WATERSHED MODELING FOR WATER RESOURCE MANAGEMENT

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Contents

Summary

This chapter presents a perspective of watershed modeling for management of water resources mostly in agricultural and rural watersheds. Watershed models are useful analysis tools in water resource management and planning within a watershed. In chapter (see: *Water Resource Models*), watershed models are introduced and eleven of them are summarized. Three of those models are selected as promising models based on their simulation capabilities (simulations of hydrology, sediment, and chemicals in upland areas and stream network) and computational efficiencies. Those are 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. SWAT and HSPF are parts of USEPA’s BASINS modeling system with GIS and user interfaces and are available from its website. Links to databases needed to run these models are provided there. Data and parameters of SWAT and DWSM are interchangeable and, therefore, data and parameters of DWSM can be derived from data and parameters of SWAT. In this chapter, applications of these three models, as found in the literature, are summarized and their performances and uses for water resource management are discussed. Major efforts went into calibration and validation of the models, a critical step. The applications provide examples of some beneficial uses of these three models and perhaps some guidelines on using these and other watershed models to predict future impacts of natural (e.g., climate change) or man made (e.g., land use and BMP) changes

within a watershed. More research is needed in combining strengths and overcoming weaknesses of the existing models, extending their applications with other techniques and procedures, and testing them on a wide range of watershed conditions.

1. Introduction

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 United States (US) and throughout the world. 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. Watershed-scale hydrologic and nonpoint-source pollution models, the most comprehensive water resources models, are useful tools in assessing the environmental conditions of a watershed and evaluating land use changes and best management practices (BMP), 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 of the US.

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. 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. Combined use of long-term continuous and storm event simulation models is needed to adequately manage water resources, watersheds in particular, 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.

Eleven watershed-scale hydrologic and nonpoint-source pollution models are described, analyzed, and compared in chapter (see: *Water Resource Models*), including Agricultural Nonpoint Source model (AGNPS), Annualized AGNPS (AnnAGNPS), Areal Nonpoint Source Watershed Environment Response Simulation (ANSWERS), ANSWERS-continuous, CASCade of planes in 2-Dimensions (CASC2D), Dynamic Watershed Simulation Model (DWSM), Hydrologic Simulation Program – Fortran (HSPF), KINematic runoff and EROSion model (KINEROS), the European Hydrological System model (MIKE SHE), Precipitation-Runoff Modeling System (PRMS), and Soil and Water Assessment Tool (SWAT). Based on these comparisons, 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 are selected to demonstrate their use in water resource management. Model comprehensiveness and robustness were the primary criteria of the selections. The models are 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 simulation model for agricultural and suburban watersheds. These models have all the three major components (hydrology, sediment, and chemical), simulate upland and stream processes, and have robust model algorithms.

Both the long-term continuous simulation models SWAT and HSPF are parts of US Environmental Protection Agency's (USEPA) Better Assessment Science Integrating Point and Nonpoint Sources (BASINS) modeling system with Geographic Information System (GIS) and user interfaces. These two and a few other water resources models are available from the USEPA's BASINS website at: http://www.epa.gov/OST/BASINS/. Links to databases needed to run these models are provided at this website. 2005-2006 studies found hydrologic simulation procedures of SWAT and DWSM complementary and compatible for combining into a more comprehensive watershed model. Data and parameters of these two models are interchangeable and, therefore, data and parameters of DWSM can be derived from data and parameters of SWAT.

The primary focus of this chapter is to demonstrate applications, performances, and use of the three models (SWAT, HSPF, and DWSM) on various water resource systems (watersheds). Many applications of these models may be found in the literature; only a handful (16 SWAT, 12 HSPF, and 12 DWSM) are described and compiled here in tabular form. Major efforts went into calibration and validation of the models for the water resource systems studied, which is a critical step in using models. Some applications involve simply calibration or calibration-validation to make sure that the model is suitable for water resource management and analysis in the system studied.

2. SWAT Applications

Sixteen applications of SWAT as found in the literature are summarized and compiled in Table 1. Watershed location and size, model calibration, model validation, management or other model use, and finally some evaluation comments are noted in the compilation table for each of the 16 applications.

atershed	Model calibration	Model validation	Management or other use	Comments
Richland and Chambers (RC) Creeks watershed, Upper Trinity River basin, Texas. 5 080 km^2.	Monthly flow and six-year sediment yield.	Monthly flow and three- and seven-year sediment yields.	No information.	SWAT performed well for monthly flows and multiyear sediment yields.
Ariel Creek watershed, Pennsylvania. 39.4 km^2.	Daily flow: deviation of runoff volumes (D_v) = 39.9 % and Nash-Sutcliffe coefficient (NSC) = 0.04. Monthly flow: NSC=0.14.	No information.	No information.	SWAT requires calibration, and is better suited to longer period (monthly) simulations, and not adequate for severe single events.
Warner Creek watershed, Maryland. 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.	No information.	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. 538 km^2.	Monthly flow: COD=0.74.	No information.	Climate (precipitation) variations.	SWAT was useful in predicting effects of precipitation variations on monthly water budgets.
Cannonsville Reservoir watershed, New York. 1 178 km^2.	Monthly and daily flows and monthly sediment yield.	No information.	No information.	SWAT requires a significant amount of data and empirical parameters and its sediment routing is weak.
Ali Efenti watershed, Greece. 2 796 km^2.	Daily flow: NSC=0.62. Monthly flow NSC=0.81. Monthly nitrate-N.	No information.	Impacts of climate change (temperature and precipitation) on surface, lateral, and ground-water 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.	Monthly flows: COD for Walnut and Buck = 0.67 and 0.64, respectively. Monthly sediment and nitrate-N loads.	No information.	Impacts of three BMP scenarios on annual sediment and nitrate loadings.	SWAT was useful in evaluating BMP scenarios.

