WATERSHED−SCALE HYDROLOGIC AND NONPOINT−SOURCE POLLUTION MODELS: REVIEW OF APPLICATIONS

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ABSTRACT. *Three watershed−scale hydrologic and nonpoint−source pollution models, all having the three major components (hydrology, sediment, and chemical), were selected based on a review of eleven models (AGNPS, AnnAGNPS, ANSWERS, ANSWERS−Continuous, CASC2D, DWSM, HSPF, KINEROS, MIKE SHE, PRMS, and SWAT) presented in a companion article. Those selected were SWAT, a promising model for long−term continuous simulations in predominantly agricultural watersheds; HSPF, a promising model for long−term continuous simulations in mixed agricultural and urban watersheds; and DWSM, a promising storm event (rainfall) simulation model for agricultural and suburban watersheds. In this article, applications of these three models, as reported and found in the literature, are reviewed and discussed. Seventeen SWAT, twelve HSPF, and eighteen DWSM applications are compiled. SWAT and HSPF require a significant amount of data and empirical parameters for development and calibration. DWSM has efficient physically (process) based simulation routines and therefore has a small number of calibration parameters. SWAT and HSPF were found suitable for predicting yearly flow volumes, sediment, and nutrient loads. Monthly predictions were generally good, except for months having extreme storm events and hydrologic conditions. Daily simulations of extreme flow events were poor. DWSM reasonably predicted distributed flow hydrographs, and concentration or discharge graphs of sediment, nutrient, and pesticides at small time intervals resulting from rainfall events. Combined use of these complementary models and perhaps other models having different strengths is warranted to adequately address water quantity and quality problems and their solutions.*

Keywords. *Agrochemical, Continuous modeling, Hydrology, Model applications, Nonpoint−source pollution, Sediment, Storm event modeling, 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 (Borah et al., 2002a, 2003). Understanding the natural processes leading to these problems has been a continued challenge for scientists and engineers. Mathematical models simulating and simplifying these complex processes are useful analysis tools to understand the problems and find solutions through land use changes and best management practices (BMP). Watershed−scale hydrologic and nonpoint−source pollution models are useful tools in assessing the environmental conditions of a watershed and evaluating BMPs, implementation of which can help reduce the damaging effects of storm water runoff on water bodies and the landscape. The models are useful in the development and implementation of total maximum daily load (TMDL) to meet various water quality standards, as required by the Clean Water Act.

Numerous watershed simulation models are available today. It is difficult to choose the most suitable model for a particular watershed to address a particular problem and find solutions. Many of the commonly used watershed models are continuous simulation models, useful for analyzing long−term effects of hydrological changes and watershed management practices, especially agricultural practices. Some of the watershed models are storm event models, useful for analyzing severe actual or design storm events and evaluating watershed management practices, especially structural practices. Event models are of particular interest because intense storms cause flooding and carry most of the yearly loads of sediment and pollutants (David et al., 1997; Borah et al., 2003). The importance and urgent need of storm event models are shared by other scientists (Johnston, 2002) as well. Only a few of the models have both long−term continuous and storm event simulation capabilities. Those models also have strengths in certain areas and weaknesses in others. Perhaps combined use of long−term continuous and storm event simulation models is needed to adequately manage watersheds and address water quantity and quality problems. It is, therefore, important to investigate and recognize the long−term continuous and storm event simulation capabilities in the models. It is also important to have a clear understanding of a model for its appropriate use and avoiding possible misuses. Finally, the models must be thoroughly tested by applying them to various watersheds before using them in management decisions.

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Eleven watershed−scale hydrologic and nonpoint−source pollution models were reviewed, discussed, and presented in a companion article (Borah and Bera, 2003a). These were: 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). The flow−governing equations and solution methods used in each of these models were investigated and discussed. Long−term continuous and short−duration storm event models were identified. Simulation capabilities and key features of the models and mathematical bases of different components were identified and compiled in tabular form. The compilation would be useful to select the most suitable model for an application depending on 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.

Based on the above investigations, two long−term continuous simulation models (one for primarily agricultural watersheds, and the other for mixed agricultural and urban watersheds) and one storm event model for agricultural and suburban watersheds were selected for further investigations. Those were SWAT, a promising model for long−term continuous simulations in predominantly agricultural watersheds; HSPF, a promising model for long−term continuous simulations in mixed agricultural and urban watersheds; and DWSM, a promising storm event (rainfall) simulation model for agricultural and suburban watersheds. These models have all the three major components: hydrology, sediment, and chemical. Both of the long−term continuous simulation models (SWAT and HSPF) are part of U.S. Environmental Protection Agency's (USEPA) Better Assessment Science Integrating Point and Nonpoint Sources (BASINS) modeling system, developed by Tetra Tech, Inc. (Lahlou et al., 1998).

The primary objective of this article is to investigate the performances of the three models (SWAT, HSPF, and DWSM) on various watersheds. Many applications of these models were found in the literature, some of which (representative ones) were reviewed and compiled in tabular form. These compilations are presented and discussed here. Some of the preliminary reviews and compilations were presented in Borah and Bera (2003b, 2003c, 2003d). Sources, brief backgrounds, and mathematical bases of the three models were presented in the companion article (Borah and Bera, 2003a), along with the other eight models.

SWAT Applications

Seventeen applications of SWAT as found in the literature were reviewed: Srinivasan et al. (1998b), Peterson and Hamlett (1998), Shirmohammadi et al. (2001), Van Liew and Garbrecht (2001), Benaman et al. (2001), Varanou et al. (2002), Vache et al. (2002), Santhi et al. (2001), Qiu and Prato (2001), Stone et al. (2001), Spruill et al. (2000), Arnold et al. (2000), Rosenthal et al. (1995), Stonefelt et al. (2000), Rosenthal and Hoffman (1999), King et al. (1999), and Bingner (1996). Watershed location, size, and source; model calibration; model validation; BMP evaluation or other model use; and finally some evaluation comments are summarized and compiled in table 1 for each of the seventeen applications.

While applying SWAT to the Cannonsville Reservoir watershed (1,178 km^2) in New York (table 1), Benaman et al. (2001) found that the model required a significant amount of data and empirical parameters for development and calibration. Most of the calibration and validation of the model were based on monthly flow volumes or monthly average flows (table 1). As shown in the applications to the Warner Creek watershed (3.46 km^2) in Maryland; the Upper Mississippi River basin (491,700 km^2) in Minnesota, Wisconsin, Iowa, Missouri, and Illinois; and the Lower Colorado River basin (8,927 km^2) in Texas (table 1), SWAT predicted monthly flows well, except during extreme hydrologic conditions. SWAT's daily flow predictions were not as good as its monthly flow predictions. While applying the model to University of Kentucky Animal Research Center (5.5 km^2 farm) in Kentucky (table 1), Spruill et al. (2000) found that daily flow comparisons for calibration and validation periods yielded much lower Nash−Sutcliffe coefficients (Nash and Sutcliffe, 1970) or NSC (0.19 and −0.04), respectively, than monthly comparisons (0.89 and 0.58). The monthly totals tend to smooth the data, which in turn increases the NSC. Daily flow predictions were made in five of the watersheds (table 1): Areal Creek (39.4 km^2) in Pennsylvania, Cannonsville Reservoir, Ali Efenti (2,796 km^2) in Greece, University of Kentucky Animal Research farm, and Goodwin Creek (21.3 km^2) in Mississippi (King et al., 1999). Performances in the Ali Efenti and Goodwin Creek were fair (NSC = 0.62 and 0.43, respectively) and poor in the remaining applications (NSC ranging from −0.04 to 0.19). In one of the 8−year simulations in the Goodwin Creek watershed (1984), the daily NSC value was 0.78. In this watershed, the model was run with no calibration (King et al., 1999). Using an automated calibration routine, Eckhardt and Arnold (2001) improved daily simulations with NSC values of 0.70 to 0.73 on the 81 km^2 Dietzholze catchment in Germany (not compiled in table 1).

