Hydrol. Earth Syst. Sci. Discuss., 8, 3421–3468, 2011
www.hydrol-earth-syst-sci-discuss.net/8/3421/2011/
doi:10.5194/hessd-8-3421-2011

Hydrology and
Earth System
Sciences
Discussions

Evaluating the impacts of land use changes on hydrologic responses in the agricultural regions of Michigan and Wisconsin

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Received: 22 March 2011 – Accepted: 31 March 2011 – Published: 6 April 2011

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Hydrologic fluxes in the Great Lakes region have been altered relative to pre-settlement conditions in response to major land use changes during the past 150 yr. Land surface characteristics and processes including leaf area index, roughness, albedo, soil moisture, and rates of momentum, energy and water vapor exchange are strongly influenced by land use. Changes in land use including urbanization and de(/re)forestation continue to affect the nature and magnitude of groundwater – surface water interactions and water availability influencing ecosystems and their services. One of the goals of the present work is to develop a baseline scenario relative to which the impacts of land use changes on hydrological and environmental processes can be evaluated. In addition, the study can help in quantifying the potential impacts of future projected changes in land use in order to mitigate the negative impacts of these changes on goods and services of value to society. The present study explores the relationship between land use changes and hydrologic indicators within the agricultural regions of Michigan and Wisconsin. Two sets of land use data, the circa 1800 County Base and the 2001 National Land Cover Dataset, were used to setup the Soil and Water Assessment Tool (SWAT) model. First, sensitivity analyses were performed both based on pre-settlement and current land use scenarios and the most sensitive parameters were identified. Then, the model was calibrated against measured daily stream flow data obtained from eight United States Geological Survey gauging stations. The impacts of land use changes were studied at three scales: subbasin-level, watershed-level, and basin-level. At the subbasin level, most of the hydrologic behavior can be described by percent change in land cover. At the watershed scale, significant differences were observed based on the long-term average hydrologic fluxes under the current and pre-settlement scenarios. In addition, an overall increase in the amount of evapotranspiration and overland flow and overall decrease in the amount of baseflow and water yield were observed. However, at the basin-level, the majority of the area experienced increased overland flow, decreased baseflow, lateral flow, and recharge to aquifers, and minor changes in evapotranspiration and water yield.

1 Introduction

Land cover plays a key role in controlling the hydrologic response of watersheds in a number of important ways (Schilling et al., 2008; Mao and Cherkauer 2009; Elfert and Bormann, 2010; Elfert et al., 2010; and Ghaffari et al., 2010). Changes in land cover can lead to significant changes in leaf area index, evapotranspiration (Mao and Cherkauer, 2009), soil moisture content and infiltration capacity (Fu et al., 2000; Costa et al., 2003), surface and subsurface flow regimes including baseflow contributions to streams (Tu, 2009) and recharge, surface roughness (Feddema et al., 2005), runoff (Burch et al., 1987), as well as soil erosion through complex interactions among vegetation, soils, geology, terrain and climate processes. Furthermore, land use modifications can also affect flood frequency and magnitude (Ward et al., 2008; Remo et al., 2009; Benito et al., 2010; Qiu et al., 2010) and regional climate (Wang et al., 2006; Kueppers et al, 2007; Paeth et al., 2009).

Significant changes in land cover have occurred in the Great Lakes region over the last 150 yr including a major decrease in the forest cover and changes in composition from hardwood and conifer types to successional species such as aspen. Considerable progress has already been made in understanding the linkages between climate change and land use changes and their interactions (Copeland et al., 1996). Recently, Mao and Cherkauer (2009) examined the effects of land use change on hydrologic responses in the Great Lakes basin using the Variable Infiltration Capacity (VIC) model. They examined the changes in annual average fluxes of ET, total runoff, soil moisture and snow water equivalent (SWE) between current and pre-settlement land uses as well as the geographic shifting of center of gravity for each vegetation class. They reported an increase (relative to pre-settlement land use) in total runoff and SWE in more than half of their study area.

Since land use and climate change often influence the hydrology in complex ways exhibiting thresholds and positive or negative feedbacks among processes, it may be an insufficient task to study these effects in isolation. Based on a 25-yr experiment conducted in small Iowa watersheds with and without conservation tillage, Tomer and Schilling (2009) proposed a method to distinguish the hydrologic effects of land use change from climate change. Examining the increasing stream flow trends in the US Midwest watersheds, they conclude that climate change has been the larger of the two drivers since land use changes have plateaued in the agricultural regions of the Midwest since the 1970s. The recognition that climate change is a key driver behind increasing stream flows in the Midwest also means increased susceptibility to nutrient losses from agricultural landscapes contributing to degradation in water quality and Gulf of Mexico hypoxia. Johnston and Shmagin (2008) examined historical stream flow trends in the Great Lakes region using empirical orthogonal functions and principal component and factor analyses and identified five regions of the US Great Lakes basin with statistically distinct stream discharge patterns. One of the five distinct regions identified in their work is the predominantly agricultural region in the lower peninsula of Michigan and northern Wisconsin. Of the five regions, this is the only region that exhibited the consistent trend of increasing annual stream discharges for the period 1956–1988 (the period of their study).

In view of the importance of the agricultural regions of the Midwest and their role in contributing to the Gulf of Mexico hypoxia, detailed watershed modeling and analysis are needed including an assessment of how land use changes at different scales (e.g., from the hydrologic response unit to the basin scale) have influenced the hydrologic responses in this region. This is one of the objectives of this paper. A careful review of the literature indicated that land use change impact assessments on runoff have mainly been done through small-scale catchment experiments and varying results have been obtained, including opposing findings. For example, opposing results were reported concerning the impacts of deforestation on water yield. While Hibbert (1967) showed significant relationship between deforestation and increased in water yield, Langford (1976) study showed no relationship. (Hundecha and Ba'rdossy, 2004). Relative impacts of different land use types on surface water have not yet been established and quantified, especially for large watersheds (Tong and Chen, 2002; Qi et al., 2009).

Mechanisms underlying the impact of land use/land cover changes on hydrological processes (Wang et al., 2007) are not fully understood. Field data and experiments have the potential to demonstrate the consequences of land use change, but modeling studies are more likely to reveal the key mechanisms (Li et al., 2007). Studies regarding hydrologic sensitivity assessments of current and historic land use data at the large scale have not been conducted.

Therefore, case studies are needed in representative regions to understand the underlying mechanisms and to establish theory regarding the effects of land use and land cover changes on hydrologic processes. The aim of this paper is to use a comprehensive approach to examine the effects of land use change on hydrologic fluxes at both local and regional scales. In particular, the objectives are to: (a) determine how land use has changed in the agricultural regions of Michigan and Wisconsin area over a period of 200 yr (b) perform a hydrologic sensitivity assessment (c) quantify the magnitudes of hydrologic responses to land use changes and (d) test the Soil and Water Assessment Tool (SWAT) for modeling the hydrologic variability within the agricultural regions of Michigan and Wisconsin due to land use change. The results from this study are expected to aid the effort of managing land use changes to achieve sustainable water resources goals.

2 Material and methods

2.1 Study region

This focus of this paper is on the predominantly agricultural regions of Michigan and Wisconsin. Watersheds in nine accounting units were selected, which include hydrologic unit code (HUC) 070700 (Wisconsin), 040301 (Northwestern Lake Michigan), 040400 (Southwestern Lake Michigan), 040302 (Fox), 70900 (Wisconsin portion of Rock), 040500 (Southeastern Lake Michigan), 040900 (St. Clair-Detroit), 040801 (Southwestern Lake Huron), 040802 and Saginaw. The study area is shown in Fig. 1.

