INITIAL CALIBRATION AND VALIDATION OF THE SWAT MODEL FOR THE UPPER MISSISSIPPI RIVER BASIN

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ABSTRACT
A simulation study using the Soil and Water Assessment Tool (SWAT) model (Arnold et al., 1998) has been initiated to assess current and alternative nutrient, cropping, and management practices in the Upper Mississippi River Basin (URMB), in an effort to help mitigate water quality problems in the Mississippi River and it's tributaries. The framework for the simulation is constructed around the National Resources Inventory (NRI) database that contains extensive cropping history, conservation practice, and other landuse information for the entire United States. Crop rotation and management practices derived from the NRI and/or other data sources are used to configure SWAT for both baseline conditions and scenarios depicting alternative cropping and management practices. The i_SWAT software system has been constructed to manage the input and output data for the SWAT simulations, and the execution of the model for each scenario. An overview of the modeling structure that has been developed for the UMRB is presented, including the spatial representation of the region within SWAT. Initial results for the baseline simulation are also presented for monthly stream flows near the outlet of the UMRB and a subwatershed located in Iowa, and for annual stream flows for the UMRB and several subwatersheds.

Keywords: Water quality, watershed modeling, cropping practices, nutrient management

INTRODUCTION
The Mississippi River Watershed covers 3.2 million km^2 across parts or all of 31 U.S. states and two Canadian provinces (Figure 1). Excess nitrogen, phosphorus, and sediment loadings have resulted in water quality degradation within the Mississippi and its tributaries. The nitrate load discharged from the mouth of the Mississippi River has also been implicated as the primary cause of the seasonal oxygen-depleted hypoxic zone that occurs in the Gulf of Mexico, which covered nearly 20,000 km^2 in 1999 (Rabalais et al., 2002). Approximately 90% of the nitrate load to the Gulf is attributed to nonpoint sources; 56% of this nonpoint source load is estimated to originate above the confluence of the Ohio and Mississippi Rivers (CENR, 2000). The Upper Mississippi River Basin (UMRB), which is located primarily in a five-state region (Figure 1), is the major source of the nitrate load that originates upstream from the Ohio River. Cropland and pasture are the dominant landuses, which together are estimated to account for nearly 67% of the total UMRB area (NAS, 2000). Nutrient inputs via fertilizer and/or livestock manure on cropland and pasture areas are the primary sources of diffuse nutrient pollution to the UMRB stream system.

These water quality issues are the catalyst for a simulation study using the Soil and Water Assessment Tool (SWAT) model (Arnold et al., 1998), that has been initiated to provide insights that could help mitigate nutrient and sediment losses from UMRB cropland and pastures. The simulation methodology consists of assessing the diffuse pollution impacts of alternative nutrient, tillage, and cropping practices relative to baseline conditions, to ascertain which cropping and management strategies could yield environmental benefits over current practices. The environmental analysis will also be coupled with an economic assessment, to provide a two-dimensional view of the impacts of each scenario. A description of the simulation approach that has been developed to perform the SWAT simulations is provided here. Initial results of SWAT stream flow predictions for a subwatershed located in Iowa and for the Mississippi River at Grafton, Illinois (Figure 1) are also presented.

SIMULATION METHODOLOGY
The SWAT model is a conceptual, physically based long-term continuous watershed scale simulation model that operates on a daily time step. The model is capable of simulating a high level of spatial detail by allowing the division of a watershed into a large number of subwatersheds. In SWAT, a watershed is divided into multiple subwatersheds, which are then further subdivided into Hydrologic Response Units (HRUs) that consist of homogeneous landuse, management, and soil characteristics. Flow generation, sediment yield, and non-point-source loadings from each HRU in a subwatershed are summed, and the resulting loads are routed through channels, ponds, and/or reservoirs to the watershed outlet. Key components of SWAT include hydrology, plant growth, erosion, nutrient transport and transformation, pesticide transport and management practices. Previous applications of SWAT for flow and/or pollutant loadings have compared favorably with measured data for a variety of watershed scales (Arnold and Allen, 1996; Srinivasan et al., 1998; Arnold et al., 1999; Arnold et al., 2000; Saleh et al., 2000; Santhi et al., 2001).

