershed-scale hydrologic and nonpoint-source pollution models: single-event models (continued).

Description/ Criteria	AGNPS	ANSWERS	CASC2D	DWSM	KINEROS	PRMS Storm Mode
Reservoir sediment	Sediment routing through impoundments associated with terrace systems having pipe outlets.	Not simulated.	Not simulated.	Assumes all sediments are trapped and no downstream discharge.	For shallow ponds, erosion and deposition are simulated with a mean particle diameter; for reservoirs, deposition is simulated with a particle size distribution.	Not simulated.
Chemical simulation	Nitrogen and phosphorous in runoff using extraction coefficients, and sediment using enrichment ratios and chemical oxygen demand in runoff water assuming accumulative without loss.	Not simulated.	Not simulated.	Nutrients and pesticides are simulated in dissolved and adsorbed phases with water and sediment, respectively, through mixing and exchange between rainfall, runoff, soil, and pore water, and routing through overland and channel segments using approximate analytical solutions of spatially and temporarily varying continuity equations.	Not simulated.	Not simulated.
BMP evaluation	Agricultural management.	Agricultural management.	No information.	Detention basins, alternative ground covers, and alterations to hydrologic and hydraulic conditions.	Detention basins and alterations to hydrologic and hydraulic conditions.	No information.

and single-storm modes. The long-term mode of PRMS is only a hydrological model. The storm mode of PRMS has a sediment component as well. Therefore, only PRMS Storm Mode is considered and discussed here.

SWAT, the Soil and Water Assessment Tool (Arnold et al., 1998; Neitsch et al., 2002), was developed at the USDA-ARS Grassland, Soil, and Water Research Laboratory in Temple, Texas. It emerged mainly from SWRRB (Arnold et al., 1990) and features from CREAMS (Knisel, 1980), GLEAMS (Leonard et al., 1987), EPIC (Williams et al., 1984), and ROTO (Arnold et al., 1995). It was developed to assist water resources managers in predicting and assessing the impact of management on water, sediment, and agricultural chemical yields in large ungauged watersheds or river basins. The model is intended for long-term yield predictions and is not capable of detailed single-event flood routing. It is an operational or conceptual model that operates on a daily time step. The model has eight major components: hydrology, weather, sedimentation, soil temperature, crop growth, nutrients, pesticides, and agricultural management. Although most of the applications of SWAT have been on a daily time step, recent additions to the model are the Green and Ampt (1911) infiltration equation using rainfall input at any time increment, and channel routing at an hourly time step (Arnold, 2002). Similar to HSPF, SWAT is also incorporated into the USEPA's BASINS for nonpoint-source simulations on agricultural lands.

Flow-Governing Equations

Flow-governing equations are basic to all the hydrologic models as well as nonpoint-source pollution models. Performance and applicability of a model depends largely on these basic equations.

Dynamic Wave Equations

The basic flow-governing equations are the dynamic wave equations, often referred to as the St. Venant equations or shallow water wave equations. These consist of the equations of continuity and momentum for gradually varied unsteady flow, respectively, expressed as (Singh, 1996):

$$\frac{\partial h}{\partial t} + \frac{\partial Q}{\partial x} = 0 \qquad (1)$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + g\frac{\partial h}{\partial x} = g\left(S_0 - S_f\right) \qquad (2)$$

where

h = flow depth (m)
Q = flow per unit width (m^3 s^{-1} m^{-1})
u = water velocity (m s^{-1})
g = acceleration due to gravity (m s^{-2})
S_0 = bed slope (m m^{-1})
S_f = energy gradient (m m^{-1})
t = time (s)
x = longitudinal distance (m).

There is no analytical solution of equations 1 and 2. Approximate numerical solutions of these two equations have been used in river flood routing models, such as the U.S. Army Corps of Engineers' Unsteady flow through a full NETwork of open channels (UNET) model (Barkau, 1993), the National Weather Service's OPERational Dynamic Wave (DWOPER) model (Fread, 1978), and models by Balloffet and Scheffler (1982), Strelkoff (1970), and Amein and Fang (1970), to name a few.

The dynamic wave equations have not been used in watershed models because of their computationally intensive numerical solutions. Only the CASC2D model uses these equations on a limited basis. Some of the models use approximations of these equations, ignoring certain terms in the momentum equation (eq. 2), as discussed below.

Diffusive Wave Equations

The diffusive wave equation consists of the continuity and simplified momentum equations, respectively expressed as (Singh, 1996):

$$\frac{\partial h}{\partial t}+\frac{\partial Q}{\partial x}=q \qquad (3)$$

$$\frac{\partial h}{\partial x}=S_0-S_f \qquad (4)$$

where q is the lateral inflow per unit width and per unit length ($m^3\ s^{-1}\ m^{-1}\ m^{-1}$).

The continuity equation (eq. 3) includes lateral inflow. The simplified momentum equation (eq. 4) expresses the pressure gradient as the difference between the bed slope and energy gradient, and is derived from equation 2 after ignoring the first two terms, representing respectively the local and convective accelerations.

