Impact of land use and land cover change on the water balance of a large agricultural watershed: Historical effects and future directions

Keith E. Schilling,[1] Manoj K. Jha,[2] You-Kuan Zhang,[3] Philip W. Gassman,[2] and Calvin F. Wolter[1]

Received 9 November 2007; revised 7 May 2008; accepted 23 July 2008; published 19 November 2008.

[1] Over the last century, land use and land cover (LULC) in the United States Corn Belt region shifted from mixed perennial and annual cropping systems to primarily annual crops. Historical LULC change impacted the annual water balance in many Midwestern basins by decreasing annual evapotranspiration (ET) and increasing streamflow and base flow. Recent expansion of the biofuel industry may lead to future LULC changes from increasing corn acreage and potential conversion of the industry to cellulosic bioenergy crops of warm or cool season grasses. In this paper, the Soil and Water Assessment Tool (SWAT) model was used to evaluate potential impacts from future LULC change on the annual and seasonal water balance of the Raccoon River watershed in west-central Iowa. Three primary scenarios for LULC change and three scenario variants were evaluated, including an expansion of corn acreage in the watershed and two scenarios involving expansion of land using warm season and cool season grasses for ethanol biofuel. Modeling results were consistent with historical observations. Increased corn production will decrease annual ET and increase water yield and losses of nitrate, phosphorus, and sediment, whereas increasing perennialization will increase ET and decrease water yield and loss of nonpoint source pollutants. However, widespread tile drainage that exists today may limit the extent to which a mixed perennial-annual land cover would ever resemble pre-1940s hydrologic conditions. Study results indicate that future LULC change will affect the water balance of the watershed, with consequences largely dependent on the future LULC trajectory.

Citation: Schilling, K. E., M. K. Jha, Y.-K. Zhang, P. W. Gassman, and C. F. Wolter (2008), Impact of land use and land cover change on the water balance of a large agricultural watershed: Historical effects and future directions, *Water Resour. Res.*, *44*, W00A09, doi:10.1029/2007WR006644.

1. Introduction

[2] Over the last century, the face of agriculture in the United States Corn Belt region has undergone significant change in response to many factors, including advances in technology, improved fertilizer and pest management, and changing market forces. Land use and land cover (LULC) change is probably the most visible response of the agricultural community to these external factors. Farmers adapt to changing conditions by utilizing their land in a manner which yields the greatest return on their investment of time, energy and money. In the past, the effects of LULC changes on water resources were largely neglected or considered a byproduct of advancement (i.e., "not planned" [*Scanlon et al.*, 2005]), but today it is recognized that an evaluation of historical effects may be used to understand our current situation and predict consequences of future LULC change on water resources. External factors that contributed to the shift in LULC change in the past continue to shape the direction of LULC change in the future.

[3] The major LULC change in the 20th century in the agricultural Midwest (see http://en.wikipedia.org/wiki/Midwest) was the shift from diversified rotations of annual and perennial cropping systems to a dominantly annual cropping system of corn (*Zea mays* L.) and soybean (*Glysine max* L.) row crops [*Zhang and Schilling*, 2006; *Schilling and Libra*, 2003; *Jackson*, 2002]. More specifically, soybean production expanded greatly in the mid-20th century [*Donner*, 2003], with most of the land for soybean production coming at the expense of previously untilled land (pastures) or other sod-based crops (i.e., oats, alfalfa, and hay) [*Schilling and Libra*, 2003; *Jackson*, 2002].

[4] While the last few decades have seen relatively consistent land use percentages, the emergence of biofuels and biomass energy crops has begun to drastically alter the agricultural landscape in the Midwest in ways that rival the mid-20th century changes. Recent rapid expansion of ethanol production (150 percent increase from 2000 to 2005; see Statement of Keith Collins, chief economist, U.S. Department of Agriculture before the U.S. Senate Committee on

[1]Iowa Geological Survey, Iowa City, Iowa, USA.
[2]Center for Agricultural and Rural Development, Iowa State University, Ames, Iowa, USA.
[3]Department of Geoscience and IIHR Hydroscience and Engineering, University of Iowa, Iowa City, Iowa, USA.

0043-1397/08/2007WR006644

Environment and Public Works, available at http://www.usda.gov/oce/newsroom/archives/testimony/2007.htm) has led to more land targeted for corn production. From 2006 to 2007 alone, corn acreage was expected to increase by as much as 10 to 15 percent in the United States (National Agriculture Statistics Service, Corn acres expected to soar in 2007 USDA says, news release, 2007, available at http://www.nass.usda.gov/Newsroom/printable/03_30_07.pdf), with annual projected corn acreage leveling to about 93–95 million acres by 2008 to 2016 [*Tokgoz et al.*, 2007]. The increase in corn planting area is largely offset by decreasing soybean area and other crops, although recent congressional testimony suggested that land currently enrolled in the Conservation Reserve Program may provide a source of additional crop acreage (see http://www.usda.gov/oce/newsroom/archives/testimony/2007.htm). The current shift of cropping systems and conversion of perennial grassland to annual row crop is similar to conditions experienced in the mid-20th century, suggesting that LULC change in the Midwest is not simply a historical artifact but an integral part of a continuum of agricultural adaptation to external market forcing. Beyond the next decade, another shift in LULC is predicted to occur when production of ethanol from cellulosic biomass becomes commercialized and energy crops become viable such as warm season grasses like switchgrass or cool season grasses like miscanthus [*Fixen*, 2007; *Sanderson et al.*, 2006]. Should this technology develop as predicted, LULC patterns in the Midwest may return to pre-1940s conditions when sod-based perennial crops were roughly balanced by annual row crops.

[5] Evidence from the Upper Mississippi River (UMR) basin and river basins in Iowa strongly suggest that the historical LULC change has impacted the basin-scale water balance [*Schilling and Libra*, 2003; *Zhang and Schilling*, 2006]. Since the mid-20th century, many Iowa rivers have had increasing trends in annual streamflow, minimum streamflow, annual base flow and the ratio of annual base flow to streamflow [*Schilling and Libra*, 2003]. The increasing streamflow trends were found to be greater than increasing precipitation alone could explain. Increasing annual base flow was significantly related to increasing row crop intensity in their watersheds [*Schilling*, 2005]. Similar analysis extended to the UMR basin indicated that streamflow in many large rivers draining row crop–dominated states showed evidence for increasing trends over the last 60 years [*Zhang and Schilling*, 2006]. The observed streamflow changes can be explained by considering the water balance for a large watershed over a long period of time (multiple years) when the change in storage can be neglected [*Gupta*, 1989]:

$$\mathrm{P} = \mathrm{Q} + \mathrm{ET} \tag{1}$$

where P is precipitation, Q is streamflow out of the basin, and ET is evapotranspiration. Also assumed in equation (1) is that anthropogenic withdrawals (i.e., pumping) is negligible. On the basis of equation (1) and assuming there is no change in P, Q becomes greater for watersheds dominated by seasonal crops compared to watersheds dominated by perennial vegetation because there is less annual ET loss from seasonal row crops compared to perennial vegetation [*Brye et al.*, 2000; *Food and Agriculture Organization of the United Nations*, 1998]. Since Q is composed of base flow (Qb) and stormflow (Qs), increasing Q in a watershed may be the result of increasing Qb, Qs or both. Hydrograph separation of streamflow records in Iowa and the UMR indicate that Qs stays more or less constant and that the increasing annual streamflow was primarily due to an increase in base flow or groundwater discharge to a river [*Schilling and Libra*, 2003; *Zhang and Schilling*, 2006]. Much of the increasing streamflow and base flow can be traced to increased groundwater recharge during the spring when seasonal crop fields are freshly plowed or fallow [*Zhang and Schilling*, 2006].

[6] By itself, changing LULC that resulted in increased water export from agricultural watersheds would not be considered a critical issue. However, since water is the carrier of agricultural pollutants, changing the water balance of a watershed has potential to affect the pollutant delivery to streams and ultimately to the Gulf of Mexico. For example, nitrate-nitrogen (nitrate) is primarily delivered to streams through base flow and tile drainage [*Hallberg*, 1987; *Schilling and Zhang*, 2004], so an increase in annual base flow may contribute to more nitrate delivered to surface water. Twofold and threefold increases in nitrate concentration have been observed in Iowa rivers during the 1940–2000 period (National Agricultural Statistics Service, Quick Stats, 2006, http://www.nass.usda.gov/QuickStats/Create_County_All.jsp). A shift in the annual water balance to more surface water runoff would result in increasing phosphorus export from a watershed [*Steegen et al.*, 2001; *McDowell et al.*, 2001]. Excessive losses of nitrate and phosphorus to the Mississippi River from the agricultural Midwest have been implicated in contributing to Gulf of Mexico hypoxia [*Goolsby et al.*, 1999; *Rabalais et al.*, 2002].

