Climate Change Sensitivity Assessment on Upper Mississippi River Basin Streamflows Using SWAT

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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 percent. An average annual flow decrease of 15 percent was estimated for a constant temperature increase of 4°C. Essentially linear impacts were predicted among precipitation change scenarios of -20, -10, 10, and 20 percent, which resulted in average annual flow changes at Grafton, Illinois, of -51, -27, 28, and 58 percent, 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 percent in response to these climatic changes. Overall, the results indicate that the UMRB hydrology is very sensitive to potential future climate changes and that these changes could stimulate increased periods of flooding or drought.

Keywords: climate change, flow, hydrology, simulation, spatial patterns, watershed.

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

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 1.4ºC and 5.8ºC would be expected following a doubling of carbon dioxide (CO_2) 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 percent 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, Lewin, and Nagy 1993) shows that stomatal conductance of some plants declines as CO_2 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 were 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 an approach that coupled climate models with hydrologic models. 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 conterminous region) and for specific watersheds. Many of the studies have been performed for watersheds in the western section of the United States, including all or portions of the Colorado River Basin (Nash and Gleick 1991; Christensen et al. 2003; Gleick and Chaleki 1999; Wilby, Hay, and Leavesley 1999; Wolock and McCabe 1999; Rosenberg et al. 2003), the 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, Fontaine, and Hotchkiss 2000; Stone et al. 2001; Stone, Hotchkiss, and Mearns 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 because of the intersection within the region of the three air masses (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 (last 10,000 years) sediment core data from lakes (Dean 1999) and streams (Knox 2002) in the region. The stream sediment data indicate that climatic change and extreme floods have a highly sensitive relationship. Shifts in precipitation and other climatic conditions in the UMRB region could also have major environmental consequences. Nitrate 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, Turner, and Scavia 2002). Goolsby et al. (2001) estimated that 35 percent of the nitrate 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 URMB has 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 the 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 percent 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 major U.S. water resource regions by linking a simple water balance model to two different GCMs: the Canadian Centre for Climate Modeling and Analysis model (CGCM1) (Flato et al. 2000) and the Hadley Centre for Climate Prediction and Research model (HadCM2) (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 percent for 2030 and 2095, respectively, in response to the HadCM2 inputs. Thomson et al. (2003) performed an analysis of El Niño/Southern Oscillation 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. Thomson et al. report that water yields for the UMRB can decline as much as 59 percent and increase as much as 62 percent, 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. (2003b) concentrated on analyzing the hydrologic effects of potential future climate change for the UMRB only. 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, Marinucci, and Bates (1993). The climate scenario represented a 1 percent annual increase of greenhouse gases, which was equivalent to a CO_2 level of about 480 parts per million by volume (ppmv) 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 percent for the period of 2040-49.

The goal of this study was to build upon the previous study by Jha et al. (2003b) 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 CO_2 levels) including a simplified replication of a previously reported future climate projection, which is similar to the methodology used by Stonefelt, Fontaine, and Hotchkiss (2000). Actual assessments of potential future climate changes cannot be performed by means of 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 about available GCM projections.

The specific objectives of this study are (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, Illinois, 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 CO_2, 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 watershed scale simulation model that is physically based, long term, and continuous. 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. 2002.

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 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 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, Srinivasan, and Arnold 1995; Arnold and Allen 1996; Srinivasan et al. 1998; Arnold et al. 1999; Saleh et al. 2000; Santhi et al. 2001). Next, we briefly discuss the hydrologic processes and climate change processes modeled in SWAT.

The hydrology part of the model includes snowmelt, surface runoff, evapotranspiration, groundwater percolation, lateral flow, and groundwater flow (or return flow). If the daily mean temperature is less than 0ºC, it is assumed that precipitation falls as snow. Snow is assumed to melt on days when the maximum temperature exceeds 0ºC. Partitioning of daily precipitation between surface runoff and infiltration is estimated with a modification of the Soil Conservation Service's 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 subdaily 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 CO_2 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 evapotranspiration, 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's 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 CO_2 concentrations in the range of 330-660 parts per million (ppm), following the approach developed by Stockle et al. (1992). The effects of increased CO_2 are directly accounted for in the model by changes in plant growth, biomass production, and evapotranspiration rates (Arnold et al. 1998).

Input Data

The UMRB is located in the North Central region of the 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 km^2. The primary land use is agricultural (over 75 percent) followed by forest (20 percent), 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" 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.

