Report for 2002IA1B: Modeling, GIS, and Technology Transfer in Support of TMDL Development and Implementation in Iowa

- Other Publications:
  - Tim, U.S., 2003. Biophysical modeling for environmental policy decisions: Assessing model creditability and scientific integrity (in preparation).
  - Tim, U.S., 2003. TMDL development and implementation: A review of state water quality programs and TMDL approaches. Technical Report # TMDL-01/0003. Department of Agricultural & Biosystems Engineering, Iowa State University, Ames, Iowa 50011.

Report Follows:

Problem and Research Objectives

The federal Clean Water Act (CWA) employs a variety of interrelated management and policy instruments to regulate environmental pollution and protect water quality. These instruments include the National Pollutant Discharge Elimination System or NPDES (33 US C § 1342, CWA section 402), which represents CWA's primary mechanism for achieving and enforcing water quality standards. However, Congress recognized that technology-based effluent controls (generally grouped under point source controls) alone may not be sufficient to enforce applicable water quality standards. Thus, Congress enacted section 303 (d) of the CWA that involves a complex statutory scheme which requires states (herein referred to the collection of states, territories, and authorized tribes) to identify waters where point source controls are insufficient to maintain and improve the water quality standard. The water quality management approach established by Congress forces the states to assess their waters, establish water quality standards based on designated and beneficial uses, prioritize water quality improvement need, and establish total maximum daily loads or TMDLs for such impaired waters and pollutants.

Whereas the CWA requires states to identify waters not meeting quality standards and to develop plans for cleaning them up, the TMDL program, as defined under section 303(d), is designed to determine the maximum amount of pollutant load that a waterbody can absorb and still meet the established quality standard. The program then apportions that maximum load among the various pollution sources (nonpoint and point) in order to facilitate their control. Both section 303(d) and the TMDL program identified a three-step process for moving beyond effluent based controls to more technologically based standards. First, states must establish a list of impaired waters (or water quality limited segments), and this list must identify and priority-rank the waters where point source controls alone would be insufficient to achieve desirable quality standards. Next, for each waterbody identified in the 303(d) list, each state must establish a TMDL or load capacity assessment consistent with the priority ranking in the 303(d) list. Finally, the TMDLs are to be incorporated into, and implemented pursuant to, the state's water quality management plans established under section 303(e) and defined under section 305(b) of CWA. The states are to submit the 303(d) list and the respective calculations for EPA approval. In turn, EPA is required to review the list and TMDLs and either approve or disapprove them as appropriate. If, for example, the 303(d) list and the TMDL implementation plan meet EPA approval, they are then incorporated into the state's water quality management plans. Disapproval, on the other hand, mandates the identification and/or establishment of the TMDL by EPA. Furthermore, if a state fails to establish an acceptable 303(d) list or TMDL, the EPA is also required to intervene and perform the state's duties.

Defined as "the sum of the individual waste load allocations for point sources and load allocations from nonpoint sources and natural backgrounds" (40 CFR 130.2) , the TMDL program forms the basis for developing best management practices (BMPs) for water quality control and plays a key role in stakeholder involvement in watershed management. All stages in the TMDL development process require sound science and the ability to translate complex water quality data into coherent, concise packages so that agencies and stakeholders can understand the issues and evaluate alternative management options. The basis for TMDL development rests on a wide range of factors, including source water assessments, expected ability to meet the TMDL limits, terrestrial and aquatic ecosystem monitoring and modeling, in addition to resource economics. To assist the states, EPA has provided a compendium of tools and models to aid in the TMDL development and implementation plan. However, the reliability of these models for general applications remains questionable. There is still a considerable gap between models developed for the prediction of point and nonpoint source pollution and those that can be used to support TMDL analyses and load allocation. Consequently, many in the production agriculture and natural resource management communities have expressed concerns over the lack of science behind the TMDL modeling and planning process. For example, the former Secretary of Agriculture, Mr. Dan Glickman and many others have expressed concern over the TMDL program. In particular, Mr. Glickman stated: "*the USDA is concerned about the science being used in assessing and attributing the effects of nonpoint source pollution. These models have a high degree of uncertainty and there are gaps in the data regarding what is natural background pollution versus what is caused by human activity.*" Given these uncertainties, there is a critical need for an objective evaluation of existing ecological models and analytical tools that are used in the TMDL development. There is equally a need for a concise demonstration of how these models can be used to establish quantitative measures of the relationship between pollutant sources and water quality impacts. Equally critical is the need to suggest possible areas of improvement of these models for a more proactive and adaptive implementation of the TMDL program by stakeholders.

The problems faced by states in developing TMDLs vary widely across water quality issues and problems. Efficient and equitable development of TMDL requires a sound scientific and technical base and appropriate tools not currently available. Successful water quality management in the United States has always depended on applying good science and on the efficacy of modeling techniques. This research was established to provide enhanced decision support for TMDL analysis by: (1) critically evaluating existing terrestrial and aquatic models and TMDL planning tools to insure that they are based on sound science and are used in a sound manner; (2) providing tools for estimating waste loads associated with biological pollutants under different watershed conditions and management practices; (3) developing objective criteria for choosing among models, data sources, and implementation plans based on the priorities of all stakeholders; and (4) demonstrating the use of integrated models for assessing the potential ecological benefits of TMDL implementation at the watershed scale. The specific project objectives are:

1. To undertake a science-based evaluation of existing models for their use in TMDL development and implementation and suggest areas for future refinements.

2. To integrate algorithms developed for waterborne pathogens (specifically bacteria) into the SWAT biophysical model to facilitate use in development of nutrients and microbial TMDLs in tiled drained watersheds in Iowa.

3. To assess the potential ecological and water quality benefits of TMDL implementation in an agriculturally dominated watershed in Iowa to serve as a case study.

The overarching goal of the project is to enhance the effectiveness of watershed water quality management efforts and improve the scientific basis and computer models for TMDL development and implementation. The products from this research should increase the likelihood of acceptance of the TMDL process by regulators and stakeholders and help assure that the entire TMDL development process meets the desired water quality goals.

Methodology

Objective 1: To undertake a science-based evaluation of existing models for their use in TMDL development and implementation and suggest areas for future refinements.

Several recent reports have identified many inconsistencies in the methodologies used by states in their TMDL program and the lack of sound scientific principles in the choice of models for prediction pollutant loads. In a report titled "Water Quality—Inconsistent State Approaches Complicate Nation's Efforts to Identify Its Most Polluted Waters" the General Accounting Office (GAO) concluded that "states have developed varied approaches to setting water quality standards, monitoring water quality, and assessing water quality data to make listing determinations" and recommended that the EPA "provide additional guidance to the states on carrying out the key functions….that influence how states identify the waters for their section 303(d) lists" (GAO, 2000). Another report by the National Research Council (NRC) examined the scientific basis of the TMDL program and recommended development of mathematical models that can more effectively link environmental stressors to biological responses of ecosystems (NRC, 2001). Yet another report by the EPA's Federal Advisory Committee (FACA) recommended that EPA's top priorities for science and model development should include improving monitoring and modeling capabilities and providing technical assistance to the states (EPA 2002). These reports and other similar studies point to the need for a more rigorous, unbiased review of the scientific basis of the TMDL program, particularly the methodologies and models used in characterizing pollution sources and pollutant loads.

