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Watershed Modeling of Potential Impacts of Biofuel Feedstock Production in the Upper Mississippi River Basin

Environmental Science Division

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WATERSHED MODELING OF POTENTIAL IMPACTS OF BIOFUEL FEEDSTOCK PRODUCTION IN THE UPPER MISSISSIPPI RIVER BASIN

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EXECUTIVE SUMMARY

As part of the nation's efforts to achieve energy independence, in 2007 the United States Congress passed the Energy Independence and Security Act (EISA), which sets an annual biofuel production mandate of 36 billion gallons by 2022. This increase in biofuel production is expected to reduce greenhouse gas emissions, revitalize rural communities, and strengthen the nation's energy security. However, its effect on water use and quality in river basins is still uncertain and requires detailed assessment to avoid unintended consequences for regional and local water resources. This report presents an application of the Soil and Water Assessment Tool (SWAT) to evaluate the potential effects of conventional and cellulosic biofuel feedstock production in the upper Mississippi River basin (UMRB). The model was constructed specifically to account for dynamic land use, incorporate key elements associated with biofuel crop production, and provide a flexible modeling tool allowing evaluation of future biofuel production developments in the region. It was calibrated and validated by using 18 yr of observed water quality and stream discharge data from nine U.S. Geological Survey gauges along the river's main stream and tributaries. The model's ability to estimate spatially varying crop growth and biomass production was evaluated through comparison with observed corn and soybean yields for the 2006 baseline year. The results verified the model's ability to simulate both agricultural and hydrologic processes in the UMRB. The calibrated model was applied to evaluate the basin responses to changes in land use, corn-related crop rotations, harvesting of agricultural residues, soil and crop growth properties, tillage practices, and fertilizer application rates, which are potentially affected by the expected increase in biofuel production. The results demonstrate a non-linear, spatially varying relationship among nitrate application rate, crop yield, and nutrient loads that can be used further to assist in designing and implementing appropriate agricultural management practices to mitigate water quality issues associated with biofuel production.

Compared to the earlier watershed models developed for the region, the SWAT model developed in this study uses the most recent, most detailed data on land use and management

practices; accounts for dominant crop rotations in the watershed; is calibrated to observed stream discharge, water quality, and crop yields; and incorporates key modeling parameters to represent current and future crop biomass and residue production for biofuel. These improvements increase the comprehensiveness of our watershed assessment and make it representative of future combinations of biofuel feedstock production. The model is flexible enough to address technical issues relevant to simulation of large-scale, diverse biofuel feedstock production through corn, agricultural residue, improved crop yield, and perennial cellulosic feedstock. In general, the study is expected to broaden the sustainability analyses of biofuels by addressing potential implications for water resources and quality, which can then be used for optimal and sustainable design of biofuel feedstock production.

PROJECT OBJECTIVES

- Develop a watershed hydrologic model for the upper Mississippi River basin's (UMRB's) current and historical land uses, associated management practices, and climate conditions by using the Soil and Water Assessment Tool (SWAT).

- Provide an integrated assessment by simulating changes in various factors of the feedstock production process — environmental conditions, management programs and practices, and cellulosic feedstock — to quantify the impacts on regional and local water quality and hydrology in the UMRB.

- Implement a future scenario proposed by *U.S. Billion Ton Update — Biomass Supply for a Bioenergy and Bioproduct Industry* (U.S. DOE 2011), and compare the result with a business-as-usual (BAU) scenario in the UMRB by using the SWAT model for impact analysis.

MAJOR FINDINGS

- The calibrated SWAT model simulated the flow and water quality in the UMRB reasonably well, with the Nash-Sutcliffe efficiency > 0.5 and the square of the correlation coefficient > 0.8 for most of the flow and nutrient predictions.

- The calibrated SWAT model simulated spatially varying crop growth and biomass production in the UMRB reasonably well, with overall differences of 1.70% and -1.88% for corn and soybean yields during the 2006 baseline year, respectively.

- The model simulation predicted that a shift of crop rotation pattern in the corn-soy rotation land in the UMRB from the current one- or two-year corn to three-year corn in the four-year rotation period would increase corn production by 40%; increase evapotranspiration, suspended sediment, and nitrogen and phosphorus loadings from subbasins by 0.9%, 4.6%, 4.3%, and 7.7%, respectively; and decrease soil moisture and flow by 1.2% and 3.4%, respectively, on average.

- At the current nitrogen fertilizer application level, further increases in nitrogen input would not result in significant gains in crop yield. In addition, nitrogen loading appears more sensitive to an increase in fertilizer input rate than to a decrease. Increasing the nitrogen fertilizer application rate for cornfields by 50% from the current rate leads to a relatively small increase in corn yield (4.5%) but a large increase in total nitrogen loading at the basin outlet (34%). A 50% reduction in the nitrogen fertilizer decreases nitrogen loading by only about 22%. A similar analysis for phosphorus did not show a noticeable change in corn yields with increased application rate, indicating that the current rate of phosphorus application might already be adequate or higher than is required for corn growth in this region.

- The response of the watershed to stover harvest shows gradual decreases in biomass per unit of production area, stream discharge, suspended sediment, and nitrogen and phosphorus loadings when corn stover harvest is increased from 0% to 20%, 40%, 60%, and 80%.

- In comparison with the unadjusted soil properties, considering soil property changes in accordance with the level of stover harvest would increase flow and sediment loading by 4% and nitrogen by 9% at the basin outlet, while the impact on phosphorus loading could be positive or negative, depending on the level of stover harvest. Since soil property change is a relative slow process, these results highlight the need for further study of the long-term effect of harvesting corn stover on soil hydraulic properties, as well as for its accurate representation in watershed modeling.

- The land use and corn stover harvest analyses from the BT2 study (based on assumptions of the USDA baseline corn yield scenario and a price of $50 per dry ton in 2022) confirm that the UMRB plays a critical role in future U.S. crop/residue-based biofuel production. An estimated 48 million dry tons (MDT) of stover biomass will be collected from the UMRB's corn farms. This translates to 4.2 billion gallons of biofuel at a biofuel-stover conversion rate of 87.1 gal per dry ton. Corn grain production is also expected to increase by 28% in 2022, from nearly 95 MDT in 2006. In response to these changes, the annual evapotranspiration from the basin will increase slightly, leading to a decrease in annual soil moisture content and runoff from the basin. However, unlike to the impacts on hydrology, the impacts on annual water quality are mixed, with increased sediment and phosphorus loading but decreased nitrogen loading from the basin. In addition, water quality changes vary substantially in intensity and location within the UMRB.

1 INTRODUCTION

A rapid increase of domestic biofuel feedstock production is expected to meet the 36 billion gallons of biofuel mandated by the Energy Independence and Security Act (EISA) (U.S. Congress 2007). Much of the feedstock required to achieve this target will come from increased production of corn and cellulosic biofuel feedstock such as switchgrass and corn stover (USDOE, 2011). The associated impacts to water resources vary depending on the type of feedstock and the agricultural practices used, with corn-based biofuel development having a higher chance of negative impact if proper tillage, fertilizer, and irrigation practices are not deployed (Donner and Kucharik 2008; NRC, 2008; Thomas et al. 2008;USEPA 2010). Alternatively, impacts of perennial-based cellulosic biofuel crops such as switchgrass vary, depending on the land use that the switchgrass replaces (e.g., Costello et al. 2009). The analyses in this report focus on corn based – both grain and residue – biofuel, which accounts for the vast majority of the increased in biofuel production in the United States over the past decade as well as the near future.

Corn is currently the major feedstock used for U.S. ethanol production, accounting for approximately 98% of the total ethanol produced in 2007 (USACE 2007). A further increase in corn production will require more water, fertilizer, pesticide, and tillage (Koshel and McAllister 2010; Simpson et al. 2008; Wu et al. 2009; USEPA 2010). The nitrogen usage efficiency for corn is only 40-60% of the applied nitrogen fertilizer (USEPA 2010) and the remaining nitrogen often leave the field as runoff to surface water , leach to groundwater, and volatilize to the atmosphere. David et al. (2010) estimated that 5-30% of nitrogen fertilizer applied to agricultural fields enters the river systems in the lower and upper Mississippi River basins, respectively. In addition, majority of the phosphorus input tends to leave the corn and soybean farm along with the eroded sediment (Alexander et al. 2008).

Historically, nitrogen loss from agricultural lands (particularly corn and soybean farms) in the Mississippi and Atchafalaya River basins has been associated with hypoxia in the Gulf of Mexico (Baker et al. 2008; CENR 2000; David et al. 2010; Goolsby et al. 1999; Rabalais et al. 1996; Rabotyagov et al. 2010; SAB 2007). Alexander et al. (2008) indicated that agriculture in these same basins contributes more than 70% of the nitrogen and phosphorus delivered to the Gulf of Mexico, with corn and soybean farms accounting for about 52% of the nitrogen and 25% of the phosphorous. Donner and Kucharik (2008) estimated a future 10-34% increase in dissolved inorganic nitrogen in the Mississippi and Atchafalaya River basins as a result of the projected increase in corn production to meet the EISA biofuel production target in 2022. The upper Mississippi River basin (UMRB), which is one of the six major Mississippi River subbasins and the area of interest for our analyses, generates approximately 43% of nitrogen and 27% of phosphorous loads to the Gulf of Mexico (Aulenbach et al. 2007). Most of the current and future ethanol productions are expected to come from the UMRB, which represents about 42.3% of the U.S. production (USEPA 2010). Thus, a quantitative assessment of water quality and quantity is essential for addressing the long-term sustainability of biofuel production in the region. The results from such assessment will help to identify key elements in reducing nutrient load in the waterway, thereby assisting decision makers in minimizing unintended water quality consequences while producing the targeted biofuel feedstock.

Previously, many modeling studies have described water quality and quantity issues associated with agricultural production and climate change in the Mississippi River basin. Srinivasan et al. (2010) recently used the Soil and Water Assessment Tool (SWAT; Arnold et al. 1998) to develop an ungauged watershed model and estimate biofuel-biomass production potential and water budget in the UMRB by converting all agricultural lands to switchgrass. However, their analyses did not include water quality and validation of the model's ability to simulate nutrient and sediment load in the streams. The USEPA (2010) also applied SWAT for the UMRB and estimated higher increases in stream nutrient load during the first few years, followed by a decline as more corn is produced at 1.23% annual increase of yield. Their analysis, however, only reflects the impacts of increase use of corn grain without taking into account the possible use of corn stover and higher fertilizer application to meet the future biofuel demand. Other modeling studies have used the Monte Carlo approach to predict nitrogen loading to the Gulf of Mexico associated with increased corn production (Donner and Kucharik 2008) or cellulosic feedstock (Costello et al. 2009) in the Mississippi and Atchafalaya River basins to meet the ethanol production goal. Other recent studies to estimate water quality impacts in the UMRB due to increased corn production for ethanol include regression-based analyses by Alexander et al. (2008) and Robertson et al. (2009) and a life cycle analysis by Evan and Cohen (2009).

Previous studies have also applied the SWAT model in the UMRB to assess water resources, best management practices, and climate and land use changes. SWAT was applied to simulate groundwater recharge and discharge in the basin (Arnold et al. 2000), to evaluate the effects of climate change on water balance (Jha et al. 2004), to quantify the cost of conservation practices needed to control the nitrogen and phosphorus flux to the Gulf (Jha et al. 2009; Rabotyagov et al. 2010; Secchi et al. 2007; Wu and Tanaka 2005), to determine the potential benefits of wetland filters in controlling nitrate loading (Crumpton et al. 2006), and to assess water quality improvement related to alternative land use and management practices (Gassman et al. 2006). The USDA-NRCS (2010) used SWAT together with APEX (Williams et al. 2000) to study effective conservation practices in the UMRB.

Nevertheless, several modeling issues remain if hydrologic models are to estimate reliably the water quality impacts associated with various biofuel production scenarios. Among these are validation of model ability to simulate (1) the observed stream water quality and crop yield; (2) feedstock production under different agricultural and climate conditions, as emphasized by Moriasi et al. (2007); (3) future technological advances in crop biomass production and agricultural practices; (4) crop rotations, which could significantly affect land management and nutrient loading estimates; and (5) long-term implications for soil hydraulic properties of biofuel feedstock production.

The overall objective of this study was to develop a SWAT model for the UMRB and quantify the long-term water quality and quantity impacts associated with land use and management changes to increase production of biofuel from conventional and cellulosic feedstock. We conducted baseline simulation to represent the watershed condition prior to the 2007 large-scale biofuel production in the region and applied the model to simulate the watershed responses to possible biofuel production related changes in fertilizer application rates, feedstock types, soil properties, residue harvest, and crop rotations. Compared to the earlier

watershed models developed for the region, we took extra steps to address some of the modeling issues listed in the previous paragraph. Specifically, the SWAT model developed in this study uses detailed and most recent land use and management practices; accounts for dominant crop rotations in the watershed; is calibrated to observed stream discharge, water quality, and crop yields; and incorporates key modeling parameters to represent current and future crop biomass and residue productions for biofuel. The study accounts for the majority of possible changes in the watershed associated with the increased biofuel production in order to provide a more realistic assessment of the potential implications of biofuel on the region water resources. Such changes include land use, crop rotations, residue harvest, crop genetics, fertilizer application, tillage, and soil properties. Thus, the model is believed to be flexible enough to address the technical issues relevant to simulation of large-scale and diverse biofuel feedstock production through corn, agriculture residue, improved crop yield, and perennial cellulosic feedstock.

2 UMRB SWAT MODEL

2.1 SWAT MODEL

SWAT (Arnold et al. 1998) is a physically based, semi-distributed watershed-scale model that can simulate daily or hourly hydrology and nutrient cycles, as well as plant growth under varying soil, climate, land use, and management conditions. SWAT's main strength is its ability to simulate the couple watershed processes associated with the hydrologic cycle, nutrient cycle, plant growth, and routing, with the least data and computational requirements. The model can be applied readily to a large, complex watershed such as the UMRB, and it has been satisfactorily validated under different watershed and climate conditions (Arnold and Fohrer 2005; Gassman et al. 2007; Jayakrishnan et al. 2005). These make the model an appropriate tool to study the water quality and resources implications of biofuel under alternative feedstock production scenarios.

Instead of using predefined cell discretization, SWAT uses spatial discretization of similar climate, land use, soil, topology, and land use management to determine the model's smallest computational unit — the hydrologic response unit (HRU). Daily or sub-daily calculations of water budget, plant growth, nutrient cycles, and soil erosion at the HRU level are aggregated to subbasin values using the weighted sum technique. The resulting flow and loads from the subbasin outlets are routed through channels and reservoirs to the watershed outlet. Detail descriptions of the SWAT model and comprehensive reviews of its applications are provided by Neitsch et al. (2005) and Grassman et al. (2007), respectively.

We used the SWAT 2005 version for model development. Specific considerations for the UMRB application included (1) developing a SWAT model emphasizing incorporation of recent crop management data; (2) identifying 4 yr of crop rotations related to corn, soybean, wheat, and hay in the 2003-2006 Cropland Data Layer (CDL) of USDA's National Agricultural Statistics Service; 3) validating model ability to simulate flow, soil erosion, nutrient loadings, and biomass and crop residue productions, and (4) evaluating the watershed responses to changes in cropping pattern or rotations, land use changes, harvest of crop residue, crop genetics, soil properties, and fertilizer application rate, as driven by the expected increase in biofuel feedstock production.

2.2 STUDY AREA (UMRB)

The UMRB includes more than 2,012 km of the Mississippi River (Figure 1), from its headwaters at Lake Itasca in Minnesota to the confluence of Mississippi and Ohio Rivers at Cairo, Illinois. The river system drains an area covering approximately 49 million hectares across seven Midwestern Corn Belt states, with main tributaries including the Minnesota, Wisconsin, Iowa, Des Moines, Illinois, and Missouri Rivers. The U.S. Geological Survey (USGS) divided the basin into 131 subbasins as 8-digit HUCs with an average drainage area of 376,000 hectares. The basin land use is predominantly agriculture. Corn and soybean farms constituted about 41% of the total land in 2006, representing over 35% and 30% of U.S. corn and

soybean production, respectively (USDA-NASS 2006b). The soil types range from heavy, poorly drained clay soil to light, well-drained sands, with silty loam and loam soils covering about 66% of the total UMRB area. The topography is characterized by flat to gently rolling terrain, with 55% of the area having less than a 2% slope and an average elevation of 280 m. Precipitation generally increases from north to south. Average annual precipitation of 900 mm during the calibration period (1990-2006) occurred mostly between April and October. The average daily minimum and maximum temperatures during crop growth seasons ranges from 12.8°C to 16.7°C in the north and 18.1°C to 22.6°C in the south.

Human activities across the basin affecting water quality along the Mississippi River main stream and the Gulf of Mexico over the past two centuries include widespread corn and soybean production, tile drains, recent corn-based ethanol production, navigation dams and locks, and numerous industrial and municipal wastewater treatment facilities that deliver effluent water to streams. There are 27 locks and dams on the mainstream, which help maintain a nine-foot depth stream for navigation by creating a stairway of reservoirs from Minneapolis, Minnesota, to St. Louis, Missouri. These human interferences in the basin contribute numerous water quality issues that vary in magnitude in different parts of the river. Thus, a spatially distributed watershed-scale hydrologic model is required to study stream quality under current and possible future conditions.

2.3 MODEL INPUTS

SWAT requires a significant amount of watershed-specific data and empirical parameters for its development and calibration. Main input data of the model include land use, agricultural operations and management, soil properties, topography, daily climate, reservoirs and ponds, point source pollution, and water consumption by different sectors. In most cases, these data are readily available for watershed in the United States or can easily be generated by using some of the GIS functionalities. The main data sources used to construct the model include the USGS's National Map Seamless Server for 30-m digital elevation and 8-digit level predefined subbasin maps; USGS's National Water Information System for observed discharge and loads data used for calibration; USEPA's Reach File 1 (RF1) for predefined stream network; NOAA's National Climatic Data Centers (NCDC) for weather data; USDA's National Agricultural Statistics Service (NASS) for land use, crop yield, and soil maps; USDA's Economic Research Service (ERS) for commercial fertilizer applications; Conservation Tillage Information Center (CTIC) for tillage survey data; and USGS's estimates for water use and irrigation data. The GIS interface of SWAT, ArcSWAT (Winchell et al., 2007) and Visual Basic programs that we developed to pre-process the model inputs and to specify and modify model parameters during calibration. This section describes the main input data, assumptions, and processes involved in developing the SWAT model for UMRB.

