The Impacts of Climate Change on Stream Flow in the Upper Mississippi River Basin: A Regional Climate Model Perspective

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

Working Paper 03-WP 337
July 2003

Center for Agricultural and Rural Development
Iowa State University
Ames, Iowa 50011-1070
www.card.iastate.edu

Manoj Jha is a graduate research assistant in the Department of Civil, Construction and Environmental Engineering; Zaitao Pan is a research scientist in the Department of Agronomy; Eugene Takle is a professor of agricultural meteorology in the Department of Agronomy and a professor of atmospheric science in the Department of Geological and Atmospheric Sciences; Roy Gu is an associate professor in the Department of Civil, Construction and Environmental Engineering; all at Iowa State University.

For questions or comments about the contents of this paper, please contact Manoj Jha, 497 Town Engineering, Iowa State University, Ames, IA 50011; Ph: 515-294-6346; Fax: 515-294-8216; E-mail: manoj@iastate.edu.

Abstract

We evaluate the impact of climate change on stream flow in the Upper Mississippi River Basin (UMRB) by using a regional climate model (RCM) coupled with a hydrologic model, the Soil and Water Assessment Tool (SWAT). The SWAT model was calibrated and validated against measured stream flow data using observed weather data and inputs from the Environmental Protection Agency's BASINS (Better Assessment Science Integrating Point and Nonpoint Sources) geographical information/database system. The combined performance of the SWAT and RCM was examined using observed weather data as a lateral boundary condition in the RCM. The SWAT and RCM were found to perform well, especially on an annual basis. The potential impacts of climate change on water yield and other hydrologic budget components were then quantified by driving SWAT with current and future climates. A 21 percent increase in future precipitation simulated by the RCM produced an 18 percent increase in snowfall, a 51 percent increase in surface runoff, and a 43 percent increase in groundwater recharge, resulting in a 50 percent net increase in total water yield in the UMRB on an annual basis. Uncertainty analysis showed that the simulated change in stream flow substantially exceeded model biases of the combined modeling system (with the largest bias being 18 percent), giving us relatively high confidence in the results.

Keywords: climate change, hydrological modeling, RCM, SWAT, uncertainty analysis, Upper Mississippi River Basin.

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

Introduction

Hypoxia (defined as an oxygen concentration of less than 2 mg/L) in the Gulf of Mexico has been linked to excessive amounts of nitrogen (about 2 million tons of nitrogen each year) exported from the U.S. Midwest by the Mississippi River. The Upper Mississippi River Basin (URMB) (Figure 1) constitutes a minor portion (15 percent) of the Mississippi River Basin system but is recognized as a major contributor (more than 50 percent) of nitrogen transported to the Gulf of Mexico (Goolsby, Battaglin, and Hooper 1997). Agricultural activities frequently are implicated as the source of the excess nitrogen.

Improving environmental quality in such a large and complex landscape with its 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 change that will impose as yet unknown new conditions on the region. Major changes to the landscape to suppress fugitive chemical loss, such as terracing, reintroducing perennial vegetation, or using buffer strips along waterways, require time and expense to install and have lifetimes comparable to those of expected changes in climate.

Understanding different hydrological processes within the watershed is therefore important for assessing the future environmental and socioeconomic status of 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.

Future scenarios on climates for the middle to the end of the twenty-first century, as simulated by global climate models, show a general warming over the United States. Large uncertainties accompany the projections of global models on future changes in precipitation, but it seems likely that precipitation will increase on an annual basis.

FIGURE 1. The Upper Mississippi River Basin and delineated eight-digit Hydrologic Unit Codes

Regional climates consistent with global changes are created by downscaling the results of a global climate model (GCM) using either statistical or dynamic (regional climate model—RCM) methods. Giorgi, Brodeur, and Bates (1994) showed that a nested regional model produces a more realistic simulation of precipitation over the United States than does using a driving global model alone. They also found that the estimated changes in climate are different: precipitation changes differ locally in magnitude, sign, and spatial and seasonal details.

Several studies have investigated the impacts of climate change on the hydrology of a watershed. Hubbard and Hotchkiss (1997) used RegCM (Giorgi et al. 1993) to assess the impacts of climate change on water resources in the Missouri River Basin. They found a dramatic increase in water yield (100 percent or more) for the northern region of the basin while the southern region decreased up to 80 percent. Lettenmaier et al. (1999), in their study of six North American watersheds of various sizes representing a variety of physiographic and geographic conditions, used the output from three transient GCMs and

one equilibrium (double carbon dioxide) GCM to evaluate the potential effects of climate change. They found that the water yield decreased by 6, 24, and 34 percent for the transient climate scenarios and increased by 2 percent for the $2 \times CO_2$ scenario. They also suggested that altered precipitation causes generally higher correlation with runoff changes than do temperature changes.

In our study we used 10-year simulations of current and future scenario climates for the United States to provide a physically consistent set of climate variables for use in a watershed scale simulation model. The objective of the study was to quantify the effect of future climate on hydrology of the UMRB. We assessed the confidence in the results of our coupled modeling system for analyzing the impact of climate change by comparing model results with observations for later decades of the twentieth century. The study provides a first step toward understanding how hydrologic conditions of the region might change with a plausible scenario of global warming and hence how water quality and quantity might be affected.

Models and Input Data

Brief Description of the Soil and Water Assessment Tool (SWAT) Model

The SWAT model (Arnold et al. 1998) is a long-term, continuous model for watershed simulation. 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 details by allowing the watershed to be divided into a large number of subwatersheds. Major model components include weather, hydrology, soil temperature, plant growth, nutrients, pesticides, and land management. The model has been validated for several watersheds.

In SWAT, a watershed is divided into multiple subwatersheds, which are then further subdivided into unique soil/land-use 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 subwatershed are summed, and the resulting loads are routed through channels,

ponds, and/or reservoirs to the watershed outlet. Hydrologic processes are based on the following water balance equation:

$$SW_t = SW + \sum_{t=1}^{t}(R_i - Q_i - ET_i - P_i - QR_i) \qquad (1)$$

where SW is the soil water content minus the wilting-point water content, and R, Q, ET, P, and QR are the daily amounts (in mm) of precipitation, runoff, evapotranspiration, percolation, and groundwater flow; 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 predict 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 the 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. The contribution of groundwater flow to the total stream flow is simulated by routing a shallow aquifer storage component to the stream (Arnold, Allen, and Bernhardt 1993).