Similar to the dynamic wave equations, there is no analytical solution of the diffusive wave equations (eqs. 3 and 4). Watershed models CASC2D and MIKE SHE use approximate numerical solutions of these equations for routing surface runoff over overland planes and through channel segments. CASC2D uses two different numerical methods to solve equations 3 and 4 for overland flow and channel flow (Ogden and Julien, 2002). While solving these equations, Manning's formula is used to compute flow, which is expressed as:

$$Q=\frac{1}{n}AR^{2/3}S_f^{1/2} \qquad (5)$$

where

n = Manning's roughness coefficient
A = flow cross-sectional area per unit width ($m^2\ m^{-1}$)
R = hydraulic radius (m).

Kinematic Wave Equations

The kinematic wave equations are the simplest form of the dynamic wave equations. Lighthill and Whitham (1955) developed the kinematic wave theory and used it to describe the movement of flood waves in long rivers. Kinematic wave theory is now a well-accepted tool for modeling a variety of hydrological processes (Singh, 1996). The governing equations consist of the continuity equation and the simplest form of the momentum equation, ignoring all the acceleration and pressure gradient terms of equation 2, respectively expressed as:

$$\frac{\partial h}{\partial t}+\frac{\partial Q}{\partial x}=q \qquad (6)$$

$$S_0=S_f \qquad (7)$$

The momentum equation (eq. 7) expresses simply as energy gradient equal to bed slope. Any suitable law of flow resistance can be used to express this equation as a parametric function of the stream hydraulic parameters. A widely used expression is:

$$Q=\alpha h^m \qquad (8)$$

where α is the kinematic wave parameter, m is the kinematic wave exponent, and α and m are related to channel (or plane) roughness and geometry. Manning's formula (eq. 5) may be used to define α and m in terms of Manning's roughness coefficient (n) and channel or plane geometry (Borah, 1989a).

Equations 6 and 8 constitute the kinematic wave equations. The advantage of these equations is that they have an analytical solution through using the method of characteristics (Borah et al., 1980). The equations generate only one system of characteristics, which means that they cannot represent waves traveling upstream, as in the case of backwater flow. Research suggests that for most cases of hydrological significance, the kinematic wave solution would give accurate results (Singh, 2002). In open channel flow, dynamic waves always occur. The friction and slope terms modify the wave amplitudes, and modifications are made to such a degree that dynamic waves rapidly become negligible and the kinematic wave assumes the dominant role.

The analytical solution of equations 6 and 8 does not apply when two characteristics intersect, forming a shock wave and physically representing a larger and faster wave superseding a smaller and slower wave. Approximate numerical solutions of equations 6 and 8, such as the ones presented by Li et al. (1975) and Smith et al. (1995) do not recognize the shocks. Therefore, the numerical solutions can be used under any situation. However, the numerical solutions smooth out the waves and the hydrographs (Borah et al., 1980), thus undermining the fundamental reason why Lighthill and Whitham (1955) introduced this simple theory. With the analytical solution, the kinematic wave theory represents salient features of a hydrograph, including the sharp rising part under shock-forming conditions (Borah et al., 1980).

Watershed models DWSM, KINEROS, and PRMS are based on the kinematic wave equations. KINEROS (Smith et al., 1995) and PRMS (Leavesley and Stannard, 1995) use approximate numerical solutions of equations 6 and 8, while DWSM uses the analytical and an approximate shock-fitting (closed form) solution (Borah, 1989a; Borah et al., 1980).

Storage-Based or Nonlinear Reservoir Equations

Many of the models, such as ANSWERS, ANSWERS-Continuous, and HSPF, use the simple storage-based (nonlinear reservoir) equations for flow routing. The equations consist of the spatially uniform and temporarily variable continuity equation and a flow equation expressed in terms of channel (or plane) roughness and geometry, such as Manning's equation, as expressed below:

$$\frac{ds}{dt} = I - O \quad (9)$$

$$Q = \frac{1}{n} AR^{2/3} S_0^{1/2} \quad (10)$$

where

s = storage volume of water (m^3)

I = inflow rate ($m^3\ s^{-1}$)

O = outflow rate ($m^3\ s^{-1}$).

Equations 9 and 10 assume a leveled water surface throughout the overland plane or channel segment and do not represent any waveforms. Equation 9 is more appropriate for flood routing in lakes and reservoirs.

Curve Number and Empirical Equations

Many of the models, such as SWAT, AGNPS, and AnnAGNPS, do not route water using mass conservation-based continuity equations as described above. SWAT and AnnAGNPS maintain water balance through accounting daily or subdaily water budgets. All three of them use the USDA Soil Conservation Service runoff curve number method (SCS, 1972) to compute runoff volumes and other empirical relations similar to the Rational formula (Kuichling, 1889) to compute peak flows, which may be expressed as:

$$Q_r = \frac{(P - 0.2S_r)^2}{P + 0.8S_r} \quad (11)$$

$$S_r = \frac{25400}{CN} - 254 \quad (12)$$

$$Q_p = 0.0028CiA \quad (13)$$

where

Q_r = direct runoff (millimeters or mm)

P = accumulated rainfall (mm)

S_r = potential difference between rainfall and direct runoff (mm)

CN = curve number representing runoff potential for a soil cover complex (values 2 to 100)

Q_p = peak runoff rate ($m^3\ s^{-1}$)

C = the runoff coefficient (values 0.02 to 0.95)

i = rainfall intensity (mm h^{-1})

A = watershed area (ha).