Sediment yields were verified and reported in four of the applications (table 1). Srinivasan et al. (1998b) calibrated and validated sediment yield predictions on the Richland and Chambers Creeks watershed (5,080 km^2) in Texas based on multiyear (3 to 7 year) sediment yields. While simulating sediment loadings in the Cannonsville Reservoir watershed, Benaman et al. (2001) noted that the model generally simulated watershed response on sediment, but it grossly underpredicted sediment yields during high−flow months. Vache et al. (2002) compared monthly sediment load predictions in the Buck Creek watershed (88.2 km^2) in Iowa with sediment load estimates from observed flow and an average total suspended sediment (TSS) concentration of 150 mg/L, determined from low flow samplings, and used the parameters to simulate the nearby Walnut Creek watershed (51.3 km^2). This shows that data are still scarce for

Table 1. Application summary of SWAT.

Watershed	Model Calibration	Model Validation	BMP or Other Use	Comments
Richland and Chambers (RC) Creeks watershed, Upper Trinity River basin, Texas (Srinivasan et al., 1998b); 5,080 km^2.	Monthly flow and six−year sediment yield.	Monthly flow and three− and seven−year sediment yields.	None	SWAT performed well for monthly flows and multiyear sediment yields.
Ariel Creek watershed, Pennsylvania (Peterson and Hamlett, 1998); 39.4 km^2.	Daily flow: deviation of runoff volumes (D_v) = 39.9%, and Nash−Sutcliffe (1970) coefficient (NSC) = 0.04. Monthly flow: NSC = 0.14.	None	None	SWAT requires calibration, and is better suited to longer−period (monthly) simulations and not adequate for severe single events.
Warner Creek watershed, Maryland (Shirmohammadi et al., 2001); 3.46 km^2.	Monthly flow. Monthly nitrate−N load: coefficients of determination (COD or r^2) = 0.27.	Monthly flow and nitrate−N. Yearly nitrate−N load: COD = 0.96.	None	SWAT predicted monthly flows well, except in extreme weather. Monthly nitrate−N predictions were poor, but did well on annual loadings.
Little Washita River Experimental Watershed, Oklahoma (Van Liew and Garbrecht, 2001); 538 km^2.	Monthly flow: COD = 0.74.	None	Climate (precipitation) variations.	SWAT was useful in predicting effects of precipitation variations on monthly water budgets.
Cannonsville Reservoir watershed, New York (Benaman et al., 2001); 1,178 km^2.	Monthly and daily flows and monthly sediment yield.	None	None	SWAT requires a significant amount of data and empirical parameters, and its sediment routing is weak.
Ali Efenti watershed, Greece (Varanou et al., 2002); 2,796 km^2.	Daily flow: NSC = 0.62. Monthly flow: NSC = 0.81. Monthly nitrate−N.	None	Impacts of climate change (temperature and precipitation) on surface, lateral, and groundwater flows, and N losses.	SWAT was useful in studying climate change. Monthly flow predictions were better than daily. Seasonal nitrate−N trends were predicted well.
Walnut (51.3 km^2) and Buck Creek (88.2 km^2) watersheds, Iowa (Vache et al., 2002).	Monthly flows: COD for Walnut and Buck = 0.67 and 0.64, respectively. Monthly sediment and nitrate−N loads.	None	Impacts of three BMP scenarios on annual sediment and nitrate loadings.	SWAT was useful in evaluating BMP scenarios.
Bosque River watershed, Texas (Santhi et al., 2001); 4,277 km^2.	Annual and monthly flows: COD > 0.6 and NSC > 0.72. Monthly sediment yield: COD > 0.81 and NSC > 0.69. Monthly organic N and P yields: COD > 0.6 and NSC > 0.57. Mineral N and P yields.	Monthly flow volumes, sediment yields, and nutrient yields (organic N and P, mineral N and P).	Impacts of management practices on dairy manure and WWTP effluents on P loadings.	SWAT was found adequate in predicting annual and monthly responses, and useful in analyzing management of dairy manure applications and WWTP effluents.
Goodwater Creek watershed, Missouri (Qiu and Prato, 2001); 77.42 km^2.	No information.	No information.	Surface water quality impacts (sediment yield and concentrations of N and atrazine) of riparian buffers.	SWAT provided a tool to estimate surface water quality impacts from riparian buffers while determining their economic values.
Missouri River basin (Stone et al., 2001).	None	None	Changes in basin water yield from doubled CO_2 climate.	SWAT was useful in studying impact of climate change (doubled CO_2) on water yield.
University of Kentucky Animal Research Center, Kentucky (Spruill et al., 2000); 5.5 km^2.	Daily and monthly flows: NSC = 0.19 and 0.89, respectively.	Daily and monthly flows: NSC = −0.04 and 0.58, respectively.	Sensitive parameters determined: saturated hydraulic conductivity, alpha base flow factor, recharge, drainage area, and channel length and width.	Daily flows yielded much lower NSC than monthly. Simulated peak and recession flows were often faster than the observed.
Upper Mississippi River basin at Cairo, Illinois (Arnold et al., 2000); 491,700 km^2.	Average annual flows at 131 hydrologic unit areas ("8−digit" watersheds): COD = 0.89. Monthly flows at Alton, Illinois (90% of the basin): COD = 0.63.	Monthly flows at Alton: COD = 0.65.	Groundwater discharge (base flow) and recharge were verified with estimates from: (1) digital recursive filter to separate base flow from total daily flow, and (2) modified hydrograph recession curve displacement technique to estimate groundwater recharge, respectively.	SWAT reasonably predicted annual flow volumes at the 131 eight−digit watersheds and monthly flows near the outlet. The model underpredicted spring peaks and sometimes overpredicted fall flows.

Table 1. Application summary of SWAT (concluded).

