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CLIMATE CHANGE SENSITIVITY ASSESSMENT ON UPPER MISSISSIPPI RIVER BASIN STREAMFLOWS USING SWAT[1]

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ABSTRACT: The Soil and Water Assessment Tool (SWAT) model was used to assess the effects of potential future climate change on the hydrology of the Upper Mississippi River Basin (UMRB). Calibration and validation of SWAT were performed using monthly stream flows for 1968-1987 and 1988-1997, respectively. The R^2 and Nash-Sutcliffe simulation efficiency values computed for the monthly comparisons were 0.74 and 0.69 for the calibration period and 0.82 and 0.81 for the validation period. The effects of nine 30-year (1968 to 1997) sensitivity runs and six climate change scenarios were then analyzed, relative to a scenario baseline. A doubling of atmospheric CO_2 to 660 ppmv (while holding other climate variables constant) resulted in a 36 percent increase in average annual streamflow while average annual flow changes of -49, -26, 28, and 58 percent were predicted for precipitation change scenarios of -20, -10, 10, and 20 percent, respectively. Mean annual streamflow changes of 51, 10, 2, -6, 38, and 27 percent were predicted by SWAT in response to climate change projections generated from the CISRO-RegCM2, CCC, CCSR, CISRO-Mk2, GFDL, and HadCM3 general circulation model scenarios. High seasonal variability was also predicted within individual climate change scenarios and large variability was indicated between scenarios within specific months. Overall, the climate change scenarios reveal a large degree of uncertainty in current climate change forecasts for the region. The results also indicate that the simulated UMRB hydrology is very sensitive to current forecasted future climate changes.
(KEY TERMS: climate change; general circulation model (GCM); simulation; hydrologic cycle, streamflow; Soil and Water Assessment Tool (SWAT)).

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INTRODUCTION

Many coupled atmospheric ocean general circulation model (AOGCM) 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 (Houghton *et al.,* 2001). Changes in precipitation are more speculative than temperature projections, especially for smaller regions. Although the regional distribution is uncertain, precipitation is generally expected to increase worldwide, especially in higher latitudes (Houghton *et al.,* 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. Numerous studies (e.g., Saxe *et al.,* 1998; Wullschleger *et al.,* 2002b)

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have found that vegetative characteristics such as stomatal conductance and leaf area have also been found to change as a result of elevated CO_2 concentrations, which in turn impact the rate of potential evapotranspiration.

These projected effects of potential future climate change would have significant impacts on many hydrologic systems. 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). Numerous studies have been conducted at scales ranging from small watersheds to the entire globe to assess the impacts of climate change on hydrologic systems. Arnell *et al.* (2001) list nearly 80 studies published in the late 1990s in which climate change impacts for one or more watersheds were analyzed using a coupled climate model hydrologic model approach. These studies represented various subregions of the six inhabited continents; over half of the studies were performed for watersheds in Europe. Studies in the U.S. 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 portion of the U.S. including all or portions of the Colorado River Basin (Nash and Gleick, 1991; Gleick and Chaleki, 1999; Wilby *et al.,* 1999; Wolock and McCabe, 1999; Rosenberg *et al.,* 2003; Christensen *et al.,* 2004; Barnett *et al.,* 2004), Columbia River Basin (Hamlet and Lettenmaier, 1999; Lettenmaier *et al.,* 1999; Wolock and McCabe, 1999; Miles *et al.,* 2000; Mote *et al.,* 2003; Rosenberg *et al.,* 2003; Payne *et al.,* 2004; Barnett *et al.,* 2004), and Missouri River Basin (Revelle and Waggoner, 1983; Frederick, 1993; Fontaine *et al.,* 2001; Hubbard, 1998; Lettenmaier *et al.,* 1999; Wolock and McCabe, 1999; Stonefelt *et al.,* 2000; Stone *et al.,* 2001; Stone *et al.,* 2003; Rosenberg *et al.,* 2003).

Comparatively few studies have been performed for the Upper Mississippi River Basin (UMRB) region. According to the U.S. Geological Survey (USGS, 1999), the UMRB is very sensitive to climate change due to 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 (USGS, 1999) and streams (Knox, 2002) in the region. The stream sediment data indicate that extreme floods are especially sensitive to climatic change. Shifts in precipitation and other climatic conditions in the UMRB region could also have major environmental consequences. Nitrate loads discharged from the mouth of the Mississippi River have been implicated as the primary cause of the Gulf of Mexico seasonal oxygen depleted hypoxic zone, which covered nearly 20,000 km^2 in 1999 (Rabalais *et al.,* 2002). Goolsby *et al.* (2001) estimated that 35 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 UMRB have been performed within the context of larger national or regional studies. Frederick (1993) conducted an assessment of the effects of an analog "dust bowl" climate (1931 to 1940), 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. Wolock and McCabe (1999) performed a national assessment of projected future climate trends on the hydrology of 18 U.S. major water resource regions by linking a simple water-balance model to two different AOGCMs: the Canadian Centre for Climate Modelling and Analysis CGCM1 model (Flato *et al.,* 2000) and the Hadley Centre for Climate Prediction and Research HadCM2 model (Johns *et al.,* 1997). 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). In contrast to these studies, Jha *et al.* (2004) concentrated on analyzing the hydrologic effects of potential future climate change for just the UMRB. Climate projections for the study were generated for years 2040 to 2049 by downscaling a HadCM2 climate scenario with a regional climate model (RegCM2) developed by Giorgi *et al.* (1993).

This study builds on previous UMRB studies by using SWAT to assess the impacts of simple sensitivity scenarios and a suite of climate change scenarios on the hydrologic responses of the UMRB. The climate sensitivity assessment is similar to the approach used by Stonefelt *et al.* (2000) and includes temperature, precipitation, and/or atmospheric CO_2 sensitivity scenarios. Actual assessments of potential future climate changes cannot be performed via sensitivity change scenarios. However, Arnell *et al.* (2001, p. 203) state that such scenarios do "provide extremely valuable insights into the sensitivity of hydrological systems to changes in climate." Wolock and McCabe (1999) further state that sensitivity studies of temperature and precipitation variations can provide important insight regarding the responses and vulnerabilities of different hydrologic systems to climate change, especially when there is a great deal of uncertainty between available AOGCM projections. The climate change scenarios are based on monthly projections for a single downscaled climate scenario reported by Giorgi *et al.* (1998) and five AOGCM simulations performed for the A2 "Differentiated World" scenario that is described in Carter *et al.* (2001). These six scenarios represent a range of future temperature and precipitation projections for the UMRB region that provide important insight regarding the sensitivity of the UMRB stream system to future climate change.

The specific objectives of this study are to: (1) calibrate and validate the SWAT hydrologic component over a 30-year period (1968 to 1997) by using historical climate data and comparing simulated output with observed streamflows measured at a gauge located near Grafton, Illinois; and (2) estimate fluctuations in UMRB seasonal and average annual streamflows with SWAT in response to nine climate sensitivity scenarios and six climate change scenarios.

MODEL DESCRIPTION

A brief description of the SWAT model is provided here, with an emphasis on model functions that are focused on reflecting the impacts of climate change. Detailed descriptions of the different model components can be found in Arnold *et al.* (1998) and Neitsch *et al.* (2002a).

The SWAT model is a conceptual, physically-based, long term continuous watershed scale simulation model. The model is capable of simulating a high level of spatial detail by allowing the division of a watershed into a large number of subwatersheds. In SWAT, a watershed is divided into multiple subwatersheds that are then further subdivided into unique soil/land-use characteristics called hydrologic response units (HRUs). Flow generation, sediment yield, and nonpoint source loadings are summed across all HRUs in a subwatershed, and the resulting loads are then routed through channels, ponds, and/or reservoirs to the watershed outlet. The model integrates functionalities of several other models, allowing for the simulation of climate, hydrology, plant growth, erosion, nutrient transport and transformation, pesticide transport, and management practices. Previous applications of SWAT for flow and/or pollutant loadings have compared favorably with measured data for a variety of watershed scales (e.g., Rosenthal *et al.,* 1995; Arnold and Allen, 1996; Srinivasan *et al.,* 1998; Arnold *et al.,* 1999; Saleh *et al.,* 2000; Santhi *et al.,* 2001).