[7] Given the impacts of historical LULC change on water resources in the Midwest, the purpose of this study was to consider the possible consequences of future LULC change from biofuel expansion on the water balance of the Raccoon River watershed, an intensively cropped region typical of much of Iowa. Several different LULC scenarios of expanded continuous corn, warm season grass, or cool season grass land use were analyzed for the study watershed, which serve as a platform for quantifying water resource impacts from observed historical and hypothesized future LULC change. The Soil and Water Assessment Tool (SWAT) model [*Arnold and Fohrer*, 2005; *Gassman et al.*, 2007] was used to evaluate potential impacts from future LULC change on the annual and seasonal water balance of the basin, building on previous Raccoon River applications described by *Jha et al.* [2007] and *Schilling and Wolter* [2007]. Specifically, our study objectives were (1) to summarize the effects of historical LULC change on water resources in the Raccoon River watershed, (2) to quantify the potential impacts of future LULC change on the annual and seasonal water balance of the basin using the SWAT model, and (3) to evaluate the potential water quality implication of changing the basin-scale water balance on nonpoint source pollution export. The study demonstrates that historical effects and future directions of LULC change are part of a continuum of adaptive agricultural management

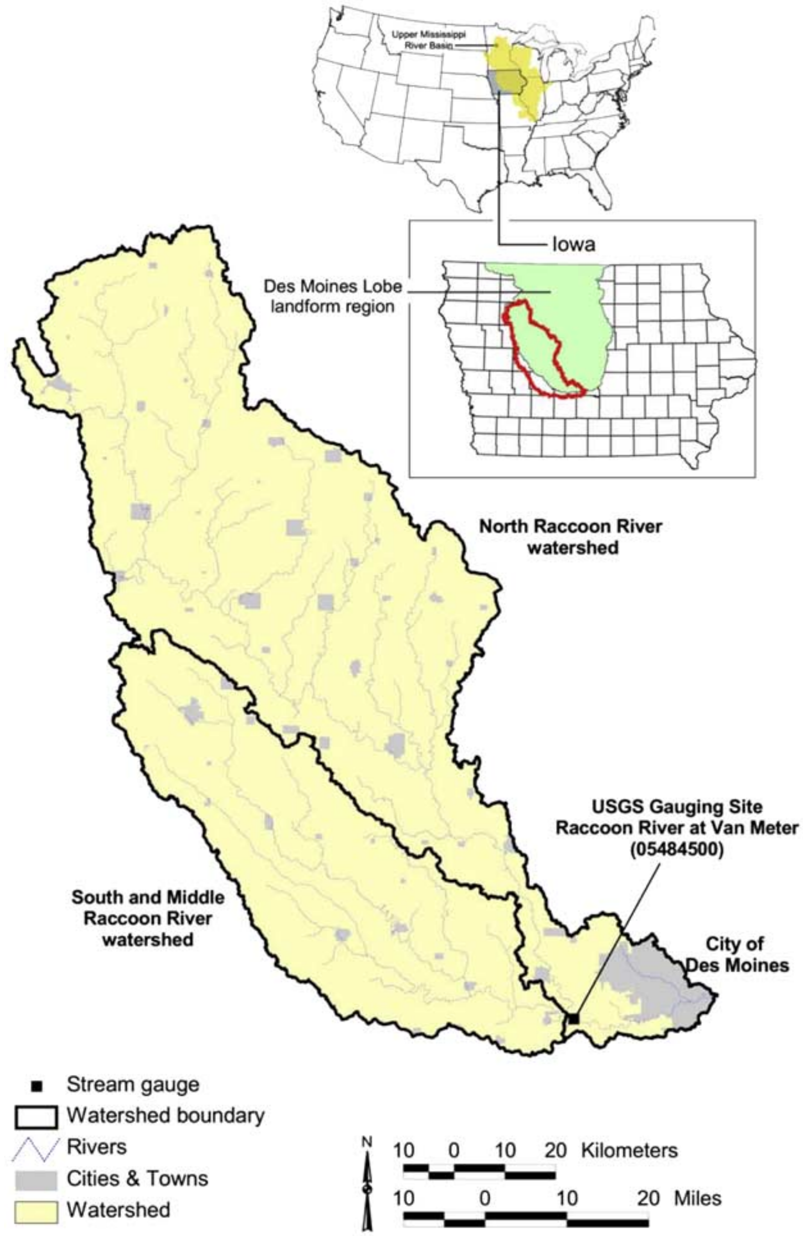

Figure 1. Location of Raccoon River watershed (latitude 42°56′30.74″–41°27′38.47″, longitude 95°19′6.48″–93°6′47.21″).

decisions that ultimately impact water resources in the Raccoon River watershed.

2. Historical LULC Changes and Their Effects on the Watershed Water Balance

[8] The Raccoon River watershed is a typical Midwest agricultural basin. It drains a watershed of 9364 km^2 above the city of Van Meter in west-central Iowa (Figure 1). The North, Middle and South Raccoon rivers form major tributary branches to the Raccoon River. The North and Middle Raccoon Rivers flow through the recently glaciated Des Moines Lobe landform region of Iowa, a region dominated by low relief and poor surface drainage [*Prior*, 1991]. The South Raccoon river drains an older pre-Illinoian glacial landscape with higher relief and well-developed drainage. The use of subsurface tile drainage is extensive in the North and Middle Raccoon River subwatersheds but is not as prevalent in the South Raccoon region; overall; 51% of the watershed is estimated to need subsurface drainage to support row crop production. Current land use in the Raccoon River watershed is predominantly agricultural with row crops of corn and soybean comprising 76% of the watershed. Agricultural grasslands (alfalfa, brome, pasture and CRP) comprise 17% of the basin, whereas forest (4%), urban areas (2%) and water (1%) comprise the remaining land area. Average annual nitrate yield from the Raccoon River is approximately 26 kg ha^{-1} [*Schilling and Zhang*, 2004], much of which escapes the cropped landscapes via subsurface tile drains. This average ranked the Raccoon River among the highest nitrate loss export regions of 42

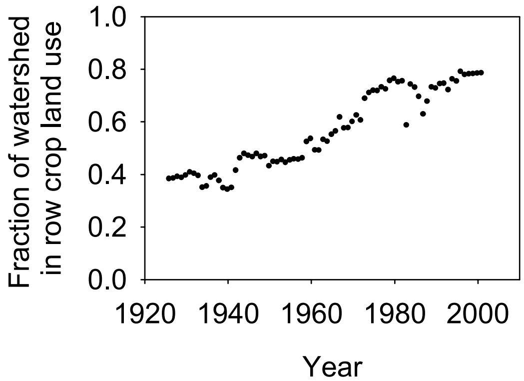

Figure 2. Changes in row crop land use in the Raccoon River watershed.

subbasins analyzed across the Mississippi River watershed [*Goolsby et al.*, 1999].

[9] Like much of the agricultural Midwest, land use in the Raccoon River watershed changed substantially in the 20th century, particularly with respect to the amount of annual row crop acreage (Figure 2). Using county-level land use data from the Iowa Agricultural Statistics database (National Agricultural Statistics Service, http://www.nass.usda.gov/QuickStats/Create_Country_All.jsp, 2006) and weighting the county data according to the percentage of the county in the watershed, the percentage of land in row crop acreage was estimated [*Schilling*, 2005]. Row crop area in the Raccoon River watershed increased from about 40% in 1940 to 76% in 2005, with much of the increase occurring after about 1960 (Figure 2). J. L. Hatfield et al. (Nitrate-N patterns in the Raccoon River related to agricultural practices, submitted to *Journal of Soil Water Conservation*, 2008) approached the land use change in the Raccoon River watershed from the perspective of reducing land cover devoted to small grains, such as wheat (*Triticum vulgare* L.), oats (*Avena sativa* L.) barley (*Hordeum vulgare* L.) and alfalfa (*Medicago sativa* L.). They noted that the fraction of land area in small grain decreased from 40% in 1949 to 3% in 1997.