In addition, SWAT uses an empirical procedure to route water through the channels. The SCS runoff curve number method (eqs. 11 and 12) is also used repeatedly by DWSM to compute rainfall excess rates at discrete time intervals in addition to an interception-infiltration alternative procedure (table 2). Interception-infiltration routines are used by other models as well: ANSWERS, ANSWERS-Continuous, CASC2D, HSPF, KINEROS, MIKE SHE, and PRMS (tables 1 and 2). The latest version of SWAT (Neitsch et al., 2002) has an option for using an infiltration equation for any time increment.

Mathematical Bases of the Watershed Models

Mathematical bases or computational techniques of different components of the eleven models listed above, along with some important features or structures of the models, were identified and compiled. The compilation is presented in tabular form: table 1 for the continuous models, and table 2 for the single-event models. As outlined above, AnnAGNPS, ANSWERS-Continuous, HSPF, and SWAT are long-term continuous simulation models, and AGNPS, ANSWERS, DWSM, KINEROS, and PRMS Storm Mode are single-event models. MIKE SHE and CASC2D have both long-term and single-event simulation capabilities. These two models are listed separately; MIKE SHE is presented in table 1 with the continuous models, and CASC2D is listed in table 2 with the single-event models.

The compilation of the mathematical bases of the models shown in tables 1 and 2 would help to determine the problems, situations, or conditions for which the models are most suitable, the accuracies and uncertainties expected, their full potential uses and limitations, and directions for enhancements or new developments. A few examples are cited below.

Long-Term Continuous and Short-Term Storm Event Models

AnnAGNPS, ANSWERS-continuous, HSPF, and SWAT (table 1) are continuous simulation models and are useful for analyzing long-term effects of hydrological changes and watershed management practices, especially agricultural practices. HSPF is capable of simulating urban and suburban land uses as well. Due to its use of daily time steps, SWAT does not simulate single-event storms adequately. HSPF can use time steps smaller than a day and, therefore, can simulate individual storm events. However, due to its conceptualization of the overland (sub-basin) areas as leveled detention storage and use of the storage-based or nonlinear flow equations in routings, HSPF is not adequate for simulating intense single-event storms, especially for large sub-basins and long channels. It is unable to represent single-event flood waves. Similarly, AnnAGNPS and ANSWERS-Continuous are also not adequately formulated to simulate intense single-event storms. Intense single-event storms are critical when most of the yearly sediment and pollutant loads are carried through and out of a watershed (David et al., 1997; Borah et al., 2003). Certain BMPs, such as structural BMPs, must be designed to withstand certain single-event design storms. This is recognized by other scientists as well: "Event simulation at a number of scales is critical, as is the simulation of actual topography and riparian zone function for hydro and sediments" (Johnston, 2002).

Single storm event models, such as AGNPS, ANSWERS, DWSM, KINEROS, and PRMS Storm Mode (table 2), are needed for analyzing severe actual or design single-event storms and evaluating watershed management practices, especially structural practices. The conceptual design and mathematical formulations of these models are different. AGNPS (table 2) is a single-event, empirically based, lumped-parameter model using one time step (storm duration) and generating a single value for each of the output variables: runoff volume, peak flow, sediment yield, and average concentrations of nutrients. It is used to study the overall response from a single severe or design storm, but it is not suitable for analyzing a storm when the flow and constituent concentrations and loads vary drastically. Use of AGNPS in studying impacts of BMPs is also qualitative (Borah et al., 2002a). CASC2D (table 2) and MIKE SHE (table 1) are both single-event and long-term continuous simulation models.

Model Algorithms and Efficiencies

CASC2D and MIKE SHE are both physically based models using multi-dimensional flow-governing equations with numerical solution schemes, which make the models computationally intensive and subject to numerical instabilities, inherent to the numerical solutions. Both models use the diffusive wave equations (eqs. 3 and 4), and CASC2D uses the full dynamic wave equations (eqs. 1 and 2) on a limited basis, i.e., stream channels less than 0.3 percent slope (Ogden and Julien, 2002). Molnar and Julien (2000) examined the effects of grid size on the calculation of surface runoff when using the CASC2D model. A sufficiently small time step is necessary to keep the model stable. The time step is of the order of 5 seconds for a 150 m grid size but decreases to about 1 second when using standard 30 m GIS grid sizes. Calculation time can become prohibitive when the number of model grid cells exceeds 100,000 (Ogden and Julien, 2002). Therefore, CASC2D and MIKE SHE would be suitable for small areas or watersheds for detailed studies of hydrology and nonpoint-source pollution under single rainfall events or for long-term periods in continuous mode.

Similar to CASC2D and MIKE SHE, the ANSWERS, KINEROS, and PRMS Storm Mode models (table 2) are also physically based using numerical solutions while solving the flow equations. ANSWERS uses the storage-based equations (eqs. 9 and 10), and PRMS and KINEROS use the kinematic wave equations (eqs. 6 and 8). These models were developed for single rainfall events using one-dimensional flow equations only, and therefore are less computationally intensive than CASC2D and MIKE SHE. However, potential numerical problems inherent to the numerical solutions exist. Smith et al. (1995) suggested that KINEROS does a relatively good job of simulating runoff and sediment yield at watershed scales of up to approximately 1000 ha. Therefore, applications of these models are limited to small watersheds and specific combinations of space and time increments for maintaining stability of the numerical solutions. DWSM (table 2), also a physically based model, uses analytical and approximate analytical solutions of the governing equations and is not limited to space and time increment sizes. It uses the kinematic wave flow-governing equations (eqs. 6 and 8). Due to its robust closed-form solutions and algorithms, DWSM could potentially be used for large watersheds.