Climate change impacts are simulated directly in SWAT by accounting for the effects of increased CO_2 on plant development and evapotranspiration (Neitsch *et al.,* 2002a). 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. Conversion of intercepted light into biomass is simulated assuming a plant species specific radiation use efficiency (RUE). The RUE quantifies the efficiency of a plant in converting light energy into biomass and is assumed to be independent of the plant's growth stage. The RUE values are adjusted in SWAT as a function of CO_2 concentrations in the range of 330 to 660 parts per million by volume (ppmv), following the approach developed by Stockle *et al.* (1992). The effect of increasing vapor pressure deficit, which can result in decreased RUE, is factored into the RUE adjustment.

Three options are provided in SWAT to simulate 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, again in the range of 330 to 660 ppmv. Initially, the impact of CO_2 on leaf stomatal conductance is computed following the modification used by Easterling *et al.* (1992), which assumes a 40 percent reduction in leaf conductance at an atmospheric CO_2 concentration of 660 ppmv, as found by Morison and Gifford (1983). The impact of elevated CO_2 on transpiration is then further accounted for by simulating the effect of vapor pressure deficit on leaf stomatal conductance, based on the approach used by Stockle *et al.* (1992).

Implications of SWAT CO_2 Assumptions

The assumption that higher atmospheric CO_2 concentrations will result in reduced leaf stomatal conductance has been confirmed across numerous experimental and review studies conducted for a wide variety of vegetative species (e.g., Morison and Gifford, 1983; Morison, 1987; Hendry *et al.,* 1993; Tyree and Alexander, 1993; Field *et al.,* 1995; Saxe *et al.,* 1998; Wand *et al.,* 1999; Medlyn *et al.,* 2001; Wullschleger *et al.,* 2002b). However, Wullschleger *et al.* (2002b) point out that there is a broad range of stomatal conductance responses between different plant species in response to elevated CO_2 levels. Leaf stomatal conductance reductions ranging from 27 to 40 percent have been measured for herbaceous plant species for elevated CO_2 environments (Morison and Gifford, 1983; Morison, 1987; Field *et al.,* 1995), but lower or no impacts have been found for different tree species (Saxe *et al.,* 1998; Wullschleger *et al.,* 2002a,b). In addition, it has been found that the total leaf area of different plant types can increase in response to increasing levels of atmospheric CO_2 (e.g., Wand *et al.,* 1999; Pritchard *et al.,* 1999; Saxe *et al.,* 1998), which potentially can offset the effect of stomatal conductance reduction. Eckhardt and Ulbrich (2003) have directly addressed variable stomatal conductance and leaf area responses by incorporating different stomatal conductance decline factors and leaf area index (LAI) values, as a function of five main vegetation types, into a modified version of SWAT, but such an approach has not yet been adopted for the standard version of SWAT used here.

Other research has further indicated that the effects of CO_2 measured at the leaf or plant level may be reduced or negated at the broader field or regional levels, due to a number of different factors (Jarvis and McNaughton, 1991; Polley *et al.,* 2002; Wullschleger *et al.,* 2002a). However, Kimball *et al.* (1999) and Wullschleger *et al.* (2002b) describe or cite other results that show that regional impacts can be expected to occur, at least for some plant species and environmental conditions. For the present study, it can be expected that the current approach used in SWAT will result in decreased evapotranspiration rates and subsequent increases in streamflows across the UMRB. Previous applications of the standard SWAT model focused solely on evaluating the effects of a doubled atmospheric CO_2 concentration report a wide range of impacts on average annual streamflow, including 0.4 percent for the 5,000 km^2 Upper Wind River Basin in northwestern Wyoming (Stonefelt *et al.,* 2000), 16 percent for 427 km^2 Spring Creek Watershed located in the Black Hills of South Dakota (Fontaine *et al.,* 2001), and 13 to 38 percent for five major subwatersheds of the Missouri River Watershed (Chen, 2001).

INPUT DATA

The UMRB is located in the north central United States (Figure 1). The UMRB extends from the source of the river at Lake Itasca in Minnesota to a point just north of Cairo, Illinois. The entire UMRB covers

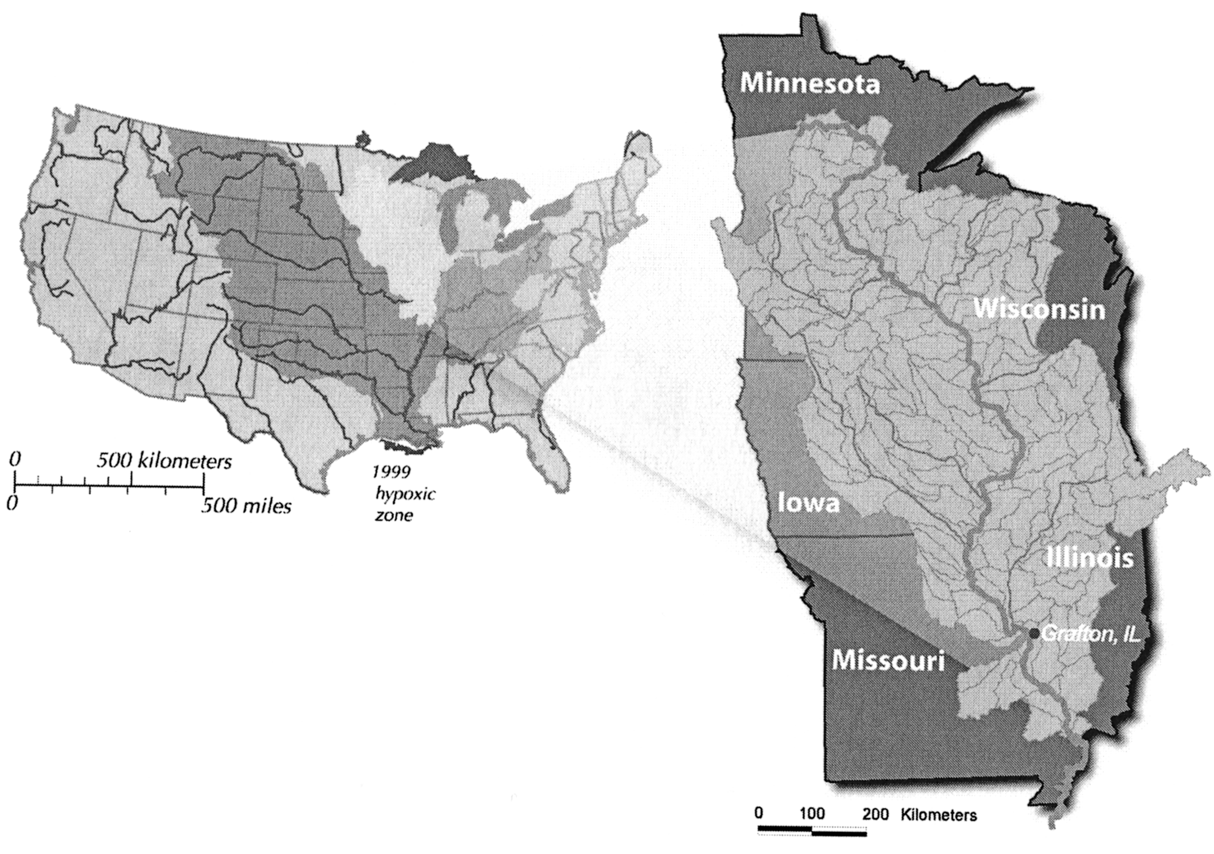

Figure 1. Location of Grafton, Illinois, and the 131 USGS 8-Digit Watersheds Within the Upper Mississippi River Basin (UMRB), and the Location of the UMRB Within the Mississippi River Basin.

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

The management operations were based on default assumptions provided 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, and the management assumptions have only minor impact on the SWAT hydrologic estimates.