[10] Effects of historical LULC change on the water balance in the Raccoon River watershed were evaluated by gathering available hydrologic information. Precipitation data were downloaded from the Iowa Environmental Mesonet server at Iowa State University (http://mesonet.agron.iastate.edu/) for weather stations located in the watershed at Storm Lake and Guthrie Center (Figure 1). For this paper, annual and monthly precipitation data were averaged between the two stations. Daily streamflow records from the U.S. Geological Survey gauging station at Van Meter (05484500) were retrieved for the 1917–2004 period. Daily streamflow records were separated into base flow and stormflow components using an automated hydrograph separation program [*Rutledge*, 1998]. Annual ET was estimated as the difference between annual P and Q according to equation (1).

[11] From 1917 to 2004, annual P in the Raccoon River basin increased approximately 66 mm, although the least squares trend was not significant ($p = 0.18$) (Figure 3). On the other hand, annual streamflow and base flow as a fraction of P in the Raccoon River showed a statistically significant increase from 1917 to 2004 ($p < 0.005$ for Q and Qb; Figure 3). Likewise, estimated annual ET as a fraction of P showed a significant decrease from 1917 to 2004 (note that the relation of ET to P is simply the inverse of Q/P). On a monthly basis, the relation of ET to P varied by month during the nonwinter season from March to November (Figure 4). Statistically significant decreasing trends in monthly ET as a fraction of P occurred during the months of May to July, whereas the remaining months did not show a significant relation over time.

[12] The historical data from the Raccoon River watershed suggest that the water balance of the basin shifted in the 87-year time period. While annual P may have been nominally increasing, the fraction of P delivered as streamflow and base flow in the river significantly increased whereas the fraction of P lost to ET decreased significantly. These shifts in the water balance are consistent with the replacement of perennial vegetation with seasonal crops in the watershed [*Schilling and Libra*, 2003; *Zhang and Schilling*, 2006]. Indeed, increased streamflow and base flow as a fraction of P in the Raccoon River was significantly related to the increasing percentage of land devoted to row crops ($p < 0.005$ and $p < 0.0005$, respectively). The monthly data suggest that less ET occurring in the late spring and early summer was largely responsible for the observed change in the annual water balance, consistent with less water use during the period when seasonal crops have been planted and yet to reach maturity. This is consistent with the findings of Hatfield et al. (submitted manuscript, 2008), who noted a negative correlation between the fraction of land in small grain and the fraction of water lost in the period between April and June. Average water use by small grain or hay from April to mid-June is approximately 2 mm d^{-1} compared to bare soil in corn-soybean rotation of 0.2 mm d^{-1} [*Pruegar et al.*, 1998; Hatfield et al., submitted manuscript, 2008]. The difference

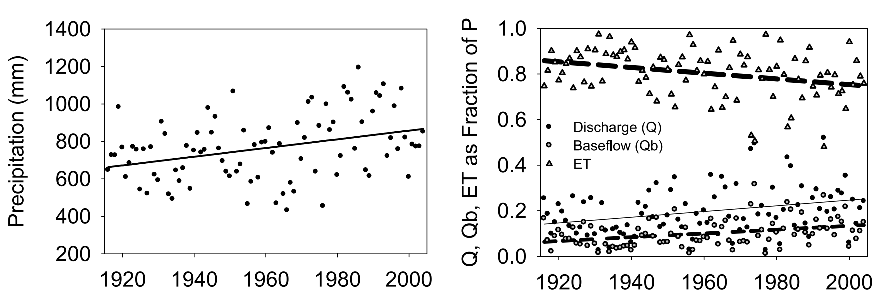

Figure 3. Changes in annual precipitation and ratio of discharge, base flow, and evapotranspiration to precipitation in the Raccoon River watershed.

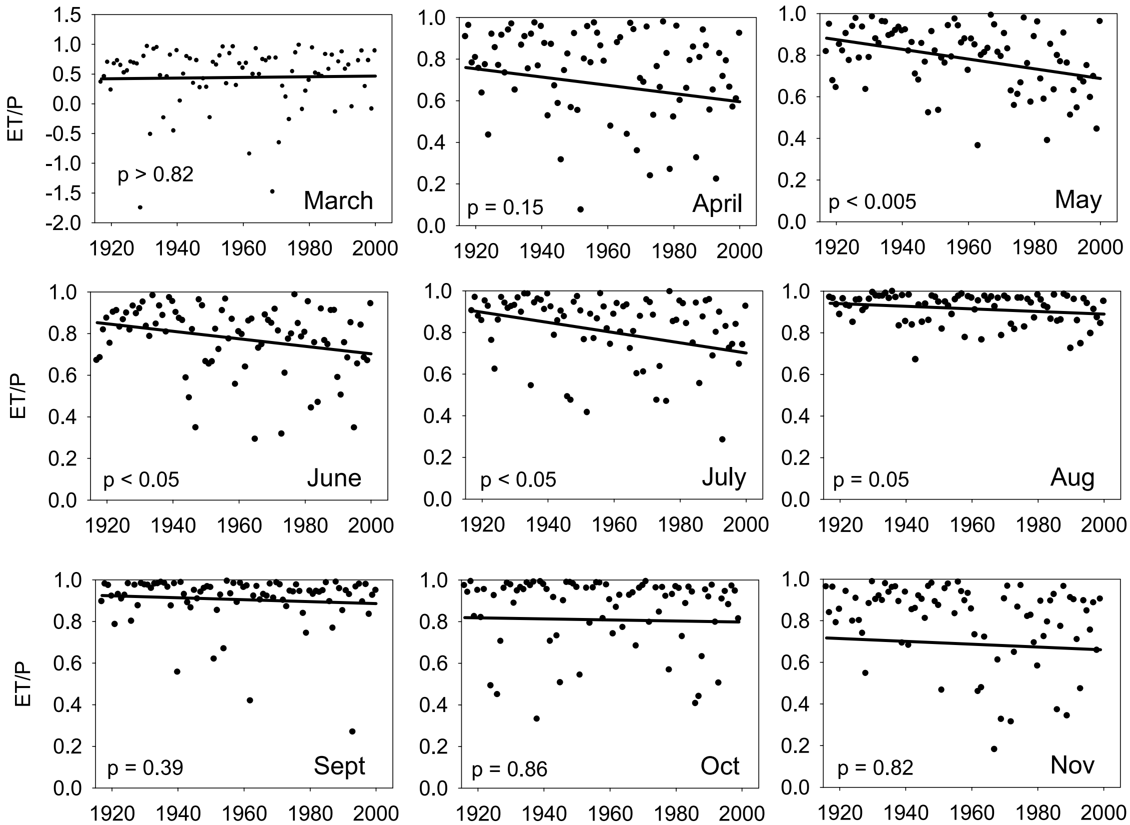

Figure 4. Changes in monthly ratio of ET to P in the Raccoon River watershed. Statistical significance of least squares trend line is indicated.

in water use over the time period (135 mm) would be sufficient to cause an increase in stream base flow in the Raccoon River.

[13] Other factors coincident with expanding row crop acreage contributed to the shift in the basin-scale water balance. First, in the North Raccoon watershed in the Des Moines Lobe landform region, subsurface drainage tiling is widespread. Recent assessment suggests that 77.5% of the row crop land in the North Raccoon River watershed is tile-drained compared to 42.1% in the South Raccoon River basin [*Schilling and Wolter*, 2007]. Shifting marginal wet perennial land to seasonal cropping would involve installing or expanding artificial drainage to improve soil conditions for crops. This, in turn, would yield greater water flux per unit area than would normally discharge to streams [*Schilling and Wolter*, 2005]. Second, improved soil conservation practices on sloping lands, such as terraces, conservation tillage and contour cropping, would likely have accompanied expanding row crop acreage on marginal sloping landscapes. These practices reduce sediment discharge during storm events by decreasing runoff and increasing soil infiltration [*Gebert and Krug*, 1996; *Kramer et al.*, 1999]. Combined with changing ET patterns, these factors would favor an increase in watershed water yield corresponding with expansion of row crop acreage.