INPUT DATA

Previous SWAT applications have been performed for the UMRB that assumed only monoculture cropping and simplified depictions of nutrient applications and tillage (Arnold et al., 1999; Arnold et al., 2000). This study builds on the earlier work by incorporating more detailed crop rotations and an array of nutrient and tillage management schemes, derived from USDA survey data and other sources, that more accurately reflect current practices in the UMRB and better facilitate policy analyses for the region. The primary data source for the current study is the U.S. Department of Agriculture (USDA) National Resources Inventory (NRI) database (Nusser and Goebel, 1997), which is considered the most comprehensive database of its kind that has been developed anywhere in the word (http://www.nrcs.usda.gov/technical/NRI/)

Figure 1. Location of the Upper Mississippi River Basin (UMRB) within the Mississippi River Basin, the 131 8-digit watersheds located within the UMRB, and the location of Grafton, IL.

The NRI is a statistically based database that was updated every five years from 1982 to 1997 (more recent data has not yet been released) for the entire U.S. with information such as soil type, landscape features, cropping histories, and conservation practices for roughly one million nonfederal land "points." Each of the points actually represents an area assumed to consist of homogeneous landuse, soil, and other characteristics that can generally range from a few hundred to several thousand hectares. Crop rotations incorporated in the baseline SWAT simulation are derived from cropping histories reported in the NRI; other landuse delineations required for the simulation are also based on NRI data. The simulated baseline conservation, fertilizer, and tillage practices are based on NRI data and/or USDA 1990-95 Cropping Practices Survey (CPS) data (the data can be accessed by using the search tool at http://usda.mannlib.cornell.edu/usda/ess_entry .html).

Historical precipitation, maximum temperature, and minimum temperature data were obtained, from a single representative climate station for each 8-digit watershed, to perform the SWAT baseline simulation (data obtained from C. Santhi. 2002. Personal communication, Blacklands Research Lab., Temple, Texas). The climate records span from 1967-98; however, only a 20-year portion (1971-90) was used for the current SWAT baseline simulation described here. The soil layer data required for the SWAT simulations is input from a soil database that contains soil properties consistent with those described by Baumer et al. (1994), with the additional enhancement of ID codes that allow direct linkage to NRI points.

UMRB SPATIAL REPRESENTATION IN SWAT

A key aspect of the data development and input process is the delineation of the study region into smaller spatial units to facilitate the depiction of the wide range of climate, soils, management practices, cropping sequences, and other landuse that exists in the region. Delineation of the UMRB into smaller spatial units suitable for the SWAT simulations consists of two steps: (1) subdividing the overall basin into 131 subwatersheds (Figure 1) that coincide with the boundaries of U.S.

Geological Survey (USGS) 8-digit Hydrologic Cataloging Unit (HCU) watersheds (Seaber et al., 1987), and (2) creating smaller HRUs located within each of the 131 8-digit watersheds. The HRUs represent "lumped areas" of similar landuse and soil types that are distributed throughout an 8-digit subwatershed; exact spatial locations of the HRUs are not incorporated in the SWAT simulation. In SWAT, nutrient and sediment losses are simulated at the HRU level, then aggregated to the 8-digit watershed level, and finally routed to the UMRB outlet.

The HRUs required for the SWAT UMRB baseline simulation were created by aggregating NRI points together that possess common landuse, soil, and management characteristics. For landuse, all of the points within a given category were clustered together within each 8-digit watershed, except for the cultivated cropland. For the cultivated cropland, the NRI points were first aggregated into 15 different crop rotation landuse clusters within each 8-digit watershed, based on the NRI cropping histories. These crop rotation aggregations were then subdivided based on permutations of rotations; e.g., corn-soybean versus soybean-corn.

Nearly 21,000 soils are distributed across the NRI points in the region, which far exceeded the practical limits of the HRU methodology used for the baseline simulation. Thus a subset of representative soils were used for constructing the HRUs that were previously determined via a statistically-based soil clustering process that was performed for NRI-linked soils for most of the U.S. (D. Goss. 2001. Personal Communication. Blacklands Research Lab. Temple, TX). The result of the process for the region defined by the UMRB boundaries was 417 representative soils (corresponding to 417 soil clusters). These 417 soils define the global set of UMRB soils for performing aggregations of NRI points on the basis of soil types; much smaller subsets of the 417 soils were used for aggregating NRI points within specific 8-digit watersheds.

The third main component of developing the HRUs required aggregation across NRI points according to the following management characteristics: type of tillage (conventional, reduced, mulch, or no-till), fertilizer application rates and timing, tile drainage (yes or no), and whether conservation practices (terracing, contouring, and/or strip cropping) were present. Management data derived from the CPS was imputed to the NRI points prior to the aggregation phase using a weighted distribution process.

