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Advances in the application of the SWAT model for water resources management

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Abstract:

Developments in computer technology have revolutionized the study of hydrologic systems and water resources management. Several computer-based hydrologic/water quality models have been developed for applications in hydrologic modelling and water resources studies. Distributed parameter models, necessary for basin-scale studies, have large input data requirements. Geographic information systems (GIS) and model–GIS interfaces aid the efficient creation of input data files required by such models. One such model available for the water resources professional is the Soil and Water Assessment Tool (SWAT), a distributed parameter model developed by the United States Department of Agriculture. This paper describes some recent advances made in the application of SWAT and the SWAT–GIS interface for water resources management. Four case studies are presented. The Hydrologic Unit Model for the United States (HUMUS) project used SWAT to conduct a national-scale analysis of the effect of management scenarios on water quantity and quality. Integration of the SWAT model with rainfall data available from the WSR-88D radar network helps us to incorporate the spatial variability of rainfall into the modelling process. This study demonstrates the usefulness of radar rainfall data in distributed hydrologic studies and the potential of SWAT for application in flood analysis and prediction. A hydrologic modelling study of the Sondu river basin in Kenya using SWAT indicates the potential for application of the model in African watersheds and points to the need for development of better model input data sets in Africa, which are critical for detailed water resources studies. The application of SWAT for water quality analysis in the Bosque river basin, Texas demonstrates the strength of the model for analysing different management scenarios to minimize point and non-point pollution, and its potential for application in total maximum daily load (TMDL) studies. Copyright © 2005 John Wiley & Sons, Ltd.

KEY WORDS hydrology; basin-scale modelling; distributed modelling; streamflow; SWAT; HUMUS; WSR-88D; water quality

INTRODUCTION

Water resources management and hydrologic modelling studies are intrinsically related to the spatial processes of the hydrologic cycle. Developments in computer technology have revolutionized the study of hydrologic systems. Many computer models have been developed for hydrologic modelling and water resources management applications. Lumped hydrologic models simulate a spatially averaged hydrologic system, while distributed models involve a more accurate representation of the hydrologic system by considering the spatial variability of model parameters and inputs (Chow *et al.*, 1988). Distributed parameter hydrologic models, such as the Soil and Water Assessment Tool (SWAT; Arnold *et al.*, 1998), generally subdivide the watershed into smaller sub-basins and require data on model inputs such as soil and land use for each of those sub-basins. Though this results in a better representation of the natural hydrologic system, data assembly and input files development for such models require enormous effort and time on the part of the hydrologist. This issue becomes more serious when simulating large river basins. Development of spatial databases together

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with geographic information systems (GIS) and advances made in distributed hydrologic modelling led to tremendous progress in detailed spatially distributed analysis of hydrologic and water resources systems in the 1990s. Several international conferences held during the 1990s focused on the applications of GIS for water resources management (Kovar and Nachtnebel, 1993; Singh and Fiorentino, 1996). The ready availability of digital spatial data necessary for water resources studies and advances made in GIS technology led to the development of interfaces between hydrologic models and GIS. These interfaces aid in assembling the required spatial data from GIS coverages and creating the necessary input files efficiently, and enable water resources professionals to study large watershed systems with significant savings in time and cost. The SWAT model developed by the United States Department of Agriculture in the 1990s is a distributed parameter basin-scale hydrologic/water quality model. GIS interfaces have been developed for SWAT to efficiently develop input data files from GIS coverages. These interfaces facilitate analysis of the impact of different watershed management scenarios on water yield and quality. This paper describes one such GIS interface developed for SWAT and some recent advances made in the application of SWAT for water resources assessment and watershed/water quality management. The interested reader is referred to Arnold *et al.* (1998) for a detailed description of the SWAT model and its components.

HYDROLOGIC UNIT MODEL FOR THE UNITED STATES (HUMUS)

Water quality and quantity are ever-increasing environmental concerns. Damage from soil erosion alone, which does not include nutrient and pesticide contamination, is estimated at several tens of billion dollars in the United States (Committee on Conservation Needs and Opportunities, 1986). The Resource Conservation Act of 1977 as amended (RCA) requires the United States Department of Agriculture to appraise the status, condition and trends in the uses and conservation of non-federal soil and water-related natural resources. The HUMUS project was designed to provide the technical basis for conducting the appraisal of water resources for the 1997 RCA Appraisal Report. It was intended to provide better information than has ever been obtained before about the uses of water on irrigated and non-irrigated agricultural lands, and the physical and economic effects of changing agricultural practices and cropping patterns on the future water needs and supplies.

HUMUS was a national-scale project developed to analyse the effect of management scenarios on water quantity and quality using SWAT, a basin-scale, continuous-time, distributed parameter hydrologic/water quality model, and GIS. The management scenarios included agriculture and municipal water use, tillage trends in agricultural lands, cropping systems, fertilizer and animal waste management and flood control structures. Major components of the HUMUS system were: (1) SWAT to model the surface and subsurface water quantity and quality; (2) a GIS to collect, manage, analyse and display the spatial and temporal inputs and outputs; and (3) relational databases needed to manage the non-spatial data and drive the model. The most critical component of the HUMUS system was collection of the required data to drive the model. For approximately 2150 watershed areas [hydrologic cataloguing units delineated by the United States Geological Survey (USGS)], data on historical weather, soil, topography, natural vegetation, cropped areas, irrigation and agricultural practices were collected from several government agencies. GIS played a very important role in managing the spatial data and developing model inputs from the spatial and relational databases.