As a major component of this research project, our goal was to conduct a comprehensive yet critical review of existing water quality models that are used in the TMDL program and to identify their strengths and weaknesses. Some of the issues addressed in the research included the following: What are the scientific principles behind the existing terrestrial and aquatic ecosystem models? Is the philosophical basis of these models in concert with current scientific understanding of biotic and abiotic processes? Does the model address the environmental attributes that are required in the TMDL program? Are the existing water quality models supported by data routinely collected from monitoring programs? What are the physical, biological, and chemical processes incorporated into these models?

Indeed, the past decades have witnessed an increased interest in the use of ecological models in a wide variety of applications. With this explosive growth in model development have come increased concerns about the models' suitability and reliability in policy situations. Users of ecosystem models have begun to ask very specific questions such as: How can we tell if a model of a highly complex ecosystem is a good model for the existing conditions? Is the use of a simple model instead of a complex model justified? How can we judge the relative merits (strengths and limitations) of different models? What is the "best available" ecological model, given the nature of the landscape and waterscape? How do we judge the reliability of the predictions that models provide? Modelers and stakeholders alike are interested in identifying terrestrial and aquatic ecosystem models that are optimal for applications in the TMDL program.

In evaluating and identifying a suitable terrestrial and aquatic ecosystem model for TMDL development, particularly the prediction of pollutant loads, many factors must be considered. In addition to those questions identified earlier, other issues prevail. For example: What is the appropriate scale of resolution—temporal and spatial? What are the various uncertainties associated with the data and the model? How can these model uncertainties be quantified and applied to the estimation of total maximum pollutant load? This research focused on addressing some of these issues by creating a model evaluation protocol with the goal of identifying "best available" models for use in TMDL development under varying landscape conditions and management regimes.

The steps used in the model evaluation process include assembling, through comprehensive review of the literature (e.g., reports, proceedings, and compendia), candidate models that are available for predicting pollutant fate and transport in terrestrial and aquatic environments. Other sources of information on models include Web-based digital libraries and resource agency publications. Through these sources, about 250 different terrestrial models and 60 aquatic ecosystem models having different spatial and temporal resolution and philosophical principles were identified. From this list about 130 terrestrial and 35 aquatic ecosystem models were selected. At this stage of model evaluation, a model was removed from further consideration if it failed to meet prescribed qualitative benchmarks (e.g., technical support, ease of use, documentation, availability, etc.).

The second phase of model evaluation involved assembling basic information on each model and developing a set of evaluation criteria and matrix. The evaluation criteria involved 30 different philosophical, scientific, and technical aspects upon which to judge the merits of a model. Examples include: modeled biophysical processes, spatial and temporal scale, model documentation, availability of model source code, modifiability of model source code, level of technical support, the availability of documentation, ease of use, and data requirements. For each criterion, an evaluation matrix that consisted of ratings (ranging from 0 to 5) was used to derive a cumulative score for a model. A model whose score exceeded a specified cumulative value was identified for a third-level, more rigorous and critical review. This third level of model evaluation focused on model applicability to the TMDL program, ease of model refinements, and many other software engineering issues. Evaluation criteria considered under this level of model review include: Does the model provide reliable simulation of the water quality constituents required in the TMDL program? Do the modeling components allow for simulation of watershed with mixed land use? How does the model handle low flows or storm events? Is the model robust and scientifically defensible? Is the model implementation commensurate with available resources and technical expertise? How explicit are the modeling and parameter uncertainties treated in the model? Through this process 10 terrestrial models and 7 aquatic ecosystem models were identified as “optimal” models for the TMDL program.

The fourth and final level of model evaluation involved examination of the critical components of each of the “optimal” models for their applicability to the estimation of daily pollutant loads. We also examined the potential for refinement of each model to address some of the limitations identified in the model review. Since the majority of the TMDLs require estimation of pollutant loads from nonpoint sources, the models selected were those that are watershed-based or can be integrated with standard graphical interface with tools such as the geographic information systems (GIS). The models that we recommended were those that can easily be linked, either loosely or closely, with an aquatic ecosystem (or receiving water) model to provide a more comprehensive, integrated tool for pollutant load estimation in receiving waterbodies. Details of the evaluation process including the evaluation criteria and matrix can be obtained from the PIs.

Objective 2: To integrate algorithms developed for waterborne pathogens (specifically bacteria) into the SWAT biophysical model to facilitate use in development of nutrients and microbial TMDLs in tiled drained watersheds in Iowa.

Comprehensive models that not only predict the fate and transport of toxic substances in agro-ecosystems are needed for the implementation of the TMDL program. Newer, faster computers have made possible the development of sophisticated and highly complex models that predict the movement of nutrients and pesticides in fields and watersheds. However, very few of these models have incorporated functional components that predict microbial fate and transport in terrestrial environment. Furthermore, for many of the existing models that estimate bacterial transport, very simplified functional relationships are used. For example, the movement of microbial pathogens has been simulated assuming standard biophysical relationships developed for non-conservative pollutants. The modeling of microbial fate and transport in urban and rural landscape require significantly different approaches, as well as process-based functional relationships, from those used for conventional pollutants such as nutrients and pesticides.

In this research, we developed a process-based component functional model for incorporation into the Soil and Water Assessment Tool or SWAT model (Arnold et al., 1998) to provide a more comprehensive and robust analytical tool for developing TMDLs for watersheds impaired by both chemical and biological pollutants. Constitutive equations that govern the fate and transport of microorganisms (bacteria) in soil and water were developed based on governing abiotic and biotic processes in agricultural landscapes.

The SWAT model is the latest of the family of field-scale and watershed-scale models developed by researchers at the Agricultural Research Services of the U.S. Department of Agriculture. In particular, SWAT was developed as a replacement to the SWRRBWQ model designed to evaluate hydrology and water quality of agricultural fields under different management practices and the ROTO model that allows simulation of subsurface hydrology. The SWAT model predicts the effects of agricultural management, climate, reservoir management, groundwater withdrawals, and water transfer on hydrology, sediment transport, and chemical yields on large agricultural watersheds. In terms of spatial scale, SWAT can be used to analyze watersheds and catchments of up to 100 square miles by subdividing the landscape into homogeneous land units. Temporally, simulations with the SWAT model can be performed on an event basis or continuously on a daily basis for up to 100 years.

A unique feature of the SWAT model that differentiates it from the SWRRBWQ model is subdivision of the watershed or land area into subunits or subwatersheds and the further division of these subunits into smaller homogeneous areas or hydrological response units (HRUs) according to spatial variability of soil, topography, and land cover. The SWAT model is designed to preserve the spatially-distributed parameters of the entire watershed as well as the homogeneity of the subwatersheds. From the biogeochemical cycling perspective, the components of the SWAT model include: hydrology, which estimates water budget and incorporates components such as weather, surface runoff, return flow, percolation, evapo-transpiration, transmission losses, ponds and reservoir storage, crop growth, irrigation water transfer, groundwater flow, and channel routing; sediment yields including erosion from agricultural land management; soil temperature; climate; and agricultural chemical transport, which predicts the fate, cycling, and transport of nitrogen, phosphorus, and pesticides in soil and water. The primary inputs required by the model include weather (e.g., daily precipitation, daily maximum and minimum temperatures, solar radiation, and relative humidity), soils, topography (e.g., land elevation), vegetation cover, and agricultural land management practices. With these inputs, SWAT simulates standard water quality parameters such as total nitrogen concentration, peak flow, runoff volume, and sediment yield.