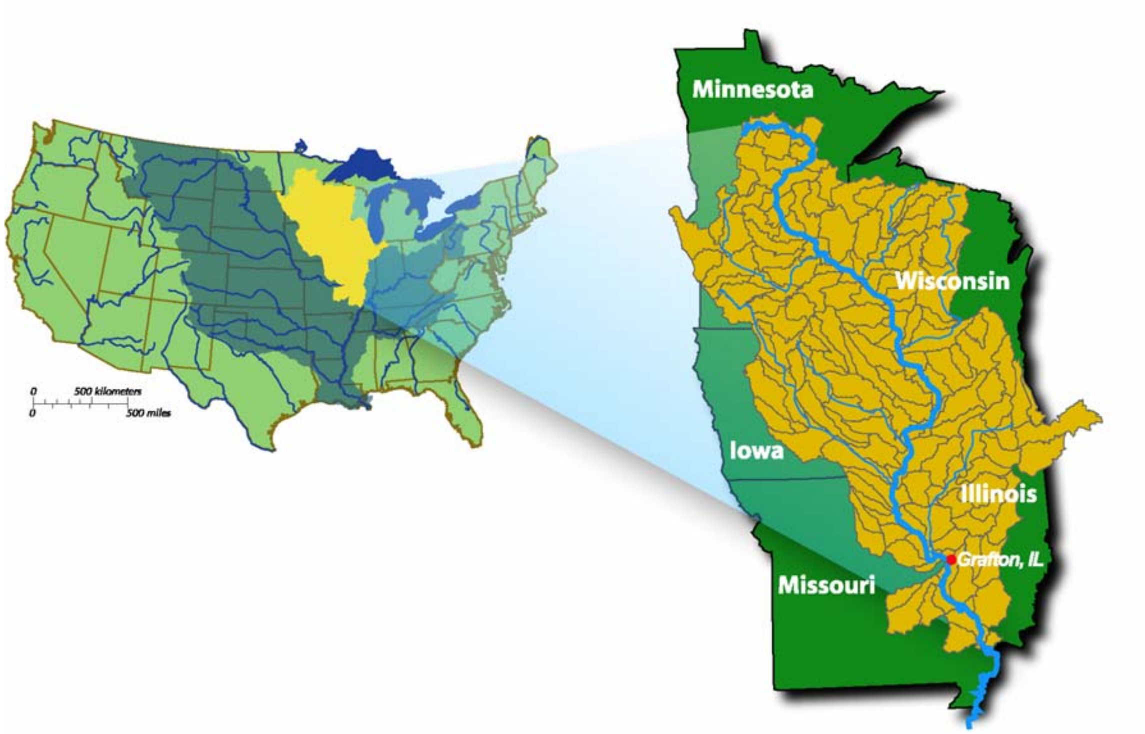

FIGURE 1. Location of Upper Mississippi River Basin, detailing 131 eight-digit watersheds and the streamflow testing site at Grafton, Illinois

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 data.

The management operations were defaulted by the SWAT2000 ARCVIEW interface (AVSWAT), developed by Di Luzio et al. (2002), 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 the watershed (Personal communication with C. Chinnasamy, Blacklands Research and Extension Lab, Temple, TX, 2002). 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 Digital Elevation Model data. Stream network data available from the U.S. Geological Survey (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 closely as possible with 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 eight-digit Hydrologic Cataloging Unit watersheds as defined by the USGS (Seaber, Kapinos, and Knapp 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., the Mississippi River at Grafton, IL). This point constitutes a drainage area of 431,000 km^2 that drains approximately 90 percent 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 land use 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 URMB 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, Illinnois (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 land use, 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 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 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. (2003a) and are listed in Table 1. The initial values of each calibration parameter were

TABLE 1. Hydrologic calibration parameters and their values for the Upper Mississippi River Basin

Calibration Parameter[a]	Symbol	Initial Estimates	Calibrated Values
Curve Number for moisture condition II	CN2	-[b]	- 10%[c]
Soil evaporation compensation factor	ESCO	0.9	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

[a]Detailed descriptions are given in Neitsch et al. (2002).
[b]A 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) land use area.
[c]All CN2 values were reduced by 10% for the final calibrated simulations.
[d]All SOL_AWC values were reduced by 0.02 mm for the final calibrated simulations.

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 the watershed outlet; no changes were made to the calibrated parameters during the 10-year validation simulation. The curve numbers (CN2) were allowed to vary ±10 percent 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 of 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 base flow to occur (GWQMN) and for re-evaporation to occur (REVAPMN) were varied to adjust the amount of groundwater flow.

Scenario Baseline

A scenario baseline, which was assumed to reflect current conditions, was initially executed prior to performing the scenario simulations. 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, because of climatic variations that have occurred between different time periods. Arnell (1996) reviewed 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 the 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 CO_2 (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 because of changes in CO_2 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 CO_2 concentrations on plant growth, or (2) simulating temperature and/or precipitation changes that serve as a proxy for assumed (but not simulated) increases in CO_2 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 CO_2 emissions and changes in climatic inputs can be simulated simultaneously in SWAT, which was the approach used for Scenario 8.