The study area covers 122 924 km^2, which includes 41 HUC 8 digit watersheds (Fig. 1) or nine HUC 6 digit watersheds (Table 1). Crop production is the main land usage (47.0 percent) for the study area. Forest is the second largest land usage at 23.5 percent. Wetlands, urban, rangeland and water areas constitute the remaining 16.2 percent of land cover (NLCD, 2001). The area of interest has gone though a significant land use changes in the past 200 yr. The forested areas were removed in a massive scale. More than 6.3 million hectares of forest land (51.4% of total area), 0.47 million hectares of wetlands (3.8% of total area), and 0.49 million hectares of rangeland (4.0% of total area) were lost mainly to agricultural production and urbanization (Table 1).

2.2 Model description

SWAT is a computationally efficient model that is well-suited for studying the large-scale impacts of land use changes as described in a series of papers based on the LUCHEM (Land Use Change on Hydrology by Ensemble Modeling) project (Breuer et al., 2009). The model was designed to predict the impact of land management practices on water, sediment, and agricultural chemical yields in watersheds with varying soils, land use, and management practices over long time periods. Components of the model include weather, hydrology, soil characteristics, plant growth, nutrients, pesticides, and land management (Gassman et al., 2007). In SWAT, a watershed is divided into subbasins, which are further divided into hydrologic response units (HRUs) based on similar land use, soil distribution, and slope. Hydrology components of SWAT include canopy storage, infiltration, redistribution, evapotranspiration, lateral subsurface flow, surface runoff, ponds, tributary channels, and return flow. A daily water budget in each HRU is calculated based on daily precipitation, runoff, evapotranspiration, percolation, and return flow from subsurface and groundwater flow (Nelson et al., 2006). In the following section, different components of water budget in the SWAT model will be discussed.

Surface runoff

Two methods for estimating surface runoff are provided in SWAT: the SCS curve number procedure (SCS, 1972) and the Green & Ampt infiltration method (1911). In this study, the SCS method was used. In addition, peak runoff rate is calculated with a modified rational method. The SCS curve number method estimates surface runoff from daily rainfall using initial abstractions (surface storage, interception, and infiltration prior to runoff) and a retention parameter (varies based on changes in soil, land use, management, and slope as well as temporarily due to changes in soil water content).

Evapotranspiration

Potential evapotranspiration (PET) is the volume of water that can be evaporated and transpired if enough water is available. SWAT estimates daily PET using one of three methods requiring varying inputs: Penman-Monteith, Hargreaves, or Priestly-Taylor. Daily PET values obtained from monitoring can also be incorporated into the model. After total PET is determined, actual evaporation is calculated. Rainfall intercepted by the plant canopy is evaporated first. Next, maximum amount of transpiration and sublimation/soil evaporation will be estimated. Actual amount of sublimation and evaporation from the soil is then calculated. Sublimation occurs if snow is present in an HRU, although no-snow conditions must be in effect for evaporation from the soil to occur (Neitsch et al., 2005).

Soil water relationship

Water that enters the soil may move along various pathways, including: removal from soil by plant uptake or evaporation, percolation past the soil profile to become aquifer recharge, or lateral movement in the profile and contribute to streamflow. SWAT uses a kinematic storage model developed by Sloan et al. (1983) to estimate lateral flow. This model simulates subsurface flow in a two-dimensional cross – section along a flow path down a steep hill slope. SWAT uses storage routing methodology to calculate percolation for each soil layer in the profile. If the soil is frozen during the simulation period, percolation in the soil layer is equal to zero (Neitsch et al., 2005).

Groundwater

The groundwater system in SWAT consists of shallow and deep aquifers. Shallow aquifer water balance consists of recharge entering the aquifer, groundwater flow, or base flow into the main channel, the amount of water moving into the soil zone in response to water deficiencies, and the amount of water removed from the shallow aquifer due to pumping. The deep aquifer water balance consists of percolation from the shallow aquifer to the deep aquifer and the amount of water removed from the deep aquifer due to pumping. SWAT uses empirical and analytical techniques to account for the above components (Neitsch et al., 2005).

Water Routing: in SWAT, water is routed through the channel network using the variable storage routing method (Williams, 1969) or the Muskingum River routing method (Chow et al., 1998). Each routing method is a variation of the kinematic wave mode (Neitsch et al., 2005).

2.3 Data sources

2.3.1 Physiographic characteristics

Two main sets of land use/land cover data were used in this study (Fig. 2a and b). For the current land use, 2001 National Land Cover Data (NLCD 2001) was used. NLCD 2001 products include 21 classes of land cover at 30 m cell resolution. Pre-settlement land uses are available at the state level; therefore, three different sets of datasets were obtained including (1) Michigan Natural Features Inventory (MNFI) (2) Original Vegetation Cover of Wisconsin (3) Land Cover of Illinois for the early 1800's. The MNFI was developed based on the surveyed performed by the General Land Office in mid-1800. The map is called vegetation circa 1800 and available through the MNFI website (http://web4.msue.msu.edu/mnfi/data/veg1800.cfm). This dataset contains 30 different landcover classes. The Original Vegetation Cover of Wisconsin was obtained from Wisconsin Department of Natural Resources (http://dnr.wi.gov/maps/gis/documents/orig_vegetation_cover.pdf) based on the survey performed in mid-1800. The scale of the original map is 1:500 000 and contains 21 different landcover classes. The Land Cover of Illinois for the early 1800's was obtained from the Institute of Natural Resource Sustainability at the University of Illinois at Urbana-Champaign. Twelve different landcover classes are identified in this map.

In the next step, and before introducing the pre-settlement datasets to the watershed model (SWAT), pre-settlement land cover maps were reclassified to the NLCD 2001 classes to provide consistency between land cover maps. The reclassified land cover maps were then incorporated into the model for further investigations. USGS 1:250 000-scale Digital Elevation Model Grid (DEMG) at three arc-second (100 m) resolution was obtained for the study area (http://seamless.usgs.gov/). This dataset was used to derive the topographic characteristics of the watershed such as watershed boundary, slope, etc. Based on the data presented in Table 2, average elevation for the watersheds in Wisconsin is higher than Michigan's watersheds (341.8 m to 284.6 m, respectively). In addition, elevation differences for watersheds in Wisconsin are larger than the ones in Michigan (348.5 m to 235.5 m, respectively). These differences may have significant impacts on watershed hydrologic responses such as stream flow and evaporation in two regions (Mohamoud, 2004). A stream network dataset can be superimposed onto the DEM to define the location of stream network. In this study, river networks for the study areas were obtained from the National Hydrography Dataset (www.horizon-systems.com/nhdplus/). The NHD dataset was used to improve hydrologic segmentation and subwatershed boundary delineation (Winchell et al., 2007).

2.3.2 Gauging stations

Eight different US Geological Survey (USGS) gauging stations were used for the SWAT model calibration and validation. At least nineteen years of daily stream flow records are available for each station (Fig. 3). The stations include USGS gauging station 04079000 on the Wolf River, USGS gauging station 04087000 on the Milwaukee River, USGS gauging station 04119000 on the Grand River, USGS gauging station 04142000 on the Rifle River, USGS gauging station 04157000 on the Saginaw River, USGS gauging station 04174500 on the Huron River, USGS gauging station 05404000 on the Wisconsin River, and USGS gauging station 05437500 on the Rock River.