Objective 3: To assess the potential ecological and water quality benefits of TMDL implementation in an agriculturally dominated watershed in Iowa to serve as a case study.

Under this objective, our primary goal was to demonstrate the application of an ecological model as a tool for the TMDL program through a simplified case study. Because sufficient data was not available to check the microbial fate and transport equations assembled under Objective 3, we decided to examine the performance of the SWAT model in predicting nutrient load in a relatively large agricultural watershed. The modeling experiences obtained from this case study mirror similar experiences of state resource managers. Thus, our observations matched those of other researchers and resource planners and identified the limitations in many of the widely used watershed water quality models including SWAT. Below is a description of the research methods and results.

SWAT Modeling. As described previously, SWAT is a biophysical, semi-distributed, continuous, daily time step model designed to simulate water yield, sediment delivery, and nutrient and pesticide loading from large, ungauged watersheds. The model uses datasets typically available from government agencies. It is capable of predicting the relative impact of agricultural management and land use over long time periods. The SWAT model is also equipped with a pre- and post-processing interface that is built upon the ArcView GIS interface system.

The GIS interface of SWAT is set up as an extension of ArcView®. This configuration gives the interface the flexibility to use special features available in other ArcView® extension packages. The ArcView SWAT version of the model allows geo-referenced data to be pre-processed for entry into the model. After model simulation, the GIS component post-processes the model output and displays the data as graphics, charts or tables. The key processes, which impact water quality, are discussed below.

Hydrology. The water balance is the basic hydrodynamic component of the model. The water balance equation used is:

$$SW_t = SW_0 + \sum(R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw})$$

where SW_t is the final soil water content (mm water), SW_0 is the initial soil water content (mm water), R_{day} is the amount of precipitation for the day (mm water), Q_{surf} is the amount of surface runoff for the day (mm water), E_a is the amount of evapo-transpiration for the day (mm water), w_{seep} is the amount of water entering the vadose zone from the soil profile for the day (mm water), and Q_{gw} is the amount of return flow for the day (mm water). Because SWAT uses a daily time step, the water balance is calculated every day of the simulation period. The predicted water yield from a given land area is important because it determines the concentration of pollutants being removed from the land area. The major component of water yield is surface runoff. The quantity of surface runoff impacts the amount of soil and chemicals transported to a receiving waterbody.

Sediment Yield. The predicted soil erosion rate and sediment yield is calculated for each hydrologic response unit (HRU) with the Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975). This equation uses surface runoff volume and peak rate to predict erosion rate and sediment delivery from small watersheds. MUSLE is derived from the Universal Soil Loss Equation (USLE) developed by Wischmeier and Smith (1978). The MUSLE equation adapted for use in the model is:

$$Sed = 11.8 \cdot (Q_{surf} \cdot q_{peak} \cdot area_{hru})^{0.56} \cdot K_{USLE} \cdot C_{USLE} \cdot P_{USLE} \cdot LS_{USLE}$$

where *Sed* is the sediment yield (metric tons), 11.8 is a unit conversion constant, Q_{surf} is the surface runoff volume (mm water/ha), q_{peak} is the peak runoff rate (m^3/s), $area_{hru}$ is the area of the hydrologic unit area (HRU) in hectares, K_{USLE} is the USLE soil erodibility factor, C_{USLE} is the USLE cropping and management factor, P_{USLE} is the USLE conservation support practices factor, and LS_{USLE} is the USLE slope length and steepness factor. The Q_{surf} and q_{peak} are calculated every day precipitation occurs. If surface runoff occurs, then sediment yield is calculated for that day. Because crop growth affects Q_{surf} and q_{peak}, C_{USLE} is also updated daily to reflect changes in the plant growth and land cover.

Crop Growth. Crop growth is simulated in SWAT by using the modeling approach used in the Erosion Productivity Impact Calculator (EPIC) model (Williams et al., 1983). The EPIC model allows for the variation in growth for different plant species and variation due to climate and growth conditions.

Nutrients. Nitrogen (N) and phosphorus (P) management and movement are simulated in SWAT using the modeling approaches in the GLEAMS model (Leonard et al., 1987). Thus SWAT simulates the movement and transformations of nitrogen between two mineral (ammonium and nitrate) and three organic (active, stable and fresh) soil nitrogen pools. Monitoring three mineral (labile in solution, labile on soil surface and fixed in soil) and three organic pools (active, stable and fresh) of soil phosphorus simulates soil phosphorus movement and transformation.

SWAT Modeling Database. The modeling database consisted of those elements that represent the agricultural landscape and the spatially varying characteristics of land use, land cover, and climate. The landscape terrain was represented by the digital elevation model or DEM, a graphical representation of the land slope steepness and aspect (direction). The DEM is prepared as a 30-meter grid polygon format. Each “cell” of this 30-meter by 30-meter grid is given a single elevation value. This GIS coverage (Figure 1) determines watershed and sub-basin (subwatershed) boundaries and can be used to derive hydrologic parameters including land slope, aspect, and flow accumulation. The DEM is available through the Iowa Department of Natural Resources Geological Services Bureau (IDNR-GSB).

The digitized streams are line representations of accumulated perennial water flow over the soil surface. This coverage is important for the routing (i.e. movement and transformation) of runoff and pollutants originating in the watershed. The stream coverage was created by the hydrologic modeling component of SWAT utilizing the DEM.

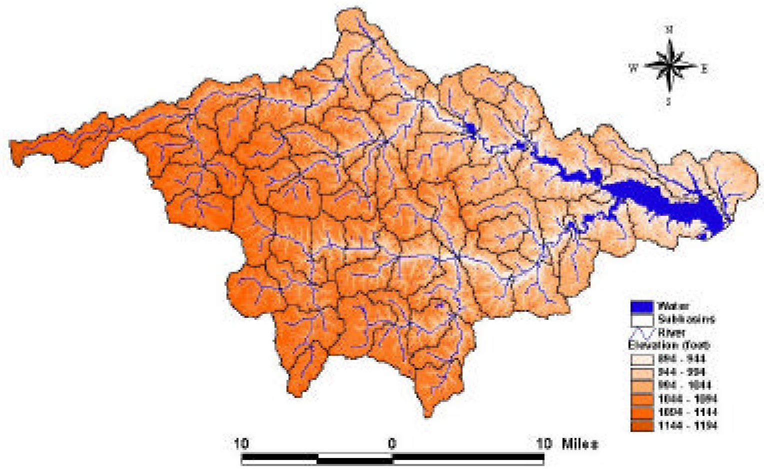

Figure 1. Digitized Elevation Model of the watershed

Sub-basin outlets are geo-referenced points on a stream or river. Outlets may occur in series on larger streams such that the outlet of one sub-basin contributes channel flow to a downstream sub-basin. A sub-basin is the land area contributing surface runoff to the sub-basin outlet. The sub-basin file was created in-house following Natural Resources Conservation Service (NRCS) and USGS criteria for developing 14-digit Hydrologic Units.