Many analyses of potential climate change impacts on hydrology and water resources have relied on one of two standard CO_2 emission scenarios. The first emission scenario simply assumes that CO_2 concentrations could double in the near future, as described by Rosenberg et al. (1999). The second scenario assumes that a transient

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

Scenario	Climate Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	CO_2 (ppm)	2×	2×	2×	2×	2×	2×	2×	2×	2×	2×	2×	2×
2	Temperature (ºC)	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 (ºC)	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 (ºC)	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

Note: Scenarios 1-6 reflect hypothetical changes in CO_2 emissions or climate responses chosen for this study; Scenarios 7 and 8 are based on the climate projection by Giorgi et al. (1998).

increase in greenhouse gas emissions occurs at a rate of 1 percent per year in GCMs (Doherty and Mearns 1999). In this study, Scenario 1 (Table 2) reflects the impact of a direct doubling of CO_2 ($2xCO_2$) concentration from 330 to 660 ppmv. 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 attributable to evapotranspiration changes. However, projected changes in precipitation and temperature associated with the CO_2 increase (regardless of GCM source) could not be accounted for in this scenario.

Climate change scenarios with a temperature increase, and with a precipitation increase and decrease, were also incorporated in this study to examine further 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 the Intergovernmental Panel on Climate Change (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 the National Science Foundation (NSF) (2001), precipitation in much of the Midwest, including the UMRB region, has increased by 10 to 20 percent over the past century. Recent projections with the CGCM1 and HadCM2 (NSF 2001) and the HadCM3 (Hadley Centre 2003) point to continuing trends of increased rainfall through the next century. Similar results have also been reported in other studies (Giorgi et al. 1998; Pan et al. 2001). Two scenarios depicting increased precipitation levels of 10 and 20 percent were incorporated in the study to reflect these projected trends; contrasting scenarios reflecting decreased precipitation levels of 10 and 20 percent 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 five-year present-day scenario representing current atmospheric carbon levels (330 ppvm) and a five-year scenario reflecting 2xCO_2 concentration conditions (660 ppmv) were simulated in the study. The 2xCO_2 climate was assumed to represent future conditions when atmospheric CO_2 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 2xCO_2 concentration of 660 ppvm was also accounted for in Scenario 8 to assess the direct effect of increased CO_2 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, Illinois, 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 overpredicted and some of the low-flow months were underpredicted. 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, Illinois. The predicted flows closely followed the corresponding measured flows, with less overprediction of peak-flow months and less underprediction of low-flow months, as compared with the calibration period. The regression plot for the validation period (Figure 5) again shows good agreement between

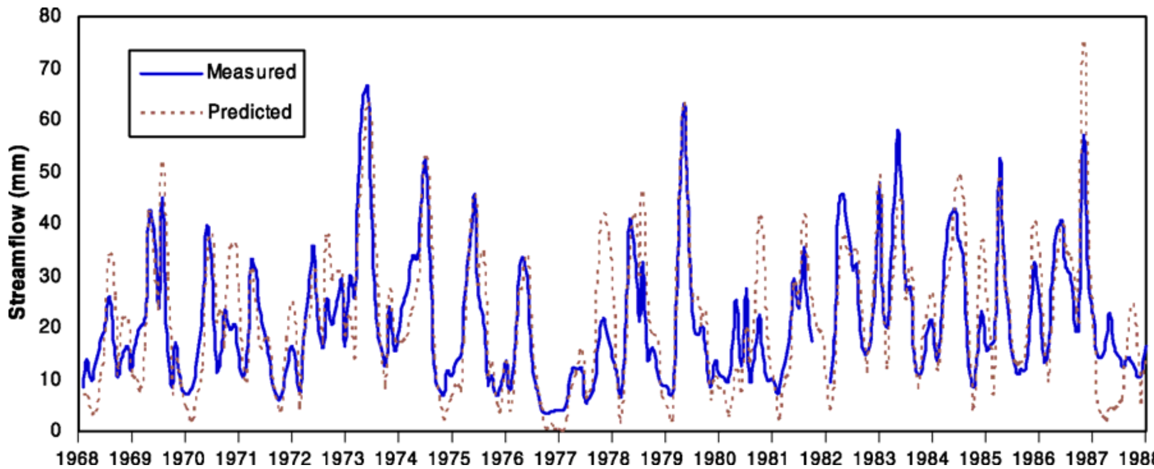

FIGURE 2. Monthly time-series comparison of measured versus predicted streamflow at Grafton, Illinois, during the 20-year calibration period (1968-87)