3. SWAT Modeling System

[14] Both the current hydrologic conditions and future LULC scenarios for the Raccoon River watershed were modeled using SWAT version 2005 (SWAT2005), a hydrologic and water quality model developed by the U.S. Department of Agriculture (USDA) Agricultural Research Service (ARS) [*Arnold and Fohrer*, 2005; *Gassman et al.*, 2007]. SWAT is a long-term, continuous, watershed-scale, simulation model that operates on a daily time step and is designed to assess the impact of land use and different land management practices on water, nutrient and bacteria yields. The model includes major components of weather, hydrology, soil temperature, crop growth, nutrients, bacteria and land management. SWAT2005 features several improvements, including an improved subsurface tile drainage routine as described by *Du et al.* [2005, 2006] and *Green et al.* [2006]. Watersheds are subdivided into subwatersheds in SWAT, which are further delineated by hydrologic response units (HRUs) that consist of homogeneous soil, land use, and management characteristics. The HRUs represent percentages of a subwatershed area and thus are not spatially defined in the model. Routing of water and pollutants are simulated in the model from the HRUs to the subwatershed level, and then through the stream network to the watershed outlet. *Neitsch et al.* [2005a, 2005b] provide detailed documentation of the current SWAT2005 model.

[15] SWAT validation and scenario applications have been reported worldwide for a wide variety of watershed scales and environmental conditions, including a number of studies which focused on the impacts of historical or hypothetical land use changes on hydrology and/or pollutant loss [*Gassman et al.*, 2007]. *Pikounis et al.* [2003] report the impacts of expanded agricultural land, increased urban land, and deforestation SWAT scenarios on stream discharge

Table 1. Summary of Basic SWAT Inputs for the Calibrated Raccoon River Watershed Model

Input Description	Source of Data
30-m digital elevation model	http://seamless.usgs.gov
2002 15-m land cover grid	http://www.igsb.uiowa.edu/nrgislibx/
12-digit hydrologic unit code boundaries	http://www.igsb.uiowa.edu/nrgislibx/
Daily climate	http://mesonet.agron.iastate.edu/index.phtml
Soil survey	http://SoilDataMart.nrcs.usda.gov/
Animal feeding operations	http://www.igsb.uiowa.edu/nrgislibx/
Census data	http://www.igsb.uiowa.edu/nrgislibx/

for a watershed in Greece. The impacts of hypothetical land use scenarios (such as increased grassland) on various water balance components have been evaluated with SWAT or SWAT-G (modified SWAT model) in several studies for German watershed conditions [e.g., *Weber et al.*, 2001; *Huisman et al.*, 2004; *Lorz et al.*, 2007]. Conversion of cropland to switchgrass in the Delaware River basin in Kansas was predicted with SWAT to result in runoff and pollutant reductions ranging from 34 to 99% [*Nelson et al.*, 2006]. Reductions in stream discharge and pollutant loss are also described by *Santelmann et al.* [2004] for scenarios of increased perennial grassland, close grown crops, and/or woodland for two Iowa watersheds evaluated with SWAT. However, the impacts of warm versus cool season grasses on watershed hydrology and pollutant loss have not been reported in these or any other previous SWAT studies, which further underscores the relevance of the present research.

[16] Basic data input required for the SWAT model include weather, topography, land use, soil and management data. A total of 112 subbasins and 3640 HRUs were created for the Raccoon River watershed SWAT simulations. Climate data were input into the model from nine climate stations as described by *Jha et al.* [2007]. The baseline land use for the Raccoon River watershed model was derived from a 2002 land cover grid which was then modified to reflect the different hypothetical future LULC scenarios. Soil layer data obtained from the Soil Survey Geographic (SSURGO) database (U.S. Department of Agriculture, 2006, available at http://www.soils.usda.gov/survey/geography/ssurgo/) were used to characterize the soil properties in the watershed. A summary of the climate, land use, soil, and other data sources used to develop the Raccoon River SWAT model is provided in Table 1. Additional modeling details for the baseline configuration are provided by *Schilling and Wolter* [2007].

[17] The Raccoon River SWAT model was executed for a total simulation period of 19 years (1986–2004) to test the accuracy of the model for baseline conditions prior to performing the scenario simulations. Calibration was performed for 1986 to 1995 followed by a validation period of 1996 to 2004. The model was calibrated by comparing the simulated hydrology at the Raccoon River Van Meter gage (Figure 1) with measured values at annual and monthly time steps (Figure 5). The Van Meter site was used for flow

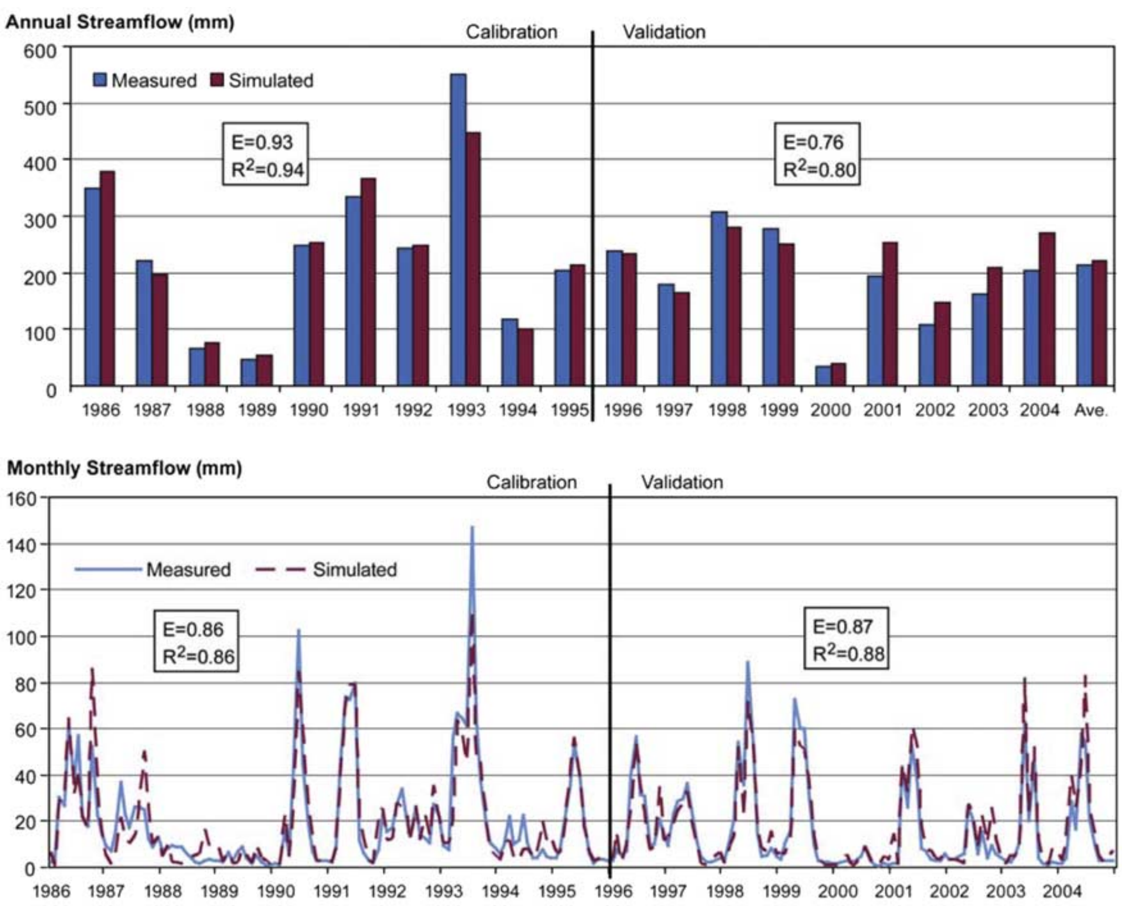

Figure 5. Annual and monthly flow calibration for the Raccoon River watershed at Van Meter gauge.

Table 2. Summary of SWAT Calibration Parameters for the Raccoon River Watershed Model

SWAT Calibration Parameter	Final Calibrated Value
Streamflow	
Curve number[a]	
Corn	67
Soybean	68
Grass	59
Alfalfa	59
Urban	66
Forest	66
Surface runoff lag (SURLAG)	4 days
Soil evaporation compensation coefficient (ESCO)	0.95
Groundwater delay (GW_Delay)	30 days
Alpha base flow factor (Alpha_BF)	0.048 days
Hargreaves ET method	
Sediment	
Linear components	0.0004
Exponent components	2.5
Channel cover factor	0.5
Nutrients	
Initial organic nitrogen	1200 mg kg^{-1}
Initial organic phosphorus	240 mg kg^{-1}
Initial mineral phosphorus	1 mg kg^{-1}
Biological mixing efficiency	0.3
Residue decomposition factor	0.05
Ammonia fertilizer rate	170 kg ha^{-1}
Di-ammonium phosphate fertilizer rate	175 kg ha^{-1}
Nitrogen percolation coefficient (NPERCO)	0.8
Phosphorus percolation coefficient (PPERCO)	0.10

[a]The curve numbers were adjusted from standard table values [*Natural Resources Conservation Service*, 2004] for hydrologic group B in good or fair hydrologic condition, including 78 for row crops, 69 for grassland, 69 for urban areas, and 60 for woodland. The hydrologic group B soils cover close to 90% of the watershed.

calibration because of the link to historical conditions described in section 2.