The land use/land cover information for the study area was prepared as a 30-meter grid polygon format. Each "cell" of this 30-meter by 30-meter grid is designated a single land cover type. This coverage (see Figure 2) is used to define the plant growth characteristics SWAT will use to simulate the area. This coverage is part of the USGS National Land Cover Dataset using 1992 Landsat Thematic Mapper imagery and supplemental data (USGS, 2000).

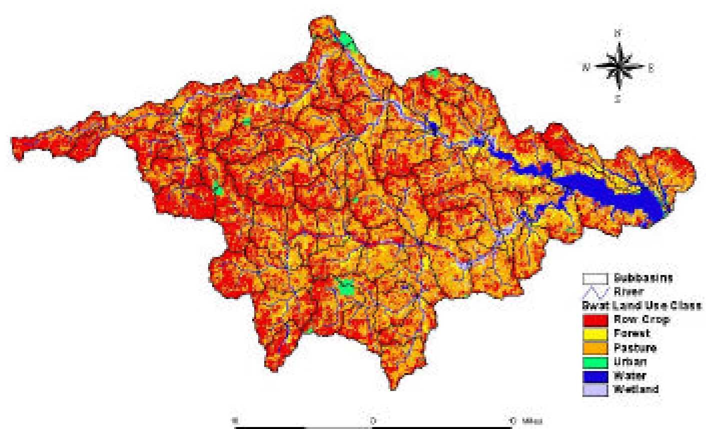

Figure 2. Land use, land cover coverage for SWAT modeling

Soils data and the spatial distribution of soil properties within the study area were also prepared as a 30-meter grid polygon format. Each "cell" of this 30-meter by 30-meter grid is designated a single soil type. This coverage is used to define the soil chemical and physical properties SWAT will use to simulate the area. The township digital soil coverage of Appanoose, Clark, Decatur, Lucas, Monroe, and Wayne Counties and the Iowa Soil Properties and Interpretations Database (ISPAID) are the original sources of the information for the soils coverage (see Figure 3). The Iowa soils data was linked to the SWAT soils database by use of the SCS Soils 5 column of ISPAID and the S5ID number from the soilsia.dbf in SWAT.

Figure 3. Soils digital information used in the SWAT modeling

Three types of files are maintained to simulate weather. These files are the measured daily maximum and minimum temperature file, the measured daily precipitation file, and weather generator input file. The SWAT model comes complete with a climate generation model and the monthly average parameters for more than 1100 weather stations throughout the contiguous United States. For this project, measured daily maximum and minimum temperature and precipitation data from four long-term recording stations close to the watershed were obtained from local sources. The monthly data for these recording stations were obtained from the Iowa State University Agronomy Department Agricultural Meteorology website at: http://www.agron.iastate.edu/climodat/. The weather stations are located near the towns of Centerville, Chariton, Corydon and Osceola (see Figure 4). SWAT simulates the weather by sub-basin. If data from multiple weather stations is available, the distance from the centroid of each sub-basin to each weather station is calculated. The sub-basins are then assigned to the closest weather station for their respective climate data.

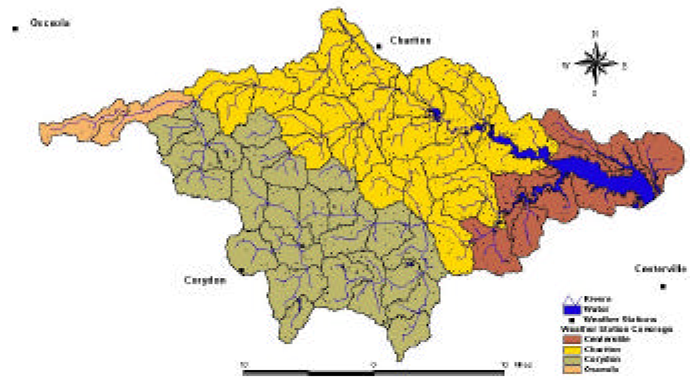

Figure 4. Spatial location of the weather stations used in the modeling

Nutrient management database used in the SWAT model contains 54 commonly available chemical fertilizers, organic fertilizers, and animal manures. Table 1 lists the chemical and physical properties of fertilizers needed by the model for anhydrous ammonia (82-0-0), diammonium phosphate (18-46-0), and urea (45-0-0) fertilizer. The definitions of the fertilizer characteristics were obtained from the SWAT User's Manual.

Table 1. Nutrient inputs used in the SWAT modeling case study

Fertilizer Name	FMINN	FMINP	FORGN	FORGP	FNH3N
Anhydrous Ammonia	0.82000	0.00000	0.00000	0.00000	1.00000
Urea	0.45000	0.00000	0.00000	0.00000	1.00000
Diammonium Phosphate	0.18000	0.20200	0.00000	0.00000	0.00000
FMINN	Fraction of mineral N (NO3 and NH4) in fertilizer (kg min-N/kg fertilizer)				
FNH3N	Fraction of mineral N in fertilizer applied as ammonia (kg NH3-N/kg min-N)				

Implementing SWAT to Rathbun Lake Watershed. Because SWAT is a semi-distributed model, it can simulate discrete, small homogeneous areas within a sub-basin. However, to effectively use this small-scale capability, one must know the assumptions made within the model and the limitations imposed due to the variability of each of the inputs and the resolution of the spatial databases. The amount of detail required of the model will be determined, in part, by selected project objectives. One objective of this project was to demonstrate the predictive capability of the SWAT model and its relevance to the TMDL program. One approach was to rank watershed areas (i.e., the 61 sub-basins in the watershed) according to their relative environmental impact.

Delineating Hydrologic Response Units. Hydrologic Response Units or HRUs are the unique combinations of land use and soil that occur within an individual sub-basin. The SWAT model allows the user to select how an HRU is defined (see Figure 5). One option is to select the predominant land use and predominant soil for each sub-basin. This would then be a single HRU for each sub-basin. The second option is to select multiple HRUs by moving adjustable threshold scale bars for land use and soil that define the threshold criteria. To develop a multiple HRU option, the threshold for land use was first selected. The sliding threshold scale bar ranges from 1% to the maximum percent of any land use in any sub-basin in the watershed. For example, if 10% threshold for land use was selected, this means that within each sub-basin, only those land uses that have at least 10% areal coverage in the sub-basin will be used to define HRUs. Land uses comprising less than 10% areal coverage within the sub-basin will not be simulated. The land area where these minor land uses exist will be distributed back to the remaining land uses in relative proportion to the initial extent of these land uses within the sub-basin. This last step is done so that all of the land areas within a sub-basin have an assigned HRU.