Watershed	Model Calibration	Model Validation	BMP or Other Use	Comments
Lower Colorado River basin, Texas (Rosenthal et al., 1995); 8,927 km^2.	Monthly flows near the outlet: COD = 0.66.	None	Land use change scenarios: changing irrigated rice fields to dry lands and increase urban developments.	SWAT closely simulated monthly flows, but underpredicted during extreme events.
Upper Wind River basin, Wyoming (Stonefelt et al., 2000); 5,000 km^2.	Monthly water yields: COD = 0.91.	None	Potential impacts on water yield from climate change: temperature, precipitation, CO_2, radiation, and humidity.	SWAT was useful in this climate change study. Precipitation was the most influential variable on annual water yield, and temperature on timing of streamflow.
Leon River watershed, Texas (Rosenthal and Hoffman, 1999); 9,000 km^2.	Monthly flows: correlation coefficient (r) = 0.83 and NSC = 0.57.	None	Locations of new monitoring stations were selected based on higher per−acre average annual sediment yield predictions.	SWAT was useful in selecting new monitoring station locations.
Goodwin Creek watershed, Mississippi (King et al., 1999); 21.3 km^2.	No calibration performed.	Monthly and daily runoff using SCS runoff curve number method: NSC = 0.84 and 0.43 (0.78 in one of the 8−year simulations − 1984), respectively.	Green−Ampt Mein−Larson (GAML) excess rainfall method (Green and Ampt, 1911; Mein and Larson, 1973) was added, which yielded NSC = 0.69 and 0.53 (0.63 in 1984) in monthly and daily runoff simulations, respectively. Storm event simulations yielded reasonable hydrographs.	The GAML excess rainfall method was added to SWAT for subdaily time step simulations, but no significant advantage was gained. The model was run for eight years using non−calibrated methodology, and the results were not calibrated.
Goodwin Creek watershed, Mississippi (Bingner, 1996); 21.3 km^2.	Annual runoff vol. for 14 subbasins: COD > 0.80 for individual storms.	None	None	SWAT simulated the relative trends of annual runoff in the subbasins. Simulations of individual storm events were less accurate.

adequate model calibration and validation, and it warrants continued collection of good quality data. Santhi et al. (2001) compared monthly sediment yield (metric tons per hectare or t/ha) predictions with observed data from the Bosque River watershed (4,277 km^2) in Texas, yielding a coefficient of determination or COD (r^2) and NSC above 0.81 and 0.69, respectively.

Nutrients were simulated and reported in four of the applications (table 1). Shirmohammadi et al. (2001) found comparisons of simulated and observed monthly nitrate−N loadings poor (r^2 = 0.27) in the Warner Creek watershed. Varanou et al. (2002) calibrated the model for monthly nitrate−N and total N in the Ali Efenti basin. Seasonal trends were simulated quite well, although the instream routine was not used. Vache et al. (2002) compared simulated and observed cumulative monthly nitrate−N loads from the Walnut Creek watershed in Iowa. The comparisons were reasonable after the first two years. Santhi et al. (2001) compared monthly organic N and P yield (kg/ha) predictions with observed data from the Bosque River watershed, yielding COD and NSC values above 0.60 and 0.57, respectively. Mineral N and P yield (kg/ha) comparisons yielded similar results, except for mineral N at the Valley Mills station (70% of the watershed), where NSC was −0.08.

The primary purpose for most of the above applications was to test the SWAT model and some of its routines on watersheds through calibrations and validations, although validations were conducted only in five of the applications (table 1). Calibrations were conducted mostly on monthly, yearly, and multiyear bases. Four of the applications, namely, Little Washita River (538 km^2) in Oklahoma, Ali Efenti, Missouri River, and Upper Wind River (5,000 km^2) in Wyoming (table 1), involved studying impacts of climate change on water yields or water budgets. Results from these studies are interesting, although hypothetical. Five other applications involved investigating impacts of various management scenarios (table 1). Vache et al. (2002) studied the impacts of three management scenarios on annual sediment and nitrate loadings in the Walnut and Buck Creek watersheds. Santhi et al. (2001) studied several management practices on dairy manure and wastewater treatment plant effluents in reducing minimum P loadings in the Bosque River watershed. Rosenthal et al. (1995) investigated the conversion of irrigated rice fields to dry land and increasing urban development in the Lower Colorado River basin. Rosenthal and Hoffman (1999) used annual sediment yield predictions to select locations of monitoring stations in the Leon River watershed (9,000 km^2) in central Texas (table 1). Qiu and Prato (2001) used SWAT to estimate surface water quality impacts from riparian buffers in the Goodwater Creek watershed (77.42 km^2) in Missouri while determining their economic impacts (table 1). Most of the results from these applications are qualitative because of uncertainty in the empirical parameters, which cannot be validated against the scenarios.

More studies were found in the literature on SWAT applications that are not part of table 1. Bingner et al. (1997) studied effects of watershed subdivision on simulations of runoff and fine sediment yield while applying SWAT to the Goodwin Creek watershed (table 1; King et al., 1999; Bingner, 1996). Manguerra and Engel (1998) developed parameterization techniques for runoff predictions using SWAT at two locations: the Animal Science (3.28 km^2) and Greenhill (113.38 km^2) watersheds in Indiana (one is a subwatershed of the other), and the Camp Shelby watershed (22.48 km^2) in Mississippi. Saleh et al. (2000) also described application of SWAT on the Upper Bosque River watershed. Harmel et al. (2000) used SWAT to test three weather generation programs through their applications to the USDA−ARS Riesel watershed Y2 study site (53 ha) in Texas. Limaye et al. (2001) used the basic soil moisture simulation component of SWAT and combined it with triangular unit hydrograph and the Muskingum−Cunge routing method to assess General Circulation Model (GCM) predictions of climatic changes on the Dale Hollow reservoir watershed (2,435 km^2) in Tennessee.

HSPF Applications

The EPA Chesapeake Bay Program (Donigian et al., 1986a) used HSPF as a framework for the Chesapeake Bay Watershed Model to determine total watershed contributions of flow, sediment, and nutrients (and associated constituents such as water temperature, DO, BOD, etc.) to the tidal region of the Chesapeake Bay. Donigian et al. (1986b) and Donigian and Mulkey (1992) developed a system called STREAM for the USEPA to rapidly evaluate pesticide impacts on a regional basis. They applied HSPF to various watersheds in agricultural regions across the U.S., and then performed sensitivity analysis on key pesticide parameters to generate cumulative frequency distributions of pesticide concentrations and loadings in each region for each of the major crops grown in that region.

HSPF has been widely applied after becoming a part of USEPA’s BASINS system for TMDL analysis and development. Some of these applications and a few earlier independent application studies (a total of twelve), as available in the literature, were reviewed: Srinivasan et al. (1998a), Engelmann et al. (2002), Carrubba (2000), Bergman and Donnangelo (2000), Bledsoe and Watson (2001), Brun and Band (2000), Laroche et al. (1996), Rahman and Salbe (1995), Chew et al. (1991), Moore et al. (1988), Dorn et al. (2001), and Johnson et al. (2001). Watershed location, size, and source; model calibration; model validation; BMP evaluation or other model use; and finally some evaluation comments are summarized and compiled in table 2 for each of the application studies.

Most of the applications were on relatively small watersheds with sizes ranging from 0.18 to 170 km^2 (table 2). One application (Rahman and Salbe, 1995) was on the 416 km^2 South Creek catchment near Sydney, Australia (table 2), in which HSPF was used to study the impact of urbanization and point−source pollution management scenarios. The model generated flow and water quality (total P and total N) results for different management scenarios, although the accuracies of these results are unknown since no calibration and validation results were presented. In another study (Carrubba, 2000), HSPF was applied to three watersheds of sizes over 1,000 km^2 located in three different geographical areas of the U.S. (table 2). These were USGS 8−digit watersheds and parts of the large river basins: the White River (WR) basin in Indiana, the Albemarle−Pamlico River (APR) basin in Virginia and North Carolina, and the Apalachicola−Chattahoochee−Flint River (ACFR) basin in Alabama, Georgia, and Florida. Drainage areas of the 8−digit watersheds in the WR, APR, and ACFR basins are 1,230, 1,900, and 1,610 km^2, respectively. The model was calibrated and validated for daily flows, which resulted in COD from 0.44 to 0.75 and NSC from −0.66 to 0.45. According to the investigator, the watershed in the ACFR basin proved the most difficult to calibrate, indicating that HSPF might not be as useful in some geographic locations.