Climate data required by the model are daily precipitation, maximum/minimum air temperature, solar radiation, wind speed and relative humidity. These daily climatic inputs can be entered from historical records, and/or generated internally in the model using monthly climate statistics that are based on long-term weather records. In this study, historical precipitation and temperature records for the UMRB were obtained for 111 weather stations located in and around of the watershed (C. Santhi, personal communication, Blacklands Research and Extension Laboratory, Temple, Texas, 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 DEM data. USGS stream network data obtained from USEPA (2001) were 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 to the USGS referenced stream network. Similarly, the subwatershed outlets were also adjusted so that the subwatershed boundaries were as consistent as possible with the boundaries of 8-digit hydrologic cataloging units watersheds as defined by the USGS (Seaber *et al.,* 1987). A total of 119 subwatersheds were delineated up to the point just before the confluence of the Missouri River into the Mississippi River (i.e., Mississippi river at Grafton, Illinois). This point constitutes a drainage area of 447,500 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 UMRB hydrology. The following model options were used for all of the UMRB simulations performed in both phases: curve number (CN) method for the partitioning of precipitation between surface runoff and infiltration, Muskingum method for channel routing, and modified 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, Illinois (Station No. 05587450) (NWIS, 2001). 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 values are close to zero, and the E values are less than or close to zero, then the model prediction is unacceptable. If the values equal one, the model predictions are considered perfect.

The selection of parameters for the streamflow calibration and the final calibrated values of those parameters (Table 1) were based on guidelines given in Neitsch *et al.* (2002b) or on previous SWAT streamflow calibration results reported by Santhi *et al.* (2001) and Jha *et al.* (2003). Detailed descriptions of each of the calibration parameters are provided in Neitsch *et al.* (2002a). The initial values of each calibration parameter were generated by AVSWAT (Table 1). The parameters were then allowed to vary during the calibration process within suggested ranges across the basin until an acceptable fit between the measured and simulated values was obtained at watershed outlet. No changes were made to the calibrated parameters during the 10-year validation simulation.

Scenario Baseline

A scenario baseline, assumed to reflect current conditions, was executed prior to performing the sensitivity and climate 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, due to climatic variations that have occurred between different time periods. Arnell (1996) summarized simulation periods used in several hydrological climate change impact studies and found that a 30-year period from 1951 to 1980 (or shorter) was assumed for many climate change studies to define baseline conditions. Thus, the 30-year period from 1968 to 1997, which was used for the calibration and validation phase, was selected to represent baseline conditions for this study. An atmospheric CO_2 concentration of 330 ppmv was assumed for the baseline scenario.

Climate Sensitivity Runs

A complete depiction of climate change consists of two components: emission of CO_2 (and potentially other greenhouse gases) and a corresponding climate response. The emission component reflects the concentration of greenhouse gases in the atmosphere at any given time while the climate response portion defines the changes in climate that occur due to changes in CO_2 concentrations. The impacts of these two climate change components on watershed hydrology can be simulated simultaneously in SWAT or accounted for separately by simulating only the effect of an increase in atmospheric CO_2 concentrations on plant growth and evapotranspiration, or simulating temperature, precipitation and/or other climatic changes that serve as a proxy for assumed (but not simulated) increases in CO_2 concentrations. Decoupling of the atmospheric CO_2 effects from the climatic inputs facilitates sensitivity analyses of different climate change influences on hydrologic responses; thus

TABLE 1. Hydrologic Calibration Parameters and Their Values for the UMRB.

Calibration Parameter[a]	Symbol	Guidelines[b]	Initial Estimates	Calibrated Values
Curve Number for Moisture Condition II	CN2	±10%	–[c]	-10%
Soil Evaporation Compensation Factor	ESCO	0.0-1.00	0.95	0.75
Soil Available Water Capacity (mm)	SOL_AWC	±0.04	–[d]	- 0.02
Ground Water Revap Coefficient	GW_REVAP	max.: 0.2	0.02	0.02
Ground Water Delay Time (day)	GW_DELAY	–	31	20
Surface Runoff Lag Coefficient	SURLAG	–	4	2

[a]Detailed descriptions are given in Neitsch *et al.* (2002b).
[b]CN2 and ESCO guidelines are given in Santhi *et al.* (2001); SOL_AWC and GW_REVAP guidelines are given in Neitsch *et al.* (2002b); GW_DELAY and SURLAG calibration based on results reported by Jha *et al.* (2003).
[c]A range of values was used for CN2; e.g., 67, 77, 83, and 87 were the original CN2 values selected by AVSWAT for the agricultural (AGRL) land-use area for soil hydrologic group A, B, C, and D, respectively.
[d]A range of values was used for the SOL_AWC based on guidance given by USDA (1994).

the two CO_2 sensitivity runs reported here were executed independently of other climatic changes while the remaining sensitivity runs were performed without any changes in CO_2 levels.

Table 2 lists the nine primary climate sensitivity simulations that were performed for this study. The first two sensitivity runs focused on multiplying the baseline daily atmospheric CO_2 level of 330 ppmv by factors of 1.5 and 2.0, which follows the direct CO_2 doubling ($2xCO_2$) approach described by Rosenberg *et al.* (1999) and are within the range of atmospheric concentration projections for the second half of the twenty-first century (Carter *et al.,* 2001). Sensitivity Runs 3 to 5 depict daily increases of 2, 4, and 6°C to the maximum and minimum temperatures simulated in the 30-year baseline run. These temperature sensitivity simulations reflect the trends of increased global temperatures forecast by current AOGCMs (Houghton *et al.,* 2001). Sensitivity Runs 6 to 9 represent adjustments of -20, -10, 10, and 20 percent to the daily precipitation amounts incorporated in the baseline scenario. The 10 and 20 percent sensitivity runs reflect trends reported by the National Science Foundation (NSF, 2001) that precipitation in much of the Midwest including the UMRB region has increased by 10 to 20 percent over the past century, and recent projections by some AOGCMs that point to continuing trends of increased rainfall in the region across the next century (NSF, 2001: Hadley Centre, 2003; Giorgi *et al.,* 1998; Pan *et al.,* 2001). However, the contrasting scenarios of 10 and 20 percent precipitation decreases were also simulated because some AOGCM $2xCO_2$ climate projections point to the potential for decreased precipitation in the region, at least over much of the year (e.g., RO-Mk2 projection described below). Four other sensitivity runs were attempted (not shown in Table 2) that included three variations of solar radiation levels (-10 percent, +10 percent, and +15 langleys) and one relative humidity sensitivity simulation (+5 percent). The impacts of these four additional simulations were mostly minor as described in the Results and Discussion section.

Climate Change Scenarios

The monthly precipitation and temperature fluctuations simulated for the six climate change scenarios are listed in Table 3. The CSIRO-RegCM2 scenario was based on a future climate projection reported by Giorgi *et al.* (1998) that was generated for the Missouri-Iowa-Nebraska-Kansas (MINK) region by nesting RegCM2 within the Australian Commonwealth Scientific and Industrial Research Organization (CSIRO) AOGCM, described by Watterson *et al.* (1995). A five-year scenario reflecting $2xCO_2$ concentration conditions (660 ppmv) was simulated in the study conducted by Giorgi *et al.* (1998); the $2xCO_2$ climate was assumed to represent future conditions and was not referenced to any specific time period. For this study, the average monthly temperature and precipitation changes (Table 3) projected by RegCM2 over the five-year period for the MINK region were assumed to represent potential future UMRB intraseasonal precipitation and temperature shifts over the 30-year SWAT simulation period, in combination with the $2xCO_2$ climate. A second 30-year SWAT CSIRO-RegCM2 scenario was also performed in which the precipitation and temperature projections were interfaced with the baseline atmospheric CO_2 concentration of 330 ppmv, to provide further insight into the sensitivity of SWAT to climatic variations.

TABLE 2. Assumed Changes in Relevant Climate Parameters for the Nine Climate Sensitivity Simulations.

Sensitivity Run	Modified Climate Parameter	Magnitude of Change*	Run ID
1	CO_2 (ppmv)	1.5 x 330	$1.5xCO_2$
2	CO_2 (ppmv)	2.0 x 330	$2.0xCO_2$
3	Temperature (ºC)	+2	+2C
4	Temperature (ºC)	+4	+4C
5	Temperature (ºC)	+6	+6C
6	Precipitation (%)	-20	-20%
7	Precipitation (%)	-10	-10%
8	Precipitation (%)	+10	+10%
9	Precipitation (%)	+20	+20%

*The changes shown here were applied uniformly across each day of the 30-year baseline simulation period (the baseline atmospheric CO_2 concentration was 330 ppmv).