[18] The calibration steps were similar to those reported by *Jha et al.* [2007] for the Raccoon River watershed, and were achieved by adjusting several hydrologic parameters within their acceptable ranges including the runoff curve numbers, soil available water capacity, evaporation compensation coefficient, and groundwater delay (Table 2). The resulting calibrated values differ from those reported for the previous Raccoon River watershed SWAT application reported by Jha et al., primarily for two reasons: (1) the updated SWAT2005 version used for this study that includes the improved tile drainage routine as compared to the previous SWAT2000 version used by Jha et al. and (2) the refined land use, soil, and management input data that were used for this study relative to the more aggregated inputs used in the previous *Jha et al.* [2007] study. Jha et al. reported annual tile flow contributions of 21 mm to streamflow in their study and further stated that this was likely an underprediction of the true tile flow discharge. The annual tile flow contributions were predicted to be 56.4 mm in this study, which reflects the effects of the improved tile flow component in SWAT2005 in combination primarily with the reduced curve numbers reported in Table 2. The larger row crop curve number reductions, relative to those reported by Jha et al., were used to ensure adequate predictions of flow from subsurface tiles. Most of the other calibrated parameters in Table 2 had minor effects on the streamflow predictions; e.g., shifting the Surface Runoff Lag (SURLAG) from 4 to 1 or the Groundwater Delay (GW_DELAY) from 30 to 60 had negligible effects on the monthly and annual streamflow predictions.

[19] The calibration results shown in Figure 5 indicates that SWAT accurately tracked the annual and monthly streamflow trends across both the 10-year calibration period and 9-year validation period. The R^2 and E statistics exceeded 0.75 for all of the annual and monthly streamflow comparisons, and the majority of the statistics exceeded 0.85. The somewhat weaker statistics found for the annual streamflow validation period primarily reflect a trend in overpredictions by SWAT during 2001 to 2004. The modeled average annual average streamflow at Van Meter (193 mm) was close to the measured value (202 mm), whereas the modeled average monthly water yield (15.9 mm) closely matched the measured monthly average (16.9 mm) over the 228 month simulation period.

[20] The scenario simulations were based on the last 10 years (1995–2004) of the 19-year testing period. The R^2 and Nash-Sutcliffe simulation efficiency (E) [*Nash and Sutcliffe*, 1970] statistics for the scenario period were 0.81 and 0.79 for the annual comparisons and 0.88 and 0.88 for monthly comparisons, respectively, which varied only slightly from the validation period statistics shown in Figure 5.

[21] The average annual water balance components for the Raccoon River watershed for the current LULC baseline condition suggests that streamflow (water yield) comprises 24% of annual P whereas ET comprises 76% (Table 3). The amount of annual ET predicted by the model (610 mm) was similar to an estimate of 648 mm determined using a water balance approach from a 28-year record [*Schilling and Zhang*, 2004]. Base flow was assessed in the SWAT model by combining tile flow and groundwater flow and was

Table 3. Summary of the Annual Water Balance in the Raccoon River Watershed Under Baseline and Future LULC Scenarios

	Surface Runoff (mm)	Tile Flow (mm)	GW Flow (mm)	Base-flow (mm)	ET (mm)	Water Yield (mm)	Q/P (%)	ET/P (%)
Baseline	84	51	58	109	610	193	24	76
Scenario 1 (CORN-1)	84	51	58	109	610	193	24	76
Scenario 2 (CORN-2)	91	51	58	109	603	200	25	75
Scenario 3 (CORN-3)	91	57	61	118	594	209	26	74
Scenario 4 (WARM-1)	72	50	55	105	626	177	22	78
Scenario 5 (WARM-2)	60	49	54	103	642	163	20	80
Scenario 6 (WARM-3)	37	47	55	102	668	139	17	83
Scenario 7 (COOL-1)	73	51	56	107	622	180	22	78
Scenario 8 (COOL-2)	62	50	57	107	635	169	21	79
Scenario 9 (COOL-3)	41	50	56	106	657	147	18	82

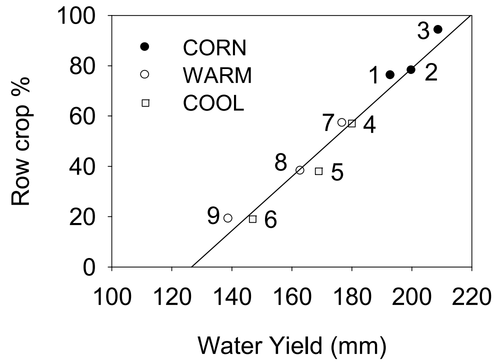

Figure 6. Changes in annual water yield with percentage of land in row crop land use simulated by model. Scenarios correspond to those presented in Table 3.

estimated to be 109 mm for the 10-year modeling period, or 13 percent of P. Tile flow represented about half of the base flow flux, and a quarter of total streamflow, suggesting that flow from drainage tiles is an important component of the basin-scale water balance. The base flow fraction was modeled to be 56.5 percent which was similar to the value of 54 percent reported by *Schilling and Zhang* [2004] for the 1972 to 2000 period.

4. Future LULC Change and Its Effects on the Basin-Scale Water Balance

4.1. Model Scenarios

[22] The calibrated model was used to assess the effects of potential future LULC change on the water balance in the Raccoon River watershed. On the basis of projections for future ethanol expansion, three primary scenarios for LULC change were evaluated which were (1) an incremental expansion of corn acreage in the watershed (CORN case), (2) an incremental expansion of land using warm season grasses for ethanol biofuel (WARM case), and (3) an incremental expansion of land for ethanol using cool season grasses (COOL case). Three scenario variants were performed in each of these three primary scenario categories. All of the scenarios utilized the same 10-year climate patterns used in the baseline model simulations, with an average annual precipitation of 805 mm.

[23] In the CORN case, we envisioned increasing amounts of land acreage devoted to growing corn for ethanol production. In scenario 1 (or CORN-1), all grasslands currently enrolled in the USDA CRP program are converted to growing continuous corn, encompassing an expansion of corn acreage by 2% in the watershed. In scenario 2 (or CORN-2), all current grasslands in the watershed are converted to continuous corn. This conversion would take current alfalfa, pastures, other grazing lands and CRP grasslands and convert an additional 18% of the watershed to continuous corn production. In scenario 3 (or CORN-3), all grasslands are converted to continuous corn (scenario 2) with the addition that all soybean acreage in the watershed is also converted to continuous corn. Hence, in scenario 3, 93% of the watershed is planted in corn. All continuous corn scenarios included the use of mulch tillage as a conservation practice. Fertilizer application and management were consistent with the baseline corn simulations.

[24] In the WARM case, we envisioned that switchgrass will be used as a biofuel for ethanol production [*Sanderson et al.*, 2006; *Babcock et al.*, 2007]. In scenarios 4, 5 and 6 (or WARM-4, WARM-5 and WARM-6), increasing amounts of cropland are converted to switchgrass production on the basis of the designation of highly erodible land (HEL). In scenario 4, 25% of the highest-sloping cropland was converted to warm season grass (1769 km^2). In scenarios 5 and 6, 50% (3538 km^2) and 100% (7076 km^2) of the cropland was converted to warm season grass. The remainder of the land use in the watershed was assumed to remain as modeled in the baseline simulation (i.e., mix of grasses, pastures, forest, etc.), thus, only the amount of cropland was adjusted. Switchgrass was assumed to have a planting date of May 1 and harvest date of 15 October. No tillage of the soil was undertaken and 157 kg ha^{-1} (140 lbs ac^{-1}) of nitrogen fertilizer was applied one week before planting.