The surface runoff from daily rainfall is estimated with the modified U.S. Department of Agriculture–Soil Conservation Service curve number method, which estimates the amount of runoff based on local land use, soil type, and the antecedent moisture condition. A provision for estimating runoff from frozen soil is also included. Snow melts on days when the 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 the potential evapotranspiration 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 evapotranspiration, 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.

Watershed Configuration

The UMRB has a drainage area of 431,000 km^2 up to the point just before conflu-ence of the Missouri and Mississippi Rivers (near Grafton, Illinois) and covers parts of seven states: Minnesota, Wisconsin, South Dakota, Iowa, Illinois, Missouri, and Indiana (Figure 1). Land cover in the basin is diverse, and includes agricultural lands, forest, wet-lands, lakes, prairies, and urban areas. The river system supports commercial navigation, recreation, and a wide variety of ecosystems. In addition, the region's more than 30 mil-lion residents rely on river water for public and industrial supplies, power plant cooling, wastewater assimilation, and other uses.

The SWAT model requires a variety of detailed information describing the water-shed. 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 percent of the area.

The soil data available in BASINS come from the State Soil Geographic (STATSGO) data base (USDA 1994), which contains soil maps at a 1:25,000 scale. The STATSGO map unit is linked to the Soil Interpretations Record attribute data base 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 net-works, 119 subwatersheds were then delineated up to the point just before the confluence with the Missouri River (see Figure 1). The delineated subwatersheds follow the bounda-ries of the eight-digit Hydrologic Unit Codes (HUCs) defined by the U.S. Geological Survey (USGS). The HRUs were then created by considering the dominant soil/land-use category within each subwatershed; that is, each subwatershed was assumed to be consti-tuted 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 automatically applying fertilizer 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.

Climate Data

We used four sources of climate data to drive SWAT as shown in the left-hand column of the boxes in Figure 2: one observed data set from stations and three sets of RCM simulated climate data. The observed climate—daily precipitation and maximum and minimum temperatures—was extracted from the U.S. Cooperative Observer Program atabase (NCDC 2003), as compiled by the Variable Infiltration Capacity group (see <www.ce.washington.edu/pub/HYDRO/edm/>). These data were obtained for 99 weather stations located in or near the watershed.

The remaining three sets of climate data were generated using the RCM known as RegCM2 (Giorgi et al. 1993). The model simulation has a horizontal grid spacing of 52 km
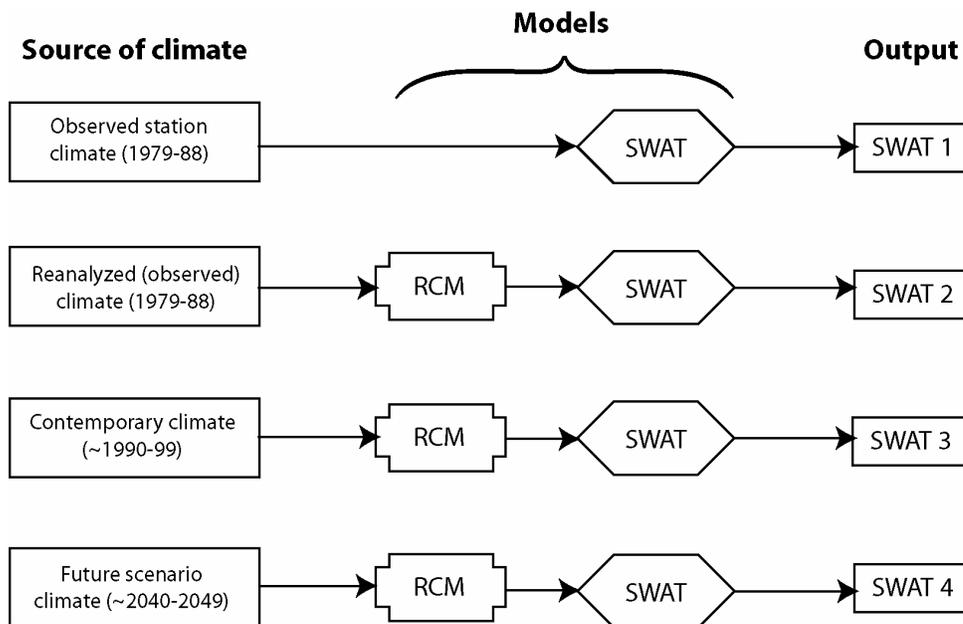

FIGURE 2. Schematic diagram of RCM/SWAT simulation runs

(Pan et al. 2001), thereby providing approximately 160 grid points within the UMRB. The simulation domain, centered at 100° W and 37.5^o N, covers the continental United States 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 six-hour data from the re-analysis 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 re-analysis dataset (Kalnay et al. 1996) from the National Centers for Environmental Prediction (NCEP) and National Center for Atmospheric Research (NCAR), a 1.875^o x 1.875^o grid over the entire globe, was downscaled onto a RCM grid of 52 x 52 km. The NCEP re-analysis combined all available observations for a 40-year period, including the 10-year period of the current study, with a dynamic model to maximize internal physical consistency. It 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 to examine the RCM's capability in producing observed climate data for the specific period (1979–88).

The other two downscaling simulations are based on GCM climates (rather than on NCEP re-analysis). The results of the GCM of the Hadley Centre (HadCM2; see Johns 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 is a coupled atmosphere-ocean model that uses a finite-difference grid of 2.5^o latitude by 3.75^o 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 hydrological processes. We nested an RCM with a fine grid resolution (RegCM2) into a coarse-grid global model to dynamically downscale global information to the continental United States. The GCM contemporary climate represented by a 10-year window corresponds roughly to that of the 1990s, selected from the HadCM2 simulations without enhanced greenhouse gas (GHG) forcing (Johns et al. 1997). The future scenario climate is from a transient simulation that assumed a 1 percent 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 the years 2040–2049 with CO_2 of about 480 ppm.

