

2004

Hydrologic modeling and climate change study in the Upper Mississippi River Basin using SWAT

Manoj Kumar Jha
Iowa State University

Follow this and additional works at: <https://lib.dr.iastate.edu/rtd>

 Part of the [Hydrology Commons](#)

Recommended Citation

Jha, Manoj Kumar, "Hydrologic modeling and climate change study in the Upper Mississippi River Basin using SWAT " (2004).
Retrospective Theses and Dissertations. 951.
<https://lib.dr.iastate.edu/rtd/951>

This Dissertation is brought to you for free and open access by the Iowa State University Capstones, Theses and Dissertations at Iowa State University Digital Repository. It has been accepted for inclusion in Retrospective Theses and Dissertations by an authorized administrator of Iowa State University Digital Repository. For more information, please contact digirep@iastate.edu.

**Hydrologic modeling and climate change study in the Upper Mississippi River Basin
using SWAT**

by

Manoj Kumar Jha

A dissertation submitted to the graduate faculty
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Major: Civil Engineering (Environmental Engineering)

Program of Study Committee:

Roy R. Gu, Major Professor

Larry L. Northup

Rameshwar S. Kanwar

James L. Baker

Shihwu Sung

Iowa State University

Ames, Iowa

2004

Copyright © Manoj Kumar Jha, 2004, All rights reserved.

UMI Number: 3145651

INFORMATION TO USERS

The quality of this reproduction is dependent upon the quality of the copy submitted. Broken or indistinct print, colored or poor quality illustrations and photographs, print bleed-through, substandard margins, and improper alignment can adversely affect reproduction.

In the unlikely event that the author did not send a complete manuscript and there are missing pages, these will be noted. Also, if unauthorized copyright material had to be removed, a note will indicate the deletion.

UMI[®]

UMI Microform 3145651

Copyright 2004 by ProQuest Information and Learning Company.

All rights reserved. This microform edition is protected against unauthorized copying under Title 17, United States Code.

ProQuest Information and Learning Company
300 North Zeeb Road
P.O. Box 1346
Ann Arbor, MI 48106-1346

Graduate College
Iowa State University

This is to certify that the doctoral dissertation of

Manoj Kumar Jha

has met the dissertation requirements of Iowa State University

Signature was redacted for privacy.

Major Professor

Signature was redacted for privacy.

For the Major Program

TABLE OF CONTENTS

LIST OF FIGURES	v
LIST OF TABLES	ix
LIST OF SYMBOLS AND ABBREVIATIONS	xi
ABSTRACT	xiv
CHAPTER 1. GENERAL INTRODUCTION	1
Introduction	1
Study Objectives	5
Dissertation Organization	6
References	8
CHAPTER 2. HYDROLOGIC SIMULATIONS OF THE MAQUOKETA RIVER WATERSHED WITH SWAT	10
Abstract	10
Introduction	11
Materials and Method	14
Results and Discussion	19
Conclusion	22
References	23
CHAPTER 3. CLIMATE CHANGE SENSITIVITY ASSESSMENT ON UPPER MISSISSIPPI RIVER BASIN STREAMFLOWS USING SWAT	35
Abstract	35
Introduction	36
Model Description	41
Input Data	43
Simulation Methodology	45
Results and Discussion	51
Conclusions	58
References	60
CHAPTER 4. IMPACTS OF CLIMATE CHANGE ON STREAM FLOW IN THE UPPER MISSISSIPPI RIVER BASIN: A REGIONAL CLIMATE MODEL PERSPECTIVE	79
Abstract	79
Introduction	80
Models and Input Data	83
Model Uncertainties and Experimental Design	91

Results and Discussion	94
Limitation of Coupled Modeling System	103
Summary and Conclusions	105
Acknowledgements	106
References	107
CHAPTER 5. APPLICATION OF SWAT FOR THE UPPER MISSISSIPPI RIVER BASIN, PART I: METHODOLOGY	124
Abstract	124
Introduction	125
Description of the UMRB	126
Overview of the UMRB Modeling System	128
Input Data and Assumptions	131
Conclusions	147
References	148
CHAPTER 6. APPLICATION OF SWAT FOR THE UPPER MISSISSIPPI RIVER BASIN, PART II: CALIBRATION AND VALIDATION	168
Abstract	168
Introduction	169
SWAT Model	171
Simulation Methodology and Input Data	173
Calibration and Validation	174
Next Phase of the Research	180
Conclusions	181
References	182
CHAPTER 7. GENERAL CONCLUSIONS	193
Evaluation of the SWAT Model	193
Impacts of Climate Change on UMRB	194
SWAT Validation and Modeling Framework for the UMRB	195
Recommendations	197
ACKNOWLEDGEMENTS	198

LIST OF FIGURES

CHAPTER 1. GENERAL INTRODUCTION

- Figure 1. Location of the Upper Mississippi River Basin 6

CHAPTER 2. HYDROLOGIC SIMULATIONS OF THE MAQUOKETA RIVER WATERSHED WITH SWAT

- Figure 1. Location of the Maquoketa River Watershed (Northeast Iowa), and weather stations in and around the watershed. 26

- Figure 2. Land use categories in Maquoketa Watershed. 27

- Figure 3. Sensitivity of surface runoff and baseflow to (a) CN, (b) ESCO, and (c) SOL_AWC. 29

- Figure 4. Monthly time series of predicted and measured streamflow at USGS gauge 05418500 (located on the Maquoketa river near Maquoketa, IA) for the 1988-93 calibration period. 30

- Figure 5. Monthly time series of predicted and measured streamflow at USGS gauge 05418500 (located on the Maquoketa river near Maquoketa, IA) for the 1982-87 validation period. 31

CHAPTER 3. CLIMATE CHANGE SENSITIVITY ASSESSMENT ON UPPER MISSISSIPPI RIVER BASIN STREAMFLOWS USING SWAT

- Figure 1. Location of Grafton, IL and the 131 USGS 8-digit watersheds within the Upper Mississippi River Basin (URMB), and the location of the UMRB within the Mississippi River Basin. 67

- Figure 2. Monthly time-series comparison of measured versus predicted streamflow at Grafton, IL during the 20-year calibration period (1968-87). 68

- Figure 3. Regression plot of predicted versus measured monthly streamflow values for the 20-year calibration period (1968-87). 68

- Figure 4. Monthly time-series comparison of measured versus predicted streamflow at Grafton, IL during the 10-year validation period (1988-97). 69

Figure 5.	Regression plot of predicted versus measured monthly streamflow values for the 10-year validation period (1988-97).	69
Figure 6.	Change in average monthly streamflows predicted for scenarios 1-6 relative to the baseline over the 20-year simulation period.	70
Figure 7.	Change in average monthly streamflows predicted for scenarios 7 and 8 relative to the baseline over the 20-year simulation period.	70
Figure 8.	Spatial distribution of predicted streamflows for the UMRB baseline scenario, shown as a function of 8-digit watersheds.	71
Figure 9.	Spatial distribution of predicted streamflows for the UMRB scenario 7, shown as a function of 8-digit watersheds.	72
Figure 10.	Spatial distribution of predicted streamflows for the UMRB scenario 8, shown as a function of 8-digit watersheds.	73
 CHAPTER 4. IMPACTS OF CLIMATE CHANGE ON STREAM FLOW IN THE UPPER MISSISSIPPI RIVER BASIN: A REGIONAL CLIMATE MODEL PERSPECTIVE		
Figure 1.	The Upper Mississippi River Basin (UMRB) and delineated 8-digit HUCs.	110
Figure 2.	Schematic diagram of RCM/SWAT simulation runs.	111
Figure 3.	Measured and simulated annual stream flows at USGS gauge 05587450, Mississippi River near Grafton, IL for calibration.	112
Figure 4.	Time series of measured and simulated monthly stream flows at USGS gauge 05587450, Mississippi River near Grafton, IL for calibration.	112
Figure 5.	Same as Fig. 3, but for validation.	113
Figure 6.	Same as Fig. 4, but for validation.	113
Figure 7.	Comparison of hydrological components between RegCM2 and SWAT: (a) snowfall, (b) runoff, (c) evapotranspiration, and (d) snowmelt. All values are averaged for 1980-88 for the NNR runs.	115

Figure 8.	Annual stream flows produced by SWAT driven by the RCM with NNR lateral boundary conditions, compared with measured stream flows at USGS gauge 05587450, Mississippi River near Grafton, IL.	116
Figure 9.	Comparison of measured mean monthly stream flows and those produced by SWAT driven by the RCM downscaled NNR data for validation period (1980-1988).	116
Figure 10.	Same as Fig. 8, but for precipitation.	117
Figure 11.	Precipitation generated by the RCM for contemporary and future scenario climates.	117
Figure 12.	Mean monthly stream flow simulated by SWAT for contemporary and future scenario climates.	118
Figure 13.	Comparisons of climate change with annual biases in simulated stream flow.	118
Figure 14.	Relationship between annual stream flow and annual precipitation for various climates.	119
CHAPTER 5. APPLICATION OF SWAT FOR THE UPPER MISSISSIPPI RIVER BASIN, PART I: METHODOLOGY		
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.	152
Figure 2.	HRU distribution in the UMRB for SWAT simulations.	153
Figure 3.	Cropland (Corn and soybean) as % of subwatershed area.	154
Figure 4.	Grassland (hay and pasture) as % of subwatershed area.	155
Figure 5.	CRP (Conservation Reserve Program) area as % of subwatershed area.	156
Figure 6.	Tile drainage area as % of subwatershed area.	157
Figure 7.	Conservation tillage practices area as % of subwatershed area.	158

Figure 8.	Example histogram of nitrogen application rates for farmers surveyed during the 1990-92 CPS survey who planted corn following corn in Iowa.	159
Figure 9.	Distribution of soil clusters per 8-digit level of subwatershed in the UMRB.	160
Figure 10.	Locations of the 111 climate stations within the UMRB, relative to 131 subwatersheds and the location of Grafton, IL.	161
 CHAPTER 6. APPLICATION OF SWAT FOR THE UPPER MISSISSIPPI RIVER BASIN, PART II: CALIBRATION AND VALIDATION		
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.	184
Figure 2.	Configuration of Iowa and Des Moines River Watersheds in the UMRB.	185
Figure 3.	Monthly time-series of measured and simulated streamflow for Iowa River Watershed.	186
Figure 4.	Monthly time-series of measured and simulated sediment yield for Iowa River Watershed.	186
Figure 5.	Monthly time-series of measured and simulated stream flow for Des Moines River Watershed.	187
Figure 6.	Monthly time-series of measured and simulated sediment yield for Des Moines River Watershed.	187
Figure 7.	Annual measured and simulated streamflow at Grafton, IL for the calibration and validation periods.	188
Figure 8.	Monthly time-series of measured and simulated streamflow at Grafton, IL for the calibration and validation periods.	188
Figure 9.	Annual measured and simulated sediment yield at Grafton, IL for the calibration and validation periods.	189
Figure 10.	Monthly time-series of measured and simulated sediment yield at Grafton, IL for the calibration and validation periods.	189

LIST OF TABLES

CHAPTER 2. HYDROLOGIC SIMULATIONS OF THE MAQUOKETA RIVER WATERSHED WITH SWAT

Table 1.	Parameter ranges and initial values used in the sensitivity analysis.	32
Table 2.	Sensitivity indices of model parameters.	33
Table 3.	Final calibrated values of SWAT parameters for Maquoketa River Watershed.	34

CHAPTER 3. CLIMATE CHANGE SENSITIVITY ASSESSMENT ON UPPER MISSISSIPPI RIVER BASIN STREAMFLOWS USING SWAT

Table 1.	Hydrologic calibration parameters and their values for the UMRB.	74
Table 2.	Assumed changes in relevant climate parameters on a monthly basis for each of the eight climate scenarios.	75
Table 3.	Comparison between measured and predicted annual average streamflows during 1971-90 for the Mississippi River at Grafton, Illinois and 11 upstream subwatersheds.	76
Table 4.	Average annual hydrologic balance components simulated by SWAT for the UMRB baseline and eight climate scenarios.	77
Table 5.	Predicted relative changes in flows for the Mississippi River at Grafton, IL for eight climate change scenarios.	78

CHAPTER 4. IMPACTS OF CLIMATE CHANGE ON STREAM FLOW IN THE UPPER MISSISSIPPI RIVER BASIN: A REGIONAL CLIMATE MODEL PERSPECTIVE

Table 1.	Definition of errors in simulated stream flows and climate change.	120
Table 2.	Hydrologic component comparison between RegCM2 and SWAT.	120

Table 3.	Simulated hydrologic budget components by SWAT under different climates.	121
Table 4.	Bias and RMSE in various simulations of water yield of the Mississippi River at Grafton, IL.	122
Table 5.	Regression analysis: stream flow vs. precipitation.	123
CHAPTER 5. APPLICATION OF SWAT FOR THE UPPER MISSISSIPPI RIVER BASIN, PART I: METHODOLOGY		
Table 1.	NRI points in the UMRB by state.	162
Table 2.	1997 NRI broad land use categories.	163
Table 3.	UMRB crop rotations, and associated number of NRI points, areal extent, and required CPS crop sequences.	164
Table 4.	Total number of CPS surveys performed during 1990-92 in the north central region by state and crop.	165
Table 5.	Lower and upper bound corn nitrogen fertilizer application rates by state.	166
Table 6.	Soil layer data required for SWAT.	167
CHAPTER 6. APPLICATION OF SWAT FOR THE UPPER MISSISSIPPI RIVER BASIN, PART II: CALIBRATION AND VALIDATION		
Table 1.	Land use categories in Iowa and Des Moines River Watersheds.	190
Table 2.	Evaluation of SWAT simulated stream flow and sediment yield for the Iowa and Des Moines River Watersheds.	191
Table 3.	Scenario results for Iowa and Des Moines River Watersheds.	192

LIST OF SYMBOLS AND ABBREVIATIONS

AGNPS	Agricultural Non-Point Source
AGRL	Agricultural Land-Generic
ALPHA_BF	Baseflow alpha factor
ARMS	Agricultural Resource Management Study
AVSWAT	ArcView interface of the SWAT model
BASINS	Better Assessment Science Integrating Point and Nonpoint Sources
C	Cover and management factor
CARD	Center for Agricultural and Rural Development
CC	Continuous corn rotation
CCS	Corn-corn-soybean rotation
CENR	Committee on Environment and Natural Resources
CGCM1	Canadian Centre for Climate Modeling and Analysis
CN	Curve Number
CNMP	Comprehensive Nutrient Management Plan
CO ₂	Carbon dioxide concentration
CPS	Cropping Practice Surveys
CREAMS	Chemical, Runoff, and Erosion from Agricultural Management Systems
CRP	Conservation Reserve Program
CS	Corn soybean rotation
CSIRO	Commonwealth Scientific and Industrial Research Organization
CTIC	Conservation Tillage Information Center
CTL	Contemporary climate
DEM	Digital Elevation Model
E	Nash-Sutcliffe simulation efficiency
ENSO	El Niño/Southern Oscillation weather phenomena
EPA	U.S. Environmental Protection Agency
EPCO	Plant uptake compensation factor
EPIC	Erosion-Productivity Impact Calculator
ESCO	Evaporation compensation factor
ET	Evapotranspiration
F	Response variable
F _m	Mean of lowest and highest values of the range for explanatory parameter
GCM	Global Circulation Model
GHG	Greenhouse gas
GIS	Geographic Information Systems
GW_RAVAP	Groundwater revap coefficient
GWQMN	Threshold depths for baseflow to occur

HadCM2	Hadley Centre for Climate Prediction and Research model
HCU	Hydrologic Cataloging Units
HEC-HMS	Hydrologic Modeling System
HRU	Hydrologic Response Unit
HSPF	Hydrological Simulation Program - FORTRAN
HUMUS	Hydrologic Unit Model for the United States
i_SWAT	Interactive SWAT model interface for SWAT2000
I_a	Initial abstractions
IPCC	Intergovernmental Panel on Climate Change
K	Soil erodibility factor
km^2	Square kilometers
LS	Slope length and steepness factor
mg/L	Milligrams per liter
MINK	Missouri, Iowa, Nebraska, and Kansas region
MLRA	Major Land Resource Area
mm	Millimeters
m^3/s	Cubic meters per second
MRW	Maquoketa River Watershed
MT	Metric Tons
MUSLE	Modified Universal Soil Loss Equation
N	Nitrogen
NASS	National Agricultural Statistic Survey
NCAR	National Center for Atmospheric Research
NCDC	National Climatic Data Center
NCEP	National Centers for Environmental Prediction
NLCD	National Land Cover Dataset
NNR	NCEP/NCAR reanalysis dataset
NRCS	Natural Resources Conservation Service
NRI	National Resources Inventory
P	Cropping practice factor
P_m	Mean of lowest and highest values of the range for response variable
ppm	Parts per million
Q_m	Measured streamflow
Q_{perc}	Percolation
QR	Groundwater flow
Q_s	Simulated streamflow
Q_{surf}	Surface runoff
R	Precipitation
R^2	Coefficient of determination
RCM	Regional Climate Model

RECHRG_DP	Deep aquifer percolation coefficient
REVAPMN	Threshold depths for re-evaporation to occur
RMSE	Root Mean Square Error
RUE	Radiation Use Efficiency
S	Retention parameter
SC	Soybean corn rotation
SCS-CN	Conservation Services Curve Number method
Sed	Sediment erosion
SNR	Future scenario climate
SOL_AWC	Soil available water capacity
SSC	Soybean-soybean-corn rotation
STATSGO	State Soil Geographic database
SW	Soil water content
SWAT	Soil and Water Assessment Tool
SWRRB	Simulator for Water Resources in Rural Basins
T _{max}	Maximum daily temperature
T _{min}	Minimum daily temperature
UMRB	Upper Mississippi River Basin
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey
VIC	Variable Infiltration Capacity group

ABSTRACT

This dissertation describes the modeling efforts on the Upper Mississippi River Basin (UMRB) using the Soil and Water Assessment Tool (SWAT) model. The UMRB extends from the source of the river at Lake Itasca in Minnesota to a point just north of Cairo, Illinois, and covers a drainage area over 490,000 km². SWAT is a long term, continuous watershed scale hydrologic model that was developed to predict the impact of land management on water, sediment, and agricultural chemical yields. The main goal of this study is to apply the SWAT model to the UMRB and selected subwatersheds to evaluate the model as a tool for agricultural policy analysis and climate change impact analysis.

The SWAT model was first applied to the Maquoketa River Watershed, which covers approximately 5,000 km² area in Northeast Iowa. A sensitivity analysis using influence coefficient method was conducted for eight selected hydrologic input parameters to identify the most to the least sensitive parameters. A further detailed sensitivity analysis was performed for the three most sensitive parameters: curve number (CN), evaporation compensation factor (ESCO), and soil available water capacity (SOL_AWC). Calibration and validation of SWAT, facilitated by the sensitivity analysis, were performed for streamflow on annual and monthly basis. Model performance was evaluated by two statistical measures: the coefficient of determination (R^2) and the Nash-Sutcliffe simulation efficiency (E). These values computed for the monthly comparisons were 0.86 and 0.85 for the calibration period and 0.69 and 0.61 for the validation period. After the model was well validated for the Maquoketa Watershed, it was then validated for the entire UMRB streamflow at Grafton, IL and evaluated for a climate change impact analysis. Calibration and validation were

performed for 1968-87 and 1988-97, respectively; R^2 and E values computed for the monthly comparisons were 0.74 and 0.65 for the calibration period and 0.81 and 0.75 for the validation period. The impacts of eight climate change scenarios (changes in temperature, precipitation, and/or CO₂ levels) including a simplified replication of a previously reported future climate projection were then analyzed, relative to a baseline scenario. The results indicate that the UMRB hydrology is very sensitive to potential future climate changes, resulting in increased periods of flooding or drought.

The impact of future climate change was then explored for the streamflow by using two 10-year scenario periods (1990s and 2040s) generated by introducing a regional climate model (RegCM2) to dynamically downscale global model (HadCM2) results. The combined GCM-RCM-SWAT model system produced an increase in future scenario climate precipitation of 21% with a resulting 18% increase in snowfall, 51% increase in surface runoff, 43% increase in groundwater recharge and 50% increase in total water yield in the UMRB. Furthermore, evaluation of model-introduced uncertainties due to use of SWAT, GCM, and RCM models yielded the highest percentage bias (18%) for the GCM downscaling error. Change in stream flow (50%) due to climate change exceeds both the individual model biases and also the combined-model bias, thereby providing a relatively high confidence in the prediction.

Building upon the above SWAT validation for the entire UMRB with less detailed input data available in the Better Assessment Science Integrating Point and Nonpoint Sources (BASINS) package, a SWAT modeling framework was constructed for the entire UMRB. The framework incorporates more detailed input data and is designed to assess the effects of land use, climate, and soil conditions on streamflow and water quality. An application of

SWAT is presented for the Iowa and Des Moines River watersheds within the modeling framework constructed for the UMRB. In general, SWAT accurately tracked the measured stream flows and sediment yields for both the annual and monthly time steps, as evaluated by R^2 and E values. A scenario run was conducted for each watershed in which conservation tillage adoption increased to 100%, and the results showed a small sediment reduction of 5.8% for Iowa River Watershed and 5.7% for Des Moines River Watershed. On a per-acre basis, sediment reductions for the Iowa and Des Moines River Watersheds were found to be 1.86 and 1.18 metric tons respectively, which indicates that Iowa River Watershed would be a better candidate area for “green payments”. Furthermore, an attempt was made to validate the model for the entire UMRB. Streamflow and sediment yield data at USGS gage at Grafton, IL were used for model calibration and validation. Statistical evaluation of the model performance indicated that annual flow and sediment yield simulated by SWAT corresponded very well with the measured values. Monthly simulation results are not as strong as the annual results; however, the model was able to track the seasonal trends very well. The next step of the research will focus on validation of the model for nitrogen and phosphorus, and simulation of the agricultural policy scenarios for the region.

CHAPTER 1. GENERAL INTRODUCTION

Introduction

The realization that nonpoint sources of nutrients, specifically nitrogen (N) and phosphorus (P) from agricultural lands, represent a significant water quality issue is relatively recent (Keeney, 2002). In the 1960-80 era, federal and state programs were directed largely to controlling point nutrient sources such as sewage treatment plants and industrial outfalls. While largely successful in reducing P and Biological Oxygen Demand (BOD) loads to waters, these programs often did not significantly improve water quality. Nonpoint nutrient sources were soon recognized as a major part of the nutrient budgets of many lakes, streams and reservoirs. Excess nitrogen (N) in the rivers, lakes and groundwater can be toxic to humans (as nitrate), and causes water quality problems in natural water systems (Hallberg and Keeney, 1993). Excess N in the estuaries of the oceans enhances growth of aquatic organisms to the point that they affect water quality and lower dissolved oxygen levels to hypoxia levels (Downing, 1999; Rabalais et al., 2001).

The Gulf of Mexico, like many other estuaries and coastal areas in the world, has seen major ecosystem changes because of low oxygen levels caused by excessive input of sediments and nutrients arising from industrial and agricultural activities in the Mississippi River Watershed. The apparent result of the dramatic increase in N input to the Gulf of Mexico has been a major change in the ecology of the Gulf. Higher productivity of phytoplankton because of increased nutrient input has provided more organic residue from dead cells. This has led to increased oxygen consumption during decomposition of the material. The result has been the development of an extensive region of oxygen deficiency

consisting of less than 2 mg/L of dissolved oxygen, commonly referred to as hypoxia (Rabalais et al., 2001). This level of dissolved oxygen, which is below the threshold for survival of most aquatic organisms thus relating to the term “dead zone,” runs roughly directly west from Louisiana to Texas and is the third largest hypoxia zone in the world. The area varies between 12,000 to nearly 20,000 square kilometers in mid-summer during normal to high rainfall years, but is smaller during drought years (Rabalais et al., 2002). The area of hypoxia zone in the Gulf of Mexico fluctuates widely, but is generally on the increase over time (Rabalais et al., 2002). Nitrogen is commonly a key causal factor for hypoxia in salt water, while P tends to be a limiting nutrient in fresh water systems. The total amount of N load from the Mississippi River to the Gulf of Mexico has increased over the last 30 years; in particular, the nitrate (NO_3) load is three times greater than 30 years ago (Goolsby et al., 2001). In an average year, the Mississippi River discharges 1.57 million metric tons of N into the Gulf of Mexico (Goolsby et al., 2001). The principle sources of N inputs include soil mineralization, fertilizer, legumes and pastures, animal manures, atmospheric deposition, and municipal and industrial point sources. The largest change in annual N input has been in fertilizer, which has increased more than six-fold since the 1950's. Five states (Illinois, Indiana, Iowa, Ohio, and Minnesota) have the greatest amount of artificially drained soil, the highest percentage of total land in agriculture (corn and soybean) and the highest use of nitrogen fertilizers in the nation. The region has abundant precipitation most years for crop growth and only rarely suffers major yield declines because of drought. Approximately 90% of the NO_3 -N load to the Gulf is attributed to nonpoint sources. A significant portion of this load originates from the Upper Mississippi River Basin (UMRB), which covers only 15% of the total Mississippi drainage area (Figure 1), from the source at Lake Itasca to just north of

Cairo, Illinois. Goolsby et al. (1999) estimated that the UMRB was the source of nearly 39% of the Mississippi $\text{NO}_3\text{-N}$ load discharged to the Gulf between 1980 and 1996; 35% of this load was attributed solely to Iowa and Illinois tributary rivers for average discharge years during the same time period (Goolsby et al., 2001).

The CENR (Committee on Environment and Natural Resources) reports suggest that total reductions in N load of between 20 percent and 30 percent would be sufficient to increase dissolved oxygen concentrations in bottom water of Gulf of Mexico by 15 percent to 50 percent (Brezonik et al., 1999; CENR, 2000). To achieve this goal, significant changes will be required in the agriculture practices including N use within the basin. Numerous state and federal programs have been initiated to address these concerns, including the Conservation Reserve Program, the Environmental Quality Incentives Program, Total Maximum Daily Load requirements, and the conservation component of the 2002 farm bill.

Improving environmental quality in such a large and complex landscape with intensive landscape management and widespread use of chemical fertilizers presents a challenge. Added to this complexity is the prospect of climate variability and long-term climate change that will impose unknown new conditions on the region. Both water quantity and quality are sensitive to climate change. Water quality may improve if higher flows are available for diluting contaminants; however, water quality may deteriorate under rising temperatures and increased overland flow. Climate models have predicted an increase in mean annual temperature over the U.S. for the second half of 21st century (IPCC, 2001).

Nonpoint source pollution complexities and global climate change uncertainties pose major challenges for scientists who are studying methods of improving water quality. One challenge is the lack of integrated, scientifically sound approaches to identify problems in

watersheds and to predict the results of potential control actions. This necessitates using several techniques, models, or analytical tools in assessing different components of the complex watershed system. In this regard, simulation models are used extensively in water quality planning and pollution control. These models offer a sound scientific framework for watershed analyses of water pollutant movement. Integrated modeling systems link the models, data, and user interface within a single system. New developments in modeling systems have increasingly relied on geographic information systems (GIS) such as ArcView and database management systems such as Access[®] to support modeling and analysis.

In the case of the UMRB, where nonpoint source pollution is responsible for the majority of water quality problems, an integrated modeling framework is required that can accurately reflect the current practices in the watershed. This includes development of a simulation model which can simulate watershed hydrology very well. Accurate tracking of the water movement such as precipitation, evapotranspiration, and infiltration within the watershed leads to accurate prediction of sediment yield and chemicals. The simulation methodology should facilitate policy analyses of the region such as assessment of the impacts of alternative nutrient, tillage, and cropping practices as well as climate change to the baseline conditions, to ascertain which cropping and management strategies could yield environmental benefits over current practices. Moreover, the environmental analysis should be coupled with an economic assessment, to provide a two-dimensional view of the impacts of each scenario.

Study Objectives

The main goals of this study are (1) to evaluate the performance and reliability of a watershed scale hydrological simulation model - Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998), and (2) to analyze the impacts of global climate change on watershed hydrology using SWAT. The research was performed on the UMRB (Figure 1) and selected watersheds, in support of current water quality studies at the Center for Agricultural and Rural Development (CARD) in the Department of Economics, Iowa State University.

Specific objectives of the research are to:

- ◆ Apply SWAT to a watershed to evaluate its ability to simulate watershed hydrology.
- ◆ Analyze sensitivity of the SWAT model against model input parameters for hydrology and climate change study.
- ◆ Quantify the impacts of global climate change on hydrology of the UMRB coupling SWAT with the climate models.
- ◆ Develop a SWAT model simulation framework for the UMRB, including detailed input data preparation, development of a user interface, and model calibration and validation.

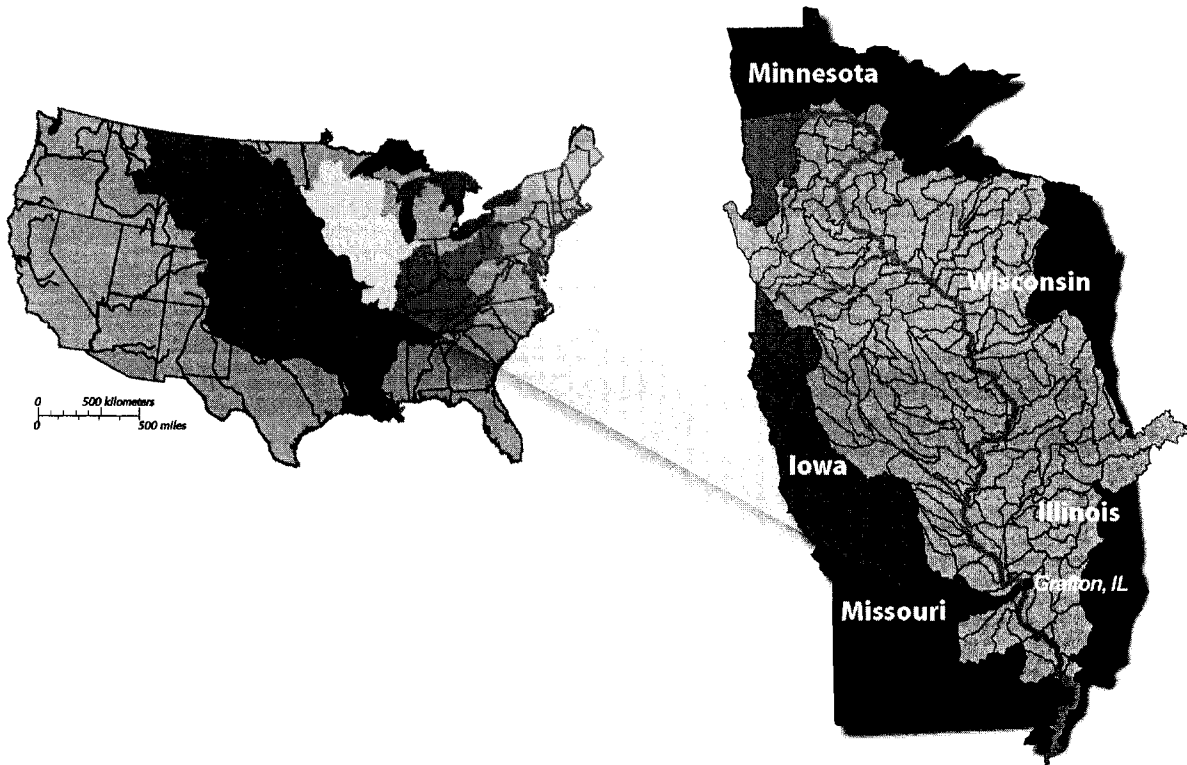


Figure 1. Location of the Upper Mississippi River Basin (UMRB).

Dissertation Organization

This dissertation consists of general introduction, five journal papers, and general conclusions. The first paper describes the application of the SWAT model to the Maquoketa River Watershed, a 4,867 km² watershed in Northeast Iowa. A sensitivity analysis was performed using an influence coefficient method to evaluate model performance in terms of variations in surface runoff and baseflow in response to the changes in selected eight model input hydrologic parameters. Facilitated by sensitivity analysis, model calibration and

validation was performed and the model performance was evaluated by two statistical methods: the coefficient of determination and the Nash-Sutcliffe simulation efficiency.

The second paper presents the climate change impact study using SWAT. The model was calibrated and validated for the streamflow for the entire UMRB based on the simplistic data available from Better Assessment Science Integrating Point and Nonpoint Sources (BASINS) package. Several climate change scenarios were developed including hypothetical changes in carbon dioxide concentration (CO_2), temperature and precipitation, and monthly temperature and precipitation variations predicted by a regional climate model (based on a previous study) for the future climate to examine the climate change impacts on hydrological variables and streamflow in the watershed. This paper was submitted to the Journal of American Water Resources Association and the first round of revision is underway.

The third paper demonstrates the external coupling of the SWAT model with a climate model to assess the impact of future climate on UMRB streamflow. The calibrated model was driven by two sets of climate data, represented by current and future CO_2 concentrations, generated by nesting a regional climate model into a global climate model to downscale the climate data. This study also quantifies the model-introduced uncertainty due to global model, climate model and SWAT in the prediction of future streamflow in the UMRB. This paper is published in the Journal of Geophysical Research (Jha et al., 2004).

The fourth and fifth papers are a two-paper series describing the application of SWAT model to the UMRB. The fourth paper describes the simulation approach and the methodology involved in the preparation of input data for the SWAT model including land use data, management practice data, soil data, climate data, and reservoirs, ponds and wetland data. The fifth paper presents the SWAT model calibration and validation for

streamflow and sediment yield. Results are produced for two subbasins of UMRB (Iowa and Des Moines River Watersheds) as well as for the entire UMRB.

References

- Arnold, J.G., R. Srinivasan, R.S. Muttiah, and J.R. Williams. 1998. Large area hydrologic modeling and assessment Part I: Model development. *J. Amer. Wat. Res. Assoc.* 4(1):73-89.
- Brezonik, P.L., V.J. Bierman, Jr., R. Alexander, J.B. Anderson, M. Dortch, L. Hatch, G.L. Hitchcock, D. Keeney, D. Mulla, V. Smith, C. Walker, T. Whitley, and W.J. Wiseman, Jr. 1999. Effects of reducing nutrient loads to surface waters within the Mississippi River Basin and Gulf of Mexico: Topic 4 Report for the integrated assessment on Hypoxia in the Gulf of Mexico. NOAA Coastal Ocean Program Decision Analysis Series No. 18. NOAA Coastal Ocean Program, Silver Spring, MD.
- CENR (Committee for Environment and Natural Resources). 2000. Integrated assessment of Hypoxia in the Northern Gulf of Mexico. National Science and Technology Council, May 2000.
- Downing, J.A., N.N. Rabalais, R.J. Diaz, R.J. Zimmerman, J.L. Baker, and T. Prato. 1999. Gulf of Mexico Hypoxia: Land and Sea Interactions. Council for Agricultural Science and Technology, Task Force Report. Ames, IA.
- Goolsby, D.A., W.A. Battaglin, B.T. Aulenbach, and R.P. Hooper. 2001. Nitrogen input to the Gulf of Mexico. *J. Env. Qual.* 30:329-336.
- Goolsby, D. A., W.A. Battaglin, G.B. Lawrence, R.S. Artz, B.T. Aulenbach, R.P. Hooper, D.R. Keeney, and G.J. Stensland. 1999. Flux and sources of nutrients in the Mississippi-Atchafalaya River Basin: Topic 3 report for the integrated assessment on hypoxia in the Gulf of Mexico. NOAA Coastal Ocean Program Decision Analysis Series No. 17. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Centers for Coastal Ocean Science, Silver Spring, Maryland. Available at http://www.nos.noaa.gov/products/pubs_hypox.html#Topic3. Accessed in July 18, 2004.
- Hallberg, G.R., and D.R. Keeney. 1993. Nitrate. pp 297-332. In *Regional Ground-Water Quality*, W.M. Alley ed., Van Norstrand Reinhold, N.Y.
- IPCC (Intergovernmental Panel on Climate Change). 2001. *Climate change 2001 - The scientific basis*, J.T. Houghton, T.Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, and D. Xiaosu (Eds.), 944pp., Cambridge Univ. Press, Cambridge.

Jha, M., Z. Pan, E.S. Takle, and R. Gu. 2004. Impacts of climate change on stream flow in the Upper Mississippi River Basin: A regional climate model perspective. *J. Geophys. Res.* 109:D09105.

Keeney, D. 2002. Reducing nonpoint nitrogen to acceptable levels with emphasis on the Upper Mississippi River Basin. *Estuaries* 25(4b):720-726.

Rabalais, N.N., R.E. Turner, and D. Scavia. 2002. Beyond science into policy: Gulf of Mexico hypoxia and the Mississippi River. *BioScience* 52(2):129-142.

Rabalais, N.N., R.E. Turner, and W.J. Wiseman, Jr. 2001. Hypoxia in the Gulf of Mexico. *J. Env. Qual.* 30:320-329.

CHAPTER 2. HYDROLOGIC SIMULATIONS OF THE MAQUOKETA RIVER WATERSHED WITH SWAT

A paper to be submitted to the *Transactions of the ASAE*

Manoj Jha, Philip W. Gassman, and Roy Gu

Abstract

This paper describes the application of the Soil and Water Assessment Tool (SWAT) model to the Maquoketa River Watershed, located in northeast Iowa. The inputs to the model were taken from the EPA BASINS GIS/database system. Available weather data from six weather stations in and around the watershed and streamflow data from a USGS stream gauge station were used in sensitivity analysis, and model calibration and validation for flows. A sensitivity analysis was performed using an influence coefficient method to evaluate surface runoff and baseflow variations in response to changes in model input hydrologic parameters. The curve number (CN), evaporation compensation factor (ESCO), and soil available water capacity (SOL_AWC) were found to be the most sensitive parameters among eight selected parameters when applying SWAT to the Maquoketa River Watershed. Model calibration, facilitated by the sensitivity analysis, was performed for the period of 1988 through 1993. Model validation was performed for 1982 through 1987. The model performance was evaluated by a well-established statistical method and was found to explain at least 86 percent and 69 percent of the variability in the measured streamflow data for the calibration and validation periods, respectively. This initial hydrologic modeling analysis will facilitate future applications of SWAT to the Maquoketa River Watershed in the evaluation of various scenarios developed for the reduction of sediment and nutrient losses to the Maquoketa River system.

KEY TERMS: hydrologic simulation; calibration and validation; sensitivity analysis.

Introduction

Hydrology is the main governing backbone of all kinds of water movement and hence water related pollutants. Understanding the hydrology of a watershed and modeling different hydrological processes within a watershed are therefore very important for assessing the environmental and economical well-being of the watershed. In this regard, simulation models are used extensively for water resources planning and management. These models can offer a sound scientific framework for watershed analyses of water movement and provide reliable information on the behavior of the system. New developments in modeling systems have increasingly relied on geographic information systems (GIS) such as ArcView GIS that have allowed large area simulation to be feasible, and database management systems such as MS Access[®] to support modeling and analysis.

Several watershed scale models such as HSPF (Hydrological Simulation Program - FORTRAN) (Johansen et al., 1984), HEC-HMS (Hydrologic Modeling System) (USACE-HEC, 2002), CREAMS (Chemical, Runoff, and Erosion from Agricultural Management Systems) (Knisel, 1980), EPIC (Erosion-Productivity Impact Calculator) (Williams et al., 1984), AGNPS (Agricultural Non-Point Source) (Young et al., 1989), and SWRRB (Simulator for Water Resources in Rural Basins) (Arnold et al., 1990) have been developed but for their specific reasons and are generally limited. These limitations include inappropriate scale, inability to perform continuous-time simulations, inadequate maximum number of subwatersheds, and the inability to characterize the watershed in enough spatial detail (Saleh et al., 2000). SWAT (Soil and Water Assessment Tool) (Arnold et al., 1998), a

watershed scale physically-based simulation model, was developed to overcome these limitations. The model offers continuous-time simulation, high level of spatial detail, unlimited number of watershed subdivisions, efficient computation, and capability to simulate changes in land-management. An early application of the model compared the results of SWAT to historical streamflow and groundwater flow on three Illinois watersheds (Arnold and Allen, 1996). They found that SWAT was able to simulate all the components of the hydrologic budget within acceptable limits on both annual and monthly time steps. The Natural Resources Conservation Service (NRCS) used the SWAT model in the 1997 Resource Conservation Appraisal. The model was validated against measured streamflow and sediment loads across the entire U.S. (Arnold et al., 1999). The effect of spatial aggregation on SWAT was examined by FitzHugh and Mackay (2000) and Jha et al. (2004a). SWAT applications for flow and/or pollutant loadings have compared favorably with measured data for a variety of watershed scales (Srinivasan et al., 1998; Arnold et al., 1999; Saleh et al., 2000; Santhi et al., 2001). The SWAT model was successfully applied to assess the impact of climate change in hydrology of the Upper Mississippi River Basin (Jha et al., 2004b) and the Missouri River Basin (Stone et al., 2001). SWAT is used worldwide and has been chosen by the Environmental Protection Agency to be one of their better assessment science integrating point and nonpoint sources (BASINS) models (Whittemore, 1998).

Besides successful application of physically-based models, there are several issues that question the model output such as uncertainty in input parameters, nonlinear relationships between hydrologic input features and hydrologic response, and the required calibration of numerous model parameters. In this regard, sensitivity analyses of the model parameters help identify sensitive parameters with respect to their impact on model output. Focus on

sensitive parameters can lead to a better understanding and to better estimated values and thus reduced uncertainty (Lenhart et al., 2002). Knowledge of sensitive input parameters is beneficial for model development and leads to its successful application. Arnold et al. (2000) performed a sensitivity analysis of three hydrologic input parameters of the SWAT model against surface runoff, baseflow, recharge, and soil evapotranspiration on three different basins within the Upper Mississippi River Basin. They found that all three hydrologic variables: soil evaporation compensation coefficient, plant available soil water capacity, and runoff curve number condition II were very sensitive and showed different level of sensitivity for different basins. Spruill et al. (2000) selected fifteen hydrologic input variables of the SWAT model and varied them individually within acceptable ranges to determine model sensitivity in daily streamflow simulation. They found that the determination of accurate parameter values is vital for producing simulated streamflow data in close agreement to measured streamflow data. Two simple approaches of sensitivity analysis were compared by Lenhart et al. (2002) using SWAT model on an artificial catchment. In both approaches, one parameter was varied at a time while holding the others fixed except that the way of defining the range of variation was different; the first approach varied the parameters by a fixed percentage of the initial value and the second approach varied the parameters by a fixed percentage of the valid parameter range. They found similar results for both approaches and suggested that the parameter sensitivity may be determined without the results being influenced by the chosen method. The paper identified several most sensitive hydrologic and plant specific parameters, but emphasized that sensitivities can be different for a natural catchment due to oversimplification of the processes in the chosen artificial catchment.

In this study, SWAT was applied to the Maquoketa River Watershed (MRW), located in northeast Iowa (Figure 1). The objectives of this study were to identify the SWAT's hydrologic sensitive parameters relative to the estimation of surface runoff and baseflow, and to calibrate and validate the model for streamflow. The influence coefficient method was used to examine surface runoff and baseflow responses to changes in model input parameters. The parameters were ranked according to the magnitude of response variable sensitivity to each of the model parameters, which divide high and low sensitivities. Model calibration and validation, facilitated by the sensitivity analysis, were performed by comparing simulated streamflow with measured streamflow at the watershed outlet. This study will facilitate future applications of SWAT to the MRW, which will support efforts to mitigate water quality problems in the region.

Materials and Methods

The SWAT Model

The SWAT model is a long term, continuous simulation watershed model. It operates on a daily time step and is designed to predict the impact of management on water, sediment, and agricultural chemical yields. The model is physically based, computationally efficient, and capable of simulating a high level of spatial detail by allowing the division of watersheds into smaller subwatersheds. SWAT models water flow, sediment transport, crop/vegetation growth, and nutrient cycling. The model facilitates users to model watersheds with less monitoring data and to assess predictive scenarios using alternative input data such as climate, land use practices, and land cover, on water movement, nutrient cycling, water quality, and other outputs. Major model components include; weather, hydrology, soil

temperature, plant growth, nutrients, pesticides, and land management. Several model components have been previously validated for a variety of watersheds.

In SWAT, a watershed is divided into multiple subwatersheds, which are then further subdivided into Hydrologic Response Units (HRUs) that consist of homogeneous land use, management, and soil characteristics. The HRUs represent percentages of the subwatershed area and are not identified spatially within a SWAT simulation. The water balance of each HRU in the watershed is represented by four storage volumes: snow, soil profile (0-2 meters), shallow aquifer (typically 2-20 meters), and deep aquifer (more than 20 meters). The soil profile can be subdivided into multiple layers. Soil water processes include infiltration, evaporation, plant uptake, lateral flow, and percolation to lower layers. Flow, sediment, nutrient, and pesticide 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. Detailed descriptions of the model and model components can be found in Arnold et al. (1998) and Neitsch et al. (2002).

Maquoketa River Watershed and SWAT Input Data

Maquoketa River Watershed (MRW) covers 4867 km² of predominantly agricultural land in northeast Iowa (Figure 1). The MRW is one of 13 tributaries of the Mississippi River that have been identified as contributing some of the highest levels of suspended sediments, N, and P to the Mississippi stream system. These pollution loads are attributed mainly to agricultural nonpoint sources and result in degraded water quality within each watershed, in the Mississippi River, and ultimately in the Gulf of Mexico.

Land use, soil, and topography data required for simulating the watershed were obtained from the Better Assessment Science Integrating Point and Nonpoint Sources (BASINS) package version 3 (USEPA, 2001). Topographic information is provided in BASINS in the form of Digital Elevation Model (DEM) data. The DEM data were used to generate variations in subwatershed configurations such as subwatershed delineation, stream network delineation, slope and slope lengths, etc. using the ArcView interface for SWAT 2000 (AVSWAT), developed by Di Luzio et al. (2000). Land use categories provided in BASINS are relatively simplistic, including only one category for agricultural land (defined as “Agricultural Land-Generic” or AGRL). Agricultural lands cover almost 90 percent of the MRW; the remaining area is mostly forest (Figure 2). The soil data available in BASINS comes from the State Soil Geographic (STATSGO) database (USDA, 1994), which contains soil maps at a 1:250,000 scale. Each STATSGO map unit is linked to the Soil Interpretations Record attribute database that provides the proportionate extent of the component soils and soil layer properties. The STATSGO soil map units and associated layer data were used to characterize the simulated soils for the SWAT analyses.

The daily climate inputs consist of precipitation, maximum and minimum temperatures, solar radiation, wind speed, and relative humidity. In case of missing observed data or the absence of complete data, the weather generator within SWAT uses its statistical database to generate representative daily values for the missing variables for each sub-watershed. In this study we supplied historical daily precipitation and daily maximum and minimum temperatures to SWAT, which were obtained from six climate stations (U.S. Department of Commerce, 1982-93) located in or near the watershed (see Figure 1). The management

operations required for the HRUs were defaulted by AVSWAT and consisted simply of planting, harvesting, and automatic fertilizer applications for the agricultural HRUs.

Sensitivity Analysis

The influence coefficient method is one of the most common methods for computing sensitivity coefficients in surface and ground water problems (Helsel and Hirsch, 1992). The method evaluates the sensitivity by changing each of the independent variables, one at a time. A sensitivity coefficient represents the change of a response variable that is caused by a unit change of an explanatory variable, while holding the rest of the parameters constant:

$$\frac{\Delta F}{\Delta P} = \frac{F(P_1, P_2, \dots, P_i + \Delta P_i, \dots, P_N) - F(P_1, P_2, \dots, P_i, \dots, P_N)}{\Delta P_i} \quad (1)$$

where, F is response variable, P is independent parameter, N is the number of parameters considered. The sensitivity coefficients can be positive or negative. A negative coefficient indicates an inversely proportional relation between a response variable and an explanatory parameter.