Fully Developed Continuous Models

AnnAGNPS, ANSWERS-Continuous, HSPF, MIKE SHE, and SWAT are long-term continuous simulation models having hydrology, sediment, and chemical components, applicable to watershed-scale catchments. SWAT is a promising continuous model for agricultural and forest land uses, and HSPF is suitable for urban, and mixed-urban, agricultural, and forest land uses. Both models have subsurface flow components, which are useful for flat Midwestern watersheds. Both models were extensively used in recent years due to their adoption in the USEPA's BASINS for developing TMDL standards and guidelines. With BASINS, both models have graphical user interfaces for data analysis, data processing, and graphical presentation of model outputs, which are useful for model calibration, validation, and analysis of BMPs and dissemination of model results.

The basic principles and procedures of AnnAGNPS (table 1) are similar to those of SWAT. AnnAGNPS is a recent upgrade of the single-event AGNPS model. Similarly, ANSWERS-Continuous is a recent upgrade of the single-event ANSWERS model with extensive upland process simulations. However, ANSWERS-Continuous does not have channel erosion and sediment transport routines, and therefore the sediment and chemical components are not applicable to watersheds. Due to the computationally intensive numerical schemes, MIKE SHE may become prohibitive for long-term continuous simulations in medium to large-sized watersheds.

Fully Developed Storm Event Models

AGNPS, DWSM, and MIKE SHE are the single storm event models having hydrology, sediment, and chemical components that are applicable to watershed-scale catchments. DWSM is a promising storm event model for agricultural and rural watersheds. A subsurface flow component was recently added to the model (Borah et al., 2000), and therefore the model is suitable for flat Midwestern watersheds with extensive tile-drained lands. Tile drainage is lumped with the subsurface flow through a parameter called the effective lateral saturated hydraulic conductivity, mostly estimated through model calibration and validation with observed flow data. The model has given satisfactory results from Illinois watersheds having flat topography and extensive tile drainage (Borah et al., 2000, 2001, 2002c).

AGNPS (table 2) is a lumped-parameter model using one time step (storm duration) and generating a single value for each of the output variables; it therefore cannot predict time-varying water, sediment, and chemical discharges, which are critical in certain analyses. For example, peak flows, peak constituent concentrations, and their timings are crucial information in flood warning, floodwater management, watershed assessment, and BMP evaluations. Additionally, AGNPS does not have a subsurface flow component. As mentioned earlier, due to the computationally intensive numerical schemes, MIKE SHE may become prohibitive for medium to large-sized watersheds. Therefore, DWSM provides a balance between the simple (lumped) and complicated (computationally intensive) models.

Further Uses of Tables 1 and 2

The descriptions presented in tables 1 and 2 may not be extensive, but they provide a basis for objectively comparing the models for appropriate uses and applications. The descriptions presented in these tables can be used to make preliminary selection of a model for an application depending on the problem, watershed size, desired spatial and temporal scales, expected accuracy, user's skills, etc. These tables could be also used to find strengths, weaknesses, and directions for enhancements of the models, or perhaps new developments. These tables can be expanded with other aspects of modeling, such as level of effort and computer resources needed to run each of the models.

Summary and Conclusions

Eleven watershed-scale hydrologic and nonpoint-source pollution models were reviewed: AGNPS, AnnAGNPS, ANSWERS, ANSWERS-Continuous, CASC2D, DWSM, HSPF, KINEROS, MIKE SHE, PRMS Storm Mode, and SWAT. The mathematical bases of different components of these models were identified, compiled, and documented in tabular form. The compilation will be useful for selecting the most suitable model for an application depending upon the problem, watershed size, desired spatial and temporal scales, expected accuracy, user's skills, computer resources, etc. It would be also helpful to find strengths, weaknesses, and directions for enhancements of the models, or perhaps new developments.

AnnAGNPS, ANSWERS-Continuous, HSPF, and SWAT are useful for long-term continuous simulations and assessments of hydrological changes and watershed management practices, especially agricultural practices. AGNPS, ANSWERS, DWSM, KINEROS, and PRMS Storm Mode are useful in studying single severe or design storms and evaluating watershed management practices, especially structural practices. CASC2D and MIKE SHE are suitable for the study of both long-term conditions and single-event storms.

AGNPS, AnnAGNPS, DWSM, HSPF, MIKE SHE, and SWAT have all the three major components: hydrology, sediment, and chemical. CASC2D and KINEROS have complete hydrology and sediment components, but no chemical. ANSWERS and PRMS Storm Mode have hydrology and overland sediment, but no chemical component, and no sediment simulation in stream channels. ANSWERS-Continuous has hydrology and overland sediment and chemical components, but does not have stream sediment and chemical processes. In addition, AGNPS, CASC2D, KINEROS, and PRMS Storm Mode have no subsurface flow simulations.

CASC2D, DWSM, KINEROS, MIKE SHE, and PRMS use physically based flow-governing equations and are capable of representing flood wave propagation from single rainfall events. ANSWERS, ANSWERS-Continuous, and HSPF use storage-based flow equations and are not capable of representing flood waves. AGNPS, AnnAGNPS, and SWAT use SCS runoff curve number and other empirical relations to compute runoff volumes and peak flows and are not capable of representing flood waves.