Model Uncertainties and Experimental Design

Sources of Error

This study was 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 the impact of climate change on the stream flow come from (1) uncertainty in the assumption of future GHG scenarios, (2) errors in the GCM that translates the GHG emissions into the future scenario global climate, (3) errors in the downscaling of global results to the regional climate (in our case, done by an RCM), (4) errors in SWAT, and (5) errors that come from combining the models.

For this study, we had access to only one global model run for one GHG scenario, so we were unable to assess error (1). The GCM has errors in describing the current climate and hence presumably also in the future climate for the same (whatever) reasons. It is customary to assume, by calculating the difference between the future and the contemporary climate, both being simulated by the GCM, that the GCM bias will cancel. 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 error 2a and the additional error due to changes in GHGs as error 2b. When models are linked together, the error arising from the linkage likely is not represented by a linear combination of individual model errors. By using various combinations of input conditions in RCM and SWAT, we can calculate and compare different end-product stream flows, thereby gaining at least qualitative assessment of these combined errors.

Experimental Design

Figure 2 shows different SWAT runs with historical and RCM generated climates. Results of the first SWAT simulation (SWAT 1 in Figure 2) with the observed station climate from 1979–88 were compared with measured stream flows at Grafton, Illinois, during that same period to evaluate SWAT capability representing observed discharges in

the UMRB. The error introduced by the RCM was assessed by using RCM output from a run driven by observed climate data interpolated to the RCM grid (re-analysis, 1979–88) as input to SWAT for comparison against output of SWAT driven by the observed station climate (SWAT 1). This eliminates biases introduced by SWAT. Error 2a from the global model was 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 re-analysis (SWAT 2).

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.

Error Assessment

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

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

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

Comparisons	Evaluation
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

and

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^{N} \left(Q_{s_i} - Q_{m_i}\right)^2} \qquad (3)$$

where subscripts *m* and *s* indicate measured and simulated stream flow respectively, and *N* is the number of years of stream flow data. The bias provides a measure of systematic errors revealed by 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).

Results and Discussion

Model Validation

SWAT Calibration and Validation. Measured stream flows during 1989–97 at USGS gauge station 05587450, the Mississippi River near Grafton, Illinois, were used to calibrate SWAT. The criterion used for calibrating the model was to minimize the difference between measured and predicted 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, soil evaporation compensation factor, plant uptake compensation factor, re-evaporation coefficient, and groundwater delay were adjusted from the model's initial estimates defaulted by AVSWAT to fit the predicted flows to the observed ones. A detailed explanation of calibrated parameters can be found in the SWAT theoretical documentation, which is available online at <http://www.brc.tamus.edu/swat>. A comparison of annual flow (Figure 3) and a time series (Figure 4) of monthly stream flow at the watershed outlet shows that the magnitude and trend in the predicted stream flows agreed with the measured data quite well. The performance of the model was evaluated by the coefficient of determination (R^2) and Nash-Sutcliffe simulation efficiency (E) (Nash and Sutcliffe 1970). If R^2 and E values are less than or very close to 0, the model prediction is considered unacceptable. If the values approach 1, the model predictions become perfect. Statistical evaluation for annual prediction yielded an R^2 value of 0.91
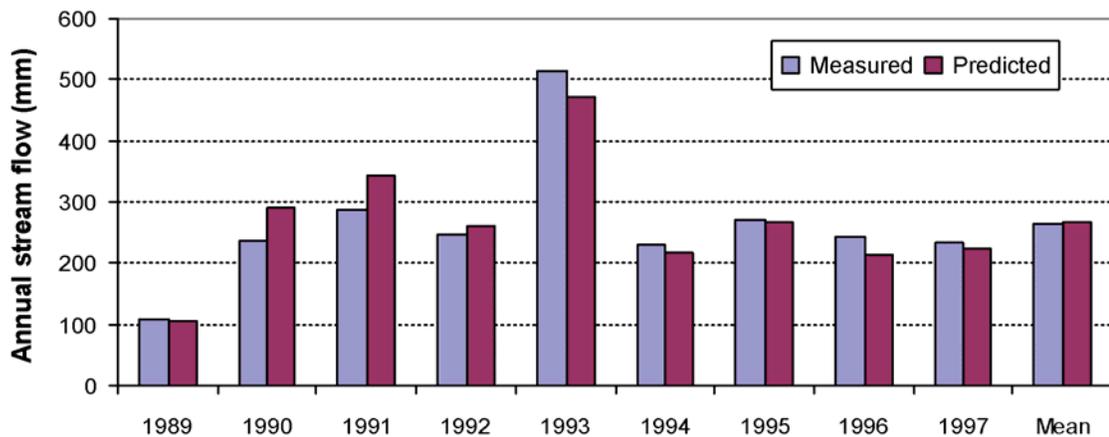
FIGURE 3. Measured and predicted annual stream flows at USGS gauge 05587450, Mississippi River near Grafton, IL, for calibration
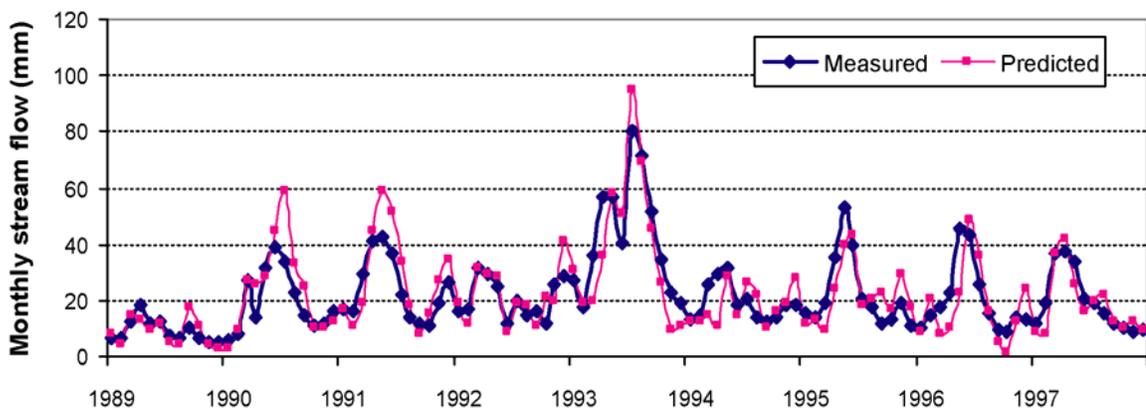

FIGURE 4. Measured and predicted monthly stream flows at USGS gauge 05587450, Mississippi River near Grafton, IL, for calibration

and an E value of 0.91, indicating a reasonable agreement between the measured and predicted flows. Similarly, an R^2 value of 0.75 and an E value of 0.67 were obtained for monthly predictions.