In the smaller watersheds, namely Hellbranch Run (103 km^2) in Ohio, the experimental watershed (18 ha) at Agricenter International in Shelby County, Tennessee, and North Reelfoot Creek (146 km^2) in Tennessee (table 2), annual and monthly flow simulations were generally good, except for the months with severe weather. Similarly, daily simulations for extreme events in the Hellbranch Run and North Reelfoot Creek watersheds, and in the Purdy Creek (23 km^2) and Ariel Creek (39.4 km^2) watersheds in Pennsylvania (table 2), were found poor. Daily simulations without the extreme events were found reasonable. While simulating the Irondequoit Creek watershed (100.2 km^2) in New York (table 2), Johnson et al. (2001) compared daily flow predictions of HSPF with the Soil Moisture Routing (SMR) model from Cornell University and found daily flow predictions during winter months were better with HSPF due to its superior snowmelt simulations. From calibration and validation of daily, weekly, and monthly streamflows in the 78 ha Agricultural Canada experimental farm in Canada (table 2), Laroche et al. (1996) found that as the time interval got smaller, the model became less precise.

Sediment was simulated in five of the applications (table 2): Hellbranch Run, West Branch in Maryland, South Creek, Agricenter International, and North Reelfoot Creek. Annual and monthly sediment predictions were reasonable, except for the months with severe weather. Daily sediment predictions were made only in the Hellbranch Run and North Reelfoot Creek watersheds and found poor (table 2). While simulating the Hellbranch Run watershed, Engelmann et al. (2002) remarked, “The sediment calibration process proved to be a very painstaking task. Over 200 runs were performed without any significant changes in the resulting correlation between the observed and predicted values.”

Atrazine was simulated in the two experimental watersheds: the Agricultural Canada Experimental farm and Agricenter International in Tennessee (table 2). The simulated results were found to be reasonable. In the Agricenter International watershed, nutrients were also simulated (table 2). The mass fluxes of nitrate and ammonia N were poorly simulated. The total Kjeldahl N (TKN) response was good, although the peak discharges were over and under simulated. South Creek catchment is the only other watershed where nutrients were simulated; however, model performance was not reported.

Bergman and Donnangelo (2000) used HSPF to regionalize its parameters in a 16% ungauged portion of the Sebastian River basin in Florida through calibration and validation on a few of the tributary watersheds (table 2): North Prong (93 km^2), South Prong (146 km^2), Fellsmere Water Control District East (97 km^2), and Goat Creek (24 km^2). They were successful in obtaining reliable discharges from the ungauged portion of the basin through parameter regionalization and calibration−validation of the model on those tributary watersheds using only a few years (1991−1996) of newly collected data. Bledsoe and Watson (2001) used HSPF to simulate 40 years of daily maximum flows on the Hylebos and Des Moines Creek watersheds (15.1 and 14.7 km^2,

Table 2. Application summary of HSPF.

Watershed	Model Calibration	Model Validation	BMP or Other Use	Comments
Purdy Creek and Ariel Creek watersheds, Pennsylvania (Srinivasan et al., 1998a); 23 km^2 and 39.4 km^2, respectively.	Runoff volume in Purdy for June 1992 to December 1993: D_v = 0.05. Daily flow: D_v = 0.05 and NSC = 0.55.	Daily flows in Ariel Creek with Purdy Creek parameters: D_v = 0.17 and NSC = 0.57.	None	HSPF simulated daily flows well except for peak flow rates during extreme events.
Hellbranch Run watershed, Ohio (Engelmann et al., 2002); 103 km^2.	Monthly discharge: COD = 0.94. Monthly sediment concentrations: NSC = 0.49 and COD = 0.74. Daily flows were grossly overpredicted, and daily sediment concentrations were zeroes.	Mean monthly discharge: COD = 0.74. Mean monthly sediment concentration: NSC = −2.46 and COD = 0.23.	None	HSPF predicted monthly flows well. Monthly sediment was good in calibration and poor in validation. Daily flow and sediment predictions during a storm event were poor.
Three USGS 8−digit watersheds, one from each: White River (WR) basin in Indiana, Albemarle−Pamlico River (APR) basin in Virginia and North Carolina, and Apalachicola−Chattahoochee−Flint River (ACFR) basin in Alabama, Georgia, and Florida (Carrubba, 2000); 1,230, 1,900, and 1,610 km^2, respectively.	Daily flows: COD = 0.75, 0.44, and 0.69 for WR, APR, and ACFR, respectively. NSC ranged from −0.66 to 0.45.	Daily flows: COD = 0.71, 0.69, and 0.64 for WR, APR, and ACFR, respectively. NSC ranged from 0.31 to 0.37.	None	HSPF predicted daily flows with low COD and NSC values. The ACFR watershed proved the most difficult to calibrate, indicating that HSPF might not be as useful in some geographic locations.
North Prong, South Prong, Fellsmere Water Control District East (FWCDE), and Goat Creek watersheds, Florida (Bergman and Donnangelo, 2000); 93, 146, 97, and 24 km^2, respectively.	Daily flow: North Prong was calibrated and results were presented in combination with validation.	North Prong: underpredictions and overpredictions were less than 10%.	Regionalization of parameters. North Prong parameters were applied to South Prong and FWCDE, and runoff volumes were reported to be within allowed error limits. The parameters were tested on the Goat Creek, and minor adjustments to a few parameters were made.	HSPF was used to obtain water discharge from a 16% ungauged portion of the Sebastian River basin through regionalization of parameters using a few years of newly collected data.
Hylebos and Des Moines Creek watersheds, Washington (Bledsoe and Watson, 2001); 15.1 and 14.7 km^2, respectively.	King County project reports.	King County project reports.	Daily maximum flows were simulated for 40 years with predevelopment forest conditions and existing land uses, and relationships for flow and number of exceedences under predevelopment and different imperviousness were developed.	HSPF was used in studying impacts of urbanization on daily flows.
Upper Gwynns Falls watershed, Maryland (Brun and Band, 2000); 91 km^2.	Base flows.	Weekly flow volumes: COD = 0.69.	Studied 21 combinations of land uses, and meteorological conditions, and two 3D relationships were developed: (1) runoff ratio, percent impervious, and percent soil saturation; and (2) base flow, percent impervious, and percent soil saturation.	HSPF was used in studying urbanization. Base flow predictions were good when it is less than 0.5 mm, but poor during some high−flow events.
West Branch watershed, Maryland (Dorn et al., 2001).	GIS data and calibrated model were obtained from BASINS training package by Aquaterra Consultants. Simulated total suspended solids (TSS).	None	A BASINS Strategy, Analysis, and Reporting (STAR) system was introduced, based on genetic algorithm optimization coupled with uncertainty propagation, to assist in exploring alternative management strategies and decision making.	HSPF needs extensive data and calibration parameters, takes long time to set up, and is cumbersome to use. Computer run time for the BASINS−STAR was 2 to 2.5 days.