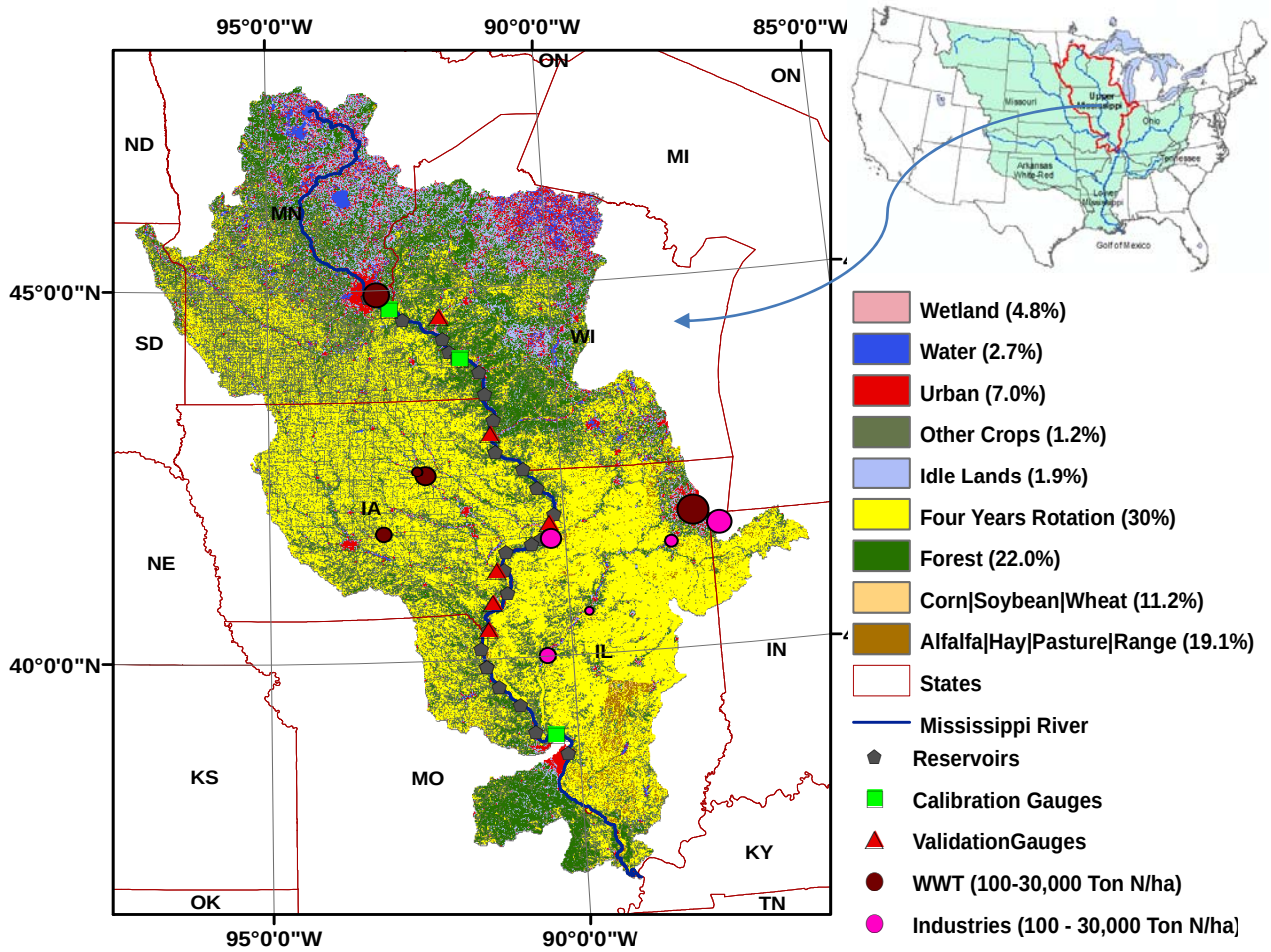


Figure 1 Upper Mississippi River Basin location and the spatial distribution of land cover, major reservoirs, point sources, and calibration and validation gauges.

2.3.1 Watershed delineation

The first step in SWAT model development is to define the watershed boundaries and the corresponding drainage areas or subbasins either by using the digital elevation map to delineate the subbasins or directly importing the pre-defined watershed and stream network into the model if they are available. In this study, the pre-defined option was used, with the USGS's 8-digit HUC and the USEPA's Reach File 2 (RF2) maps for delineating the subbasins and the stream network, respectively. The stream networks were pre-processed to have one stream per subbasin with its output coinciding with the subbasin boundary and to have consistent topological representation with the correct "in and out nodes" hierarchal structures. The 60-m digital elevation model (DEM), resampled from the USGS 30-m DEM, was used by ArcSWAT to determine average slope and slope length for each subbasin and characteristics of the stream network, such as channel slope, length, and width. The subbasins were further discretized to 14,200 HRUs by using cutting thresholds of 5% for land use and 10% for soil and slope. Forest,

urban, major agriculture land uses, and crop in rotations were exempted from the 5% cutoff threshold.

2.3.2 Land use

Land use input is critical in SWAT model development because it determines model structure and associated management practices. Multiple year data were used to generate accurate, realistic land use and management data in the UMRB. The CDL for agricultural land classifications — coupled with the USGS 2001 National Land Cover Data for non-agricultural land classifications — was used to develop the land use categories for the 2006 baseline year, with associated crop rotations over 4 yr (2003-2006) related to corn, soybean, wheat, and hay. The crop rotations over 4 yr were determined by overlaying the 2003-2006 CDL data for each state and identifying the different combinations of land use grids that were used at least once for growing corn, soybean, wheat, or hay. For states that do not have complete 4-yr CDL data, only the available data were used to estimate the 4-yr rotations. More than 90% of the crop rotations related to the above four crops were identified and incorporated into the model. Figure 2 shows the decision tree algorithm used to determine the four years crop rotations.

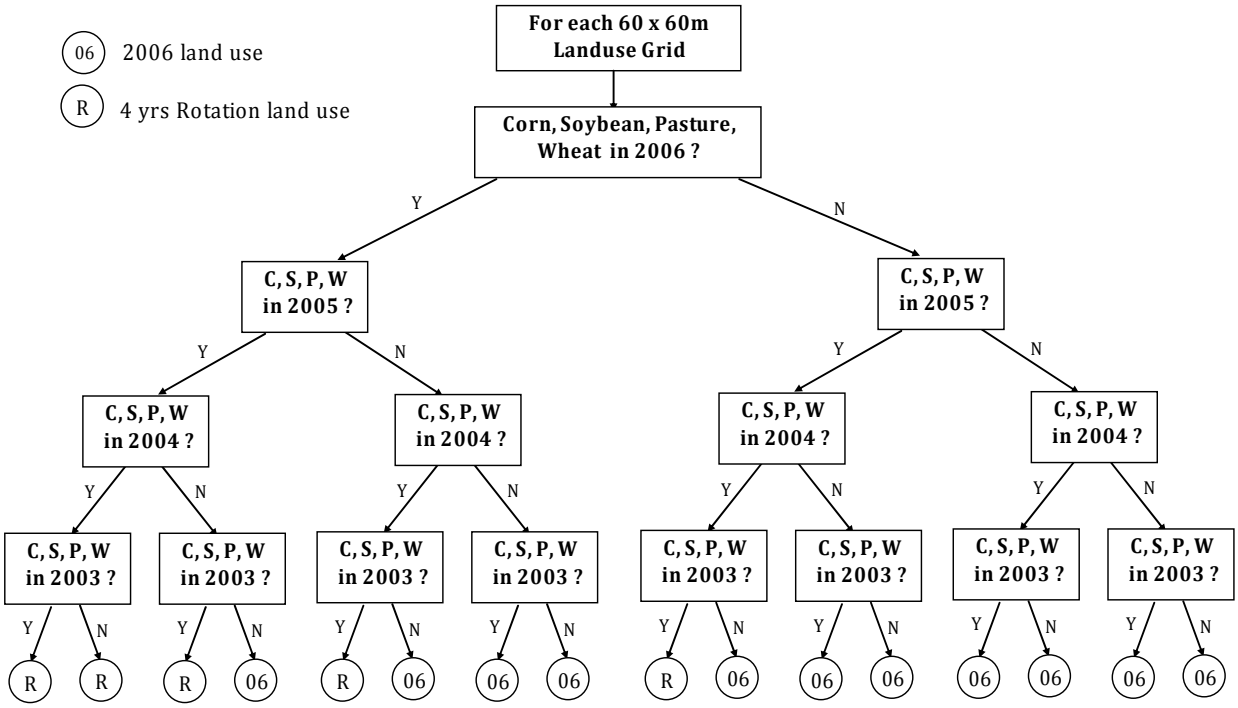


Figure 2 The decision tree algorithm to identify the 4-yr crop rotations related to corn soybean, wheat, and pasture rotations**.**

Figure 3 shows the spatial distributions of corn intensities (or number of years corn are grown within the 4-yr rotations) as percentage of the total corn area for each subbasin. Most of the 1-yr corn intensities (Figure 3a), which cover about 1.6 million ha (or 9.1% of corn areas used within the four years), are located in the southern section of the basin, perhaps because of the introduction of new corn land or corn rotated with the other dominant crops (soybean, wheat, and hay). In general, the 2-yr corn intensity was the most common type of rotation in the region, covering about 9.7 million ha (55.2% of the corn areas) in the western and middle sections of the basin (Figure 3b). The 3-yr and 4-yr corn intensities were mostly in the middle and eastern sections of the basin and cover about 3.6 (20.3%) and 2.7 (15.3%) million ha, respectively (Figures 3c, 3d).

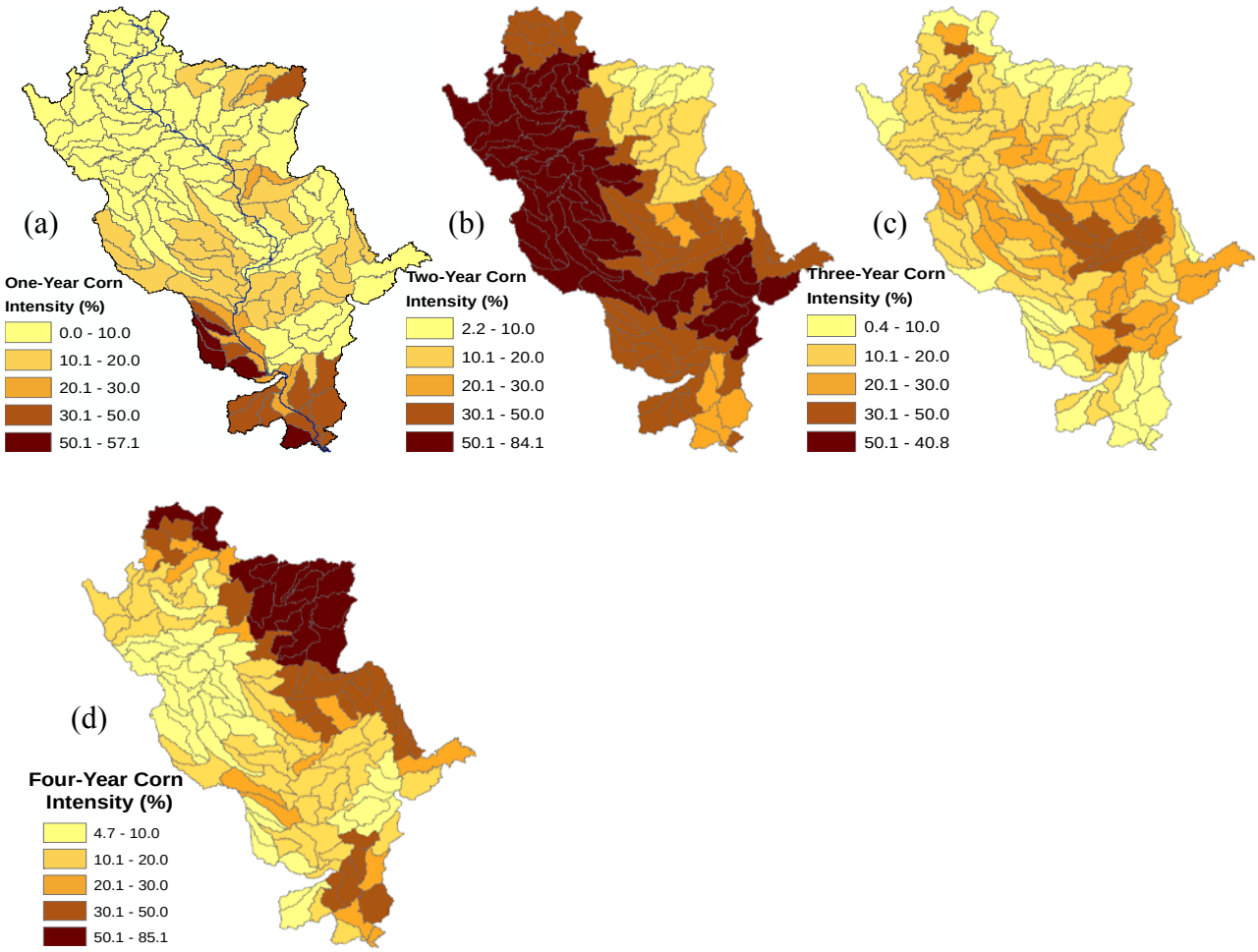


Figure 3 Corn intensities within the 4-yr rotations. In 2003-2006, corn was cultivated for (a) only 1 yr, (b) 2 yr, (c) 3 yr, and (d) 4 yr (continuously).

The final land use map consists of 95 different land use classifications, including 43 classifications related to the 4-yr rotations of corn, soybean, wheat, and hay. Most of the land (64%) is agricultural, pasture, and hay, with about 22% forest and 7% urban. Most croplands (about 31% of the total basin area) are under the 4-yr land use rotations, indicating the importance of accounting for land use sequences in model construction. The distribution of crops for the baseline year was summed by county and validated against the 2006 USDA-NASS (2006b) agricultural statistics and CDL map. The difference in the total crop areas between the model's land use and the CDL data was less than 4%. Finally, the SWAT crop database, which is used by the model to define crop growth parameters for the land use map, was modified to include the crop rotations. This is necessary only to determine the HRUs related to the crop rotations using the ArcSWAT interface. Otherwise, the crop rotations are incorporated in the model simulation by modifying the crop management database. The resulted land use map was reclassified into SWAT land cover/plant types by using a look-up table to identify the SWAT code for the different categories of land use and rotation in the modified crop database, as per the required format.

2.3.3 Soil Map

The soils data were obtained from the National Resources Conservation Service (NRCS) State Soil Geographic (STATSGO) database, which was downloaded as part of the ArcSWAT model. The STATSGO soil database was selected because this database was designed primarily for regional, multistate, and river basin applications. However, future modeling work using more detailed soil classifications, as in the Soil Survey Geographic (SSURGO) database, might help improve the accuracy of the model results. The soils in the STATSGO database are classified to hydrologic groups A, B, C, and D on the basis of their properties related to runoff potential and infiltration rate under similar storm and cover conditions. According to this classification, the soil type in the UMRB consists of 65.5% silty-loam or loam soils with a moderate infiltration potential, 17.5% sandy clay loam soils with a slow infiltration potential, 9% sandy soil with high infiltration potential, and 8% heavy and poorly drained clay and clay loam soil with low infiltration potential.

2.3.4 Weather

Weather is another important model input in SWAT that controls water balance and the relative importance of the components of the hydrologic cycle. SWAT requires daily precipitation, minimum and maximum temperature, relative humidity, solar radiation, and wind speed to simulate daily or sub-daily watershed responses. The daily precipitation or snowfall (or precipitation if the average daily temperature is below zero degrees centigrade) introduces water to the watershed. On the other hand, the daily solar radiation controls the evapotranspiration rate, which is the primary water removal mechanism in the watershed. The daily air temperature controls the soil temperature, which, in turn, affects the plant growth and decomposition rate of organic matter. Daily wind speed is optional data, which is only required if the Penman-Monteith equation is used to estimate potential evapotranspiration. Similarly, the relative humidity is only

required if the Penman-Monteith or Priestley-Taylor equation is used to estimate the potential evapotranspiration.

Daily rainfall and temperature measurements for 1960-2009 were downloaded from 500 and 367 NOAA's National Climatic Data Center (NCDC) weather stations in and around the UMRB, respectively. SWAT assumes homogeneous weather conditions within a subbasin and thus requires one weather station per subbasin. The observed precipitation and temperature were interpolated to the centroids of the 131 subbasins by using the inverse distance weighting interpolation method (Shepard, 1968) over five nearest-neighbor weather stations, as a shown below:

$$W(t)_c = \frac{\sum_{n=1}^{N} d(t)_n w(t)_n}{\left(\sum_{n=1}^{N} d(t)_n\right)^p}$$

$$\textit{where } d(t)_n = \sqrt{\left(c(x)-n(x)\right)^2 + \left(c(y)-n(y)\right)^2 + \left(c(z)-n(z)\right)^2}$$

where $W(t)_c$ is the interpolated weather data (precipitation and temperature) at the centroid *c* of a subbasin, $w(t)_n$ is the observed weather data from weather station *n*, $d(t)_n$ is Euclidian distance between the subbasin's centroid *c* and weather station *n*, *N* is the number of closest weather stations, which is five in our case, and *p* is power of the distance and determines the significance of the data from neighboring points, with higher value giving more weight to the closest neighboring stations. The commonly used inverse-distance weighting interpolation method is a specially form of instance-based weighting method with p = 2, and applied in this study. The interpolations were conducted at daily time steps *t* and selected the next closest station in the case of missing data. The daily radiation, relative humidity, and wind speed data were generated by using SWAT's built-in weather generator, WXGEN (Sharply and Williams, 1990). The spatial and temporal variations of the total precipitation and average daily maximum temperature during the crop growing season (April 15-October 15) were illustrated in Figure 4. In general, the daily temperature and precipitation increase as we go from northern to southern section of the basin.