Flow validation was conducted using the stream flow data for the period 1980–88. The simulated stream flow of this period provides the output labeled SWAT 1 in Figure 2. During the validation process, the model was run with input parameters calibrated earlier without any change. Measured and predicted annual (Figure 5) and monthly (Figure 6) stream flow show a good agreement between predicted stream flows and the measured
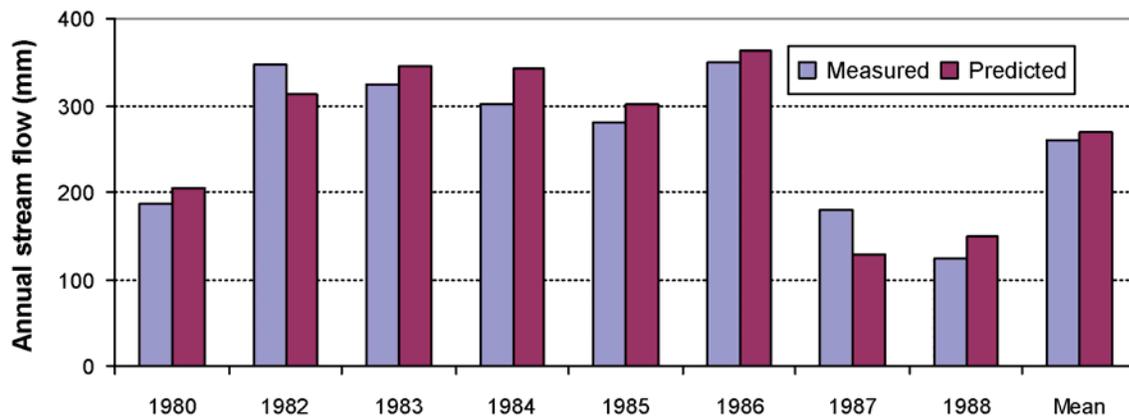
FIGURE 5. Measured and predicted annual stream flows at USGS gauge 05587450, Mississippi River near Grafton, IL, for validation
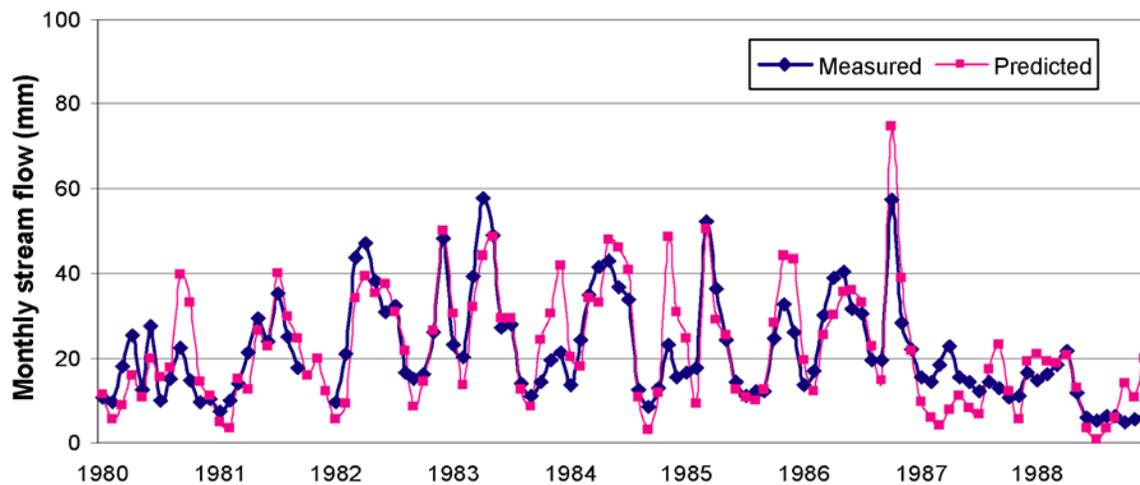

FIGURE 6. Measured and predicted monthly stream flows at USGS gauge 05587450, Mississippi River near Grafton, IL, for validation

val-ues. The annual prediction yielded an R^2 value of 0.89 and an E value of 0.86, while an R^2 value of 0.70 and an E value of 0.59 were obtained for monthly predictions. Overall, the model was able to predict stream flow with a reasonable accuracy.