SWAT–GRASS interface

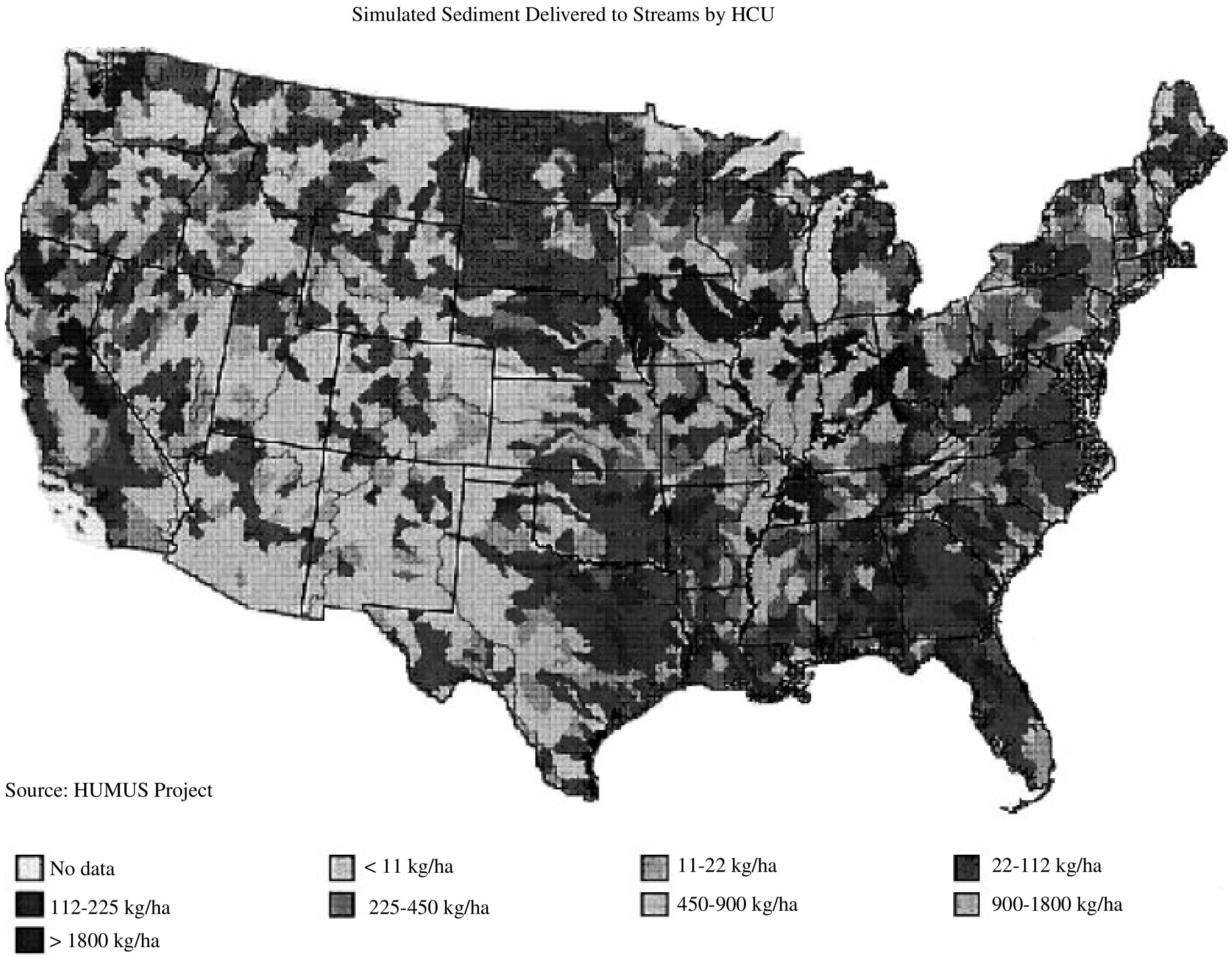
The GIS tool chosen for the HUMUS system was GRASS (Geographic Resources Analysis Support System; US Army, 1993), a public domain raster GIS designed and developed by the Environmental Division of the US Army Construction Engineering Research Laboratory in Champaign, IL. GRASS is a general purpose, raster graphic modelling and analysis package and is highly interactive and graphically oriented, providing tools for developing, analysing and displaying spatial information. A GRASS interface was developed for the SWAT model, utilizing a toolbox rationale to provide a collection of GIS programs assisting with the data development and analysis requirements of SWAT (Srinivasan and Arnold, 1994; Srinivasan *et al.*, 1996; http://www.brc.tamus.edu/swatgrass/index.html). The SWAT–GRASS interface programs and tools were integrated with the GRASS libraries and run under the UNIX environment.

The input interface tools assist with preparation and extraction of data from the GIS database for use with the SWAT model. The input interface was designed to perform three tasks: (1) project management, (2) extraction and aggregation of inputs for the model, and (3) viewing, editing and checking the input data. The function of the project manager is to interact with the user to collect, prepare, edit and store basin and sub-basin information to be formatted into a SWAT input file. The extraction and aggregation step uses a variety of hydrologic tools and GIS layers including sub-basin, soil, land use, elevation, weather network and pesticide application data. In addition, data on reservoirs, lakes, ponds and point inflows such as interbasin water transfers can be entered directly by the user. In the third step, the user can view, check and edit the data extracted by the previous step using a sub-basin number as the input. This interface helps to reduce the input data development and manipulation time by several orders, especially for basin-scale hydrologic analyses such as the HUMUS system. It also allows rapid modification of the various management practices and prepares data for subsequent model runs to analyse the effects of different watershed and agricultural best management practices on water yield and quality. It can also be used to perform model sensitivity analysis by modifying the GIS layers and/or choosing different aggregation methods for various input data.

The SWAT–GRASS output interface is an analytical tool that extracts the model output data from the ASCII output files of SWAT and allows the user to graphically visualize and analyse the outputs. This tool can be used to develop scatter plots, line graphs, pie and bar charts of the model outputs. Users can select to view or analyse the results of one particular sub-basin or the entire watershed, and also compare results between sub-basins. Using the statistics option of this tool, validation of the simulated data can easily be performed by comparison with the observed data, and regression curves can be displayed graphically. Another major advantage of this tool is to obtain customized hardcopy outputs for reports. Another SWAT–GIS interface is available for the more popular ArcView desktop GIS package running on personal computers (Di Luzio *et al.*, 2002); this interface also includes sophisticated tools to assist with the preparation of model inputs, simulations and output analysis.