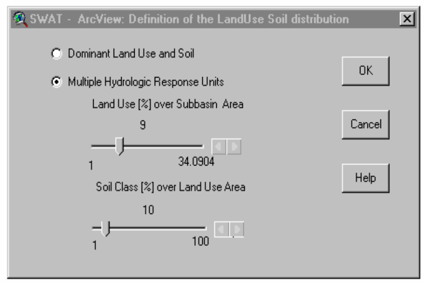

Figure 5. Screen layout for delineating HRU

The same procedure can be applied to delineating HRUs on the basis of the soil criterion. However, when selecting the soils threshold level, the threshold applies to the areal extent of the soils within a specific land use within a sub-basin. The scale bar for soils ranges from 1% to the maximum extent of any soil within any land use within any sub-basin. The scale bars of the land use and soils operate independently of each other (see Figure 5). Therefore, one can, for example, select 10% land use threshold and 20% soil threshold.

The multiple HRU option was selected for this project. The threshold limits set for creating HRUs was 9% land use and 10% soils. This resulted in creating and simulating 513 HRUs within the 1427 km^2 watershed for the baseline scenario. These thresholds were selected for this project based upon details of the land use and soil coverages. Table 2 summarizes how the multiple HRU land use threshold impact selection of HRUs and the respective land uses compared to the original data in the GIS database.

Table 2. Impact of threshold choice on HRU delineation and watershed land use simulated.

Land use	GIS coverage (ha)	1% SWAT threshold (ha)	9% SWAT threshold (ha)
Forest (mixed, deciduous)	13,536	13,574 (100%)	10,505 (78%)
Urban (residential, quarries commercial, urban grass, barren rock)	3,010	2,856 (95%)	538 (19%)
Wetland (wooded, herbaceous)	6,798	6,798 (100%)	1,752 (26%)
Water	5,455	5,113 (94%)	4,424 (81%)

The multiple HRU option determines the number of unique land use and soil combinations simulated and, therefore, the amount of detail to be simulated.

Model Calibration and Validation. There is a widely accepted axiom in watershed hydrologic modeling that if the water balance is estimated accurately, then other processes and parameters that utilize these estimates will also be accurately predicted. Thus, the model reliability assessment was focused on establishing the trustworthiness of the SWAT hydrologic modeling component. In the model reliability assessment, the water yield prediction from the SWAT model was compared to measured stream flow from USGS stream gage #06903400 on the Chariton River near the town of Chariton. The basis of comparison was yearly average stream flow from 1966 to 1986. The SWAT model was calibrated by adjusting selected input parameters that yield predictions of water flow within acceptable values of the observed flow. The t-statistic was calculated as follows:

$$t_{calculated} = \frac{\bar{x} - \bar{y}}{s / \sqrt{n}}$$

where $\bar{x}$ = the average of the predicted stream flow values, $\bar{y}$ = the average of the observed stream flow values, s is the standard deviation of the predicted stream flow values, and n is the number of observations (years). The t-statistic calculated was $|0.617|$. The tabular t-statistic at 0.05 probability and 20 degrees of freedom is 1.725. Based upon these t-statistic values, the null hypothesis cannot be rejected; that is, there is no difference between the observed and predicted stream flow. Figure 6 shows the correspondence between the observed and predicted average annual stream flow at the indicated gage station. It is noted that the years 1973 and 1982 appear as outliers to the rest of the data. Both years exceeded long-term average precipitation by 50% and 43%, respectively. In general, the model predictions appear to be within reasonable and acceptable range of uncertainty.

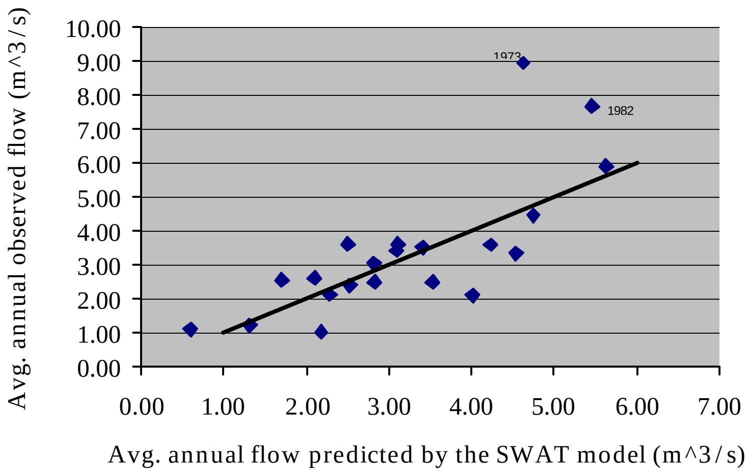

Figure 6. Relationship between SWAT predicted and field observed water yields.

Other standard performance measures were used to explain the reliability of the SWAT model prediction and measured values of the water yield. Table 3 summarizes the values of the performance measures of model reliability compared to the ideal values.

Table 3. Comparison of model performance using standard measures of reliability.

Performance measure	Ideal value	Calculated value (1966-1986 data)	Calculated value (1987-1999 data)
Maximum Error (ME)	0	4.32	4.22
Root Mean Square Error (RMSE)	0	38	40
Modeling Efficiency (EF)	1	0.56	0.59
Coefficient of Determination (CD)	1	2.19	3.03
Coefficient of Residual Mass (CRM)	0	0.05	0.17

Principal Findings and Significance

Simulation Setup. The initial conditions included setting fraction of soil water field capacity in the basin file to 0.6 and all other adjustments were made during the calibration process. The simulation period for all the output maps discussed below was from 1990 to 1999. This time frame was selected because the model GIS land use coverage most closely approximates the current watershed land use. The revised crop, pesticide, fertilizer, and weather databases discussed earlier were used. Model output is presented as average annual output for the ten-year period.

Typical Simulation Results. The results of the SWAT model demonstration component of the research are presented as a series of tables and maps produced from the SWAT model simulated output. The SWAT model was developed as a tool for understanding the processes occurring in watersheds and for documenting the relative changes that can be expected by manipulating the model inputs. Figure 7 identifies the sub-basin numbers, while Table 4 provides the sub-basin ranking of six output parameters discussed for the current land use conditions.

Figure 7. Sub-basin identification and numbering.

Table 4. Selected SWAT-generated model output under current land use and land management condition.