Most of the models using physically based flow-governing equations (CASC2D, KINEROS, MIKE SHE, and PRMS) use approximate numerical solutions of the equations, which are subject to numerical instability problems and limited on space and time increments and watershed sizes. Only DWSM uses robust analytical and approximate analytical solutions of the equations, is not limited by space and time increments, and has potential for large watersheds.

AnnAGNPS, HSPF, MIKE SHE, and SWAT are the long-term continuous simulation models having all the three major components (hydrology, sediment, and chemical) that are applicable to watershed-scale catchments. AGNPS, DWSM, and MIKE SHE are the storm event simulation models having all three components. SWAT is a promising model for continuous simulations in predominantly agricultural watersheds, and HSPF is suitable for mixed agricultural and urban watersheds. AnnAGNPS, which is a relatively newer model, is similar to SWAT. Among the single-event models, DWSM is a promising model for agricultural and rural watersheds. AGNPS is simple and lumped for single-event storms, in addition to its lack of subsurface flow routine, and MIKE SHE is too complicated for efficient applications in large watersheds. DWSM provides a balance and compromise between the simple and the complicated storm event models.

The model comparisons (tables 1 and 2) presented here may not be complete; however, they provide a basis for objective comparison of the models and for expanding the comparison with other aspects of modeling. Human and computer resources needed to use each of the models must be assessed. User friendliness in processing input data and analyzing output results while conducting calibration and validation must be also taken into account. Finally, the models must be applied to watersheds with different sizes and from different climatic, hydrologic, and geologic conditions to evaluate their performances and suitability.

Acknowledgements

This article is based on work supported by the Illinois Council on Food and Agricultural Research (Contract No. 02Si-009-5A) and the Illinois State Water Survey (ISWS). We thank Alena Bartosova, ISWS; Prasanta K. Kalita, Agricultural Engineering Department, University of Illinois at Urbana-Champaign; John E. Gilley, USDA-ARS, Lincoln, Nebraska; and the three anonymous peer reviewers for reviewing and editing the manuscript and providing useful comments and suggestions.

References

Abbott, M. B., J. C. Bathurst, J. A. Cunge, P. E. O'Connell, and J. Rasmussen. 1986a. An introduction to the European Hydrological System - Système Hydrologique Européen, "SHE", 1: History and philosophy of a physically based distributed modeling system. *J. Hydrology* 87(1-2): 45-59.

Abbott, M. B., J. C. Bathurst, J. A. Cunge, P. E. O'Connell, and J. Rasmussen. 1986b. An introduction to the European Hydrological System - Système Hydrologique Européen, "SHE", 2: Structure of a physically based distributed modeling system. *J. Hydrology* 87(1-2): 61-77.

Amein, M., and C. S. Fang. 1970. Implicit flood routing in natural channels. *J. Hydraulics Division, Proc. ASCE* 96(12): 2481-2500.

Arnold, J. G. 2002. Personal communication on 4 September 2002. Temple, Texas: USDA-ARS Grassland, Soil, and Water Research Laboratory.

Arnold, J. G., J. R. Williams, A. D. Nicks, and N. B. Sammons. 1990. *SWRRB - A Basin-Scale Simulation Model for Soil and Water Resources Management*. College Station, Texas: Texas A&M Press.

Arnold, J. G., J. R. Williams, and D. R. Maidment. 1995. Continuous-time water and sediment-routing model for large basins. *J. Hydraulic Eng.* 121(2): 171-183.

Arnold, J. G., R. Srinivasan, R. S. Muttiah, and J. R. Williams. 1998. Large-area hydrologic modeling and assessment: Part I. Model development. *J. American Water Resources Assoc.* 34(1): 73-89.

Ashraf, M. S., and D. K. Borah. 1992. Modeling pollutant transport in runoff and sediment. *Trans. ASAE* 35(6): 1789-1797.

Balloffet, A., and M. L. Scheffler. 1982. Numerical analysis of the Teton dam failure flood. *J. Hydraulic Research* 20(4): 317-328.

Barkau, R. L. 1993. *UNET: One-Dimensional Unsteady Flow through a Full Network of Open Channels: User's Manual*. Davis, Cal.: U.S. Army Corps of Engineers, Hydrologic Engineering Center.

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

Bicknell, B. R., J. C. Imhoff, J. L. Kittle, Jr., A. S. Donigian, Jr., and R. C. Johanson. 1993. *Hydrologic Simulation Program - FORTRAN (HSPF): User's Manual for Release 10*. Report No. EPA/600/R-93/174. Athens, Ga.: U.S. EPA Environmental Research Lab.

Bingner, R. L., and F. D. Theurer. 2001. *AnnAGNPS Technical Processes: Documentation Version 2*. Available at www.sedlab.olemiss.edu/AGNPS.html. Accessed 3 October 2002.

Borah, D. K. 1989a. Runoff simulation model for small watersheds. *Trans. ASAE* 32(3): 881-886.

Borah, D. K. 1989b. Sediment discharge model for small watersheds. *Trans. ASAE* 32(3): 874-880.

Borah, D. K. 2002. Watershed-scale nonpoint-source pollution models: Mathematical bases. ASAE Paper No. 022091. Presented at the 2002 ASAE Annual International Meeting/CIGR World Congress. St. Joseph, Mich.: ASAE.