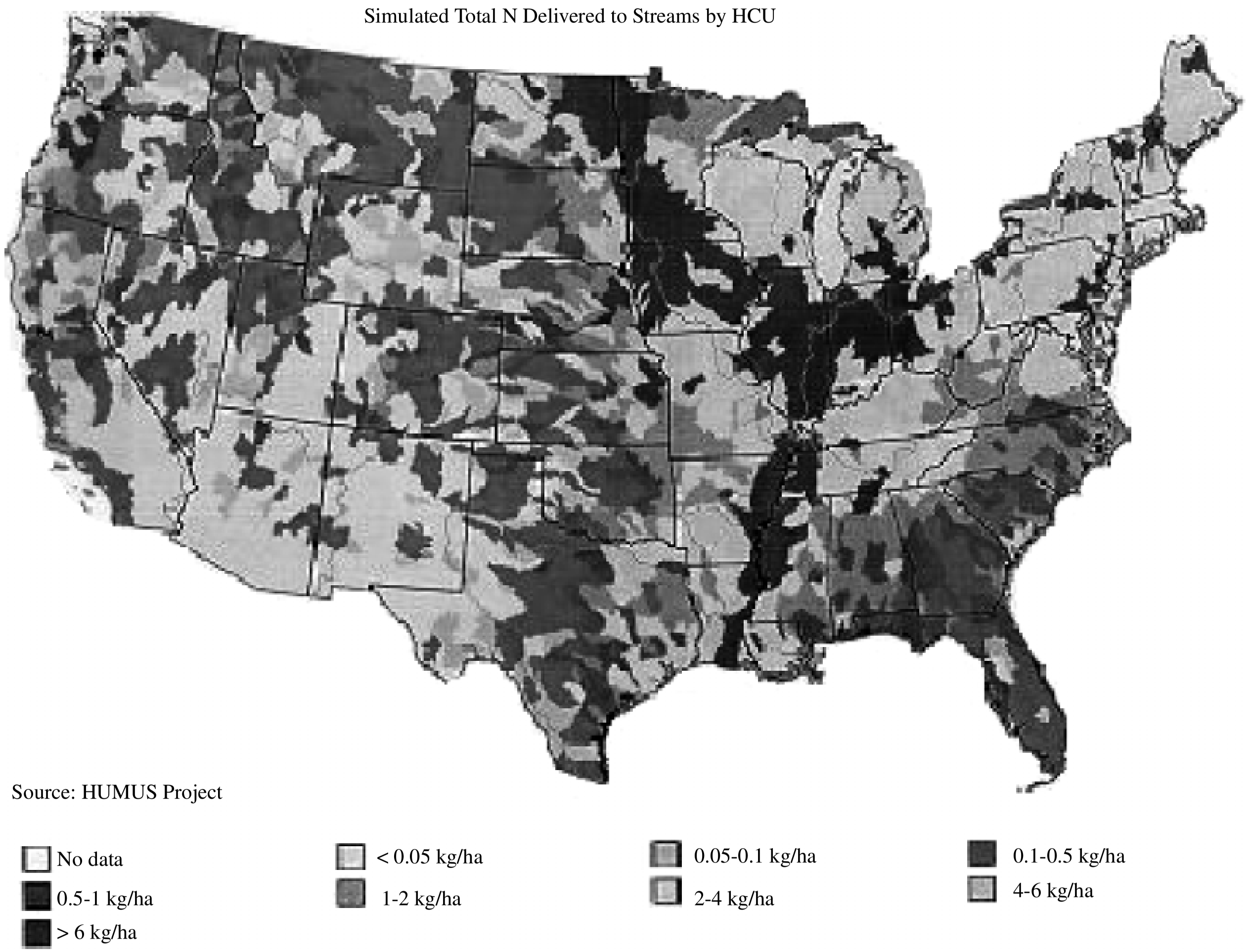
SWAT application

HUMUS databases were used as input to the SWAT model to simulate water balance in 18 hydrologic regions (river basins) covering the continental United States. The SWAT–GRASS input interface was used to automate the assembly of all necessary input files for SWAT runs. National-scale GIS databases on land use, soil and elevation were used. Also, observed daily precipitation and temperature data from more than 5000 weather stations were assembled and input into the model. Missing weather data were generated using the weather generator of SWAT. The hydrologic balance for each soil association polygon was simulated without model parameter calibration for 20 years. The model was validated by comparing simulated average annual runoff with observed long-term average annual runoff from streamgauge records. Over 45% of the modelled area was within 50 mm of measured runoff, and 18% was within 10 mm without model calibration (Arnold *et al.*, 1999). Maps of observed and simulated runoff and simulated evapotranspiration for the continental United States are given by Arnold *et al.* (1999). Figure 1 shows a map of average annual sediment load to streams simulated by SWAT using hydrologic cataloguing units (HCUs). HCUs in the mid-west and Pacific coast show the highest sediment loads. The SWAT-simulated average annual total nitrogen delivered to streams by HCUs is given in Figure 2. The agriculturally intensive mid-western region, HCUs along the Mississippi River, northeastern USA and Pacific northwest show the highest total nitrogen loads to streams. Though the model was not calibrated for sediment and nutrient loads to streams in this study, the results were found to be in agreement with subsequent studies conducted at specific basins. Further, nutrient loading results obtained in the HUMUS project agreed well with those obtained using the SPARROW watershed model developed by the United States Geological Survey (Alexander *et al.*, 2001).