2.3.5 Tillage

SWAT simulates different land-management practices in a watershed. Tillage is one of such practice, which is often applied in agricultural fields primarily to redistribute soil nutrients and crop residues and to control weeds. It plays an important role in controlling nutrient and sediment losses from agricultural watersheds. For instance, conservation tillage, such as no till and ridge till, leaves the previous year's crop residue on the field, covering at least 30% of the area and controlling soil erosion by runoff and wind. SWAT simulates tillage types on the basis of depth and efficiency of mixing. Since the tillage practice is dominant for crop fields, we applied tillage only to crop related HRUs. Table 1 summarizes the areas of the common tillage

practices for corn and soybean in the UMRB, as reported in 2004 survey data from the Conservation Tillage Information Center (CTIC).

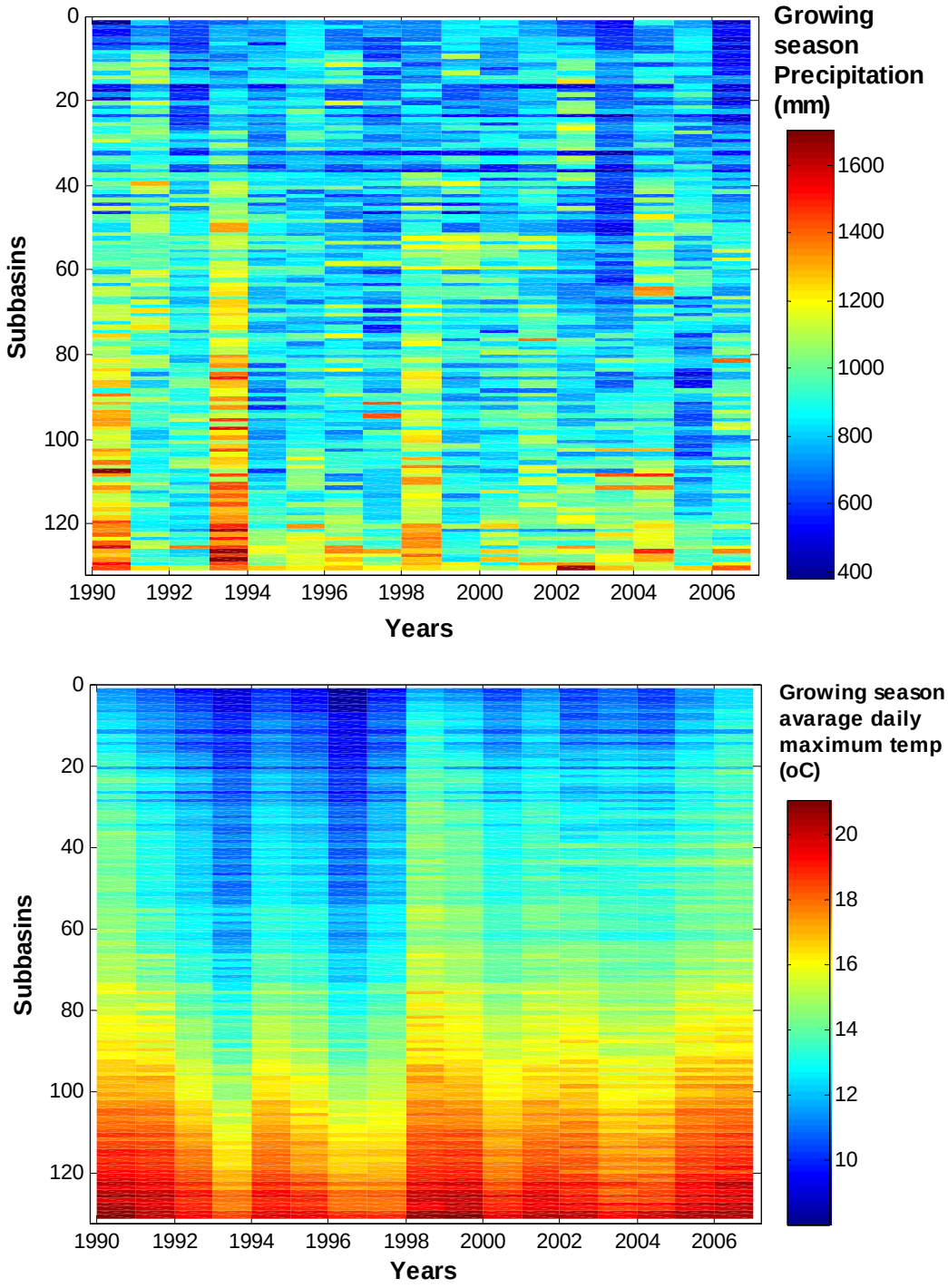


Figure 4 Spatial and temporal variations of the total precipitation and average daily maximum temperature during the growing season.

Table 1 Tillage types applied to corn and soybean lands in the UMRB.

Tillage Types	Corn Area (million acre)	Soybean Area (million acre)
No Till	2.85	7.31
Ridge Till	0.07	0.09
Mulch Till	5.39	8.26
Reduced Till	8.52	4.39
Intensive Till	11.31	2.81

To use these data for SWAT, first the county-level tillage acreages, $A\left(\boldsymbol{till_t} \mid \boldsymbol{crop_k}, \boldsymbol{cnty_i}\right)$ from CTIC were aggregated to subbasin acreages, $A\left(\boldsymbol{till_t} \mid \boldsymbol{crop_k}, \boldsymbol{sub_j}\right)$, by using the area-based weighted-average method shown below:

$$A(\boldsymbol{till_t} \mid \boldsymbol{crop_k}, \boldsymbol{sub_j}) = \sum_{i=1}^{N_j} \frac{A\left(\boldsymbol{crop_k} \mid \boldsymbol{cnty_i}, \boldsymbol{sub_j}\right)}{A\left(\boldsymbol{crop_k} \mid \boldsymbol{cnty_i}\right)} A\left(\boldsymbol{till_t} \mid \boldsymbol{crop_k}, \boldsymbol{cnty_i}\right)$$

where: $A\left(\boldsymbol{till_t} \mid \boldsymbol{crop_k}, \boldsymbol{sub_j}\right)$ is area of tillage type *t* for crop type *k* in subbasin *j*; $A\left(\boldsymbol{till_t} \mid \boldsymbol{crop_k}, \boldsymbol{cnty_i}\right)$ is area of tillage type *t* for crop type *k* and county *i*, as obtained from CTIC survey data; $A\left(\boldsymbol{crop_k} \mid \boldsymbol{cnty_i}\right)$ is area of crop type *k* in county *i,* as obtained by overlapping the land use map with the county map; $A\left(\boldsymbol{crop_k} \mid \boldsymbol{cnty_i}, \boldsymbol{sub_j}\right)$ is area of crop type *k* in county *i* and subbasin *j,* as obtained by overlaying the land use map with county and subbasin maps; and N_j is the number of counties within subbasin *j*. The calculation was adjusted for counties at the edge of the watershed, some of which are only partly in the watershed. Finally, fractions of crop area under different tillage practices, $A(\boldsymbol{till_t} \mid \boldsymbol{crop_k}, \boldsymbol{sub_j}) / A(\boldsymbol{crop_k} \mid \boldsymbol{sub_j})$, were computed for the individual crops at the subbasin level. These fractions were used in SWAT to redistribute the different tillage types proportionally to specific croplands that are not in yearly rotations. For crops under the 4-yr rotations, the dominant tillage types for specific crops and subbasins were used.

2.3.6 Fertilizer and manure application

Commercial fertilizer and animal manure are important sources of nutrients to crops. Table 2 shows that an average of 151 kg/ha of nitrogen was applied to 96% of the corn area planted in 2005 in the UMRB states, while phosphate and potash were applied at average rates of 67 and 88 kg/ha over 82% and 74% of the corn area, respectively (USDA-NASS 2006a). Overall, about 3 million tons of nitrogen and 1.2 million tons of phosphorus fertilizers were applied in the UMRB states during 2005. Another 0.28 million tons of nitrogen and 0.27 million tons of phosphorus were applied as manure. However, the distribution of fertilizer applications within the states is not well known, because the collection of county-level agricultural chemical

use data by USDA was discontinued in 1990. Instead, state-level commercial fertilizer use over the croplands and hay lands, $\boldsymbol{F(crop_k \mid states_s)}$, in 2005 and 2006 was distributed to county-level data, $\boldsymbol{F(crop_k \mid cnty_i)}$, by assuming that county-level fertilizer use is directly proportional to a county's crop yield, as follow:

$$\boldsymbol{F(crop_k \mid cnty_i) = \frac{Y(crop_k \mid cnty_i)}{Y(crop_k \mid states_s)} F(crop_k \mid states_s)}$$

where $\boldsymbol{Y(crop_k \mid cnty_i)}$ and $\boldsymbol{Y(crop_k \mid states_s)}$ are yields of crop *k* from county *i* and state *s*, respectively; $\boldsymbol{F(crop_k \mid states_s)}$ is fertilizer application rate over crop type *k* in state *s,* obtained from USDA-NASS (2006a) (Table 2). The county-level fertilizer application rates were then aggregated back to the subbasin level by using crop area and the weighted-average method given below, by assuming that subbasin application is directly proportional to crop acreage as in David et al. 2010.

$$\boldsymbol{F(crop_k \mid sub_j) = \frac{\sum_{i=1}^{N_j} F(crop_k \mid cnty_i) A(crop_k \mid cnty_i, sub_j)}{\sum_{i=1}^{N_j} A(crop_k \mid cnty_i, sub_j)}}$$

Here $\boldsymbol{F(crop_k \mid sub_j)}$ and $\boldsymbol{F(crop_k \mid cnty_i)}$ are fertilizer application rates over crop type *k* in subbasin *j* and county *i*, respectively, and $\boldsymbol{A(crop_k \mid cnty_i, sub_j)}$ is area of crop in county *i* and subbasin *j*.

Table 2 Commercial fertilizer and irrigation applied to corn lands in the UMRB states.

		Nitrogen for corn lands		Phosphorus for corn lands		Potash for corn lands		Irrigation for entire agricultural lands	
States	Corn planted in 2005 (1000 acres)	Area %	Kg/ha	Area %	Kg/ha	Area %	Kg/ha	SW (thousand. m^3/day)	GW (thousand. m^3/day)
IA	12,800	92	156	70	72	71	93	6	120
IL	12,100	98	162	84	85	84	127	93	1,813
IN	5,900	100	164	93	85	88	139	204	369
MN	7,300	94	154	86	67	77	79	107	818
MO	3,100	99	177	79	68	78	83	147	5,072
SD	4,450	95	126	79	49	37	28	541	564
WI	3,800	93	120	84	41	84	67	58	1,465

Manure was applied over the crop and pasture lands. Its production was estimated for beef cattle, dairy cow, and swine grown in the UMRB states. Manure production was estimated for beef cattle, dairy cow, and swine grown in the UMRB according to USDA-NASS (2006a) county-level animal inventory data for 2005 (when available) or for the nearest year. Average

manure output was calculated for beef, dairy, and swine according to a nutrient management program (University of Wisconsin Extension 2009). The county-level manure production was then distributed to the crop and hay lands in subbasins by using an equation similar to Equation 4. Since SWAT requires dry fresh manure without urine and feces, the observed fresh manure data were converted to dry weight via solids fractions of 14%, 14.7%, and 13.1% for dairy, beef, and swine, respectively (ASAE, 2003).

Furthermore, there are noticeable discrepancies between the values used in SWAT and the ASAE (2003) standard for nutrient content in the manure (total nitrogen, ammonium, organic phosphorus, and mineral phosphorus). For example, organic nitrogen in dairy manure is 0.038 lb/lb dry weight, as recommended by ASAE (2003), while it is 0.031 lb/lb dry weight in SWAT. In particular, SWAT default values for swine differ significantly from the default ASAE values. The amount of organic nitrogen in swine manure suggested by ASAE (0.047 lb/lb dry weight) is more than twice that in SWAT (0.021 lb/lb dw), and the value of organic phosphorus suggested by ASAE is almost ten-fold higher than the SWAT value. For this modeling effort, we used the ASAE (2003) value to calculate the amount of nutrients in the manure and modify the existing SWAT fertilizer database.

2.3.7 Irrigation

Water usage data for irrigation and other sectors were obtained from the 2005 USGS National Water Use Program database (Kenny et al. 2009), which contains county-level water consumption data by various sectors. Irrigation water use accounts for only about 6% of the total water use in the seven states. Groundwater was the primary source (90%) for irrigation water (Table 2). Since the exact irrigation scheduling was not known, irrigation was applied by using SWAT's auto-irrigation scheduling option, which automatically allows irrigation whenever the crops experience water stress. Water consumption by other sectors was also assigned by redistributing the county-level data to the subbasin level. SWAT considers this water consumption as lost from the system.

2.3.8 Tile drains

Subsurface drainage is commonly used in agriculture lands to remove excess water from poorly drained land so that crops can be planted and grown. The soils in the UMRB are predominantly Mollisols and Alfisols, which are highly productive but have poor internal drainage (Keeney and Muller 2000). Thus, subsurface tile drainage is necessary for crop production. Numerous studies confirmed that the highest tile drainage in the United States occurs in the Upper Mississippi and Ohio-Tennessee River Basins (e.g., Crumpton et al., 2006 and Devine et al., 2008). However, the regional distributions are not well known, because installation records are incomplete or missing. We applied a procedure like that of Srinivasan et al. (2010) and USEPA (2010) to estimate the tile drainage locations by overlaying soil, land use, and slope maps. Crops grown on poorly drained soils (e.g., hydrology group C and D) over relatively flat surfaces with slope less than 1% were assumed to have subsurface tile drains. The depth to the tile drain was set at 850 mm, while the time to drain soil to field capacity and the time until water

enters the stream channels after entering tiles were set at 48 h and 12 h, respectively, per Brown and Ward (1997). The model sensitivity to tile depth and drainage time was examined by rerunning the calibrated model for tile depths of 700-1,100 mm and drainage times of 20-60 h. The percentage differences in the model estimates of annual flow and nutrients at the basin outlet versus the calibrated model results were in the order of 10^{-1} and less. However, the two drainage parameters might have opposite effects, because smaller tile drain depths might imply longer drainage times for water to reach the tiles and *vice versa*.

2.3.9 Reservoirs

The 1930 Rivers and Harbors Act to improve the upper Mississippi River channel for navigation led to the construction of numerous locks and dams to maintain a 2.75-m-deep channel with a minimum width of 122 m. The navigation dams created a stairway of 27 reservoirs from Minneapolis to St. Louis. To simulate reservoirs, SWAT requires reservoir storage capacity, equilibrium concentrations of sediments, and water release rates. Because of limited access to information for the 27 locks and dams, reservoir bathymetry data from the USGS Upper Midwest Environmental Sciences Center were used to estimate reservoir storage volume capacities and surface areas at both emergency and principal spillways. Average annual water release rates and equilibrium sediment concentrations were calculated for reservoirs having USGS gauges at their outlets. The median particle diameters (D_{50}) of sediments in the reservoirs were computed by Equation 4, adapted from SWAT model (Neitsch et al. 2005).

$$D_{50} = \exp\left(0.41\frac{m_{clay}}{100} + 2.71\frac{m_{silt}}{100} + 5.7\frac{m_{sand}}{100}\right)$$

Where D_{50} is the median sediment size in micrometers, and m_{clay}, m_{silt}, and m_{sand} are percents of clay, silt, and sand, respectively, in the surface soil layer, as determined for each reservoir on the basis of the upstream soil compositions of clay, silt, and sand.

2.3.10 Point source pollution

Non-point sources, especially from agriculture activities, are widely considered to be the main sources of nutrient load in the Mississippi River. However, a number of municipal wastewater treatment plants for major cities (such as Chicago and Minnesota's Twin Cities) and industrial facilities (e.g., meat processing plants) generate effluent that can affect local water quality significantly. Smith and Alexander (2000) estimated point source contributions to total UMRB nitrogen and phosphorous at about 0.8% and 3.6%, respectively. On the basis of data obtained from the USEPA's Permit Compliance System, the model includes point sources with effluent discharge of total nitrogen < 300,000 kg/yr at wastewater treatment plants and 100,000 kg/yr at major industrial facilities.

Finally, SWAT requires assignment of management operations to each land use type or HRU. The timing of the operations may be defined by a date or as a fraction of the total heat units required by the crop. The scheduling for agricultural management operations was set per

the heat unit concept, which activates operations when plants reach certain levels of growth, as expressed by the amount of heat accumulated by the plant. This approach is advantageous for regional-scale models with spatially and temporally varying climate conditions, which otherwise require detailed local and annually varying scheduling information. Another agricultural practice we considered is a filter strip applied at the down-slope edges of agricultural fields to control transport of nutrients and sediment (Helmers et al. 2008). In the absence of actual data about filter strips, we estimated their locations from land use and slope. A minimum 5-m filter strip width (USDA-NRCS, 2008) was assigned to agricultural lands with landscape slope greater than 8%. The State Soil Geographic (STATSGO) database was used for soils input.

2.4 MODEL CALIBRATION AND VALIDATION

In addition to the above physically based data sets, the SWAT model requires many basin-specific model parameters to simulate and predict watershed responses. To improve calibration efficiency and reduce the number of parameters to be calibrated, the calibration process includes (1) parameter specification using sensitivity analysis and previous study results and (2) model calibration by adjusting selected parameters that affect model response. Model validation is required to evaluate the calibrated model's ability to predict watershed responses that are not used for calibration.

2.4.1 Parameter specification

As expected in a complex, regional-scale watershed model, SWAT model calibration for the UMRB involves a large number of parameters and possibly high degrees of correlation among some parameters. This makes calibration challenging and time-consuming. Sensitivity analysis is necessary to screen model parameters for calibration. However, because of the size of the UMRB model, a detailed sensitivity analysis was not warranted. Instead, a preliminary sensitivity analysis was conducted for parameters related to the hydrologic cycle. The parameters for sensitivity analysis were selected by reviewing the SWAT manual and previous modeling studies. The model parameters specific to sediment and nutrient transport were selected on the basis of recommendations from previous studies (e.g., Santhi et al. 2001) and model fitting to corresponding measured data sets.