To meaningfully compare different sensitivities, the sensitivity coefficient was normalized by reference values, which represent the ranges of each pair of dependent variable and independent parameter. The normalized sensitivity coefficient is called the sensitivity index and is given as (Gu and Li, 2002):

$$s_i = \frac{P_m}{F_m} \frac{\Delta F}{\Delta P} \quad (2)$$

where, s_i is the sensitivity index. and F_m and P_m are the mean of lowest and highest values of the selected range for explanatory parameter and response variable, respectively. Higher absolute value of sensitivity index indicates higher sensitivity and a negative sign shows inverse proportionality.

Simulation Approach

The AVSWAT model (ArcView interface of the SWAT model) was used in the watershed delineation process, which includes processing of DEM data for stream network delineation followed by subwatershed delineation. A total of 25 subwatersheds were delineated for the entire MRW (see Figure 1). The subwatersheds were then further subdivided into HRUs that were created for each unique combination of land use and soil. User-specified land cover and soil area thresholds were applied to limit the number of HRUs in each subwatershed.

After the model setup, SWAT was executed with the following simulations options: (1) the Runoff Curve Number method for estimating surface runoff from precipitation, (2) the Hargreaves method for estimating potential evapotranspiration generation, and (3) the variable-storage method to simulate channel water routing. A simulation period of 1988 through 1993 was selected for the sensitivity analysis. Several model runs were executed for each input parameter with range of values, keeping simulation options and other parameters' values constant. The sensitivity index was calculated for each parameter from the average

annual values for surface runoff and baseflow separately. The analysis provides information on the most to least sensitive parameters for flow response of the watershed.

Facilitated from the sensitivity analysis, the model was calibrated on the same period against the measured streamflow data at the U.S. Geological Survey (USGS) stream gage (Station # 05418500). The model was then validated for the period of 1982 through 1987. Two statistical approaches were used to evaluate the model performance - coefficient of determination (R^2) and Nash-Sutcliffe simulation efficiency (E). The R^2 value is an indicator of the strength of relationship between the observed and simulated values. E indicates how well the plot of observed versus simulated value fits the 1:1 line. If R^2 value is close to zero and E value is less than or close to zero, the model prediction is considered unacceptable. If the values approach one, the model predictions become perfect.

Results and Discussion

Sensitivity Results

Based on the personal experience with the model and extensive literature review of the SWAT model application such as Spruill et al. (2000), Santhi et al. (2001), and Lenhart et al. (2002), a total of eight model input parameters were selected for sensitivity analysis. The parameters were curve number (CN), soil evaporation compensation factor (ESCO), plant uptake compensation factor (EPCO), soil available water capacity (SOL_AWC), baseflow alpha factor (ALPHA_BF), groundwater revap coefficient (GW_RAVAP), and deep aquifer percolation coefficient (RECHRG_DP). Table 1 lists the model parameters along with their initial estimates and acceptable ranges. Details on the model parameters and their functions can be found in Neitsch et al. (2002). Initial estimate value of a model parameter is the

average and most applicable value for that particular parameter, and is defaulted by the model interface. Most of the model inputs in the SWAT model are physically based (that is, based on readily available information) except a few important variables such as runoff curve number, evaporation coefficients, and others that are not well defined physically. These parameters, therefore, must be constrained by their applicability limits. Based on the previous studies done by Arnold et al. (2000) and Santhi et al. (2001), acceptable values were chosen within which model parameters can be varied.

In the sensitivity analysis, surface runoff and baseflow were treated as the response or dependent variables, while model parameters were the explanatory or independent variables. The sensitivity coefficients and indices were examined to characterize surface runoff and baseflow under different parameter ranges. Table 2 summarizes the sensitivity coefficients and sensitivity indices of all parameters corresponding to the changes in surface runoff and baseflow volumes in response to changes in the model parameter. In general, the higher the absolute values of sensitivity index the higher the sensitivity of the corresponding parameter. A negative sign indicates inverse relationship between the parameter and response variable. Results in Table 2 indicate that the surface runoff is sensitive, from most to least, to CN, ESCO, SOL_AWC, and EPCO for the selected variation range, while baseflow is sensitive, from most to least, to CN, ESCO, SOL_AWC, RECHRG_DP, GW_REVAP, ALPHA_BF, and GW_DELAY. Surface runoff was not found sensitive at all for ALPHA_BF, GW_REVAP, GW_DELAY, and RECHARG_DP, while baseflow was found sensitive for all the parameters selected for the study.

The top three most influencing parameters are CN, ESCO, and SOL_AWC. A further detailed sensitivity analysis was performed for these three parameters. CN was found to be

extremely sensitive parameter for flow. CN is a dimensionless number that is related to land use and soil type. Figure 3(a) shows the response of surface runoff and baseflow when CN was changed from -10% to +10%. Larger CN values resulted in increased surface runoff and at the same time decreased infiltration. Baseflow is inversely proportional to CN. The second most sensitive parameter, ESCO, was found to have impact more on baseflow than surface runoff (Figure 3b). ESCO adjusts the depth distribution for evaporation from the soil to account for the effect of capillary action, crusting and cracking. Decreasing ESCO allows lower soil layers to compensate for water deficit in upper layers and causes higher soil evapotranspiration, which in turn reduces both surface runoff and baseflow. Figure 3(c) shows the sensitivity of the model to SOL_AWC. Increasing SOL_AWC leads to higher soil water capacity, which increases both surface runoff and baseflow. Conversely, decreasing soil water capacity resulted in higher water availability for surface runoff and baseflow. Overall, these sensitivity analyses demonstrate that the SWAT model is able to simulate water movement very well, and the knowledge of model sensitivity to input parameters helps better understand the model for its validation and application.

Calibration and Validation

The SWAT model was calibrated and validated for streamflow using the measured data at USGS gauge station 05418500 on the Maquoketa River near Maquoketa, IA. The available data was divided into two parts: 1988 to 1993 for calibration and 1982-1987 for validation. During the calibration process, the model's input parameters were, as guided by the sensitivity analysis, adjusted to match the observed and simulated streamflows. Table 3 lists the final calibrated values of the model variables. A time-series plot of the measured

and simulated monthly streamflows (Figure 4) shows that the magnitude and trend in the simulated monthly flows closely followed the measured data most of the time. The measured and simulated average monthly flow volumes are 22.28 and 24.08 mm, respectively. The statistical evaluation yielded an R^2 value of 0.86 and an E value of 0.85, indicating a strong correlation between the measured and predicted flows.

Flow validation was conducted using the streamflow data for the period from 1982 to 1987. In the validation process, the model was run with input parameters set during the calibration process without any change. Figure 5 shows the time series plot of monthly measured and simulated monthly streamflows, and indicates an acceptable correspondence of simulated streamflows with the measured values. The measured and simulated average monthly flow volumes for the validation period were 23.40 and 23.44 mm, respectively. The R^2 and E values between the measured and simulated streamflows are 0.69 and 0.61, respectively. Overall, the model was able to predict streamflow with a reasonable accuracy.

Conclusion

Knowledge of model sensitivity to some input parameters is beneficial for model development and leads to its successful application. This study identified the input hydrologic parameters to which the SWAT model is the most sensitive using the influence coefficient method, as determined in an application to the Maquoketa River Watershed. It was found that the surface runoff is sensitive, from most to least, to CN, ESCO, SOL_AWC, and EPCO for the selected variation range, while baseflow is sensitive, from most to least, to CN, ESCO, SOL_AWC, RECHRG_DP, GW_REVAP, ALPHA_BF, and GW_DELAY. Surface runoff was not found sensitive at all for ALPHA_BF, GW_REVAP, GW_DELAY,

and RECHARG_DP, while baseflow was found sensitive for all the parameters chosen in this study. Model sensitivities to the top three most influencing parameters for both surface runoff and baseflow: CN, ESCO, and SOL_AWC, were further evaluated. Sensitivity analysis provides good insight on model input parameters and supports that the model is able to simulate hydrological processes very well.

Based on the assessment of input parameters to which the model is most to least sensitive, SWAT was calibrated and validated for streamflow at the watershed outlet. The calibration process used the measured data from the period of 1988 through 1993 and yielded a strong correlation ($R^2 = 0.86$ and $E = 0.85$) between measured and simulated flow volumes. Model validation was performed for 1982-1987 and generated an R^2 value of 0.69 and E value of 0.61. This study indicates that the SWAT model can be an effective tool for accurately simulating the hydrology of the Maquoketa River Watershed. Accurate flow simulations are required to accurately predict sediment loads and chemical concentrations, and for simulating various scenarios related to cropping and alternative management to mitigate water quality problems in the region.

References

- Arnold, J.G., J.R. Williams, A.D. Nicks, and N.B. Sammons, 1990. SWRRB: A Basin Scale Simulation Model for Soil and Water Resources Management. Texas A & M University Press, College Station, Texas.
- Arnold, J.G., and P.M. Allen, 1996. Simulating Hydrologic Budgets for Three Illinois Watersheds. *Journal of Hydrology* 176:57-77.
- Arnold, J.G., R.S. Muttiah, R. Srinivasan, and P.M. Allen, 2000. Regional Estimation of Base Flow and Groundwater Recharge in the Upper Mississippi River Basin. *Journal of Hydrology* 227:21-40.

- Arnold, J.G., R. Srinivasan, R.S. Muttiah, P.M. Allen, and C. Walker, 1999. Continental Scale Simulation of the Hydrologic Balance. *Journal of American Water Resources Association* 35(5):1037-1052.
- Arnold, J.G., R. Srinivasan, R.S. Muttiah and J.R. Williams, 1998. Large Area Hydrologic Modeling and Assessment Part I: Model Development. *Journal of American Water Resources Association* 34(1):73-89.
- Di Luzio, M., R. Srinivasan, J.G. Arnold, and S.L. Neitsch, 2000. Soil and Water Assessment Tool: ArcView GIS Interface Manual, Version 2000. Texas Water Resources Institute TR-193, GSWRL 02-03, BRC 02-07, 345 pages.
- FitzHugh, T.W., and D.S. Mackay, 2000. Impacts of Input Parameter Spatial Aggregation on an Agricultural Nonpoint Source Pollution Model. *Journal of Hydrology* 236(1-2):35-53.
- Gu, R. and Y. Li, 2002. River Temperature Sensitivity to Hydraulic and Meteorological Parameters. *Journal of Environmental Management* 66(1):43-56.
- Helsel, D.R. and R.M. Hirsch, 1992. *Statistical Methods in Water Resources*. Elsevier, New York.
- Jha, M., P.W. Gassman, S. Secchi, R. Gu, and J.G. Arnold, 2004a. Effect of Watershed Subdivision on SWAT Flow, Sediment, and Nutrient Predictions. *Journal of American Water Resources Association* 40(3):811-825.
- Jha, M., Z. Pan, E.S. Takle, and R. Gu, 2004b. Impacts of Climate Change on Stream Flow in the Upper Mississippi River Basin: A Regional Climate Model Perspective. *Journal of Geophysical Research* 109:D09105.
- Johansen, N.B., J.C. Imhoff, J.L. Kittle, and A.S. Donigian, 1984. Hydrologic Simulation Program - FORTRAN (HSPF): User's Manual for release 8, EPA-600/3-84-066, Athens, GA, U.S. Environmental Protection Agency.
- Knisel, W.G., ed., 1980. CREAMS: A Field-Scale Model for Chemicals, Runoff, and Erosion from Agricultural Management Systems. Conservation Research Report No. 26, Washington, D.C.: USA-SEA.
- Lenhart, T., K. Eckhardt, N. Fohrer, H.-G. Frede, 2002. Comparison of Two Different Approaches of Sensitivity Analysis. *Physics and Chemistry of the Earth* 27:645-654.
- Neitsch, S.L., J.G. Arnold, J.R. Kiniry and J.R. Williams, 2002. Soil and Water Assessment Tool Theoretical Documentation, Version 2000 (Draft). Blackland Research Center, Texas Agricultural Experiment Station, Temple, Texas.
<http://www.brc.tamus.edu/swat/swat2000doc.html> (accessed in July 18, 2004).

- Saleh, A., J.G. Arnold, P.W. Gassman, L.M. Hauck, W.D. Rosenthal, J.R. Williams, and A.M.S. McFarland, 2000. Application of SWAT for the Upper North Bosque River Watershed. *Transactions of the ASAE* 43(5):1077-1087.
- Santhi, C., J.G. Arnold, J.R. Williams, W.A. Dugas, R. Srinivasan and L.M. Hauck, 2001. Validation of the SWAT Model on a Large River Basin with Point and Nonpoint Sources. *Journal of American Water Resources Association* 37(5):1169-1188.
- Spruill, C.A., S.R. Workman and J.L. Taraba, 2000. Simulation of Daily and Monthly Stream Discharge from Small Watershed Using the SWAT Model. *Transactions of the ASAE* 43(6):1431-1439.
- Srinivasan, R., T.S. Ramanarayanan, J.G. Arnold, and S.T. Bednarz, 1998. Large Area Hydrologic Modeling and Assessment: Part II - Model Application. *Journal of American Water Resources Association* 34(1):91-102.
- Stone, M.C., R.H. Hotchkiss, C.M. Hubbard, T.A. Fontaine, L.O. Mearns, and J.G. Arnold, 2001. Impacts of Climate Change on Missouri River Basin Water Yield. *Journal of American Water Resources Association* 37(5):1119-1130.
- U.S. Army Corps of Engineers Hydrologic Engineering Center (USACE-HEC), 2002. HEC-HMS Hydrologic Modeling System user's manual, USACE-HEC, Davis, Calif.
- U.S. Department of Agriculture (USDA), 1994. State Soil Geographic (STATSGO) Data Base: Data Use Information. Misc. Publication Number 1492, Natural Resource Cons. Service. National Soil Survey Center, Lincoln, Nebraska.
- U.S. Department of Commerce. 1982-93. Climatological data. National Oceanic and Atmospheric Administration, National Climatic Data Center, Asheville, NC.
- U.S. Environmental Protection Agency (USEPA), 2001. BASINS 3.0: Better Assessment Science Integrating Point and Nonpoint Sources. U.S. Environmental Protection Agency, Office of Water, Office of Science and Technology, Washington, D.C.
<http://www.epa.gov/ost/BASINS/> (accessed in July 18, 2004).
- Whittemore, R.C., 1998. The BASINS Model. *Water Environment and Technology* 10:57-61.
- Williams, J.R., C.A. Jones, and P.T. Dyke, 1984. A Modeling Approach to Determining the Relationship Between Erosion and Soil Productivity. *Transactions of the ASAE* 27:129-144.
- Young, R.A., C.A. Onstad, D.D. Bosch, and W.P. Anderson, 1989. AGNPS: A Non-Point Source Pollution Model for Evaluating Agricultural Watersheds. *Journal of Soil and Water Conservation* 44(2):168-173.

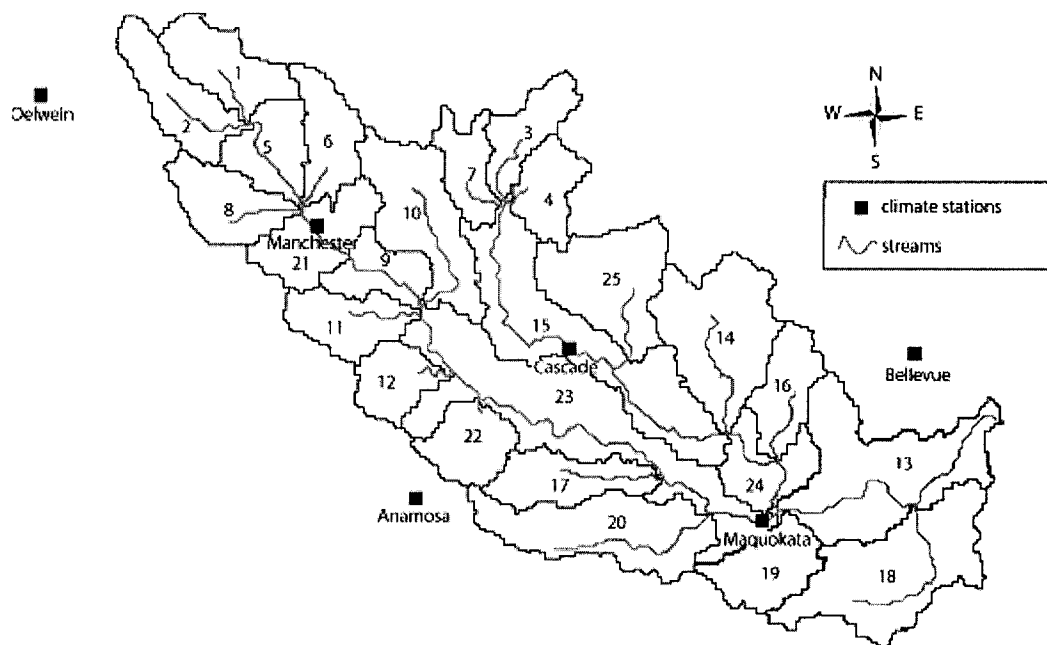


Figure 1. Location of the Maquoketa River Watershed (Northeast Iowa), and weather stations in and around the watershed.

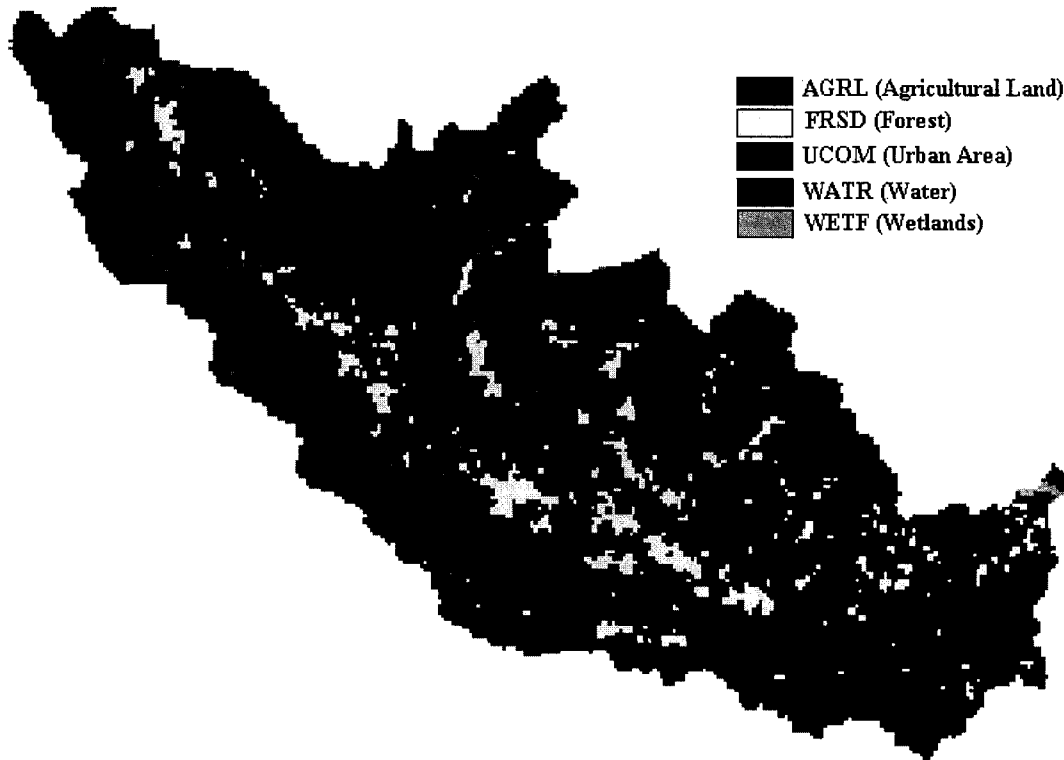
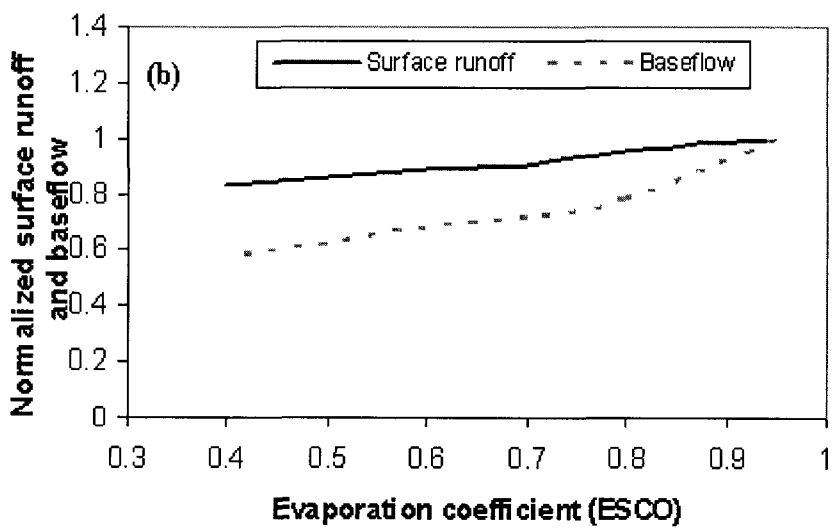
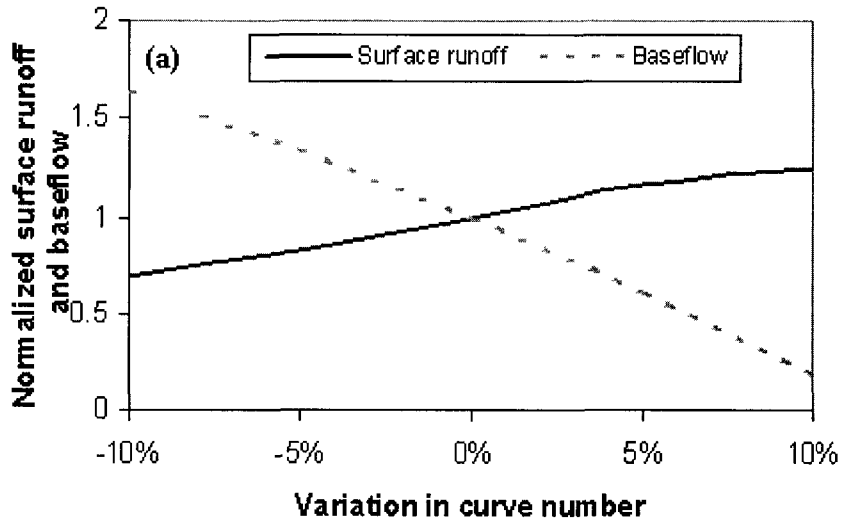


Figure 2. Land use categories in Maquoketa Watershed.



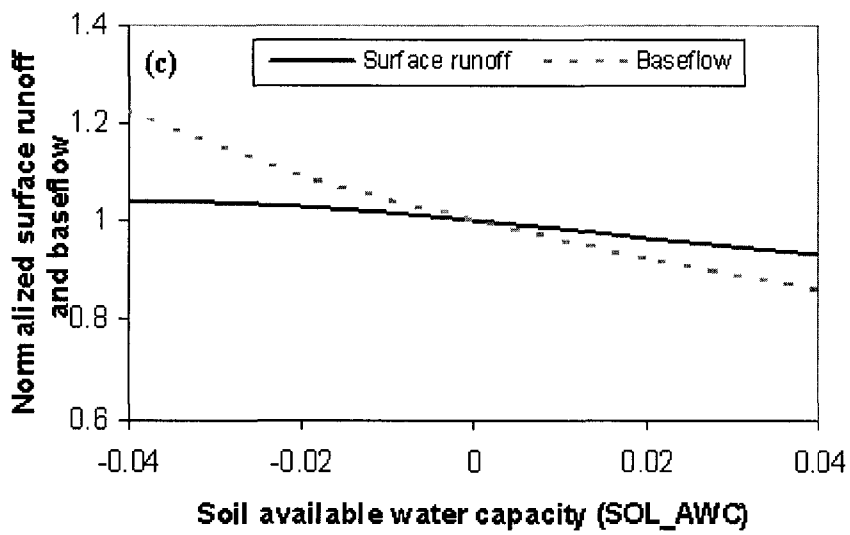


Figure 3. Sensitivity of surface runoff and baseflow to (a) CN, (b) ESCO, and (c) SOL_AWC.

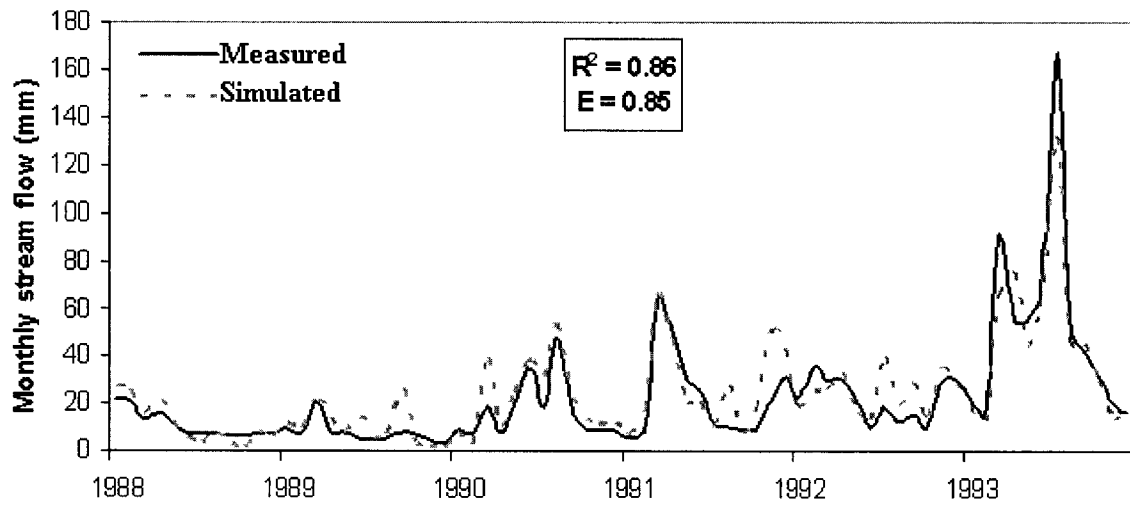


Figure 4. Monthly time series of predicted and measured streamflow at USGS gauge 05418500 (located on the Maquoketa river near Maquoketa, IA) for the 1988-93 calibration period.

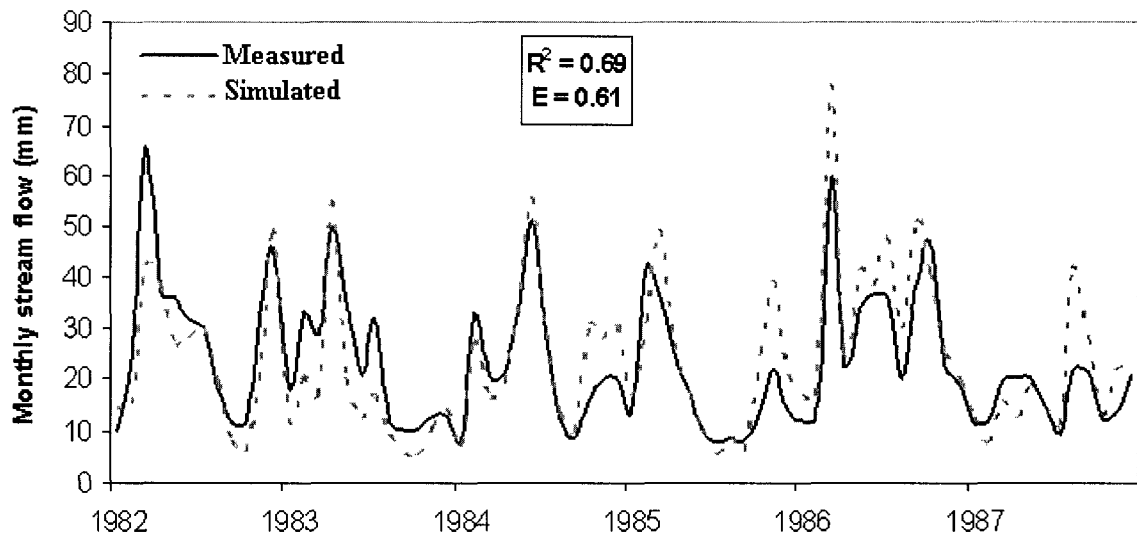


Figure 5. Monthly time series of predicted and measured streamflow at USGS gauge 05418500 (located on the Maquoketa river near Maquoketa, IA) for the 1982-87 validation period.

Table 1. Parameter ranges and initial values used in the sensitivity analysis.

Parameter*	Variable name	Range	Model initial estimates
Curve Number (for AGRL)	CN	69-85	77
Soil evaporation compensation factor	ESCO	0.5 -0.95	0.95
Plant uptake compensation factor	EPCO	0.01-1	1
Soil available water capacity (mm)	SOL_AWC	±0.04	
Baseflow alpha factor	ALPHA_BF	0.05-0.8	0.048
Groundwater revap coefficient	GW_REVAP	0.02-0.2	0.02
Groundwater delay time (day)	GW_DELAY	0-100	31
Deep aquifer percolation fraction	RECHRG_DP	0-1	0.05

*Detailed descriptions are given in the SWAT theoretical documentation (Neitsch et al., 2002).

Table 2. Sensitivity indices of model parameters.

Parameter	Initial value	Parameter				Response variable (Surface Runoff)						Response variable (Baseflow)					
		P1	P2	ΔP	Mean Pm	F1	F2	ΔF	Mean Fm	$\frac{\Delta F}{\Delta P}$	$\frac{P_m}{F_m} \frac{\Delta F}{\Delta P}$	F1	F2	ΔF	Mean Fm	$\frac{\Delta F}{\Delta P}$	$\frac{P_m}{F_m} \frac{\Delta F}{\Delta P}$
CN	77	85	69	16	77	310	173	137	241	8.57	2.73	21	181	-160	101	-10.0	-7.63
ESCO	0.95	0.5	1	0.5	0.75	214	249	-34	231	-68.9	-0.22	69	110	-41	90	-82.2	-0.69
EPCO	1	0.01	1	0.99	0.505	264	249	15	256	15.09	0.03	124	110	14	117	14.1	0.06
SOL_AWC		0.04	-0.04	0.08	0.04	232	259	-27	246	-336	-0.05	95	135	-40	115	-503	-0.17
ALPHA_BF	0.05	0.05	0.8	0.75	0.42	249	249	0	249	0	0	110	114	-4	112	-4.7	-0.02
GW_REVAP	0.02	0.02	0.2	0.18	0.11	249	249	0	249	0	0	110	95	15	102	85.6	0.09
GW_DELAY	31	0	100	100	50	249	249	0	249	0	0	108	106	1	108	0.0	0.01
RECHARG_DP	0.05	0	1	1	0.5	249	249	0	249	0	0	113	91	22	102	22.3	0.11

Table 3. Final calibrated values of SWAT parameters for Maquoketa River Watershed.

Parameter	Value	Parameter	Value
CN (for AGRL only)	72	REVAP	0.15
ESCO	0.85	DELAY	50
AWC	-0.04	RECHRG_DP	0.5

CHAPTER 3. CLIMATE CHANGE SENSITIVITY ASSESSMENT ON UPPER MISSISSIPPI RIVER BASIN STREAMFLOWS USING SWAT

A paper submitted to the *Journal of American Water Resources Association*

Manoj Jha, Jeff G. Arnold, Philip W. Gassman, and Roy Gu

ABSTRACT

The Soil and Water Assessment Tool (SWAT) model was used to assess the impacts of potential future climate change on the hydrology of the Upper Mississippi River Basin (UMRB). Calibration and validation of SWAT were performed on a monthly basis for 1968-87 and 1988-97, respectively; R^2 and Nash-Sutcliffe simulation efficiency (E) values computed for the monthly comparisons were 0.74 and 0.65 for the calibration period and 0.81 and 0.75 for the validation period. The impacts of eight 20-year (1971-90) scenarios were then analyzed, relative to a scenario baseline. A doubling of atmospheric CO_2 concentrations was predicted to result in an average annual flow increase of 35%. An average annual flow decrease of 15% was estimated for a constant temperature increase of 4° C. Essentially linear impacts were predicted between four precipitation change scenarios of -20, -10, 10, and 20%, which resulted in average annual flow changes at Grafton of -51, -27, 28, and 58%, respectively. The final two scenarios accounted for variable monthly temperature and precipitation changes obtained from a previous climate projection, with and without the effects of CO_2 doubling. The resultant average annual flows were predicted to increase by 15 and 52% in response to these climatic changes. Overall, the results indicate that the UMRB hydrology is very sensitive to potential future climate changes, resulting in increased periods of flooding or drought.

Key Words: climate change, watershed, simulation, hydrology, flow, spatial patterns

INTRODUCTION

Many global circulation model (GCM) experiments have been performed in the past two decades to investigate the effects of increasing greenhouse gas concentrations. These studies indicate that a rise in global mean temperature of between 1.4°C and 5.8°C would be expected following a doubling of carbon dioxide (CO₂) concentrations (IPCC, 2001). Changes in precipitation are more speculative than temperature projections, especially for smaller regions. Although the regional distribution is uncertain, precipitation is expected to increase worldwide, especially in higher latitudes (IPCC, 2001). Global warming is also projected to alter potential evaporation. The most immediate effect will be an increase in the air's ability to absorb water as temperature rises. Budyko (1982) estimated that potential evapotranspiration would increase by 4% for every degree Celsius increase in temperature. Vegetative characteristics can also be expected to change as a result of global warming leading to a change in the rate of potential evapotranspiration. Experimental evidence (Tyree and Alexander, 1993; Hendry et al., 1993) shows that stomatal conductance of some plants declines as CO₂ increases, resulting in a reduction in transpiration.

The assessment of climate change effects generally follows an "impact approach" for hydrological and water resource studies (Carter et al., 1994). The impact approach is a linear analysis of cause and effect: if climate was to change in a defined way, what would happen? The impact assessment scenarios include arbitrary changes, temporal analogues, spatial analogues, and scenarios developed using climate models (Arnell, 1996). An arbitrary change scenario is a sensitivity analysis examining the sensitivity of a watershed hydrological system to changes in climatic inputs. The temporal analogue assumes that information from the past

can provide an analogue for future conditions, while the spatial analogue assumes that the future climate of a region can be described by the current climate of another region.

Scenarios based on climate models investigate the effects of increasing greenhouse gas concentrations on watershed hydrologic responses by superimposing projected future climate trends directly from GCMs, or from GCM projections that are downscaled via regional climate models (RCMs), upon a hydrologic model.

Numerous studies have been conducted at scales ranging from small watersheds to the entire globe to assess the impacts of climate change on hydrologic systems. Arnell et al. (2001) list nearly 80 studies published in the late 1990s in which climate change impacts for one or more watersheds were analyzed using a coupled climate model-hydrologic model approach. These studies represented various subregions of the six inhabited continents; over half of the studies were performed for watersheds in Europe. U.S. studies have been performed at both a national scale (48-state contiguous region) and for specific watersheds. Many of the studies have been performed for watersheds in the western portion of the U.S. including all or portions of the Colorado River Basin (Nash and Gleick, 1991; Christensen et al., 2003; Gleick and Chaleki, 1999; Wilby et al., 1999; Wolock and McCabe, 1999; Rosenberg et al., 2003), Columbia River Basin (Hamlett and Lettenmaier, 1999; Lettenmaier et al., 1999; Wolock and McCabe, 1999; Miles et al., 2000; Payne et al., 2003; Mote et al., 2003; Rosenberg et al., 2003), and the Missouri River Basin (Revelle and Waggoner, 1983; Frederick, 1993; Klassen, 1997; Hubbard, 1998; Lettenmaier et al., 1999; Wolock and McCabe, 1999; Stonefelt et al., 2000; Stone et al., 2001; Stone et al., 2003; Rosenberg et al., 2003)

Comparatively few studies have been performed for the Upper Mississippi River Basin (UMRB) region. According to Dean (1999), the UMRB is very sensitive to climate change due to the intersection within the region of the three airmasses (Pacific, Arctic, and Gulf of Mexico) that control the climate of North America. This sensitivity to climate change has been confirmed by analysis of Holocene (past 10,000 years) sediment core data from lakes (Dean, 1999) and streams (Knox, 2002) in the region. The stream sediment data indicates that extreme floods are especially sensitive to climatic change. Shifts in precipitation and other climatic conditions in the UMRB region could also have major environmental consequences. Nitrate (NO_3) loads discharged from the mouth of the Mississippi River have been implicated as the primary cause of the Gulf of Mexico seasonal oxygen-depleted hypoxic zone, which covered nearly 20,000 km^2 in 1999 (Rabalais et al., 2002). Goolsby et al. (2001) estimated that 35% of the NO_3 load discharged to the Gulf originated from tributary rivers located in Iowa and Illinois during average discharge years between 1980 and 1996. It is possible that changes in UMRB flow characteristics due to future climate change could further exacerbate this nitrate loading problem.

The majority of studies that include an assessment of future climate change impacts on the hydrology of the UMRB have been performed within the context of larger national or regional studies. Frederick (1993) conducted an assessment of the effects of an analog “dust bowl” climate (1931-40), assumed to represent potential future climate conditions of reduced precipitation and higher temperatures, on the streamflows of the Missouri, Upper Mississippi, and Arkansas River basins. The analysis was carried out as part of a larger climate change study performed for Missouri, Iowa, Nebraska, and Kansas (MINK) region (Rosenberg et al., 1993). The study was performed by using historical streamflow records in combination with

comparisons of reservoir evaporation estimates between the 1931-40 analog climate and the control climate of 1951-80. The average total streamflows for the Upper Mississippi were predicted to decline by 29% in response to the analog climate conditions. Wolock and McCabe (1999) performed a national assessment of projected future climate trends on the hydrology of 18 U.S. major water resource regions by linking a simple water balance model to two different GCMs: the Canadian Centre for Climate Modeling and Analysis CGCM1 model (Flato et al., 2000) and the Hadley Centre for Climate Prediction and Research HadCM2 model (Johns et al., 1997). Future UMRB runoff levels were predicted to decline by 42 mm and stay unchanged, relative to baseline conditions, for the decades of 2025-2034 and 2090-2099 in response to the CGCM1 climate inputs. However, increases of 42 and 133 mm were predicted for 2025-2034 and 2090-2099 based on the HadCM2 scenario.

Rosenberg et al. (2003) also analyzed the impact of HadCM2 projections for the 18 major water resource regions, using the Soil and Water Assessment Tool (SWAT) watershed model (Arnold et al., 1998) within the Hydrologic Unit Model for the United States (HUMUS) modeling framework (Arnold et al., 1999). The climate scenarios were constructed by downscaling HadCM2 projections into weather records representative of future time periods encompassing 2030 and 2095. Water yields were predicted to increase by about 12 and 50% for 2030 and 2095, respectively, in response to the HadCM2 inputs. Thomson et al. (2003) performed an analysis of El Niño/Southern Oscillation (ENSO) weather phenomena, again for the same 18 major U.S. river basins used in the Wolock and McCabe (1999) and Rosenberg et al. (2003) studies. The analysis was performed by simulating hydrologic impacts with SWAT (within HUMUS) in response to 30-year climate analogues of El Niño, strong El Niño, or La Niña weather patterns. They report that water yields for the UMRB can

decline as much as 59% and increase as much as 62%, relative to baseline conditions, depending on the season of the year and the dominant weather pattern.

In contrast to the previously described studies, Jha et al. (2004) concentrated on analyzing the hydrologic effects of potential future climate change for just the UMRB. Climate projections for the study were generated for 2040-2049 by downscaling a HadCM2 climate scenario with a regional climate model (RegCM2) developed by Giorgi et al. (1993). The climate scenario represented a 1% annual increase of greenhouse gases, which was equivalent to a CO₂ level of about 480 ppm during the period of 2040-2049. The projected climate was then input into SWAT, resulting in a predicted total streamflow increase for the UMRB of 50% for the period of 2040-49.

The goal of this study was to build upon the previous study by Jha et al. (2004) by further assessing the impacts of climatic trend variations on the hydrologic responses of the UMRB using SWAT. The approach used here includes a mix of sensitivity scenarios (changes in temperature, precipitation, and/or CO₂ levels) including a simplified replication of a previously reported future climate projection, which is similar to the methodology used by Stonefelt et al. (2000). Actual assessments of potential future climate changes cannot be performed via sensitivity change scenarios. However, Arnell et al. (2001) state that such scenarios do, “provide extremely valuable insights into the sensitivity of hydrological systems to changes in climate.” Wolock and McCabe (1999) further state that sensitivity studies of temperature and precipitation variations can provide important insight regarding the responses and vulnerabilities of different hydrologic systems to climate change, especially when there is a great deal of uncertainty between available GCM projections.

The specific objectives of this study were: (1) to calibrate and validate the SWAT hydrologic component over a 30-year period (1968-97) by using historical climate data and comparing simulated output with observed stream flows measured at a gauge located near Grafton, IL, and (2) to estimate fluctuations in UMRB seasonal and annual stream flows with SWAT in response to eight climate scenarios that include a doubling of CO₂, arbitrary changes in temperature and precipitation, and the effects of a projected climate scenario reported by Giorgi et al. (1998).

MODEL DESCRIPTION

The SWAT model is a conceptual, physically-based long-term continuous watershed scale simulation model. 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. A brief overview of the key model components is given here. Further details on these and other model components can be found in Arnold et al. (1998) and Neitsch et al. (2001).

In SWAT, a watershed is divided into multiple subwatersheds which are then further subdivided into unique soil/landuse characteristics called hydrologic response units (HRUs). The water balance of each HRU is represented by four storage volumes: snow, soil profile (0-2 m), shallow aquifer (typically 2-20 m), and deep aquifer (>20 m). Flow generation, sediment yield, and nonpoint-source loadings are summed across all HRUs in a subwatershed, and the resulting loads are then routed through channels, ponds, and/or reservoirs to the watershed outlet. The model integrates functionalities of several other models, allowing for the simulation of climate, 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 (e.g., Rosenthal et al., 1995; Arnold and Allen, 1996; Srinivasan et al., 1998; Arnold et al., 1999; Saleh et al., 2000; Santhi et al., 2001). In this paper, hydrologic processes and climate change processes modeled in SWAT are briefly discussed.

The hydrology part of the model includes snowmelt, surface runoff, evapotranspiration, ground water percolation, lateral flow, and groundwater flow (or return flow). If the daily mean temperature is less than 0°C, it is assumed that precipitation falls as snow. Snow is assumed to melt on days when the maximum temperature exceeds 0°C. Partitioning of daily precipitation between surface runoff and infiltration is estimated with a modification of the SCS Runoff Curve Number (CN) method (Mockus, 1969). Partitioning of snowmelt between runoff and percolation is treated in the same manner as precipitation with the CN method. The Green-Ampt method can also be used to estimate surface runoff if rainfall is available at a sub-daily time step.

Three methods are available to model potential evapotranspiration: Priestley-Taylor, Hargreaves, and Penman-Monteith. A modified version of the Penman-Monteith method is used in SWAT that accounts for the effects of changing atmospheric CO₂ in the transpiration computations based on the methodology described by Stockle et al. (1992). The Penman-Monteith method requires solar radiation, air temperature, wind speed, humidity, and vegetation parameters as input. The model computes evaporation from soils and plants separately. Actual soil water evaporation is estimated using exponential functions of soil depth and water content. Plant water evaporation is simulated as a linear function of potential ET, leaf area index, and root depth and can be limited by soil water content.

The plant growth component of SWAT utilizes routines for phenological plant development based on plant-specific input parameters such as energy and biomass conversion, precipitation, and temperature constraints, canopy height and root depth, and shape of the growth curve. These parameters have been developed (and provided in a crop database of the model) for plant species such as agricultural crops, forests, grassland, and rangeland. Conversion of intercepted light into biomass is simulated assuming a plant species-specific radiation use efficiency (RUE). The RUE quantifies the efficiency of a plant in converting light energy into biomass and is assumed to be independent of the plant's growth stage. The RUE values are adjusted in SWAT as a function of CO₂ concentrations in the range of 330-660 ppm, following the approach developed by Stockle et al. (1992). The effects of increased CO₂ are directly accounted for in the model by changes in plant growth and biomass production, and evapotranspiration rates (Arnold et al., 1998).

INPUT DATA

The UMRB is located in the north central United States (Figure 1). The UMRB extends from the source of the river at Lake Itasca in Minnesota to a point just north of Cairo, Illinois. The entire UMRB covers a drainage area of approximately 491,700 km². The primary land use is agricultural (over 75%) followed by forest (20%), wetlands, lakes, prairies, and urban areas.

Land use, soil, and topography data required for simulating the UMRB in SWAT were obtained from the Better Assessment Science Integrating Point and Nonpoint Sources (BASINS) package version 3 (USEPA, 2001). Land use categories available from BASINS are relatively simplistic; for example, only one category for agricultural use that is defined as

“Agricultural Land-Generic” (AGRL) is provided. The BASINS soil data comes from the U.S. Department of Agriculture (USDA) State Soil Geographic (STATSGO) database (USDA, 1994), which contains soil maps at a scale of 1:250,000. The STATSGO map unit is linked to a soil interpretations record attribute database that provides the proportionate extent of the component soils and soil layer physical properties (texture, bulk density, available water capacity, saturated conductivity, soil albedo, and organic carbon) for up to 10 layers. Topographic information is provided in BASINS in the form of 90 m resolution Digital Elevation Model (DEM) data.

The management operations were defaulted by SWAT2000 ARCVIEW interface (AVSWAT), developed by Di Luzio et al. (2001), and consisted simply of planting, harvesting, and automatic fertilizer applications for the agricultural lands. No attempt was made to improve the management data because the main intent was to assess the sensitivity of climate change on streamflow rather than on water quality.

Climate data required by the model are daily precipitation, maximum/minimum air temperature, solar radiation, wind speed, and relative humidity. These daily climatic inputs can be entered from historical records, and/or generated internally in the model using monthly climate statistics that are based on long-term weather records. In this study, historical precipitation and temperature records for the UMRB were obtained for 111 weather stations located in and around of the watershed (C. Chinnasamy. 2002. Personal communication. Blacklands Research and Extension Lab., Temple, TX). Missing data in the precipitation and temperature records, as well as daily solar radiation, wind speed, and relative humidity inputs, were generated internally in SWAT.

The UMRB stream network and subwatersheds were delineated using AVSWAT, following specification of the threshold drainage area and the watershed outlet. The threshold area is the minimum drainage area required to form the origin of the stream. The accuracy of the delineation depends upon the accuracy of the DEM data. Stream network data available from the USGS was used as a reference to ensure that the stream system and associated subwatersheds were accurately delineated, which is an important component of simulating the water routing process. Several iterations were performed to align the delineated stream network as close as possible to the USGS referenced stream network. Similarly, the subwatershed outlets were also adjusted so that the subwatershed boundaries were as consistent as possible with the boundaries of 8-digit HCU (Hydrologic Cataloging Units) watersheds as defined by the USGS (Seaber et al., 1987). A total of 119 subwatersheds were delineated up to the point just before the confluence of the Missouri River into the Mississippi River (i.e., Mississippi river at Grafton, IL). This point constitutes a drainage area of 431,000 km² that drains approximately 90% of the entire UMRB, and was assumed to be the UMRB outlet for this analysis. Multiple HRUs were created automatically with AVSWAT within each subwatershed, as a function of the dominant landuse and soil types within a given subwatershed.

SIMULATION METHODOLOGY

The SWAT UMRB simulation methodology consisted of an initial calibration and validation phase followed by a second phase in which the impact of variations in climatic inputs was assessed for the UMRB hydrology. The following model options were used for all of the UMRB simulations performed in both phases: (1) CN method for the partitioning of

precipitation between surface runoff and infiltration, (2) Muskingum method for channel routing, and (3) Penman Monteith method for potential evapotranspiration.

Calibration and Validation of SWAT

The SWAT model was calibrated and validated using measured streamflow data collected at a USGS stream gauge located on the Mississippi River at Grafton, IL (Station # 05587450). The total available historical weather data (1967-1997) were divided into two sets: 20 years (1968-1987) for calibration (1967 was assumed to be an initialization year) and 10 years for validation (1988-1997). The watershed characteristics, including landuse, soil properties, and anthropogenic effects (e.g., agricultural management), were held constant throughout the simulation period. The coefficient of determination (R^2) and Nash-Sutcliffe simulation efficiency (E) were used to evaluate the model predictions for both time periods. The R^2 value is an indicator of strength of relationship between the observed and simulated values. The E value indicates how well the plot of the observed versus the simulated values fits the 1:1 line. If the R^2 value is close to zero and E value is less than or close to zero, the model prediction is considered unacceptable. If the values approach one, the model predictions are considered perfect.