Source: HUMUS Project

Figure 1. Simulated average annual sediment load to streams by hydrologic cataloguing units from the HUMUS study



Source: HUMUS Project

Figure 2. Simulated average annual total nitrogen delivered to streams by hydrologic cataloguing units from the HUMUS study

INTEGRATION OF SWAT AND RADAR RAINFALL DATA

Rainfall is the driving force behind all hydrologic processes occurring in a watershed. It is characterized by spatial and temporal variability. Representation of this variability in models can be expected to improve short-term and long-term simulation results. Most of the hydrologic studies rely on rainfall data available from raingauges. Raingauge networks that provide rainfall data necessary for hydrologic simulation are usually sparse and not sufficient to capture the spatial variability of rainfall across a watershed. Recording-type raingauges are necessary to provide temporally varied rainfall data. Such raingauges are generally available only for experimental/research watersheds. Another source of rainfall data is weather radar, such as the Next Generation Weather Radar (NEXRAD) of the National Weather Service (NWS) in the United States. It is formally known as the Weather Surveillance Radar-1988 Doppler (WSR-88D). Weather radars estimate precipitation using remote sensing techniques by transmitting and receiving electromagnetic signals. They provide rainfall data that have much better spatial and temporal resolution compared to raingauge networks. But there are concerns about the quality of radar rainfall data since radar estimates suffer from several sources of errors and possibilities of 'data contamination' (Sauvageot, 1994; Legates, 2000) and data quality control is very important for operational weather radar networks. WSR-88D rainfall data processing algorithms involve several data quality control measures, including calibration using real-time ground truth rainfall data obtained from recording raingauge networks in three stages of data processing (Crum and Alberty, 1993). These algorithms are being continuously improved by NWS to provide better rainfall estimates over large areas with high spatial and temporal resolution. Stage III rainfall data available from the WSR-88D network are a promising means for incorporating the spatial and temporal variability of rainfall into hydrologic/water quality simulation, especially in watershed level analyses that use distributed parameter models like SWAT. This study focused on the development of algorithms to create SWAT precipitation input files from Stage III WSR-88D rainfall data files and simulation of streamflow in four large watersheds in Texas using SWAT.

Algorithms to process Stage III WSR-88D data

Stage III WSR-88D rainfall data are defined for 4 km × 4 km grids known as the Hydrologic Rainfall Analysis Project (HRAP) grids. HRAP grids were originally defined in polar stereographic projection, which is not used in general GIS databases of interest to the water resources professional. Most of the spatial data needed by hydrologic simulation models are in more common map projections such as the Albers Equal Area (AEA) projection or the Universal Transverse Mercater (UTM) projection. Development of the HRAP grid map in such projections was necessary for georeferencing WSR-88D rainfall data serving as SWAT model input. GIS played a major role in developing the HRAP grid map in this effort. Reed and Maidment (1999) presented an algorithm to develop the HRAP grid GIS layer in ARC/INFO GIS. Their algorithm was modified to develop a HRAP grid map that would uniquely identify each HRAP grid with a 6-digit number formed using the X and Y HRAP coordinates of the lower left-hand corner of each grid. This vector coverage was developed in the AEA projection of ARC/INFO GIS and was converted to an ARC/INFO GRID using the conversion tool available within ARC/INFO GIS. It was then exported as an ASCII file and imported into GRASS GIS to develop the raster map layer of HRAP grids for each watershed with unique identity number for each HRAP grid (Jayakrishnan, 2001). Statistics obtained on this HRAP grid raster layer using the r.report tool of GRASS GIS provided the list of HRAP grids and their area within each watershed. Algorithms were developed to extract hourly rainfall data of every HRAP grid within the study watersheds from the archive files of Stage III WSR-88D rainfall data obtained from NWS and to accumulate them to daily rainfall. Information on the list of HRAP grids within each watershed obtained using GRASS GIS was used by these algorithms. The daily radar rainfall of each HRAP grid was written out in the format required by the SWAT–GRASS input interface. The SWAT–GRASS input interface was used to process the extracted daily radar rainfall data files and create the precipitation input files necessary for SWAT simulations.

SWAT simulations

HRAP grid maps were developed as GRASS raster coverages for Big Sandy Creek, Walnut Creek, Village Creek and San Bernard River watersheds in Texas using the algorithms described in the previous section. The drainage area of the watersheds ranges from 196 km^2 to 2227 km^2 (Table I). HRAP grids served as the sub-basins for streamflow simulations and their raster layers were input into the SWAT–GRASS input interface as sub-basin maps. Figure 3 shows the HRAP grid sub-basin configuration for the San Bernard River watershed. Hourly WSR-88D rainfall data pertaining to the four watersheds were extracted from Stage III WSR-88D archive files obtained from NWS for the period 1995–1999 and were accumulated to daily rainfall. Rainfall data from the raingauges located in and around each watershed were also collected from NWS to compare the simulation performance with that obtained using WSR-88D rainfall data. Land use, soil and elevation data for the study watersheds were obtained from the HUMUS database as GRASS layers. The SWAT–GRASS input interface was used to develop input data files required by SWAT from these GIS layers and rainfall data files. The dominant land use and soil within each HRAP grid, as obtained from the GIS layers, were used for each sub-basin.

Streamflow was simulated using the SWAT model in each study watershed for the five-year period. Two separate SWAT projects were developed using the SWAT–GRASS input interface, one with precipitation data from WSR-88D and the other with precipitation data from raingauges. Except rainfall input, all other model inputs were kept the same for both projects to compare the effect of each rainfall data source on simulated results. Model parameter calibration was not attempted. Simulated mean monthly streamflow at the watershed outlets was compared with observed mean monthly flow obtained from USGS (Jayakrishnan, 2001). Table I gives the comparison of monthly streamflow simulation in each watershed using both rainfall data sources. SWAT simulation using raingauge data resulted in overprediction of streamflow in the study watersheds, while simulation using WSR-88D data produced relatively better results. In general, mean monthly simulated streamflows obtained using WSR-88D were closer to the observed mean than those obtained using raingauge data. But the Nash–Sutcliffe simulation efficiency (Nash and Sutcliffe, 1970) was negative at three streamgauges using both rainfall data sources, indicating poor simulation performance (Table I). WSR-88D data gave a simulation efficiency of 0·59 at Boling, TX streamgauge in the San Bernard River watershed; the simulation efficiency obtained using raingauge rainfall data was only 0·22. Figure 4 shows the time series plots of observed and simulated monthly streamflow at this location, along with the mean areal precipitation over the watershed area. Differences between the mean areal precipitation values obtained using both rainfall data sources indicate the spatial variability of rainfall and the ability of the WSR-88D network to capture this variability. Except for a few months, the simulated time series obtained using the WSR-88D data compare well with the observed time series. Simulation using rainfall data obtained from the raingauge network produced several high peaks that were not present in the observed streamflow time series.