2.3.3 Weather and climatological datasets

Daily precipitation records along with minimum and maximum temperature were acquired from 195 precipitation stations and 158 temperature stations within and around the study area (Fig. 1) for 19 yr (1990–2008). The long-term average precipitation within the study area is 962 mm. However, the average precipitation within the study areas in Wisconsin (WI) is 945 mm (varies from 674 mm to 1115 mm) and for Michigan (MI) is 980 mm (varies from 667 mm to 1128 mm). In addition, 13.5 and 15.3 percent of precipitation is in the form of snowfall for WI and MI, respectively. Average long-term maximum temperature varies between 13.3 to 15 °C for the study area. However, the average long-term minimum temperature varies from 1.1–2.8 °C for WI part of the study area to 2.8–4.4 °C for MI part of the study area.

2.4 Sensitivity analysis

Sensitivity analysis is used to explain how the variation in model output can be attributed to different sources of variation in the model input. However, it is important to note that some of the results of sensitivity analysis, depending on their placement in model algorithms, may not in fact have significant physical meaning. In this study the sensitivity analysis concerning daily flow rate was performed on 42 different SWAT parameters. The process was repeated on the nine HUC 6 digit watersheds both based on current and pre-settlement land use maps and results are summarized in Tables 3a and b. Sensitivity analysis helps in identifying a series of parameters for the SWAT model calibration.

2.5 Model calibration and validation

For most watershed models including SWAT, calibration is an iterative process that compares simulated and observed data of interest (typically streamflow data) through parameter evaluation. The goal of validation is to assess whether the model is able to predict field observations for time periods different from the calibration period (Donigan, 2002). As mentioned earlier, eight different USGS gauging stations were used for the SWAT model calibration and validation. Daily streamflow data are available for all of these stations for the period of (1990–2008). Before performing the calibration and validation processes, one should identify the simulation period in which a broad range of climatological conditions are captured. In the first step, we plotted the average annual precipitation data from 1990 to 2008 for the study area. We selected the period of 2002–2007 for the model calibration and validation because this period includes dry, wet, and normal climate conditions based on long term average precipitation records. Year 2002 was selected as the model warm-up year.

Some parameters identified as sensitive were not modified during calibration, while others that were not identified during sensitivity analysis were modified during calibration. Parameters that were not identified as sensitive but used in calibration were applied to match the model with naturally occurring processes in the watershed. Additionally, parameters not identified as sensitive in the sensitivity analysis must be adjusted due to error observed in predicted variables. Parameters chosen other than those identified by the sensitivity analysis were based on calibration parameters identified in other published results (White and Chaubey, 2005).The following parameters were used for the model calibrations in different watersheds: *Alpha_Bf* (baseflow recession constant), *Cn2* (moisture condition II curve number), *EPCO* (plant uptake compensation factor), *ESCO* (soil evaporation compensation coefficient), *Rchrg_Dp* (deep aquifer percolation fraction), *Surlag* (surface runoff lag coefficient), *TIMP* (snow coefficient lag factor).

Since long-term daily precipitation records, minimum and maximum temperature, etc. are not available for the study area during the mid-1800s, it is not possible to precisely calibrate the model or estimate the flow regime under the pre-settlement scenario. However, by setting up the model for pre-settlement scenario based on current climatological variables (e.g. precipitation temperature, etc. for the period of 1990–2008) we can accurately compare the results of land use changes in the region while eliminating the climatological difference. In addition, the same adjustments were made to the calibration parameters under pre-settlement scenario as they were under current land use scenario. This will allow us to minimize a possible bias caused by calibration process. It is important to note that applying the same calibration parameter values to the presettlement scenario may adversely impact the model results. However, the underlying assumption is that models such as SWAT were developed to evaluate hydrologic and water quality impacts of landuse change without limitation regarding the type, amount, and nature of landuse change. In addition, it is safe to say that as the landuse change from calibrated scenario becomes more drastic, the uncertainty of model predictions is increased.

In addition, it is expected that agricultural practices (such as drainage system, irrigation, type of crop, crop rotation, etc.) have impacts on hydrological fluxes (Raymond et al., 2008). However, collecting and incorporating this information to the model is very difficult and in some cases impossible due to the lack of datasets. Therefore, ignoring some or all of the above practices will increase the level of uncertainty in the model prediction.

3 Results and discussions

As land use changes from forest to agriculture, the soil structure generally deteriorates. This deterioration is evidenced by reduced pore space, increased bulk density, increased compaction, reduced content of water-stable aggregates, and reduced rates of infiltration. Soil deterioration effects surface water runoff, stream flow, and sedimentation (Carmen, 1954). In the following section, we will study the hydrologic effects of land use change at both a regional and a local scale by (1) performing a hydrologic sensitivity assessment and quantifying the magnitudes of hydrologic response to possible land use changes and (2) quantifying the magnitudes of hydrologic response to land use changes using the SWAT model.

3.1 Sensitivity analysis

Among the 42 parameters that were used for sensitivity analysis, 15 parameters were selected for further investigation. These parameters directly or indirectly influence the daily flow rate and ranked higher than others. Two criteria (mean and median) were selected to identify the most influential parameters, which affect daily flow rates. Mean and median were calculated for the top 15 parameters based on their position in the sensitivity analysis ranking table. Comparing Tables 3a and b illustrates significant shifts in overall ranking of some parameters, while ranking of other parameters are slightly sensitive or insensitive to the land use changes.

Among the parameters, a significant shift in overall ranking can be observed in *Cn2* (initial SCS curve number for moisture condition II), *Sol_Z* (depth from soil surface to bottom of layer), *Rchrg_Dp* (deep aquifer percolation fraction), and *Canmx* (maximum canopy storage).

Cn2 and *Rchrg_Dp* parameters: In general, flow rate is the most sensitive to *Cn2* based on current land use map while *Rchrg_Dp* was the most influential parameter under the pre-settlement scenario. In SWAT, the upper and lower boundaries for *Cn2* can be varied by ±25% while *Rchrg_Dp* is substituted by a value between 0 to 1. The aforementioned shift in ranking of *Cn2* and *Rchrg_Dp* parameters can be explained by runoff curve number values because the SWAT model does not assign different *Rchrg_Dp* values to different land uses. In SWAT, the assigned curve number values for forested land cover (31–79) is generally smaller than other land use/land cover classes such as croplands (67–89). Therefore, a switch in ranking of *CN2* and *Rchrg_Dp* parameters in the sensitivity table is only caused by the *Cn2* parameter resulting in more recharge and less runoff.

Canmx parameter: plant canopy can significantly affect infiltration, surface runoff, and evapotranspiration. In SWAT, the maximum amount of water that can be contained in canopy storage (can_{day}) varies daily as a function of the leaf area index (LAI).

$$can_{\text{day}} = can_{\text{mx}} \cdot \frac{\text{LAI}}{\text{LAI}_{\text{mx}}} \tag{1}$$

where, LAI_{max} is the maximum leaf area index for a plant.

The results of the sensitivity analysis revealed that the *Canmx* parameter (the maximum amount of water that can be trapped in the canopy when the canopy is fully developed) was dropped from rank four in the pre-settlement scenario to rank eight for the current land use scenario. This drop can be explained by excessive deforestation within the study area (6.3 million hectares of forest land was converted to urban and agricultural lands). In general, a lower *Canmx* value was assigned to agricultural lands (e.g. row crops) in comparison to forest land; therefore affecting overall canopy storage within the study area that alters hydrology in the region.