The selection of parameters for the streamflow calibration was based partially on previous streamflow calibration results reported by Santhi et al. (2001) and Jha et al. (2003) and are listed in Table 1. The initial values of each calibration parameter were generated by AVSWAT. The parameters were allowed to vary during the calibration process within acceptable ranges across the basin until an acceptable fit between the measured and simulated values was obtained at watershed outlet; no changes were made to the calibrated

parameters during the 10-year validation simulation. The curve numbers (CN) were allowed to vary $\pm 10\%$ to account for uncertainty in the hydrologic condition of the basin. The soil evaporation compensation factor (ESCO) adjusts the depth distribution for evaporation from the soil to account for the effect of capillary action, crusting, and cracking and was allowed to vary between 0.75 and 1.0, where a value of 1.0 means no compensation with depth. The plant uptake compensation factor (EPCO) was allowed to vary between 0.01 and 1.0; as this variable approaches 1.0, the model allows more of the water uptake demand to be met by lower layers in the soil. The soil available water capacity (SOL_AWC) was adjusted within a range of ± 0.04 mm for each soil included in the simulation. The groundwater delay time (GW_DELAY) is the lag between the time that water exits the soil profile and enters the shallow aquifer. It depends on the depth to the water table and the hydraulic properties of the geologic formation in the vadose and groundwater zones and was allowed to vary between 0 and 100 days. The threshold depths for baseflow to occur (GWQMN) and re-evaporation to occur (REVAPMN) were varied to adjust the amount of groundwater flow.

Scenario Baseline

A scenario baseline was initially executed prior to performing the scenario simulations which was assumed to reflect current conditions. Each scenario was then run for the same simulation period, except with modified climate inputs, to provide a consistent basis for comparison of the scenario impacts. The predicted outcomes can be affected by the choice of time period for the baseline, due to climatic variations that have occurred between different time periods. Arnell (1996) summarized simulation periods used in several hydrological climate change impact studies and found that a 30-year period from 1951 to 1980 (or shorter)

was assumed for many climate change studies to define baseline conditions. The 20-year period from 1971 to 1990 was selected to represent baseline conditions for this study. Average annual and average monthly values of the streamflow from Mississippi River (at Grafton, IL) were computed to form a basis of comparison for the climatic scenarios.

Climate Change Scenarios

A complete depiction of climate change consists of two components: emission of CO₂ (and potentially other greenhouse gases) and a subsequent climate response. The emission component reflects the concentration of greenhouse gases in the atmosphere at any given time while the climate response portion defines the changes in climate that occur due to changes in CO₂ concentrations. The impacts of these two climate change components on watershed hydrology can be accounted for separately in SWAT by: (1) simulating only the effect of an increase in atmospheric CO₂ concentrations on plant growth, or (2) simulating temperature and/or precipitation changes that serve as a proxy for assumed (but not simulated) increases in CO₂ concentrations. This approach facilitates sensitivity analyses of different climate change influences on hydrologic responses and was the basis of Scenarios 1-8 (Table 2) performed for this study. Alternatively, an increase in CO₂ emissions and changes in climatic inputs can be simulated simultaneously in SWAT, which was the approach used for Scenario 8 (Table 2).

Many analyses of potential climate change impacts on hydrology and water resources have relied on one of two standard CO₂ emission scenarios. The first emission scenario simply assumes that CO₂ concentrations could double in the near future, as described by Rosenberg et al. (1999). The second standard emission scenario assumes that a transient

increase in greenhouse gas emissions occurs at a rate of 1% per year in GCMs (Doherty and Mearns, 1999). In this study, Scenario 1 (Table 2) reflects the impact of a direct doubling of CO₂ (2xCO₂) concentration from 330 to 660 ppm. Direct impacts on plant growth were simulated in Scenario 1, as were subsequent effects on plant nutrient uptake and increases or decreases in surface runoff due to evapotranspiration changes. However, projected changes in precipitation and temperature associated with the CO₂ increase (regardless of GCM source) could not be accounted for in this scenario.

Climate change scenarios of temperature increase, and precipitation increase and decrease, were also incorporated in this study to further examine the sensitivity of the hydrology of the UMRB (Scenarios 2 to 6 in Table 2). These scenarios consisted of changing the baseline daily temperature or precipitation levels by the amounts or percentiles listed in Table 2, depending on what month each day was in. The temperature increase scenario (Scenario 2) reflects the general trend of increased global temperatures forecasted by current GCMs. The assumption of an average monthly increase of 4°C for Scenario 2 lies within the upper end of the current GCM projected temperature range reported by IPCC (2001). Increased temperatures will have a direct effect on plant productivity and evapotranspiration rates, which will in turn impact surface and subsurface runoff to the UMRB stream system.

According to NSF (2001), precipitation in much of the Midwest, including the UMRB region, has increased by 10 to 20% over the past Century. Recent projections with the CGCM1 and HadCM2 GCMs (NSF, 2001), and HadCM3 GCM (Hadley Centre, 2003), point to continuing trends of increased rainfall across the next century. Similar results have also been reported for other studies (Giorgi et al., 1998; Pan et al., 2001). Two scenarios depicting increased precipitation levels of 10 and 20% were incorporated in the study to reflect these

projected trends; contrasting scenarios reflecting decreased precipitation levels of 10 and 20% were also included in the analysis to facilitate a more complete assessment of SWAT's response to precipitation changes (Scenarios 3-6). Decreased precipitation rates will result in decreased soil moisture levels, which will potentially have detrimental effects on plant productivity and streamflow. In contrast, increased precipitation will lead to greater soil moisture levels and likely greater streamflows.

Scenarios 7 and 8 were based on a future climate projection reported by Giorgi et al. (1998) that was generated with RegCM2 nested within the Australian Commonwealth Scientific and Industrial Research Organization (CSIRO) GCM, which is described by Watterson et al. (1995). Both a 5-year present-day scenario representing current atmospheric carbon levels (330 ppm) and a 5-year scenario reflecting 2xCO₂ concentration conditions (660 ppm) were simulated in the study. The 2xCO₂ climate was assumed to represent future conditions when atmospheric CO₂ concentrations are twice those of current levels, and was not referenced to any specific time period. For this study, average monthly temperature and precipitation changes (Table 2) projected by RegCM2 for the MINK region were assumed to represent potential future UMRB intra-seasonal precipitation and temperature shifts for scenarios 7 and 8. The 2 xCO₂ concentration of 660 ppm was also accounted for in scenario 8, to assess the direct effect of increased CO₂ levels in combination with the changes in precipitation and temperature. These two scenarios do not reflect true downscaling of GCM projections for the UMRB and thus are also best viewed as sensitivity scenarios.

RESULTS AND DISCUSSION

Figure 2 shows the time-series comparison of predicted and measured cumulative monthly streamflows for the Mississippi River at Grafton, IL over the 20-year (1968-87) calibration period. In general, SWAT accurately tracked the measured streamflows for the time period, although some peak flow months were over-predicted and some of the low-flow months were under-predicted. A regression plot of the predicted versus measured cumulative monthly streamflows is shown in Figure 3. The plot reveals a strong correlation between the predicted and measured values, which is reinforced by the R^2 and E values of 0.74 and 0.65.

The time series comparison of predicted and measured cumulative monthly streamflows for the 10-year (1988-97) validation period is shown in Figure 4, again for the Mississippi River at Grafton, IL. The predicted flows closely followed the corresponding measured flows, with less over-prediction of peak-flow months and less under-prediction of low-flow months, as compared to the calibration period. The regression plot for the validation period (Figure 5) again shows good agreement between the predicted and measured values. This is further underscored by R^2 and E values of 0.81 and 0.75, which were even stronger than the corresponding statistics determined for the calibration period. These validation results indicate that SWAT accurately replicated the UMRB monthly streamflow characteristics at Grafton for the simulated time period.

Comparisons between measured and predicted annual average streamflows for 1971-90 for the Mississippi River at Grafton and 11 upstream subwatersheds were also conducted (Table 3), to provide an additional assessment of how well SWAT tracked flows throughout the UMRB. The differences between the predicted and measured annual average streamflows were 6% or less for nine of the 12 watersheds. The largest error occurred for the station near

Valley City, Illinois; the streamflows for this subwatershed were overpredicted by about 14%. An R^2 of 0.95 was determined between the 12 simulated average annual flows and corresponding measured flows, indicating that the model accurately tracked the average annual flows across the region. Overall, these average annual results further confirm that SWAT was able to reflect actual hydrologic conditions in the UMRB.

As a final check, hydrologic budgets were computed for the scenario baseline and the eight climate change scenarios (Table 2) for the 20-year period of 1971-90. Table 4 shows the components of the average annual hydrologic budgets estimated by SWAT for the baseline and the seven scenarios. The shifts in the predicted hydrologic budget components between the baseline and the scenarios exhibit intuitive patterns and confirm that SWAT responded logically to the simulated climatic changes incorporated in Scenarios 1-8.

CO₂, Temperature, and Precipitation Sensitivity Scenarios

Table 5 lists the average monthly streamflows predicted for the UMRB outlet at Grafton, IL for the scenario baseline and the corresponding relative differences in the average monthly streamflows for each of the eight scenarios. The average monthly streamflows for the baseline and Scenarios 1-6 are plotted in Figure 6 to further illustrate the predicted seasonal effects of the assumed climate changes on the Mississippi flows at Grafton. The results obtained here for Scenarios 1-6 are compared with identical scenarios simulated in previous studies or with results obtained from relevant scenarios previously performed for the UMRB. These are intended to be primarily qualitative comparisons, due to differences in watershed characteristics and/or climatic scenarios between the studies.

Relative water yield increases ranging from 17 to 51% were predicted by SWAT in response to the 2xCO₂ scenario (Scenario 1), with the greatest relative increases occurring between July and November (Table 5). The trends shown in Figure 6 indicate that the magnitude of flow increase was relatively consistent outside of the winter months of December through February (Figure 6). Overall, the average annual flow increase was 35% over the 20-year period. The magnitude of flow increase found here for the 2xCO₂ scenario was much greater than that reported by Stonefelt et al. (2000), who used SWAT to assess the effects of a 2xCO₂ sensitivity scenario for the 5,000 km² Upper Wind River Basin in northwestern Wyoming. They reported only a slight increase of 0.4% in annual average flow; this was attributed primarily to the fact that only tundra-type vegetation grows in the alpine areas of the watershed, which is essentially unimpacted by increases in atmospheric CO₂. Klassen (1997) also performed a 2xCO₂ sensitivity analysis with SWAT on the hydrology of the 427 km² Spring Creek Watershed, located in the Black Hills of South Dakota. Relative annual flow increases predicted by SWAT in response to the increased CO₂ levels ranged between 4 and 74%. However, the magnitudes of the flow increases were much smaller than those found here (Figure 6). Overall, the Scenario 1 results suggest that the hydrology of the UMRB region is potentially very sensitive to increased atmospheric CO₂ concentrations. The predicted flow increases are also consistent with expectations; i.e., that transpiration will decrease in response to increased CO₂ levels, resulting in greater soil moisture levels and in turn higher flow.

Mixed streamflow results at Grafton were predicted by SWAT in response to the consistent average monthly increase in temperature of 4° C (Scenario 2). Increased flows were predicted for most of the fall and winter months while decreased flows were predicted

during the spring and summer (Table 5). The magnitude of the flow increases were much greater during the spring and summer months (Figure 6). On an annual average basis, the UMRB flows were predicted to decrease by about 15% (Table 5) during the simulation period. The overall UMRB flow impacts were both greater and similar to results obtained by Stonefelt et al. (2000) and Nash and Gleick (1991), who performed 4° C temperature increase scenarios for hydrologic systems in the western U.S. that are dominated by snowmelt. Stonefelt et al. (2000) found an annual average flow decrease of 7.7% for the Upper Wind River Basin, while Nash and Gleick (1991) reported average annual flow decreases of 8.7 to 16.5% for three different river systems in the Upper Colorado River Basin.

Two key effects of the increased temperature of Scenario 2 were a decrease in snowpack levels accompanied by an increase in snowmelt runoff, which resulted in the increased flows in the winter months at Grafton. The decrease in snowpack levels is consistent with the results reported by Nash and Gleick (1991), Leavesley et al. (1994), McCabe and Wolock (1999), Stonefelt et al. (2000), and Christensen et al. (2003) for studies focused on climate change impacts on snowmelt dominated watersheds. However, the flow pattern response that occurred for Scenario 2 (Figure 6) was very different than that reported for some studies conducted in the western U.S., including Stonefelt et al. (2000), Nash and Gleick (1991), Christensen et al. (2003), and van Katwijk et al. (1993). In each case, they showed that the annual peak runoff period that occurs due to snowmelt was predicted to shift from June to May or April, in response to higher temperatures or GCM-driven climate change scenarios. The UMRB response predicted at Grafton in this study (Table 5 and Figure 6) show slight increases in flow during December and January due to increased snowmelt and precipitation

in the form of rainfall, but large decreases in flow were predicted from February through August.

Essentially linear changes in the UMRB streamflows were predicted for the simulated decreases or increases in precipitation, which were incorporated in Scenarios 3-6 (Table 5 and Figure 6). The relative average monthly flow decreases were near or greater than 50% for nine of the twelve months for Scenario 3 (-20% precipitation decline). Even greater relative average monthly flow changes were predicted for Scenario 6, which reflected a 20% increase in precipitation. The predicted average annual relative flow changes were -51, -27, 28, and 58% for scenarios 3, 4, 5, and 6 (Table 5). A regression analysis of the flow responses for the four precipitation decrease and increase scenarios resulted in a slope of 2.6, indicating that a unit increase in precipitation produced a 2.6% increase in flow for the UMRB. This result is consistent with the “amplification factor” described by Karl and Riebsame (1989), which they state can be as high as 4.5 between a unit increase in precipitation and resulting runoff. The flow responses estimated by SWAT for these four scenarios reveal that the UMRB hydrologic system is very sensitive to fluctuations in precipitation levels.

Stonefelt et al. (2000) and Boorman and Sefton (1997) both report results of +10 and -10% precipitation change scenarios for the Upper Wind River Basin and three United Kingdom watersheds ranging in size from 86 to 117 km², respectively. Mean annual runoff impacts were predicted to range from about +16 to -15% in both studies, which were less than what was found in this study for the comparable Scenarios 4 and 5. The predicted decrease in water yield of over 50% for a 20% decline in precipitation (Scenario 3) was considerably higher than the 29% decrease in UMRB flows reported by Frederick (1993) for

an analogue dust bowl climate. His results were also influenced by the effects of higher temperature, which were incorporated into the analogue climate scenario. The effects of a 20% precipitation decrease (Scenario 3) simulated here (Table 5) were similar to seasonal flow impacts reported by Thomson et al. (2003) in response to El Niño conditions simulated for the UMRB, which ranged from -59% in summer to -33% in spring. Thomson et al. (2003) also report that the impacts of a Strong El Niño climate pattern was predicted to result in increased water yields ranging from 37% in summer to 62% in winter, which are similar to the percentage increases predicted in this study for Scenario 6 (Table 5). However, the largest flow increases were predicted to occur during the summer or fall in the present study, which is essentially opposite of what Thomson et al. (2003) found. The Los Niños scenarios simulated by Thomson et al. (2003) also reflect the effects of temperature changes as well as precipitation fluctuations.

Climate Change Projection Sensitivity Scenarios

A different pattern emerged for the streamflow trends predicted for Scenarios 7 and 8 (Figure 7), relative to the trends predicted for Scenarios 1-6 (Figure 6). The flow trends predicted for these scenarios reflect the shifts in seasonal temperature and precipitation, and the effects of twice as much atmospheric CO₂ (for Scenario 8), that were derived from the projections reported by Giorgi et al. (1998). Incorporation of the CO₂ concentrations of 660 ppm for Scenario 8 resulted in a large increase in predicted future flows, compared to the flows estimated for Scenario 7. The variations in the predicted average monthly flows at Grafton, relative to the baseline, ranged between -22 and +63% for Scenario 7 and 10 to 92% greater for Scenario 8 (Table 5). Overall, the annual average flows at Grafton were estimated

to increase by 15 and 52% (Table 5) in response to the climate perturbations imbedded in Scenarios 7 and 8, respectively.

The Scenario 7 results were comparable to the 2030 outcomes reported by Rosenberg et al. (2003), who found that the average annual UMRB water yields predicted by SWAT would increase by 11 and 16%, respectively, in response to downscaled HadCM2 inputs with and without a CO₂ concentration level of 560 ppm. The corresponding flow increases reported by Rosenberg et al. (2003) for 2095 were 48 and 53%, which were similar to the Scenario 8 results found here (Table 5). However, the seasonal pattern of the predicted flows shown in Figure 6 was considerably different from those reported by Rosenberg et al. (2003) for most months of the year. The Scenario 8 results were also similar to the 50% UMRB flow increase reported by Jha et al. (2004) for 2040-2049, that were also predicted via downscaled HadCM2 inputs into SWAT. However, no direct accounting of the CO₂ concentrations (assumed to be 480 ppm) was included in the simulations performed by Jha et al. (2004). Mirror opposite shifts of -22 and +22% in 2030 UMRB water yields were found by Wolock and McCabe (1999), in response to CGCM1 and HadCM2 climate projection inputs, respectively. Water yields driven by the 2095 HadCM2 projections were predicted to increase by 68% for the UMRB (Wolock and McCabe, 1991); the CGCM1 inputs had no effect on the flows. The UMRB flow changes predicted by Wolock and McCabe with HadCM2 were somewhat stronger than the flow predictions found in this study and reported by Rosenberg et al. and Jha et al., while the CGCM1 results were radically different than any results reported here or in the literature. Similar results between this and other studies as discussed here can only be viewed as anecdotal comparisons, due to differences in GCMs, the boundaries of the GCM projection regions, downscaling methods, and simulated time

periods. However, it is noteworthy that several studies point to the potential of UMRB flow increases equal to or exceeding 50% within the next century.

Figures 8-10 show the spatial distribution of UMRB streamflows predicted by SWAT as a function of 8-digit watersheds for the scenario baseline, Scenario 7, and Scenario 8, respectively. A comparison between the three sets of outcomes clearly reveals that the predicted flows increased significantly across most of the UMRB in response to the precipitation and temperature changes simulated in Scenarios 7 and 8, and the additional increased CO₂ levels simulated in Scenario 8. These results underscore that the impact of climate changes within the UMRB could be widespread and would not be limited to only localized areas.

CONCLUSIONS

The results indicate that the UMRB hydrologic system is very sensitive to climatic variations, both on a seasonal basis and over longer time periods. The scenario outcomes indicate that precipitation and CO₂ fertilization shifts would have a much greater impact on future flow changes, as compared to increased temperature impacts. The results also show that the effects will vary spatially across the UMRB, as demonstrated for Scenarios 7 and 8 relative to baseline conditions. The climatic scenarios that were simulated here were hypothetical in nature and thus cannot be viewed as assessments of absolute future climatic conditions. However, these SWAT predictions do provide insight into the potential magnitude of streamflow changes that could occur as a result of future climatic changes.

Climatic changes forecast by GCMs point towards a trend of increasing precipitation rates in the UMRB region (e.g., NFS, 2001; Hadley Centre, 2003). If these forecasted trends

are correct then the results found here, for increased precipitation scenarios, would indicate that future Mississippi River and tributary flooding episodes could intensify relative to current events. These results are generally consistent with the outcomes found by Wolock and McCabe (1999), Jha et al. (2004), and Rosenberg et al. (2003), who assessed the impacts of various future climate projections for the UMRB. However, the SWAT results also clearly show that significant decreases in streamflows could also occur, if climatic trends were to go the opposite direction of what is currently being forecasted. Wolock and McCabe (1991) reported that future UMRB flows could decrease in 2030, based on the climate projections obtained from CGCM1. As shown by Arnell et al. (2001), Arnell (1999) also found that runoff would greatly decrease in 2050 for the UMRB region based on HadCM3 projections, in spite of the fact that HadCM3 forecasts increased future precipitation levels in the region (Hadley Centre, 2003). These contrasting findings underscore that considerable uncertainty persists regarding climate projections and associated streamflow impacts for future UMRB conditions.

The results of this study point to the need to perform a more extensive assessment of potential climate change impacts on UMRB hydrology by simulating the same downscaled climate change scenario(s) with several GCMs (e.g., CSIRO, HadCM3) in tandem with one or more RCMs. Future UMRB climate change studies should also be performed with improved land use data, such as approach initiated by Gassman et al. (2003) using land use data provided by the USDA National Resources Inventory (NRI) database (Nusser and Goebel, 1997), that facilitates the assessment of both flow and environmental impacts for current and potential future climate patterns. Finally, analysis of both extreme flow events and average flow conditions, similar to the procedures described by Boorman and Sefton

(1997), is needed to provide a more complete picture of the potential impacts of projected future climates on URMb hydrology.

REFERENCES

- Arnell, N.W. 1996. Global warming, river flows and water resources. Water Science Series, Institute of Hydrology, John Wiley & Sons. ISBN#0-471-96599-5.
- Arnell, .N.W. 1999. Climate Change and Global Water Resources. *Global Environmental Change* 9(1):S31-S49.
- Arnell, N.W., C. Liu, R. Compagnucci, L. da Cunha, K. Hanaki, C. Howe, G. Mailu, I. Shiklomanov, and E. Stakhiv. 2001. Chapter 4: Hydrology and Water Resources. *In: Climate Change 2001: Impacts, Adaptation, and Vulnerability..* JJ. McCarthy, O. Canziani, N.A. Leary, D.J. Dokken, and K.S. White (Editors). Cambridge University Press, Cambridge, UK. pp. 193-233.
- Arnold, J.G. and Allen, P.M. 1996. Estimating Hydrologic Budgets for Three Illinois Watersheds. *Journal of Hydrology* 176:57-77.
- Arnold, J.G., R. Srinivasan, R.S. Muttiah, and J.R. Williams. 1998. Large Area Hydrologic Modeling and Assessment Part I: Model Development. *Journal of the American Water Resources Association* 34(1):73-89.
- Arnold, J.G., R. Srinivasan, R.S. Muttiah, and P.M. Allen. 1999. Continental Scale Simulation of the Hydrologic Balance. *Journal of American Water Resources Association* 35(5):1037-1051.
- Boorman, D.B. and C.E.M. Sefton. 1997. Recognizing the Uncertainty in the Quantification of the Effects of Climate Change on Hydrological Response. *Climatic Change* 35:415-434.
- Budyko, M.I. 1982. *The Earth's Climate: Past and Future*. International Geophysics Series. Vol. 29. Academic Press: New York.
- Carter, T.R., M.L. Parry, S. Nishioka, and H. Harasawa. 1994. *Technical Guidelines for Assessing Climate Change Impacts and Adaptations*. Intergovernmental Panel on Climate Change (IPCC), University College London, and Center for Global Environmental Research, Tsukuba, 51pp.

- Christensen, N.S., A.W. Wood, N. Voisin, D.P. Lettenmaier, and R.N. Palmer. 2003. The Effects of Climate Change on the Hydrology and Water Resources of the Colorado River Basin. *Climatic Change* (in press).
- Dean, W.E. 1999. Evidence of Climate Change over the Last 10,000 Years from the Sediments of Lakes in the Upper Mississippi Basin. U.S Geological Survey Fact Sheet FS-059-99. U.S. Geological Survey, Denver, CO. <http://pubs.usgs.gov/fs/fs-0059-99/> (accessed in July 18, 2004).
- Di Luzio, M., R. Srinivasan, J.G. Arnold, and S. Neitsch. 2002. ARCVIEW Interface for SWAT 2000 User's Guide. Blackland Research Center. Texas Agricultural Experiment Station, Temple, Texas. <http://www.brc.tamus.edu/swat/swat2000doc.html> (accessed in July 18, 2004).
- Doherty, R. and L.O. Mearns. 1999. A Comparison of Simulations of Current Climate from Two Coupled Atmosphere-Ocean Global Climate Models against Observations and Evaluation of their Future Climates. Report to the National Institute for Global Environmental Change (NIGEC). Environmental and Societal Impacts Group, National Center for Atmospheric Research, Boulder, CO. <http://www.esig.ucar.edu/doherty/> (accessed in July 18, 2004).
- Flato, G.M., G.J. Boer, W.G. Lee, N.A. McFarlane, D. Ramsden, M.C. Reader, and A.J. Weaver. 2000. The Canadian Centre for Climate Modeling and Analysis Global Coupled Model and its Climate. *Climate Dynamics* 16:451-467.
- Frederick, K.D. 1993. Climate Change Impacts on Water Resources and Possible Responses in the MINK Region. *Climatic Change* 24:83-115.
- Gassman, P.W., M. Jha, S. Secchi, and J.G. Arnold. 2003. Initial Calibration and Validation of the SWAT Model for the Upper Mississippi River Basin. Proceedings of the 7th International Water Association Conference on Diffuse Pollution, 17-22 August, Dublin, Ireland pp. 10-35 -10-40.
- Giorgi, F., M.R. Marinucci, and G.T. Bates. 1993. Development of a Second Generation Regional Climate Model (RegCM2): Boundary Layer and Radiative Transfer Processes. *Monthly Weather Review* 121(10):2794-2813.
- Giorgi, F., L.O. Mearns, C. Shields, and L. McDaniel. 1998. Regional Nested Model Simulations of Present Day and 2×CO₂ Climate over the Central Plains of the U.S. *Climatic Change* 40(3-4):457-493.
- Gleick, P.H. and E.L. Chaleki. 1999. The Impacts of Climate Changes for Water Resources of the Colorado and Sacramento-San Joaquin River Basins. *Journal of the American Water Resources Association* 35(6):1429-1441.

- Goolsby, D.A., W.A. Battaglin, B.T. Aulenbach, and R.P. Hooper. 2001. Nitrogen Input to the Gulf of Mexico. *Journal of Environmental Quality* 30:329-336.
- Gordon, C., C. Cooper, C.A. Senior, H. Banks, J.M. Gregory, T.C. Johns, J.F.B. Mitchell and R.A. Wood. 2000. The Simulation of SST, Sea Ice Extents and Ocean Heat Transports in a Version of the Hadley Centre Coupled Model without Flux Adjustments. *Climate Dynamics* 16(2-3):147-168.
- Hadley Centre. 2003. *Climate Change Observations and Predictions: Recent Research on Climate Change Science from the Hadley Centre*. Hadley Centre, Met Office, Department for Environment, Food and Rural Affairs. Exeter, United Kingdom. <http://www.met-office.gov.uk/research/hadleycentre/pubs/brochures/> (accessed in July 18, 2004).
- Hamlet, A.F. and D.P. Lettenmaier. 1999. Effects of Climate Change on Hydrology and Water Resources Objectives in the Columbia River Basin. *Water Resources Bulletin* 35(6):1597-1623.
- Hendry, G.R., K.F. Lewin, and K.F., Nagy. 1993. Free Air Carbon Dioxide Enrichment: Development, Progress, Results. *Vegetatio* 104/105:17-31.
- Hubbard, C.M. 1998. *Hydrologic Modeling of the Missouri River in a Climate Change Model*. MS Thesis. University of Nebraska-Lincoln, Lincoln, Nebraska.
- IPCC. 2001. *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. J.T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell, and C.A. Johnson (Editors). Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom.
- Jha, M., Z. Pan, E.S. Takle, and R. Gu. 2004. Impacts of Climate Change on Stream Flow in the Upper Mississippi River Basin: A Regional Climate Model Perspective. *Journal of Geophysical Research* 109:D09105.
- Jha, M., Gassman, P.W., Secchi, S., Gu, R., Arnold, J.G., 2003b. Hydrological simulations of the Maquoketa River Watershed. *In: Proceedings of the AWRA Specialty Conference: Agricultural Hydrology and Water Quality, Kansas City, Missouri, 12-14 May, 2003*. Eds.: J.D. Williams and D.W. Kolpin. American Water Resources Association, Middleburg, Virginia.
- Johns, T.C., R.E. Carnell, J.F. Crossley, J.M. Gregory, J.F.B. Mitchell, C.A. Senior, S.F.B. Tett, and R.A. Wood. 1997. The Second Hadley Centre Coupled Ocean-Atmosphere GCM: Mode Description, Spinup and Validation. *Climate Dynamics* 13:103-134.

- Karl, T.R. and W.R. Riebsame. 1989. The Impact of Decadal Fluctuations in Mean Precipitation and Temperature on Runoff: A Sensitivity Study over the United States. *Climatic Change* 15:423-43.
- Klassen, J.F. 1997. Climate Change Impacts on the Hydrology of Spring Creek Basin in the Black Hills of South Dakota Using Soil and Water Assessment Tool. MS Thesis, South Dakota School of Mines and Technology, Rapid City, South Dakota, 67pp.
- Knox, J.C. 2002. Sensitivity of Large Upper Mississippi River Floods to Climate Change. http://gsa.confex.com/gsa/2002AM/finalprogram/abstract_46957.htm (accessed in July 18, 2004).
- Leavesley, G.H. 1994. Modeling the Effects of Climate Change on Water Resources: A Review. *Climatic Change* 28:159-177.
- Lettenmaier, D.P., A.W. Wood, R.N. Palmer, E.F. Wood, and E.Z. Stakhiv. 1999. Water Resources Implications of Global Warming: A U.S. Regional Perspective. *Climatic Change* 43:537-579.
- McCabe, G.J. and D.M. Wolock. 1999. General-Circulation-Model Simulations of Future Snowpack in the Western United States. *Journal of the American Water Resources Association* 35(6):1473-1484.
- Miles, E.L., A.K. Snover, A.F. Hamlet, B. Callahan, and D. Fluharty. 2000. Pacific Northwest Regional Assessment: The Impacts of Climate Variability and Climate Change on the Water Resources of the Columbia River Basin. *Journal of the American Water Resources Association* 36(2):399-420.
- Mockus, V. 1969. Hydrologic soil-cover complexes. *In: SCS National Engineering Handbook, Section 4, Hydrology*. U.S. Department of Agriculture, Soil Conservation Service, Washington, D.C. p. 10.1-10.24.
- Mote, P.W., E.A. Parson, A.F. Hamlet, W.S. Keeton, D. Lettenmaier, N. Mantua, E.L. Miles, D.W. Peterson, D.L. Peterson, R. Slaughter, and A.K. Snover. 2003. Preparing for Climatic Change: The Water, Salmon, and Forests of the Pacific Northwest. *Climatic Change* 61(1):45-88.
- Nash, L. and Gleick, P.H. 1991. Sensitivity of Streamflow in the Colorado Basin to Climate Change. *Journal of Hydrology* 125:221-241.
- Neitsch, S.L., J.G. Arnold, J.R. Kiniry, and J.R. Williams. 2002. Soil and Water Assessment Tool Theoretical Documentation, Version 2000 (Draft). Blackland Research Center, Texas Agricultural Experiment Station, Temple, Texas. <http://www.brc.tamus.edu/swat/swat2000doc.html> (accessed in July 18, 2004).

- NSF. 2001. Climate Change Impacts on the United States: The Potential Consequences of Climate Variability and Change. Foundation: A Report of the National Assessment Synthesis Team, U.S. Global Change Research Program. National Science Foundation. Cambridge University Press, Cambridge, United Kingdom.
<http://www.usgcrp.gov/usgcrp/Library/nationalassessment/foundation.htm> (accessed in July 18, 2004).
- Nusser, S.M. and J.J. Goebel. 1997. The National Resources Inventory: a Long-Term Multi-Resource Monitoring Programme. *Environmental and Ecological Statistics* 4:181-204.
- Pan, Z., J.H. Christensen, R.W. Arritt, W.J. Gutowski, Jr., E.S. Takle, F. Otieno. 2001. Evaluation of Uncertainties in Regional Climate Change Simulations. *Journal of Geophysical Research* 106(D16):17,737-17,751.
- Payne, J.T., A.W. Wood, A.F. Hamlet, R.N. Palmer, and D.P. Lettenmaier. 2003. Mitigating the Effects of Climate Change on the Water Resources of the Columbia River Basin. *Climatic Change* (in press).
- Rabalais, N.N., R.E. Turner, and D. Scavia. 2002. Beyond Science into Policy: Gulf of Mexico Hypoxia and the Mississippi River. *BioScience* 52(2):129-142.
- Revelle, R.R., and P.E. Waggoner. 1983. Effects of a Carbon Dioxide Induced Climate Change on Water Supplies in the Western United States. *In*: *Changing Climate*. Report to the Carbon Dioxide Assessment Committee. National Academy Press, Washington D.C.
- Rosenberg, N.J., R.A. Brown, R.C. Izaurralde, and A.M. Thomson. 2003. Integrated Assessment of Hadley Centre (HadCM2) Climate Change Projections on Agricultural Productivity and Irrigation Water Supply in the Conterminous United States I. Climate Change Scenarios and Impacts on Irrigation Water Supply Simulated with the HUMUS Model. *Agricultural and Forest Meteorology* 117(1-2):73-96.
- Rosenberg, N.J., P.E. Crosson, K.D. Frederick, W.E. Easterling, III, M.S. McKenney, M.D. Bowes, R.A. Sedjo, J. Darmstadter, L.A. Katz, and K. M. Lemon. 1993. The MINK Methodology: Background and Baseline. *Climatic Change* 24:
- Rosenberg, N.J., D.J. Epstein, D. Wang, L. Vail, R. Srinivasan, and J.G. Arnold. 1999. Possible Impacts of Global Warming on the Hydrology of the Ogallala Aquifer Region. *Climatic Change* 42:677-692.
- Rosenthal, W.D., R. Srinivasan, and J.G. Arnold. 1995. Alternative River Management using a Linked GIS-Hydrology Model. *Transactions of the ASAE* 38(3), 783-790.
- Saleh, A., J.G. Arnold, P.W. Gassman, L.M. Hauck, W.D. Rosenthal, J.R. Williams, and A.M.S. McFarland. 2000. Application of SWAT for the Upper North Bosque River Watershed. *Transactions of the ASAE* 43(5):1077-1087.

- Santhi, C., J.G. Arnold, J.R. Williams, W.A. Dugas, R. Srinivasan, and L.M. Hauck. 2001. Validation of the SWAT Model on a Large River Basin with Point and Nonpoint Sources. *Journal of the American Water Resources Association* 37(5):1169-1188.
- Seaber, P.R., F.P. Kapinos, and G.L. Knapp. 1987. Hydrologic Units Maps. U.S. Geological Survey Water-Supply Paper 2294. Reston, VA.
- Srinivasan, R., T.S. Ramanarayanan, J.G. Arnold, and S.T. Bednarz. 1998. Large Area Hydrologic Modeling and Assessment Part II: Model Application. *Journal of the American Water Resources Association* 34(1):73-89.
- Stockle, C.O., J.R. Williams, N.J. Rosenberg, and C.A. Jones. 1992. A Method for Estimating the Direct and Climatic Effects of Rising Atmospheric Carbon Dioxide on Growth and Yield of Crops: Part I – Modification of the EPIC Model for Climate Change Analysis. *Agriculture Systems* 38:225-238.
- Stone, M.C., R.H. Hotchkiss, C.M. Hubbard, T.A. Fontaine, L.O. Mearns, and J.G. Arnold. 2001. Impacts of Climate Change on Missouri River Basin Water Yield. *Journal of the American Water Resources Association* 37(5):1119-1130.
- Stone, M.C., R.H. Hotchkiss, and L.O. Mearns. 2003. Water Yield Responses to High and Low Spatial resolution climate change scenarios in the Missouri River Basin. *Geophysical Research Letters* 30(4): 35-1-35-4.
- Stonefelt, M.D., T.A. Fontaine, and R.H. Hotchkiss. 2000. Impacts of Climate Change on Water Yield in the Upper Wind River Basin. *Journal of the American Water Resources Association* 36(2):321-336.
- Thomson, A.M., R.A. Brown, N.J. Rosenberg, R.C. Izaurralde, D.M. Legler, and R. Srinivasan. 2003. Simulated Impacts of El Niño/Southern Oscillation on United States Water Resources. *Journal of the American Water Resources Association* 39(1):137-148.
- Tyree, M.T. and Alexander, J.D. 1993. Plant Water Relations and the Effects of Elevated CO₂: A Review and Suggestions for Future Research. *Vegetatio* 104/105:47-62.
- USDA. 1994. State Soil Geographic (STATSGO) Data Base: Data Use Information. Miscellaneous Publication Number 1492. U.S. Department of Agriculture, Natural Resource Conservation Service, National Soil Survey Center, Lincoln, Nebraska.
- USEPA. 2001. BASINS 3.0: Better Assessment Science Integrating Point and Nonpoint Sources. U.S. Environmental Protection Agency, Office of Water, Office of Science and Technology, Washington, D.C. <http://www.epa.gov/ost/BASINS/> (accessed in July 18, 2004).

- van Katwijk, V.F., A. Rango, and A.E. Childress. 1993. Effect of Simulated Climate Change on Snowmelt Runoff Modeling in Selected Basins. *Water Resources Bulletin* 29(5):755-766.
- Watterson, I.G., M.R. Dix, H.B. Gordon, and J.L. McGregor. 1995. The CSIRO Nine-Level Atmospheric General Circulation Model and Its Equilibrium Present and Doubled CO₂ Climates. *Australian Meteorology Magazine* 44:111-125.
- Wilby, R.L., L.E. Hay, and G.H. Leavesley. 1999. A Comparison of Downscaled and Raw GCM Output: Implications for Climate Change Scenarios in the San Juan River Basin, Colorado. *Journal of Hydrology* 225:67-91.
- Wolock, D.M. and G.J. McCabe. 1999. Estimates of Runoff Using Water-Balance and Atmospheric General Circulation Models. *Journal of the American Water Resources Association* 35(6):1341-1350.

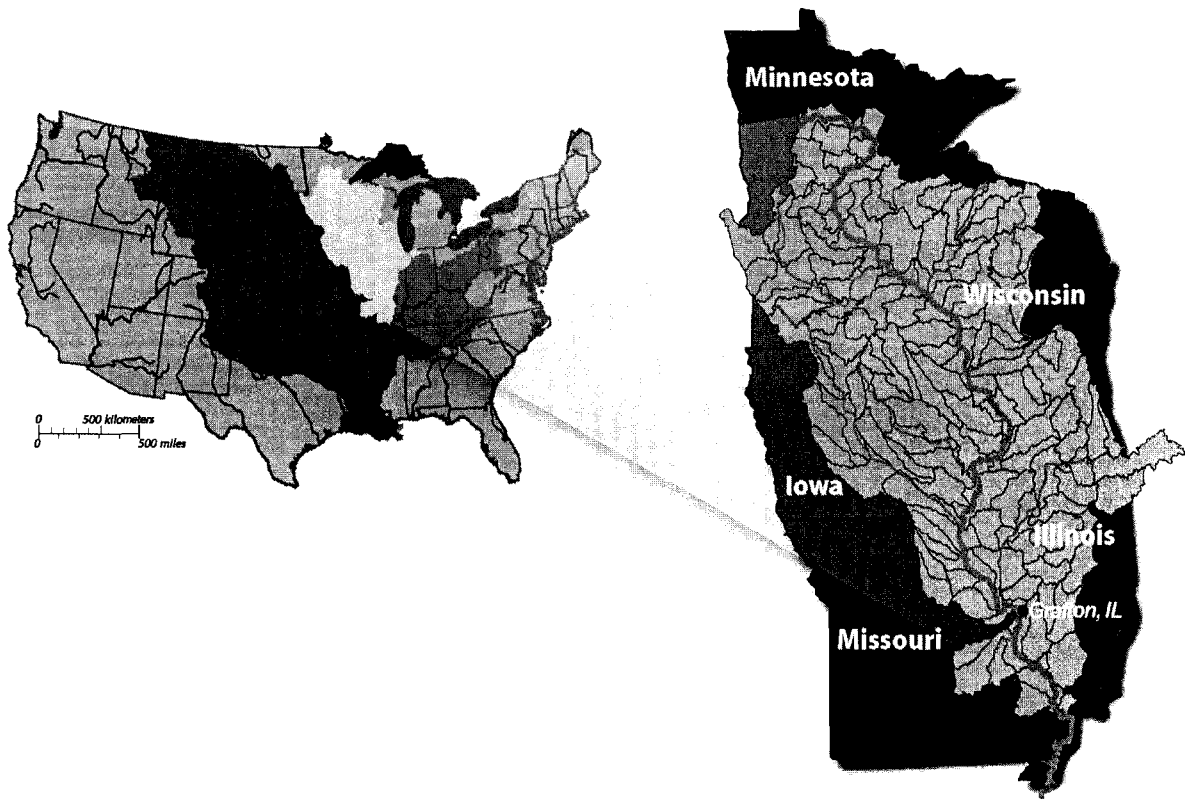


Figure 1. Location of Grafton, IL and the 131 USGS 8-digit watersheds within the Upper Mississippi River Basin (URMB), and the location of the UMRB within the Mississippi River Basin.

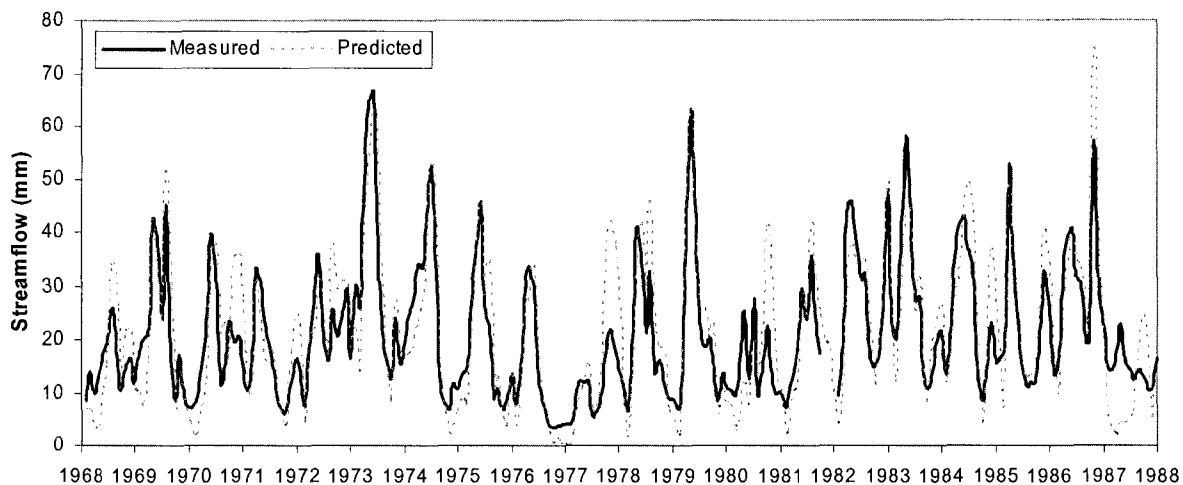


Figure 2. Monthly time-series comparison of measured versus predicted streamflow at Grafton, IL during the 20-year calibration period (1968-87).

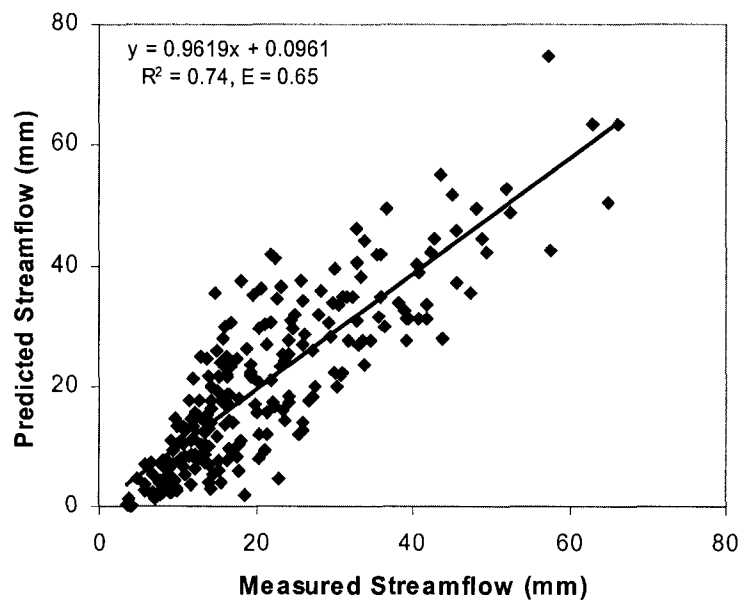


Figure 3. Regression plot of predicted versus measured monthly streamflow values for the 20-year calibration period (1968-87).

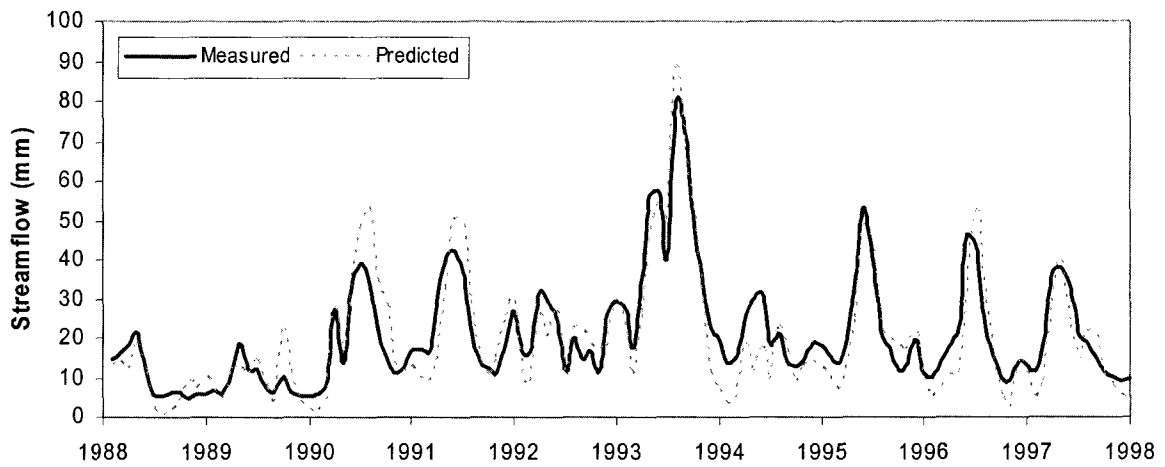


Figure 4. Monthly time-series comparison of measured versus predicted streamflow at Grafton, IL during the 10-year validation period (1988-97).

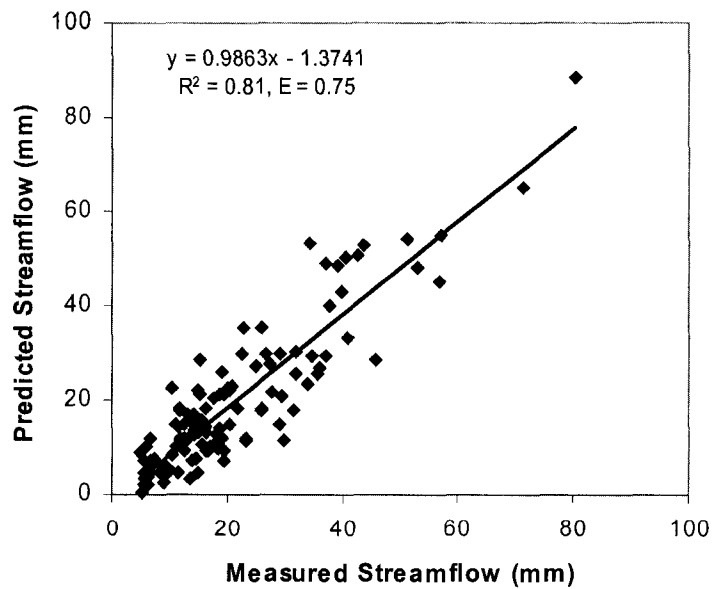


Figure 5. Regression plot of predicted versus measured monthly streamflow values for the 10-year validation period (1988-97).