[25] In the COOL case, we hypothesized that a cool season grass may be used in the future as the biofuel. While *Miscanthus* is a cool season grass currently given much consideration [*Heaton et al.*, 2004, 2008], plant growth properties for this species have not been adequately developed. Thus, we used fescue to simulate plant growth and water uptake from a typical cool season grass. Scenarios 7, 8 and 9 (or COOL-7, COOL-8, and COOL-9), cropland was converted to cool season grass following the same HEL hierarchy used for the WARM scenarios. The planting and harvest dates for fescue were assumed to be 1 April and 30 October, respectively, and 90 kg ha^{-1} (80 lbs ac^{-1}) of nitrogen fertilizer were applied one week before planting.

4.2. Effects of Future LULC Change on the Annual Water Balance

[26] A summary of the annual water balance in the Raccoon River watershed for the baseline simulation and the nine future use conditions is provided in Table 3. Results suggest that future LULC change from biofuel expansion may have profound effects on the annual water balance in the watershed. Under the increasing CORN scenarios, average annual ET decreased with increasing corn acreage, but average annual surface runoff and base flow increased. Water yield increased from 193 to 209 mm and the Q/P fraction increased to 26% (Table 3). In contrast, with increasing amounts of land devoted to perennial grass bioenergy crops, the amount of water utilized for crop ET increased substantially, whereas water lost to surface runoff decreased (Table 3). With perennial cover on the landscape throughout the year, the amount of water lost to surface runoff decreased by nearly one half. Surface runoff was infiltrated into the soil and used mainly for plant ET. Under the maximum WARM-6 scenario, annual water yield decreased from the baseline condition of 193 mm to 139 mm, and under the maximum COOL-9 scenario, annual water yield decreased from 193 mm to 147 mm. The fraction of precipitation lost to streamflow decreased to 17% and 18% for the maximum WARM-6 and COOL-9 scenarios, respectively. Overall, the annual water yield was related to the fraction of the watershed in row crop (Figure 6).

[27] Although annual base flow losses were observed to shift slightly during the model simulations, the amount of base flow decrease under the perennial simulations was less

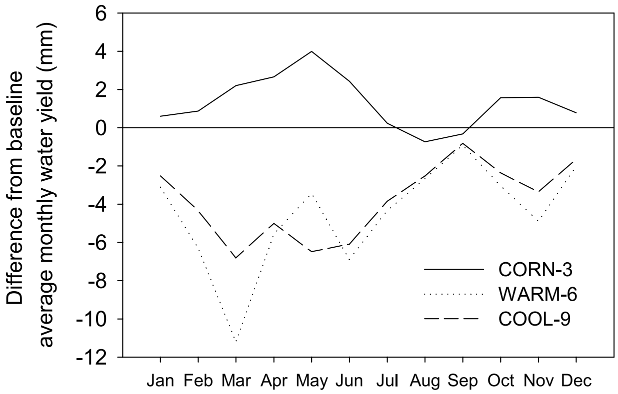

Figure 7. Differences in average monthly water yield from maximum LULC change scenarios to baseline (current use) scenario.

than anticipated. However, this was likely due to the use of baseline tile drainage conditions in the simulations. Except for the maximum corn simulation (CORN-3), annual water losses to tile drainage did not change appreciably during any of the other simulations. Although tile flow decreased slightly under the perennial simulations, it did not increase in magnitude compared to the decrease in surface water runoff. The infiltrated surface runoff water appeared to be captured by low soil moisture conditions resulting from greater perennial ET rather than leaving the groundwater system with tile drainage. However, a change in annual crop had a substantial effect on tile flow, with a large increase from CORN-2 to CORN-3 associated with conversion of all cropland from a corn-soybean rotation to continuous corn.

[28] On a seasonal basis, comparing the maximum land cover changes to the baseline condition suggests that expanding to continuous corn would result in greater water yield during the spring and late fall (Figure 7). In contrast, maximum perennialization using warm and cool season grasses would export considerably less water during nearly all months, largely inverse with the annual crop increase.

4.3. Relation of Future Water Balance to Historical LULC Change

[29] The modeled effects of future LULC change on the water balance of the Raccoon River watershed are consistent with, and largely mirror, the historical changes in the basin-scale water balance. In the 20th century, conversion of agricultural land from mixed perennial and annual systems to primarily annual row crops resulted in an increase in streamflow in the watershed. Modeling results suggest that this trend would continue in the future with expansion of row crop acreage for corn-based ethanol. Conversion of grasslands to corn production, and conversion of current soybean acreage to corn production, would result in decreasing annual ET and increasing water yield by nearly 10 percent in the watershed. On the other hand, conversion of current row crop acreage to perennial-based bioenergy systems would result in increasing ET and a decrease in annual water yield with increasing perennialization of the landscape (scenarios 4 to 9; Table 3). With maximum perennialization, the basin-scale water balance would approach conditions similar to the early to mid-1900s when the ratio of streamflow to precipitation was less than 20 percent (Figure 8). However, in order to achieve a return to 1940s water yield, modeling results suggest that virtually all cropland must be converted to warm or cool season grass. With incremental perennialization of the landscape (scenarios 4, 5, 7, 8), annual water yield may only approach conditions observed in the 1960s to 1980s (Figure 8).

[30] Although the watershed landscape with mixed perennial and annual crops simulated in scenarios 4, 5, 7, and 8 would resemble LULC conditions in the early 20th century, the annual water yields were higher in the simulations than observed in the historical streamflow records. The major reason for this is the use of a model based on current conditions to compare to historical watershed conditions. In particular, the modern extent of tile drainage likely exceeds the pre-1940s extent to a large degree. While the true extent of tile drainage is unknown, major periods of agricultural drainage in the United States occurred pre-1920 and between 1940 to 1960 [*Beauchamp*, 1987; *Zucker and Brown*, 1998], with the latter period coinciding with increasing base flow in many Iowa rivers [*Schilling and Libra*, 2003]. Thus, with the magnitude and extent of tile drainage in the watershed, it is unlikely that a return to the mixed perennial-annual landscape of the pre-1940s period would ever produce similar streamflow and base flow of the earlier time. Tile drainage contributes to streamflow regardless of land cover and produces higher watershed water yields than would be expected without tile drainage. Indeed, for the model LULC simulations, water yield from tile flow varied within a narrow range of values (±10 mm) compared to the range of values for surface runoff (±54 mm) and ET (±74 mm).

[31] Seasonally, greater water export during spring and late fall from increasing corn production (Figure 6) is consistent with historical changes in the monthly water balance in the Raccoon River basin (Figure 4). Historically, the months of May to July showed the greatest decrease in monthly ET in the 20th century (and thereby having an increase in Q) and these months were shown by the model to be most sensitive to changing LULC in the watershed.

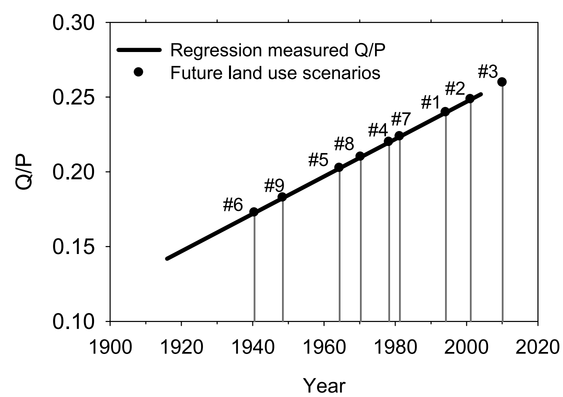

Figure 8. Relation of annual Q/P from simulated conditions to measured Q/P regression line (from Figure 3). Drop lines indicate the year that the simulation corresponds with regards to historical LULC conditions.

Table 4. Annual Export of Nonpoint Source Pollutants From Raccoon River Watershed Under Baseline (Current) Conditions and Future LULC Scenarios

	NO_3-N Loss (kg/ha)	Total P Loss (kg/ha)	Sediment Loss (T/ha)
Baseline	25.5	1.15	3.56
Simulation 1	26.4	1.21	3.82
Simulation 2	33.9	1.53	5.12
Simulation 3	39.6	1.47	4.93
Simulation 4	24.7	0.56	1.30
Simulation 5	24.1	0.33	0.75
Simulation 6	22.7	0.03	0.08
Simulation 7	21.5	1.30	0.56
Simulation 8	17.3	0.33	0.75
Simulation 9	8.9	0.03	0.08

Less water yield throughout the spring and late fall months with maximum perennialization is consistent with greater monthly ET from small grains and hay observed in the Raccoon River basin pre-1940.