Sol_Z parameter: the results of the sensitivity analysis shows that the overall ranking of the *Sol_Z* was improved from rank nine to rank six. *Sol_Z* is one of the characteristics of soil type and will not be adjusted by land use change. In SWAT, *Sol_Z* affects potential water uptake, soil temperature, etc. Potential water uptake ($w_{\text{up},z}$) from the soil surface can be estimated using the following Eq.:

$$w_{\text{up},z} = \frac{E_t}{[1-\exp(-\beta_w)]}\left[1-\exp\left(-\beta_w \frac{Sol\_Z}{z_{\text{root}}}\right)\right] \tag{2}$$

where, E_t is the maximum plant transpiration on a given day, β_w is the water-use distribution parameter, and z_{root} is the depth of root development in the soil.

SWAT assumes trees have roots down to the maximum soil depth while annual plants have a simulated root depth that varies linearly form 10 mm to maximum plant rooting depth. In addition, depth of root development (z_{root}) on agricultural land is smaller than on forest land. As it was discussed above, the *Sol_Z* parameter is independent of land use changes; however, since z_{root} changes in different land use, the ratio of *Sol_Z* to z_{root} changes. This affects plant water uptake and ultimately improves the ranking for *Sol_Z* in the current landuse.

In addition to the overall ranking of parameters, some drastic changes also observed at the watershed level. For example, in the Wisconsin portion of Rock watershed (HUC 70900), *Rchrg_Dp* parameter was ranked third under pre-settlement landuse scenario and it was pushed to rank sixth under current landuse scenario. Closer study of landuse change in this watershed illustrated that this watershed experienced the most extreme expansion of agricultural land within the basin (75.5% increase in agricultural land), while deforestation resulted in reduction of forested land to less than 10% of the watershed area (8.9%). Therefore, it is expected that the overall recharge decrease in this watershed.

As demonstrated, parameter sensitivity analysis may not always explain how the variation in model output can be attributed to different sources of variation in the model input. Therefore, attention should be taken to determine the true importance of sensitive parameters by considering their placement in model algorithms and the most sensitive parameters may not always be appropriate for use in model calibration.

3.2 Model calibration and validation results

We evaluated model performance using a number of metrics including the coefficient of determination (R^2), the Nash-Sutcliffe coefficient of efficiency (E_{NS}), and the root-mean-square error (RMSE),all of which are well-known in the hydrology literature (Eqs. (3), (4), and (5) below).

Coefficient of determination (R^2): The coefficient of determination is defined as the square of the correlation coefficient (Krause et al., 2005):

$$R^2 = \left(\frac{\sum_{i=1}^{n} (O_i - \bar{O})(P_i - \bar{P})}{\sqrt{\sum_{i=1}^{n} (O_i - \bar{O})} \sqrt{\sum_{i=1}^{n} (P_i - \bar{P})}} \right) \tag{3}$$

where O is the observed value, P is the predicted value, n is the number of samples, and $\bar{O}$ and $\overline{P}$ denote the average observed and predicted values respectively.

The range of R^2 is from 0 to 1, which describes how much of the observed dispersion is explained by the prediction. A value of zero equates to no correlation, while a value of 1 represents dispersion of the prediction equal to that of the observation. The drawback of using R^2 for model evaluation is that R^2 results can be misleading if the model in general is over- or underpredicting (Krause et al., 2005). This problem can be detected by comparing predicted and observed values within the period of study (Fig. 4).

Nash-Sutcliffe coefficient of efficiency (E_{NS}): Nash-Sutcliffe coefficient of efficiency calculates the normalized relative magnitude of residual variance in comparison with the measured data variance (Moriasi et al., 2007):

$$E_{\mathrm{NS}} = 1 - \frac{\sum_{i=1}^{n} (O_i - P_i)^2}{\sum_{i=1}^{n} (O_i - \bar{O})^2} \tag{4}$$

The range of E_{NS} lies between 1.0 (perfect fit) and $-\infty$.

Since the difference between observed and model results is squared in this method, the impacts of low values in time series (e.g. baseflow or lateral flow) are neglected. In addition, Nash-Sutcliffe coefficient of efficiency is not sensitive to over- or underpredictions for low flow scenarios (Krause et al., 2005).

Root mean square error (RMSE): Root mean square error calculates the square root of the variance. Smaller values of RMSE indicated better model performance. An RMSE value of 0.0 indicates a perfect simulation of the observed data (Chu et al., 2004).

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n} (O_i - P_i)^2}{n}} \tag{5}$$

Moriasi et al. (2007) developed general evaluation guidelines based on a model performance rating. Based on these guidelines, a model performance can be evaluated as “satisfactory” for a monthly time step series if $E_{\mathrm{NS}} > 0.50$. In addition, $R^2 > 0.5$ has been used in other studies such as Nejadhashemi et al. (2008) and Chinkuyu et al. (2004) as one of the criteria to evaluate a satisfactory model performance.

Guidelines for model evaluation presented above apply to the case of continuous, long-term flow simulation on a monthly time step. Model evaluation guidelines must be adjusted on an application to application basis because of the diversity of modeling uses. Guidelines should be modified based on numerous factors such as single-event simulation, quantity and quality of observed data, model calibration procedures, evaluation time step, and project scope and magnitude (Moriasi et al., 2007).

In general, shorter time steps have poorer model simulations than longer time steps (Moriasi et al., 2007). Performance ratings presented above for E_{NS} statistics are for a monthly time steps and must be modified for a daily time step to be applicable in this study. In order to do so, a series of studies on SWAT model performance on daily basis were reviewed. For example Benham et al. (2006) reported R^2 of 0.4 and E_{NS} of 0.21, Coffey et al. (2004) reported R^2 of 0.4 and E_{NS} of 0.15, and Di Luzio and Arnold (2004) reported R^2 of 0.24 and E_{NS} of 0.15 for satisfactory SWAT calibration. Based on the above studies, the following criteria are considered to evaluate satisfactory model performances on daily basis: $E_{\mathrm{NS}} > 0.20$ and $R^2 > 0.4$.

As it was previously discussed, all watersheds were calibrated for the period of 2003–2005 and validated for the period of 2006–2007; year 2002 was selected as the model warm-up year. The only exception to the above rule is watershed 070700. The watershed 070700 is unique in the sense that flow is regulated by 24 reservoirs above the station that was used for the model calibration (US Geological Survey gauging station 05404000 on Wisconsin River near the Wisconsin Dells). Based on the Wisconsin River Reservoir System Operating Plan report (WVIC, 2010), maintaining uniform flow on the Wisconsin River and meteorological conditions (volume and timing of precipitation and snowmelt) are the factors considered in the reservoir operation cycle. In July 1996, four particular operating rules for the reservoir system are specified, including (1) maximum and minimum water levels in each reservoir; (2) minimum flow for each reservoir; (3) flow goals; and (4) storage balancing using index levels (WVIC, 2010), which alters the flow regime in the Wisconsin River after 1996. Therefore, the model was calibrated and validated for the period of 1991–1996, while the year 1991 was selected for the model warm-up. Comparisons between the observed (USGS) and simulated streamflows in representative watersheds are shown in Fig. 4 while results obtained from the SWAT model calibration, validation, and combined statistical analysis are summarized in Table 4. From the comparisons and the associated statistics, we note that the model performance in all watersheds can be considered as satisfactory.