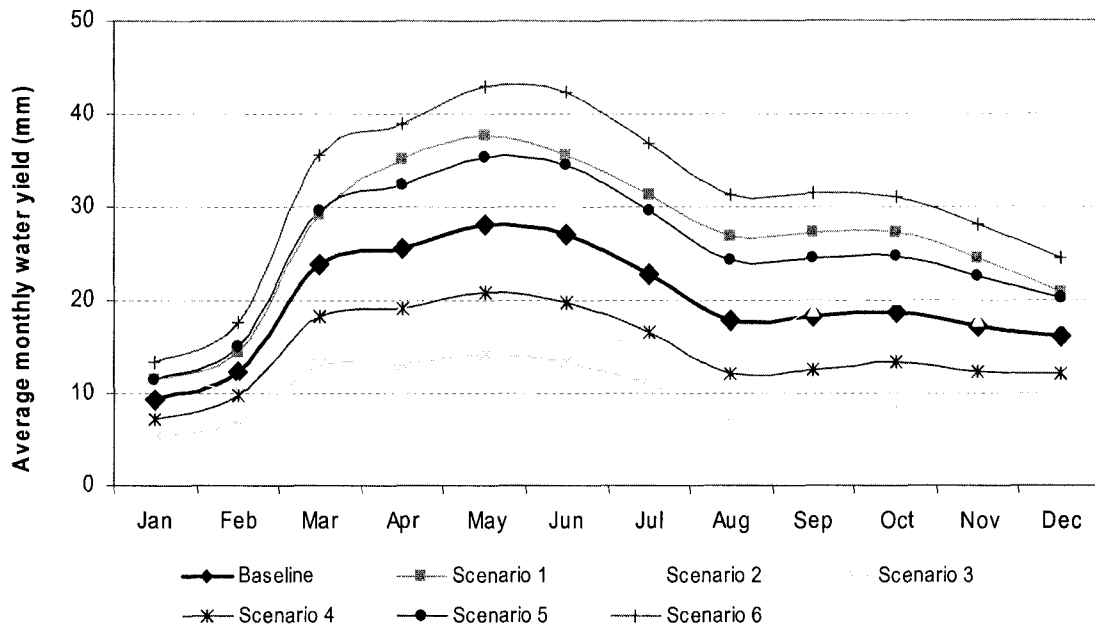


Figure 6. Change in average monthly streamflows predicted for scenarios 1-6 relative to the baseline over the 20-year simulation period.

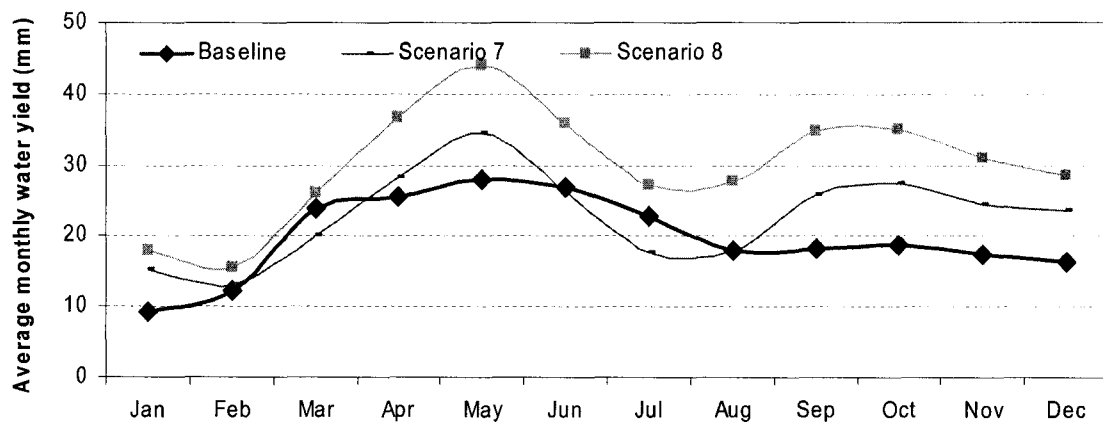


Figure 7. Change in average monthly streamflows predicted for scenarios 7 and 8 relative to the baseline over the 20-year simulation period.

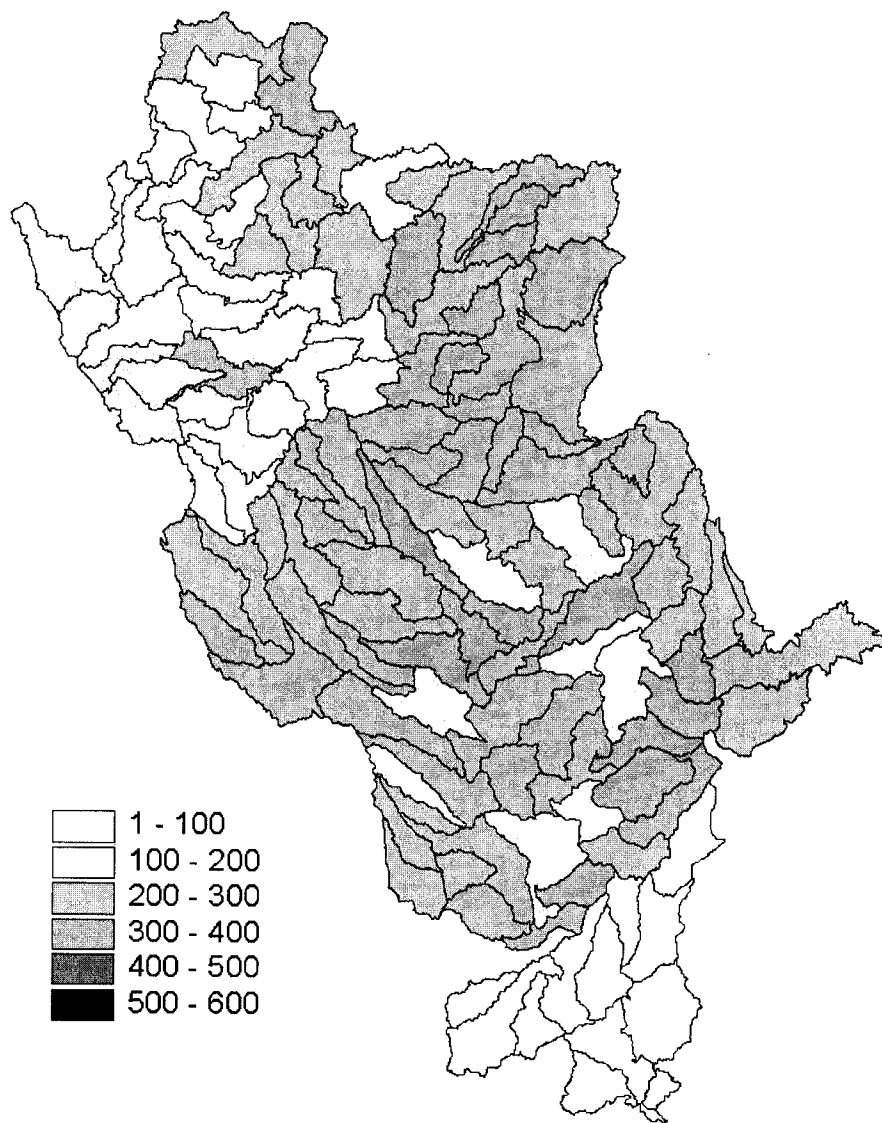


Figure 8. Spatial distribution of predicted streamflows for the UMRB baseline scenario, shown as a function of 8-digit watersheds.

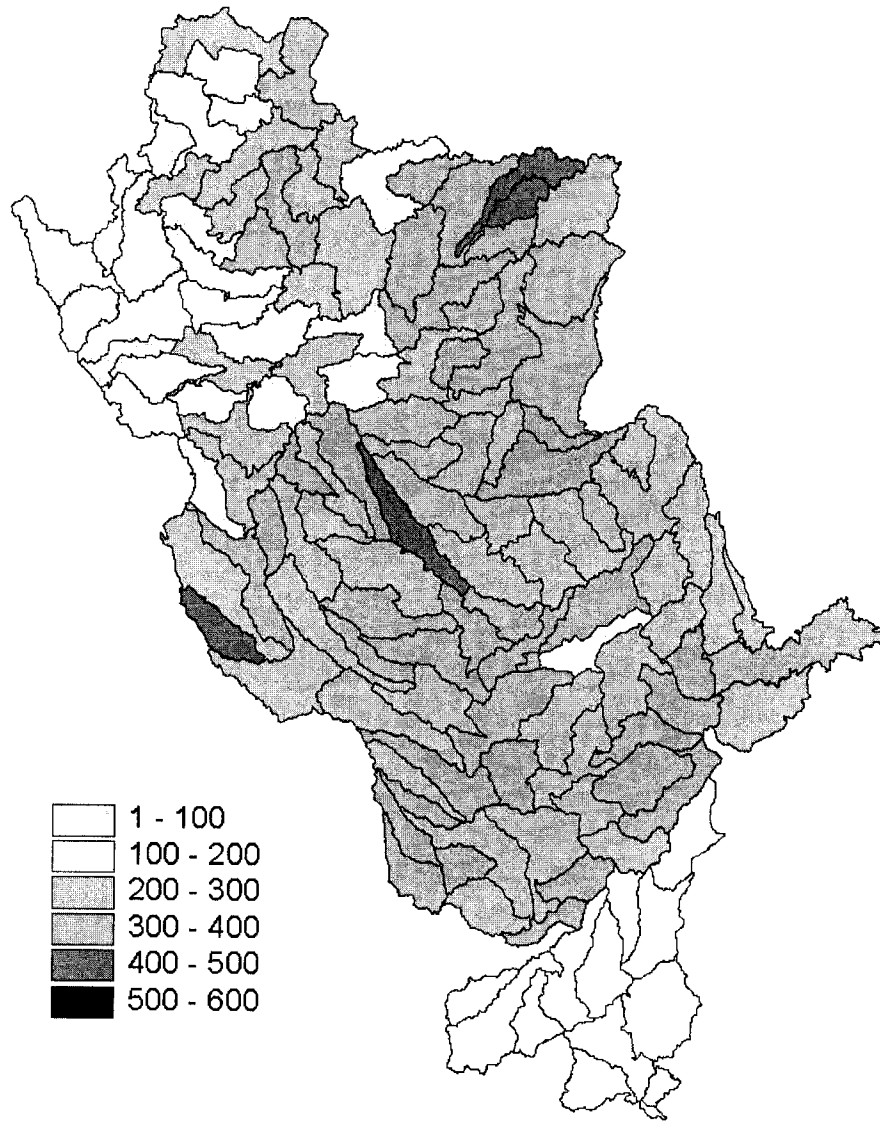


Figure 9. Spatial distribution of predicted streamflows for the UMRB scenario 7, shown as a function of 8-digit watersheds.

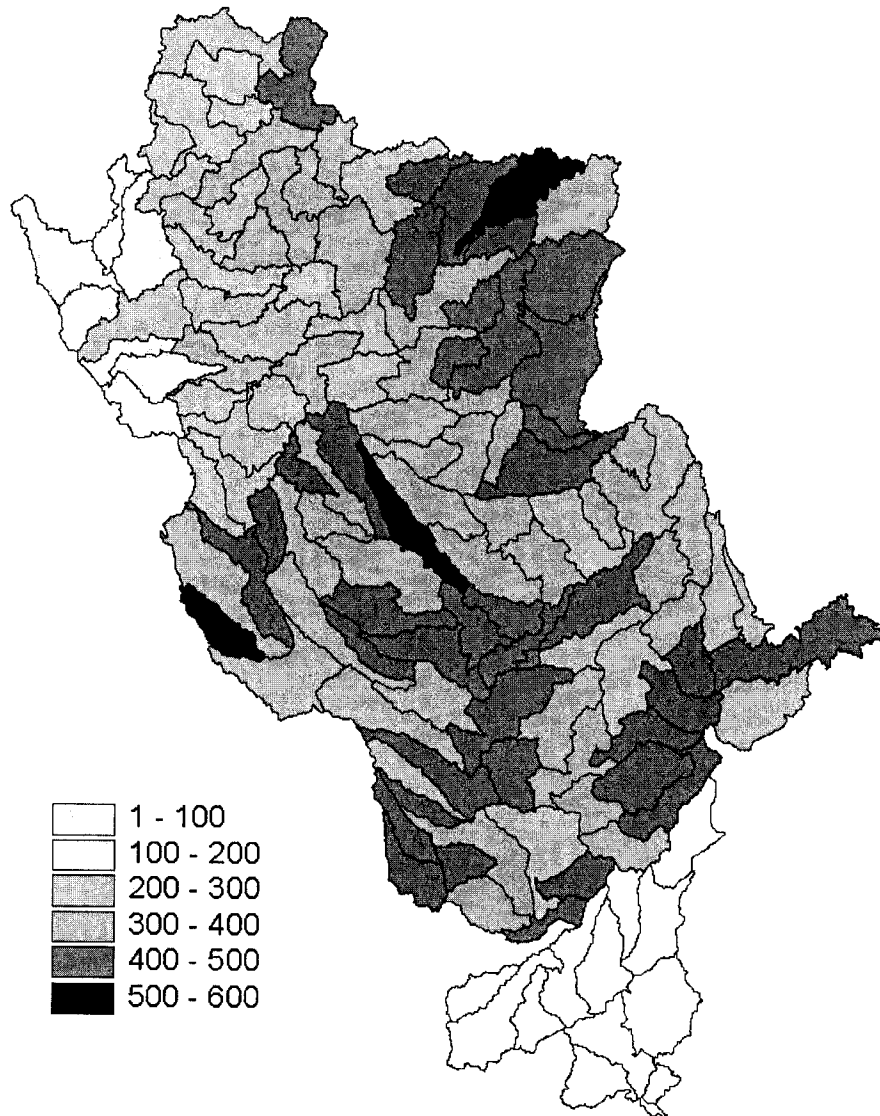


Figure 10. Spatial distribution of predicted streamflows for the UMRB scenario 8, shown as a function of 8-digit watersheds.

Table 1. Hydrologic calibration parameters and their values for the UMRB.

Calibration parameter ^a	Symbol	Initial Estimates	Calibrated values
Curve Number for moisture condition II	CN2	- ^b	- 10% ^c
Soil evaporation compensation factor	ESCO	0.95	0.80
Plant uptake compensation factor	EPCO	1.0	1.0
Soil available water capacity (mm)	SOL_AWC	- ^b	- 0.02 ^d
Groundwater revap coefficient	GW_REVAP	0.02	0.02
Groundwater delay time (day)	GW_DELAY	31	4
Threshold depth for baseflow to occur (mm)	GWQMN	0	0
Threshold depth for re-evaporation to occur (mm)	REVAPMN	1.0	1.0

^aDetailed descriptions are given in Neitsch et al. (2001).

^bA range of values were used for CN2 and SOL_AWC; e.g., 60, 69, 75, and 78 were the original CN2 values selected by AVSWAT for the agricultural (AGRL) landuse area.

^cAll CN2 values were reduced by 10% for the final calibrated simulations.

^dAll SOL_AWC values were reduced by 0.02 mm for the final calibrated simulations.

Table 2. Assumed changes in relevant climate parameters on a monthly basis for each of the eight climate scenarios^a.

Scenario	Climate parameter	Month											
		J	F	M	A	M	J	J	A	S	O	N	D
1	CO ₂ (ppm)	2×	2×	2×	2×	2×	2×	2×	2×	2×	2×	2×	2×
2	Temperature (°C)	4	4	4	4	4	4	4	4	4	4	4	4
3	Precipitation (%)	-20	-20	-20	-20	-20	-20	-20	-20	-20	-20	-20	-20
4	Precipitation (%)	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10
5	Precipitation (%)	10	10	10	10	10	10	10	10	10	10	10	10
6	Precipitation (%)	20	20	20	20	20	20	20	20	20	20	20	20
7	Temperature (°C)	4.6	7.2	7.8	5.6	3.6	4.3	4.8	4.4	5.3	4.3	5.8	4.0
	Precipitation (%)	11	11	24	24	24	6	6	6	14	14	14	11
8	CO ₂ (ppm)	2×	2×	2×	2×	2×	2×	2×	2×	2×	2×	2×	2×
	Temperature (°C)	4.6	7.2	7.8	5.6	3.6	4.3	4.8	4.4	5.3	4.3	5.8	4.0
	Precipitation (%)	11	11	24	24	24	6	6	6	14	14	14	11

^aScenarios 1-6 reflect hypothetical changes in CO₂ emissions or climate responses chosen for this study; scenarios 7 and 8 are based on the climate projection by Giorgi et al. (1998).

Table 3. Comparisons between measured and predicted annual average streamflows during 1971-90 for the Mississippi River at Grafton, Illinois and 11 upstream subwatersheds.

USGS Station Name	USGS Station#	Drainage Area (km ²)	Measured flow (mm)	Predicted flow (mm)	Difference (%)
Mississippi River near Royalton, MN	5267000	30,175	165	173	4.8
Minnesota River near Jordan, MN	5330000	43,715	93	105	12.9
St Croix River at St Croix Falls, WI	5340500	20,030	238	246	3.4
Chippewa River at Durand, WI	5369500	24,722	322	319	-0.9
Wisconsin River at Muscoda, WI	5407000	28,926	306	310	1.3
Rock River near Joslin, IL	5446500	25,401	271	269	-0.7
Iowa River at Wapello, IA	5465500	32,796	245	239	-2.4
Skunk River at Augusta, IA	5474000	11,246	243	234	-3.7
Des Moines River at St Francis, IA	5490500	37,496	192	197	2.6
Illinois River at Valley City, IL	5586100	74,603	323	279	-13.6
Maquoketa River at Maquoketa, IA	5418500	4,827	261	232	-11.1
Mississippi River at Grafton, IL	5587450	447,539	243	228	-6.2

Table 4. Average annual hydrologic balance components simulated by SWAT for the UMRB baseline and eight climatic scenarios.

Hydrologic budget components	Baseline	Scenario							
		1	2	3	4	5	6	7	8
----- mm -----									
Precipitation	836	836	836	669	753	920	1004	949	949
Snowfall	92	92	54	74	83	102	111	47	47
Snowmelt	91	91	54	73	82	100	109	46	46
Surface runoff	97	115	74	48	71	126	158	99	116
Groundwater flow	146	213	132	73	108	185	224	181	250
Evapotranspiration	588	503	623	545	569	603	615	661	574

Table 5. Predicted relative changes in flows for the Mississippi River at Grafton, IL for the eight climate change scenarios.

Month	Baseline (mm)	Scenario							
		1	2	3	4	5	6	7	8
		----- % change -----							
Jan	9.3	23	25	-45	-23	22	45	63	92
Feb	12.4	17	-12	-43	-22	22	43	6	25
Mar	23.8	23	-37	-46	-23	24	49	-16	10
Apr	25.6	37	-25	-49	-25	26	52	10	43
May	28.1	34	-20	-49	-26	26	53	23	57
Jun	27.0	32	-28	-51	-26	28	57	-3	33
Jul	22.8	37	-39	-52	-27	30	61	-22	19
Aug	17.8	51	-22	-58	-31	36	76	0	55
Sep	18.2	49	5	-57	-31	35	72	42	91
Oct	18.8	45	7	-54	-29	32	65	45	86
Nov	17.3	41	4	-54	-29	30	62	42	79
Dec	16.2	29	11	-48	-25	25	51	45	76
Annual Avg.	237.3	35	-15	-51	-27	28	58	15	52

CHAPTER 4. IMPACTS OF CLIMATE CHANGE ON STREAM FLOW IN THE UPPER MISSISSIPPI RIVER BASIN: A REGIONAL MODEL PERSPECTIVE

A paper published in the *Journal of Geophysical Research* (May, 2004)

Manoj Jha, Zaitao Pan, Eugene S. Takle, and Roy Gu

Abstract

Impact of climate change on stream flow in the Upper Mississippi River Basin is evaluated by use of a regional climate model (RCM) coupled with a hydrologic model - Soil and Water Assessment Tool (SWAT). The RCM we used resolves, at least partially, some fine-scale dynamical processes that are important contributors to precipitation in this region and that are not well simulated by global models. The SWAT model was calibrated and validated against measured stream flow data using observed weather data and inputs from the EPA BASINS GIS/database system. Combined performance of the SWAT and RCM was examined using observed weather data as lateral boundary conditions in the RCM. The SWAT and RCM performed well, especially on an annual basis. Potential impacts of climate change on water yield and other hydrologic budget components were then quantified by driving SWAT with current and future scenario climates. Twenty one percent increase in future precipitation simulated by the RCM produced 18% increase in snowfall, 51% increase in surface runoff, and 43% increase in groundwater recharge, resulting in 50% net increase in total water yield in the UMRB on an annual basis. Uncertainty analysis showed the simulated change in stream flow substantially exceeded model biases of the combined modeling system (with largest bias of 18%). While this does not necessarily give us high confidence in the actual climate change that will occur, it does demonstrate that the climate

change “signal” stands out from the climate modeling (global + regional) and impact assessment modeling (SWAT) “noise.”

1. Introduction

Stream flow characteristics, both mean and interannual variability, of the Upper Mississippi River (UMRB) have far-reaching implications for the Central US. Following closely on the heels of the massive drought of 1988 in this region, which stranded barges below St. Louis, MO [*Glantz*, 1988], the Great Flood of 1993 created an \$18 billion impact [*Changnon*, 1996]. Analysis of this event exposed the profound range of implications, including environmental effects, economic effects, impacts on government entities, social impacts, and impact on a wider range of public policies [*Changnon*, 1996]. On the basis of a substantial amount of scientific analysis and retrospective diagnosis of decision-maker actions before, during and after this event, the summary of *Changnon* [1996] concluded with seven ‘lessons learned’ and some ‘unresolved key issues,’ among them being “...a great need to develop more sophisticated river basin models that allow drastically improved flood forecasts.” [*Changnon*, 1996; p. 318].

We have examined this need for more sophisticated modeling procedures in the context of climate change to expose the strengths and weaknesses of linking global and regional climate models to a stream flow model to calculate stream flows consistent with a future climate scenario.

Future scenario climates for mid to end of the 21st century as simulated by global climate models show generally a warming over the U.S. Large uncertainties accompany global model projections of future changes in global mean precipitation, but increase on annual

basis seems to be most likely. Estimates of inter-model consistency in downscaled precipitation from global climate models [IPCC, 2001] for the Central U.S. show a small increase in December-January-February but lack of consistency on the sign of change or possibly a small decrease for June-July-August.

Regional climates consistent with global changes are created by downscaling global climate model (GCM) results either by statistical or dynamical (regional climate model - RCM) methods. Numerous studies based on statistical methods for exploring impact of climate change at the watershed scale are summarized in the latest IPCC impacts report [IPCC, 2001b]. *Giorgi et al.* [1994] showed that a nested regional model produced a more realistic simulation of precipitation over the U. S. than the driving global model alone and also the estimated changes in climate were different: precipitation changes differed locally in magnitude, sign, and spatial and seasonal details.

Several studies have investigated the impacts of climate change on the hydrology of a watershed. *Stone et al.* [2001] used RegCM [*Giorgi et al.*, 1993] to assess the impacts of climate change on water resources in the Missouri River Basin. They found dramatic increase in water yield (100% or more) for the northern region of the basin while the southern region showed a decrease of up to 80%.

In a follow-up study, *Stone et al.* [2003] examined the impact of model resolution on water yield by using the SWAT model on the Missouri River Basin for a 25-yr historic period and for GCM and RCM doubled CO₂ scenarios used to modify the historic data. They found that, compared to the historic climate, water yields were significantly greater for the doubled CO₂ scenarios for both GCM and RCM. They also found that yields produced by SWAT from RCM results were significantly greater than those simulated from GCM

results and that there were substantial differences in RCM- and GCM-induced water yields across sub-basins. They concluded that choice of climate model resolution affects estimation of water yield under climate change.

Arnell et al. [2003] analyzed different ways of constructing climate change scenarios from a single climate model and found that these different scenarios could lead to differences in runoff of 10 to 20%. They use a regional climate model as their primary downscaling method and compare results with different downscaling techniques, including simple interpolation of global-model results and a time-slice experiment. They also examine the relative merits of using climate model data directly to assess impacts of climate change vs. applying a climate change signal to an observed baseline climate. The reports of both *Stone et al.* [2003] and *Arnell et al.* [2003] address uncertainties relating to spatial scales of the scenarios, but our study goes one step further to explicitly look at error in impacts resulting from the RCM itself. The availability of reanalysis data over a data-rich region such as the continental US allows comparison of impacts resulting from an RCM driven by reanalyzed observations vs. impacts derived from observed surface data, thereby allowing RCM error to be quantified.

We have used 10-year simulations of contemporary (current) and future scenario climates for the U.S. to provide a physically consistent set of climate variables for input to a watershed scale simulation model. The objective of this study was to explore stream flow, and model-introduced uncertainty thereof, in a future scenario climate by introducing a regional climate model to dynamically downscale global model results to create data required by the stream flow model. The regional climate model is driven by a global model or global reanalysis of observed data to explore the accuracy of such a modeling system to simulate

current conditions and to explore the precision (not accuracy) of the system for projecting stream flows consistent with a future scenario climate. By its use of three sets of 10-year simulations of climate for the region, this study provides a first step in exploring the potential impact on stream flow of fine scale dynamics such as the low-level jet (as opposed to the role of orographically induced precipitation) that are known to influence precipitation in this region.

2. Models and Input Data

2.1. SWAT Model

The SWAT model [Arnold *et al.*, 1998] is a long-term, continuous watershed simulation model. It operates on a daily time step and is designed to assess the impact of management on water, sediment, and agricultural chemical yields. The model is physically based, computationally efficient, and capable of simulating a high level of spatial details by allowing the watershed to be divided into a large number of sub-watersheds. Major model components include weather, hydrology, soil temperature, plant growth, nutrients, pesticides, and land management. The model has been validated for several watersheds [Rosenthal *et al.*, 1995; Arnold and Allen, 1996; Srinivasan *et al.*, 1998; Arnold *et al.*, 1999; Saleh *et al.*, 2000; Santhi *et al.*, 2001].

In SWAT, a watershed is divided into multiple sub-watersheds, which are then further subdivided into unique soil/landuse characteristics called hydrologic response units (HRUs). The water balance of each HRU in SWAT is represented by four storage volumes: snow, soil profile (0-2m), shallow aquifer (typically 2-20m), and deep aquifer (>20m). Flow generation, sediment yield, and non-point-source loadings from each HRU in a sub-

watershed are summed, and the resulting loads are routed through channels, ponds, and/or reservoirs to the watershed outlet. Hydrologic processes are based on the water balance equation:

$$SW_t = SW_0 + \sum_{i=1}^t (R - Q_{surf} - ET - Q_{perc} - QR) \quad (1)$$

where SW_t is the final soil water content (mm), SW_0 is the initial soil water content on day i (mm), and R , Q_{surf} , ET , Q_{perc} , and QR are the daily amounts (in mm) of precipitation, runoff, evapotranspiration, percolation, and groundwater flow on day i respectively. The soil profile is subdivided into multiple layers that support soil water processes including infiltration, evaporation, plant uptake, lateral flow, and percolation to lower layers. The soil percolation component of SWAT uses a storage routing technique to simulate flow through each soil layer in the root zone. Downward flow occurs when field capacity of a soil layer is exceeded and the layer below is not saturated. Percolation from the bottom of the soil profile recharges the shallow aquifer. If temperature in a particular layer is 0°C or below, no percolation is allowed from that layer. Lateral subsurface flow in the soil profile is calculated simultaneously with percolation. Groundwater flow contribution to total stream flow is simulated by routing a shallow aquifer storage component to the stream [Arnold *et al.*, 1993].

Surface runoff from daily rainfall is estimated with the modified SCS curve number method, which estimates the amount of runoff based on local land use, soil type, and antecedent moisture condition. A provision for estimating runoff from frozen soil is also included. Snow melts on days when the daily maximum temperature exceeds 0°C . Melted

snow is treated the same as rainfall for estimating runoff and percolation. Channel routing is simulated using the Muskingum method. The model computes evaporation from soils and plants separately. Potential evapotranspiration is modeled with the Hargreaves method. Potential soil water evaporation is estimated as a function of potential ET and leaf area index (area of plant leaves relative to the soil surface area). Actual soil evaporation is estimated by using exponential functions of soil depth and water content. Plant water evaporation is simulated as a linear function of potential ET, leaf area index and root depth and can be limited by soil water content. More detailed descriptions of the model can be found in *Arnold et al.* [1998].

2.2. UMRB Watershed

The UMRB has a drainage area of approximately 445,000 km² up to the point just before confluence of the Missouri and Mississippi Rivers (Grafton, IL) and covers parts of seven states: Minnesota, Wisconsin, South Dakota, Iowa, Illinois, Missouri, and Indiana (Fig. 1). Land cover in the basin is diverse, including agricultural lands, forest, wetlands, lakes, prairies, and urban area. The river system supports commercial navigation, recreation, and a wide variety of ecosystems. In addition, the region's more than 30 million residents rely on river water for public and industrial supplies, power plant cooling, wastewater assimilation, and other uses.

The UMRB is in the region unique to the U.S. where summertime mesoscale convective precipitation [*Wallace and Hobbs*, 1977] is dependent on nocturnal water vapor flux convergence [*Anderson et al.*, 2003]. Neither the NNR [*Higgins et al.*, 1997] nor global climate models [*Ghan et al.*, 1995] capture this essential mechanism. Finer grid spacing is

needed to resolve the fine-scale dynamical processes that lead to timing, location, and amounts of precipitation [Anderson, *et al.*, 2003]. Most, but not all, regional models (including the one used herein) are able to capture the nocturnal maximum in hourly precipitation in this region [Anderson *et al.*, 2003], which is an indicator that nocturnal moisture convergence at the outflow of the low-level jet is being simulated. For this reason, we expect that use of a regional climate model will improve on stream flow simulations driven by either reanalysis or global climate models.

The SWAT model requires a variety of detailed information describing the watershed. Land use, soil and topography data of the UMRB were obtained from the Better Assessment Science Integrating Point and Nonpoint Sources (BASINS) package version 3 [USEPA, 2001]. Land use categories available from BASINS are relatively simplistic, providing (for instance) only one category for agricultural use (defined as “Agricultural Land-Generic”). Agricultural lands cover almost 75% of the area. The soil data available in BASINS come from the State Soil Geographic (STATSGO) database [USDA, 1994], which contains soil maps at a 1:25,000 scale. The STATSGO map unit is linked to the Soil Interpretations Record attribute database that provides the proportionate extent of component soils and soil layer physical properties (texture, bulk density, available water capacity, saturated conductivity, soil albedo, and organic carbon) for up to 10 layers. The STATSGO soil map units and associated layer data were used to characterize the simulated soils for the SWAT analyses. Topographic information is provided in BASINS in the form of Digital Elevation Model (DEM) data. The DEM data were used to generate stream networks using the ArcView interface of SWAT (called AVSWAT). Based on the generated stream networks, 119 sub-watersheds were then delineated up to the point just before the confluence with the

Missouri River (see Fig. 1). The delineated sub-watersheds follow the boundaries of the USGS defined 8-digit HUCs (Hydrologic Unit Codes). The HRUs were then created considering dominant soil/landuse category within each sub-watershed, i.e. each sub-watershed was assumed to be constituted with a single soil type and land use. The management operations for each HRU were the default values produced by AVSWAT. These management operations consist of planting, harvesting, and automatic fertilizer applications for the agricultural lands. No attempt was made to improve the management data because the main intent of the present study was to assess the impacts of climate change on hydrology, rather than on water quality of the region.

2.3. Climate Data

SWAT requires daily precipitation, maximum/minimum air temperature, solar radiation, wind speed and relative humidity as meteorological input. In the absence of supplied observations, the weather generator within SWAT uses its statistical database to generate representative daily values for the missing variables for each sub-watershed. Ideally, at least 20 years of records are desired for the weather generator database. The data not supplied from the observations input file were generated internally by the model's weather generator. In this study we supplied daily precipitation and daily maximum and minimum temperature to SWAT either from observations or from the RCM. SWAT defines precipitation to be snow based on the relation of mean surface air temperature (determined from the daily minimum and maximum as $[(T_{\max} + T_{\min})/2]$) to a threshold value established in calibration process.

SWAT accepts one set of weather information for each sub-watershed. The SWAT modeling framework has 119 sub-watersheds upstream of Grafton, IL, so the model requires 119 sets of weather information to produce the observations-driven simulations (e.g., output later referred to as SWAT 1). If more than one observing station falls within a sub-watershed, SWAT chooses the one nearest the sub-watershed centroid. A few sub-watersheds have no observing station within their boundaries, so adjacent stations are used to provide temperature and precipitation data used by SWAT. For these reasons 99 of a possible 160 weather stations within the UMRB were used in this analysis.

We used four sets of climate data to drive SWAT as shown in the left-hand column of boxes in Fig. 2: one observed data set from stations and three sets of RCM simulated climate data. Observed data were extracted from the US COOP database [NCDC, 2003], as compiled by the Variable Infiltration Capacity group (VIC, <http://www.ce.washington.edu/pub/HYDRO/edm/>).

The remaining three sets of climate data were generated using the regional climate model RegCM2 [Giorgi *et al.*, 1993]. The model simulation has a horizontal grid spacing of 52 km [Pan *et al.*, 2001], thereby providing approximately 160 grid points within the UMRB. The simulation domain centered at (100°W, 37.5°N) covers the continental U.S. and includes a buffer zone near the lateral boundaries (far from the UMRB) where the global information was introduced. Lateral boundary data were supplied for every model time step by interpolating 6-hourly data from the reanalysis and GCM. More details on the domain and implementation of boundary conditions for the regional model are described by Pan *et al.* [2001] and Takle *et al.* [1999].

The NCEP/NCAR reanalysis (NNR) dataset [Kalnay *et al.*, 1996] $1.875^\circ \times 1.875^\circ$ grid over the entire globe was downscaled onto RCM 52×52 km grids. NNR combined all available observations for a 40-year period, including the 10-year period of the current study, with a dynamical model to maximize internal physical consistency and is considered to be most accurate in regions such as the UMRB where a relatively dense network of observing stations has provided the raw data. This downscaling simulation was used to examine the RCM's capability in producing observed climate for the specific period (1979-1988).

The other two downscaling simulations are based on the GCM climates (rather than the NNR). The results of the GCM of the Hadley Centre (HadCM2, [Jones *et al.*, 1997]) were used to provide the basic climate information for assessing the impact of climate change and uncertainty in this assessment. The HadCM2 [Jones *et al.*, 1997] is a coupled atmosphere-ocean model that uses a finite difference grid of 2.5° latitude by 3.75° longitude (about 300 km in mid-latitudes). Only three grid points fall within the boundaries of the UMRB, which does not provide sufficient spatial climate detail to capture within-basin heterogeneity of atmospheric dynamical or hydrological processes. We nested a fine grid resolution RCM (RegCM2) into the coarse grid global model to dynamically downscale global information over the continental U.S. The GCM contemporary climate represented by a 10-year window corresponds roughly to 1990's, selected from the HadCM2 simulations without enhanced greenhouse gas (GHG) forcing [Jones *et al.*, 1997]. The future scenario climate is from a transient simulation that assumed a 1% per year increase in effective GHGs after 1990. Sulfate aerosol effects (of secondary importance for this region) were not included in the transient GHG simulations used in this paper. The 10-year window selected for the scenario

climate corresponds to 2040-2049 with CO₂ about 480 ppm. A more detailed description can be found in *Pan et al.* [2001].

Any climate-impacts study based on RCM results will depend strongly on the particular GCM and particular emissions scenario used to force the RCM for future climate. We used the HadCM2 model, which has a transient climate response of 1.7 (1.7° C global temperature rise at time of CO₂ doubling) compared to a mean (standard deviation) value of 1.8 (0.43) for the 19 models listed by the IPCC [*IPCC*, 2001]. The equilibrium sensitivity of HadCM2 is 4.1 whereas the 17 models tabulated by the IPCC have mean (standard deviation) of 3.4 (0.95). For global precipitation change, HadCM2 produced slightly above the mean of models plotted.

Although our regional modeling procedure downscales global fields from outside the continental US and is therefore not dependent on HadCM2 results within the UMRB, it is informative to compare HadCM2 results over UMRB with those of other global models. On a regional basis, HadCM2 had lowest warming of 5 models (3.8 °C vs. mean of 5.2°C) summarized by the IPCC report for central North America for climate change between 2071-2100 and 1961-1990. Global models are highly inconsistent for precipitation amounts in the central North America with means (standard deviations) of +9% (6%) in winter and -9% (18%) in summer. HadCM2 gave about +16% for both seasons.

In summary, HadCM2 is quite near the center of the range of climate sensitivities of global climate models, and for the specific region of our study HadCM2 results are somewhat wetter and slightly cooler than average for global models reported by the *IPCC* [2001].

3. Model Uncertainties and Experimental Design

3.1. Sources of Error

This study is designed to evaluate both the projected change in stream flow due to climate change and the uncertainty or level of confidence in the results. Errors in estimating impact of climate change on stream flow come from (1) uncertainty in the assumption of future GHG scenarios, (2) errors in GCM that translates the GHG emission into future scenario global climate, (3) errors in the downscaling of global results to regional climate (in our case, done by an RCM), (4) errors in SWAT, and (5) errors arising from choices made in combining models (e.g., use of evapotranspiration from the RCM or SWAT).

For this study we have access to only one global model run for one GHG scenario, so we are unable to assess error (1). The GCM has errors in describing the current climate, and hence presumably in the future climate for the same (whatever) reasons. However, the GCM future scenario climate also may have errors emerging from the changes in GHG concentrations or their feedbacks that are not present in simulations of the contemporary climate. We term the GCM error for the contemporary climate as 2a and the additional error due to changes in GHGs as 2b. When models are linked together, the error arising from the linkage is likely not represented by a linear combination of individual model errors. By using various combinations of input conditions to the RCM and SWAT, we can calculate and intercompare different end-product stream flows, thereby gaining at least qualitative assessment of these combinational errors. This builds on the method used by *Pan et al.* [2001] but goes beyond the procedure used therein to include the impacts model in addition to the climate models.

3.2. Experimental Design

Figure 2 shows different SWAT runs with historical and RCM generated climates. Results of the first SWAT simulation (SWAT 1 in Fig. 2) with the observed station climate from 1979-88 are compared with measured stream flows at Grafton, IL during that same period to evaluate the capability of SWAT in representing observed discharges in the UMRB. It is not possible to make an unambiguous estimate of error introduced by the RCM, but a good proxy for this is a comparison of SWAT results produced when an RCM run driven by observed climate interpolated to the RCM grid (NNR, 1979-88) with SWAT results produced by the observed climate (SWAT 1). This procedure minimizes impact of errors in SWAT but includes stream flow errors that may have originated in the reanalysis used to create input to the RCM. The contribution of NNR errors to this result is minimized by our choice of lateral boundaries far from the UMRB and the fact that the RCM incorporates surface boundary influences at a higher spatial resolution than the NNR. Error 2a from the global model is evaluated by comparing output of SWAT driven by the RCM driven by the GCM for the contemporary climate (SWAT 3) with output of SWAT driven by the RCM driven by the reanalysis (SWAT 2). Daily maximum and minimum temperatures from the HadCM2 were not available to be used (along with daily precipitation) as input to SWAT, thereby precluding a more direct evaluation of the added value of the RCM.

Errors arising within individual models may be amplified or compensated for when models are used in combination. Measured stream flow and various SWAT outputs can be combined in other ways to give additional insight on errors arising from the combined models. Table 1 lists various combinations that are available. The three individual model errors and three model-combination errors provide a backdrop for interpreting the change in

stream flow due to climate change as determined by comparing results of SWAT driven by the RCM forced by the GCM results for the future scenario climate (SWAT 4) with SWAT 3.

3.3. Error Assessment

Ability of the hydrologic model and the climate model to simulate water yield was evaluated by computing bias and root mean square error (RMSE):

$$Bias = \frac{1}{N} \sum_{i=1}^N (Q_{s_i} - Q_{m_i}) \quad (2)$$

and,
$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^N (Q_{s_i} - Q_{m_i})^2} \quad (3)$$

where Q_m and Q_s are the measured and simulated stream flow respectively, and N is number of years of stream flow data. The bias provides a measure of systematic errors revealed from comparing model results with measurements. The RMSE gives an estimate of the variability of the model compared with observations, which is used to assess the validity of the model in reproducing the seasonal cycle ($N = 12$).

4. Results and Discussion

4.1. Model Validation

4.1.1. SWAT Calibration and Validation

Measured stream flows during 1989-1997 at USGS gauge station 05587450, Mississippi River near Grafton, IL were used to calibrate SWAT. The criterion used for calibrating the model was to minimize the difference between measured and simulated stream flow at the watershed outlet. No attempt was made to calibrate baseflow and surface runoff independent of total stream flow, since only total flow data were available. The flow-related model parameters such as runoff curve number (CN), soil evaporation compensation factor (ESCO), plant uptake compensation factor (EPCO), re-evaporation coefficient (REVAP), groundwater delay, and rain/snow temperature threshold were adjusted from the model initial estimates defaulted by AVSWAT to fit simulated flows to the observed ones. Detailed explanation of calibrated parameters can be found in the SWAT theoretical documentation, which is available online at <http://www.brc.tamus.edu/swat>. Comparison of annual flow (Fig. 3) and time-series (Fig. 4) of monthly stream flow at the watershed outlet shows that the magnitude and trend in the simulated stream flows agreed with measured data quite well. Model performance was evaluated by the coefficient of determination (R^2) and Nash-Sutcliffe simulation efficiency (E) [Nash and Sutcliffe, 1970]. If R^2 value is close to zero and E value is less than or very close to zero, the model simulation is considered unacceptable. If the values approach one, the model simulations would be perfect. Statistical evaluation for annual simulation yielded an R^2 value of 0.91 and E value of 0.91, indicating a reasonable agreement between the measured and simulated flows. For monthly simulations we calculated an R^2 value of 0.75 and E value of 0.67.

Flow validation was conducted using the stream flow data for the period from 1980 to 1988. Simulated stream flow for this period provides the output labeled SWAT 1 in Fig. 2. During the validation process, the model was run with input parameters calibrated earlier without any change. Measured and simulated annual (Fig. 5) and monthly (Fig. 6) stream flow show a good agreement between simulated stream flows and the measured values. Annual simulations yielded an R^2 value of 0.89 and E value of 0.86, while an R^2 value of 0.70 and E value of 0.59 were obtained for monthly simulations. Overall, the model was able to simulate stream flow with a reasonable accuracy. Other SWAT application papers considered the R^2 values of more than 0.7 and E values of more than 0.5 as sufficient conditions for model validation on a watershed scale [*Srinivasan et al.*, 1998; *Santhi et al.*, 2001].

4.1.2. Hydrological Components of SWAT and RegCM2

RegCM2 has its own surface hydrology package, but lacks a stream-flow routing process, as contained in SWAT, that is an essential ingredient of this study. It is, however, informative to compare the hydrological components of RegCM2 and SWAT to shed light on whether uncertainty introduced by the RCM-SWAT combination might be attributable to discrepancies between these components. The key hydrological components are evapotranspiration, runoff, and snowmelt. Recall that precipitation is identical for both the models. The 10-year annual means of these components differ by only 6-10% between the two models (Table 2), which is perhaps surprising, given large differences in formulations of models' hydrology.

Both RegCM2 and SWAT captured the seasonal trend of runoff that peaks in April. The SWAT-simulated peak is slightly earlier than that of RegCM2 (Fig. 7b). The annual mean runoff values simulated by SWAT and RegCM2 are 12.6 mm and 13.8, respectively, within 10% agreement.

Runoff is largely controlled by precipitation minus evapotranspiration (P-ET). Although P is common to both models, ET can be different. RegCM2 simulated about 15% more ET than SWAT in June and July (Fig. 7c), possibly associated with positive feedback between precipitation and evapotranspiration in RegCM2 that is not simulated in SWAT.

RegCM2 produces a smooth curve of snowmelt that monotonically increases from a small value in October to a maximum in March and then drops to near zero in May (Fig. 7d). In contrast, SWAT produces a November secondary maximum followed by a slight decrease through February before increasing to a March primary maximum and then decreasing to essentially zero in May. In RegCM2 the snow/rain threshold is established to be when the surface air temperature is 2.2°C. The value is 2.2 instead of zero because the precipitation temperature is typically lower than that of surface air. In RegCM2, the surface temperature is updated every time step, so a rain/snow decision is made every time step. SWAT, by contrast, defines the daily total precipitation to be snow if the mean surface air temperature (determined from the daily minimum and maximum as $[(T_{\max} + T_{\min})/2]$) is equal to or below the rain/snow threshold temperature, determined in the calibration process to be 2.0°C. Despite of the difference in threshold values and the RCM time-step vs. SWAT daily partitioning, the resultant snowfall is very similar for the two models in all months except April and May when RegCM2 produces, respectively, 15 and 5 mm more snow water equivalent than SWAT (Fig. 7a). Annual totals agree to within 5%.

4.1.3. Combining SWAT with the RCM

The calibrated SWAT model was run with weather inputs (precipitation and temperature) generated from the RCM model for the period 1979-1988 (labeled as NNR). The output is labeled as “SWAT 2” in Fig. 2. Annual simulation matched well with the measured data, as shown in Fig. 8. It is noteworthy that the year having the largest error was 1988, a year of extreme drought in the central U.S. Statistical evaluation revealed that the model was able to explain at least 77% of the variability in the measured stream flow ($R^2 = 0.77$), showing a reasonably good agreement between measured and simulated stream flows.

Stream flow is an integrator of climate processes, both spatially and temporally. Since there is essentially no change in in-basin storage from year to year, what goes in as precipitation must come out at stream flow. The RCM gives a very good estimate of mean annual precipitation (Fig. 10) and interannual variability of annual stream flow (Fig. 8) over the basin. However on sub-annual time scales, errors in the regional model, in addition to errors in routing and timing of snowmelt can introduce errors in stream-flow that put additional limitations on this method for impacts assessment on such time scales. This shortcoming at shorter times scales and their compensating tendency for the annual total provides a measure of caution for interpreting the errors in annual estimates.

Mearns et al. [1997] examine the impact of changes in both mean and variance of climate on output of a crop model and demonstrated the importance of including variability. A more in-depth study using the *Mearns et al.* [1997] procedure is needed to investigate the extent to which the integrating nature of stream flow would suppress the importance of short-term variability in climate.

Errors in simulating monthly stream flow are shown in Fig. 9. In spring, stream flow is very sensitive to surface and subsurface temperatures and to whether precipitation falls as rain or snow, this latter feature also being a sensitive function of temperature near the ground. In a comparison of RegCM2 climate variables with observations for three snowfall-dominated basins, *Hay et al.* [2002] found that model errors in temperature were more detrimental than errors in precipitation in assessing time-integrated run-off. RegCM2 has a warm bias for winter daily minimum temperatures, which likely is contributing to excessive early spring runoff and amplification of the seasonal cycle (Fig. 9). Seasonal distribution of precipitation shown in Fig. 10 suggests that excesses in model-generated precipitation in winter also contributed to the excess spring stream flow. Similarly, lower estimated precipitation in summer months likely contributed, along with excessive early season runoff previously mentioned, to the low stream flow simulated for August through November. This is also evident in the analysis of hydrological budget components discussed in a later section of this paper.

Giorgi et al. [1994] analyzed the surface hydrology of a multi-year simulation of the climate over the U.S. with an RCM (RegCM) nested within a GCM and compared results with available observations. For the Mississippi River Basin, they found that the model under-predicted precipitation, evaporation and surface runoff, and over-predicted the temperature on an average annual basis. When the RCM-produced precipitation and temperature were used herein to drive SWAT for the UMRB simulation, a similar under-prediction was observed for evaporation, but surface runoff was reproduced very well (by SWAT rather than the RCM) on an average annual basis (see Table 3). By introducing SWAT for the hydrologic components we were able to compare our results against measured

stream flow rather than runoff as was done by *Giorgi et al.* [1994]. The combined modeling system simulated the hydrology very well on an annual basis probably due to more accurate representation of topography, land use, and soil characteristics.