Borah, D. K., and M. Bera. 2003a. HSPF model evaluation based on formulations and applications. In *Proc. 2003 Spring Specialty Conference on Agricultural Hydrology and Water Quality*, CD-ROM. Middleburg, Va.: American Water Resources Association.

Borah, D. K., and M. Bera. 2003b. SWAT model background and application reviews. ASAE Paper No. 032054. Presented at the 2003 ASAE Annual International Meeting. St. Joseph, Mich.: ASAE.

Borah, D. K., and M. Bera. 2003c. Watershed-scale hydrologic and nonpoint-source pollution models for long-term continuous and storm event simulations. In *Proc. Total Maximum Daily Load Environmental Regulations Conference*, 161-167. St. Joseph, Mich.: ASAE.

Borah, D. K., S. N. Prasad, and C. V. Alonso. 1980. Kinematic wave routing incorporating shock fitting. *Water Resources Research* 16(3): 529-541.

Borah, D. K., C. V. Alonso, and S. N. Prasad. 1981. Single-event numerical model for routing water and sediment on small catchments. Appendix 1 in *Stream Channel Stability.* Oxford, Miss.: USDA Sedimentation Laboratory.

Borah, D. K., M. Bera, S. Shaw, and L. Keefer. 1999. Dynamic modeling and monitoring of water, sediment, nutrients, and pesticides in agricultural watersheds during storm events. Contract Report No. 655. Champaign, Ill.: Illinois State Water Survey.

Borah, D. K., R. Xia, and M. Bera. 2000. Hydrologic and water quality model for tile-drained watersheds in Illinois. ASAE Paper No. 002093. Presented at the 2000 ASAE Annual International Meeting. St. Joseph, Mich.: ASAE.

Borah, D. K., R. Xia, and M. Bera. 2001. DWSM - A dynamic watershed simulation model for studying agricultural nonpoint-source pollution. ASAE Paper No. 012028. Presented at the 2001 ASAE Annual International Meeting. St. Joseph, Mich.: ASAE.

Borah, D. K., M. Demissie, and L. Keefer. 2002a. AGNPS-based assessment of the impact of BMPs on nitrate-nitrogen discharging into an Illinois water supply lake. *Water International* (International Water Resources Association) 27(2): 255-265.

Borah, D. K., R. Xia, and M. Bera. 2002b. DWSM - A dynamic watershed simulation model. Chapter 5 in *Mathematical Models of Small Watershed Hydrology and Applications*, 113-166. V. P. Singh and D. K. Frevert, eds. Highlands Ranch, Colo.: Water Resources Publications.

Borah, D. K., R. Xia, and M. Bera. 2002c. 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. Lisse, The Netherlands: A.A. Balkema Publishers.

Borah, D. K., M. Bera, and S. Shaw. 2003. Water, sediment, nutrient, and pesticide measurements in an agricultural watershed in Illinois during storm events. *Trans. ASAE* 46(3): 657-674.

Bouraoui, F., and T. A. Dillaha. 1996. ANSWERS-2000: Runoff and sediment transport model. *J. Environ. Eng.* 122(6): 493-502.

Bouraoui, F., I. Braud, and T. A. Dillaha. 2002. ANSWERS: A nonpoint-source pollution model for water, sediment, and nutrient losses. Chapter 22 in *Mathematical Models of Small Watershed Hydrology and Applications*, 833-882. V. P. Singh and D. K. Frevert, eds. Highlands Ranch, Colo.: Water Resources Publications.

Chen, Y. D. 2001. Watershed modeling for nonpoint-source water quality simulation: History, recent development, and new trends. In *Proc. 5th Int'l Conf. on Diffuse/Nonpoint Pollution and Watershed Management*, CD-ROM. Milwaukee, Wisc.: IWA and Marquette University.

CWM. 1999. *New Strategies for America's Watersheds*. Washington, D.C.: Committee on Watershed Management, National Research Council, National Academy Press.

Crawford, N. H., and R. K. Linsley. 1966. Digital simulation on hydrology: Stanford Watershed Model IV. Stanford University Tech. Rep. No. 39. Palo Alto, Cal.: Stanford University.

David, M. B., L. E. Gentry, D. A. Kovacic, and K. M. Smith. 1997. Nitrogen balance in and export from an agricultural watershed. *J. Environ. Quality* 26(4): 1038-1048.

Day, G. N. 1985. Extended streamflow forecasting using NWSRFS. *J. Water Resources Planning and Management* 111(2): 157-170.

Demissie, M., T. W. Soong, and N. G. Bhowmik. 1988. Hydraulic investigation for the construction of artificial islands in Peoria Lake. ILENR/RE-WR-88/15. Springfield, Ill.: Illinois Department of Energy and Natural Resources.

Demissie, M., L. Keefer, D. Borah, V. Knapp, S. Shaw, K. Nichols, and D. Mayer. 1996. Watershed monitoring and land use evaluation for the Lake Decatur Watershed. Miscellaneous Publication No. 169. Champaign, Ill.: Illinois State Water Survey.

Donigian, A. S., Jr., and H. H. Davis. 1978. *User's Manual for Agricultural Runoff Management (ARM) Model*. Report No. EPA-600/3-78-080. Athens, Ga.: U.S. EPA Environmental Research Lab.

Donigian, A. S., Jr., and N. H. Crawford. 1979. *User's Manual for the Nonpoint Source (NPS) Model*. Unpublished Report. Athens, Ga.: U.S. EPA Environmental Research Lab.