Table 2. Application summary of HSPF (concluded).

Watershed	Model Calibration	Model Validation	BMP or Other Use	Comments
Irondequoit Creek watershed, New York (Johnson et al., 2001); 100.2 km^2.	Daily flow comparison showed good agreement, although there was a tendency towards underprediction of summer flows.	None	HSPF results were compared with results from the Soil Moisture Routing (SMR) model from Cornell University.	HSPF predicted better in winter, while SMR was more accurate in summer. HSPF was five times more labor intensive than SMR.
Agricultural Canada experimental farm, Lennoxville, Quebec, Canada (Laroche et al., 1996); 78 ha.	Adjusted ten flow parameters. Daily, weekly, and monthly flows: COD = 0.73, 0.87, and 0.90 and NSC = 0.51, 0.69, and 0.66, respectively. Atrazine.	Daily, weekly, and monthly flows: Correlation coefficient (r) = 0.67, 0.91, and 0.93 and NSC = 0.12, 0.76, and 0.79, respectively.	Simulated with increasing area and rate of atrazine application.	HSPF has too many parameters. As time interval got smaller, the model became less precise.
South Creek catchment near Sydney, Australia (Rahman and Salbe, 1995); 416 km^2.	Flow, sediment, and water quality (DO, BOD, N, P and algal growth).	None.	Six scenarios on present and projected land use and point−source management.	HSPF was used to study impacts of land use and point−source management scenarios. However, authenticity of the results is unknown without model validation.
Experimental watershed at Agricenter International in Shelby County, Tennessee (Moore et al., 1988); 18 ha field, part of a 4 km^2 agricultural demonstration facility.	Adjusted 7 flow, 6 sediment, 7 atrazine, and 20 N parameters. Water volume for 1.5 years: D_v = −15%. Monthly runoff volumes: reasonable, except underestimation during intense storms. Peak flow: oversimulated nearly three times. Sediment yield for 1.5 years: D_v = 12%. Monthly sediment yield: reasonable, except four times oversimulation in one month. Sediment discharges: reasonable, except D_v = 75% for one peak. Atrazine: over−simulated. Annual nitrate: D_v = 40%. Monthly nitrate: good, except D_v = 85% in one month. Monthly sediment associated N and total N: grossly undersimulated. Peak nitrate−N discharge: undersimulated by five times. Ammonia N discharge: poor, nearly zero, against observations up to 35 g/min. TKN: good although peak discharge oversimulated by 167%.	None	None	HSPF has too many parameters to adjust. Monthly runoff simulations were reasonable, except for the months having intense thunderstorms. Sediment yield simulations were reasonable, but discharges were poor for some of the peaks. Mass flux of nitrate and ammonia N was poor. TKN response was good, although the peak discharges were poor.
North Reelfoot Creek watershed, Tennessee (Chew et al., 1991); 146 km^2.	Adjusted 7 flow and 15 sediment (9 washoff and 6 transport) parameters. Annual runoff volumes: D_v ranged from −16% to +9%. Monthly flow: significant undersimulation during major storms. Daily flow: undersimulation of peak flow by less than one−third of observed. Annual sediment yield: D_v ranged from −4% to +27%. Monthly sediment: varied from good to poor. May 1994 sediment yield was oversimulated by more than double, although runoff was undersimulated significantly. Daily peak sediment concentration in October 1984: overpredicted by more than three times.	Annual runoff volumes: D_v ranged from −0.2% to −0.6%. Monthly flow: reasonable. Annual sediment yield: D_v varied from −17% to −21%. Monthly sediment yield: good to poor.	Parameters were carefully adjusted to incorporate BMPs implemented through Rural Clean Water Program.	HSPF simulated annual and monthly flow and sediment well, except for the months with severe weather. Daily simulations for extreme events were poor, peak flows were undersimulated, and sediment concentrations were oversimulated.

respectively) in King County, Washington (table 2). They developed relationships of flow and the number of exceedences (of the flows) under predevelopment and under different percentages of imperviousness in those two urbanizing watersheds. Brun and Band (2000) calibrated and validated HSPF for weekly streamflow on the 91 km^2 Upper Gwynns Falls watershed in Maryland (table 2) and studied different combinations of percent impervious cover (urbanization) and meteorological conditions. They developed two 3−dimensional relations: (1) runoff ratio, percent imperviousness, and percent soil saturation; and (2) base flow, percent imperviousness, and percent soil saturation. Laroche et al. (1996) ran the calibrated and validated HSPF on the 78 ha Agricultural Canada experimental farm (table 2) with increasing percentage area treated with atrazine for three different application rates (1.5, 4.5, and 9.0 kg/ha). They developed relationships between number of days per year with atrazine concentration above 2 μg/L, percent area of the treated watershed, and application rate. While applying HSPF on the North Reelfoot Creek watershed (table 2), Chew et al. (1991) accounted for BMPs implemented in the watershed through the Rural Clean Water Program by carefully adjusting the model parameters. Most of the results from these applications are qualitative because of uncertainties in the empirical parameters, which were not validated against the BMPs or management scenarios.

Many of the investigators (Engelmann et al., 2002; Laroche et al., 1996; Moore et al., 1988; Dorn et al., 2001; Johnson et al., 2001) acknowledged that HSPF had too many parameters to calibrate and was therefore cumbersome to use. Laroche et al. (1996) adjusted ten parameters in hydrologic simulations of the Agricultural Canada experimental farm (table 2). Moore et al. (1988) adjusted seven hydrologic, six sediment, seven atrazine, and twenty nitrogen parameters while simulating the Agricenter International watershed (table 2). Data needs for the model are also extensive; therefore, human resources requirements are intensive. Johnson et al. (2001) found that HSPF was five times more labor intensive than SMR while simulating the Irondequoit Creek watershed (table 2) with both models.

DWSM Applications

DWSM and its earlier versions, namely SEDLAB (Borah et al., 1980, 1981) and RUNOFF (Borah, 1989a, 1989b; Ashraf and Borah, 1992), were applied, tested, and used in various research and practical engineering projects. It has been applied to different laboratory flumes, field plots, and watersheds or catchments of sizes ranging from 0.16 ha to 2,400 km^2. Eighteen of these applications were reviewed. Table 3 shows a compilation of location, size, and sources of the applied watershed, catchment, or flume; model calibration; model validation; BMP evaluation or other model use; and some evaluation comments for each of the applications.

One of the unique features of DWSM is its efficient runoff routing scheme used in routing of runoff over overland planes and through channel segments, based on analytical and approximate shock−fitting solution of the kinematic wave equations. The early applications of this scheme to the hypothetical kinematic cascade of Kibler and Woolhiser (1970) and experimental flume of Iwagaki (1955) by Borah et al. (1980) confirmed its accuracy and efficiency over other leading schemes, based on numerical solutions of the equations (table 3). Its reproduced hydrograph was almost identical to the hydrograph from the more accurate kinematic wave analytical and iterative shock−routing scheme of Kibler and Woolhiser (1970). Stable and efficient performance of the analytical and approximate shock−fitting solution scheme over numerical solutions was also demonstrated on watershed−scale applications by Borah et al. (1990), when RUNOFF was applied to the 32 km^2 South Branch Rockaway Creek watershed in New Jersey (table 3) and results were compared with results from U.S. Army Corps of Engineers' (1985) HEC−1 model. HEC−1, based on a numerical solution of the kinematic wave equations, was found unstable near the peak flows, whereas RUNOFF was stable and predicted more accurate peak flows.