Coupling SWAT with RCM. The calibrated SWAT model was run with weather inputs (precipitation and temperature) generated from the RCM model for the period 1979–88 (labeled NCEP). The output is labeled SWAT 2 in Figure 2. Annual prediction matched well with the measured data, as shown in Figure 7. It is noteworthy that the year having the largest error was 1988, a year of extreme drought in the central United States.
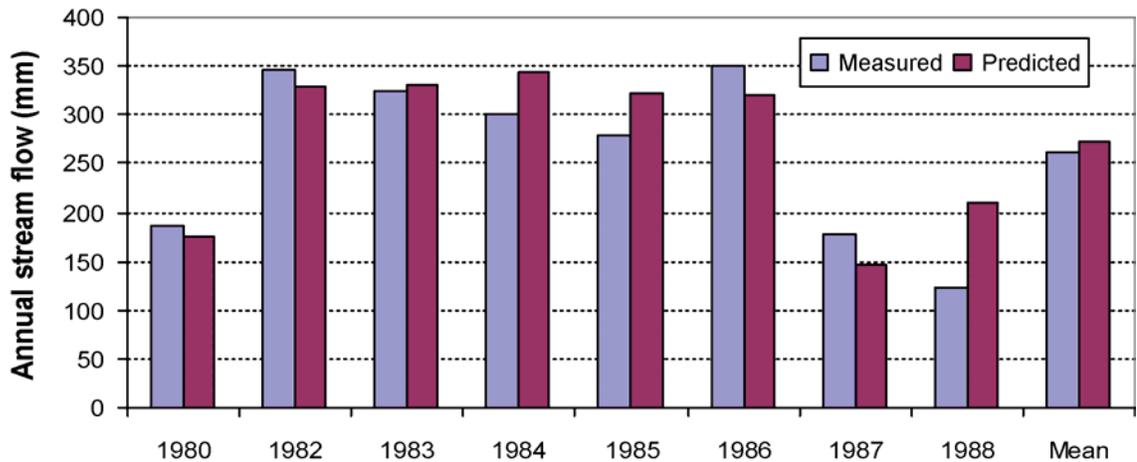
FIGURE 7. Annual stream flows produced by SWAT, driven by the RCM with NCEP lateral boundary conditions, compared with measured stream flows at USGS gauge 05587450, Mississippi River near Grafton, IL

Statistical evaluation revealed that the model was able to explain at least 77 percent of the variability in the measured stream flow ($R^2 = 0.77$), showing a reasonably good agreement between measured and predicted stream flows.

Poor performance was found in predicting seasonal trends. Figure 8 shows the nine-year averages of monthly totals of measured stream flows and that driven by RCM/NCEP with some discrepancy. In the spring, the stream flow is very sensitive to surface and sub-surface temperatures and to whether precipitation falls as rain or snow, this latter feature also being sensitive to 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 are more detrimental than errors in precipitation in assessing time-integrated runoff. 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 (Figure 8). The seasonal distribution of precipitation shown in Figure 9 suggests that excesses in model-generated precipitation in winter also contributed to the excess stream flow in the spring. Similarly, lower estimated precipitation in summer months likely contributed, along with the excessive early-spring runoff previously mentioned, to the low stream flow simulated for August through November. This is also evident in the analysis of hydrological budget components, which we discuss in a later section.
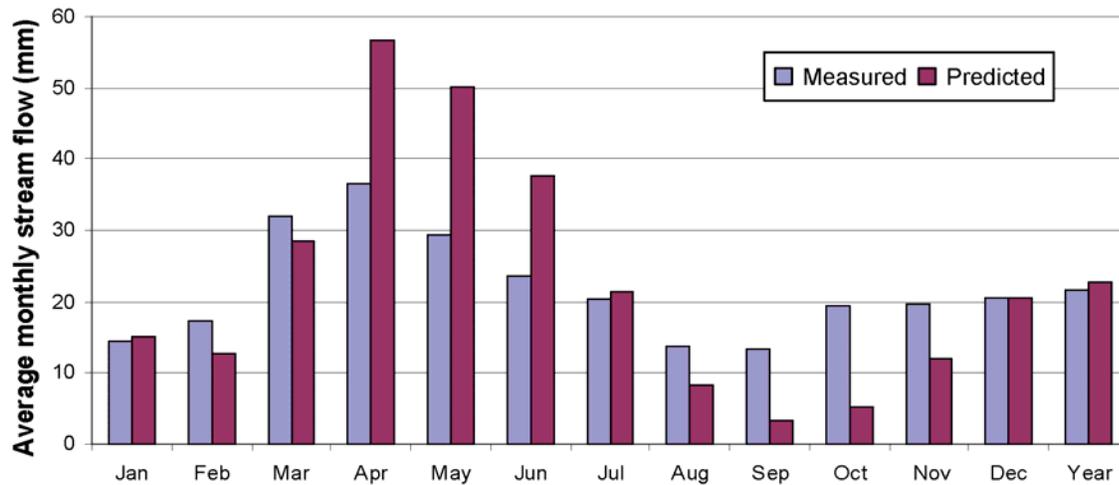
FIGURE 8. Comparison of measured mean monthly stream flows and that produced by SWAT driven by the RCM downscaled NCEP data for the validation period 1980–1988
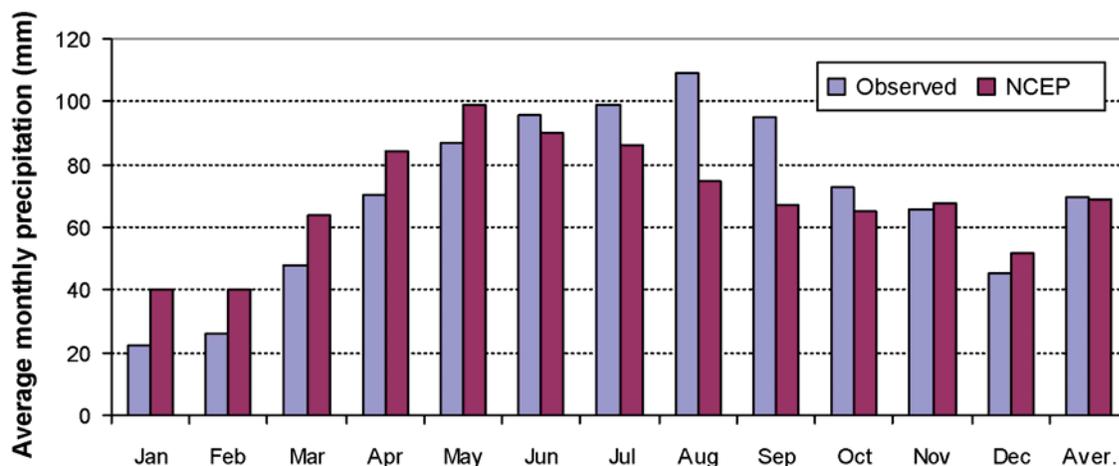

FIGURE 9. Comparison of measured mean monthly precipitation and that produced by SWAT driven by the RCM downscaled NCEP data for the validation period 1980–1988

Climate Change Impact Assessment

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

The comparison of precipitation generated for contemporary and future scenario climates (Figure 10) suggests higher average values of monthly flows throughout the year in the future scenario, except for November, which has 2 percent, lower than the current precipitation. Projected increases in precipitation for this region are consistent with trends over the last decades of the twentieth century (IPCC 2001). The mean annual precipitation is projected to increase by 21 percent.