4.2. Climate Change Impact Assessment

The impact of climate change on hydrology was quantified by driving the calibrated SWAT model with RCM generated weather corresponding to the contemporary (labeled as CTL) and future scenario (labeled as SNR) climates nested in the global model as denoted by SWAT 3 and SWAT 4, respectively, in Fig. 2. The analysis was performed on a monthly basis for stream flows and annual basis for hydrological budget components.

Comparison of precipitation generated for contemporary and future scenario climates (Fig. 11) suggests higher average values of monthly flows throughout the year in the future scenario, except for November, which has 2% lower than the current precipitation. Projected increases in precipitation for this region are consistent with trends over the last decades of the 20th century [*IPCC*, 2001]. The mean annual precipitation is projected to increase by 21%.

Climate-induced stream flow changes are inferred by evaluating differences produced by SWAT when driven by future scenario and contemporary climates. Annual average stream flow increased by 50% due to climate change (Fig. 12), with the largest increase occurring in spring and summer. This disproportionate change, i.e. 50% increase in average annual stream flow vs. 21% increase in average annual precipitation, can be attributed to more precipitation falling on saturated soils, which creates disproportionately large runoff. For instance, for a rain event producing, say, 10 cm of precipitation, the last several cm likely

contribute completely to runoff and immediately to stream flow rather than soil infiltration that delays contribution to stream flows.

Simulated hydrologic budget components under different sources of climate data (Table 3) provide insight into major sources of uncertainty in this combined-model study. Precipitation, being the primary input to the hydrological system, ranges from 831 to 898 mm per year (a variation of 8%) for the various contemporary climates (e.g., all columns except SNR). This remarkable consistency, however, masks RCM problems with monthly distributions as previously discussed. Other components except actual ET are far less consistent among the various contemporary climates, which suggests substantial interdecadal variability in the climate for these components, e.g., snowfall and snowmelt in calibration vs. validation decades, and/or model-generated differences, e.g., differences between validation and NNR columns. Largest variations were found in snowfall and related snowmelt and potential evapotranspiration estimation. These can be attributed, in part, to the error in seasonal precipitation simulation by the RCM (Fig. 10).

Despite large variations in budget components, annual simulations of total water yield are quite similar, especially between observed (validation period) and NNR conditions. Proportionate but higher values of budget components were found for CTL compared to NNR simulation runs, although they represent similar time domains, suggesting the GCM is biased toward high precipitation and a more intense hydrological cycle. This consistent bias among hydrological components can be expected in both GCM contemporary and future scenario climates.

With the 21% increase in precipitation and accompanying changes in temperatures for the future scenario climate as simulated by the RCM, SWAT produced an 18% increase in

snowfall, a 19% increase in snowmelt, a 51% increase in surface runoff, and a 43% increase in recharge, leading to a 50% net increase in total water yield in the UMRB. Uncertainties in these projections are analyzed by the plan mapped out in Fig. 2.

4.3. Uncertainties in Climate Change Impact Assessment

Table 4 lists the absolute and relative bias and RMSE for all sources of errors in simulations of water yield of the Mississippi River at Grafton, IL. The highest percentage bias (18%) was found for GCM downscaling error. However, the highest individual model RMSE (14.3 mm) was found in RCM performance. RCM model simulation error was low on the annual basis (Fig. 8), but high for seasonal values (Fig. 9).

The magnitude of the climate change can be considered a “signal” that we can compare to uncertainties arising from the various components of the modeling system, which can be considered “noise.” A high signal to noise ratio is a necessary (but not sufficient) condition for high confidence in using this modeling approach to accurately project future stream flows in the UMRB. As shown in Fig. 13, change in stream flow (50%) due to climate change exceeds both individual model biases and also the combined-model bias, thereby providing a high signal-to-noise ratio. This result does not of itself ensure accuracy of the projection of future stream flow (i.e., does not provide the sufficient condition); however, if future global climate models are judged to be able to produce accurate future scenario climates with high confidence, then the combined-modeling procedure we have described provides a means of assessing confidence in the resulting stream flow.

Annual stream flow tends to have a quasi-linear relationship with annual precipitation. We used regression analysis to evaluate this relationship (Fig. 14) for the five options

depicted in Fig. 2. Table 5 lists the 5 regressions with their slope values. The regression line plotted represents measured annual stream flow vs. observed annual precipitation for 1980 through 1997. We applied the pooled t-test to the regression-line slopes for the various sets of simulated results to determine whether any of these climates have relationships between stream flow and precipitation that differ significantly (at the 5% significance level) from observed. We found that the slopes for SWAT1 and SWAT3 are not different from the observed but that SWAT2 and SWAT4 are different from the observed data and different from each other. This means that SWAT produces the same relationship between precipitation and stream flow as is observed and that SWAT driven by a regional model used to downscale global climate model results does also. However more stream flow per unit of precipitation is produced when the NNR drives the regional model. And the future scenario climate as represented by the combined models has an even higher ratio.

It is perhaps notable that the RCM/NNR results show the lowest annual stream flow bias (Fig. 13) but the largest bias in the regression of annual stream flow with annual precipitation for the current climate (items 1-4 in Table 5). We suspect this might be further evidence of RCM inadequacies in simulating accurately the annual cycle of precipitation, although we have not done confirming experiments. Although the RCM produces an accurate annual total precipitation (Fig. 10), it produces too much precipitation from November-May and less than observed from June-October. Warm-season precipitation contributes much more than cold-season precipitation to moisture recycling. But recycled moisture does not contribute to stream flow (presuming it falls, evaporates, and re-falls within the basin): recycling allows higher annual precipitation for a given stream flow, and recycled moisture will contribute a larger absolute amount to annual precipitation in wet years. Therefore, a model that is

deficient in moisture recycling during the year will have a larger slope in the plot of annual stream flow vs. annual precipitation.

Then why is the RCM/CTL slope comparable to that of the observations rather than that of the RCM/NNR model, since the RCM presumably does not capture the seasonal cycle for the contemporary climate? We suspect the answer lies in the June-August rainfall totals, which approximate the observed values for the contemporary climate but are 18% low for the RCM/NNR climate (Figs. 10 and 11). These mid-summer rains recharge the region's soils that are deep and have high moisture-holding capacity. Crops in the region develop deep roots by late summer and therefore efficiently contribute to moisture recycling by drawing moisture from the deep-soil reservoir that has been fully charged near the summer solstice.

The seasonal trend in precipitation in the GCM future scenario climate (SNR) follows that in the CTL climate but with higher magnitude in all months. The regression slope calculated for the SNR climate was 1.16, a factor of 2 more than those of the contemporary climates. It should be noted that the slope greater than 1 does not mean more runoff than precipitation, but simply reflects larger portion of rainfall transported as runoff because of high intensity rainfall events in future climate [*IPCC*, 2001].

5. Limitation of Coupled Modeling System

Hydrological budget components provide an internally consistent view of the water cycling within a watershed. Each component should be calibrated and validated against the measurements before being used to simulate future climates. However, limited data availability does not afford such luxury. Total water yield from the watershed typically is available only in terms of stream flow. In this study, only stream flow is calibrated and

validated at the watershed outlet since measurements of snowmelt, groundwater flow and evapotranspiration are not available. The resulting budget components, after the model is calibrated for total water yield, are believed to be in the appropriate range assuming that the model can simulate the process realistically. Other reported studies show that SWAT is capable of providing watershed scale analysis and has been validated on many small and large watersheds for total water yield, evapotranspiration, and groundwater recharge depending upon the data availability. *Arnold and Allen* [1996] validated SWAT for all components of the water balance including groundwater recharge for three river basins in Illinois.

In simulating the hydrologic cycle with RCM generated weather data, care should be taken to ensure that all budget components are changing in a proportional way. Known weaknesses in RCM simulation of snow water equivalent and high sensitivity of snow melt to air temperatures led to large errors in monthly stream flow beginning in spring. For these reasons we have low confidence in the ability of this coupled-model system to represent month-to-month stream flow.

An additional limitation of this modeling procedure is the climate database used by the weather generator within SWAT. The statistical relationships used to find meteorological conditions not supplied by the RCM may be different in a future scenario climate from those used for the current climate. No allowance has been made for this potential difference in the present study. In principle, this limitation could be circumvented by allowing SWAT to ingest all the surface hydrological cycle information from the RCM. However, SWAT has far more detail on influences of land characteristics that would be lost in such a strategy. Alternatively, the future scenario climate of the RCM could be used to provide a more

concurrent future scenario statistical database for the SWAT weather generator [Mearns *et al.*, 1997]. This might be a more suitable alternative, short of disassembling SWAT and reassembling it within the RCM.

6. Summary and Conclusions

A regional climate model that generated two 10-year simulated climates for the continental U.S. corresponding to current and future scenario climates at 50 km horizontal resolution was used to drive a hydrological model, Soil and Water Assessment Tool (SWAT), over the entire UMRB. The objective of the study was to explore stream flow, and model-introduced uncertainty thereof, in a future scenario climate by introducing a regional climate model to dynamically downscale global model results to create temperature and precipitation data required by the stream flow model. Hydrologic components of the SWAT model were calibrated and validated using measured stream flow data at USGS gauge No. 05587450, Mississippi River near Grafton, IL. The model produced stream flow with a reasonable accuracy on annual and monthly basis. Combined performance of SWAT and the RCM was first evaluated by driving SWAT with NNR data used as the RCM's lateral boundary conditions. This combined model system reproduced annual stream flow values well but failed to capture seasonal variability. Impact of climate change was then assessed by using two 10-year scenario periods (1990s and 2040s) generated by nesting the RCM into a coarse grid resolution global model (HadCM2). The combined GCM-RCM-SWAT model system produced an increase in future scenario climate precipitation of 21% with a resulting 18% increase in snowfall, 51% increase in surface runoff, 43% increase in recharge and 50% increase in total water yield in the UMRB. This disproportionate change can be attributed to

more intense precipitation events in future climates and the non-linear nature of hydrologic budget components, such as snowmelt, evapotranspiration, surface runoff, and groundwater flow.

For the global climate model future scenario we used we have shown that the climate change signal is large relative to errors arising from the modeling procedure, with the largest error being attributable to the GCM downscaling error (18%), compared to a simulated change of 50% in annual stream flow. This gives confidence that such a downscaling procedure has value for impacts assessment provided the quality of the global model driving the RCM is high.

Our results also suggest that the relationship of annual stream flow to annual precipitation may change in a future climate in that a unit increase in precipitation will cause a larger increase in stream flow. This may be due to increased recycling of moisture more uniformly from year to year in a future wetter climate. It also may be attributable to more intense precipitation events associated with mesoscale convective complexes that produce a larger fraction of run-off due to a more full soil profile in mid summer. It is known [Anderson *et al.*, 2003] that RCMs capture such mesoscale events more accurately than global models, strengthening the case for fine-scale resolution of the dynamics of the hydrological system, even in regions of little orographic forcing of precipitation, as being essential for driving hydrological impacts models.

Acknowledgement

This research was sponsored by the Iowa State University Agronomy Department Endowment Funds, University of Iowa Center for Global and Regional Environmental

Research, and the Biological and Environmental Research Program (BER), U.S. Department of Energy through the Great Plains Regional Center of National Institute of Global Environmental Change under Cooperative Agreement No 26-6223-7230-007. Computer resources used for this study were partly provided by NCAR CSL facility. We acknowledge perceptive comments of two anonymous reviewers that led to substantial improvement of the paper.

References

- Anderson, C.J., R.W. Arritt, E.S. Takle, Z. Pan, W.J. Gutowski, Jr., F.O. Otieno, R. da Silva, D. Caya, J.H. Christensen, D. Luthi, M.A. Gaertner, C. Gallardo, F. Giorgi, S.Y. Hong, C. Jones, H.M.H. Juang, J.J. Katzfey, W.M. Lapenta, R. Laprise, J.W. Larson, G. E. Liston, J.L. McGregor, R.A. Pielke, Sr., J.O. Roads, and J.A. Taylor, Hydrological processes in regional climate model simulations of the central United States flood of June-July 1993, *J. Hydrometeor.*, 4, 584-598, 2003.
- Arnell, N.W., D.A. Hudson, and R.G. Jones, Climate change scenarios from a regional climate model: Estimating change in runoff in south Africa, *J. Geophys. Res.*, 108(D16), 4519, doi:10.1029/2002JD002782, 2003.
- Arnold, J.G., P.M. Allen, and G. Bernhardt, A comprehensive surface-groundwater flow model, *J. Hydrol.*, 142, 47-69, 1993.
- Arnold, J.G., and P.M. Allen, Estimating hydrologic budgets for three Illinois watersheds, *J. Hydrol.*, 176, 57-77, 1996.
- Arnold, J.G., R. Srinivasan, R.S. Muttiah, and J.R. Williams, Large area hydrologic modeling and assessment Part I: Model development, *J. Amer. Wat. Res. Assoc.*, 34, 73-89, 1998.
- Arnold, J.G., R. Srinivasan, R.S. Muttiah, and P.M. Allen, Continental scale simulation of the hydrologic balance, *J. Amer. Wat. Res. Assoc.*, 35(5), 1037-1051, 1999.
- Changnon, S.A., ed., *The Great Flood of 1993: Causes, Impacts and Responses*, Westview Press, Boulder CO., 321 pp., 1996.
- Ghan, S.J., X. Bian, and L. Corsetti, Simulation of the Great Plains low-level jet and associated clouds by general circulation models, *Mon. Wea. Rev.*, 124, 1388-1408, 1995.

- Giorgi, F., M.R. Marinucci, G.T. Bates, and G. De Canio, Development of a second-generation regional climate model (RegCM2), I, Boundary-layer and radiative transfer, *Mon. Wea. Rev.*, *121*, 2794-2813, 1993.
- Giorgi, F., C.S. Brodeur, and G.T. Bates, Regional climate change scenarios over the United States produced with a nested regional climate model, *J. Clim.*, *7*, 375-399, 1994.
- Giorgi, F., S.W. Hostetler, C.S. Brodeur, Analysis of the Surface Hydrology in a Regional Climate Model, *Quart. J. Royal Meteor. Soc.*, *120*(515), 161-183, 1994.
- Glantz, M.H., ed., *Societal Responses to Regional Climatic Change: Forecasting by Analogy*, Westview Press, Boulder, CO., 428 pp., 1988.
- Hay, L.E., M. P. Clark, R. L. Wilby, W. J. Gutowski, Jr., G. H. Leavesley, Z. Pan, R. W. Arritt, and E. S. Takle, Use of regional climate model output for hydrologic simulations, *J. Hydromet.*, *3*, 571-590, 2002.
- Higgins, R.W., Y. Yao, E.S. Yarosh, J.E. Janowiak, and K.C. Mo, Influence of the Great Plains low-level jet on summer time precipitation and moisture transport over the central United States, *J. Clim.*, *10*, 481-507, 1997.
- IPCC (Intergovernmental Panel on Climate Change), *Climate change 2001 - The scientific basis*, J.T. Houghton, T.Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, and D. Xiaosu (Eds.), 944pp., Cambridge Univ. Press, Cambridge, 2001.
- IPCC (Intergovernmental Panel on Climate Change), *Climate change 2001: Impacts, adaptation, and vulnerability*, J.J. McCarthy, O.F. Canziani, N.A. Leary, D.J. Dokken, and K.S. White, 1032 pp., Cambridge University Press, Cambridge, 2001.
- Jones, T.C., R.E. Carnell, J.F. Crossley, J.M. Gregory, J.F.B. Mitchell, C.A. Senior, S.F.B. Tett, and R.A. Wood, The second Hadley Centre coupled ocean-atmosphere GCM: model description, spinup, and validation, *Clim. Dyn.*, *13*, 103-134, 1997.
- Kalnay, E., and Coauthors, The NCEP/NCAR 40-year reanalysis project, *Bull. Amer. Meteor. Soc.*, *77*, 437-471, 1996.
- Mearns, L.O., C. Rosenzweig, and R. Goldberg, Mean and variance change in climate scenarios: methods, agricultural applications, and measures of uncertainty, *Cli. Change*, *35*, 367-396, 1997.
- Miller, J.R., and G.L. Russell, The impact of global warming on river runoff, *J. Geophys. Res.*, *97*(D3), 2757-2764, 1992.
- Nash, J.E., and J.V. Sutcliffe, River flow forecasting through conceptual models. Part I A discussion of principles, *J. Hydrol.*, *10*(3), 282-290, 1970.

- NCDC, Cooperative Observer Program (COOP, <http://www.coop.nws.noaa.gov/Publications/coop.pdf>), Accessed in July 18, 2004.
- Pan, Z., J.H. Christensen, R.W. Arritt, W.J. Gutowski, Jr., E.S. Takle, and F. Otieno, Evaluation of uncertainties in regional climate change simulations, *J. Geophys. Res.*, *106*(D16):17,737-17,751, 2001.
- Rosenthal, W.D., R. Srinivasan, and J.G. Arnold, Alternative river management using a linked GIS-hydrology model, *Trans. ASAE* *38*(3), 783-790, 1995.
- Saleh, A., J.G. Arnold, P.W. Gassman, L.M. Hauck, W.D. Rosenthal, J.R. Williams, and A.M.S. McFarland, Application of SWAT for the Upper North Bosque River Watershed, *Tran. ASAE*, *43*(5), 1077-1087, 2000.
- Santhi, C., J.G. Arnold, J.R. Williams, W.A. Dugas, R. Srinivasan, and L.M. Hauck, Validation of the SWAT model on a large river basin with point and nonpoint sources, *J. Amer. Wat. Res. Assoc.*, *37*(5), 1169-1188, 2001.
- Srinivasan, R., T.S. Ramanarayanan, J.G. Arnold, and S.T. Bednarz, Large area hydrologic modeling and assessment: Part II - model application, *J. Amer. Wat. Res. Assoc.*, *34*(1), 91-102, 1998.
- Stone, M.C., R.H. Hotchkiss, C.M. Hubbard, T.A. Fontaine, L.O. Mearns, and J.G. Arnold, Impacts of climate change on Missouri River Basin water yield, *J. Amer. Wat. Res. Asso.*, *37*(5), 1119-1130, 2001.
- Stone, M.C., R.H. Hotchkiss, and L.O. Mearns, Water yield responses to high and low spatial resolution climate change scenarios in the Missouri River Basin, *Geophys. Res. Lett.*, *30*(4), February 23, 2003
- Takle, E. S., W. J. Gutowski, Jr., R. W. Arritt, Z. Pan, C. J. Anderson, R. Ramos da Silva, D. Caya, S.-C. Chen, J. Hesselbjerg Christensen, S.-Y. Hong, H. M. (Henry) Juang, J. Katzfey, W. M. Lapenta, R. Laprise, P. Lopez, J. Mc Gregor, and J. O. Roads, Project to intercompare regional climate simulations (PIRCS): Description and initial results, *J. Geophys. Res.*, *104*, 19,443-19,462, 1999.
- U.S. Department of Agriculture (USDA), State Soil Geographic (STATSGO) Data Base: Data Use Information, Miscellaneous Publication Number 1492, Natural Resource Conservation Service, National Soil Survey Center, Lincoln, Nebraska, 1994.
- U.S. Environmental Protection Agency (USEPA), BASINS 3.0: Better Assessment Science Integrating Point and Nonpoint Sources, U.S. Environmental Protection Agency, Office of Water, Office of Science and Technology, Washington, D.C., 2001.

Wallace J.M., and P.V. Hobbs, *Atmospheric Science: An Introduction*, Academic Press, New York, 467pp., 1977.

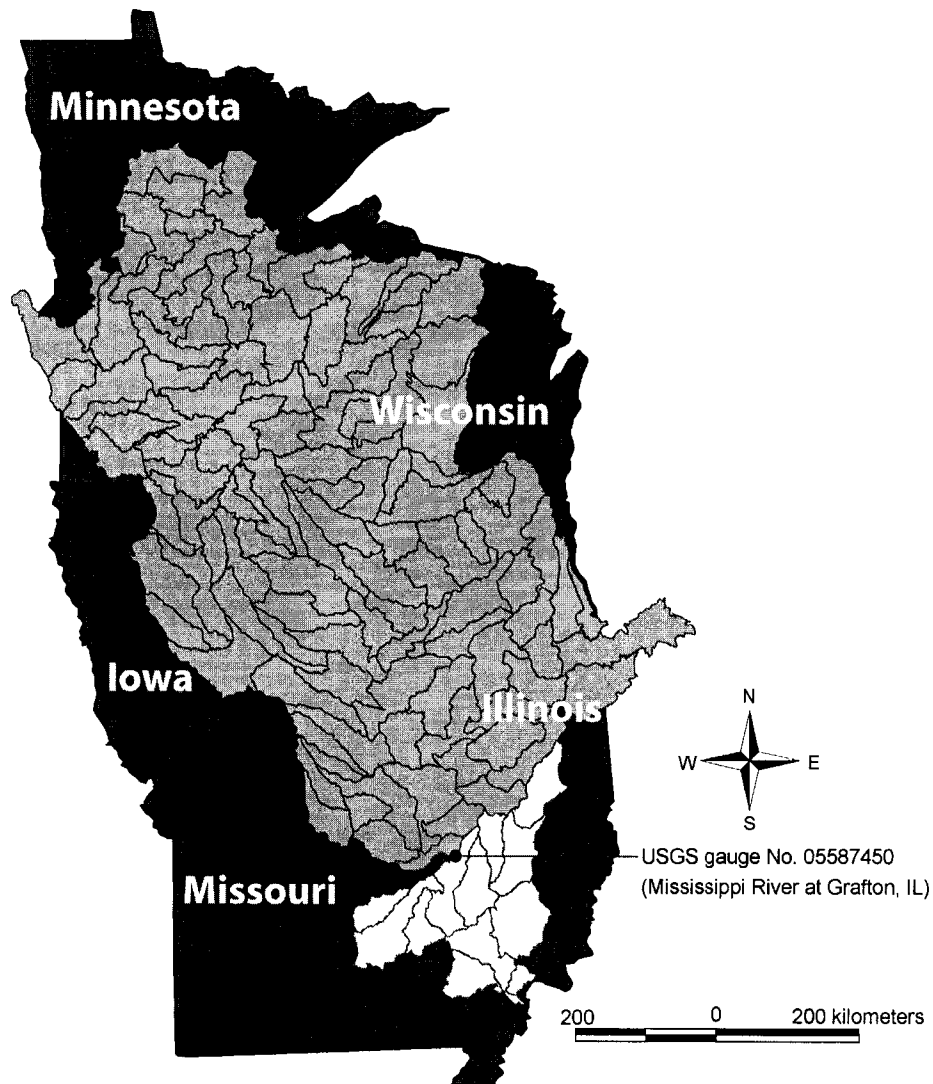


Fig. 1. The Upper Mississippi River Basin (UMRB) and delineated 8-digit HUCs.

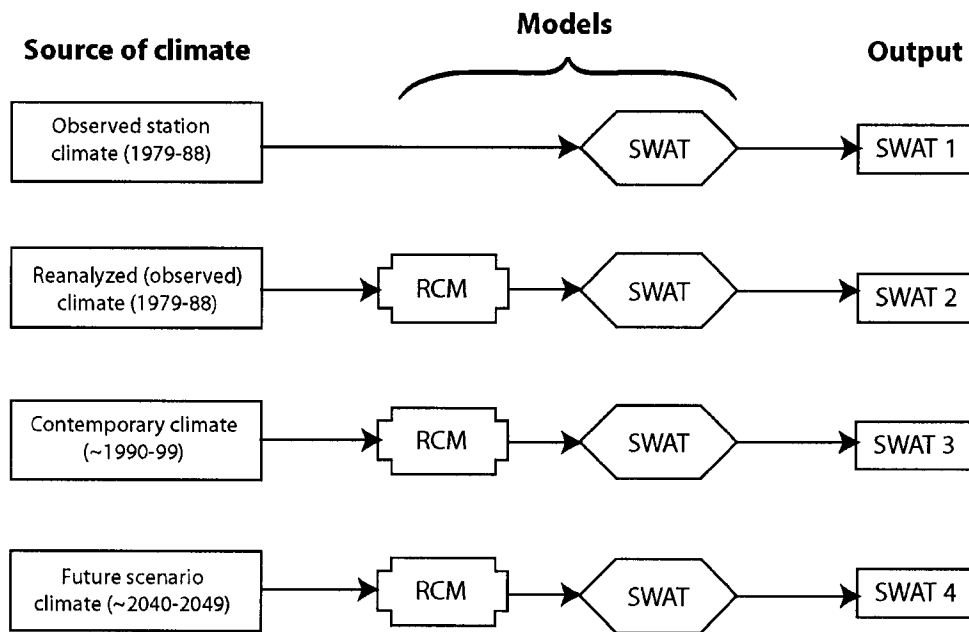


Fig. 2. Schematic diagram of RCM/SWAT simulation runs.

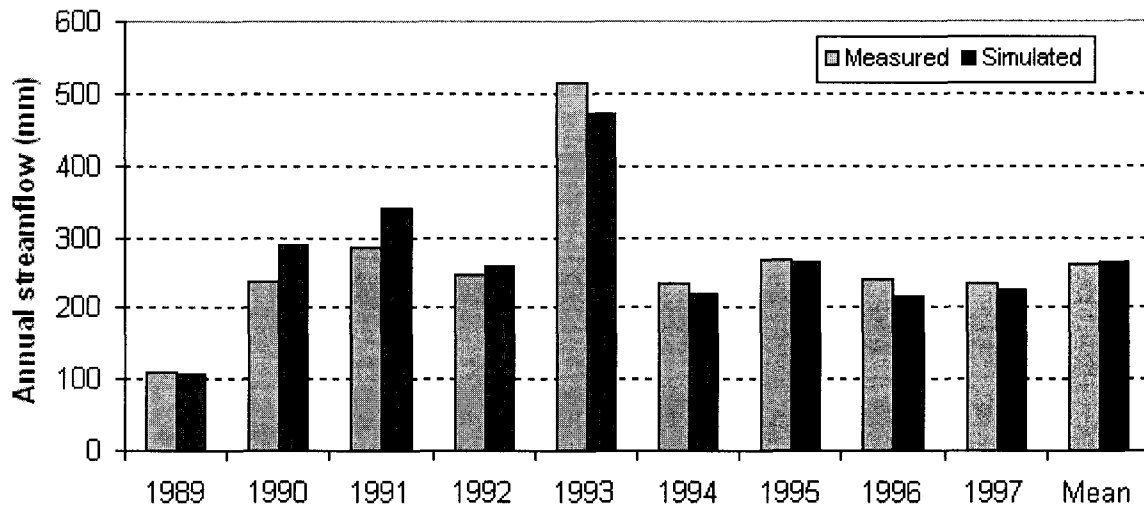


Fig. 3. Measured and simulated annual stream flows at USGS gauge 05587450, Mississippi River near Grafton, IL for calibration.

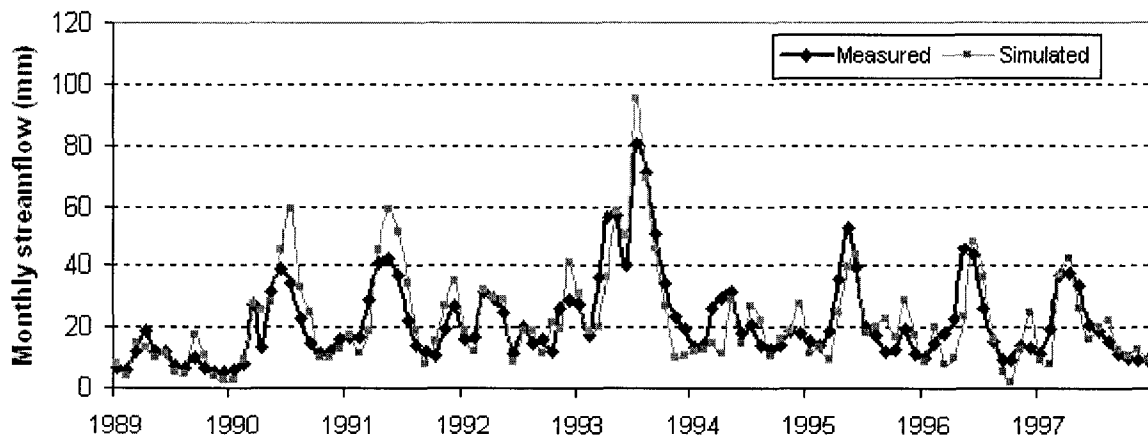


Fig. 4. Time series of measured and simulated monthly stream flows at USGS gauge 05587450, Mississippi River near Grafton, IL for calibration.

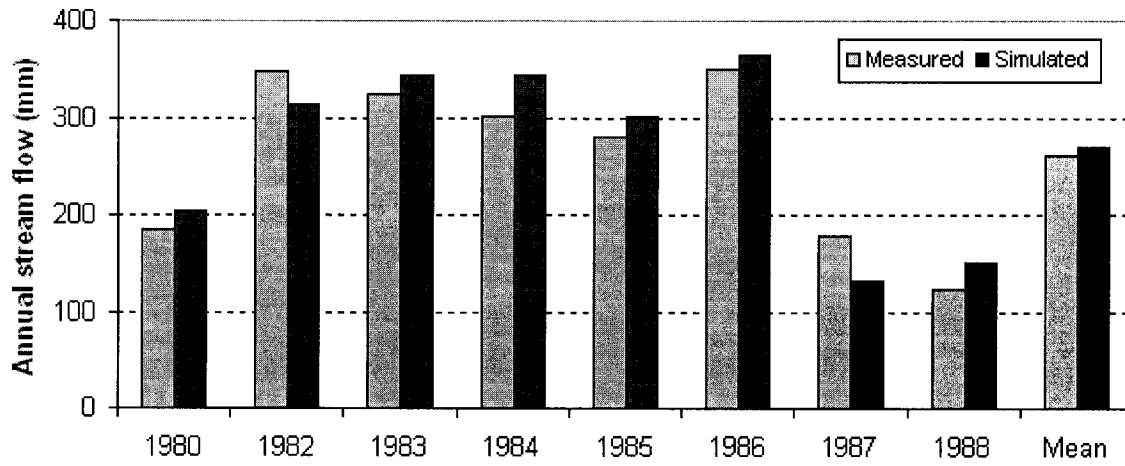


Fig. 5. Same as Fig. 3, but for validation.

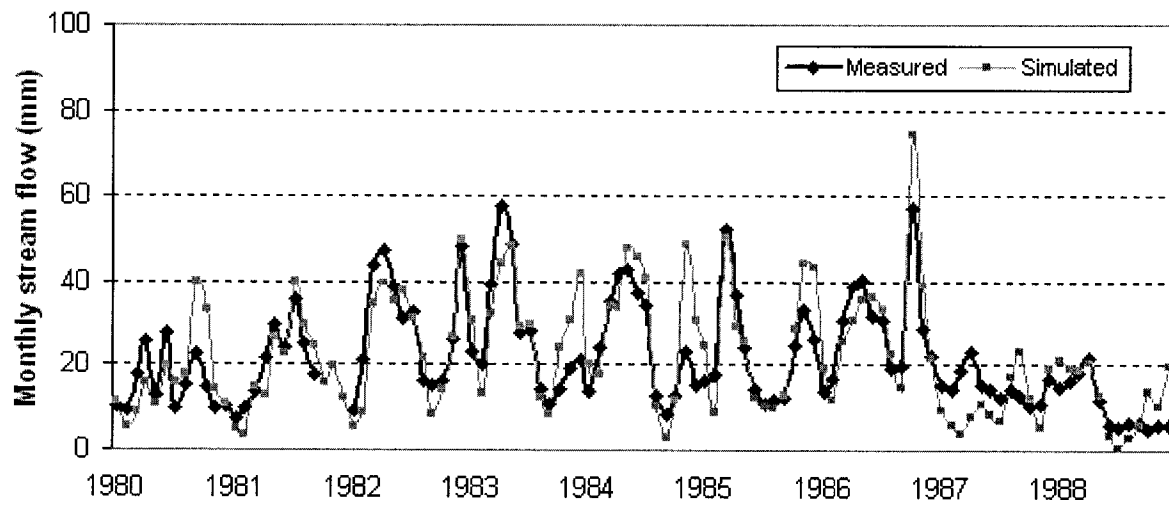
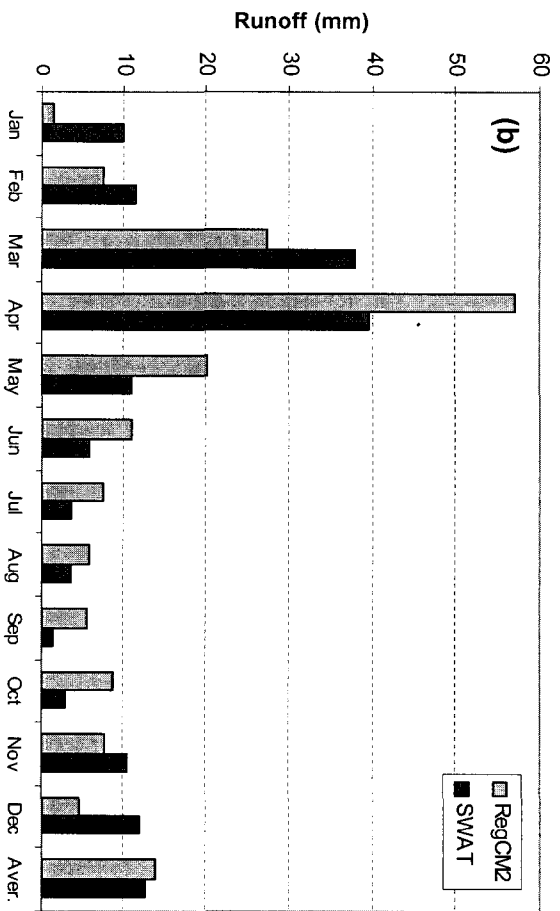
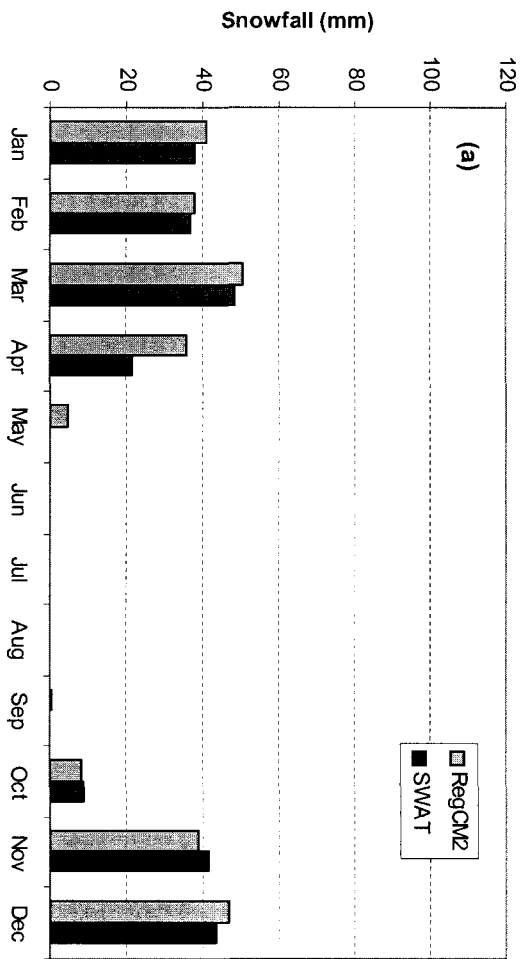


Fig. 6. Same as Fig. 4, but for validation.



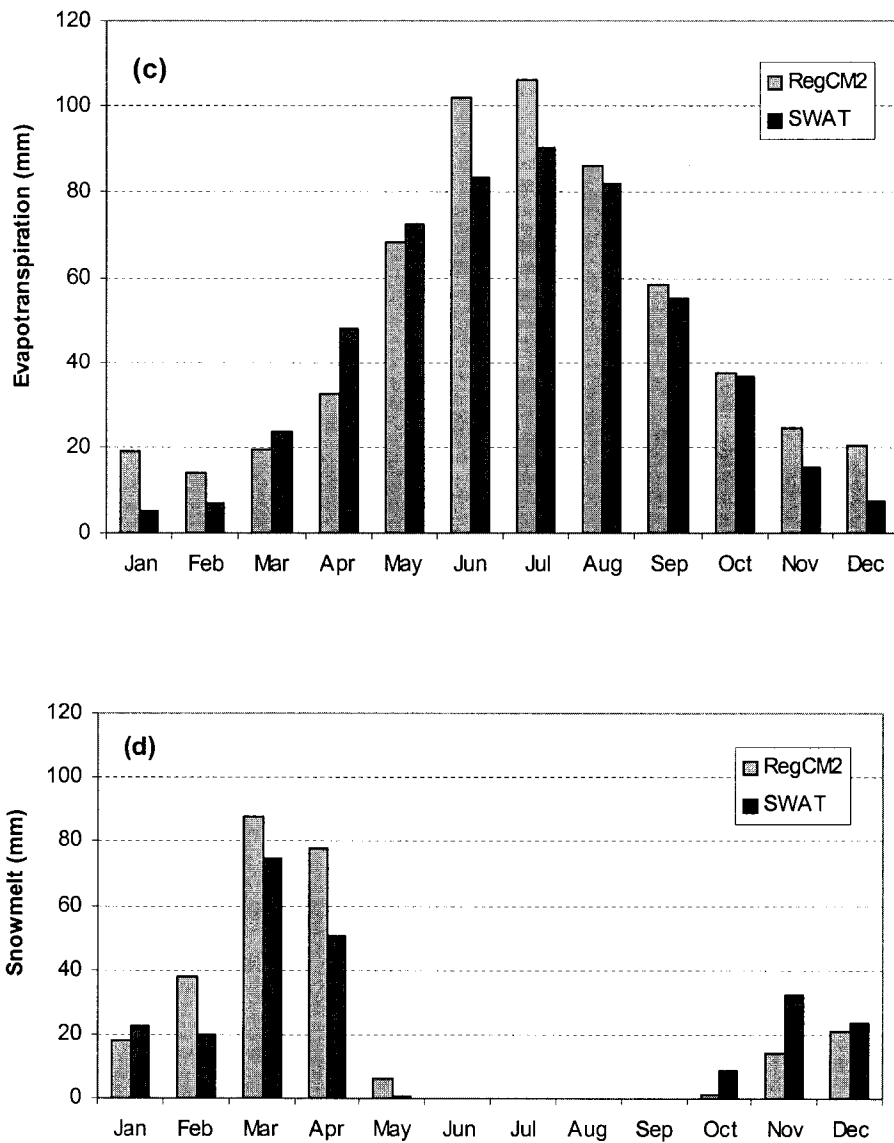


Fig. 7. Comparison of hydrological components between RegCM2 and SWAT: (a) snowfall, (b) runoff, (c) evapotranspiration, and (d) snowmelt. All values are averaged for 1980-88 for the NNR runs.

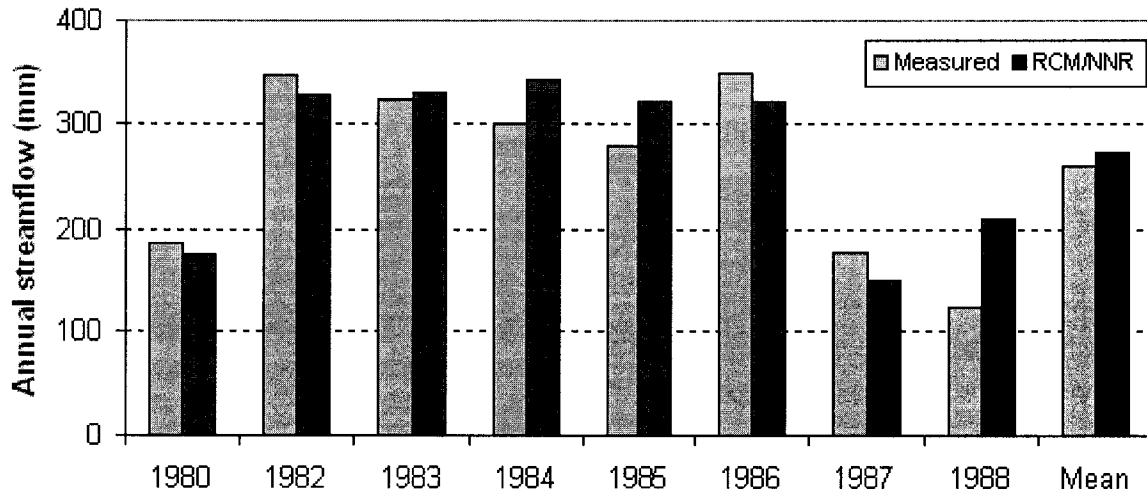


Fig. 8. Annual stream flows produced by SWAT driven by the RCM with NNR lateral boundary conditions, compared with measured stream flows at USGS gauge 05587450, Mississippi River near Grafton, IL.

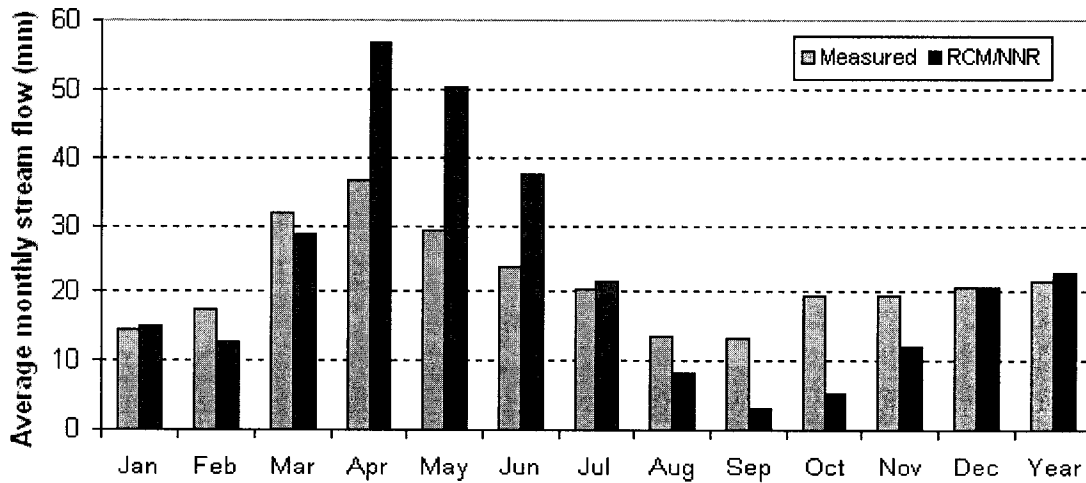


Fig. 9. Comparison of measured mean monthly stream flows and those produced by SWAT driven by the RCM downscaled NNR data for the validation period (1980-1988).

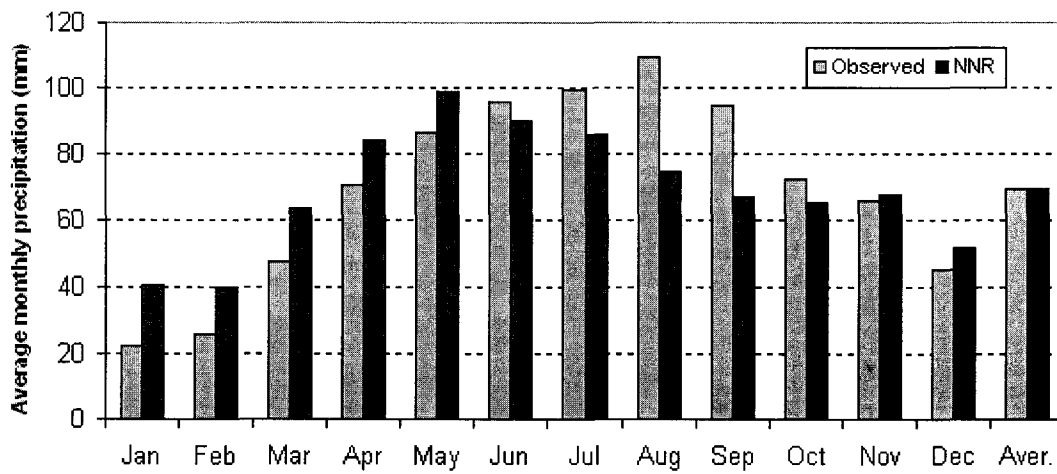


Fig. 10. Same as Fig. 9, but for precipitation.

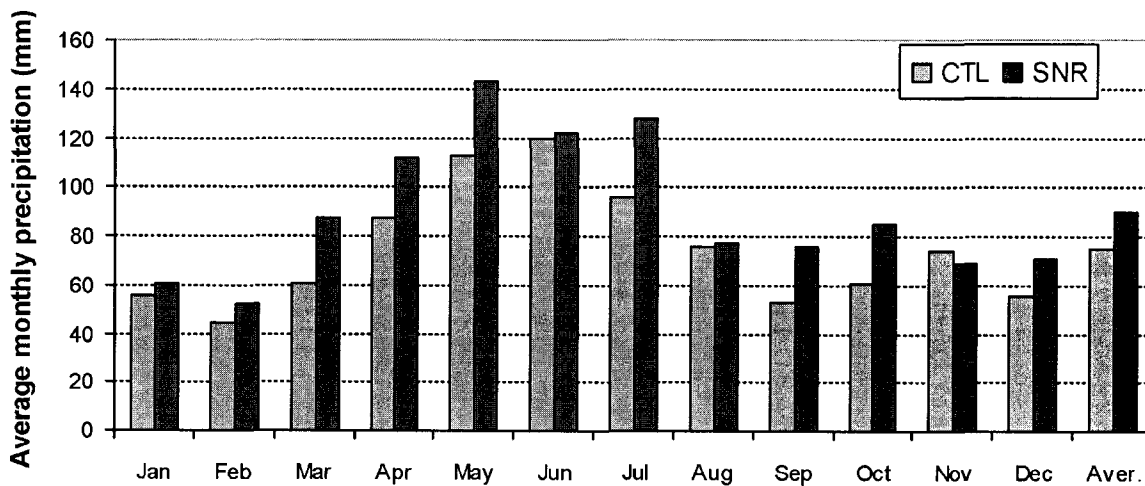


Fig. 11. Precipitation generated by the RCM for contemporary and future scenario climates.

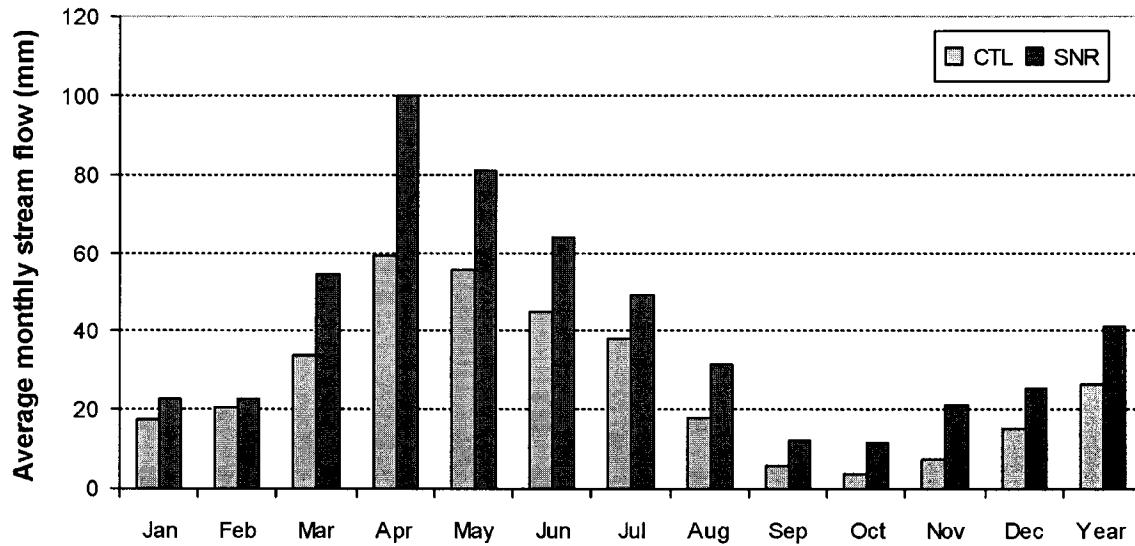


Fig. 12. Mean monthly stream flow simulated by SWAT for contemporary and future scenario climates.