Xiong (2002) independently confirmed the superior performance of DWSM's kinematic wave routing scheme over the storage−based or nonlinear reservoir routing scheme used by other models, such as the Runoff Block of Storm Water Management Model (SWMM) (Huber and Dickinson, 1988), HSPF, and ANSWERS. She applied both schemes to 68 simulated rainfall events on experimental rainfall−runoff plots of Chow and Yen (1974). NSC values from DWSM applications (0.80 to 0.93) were much higher than NSC values from the Runoff Block of SWMM (0.07 to 0.88) (table 3). SWMM's more accurate Extended Transport (EXTRAN) Block for channel routing, based on an intensive numerical solution of the dynamic wave (St. Venant) equations was not compared against DWSM's robust analytical and approximate shock−fitting solutions of the kinematic wave equations. However, as discussed in the companion article (Borah and Bera, 2003a), numerical solutions of the dynamic or diffusive wave equations (e.g., CASC2D) make models inefficient, and sometimes prohibitive, for large watershed applications.

The soil erosion and sediment routing scheme of DWSM (SEDLAB) was first tested on the experimental flume data of Kilinc and Richardson (1973), generating water and sediment discharges comparable with those measured (table 3). DWSM's (RUNOFF) agrochemical simulation was first tested on experimental box data of Hubbard et al. (1989a, 1989b), where simulated concentration graphs of nitrate, phosphate, and cyanazine compared very well with the observed values (table 3). All three components of DWSM (RUNOFF), namely hydrology, sediment, and agrochemical, were tested on two feed lot plots at the Price's Fork Agricultural Farm of Virginia Water Resources Research Center near Blacksburg, Virginia (table 3), where simulated water and sediment discharges and concentrations of ammonium and orthophosphate compared very well with observed data (COD of 0.98 to 0.99).

The first watershed−scale application of DWSM (SEDLAB) was on the USDA experimental watershed W−5 (450 ha) near Holly Springs, Mississippi (table 3), where the hydrology and sediment components of the model were extensively tested, through calibration, validation, sensitivity analysis, and investigation of seasonal variation of model parameters. The model performed well on this agricultural and rural watershed, simulating discrete space and time varying runoff, soil erosion, and sediment transport resulting from rainfall events. SEDLAB was subsequently tested on three more watersheds (table 3): USDA experimental watershed R−5 (9.6 ha) near Chickasha, Oklahoma, a USDA

Table 3. Application summary of DWSM.

Watershed	Model Calibration	Model Validation	BMP or Other Use	Comments
Upper Sangamon River watershed, Illinois (Borah et al., 1999, 2000); 2,400 km^2.	Flow parameters, calibrated earlier in AGNPS application (Borah et al., 2002a).	Flow hydrographs at four tributary stations (100 to 290 km^2): good.	A subsurface flow (combined interflow, tile, and base flow) routine was added to the model.	DWSM hydrology performed well for intense rainfall events. Addition of the subsurface flow routine improved recession and base flow predictions.
Court Creek watershed, Illinois (Borah and Bera, 2000; Borah et al., 2001a, 2001b); 251 km^2.	Flow hydrographs at three tributaries and watershed outlet, and sediment discharges at two tributaries: reasonable.	Flow hydrographs at two tributaries and watershed outlet, and sediment discharges at one tributary: reasonable.	Overland planes and stream reaches were ranked based on peak flows and sediment yields for prioritization in restoration planning. Impacts of detention basins (BMP) on downstream water and sediment discharges were analyzed.	DWSM was useful in predicting storm event water and sediment discharges and ranking overland planes and stream reaches for state and local officials and citizen groups who used those to prioritize critical areas and educate landowners.
Big Ditch watershed, Illinois (Borah and Bera, 2002; Borah et al., 1999, 2000, 2001a, 2002b, 2002c); 100 km^2.	Flow hydrographs and sediment discharges at watershed outlet: reasonable. Phosphate−P trends and magnitudes: reasonable.	Flow hydrographs and sediment discharges at watershed outlet: reasonable. Phosphate−P trends and magnitudes: reasonable.	Effects of different watershed division sizes (scaling) on model parameters and simulated water and sediment discharges were analyzed.	DWSM was useful in simulating water, sediment, and phosphate−P during intense rainfall events, and studying scaling effects, an important modeling issue.
USDA Experimental watershed W−5, near Holly Springs, Mississippi (Borah et al., 1980, 1981; Borah, 1989a, 1989b; Borah and Ashraf, 1990; Borah et al., 2002b); 450 ha.	Flow hydrograph and sediment discharge graph: almost perfect.	Flow hydrograph and sediment discharge graph: reasonably well.	Sensitivities of runoff curve number (CN), Manning's roughness coefficient, and flow detachment coefficient (FDC) on model results were analyzed. Seasonal variations of CN and FDC were analyzed.	The earlier version of DWSM (RUNOFF) was a useful tool in predicting storm event water and sediment discharges in an agricultural watershed.
Lan River watershed, Shanxi Province, People Republic of China (Van Liew, 1998); 1,142 km^2.	Sediment yields from 24 storm events: COD = 0.96.	Included in calibration with 24 storm events.	Sensitivities of interrill−rill and flow detachment coefficients were analyzed.	RUNOFF was useful in predicting storm event sediment yields in the loessal region of north central China.
Lawrence Brook watershed, New Jersey (Borah, 1995; Omni, 1994); 122 km^2.	Flow hydrograph of one storm: good.	Flow hydrographs of five storms: good. Runoff volumes and peak flows: D_v ranged from 9% to 29% and from 1% to 13%, respectively. Time to peaks: within an hour, except one 2 and another 3 hours.	Flood forecasting (height and inundation) for 11 design (frequency−duration) storms. Effects of rainfall pattern on peak flow and timing. Several storm water management scenarios.	RUNOFF was useful in this flood management and flood prevention study for the Borough of Milltown, N.J.
USDA−USEPA Experimental watershed P4, near Watkinsville, Georgia (Borah and Ashraf, 1992, 1993b; Borah et al., 2002b); 1.4 ha.	Water, sediment, ammonium, and atrazine discharge graphs during a storm: good.	Water, sediment, ammonium, and atrazine discharge graphs during a second storm: good.	Sensitivity analysis on chemical parameters − interaction constant *b* and partition coefficient K.	RUNOFF3 (original version of DWSM−Agchem) was useful in predicting storm event space and time varying agrochemical discharges, in addition to water and sediment.
South Branch Rockaway Creek watershed, New Jersey (Borah et al., 1990); 32 km^2.	Flow hydrograph for one storm: good.	Flow hydrograph for a second storm: good. Runoff volumes, peak flows, and their timings of seven other storms: reasonable.	Results of the nine storms were compared with results from U.S. Army Corps of Engineers' (1985) HEC−1 model: almost identical, except RUNOFF's peak flows closer to the observed.	Due to analytical solution of the kinematic wave (KW) equations, RUNOFF predicted more accurate peak flows than HEC−1. HEC−1 showed instabilities near the peak due to its numerical solutions of the same equations.