Climate-induced stream flow changes are inferred by evaluating differences produced by SWAT when driven by future scenario and contemporary climates. The annual average stream flow increased by 50 percent because of climate change (Figure 11), with the largest increase occurring in spring and summer. This disproportionate change—that is, a 50 percent increase in average annual stream flow versus a 21 percent increase in average annual precipitation—can be attributed to more precipitation falling on saturated soils, which creates a 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 to soil infiltration that delays the contribution to stream flows.

Simulated hydrologic budget components under different climate conditions (Table 2) 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 percent) for the various contemporary climates. This remarkable consistency, however, masks RCM problems with monthly distributions as previously discussed. Other components except actual evapotranspiration are far less consistent among the various contemporary climates, which suggests substantial interdecadal variability in the climate for these components, for example, snowfall and snowmelt in calibration versus validation decades, and/or model-generated differences, for example, differences between validation and NCEP columns. The 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 prediction by the RCM (Figure 9).

Despite large variations in budget components, annual predictions of total water yields were quite similar, especially between observed (validation period) and NCEP
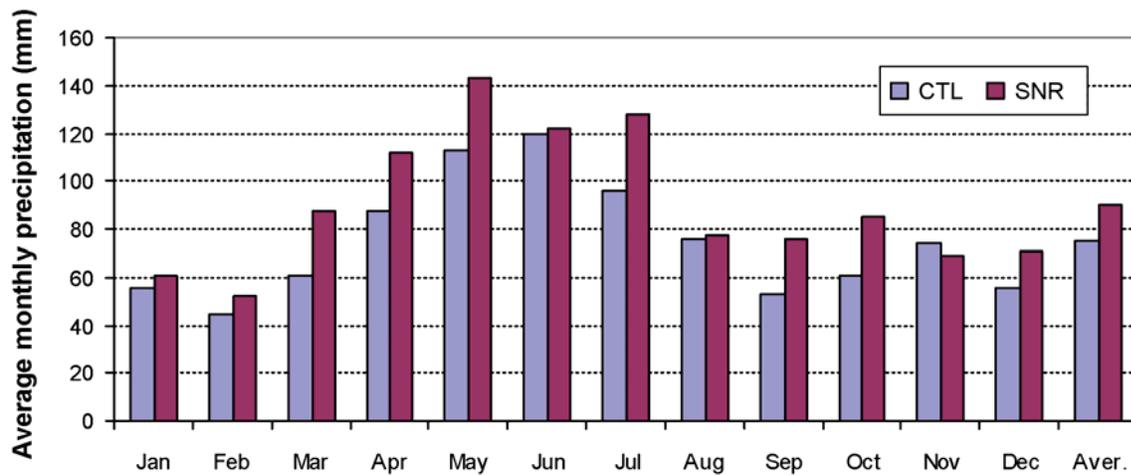
FIGURE 10. Precipitation generated by RCM for contemporary and future scenario climates
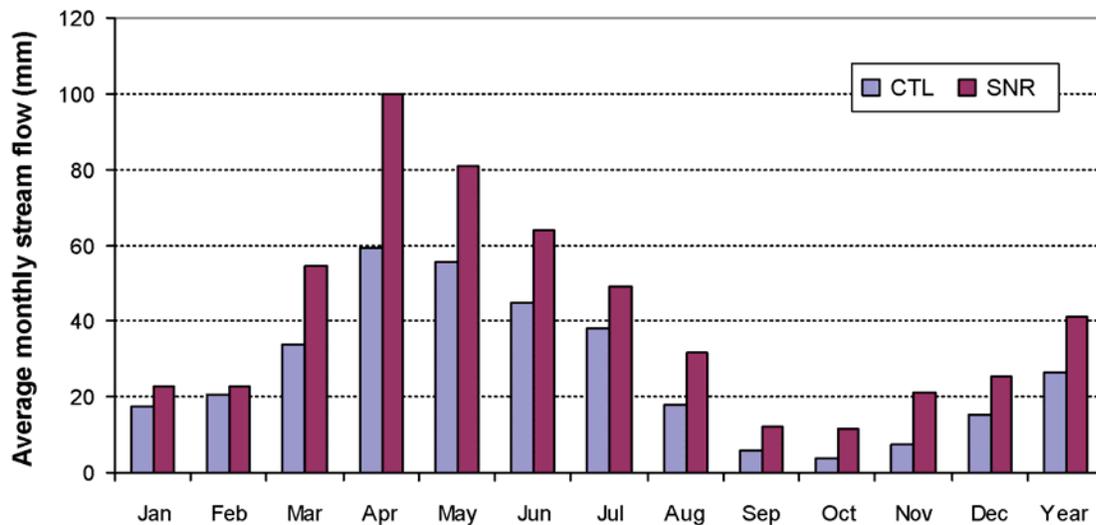
FIGURE 11. Mean monthly stream flow predicted by SWAT for contemporary and future scenario climates

conditions. Proportionate but higher values of budget components were found for CTL compared to NCEP simulation runs, although they both represent similar time domains, suggesting that 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.

TABLE 2. Simulated hydrologic budget components by SWAT under different climates

Hydrologic Budget Components	Calibration (1989–1997)	Validation (1980–1988)	NCEP (1980–1988)	CTL (around 1990s)	SNR (around 2040s)	% Change (SNR-CTL)
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.

The 21 percent increase in precipitation for the future scenario climate produced an 18 percent increase in snowfall, a 19 percent increase in snowmelt, a 51 percent increase in surface runoff, and a 43 percent increase in recharge, leading to a 50 percent net increase in the total water yield in the UMRB. Uncertainties in these projections were analyzed by using the research plan mapped out in Figure 2.