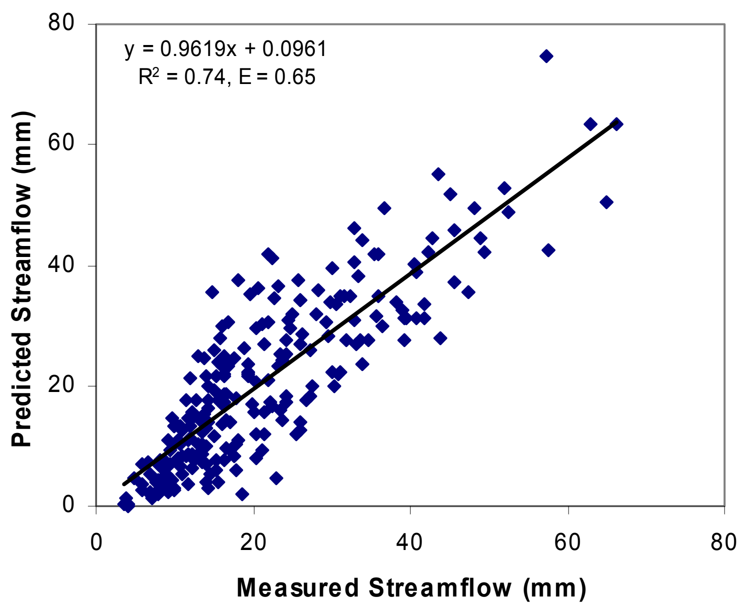

FIGURE 3. Regression plot of predicted versus measured monthly streamflow values for the 20-year calibration period (1968-87)

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

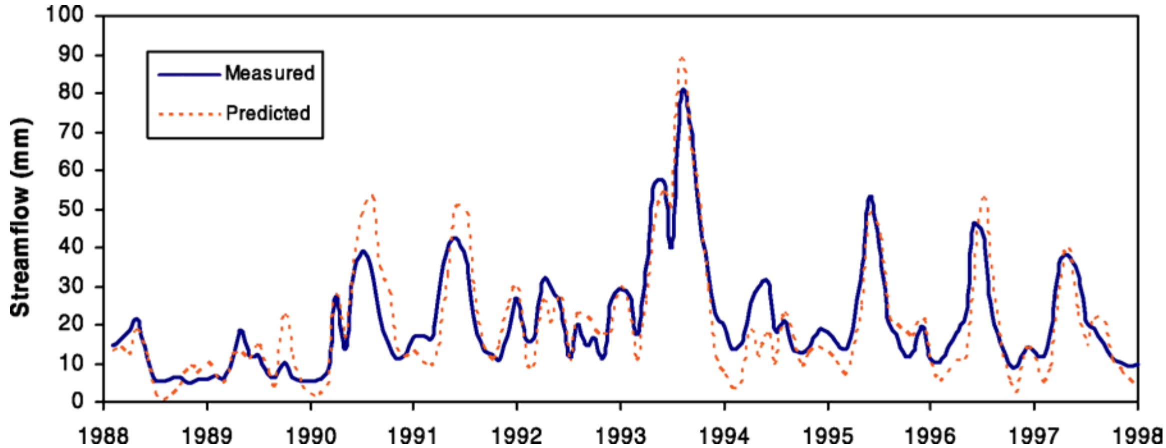

FIGURE 4. Monthly time-series comparison of measured versus predicted streamflows at Grafton, Illinois, during the 10-year validation period (1988-97)

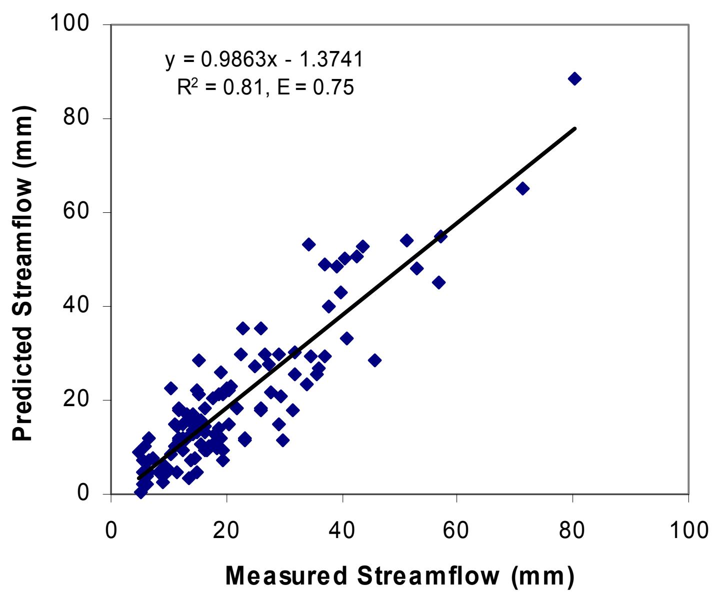

FIGURE 5. Regression plot of predicted versus measured monthly streamflow values for the 10-year validation period (1988-97)

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 percent or less for 9 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 percent. An R^2 of 0.95 was determined between the 12

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 Jorden, 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 Keosaqua/ 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

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.