Table 3. Application summary of DWSM (concluded).

Watershed	Model Calibration	Model Validation	BMP or Other Use	Comments
Experimental watersheds W−1 and W−2, near Treynor, Iowa (Van Liew and Saxton, 1984a, 1984b); 30.1 and 33.5 ha, respectively.	Runoff volume, peak flow and its timing, and sediment yield and peak of 24 storms on W−1: good. Storm hydrograph and sediment graph: reasonable.	Validation on W−1 was included in the calibration with 24 storms.	The W−1 parameters were used in nearby W−2 watershed simulations of four storms. Runoff volume, peak flow and timing, and sediment yield and peak were comparable to observed data.	SEDLAB, original version of DWSM, produced reasonable flow and sediment results on the paired watersheds, indicating that the model may be transferable to similar ungauged watersheds.
USDA Experimental watershed R−5, near Chickasha, Oklahoma (Borah et al., 1981); 9.6 ha.	Flow hydrograph for a rainfall event: good.	Runoff volume and peak flow for another storm: reasonable.	None	SEDLAB proved its applicability to an agricultural watershed in simulating rainfall event hydrographs.
USDA Experimental watershed near Tombstone, Arizona (Borah, 1979); 1.2 ha.	Hydrograph and sediment discharge graph for a storm: good.	None	Results were compared with another model (Smith, 1978), and found comparable.	SEDLAB proved its applicability to this rangeland watershed in simulating rainfall event hydrograph and sediment discharge graph.
An urban catchment (Borah et al., 1980); 0.16 ha impervious parking lot.	Hydrograph for a storm event (Schaake, 1970): good.	None	Results were compared with results from a numerical solution of the KW equations.	SEDLAB's analytical solution of the KW equations performed better than a numerical solution on this 100% urban catchment.
Feedlot plots QF3 and QF6 (5.5×18.3 m), Price's Fork Agricultural Farm, Virginia Water Resources Research Center near Blacksburg, Virginia (Ashraf and Borah, 1991; Borah and Ashraf, 1993a).	Flow hydrograph, sediment discharge and concentration graphs of ammonium and orthophosphate from three rainfall applications: good. Flow volumes and yields of the three constituents: COD ranged from 0.98 to 0.99.	Combined with calibration with the three rainfall events.	None	RUNOFF3 performed very well on these two feedlot plots while simulating runoff, sediment, and nutrients under rainfall events.
Experimental rainfall−runoff plots (12×12 m) of Chow and Yen (1974), University of Illinois at Urbana−Champaign, Illinois (Melching, 2002; Xiong, 2002).	Hydrographs of eight events: very well. Hydrograph of 68 events: average NSC = 0.928 for rainstorms longer than or equal to 120 s, and 0.8 for storms shorter than or equal to 60 s.	Validation was included in calibration while running 68 rainstorm events.	Results compared with SWMM (Huber and Dickinson, 1988): DWSM hydrographs were better than SWMM for the eight events. Average NSC from 68 SWMM runs was 0.88 for rainstorms longer than or equal to 120 s, and 0.07 for storms shorter than or equal to 60 s.	DWSM with KW routing performed much better than SWMM with storage−based or nonlinear reservoir routing of runoff, which is also used in HSPF.
Experimental boxes ($1.0 \times 0.5 \times 0.8$ m^3) of Hubbard et al. (1989a, 1989b) under simulated rainfall (Ashraf and Borah, 1992).	Concentration graphs of nitrate, phosphate, and cyanazine for 15 rainfall events: very good. Yields: COD = 0.97, 0.88, and 0.88, respectively.	Validation was included in calibration while simulating the 15 events.	None	DWSM−Agchem is promising in simulating storm event nutrients and pesticides on agricultural lands.
Experimental flume ($4.6 \times 1.5 \times 1.2$ m^3) of Kilinc and Richardson (1973) (Borah, 1979).	Water and sediment discharges for ten experimental events: good.	Validation was included in calibration while simulating the ten events.	None	The original runoff and sediment routines of DWSM (SEDLAB) were promising.
Experimental flume of Iwagaki (1955); 7.3m (Borah et al., 1980).	Hydrographs of three experimental events: very good.	Validation was included in calibration while simulating the three events.	Results were compared with a numerical solution of the KW equations.	DWSM with analytical solution of the KW equations preserved critical features of the hydrographs, particularly the rising parts where shocks are present, better than a numerical solution−base scheme.
Hypothetical kinematic cascade of Kibler and Woolhiser (1970) with three planes, each 122 m long (Borah et al., 1980).	Hydrograph from DWSM's analytical and approximate shock−fitting solution of KW was almost identical with Kibler and Woolhiser's KW analytical and an iterative shock−routing scheme.	None	Results were compared with a finite difference numerical solution of the KW equations. The numerical solution was unable to reproduce the unique rising and peak portions of the hydrograph.	DWSM's analytical and approximate shock−fitting solution of KW reproduced hydrograph almost identical to more accurate Kibler and Woolhiser's KW analytical and iterative shock−routing scheme. The latter is less efficient, and perhaps impractical for watershed simulations.

experimental watershed (1.2 ha) near Tombstone, Arizona, and an impervious (urban) catchment (0.16 ha). The model performed well in simulating surface runoff (flow hydrograph) in all the three watersheds and sediment discharges in the second watershed. As shown by Borah et al. (1980), SEDLAB's analytical and shock−fitting solution of the kinematic wave equations generated better hydrographs on the third watershed than a numerical solution of those equations.

Van Liew and Saxton (1984a, 1984b) applied SEDLAB to two experimental watersheds, namely W−1 (30.1 ha) and W−2 (33.5 ha) near Treynor, Iowa (table 3), with model modifications on flow resistance and land cover effects on soil erosion. The investigators successfully transferred W−1 parameters to W−2, showing that the model may be transferred to similar uncalibrated and ungauged watersheds. Water and sediment results for 24 storms on W−1 and for four storms on W−2 were comparable with observed values. Van Liew (1998) applied RUNOFF to the Lan River watershed (table 3), a larger watershed (1,142 km^2) in China, where he simulated 24 storm events and compared their sediment yields with observed values, showing good agreement (COD = 0.96). He conducted sensitivity analysis of sediment parameters.

A practical application of RUNOFF was to the 122 km^2 Lawrence Brook watershed in New Jersey (table 3) as part of a flood management and flood prevention study for the Borough of Milltown (Omni, 1994; Borah, 1995). The hydrology model was calibrated and validated by simulating six storm events. Simulated hydrographs, runoff volumes, peak flows, and time to peaks compared well with observed data. The model was used to develop a flood forecasting database of design storms and predict effects of different storm water management scenarios (table 3).

Testing of all the three components of DWSM (RUNOFF), namely hydrology, sediment, and agrochemical, to watershed−scale catchment was first done on USDA−USEPA experimental watershed P4 (1.4 ha) near Watkinsville, Georgia (table 3), where RUNOFF was calibrated and validated to match observed water, sediment, ammonium, and atrazine discharge graphs resulting from two different rainfall events. As presented in Borah and Ashraf (1992, 1993b) and Borah et al. (2002b), the model performed well in simulating runoff and its constituents resulting from rainfall events. A sensitivity analysis was performed, which showed that the interaction constant and the partition coefficient were, respectively, highly and moderately sensitive to chemical mass load.