Uncertainties in the Climate Change Impact Assessment

Table 3 lists the absolute and relative bias and RMSE for all sources of errors. The highest percentage bias (18 percent) was found for the GCM downscaling error. However, the highest individual model RMSE (14.3 mm) was found in RCM performance. The RCM model prediction error was low on the annual basis, but high for the seasonal values (Figure 8).
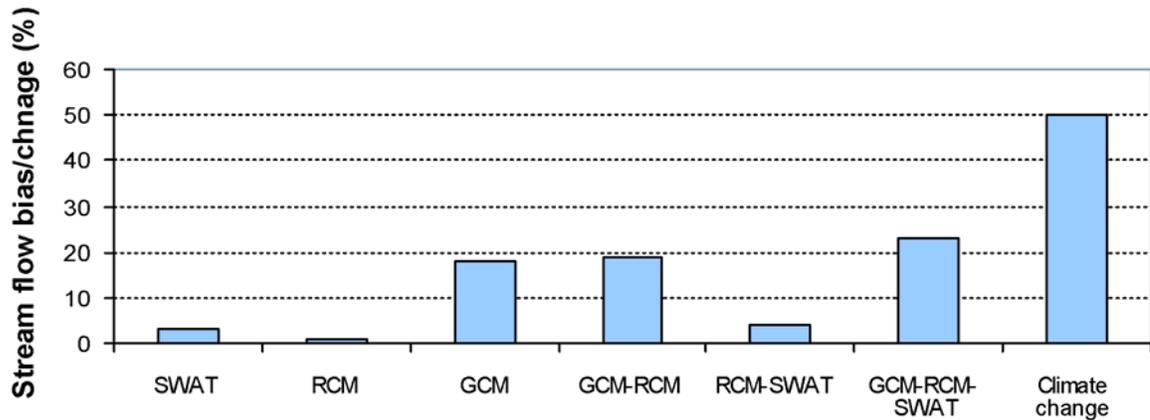
We contrasted the climate change signal with various biases in order to assess the confidence in simulating the stream flow response to climate change. As shown in Figure 12, the change in stream flow (50 percent) due to climate change exceeds both individual model biases and also the combined-model bias, giving us relatively high confidence that climate change, as represented by the global model used herein, will substantially increase stream flow.

Annual stream flow tends to have a quasi-linear relationship with annual precipitation. We used regression analysis to evaluate this relationship (Figure 13) for the five options depicted in Figure 2. Table 4 lists the five regressions with their slope values. The

TABLE 3. Bias and RMSE in various simulations

Modeling error	Absolute and Relative Bias in Average Monthly Prediction (mm)	RMSE in average monthly prediction (mm)
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.

FIGURE 12. Comparisons of climate change with annual biases in simulated stream flow
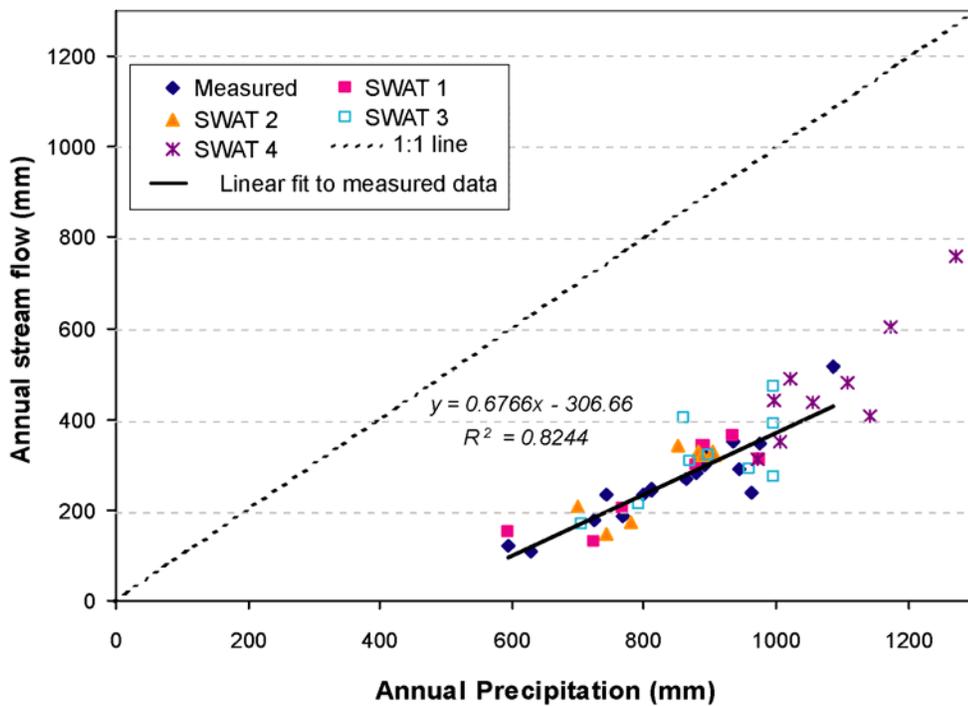

FIGURE 13. Relationship between annual stream flow and precipitation for various climates

TABLE 4. Regression analysis: stream flow versus precipitation

Stream flow vs. precipitation	Scenario	Slope
1. Measured stream flow vs. observed precipitation (1980-1997)	Observed	0.66
2. Predicted stream flow vs. observed precipitation (1980-1988)	SWAT 1	0.65
3. Predicted stream flow vs. NCEP precipitation (1980-1988)	SWAT 2	0.87
4. Predicted stream flow vs. CTL precipitation (around 1990s)	SWAT 3	0.64
5. Predicted stream flow vs. SNR precipitation (around 2040s)	SWAT 4	1.16

regression line plotted represents measured stream flow versus observed precipitation for the period 1980–97. Stream flow values produced by SWAT driven by observed precipitation (SWAT 1) and GCM/RCM CTL precipitation (SWAT 3) give regression slopes in close agreement with observations. However, the RCM driven by NCEP conditions gives a regression line with a greater slope, showing a larger increase in stream flow for a given increase in precipitation as compared to the observed trend. The GCM future scenario climate (SNR) follows a similar trend of CTL climate but with higher precipitation. The 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 greater-than-1 slope value here does not mean more runoff than precipitation but simply reflects the larger portion of rainfall transported as runoff because of high-intensity rainfall events in the future climate (IPCC 2001). Overall, the projections tend to follow the observed regression line but with an upward trend in the future climate.