4.4. Water Quality Implications of LULC Change

[32] Changing the water balance of an agricultural watershed has implications for affecting water quality and pollutant export. What little historic water quality data that exists for the Raccoon River suggests that changing LULC in the basin has had an impact on stream water quality. Surface water samples collected as 10-day composite samples in Water Year 1946 (n = 38) were analyzed for nitrate concentrations and had an annual mean value of 2.7 mg L^{-1} [*Iowa Geological Survey*, 1955]. For the same mean annual base flow in WY1946 compared to a 28-year record from 1972 to 2000, mean annual nitrate concentrations were more than three times higher (8.5 mg L^{-1}) in the 1972–2000 time period [*Schilling and Lutz*, 2004]. This is consistent with a longer monitoring record from the Cedar River in eastern Iowa which showed a linear increase in stream nitrate concentrations from 1907 to 2000 that correlated with increasing row crop production in its watershed and increasing stream base flow [*Schilling*, 2005]. Thus, limited historical data suggests that LULC change in the Raccoon River watershed has likely contributed to higher stream nitrate concentrations.

[33] The water quality implications of future LULC change in the Raccoon River watershed simulated with the SWAT model are consistent with historical trends (Table 4). From a baseline current use scenario, annual nitrate export increased from 25.5 to nearly 40 kg ha^{-1} with maximum corn production in the watershed. Annual P and sediment loss also increased to 1.5 kg ha^{-1} and 5 t ha^{-1} with increasing corn production. In contrast, increasing perennialization of the watershed for cellulosic bioenergy crops reduced nitrate, phosphorus and sediment export from the basin (Table 3). Nitrate load reduction under the cool season grass scenarios was greater than for warm season grass scenarios because of differences in fertilization requirements between the two grasses. For both grass scenarios, fertilizer application was required to maintain annual growth and harvest for bioenergy. Greater load reduction was evident in total phosphorus and sediment, with significant reductions occurring with a fraction of the cropland converted to grassland.

[34] Overall, while changing LULC in the watershed clearly affects the water balance, the implications of LULC change primarily lie in how stream water quality may be affected. Historically, the effects of LULC change on water quality have been poorly documented, but limited data indicates water quality degradation with increasing row crop LULC. At the brink of another large-scale LULC change in agriculture, we are better prepared to document how future LULC change will affect stream water quality. Modeling results provide a good indication that stream water quality may either degrade or improve depending on the future LULC trajectory.

5. Summary

[35] Agricultural LULC in the Corn Belt region (see http://en.wikipedia.org/wiki/Corn_Belt#Corn_Belt) of the United States will not remain static in the 21st century but, as the 20th century demonstrated, will change in response to many external factors. Rapid expansion of the ethanol industry will likely provide an impetus for future LULC change that may rival any LULC change observed in the past. In the Raccoon River watershed, history demonstrated that the basin-scale water balance was changed in the 20th century from conversion of a perennial/annual cropping system to an annual cropping system of corn and soybean row crops. Annual ET in the watershed decreased, more precipitation was routed into streamflow and base flow, and land management favored draining more of the land for row crop production.

[36] Modeling results suggest that future LULC change will similarly affect the water balance of the watershed, with consequences largely dependent on technological developments within the biofuels industry. In the near term, production from corn-based ethanol will likely expand and drive the agricultural community to plant more corn. Using the Raccoon River watershed as a typical Midwestern example, increasing corn production at the expense of grasslands will decrease annual ET, increase the surface runoff and ultimately increase the water yield from the watershed, thereby increasing stream nitrate and phosphorus loads and sediment loss. With potential technological advances in cellulosic ethanol production from warm and cool season grasses, future LULC change may be driven by expansion of grassland acreage. Again, the water balance of a basin would shift, in this case, resulting in more ET, less surface runoff and less water yield. Water quality could improve with the water balance shift to perennial grasslands, with less nitrate, phosphorus and sediment delivered to streams. Regardless of the future trajectories for LULC change, with the historical effects as a guide, we cannot be caught unaware or unprepared of the potential consequences of future LULC change on the water resources of Iowa and the agricultural Midwest.

[37] It can also be expected that future improvements to SWAT will result in enhanced ability to perform the types of scenarios reported here as well as other management and land use scenarios. *Gassman et al.* [2007] describe several specific enhancements that are needed for SWAT including (1) the ability to spatially represent HRUs in the model and (2) more accurate estimation of precipitation partitioning between infiltration and surface runoff using modified runoff curve number approaches and/or alternative methods.

These improvements would result in more reliable estimates of the hydrologic balance at the HRU level and estimation of flow and pollutant routing within subwatersheds, and ultimately improved estimates of streamflow and pollutant loss at the outlets of simulated watersheds.

References

Arnold, J. G., and N. Fohrer (2005), Current capabilities and research opportunities in applied watershed modeling, *Hydrol. Processes*, *19*, 563–572, doi:10.1002/hyp.5611.

Babcock, B. A., P. W. Gassman, M. J. Jha, and C. L. Kling (2007), Adoption subsidies and environmental impacts of alternative energy crops, CARD *Briefing Pap.07-BP 50*, Cent. for Agric. and Rural Dev., Iowa State Univ., Ames, Iowa.

Beauchamp, K. H. (1987), A history of drainage and drainage methods, in *Farm Drainage in the United States: History, Status, and Prospects, Misc. Publ.*, vol. 1455, pp. 13–28, Econ. Res. Serv., U.S. Dep. of Agric., Washington, D. C.

Brye, K. R., J. M. Norman, L. G. Bundy, and S. T. Gower (2000), Water budget evaluation of prairie and maize ecosystems, *Soil Sci. Am. J.*, *64*, 715–725.

Donner, S. D. (2003), The impact of cropland cover on river nutrient levels in the Mississippi River basin, *Global Ecol. Biogeogr.*, *12*, 341–355, doi:10.1046/j.1466-822X.2003.00032.x.

Du, B., J. G. Arnold, A. Saleh, and D. B. Jaynes (2005), Development and application of SWAT to landscapes with tiles and potholes, *Trans. ASAE*, *48*(3), 1121–1133.

Du, B., A. Saleh, D. B. Jaynes, and J. G. Arnold (2006), Evaluation of SWAT in simulating nitrate nitrogen and atrazine fates in a watershed with tiles and potholes, *Trans. ASABE*, *49*, 949–959.

Fixen, P. E. (2007), Potential biofuels influence on nutrient use and removal in the U.S., *Better Crops*, *91*, 12–14.

Food and Agriculture Organization of the United Nations (1998), Crop evapotranspiration: Guidelines for computing crop water requirements, *Irrig. Drain. Pap. 56*, Rome.

Gassman, P. W., M. R. Reyes, J. G. Arnold, and C. Green (2007), The Soil Water Assessment Tool: Developmental history, applications and future directions, *Trans. ASABE*, *50*, 1211–1250.

Gebert, W. A., and W. R. Krug (1996), Streamflow trends in Wisconsin's driftless area, *Water Resour. Bull.*, *32*, 733–744.

Goolsby, D. A., W. A. Battaglin, G. B. Lawrence, R. S. Artz, B. T. Aulenbach, R. P. Hooper, D. R. Keeney, and G. J. Stensland (1999), Flux and sources of nutrients in the Mississippi-Atchalfalalya River Basin, *Decis. Anal. Ser. 17*, Coastal Ocean Program, NOAA, Silver Spring, Md.

Green, C. H., M. D. Tomer, M. Di Luzio, and J. G. Arnold (2006), Hydrologic evaluation of the Soil and Water Assessment Tool for a large tile-drained watershed in Iowa, *Trans. ASABE*, *49*, 413–422.

Gupta, R. S. (1989), *Hydrology and Hydraulic System*, Prentice-Hall, Englewood Cliffs, N. J.

Hallberg, G. R. (1987), Nitrates in ground water in Iowa, in *Rural Ground Water Contamination*, edited by F. M. D'Itri and L. G. Wolfson, pp. 23–68, Lewis, Chelsea, Mich.

Heaton, E. A., T. Voigt, and S. P. Long (2004), A quantitative review comparing the yields of two candidate C4 perennial biomass crops in relation to nitrogen, temperature and water, *Biomass Bioenergy*, *27*, 21–30, doi:10.1016/j.biombioe.2003.10.005.