3.3 Subbasin-level impacts of land use changes

The objective of this section is to understand whether land use conversion can explain hydrological behavior at the subbasin level. In order to estimate the percentage of land use conversion within each of the 2308 subbasins (Fig. 5), the pre-settlement and current land use maps were intersected. This allows partitioning of the subbasin to smaller units based on intersected area of pre-settlement and current landuse scenarios (Fig. 6). Then the top 14 land use conversion classes were identified and the percentage of landuse conversion within each of the 14 classes to the total subbasin area was calculated for all 2308 subbasins. In the next step, the degree of relationship (correlation) between percent of land use conversion within a subbasin and seven different hydrologic characteristics were assessed (actual evapotranspiration, soil water content, water percolation, surface runoff, baseflow, water yield, lateral flow). As shown in Table 5, changes in hydrologic characteristics are examined by considering the percentage change in a variable relative to its pre-settlement value (P1, P2, P3 etc.) as well as the absolute difference in the variable (D1, D2 etc.) – therefore a total of 14 variables are listed in Tables 5 and 6.

Normality was assessed using normal probability plots and the Kolmogorov-Smirnov test. The null hypothesis of normal distribution was rejected in all the studied variables. Most of the hydrological variables expressed as percent showed skewed distributions deviating from normality (e.g. percent changes in water content, percolation, surface runoff, lateral flow), some variables showed strong evidence of outliers (e.g. percent changes in water content, percolation and surface runoff). Percent of land use conversion was not normally distributed as indicated by the Kolmogorov-Smirnov test ($D = 0.26$, $p < 0.01$). Since all of the variables involved in this study deviate from normal distribution, nonparametric measures of association were used (Sprent and Smeeton, 2000). The Spearman rank-order correlation is a measure of association based on the rank of the data values, and Hoeffding's measure of dependence is a measure of association that detects more general departures from independence and is typically used to infer nonlinear and non-monotonic associations. Fujita et al. (2009) recently demonstrated that Hoeffding's method outperforms Pearson's and Spearman's methods in identifying nonlinear associations. The authors also demonstrate that Hoeffding's method is less sensitive to outliers. The null hypothesis in the test of association in both methods assumes no correlation, thus rejecting null hypothesis indicates a significant association.

Based on Spearman's method several significant correlations were found even at the 0.01 level (Table 5). Some differences were observed in the correlations expressed as the absolute differences as compared to the percent differences. However, there is a clear correlation between percent change of area and all hydrological properties

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in land use conversation from mixed forest to urban and agriculture. Meanwhile, the magnitudes of the correlation coefficients were rather low for all correlations (e.g. typically lower than 0.5). Based on Hoeffding's D measure, significant association was observed across all variables and hydrological variables with few exceptions, for example percent change actual evapotranspiration, soil water content, surface runoff and water yield in land use conversion code 53 (evergreen forest to rangeland). Most of the associations expressed a significant level lower than 0.01. Most of the significant associations were observed in the change from mixed forest to urban, rangeland or agriculture. The lower number of association was observed for the change from evergreen forest to urban, rangeland and agriculture.

3.4 Watershed-level impacts of land use changes

A summary of watershed-level impacts of land use change on changes in the hydrologic fluxes is presented in Table 7. The objective in this analysis is to compare hydrological variables in pre-settlement and current land use at watershed level. The sample size for this analysis is rather low because only the means of eight HUC-6 digit watersheds are available, which makes difficult to test statistical assumptions (i.e. normality). In addition, the eight watersheds used for pre-settlement and current land use were the same, making this a paired dataset in which independence between subjects (i.e. watershed) is not found. A nonparametric test suitable for paired samples and small sample size is the Wilcoxon Signed Rank Sum, S-test (Sprent and Smeeton, 2000). This is a nonparametric version of a paired samples t-test that can used when difference between the two variables is not assumed to be normally distributed. The null hypothesis assumes no difference between the samples, thus rejecting null hypothesis implies significant differences in hydrological variables between pre-settlement and current land use. The null hypothesis was rejected for all variables except for water yield ($S = -4$, $p = 0.64$). In general, water yield is a function of several complex hydrologic processes, therefore, it is very difficult to explain behavior of water yield with respect to changes in one factor (landuse). Meanwhile, evidence of significant difference between pre-settlement and current land use were observed for: evapotranspiration ($S = 16$, $p = 0.023$), recharge ($S = -18$, $p = 0.007$), surface runoff ($S = 15$, $p = 0.039$) and baseflow ($S = -18$, $p = 0.007$). Significant differences were also found for the absolute values of evapotranspiration ($S = 15$, $p = 0.04$) and surface runoff ($S = 14$, $p = 0.05$).

By studying the percentage of different land coverage (Table 1), it should be noticed that watershed 040900 has the highest percentage of urban development (38.1%) among all studied watersheds. In addition, the highest evapotranspiration change is assigned to watershed 070900, which has the greatest percentage of agricultural lands within a watershed (72.5%).

All watersheds demonstrated a reduction in recharge potential and groundwater contributions to streamflow (baseflow) relative to the pre-settlement scenario. This can be attributed to the lost of forestlands between 38.6% to 70.4% of total watersheds' areas (Table 1), while agricultural lands and urban areas present lower potential for recharge compared to forested lands due to increased runoff. The impact of land use change on overall surface runoff pattern is also presented in Table 6. All watersheds except 040302 exhibit an increase in surface runoff generation except HUC 040302. This may be caused by a low percentage of urbanization (7.5%), and an overall lower ratio of deforestation to agricultural land expansion compared to other watersheds studied. The last hydrologic characteristic that will be discussed is water yield. Water yield is a summation of surface runoff, lateral flow, and baseflow minus transmission loss. Therefore, explaining the variation in water yield at a watershed scale is not simple. However, reductions in total water yield were observed in the majority of watersheds, excluding HUCs 040900 and 070900. A closer examination of model outputs revealed that water yield in agricultural areas are the lowest among all studied land uses, while urban area has the highest median value for water yield. Almost 38% of the area in watershed 040900 is in urban, while 33% is under cultivation (Table 1). This is the highest percentage of the developed areas within a single watershed among all studied watersheds. Therefore, the existence of the developed area increases the overall water yield value for this watershed. However, in watershed 070900, the percentage of urban areas is low (8.5%) while percentage of agricultural land is high. However, this watershed had the highest percent of rangeland in mid-1800 (24.8%). Based on the current land use scenario the rangeland was reduced by 93%. The combination of the above factors and unique physiographic characteristics may cause the slight increase in long-term average water yield in this watershed.

3.5 Basin-wide impacts of land use changes

Basin-wide impacts of land use changes on hydrologic characteristics are presented in Fig. 7 through Fig. 10. In general, the basin was divided into to three major classes. (1) positive high: if percent change in hydrologic characteristics is equal or more than 10% of the original value; (2) modest: if percent change in hydrologic characteristics is between −10% to 10% of the original value and; (3) negative high: if percent change in hydrologic characteristics is equal or less than −10% of the original value (Fig. 10). Figures 7a and 10 demonstrate that percent change in evapotranspiration is modest in the majority of the basin, particularly in the northwest region of the study area in which forested lands are generally preserved. In addition, decreases in evapotranspiration can be observed especially in heavily populated areas such as Detroit (MI) and Milwaukee (WI). More than 70% of the study area is classified as negative high with respect to baseflow and recharge to aquifers. This can be attributed to conversion of forestlands to agricultural lands that have lower recharge potentials (Figs. 7b and 9a). Between the hydrologic parameters that are discussed here, overland flow contribution to streamflow (*Surf_Q*) was increased in majority of the region in comparison to pre-settlement scenario. In fact, more than 65% of the study area is classified as positive high with respect to overland flow. This can be explained by the vast expansion of agricultural lands in the region. Regarding water yield, the majority of the region experiences modest changes, while about 15% of region is classified as positive high and 24% is classified as negative high. The positive high region mostly corresponds to urbanization and the negative high region is mostly associated to conversion of wetlands, rangeland and forested areas to agricultural production.