Table I. Monthly streamflow simulation results using raingauge and WSR-88D rainfall data (1995–99)

Streamgauge (watershed)	Drainage area (km^2)	Observed streamflow (mm)	Mean monthly rainfall (mm)		Raingauge		WSR-88D	
			Raingauge	WSR-88D	Simulated flow (mm)	*E*	Simulated flow (mm)	*E*
Bridgeport, TX (Big Sandy Creek)	863	4·2	74	55	18·8	−7·42	6·6	−0·75
Reno, TX (Walnut Creek)	196	7·6	65	60	17·2	−0·41	12·4	−0·20
Boling, TX (San Bernard River)	1883	27·0	99	76	46·2	0·22	30·1	0·59
Kountze, TX (Village Creek)	2227	33·5	122	92	48·6	−0·04	25·1	−0·06

Note: Streamflow values represent mean monthly flow during the study period; *E* is the Nash–Sutcliffe simulation efficiency.

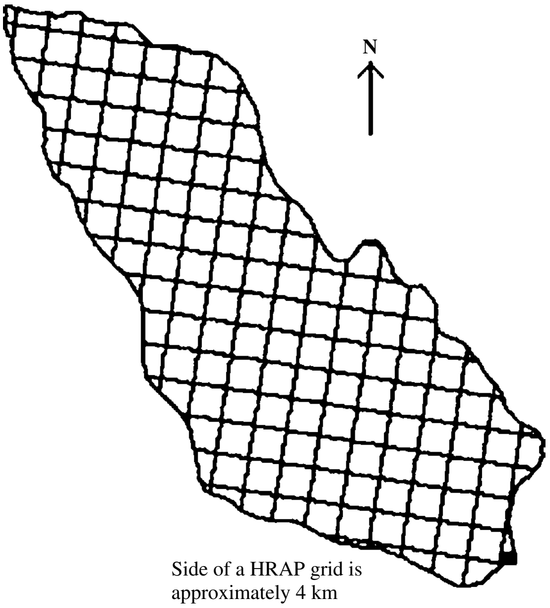


Figure 3. HRAP grid sub-basin configuration for the San Bernard river basin in Texas

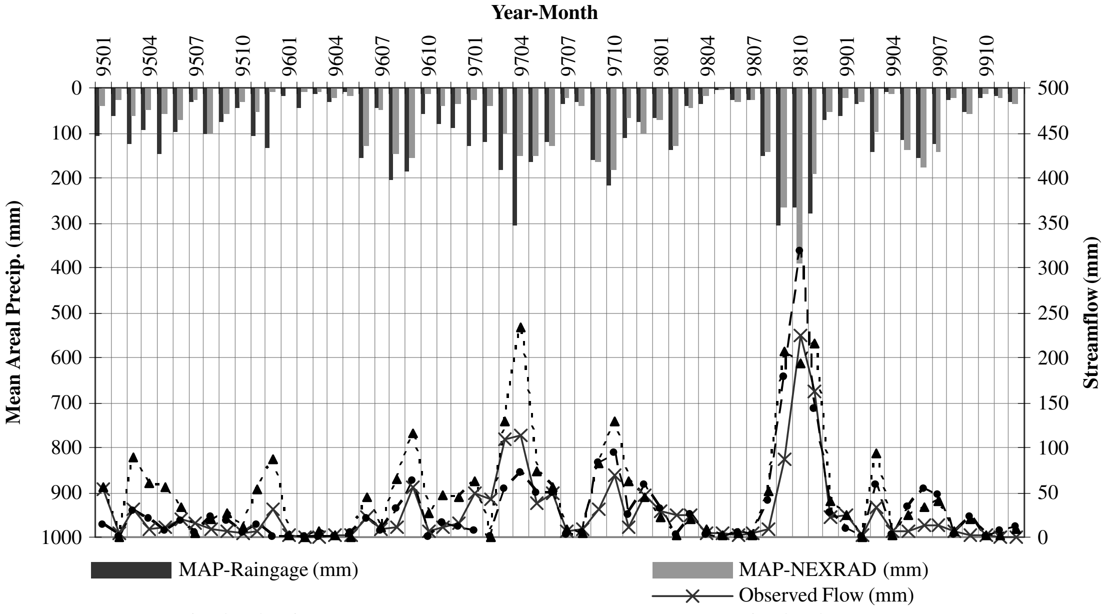


Figure 4. Comparison of observed and simulated monthly streamflow in the San Bernard river basin using raingauge and WSR-88D rainfall data

Use of the WSR-88D precipitation data with the SWAT model produced relatively better simulation results even without model calibration. This is an encouraging result, especially in the case of ungauged watersheds where model calibration is not possible. Since radar estimates involve several sources of error, daily rainfall from the WSR-88D network can be compared with the daily data from raingauges used in this study and radar data can be 'calibrated' using raingauge data. This may improve the simulation results further. Model parameter calibration using such improved radar data should produce better simulation results. Further research is being carried out in this direction. Also, a real-time flood forecasting system using the SWAT model, GIS and hourly WSR-88D rainfall data is being developed to perform hourly simulations that would aid flood control studies.

SWAT APPLICATION IN SONDU RIVER BASIN OF KENYA

Several parts of Africa are affected by extreme climatic conditions leading to frequent drought and famine. Proper management of the limited water resources and watershed is important for sustainable domestic and agricultural water supply in Africa and also to minimize the impacts of human activities on water resources. Basin-level assessment of water resources availability and evaluation of watershed management alternatives to reduce sediment and pollutants load to waterbodies require distributed parameter models like SWAT having large input data requirements including soil, land use and climate data. In the United States, federal agencies have developed national-scale digital data on model inputs like soil and land use, which are readily available for hydrologic analysis and modelling studies. The availability of detailed model input data at such scales is very limited outside the United States, especially in Africa. In this study, an attempt was made to model the hydrology of the Sondu river basin, located in western Kenya, using the SWAT model and limited digital data on land use, soil and elevation available for this river basin. This study was part of a research project that focused on assessing the impact of modern technology on the smallholder dairy industry in Kenya. The adoption of modern technology in the smallholder dairy industry of Kenya leads to changes in land use, and the environmental impacts of such changes need to be assessed to provide for sustainable development.