Limitations of the 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 a luxury. The total water yield from the watershed typically is available only in terms of stream flow. In this study, only stream flow was

calibrated and validated at the watershed outlet since other data such as snowmelt, groundwater flow, and evapotranspiration are not available as measured data. 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 studies reported in the literature show that SWAT is capable of providing watershed-scale analysis, and this has been validated on many small and large watersheds for total water yield, evapotranspiration, and groundwater recharge, depending upon the availability of data. 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 the RCM simulation, such as the snow water equivalent and high sensitivity of snow melt to air temperatures, led to large errors in the monthly stream flow beginning in the spring. For these reasons, we have low confidence in the ability of this coupled-model system to represent month-to-month stream flow. However, results for annual values are produced with higher confidence.

Summary and Conclusions

A regional climate model that generated two 10-year simulated climates for the continental United States corresponding to current and future scenario climates on a 50-km horizontal grid was used to drive a hydrological model, the SWAT model, for the entire UMRB. The objective of the study was to quantify the effect of future climate change on the hydrology of the UMRB. Hydrologic components of the SWAT model were calibrated and validated using measured stream flow data at USGS gauge no. 05587450, the Mississippi River near Grafton, Illinois. The model produced stream flow with reasonable accuracy on an annual and monthly basis. The combined performance of SWAT and the RCM was first evaluated by driving SWAT with output of the RCM runs downscaling NCAR/NCEP re-analysis 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. The 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 predicted an increase in future scenario climate precipitation of 21 percent with a resulting 18 percent increase in snowfall, a 51 percent increase in surface runoff, a 43 percent increase in recharge, and a 50 percent increase in the total water yield in the UMRB. This disproportionate change can be attributed to more heavy precipitation events in future climates and the nonlinear nature of hydrologic budget components, such as snowmelt, evapotranspiration, surface runoff, and groundwater flow.

We assessed the confidence in estimating impacts of climate change on stream flow by quantifying SWAT, RCM, and GCM errors and the errors that come from combining the models. The largest contribution to the total error or bias was attributable to GCM downscaling error (18 percent). However, the simulated change in stream flow (a 50 percent increase in water yield) exceeded individual model and total biases of the combined modeling system, giving us relatively high confidence in the results.

References

Arnold, J.G., and P.M. Allen. 1996. "Estimating Hydrologic Budgets for Three Illinois Watersheds." *J. Hydrol.* 176: 57-77.

Arnold, J.G., P.M. Allen, and G. Bernhardt. 1993. "A Comprehensive Surface-Groundwater Flow Model." *J. Hydrol.* 142: 47-69.

Arnold, J.G., R. Srinivasan, R.S. Muttiah, and J.R. Williams. 1998. "Large Area Hydrologic Modeling and Assessment." Part I: Model Development. *J. Am. Wat. Res. Asso.* 34: 73-89.

Giorgi, F., M.R. Marinucci, G.T. Bates, and G. De Canio. 1993. "Development of a Second-Generation Regional Climate Model (RegCM2)." Part I: Boundary-Layer and Radiative Transfer. *Mon. Wea. Rev.,* 121: 2794-2813.

Giorgi, F., C.S. Brodeur, and G.T. Bates. 1994. "Regional Climate Change Scenarios Over the United States Produced with a Nested Regional Climate Model." *J. Clim.,* 7: 375-99.

Goolsby, D.A., W.A. Battaglin, R.P. Hooper. 1997. "Sources and Transport of Nitrogen in the Mississippi River Basin." Paper presented at the American Farm Bureau Federation Workshop. St. Louis, MO, July 14-15.

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. 2002. "Use of Regional Climate Model Output for Hydrologic Simulations." *J. Hydromet.* 3: 571-90.

Hubbard, C.M., and R.H. Hotchkiss. 1997. "Hydrologic Modeling of the Missouri River in a Climate Change Model." Paper presented at the American Water Resources Association Symposium. Keystone, CO, June.

Intergovernmental Panel on Climate Change (IPCC). 2001. *Climate Change 2001—The Scientific Basis.* Edited by J.T. Houghton, T.Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, and D. Xiaosu. Cambridge: Cambridge University Press.

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: Model Description, Spinup, and Validation." *Clim. Dyn.* 13: 103-34.

Kalnay, E., M. Kanamitsu, R. Kistler, W. Collins, D. Deaven, L. Gandin, et al. 1996. "The NCEP/NCAR 40-Year Reanalysis Project." *Bull. Amer. Meteor. Soc.* 77: 437-71.

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." *Clim. Change* 43: 537-79.

Miller, J.R., and G.L. Russell. 1992. "The Impact of Global Warming on River Runoff." *J. Geophys. Res.* 97(D3): 2757-64.

Nash, J.E., and J.V. Sutcliffe. 1970. "River Flow Forecasting through Conceptual Models." Part I: A Discussion of Principles. *J. Hydrol.* 10(3): 282-90.

National Climate Data Center (NCDC) 2003. Cooperative Observer Program. <http://www.coop.nws.noaa.gov/Publications/coop.pdf> (accessed April).

Pan, Z., J.H. Christensen, R.W. Arritt, W.J. Gutowski, Jr., E.S. Takle, and F. Otieno. 2001. "Evaluation of Uncertainties in Regional Climate Change Simulations." *J. Geophys. Res.* 106(D16): 17,737-751.

Takle, E.S., W.J. Gutowski, Jr., R.W. Arritt, Z. Pan, C.J. Anderson, R. Ramos da Silva, et al. 1999. "Project to Intercompare Regional Climate Simulations (PIRCS): Description and Initial Results." *J. Geophys. Res.* 104: 19,443-462.

U.S. Department of Agriculture (USDA). 1994. "State Soil Geographic (STATSGO) Data Base: Data Use Information." Miscellaneous Publication Number 1492. Natural Resource Conservation Service, National Soil Survey Center, Lincoln, NE.

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.