A total of 15,498 HRUs were created for the UMRB for the SWAT baseline simulation. The HRU densities for the UMRB SWAT simulations are shown here as a function of 8-digit watersheds (Figure 2). The density of the HRUs are much greater in the UMRB regions that are dominated by intensive agriculture, to facilitate the accuracy required to assess the impacts in variations between agricultural management practices and cropping systems. Further sensitivity analyses will be performed to determine what the optimal number of HRUs is for the URMB simulations; the total number of HRUs may ultimately be reduced, especially in the areas dominated by agriculture.

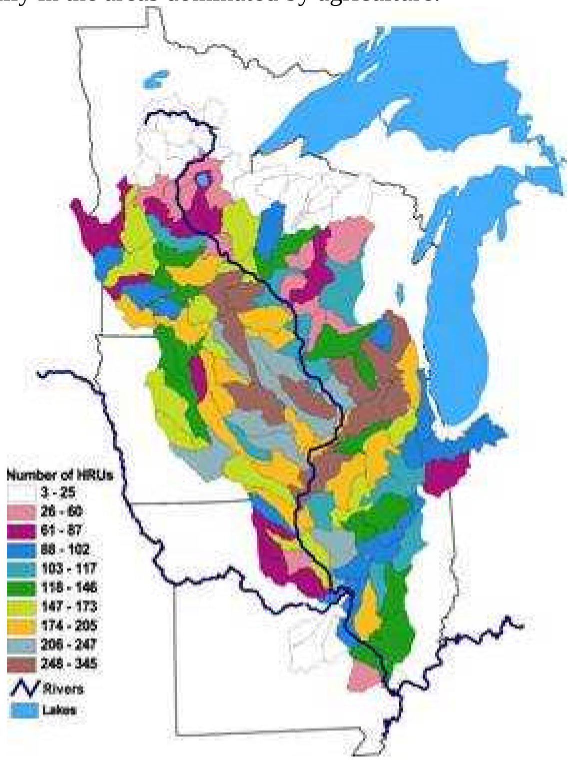

Figure 2. HRU densities as a function of 8-digit watersheds within the URMB.

SIMULATION MANAGEMENT USING I_SWAT

The input data and run execution process for the UMRB SWAT baseline simulation was managed with the interactive SWAT (i_SWAT) software package (http://www.public.iastate.edu/~elvis/), which translates the input data from an Access® database into the required SWAT input formats, executes SWAT, and extracts and stores desired outputs back into the Access database. A pre-processing step was required prior to using i_SWAT, in which data from disparate databases such as the NRI and CPS were converted from their original formats into tables within the Access database. Storage of the data in Access allows relatively easy modifications of specific input variables as needed, and also provides greater flexibility in viewing and processing output data.

RESULTS AND DISCUSSION

The initial testing of SWAT for UMRB baseline conditions has been limited to comparisons between predicted and measured stream flows. Preliminary steam flow comparisons performed for both the gauge location at Grafton, Illinois and several upstream points located at the outlets of various UMRB subwatersheds are reported here. Additional SWAT simulations are also being performed for selected subwatersheds in the UMRB to provide more in-depth sensitivity analyses of selected input parameters and further calibration and validation of the model. Initial stream flow results are discussed here for two simulations of the Raccoon River Watershed, a URMB subwatershed that comprises two USGS 8-digit watersheds in Iowa (Figure 3).

Raccoon River Watershed SWAT Simulations

Two uncalibrated 14-year (1981-94) SWAT simulations have been performed for the Raccoon River Watershed so far (Figure 3): (1) a 2-subwatershed simulation reflective of the UMRB simulation methodology, and (2) a more refined simulation that used 38-subwatersheds. An identical set of 294 HRUs that were generated from the NRI was used for both simulations. However, guidance from other landuse data (Vogelmann et al., 2001) was used to help determine which subwatersheds the HRUs should be located in for the 38-subwatershed simulation. In addition, ten climate stations were used for the 38-watershed simulation (Figure 3) while only two climate stations were used for the 2-subwatershed simulation, which are represented by geographic centroid locations in Figure 3.