CO_2, Temperature, and Precipitation Sensitivity Scenarios

Table 5 lists the average monthly streamflows predicted for the UMRB outlet at Grafton, Illinois, 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 illustrate further 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 scenar-ios simulated in previous studies or with results obtained from relevant scenarios

TABLE 4. Average annual hydrologic balance components simulated by SWAT for the Upper Mississippi River Basin baseline and eight climatic scenarios (in mm)

Hydrologic Budget Components	Baseline	Scenario 1	2	3	4	5	6	7	8
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, Illinois, for the eight climate change scenarios

Month	Baseline (mm)	Scenario (% change) 1	2	3	4	5	6	7	8
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

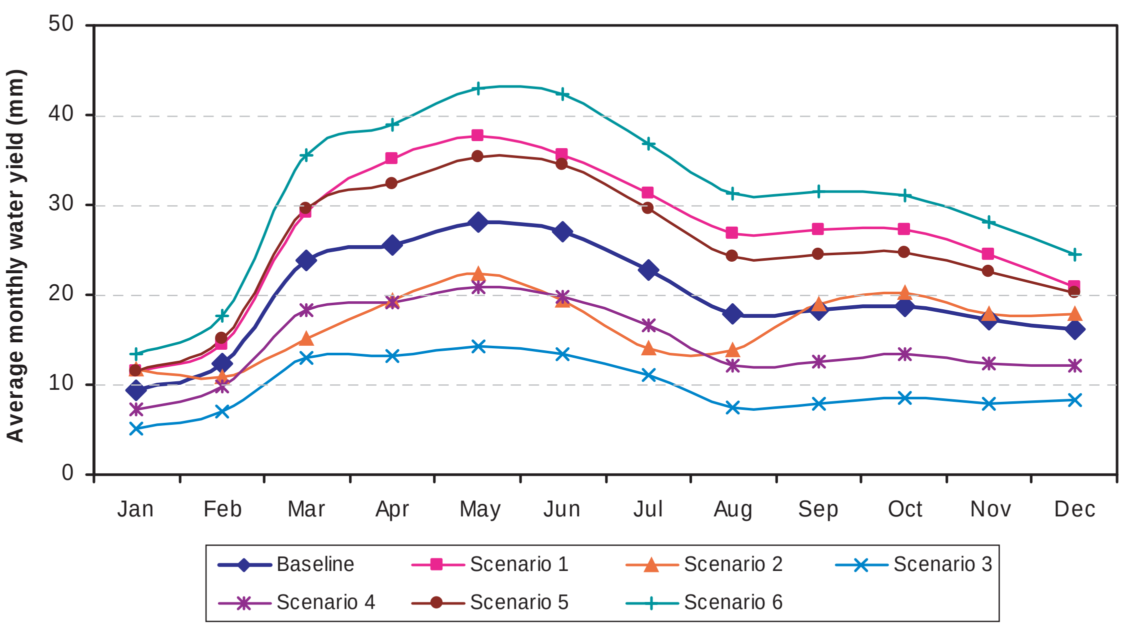

FIGURE 6. Change in average monthly streamflows predicted for Scenarios 1-6 relative to the baseline over the 20-year simulation period

previously performed for the UMRB. These are intended to be primarily qualitative comparisons, because of differences in watershed characteristics and/or climatic scenarios among the studies.