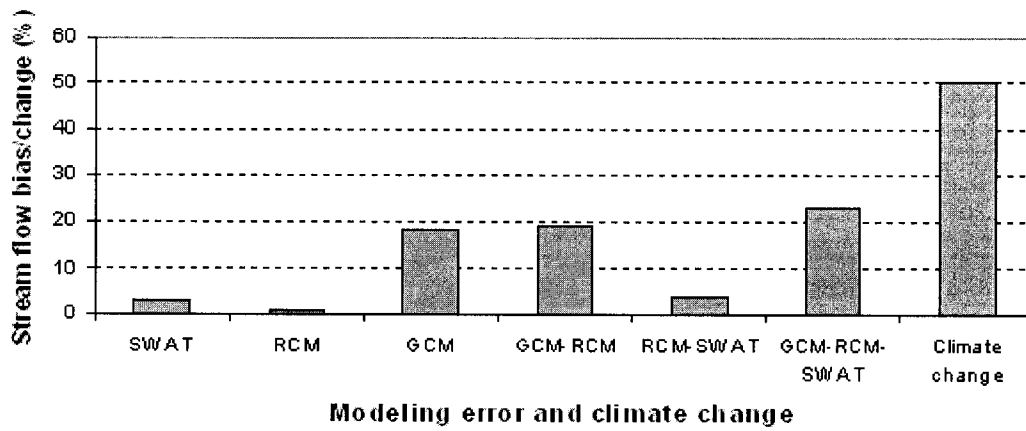


Fig. 13. Comparisons of climate change with annual biases in simulated stream flow.

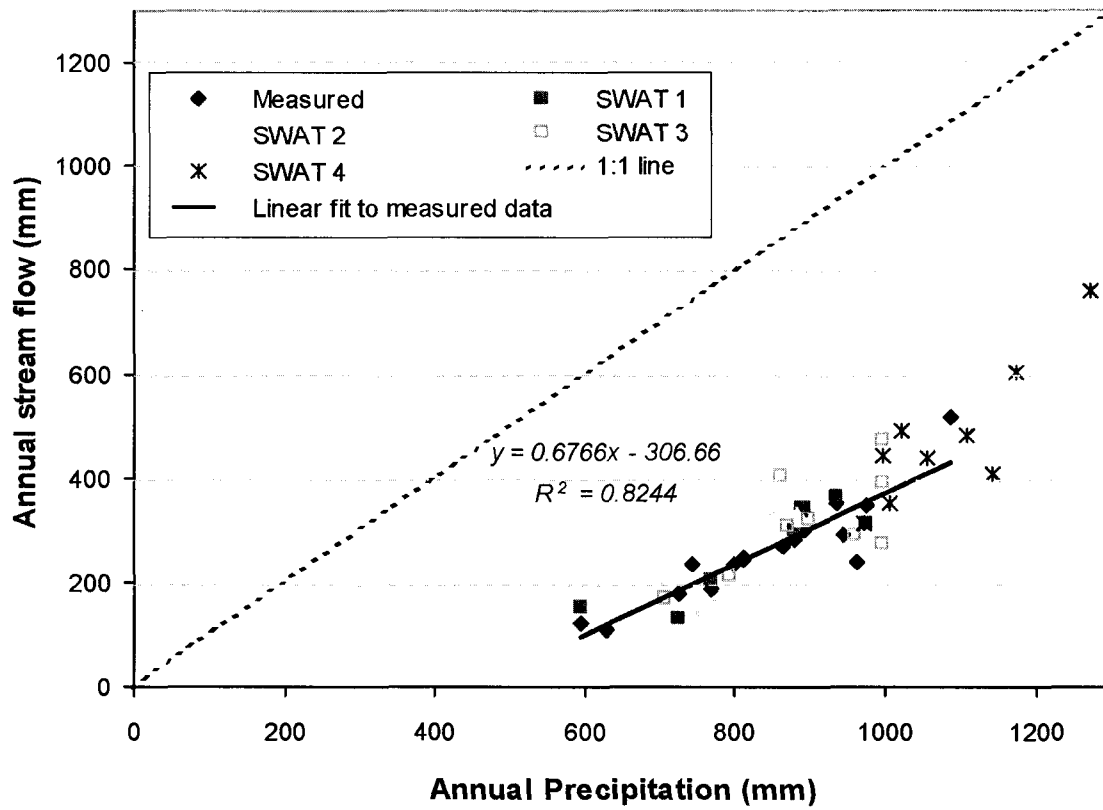


Fig. 14. Relationship between annual stream flow and precipitation for various climates.

Table 1. Definition of errors in simulated stream flows and climate change.

<i>Comparisons</i>	<i>Evaluate</i>
SWAT 1 vs. Measured	SWAT error
SWAT 2 vs. SWAT 1	RCM error
SWAT 3 vs. SWAT 2	GCM error
SWAT 3 vs. SWAT 1	GCM-RCM error
SWAT 2 vs. Measured	RCM-SWAT error
SWAT 3 vs. Measured	GCM-RCM-SWAT error
SWAT 4 vs. SWAT 3	Climate change

Table 2. Hydrological component comparison between RegCM2 and SWAT.

	<i>RegCM2</i>	<i>SWAT</i>
Evapotranspiration	588	528
Surface runoff	151	166
Snowmelt	256	240

Note: All values are in mm per year averaged for 1980-1988 in NNR run.

Table 3. Simulated hydrologic budget components by SWAT under different climates.

<i>Hydrologic budget components</i>	<i>Calibration (1989-1997)</i>	<i>Validation (1980- 1988)</i>	<i>NNR (1980- 1988)</i>	<i>CTL (around 1990s)</i>	<i>SNR (around 2040s)</i>	<i>% Change (SNR- CTL)</i>
Precipitation	856	846	831	898	1082	21
Snowfall	169	103	237	249	294	18
Snowmelt	168	99	230	245	291	19
Surface runoff	151	128	151	178	268	51
GW recharge	154	160	134	179	255	43
Total water yield	273	257	253	321	481	50
Potential ET	947	977	799	787	778	-1
Actual ET	547	541	528	539	566	5

Note: All units are in mm; precipitation for NNR, CTL and SNR are the outputs of the RCM model, precipitation for calibration and validation period are from weather stations; other components are estimated by SWAT; total water yield is the sum of surface runoff, lateral flow and groundwater flow.

Table 4. Bias and RMSE in various simulations of water yield of the Mississippi River at Grafton, IL.

<i>Modeling error</i>	<i>Absolute and relative bias in average monthly simulation (mm)</i>	<i>RMSE in average monthly simulation (mm)</i>
SWAT	+0.6 (3%)	5.5
RCM	+0.3 (1%)	14.3
GCM	+4.0 (18%)	7.2
GCM-RCM	+4.3 (19%)	18.0
RCM-SWAT	+1.0 (4%)	11.1
GCM-RCM-SWAT	+5.0 (23%)	14.5

Note: Refer to Table 1 for different modeling errors; Equation 2 for bias; and Equation 3 for RMSE.

Table 5. Regression analysis: stream flow vs. precipitation.

<i>Stream flow vs. precipitation</i>	<i>Scenario</i>	<i>Slope</i>
Measured stream flow vs. observed precipitation (1980-1997)	Observed	0.66
Simulated stream flow vs. observed precipitation (1980-1988)	SWAT 1	0.65
Simulated stream flow vs. RCM/NNR precipitation (1980-1988)	SWAT 2	0.87
Simulated stream flow vs. CTL precipitation (around 1990s)	SWAT 3	0.64
Simulated stream flow vs. SNR precipitation (around 2040s)	SWAT 4	1.16

CHAPTER 5. APPLICATION OF SWAT FOR THE UPPER MISSISSIPPI RIVER BASIN, PART I: METHODOLOGY

A paper to be submitted to the *Journal of American Water Resources Association*

Manoj Jha, Philip W. Gassman, Silvia Sechi, J.G. Arnold, and Roy Gu

ABSTRACT

A modeling system has been constructed for the Upper Mississippi River Basin (UMRB), which covers over 491,000 km² in parts of eight states in the north central U.S. The modeling system is built around the Soil and Water Assessment Tool (SWAT) watershed model, which is designed to assess the effects of land use, climate, and soil conditions on streamflow and water quality. The simulation approach accommodates a wide range of scenarios focused on shifts in cropping systems, tillage, fertilizer management, conservation practices, and/or other land use changes, which could potentially result in improved water quality within the UMRB and in the Gulf of Mexico. An overview of the modeling system is provided, including databases such as the U.S. Department of Agriculture (USDA) National Resources Inventory (NRI) and Cropping Practices Survey (CPS) databases. Key land use, crop rotation, tillage, fertilizer application, climate, and soil input data required for SWAT are described, as well as the process of generating Hydrologic Response Units (HRUs) which are the basic spatial units required to perform a SWAT simulation. Future planned applications of the modeling system are also briefly covered, including a forthcoming SWAT UMRB validation study.

Key Words: watershed, simulation, hydrology, input data

INTRODUCTION

The Mississippi River Watershed is a vast U.S. national resource that covers an area of 3.2 million km² across parts or all of 31 states and two Canadian provinces (Figure 1). There is increasing concern over ecological stresses that are impacting the watershed, including water quality degradation resulting from excess nitrogen (N), phosphorus (P), and sediment loadings to the Mississippi and its tributaries. The nitrate (NO₃-N) 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 km² in 1999 (Rabalais et al., 2002). Approximately 90% of the nitrate load to the Gulf is attributed to nonpoint sources. A significant portion of this load originates from the Upper Mississippi River Basin (UMRB), which covers only 15% of the total Mississippi drainage area (Figure 1). Goolsby et al. (1999) estimated that the UMRB was the source of nearly 39% of the Mississippi nitrate load discharged to the Gulf between 1980 and 1996; 35% of this load was attributed solely to Iowa and Illinois tributary rivers for average discharge years during the same time period (Goolsby et al., 2001). The magnitude of UMRB water quality degradation is also demonstrated by the inclusion of 1,220 stream segments and lakes on the current U.S. Environmental Protection Agency (USEPA) listing of impaired waterways (USEPA National Section 303(d) List Fact Sheet, http://oaspub.epa.gov/waters/national_rept.control).

Nutrient inputs via fertilizer and/or livestock manure on cropland and pasture areas are the primary sources of nonpoint source nutrient pollution in the UMRB stream system. Sediment losses to the UMRB stream system are a function of erosion from upland soils, especially from cropland areas, and stream bank erosion. These nonpoint source pollution

problems persist throughout the region, despite a wide range of water quality initiatives that have been undertaken at different watershed and regional scales by federal, state and/or local agencies. This underscores the need for continued assessments of specific subwatersheds and of the entire region, to determine which management and land use strategies will be the most effective approaches for mitigating nonpoint source pollution problems in the UMRB.

A simulation study using the Soil and Water Assessment Tool (SWAT) model (Arnold et al., 1998) has been initiated to address UMRB water quality issues, by providing insights that could help mitigate nutrient and sediment losses from UMRB cropland and pastures. The simulation methodology consists of assessing the nonpoint source 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, which will allow a comprehensive analysis of a broad spectrum of management practices and policy scenarios. The goal of this study is to describe the methodology that has been used to construct the UMRB SWAT modeling system. The specific objectives are to: (1) provide an overview of the UMRB and the modeling system, and (2) describe the key data sets and simulation assumptions that are incorporated within the simulation framework.

DESCRIPTION OF THE UMRB

The UMRB extends from the source of the Mississippi river at Lake Itasca in Minnesota to a point just north of Cairo, Illinois. The total drainage area is nearly 492,000 km², which lies primarily in parts of Minnesota, Wisconsin, Iowa, Illinois, and Missouri (Figure 1). Extensive channelization, lock and dam, wing dam, closing dam, and other modifications

were made to the main channel of the Mississippi River between 1866 and 1940 (Anfinson, 2003), which have greatly impacted the flow characteristics and wildlife habitat associated with the river. The Upper Mississippi River National Wildlife and Fish Refuge was created by Congress in 1924, which includes 260 miles of the Mississippi River between Wabasha, Minnesota and Rock Island, Illinois

(http://www.americasoutdoors.gov/recreation/rec_flw.asp). Today, the UMRB river system provides habitat for nearly 500 different species of fish, mammals, mussels, reptiles, and amphibians, and is also a key flyway used by 40% of North American migratory waterfowl and 60% of all North American bird species (UMRCC, 2000).

Prior to European settlement, the UMRB landscape was dominated by tallgrass prairies, oak savannas, and hardwood forest ecosystems (NAS, 2000). The majority of these native ecosystems have been converted to agro-ecosystems consisting of cropland and pastures, beginning in the 1830s in the southern portion of the UMRB and then later in the 1860s and 1870s in the northern subregions (Knox, 2001). At present, cropland and pasture are the dominant land uses in the UMRB, which together are estimated to account for over 60% of the total area (NAS, 2000). The shift into agriculturally dominated ecosystems in the UMRB has greatly impacted landscape response to precipitation-driven runoff and sediment loss in the region, as determined by studies of the alluvial stratigraphy of the Mississippi stream system (Knox, 2001).

OVERVIEW OF THE UMRB MODELING SYSTEM

SWAT Model

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 land use, 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). Further details on the SWAT components are presented in Arnold et al. (1998) and Neitsch et al. (2001).

UMRB Simulation Approach

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, which more accurately reflect current practices in the UMRB and better facilitate policy analyses for the region.

The primary data source for the modeling system is the USDA 1997 National Resources Inventory (NRI) database (Nusser and Goebel, 1997; <http://www.nrcs.usda.gov/technical/NRI/>). 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 800,000 nonfederal land “points.” Each point represents an area, generally ranging from a few hundred to several thousand hectares in size, which is assumed to consist of homogeneous land use, soil, and other characteristics. Crop rotations incorporated in the baseline SWAT simulation are derived from cropping histories reported in the NRI; other land use 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 CPS data can be accessed at http://usda.mannlib.cornell.edu/usda/ess_entry.html. The NRI clusters serve as the HRUs in the SWAT simulations, which are smaller spatial units within each subwatershed and are further described in the HRU Development Process section.

The SWAT executions, including the corresponding data flows, are managed with the interactive SWAT (i_SWAT) software, which is currently designed to support applications of SWAT2000. A single Access[®] database is used to manage both the input and output data of a SWAT simulation(s) within i_SWAT. This requires the user to convert all existing input data from ASCII files and other file formats into Access. An initial preprocessing step is required to fill the Access database tables. Once the input data have been constructed, the SWAT

simulation can be executed within i_SWAT. Output data for each simulation are scanned from standard SWAT output files and also stored in the database. Further description of the i_SWAT software is provided elsewhere (Gassman et al. (2003); <http://www.public.iastate.edu/~elvis>).

HRU Development Process

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 land use 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 land use, soil types, and management data 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 subwatershed level (i.e., 8-digit HUC level in this study) and finally routed to the UMRB outlet.

The HRUs required for the SWAT UMRB baseline simulation are created by aggregating NRI points together that possess common soil, land use, and management characteristics. First of all, common soil types were aggregated at 8-digit level. Then land use types are aggregated. For land use, all of the points within a given category such as forest, urban,

pasture, and CRP (conservation reserve program) land were clustered together, except for the cultivated cropland. For the cultivated cropland, the NRI points are first aggregated into several crop rotation land use clusters within each 8-digit watershed, based on the NRI cropping histories. The final step of developing HRUs required aggregation across NRI points according to the management characteristics such as tile drainage (yes or no), conservation practices (terracing, contouring, and/or strip cropping), and type of tillage (conventional, reduced, mulch, or no-till).

A total of 2,936 HRUs were developed for the entire UMRB for the SWAT baseline simulation. The HRU densities for the UMRB SWAT simulations are shown here as a function of 8-digit subwatersheds (Figure 2). The density of the HRUs is greater in the regions dominated by intensive agriculture, to facilitate the accuracy required to assess the impacts in variations between agricultural management practices and cropping systems.

INPUT DATA AND ASSUMPTIONS

NRI Land use Data

The NRI is scientifically-designed, longitudinal panel survey conducted by the USDA Natural Resources Conservation Service (NRCS) in cooperation with the Iowa State University (ISU) Statistical Laboratory (Nusser and Goebel, 1997). NRI surveys were conducted every five years from 1982 to 1997 to assess conditions and trends of the United States' soil, water, and related resources. The NRI points in these surveys are spatially identified at the state, Major Land Resource Area (MLRA), USGS 8-digit HCU watershed, and county levels, and are considered statistically valid for national, regional, state, and multi-county analysis (Kellogg et al., 1994). Annual NRI surveys were initiated in 2001

(<http://www.nrcs.usda.gov/technical/land/nri01/>) to provide resource information in a more timely manner. However, the 2001 data (the latest available) is considered statistically valid only at the national level and thus can not be used for the UMRB SWAT simulations, and so NRI 1997 data were used in this simulation.

There are a total of 113,851 NRI points in the UMRB, 42,467 of which are cropland and CRP land (Table 1). Broad land use categories and associated areas provided directly from the 1997 NRI are listed in Table 2. According to the NRI, the dominant land areas are cropland (42%), forest (20.2%), and pasture/hay/range (18.6%). The total NRI UMRB agricultural area (cropland, pasture/hay/range, and CRP) is estimated to be 64.6%, which is slightly lower than the estimate of 67% provided by NAS (2000) and an estimate of 66% derived by C. Santhi (Unpublished research data, Blacklands Research and Extension Center, Temple, Texas) from the USGS 1992 National Land Cover Data set (NLCD) described by Vogelmann et al. (2001).

A reapportionment of the NRI land use data was required for the UMRB SWAT simulations, due to the need to divide the federal land area into actual land use categories and to provide a more accurate accounting of wetland area. The NRI federal land category simply reflects the areas managed in the region by the federal government; no actual land use is provided for these areas in the database. Based on comparisons with federal land maps (Federal Lands and Indian Reservations, Printable Maps, <http://nationalatlas.gov/fedlandsprint.html>) and other land use maps, it was assumed that the federal land (8,738 km²) located in the Minnesota, Wisconsin, Illinois, and Missouri portions of the UMRB was forest. The remaining federal land area (756 km²) in the Iowa, South Dakota, Indiana, and Michigan parts of the UMRB was assumed to be wetland.

The NRI wetland area listed in Table 2 consists primarily of rural marshland and is significantly smaller than the 30,498 km² wetland area reported in the 1992 NLCD for the UMRB, as determined by C. Santhi (Unpublished research data, Blacklands Research and Extension Center, Temple, Texas). Additional wetland area is identified in the NRI in the form of acreage ranges of ≤ 1 , $\geq 1-5$, 5-20, or ≥ 20 ac, that are imbedded within specific NRI points. It is not possible to determine the exact amount of wetland area associated with these ranges. Thus it was assumed that the total wetland area should be set equal to the NLCD amount of 30,498 km². This additional wetland area was then distributed across the subwatersheds (USGS 8-digit watersheds) using same set of algorithms described in later part of the paper under wetland section.

Figures 3, 4, and 5 show the cropland areas, which represents corn and soybean (and corresponding rotations such as CC, CS, SC, CCS, and SSC), grassland area (hay and pasture land), and CRP land as percentage of 8-digit subwatershed area, respectively. Figure 6 shows the percentage of land area within 8-digit watersheds, which are tile-drained.

Crop Rotations Derived from the NRI

Thirteen crop rotations were selected for representing the baseline UMRB cropping systems (Table 3). These 13 rotations were originally used for a simulation study of the entire 12-state north central region that was based on the 1992 NRI database (Babcock et al., 1997) and are assumed to be representative of typical cropping patterns used in the region for the five different crops that are included in the rotations (alfalfa, corn, sorghum, soybean, and spring wheat). Algorithms were developed to translate the 1997 NRI cropping histories into these 13 crop rotations. If a cropland history could not be reasonably identified as following

one of the representative rotations, then the land use for the specific NRI point was slotted in a cropland category called “other.”

The distribution of crop rotations shown in Table 3 reveals that corn rotated with soybean is by far the most dominant cropping system in the UMRB, followed by the five-year rotation of corn and alfalfa, corn-corn-soybean, and continuous corn. The majority of the rotations that include sorghum and/or wheat were relatively minor in areal extent. Spring wheat is the dominant wheat crop grown in Minnesota and South Dakota while winter wheat is the dominant wheat crop grown in the other UMRB states (USDA, 1997). These trends were reflected in the wheat crops simulated for the UMRB in SWAT. It is assumed for the three-year corn-soybean-winter wheat rotation that winter wheat is planted in the fall after soybean harvest and then harvested the following summer, with no additional cropping performed in the year that winter wheat is harvested. For rotations where sorghum follows winter wheat, it is assumed that the winter wheat would be managed by being grazed with cattle in the early spring (not actually simulated) but then killed before harvest to allow for the planting of sorghum in the spring.

CPS Management Practices Data

Characterization of management practices for the UMRB was accomplished by using survey data collected by the USDA for the 12-state north central region. An underlying goal of using the survey data was to be able to use practices reported by individual producers, to the extent possible, rather than relying on representative management systems that are based on aggregate survey information. This approach incorporates more realistic variation in management practices within different crop rotations and tillage categories. Survey data

collected for the 1996-98 Agricultural Resource Management Study (ARMS), described by USDA-ERS (2004a), is the most ideal source of management practice information. However, data access restrictions due to confidentiality issues preclude using these data at present for this study. Thus, the predecessor Cropping Practices Survey (CPS) database (USDA-ERS, 2004b) was selected as the source of management practice data for the current UMRB SWAT application. Specific producer data can be accessed within the CPS, which supports the desired approach of simulating variation in management practices.

The CPS was conducted annually during 1990-95 for corn, cotton, fall potatoes, soybean, durum wheat, spring wheat, and winter wheat; rice surveys were also performed in 1990-92 and a sorghum survey was performed in 1991 (USDA-ERS, 2003c). Data collected in 1990-92 from the corn, soybean, spring wheat, winter wheat, and sorghum surveys were used for this study. The selected data was limited to 1990-92 due to high rainfall patterns that occurred across most of the region in 1993 and 1994 that resulted in anomalies in the reported management practices. Table 4 lists the number of specific CPS crop surveys that were performed in each north central region state during 1990-92. These data are reported only at the state level; i.e., data is not provided at more refined spatial units such as counties. A relatively high number of corn and soybean surveys were collected during 1990-92 for each state partially located in the UMRB region. Thus the management data used to characterize corn and soybean production practices in a given state was drawn only from surveys collected for that state. In contrast, the CPS survey data collected for sorghum, spring wheat, and winter wheat was relatively sparse. Thus, the management data was pooled across all the surveys collected in the north central region during 1990-92 for these crops and

assumed representative of production practices for these crops anywhere in the UMRB region.

Various production data were collected for the CPS including seed cost; tillage, planting, and other machinery; and applied fertilizers and herbicides. The machinery and fertilizer management data were the portions of the CPS information that were needed to perform the baseline SWAT simulation. The machinery data provided by the CPS includes specific tillage implements and other machinery used, timing of the implement pass (fall or spring), and the PTO power of the tractor used to pull each implement. The tillage system reported for each individual producer was also categorized as one of four tillage levels: conventional (< 15% residue cover), reduced (15-30% residue cover), mulch (>30% residue cover), and no till (no tillage implement passes). The fertilizer data includes the application rates for N, P, and Potassium (K), the timing of each fertilizer application (before spring seeding, before fall seeding, at seeding, or after seeding), and the method of fertilizer application. Only N and P fertilizer applications can be accounted for in SWAT, so the CPS potassium applications are ignored. Application of manure is also noted in the survey data (yes or no).

The CPS management data is linked to a specific cropland HRU via the CPS surveyed crop, cropping sequence, tillage level, and manure flag information. The cropping sequence is required to align the CPS data with each crop year in a given crop rotation derived from the NRI (Table 3). For example, two subsets of CPS data would be required to provide the tillage and fertilizer data required for a corn-soybean rotation: data from a corn survey in which soybean was the previous crop and vice versa. The corn survey data would define the tillage and fertilizer practices for each corn year of the corn-soybean rotation while the soybean survey data would provide the same information for the each soybean year of the

corn-soybean rotation. The actual choice of management data for the corn-soybean rotation would be further refined as a function of tillage level and manure application. Thus the tillage and fertilizer data required for an Illinois cropland HRU planted in a corn-soybean rotation, and managed with mulch till without manure applied, would be drawn from the subset of survey data that meets those criteria.

For example, a total of 334 and 1007 surveys of individual corn producers were performed in Illinois during 1990-92 that were identified as corn following corn and corn following soybean, respectively.

Selection of Tillage Practices for Cropland HRUs

Characterization of tillage patterns within the UMRB subwatersheds is relatively difficult. Only two sources of regional tillage information currently exist that can be potentially used to identify spatial tillage patterns across large regions: the 1992 NRI and survey data collected by the Conservation Tillage Information Center (CTIC) on a county basis (CTIC, 2004). Preliminary research has been performed to investigate the possibility of imputing 1996-98 CTIC county-level tillage survey data onto NRI points located within a specific county (Kurkalova and Rabotyagov, 2003). However, further research with this approach is required before it can be incorporated into the SWAT UMRB modeling system. Therefore, the 1992 NRI tillage data was used as the guide for imputing specific CPS tillage practices onto the cropland HRUs.

A three-step process is required to determine which set of CPS tillage practices should ultimately be assigned to a given cropland HRU. The initial step requires the establishment of links between the 1992 and 1997 NRI points, so that the 1992 NRI tillage data can be used

with the 1997 NRI. Then each cropland HRU created with the 1997 NRI data is identified as being managed with either conventional or conservation tillage, which are the two general tillage categories provided in the 1992 NRI. Finally, a weighted random selection process is performed to determine which specific set of CPS tillage practices should be selected for each cropland HRU, based on how frequent a specific tillage sequence (including timing) occurs within the general categories of conventional or conservation tillage. The final choice of tillage practices determines which of the four CPS tillage categories the cropland HRU is categorized as; i.e., conventional, reduced, mulch, or no till. Figure 7 shows the cropland with conservation tillage practices as percentage of subwatershed area.

Selection of CPS Fertilizer Practices for Cropland HRUs

Limitations exist with using specific CPS surveyed data, due to extremes that occur in reported fertilizer rate applications. This is illustrated in Figure 8, which shows N application rates applied to corn following corn in Iowa (without manure) that range from 0 to over 400 kg/ha. It is impossible to know the history of fertilizer rate of individual producer's fields in the CPS, which resulted in the decisions to use such extremely low and high N application rates. Simulation of these extreme rates for the cropland HRUs would result in either severely stressed crop yields due to insufficient N or large overestimations of N losses in response to excessively high application rates. The greater the HRU size, the more magnified these distortions would be.

Thus, it was assumed that lower and upper bounds of fertilizer applications should be established, to mitigate the potential distortions that could result from the extreme application rates. These bounds were assumed to be the 25th and 75th quartile application rates, which

are 25% lower and higher than the median application rate determined for a given set of application rates defined by cropping sequence and whether manure was applied or not (tillage level was not considered for establishing the bounds). The lower and upper bounds for corn following corn in Iowa (without manure) were determined to be 112 and 175 kg/ha, respectively, as shown in Figure 8. The lower and upper bounds do eliminate consideration of some application rates that would likely be considered as within the range of typical fertilizer rate applications. However, incorporating the bounds eliminates the possibility of simulating unrealistic application rates.

Table 5 lists the lower bound, median, and upper bound N fertilizer application rates (without manure) for corn following corn and corn following soybean by state, and the total number of surveys that these rates were derived from. It is clear that the N application rates vary significantly between states, with the highest rates applied in Illinois and the lowest rates applied in South Dakota and Wisconsin. It is also notable that the Indiana, Michigan, and Minnesota N application rates were higher for corn following soybean versus corn following corn, which would indicate a lack of N crediting for the previous soybean legume crop in these states. The four lower bound N application rates determined for South Dakota and Wisconsin were set equal to the Minnesota lower bound rate of 87 kg/ha for corn following corn to minimize potential N stress for the simulated corn in those states. Other adjustments were made to some of the N and P application rates, primarily to prevent distortions due to small sample sizes.

Similar lower and upper bound N application rates were determined for sorghum, soybean, spring wheat, and winter wheat, with and without manure. Corresponding P application rate bounds were also calculated for all five of the crops. It was assumed that N

fertilizer was applied to 100% of the simulated corn, sorghum, spring wheat and winter wheat, to avoid unrealistic yield stress. This is consistent with USDA National Agricultural Statistic Survey (NASS) results, which report that N use on corn usually exceeds 95% for most of the UMRB states and that N use on spring wheat or winter wheat typically exceeds 90% for Illinois, Minnesota, and Missouri, the three states in the region that produce the most wheat (e.g., USDA-NASS, 1992; USDA-NASS, 1997). The majority of CPS soybean surveys collected across the eight states reported that N was not applied to soybeans for the eight states. This again is generally consistent with the USDA-NASS survey results, which report small amounts of N fertilizer applied to 20% or less of the soybean production area in most of the UMRB states in any given year. Thus, it was assumed that all of the soybean N applications should be set to zero for the UMRB SWAT simulations. P fertilizer was assumed to be applied to most of the cropland HRUs. However, some of the P applications rates were determined to be zero for specific cropping sequences, especially for soybeans following other crops.

An initial check of the CPS derived N application rates was performed by comparing the Iowa and Illinois median rates for corn following corn and corn following soybean (Table 5) with 10-year USDA-NASS (1990-99) overall mean N application rates determined for corn in both states (that do not differentiate as to the previous crop). This does not provide a direct comparison, but does give an indication if the application rates are reasonable. The 10-year Iowa mean N application rate was computed to be 138 kg/ha based on historical data provided by Tiffany and Miller (2004), while the Illinois mean application rate was calculated to be 175 kg/ha based on historical data provided by IASS (2004). The Iowa and Illinois CPS median N application rates are in general agreement with the 10-year mean

application rates, which again reflect considerable difference in the amount of N applied on corn between the two states. Further comparisons with N application rate data reported by USDA-NASS (1992) and USDA-NASS (1997) indicate that the CPS derived N application rates are similar to those reported by NASS for different crops and cropping sequences.

A final check on the N application rates was performed by comparing the total amount of simulated N applied within SWAT for each 8-digit watershed versus fertilizer sales data (reference) that has been collected on a county basis. The comparison was performed by aggregating the county fertilizer sales data to the 8-digit watershed level, based on an areal weighting scheme. For example, if 75% of a county is in a specific 8-digit watershed, then 75% of the N fertilizer reported for the county was assumed to be applied in the given 8-digit watershed.

Manure Applications

Manure applications on cropland are a secondary source of nutrients in agricultural areas in the UMRB. Manure N and P applications will be incorporated in the UMRB SWAT modeling framework on the basis of the methodology developed by Kellogg (Kellogg, R. 2003. Personal communication. USDA Natural Resources Conservation Service, Washington, D.C.) as described in Appendix B of Edmonds et al. (2003). Kellogg developed manure N and P application rates for both current conditions (baseline) and for conditions in which livestock operations would have to manage manure in compliance with a Comprehensive Nutrient Management Plan (CNMP). The baseline manure N and P application rates will be used in the UMRB modeling system to represent baseline manure application rates in the region.

The Kellogg approach is based on representative livestock farms that were developed for different regions of the U.S. using data available from the 1997 Census of Agriculture (NASS, 1997). The application rates were calculated for each representative farm as a function of several factors including the total generated manure N and P, the total recoverable portion of the manure N and P (i.e., that was not lost due to atmospheric volatilization or other processes), the type of crop the manure was applied to, and whether the manure was applied to cropland on a manure generating farm (representative livestock farm) or to cropland on a “manure receiving farm.” The total areas required to apply the aggregate manure nutrients at the regional and county levels were then determined, for both the manure generating and manure receiving farms.

The areas within each county that are required for the manure applications were aggregated to the 8-digit watershed level by Kellogg, to facilitate the linkage of the derived manure N and P application rates to the UMRB SWAT modeling system. This aggregation step was performed by using the same areal weighting scheme as previously described for the check between the CPS fertilizer and fertilizer sales amounts at the 8-digit watershed level. The manure N and P application rates will next be applied to HRUs within each 8-digit watershed, whose combined area equals as closely as possible the aggregated manure application area calculated for the 8-digit watershed. The manure nutrients will be applied to HRUs that receive CPS-derived fertilizer application rates that are identified in the survey as having been applied in combination with manure. Priority will also be given to simulating the manure N and P applications on cropland planted to corn, to the extent possible.

In general, the total nutrient amounts that will be applied to the “manured HRUs” will greatly exceed the N and P uptake rates for corn and other crops. This is reflected by the fact

that the CPS fertilizer application rates which were identified as being applied in tandem with manure are not much lower than the corresponding CPS fertilizer rates for non-manured fields, thus implying that only limited crediting of manure nutrients was performed by the surveyed producers. The baseline manure N and P application rates calculated by Kellogg are also relatively high, reflecting assumptions that the typical producer would be applying manure at twice the N application rate without a CNMP.

Soil Data

The NRI reports a total of 20,765 different soil types distributed across the UMRB, with an average of over 158 for each of the 131 USGS 8-digit Watersheds. This extensive set of soil types far exceeds the practical limits of the HRU methodology required for the SWAT UMRB simulations. Thus a subset of representative soils was used for constructing the cropland 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 and Extension Center. Temple, TX).

The soil clusters were obtained by identifying the most important characteristics and properties through factor analysis. Soils were then grouped on the basis of linear combinations of soil properties, with the coefficients derived from the factor analysis. A detailed discussion of the statistical methodology used for the clusters can be found in Sanabria and Goss (1997). 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 cropland points on the basis of soil types; much smaller subsets of the 417 soils were used for aggregating NRI

points within specific subwatersheds. Figure 9 shows the distribution of soil clusters per 8-digit subwatersheds in the UMRB.

Only one HRU is created individually for the forest, pasture, and urban areas in each subwatershed. Thus a single soil type was selected for each of these non-cropland HRUs from the subset of the 417 representative soils that exist in a given subwatershed. The selected soil type was either: (1) the dominant soil type as determined from the NRI points that were clustered together to create the HRU, or (2) the dominant soil for the whole watershed if the dominant soil found among the clustered NRI points was not included in the representative soil subset.

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). Table 6 lists the soil layer data required by SWAT as given in Neitsch et al. (2002).

Climate Data

Climate data required by the model are daily precipitation, maximum/minimum air temperature, solar radiation, wind speed and relative humidity. These daily climatic inputs can be entered from historical records, and/or generated internally in the model using monthly climate statistics that are based on long-term weather records. For this study, historical precipitation and temperature records for the UMRB were obtained from C. Santhi (2002. Personal communication. Blacklands Research and Extension Lab. Temple, TX) for 151 weather stations located in and around of the watershed. These precipitation and temperature data were originally obtained from the National Climatic Data Center

(<http://www.ncdc.noaa.gov/oa/ncdc.html>) and were adapted for application within the Hydrologic Unit Model of the United States (HUMUS) modeling system (Arnold et al., 1999). Missing data in the precipitation and temperature records, as well as daily solar radiation, wind speed, and relative humidity inputs, were generated internally in SWAT using monthly climate statistics that are based on long-term weather records (available within the model for the entire U.S.).

A single weather station is used in SWAT to simulate the climatic inputs for a given subwatershed. The SWAT2000 ARCVIEW interface (AVSWAT), developed by Di Luzio et al. (2001), was used to determine which weather station should be used for a given subwatershed, based on the geographic centroid of each subwatershed. A total of 23 weather stations were eliminated from the simulation framework as a result of this procedure. An additional 17 weather stations were also dropped, because they are located in subwatersheds that drain into the Mississippi below Grafton, IL and thus are currently not used. The distribution of the final set of 111 weather stations within the UMRB is shown in Figure 10.

Wetlands, Ponds, and Reservoirs

The total amount of identifiable UMRB wetland area reported in the NRI appears to be a considerable underestimate of the actual wetland area, as previously discussed. Additional wetland area, that is not categorized as rural marshland (or “federal wetland area” in this study), is identified in the NRI in the form of acreage ranges of ≤ 1 , $\geq 1-5$, $5-20$, or ≥ 20 ac that are imbedded within specific NRI points. Thus it is not possible to determine the exact amount of wetland area that exists within a given NRI point. Thus a procedure was developed to estimate the actual amount of wetland area in each of the 8-digit subwatersheds,

based on the NLCD wetland area estimates for each of the 8-digit subwatersheds as determined by C. Santhi (Unpublished research data, Blacklands Research and Extension Center, Temple, Texas). The wetland estimation procedure is performed using the following three step process: (1) the wetland amount given in Table 1 and the wetland area attributed to the federal lands were subtracted from the total NLCD wetland area, (2) the remaining area was then distributed within each subwatershed using a set of algorithms that determined how much wetland area should be imputed on a given NRI point as a function of the wetland acreage range (≤ 1 , $\geq 1-5$, $5-20$, or ≥ 20 ac) identified for that point, and (3) the equivalent area, that was attributed to wetland for a specific NRI point, was subtracted from the land use category identified for that point. The final amount of total wetland incorporated in the modeling system for the UMRB will be as close to the NLCD estimate of 30,498 km² as possible.

Minimum reservoir input data are surface area and storage volume at the principal and emergency spillway level, and reservoir outflow volume. The reservoir data for the UMRB SWAT simulation were obtained from C. Santhi (2002. Personal communication. Blacklands Research and Extension Lab. Temple, TX). These data were originally obtained from the National Dam Inventory (NDI) database (<http://crunch.tec.army.mil/nid/webpages/nid.cfm/>) and were adapted for application within HUMUS modeling system (Arnold et al., 1999). A total of 61 reservoirs were simulated as uncontrolled reservoirs in the baseline simulations with an average daily principal spillway release of 0.1 m³/s.

The total water surface area, which includes surface areas of reservoirs, streams, and ponds, were derived from USGS 1992 National Land Cover Dataset (NLCD) and found to be in close vicinity of that estimated from the NRI data. For UMRB SWAT simulation, the

resulting water surface area for each subwatershed, after subtracting the sum of reservoir and stream surface areas from the total surface area within that subwatershed, were simulated as a pond.

CONCLUSIONS

A SWAT modeling system has been constructed to support analyses of agricultural policy scenarios for the UMRB. Cropping system, tillage and fertilizer management, and conservation practice detail have been incorporated into the modeling system, by using the USDA NRI and CPS databases, relative to previous SWAT applications performed for the region (e.g., Arnold et al., 1999; Arnold et al., 2000). This additional detail will facilitate the analyses of a wide range of land use, nutrient management, and conservation practices scenarios for agricultural subregions within the UMRB.

The UMRB modeling system will continue to evolve as improved data become available and/or enhancements and improvements are made to SWAT. Short term goals for improving the modeling system include replacing the 1992 NRI spatial tillage estimates and the 1990-92 CPS data with more recent data collected in the late 1990s. Developments are also underway to incorporate the ability to simulate the explicit locations, and resulting impacts, of buffer strips and other vegetative systems in riparian zones (Arnold, J. 2004. Personal Communication. Grassland, Soil and Water Research Laboratory, Temple, TX). This enhancement will be ported to the UMRB modeling system when it is released in a future version of SWAT.

The calibration and validation phase of the SWAT UMRB modeling system has been initiated. This phase will build upon previous calibration and validation work performed by

Jha et al. (2004a) and Jha et al. (2004b), who simulated climate change impacts upon the UMRB hydrologic system using less detailed land use data available in the Better Assessment Science Integrating Point and Nonpoint Sources (BASINS) package version 3 (USEPA, 2001).

REFERENCES

- AAEA. 2000. Commodity Costs and Return Estimation Handbook. Task Force, American Agricultural Economics Association, Ames, Iowa. Available at: <http://waterhome.brc.tamus.edu/care/Aaea/>. Accessed in July 18, 2004.
- Anfinson, J.O. 2003. *The River We Have Wrought: A History of the Upper Mississippi*. University of Minnesota Press. Minneapolis, Minnesota.
- Arnold, J.G. and P.M. Allen. 1996. Estimating hydrologic budgets for three Illinois watersheds. *Journal of Hydrology* 176:57-77.
- Arnold, J.G., R.S. Muttiah, R. Srinivasan, and P.M. Allen. 2000. Regional estimation of base flow and groundwater recharge in the Upper Mississippi river basin. *Journal of Hydrology* 227:21-40.
- Arnold, J.G., R. Srinivasan, R.S. Muttiah, and P.M. Allen. 1999. Continental scale simulation of the hydrologic balance. *Journal of American Water Resources Association* 35(5):1037-52.
- Arnold, J. G., R. Srinivasan, R. S. Muttiah, and J. R. Williams. 1998. Large area hydrologic modeling and assessment; part I: model development. *Journal of American Water Resources Association* 34(1):73-89.
- Baumer, O., P. Kenyon, and J. Bettis. 1994. MUUF v2.14 User's Manual. U.S. Department of Agriculture, Natural Resources Conservation Service, National Soil Survey Center, Lincoln, Nebraska.
- CTIC. 2004. National Crop Residue Management Survey Conservation Tillage Data. West Lafayette, IN. Available at <http://www.ctic.purdue.edu/CTIC/CRM.html>. Accessed in May 2004.
- Di Luzio, M., R. Srinivasan, J.G. Arnold, and S. Neitsch. 2002. ARCVIEW Interface for SWAT 2000 User's Guide. Blackland Research Center. Texas Agricultural Experiment

- Station, Temple, Texas. <http://www.brc.tamus.edu/swat/swat2000doc.html> (accessed in July 18, 2004).
- Edmonds, L., N. Gollehon, R.L. Kellogg, B. Kintzer, L. Knight, C. Lander, J. Lemunyon, D. Meyer, D.C. Moffitt, and J. Schaefer. 2003. Costs Associated with Development and Implementation of Comprehensive Nutrient Management Plans: Part 1—Nutrient Management, Land Treatment, Manure and Wastewater Handling and Storage, and Recordkeeping. U.S. Department of Agriculture, Natural Resources Conservation Service, Washington, D.C. Available at <http://www.nrcs.usda.gov/technical/land/pubs/cnmp1.html>. Accessed in July 18, 2004.
- Gassman, P.W., T. Campbell, S. Secchi, M. Jha, and J. Arnold. 2003. The i_SWAT software package: a tool for supporting SWAT watershed applications. In: SWAT2003: The 2nd International SWAT Conference, 1-4 July, Bari, Italy. Instituto di Ricerca sulle Acque, IRSA-CNR, Bari, Italy. pp. 66-69.
- Goolsby, D.A., W.A. Battaglin, B.T. Aulenbach, and R.P. Hooper. 2001. Nitrogen Input to the Gulf of Mexico. *Journal of Environmental Quality* 30:329-336.
- Goolsby, D. A., W.A. Battaglin, G.B. Lawrence, R.S. Artz, B.T. Aulenbach, R.P. Hooper, D.R. Keeney, and G.J. Stensland. 1999. Flux and sources of nutrients in the Mississippi-Atchafalaya River Basin: Topic 3 report for the integrated assessment on hypoxia in the Gulf of Mexico. NOAA Coastal Ocean Program Decision Analysis Series No. 17. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Centers for Coastal Ocean Science, Silver Spring, Maryland. Available at http://www.nos.noaa.gov/products/pubs_hypox.html. Accessed in July 18, 2004.
- IASS. 2004. Reports. Illinois Agricultural Statistics Service. Springfield, IL. Available at <http://www.agstats.state.il.us/>. Accessed in July 18, 2004.
- Jha, M., Z. Pan, E.S. Takle, and R. Gu. 2004a. Impacts of Climate Change on Stream Flow in the Upper Mississippi River Basin: A Regional Climate Model Perspective. *Journal of Geophysical Research* 109:D09105.
- Jha, M., J.G. Arnold, P.W. Gassman, and R. Gu. 2004b. Climate change sensitivity assessment on Upper Mississippi River Basin Streamflows using SWAT. *Journal of American Water Resources Association* 40(3):811-825.
- Kellogg, R.L., G. W. TeSelle, and J.J. Goebel. 1994. Highlights from the 1992 National Resources Inventory. *Journal of Soil and Water Conservation* 49(6):521-527.
- Knox, J.C. 2001. Agricultural influence on landscape sensitivity in the Upper Mississippi River Valley. *Cantena* 42(2-4):193-224.

- Kurkalova, L.A. and S. Rabotyagov. 2003. Estimation of a Discrete Choice Model When Individual Choices are Not Observable (ppt presentation). Selected paper. Presented at the Midwest Economics Association Meetings, 28-30 March, St. Louis, MO.
- NAS. 2000. The changing face of the UMR Basin; agriculture: selected profiles of farming and farm practices. National Audubon Society, Upper Mississippi River Campaign, St. Paul, Minnesota. Available at http://www.umbsn.org/news/documents/chg_face.pdf. Accessed in July 18, 2004.
- Neitsch, S.L., J.G. Arnold, J.R. Kiniry, and J.R. Williams. 2002. Soil and Water Assessment Tool Theoretical Documentation, Version 2000 (Draft). Blackland Research Center, Texas Agricultural Experiment Station, Temple, Texas. Available at <http://www.brc.tamus.edu/swat/swat2000doc.html>. Accessed in July 18, 2004.
- Osei, E., P. Gassman, A. Saleh. 2000. Livestock and the Environment: A National Pilot Project; Upper Maquoketa River Watershed, Iowa Modeling Assumptions: Technical Report. Report No. RR0001. Texas Institute for Applied Environmental Research, Tarleton State Univ., Stephenville, TX.
- Phillips, D.L., P.D. Hardin, V.W. Benson, and J.V. Baglio. 1993. Nonpoint Source Pollution Impacts of Alternative Agricultural Management Practices in Illinois: A Simulation Study. *Journal of Soil and Water Conservation* 48(5):449-457.
- Potter, S.R., J.D. Atwood, R.L. Kellogg, and J.R. Williams. 2004. An approach for estimating soil carbon using the national nutrient loss database. *Environmental Management* (forthcoming).
- Rabalais, N.N., R.E. Turner, and D. Scavia. 2002. Beyond Science into Policy: Gulf of Mexico Hypoxia and the Mississippi River. *BioScience* 52(2):129-142.
- Tiffaney, B. and G. Miller. 2004. Iowa Soil and Land Use: N Use. Iowa State University, Ames, IA. Available at <http://extension.agron.iastate.edu/soils/>. Accessed in July 18, 2004.
- USDA-ERS. 2003a. Briefing Room: Agricultural Resource Management Survey (ARMS): Publication and Use of ARMS Data. U.S. Department of Agriculture, Economics Research Service, Washington, D.C. <http://www.ers.usda.gov/briefing/ARMS/publishanduse.htm#prodprac>. Accessed in July 18, 2004.
- USDA-ERS. 2003b. Briefing Room: Agricultural Resource Management Survey (ARMS): Recommended Data. U.S. Department of Agriculture, Economics Research Service, Washington, D.C. <http://www.ers.usda.gov/briefing/ARMS/moredata.htm#cropprac>. Accessed in July 18, 2004.

- USDA-ERS. 2003c. Briefing Room: Agricultural Resource Management Survey (ARMS): Recommended Data. U.S. Department of Agriculture, Economics Research Service, Washington, D.C. <http://www.ers.usda.gov/Briefing/ARMS/armscoverage.htm>. Assessed in July 18, 2004.
- USDA-NASS. 1997. Usual Planting and Harvesting Dates for U.S. Field Crops. U.S. Agricultural Handbook Number 628. Department of Agriculture, National Agricultural Statistics Service, Washington, D.C. Available at: <http://usda.mannlib.cornell.edu/reports/nassr/field/planting/>. Accessed July 18, 2004.
- USDA-NASS. 2004. Agricultural Chemical Use: Agricultural Chemical Usage, Field Crops Summary 1992. U.S. Department of Agriculture, National Agricultural Statistics Service, Washington, D.C. Available at <http://usda.mannlib.cornell.edu/reports/nassr/other/pcu-bb/#field>. Accessed in July 18, 2004.
- USEPA. 2001. BASINS 3.0: Better Assessment Science Integrating Point and Nonpoint Sources. U.S. Environmental Protection Agency, Office of Water, Office of Science and Technology, Washington, D.C. Available at <http://www.epa.gov/ost/BASINS/>. Accessed in July 18, 2004.
- Vogelmann, J.E., S.M. Howard, L. Yang, C.R. Larson, B.K. Wylie, and N. Van Driel. 2001. Completion of the 1990s National Land Cover Data Set for the Conterminous United States from Landsat Thematic Mapper Data and Ancillary Data Sources. *Photogrammic Engineering & Remote Sensing* 67(6):650-655, 657-659, 661-662.