The sensitivity analysis was performed by using the Sequential Uncertainty Fitting (SUFI-2) procedure implemented in the SWAT Calibration and Uncertainty Programs (SWAT-CUP) developed by Abbaspour (2008). The approach uses the Latin Hypercube method to generate parameter realizations within user-specified ranges (which, in our case, are plus and minus 10% of the initial parameters values) and runs the model for different combinations of parameters to compute the calibration objective function values. The parameter sensitivities and interception coefficient, β and α in eq. 6, respectively, are then estimated by solving the following multivariate regression equation that fits a regression line to the calibration objective function values Φ against the generated parameters, b:

$$\Phi_j = \alpha + \sum_{i=1}^{m} \beta_i b_{ij} \qquad i = 1, \ldots, m; \quad j = 1, \ldots, n$$

where m is the total number of parameters included in the sensitivity analysis and n is the number of simulations. The t-test is then used to determine the relative significance of each parameter by evaluating the difference between their mean values relative to their variability (refer to Abbaspour (2008) for details). The approach assumes a linear model response to a change in parameters, and so the sensitivity values of the parameters do not vary significantly with the actual magnitude of the parameters. For large and complex watershed hydrologic models involving numerous spatially and temporally varying parameters and requiring relatively longer computational time, this assumption makes the approach computationally efficient and feasible. However, the result only represents the relative sensitivity of the objective function to a model parameter. In this study, fifty model runs were made to estimate parameter relative sensitivity. The results for relatively high-sensitivity parameters are in Table 3.

Table 3 The SWAT model hydrologic parameters selected for sensitivity analysis.

Parameters	Parameters Ranges	t-Stat	P-Value	Rank of Sensitivity
ESCO	0.2 - 0.95	8.668	1.10E-08	1
SMFMN	2 - 6	-5.918	4.94E-06	2
CN2	±10%	5.681	8.77E-06	3
GW_DELAY	15 - 40	-3.807	9.08E-04	4
SOL_AWC(1)	±10%	-2.387	2.56E-02	5
SFTMP	-3.0 - 2.0	2.364	2.69E-02	6
SNOCOVMX	0.5 - 2.5	-1.751	9.32E-02	7
CH_K2	0 - 10	-1.410	1.72E-01	8
SMFMX	2 - 6	-1.238	2.28E-01	9
SURLAG	0 - 10	-1.123	2.73E-01	10
CH_N2	0.01 - 0.09	-1.028	3.15E-01	11
SOL_K(1)	±10%	0.978	3.38E-01	12
ALPHA_BF	0.2 - 0.6	0.297	7.69E-01	13
SNO50COV	0.2 - 50	-0.155	8.79E-01	14

2.4.2 Calibration

After parameter selection by sensitivity analysis, the UMRB SWAT model was calibrated against 16 yr (1990-2006) of monthly discharge and water quality data from three USGS gauges (05331580, 05378500, and 05587455; Figure 1) located along the Mississippi River, in and near the outlet of the UMRB. Despite the primary focus on model fitting to observed data at the watershed outlet, the basin was calibrated as a whole by simultaneously evaluating the fitting results at the three calibration gauges. The drainage areas of the gauges range from 441,954 km^2 for 05587455 to 96,089 km^2 for 05331580. In addition to this variation in drainage areas, the calibration period included both extremely wet (1993) and dry (2005) years, which allowed the model to simulate a range of hydrologic and climate events. The discharge and water quality data for the gauges were obtained from the USGS National Water Information System (USGS NWIS)

database. A 3-yr warm-up (1987-1990) period was included in the model to estimate the initial soil moisture and chemical compositions.

The parameter sets identified in the preliminary sensitivity analysis (Table 3) were modified during calibration, as were water quality parameters and other important hydrologic parameters identified from literatures and fitting results to different portions of the hydrograph. This approach is consistent with White and Chaubey (2005), who emphasized the importance of adding parameters to the calibration to improve description of the processes with which fitting error is associated. Corn and soybean crop parameters, such as radiation use efficiency and base temperature for growth, were also calibrated against the USDA-NASS 2006 baseline year county-level corn and soybean yield survey data. A total of 38 parameters (18 hydrologic, 8 sediment, 9 nutrient, and 3 growth parameters; Table 4), were adjusted manually within the limits given in the SWAT user's manual (Neitsch et al. 2005). Commonly applied graphical methods such as hydrographs and frequency distribution curves were used for visual examination of the fittings between simulated and observed values.

In addition to the graphical comparison, statistical criteria such as Nash-Sutcliffe efficiency (NSE), coefficient of determination (R^2), and percent bias (PBIAS) were used to evaluate the model's predicting ability during the calibration and validation periods. The different statistical criteria can increase insight into model performance relative to observed data. The NSE indicates model performance relative to the observed mean value and is highly sensitive to occasional large error, because the squaring process gives disproportionate weight to very large errors. The R^2 measures the proportion of variability in the measured data that is captured by the model and is less affected by large errors. Both NSE and R^2 indicate the model's ability to capture variations in the observed data, but they are not very sensitive to model prediction bias, especially during low-flow periods. The PBIAS, on another hand, measures the average prediction bias as a percentage of the observed mean value and is less sensitive to large errors. In general, a lower PBIAS value indicates the model's ability to simulate the mean value of the observed data, while higher NSE and R^2 values indicate the model's ability to capture the temporal trend or variation of the observed data. More detailed explanations can be found in Krause et al. (2005) and Moriasi et al. (2007).

A systematic manual calibration procedure was employed in the study. In this procedure, the change in the basin parameters was applied uniformly over the entire subbasins, while the spatially varying parameters (such as those related to soil properties and management practices) were changed by subbasin and HRU groups. Moreover, most of the hydrological parameters are more relevant to a certain portion of the hydrograph, and so more attention was given to the fitting of the associated hydrograph portion when the hydrology parameters were calibrated. For example, snow fall and melt parameters were adjusted on the basis of the model fitting to monthly averaged flows during the winter season, while the groundwater and surface runoff parameters were calibrated on the basis of the fitting results for low- and high-flow regimes, respectively. Such a calibration approach is consistent with recommendations by Gupta et al. (1998), Boyle et al. (2000), and Moriasi et al. (2007), who emphasized the importance of applying multiple statistics and calibration procedures to sufficiently fit the different aspects of the observed hydrograph.

2.4.3 Validation

Model validation included (1) temporal validation by using flow and water quality data measured at the calibration station near the basin outlet (05587455 in Figure 1) during 2007-2008 and (2) spatial validation by using the available flow and water quality data for 1990-2008 at six additional USGS gauging stations that were not used for calibration and are located on the main river channel and its tributaries (Figure 1). The drainage area ranges from 308,209 km^2 for gauge 05474500, which is used for calibration, to 11,168 km^2 for gauge 05474000, which is used for validation. In comparison to the calibration period, the corn acreage in the validation period (2007-2008) was significantly increased because of recent increases in biofuel feedstock demand. This allowed the performance of the calibrated model to be tested under different modeling conditions.

3 RESULTS AND DISCUSSION

3.1 PARAMETER SPECIFICATION

As a result of sensitivity analysis, 14 parameters associated with the hydrologic processes were ranked in descending order, reflecting model sensitivity to parameter changes of ±10%, as shown in Table 3. The more sensitive parameters have larger absolute t-values, with near-zero p-values indicating the significance of the sensitivity. The results show that the model's estimated stream discharge is most sensitive to the soil evaporation compensation factor (ESCO), which controls the evaporation rate and thus the water yield from the subbasins, followed by the snowmelt factor (SMFMN), the Soil Conservation Service (1972) runoff curve number (CN2), groundwater delay (GW_DELAY), soil available water capacity (SOL_AWC), and other parameters in sequence. In addition to these parameters, a few others associated with hydrologic processes were selected for calibration because of their sensitivity to different portions of the hydrograph. The key parameters for sediment erosion, nutrient cycles, and crop growth were also included in the calibration process, as shown in Table 4.

3.2 CALIBRATION AND VALIDATION

After several iterations of parameter adjustment for model calibration, a set of parameters was determined (Table 4) that achieves a best fit between simulated and observed results for stream discharge, nutrient loads, and crop yields. The graphic results of the calibration and validation for the basin outlet are shown in Figure 5, while the corresponding statistics for model performance for all gauges are provided in Table 5. Figure 5 shows the monthly average hydrographs and frequency distributions of observed and predicted stream discharge, sediment and nutrient loadings at the calibration gauge near to the UMRB outlet. The flow results indicate that the model was quite capable of reproducing the general flow patterns and peak flood events at the basin outlet, with an overall values of R^2 = 0.88, NSE = 0.71, and PBIAS = -1.73% (Table 5). The average differences between the measured and simulated monthly average stream flows for all three calibration gauging stations are less than 10%.

Similarly, the model performance in predicting the nutrient and sediment load was found to be sufficiently accurate, considering the inherent uncertainties in the model simulations (Gassman et al 2007; Guse et al 2007; Krysanova and Arnold, 2009) and the observed water quality and sediment data (Harmel et al 2006). The sediment and nutrient fitting results at the UMRB outlet show reasonable correlations between measured and simulated sediment and nutrient data over the calibration and validation periods considered, with the correlation coefficients ranging from 0.65 to 0.89 and 0.71 to 0.83 for the calibration and validation, respectively. The frequency distribution figures also depict reasonable agreements between the observed and simulated frequencies distributions, indicating the ability of the model to simulate the water quality at the watershed outlet over a range of modeling conditions examined (Singh et al., 2004).

Table 4 The SWAT model parameters selected for calibration.

Calibrated Parameters	Descriptions	Files	Default Values	Allowed Range	Calibrated Value
Hydrology					
ESCO	Soil evaporation compensation factor	.bsn	0.95	0.01 - 1.0	0.68
EPCO	Plant uptake compensation factor	.bsn	1.0	0.01 - 1.0	0.4
SURLAG	Surface runoff lag time (day)	.bsn	4.0	1.0 - 24.0	3
SNOCOVMX	Minimum snow for 100% snow cover (mmH_2O)	.bsn	1.0	0.0 - 500	50
SNO50COV	Volume fraction for 50% snow cover	.bsn	0.5	0.01 - 0.99	0.5
SFTMP	Snowfall temperature (^oC)	.bsn	1.0	-5.0 - 5.0	0.0
SMFMN	Snow melt factor on Dec 21 (mm $H_2O/^oC$)	.bsn	4.5	0.0 – 10.0	3.5
SMFMX	Snow melt factor on June 21 (mm $H_2O/^oC$)	.bsn	4.5	0.0 – 10.0	5.5
GW_DELAY	Groundwater delay (day)	.gw	31.0	0.0 – 500	40
ALPHA_BF	Base flow recession constant (day)	.gw	0.048	0.0 – 1.0	0.8
REVAPMN	Threshold depth for percolation (mmH_2O)	.gw	1.0	0.0 – 500	200
GW_REVAP	Groundwater revap coefficient	.gw	0.02	0.02 – 0.2	0.1
CN2	SCS runoff curve number	.mgt	Varies	20 – 90	Varies
CH_N2	Manning coefficient for main channel	.rte	0.014	0.0 – 0.3	0.022
CH_K2	Main channel hydraulic conductivity (mm/hr)	.rte	Varies	0.0 – 150	Varies
SOL_AWC	Available water capacity (mmH_2O/mmSoil)	.sol	Varies	0.0 – 1.0	Varies
SOL_K	Saturated hydraulic conductivity (mm/hr)	.sol	Varies	0.0 – 2000	Varies
CH_K1	Tributary channel hydraulic conductivity (mm/hr)	.sub	0.5	5 – 150	12
Sediment					
USLE_P	USLE support practice factor	.mgt	Varies	0.1 – 1.0	Varies
USLE_C	USLE land cover factor	.crop	Varies	0.001 – 0.5	Varies
USLE_K	USLE soil erodibility factor	.sol	Varies	0.0 – 0.65	Varies
ADJ_PKR	Subbasin peak rate adjustment factor	.bsn	1.0	0.5 – 2.0	1.2
PRF	Channel peak rate adjustment factor	.bsn	1.0	0.0 – 2.0	1.7
CH_COV	Channel cover factor	.rte	0.0	0.0 – 1.0	0.5
CH_EROD	Channel erodibility factor	.rte	0.0	0.0 – 1.0	0.5
ROCK	Rock fragment content	.sol	Varies	-	Varies
Nutrient					
NPERCO	N Percolation coefficient	.bsn	0.2	0.01 – 1.0	0.9
PPERCO	P Percolation coefficient	.bsn	10.0	10 – 17.5	17.5
PHOSKD	P soil partitioning coefficient	.bsn	175	100 – 200	120
PSP	P sorption coefficient	.bsn	0.4	0.01 – 0.7	0.65
RSDCO	Residue decomposition coefficient	.bsn	0.05	0.02 – 0.1	0.2
N_UPDIS	N uptake distribution parameter	.bsn	20.0	-	10
P_UPDIS	P uptake distribution parameter	.bsn	20.0	-	20
CDN	Denitrification exp. rate coefficient	.bsn	1.4	0.0 – 3.0	0.8
GWSOLP	Base flow recession constant	.gw	0.0	0.0 – 1000	0.13
Crop					
BIO_E	Radiation-use efficiency for corn (Kg/ha/MJ/m^2)	.crop	39.0	0.0 – 100.0	42.2
HI	Harvest index for corn	.crop	0.5	0.0 – 1.0	0.5
BASE_T	Base temperature for corn (^oC)	.crop	8.0	-	8.5

Model performance for the rest of the gauges used for calibration is illustrated in Figure 6. Except for over-predicting the low flows (which is also evident in relatively lower NSE) at the USGS station 05378500, the model captured the flow and stream loading patterns with acceptable values of performance statistics Moriasi et al. (2007). Further adjustment of the reservoirs operation data and the base flow parameters of the model may help improving the base

flow and nitrogen loading predictions at the station. Table 5 provides the complete statistics for both calibration and validation gauges. According to Moriasi et al. (2007), the model flow simulations at most of the gauges are considered to be satisfactory, because NSE ≥ 0.50 and PBIAS ≤ ±25%. In some cases, such as validation gauge 05420500, even though R^2 is close to one and PBIAS is small, the NSE is relative small. This indicates the model's ability to capture the mean seasonal trend in stream flow much better than the monthly variations at that gauge. Compared to both R^2 and PBIAS, NSE is generally more sensitive to the fitting error with the small scale variability, which in this case is the monthly errors variability. Moriasi et al. (2007) also suggested adjusting or relaxing the above model evaluation criteria for water quality estimates, to values like PBIAS ± 55% for sediment and PBIAS ± 70% for nitrogen and phosphorus, to reflect the relatively poor quality and discontinuity of the observed data. Harmel et al. (2006) estimated measurement uncertainty for stream discharge, suspended sediment, total nitrogen, and total phosphorus under typical average hydrologic conditions to be as high as 10%, 18%, 29%, and 30%, respectively. Thus, considering the uncertainty in the observed water quality data, the performance criteria results in Table 5 can be considered satisfactory for most of the gauges.

Relatively, the monthly sediment and phosphorus predictions are not as accurate as the flow and nitrogen predictions. Several other studies have observed similar limitations of SWAT (Benaman et al. 2005; Santhi et al. 2001; Srinivasan et al. 1998; Srinivasan et al. 2010). One possible cause is uncertainty in the reservoir data and simulation. Reservoirs normally play essential roles in sediment transport and settlement, and thus more complete information regarding their capacity and operations will improve the prediction. In addition, since a majority of phosphorus in water is in the form of mineral phosphorus that becomes adsorbed onto soil particles, improving sediment transportation modeling would enhance model's prediction for phosphorus loadings. A more general discussion regarding potential sources of error associated with SWAT model input data, equations, and discretization can be found in Arabi et al. (2006), Jha et al. (2004), Kumar and Merwade (2009), Wang and Melesse (2006), and Ye et al. (2010).

The calibrated model's ability to simulate corn and soybean biomass in the region was examined to assess its simulation of spatially and temporally varying crop growth, which is essential in implementing different biofuel production scenarios. SWAT uses basin-level crop growth model parameters such as radiation use efficiency (BIO_E), base temperature for plant growth (T_BASE), and harvest index (HI) to simulate annual and perennial plant biomass and yields. Calibrating the yield estimates by using these basin-wide uniform parameters poses a formidable challenge for a large watershed, such as the UMRB, which has varying climate and land management practices. Alternatively, the crop variability across the subbasins can be represented by using different crop growth parameters in the SWAT crop growth database. However, in this study we calibrated basin-wide crop parameters and the model was able to simulate spatially varying crop biomass production with reasonable accuracy. Figure 7 depicts the simulated and observed corn and soybean yield distributions over all subbasins for the 2006 baseline year. Except for a few subbasins (located primarily in Missouri), the calibrated model simulated corn and soybean yields reasonably well, with overall differences of 1.70% and -1.88% for corn and soybean, respectively.