Relative water yield increases ranging from 17 to 51 percent were predicted by SWAT in response to the 2xCO_2 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. Overall, the average annual flow increase was 35 percent over the 20-year period. The magnitude of flow increase found here for the 2xCO_2 scenario was much greater than that reported by Stonefelt, Fontaine, and Hotchkiss (2000), who used SWAT to assess the effects of a 2xCO_2 sensitivity scenario for the 5,000 km^2 Upper Wind River Basin in northwestern Wyoming. They reported only a slight increase of 0.4 percent 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 unaffected by increases in atmospheric CO_2. Klassen (1997) also performed a 2xCO_2 sensitivity analysis with SWAT on the hydrology of the 427 km^2 Spring Creek Watershed, located in the Black Hills of South Dakota. Relative annual flow increases predicted by SWAT in response to the increased CO_2 levels ranged between 4 and 74 percent. 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 CO_2 concentrations. The predicted flow increases are also consistent with expectations, that is, that transpiration will decrease in response to increased CO_2 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 percent (Table 5) during the simulation period. The overall UMRB flow impacts were both greater and similar to results obtained by Stonefelt, Fontaine, and Hotchkiss (2000) and Nash and Gleick (1991), who performed 4°C temperature increase scenarios for hydrologic systems in the western United States that are dominated by snowmelt. Stonefelt, Fontaine, and Hotchkiss found an annual average flow decrease of 7.7 percent for the Upper Wind River Basin, while Nash and Gleick reported average annual flow decreases of 8.7 to 16.5 percent 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 (1994); McCabe and Wolock (1999); Stonefelt, Fontaine, and Hotchkiss (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 in some studies conducted in the western United States, including Stonefelt, Fontaine, and Hotchkiss 2000; Nash and Gleick 1991; Christensen et al. 2003; and van Katwijk, Rango, and Childress (1993). In each case, they showed that the annual peak runoff period that occurs because of 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) shows 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 percent for nine of the twelve months for Scenario 3 (-20 percent precipitation decline). Even greater relative average monthly flow changes were predicted for Scenario 6, which reflected a 20 percent increase in precipitation. The predicted average annual relative flow changes were -51, -27, 28, and 58 percent for Scenarios 3, 4, 5, and 6 (Table 5). A regression analysis of the flow responses for the four scenarios with a precipitation decrease and increase resulted in a slope of 2.6, indicating that a unit increase in precipitation produced a 2.6 percent 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, Fontaine, and Hotchkiss (2000) and Boorman and Sefton (1997) both report results of +10 and -10 percent precipitation change scenarios for the Upper Wind River Basin and three United Kingdom watersheds ranging in size from 86 to 117 km^2, respectively. Mean annual runoff impacts were predicted to range from about +16 to -15 percent 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 percent for a 20 percent decline in precipitation (Scenario 3) was considerably higher than the 29 percent 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 percent 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 percent in summer to -33 percent in spring. Thomson et al. also report that a strong El Niño climate pattern was predicted to result in increased water yields ranging from 37 percent in summer to 62 percent 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 essentially is the opposite of what Thomson et al. found. The Los Niños scenarios simulated by Thomson et al. 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 CO_2 (for Scenario 8), that were derived

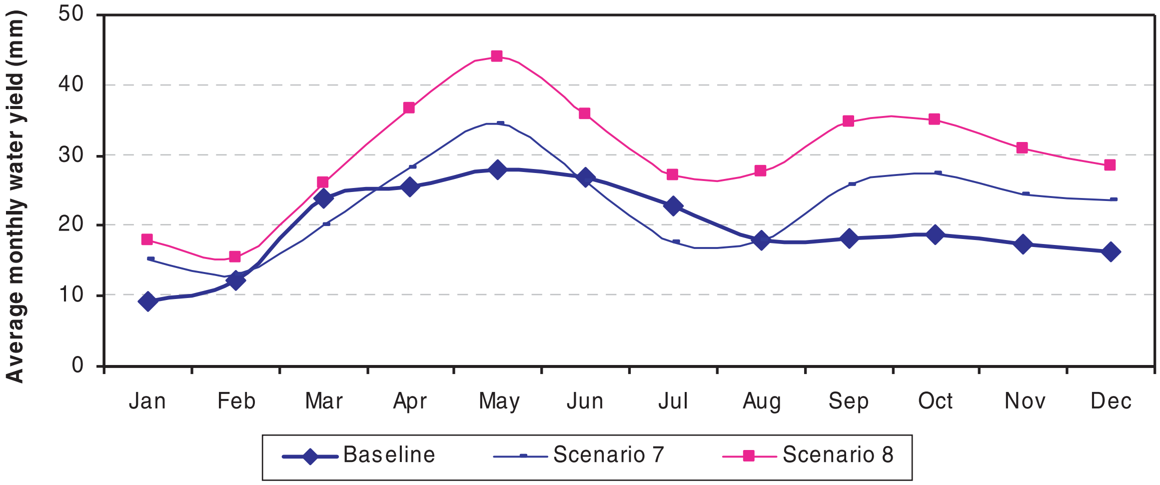

FIGURE 7. Change in average monthly streamflows predicted for Scenarios 7 and 8 relative to the baseline over the 20-year simulation period

from the projections reported by Giorgi et al. (1998). Incorporation of the CO_2 concentrations of 660 ppvm for Scenario 8 resulted in a large increase in predicted future flows compared with 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 percent for Scenario 7 and 10 to 92 percent greater for Scenario 8 (Table 5). Overall, the annual average flows at Grafton were estimated to increase by 15 and 52 percent (Table 5) in response to the climate perturbations embedded in Scenarios 7 and 8, respectively.