The average monthly precipitation and temperature projections for the other five climate change scenarios (Table 3) were obtained from the Intergovernmental Panel on Climate Change (IPCC) Data Distribution Centre (IPCC, 2005). The five AOGCM models are the Canadian Centre for Climate Modelling and Analysis CCC model (Flato *et al.,* 2000), the Centre for Climate Study Research CCSR model (Emori *et al.,* 1999), the Geophysical Fluid Dynamics Laboratory GFDL model (Delworth *et al.,* 2002), the CSIRO-Mk2 model described by Gordon and O'Farrell (1997), and the Hadley Centre for Climate Prediction and Research HadCM3 model (Johns *et al.,* 2001). The precipitation and temperature projections shown in

TABLE 3. Assumed Changes in Relevant Climate Parameters on a Monthly Basis for Each of the Six AOGCM Climate Change Scenarios.[a]

AOGCM	Climate Parameter	J	F	M	A	M	J	J	A	S	O	N	D
CSIRO-RegCM2[b]	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
CCC[c]	Temperature (ºC)	7.1	8.3	7.2	6.4	5.6	4.8	4.5	3.7	4.8	3.8	2.5	2.2
	Precipitation (%)	-4.0	5.2	8.5	12.1	15.9	-3.2	-18.9	-13.3	-11.5	3.8	1.2	8.4
CCSR[c]	Temperature (ºC)	8.6	8.0	7.8	9.3	7.2	6.7	6.5	7.1	7.6	6.6	7.9	8.7
	Precipitation (%)	13.5	15.9	11.9	9.3	15.5	0.4	10.9	4.8	-6.2	-31.3	-26.8	-7.9
CSIRO-Mk2[c]	Temperature (ºC)	7.3	7.3	6.2	8.0	4.2	4.5	5.9	6.3	5.7	3.8	4.3	6.3
	Precipitation (%)	3.0	28.8	14.2	13.0	15.5	-9.3	-28.9	-32.6	-26.7	-11.2	-3.1	7.0
GFDL[c]	Temperature (ºC)	3.9	4.9	3.5	3.5	2.8	3.0	4.6	4.6	3.2	4.3	3.4	4.1
	Precipitation (%)	16.8	22.8	10.9	15.7	10.1	-1.5	-7.0	-5.2	10.2	7.7	13.8	12.0
HadCM3[c]	Temperature (ºC)	3.6	3.8	3.3	3.6	3.9	5.0	6.0	6.1	5.9	4.6	3.4	3.3
	Precipitation (%)	9.9	21.7	11.5	22.6	17.2	-10.4	-15.6	-10.4	-8.8	21.8	14.7	0.6

[a]An atmospheric CO_2 concentration of 660 ppmv (2xCO_2) was assumed for each scenario.
[b]These projections were averaged over five years as described by Giorgi *et al.* (1998); RegCM2 is a regional model that was nested within the CSIRO AOGCM.
[c]Projections based on 30-year (2061-2090) averages of the A2 scenario, which is described by Carter *et al.* (2001).

Table 3 represent the forecasts of these five models averaged over the 30-year period 2061 to 2090 for the region bounded between latitude 37 to 50˚N and longitude 85 to 98˚W; this 30-year period represented the approximate period in which the 2xCO_2 climate (660 ppmv) was projected to occur. These projections were generated in response to the A2 "Differentiated World" scenario, one of four IPCC scenarios described by Carter *et al.* (2001). The average monthly precipitation and temperature fluctuations were then again used to simulate future UMRB hydrologic impacts in SWAT for the 30-year simulation period.

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 through 87) calibration period. In general, SWAT accurately tracked the measured streamflows for the time period, although some peak flow months were overpredicted and many of the low flow months were underpredicted. The time series comparison of predicted and measured cumulative monthly streamflows for the 10-year (1988 through1997) validation period is shown in Figure 3, 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 to the calibration period. Daily, monthly, and annual flow statistics computed for the calibration and validation periods (Table 4) also show a strong correlation between the simulated and measured flows. The validation period statistics were stronger than those computed for the calibration period (e.g., monthly validation R^2 and E values of 0.82 and 0.81 versus corresponding values of 0.74 and 0.69 for the calibration period). A positive bias was found for all of the predicted streamflows, which was over 6 percent for the calibration period and under 4 percent for the validation period. Regression lines plotted between the simulated and measured monthly values reveal that this overprediction occurred primarily for lower flows (Figure 4).

Comparisons between measured and predicted annual average streamflows for 1968 to 1997 for the Mississippi River at Grafton and 11 upstream subwatersheds were also conducted (Table 5), to provide an additional assessment of how well SWAT tracked flows throughout the UMRB. No calibration was performed for the streamflow estimates for the 11 upstream subwatersheds. The differences between the predicted and measured annual average streamflows were 13 percent or less for 8 of the 12 watersheds. The largest error occurred for the station near

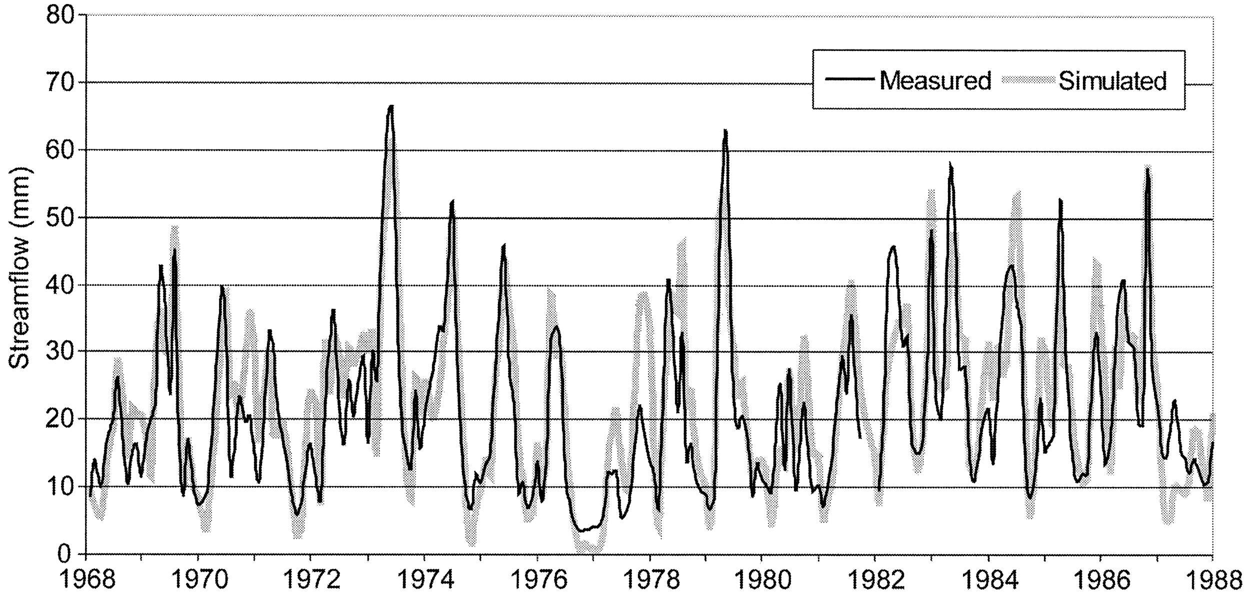

Figure 2. Monthly Time Series Comparison of Measured Versus Predicted Streamflow at Grafton, Illinois, During the 20-Year Calibration Period (1968-1987).