(Sorted by output columns, maximum to minimum values)													
SUB*	WYLD** mm/yr	SUB	SYLD+ Mg/ha/yr	SUB	ORGN++ kg N/ha/yr	SUB	SEDP# kg P/ha/yr	SUB	NSURQ@ kg N/ha/yr	SUB	SOLP% kg P/ha/yr
4	250	38	0.242	9	50	9	9	23	7.8	37	0.6
59	233	33	0.195	37	40	21	8	26	7.5	2	0.6
37	225	18	0.184	24	40	37	8	38	7.5	53	0.6
2	224	48	0.179	38	39	4	8	27	6.7	30	0.6
53	222	56	0.165	4	39	38	8	49	6.5	25	0.6
25	222	40	0.162	30	36	24	8	42	6.5	52	0.6
29	222	46	0.147	21	36	59	7	53	6.4	6	0.6
49	218	9	0.146	2	34	14	7	2	6.3	29	0.6
52	218	4	0.123	35	33	41	7	20	6.3	49	0.6
32	211	37	0.116	29	33	26	7	25	6.2	4	0.5
31	206	30	0.106	41	33	2	7	43	6.1	40	0.5
27	206	17	0.102	33	33	33	7	37	6.1	46	0.5
9	206	42	0.097	59	32	30	7	31	6.0	9	0.5
17	206	19	0.092	14	32	27	7	5	6.0	35	0.5
6	205	36	0.092	52	32	23	7	56	5.9	18	0.5
30	204	51	0.090	53	31	44	6	50	5.8	31	0.5
18	203	50	0.087	25	31	25	6	60	5.7	58	0.5
46	203	31	0.087	8	31	29	6	29	5.7	15	0.5
40	201	47	0.086	18	31	28	6	4	5.6	26	0.5
24	197	32	0.084	36	30	56	6	11	5.6	8	0.5
48	196	23	0.084	26	30	52	6	30	5.5	24	0.5
26	195	24	0.083	40	30	18	6	52	5.5	33	0.5
3	193	25	0.082	7	29	35	6	40	5.4	48	0.5
22	193	58	0.082	48	29	5	6	12	5.3	34	0.5
38	192	8	0.082	13	28	40	6	46	5.3	59	0.5
33	187	49	0.079	10	28	13	6	51	5.3	27	0.5
23	187	39	0.078	28	28	12	6	47	5.3	42	0.5
8	187	52	0.078	44	28	8	6	18	5.2	17	0.5
35	187	29	0.077	5	27	53	6	32	5.2	47	0.5
58	185	44	0.073	27	27	7	6	15	5.1	7	0.5
42	184	53	0.072	56	26	36	6	6	5.1	50	0.5
34	184	2	0.071	23	25	10	5	57	5.0	43	0.4
36	181	21	0.070	12	25	48	5	9	4.9	38	0.4
21	179	20	0.068	50	25	19	5	58	4.9	36	0.4
5	178	57	0.066	16	24	50	5	35	4.8	5	0.4
7	177	45	0.066	42	24	42	5	19	4.8	12	0.4
47	177	27	0.063	34	24	51	5	48	4.8	32	0.4
15	176	14	0.063	51	24	54	5	59	4.7	23	0.4
61	175	41	0.062	54	24	16	5	17	4.7	51	0.4
43	173	59	0.059	22	24	20	5	28	4.7	21	0.4
12	173	26	0.059	46	23	11	5	8	4.6	56	0.4
51	172	43	0.057	55	23	22	5	39	4.5	16	0.4
19	166	35	0.057	17	22	55	4	34	4.5	3	0.4

Table 4 (continued)

SUB*	WYLD** mm/yr	SUB	SYLD+ Mg/ha/yr	SUB	ORGN++ kg N/ha/yr	SUB	SEDP# kg P/ha/yr	SUB	NSURQ@ kg N/ha/yr	SUB	SOLP% kg P/ha/yr
41	166	16	0.051	19	21	34	4	16	4.5	41	0.4
16	165	1	0.042	43	21	46	4	33	4.4	39	0.4
1	159	60	0.042	31	21	60	4	24	4.4	20	0.4
56	156	34	0.040	11	21	43	4	36	4.4	54	0.4
10	154	5	0.037	49	21	17	4	45	4.3	19	0.4
50	152	28	0.036	20	20	57	4	21	4.2	10	0.4
39	150	61	0.033	57	20	31	4	7	4.1	55	0.4
54	147	13	0.032	39	20	39	4	14	4.1	60	0.4
55	145	12	0.029	47	19	49	4	13	3.8	11	0.3
11	142	10	0.028	60	19	45	4	22	3.6	22	0.3
20	140	7	0.028	45	18	47	4	44	3.6	45	0.3
45	132	22	0.026	58	17	3	4	41	3.5	13	0.3
14	131	15	0.025	32	17	32	3	3	3.5	57	0.3
60	127	54	0.024	6	16	6	3	1	3.4	14	0.3
57	126	11	0.024	3	15	58	3	10	2.9	28	0.3
44	123	6	0.018	61	14	15	3	54	2.8	61	0.3
28	122	55	0.015	15	14	61	2	55	2.8	1	0.3
13	117	3	0.008	1	8	1	2	61	2.5	44	0.3

* Sub-basin number
** Water yield
\+ Sediment yield
++ Organic nitrogen yield attached to the sediment
\# Phosphorus yield attached to the sediment
@ Soluble nitrogen yield
% Soluble phosphorus yield

Water Yield. Water yield is the amount of water that eventually flows in the stream and exits the watershed outlet. The water originates from precipitation falling on the watershed or is added to the system through irrigation and is partitioned into several pathways. The three pathways contributing to water yield are: surface runoff, lateral flow of water through the soil profile to the stream, and stream recharge from the shallow aquifer. Surface runoff is the dominant pathway contributing to water yield. Therefore, factors that increase surface runoff will increase water yield. Table 5 shows the effects that soil type and land use have on simulated water yield. Water yield increases as percent imperviousness of land use increases (e.g., Forest WYLD < Row Crop WYLD < Urban WYLD). Water yield also tends to increase with decreasing soil water infiltration (e.g., soil hydrologic group B WYLD< soil hydrologic group C WYLD< soil hydrologic group D WYLD). Definitions for the soil hydrologic groups can be found in the SWAT User's Manual. Figure 8 illustrates the water yield from the 61 sub-basins for the current land use and land management practices.

Table 5. SWAT model simulated water yield by soil type and current land use categories.

Soil	Hyd Grp[1]	Landuse[2]					
		AGRL	FRSD	PAST	URMD	WATR	WETL
		--mm/yr--					
IA004	B	169	136	121			105
IA031	B			136			
IA033	B		134				
IA044	B						99
IA065	B	135	112	81			
KS111	B	178		117	169		
KS146	B	167	89	101	159		
KS175	B	211			190		
MO003	B					0	77
MO007	B	158		87			
IA040	C	273		216	256		
IA043	C				228		
IA053	C		178				
MO009	C			166	222		
MO011	C			187			
MO012	C		182				187
MO018	C	248	181	198			169
MO023	D		293	208			
MO031	D	238	240	203	280		

[1]Soil Hydrologic Group

[2]Landuse Categories for HRUs: AGRL = Agricultural Land, FRSD = Forest, PAST = Pasture, URMD = Urban Land, WATR = Water, and WETL = Wetland

Sediment Yield. Sediment yield is the amount of soil eroded from the sub-basin and delivered to the stream reach. SWAT uses the MUSLE equation to estimate this amount of sediment produced. Sediment deposition in streams and water bodies clogs the drainage network, destroys vital habitat for fish and other invertebrates, and reduces storage capacity and water depth in lakes and reservoirs. Sediment in the water column causes turbidity and reduces light penetration. In addition, sediment is an important parameter for water quality because other potential pollutants are bound to the sediment. Therefore, as the quantity of sediment increases, the potential for other pollutants to be present increases. Table 6 shows the effect soil type and land use has on sediment yield. Agricultural land (row crop) is the dominant source of upland sediment per hectare. Sediment yield tends to increase as water infiltration decreases (e.g., soil hydrologic group B SYLD< soil hydrologic group C SYLD< soil hydrologic group D SYLD).