4 Conclusions

The Great Lakes region has been experiencing substantial land use changes from pre-settlement conditions over the past 150 yr. This study focused on some of these changes within the agricultural regions of Michigan and Wisconsin including massive deforestation (51% of the total area), loss of wetlands and rangelands (8% of the total area) to agricultural production and urbanization. Several land surface characteristics and processes are greatly affected by land use change, including leaf area, roughness, albedo, soil moisture, and momentum, energy, and water vapor exchange rates. Land use changes such as urbanization, deforestation, and reforestation continue to affect groundwater-surface water interactions including percolation or recharge, groundwater contributions to streams, and soil moisture as summarized in Tables 5 and 6 as well as water availability influencing ecosystem services. This research used a comprehensive approach to examine land use change effects on hydrology at both local and regional scales.

Pre-settlement land use maps were used to develop a baseline scenario relative to the current landuse map in which the impacts of land use changes on hydrological and environmental processes can be evaluated.

Sensitivity analysis is one of the tools used to explain how the variation in model output can be caused by model input. However, the results of this study shows that parameter sensitivity analysis may not always explain how the variation in model output can be attributed to different sources of variation in the model input. Therefore, attention should be taken to determine the true importance of sensitive parameters by considering their placement in model algorithms and the most sensitive parameters may not always be appropriate for use in model calibration. White and Chaubey (2005) also raised concern about application of relative sensitivity parameter in model evaluation especially concerning the assumption of linearity and lack of correlation between parameters.

Regarding the impacts of land use changes, three scales were used: subbasin-level, watershed-level, and the basin level. At the subbasin level, the result was aggregated from the HRU level to estimate the contribution of all fields in the watershed to the river, yet does not include in-stream routing components. At the watershed level, both contribution from individual HRUs to the subbasins and in-stream routing are considered. And finally at the basin level, the overall results of different hydrological fluxes are averaged.

At the subbasin level, based on the results of the statistical analysis, several significant correlations were found between the percentage of landuse change and both absolute and relative differences in hydrological behaviors with few exceptions, such as evergreen forest to rangeland. Concerning watershed scale impacts of land use changes, a Wilcoxon Signed Rank Sum, S-test confirmed that the long-term average fluxes under the current and pre-settlement scenarios were not the same. Similar results were reported in many studies such as Matheussen et al., 2000; Andreassian, 2004; Brown et al., 2005; Coe et al., 2009. Overall increase in evapotranspiration and surface runoff contribution to stream flow, decrease in recharge to aquifers and baseflow, and mixed impacts on water yield were detected. Finally, at the basin-level, modest changes in evapotranspiration and water yield, significant increases in overland flow generation, and significant decreases in recharge, baseflow, and lateral flow in the majority of the basin were observed.

The results of this study can be used in quantifying the potential impacts of future projected changes in land use in order to mitigate the negative impacts of these changes on goods and services of value to society.

Acknowledgements. The authors would like to acknowledge useful discussions and help from Chaopeng Shen, Scott Sowa, Jon Bartholic, Yi Shi, Mr. Sean Woznicki, and Mr. Matt Einheuser. Funding for this project was provided by the United State Department of Agriculture – Natural Resource Conservation Service as a part of the Conservation Effects Assessment Project.

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Table 1. Study area land use summary.

Current Land Use																		
Watershed	040302	040302	040301 & 040400	040301 & 040400	040801	040801	040500	040500	040900	040900	070700	070700	070900	070900	040802	040802	Total	Total
	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%
Forest	436067	27.7	100140	11.6	144129	20.2	367067	17.0	123487	15.1	1237094	41.3	147195	8.9	330425	21.7	2885603	23.5
Wetlands	235089	14.9	92769	10.8	93662	13.1	267151	12.4	75765	9.3	377686	12.6	99274	6.0	220167	14.4	1461562	11.9
Rangeland	41652	2.6	24627	2.9	41898	5.9	58727	2.7	20510	2.5	84687	2.8	29771	1.8	89100	5.8	390972	3.2
Water	100665	6.4	5770	0.7	5399	0.8	35460	1.6	15888	1.9	106712	3.6	35271	2.1	19966	1.3	325131	2.6
Agriculture	641683	40.8	508390	59.1	372424	52.1	1106698	51.3	270696	33.1	1016862	33.9	1194058	72.5	671452	44.0	5782263	47.0
Urban	117709	7.5	128418	14.9	56840	8.0	322438	14.9	311922	38.1	174652	5.8	140437	8.5	194497	12.7	1446914	11.8
Total	1572865	100	860114	100	714352	100	2157541	100	818268	100	2997693	100	1646004	100	1525607	100	12292445	100
Pre-settlement Land Use																		
Watershed	040302	040302	040301 & 040400	040301 & 040400	040801	040801	040500	040500	040900	040900	070700	070700	070900	070900	040802	040802	Total	Total
	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%
Forest	1144435	72.8	705081	82.0	532103	74.5	1561585	72.4	587132	71.8	2394177	79.9	1027008	62.4	1250806	82.0	9202328	74.9
Wetlands	275926	17.5	111316	12.9	176615	24.7	339448	15.7	187871	23.0	419935	14.0	183877	11.2	239458	15.7	1934445	15.7
Rangeland	60622	3.9	38550	4.5	1047	0.1	222084	10.3	30657	3.7	92945	3.1	408033	24.8	23127	1.5	877065	7.1
Water	91883	5.8	5167	0.6	4587	0.6	34424	1.6	12608	1.5	90636	3.0	27086	1.6	12215	0.8	278,607	2.3
Agriculture	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0
Urban	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0
Total	1572865	100	860114	100	714352	100	2157541	100	818268	100	2997693	100	1646004	100	1525607	100	12292445	100

Table 2. Physiographic and climatological summary of the study.

Watershed (HUC)	State	Annual Average Rainfall (mm)	Annual Average Snowfall (mm)	Annual Average Precipitation (mm)	Minimum Average Precipitation (mm)	Maximum Average Precipitation (mm)	Average Elevation (m)	Minimum Elevation (m)	Maximum Elevation (m)
040302	WI	791	114	905	695	944	378	176	579
040301 & 40400	WI	814	109	923	674	967	276	176	381
070700	WI	857	125	982	679	962	385	185	588
070900	WI	869	102	972	728	1115	328	135	518
040801	MI	809	132	941	704	957	309	176	441
040802	MI	822	129	951	683	1012	242	177	457
040900	MI	840	120	960	667	1043	269	173	365
040500	MI	926	140	1066	757	1128	275	176	381

Table 3a. Sensitivity analysis summary (current land use).

Watershed Parameters	040302	040301 & 040400	070700	070900	040801	040802	040900	40500	Mean	Median	Overall Ranking
	WI	WI	WI	WI	MI	MI	MI	MI			
Cn2	1	1	1	1	2	1	2	1	1.25	1.00	1
Rchrg_Dp	3	6	2	6	1	2	1	3	3.00	2.50	2
Esco	4	3	4	3	3	3	3	2	3.13	3.00	3
Alpha_BF	2	4	3	2	5	6	4	4	3.75	4.00	4
Timp	5	5	6	7	6	8	8	5	6.25	6.00	5
Sol_Z	7	2	10	8	7	4	5	7	6.25	7.00	6
Sol_Awc	9	7	8	4	8	5	7	6	6.75	7.00	7
Canmx	8	9	5	10	4	7	9	10	7.75	8.50	8
Gwqmn	6	10	9	13	9	9	6	8	8.75	9.00	9
Ch_K2	10	11	7	5	11	10	11	9	9.25	10.00	10
Blai	11	8	11	9	10	11	10	11	10.13	10.50	11
Surlag	12	12	15	11	16	12	13	12	12.88	12.00	12
Ch_N2	16	13	14	12	17	15	15	13	14.38	14.50	13
Slope	13	21	16	19	13	14	16	18	16.25	16.00	14
Sol_K	14	22	18	16	15	19	17	21	17.75	17.50	15

Table 3b. Sensitivity analysis summary (pre-settlement land use).