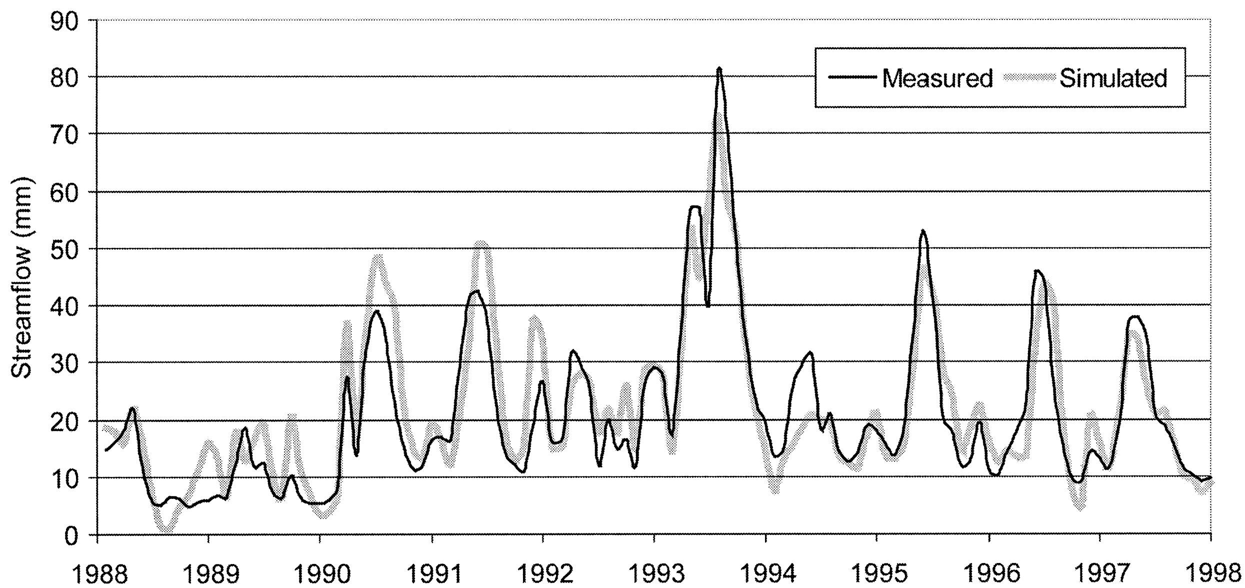

Figure 3. Monthly Time Series Comparison of Measured Versus Predicted Streamflow at Grafton, Illinois, During the 10-Year Validation Period (1988-1997).

Wapello, Iowa; the streamflows for this subwatershed were underpredicted by about 21 percent. An R^2 of 0.66 was determined between the 12 simulated average annual flows and corresponding measured flows, indicating that the model captured the average annual flow trends 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, average annual hydrologic budgets were computed for the scenario baseline and the nine sensitivity runs (Table 6) for the 30-year simulation period of 1968 to 1997. The shifts in the predicted hydrologic budget components between the baseline and the scenarios exhibit expected patterns including: (1) decreased evapotranspiration and subsequent increased surface runoff and ground water flow for

TABLE 4. Evaluation Statistics for the Simulated UMRB Streamflows at Grafton, Illinois.

Streamflow Comparison	Calibration Period (1968-1987) R^2	E	Bias (percent)	Validation Period (1988-1997) R^2	E	Bias (percent)
Annual	0.82	0.75	6.4	0.91	0.90	3.3
Monthly	0.74	0.69	6.6	0.82	0.81	3.9
Daily	0.67	0.58	6.5	0.75	0.65	3.9

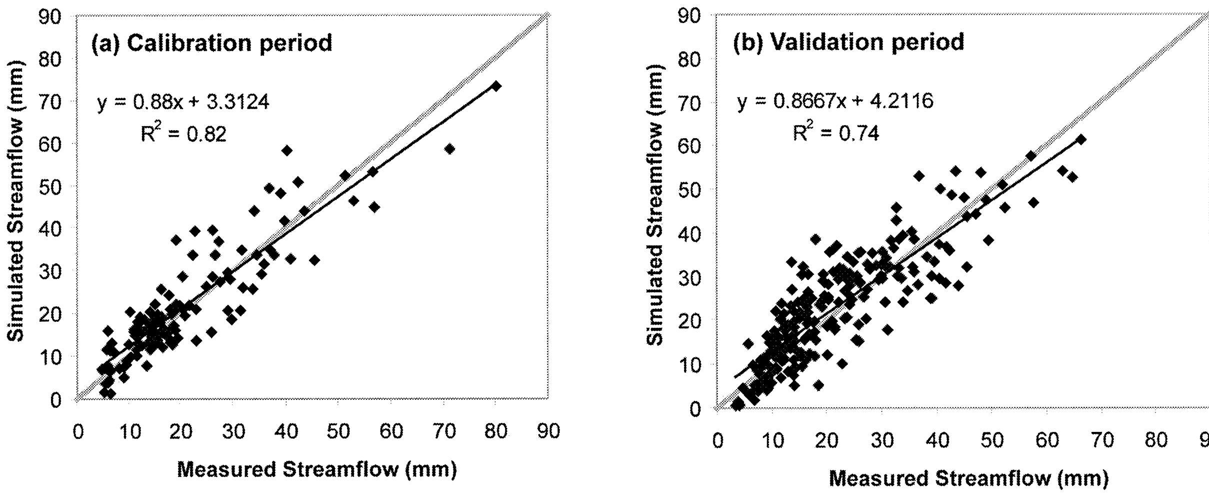

Figure 4. Regression Plots of Measured Versus Simulated Monthly Streamflows Relative to 1:1 Lines for the (a) Calibration Period (1968-1987), and (b) Validation Period (1988-1997).

TABLE 5. Comparisons Between Measured and Simulated Annual Average Streamflows During 1968 to 1997 (30 years) for the Mississippi River at Grafton, Illinois, and 11 Upstream Subwatersheds.

USGS Station Name	USGS Station No.	Drainage Area (km^2)	Measured Flow (mm)	Simulated Flow (mm)	Bias (percent)
Mississippi River near Royalton, Minnesota	05267000	30,175	168	196	17
Minnesota River near Jorden, Minnesota	05330000	43,715	121	129	11
St. Croix River at St Croix Falls, Wisconsin	05340500	20,030	227	180	-20
Chippewa River at Durand, Wisconsin	05369500	24,722	319	277	-8
Wisconsin River at Muscoda, Wisconsin	05407000	28,926	310	225	-17
Rock River near Joslin, Illinois	05446500	25,401	270	264	0.5
Iowa River at Wapello, Iowa	05465500	32,796	268	210	-21
Skunk River at Augusta, Iowa	05474000	11,246	252	283	13
Des Moines River at Keosaqua/St Francis, Iowa	05490500	37,496	207	215	7
Illinois River at Valley City, Illinois	05586100	74,603	332	282	-8
Maquoketa River at Maquoketa, Iowa	05418500	4,827	271	232	3
Mississippi River at Grafton, Illinois	05587450	447,539	253	236	-8

higher CO_2 concentrations; (2) increased evapotranspiration and decreased snowmelt, surface runoff, and ground water flow in response to increased temperatures; and (3) increased evapotranspiration, surface runoff and ground water flows when precipitation is increased (and vice versa for a precipitation decrease). Overall, the hydrologic budgets given in Table 6 confirm that SWAT responded logically to the simulated climatic changes incorporated in the sensitivity runs.

Sensitivity Runs

Table 7 lists the average monthly and average annual streamflows predicted for the UMRB outlet at Grafton, Illinois, for the scenario baseline, the corresponding relative differences in the average monthly streamflows for the nine different sensitivity runs, and the standard deviations of the streamflows that were determined for the baseline and the sensitivity runs. The average monthly streamflows for the

TABLE 6. Average Annual Hydrologic Budget Components Simulated by SWAT for the UMRB Baseline and Nine Climate Sensitivity Simulations.