Nutrient Loading. Nitrogen (N) and phosphorus (P) were the primary nutrients simulated in the study, in part because of concerns for eutrophication and the recently emerging concerns about hypoxia in the Gulf of Mexico. Both of these nutrients are present as sediment-bound (adsorbed) and as solutes in water. The nutrients dissolved in water will reach Lake Rathbun much more readily than the sediment-bound nutrients. Table 7 shows the simulated impacts of soil type and land use on sediment-bound (adsorbed) P yield. The adsorbed P is predominantly from agricultural (row crop) land

and is directly related to the quantity of sediment yield. Table 8 shows the effect soil type and land use have on soluble phosphorus yield. Soluble phosphorus tends to increase as infiltration rate decreases (e.g., soil hydrologic group B SOLP < soil hydrologic group C SOLP< soil hydrologic group D SOLP). Pasture land use also had the highest soluble phosphorus yield. Figure 9 illustrates the soluble phosphorus yield from each sub-basin for the current land use and land management.

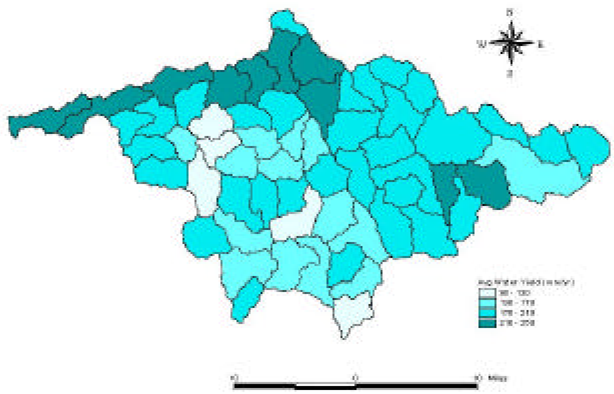

Figure 8. SWAT model predicted average water yield by sub-basin

Table 6. SWAT model simulated sediment yield by soil type and current land use categories.

Soil	Hyd Grp[1]	Landuse[2]					
		AGRL	FRSD	PAST	URMD	WATR	WETL
		--Mg/ha/yr--					
IA004	B	0.039	0.000	0.001			0.001
IA031	B			0.001			
IA033	B		0.000				
IA044	B						0.001
IA065	B	0.029	0.000	0.001			
KS111	B	0.095		0.003	0.000		
KS146	B	0.051	0.000	0.001	0.000		
KS175	B	0.064			0.000		
MO003	B					0.000	0.001
MO007	B	0.056		0.000			
IA040	C	0.153		0.012	0.000		
IA043	C				0.000		
IA053	C		0.000				
MO009	C			0.001	0.000		
MO011	C			0.000			
MO012	C		0.001				0.008
MO018	C	0.056	0.002	0.005			0.002
MO023	D		0.003	0.002			
MO031	D	0.239	0.002	0.010	0.000		

[1]Soil Hydrologic Group

[2]Landuse Categories for HRUs: AGRL = Agricultural Land, FRSD = Forest,
PAST = Pasture, URMD = Urban Land, WATR = Water, and WETL = Wetland

Table 7. SWAT model simulated sediment-P yield by soil type and current land use categories.

Soil	Hyd Grp[1]	Landuse[2]					
		AGRL	FRSD	PAST	URMD	WATR	WETL
		--kg/ha/yr--					
IA004	B	30.9	0.7	0.4			3.6
IA031	B			0.5			
IA033	B		0.4				
IA044	B						4.2
IA065	B	21.9	0.6	0.4			
KS111	B	49.6		1.8	1.4		
KS146	B	47.9	0.7	0.7	1.3		
KS175	B	36.1			1.4		
MO003	B					0.0	5.5
MO007	B	41.5		0.4			
IA040	C	60.6		4.0	1.4		
IA043	C				1.4		
IA053	C		1.6				
MO009	C			1.0	1.4		
MO011	C			1.1			
MO012	C		2.8				7.8
MO018	C	26.4	1.8	1.6			4.2
MO023	D		5.6	2.4			
MO031	D	47.5	4.1	4.0	1.2		

[1]Soil Hydrologic Group

[2]Landuse Categories for HRUs: AGRL = Agricultural Land, FRSD = Forest, PAST = Pasture, URMD = Urban Land, WATR = Water, and WETL = Wetland

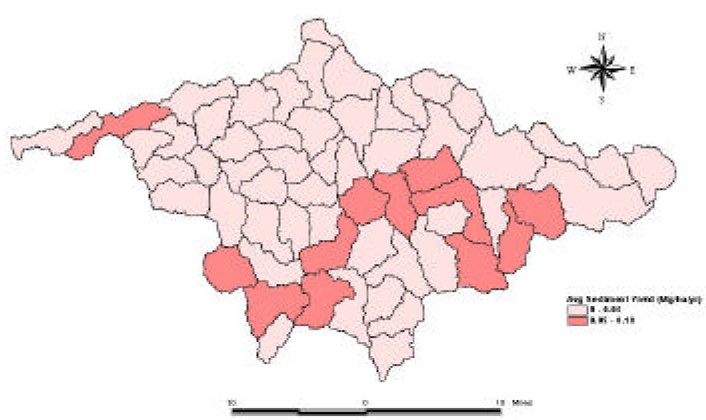

Figure 9. SWAT model predicted soluble-P load by sub-basin.

Table 8. SWAT model simulated dissolved-P by soil type and current land use categories.

Soil	Hyd Grp[1]	Landuse[2]					
		AGRL	FRSD	PAST	URMD	WATR	WETL
		--kg P/ha/yr--					
IA004	B	0.122	0.063	0.451			0.258
IA031	B			0.511			
IA033	B		0.059				
IA044	B						0.189
IA065	B	0.088	0.040	0.260			
KS111	B	0.132		0.374	0.104		
KS146	B	0.120	0.047	0.368	0.091		
KS175	B	0.149			0.120		
MO003	B					0.000	0.295
MO007	B	0.114		0.333			
IA040	C	0.218		0.789	0.102		
IA043	C				0.124		
IA053	C		0.102				
MO009	C			0.620	0.115		
MO011	C			0.674			
MO012	C		0.129				0.561
MO018	C	0.176	0.113	0.763			0.387
MO023	D		0.207	0.813			
MO031	D	0.177	0.170	0.790	0.056		

[1]Soil Hydrologic Group

[2]Landuse Categories for HRUs: AGRL = Agricultural Land, FRSD = Forest, PAST = Pasture, URMD = Urban Land, WATR = Water, and WETL = Wetland

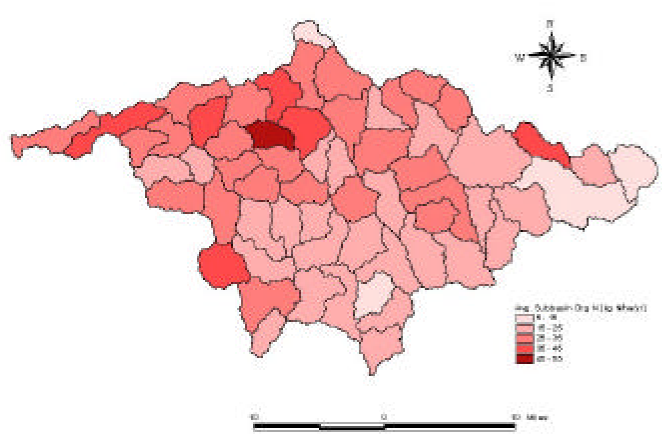

Figure 10. SWAT model predicted sediment-bound N by sub-basin.