Donigian, A. S., Jr., B. R. Bicknell, and J. L. Kittle Jr. 1986. Conversion of the Chesapeake Bay basin model to HSPF operation. Prepared by AQUA TERRA Consultants for the Computer Sciences Corporation, Annapolis, Md., and U.S. EPA Chesapeake Bay Program, Annapolis, Md.

Donigian, A. S., Jr., B. R. Bicknell, and J. C. Imhoff. 1995. Hydrological simulation program - Fortran (HSPF). Chapter 12 in *Computer Models of Watershed Hydrology*, 395-442. V. P. Singh, ed. Highlands Ranch, Colo.: Water Resources Publications.

Fitzpatrick, W. P., W. C. Bogner, and N. G. Bhowmik. 1985. Sedimentation investigation of Lake Springfield, Springfield, Illinois. Contract Report No. 363. Champaign, Ill.: Illinois State Water Survey.

Fitzpatrick, W. P., W. C. Bogner, and N. G. Bhowmik. 1987. Sedimentation and hydrologic processes in Lake Decatur and its watershed. Report of Investigation No. 107. Champaign, Ill.: Illinois State Water Survey.

Foster, G. R., and L. D. Meyer. 1972. Transport of soil particles by shallow flow. *Trans. ASAE* 15(1): 99-102.

Fread, D. L. 1978. National Weather Service operational dynamic wave model. In *Proc. ASCE 26th Annual Hydraulics Division Conference on Verification of Mathematical and Physical Models*, 455-464. Reston, Va.: ASCE.

Green, W. H., and C. A. Ampt. 1911. Studies on soil physics, I. Flow of water and air through soils. *J. Agric. Sciences* 4: 1-24.

Huggins, L. F., and E. J. Monke. 1966. The mathematical simulation of the hydrology of small watersheds. Technical Report No. 1. West Lafayette, Ind.: Purdue University, Water Resources Research Center.

Hydrocomp. 1977. *Hydrocomp Water Quality Operations Manual*. Palo Alto, Cal.: Hydrocomp, Inc.

IEPA. 2002. 2002 Draft Section 303(d) list. Springfield, Ill.: Illinois Environmental Protection Agency, Bureau of Water. Available at www.epa.state.il.us/water/watershed/reports/303d-report/index.html. Accessed 27 August 2002.

IFMRC. 1994. Sharing the challenge: Floodplain management into the 21st century. Report to the Administration Floodplain Management Task Force. Washington, D.C.: Interagency Floodplain Management Review Committee.

Johanson, R. C., J. C. Imhoff, and H. H. Davis. 1980. *User's Manual for the Hydrologic Simulation Program - FORTRAN (HSPF)*. Report No. EPA-600/9-80-105. Athens, Ga.: U.S. EPA Environmental Research Lab.

Johanson, R. C., J. C. Imhoff, J. L. Kittle, Jr., and A. S. Donigian, Jr. 1984. *Hydrologic Simulation Program - FORTRAN (HSPF) User's Manual for Release 8*. Report No. EPA-600/3-84-066. Athens, Ga.: U.S. EPA Environmental Research Lab.

Johnston, J. M. 2002. Personal communication on 9 September 2002. Athens, Ga.: USEPA-NERL.

Julien, P. Y., and B. Saghafian. 1991. *CASC2D User's Manual*. Civil Engineering Report. Fort Collins, Colo.: Colorado State University, Department of Civil Engineering.

Julien, P. Y., B. Saghafian, and F. L. Ogden. 1995. Raster-based hydrological modeling of spatially varied surface runoff. *Water Resources Bulletin, AWRA* 31(3): 523-536.

Keefer, L., M. Demissie, D. Mayer, K. Nichols, and S. Shaw. 1996. Watershed monitoring and land use evaluation for the Vermilion River Watershed. Miscellaneous Publication No. 176. Champaign, Ill.: Illinois State Water Survey.

Knisel, W. G., ed. 1980. CREAMS: A field-scale model for chemicals, runoff, and erosion from agricultural management system. Conservation Research Report No. 26. Washington, D.C.: USDA-SEA.

Kuichling, E. 1889. The relation between the rainfall and the discharge of sewers in populous districts. *Trans. ASCE* 20: 37-40.

Lahlou, M., L. Shoemaker, S. Choudhury, R. Elmer, A. Hu, H. Manguerra, and A. Parker. 1998. Better assessment science integrating point and nonpoint sources: BASINS Version 2.0. EPA-823-B98-006. Washington, D.C.: U.S. EPA. Available at www.epa.gov/OST/BASINS. Accessed 3 October 2002.

Leavesley, G. H., and L. G. Stannard. 1995. The precipitation-runoff modeling system - PRMS. Chapter 9 in *Computer Models of Watershed Hydrology*, 281-310. V. P. Singh, ed. Highlands Ranch, Colo.: Water Resources Publications.

Leavesley, G. H., R. W. Lichty, B. M. Troutman, and L. G. Saindon. 1983. *Precipitation-Runoff Modeling System - User's Manual*. USGS Water Resources Investigative Report No. 83-4238. Washington, D.C.: U.S. Geological Survey.

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.

Li, R. M., D. B. Simons, and M. A. Stevens. 1975. Nonlinear kinematic wave approximation for water routing. *Water Resources Research* 11(2): 245-252.