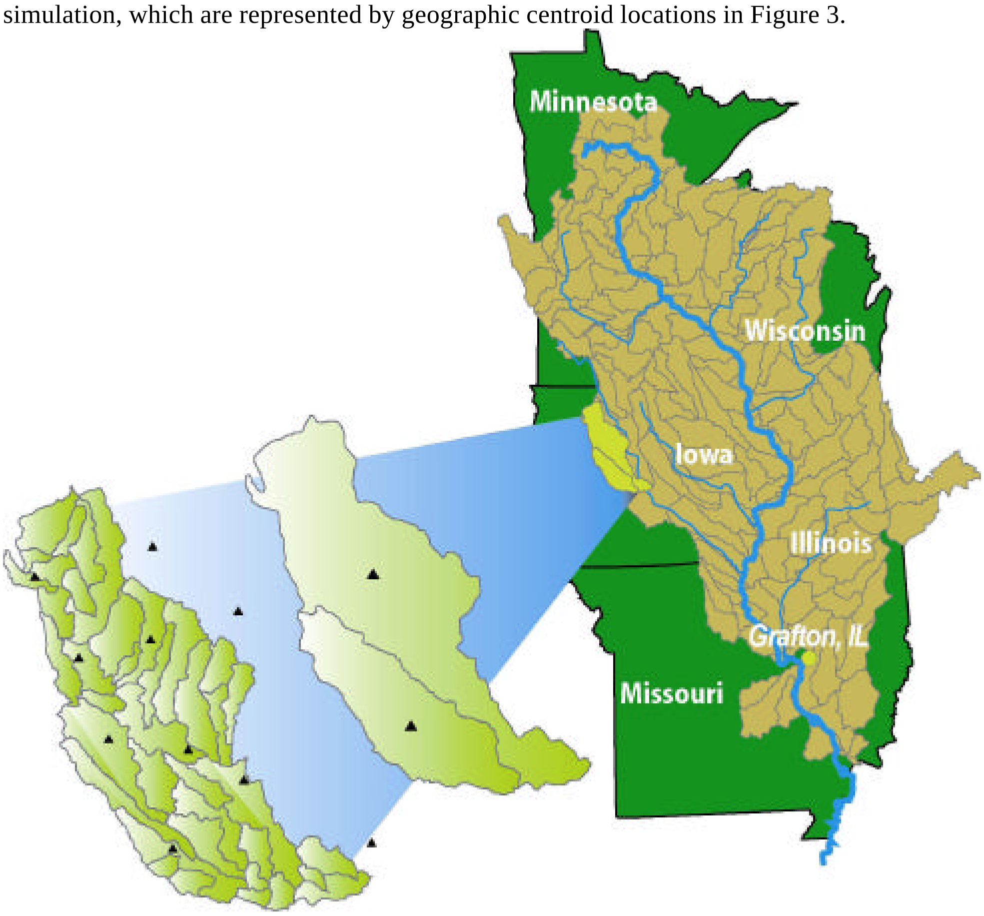

Figure 3. Location of the Raccoon River Watershed in the UMRB, configurations of the 2- and 38-subwatershed simulations, and the locations of the climate stations for the two simulations.

Figure 4 shows the predicted cumulative monthly flows for the two SWAT simulations versus the corresponding measured flows for 1981-94. The 38-subwatershed simulation accurately tracked the measured flows. The 2-subwatershed simulation also followed the general pattern of the measured flows, but did not capture the peak flow periods as well as the 38-subwatershed simulation. The improved flows for the 38-subwatershed simulation were apparently a function of the refined inputs, especially the use of additional climate stations. However, such refinements may be impractical for the simulation of the entire URMB. In addition, improved flow predictions are expected following further calibration of the 2-subwatershed approach.