Hydrologic Budget Components	Baseline (mm)	Climate Sensitivity Simulations								
		1.5xCO_2 (mm)	2xCO_2 (mm)	+2C (mm)	+4C (mm)	+6C (mm)	-20% (mm)	-10% (mm)	+10% (mm)	+20% (mm)
Precipitation	846	846	846	846	846	846	678	762	932	1,016
Snowfall	118	118	118	93	70	52	94	106	129	141
Snowmelt	116	116	116	92	69	51	93	104	127	138
Surface Runoff	92	100	110	79	70	61	47	68	120	150
Base Flow	149	178	217	145	138	131	77	111	188	228
Potential ET	1,180	1,083	949	1,288	1,394	1,503	1,186	1,186	1,184	1,184
Evapotranspiration (ET)	597	560	512	614	631	647	547	575	614	628
Total Water Yield*	235	272	321	219	203	187	120	175	302	371

*Total water yield (streamflow) = surface runoff + base flow – transmission losses; transmission losses are a minor component of the overall hydrologic balance (ranged from 4 to 7 mm).

TABLE 7. Predicted Relative Changes in Total Water Yield for the Mississippi River at Grafton, Illinois, for the Nine Climate Sensitivity Simulations.

Month	Baseline (mm)	1.5xCO_2	2xCO_2	+2C	+4C	+6C	-20%	-10%	+10%	+20%
		Percent Change								
January	11.3	13	28	19	29	30	-44	-22	24	47
February	11.9	9	20	2	-2	-9	-41	-21	21	42
March	22.0	9	20	-24	-38	-47	-45	-24	23	47
April	21.6	14	32	-16	-26	-35	-47	-24	27	55
May	25.9	16	35	-9	-20	-31	-46	-23	27	53
June	27.4	15	34	-12	-26	-41	-48	-25	27	56
July	25.3	17	39	-12	-31	-44	-50	-26	30	61
August	19.6	21	50	-13	-22	-26	-55	-29	34	72
September	17.7	21	51	-3	-2	0	-56	-31	35	74
October	17.8	20	48	3	6	7	-54	-29	32	67
November	18.4	17	41	1	2	0	-52	-28	27	60
December	16.8	15	34	10	12	9	-46	-24	26	52
Average Annual (mm)	235.5	16	36	-7	-14	-21	-49	-26	28	58
Monthly Standard Deviation	5.1	6.0	7.2	3.6	2.8	2.7	2.7	3.9	6.7	8.3

baseline and the sensitivity runs are also plotted in Figure 5 to further illustrate the predicted seasonal effects of the assumed climate changes on the Mississippi flows at Grafton.

Relative water yield increases ranging from 9 to 21 percent and 20 to 51 percent were predicted by SWAT in response to the $1.5xCO_2$ and $2xCO_2$ sensitivity runs, respectively, with the greatest increases occurring between July and November (Table 7). The trends shown in Figure 5 indicate that the flow increase magnitudes were relatively consistent outside of the winter months of December through February for both CO_2 change simulations. Overall, the average annual streamflow increases were 16 and 36 percent for the two CO_2 sensitivity runs (Table 7) over the 30-year simulation period. The corresponding standard deviations were determined to be 6.0 and 7.2, indicating greater variability occurred within the two CO_2 sensitivity runs relative to the baseline. These results suggest that the hydrology of the UMRB region is potentially very sensitive to increased atmospheric CO_2 concentrations and are consistent with expectations; i.e., 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 three temperature sensitivity runs depicting average monthly increases of 2, 4, and 6°C (Table 7 and Figure 5). A linear pattern was exhibited in the average annual streamflow decreases of -7, -14, and -21 percent predicted for the 2, 4, and 6°C sensitivity runs, respectively. This linear pattern was also evident for the relatively large decreases in streamflows predicted for all three temperature sensitivity runs for the five-month span from March to July. However, the predicted monthly flows reflect nonlinear behavior between these three simulations for most of the fall and winter months. The predicted flows for the temperature sensitivity runs tended to converge during this period, especially during the months of September to December. In general, the magnitude of the predicted flow impacts were much greater during the spring and summer months (Figure 5). Standard deviations of 3.6, 2.8, and 2.7 were determined for the 2, 4, and 6°C sensitivity runs, respectively, which were all lower than the baseline standard deviation of 5.1.

Two key effects of the increased temperature sensitivity runs 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 similar temperature increase scenarios reported by Nash and Gleick (1991), van Katwijk *et al.* (1993), and Stonefelt *et al.* (2000) for studies focused on snowmelt dominated watersheds. However, those studies showed that the annual peak runoff period that occurs due to snowmelt was predicted to shift from June to May or April; in contrast, flow increases were predicted in this study to occur 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 (Table 7 and Figure 5).

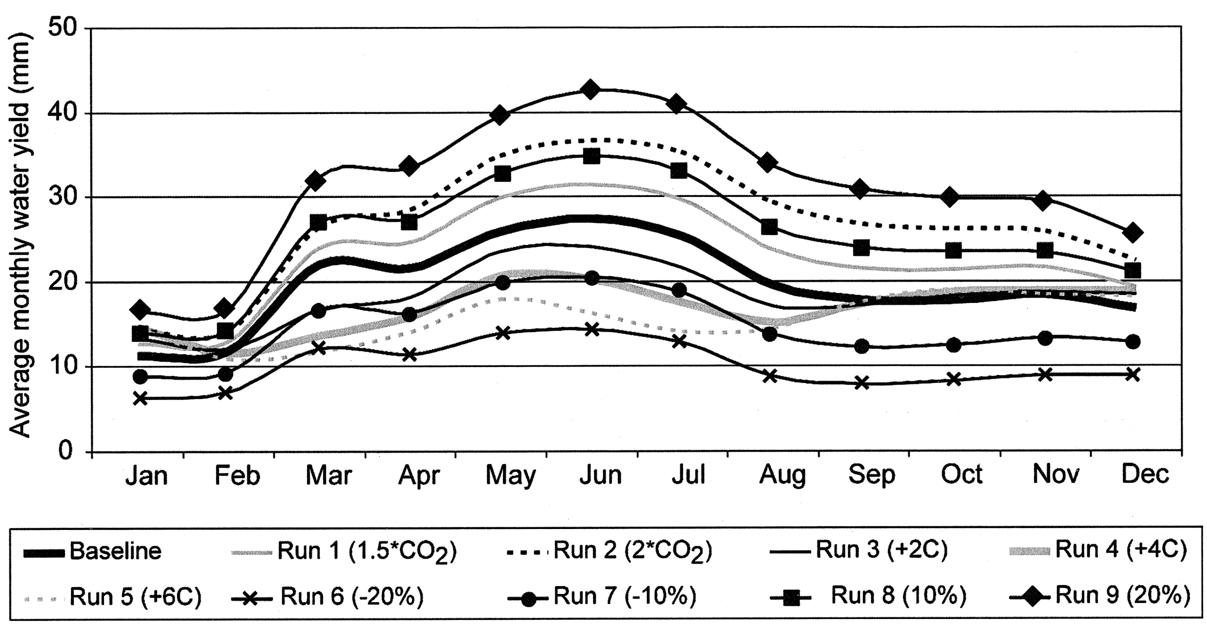

Figure 5. Change in Average Monthly Streamflows Predicted for Climate Sensitivity Runs 1-9 Relative to the Baseline Over the 30-Year Simulation Period.

Essentially linear changes in the UMRB streamflows were predicted for the simulated decreases or increases in precipitation, which were incorporated in sensitivity runs 6 through 9 (Table 7 and Figure 5). The relative average monthly flow decreases were near or greater than 50 percent for nine of the 12 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 flow changes were -49, -26, 28, and 58 percent for Scenarios 3, 4, 5, and 6 (Table 7). The standard deviations ranged from 2.7 for the -20 percent precipitation decline to 8.3 for the +20 percent precipitation increase, indicating that the streamflow variability increased with increasing precipitation. The flow responses estimated by SWAT for these four scenarios indicate that the UMRB hydrologic system is very sensitive to fluctuations in precipitation levels.

The predicted decrease in water yield of almost 50 percent for a 20 percent decline in precipitation was considerably higher than the 29 percent decrease in UMRB flows reported by Frederick (1993) for an analogue dust bowl climate, which included the effects of higher temperature. The effects of the -20 and +20 percent precipitation sensitivity runs (Table 7) were similar to UMRB seasonal flow impacts reported by Thomson *et al.* (2003), which ranged from -59 percent in summer to -33 percent in spring and 37 percent in summer to 62 percent in winter in response to El Niño and Strong El Niño climate patterns, respectively, and also included effects of temperature changes as well as precipitation fluctuations. However, the largest flow increases were predicted to occur during the summer or fall in the present study, which is essentially opposite of what Thomson *et al.* (2003) found.