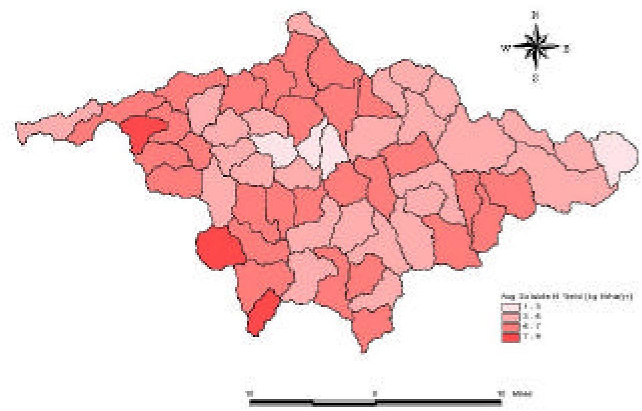

Figure 11. SWAT model predicted soluble N by sub-basin.

The model simulated loads of N and, in the adsorbed or sediment-bound phase, followed similar trends as adsorbed P and a function of soil type, land use, and land management. The source of adsorbed N to channels is predominantly from agricultural (row crop) land use and is directly related to the quantity of sediment yield. Figures 10 and 11 show the spatial distribution of adsorbed-phase and dissolved-phase N loads from each sub-basin. The effect of soil type and land use on soluble N is similar to that of soluble P. Soluble N tends to increase as infiltration rate decreases. Pasture land use also has the highest soluble N load. Overall, the results of the SWAT model application show the capability of the model in the development of nutrient TMDLs. However, during the model application, a number of shortcomings in model performance were observed. There is need to refine the SWAT model to enhance usability and to allow the specification of events with shorter durations. If provided with the requisite high quality data, the SWAT model has potential to produce reasonably accurate and acceptable estimates of pollutant loads nested to establish the assimilative capacity of a waterbody.

Conclusions

The Clean Water Act (CWA), and its many amendments, has been viewed as one of the most successful environmental regulations in terms of achieving statutory goals and has gained widespread support by interest groups and the general American public. However, during the past decade, many have questioned whether actions intended to achieve "swimmable and fishable waters" are worth the implementation costs and have called on federal agencies to conduct cost-benefit assessments of the program before widespread implementation. These criticisms have originated from many sectors of society, including industry that has opposed the imposition of stringent and potentially costly requirements on effluent discharge standards. Criticism has also come from agribusiness groups and farmers who contend that federal regulations are a costly intrusion on private land use and land management decisions. States and local jurisdictions have voiced concerns about the CWA, fearing that it imposes new unfunded mandates in the midst of tight capital and human resources. Environmental groups, on the other hand, believe that more stringent regulation and fine-tuning is not only needed to strengthen the CWA but also to address the remaining environmental degradation problems from human activities. All these concerns are legitimate, given EPA's projected $4.3 billion annual costs of TMDL implementation, the estimated 20,000 waterbodies across the U.S. that are not meeting water quality standards, and the fact that as many as 40,000 TMDLs will have to be developed by the states.

As described by the EPA, TMDL relates to the amount of pollutants a waterbody can accept on a daily basis without violating its designated/beneficial use, referred to as "assimilative capacity" or "load capacity." The process of developing a TMDL can be categorized into five basic steps: (1) identification of pollutants of concern; (2) estimation of the waterbody's loading capacity or assimilation capacity for those pollutants; (3) estimation of the pollutant loading from all sources—point and nonpoint—to the waterbody; (4) determination of the total allowable pollutant load to the waterbody; and (5) allocation of pollution loading to each source, including a margin of safety. Each of these steps requires sound scientific principles, particularly the use of existing water quality monitoring data to estimate daily load and wasteload from known and diffuse sources. It requires the use of mathematical models to establish cause-and-effect relationships between human activities and environmental responses (in the form of water quality impacts). Indeed, process-oriented mathematical models offer cost-effective alternatives to large-scale, long-term field monitoring programs that document potential benefits of watershed and waterbody restoration strategies and can be used to measure the efficacy of different land management strategies. However, the potential for substantial costs and adverse environmental and human health impacts from the improper use of a mathematical model must be recognized.

This research established a science-based approach for evaluating, reviewing, and selecting mathematical models, including those that are being used or can be used by states to support their TMDL development and implementation program. The research developed a set of qualitative criteria for model selection and identified "candidate" or "optimal" terrestrial and aquatic ecosystems for use in determining pollutant load and waste-load. The models selected were deemed to have the capacity to support the estimation and allocation of TMLD for common chemical pollutants and sediments. Some of the models identified as optimal were also deemed suitable candidates for refinements to enhance their ability to simulate fate and transport of all forms of pollutants—chemical and biological. One of the models selected as optimal was modified and applied to a relatively large agricultural watershed to serve as a case study. Specifically, the SWAT model was modified to incorporate a functional component for predicting pathogen fate and transport in agricultural landscapes, thereby providing a new modeling system for predicting impact of physical, chemical and biological processes in terrestrial ecosystems. From the experiences obtained in this research, we can conclude that in spite of the many deficiencies of mathematical models of hydrology and water quality, they continue to possess unmistakably proven capability and are invaluable analytical tools and decision-support systems in environmental management and natural resource planning.

Literature Cited

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

Arnold, J.G., J.R. Williams, R.H. Griggs, and N.B. Sammons (1990). SWRRB - A basin scale simulation model for soil and water resources management. College Station, TX: Texas A & M University Press.

Environmental Protection Agency (EPA) (2002). The twenty needs report: How research can improve the TMDL program. EPA-841-B-02-002. Washington, DC: Office of Water.

General Accounting Office (GAO) (2000). Water Quality – Key EPA and State decisions limited by inconsistent and incomplete data. GAO/RCED00-54. Washington, DC: General Accounting Office.

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

National Research Council (NRC) (2001). Assessing the TMDL approach to water quality management. Washington, DC: National Academy Press.

Williams, J.R. (1975). Sediment yield prediction with universal equation using runoff energy factor. Agric. Res. Service., ARS-S-40. Washington, DC: U.S. Department of Agriculture.

Williams, J.R., P.T. Dyke and C.A. Jones (1983). EPIC: a model for assessing the effects of erosion on soil productivity. In pp. 553-572. *Analysis of Ecological Systems: State-of-the-art in ecological modeling*. Eds. W.K. Laurenroth et al. Amsterdam: Elsevier.

Wischmeier, W.H. and D.D. Smith (1978). Predicting rainfall erosion losses, a guide to conservation planning. Agricultural Handbook No. 537. Washington, DC: U.S. Department of Agriculture.