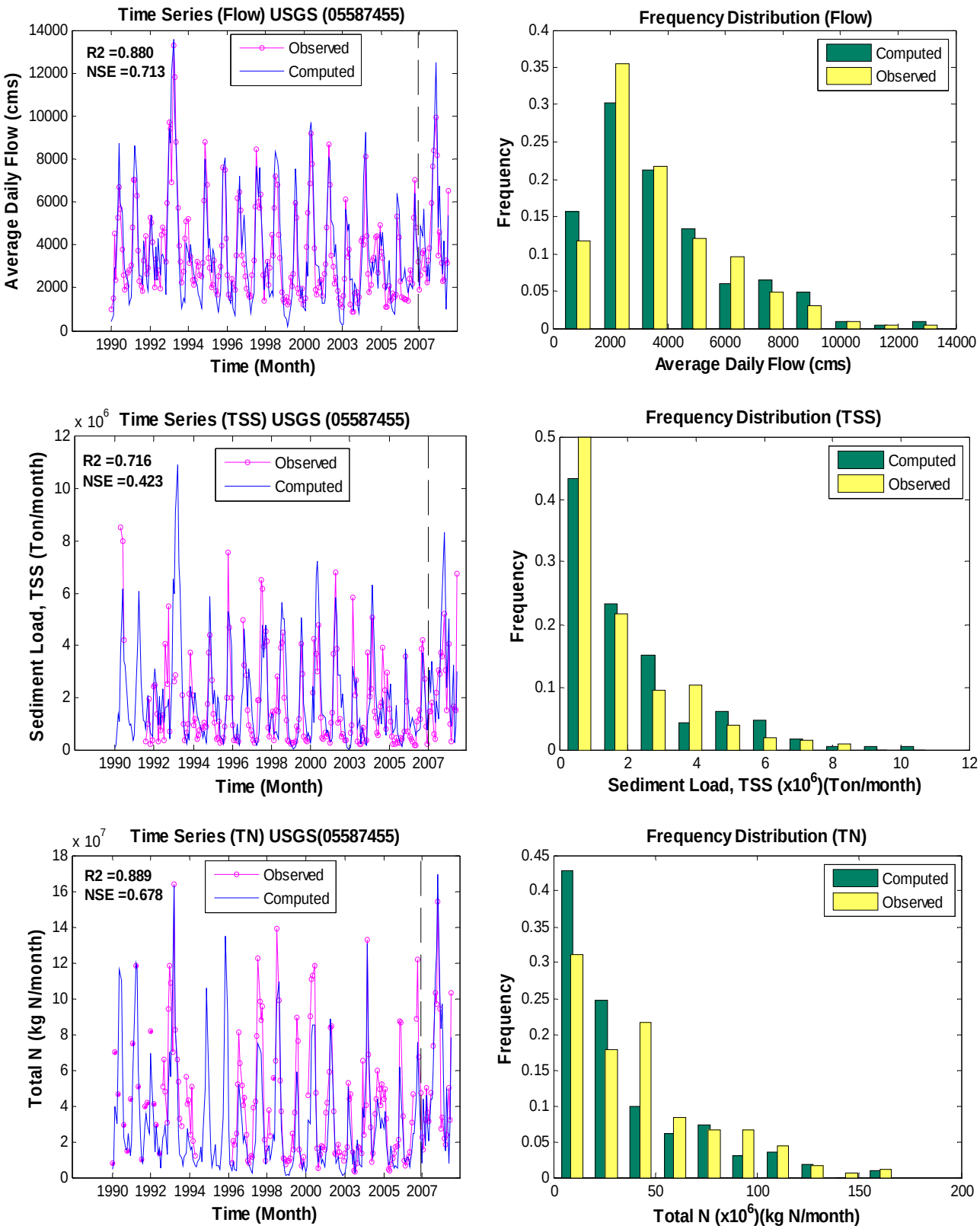
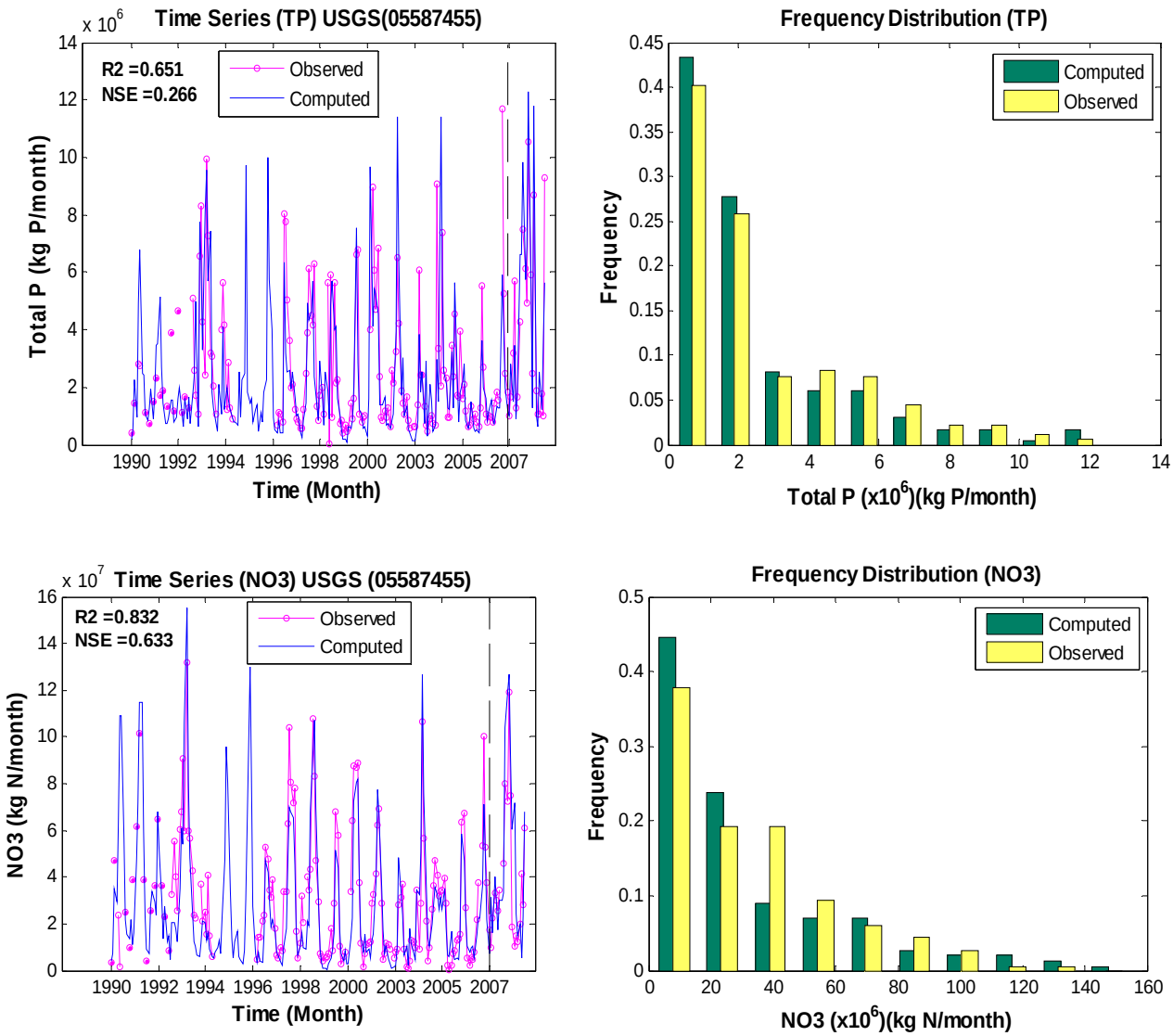


Figure 5 Predicted and observed flow, sediment and nutrient loadings during the calibration (1990-2006) and validation (2006-2009) periods at the USGS gauge – 05587455 – located close to the outlet of the UMRB.



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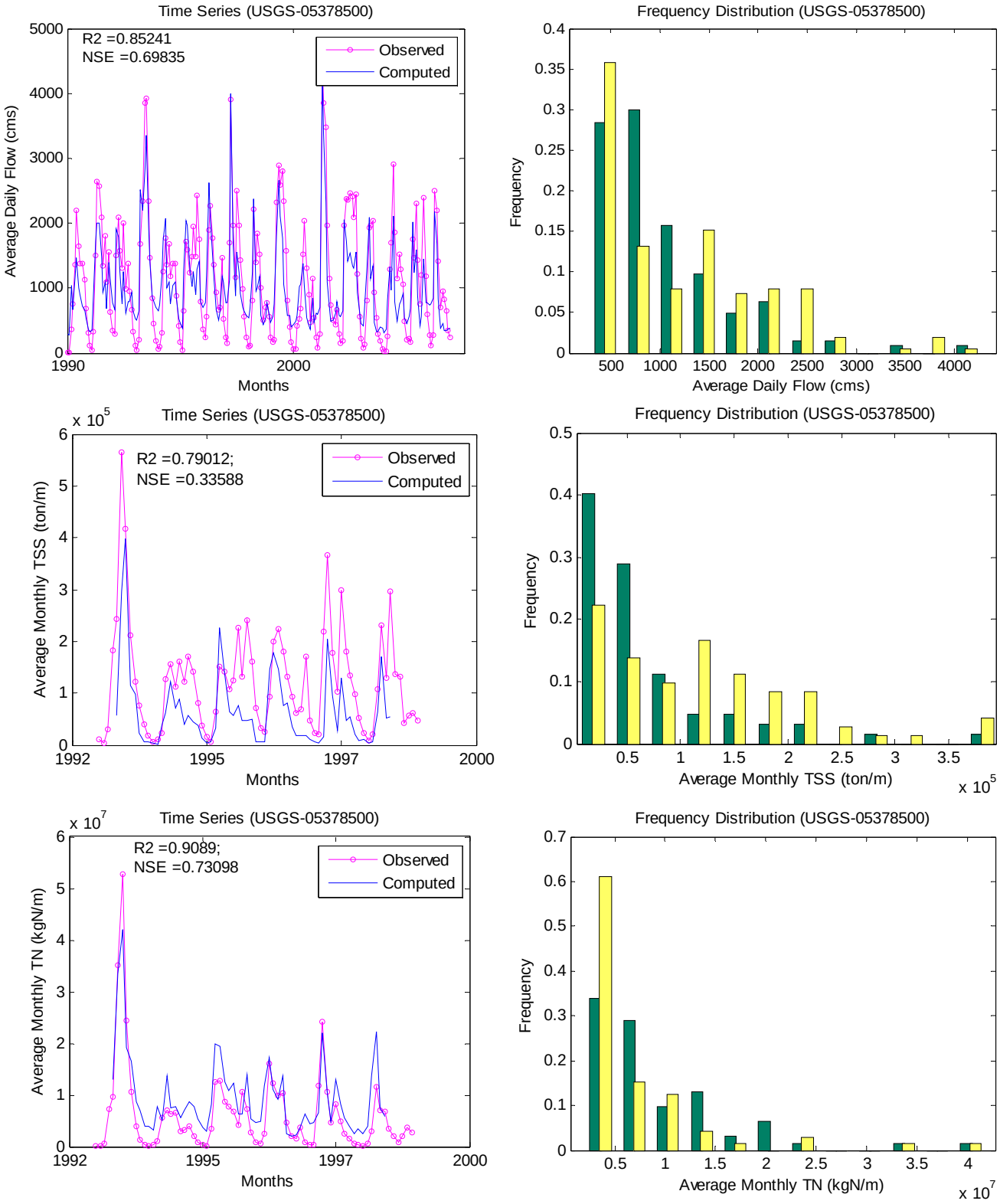
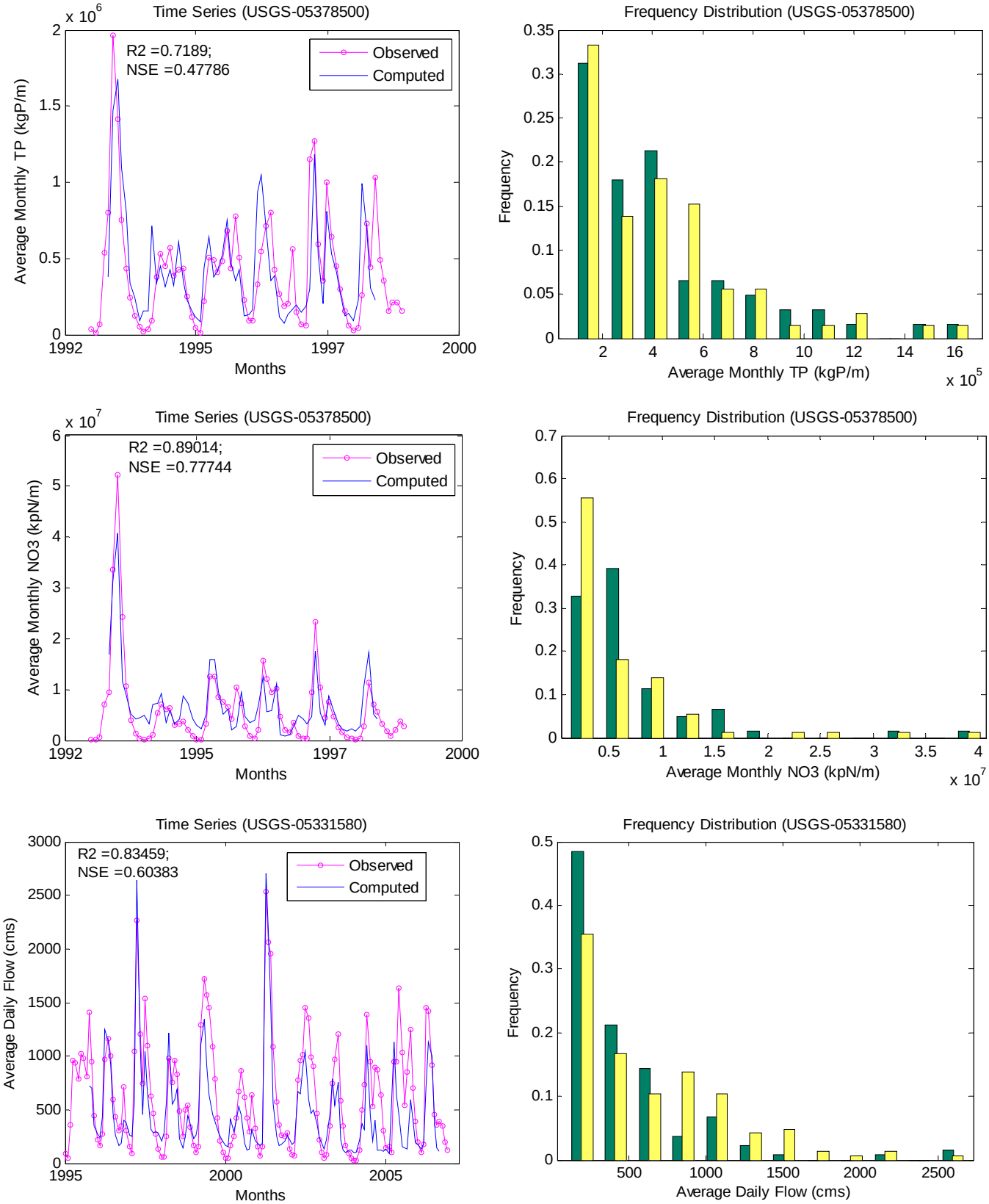


Figure 6 Observed and predicted flow and loadings at the calibration gauges located within the UMRB.



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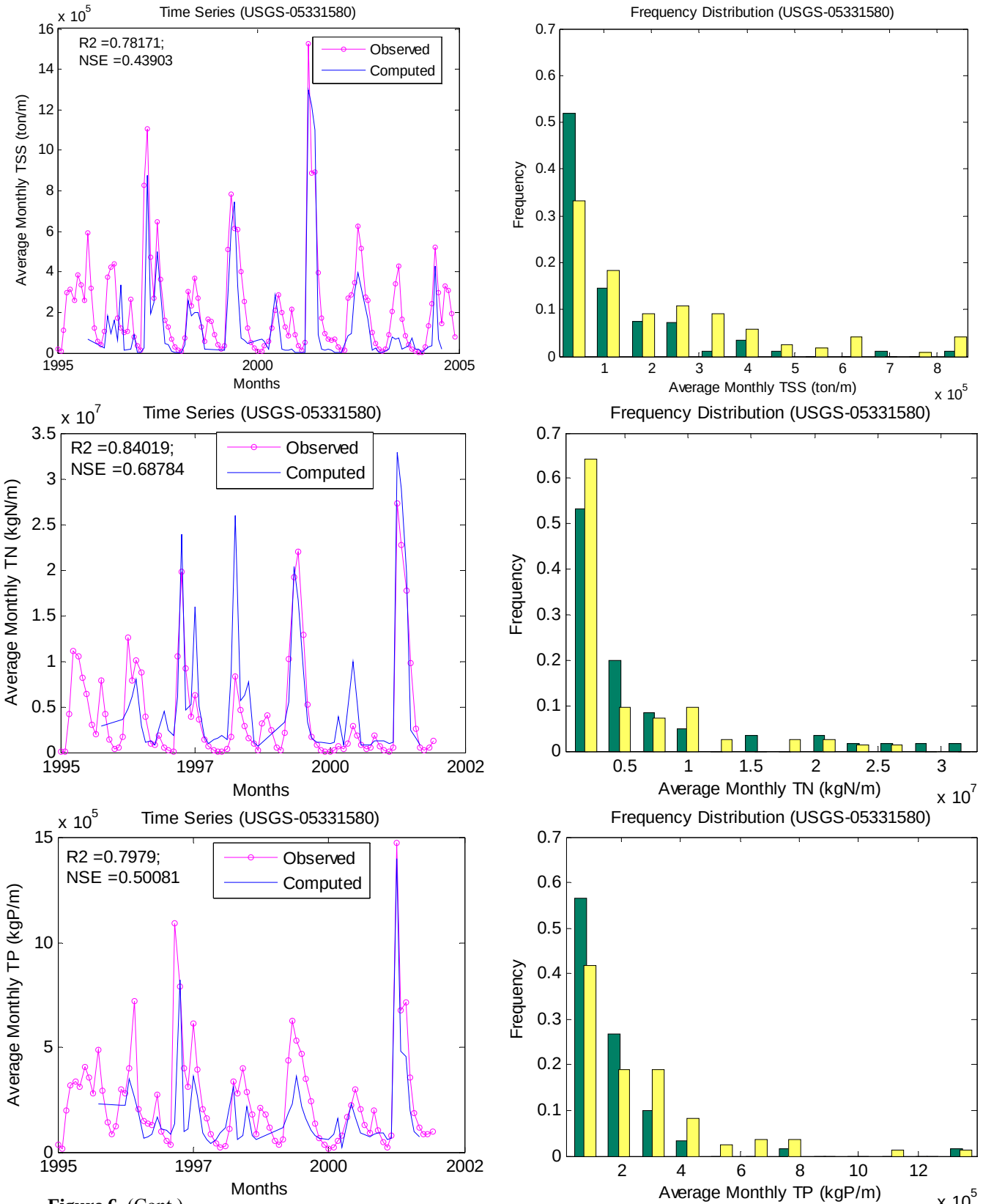