The latest applications of DWSM consisted of three watersheds in Illinois: Upper Sangamon River, Court Creek, and Big Ditch. DWSM hydrology performed reasonably well on the 2,400 km^2 Upper Sangamon River watershed (table 3). Addition of a subsurface flow routine (combined interflow, tile flow, and base flow) improved recession and base flow portions of the hydrographs. All three components of DWSM were applied to the 100 km^2 Big Ditch watershed (table 3), an extensively monitored subwatershed of the Upper Sangamon River watershed (Borah et al., 2003). The model reasonably predicted hydrographs, sediment discharge graphs, and phosphate−P trends resulting from rainfall events, including severe storms. Scaling−effect analysis yielded interesting results on the effects of watershed division sizes on model parameters and simulated water and sediment discharges.

The Court Creek watershed (251 km^2) application (table 3) demonstrated a practical application of DWSM. The model generated reasonable hydrographs and sediment discharge graphs at tributary and watershed outlet stations resulting from severe rainfall events. Rankings of overland planes and stream reaches, based on simulated unit−width peak flows and unit−width sediment yields for overland planes, and peak flows and sediment yields for stream reaches, were useful to the Illinois Department of Natural Resources and Court Creek Pilot Watershed Planning Committee in prioritizing critical areas for planning restoration projects. They were also useful to the Knox County University of Illinois Extension for educating landowners about BMPs. The model showed reasonable impacts of detention basins or reservoirs on downstream water and sediment discharges (BMP evaluation on flooding and sedimentation).

Summary and Conclusions

Applications and performances of three watershed−scale hydrologic and nonpoint−source pollution models SWAT, HSPF, and DWSM were reviewed and discussed. These three models all have three major components (hydrology, sediment, and chemical) and were selected based on reviews of eleven models and compilations of their mathematical bases presented in a companion article (Borah and Bera, 2003a). In that review, conceptual and mathematical bases of SWAT, HSPF, and DWSM were found to be sound, respectively, for long−term continuous simulations of predominantly agricultural watersheds, long−term continuous simulations of mixed agricultural and urban watersheds, and storm (rainfall) event simulations of agricultural and rural watersheds.

SWAT has been successfully applied numerous times for long−term continuous simulations of flow, soil erosion, and sediment and nutrient transport in watersheds of different sizes, and having different hydrologic, geologic, and climatic conditions. Seventeen of those applications, as found in the literature, were reviewed and compiled. The model requires a significant amount of data and empirical parameters for development and calibration. Most of the calibration and validation of the model was based on monthly flows. The model was found suitable for predicting yearly flow volumes and sediment and nutrient loads. Monthly predictions were generally good, except for months with extreme storm events and hydrologic conditions. Daily flow predictions were made in five of the applications, in which two were fair and the remaining were poor. An automated calibration routine showed improvements in daily predictions. The model has been useful to study impacts of certain climate changes on long−term water yields, and the impacts of certain management scenarios on long−term sediment and nutrient loads, in addition to water yields. Agrochemical and agricultural management simulations were found to be unique strengths of SWAT.

Twelve studies, as found in the literature, where the HSPF model was applied, were reviewed and compiled. Most of the applications were on watersheds of sizes ranging from 0.18 to 170 km^2, with one on a 416 km^2 watershed and three on watersheds over 1,000 km^2. HSPF also requires a significant amount of data and empirical parameters for development and calibration, and it is cumbersome to use. The sediment calibration process was shown to be a very painstaking task. The model was found suitable for predicting yearly and monthly flow volumes and sediment yields, except for the months with severe weather conditions. Daily simulations were found reasonable except during extreme flow events. Winter flow predictions were better than Cornell University's SMR model due to HSPF's superior snowmelt simulations. Simulation of atrazine transport was reasonable, but simulations of nutrients were mixed. The model became less precise as the time interval became smaller. HSPF was useful in studying impacts of urbanization, a unique strength of the model, and different point− and nonpoint−source pollution management scenarios. However, the results were qualitative because of uncertainties in the empirical parameters, which were not validated against the scenarios.

Eighteen applications of DWSM or its earlier versions (RUNOFF or SEDLAB) were reviewed and compiled. Some of the applications involved laboratory boxes, flumes, and catchments. One application was on field plots, and an early application was on three hypothetical cascading planes. These applications confirmed that the physically (process) based routines, used in DWSM, closely represented the physical processes and reproduced flow hydrographs and concentrations and discharges of sediment, nutrients, and pesticides that were comparable to measured values. The DWSM routing schemes, based on analytical and approximate analytical solutions of the governing equations, were shown to be robust and more accurate than other model schemes based on approximate numerical solutions of the equations.

DWSM was applied to twelve watersheds of sizes ranging from 0.16 ha to 2,400 km^2. Most of the watersheds were agricultural and rural, two were suburban, and one was completely urban (0.16 ha impervious area). Due to its physically based formulations, the model has a small number of parameters requiring calibration and validation; therefore, the calibration−validation operations were straightforward, although conducted manually. The model was able to predict distributed flow hydrographs, and concentration or discharge graphs of sediment, nutrient, and pesticides at small time intervals (seconds to hours) resulting from rainfall events. Hydrographs were predicted in watersheds of sizes up to 2,400 km^2. Water and sediment graphs were predicted in watersheds up to 251 km^2. Water, sediment, nutrient, and pesticide graphs were reasonably predicted in a 1.4 ha field−sized watershed. Preliminary results of a phosphate−P graph in the 100 km^2 Big Ditch watershed were promising. Due to its efficient routines, the model is promising for rainfall event simulations in watersheds larger than those specified above. DWSM was useful in evaluating storm water management scenarios on flood prevention and reducing downstream water and sediment discharges. The model was also useful in prioritizing critical runoff, soil erosion, and sediment potential areas for planning restorations.

SWAT and HSPF, which are part of the BASINS modeling system for TMDL analysis, are appropriate to simulate long−term yearly, monthly, and daily runoff, sediment, nutrient, and pesticide responses from predominantly agricultural watersheds and mixed agricultural and urban watersheds, although monthly and daily simulations for extreme weather need improvements in both the models. Most of the sediment and pollutants are carried during the extreme short−duration storm events; therefore, predictions of these events are crucial in issuing public warnings, abating flooding and nonpoint−source pollution problems, helping to develop and implement emerging TMDL process, and meeting various water quality standards. DWSM provides a useful tool for adequately simulating the extreme storm (rainfall) events. Combined use of these models, and perhaps other complementary models having different strengths, is warranted to adequately manage watersheds and address water quantity and quality issues.

All these models have strengths in different areas, and by combining those strengths, each of these models' predictive power could be enhanced. For example, SWAT's current hydrologic response unit (HRU) scheme does not include interaction among HRUs; therefore, by using DWSM's scheme, the model will be able take landscape position into account (Arnold, 2003). Further research is needed to enhance these and other complementary models, and test the models through extensive calibration, validation, and evaluation on a wide range of watershed conditions. Good quality monitoring data are critical in these processes, but data are still scarce, especially sediment and agrochemical data. Efforts must continue to collect good quality data.

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