The Scenario 7 results were comparable to the 2030 outcomes reported by Rosenberg et al. (2003) that the average annual UMRB water yields predicted by SWAT would increase by 11 and 16 percent, respectively, in response to downscaled HadCM2 inputs with and without a CO_2 concentration level of 560 ppmv. The corresponding flow increases reported by Rosenberg et al. for 2095 were 48 and 53 percent, 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. for most months of the year. The Scenario 8 results were also similar to the 50 percent UMRB flow increase reported by Jha et al. (2003b) for 2040-2049 that were also predicted via downscaled HadCM2 inputs into SWAT. However, no direct accounting of the CO_2 concentrations (assumed to be 480 ppmv) was included in the simulations performed by Jha et al. (2003b) Mirror opposite shifts of -22 and +22 percent 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 percent for the UMRB (Wolock and McCabe 1999); 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. (2003) and Jha et al. (2003b), while the CGCM1 results were radically different from any results reported here or in the literature. Similar results of this and other studies as discussed here can only be viewed as anecdotal comparisons, because of the 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 percent within the next century.

Figures 8 through 10 show the spatial distribution of UMRB streamflows predicted by SWAT as a function of eight-digit watersheds for the scenario baseline, Scenario 7, and Scenario 8, respectively. A comparison of 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 CO_2 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 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 CO_2 fertilization shifts would have a much greater impact on future flow changes, as compared with 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.

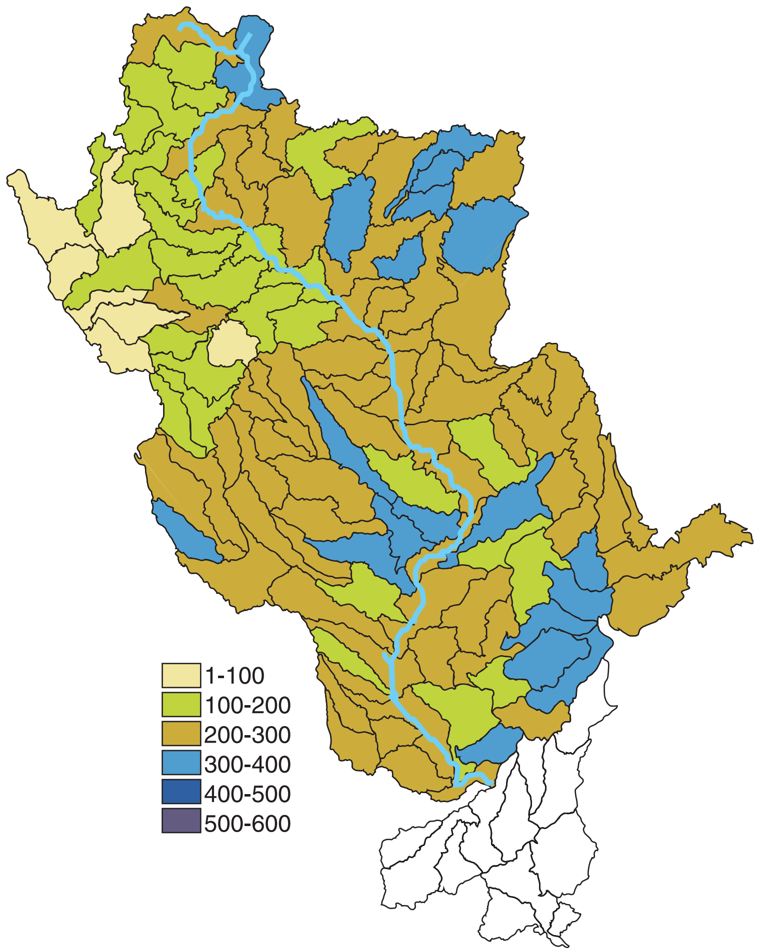

FIGURE 8. Spatial distribution of predicted streamflows for the Upper Mississippi River Basin baseline scenario, shown as a function of eight-digit watersheds