Watershed Parameters	040302	040301 & 040400	070700	070900	040801	040802	040900	40500	Mean	Median Ranking	Overall
	WI	WI	WI	WI	MI	MI	MI	MI			
Rchrg_Dp	1	5	1	3	1	1	1	1	1.75	1.00	1
Cn2	2	1	2	1	2	2	2	2	1.75	2.00	2
Esco	3	3	4	2	3	3	3	3	3.00	3.00	3
Canmx	4	4	5	5	4	4	4	4	4.25	4.00	4
Alpha_BF	5	6	3	4	5	5	5	11	5.50	5.00	5
Timp	6	7	7	8	9	6	9	5	7.13	7.00	6
Sol_Awc	7	9	8	7	8	7	8	6	7.50	7.50	7
Gwqmn	8	10	9	10	6	8	7	7	8.13	8.00	8
Sol_Z	9	2	10	9	7	9	6	8	7.50	8.50	9
Blai	10	8	11	6	10	10	10	9	9.25	10.00	10
Ch_K2	11	12	6	11	12	11	12	15	11.25	11.50	11
Surlag	14	14	15	14	15	14	13	10	13.63	14.00	12
Ch_N2	16	13	16	13	17	15	15	22	15.88	15.50	13
Slope	15	21	14	22	13	16	16	20	17.13	16.00	14
Sol_K	17	20	17	16	16	21	17	19	17.88	17.00	15

Table 4. Statistical analysis based on daily streamflow SWAT model outputs.

Watershed	Parameter	Uncalibrated Statistics	Calibration Statistics (2003–2005)	Validation Statistics (2006–2007)	Overall Statistics (2003–2007)
040302	NSE	−4.42	0.76	0.59	0.73
	RMSE	73.50	13.60	9.07	16.40
	R^2	0.016	0.80	0.73	0.75
040301 & 40400	NSE	−0.68	0.82	0.68	0.78
	RMSE	18.65	7.02	5.74	9.07
	R^2	0.20	0.82	0.71	0.78
070700	NSE	−1.01	0.40[1]	0.46[2]	0.45[3]
	RMSE	62.69	81.07[1]	96.87[2]	126.32[3]
	R^2	0.08	0.62[1]	0.56[2]	0.60[3]
070900	NSE	−8.76	0.74	0.70	0.74
	RMSE	285.70	35.64	30.57	46.95
	R^2	0.09	0.80	0.71	0.77
040801	NSE	−2.46	0.29	0.48	0.40
	RMSE	15.06	4.71	4.17	6.29
	R^2	0.17	0.47	0.55	0.50
040802	NSE	−1.38	0.77	0.83	0.80
	RMSE	206.70	48.31	35.68	60.06
	R^2	0.11	0.77	0.83	0.80
040900	NSE	−1.87	0.69	0.71	0.72
	RMSE	17.26	3.95	3.69	5.41
	R^2	0.20	0.74	0.76	0.77
040500	NSE	−2.68	0.80	0.84	0.80
	RMSE	167.56	31.62	20.46	37.7
	R^2	0.11	0.81	0.84	0.82

[1] Period of calibration 1994–1996.
[2] Period of validation 1992–1993.
[3] Period of overall model performance 1992–1996.

Table 5. Spearman correlation coefficient and its probabilities (p-value). Correlation between percent of land use conversion within a subbasin and hydrological variable. Italic p-value indicates a significant probability at 0.01 level. Bold p-value indicates significance at 0.05 level.

Pre-settlement	Current	code	(P1)	(P2)	(P3)	(P4)	(P5)	(P6)	(P7)	(D1)	(D2)	(D3)	(D4)	(D5)	(D6)	(D7)
Rangeland	Urban	32	0.07	−0.06	−0.16	0.22	−0.17	0.15	−0.25	0.05	−0.09	−0.25	0.28	−0.18	0.13	−0.17
			0.15	0.17	*0.00*	*<0.0001*	*0.00*	*0.00*	*<0.0001*	0.26	0.06	*<0.0001*	*<0.0001*	*0.00*	*0.00*	*0.00*
Rangeland	Agriculture	37	0.50	−0.23	−0.32	0.03	−0.33	−0.1	−0.33	0.49	−0.24	−0.35	0.11	−0.16	−0.12	−0.2
			<0.0001	*<0.0001*	*<0.0001*	0.55	*<0.0001*	**0.03**	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	**0.02**	*0.00*	**0.01**	*<0.0001*
Deciduous Forest	Urban	42	−0.30	0.12	0.06	0.12	0.06	0.34	−0.01	−0.29	0.15	0.08	0.16	0.07	0.34	0.01
			<0.0001	*0.00*	0.09	*0.00*	0.09	*<0.0001*	0.75	*<0.0001*	*<0.0001*	**0.02**	*<0.0001*	0.05	*<0.0001*	0.77
Deciduous Forest	Rangeland	43	0.02	−0.07	0.14	−0.35	0.14	−0.08	0.12	0.02	−0.06	0.18	−0.29	0.23	−0.08	0.11
			0.62	**0.04**	*<0.0001*	*<0.0001*	*<0.0001*	**0.02**	*0.00*	0.65	0.09	*<0.0001*	*<0.0001*	*<0.0001*	**0.02**	*0.00*
Deciduous Forest	Agriculture	47	0.27	−0.23	−0.22	−0.13	−0.22	−0.03	−0.1	0.27	−0.2	−0.12	−0.04	−0.02	−0.03	0.00
			<0.0001	*<0.0001*	*<0.0001*	*0.00*	*<0.0001*	0.34	*0.01*	*<0.0001*	*<0.0001*	*0.00*	0.21	0.51	0.43	0.93
Evergreen Forest	Urban	52	−0.18	0.11	0.21	0.09	0.21	0.11	0.09	−0.19	0.13	0.17	−0.09	0.18	0.14	0.04
			0.00	**0.04**	*<0.0001*	0.09	*<0.0001*	**0.03**	0.07	*0.00*	**0.01**	*0.00*	0.07	*0.00*	*0.01*	0.42
Evergreen Forest	Rangeland	53	−0.09	0.02	0.11	0.05	0.11	0.02	0.11	−0.1	0.02	0.11	−0.12	0.11	0.04	0.1
			0.09	0.65	**0.02**	0.36	**0.03**	0.65	**0.03**	0.06	0.66	**0.03**	**0.02**	**0.02**	0.41	0.06
Evergreen Forest	Agriculture	57	0.17	−0.26	−0.36	0.14	−0.36	−0.1	−0.24	0.18	−0.25	−0.23	0.11	−0.21	−0.08	−0.08
			0.00	*<0.0001*	*<0.0001*	**0.01**	*<0.0001*	0.09	*<0.0001*	*0.00*	*<0.0001*	*<0.0001*	0.06	*0.00*	0.14	0.17
Mixed Forest	Urban	62	−0.33	−0.14	−0.23	0.41	−0.23	0.44	−0.23	−0.32	−0.15	−0.16	0.48	−0.15	0.44	−0.16
			<0.0001	*0.00*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*
Mixed Forest	Rangeland	63	0.06	−0.24	−0.14	0.14	−0.14	0.02	−0.08	0.07	−0.29	−0.13	0.19	−0.14	0.01	−0.02
			0.10	*<0.0001*	*0.00*	*0.00*	*0.00*	0.69	**0.05**	0.08	*<0.0001*	*0.00*	*<0.0001*	*0.00*	0.87	0.59
Mixed Forest	Agriculture	67	0.29	−0.46	−0.53	0.29	−0.52	−0.11	−0.33	0.3	−0.5	−0.42	0.43	−0.43	−0.12	−0.19
			<0.0001	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*0.01*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*0.00*	*<0.0001*
Woody Wetlands	Urban	82	−0.02	0.09	−0.03	0.13	−0.03	0.02	−0.08	−0.04	0.07	−0.07	0.06	−0.09	0.03	0.00
			0.49	*0.00*	0.36	*<0.0001*	0.32	0.63	**0.01**	0.24	**0.02**	**0.02**	**0.04**	*0.00*	0.36	0.93
Woody Wetlands	Rangeland	83	0.29	−0.05	−0.07	−0.09	−0.07	−0.28	−0.04	0.27	−0.07	−0.1	−0.14	−0.1	−0.27	0.06
			<0.0001	0.13	**0.03**	*0.01*	**0.02**	*<0.0001*	0.22	*<0.0001*	**0.02**	*0.00*	*<0.0001*	*0.00*	*<0.0001*	**0.04**
Woody Wetlands	Agriculture	87	0.53	−0.19	−0.38	0.06	−0.38	−0.33	−0.23	0.53	−0.22	−0.38	0.03	−0.33	−0.33	−0.03
			<0.0001	*<0.0001*	*<0.0001*	0.05	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	0.39	*<0.0001*	*<0.0001*	0.30