The impacts of the solar radiation sensitivity runs (not shown) were relatively minor, resulting in a fluctuation range of -2 to +4 percent in average annual streamflows at Grafton. This would indicate that solar radiation shifts would be a minor factor in affecting UMRB hydrology. However, increasing relative humidity by +5 percent (not shown) resulted in an increase of 14 percent in the average annual streamflows at Grafton, due to a decrease of roughly 30 mm in average annual evapotranspiration.

Climate Change Scenarios

The climate change scenario impacts on the UMRB streamflows at Grafton are shown in Table 8 and in Figures 6 and 7. Large variations in average annual streamflows relative to the baseline were predicted by SWAT in response to the six different AOGCM scenarios (Table 8). In general, the predicted seasonal streamflow impacts varied greatly between the six climate change projections, which reflects the wide range of temperature and precipitation projections

TABLE 8. Predicted Relative Changes in Total Water Yield for the Mississippi River at Grafton, Illinois, for the Six AOGCM Climate Change Scenarios for a 2xCO_2 Climate.

Month	Baseline (mm)	CSIRO-RegCM2	CCC	CCSR	CSIRO-Mk2	GFDL	HadCM3
		Percent Change					
January	11.3	99	81	24	53	94	80
February	11.9	45	15	2	28	60	49
March	22.0	-4	-21	-28	-13	1	2
April	21.6	37	10	-3	13	34	41
May	25.9	55	24	8	25	43	55
June	27.4	37	4	-10	0	27	21
July	25.3	30	-17	2	-26	12	-6
August	19.6	48	-14	37	-46	11	-14
September	17.7	79	-1	43	-49	43	-5
October	17.8	85	21	11	-32	56	36
November	18.4	73	26	-22	-15	58	49
December	16.8	77	43	-20	16	71	58
Average Annual (mm)	235.5	51	10	2	-6	38	27
Monthly Standard Deviation	5.1	6.6	5.2	5.9	6.9	5.3	7.1

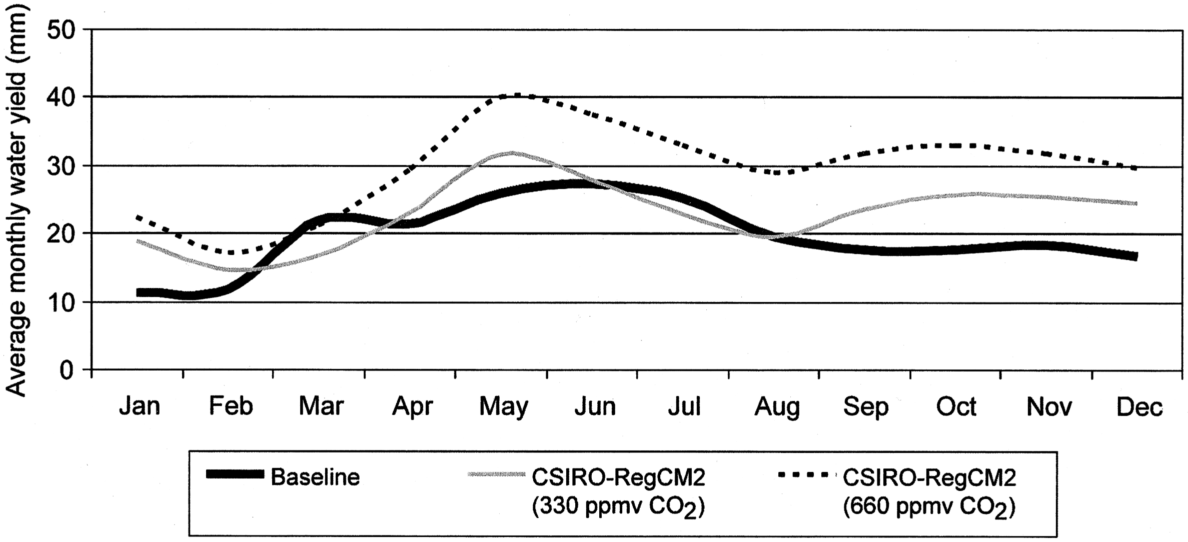

Figure 6. Change in Average Monthly Streamflows Predicted for CSIRO-RegCM2 Climate Change Scenario, With No Change in CO_2 (330 ppmv) and a $2xCO_2$ Climate (660 ppmv), Relative to the Baseline Over the 30-Year Simulation Period.

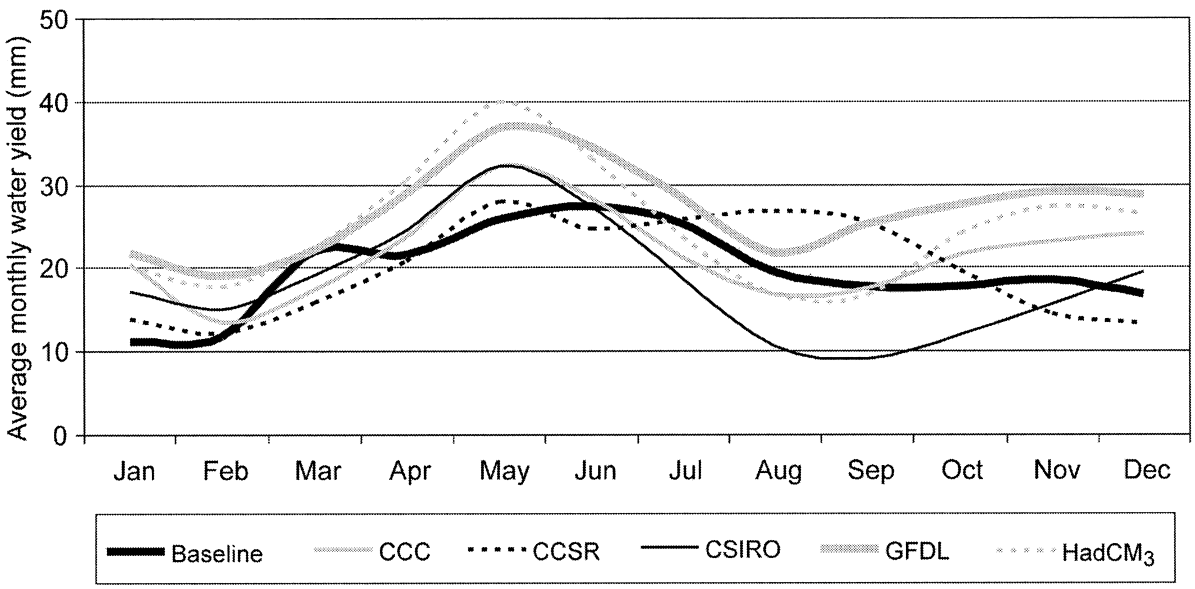

Figure 7. Change in Average Monthly Streamflows Predicted for Five AOGCM Climate Change Scenarios With $2xCO_2$ Relative to the Baseline Over the 30-Year Simulation Period.

listed in Table 3. Greater fluctuations between predicted streamflow decreases and increases occurred for the CCC, CCSR, and CSIRO-Mk2 scenarios, with noticeable differences in seasonal patterns. The predicted streamflows also varied greatly between the climate change scenarios within a single month. The most extreme differences were predicted for the month of September, for which the streamflow changes was predicted to range from -49 percent for the CISRO-Mk2 projection to 79 percent for the CISRO-RegCM2 scenario. The CISRO-RegCM2, GFDL, and HadCM3 scenarios resulted in large relative streamflow increases being predicted in most months and in the largest estimated overall average annual flow increases of 51, 38, and 27 percent, respectively. Relatively slight overall average annual streamflow increases of 10 and 2 percent were predicted for the CCC and CCSR projections. The CISRO-Mk2 scenario resulted in the only estimated average annual streamflow decrease (-6 percent), which was likely due to the large forecasted decreases in precipitation during June to October (Table 3).