Lighthill, M. J., and C. B. Whitham. 1955. On kinematic waves, 1, flood movement in long rivers. *Proc. Royal Society* Ser. A(229): 281-316.

Luepke, M. 1996. Personal communication on 13 September 1996. Springfield, Ill.: City Water Light and Power.

Lumb, A. M., J. L. Kittle, Jr., and K. M. Flynn. 1990. *User's Manual for ANNIE, A Computer Program for Interactive Hydrologic Analysis and Data Management*. USGS Water Resources Investigative Report No. 89-4080. Washington, D.C.: U.S. Geological Survey.

Mitchell, J. K., G. F. McIsaac, S. E. Walker, and M. C. Hirschi. 2000. Nitrate in river and subsurface drainage flows from an east central Illinois watershed. *Trans. ASAE* 43(2): 337-342.

Molnar, D. K., and P. Y. Julien. 2000. Grid size effects on surface runoff modeling. *J. Hydrologic Eng.* 5(1): 8-16.

Neitsch, S. L., J. G. Arnold, J. R. Kiniry, R. Srinivasan, and J. R. Williams. 2002. *Soil and Water Assessment Tool User's Manual Version 2000*. GSWRL Report 02-02; BRC Report 02-06; TR-192. College Station, Texas: Texas Water Resources Institute.

Ogden, F. L. 1998. *CASC2D Version 1.18 Reference Manual*. U-37. Storrs, Conn.: University of Connecticut, Department of Civil and Environmental Engineering.

Ogden, F. L., and P. Y. Julien. 2002. CASC2D: A two-dimensional, physically based, Hortonian hydrologic model. Chapter 4 in *Mathematical Models of Small Watershed Hydrology and Applications*, 69-112. V. P. Singh and D. K. Frevert, eds. Highlands Ranch, Colo.: Water Resources Publications.

Refsgaard, J. C., and B. Storm. 1995. MIKE SHE. Chapter 23 in *Computer Models of Watershed Hydrology*, 809-846. V. P. Singh, ed. Highlands Ranch, Colo.: Water Resources Publications.

Roseboom, D., R. L. Evans, J. Erickson, and L. G. Brooks. 1982. An inventory of Court Creek Watershed characteristics that may relate to water quality in the watershed. SWS Contract Report No. 322. Peoria, Ill.: Illinois State Water Survey.

Singh, V. P., ed. 1995. *Computer Models of Watershed Hydrology.* Highlands Ranch, Colo.: Water Resources Publications.

Singh, V. P., ed. 1996. *Kinematic Wave Modeling in Water Resources: Surface-Water Hydrology.* New York, N.Y.: John Wiley and Sons.

Singh, V. P. 2002. Kinematic wave modeling in hydrology. Invited paper submitted to ASCE-EWRI Task Committee on Evolution of Computer Methods in Hydrology. Reston, Va.: ASCE.

Singh, V. P., and D. K. Frevert, eds. 2002a. *Mathematical Models of Large Watershed Hydrology.* Highlands Ranch, Colo.: Water Resources Publications.

Singh, V. P., and D. K. Frevert, eds. 2002b. *Mathematical Models of Small Watershed Hydrology and Applications*. Highlands Ranch, Colo.: Water Resources Publications.

Sloan, P. G., I. D. Moore, G. B. Coltharp, and J. D. Eigel. 1983. Modeling surface and subsurface stormflow on steeply sloping forested watersheds. Water Resources Institute Report No. 142. Lexington, Ky.: University of Kentucky.

Smith, R. E., D. C. Goodrich, D. A. Woolhiser, and C. L. Unkrich. 1995. KINEROS - A kinematic runoff and erosion model. Chapter 20 in *Computer Models of Watershed Hydrology*, 697-732. V. P. Singh, ed. Highlands Ranch, Colo.: Water Resources Publications.

SCS. 1972. Hydrology. Section 4 in *National Engineering Handbook*. Washington, D.C.: USDA Soil Conservation Service.

Strelkoff, T. 1970. Numerical solution of Saint-Venant equations. *J. Hydraulics Division, ASCE* 96(1): 223-252.

Williams, J. R., C. A. Jones, and P. T. Dyke. 1984. A modeling approach to determine the relationship between erosion and soil productivity. *Trans. ASAE* 27(1): 129-144.

Woolhiser, D. A., R. E. Smith, and D. C. Goodrich. 1990. *KINEROS, A Kinematic Runoff and Erosion Model: Documentation and User Manual*. ARS-77. Fort Collins, Colo.: USDA Agricultural Research Service.

Young, R. A., C. A. Onstad, D. D. Bosch, and W. P. Anderson. 1987. AGNPS, Agricultural nonpoint-source pollution model: A watershed analytical tool. Conservation Research Report No. 35. Washington, D.C.: USDA.

Young, R. A., C. A. Onstad, D. D. Bosch, and W. P. Anderson. 1989. AGNPS: A nonpoint-source pollution model for evaluating agricultural watersheds. *J. Soil and Water Conservation* 44(2): 168-173.

Young, R. A., C. A. Onstad, D. D. Bosch, and W. P. Anderson. 1994. *Agricultural Non-Point Source Pollution Model, Version 4.03: AGNPS User's Guide*. Morris, Minn.: USDA-ARS North Central Soil Conservation Research Lab.