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

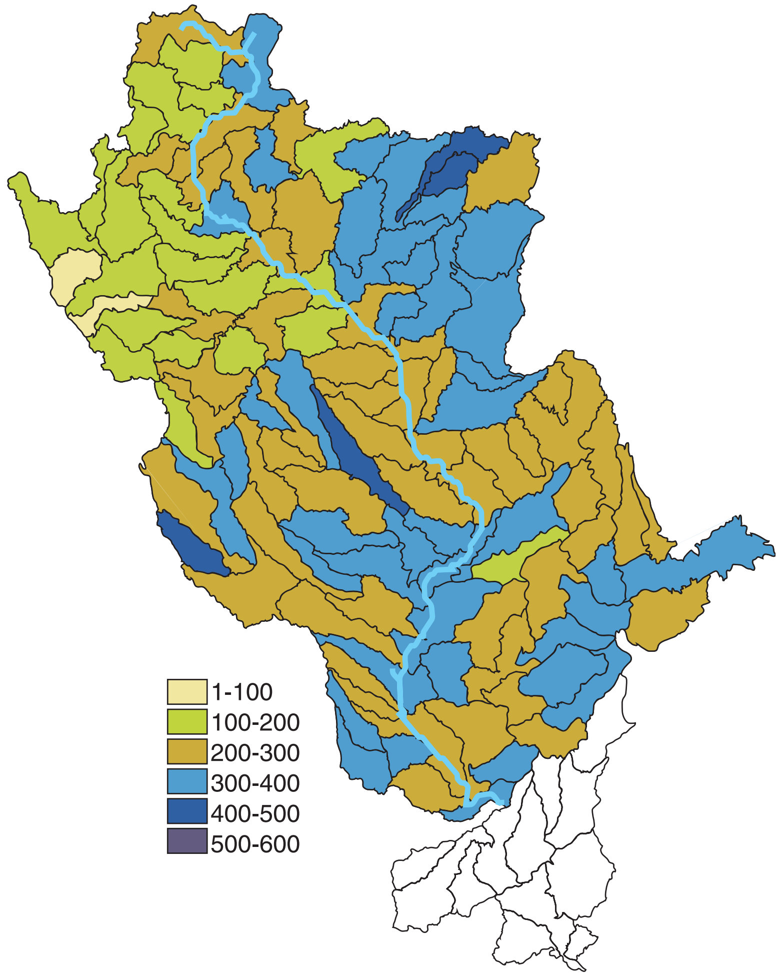

FIGURE 9. Spatial distribution of predicted streamflows for the Upper Mississippi River Basin Scenario 7, shown as a function of eight-digit watersheds

forecast. Wolock and McCabe (1999) 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 predicts 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 URMB hydrology by simulating the same down-

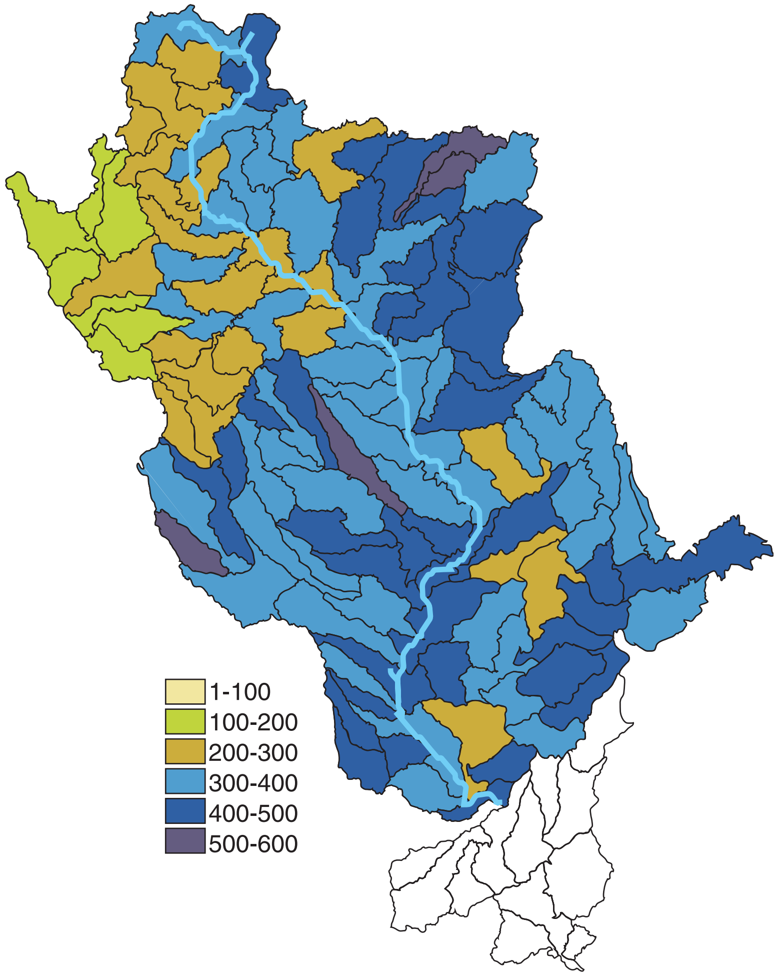

FIGURE 10. Spatial distribution of predicted streamflows for the Upper Mississippi River Basin Scenario 8, shown as a function of eight-digit watersheds

scaled 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 the 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 climates on URMB hydrology.

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