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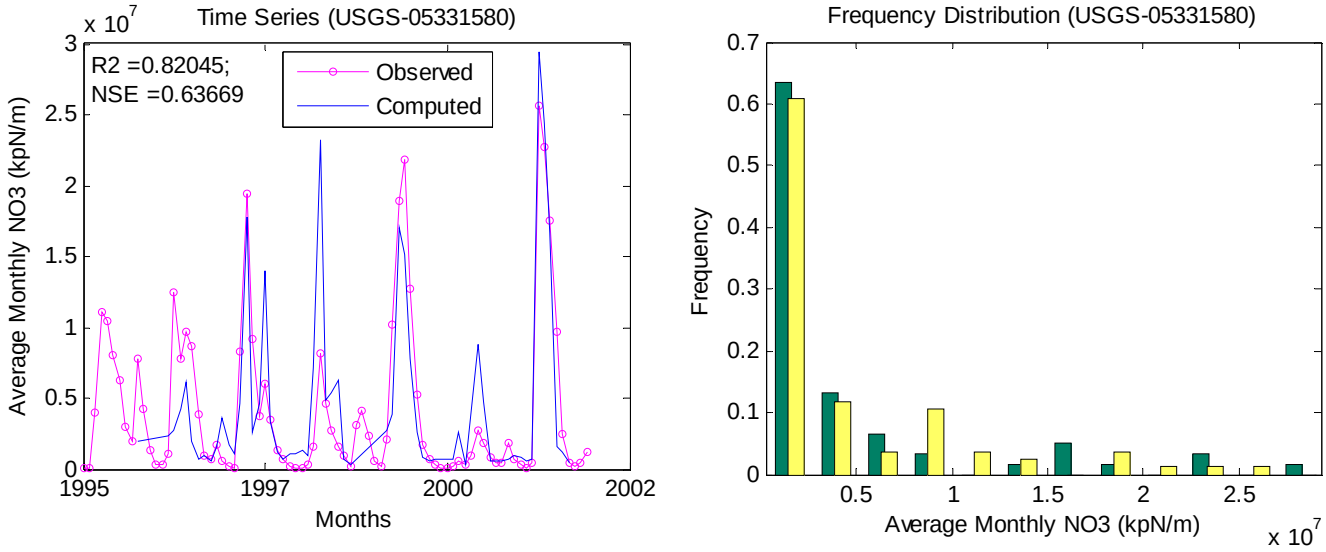

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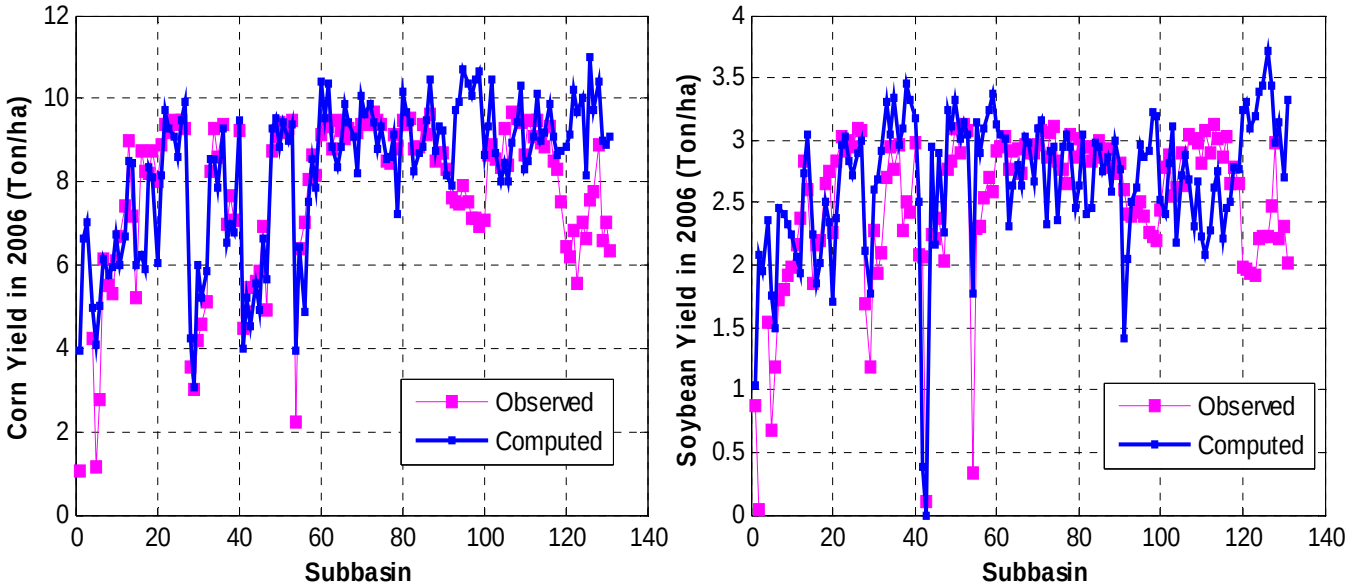

Figure 7 Observed and computed subbasin average corn and soybean yields within the UMRB during the baseline year (2006).

Table 5 Summary statistics for model performance.

Data Usage	USGS Gauges	Drainage Area (km^2)	Statistical criteria	Flow	TSS	TN	TP	NO_3^-
Calibration	05331580	96,089	R^2	0.84	0.78	0.84	0.80	0.82
			NSE	0.61	0.44	0.69	0.50	0.64
			PBIAS	25.10	35.78	-15.96	35.44	4.33
	05378500	152,736	R^2	0.85	0.79	0.91	0.72	0.89
			NSE	0.70	0.34	0.73	0.48	0.78
			PBIAS	9.56	49.92	-18.82	0.24	-7.97
	05587455	441,954	R^2	0.88	0.72	0.89	0.65	0.83
			NSE	0.77	0.42	0.68	0.33	0.64
			PBIAS	1.69	9.41	-37.50	-5.92	-9.52
Validation	05587455	441,954	R^2	0.76	0.78	0.79	0.73	0.81
			NSE	0.67	0.71	0.63	0.58	0.59
			PBIAS	4.80	14.07	10.50	16.84	21.16
	05420500	221,703	R^2	0.86	0.71	0.87	0.81	0.84
			NSE	0.42	0.36	0.66	0.55	0.31
			PBIAS	-8.18	25.47	10.80	-2.39	31.87
	05474000	11,168	R^2	0.87	0.72	0.80	-	-
			NSE	0.76	-0.11	0.54	-	-
			PBIAS	-2.74	94.68	25.61	-	-
	05389500	174,825	R^2	0.84	0.78	-	-	-
			NSE	0.36	0.56	-	-	-
			PBIAS	-7.32	-5.28	-	-	-
	05465500	32,375	R^2	0.93	0.84	-	-	-
			NSE	0.82	0.53	-	-	-
			PBIAS	19.15	38.03	-	-	-
	05369500	23,336	R^2	0.75	-	-	-	-
			NSE	0.26	-	-	-	-
			PBIAS	-9.15	-	-	-	-
	05474500	308,209	R^2	0.86	-	-	-	-
			NSE	0.50	-	-	-	-
			PBIAS	-8.32	-	-	-	-

3.3 UMRB CONTRIBUTION TO THE MISSISSIPPI RIVER

The 4-yr (2003-2006) annual average stream discharge, nutrient, and sediment loads at the basin outlet are provided in Table 6, with measured (from USDA NASS) and computed yields for corn and soybean harvest from the entire basin during baseline year 2006. The results show a reasonable match between the measured and computed values, indicating the model's ability to adequately simulate both the agricultural and hydrologic processes in the basin. The stream discharge and loading estimates at the basin outlet can be viewed as the contribution of the UMRB to the lower Mississippi River basin, and provide insight into potential impacts of increased biofuel feedstock development in the region on the greater Mississippi River basin. Based on USEPA's (2010) estimates that 33% of the corn produced in the region is used for ethanol production and USDA's estimates of 2.7 gallons of ethanol per bushel of corn conversion efficiency (Baker and Zahniser 2006), the UMRB can produce about 3.39 Billion Gallon (BGal) of ethanol during the 2006 baseline year.

Table 6 Observed and predicted stream discharge and water quality at the basin outlet (annual averaged for 2003-2006), as well as corn and soybean yields from the entire subbasin during the baseline year 2006.

	Station	Flow (cm)	Sediment (10^6 ton)	TN (10^6 kg N)	NO_3 (10^6 kg N)	TP (10^6 kg P)	Corn Yield (10^6 dry ton)[a]	Soybean Yield (10^6 dry ton)[a]	Ethanol (billion gal)[a]
Computed	Basin Outlet	3,300	22.854	336.612	290.318	27.267	96.472	24.430	3.39
	Grafton	2,960	17.278	290.171	266.876	22.034			
Observed	Grafton	2,771	15.757	329.828	259.928	23.929	94.862	24.898	

[a] Corn and soybean yields harvested during 2006 from the entire basin. The ethanol production is estimated by using 33% of the corn production and 2.7 gal per bushel ethanol conversion efficiency.

3.4 BIOFUEL SCENARIOS

An increase in corn production for biofuel could be achieved by increased corn acreage, progress in agricultural technology, changes in corn rotation, improved management practices, increased use of fertilizer, and advances in crop biotechnologies — the major contributor to a continuous increase in U.S. corn yield in the last 40 yr (Edgerton 2009; Egli, 2008; Tannura et al. 2008). In addition, next-generation biofuel will move toward high-carbon, cellulosic-based sources. Among these, agricultural residues including corn stover play an important transitional role from grain-based first-generation biofuel feedstock to cellulosic biofuel feedstock (USDOE, 2011). The harvest of corn stover for cellulosic biofuel production has been researched extensively in the past decade (Blanco-Canqui et al. 2007; Blanco-Canqui and Lal 2009; Karlen et al. 1994; Mann et al. 2002). To evaluate the potential impact of biofuel feedstock production on the UMRB, we conducted scenario analyses related to changes in the calibrated corn growth parameters representing the future increase in corn yield, crop rotations, fertilizer application rates, and stover removal for cellulosic biofuel and associated soil properties.

3.4.1 UMRB responses to change in corn rotation

Despite the sharp increase in corn production, the total number of acres planted to the major UMRB crops (corn, soybean, and hay) has been relatively constant over the last decade. The USDA-NASS estimated 23.2 million hectares in 2001 and 22.7 million hectares in 2008 planted to corn, soybean, and hay in the UMRB, an overall decrease of approximately -1.78%. However, during the same period the planted corn acreage increased by 12.1%, while the soybean and hay acreages decreased by 13.9% and 16.2%, respectively. The average corn yield increased by 12.6% over the same period. Thus, the recent increase in corn production has been accomplished largely by the conversion of existing agricultural lands from soybean and hay to corn.

Agricultural lands, including pasture and hay, cover about 64% of the UMRB area. Approximately half of these areas were under 4-yr rotations of corn, soybean, wheat, and hay in 2003-2006. All of the major 4-yr crop rotations identified in this study contain at least 1 yr of corn. We tested the watershed's response to crop rotations more dominated by corn (for

increased corn production for biofuel) by changing lands with 1 yr and 2 yr of corn in the rotations to 3-yr corn rotations. Figure 8 shows the spatial distribution of the 3-yr corn intensity after conversion of the 1-yr and 2-yr corn intensities, so that corn is grown either continuously (Figure 3d) or intensively for 3-yr out of 4-yr (Figure 8). The final land use map contains about 14.8 and 2.6 Million Ha corns under 3-yr and 4-yr rotations, respectively. The calibrated model was rerun using this new land use and adjusting the corresponding management operations. The resulting changes in discharge and water quality were analyzed at the subbasin and basin outlets.

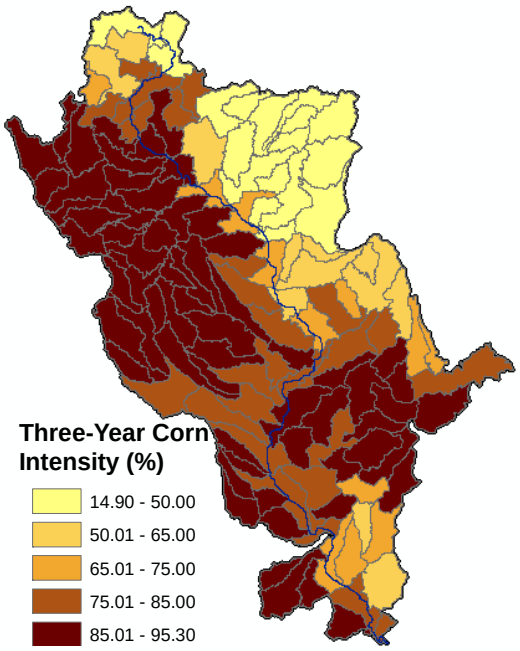

Figure 8 Spatial distribution of 3-yr corn intensity after converting 1-yr and 2-yr intensities to increase corn production for biofuel.

Figure 9 shows the 4-yr (2003-2006) average changes in corn yield, flow, sediment, total nitrogen and phosphorus, actual evapotranspiration, and soil moisture content over all subbasins as a result of the change to rotations more dominated by corn. The solid bars in the figure represent the average changes over all subbasins, while error bars represent the standard deviations of the changes and show the highest variation for suspended sediment. On average, corn yield, evapotranspiration, suspended sediment, and nitrogen and phosphorus loadings from subbasins increased by 40.9%, 0.9%, 4.6%, 4.3%, and 7.7%, respectively, while average soil moisture and flow decreased by 1.2% and 3.4%. At the UMRB outlet, the total nitrogen and phosphorus loads in the stream increased by 4.5% and 4.7%, respectively, while the flow and suspended sediment decreased by 2.6% and 3.3%, respectively. Although the average suspended sediment contribution from the subbasins increased (Figure 9), its value at the basin outlet decreased. This might be caused by decreased stream flow, which in turn leads to reduced erosion from the river channel and increased sediment deposition. The 4-yr average corn yield

from the entire UMRB increased from 91.8 to 121.8 million tons in response to the simulated change in crop rotation. Using USEPA's (2010) estimates of 33% ethanol-to-corn production ratio and USDA's estimates of 2.7 gallon per bushel corn-to-ethanol conversion ratio (Baker and Zahniser 2006), the change in the corn rotation can increase the ethanol production from 3.39 to 4.54 billion gallons (BGal). These assumptions do not include the potential change in fraction of corn production used for ethanol and increase in future corn yield, ethanol conversion efficiency, and fertilizer applications rate because of the intensive corn production.

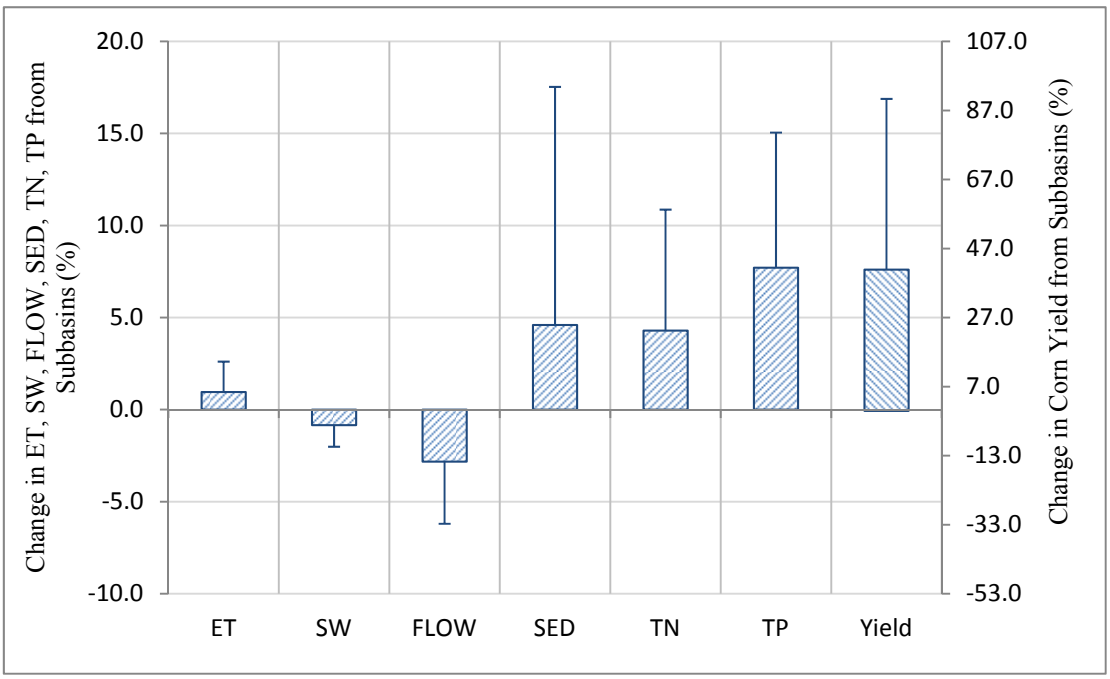

Figure 9 Effects of changes in crop rotation for biofuel on subbasin hydrology and corn yield. The solid bars represent the mean change, while the error bars represent the standard deviation of the change over the subbasins.

3.4.2 UMRB responses to crop yield improvement

Because of the advances in crop genetics, the annual-average U.S. corn yield has been steadily increased since the 1980s even as fertilizer application rates leveled off or declined (Malcolm et al. 2009). This increasing trend is expected to continue for the near future (USDA 2009). The increase in corn biomass may be achieved by increasing in Leaf Area Index (LAI) and/or increasing photosynthesis (Horton 2000). With the calibrated UMRB SWAT model, we explored the potential implications of increased corn yield resulting from increased photosynthesis by re-running the model after perturbing values of the corn radiation use efficiency (BIO_E) parameter by 10% from the calibrated values. Figure 10 illustrates that the increase in corn radiation use efficiency led to relatively minor increases in subbasins average stream discharge (up to 0.2%), sediment (up to 0.4%), and phosphorous loading (1.4%) but to a significant increase in total corn yield (6.5%) in the UMRB and a decrease in subbasins average

nitrogen loading (2.3%). The ethanol production increased to 3.61 BGal with the 10% increase in the corn radiation interception efficiency (Bio_E). The increase in flow might be explained by the increased soil moisture content near the land surface caused by reduced soil evaporation rate and the plant's ability to bring more water from the subsurface to the near-surface soil as its grows larger. Plants in the region do not normally experience serious water stress, and excess water can leave the subbasins as surface and subsurface runoff. An increase in sediment loading possibly associated with increased surface runoff might offset the better erosion control provided by large plants. The increase in phosphorous loading might be caused by increases in mineral phosphorous accompanying the increased sediment. Since the fertilizer application rate is fixed, the extra phosphorus might have come from increased amount of corn residue left on ground after harvest. The increased phosphorous may also indicates that the current or baseline rate of phosphorous application is already higher than what corn requires to grow at higher rate or that the soil has been saturated with phosphorus. Thus, not only is increased phosphorus fertilizer input unnecessary for the crop, but it could become an additional environmental burden. However, in contrast to the phosphorus response, nitrogen loading decreases as corn Bio_E increase, implying improved corn nitrogen uptake efficiency when it grows larger. Because of this improvement, the corn can absorb and use for growth more nitrogen from the same level of fertilizer input. As a result, less nitrogen fertilizer is retained in the soil to later leak to groundwater and enter surface streams via runoff, thereby reducing total nitrogen loading in the basin.