Heaton, E. A., F. G. Dohlman, and S. P. Long (2008), Meeting US biofuel goals with less land: the potential for Miscanthus, *Global Change Biol.*, *14*, 2000–2014, doi:10.1111/j.1365-2486.2008.01662.x.

Huisman, J. A., L. Breuer, and H. G. Frede (2004), Sensitivity of simulated hydrological fluxes towards changes in soil properties in response to land use change, *Phys. Chem. Earth*, *29*(11–12), 749–758.

Iowa Geological Survey (1955), Quality of surface water of Iowa, 1886–1964, *Water Supply Bull. 5*, Iowa City, Iowa.

Jackson, L. L. (2002), Restoring prairie processes to farmlands, in *The Farm as Natural Habitat*, edited by D. L. Jackson and L. L. Jackson, pp. 137–154, Island, Washington, D. C.

Jha, M. K., P. W. Gassman, and J. G. Arnold (2007), Water quality modeling for the Raccoon River watershed using SWAT, *Trans. ASABE*, *50*, 479–493.

Kramer, L. A., M. R. Burkart, D. W. Meek, R. J. Jaquis, and D. E. James (1999), Field-scale watershed evaluations in deep-loess soils: II. Hydrologic responses to different agricultural land management systems, *J. Soil Water Conserv.*, *54*, 705–710.

Lorz, C., M. Volk, and G. Schmidt (2007), Considering spatial distribution and functionality of forests in a modeling framework for river basin management, *For. Ecol. Manage.*, *248*(1–2), 17–25, doi:10.1016/j.foreco.2007.02.032.

McDowell, R., A. Sharpley, and G. Folmar (2001), Phosphorus export from an agricultural watershed: Linking source and transport mechanisms, *J. Environ. Qual.*, *30*, 1587–1595.

Nash, J. E., and J. V. Sutcliffe (1970), River flow forecasting through conceptual models: Part 1. A discussion of principles, *J. Hydrol.*, *10*, 282–290, doi:10.1016/0022-1694(70)90255-6.

Natural Resources Conservation Service (2004), Hydrologic soil-cover complexes, in *Part 630, National Engineering Handbook*, chap. 9, pp. 9.1–9.14, U.S. Dep. of Agric., Washington, D. C.

Neitsch, S. L., J. G. Arnold, J. R. Kiniry, and J. R. Williams (2005a), Soil and Water Assessment Tool theoretical documentation, version 2005, Grassland, Soil and Water Res. Lab., Agric. Res. Serv., U.S. Dep. of Agric., Temple, Tex. (Available at http://www.brc.tamus.edu/swat/doc.html)

Neitsch, S. L., J. G. Arnold, J. R. Kiniry, R. Srinivasan, and J. R. Williams (2005b), Soil and Water Assessment Tool input/output file documentation, version 2005, Grassland, Soil and Water Res. Lab., Agric. Res. Serv., U.S. Dep. of Agric., Temple, Tex. (Available at http://www.brc.tamus.edu/swat/doc.html)

Nelson, R. G., J. C. Ascough II, and M. R. Langemeier (2006), Environmental and economic analysis of switchgrass production for water quality improvement in northeast Kansas, *J. Environ. Manage.*, *79*(4), 336–347, doi:10.1016/j.jenvman.2005.07.013.

Pikounis, M., E. Varanou, E. Baltas, A. Dassaklis, and M. Mimikou (2003), Application of the SWAT model in the Pinios River basin under different land-use scenarios, *Global Nest*, *5*(2), 71–79.

Prior, J. C. (1991), *Landforms of Iowa*, Univ. of Iowa Press, Iowa City, Iowa.

Pruegar, J. H., J. L. Hatfield, and T. J. Sauer (1998), Surface energy balance partitioning over rye and oat cover crops in central Iowa, *J. Soil Water Conserv.*, *53*, 271–276.

Rabalais, N. N., R. E. Turner, and D. Scavia (2002), Beyond science into policy: Gulf of Mexico hypoxia and the Mississippi River, *BioScience*, *52*, 129–142, doi:10.1641/0006-3568(2002)052[0129:BSIPGO]2.0.CO;2.

Rutledge, A. T. (1998), Computer programs for describing the recession of ground-water discharge and for estimating mean ground-water recharge and discharge from streamflow records—Update, *U.S. Geol. Surv. Water Resour. Invest. Rep., 98–4148*.

Sanderson, M. A., P. R. Adler, A. A. Boateng, M. D. Casler, and G. Sarath (2006), Switchgrass as a biofuels feedstock in the USA, *Can. J. Plant Sci.*, *86*, 1315–1325.

Santelmann, M. V., et al. (2004), Assessing alternative futures for agriculture in Iowa, U.S.A., *Landscape Ecol.*, *19*, 357–374, doi:10.1023/B:LAND.0000030459.43445.19.

Scanlon, B. R., R. C. Reedy, D. A. Stonestrom, D. E. Prudic, and K. F. Dennehy (2005), Impact of land use and land cover change on groundwater recharge and quality in the southwestern US, *Global Change Biol.*, *11*, 1577–1593, doi:10.1111/j.1365-2486.2005.01026.x.

Schilling, K. E. (2005), Relation of baseflow to row crop intensity in Iowa, *Agric. Ecosyst. Environ.*, *105*, 433–438, doi:10.1016/j.agee.2004.02.008.

Schilling, K. E., and R. D. Libra (2003), Increased baseflow in Iowa over the second half of the 20th century, *J. Am. Water Resour. Assoc.*, *39*, 851–860, doi:10.1111/j.1752-1688.2003.tb04410.x.

Schilling, K. E., and D. S. Lutz (2004), Relation of nitrate concentrations and baseflow in the Raccoon River, Iowa, *J. Am. Water Resour. Assoc.*, *40*, 889–900, doi:10.1111/j.1752-1688.2004.tb01053.x.

Schilling, K. E., and C. F. Wolter (2005), Estimation of streamflow, baseflow and nitrate-nitrogen loads in Iowa using multiple linear regression models, *J. Am. Water Resour. Assoc.*, *41*, 1333–1346, doi:10.1111/j.1752-1688.2005.tb03803.x.

Schilling, K. E., and C. F. Wolter (2007), Water quality improvement plan for Raccoon River, Iowa total maximum daily load for nitrate and *Escherichia coli*, Iowa Dep. of Nat. Resour., Des Moines, Iowa.

Schilling, K. E., and Y. K. Zhang (2004), Baseflow contribution to nitrate-nitrogen export in a large agricultural watershed, USA, *J. Hydrol.*, *295*, 305–316, doi:10.1016/j.jhydrol.2004.03.010.

Steegen, A., G. Grovers, I. Takken, J. Nachtergaele, J. Poesen, and R. Merckx (2001), Factors controlling sediment and phosphorus export from two Belgian agricultural catchments, *J. Environ. Qual.*, *30*, 1249–1258.

Tokgoz, S., A. Elobeid, J. Fabiosa, D. J. Hayes, B. A. Babcock, T. H. Yu, F. Dong, C. E. Hart, and J. C. Beghin (2007), Emerging biofuels: Outlook of effects on U.S. grain, oilseed, and livestock markets, *Staff Rep. 07-SR 101*, Cent. for Agric. and Rural Dev., Iowa State Univ., Ames, Iowa.

Weber, A., N. Fohrer, and D. Moller (2001), Long-term land use changes in a mesocale watershed due to socio-economic factors—Effects on landscape structures and functions, *Ecol. Modell.*, *140*, 125–140.

Zhang, Y. K., and K. E. Schilling (2006), Increasing streamflow and baseflow in Mississippi River since the 1940s: Effect of land use change, *J. Hydrol.*, *324*, 412–422, doi:10.1016/j.jhydrol.2005.09.033.

Zucker, L. A., and L. C. Brown (Eds.) (1998), Agricultural drainage: Water quality impacts and subsurface drainage studies in the Midwest, *Ohio State Univ. Ext. Bull. 871*, 40 pp., Ohio State Univ., Columbus, Ohio.

P. W. Gassman and M. K. Jha, Center for Agricultural and Rural Development, Iowa State University, 578 Heady Hall, Ames, IA 50011-1070, USA.

K. E. Schilling and C. F. Wolter, Iowa Geological Survey, 109 Trowbridge Hall, Iowa City, IA 52242, USA. (kschilling@igsb.uiowa.edu)

Y.-K. Zhang, Department of Geoscience, University of Iowa, 121 Trowbridge Hall, Iowa City, IA 52242, USA.