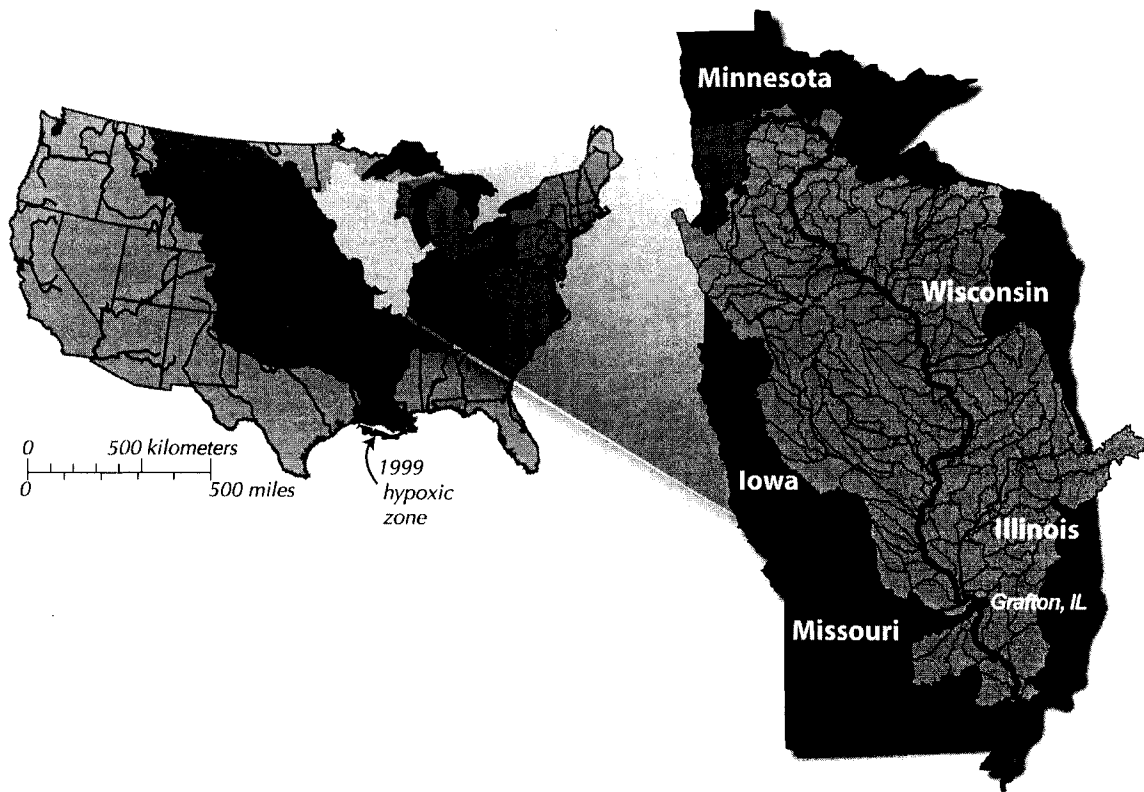


Figure 1. Location of the Upper Mississippi River Basin (UMRB) within the Mississippi River Basin, the 131 8-digit watersheds located within the UMRB, and the location of Grafton, IL.

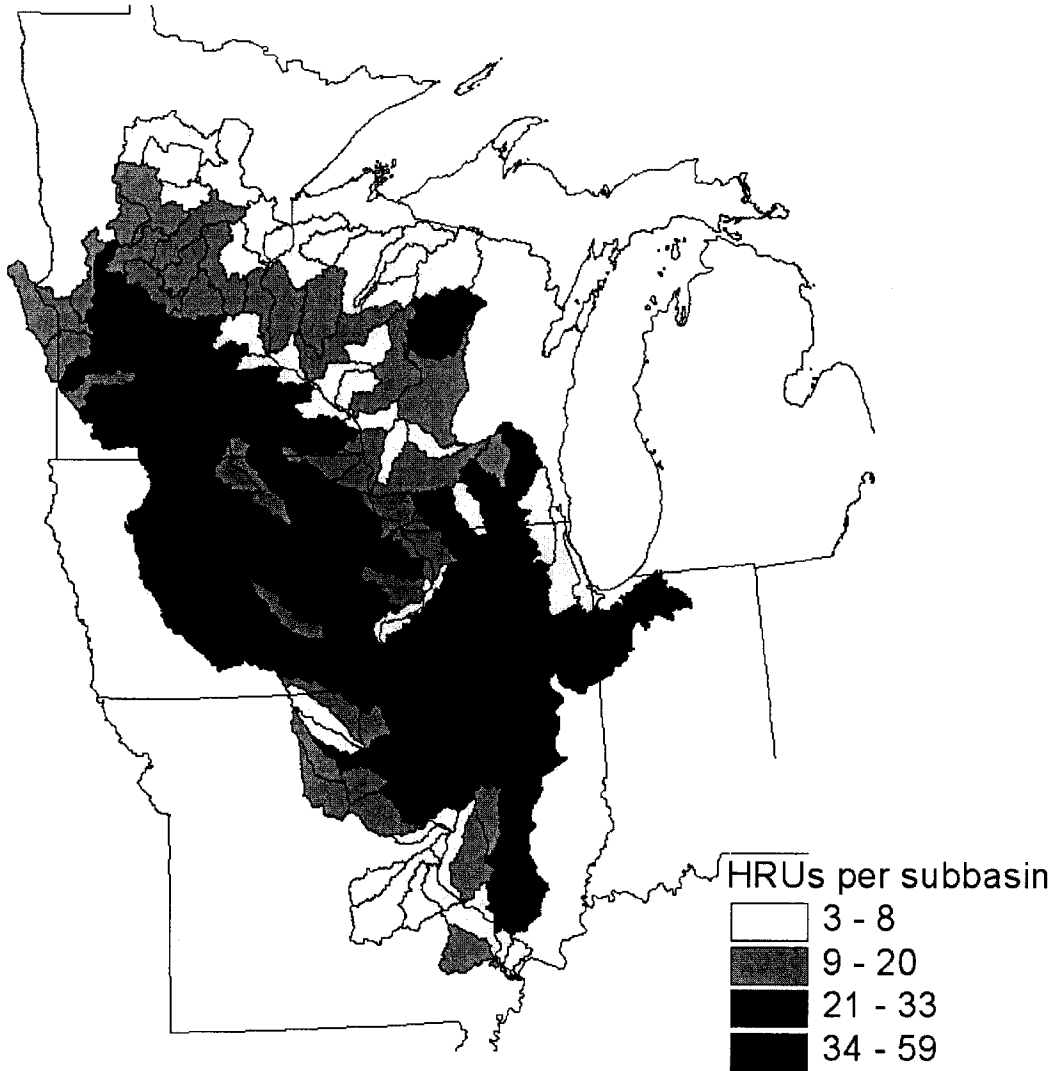


Figure 2. HRU distribution in the UMRB for SWAT simulations.

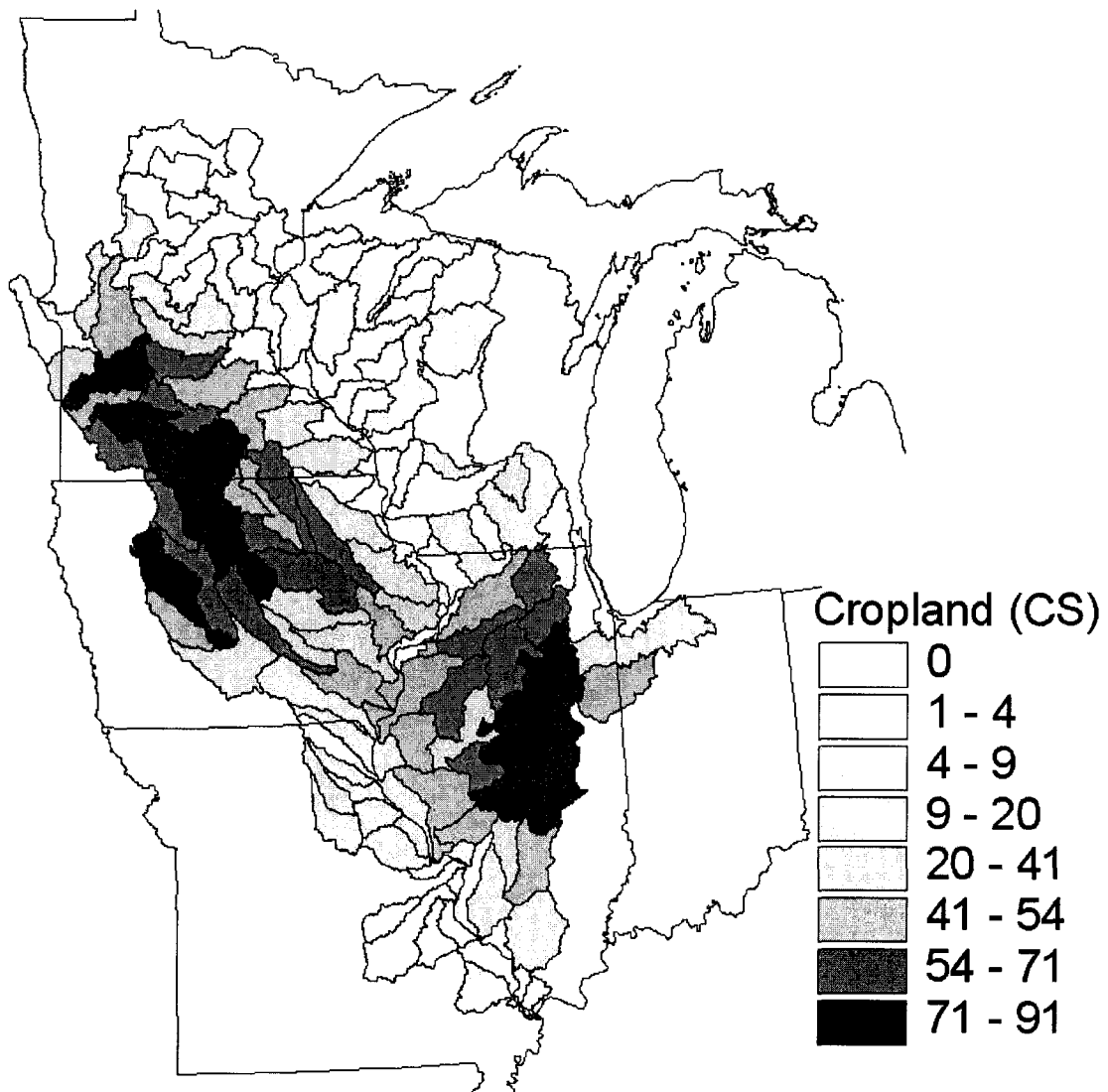


Figure 3. Cropland (Corn and soybean) as % of subbasin area.

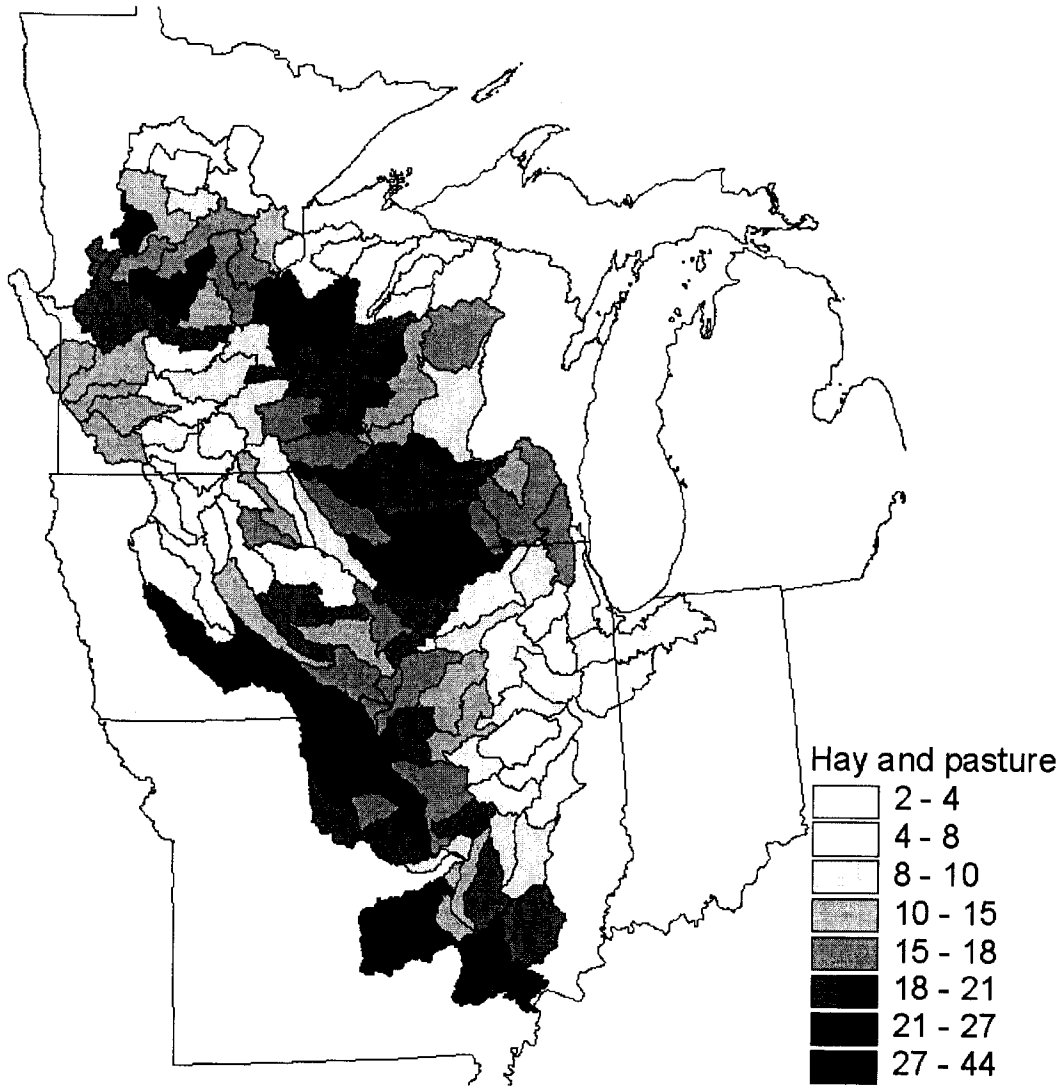


Figure 4. Grassland (hay and pasture) as % of subbasin area.

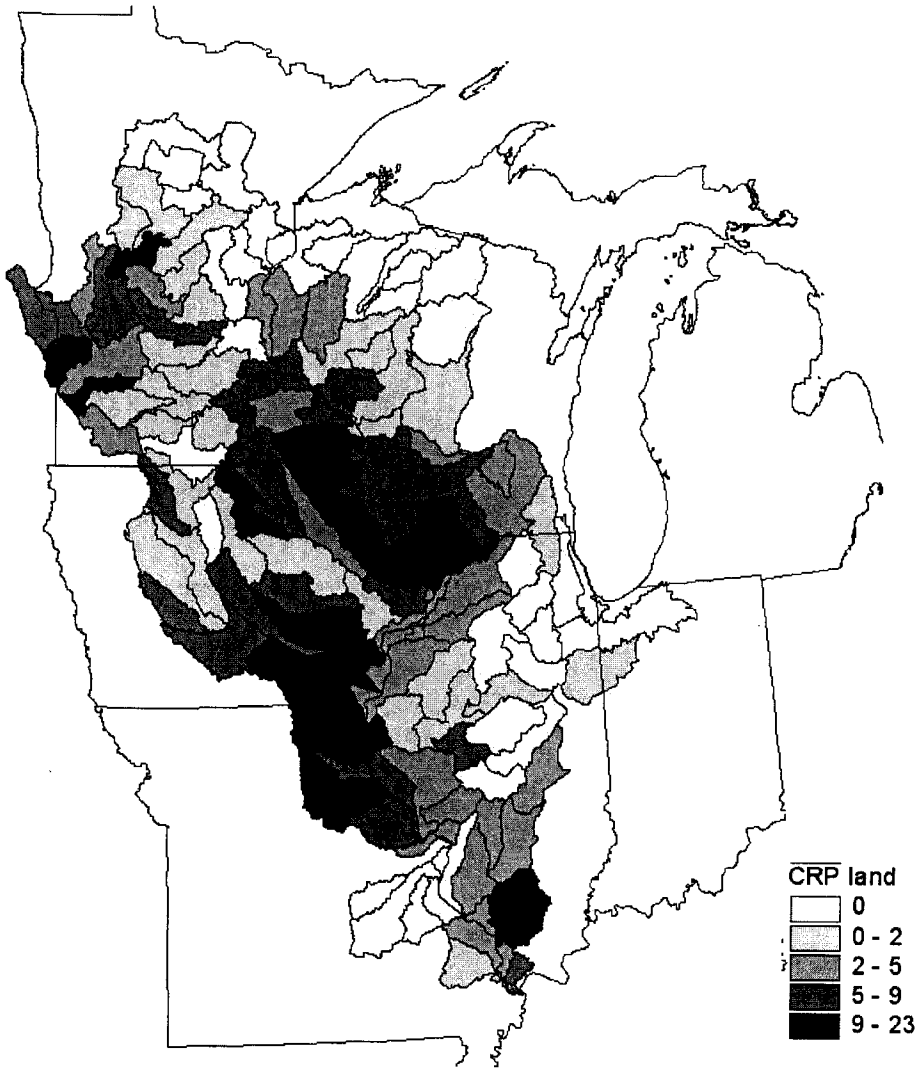


Figure 5. CRP (Conservation Reserve Program) area as % of subbasin area.

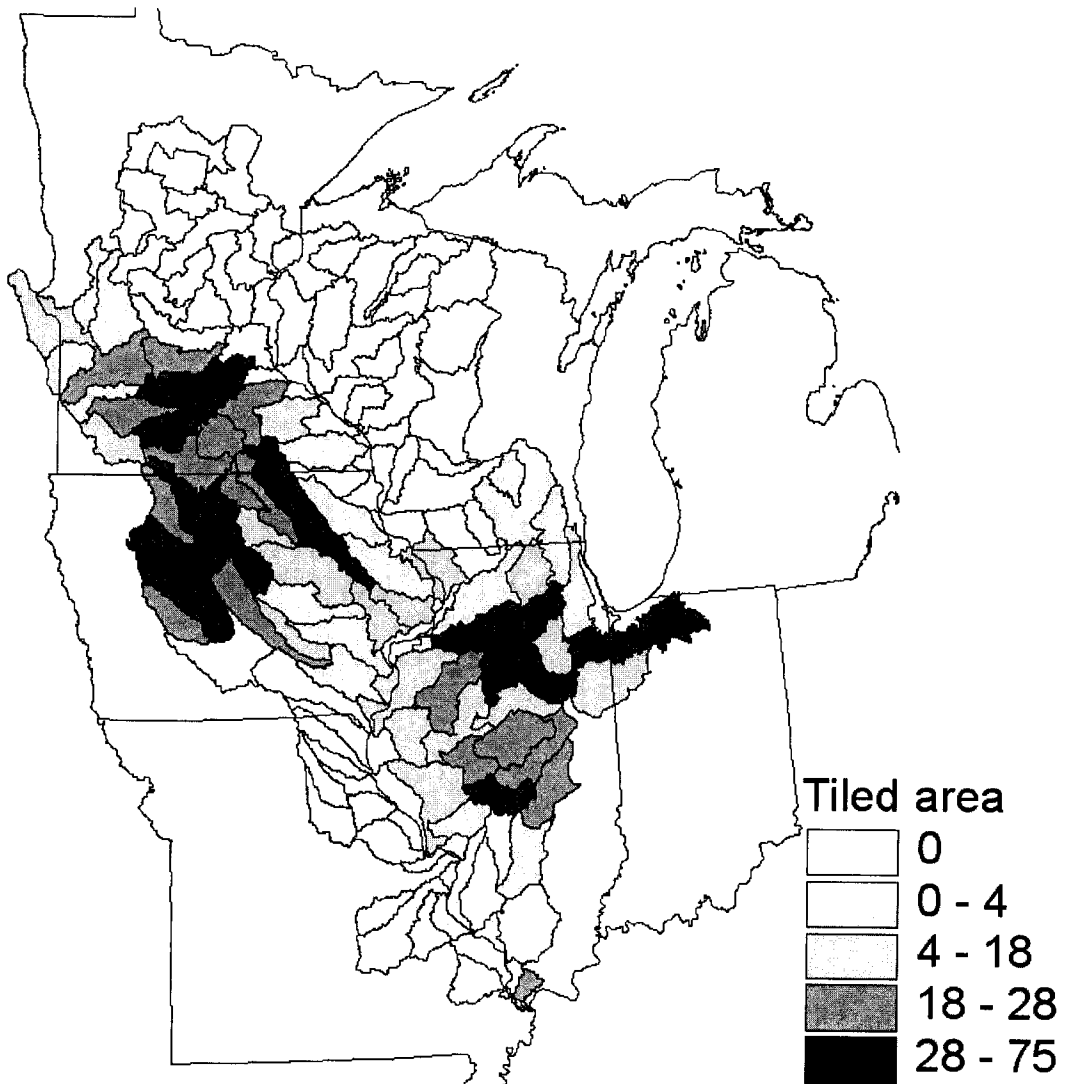


Figure 6. Tile drainage area as % of subbasin area.

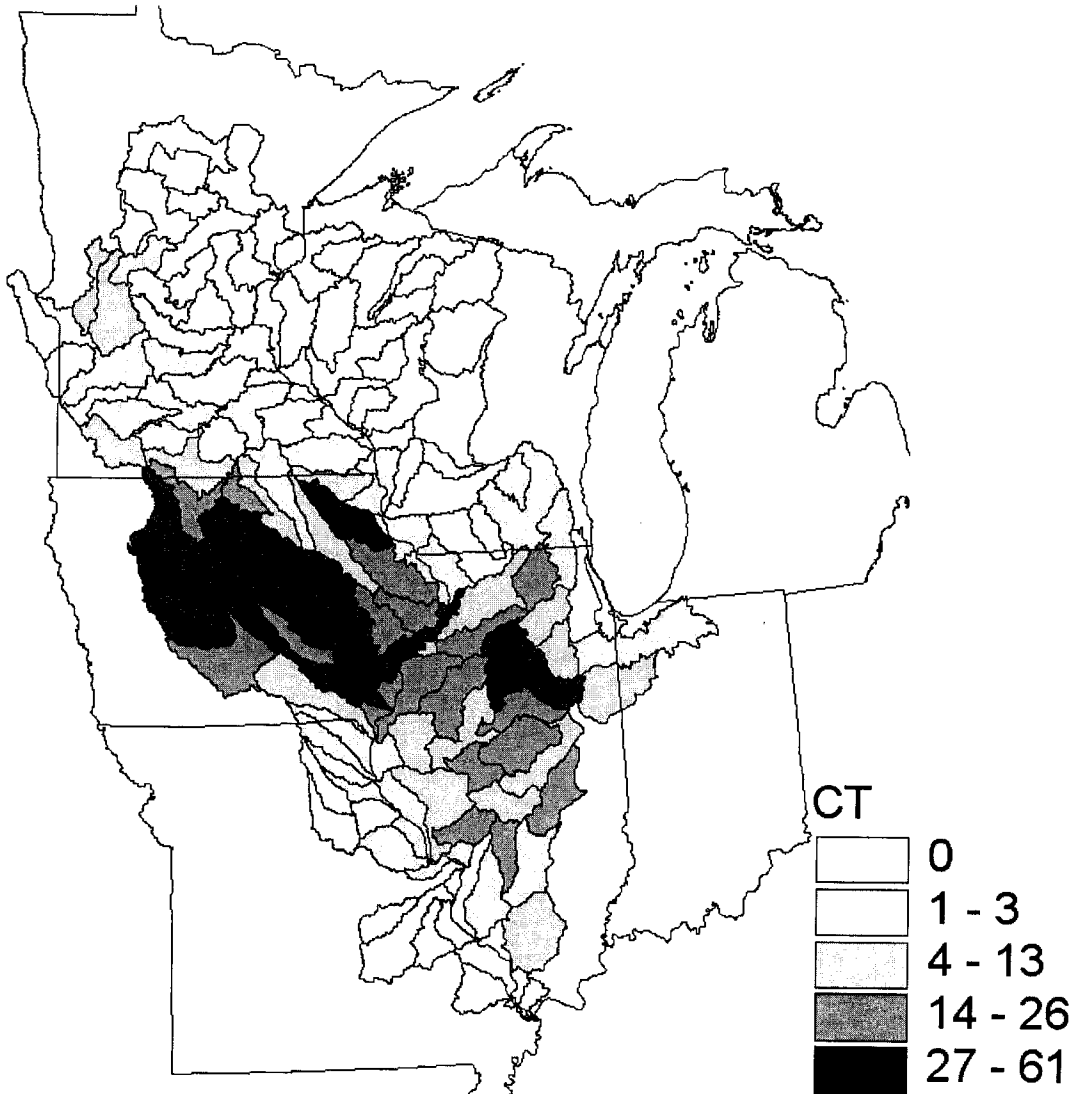


Figure 7. Conservation tillage practices area as % of subwatershed area.

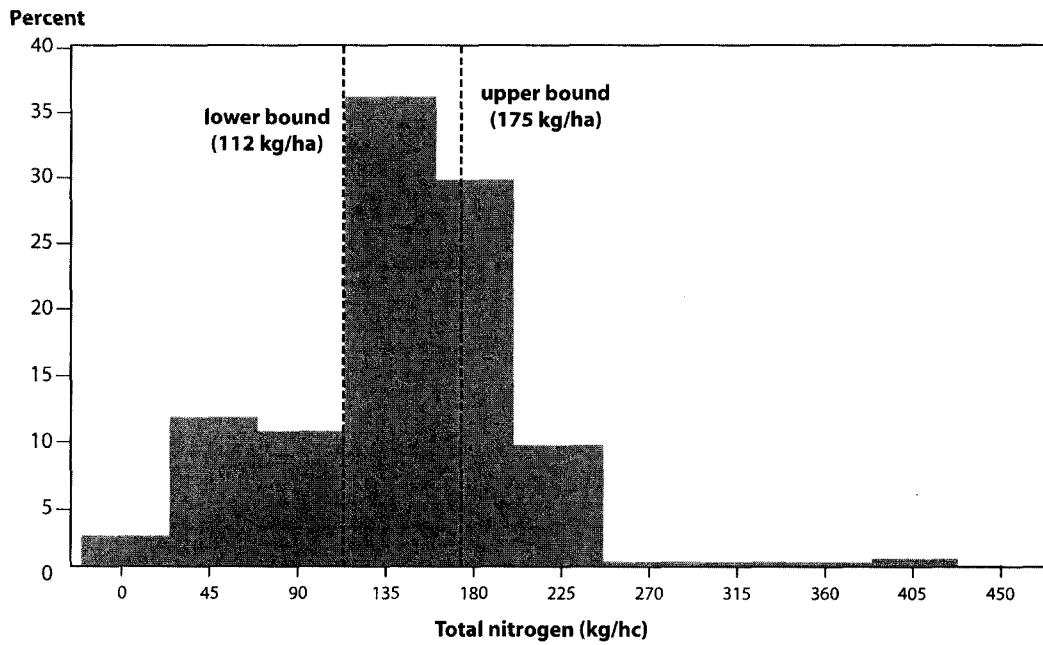


Figure 8. Example histogram of nitrogen application rates for farmers surveyed during the 1990-92 CPS survey who planted corn following corn in Iowa, including the lower and upper bounds for the nitrogen application rates simulated in SWAT which were based on the first quartile below and above the median (sample size = 394; median = 130 lb/ac; the x-axis values are approximate rates that were converted from the original CPS units of lb/ac).

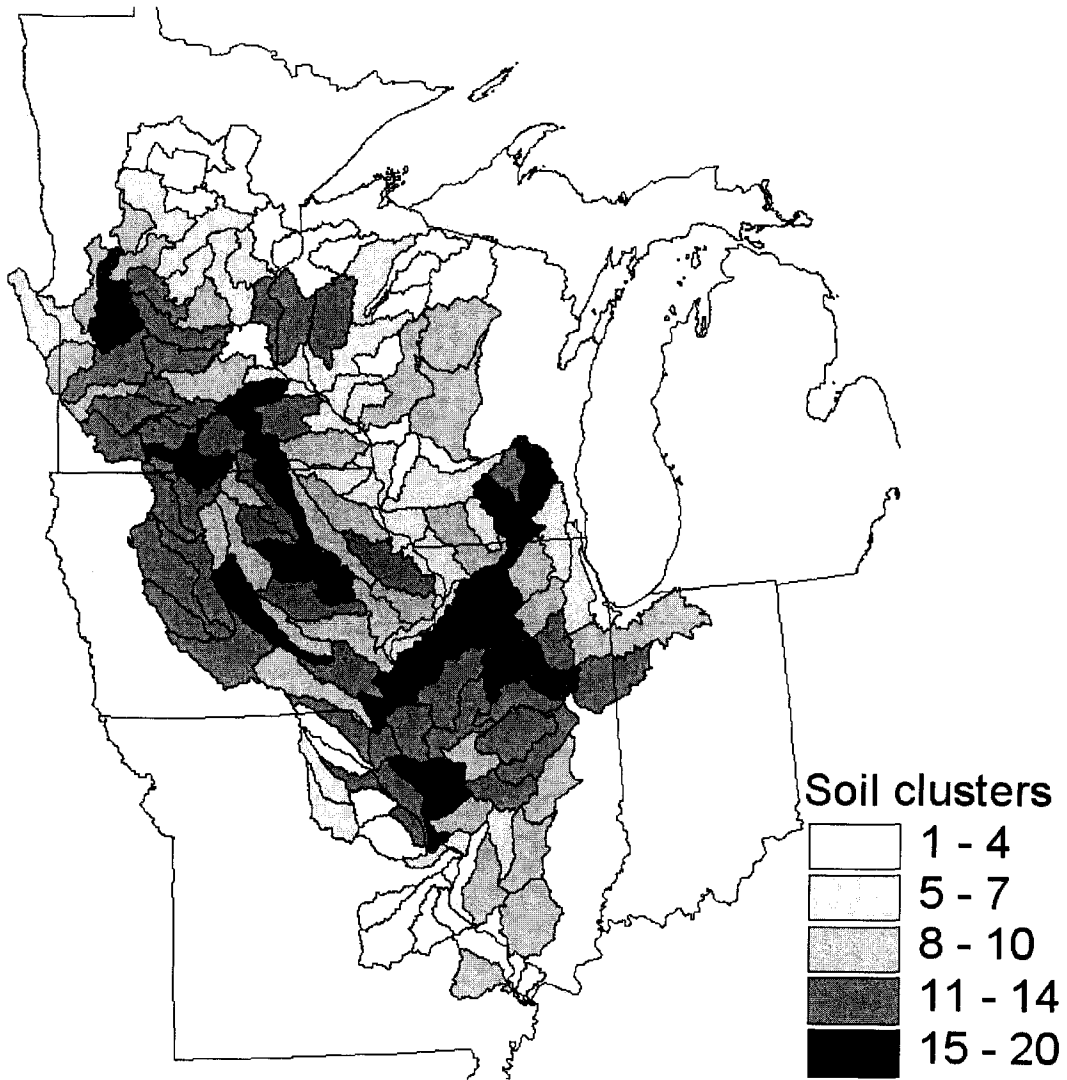


Figure 9. Distribution of soil clusters per 8-digit level of subwatershed in the UMRB.

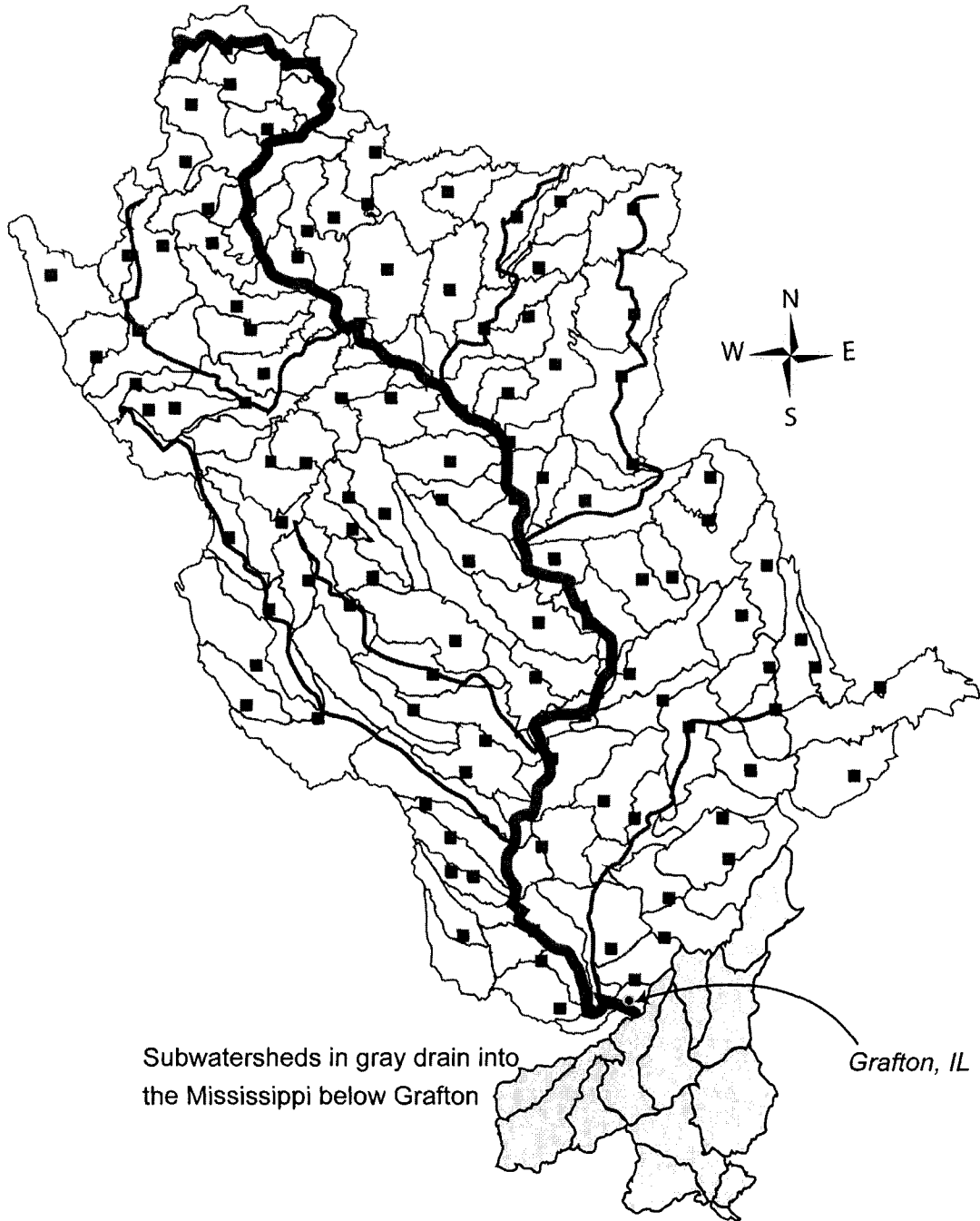


Figure 10. Locations of the 111 climate stations within the UMRB, relative to 131 subwatersheds and the location of Grafton, IL.

Table 1. NRI points in the UMRB by state.

State	Number of NRI points	Number of cropland points
Missouri	9,043	2,451
Iowa	23,498	11,154
Illinois	29,592	13,295
Indiana	2,215	1,079
Michigan	48	14
Minnesota	27,481	9,557
South Dakota	1,063	436
Wisconsin	20,911	4,481

Table 2. 1997 NRI broad land use categories.

Land Use	Area (km ²)	% of Total Area	Comments
Cropland	210,049	42.7	Row crop and small grains
Pasture/hay/range	91,463	18.6	Includes alfalfa rotated with corn
CRP	16,375	3.3	Conservation Reserve Program
Forest	99,157	20.2	
Urban/barren	43,002	8.7	Includes farmsteads & rural roads
Water	14,678	3.0	Streams, reservoirs, etc.
Wetlands	7,647	1.6	Rural marshland and rice
Federal land	9,494	1.9	No actual land use data provided
Total	491,836	100.0	

Table 3. UMRB crop rotations, and associated number of NRI points, areal extent, and required CPS crop sequences.

Crop Rotations	Rotation codes	NRI Points	Area (km ²)	Required CPS crop sequences
Continuous corn	CC	2,971	18,876	CC
Continuous soybean	SS	647	4,070	SS
Continuous wheat	WW	26	167	WW
Continuous sorghum	GG	3	26	GG
Corn-soybean	CS	21,405	138,381	CS,SC
Corn-corn-soybean	CCS	3,649	22,807	CC,CS,SC
Corn-soybean-wheat	CSW	1,377	8,067	CS,SW,WC
Soybean-soybean-corn	SSC	1,270	8,067	SS,SC,CS
Wheat-fallow	WF	1	14	WF
Wheat-sorghum-fallow	WGF	8	57	WS,SF,FW
Wheat-soybean	WS	765	4,610	WS,SW
Wheat-sorghum	WG	230	1,463	WG,GW
Corn-corn-alfalfa-alfalfa-alfalfa	CCAAA	6,292	44,394	CC,CA,AA,AC

Table 4. Total number of CPS surveys performed during 1990-92 in the north central region by state and crop.

State	Corn	Spring wheat	Sorghum	Soybean	Winter wheat
Illinois	1549	-	-	1138	214
Indiana	1279	-	-	1001	130
Iowa	1744	-	-	1473	-
Kansas	135 ^a	-	442	502 ^a	-
Michigan	625	-	-	109	-
Minnesota	1294	271	-	884	-
Missouri	660	-	-	819	215
Nebraska	399 ^a	-	98	595 ^a	-
Ohio	97 ^a	-	-	67 ^a	-
North Dakota	1027 ^a	330	-	784 ^a	-
South Dakota	653	156	-	433	193
Wisconsin	822	-	-	69	-

^aThese survey data are not used in the SWAT UMRB modeling system.

Table 5. Lower and upper bound corn nitrogen fertilizer application rates by state.

<u>Nitrogen fertilizer application rates</u>								
State	<u>Corn following corn</u>				<u>Corn following soybean</u>			
		Lower		Upper		Lower		Upper
	Total	bound	Median	bound	Total	bound	Median	bound
	surveys	(kg/ha)	(kg/ha)	(kg/ha)	surveys	(kg/ha)	(kg/ha)	(kg/ha)
Illinois	334	168	180	215	1007	151	181	213
Indiana	365	114	168	196	670	129	173	199
Iowa	394	112	146	175	949	112	138	161
Michigan	255	103	146	178	145	105	162	192
Minnesota	235	87	133	157	656	111	136	160
Missouri	156	122	157	202	426	123	146	179
S. Dakota	109	77 ^a	90	151	258	50 ^a	90	112
Wisconsin	279	65 ^a	131	160	77	33 ^a	120	151

^aThese lower bound rates were set equal to the Minnesota lower bound rate of 87 kg/ha for corn following corn to minimize nitrogen stress for the simulated corn in these states.

Table 6. Soil layer data required for SWAT.

Variable	Units	Description
SOL_Z	mm	Layer depth; from soil surface to the bottom of the layer
SOL_BD	Mg/m ³	Moist bulk density
SOL_AWC	Mm H ₂ O/mm soil	Available water capacity of the soil layer
SOL_K	mm/hr	Saturated hydraulic conductivity
SOL_CBN	% soil weight	Organic carbon content
CLAY	% soil weight	Clay content
SILT	% soil weight	Silt content
SAND	% soil weight	Sand content
ROCK	% total weight	Rock fragment content
SOL_ALB ^a	-	Moist soil albedo
USLE_K ^a	-	USLE equation soil erodibility factor

^aThese are listed as layer properties in Neitsch et al. (2002).

CHAPTER 6. APPLICATION OF SWAT FOR THE UPPER MISSISSIPPI RIVER BASIN, PART II: CALIBRATION AND VALIDATION

A paper to be submitted to the *Journal of American Water Resources Association*

Manoj Jha, Philip W. Gassman, Silvia Sechhi, J.G. Arnold, and Roy Gu

ABSTRACT

This paper describes the application of the Soil and Water Assessment Tool (SWAT) model within the framework constructed for the Upper Mississippi River Basin (UMRB) (described in Part I), which covers over 491,000 km² in parts of eight states in the north central U.S. An example application of the constructed framework was initially conducted for two subsets of UMRB: Iowa and Des Moines River Watersheds. Streamflow and sediment yield data from the USGS gage stations at the watershed outlets were used in the model calibration and validation. The model performance was evaluated statistically and was found to have strong correlation between the measured and simulated values. A scenario run was conducted for each watershed in which conservation tillage adoption increased to 100%, and found a small sediment reduction of 5.8% for Iowa River Watershed and 5.7% for Des Moines River Watershed. On a per-acre basis, sediment reduction for Iowa and Des Moines River Watersheds was found to be 1.86 and 1.18 metric tons respectively, which indicates that Iowa River Watershed would be a better candidate area for “green payments”. Furthermore, an attempt was made to validate the model for the entire UMRB. Streamflow and sediment yield data at Grafton, IL were used for model calibration and validation. Statistical evaluation of the model performance indicated that annual flow and sediment yield simulated by SWAT corresponded very well with the measured values. Monthly simulation results are not as strong as the annual results; however, the model was able to track the

seasonal trends very well. Next step of the research will focus on validation of the model for nitrogen and phosphorus, and simulation of the agricultural policy scenarios for the region.

Key Words: simulation framework, calibration, validation, sediment yield, streamflow

INTRODUCTION

Significant effort is occurring across the U.S. to address water quality problems at the watershed level. This phenomenon is being driven by the desire to manage different scales of watersheds in a holistic manner in tandem with regulatory pressures such as those required by the Total Maximum Daily Load (TMDL) process. Simulation models are increasingly being used to support these water quality assessments, both in estimating loadings from agricultural and other landscapes and/or simulating in-stream pollutant fate and transport processes (USEPA, 1997).

A wide range of simulation models have been developed to assess sediment, nutrient, and other pollutant losses from agricultural sources and/or other types of land use. Several of these models are designed to assess pollutant losses at a field scale, such as the Erosion Productivity Impact Calculator (EPIC) model (Williams, 1990; Williams et al., 1996) and the Chemical, Runoff, and Erosion from Agricultural Management Systems (CREAMS) model (Knisel, 1980). These field-scale models provide valuable insights into edge-of-field losses and have been used successfully for regional applications (e.g., Wu and Babcock, 1999; Feng et al., 2004). However, they are not capable of assessing the movement of pollutants from agricultural and other landscapes to a stream system and ultimately to a watershed outlet. Several models have been developed to perform watershed and/or river basin simulations including the Agricultural Policy EXtender (APEX) model (Williams et al., 1995), the

Agricultural Non-Point Source (AGNPS) model (Young et al., 1989), the Hydrological Simulation Program – FORTRAN (HSPF) model (Johansen et al., 1984), the Simulator for Water Resources in Rural Basins (SWRRB) model (Arnold et al., 1990) and the Soil and Water Assessment Tool (SWAT) model (Arnold et al., 1998). Several limitations exist with these and other models, including the inability to adequately characterize land use and management systems, the ability to simulate only single storm events, and/or restrictions in the number of subwatersheds that can be simulated (Saleh et al., 2000). The SWAT model offers the greatest flexibility for simulating watershed-based agricultural management scenarios, at virtually any scale, based on the following key attributes that are included in the model: (1) continuous-time simulation, (2) high level of spatial detail, (3) unlimited number of watershed subdivisions, (4) efficient computation, and (5) capability to directly simulate changes in land management.

The SWAT model has been incorporated in a modeling framework that has been constructed for the Upper Mississippi River Basin (UMRB), due to its inherent ability to simulate a broad spectrum of agricultural land use and management scenarios. The UMRB drains an area over 491,000 km² that covers part or all of eight U.S. states (Figure 1). Excess nitrogen, phosphorus, and sediment loadings from point and nonpoint sources have resulted in water quality degradation of the Mississippi River and its tributaries within the UMRB. Agriculture livestock and cropland production is the dominant land use in the UMRB, and is a major source of sediment and nutrient pollution for both the regional stream network and the Gulf of Mexico. These water quality issues are the catalyst for simulation studies using SWAT, which will be performed to provide insights that could help mitigate nutrient and sediment losses from UMRB cropland and pastures. The objectives of this current research

are to calibrate and validate the flow and sediment components of SWAT at Grafton, Illinois (Figure 1), the assumed UMRB outlet. Calibration and validation of the SWAT flow and sediment components are also presented for the Des Moines and Iowa River watersheds, at their respective outlets, to provide further insight into the model's ability to replicate UMRB conditions.

SWAT Model

SWAT is a long-term simulation model capable of predicting flow as well as sediment, nutrient, and pesticide yields from agricultural watersheds. In SWAT, a watershed is divided into multiple subwatersheds, which are then further subdivided into HRUs that consist of homogeneous land use, management, and soil characteristics. The water balance of each HRU in the watershed is represented by four storage volumes: snow, soil profile (0-2 meters), shallow aquifer (typically 2-20 meters), and deep aquifer (more than 20 meters). Soil water processes include infiltration, evaporation, plant uptake, lateral flow, and percolation to lower layers. Flow, sediment, nutrient, and pesticide 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. Detailed descriptions of the model and model components can be found in Arnold et al. (1998).

SWAT uses the Soil Conservation Services Curve Number (SCS-CN) method for predicting surface runoff (USDA-SCS, 1972), as follows:

$$Q_{surf} = \frac{(R - I_a)^2}{(R - I_a + S)} \quad (1)$$

where Q_{surf} is the accumulated runoff, R is the rainfall depth for the day, I_a is the initial abstractions which includes surface depression storage, interception and infiltration prior to runoff and is commonly approximated as $0.2S$, and S is the retention parameter. The retention parameter varies spatially due to changes in soils, land use, management and slope and temporally due to changes in soil water content. The retention parameter is defined as:

$$S = 25.4 \left(\frac{1000}{CN} - 10 \right) \quad (2)$$

where CN is the curve number for the day.

Sediment yield is estimated for each HRU in the subwatershed for each day with the Modified Universal Soil Loss Equation (MUSLE) (Williams and Berndt, 1977) as follows:

$$Sed = 11.8 (Q_{surf} \times q_{peak})^{0.56} K \times C \times P \times LS \quad (3)$$

where Sed is the sediment generation (metric tons), Q_{surf} is runoff volume (m^3), q_{peak} is peak runoff rate (m^3/s), K is soil erodibility factor, C is cover and management factor, P is cropping practice factor, and LS is slope length and steepness factor. The K -factor quantifies the cohesive or bonding character of a soil type and its resistance to dislodging and transport due to raindrop impact and overland flow. C -factor is the ratio of soil loss from land cropped under specified conditions to corresponding loss under tilled, continuous fallow conditions. It incorporates effects of: tillage management (dates and types), crops, seasonal erosivity index distribution, cropping history (rotation), and crop yield level (organic matter production potential). Practices included in the P -factor are contouring, strip cropping (alternate crops on a given slope established on the contour), and terracing. LS -factor is a topographic factor and taking into account for slope length and slope steepness.