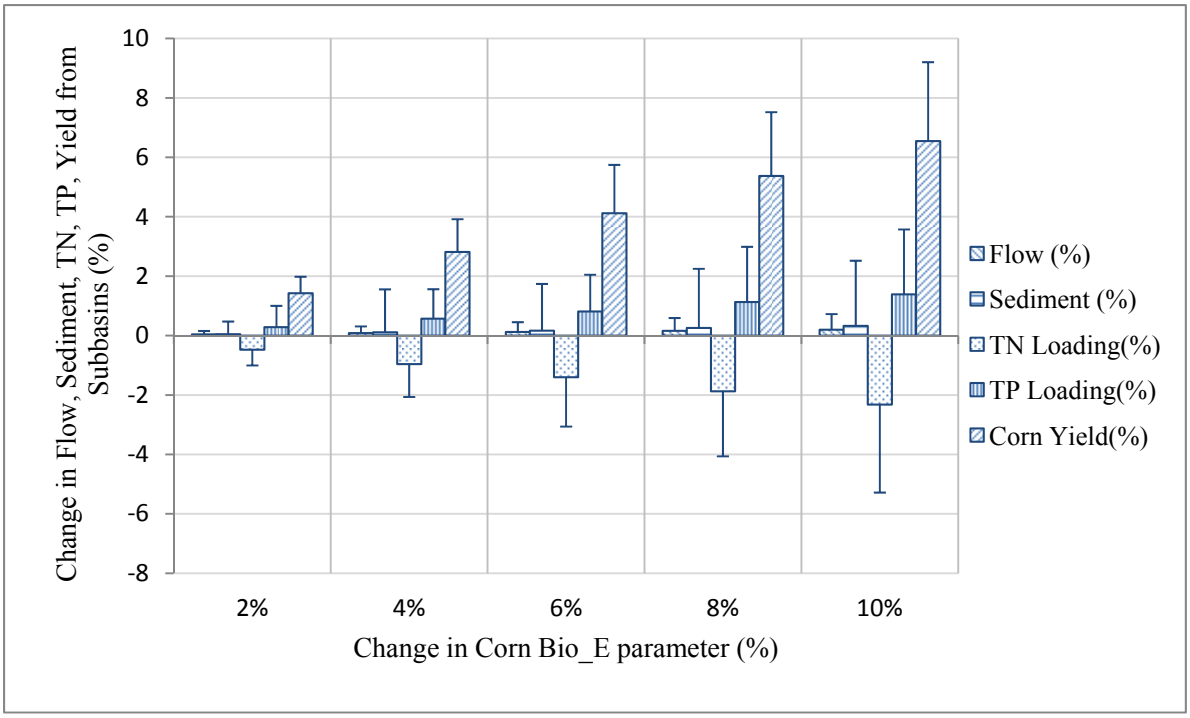

Figure 10 Effects of increased radiation use efficient (BIO_E) of corn on subbasin contributions of flow, nutrient, and yield. The solid bars represent the mean change, while the error bars represent the standard deviation of the change over the subbasins.

In general, the watershed response to change in corn growth parameter indicate that crop yield is very sensitive to the model's plant growth parameters; this could have moderate to significant effects on the stream water discharge and quality. Thus, the results suggest the importance of validating the model's performance in simulating plant growth by comparison with observed biomass production data. This is especially important when the model is applied to simulate biofuel production scenarios involving future increases in crop yield.

3.4.3 UMRB responses to change in fertilizer application rate

As market prices for corn increase because of increased demand for biofuel, producers might try to achieve greater yields on existing cropland. To increase yields per unit area and maximize profitability, corn producers often increase nitrogen and other fertilizer applications. We used the calibrated UMRB SWAT model to evaluate the potential implications of a change in fertilizer application rate over current corn land by gradually varying the application rate from -50% to +50% of the current value. The watershed's global response (Figure 11), which reflects the overall response of the basin to the induced change, was determined by considering the impact at the basin outlet, while the local responses (the spatial distribution of the impact to both corn yield and water quality, Figure 12) were determined by calculating the impact at the subbasin outlets. The subbasin results can be used to identify the most productive regions (those having higher yield and minor water quality impact) or sensitive regions for implementing effective land-management strategies to reduce water quality impacts while increasing corn yield via increased fertilizer inputs. Compared to the previous two biofuel production related changes, the watershed outlet results (Figure 11) indicate that increasing nitrogen fertilizer application rates from the current rates leads to a relatively small increase in overall corn yield (about 4.5% increase for 50% increase of nitrogen fertilizer) but a large increase in total nitrogen loading at the basin outlet (about 34% increase for 50% increase of nitrogen fertilizer). On the other hand, the nutrient loadings are more sensitive to an increase in fertilizer inputs rates than to a decrease. The nitrogen loading in the stream decreased only by about 22% with a 50% reduction in the nitrogen fertilizer application on cornfields.

Similarly, at the subbasin level, Figure 12a illustrates that a 30% increase in nitrogen application rate resulted in less than 10% increase in corn yield for about 80% of the 131 subbasins in the UMRB. The cluster of solid lines indicates that most of the subbasins did not respond to the increase in nitrogen application. On the contrary, reducing the nitrogen application rate had a significant impact on corn yield in most of the subbasins. For example, 30% reduction in the nitrogen application rate resulted in at least 10% decrease in corn yield for more than 60% of the subbasins. These results suggest that the current nitrogen application rates are very near the optimum value.

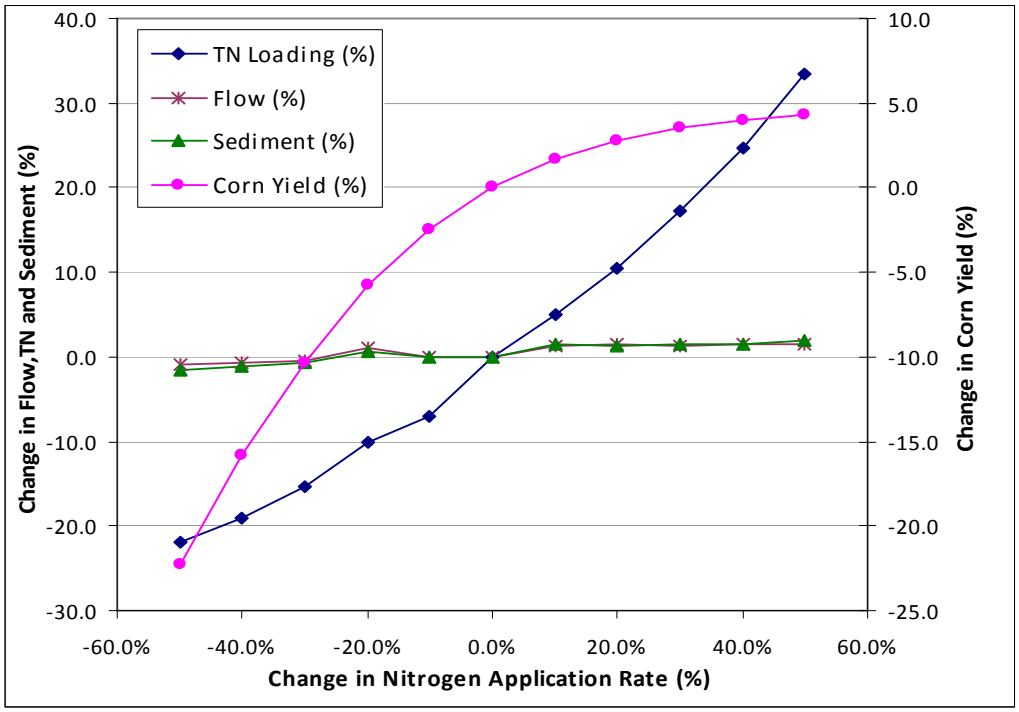

Figure 11 Effects of nitrogen fertilizer application rates on the model results at the basin outlet.

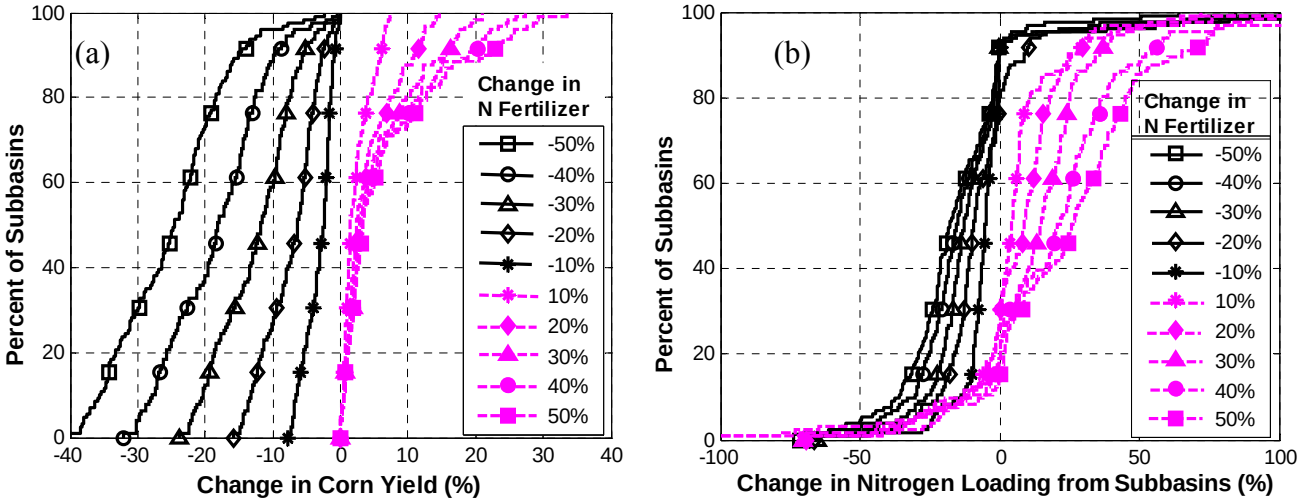

Figure 12 Effects of nitrogen fertilizer application rates on subbasin corn yield and nitrogen loading, showing the spatial distribution of the impacts of change in nitrogen application rate for cornfields.

These data further suggest that nitrogen uptake efficiency is an important limiting factor for improved corn yield. If increased nitrogen inputs are not being absorbed by the crop, a large part enters the water body. Figure 12b shows that the change in nitrogen discharge with increased nitrogen application varies among subbasins. About 30% of subbasins have no significant increase in nitrogen loading with 30-50% increases in nitrogen application, while in the other 70% (30% to 100% of subbasins as plotted in Figure 12b), nitrogen discharge increases by 10% to > 100%. Among the 70% of subbasins that are sensitive to increased nitrogen application, about 15% are responsible for more than 50% of the increased nitrogen loading at the basin outlet.

A similar analysis for phosphorus application rate did not show a noticeable change in corn yields with increased application rate, indicating that the current rate of phosphorus application is already higher than that required for corn plant growth. Unlike to nitrogen, which can easily leave the watershed by plant uptake, leaching, surface runoff, and volatilization, phosphorus can be retained in the soil for longer period, leading to possible accumulation over the years.

3.4.4 UMRB responses to corn stover harvest and associated soil properties changes

Ethanol can also be produced from existing corn land by harvesting the stalk, leaves, and cobs – materials that are also known as stover and are commonly left on the field after harvesting corn grain. The potential impact of harvesting stover on water resources are examined using different levels of stover harvest in the calibrated UMRB model. As shown in Figure 13, the watershed responds significantly to the stover harvest, showing a decrease in stream discharge, suspended sediment, nitrogen, and phosphorus loadings. The total above-ground corn biomass is also decreased as more stover is harvested from the field. The decrease in stream discharge might be caused by the resulted increase in evaporation from the soil surface as harvesting stover can lead to soil temperature increase and decrease infiltration (Flerchinger et al. 2003; Horton et al. 1996; Johnson and Barbour, 2010; Sauer et al. 1996) and thereby decreases the baseflow component of the discharge. Contrary to our expectation, the suspended sediment loading is decreased over the stover harvest levels we considered. One possible explanation is that even if the rain drop impact (or erosive force of rain) increases with stover harvest, this impact might be offset by the reduction in stream discharge within the subbasins. This tradeoff seems apparent from a gradual increase in sediment loading as more stover is being harvested (Figure 13). Harvesting stover could also remove nutrients and carbon contained in the stover, which in return leads to a decrease in nitrogen loading in the stream and a gradual decline in crop biomass production if these nutrients are not added to the soil as supplementary. Using USDA's estimate of 72 Gal of ethanol per ton of dry stover (Baker and Zahniser, 2006) conversion, 80% of the corn stover with corn grain can produce about 8.24 BGal (i.e. more than half of the 15 BGal national target) of ethanol.

Table 7 Effects of soil property changes associated with stover harvest on the model results at the basin outlet.

Stover Harvest Level (%)	Ksat (factor)	Bulk Density (% addition)	AWC (% addition)	Flow (%)	TSS (%)	TN (%)	TP (%)
20	1/1.4	2	-2	-4.24	-3.72	-9.46	2.7
40	1/2.8	4	-4	-4.38	-4.37	-8.74	0.97
60	1/4.2	6	-6	-3.98	-4.15	-7.98	0.89
80	1/5.6	8	-8	-4.07	-4.75	-7.99	-0.15
100	1/7.0	10	-10	-4.47	-5.67	-9.06	-1.05

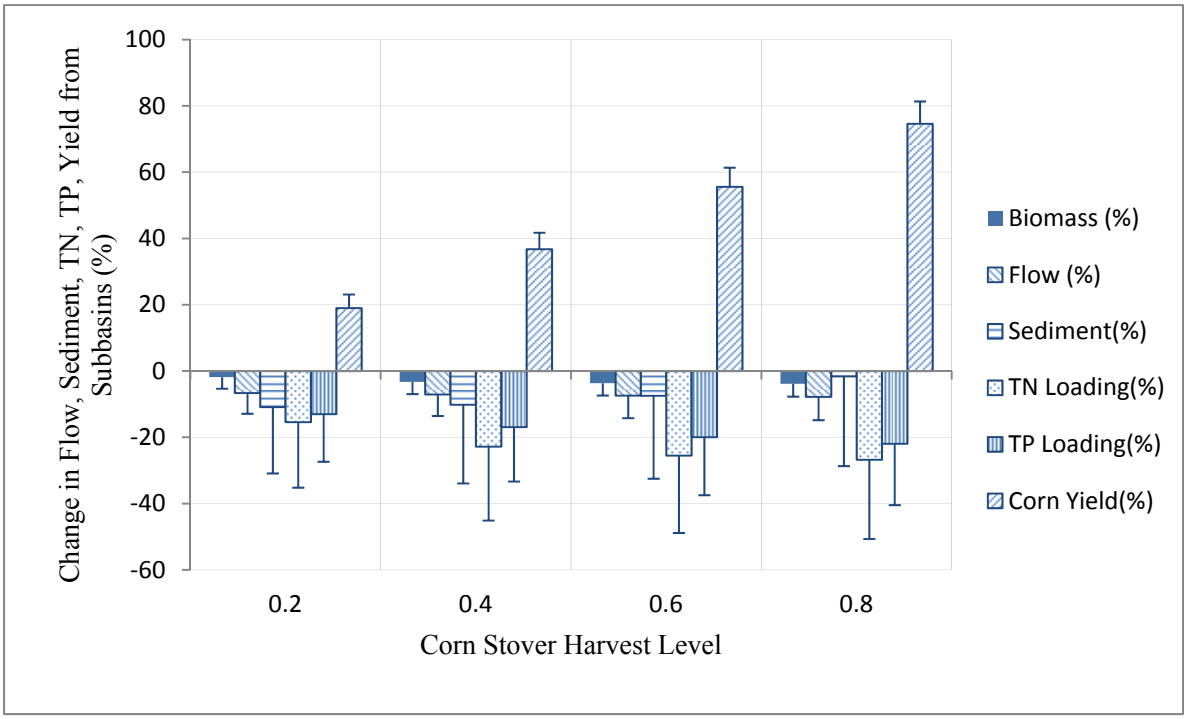

Figure 13 Effect of harvesting corn stover on subbasin contributions of flow, nutrient, and yield. The solid bars represent the mean change, while the error bars represent the standard deviation of the change over the subbasin.

Removing some of the stover at harvest might adversely affect soil quality in long-term (Blanco-Canqui et al. 2007; Blanco-Canqui and Lal 2009; Wilhelm et al. 1986).To use the calibrated UMRB SWAT model to investigate the potential implications of a change in soil properties due to harvesting of corn stover for cellulosic feedstock, we gradually adjusted relevant soil properties in accordance with levels of corn stover harvest. Based on a 10-yr field experiment in the Midwest, Karlen et al. (1994) found no noticeable change in soil properties as a result of corn stover removal. However, subsequent studies by Blanco-Canqui et al. (2007) and Blanco-Canqui and Lal (2009) indicated increased soil bulk density and surface runoff as well as decreased soil saturated hydraulic conductivity and plant available water content as more corn stover are harvested from the field. As a conservative approach to estimate the watershed response via the UMRB SWAT model, we used the estimate of Blanco-Canqui et al. (2007) for

changes in soil properties corresponding to corn stover harvest and ran the model with and without adjustments in soil properties for levels of stover harvested from 0% to 100%. Table 7 shows the resulting difference between the two model runs. In comparison with the unadjusted soil properties, considering soil property changes in accordance with the level of stover harvest would increase flow and sediment loading by 4% and nitrogen by 9% at the basin outlet. On the other hand, the impact of phosphorus loading could be positive or negative, depending on the level of stover harvest. Since soil property change is a relative slow process, these results highlight the need for further study of the long-term effect of harvesting corn stover on soil hydraulic properties, as well as for its accurate representation in watershed modeling.

3.4.5 UMRB responses to the Billion Ton Study projection of feedstock production

The recently updated "Billion Ton Study" (BT2) (USDOE 2011) assessed U.S. feedstock potential for the sustainable production of biofuel to replace 30% of the nation's transportation fuels by 2030. The study evaluated feedstock resources under different future scenarios of crop yield and feedstock prices. Assuming moderate (approximately 1%) increases in annual crop yield and a feedstock price of $40-60 per dry ton, the study estimated a potential annual increase in U.S. biomass production from the current 473 MDT to nearly 1,100 MDT by 2030. This increase in feedstock production is expected to be achieved mostly by converting croplands and pasturelands to energy crops, changing current cropping patterns and management, increasing crop yield per acre, and harvesting crop and forest residues. Consequently, nearly 8.9 million hectares of cropland and 16.6 million hectares of pasturelands could shift to energy crops by 2030. An additional 140-270 MDT of corn stover could be harvested sustainably from most no-till and reduced-till croplands by 2030.