The Sondu River drains a land area of 3050 km^2 into Lake Victoria and is located in the mountainous regions of western Kenya near the equator. This river basin is a representative watershed for the intense dairy farming regions of Kenya and includes diverse levels of technology adoption in various dairy production zones. Also, this river basin is one of the many watersheds that drain directly into Lake Victoria, and therefore it represents how land use changes impact streamflows and sediment flows into this important waterbody of Africa. The adoption of modern technology, such as improved forage crop varieties and use of fertilizers to enhance forage production, was considered to develop three dairy scenarios for this river basin: a baseline scenario using traditional cattle, unimproved forage and minimal use of modern technology (traditional dairy technology scenario), and varying levels of evolution of the dairy industry that included adoption of modern technology to develop improved scenarios (current adoption scenario and future adoption scenario).

The land use within the Sondu river basin for the three scenarios was estimated using a combination of population data and demographic survey data of 1960–90. A 30% increase in household size was assumed for the current adoption scenario, while a 30% increase in population was assumed for the future adoption scenario. The land area occupied by each household was broken down proportionally into several land use categories for the three scenarios based on the proportions of land use categories found in the survey of representative farms. It was assumed that the increase in Napier grass area from the traditional dairy technology scenario to the future adoption scenario would be at the expense of the native grass area, and that the Napier grass area for the traditional scenario was zero. For the current adoption scenario, 45% of the native grass area was converted to Napier grass, and 60% for the future adoption scenario. It was also assumed that the proportion of non-agricultural land use did not change over the years.

Available data

All digital data sets necessary for hydrologic modelling using the SWAT model were collected and assembled in GIS format. Only digital elevation data with 1-km resolution were available for the study area. A 2·5-min grid network was used to define the sub-basin configuration with 186 full or partial grids covering the Sondu river basin; each full grid was approximately 21·5 km^2 in area. Data on one soil type in the Sondu river basin were available, and this soil was assumed over the entire basin. Three World Meteorological Organization weather stations—Kisumu, Kericho and Kisii—are located in and around the Sondu river basin. Out of these three, Kericho is the nearest weather station for all sub-basins. Daily precipitation and maximum and minimum air temperature data from Kericho weather station for the period 1978–97 were collected. Missing precipitation and temperature data at Kericho were filled with data from Kisumu and Kisii weather stations as available. Observed mean daily streamflow data were available for the streamgauge located at the basin outlet from 1979 to 1996. Streamflow data were missing for several days at this streamgauge; those days were neglected in calculating the mean observed monthly streamflow values. Land use data were developed in a tabular format indicating the percentage of different crops and land uses within the 186 sub-basins for the three dairy technology scenarios as explained in the previous section. No observed sediment data were available to calibrate the sediment load simulation at the basin outlet.

SWAT simulation

All data were processed using the SWAT–GRASS input interface to develop input files necessary for SWAT model simulations of the three scenarios considered. 1978–88 was considered as the model calibration period and 1989–97 was the validation period. The SWAT model was calibrated for monthly streamflow during 1979–88 using the current technology adoption scenario curve numbers to get a reasonable match between observed and simulated mean monthly streamflow. Two model parameters, namely available water-holding capacity and soil evaporation compensation factor, were adjusted to obtain the best possible match between the observed and simulated mean monthly streamflow at the basin outlet. Streamflow and sediment loads were simulated using the calibrated parameters and current adoption scenario curve numbers for the validation period, and results were compared. The same calibrated model parameters were used with future adoption and traditional dairy technology scenario curve numbers for both calibration and validation periods, so that the simulated results could be compared across the three scenarios and the effect of changing land use on water and sediment yield due to dairy technology adoption could be assessed.

Table II presents the SWAT simulation results for traditional, current adoption and future adoption dairy scenarios during calibration and validation periods. Though the mean monthly simulated streamflow compares well with the observed data for the current adoption scenario during model validation, the Nash–Sutcliffe simulation efficiency is only 0·10. Comparison of observed and simulated time series (Figure 5) reveals large variations between the simulated and observed mean streamflow during individual months. This is mainly due to inadequate rainfall and other model input data. Only one raingauge was available for the entire river basin, and rainfall spatial variability was not represented well. This was obvious from the comparison of rainfall time series and observed flow time series (Figure 5); several months with high rainfall at Kericho weather station had low streamflow at the basin outlet and *vice versa*. Simulations of traditional technology and future adoption scenarios involved differences of up to 19% in the mean monthly streamflow compared to the observed data, resulting in poor simulation efficiencies (Table II). Further, both the traditional and the future adoption scenarios result in reduced streamflow compared to the current adoption scenario. This study is the first step in the application of detailed distributed hydrologic/water quality models in African basins, and the results should be considered only preliminary. Because of input data deficiencies, simulation efficiencies were poor, but simulated mean flows compare reasonably well with the observed data. Better elevation data and sub-basin delineation, and more detailed soil and weather data combined with detailed parameter calibration efforts, should improve the results. This study demonstrates that the application of detailed hydrologic/water quality models, developed and studied widely in the United States, to African river basins is possible and stresses the need for additional model input data collection to improve model parameter calibration and simulation results. Detailed data collection efforts are critical for sustainable management of water resources and food security in Africa.

Table II. Calibration and validation results for monthly streamflow in Sondu river basin

Dairy technology scenario	Calibration (1979–88)			Validation (1989–97)		
	OM (m^3/s)	SM (m^3/s)	E	OM (m^3/s)	SM (m^3/s)	E
Traditional	52	47	−0·69	54	44	−0·08
Current adoption	52	53	−0·72	54	54	0·10
Future adoption	52	48	−0·69	54	45	−0·08

Note: OM = observed mean flow; SM = simulated mean flow; E is the Nash–Sutcliffe simulation efficiency.