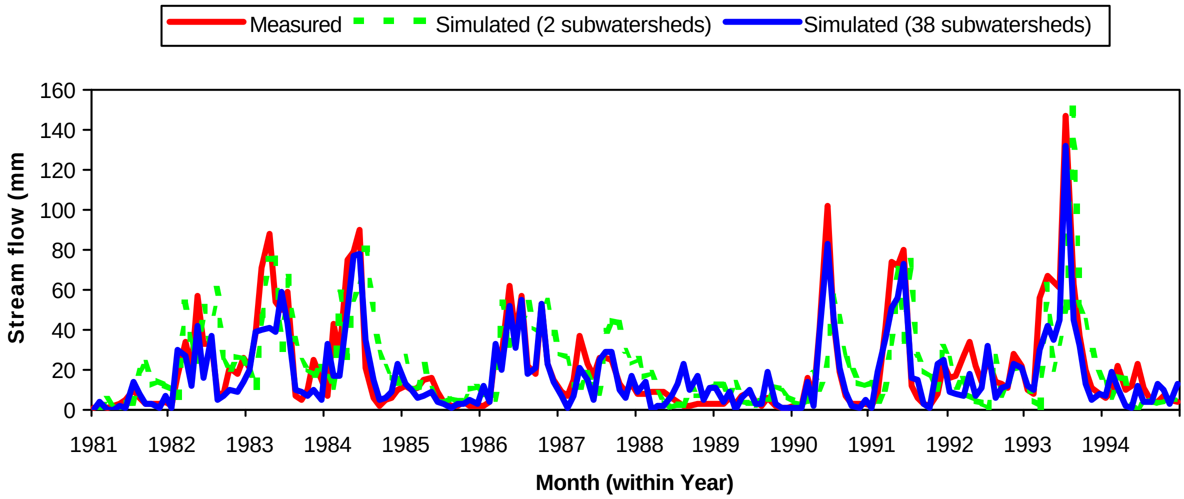

Figure 4. Measured versus predicted cumulative monthly stream flows for 1981-94 for the Raccoon River Watershed (at USGS gauge #05484500 located on the Raccoon River near Van Meter, Iowa).

Flow Comparisons at Grafton, Illinois and Other UMRB Locations

Flow comparisons between simulated and measured flows are being performed at USGS stream gauge # 05587450 located on the Mississippi River at Grafton, Illinois (Figure 1), just above the confluence of the Mississippi and Missouri Rivers. The gauge at Grafton captures flow from 119 of the 131 8-digit watersheds, which is assumed representative of the entire UMRB. An initial SWAT UMRB study was performed (Jha et al., 2003) in which topographic, landuse, and soil data were obtained from the Better Assessment Science Integrating Point and Nonpoint Sources (BASINS) package version 3 (http://www.epa.gov/ost/BASINS/). Calibration and validation of SWAT were both performed for this study (total simulation period of 30 years), resulting in a good agreement between the predicted and measured cumulative monthly flows (r^2=.79 for the 1989-96 validation period shown in Figure 5). Preliminary cumulative monthly flows obtained with limited calibration are also shown in Figure 5 for the NRI-based 20-year SWAT baseline simulation. These results for 1989-96 also tracked the measured data reasonably well (r^2=.53); however, further calibration is required to obtain more accurate results.

Table 1 lists comparisons between measured and predicted annual average stream flows for periods ranging between 4 and 17 years for the Mississippi River at Grafton and 11 upstream subwatersheds. The differences between the predicted and measured annual average flows were 10% or less for eight of the locations; the predicted annual average flows at Royalton, Minnesota and Jorden, Minnesota were nearly identical to the corresponding measured flows. Underpredictions of 22 to 29% occurred at Augusta, IA, St Francis, IA, and Joslin, IL. Overall, the results were encouraging considering the fact that the limited flow calibrations performed so far have been focused only on the predicted stream flows at Grafton.

Table 1. Comparisons between measured and predicted (NRI-based SWAT simulation) annual average stream flows for the Mississippi River at Grafton, Illinois and 11 upstream subwatersheds.

USGS Station Name	Flow Comparison Time Period[a]	Drainage Area (km^2)	Measured flow (mm)	Predicted flow (mm)
Mississippi River near Royalton, MN	1980-93	30,175	149.70	149.84
Minnesota River near Jorden, MN	1980-96	43,715	139.48	138.89
St Croix River at St Croix Falls, WI	1980-96	20,030	284.89	298.09
Chippewa River at Durand, WI	1991-96	24,722	338.93	321.10
Wisconsin River at Muscoda, WI	1980-93	28,926	316.10	352.32
Rock River near Joslin, IL	1980-93	25,401	276.69	389.18
Iowa River at Wapello, IA	1980-95	32,796	287.89	331.35
Skunk River at Augusta, IA	1980-95	11,246	265.11	338.27
Des Moines River at St Francis, IA	1980-92	37,496	204.24	273.75
Illinois River at Valley City, IL	1991-96	74,603	373.55	376.14
Maquoketa River at Maquoketa, IA	1993-96	4,827	334.56	338.46
Mississippi River at Grafton, IL	1989-96	447,539	268.01	287.80

[a]Time period variations were due to differences in readily available measured flow data records.

CONCLUSIONS

A SWAT simulation has been constructed for the UMRB based on NRI landuse data and subwatershed boundaries coincident with USGS 8-digit watershed boundaries. Preliminary results indicate that the method is viable for predicting UMRB flows, although further calibration and validation of the flows are required. Initial flow predictions for the Raccoon River Watershed, a UMRB subwatershed, indicate that refinements in subwatershed, HRU, and climate station inputs may produce more accurate predictions. However, such refinements may be impractical for the larger UMRB simulation. Calibration of the less refined approach is also likely to yield better results. The next phase of the UMRB SWAT study will focus on calibration and validation of the simulated sediment and nitrate losses, following completion of the flow testing process.

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