The calibrated SWAT model was applied to quantify the potential effects of the projected feedstock production on UMRB water resources and quality. The relatively conservative feedstock production scenario selected from the BT2 assumes a feedstock price of $50 per dry ton and an annual crop yield increase of 1%. Unlike previous biofuel-related watershed modeling studies for the UMRB (Donner et al. 2008; Secchi et al. 2011; USEPA 2010), which are restricted to corn land changes, the present work incorporates combined changes in land use types, stover harvest, fertilizer application, tillage practices, and corn yield to represent the biofuel feedstock projected by the BT2. Figure 14 shows the main changes in land use and agricultural management. Specifically, the implementation of the BT2 scenario involves changing the model's HRUs to represent the projected land use changes, adjusting the corn growth parameters to represent future advances in crop genetics, harvesting some portions of the corn stover from no-till or reduced-till areas, adjusting the fertilizer application rates for corn on the basis of the projected yield and the amount of stover harvested, and changing the tillage practices for corn per the BT2 tillage projection.

The impacts on the basin water resources and quality — including evapotranspiration; soil moisture content; stream discharge; and sediment, nitrogen, and phosphorus loadings — were analyzed by comparing the BT2 results with the results obtained from baseline and business-as-usual (BAU) scenarios having no biofuel-related land use and management changes.

The future BAU scenario used the same corn yield projection as BT2 and was applied to the model similarly. The fertilizer application rates were adjusted on the basis of projected corn yield increases. However, unlike the BT2 scenario, the BAU scenario did not involve land use changes and stover harvest for the purpose of increasing biofuel production.

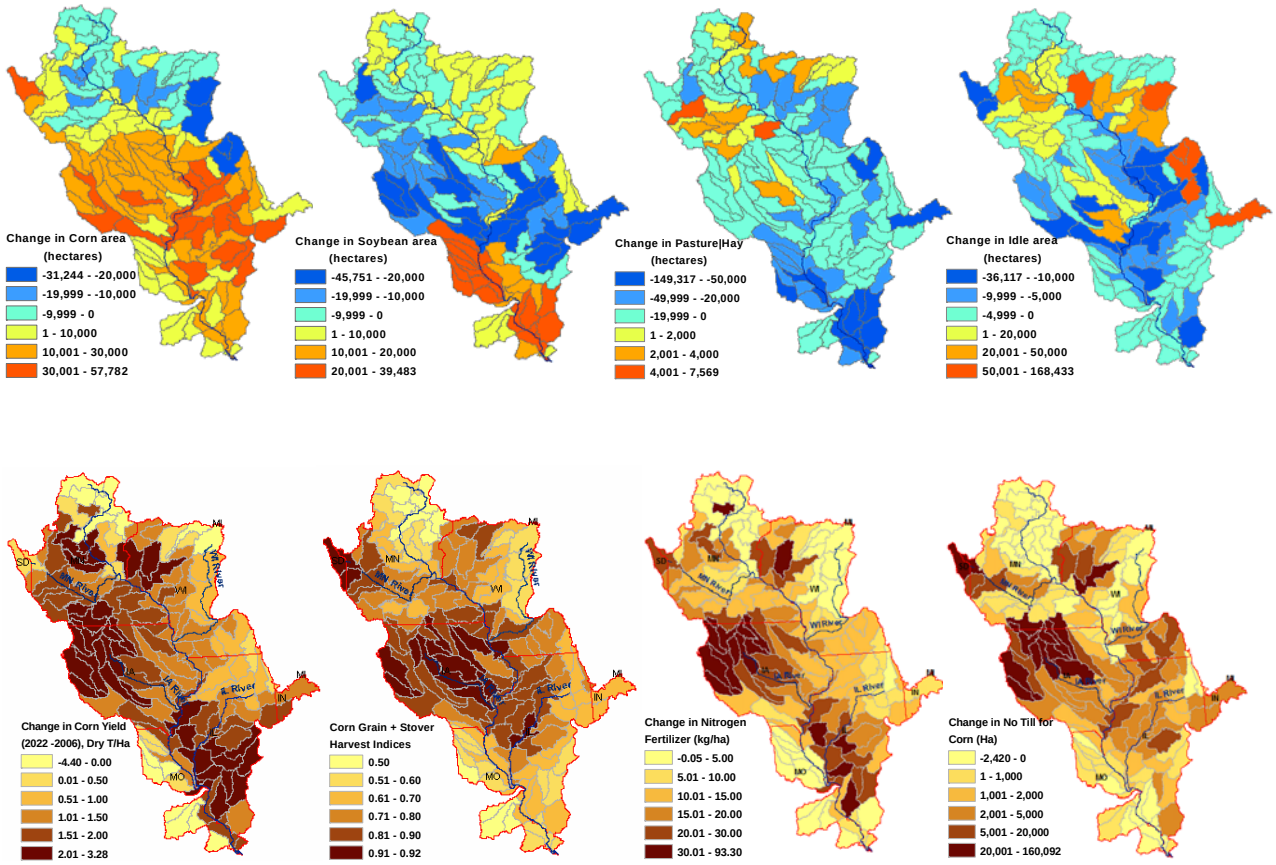

Figure 14 Spatial distributions of projected land use changes, stover harvest, corn yield increase, fertilizer application, and tillage changes in the UMRB under the BT2 scenario.

Figure 15 provides the basin average annual water quantity and quality results for the baseline and projection years. The average annual results show that projected biomass production for biofuel is expected to increase the annual rate of evapotranspiration from the UMRB by approximately 1.8% and to decrease soil water content and discharge to streams by nearly 1.9% and 4.6%, respectively. The BAU scenario, in contrast, has minor impact on the basin's annual hydrology. Although most of the crop farms in the region do not currently require irrigation, the predicted gradual reduction in soil moisture, along with the need to boost crop yield in the future, might lead to increased irrigation, which in turn could affect streams and groundwater in the region. On the positive side, because the region is frequently affected by floods, the reduction in soil moisture and runoff might decrease flooding if the future climate remains unchanged.

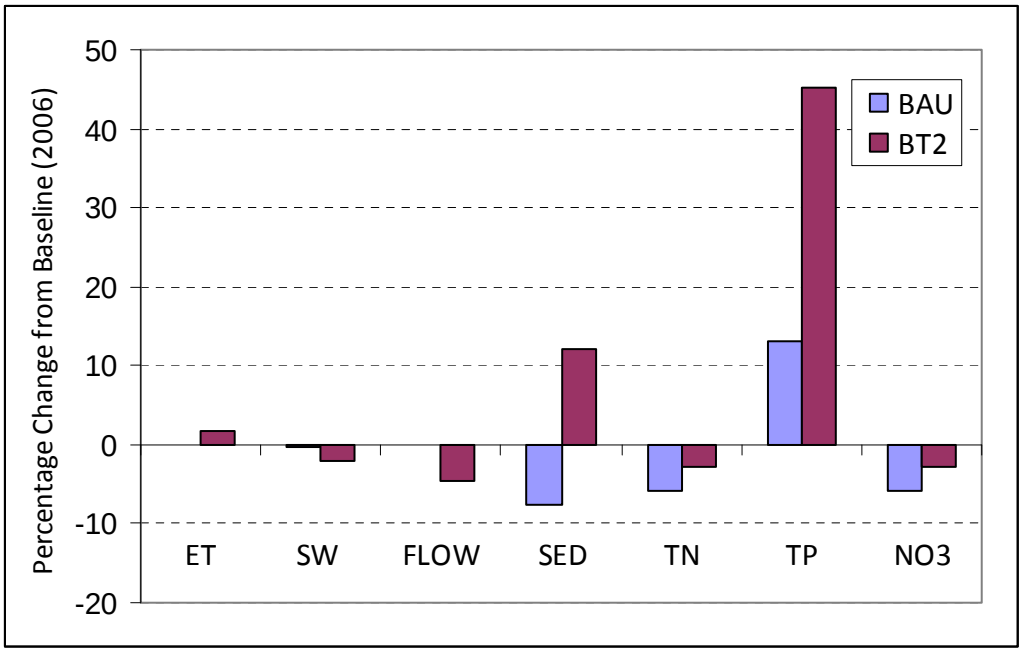

Figure 15 Effect of the BT2 and BAU scenarios, relative to the baseline, on subbasin average contributions to flow and to sediment and nutrient loadings.

Unlike the impacts on regional water quantity, the expected future biomass production has a mixed effect on water quality. The BT2 results indicate significant increases in suspended sediment (about 12%) and total phosphorus (about 45%), but decreases in total nitrogen and nitrate loads (about 3% each) in the streams. The increased phosphorus and sediment loading might be a major water quality concern in the region; in particular, the increased phosphorus loading could affect aquatic life in the region and increase the size of the Gulf of Mexico hypoxic zone if appropriate nutrient management is not applied. On the other hand, the decrease in nitrogen loading is expected to benefit the watershed and the associated aquatic ecosystem.

The expected differences in both water quantity and quality are considered to be statistically significant, with t-test probability of $p < 0.05$. However, the basin average annual results provide little insight into underlying physical causes and mechanisms that are useful to mitigate negative impacts and improve design of biofuel feedstock production. In particular, because the BT2 scenario involves numerous types of changes including land cover, corn yield, stover harvest, fertilizer, and tillage changes, detailed analyses of the model results are required to understand the basin responses.

Figure 16 compares spatial variations, relative to the BAU scenario, of the BT2 scenario impacts on subbasin hydrology and water quality. The figure shows that the BT2 scenario has relatively little hydrologic and water quality effect in the northern URMB but shows significant impacts in most of the southern subbasins. This spatial variation can be explained by the distribution of land use change types between the BT2 and baseline scenarios (Figure 14). For instance, the southern subbasins account for most of the land use conversions from pasture and idle lands to row crops, while the northern subbasins involve large changes from row crops to

idle and pastureland. Hydrology and phosphorus loading are negatively impacted in most of the subbasins, while impacts on nitrogen and sediment loadings can vary across the subbasins in the BT2 case.

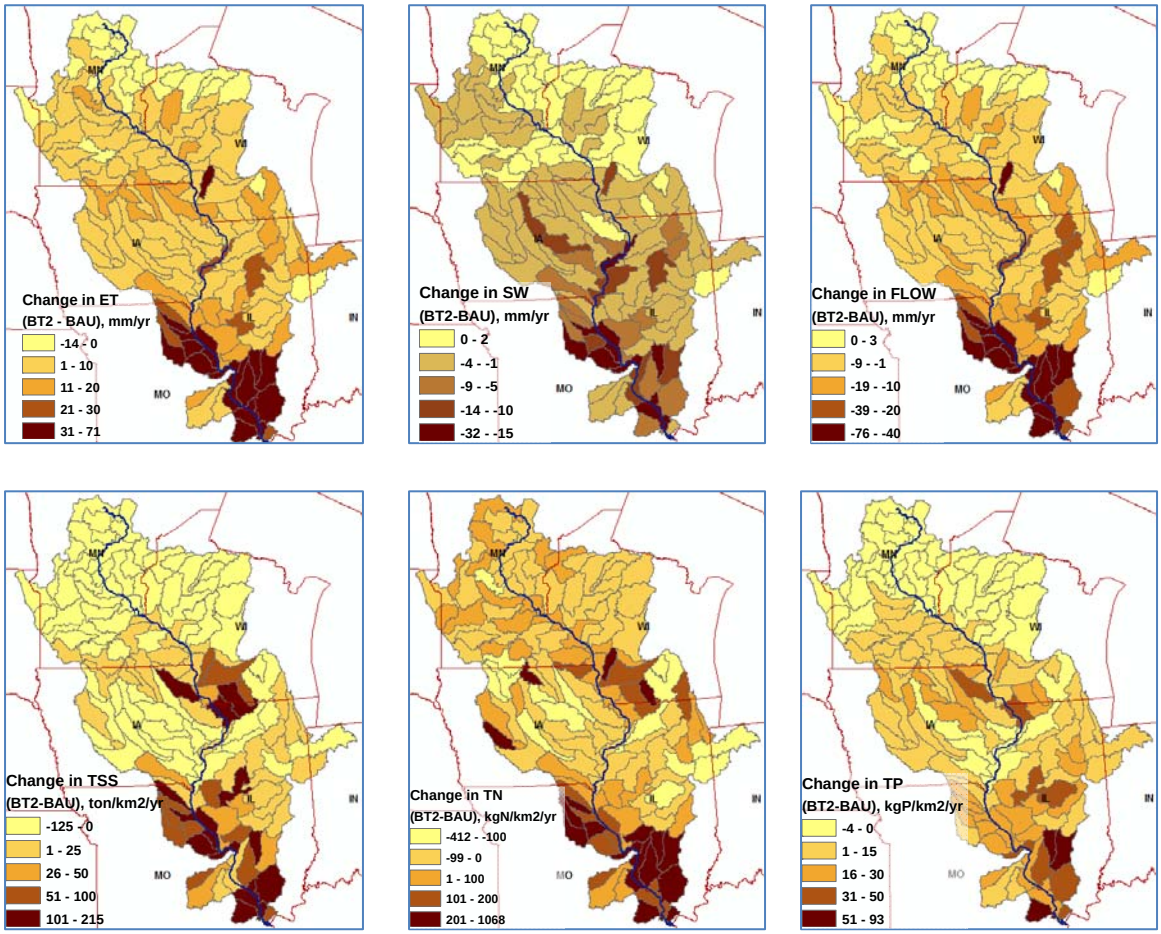

Figure 16 The spatial variations of the BT2 scenario, relative to the BAU, on subbasin contributions to flow and to sediment and nutrient loadings.

4 SUMMARY AND CONCLUSIONS

A SWAT model developed for simulating current biofuel feedstock production in the UMRB was used to estimate the spatial and temporal variation of crop and biofuel feedstock production, daily runoff, eroded sediment, nitrate, total nitrogen, and total phosphorus from both point and non-point sources in the UMRB. The model incorporates the most detailed and most recent data on land use, crop rotation, and agricultural management practices, which are essential for simulating the potential impacts of various biofuel crop production scenarios on water use and quality at regional and local scales. Extensive land use validation was implemented to improve the precision and representation of cropland use for biofuel. The results of model calibration and validation indicated that this SWAT model was able to reproduce annual and monthly stream flow, sediment, nitrate, total nitrogen, and total phosphorus for the past 18 yr and captured spatially varying corn and soybean yields for the 2006 baseline year with reasonable accuracy.

The calibrated UMRB SWAT model was applied to evaluate the basin responses to potentially increased biofuel crop production through (1) improved crop yield; (2) changes in crop rotations; (3) changes in fertilizer application rates; and (4) the harvest of corn stover, which would result in changes in soil properties. The expected increases in corn yield have a moderate to significant impact on flow discharge and water quality. In addition, the study showed the sensitivity of the model responses to crop parameters, indicating the importance of validating crop growth parameters with crop yield data to improve estimates of water quantity and quality in the UMRB. Changes in crop rotations resulted in significantly increased corn production, with highly varying production and water impacts at the subbasin level. Such results can be used further to determine suitable areas for increased corn production with minimized impact on water resources. The model predicted that increasing the fertilizer application rates from current levels would have limited effect in boosting corn yield but a detrimental impact on nitrogen loads. The level of the impact also varies spatially among 131 subbasins. Nitrogen loads from 15% of the UMRB subbasins account for more than 50% of the increased nitrogen loading at the UMRB outlet. The scenario results also suggest that in most areas of the UMRB the current application of phosphorus exceeds requirements for corn. Growing corn more intensively by increasing the frequency of corn plantings in crop rotations could reduce stream volume and increase sediment and nutrients loadings in the streams. On the other hand, harvesting corn stover results in decreased stream volume and sediment and nutrients loadings. Harvesting stover without adding supplementary fertilizer might also decrease biomass production. The discharge and nutrient loads from the basin are sensitive to changes in soil properties, such as soil bulk density, saturated hydraulic conductivity, plant-available water content, and surface runoff partitioning, which are affected by the removal of corn stover. The results indicate that without appropriate adjustment of soil properties according to the level of corn stover harvest, model simulations of stover harvest would underestimate changes in water quality.

The study also implemented the Billion Ton Study (BT2) biofuel feedstocks production projection for 2022 in the UMRB and evaluated its potential implications on the region's water quality and hydrology by using SWAT. The model implementation requires converting and splitting the HRUs of the baseline model to represent the different types of land use changes between the 2022 projection year and the 2006 baseline year, recalibrating the corn parameters to

represent the projected improvement in corn yield, and modifying the model parameters to represent stover harvest and changes in fertilizer application and tillage. The water quality and the hydrology results were evaluated at different temporal and spatial scales by comparing them with the corresponding results of a future business as usual (BAU) scenario that does not involve biofuel-related land use changes and a baseline scenario that represents the current condition of the watershed. The results show that annual evapotranspiration from the basin will increase slightly in response to the projected increase in production of biofuel feedstocks, leading to a decrease in annual soil moisture content and runoff from the basin. However, unlike the impacts on hydrology, the impacts on annual water quality are mixed, with increased sediment and phosphorus loading but decreased nitrogen loading from the basin. The subbasin level analyses revealed that the water resources in the southern section of the basin are expected to be impacted relatively more by the projected increase in biofuel feedstock production. These subbasins will also experience conversion of large areas of pasture and idle lands to corn and soybean. Overall, the hydrology and phosphorus loading in most of the subbasins will be impacted negatively to various degrees, while the potential impacts on nitrogen and sediment loadings can vary from subbasin to subbasin.

The model developed in this study can be used further to assist in the design and implementation of appropriate management practices and to develop other alternative biofuel production scenarios to address water quality issues associated with increased biofuel feedstock production in the UMRB. During model development, several data processing and visualization tools were developed to facilitate implementation of the biofuel feedstock and other scenarios in the model. These tools are able to (1) identify crop rotations from layers of land use maps for different years and incorporate them into the SWAT model; (2) distribute county- and state-level data to the model's HRUs; (3) interpolate the climate data to the model's subbasins for all time steps, accounting for missing data; (4) convert and split the model's HRUs into different land uses and adjust the corresponding land use management; and (5) assist in model calibration and validation by post-processing the results of modeling and by enabling easy adjustment of input to and parameters associated with the model.

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