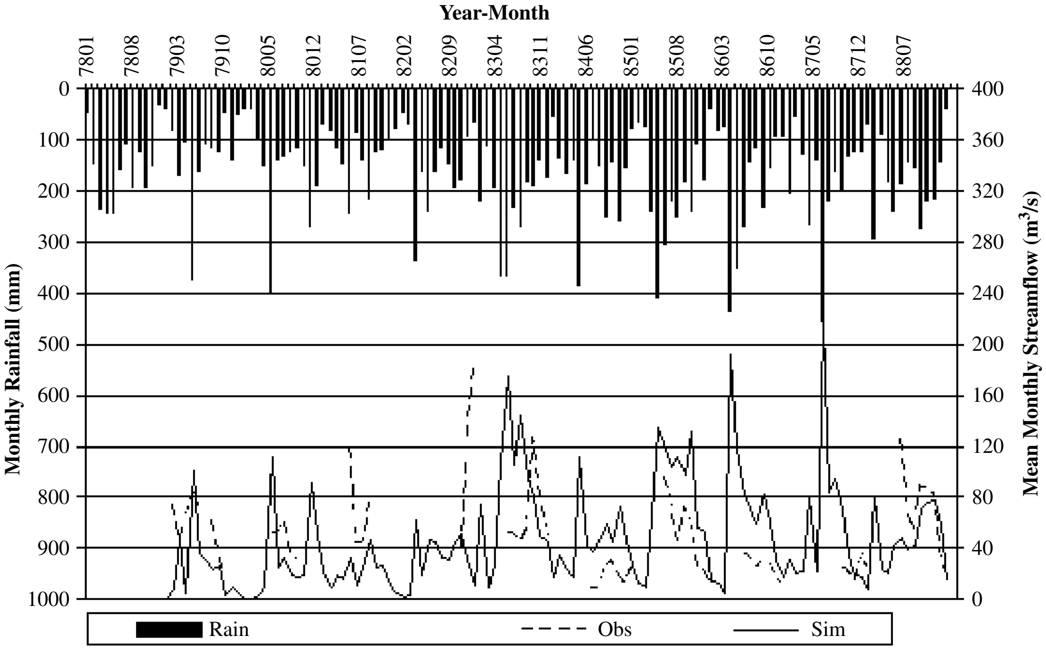


Figure 5. Rainfall input and model calibration results in the Sondu river basin for current adoption scenario

SWAT APPLICATION IN WATER QUALITY ASSESSMENT

The Bosque River watershed in Texas drains an area of 4280 km^2 into Lake Waco, which is an important domestic water supply reservoir. Point and non-point sources of pollution from municipal wastewater treatment plants (WWTPs) and dairy manure application fields, respectively, are of serious concern in this watershed. There are about 100 dairy industries in this watershed, mainly located upstream of Hico. Dairy manure is applied over an area of about 94·5 km^2 (2% of the watershed area). Application of manure to pasture or cropland contributes to major phosphorus (P) loading to the river and the lake. There are eight municipal WWTPs discharging effluent and other nutrients to the river. Because of water pollution concerns, one of the Clean Water Act programmes, known as the total maximum daily load (TMDL) programme, is being implemented by the Texas state pollution control agency to improve water quality in the Bosque River watershed.

The SWAT model along with the SWAT–GRASS interface was used to study the effects of various management scenarios for point and non-point sources of pollution. The SWAT–GRASS interface was used to develop input files necessary for hydrologic/water quality simulations from raster GIS layers. Manure application and non-application areas in each sub-basin were determined using sub-basin and waste application field raster layers. Data on flow and nutrient loading from municipal WWTPs in the watershed were input into the SWAT–GRASS interface to develop point source pollution data input files of the SWAT model.

The model was calibrated for streamflow, sediment, organic nitrogen, mineral nitrogen, organic phosphorus and soluble phosphorus on a monthly basis from 1993 through 1997, depending on the data available at each location. The five-year calibration period was chosen to capture the variations in streamflow conditions and nutrient loading. Parameters such as the runoff curve number and the available water-holding capacity of the soils were adjusted to calibrate the model for streamflow. The cover factor (C) of the universal soil loss equation and the channel sediment routing parameters were adjusted for sediment simulations, while the percolation coefficients and the initial concentrations in the soils were adjusted for nitrogen and phosphorus loading simulations during calibration. The calibrated model was validated using the rest of the monitoring data available for a year (1998). Calibration and validation statistics calculated for various model outputs are shown in Tables III and IV for two main locations along the Bosque River.

The calibrated model was used to study the long-term effects of various BMPs related to dairy manure management and WWTP loads in this watershed. The existing condition scenario considers the current dairy herd size (41 000), current manure application areas, average manure application rate (13 tonnes/ha/year), and the current discharge volumes and nutrient concentrations from WWTPs. The future condition scenario reflects the projected conditions of the watershed in the year 2020, with a projected dairy herd size of 67 000, manure application at crop nitrogen requirement rate (N rate at 46 tonnes/ha/year), manure application area calculated at N rate requirements, and the maximum permitted discharge volumes and nutrient concentrations from WWTPs. Dairy BMPs such as hauling of the solid manure from the watershed, application of manure

Table III. Monthly calibration and validation results at Hico in Bosque river basin

Model output	Calibration (1993–97)					Validation (1998)				
	OM	SM	OSD	SSD	*E*	OM	SM	OSD	SSD	*E*
Streamflow (mm)	12·11	11·79	15·06	14·82	0·79	11·58	9·000	13·12	11·29	0·87
Sediment (tonnes/ha)	0·045	0·038	0·092	0·077	0·80	0·045	0·025	0·114	0·056	0·70
Organic N (kg/ha)	0·213	0·161	0·322	0·260	0·58	0·194	0·114	0·296	0·191	0·73
Organic P (kg/ha)	0·036	0·031	0·057	0·049	0·70	0·043	0·023	0·074	0·042	0·72
Mineral N (kg/ha)	0·090	0·065	0·105	0·073	0·59	0·060	0·046	0·089	0·054	0·75
Soluble P (kg/ha)	0·026	0·021	0·042	0·030	0·59	0·024	0·012	0·033	0·017	0·53

Note: OM = observed mean; SM = simulated mean; OSD = observed standard deviation; SSD = simulated standard deviation; E is the Nash–Sutcliffe simulation efficiency.