Large relative increases in January streamflow were predicted for all of the scenarios; January increases of 80 percent or more were predicted in response to the CSIRO-RegCM2, CCC, GFDL, and HadCM3 projections. These January increases coupled with the February streamflow increases point to increased snowmelt and more precipitation in the form of rainfall during these two winter months, similar to the previously described results for the temperature sensitivity runs. These winter flow trends again differ from those reported for climate change studies focused on snowmelt-dominated watersheds in the western U.S. (Leavesley *et al.,* 1994; McCabe and Wolock, 1999; Christensen *et al.,* 2004).

Markedly different patterns emerged for the streamflow trends predicted for the AOGCM scenarios (Figures 6 and 7) relative to the trends predicted for the sensitivity runs (Figure 5). The CISRO-RegCM2 scenario was split out into a separate figure (Figure 6) to provide a comparison between a 2xCO_2 climate and baseline ambient CO_2 conditions. A nearly uniform shift of roughly 10 mm in average streamflow increase was predicted for the majority of months in response to the doubled CO_2 environment, confirming that CO_2 concentration is a key driver in the streamflow predictions estimated by SWAT. The flow patterns generated for the CCC, GFDL, and HadCM3 scenarios were similar to the CISRO-RegCM2 scenario (Figures 6 and 7) and generally resulted in predicted flow increases relative to the baseline in January and February, April to June, and September to December, and decreases or no change in flow in March, July, and August. The average monthly flow patterns generated by SWAT in response to the CCSR and CISRO-Mk2 scenarios deviated noticeably form the other scenarios during July to December. This was especially true of the CCSR scenario, which resulted in relatively large flows in August and September and then declined below the baseline during October to December.

The standard deviations determined for the six climate scenarios ranged from 5.2 to 7.1 and were all higher than the baseline standard deviation of 5.1 (Table 8), indicating that the variability in streamflows was higher for the climate change scenarios. Boxplot representations of streamflow variability are shown in Figure 8 for the baseline, climate change scenarios, and the measured streamflows. These plots further confirm the general patterns of variability, and indicate that the streamflows predicted for the CISRO-RegCM2 and GFDL scenarios were consistently higher than those predicted for the baseline and other climate scenarios. The plots also show that the median streamflow predicted for the baseline and all six climate change scenarios exceeded that found for the measured streamflows.

The results of this study and of several previous studies present a conflicting picture of potential future climate change impacts on UMRB streamflows. Rosenberg *et al.* (2003) report 2095 UMRB average annual streamflow increases of 53 and 48 percent, in response to a HadCM2 projection that was simulated with and without a doubled CO_2 concentration, respectively. Jha *et al.* (2004) report a 50 percent UMRB annual average flow increase for 2040 to 2049 that was predicted via downscaled HadCM2 inputs into SWAT, but without accounting for the CO_2 concentration level (assumed to be 480 ppmv). The

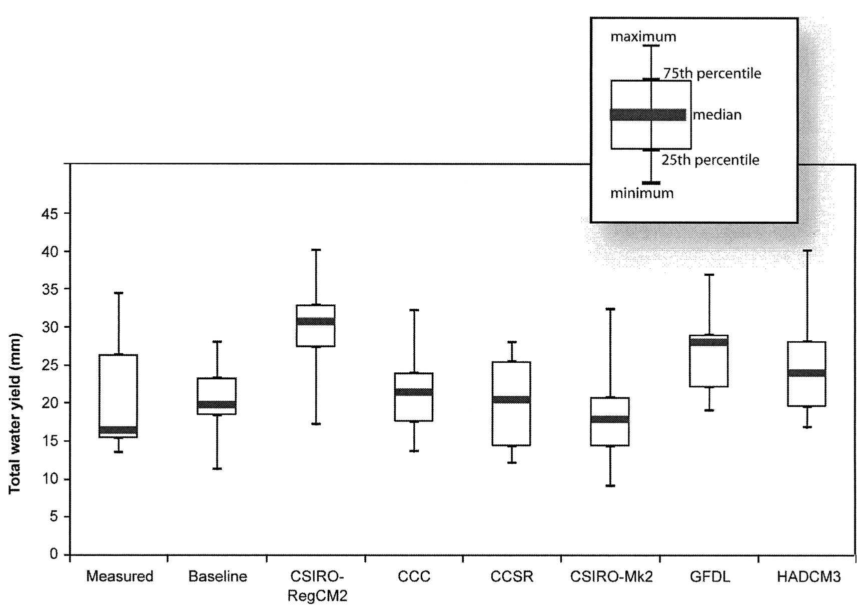

Figure 8. Box Plots Depicting the Variability of the 30-Year Average Measured, Baseline, and Climate Change Scenario Streamflows at Grafton, Illinois.

magnitude of the CISRO-RegCM2 scenario presented here was similar to the results reported in these two studies. However, exclusion of CO_2 for the CISRO-RegCM2 simulation resulted in only a 17 percent annual average flow increase at Grafton and the seasonal shifts found for both CISRO-RegCM2 simulations (Figure 5) varied considerably from those reported by Rosenberg *et al.* (2003). 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 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 results found by Wolock and McCabe reflect the large range in predicted future streamflow impacts that were found in this study with the five AOGCMs for 2061 to 2090 (Table 5).

Analyses of U.S. precipitation trends over the past century indicate that average U.S. precipitation has increased by 5 to 10 percent and the average increase in the UMRB region is even higher (NSF, 2001). Much of this precipitation increase can be attributed to an increase in the frequency and intensity of heavy and extreme precipitation events (Karl and Knight, 1998; NSF, 2001). These trends suggest that the CISRO-RegCM2, GFDL, and HadCM3 projections for the UMRB, which reflect higher future precipitation levels and greater streamflows, may be the most accurate for the region. If so, this could portend more extreme flooding events in the future for the region. Recent analyses of U.S. streamflow trends do not reveal any clear increases in extreme flow events (McCabe and Wolock, 2002; Lins and Slack, 1999), which underscores that increased rainfall levels in the future will not definitely result in increased extreme streamflow events. However, Knox (2000) states that alluvial records of UMRB paleofloods indicate that past natural floods were very sensitive to even modest changes in climate, which were similar in magnitude to current projections of climate change. The issue of extreme stream events is of less interest if the predicted streamflows found here for the CCC, CCSR, and CISRO-Mk2 projections are more indicative of future UMRB trends.

CONCLUSIONS

The results of this study indicate that the simulated UMRB hydrologic system is very sensitive to climatic variations, both on a seasonal basis and over longer time periods. The sensitivity runs showed that precipitation and CO_2 fertilization shifts would have a greater impact on future flow changes, as compared to increased temperature impacts. However, the impact of temperature clearly increased as the magnitude of temperature change was increased. Mostly minor impacts were predicted for four solar radiation and relative humidity sensitivity runs.

Changes in annual average UMRB streamflows at Grafton for 2061 to 2090 were predicted to range from -6 to +51 percent for the six AOGCM projections that were analyzed for this study. These results point to a great deal of uncertainty in current AOGCM projections for the region and make it difficult to draw any definitive conclusions about future UMRB streamflow impacts. However, it is noteworthy that several climate change studies have reported future UMRB annual average streamflow impacts of a similar magnitude to the 50 percent increase reported here for the CISRO-RegCM2 scenario, which could indicate future problems regarding extreme streamflow events in the region. The results reported here would indicate that snowmelt and rainfall would increase in January and February, and that large increases in spring streamflow could be expected.

The results of this study point to the need to perform a more extensive assessment of potential climate change impacts on UMRB hydrology by simulating the same downscaled climate change scenario(s) with several AOGCMs (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 database (Nusser and Goebel, 1997), which facilitates the assessment of both flow and environmental impacts for current and potential future climate patterns. There is also a need to incorporate a more refined method of estimating CO_2 concentration effects on crop growth and transpiration into the standard version of SWAT, which accounts for the impact of CO_2 on leaf area and stomatal conductance as a function of vegetative species. Finally, analysis of both extreme flow events and average flow conditions, similar to the procedures described by Boorman and Sefton (1997), is needed to provide a more complete picture of the potential impacts of projected future climates on UMRB hydrology.

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