SIMULATION METHODOLOGY AND INPUT DATA

A simulation framework has been constructed for the UMRB using 131 subwatersheds that coincide with the boundaries of the USGS 8-digit Hydrologic Cataloging Unit watersheds. The framework integrates micro-level land use data, agricultural practice data, soil and climate data, and other information from U.S. Department of Agriculture (USDA) surveys and other data sources, with the SWAT model and a modeling interface. A brief overview of the modeling framework is provided here; a detailed description of the modeling framework structure, including the different data sources and key input assumptions, is provided in Jha et al. (2004).

The primary data source for the modeling system is the USDA 1997 National Resources Inventory (NRI) database (Nusser and Goebel, 1997; <http://www.nrcs.usda.gov/technical/NRI/>). The database has information such as soil type, landscape features, cropping histories, and conservation practices for roughly 800,000 nonfederal land points for the entire U.S. Each point represents an area, generally ranging from a few hundred to several thousand hectares in size, which is assumed to consist of homogeneous land use, soil, and other characteristics. The NRI clusters serve as the Hydrologic Response Units (HRUs) in the SWAT simulations. HRUs are smaller spatial units within each subwatershed and represent unique combination of land use, management practices, soil type and climate. The management information on fertilizer application rates and tillage practices are based on USDA 1990-95 Cropping Practices Survey (CPS) data (http://usda.mannlib.cornell.edu/usda/ess_entry.html). Soil type data includes the data that were previously determined via a statistically-based soil clustering process that was performed for NRI-linked soils for most of the U.S. (Sanabria and Goss 1997). The

corresponding soil layer data was obtained from a soil database that contains soil properties consistent with those described by Baumer et al. (1994). Climate data such as precipitation and temperature data were obtained from the National Climatic Data Center (<http://www.ncdc.noaa.gov/oa/ncdc.html>). Missing data in the precipitation and temperature records, as well as daily solar radiation, wind speed, and relative humidity inputs, were generated internally in SWAT using monthly climate statistics that are based on long-term weather records (available within the model for the entire U.S.).

A total of 2,936 HRUs were developed for the entire UMRB for the SWAT baseline simulation. The density of the HRUs is greater in the regions dominated by intensive agriculture, to facilitate the accuracy required to assess the impacts in variations between agricultural management practices and cropping systems.

The SWAT executions, including the corresponding data flows, are managed with the interactive SWAT (i_SWAT) software (<http://www.public.iastate.edu/~elvis>; Gassman et al., 2003), which is currently designed to support applications of SWAT2000.

CALIBRATION AND VALIDATION

Calibration and validation of a physically based model such as SWAT includes adjustment of important variables that are not well defined physically, such as the runoff curve number, infiltration factors, evaporation factors, and others. Adjustment of each variable must be within a defined reasonable range. For example, acceptable limits for adjusting runoff curve numbers were set in this study as -10% to +10%, based on the recommendations given in the SWAT user's manual.

The first step in the calibration process requires a basic understanding of the physical processes taking place within the system. Therefore, calibrating models such as SWAT starts with the calibration of the water balance and streamflow, including calibration of surface runoff and subsurface flow. The next step is to calibrate the sediment yield and nutrient loadings, following calibration of the hydrologic components. Sediment yield relates closely to the surface runoff volume as well as peak runoff. Nutrient loading prediction depends on the flow prediction because the runoff volume is the dominant component that governs the amount of nutrient that will be transported to the main channel from the watershed.

SWAT Simulations for UMRB Subareas: Iowa and Des Moines River Watersheds

An application of SWAT is presented for the Iowa and Des Moines River watersheds (Figure 2) within the modeling framework constructed for the UMRB. Both watersheds are subsets of the UMRB and primarily located in Iowa. Each is comprised of nine 8-digit subwatersheds. The Iowa River Watershed covers approximately 33,000 km² whereas the Des Moines River drains over 37,000 km². The dominant land uses in both watersheds are agricultural, including 20,000 (62%) and 22,500 (60%) km² of cropland in the Iowa and Des Moines River watersheds, respectively. Both watersheds are recognized as major contributors of sediments and chemicals to the Mississippi River because of the intensive cropland production. Classification of different land use categories associated with each watershed, based on the information available from the NRI database, is presented in (Table 1).

To validate the SWAT model for the baseline watershed condition, a calibration and validation procedure was conducted to match simulated results with the measured data. The measured streamflow and sediment yield data at the watershed outlet were obtained from

http://www.umes.usgs.gov/data_library/sediment_nutrients/sediment_nutrient_page.html for USGS gage 05466500 (Iowa River at Wapello, IA) and USGS gage 05490500 (Des Moines River at Keosauqua/St. Francis, IA). SWAT was executed for several different simulation periods for calibration and validation, as shown in Table 2, depending upon the availability of measured data. The model was calibrated first for the annual stream flow. The most sensitive model parameters such as curve number (CN), soil evaporation compensation factor (ESCO) and soil available water capacity (SOL_AWC) were varied within their acceptable ranges to match the simulated flow with the measured flow. The model performance was evaluated with two statistical parameters: coefficient of determination (R^2) and the Nash-Sutcliffe Modeling Efficiency (E). The R^2 value is an indicator of strength of relationship between the measured and simulated values. The E value indicates how well the plot of the measured versus simulated values fit the 1:1 line. If the R^2 value is close to zero and E value is less than or close to zero, the model prediction is considered unacceptable. If the values approach one, the model predictions are considered perfect. R^2 and E values of more than 0.5 are considered acceptable. Calibration was performed for the monthly streamflow after initial calibration of the annual stream flows. For the validation process, the model was run without changing the model parameters that were set during the calibration process.

After the model was calibrated and validated for flow, it was calibrated and validated for the sediment yield at the watershed outlets. Several parameters such as the channel erodibility factor, channel cover factor, sediment reentrainment coefficient, and sediment reentrainment exponent were adjusted within their acceptable ranges to match the predicted sediment yields with the corresponding measured data. The model was calibrated and

validated both annually and monthly and the model performance was evaluated again with R^2 and E values. Figures 3 and 4 show the time-series comparison of the simulated and measured monthly stream flow and sediment yield (for both calibration and validation) for the Iowa River Watershed. Similar comparisons are shown for the Des Moines River Watershed in Figures 5 and 6. In general, SWAT accurately tracked the measured stream flows and sediment yields for both the annual and monthly time steps. Table 2 lists the R^2 and E values for both simulations, which were all satisfactory.

A simple scenario was simulated for each watershed to assess the impacts of increasing conservation tillage on sediment yield, where conservation tillage includes no till and mulch till systems that leave at least 30% of the soil surface covered with residue. It was assumed for this scenario that the respective baseline conservation tillage adoption rates of 54.5 and 60% (based on the 1992 NRI) for the Iowa and Des Moines River Watersheds, would be increased to 100% adoption. Overall, the estimated sediment reduction is a small percentage of the baseline sediment at the respective watershed outlets (Table 3). The small impact was likely due to reservoirs on both rivers that trapped much of the sediment and to the relatively high rate of conservation tillage that had already occurred in the baseline. On a per-acre basis, a higher reduction in sediment yield was predicted for the Iowa River Watershed, which indicates that it would be a better candidate area for “green payments” in which producers would be paid subsidies to encourage adoption of conservation tillage practices.

SWAT validation for UMRB

The UMRB outlet in this study is assumed to be at Grafton, Illinois (Figure 2), which is just above the confluence of the Missouri and Mississippi rivers. The UMRB covers a

drainage area of approximately 445,000 km² up to Grafton, which includes 119 subwatersheds out of the total of 131 subwatersheds shown in Figure 2. The measured data at Grafton were obtained from http://www.umesc.usgs.gov/data_library/sediment_nutrients/sediment_nutrient_page.html for USGS gage # 005587450 (Mississippi River at Grafton, IL). Simulation runs for the entire UMRB (with approximately 3,000 HRUs) took about 5 min. for a single year run on a 2 GHz machine. In the baseline simulation run, SWAT reproduced annual streamflow very well without calibration, as evidenced by R² and E values of more than 0.75. However, the monthly prediction was not as statistically acceptable initially. Figure 7 shows the annual measured and simulated streamflow comparison for the calibration (1982-1989) and validation (1990-1997) periods. The plot reveals a strong correlation between the measured and simulated flows as indicated by the R² and E values, which were 0.92 and 0.91 for the calibration period and 0.87 and 0.78 for the validation period, respectively.

Multiple model runs were performed to calibrate the monthly streamflow. Several hydrologic sensitive input parameters, including the curve number, soil evaporation compensation factor, groundwater delay, and others, were changed within their acceptable ranges to match the predicted flows with the simulated values. The monthly calibration results reflected weaker correlation between the measured and simulated flows, as compared to the annual results, as indicated by R² and E values of 0.58 and 0.48 (Figure 8). However, the R² and E values computed for the validation period were 0.70 and 0.65, respectively, which were stronger than the calibration period statistics. A large watershed such as the UMRB includes a high level of spatial variability. Thus calibrating the model for the entire watershed at only the watershed outlet is a challenging task. The calibration challenge is

further magnified by simplified assumptions of reservoir operating rules that may not reflect the actual situation. There are several large locks and dams above Grafton which regulate streamflow for the Mississippi, and a number of other reservoirs within the UMRB stream system. More accurate data pertaining to the operation of these reservoirs may result better prediction of monthly streamflow at Grafton. Despite large uncertainties in the input data, the SWAT model was successfully able to simulate annual streamflow very well and also simulated monthly streamflow with reasonable accuracy.

The SWAT calibration for the sediment yield was conducted after the model was validated for the streamflow. Sediment yield predicted by SWAT includes two major components: erosion at HRU level and channel erosion. Key parameters that effect the HRU sediment loading estimates include the USLE crop management factor (P), USLE slope length factor (LS), USLE crop practice factor (C), HRU slopes, and tillage operations. These parameters' values were established based on information provided from the NRI and CPS. The calibration process, therefore, focused only to calibrate the channel erosion part of the sediment yield. The calibration parameters for the channel degradation and deposition include linear and exponential parameters in channel sediment routing equation, channel erodibility factor, and channel cover factor. Several model runs were performed with different acceptable values of the calibration parameters to match the simulated sediment yield with the measured sediment yield at Grafton. The annual sediment yield comparison yielded an R^2 value of 0.95 and an E value of 0.85 for the calibration period, and corresponding values of 0.93 and 0.81 for the validation period (Figure 9), indicating a strong correlation between simulated and measured annual sediment yield. The sediment yield predictions matched very well except for 1993, probably because 1993 was a heavy flood

year. Monthly calibration and validation yielded R^2 and E values of 0.49 and 0.47 for the calibration period and 0.55 and 0.54 for the validation period, respectively (Figure 10). These results show that the correlation between the simulated and measured monthly sediment yields were not as strong as the annual results. However, the model was able to track the seasonal trends very well on a monthly basis.

NEXT PHASE OF THE RESEARCH

The traditional approach of model validation, as shown in this paper, is to break the measured time series into calibration and validation periods. In the calibration period, the model inputs are allowed to vary across the basin until an accepted fit to measured data at the basin outlet is obtained. The model is then run using the same input parameters for the validation period and the goodness-of-fit is determined. For a large watershed like the UMRB, calibrating model input parameters over the entire watershed in order to match one gage near the outlet of the watershed may not reflect a realistic watershed response and thus the simulation results may have a lot of uncertainties. Therefore, an attempt is being initiated to “spatially calibrate” the model. In the spatial calibration process, a large watershed is divided into smaller regions. The hydrologic model is then first calibrated for the gage farthest upstream. Once that gage is calibrated, the model is calibrated for the next gage downstream. It is important that as we calibrate downstream gages, we do not change parameters within the files associated with the drainage area of the upstream gages already calibrated.

CONCLUSIONS

In this second part of a two-part paper, a SWAT model application was presented for the two subsets as well as for the entire UMRB. The model was successfully calibrated and validated for the streamflow and sediment yield at the watershed outlet for the Iowa and Des Moines River Watersheds. A scenario run was conducted for each watershed in which conservation tillage adoption increased to 100%, and found a small sediment reduction of 5.8% for Iowa River Watershed and 5.7% for Des Moines River Watershed. The small impact was likely due to reservoirs on both rivers that trapped much of the sediment and to the relatively high rate of conservation tillage that had already occurred in the baseline (55% adoption in Iowa River Watershed and 60% adoption in Des Moines River Watershed). On a per-acre basis, a higher reduction in sediment yield was predicted for the Iowa River Watershed, which indicates that it would be a better candidate area for “green payments” in which producers would be paid subsidies to encourage adoption of conservation tillage practices.

The SWAT model was also applied to the entire UMRB. The model was calibrated and validated at the watershed outlet (i.e., at Grafton, IL) for the streamflow and sediment yield. Statistical evaluation of the model performance was conducted by R^2 and E. Annual values of streamflow and sediment yield predicted by SWAT corresponded very well with the measured values. Monthly simulation results are not as strong as the annual results; however, the model was able to track the seasonal trends very well.

Further efforts are underway to validate the model for the Nitrogen and Phosphorus within the constructed UMRB simulation framework. Continuous improvement of the input

data along with the enhancement and improvement of the SWAT model will improve the model performance in simulating agricultural policy scenarios of the region.

REFERENCES

- Arnold, J.G., R.S. Muttiah, R. Srinivasan, and P.M. Allen. 2000. Regional estimation of base flow and groundwater recharge in the Upper Mississippi river basin. *Journal of Hydrology* 227:21-40.
- Arnold, J.G., R. Srinivasan, R.S. Muttiah, and P.M. Allen. 1999. Continental scale simulation of the hydrologic balance. *Journal of the American Water Resources Association* 35(5):1037-52.
- Arnold, J. G., R. Srinivasan, R. S. Muttiah, and J. R. Williams. 1998. Large area hydrologic modeling and assessment; part I: model development. *Journal of the American Water Resources Association* 34(1):73-89.
- Arnold, J.G., J.R. Williams, A.D. Nicks, and N.B. Sammons. 1990. *SWRRB: A Basin Scale Simulation Model for Soil and Water Resources Management*. Texas A & M University Press, College Station, Texas.
- Baumer, O., P. Kenyon, and J. Bettis. 1994. *MUUF v2.14 User's Manual*. U.S. Department of Agriculture, Natural Resources Conservation Service, National Soil Survey Center, Lincoln, Nebraska.
- Feng, H., L. Kurkalova, C.L. Kling, and P.W. Gassman. 2004. Environmental conservation in agriculture: land retirement vs changing practices on working land. *Journal of Environmental Economics and Management* (submitted).
- Gassman, P.W., T. Campbell, S. Secchi, M. Jha, and J. Arnold. 2003. The *i_SWAT* software package: a tool for supporting SWAT watershed applications. In: *SWAT2003: The 2nd International SWAT Conference*, 1-4 July, Bari, Italy. Istituto di Ricerca sulle Acque, IRSA-CNR, Bari, Italy. pp. 66-69.
- Jha, M., S. Secchi, P.W. Gassman, J.G. Arnold, and T. Campbell. 2004. Application of SWAT for the Upper Mississippi River Basin Part I: Methodology (to be submitted).
- Johansen, N.B., J.C. Imhoff, J.L. Kittle, and A.S. Donigian. 1984. *Hydrologic Simulation Program - FORTRAN (HSPF): User's Manual for release 8*, EPA-600/3-84-066, Athens, GA, U.S. Environmental Protection Agency.

- Knisel, W.G., ed. 1980. CREAMS: A Field-Scale Model for Chemicals, Runoff, and Erosion from Agricultural Management Systems. Conservation Research Report No. 26, Washington, D.C.: USDA-SEA.
- Nusser, S.M. and J.J. Goebel. 1997. The National Resources Inventory: a Long-Term Multi-Resource Monitoring Programme. *Environmental and Ecological Statistics* 4(3):181-204.
- Saleh, A., J.G. Arnold, P.W. Gassman, L.M. Hauck, W.D. Rosenthal, J.R. Williams, and A.M.S. McFarland. 2000. Application of SWAT for the Upper North Bosque River Watershed. *Transactions of the ASAE* 43(5):1077-1087.
- Sanabria, J. and D. W. Goss. 1997. Construction of Input for Environmental Simulation Models Using Multivariate Analysis, Proceedings of South Central SAS (Statistical Analysis System) Users Meeting. Houston, TX. November 1997, pp. 217-234.
- USEPA. 1987. Compendium of Tools for Watershed Assessment and TMDL Development. EPA841-b-97-006. U.S. Environmental Protection Agency, Office of Water, Washington, D.C.
- USDA-SCS. 1972. National Engineering Handbook. Hydrology Section 4, Chapter 4-10, U.S. Department of Agriculture, Soil Conservation Service, Washington D.C.
- Williams, J. R. 1990. The erosion productivity impact calculator (EPIC) model: a case history. *Philosophical Transactions of the Royal Society of London* 329: 421-428.
- Williams and Berndt, 1977. Sediment Yield Prediction Based on Watershed Hydrology. *Transactions of ASAE* 20(6):1100-1104.
- Williams, J., M. Nearing, A. Nicks, E. Skidmore, C. Valentin, K. King, and R. Savabi. 1996. Using soil erosion models for global change studies. *Journal of Soil and Water Conservation* 51(5):381-385.
- Williams, J.R., C.A. Jones, P.W. Gassman, and L.M. Hauck. 1995. Simulation of Animal Waste Management with APEX. In: *Innovations and New Horizons in Livestock and Poultry Manure Management*, September 6-7, Austin, Texas, pp. 22-26.
- Wu, J. and B.A. Babcock. 1999. Metamodeling potential nitrate water pollution in the central United States. *J. Envr. Qual.* 28(6):1916-1928.
- Young, R.A., C.A. Onstad, D.D. Bosch, and W.P. Anderson. 1989. AGNPS: A Non-Point Source Pollution Model for Evaluating Agricultural Watersheds. *Journal of Soil and Water Conservation* 44(2):168-173.

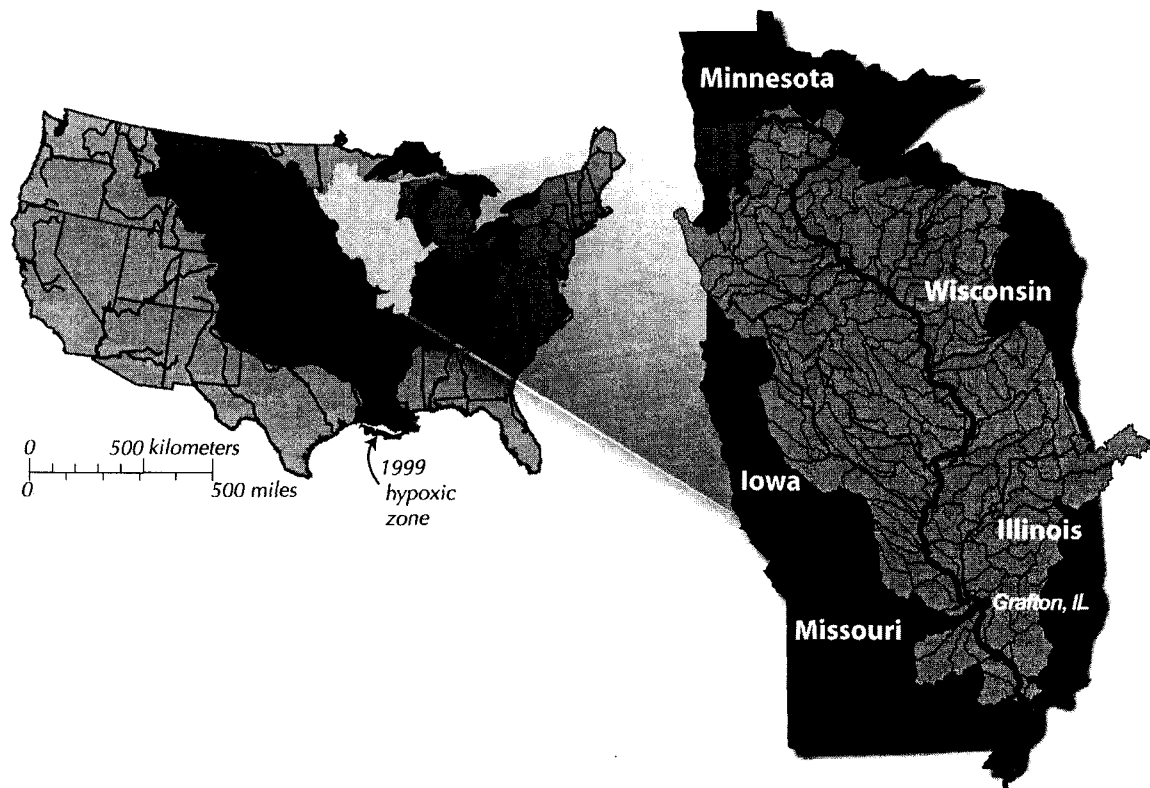


Figure 1. Location of the Upper Mississippi River Basin (UMRB) within the Mississippi River Basin, the 131 8-digit watersheds located within the UMRB, and the location of Grafton, IL.

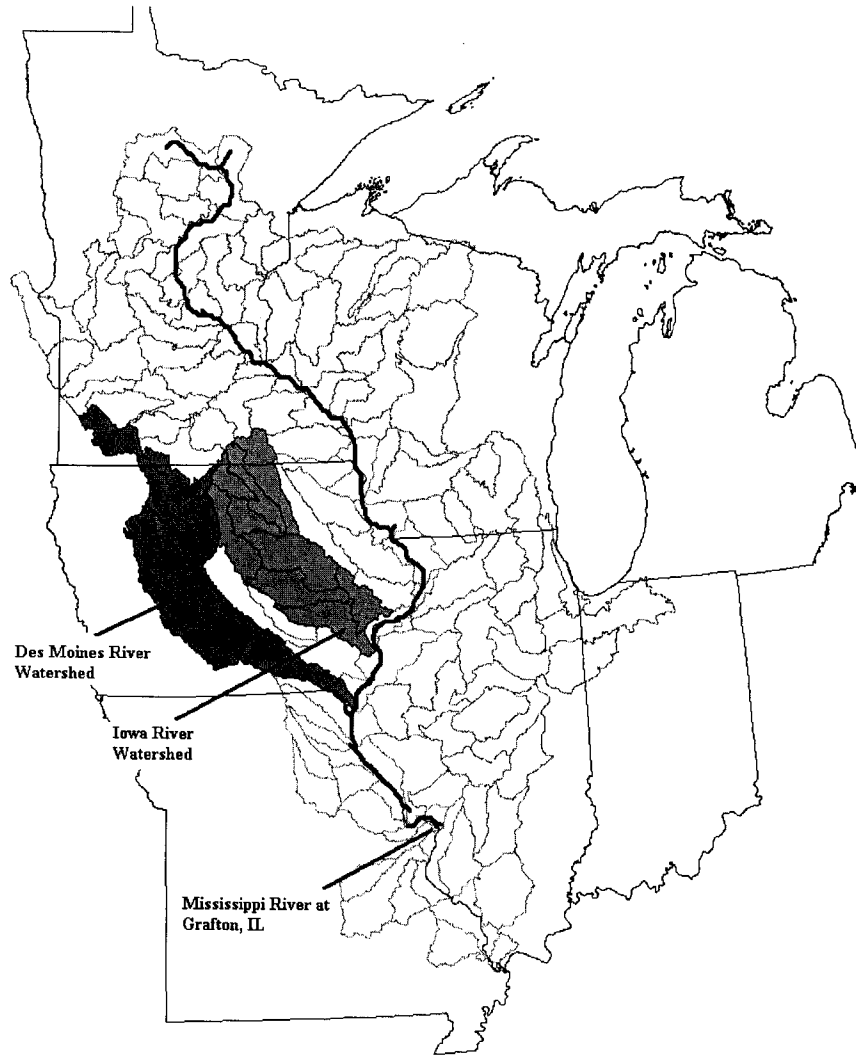


Figure 2. Configuration of Iowa and Des Moines River Watersheds in the UMRB.

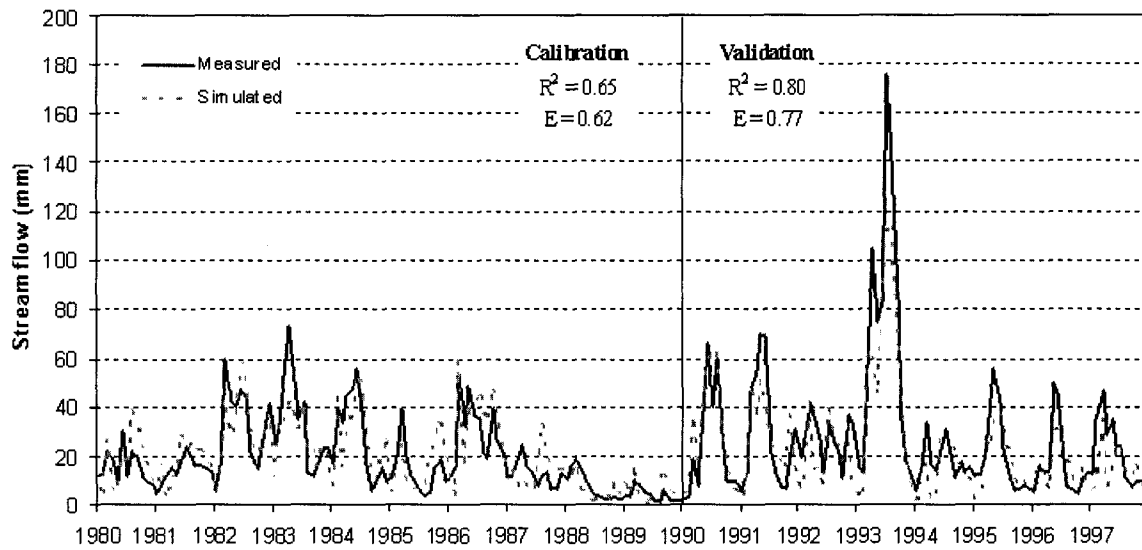


Figure 3. Monthly time-series of measured and simulated stream flow for Iowa River Watershed.

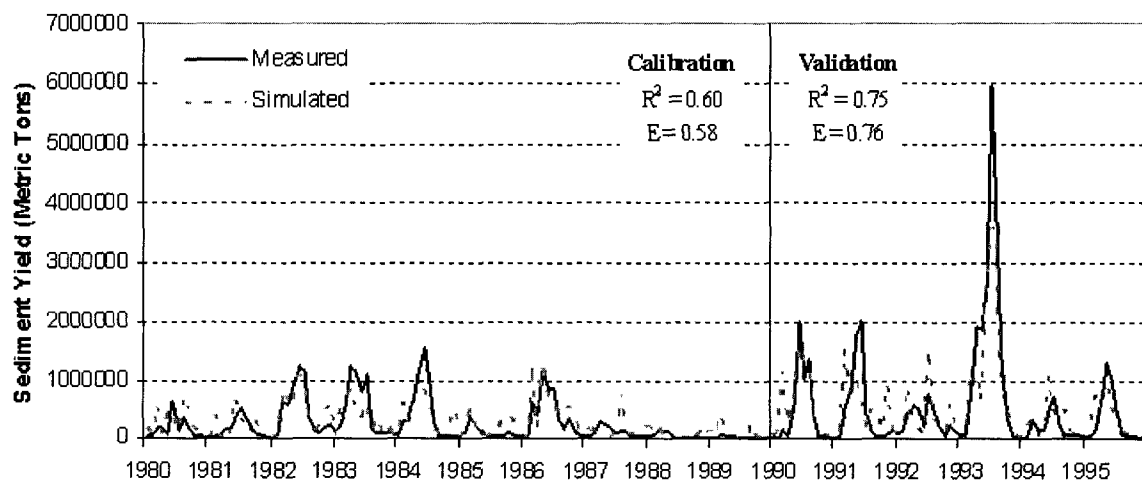


Figure 4. Monthly time-series of measured and simulated sediment yield for Iowa River Watershed.

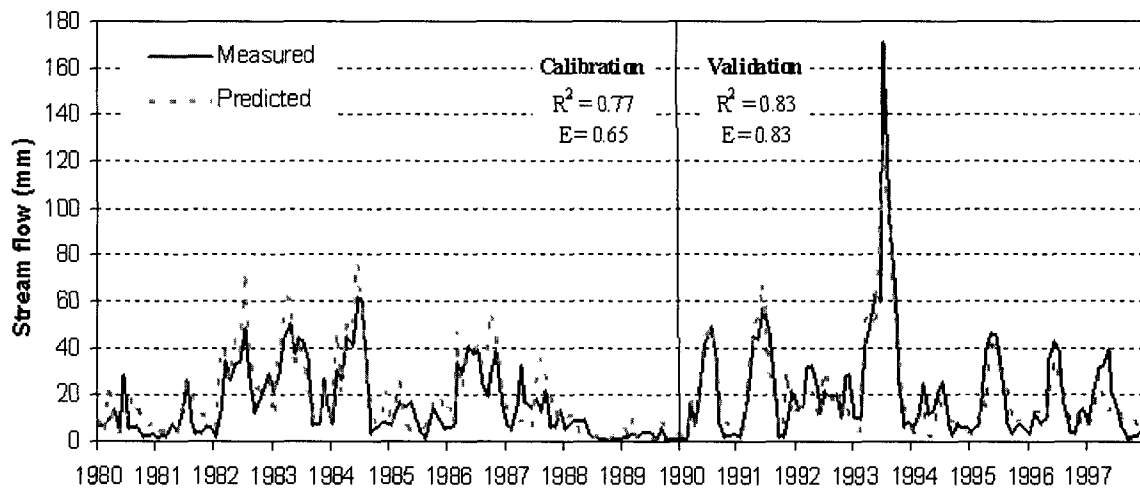


Figure 5. Monthly time-series of measured and simulated stream flow for Des Moines River Watershed.

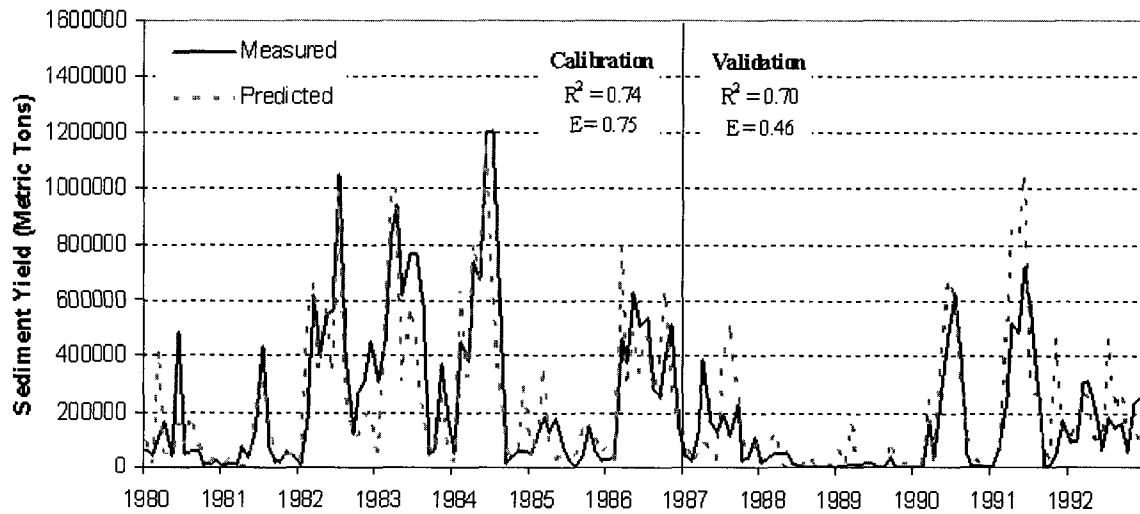


Figure 6. Monthly time-series of measured and simulated sediment yield for Des Moines River Watershed.

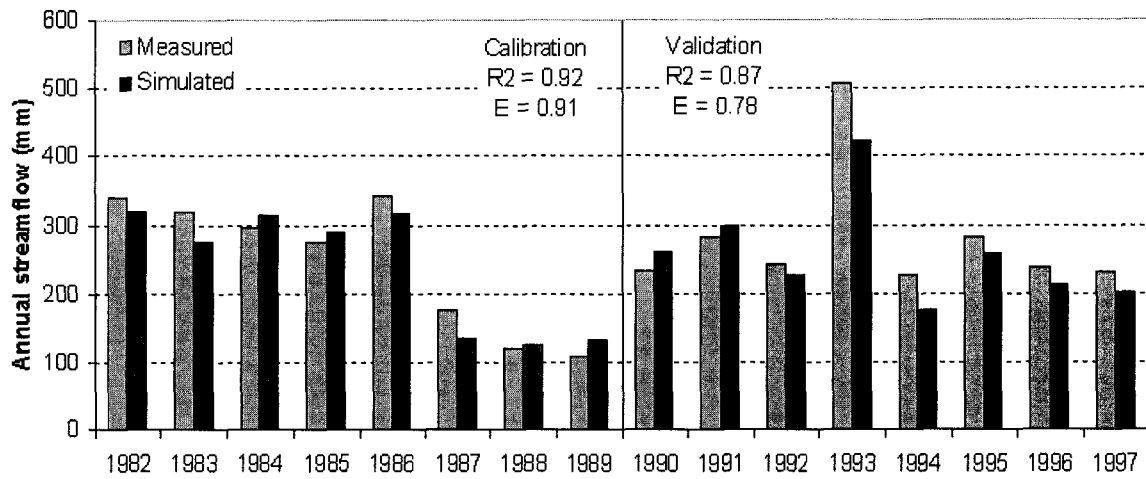


Figure 7. Annual measured and simulated streamflow at Grafton, IL for the calibration and validation periods.

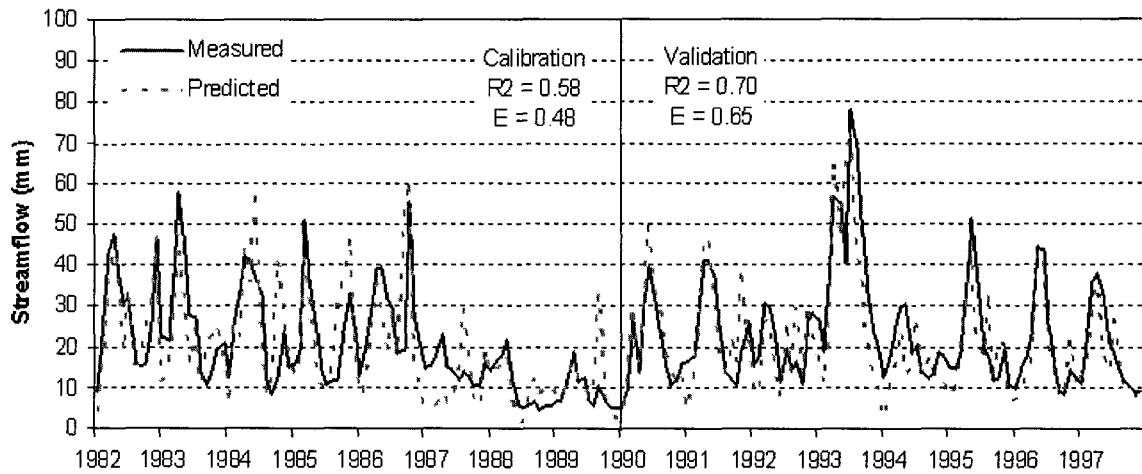


Figure 8. Monthly time-series of measured and simulated streamflow at Grafton, IL for the calibration and validation periods.

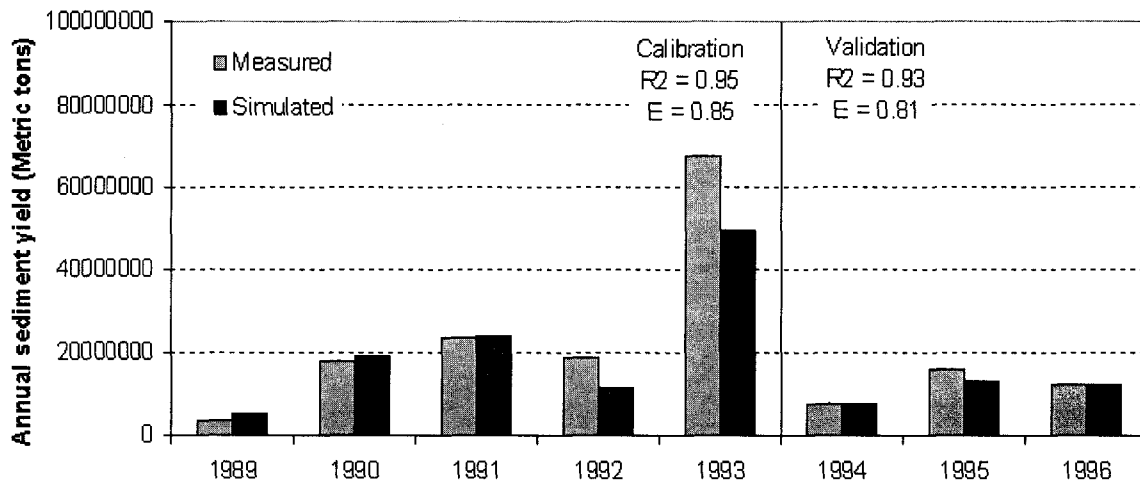


Figure 9. Annual measured and simulated sediment yield at Grafton, IL for the calibration and validation periods.

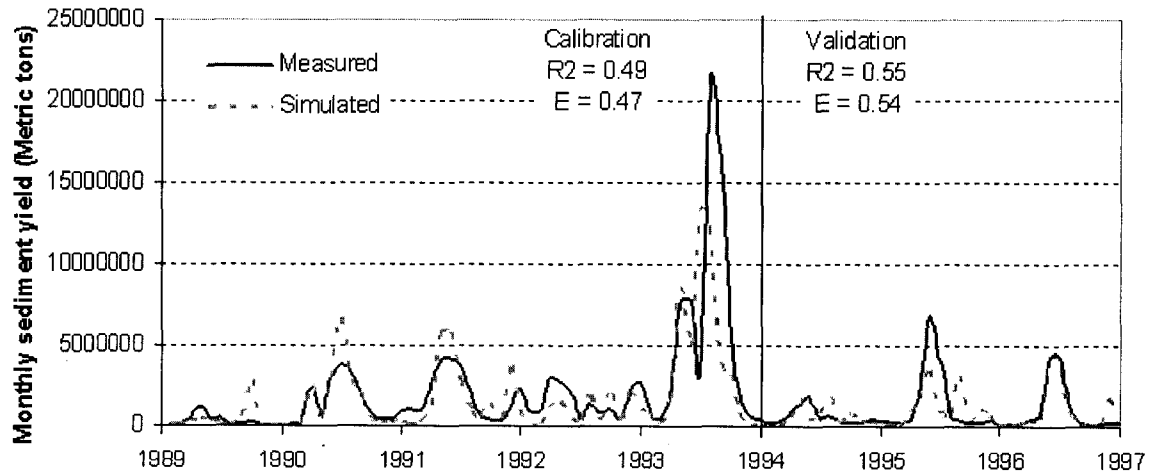


Figure 10. Monthly time-series of measured and simulated sediment yield at Grafton, IL for the calibration and validation periods.

Table 1. Land use categories in Iowa and Des Moines River Watersheds.

Land use	Area: km ² (% of watershed)	
	Iowa River Watershed	Des Moines River Watershed
Cropland (corn, soybean, and alfalfa)	20,161 (61.5)	22,634 (60.4)
Grassland (hay and pasture)	5,588 (17.0)	6,875 (18.3)
Forest	1,556 (4.7)	2,991 (8.0)
Urban	4,445 (13.6)	3,421 (9.1)
Water (reservoirs, ponds and streams)	369 (1.1)	671 (1.8)
Wetlands	678 (2.1)	902 (2.4)
Tile-drainage area	6,231 (19)	10123 (27)

Table 2. Evaluation of SWAT simulated stream flow and sediment yield for the Iowa and Des Moines River Watersheds.

			Period	Annual		Monthly	
				R ²	E	R ²	E
Iowa River Watershed	Calibration	Flow	1980-1989	0.95	0.94	0.65	0.62
		Sediment	1980-1989	0.91	0.84	0.60	0.58
	Validation	Flow	1990-1997	0.91	0.80	0.80	0.77
		Sediment	1990-1995	0.95	0.85	0.75	0.76
Des Moines River Watershed	Calibration	Flow	1980-1989	0.95	0.84	0.77	0.65
		Sediment	1980-1985	0.98	0.91	0.74	0.75
	Validation	Flow	1990-1997	0.97	0.94	0.83	0.83
		Sediment	1986-1992	0.93	0.82	0.70	0.46

Table 3. Scenario results for Iowa and Des Moines River Watersheds.

	Annual average baseline sediment yield (10 ⁶ MT)	Percentage sediment reduction (%)	Sediment reduction per acre converted to conservation tillage (MT/acre)
Iowa River in Conservation Tillage	5.0	5.8	1.86
Des Moines River in Conservation Tillage	2.85	5.7	1.18

CHAPTER 7. GENERAL CONCLUSION

Evaluation of the SWAT Model

The SWAT model was applied to the Maquoketa River Watershed, which covers approximately 5,000 km² area in Northeast Iowa. The model offers continuous-time simulation, high level of spatial detail, unlimited number of watershed subdivisions, efficient computation, and capability to simulate changes in land-management. To evaluate the model performance in simulating watershed hydrology, a sensitivity analysis was carried out for the input hydrological variables using the influence coefficient method to identify the most to least sensitive parameters. The inputs to the model were taken from the EPA BASINS GIS/database system. Surface runoff and baseflow were treated as the model responses or dependent variables, while model input parameters were the explanatory or independent variables. A total of eight hydrologic input parameters were selected for the sensitivity analysis. A further detailed sensitivity analysis was performed for the three most sensitive parameters: curve number (CN), evaporation compensation factor (ESCO), and soil available water capacity (SOL_AWC). Sensitivity analysis provides good insight on model input parameters and supports that the model is able to simulate hydrological processes very well. Facilitated by the sensitivity analysis, the model was successfully calibrated and validated for the streamflow at the watershed outlet. This study indicates that the SWAT model can be an effective tool for accurately simulating the hydrology of the Maquoketa River Watershed.

The SWAT model was next evaluated for the climate change study. The model was successfully calibrated and validated for the entire UMRB for the streamflow again using the same simplistic data from BASINS package. The UMRB extends from the source of the river

at Lake Itasca in Minnesota to a point just north of Cairo, Illinois, and covers a drainage area over 490,000 km². The impacts of eight climate change scenarios (changes in temperature, precipitation, and/or CO₂ levels) including a simplified replication of a previously reported future climate projection were then analyzed, relative to a baseline scenario. The results indicate that the UMRB hydrologic system is very sensitive to climatic variations, both on a seasonal basis and over longer time periods. The scenario outcomes indicate that precipitation and CO₂ fertilization shifts would have a much greater impact on future flow changes, as compared to increased temperature impacts. The results also show that the effects will vary spatially across the UMRB. Overall, the SWAT model was able to reflect the impacts of climate change on the watershed hydrology very well.

Impacts of Climate Change on UMRB

Climatic changes forecast by GCMs point towards a trend of increasing precipitation rates in the UMRB region. If the forecasted trends are correct (as indicated in the climate change sensitivity analysis results above) then it would indicate that future Mississippi River and tributary flooding episodes could intensify relative to current events. A more extensive assessment of potential climate change impacts on UMRB hydrology was performed by coupling the SWAT model with the climate models. The objective was to explore stream flow, and model-introduced uncertainty thereof, in a future scenario climate by introducing a regional climate model to dynamically downscale global model results to create temperature and precipitation data required by the SWAT model. Two 10-year scenario periods (1990s and 2040s) were generated by nesting the RCM into a coarse grid resolution global model (HadCM2). The combined GCM-RCM-SWAT model system produced an increase in future

scenario climate precipitation of 21% with a resulting 18% increase in snowfall, 51% increase in surface runoff, 43% increase in groundwater recharge and 50% increase in total water yield in the UMRB. This disproportionate change can be attributed to more intense precipitation events in future climates and the non-linear nature of hydrologic budget components, such as snowmelt, evapotranspiration, surface runoff, and groundwater flow.

We found that the climate change signal is large relative to errors arising from the modeling procedure, with the largest error being attributable to the GCM downscaling error (18%), compared to a simulated change of 50% in annual stream flow. This gives confidence that such a downscaling procedure has value for impacts assessment provided the quality of the global model driving the RCM is high.

SWAT Validation and Modeling Framework for the UMRB

Previous SWAT validation for the entire UMRB using input data available in the BASINS package was limited for its application due to simplified assumption on land use, soil and management data. A SWAT modeling framework has been constructed, which build upon the previous SWAT validation, for the entire UMRB to support analyses of agricultural policy scenarios. The framework incorporates more detailed input data and accommodates a wide range of scenarios focused on shifts in cropping systems, tillage, fertilizer management, conservation practices, and/or other land use changes, which could potentially result in improved water quality within the UMRB and in the Gulf of Mexico. Cropping system, tillage and fertilizer management, and conservation practice detail have been incorporated into the modeling system, by using the USDA NRI and CPS databases. Detailed description of the input data preparation was provided for the key land use, crop rotation, tillage,

fertilizer application, climate, soil, and reservoirs, ponds and wetlands. The methodology presents an approach of building a framework for a large scale watershed modeling.

An application of SWAT is presented for the Iowa and Des Moines River watersheds within the modeling framework constructed for the UMRB. The model was successfully calibrated and validated for the streamflow and sediment yield at the watershed outlet for the Iowa and Des Moines River Watersheds. A scenario run was conducted for each watershed in which conservation tillage adoption increased to 100%, and found a small sediment reduction of 5.8% for Iowa River Watershed and 5.7% for Des Moines River Watershed. The small impact was likely due to reservoirs on both rivers that trapped much of the sediment and to the relatively high rate of conservation tillage that had already occurred in the baseline. On per-acre basis, a higher reduction in sediment yield was predicted for the Iowa River Watershed, which indicates that it would be a better candidate area for “green payments” in which producers would be paid subsidies to encourage adoption of conservation tillage practices.

The SWAT model was also applied to the entire UMRB. The model was calibrated and validated at the watershed outlet (i.e., at Grafton, IL) for the streamflow and sediment yield. Statistical evaluation of the model performance was conducted by R^2 and E. Annual values of streamflow and sediment yield predicted by SWAT corresponded very well with the measured values. Monthly simulation results are not as strong as the annual results; however, the model was able to track the seasonal trends very well.

Recommendations

Present study constructed a SWAT UMRB framework that incorporates micro-level of information on land use, soil and management from NRI and CPS databases as well as information on reservoirs, ponds and wetlands for the entire UMRB. Such a large scale work requires extensive testing and validation efforts for more reliable predictions. The SWAT model should be evaluated for the effects of reservoirs, ponds, and wetlands. Enhancements of the SWAT model will be needed including filter strip simulation and controlled drainage simulation. Parameter and model uncertainties are areas of research and investigation requiring further work to better understand the limits of simulation.

A more extensive assessment of potential climate change impacts on watershed hydrology should be carried out in combination with several GCMs and RCMs. Future UMRB climate change studies should also be performed with improved land use data that facilitates the assessment of both flow and environmental impacts for current and potential future climate patterns.

ACKNOWLEDGEMENTS

I wish to express my sincere appreciation to Dr. Roy Gu, Chairman of the program committee, for his proper guidance and suggestions throughout this research period. I am thankful to Dr. Larry Northup, Dr. Ramesh Kanwar, Dr. James Baker, and Dr. Shihwu Sung for their valuable advice and for serving on my graduation committee. I would like to extend my heartfelt thank to Mr. Phil Gassman for the invaluable advice, help, guidance, and friendship throughout the research. I also would like to thank Dr. Eugene Takle for providing me an opportunity to work with him.

Sincere appreciation is extended to Mr. Phil Gassman, Mr. Todd Campbell and Dr. Silvia Secchi for the excellent team work under the leadership of Dr. Catherine Kling at the Center for Agricultural and Rural Development (CARD), without which this work may not have completed. Special thanks are due to CARD for providing me with funding support throughout the study period.

Personal thanks are due to friends and well wishers for their help in some way during this work. Special thanks are extended to my parents, in-laws, brothers and sisters for love, support and encouragement along the way. Deepest thanks go to my wife Mamta and son Dave for their love and understanding throughout the study period.