Table IV. Monthly calibration and validation results at Valley Mills in Bosque river basin

Model output	Calibration (1996–97)					Validation (1998)				
	OM	SM	OSD	SSD	*E*	OM	SM	OSD	SSD	*E*
Streamflow (mm)	15·22	14·80	25·34	17·42	0·83	9·760	10·98	20·15	9·470	0·62
Sediment (tonnes/ha)	0·086	0·069	0·214	0·112	0·69	0·132	0·039	0·386	0·064	0·23
Organic N (kg/ha)	0·236	0·308	0·522	0·418	0·57	0·257	0·211	0·715	0·224	0·43
Organic P (kg/ha)	0·045	0·048	0·104	0·065	0·59	0·055	0·034	0·144	0·039	0·39
Mineral N (kg/ha)	0·081	0·117	0·130	0·222	−0·08	0·050	0·068	0·097	0·063	0·64
Soluble P (kg/ha)	0·017	0·014	0·042	0·019	0·53	0·006	0·008	0·016	0·010	0·81

Note: OM = observed mean; SM = simulated mean; OSD = observed standard deviation; SSD = simulated standard deviation; E is the Nash–Sutcliffe simulation efficiency.

at phosphorus requirement rate of crop (P rate at 6·3 tonnes/ha/year) and reduction of the P diet in animal feed were analysed. For WWTP BMPs, concentrations of total phosphorus in WWTP effluents were reduced to 0·5, 1·0 and 2·0 mg/l. Scenarios I, II and III indicate the combinations of dairy and WWTP BMPs. For a detailed description of the BMPs, the interested reader is referred to Santhi *et al.* (2001).

Figure 6 shows the percentage reductions in soluble phosphorus concentrations with respect to the future scenario for various BMPs at three locations in this watershed. BMP analysis indicated that the flow-weighted soluble phosphorus concentration showed reductions ranging from 7 to 60% for dairy BMPs, 4 to 50% for WWTP BMPs, and 39 to 65% for combined BMPs of dairy and WWTP compared to the existing conditions scenario. Percentage reductions of phosphorus varied among scenarios, depending on the variation in manure application rate and manure application area for the dairy management and phosphorus concentration levels from WWTP. Results of this study on the impact of point and non-point pollution sources on water quality were used for decision-making in the TMDL development for this watershed. This was a national pilot project for TMDL analysis and will serve as a template for many TMDL development projects proposed in other parts of the United States.

CONCLUSIONS

Hydrologic analysis of large watersheds draining thousands of square kilometres is a tedious process. Regional and national-scale water resources management strategies and decision-making for sustainable domestic, agricultural and industrial water supply, as well as protection of the environment from the negative impacts of developmental activities, depend on such large-scale analyses. Computer-based environmental simulation models like SWAT are valuable tools for such studies. Since hydrologic systems are heterogeneous, with substantial spatial variability in model inputs such as soil and land use, the development of input files for such models for large watersheds is a time-consuming task. GIS plays a major role in developing model inputs from digital geospatial databases through model–GIS interfaces. The SWAT model and its GIS interfaces aid the water resources professional in basin-scale studies of water availability and water quality, and help reduce

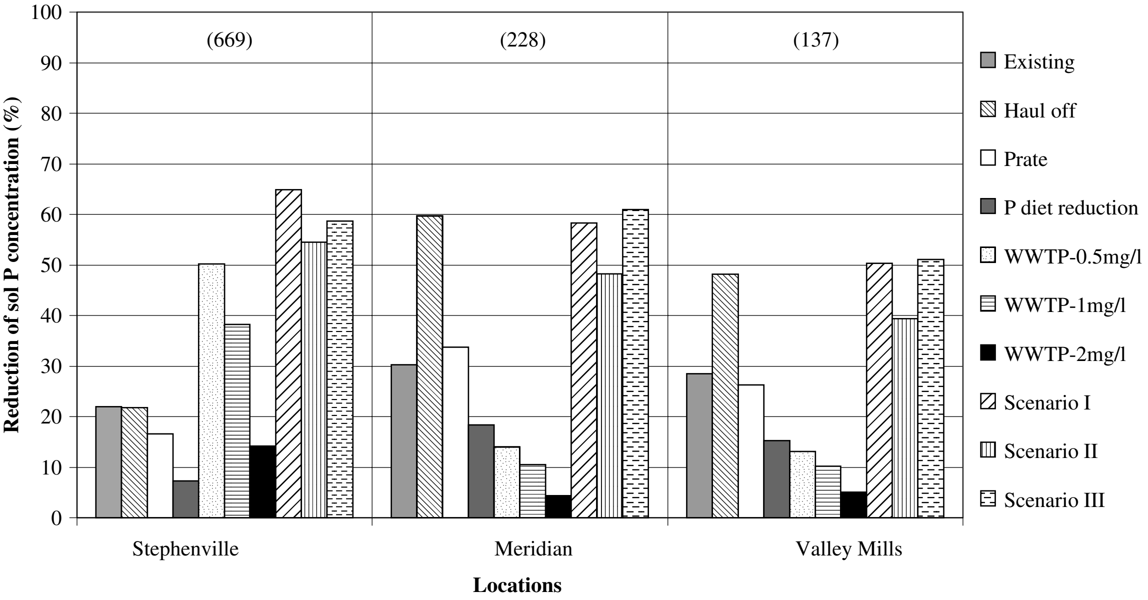


Figure 6. Percentage reductions of flow-weighted soluble phosphorus concentration from future condition scenario (reference baseline) for various BMPs

the time and cost necessary to conduct such studies several-fold compared to other distributed parameter models. The SWAT model has good potential for application in hydrologic/water quality studies in countries around the world and as a tool to develop time and cost-efficient analyses for watershed/water resources management and decision-making.

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