Table 1: Application summary of SWAT (continued)

Watershed	Model calibration	Model validation	Management or other use	Comments
Bosque River watershed, Texas. 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 waste water treatment plant (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. 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 in the US.	No information.	No information.	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. 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 baseflow 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. 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 8-digit watersheds and monthly flows near the outlet. The model under predicted spring peaks and sometimes over predicted fall flows.

Table 1: Application summary of SWAT (concluded)

Watershed	Model calibration	Model validation	Management or other use	Comments
Lower Colorado River basin, Texas. 8 927 km^2.	Monthly flows near the outlet: COD=0.66.	No information.	Land use change scenarios: changing irrigated rice fields to dry lands and increase urban developments.	SWAT closely simulated monthly flows, however under predicted during extreme events.
Upper Wind River basin, Wyoming. 5 000 km^2.	Monthly water yields: COD=0.91.	No information.	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 stream flow.
Leon River watershed, Texas. 9 000 km^2.	Monthly flows: correlation coefficient (r) = 0.83 and NSC=0.57.	No information.	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. 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 eight-year simulations – 1984), respectively.	Green-Ampt Mein-Larson (GAML) excess rainfall method 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 sub-daily 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.

Table 1: Application summary of SWAT

2.1. SWAT Calibrations and Validations

Most of the calibration and validation of the model are based on monthly flow volumes or monthly average flows (Table 1). As shown in the applications to Warner Creek watershed (3.46 km^2) in Maryland, Upper Mississippi River basin (491 700 km^2) in Minnesota, Wisconsin, Iowa, Missouri, and Illinois, and 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 monthly flow predictions. While applying the model to University of Kentucky Animal Research Center (5.5 km^2 farm) in Kentucky (Table 1), the investigators found that daily flow comparisons for calibration and validation periods yielded much lower Nash-Sutcliffe Coefficient (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. 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 eight-year simulations in Goodwin Creek watershed (1984), the daily NSC value was 0.78. In this watershed, the model was run with no calibration. Using an automated calibration routine, daily simulations were improved with NSC values of 0.70-0.73 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). Sediment yield predictions were calibrated and validated on the Richland and Chambers Creeks watershed (5 080 km^2) in Texas based on multiyear (3-7) sediment yields. While simulating sediment loadings in the Cannonsville Reservoir watershed, it was noted that the model generally simulated watershed response on sediment, but it grossly under predicted sediment yields during high flow months. Monthly sediment load predictions were compared 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^{-1}, determined from low flow samplings, and used the parameters to simulate the nearby Walnut Creek watershed (51.3 km^2). This shows that data is still scarce for adequate model calibration and validation and it warrants continued collection of good quality data. Monthly sediment yield (metric tons per hectare or t ha^{-1}) predictions were compared with observed data from the Bosque River watershed (4 277 km^2) in Texas yielding 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). Comparisons of simulated and observed monthly nitrate-N loadings were found poor (r^2=0.27) in the Warner Creek watershed. The model was calibrated for monthly nitrate-nitrogen (nitrate-N) and total N in the Ali Efenti basin. Seasonal trends were simulated quite well, although the in-stream routine was not used. Simulated and observed cumulative monthly nitrate-N loads were compared for the Walnut Creek watershed in Iowa. The comparisons were reasonable after the first two years. Monthly organic N and P yield (kg ha^{-1}) predictions were compared 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^{-1}) comparisons yielded similar results, except for mineral N at the Valley Mills station (70% of the watershed), where NSC was -0.08.

2.2. Use of SWAT in Water Resource Management

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 applications involved investigating impacts of various management scenarios (Table 1). Impacts of three management scenarios on annual sediment and nitrate loadings were studied in the Walnut and Buck Creek watersheds. Several management practices on dairy manure and waste water treatment plant effluents in reducing minimum P loadings were studied in the Bosque River watershed. Converting irrigated rice fields to dry land and increasing urban development were investigated in the Lower Colorado River basin. Annual sediment yield predictions were used to select locations of monitoring stations in the Leon River watershed (9 000 km^2) in central Texas (Table 1). Researchers 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 can not be validated against the scenarios.

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Biographical Sketch

Dr. Deva K. Borah is a hydro-environmental modeler with 27 years of water resources and hydro-environmental modeling experiences. Dr. Borah earned his Ph.D. degree in Engineering Science from the University of Mississippi and through collaborative research with the USDA-ARS National Sedimentation Laboratory, Oxford, Mississippi and worked for the University of Mississippi, TAMS Consultants, Inc., Rutgers University, OMNI Environmental Corporation, and currently for the Illinois State Water Survey. Dr. Borah is the lead developer of five state-of-the-art computer models, including the storm event watershed model DWSM, discussed in this article. He has over 150 publications published in peer-reviewed journals, conference proceedings, and as book chapters and research/project reports.