(P1): Percent changes in actual evapotranspiration.
(P2): Percent changes in soil water content.
(P3): Percent changes in water percolation
(P4): Percent changes in surface runoff contribution to streamflow.
(P5): Percent changes in groundwater contribution to streamflow.
(P6): Percent changes in water yield.
(P7): Percent changes in lateral flow contribution to streamflow.

(D1): Differences in actual evapotranspiration (mm).
(D2): Differences in soil water content (mm).
(D3): Differences in water percolation (mm).
(D4): Differences in surface runoff contribution to streamflow (mm).
(D5): Differences in groundwater contribution to streamflow (mm).
(D6): Differences in water yield (mm).
(D7): Differences in lateral flow contribution to streamflow (mm).

Table 6. Hoeffdings's D measure for association and its probabilities (p-value). Correlation between percent of land use conversion within a subbasin and hydrological variable. Italic p-value indicates a significant probability at 0.01 level. Bold p-value indicates significance at 0.05 level.

Pre-settlement	Current	code	(P1)	(P2)	(P3)	(P4)	(P5)	(P6)	(P7)	(D1)	(D2)	(D3)	(D4)	(D5)	(D6)	(D7)
Rangeland	Urban	32	0.01	0.00	0.01	0.02	0.01	0.01	0.02	0.01	0.00	0.02	0.02	0.01	0.01	0.01
			<0.0001	0.26	*0.00*	*<0.0001*	*0.00*	*0.00*	*<0.0001*	*0.00*	0.10	*<0.0001*	*<0.0001*	*<0.0001*	*0.00*	*0.00*
Rangeland	Agriculture	37	0.09	0.01	0.03	0.00	0.04	0.00	0.03	0.09	0.02	0.04	0.01	0.01	0.00	0.02
			<0.0001	*<0.0001*	*<0.0001*	**0.03**	*<0.0001*	**0.05**	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*0.00*	*<0.0001*	**0.01**	*<0.0001*
Deciduous	Urban	42	0.03	0.01	0.00	0.01	0.00	0.04	0.00	0.03	0.01	0.00	0.01	0.00	0.04	0.00
Forest			*<0.0001*	*<0.0001*	**0.02**	*<0.0001*	**0.02**	*<0.0001*	**0.05**	*<0.0001*	*<0.0001*	*0.01*	*<0.0001*	*0.01*	*<0.0001*	0.13
Deciduous	Rangeland	43	0.01	0.00	0.01	0.05	0.01	0.00	0.00	0.01	0.00	0.01	0.03	0.02	0.00	0.00
Forest			*<0.0001*	**0.02**	*<0.0001*	*<0.0001*	*<0.0001*	*0.00*	*0.00*	*<0.0001*	0.04	*<0.0001*	*<0.0001*	*<0.0001*	*0.00*	*0.00*
Deciduous	Agriculture	47	0.03	0.02	0.02	0.01	0.02	0.00	0.01	0.03	0.01	0.01	0.00	0.01	0.00	0.00
Forest			*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	0.01	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*0.00*	*<0.0001*	*0.01*	0.15
Evergreen	Urban	52	0.01	0.01	0.02	0.00	0.02	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.00
Forest			*0.00*	*0.01*	*<0.0001*	**0.04**	*<0.0001*	**0.01**	**0.02**	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	0.14
Evergreen	Rangeland	53	0.00	0.00	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.00	0.00
Forest			0.05	0.45	*0.00*	0.05	*0.00*	0.32	**0.02**	**0.02**	0.53	*0.01*	*0.00*	*0.00*	0.12	0.12
Evergreen	Agriculture	57	0.01	0.02	0.04	0.01	0.04	0.00	0.02	0.01	0.02	0.02	0.00	0.02	0.00	0.00
Forest			*0.00*	*<0.0001*	*<0.0001*	*0.01*	*<0.0001*	0.06	*<0.0001*	*0.00*	*<0.0001*	*<0.0001*	**0.02**	*<0.0001*	0.17	0.06
Mixed	Urban	62	0.04	0.01	0.02	0.06	0.02	0.06	0.02	0.04	0.01	0.01	0.08	0.01	0.06	0.01
Forest			*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*
Mixed	Rangeland	63	0.01	0.02	0.01	0.01	0.01	0.00	0.00	0.01	0.03	0.01	0.02	0.01	0.00	0.00
Forest			*0.00*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	0.07	*0.00*	*0.00*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	**0.05**	*0.01*
Mixed	Agriculture	67	0.03	0.07	0.11	0.04	0.11	0.00	0.05	0.04	0.09	0.06	0.09	0.07	0.01	0.02
Forest			*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*0.00*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*0.00*	*<0.0001*
Woody	Urban	82	0.01	0.00	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.01	0.00
Wetlands			*<0.0001*	*<0.0001*	0.22	*<0.0001*	0.18	*<0.0001*	**0.01**	*<0.0001*	*0.01*	*0.01*	*0.00*	*0.00*	*<0.0001*	*0.00*
Woody	Rangeland	83	0.02	0.00	0.00	0.00	0.00	0.02	0.00	0.02	0.00	0.00	0.01	0.00	0.02	0.01
Wetlands			*<0.0001*	**0.01**	**0.02**	*0.00*	**0.01**	*<0.0001*	**0.01**	*<0.0001*	*0.01*	*0.00*	*<0.0001*	*0.00*	*<0.0001*	*<0.0001*
Woody	Agriculture	87	0.10	0.01	0.05	0.00	0.05	0.05	0.02	0.10	0.02	0.05	0.00	0.04	0.04	0.01
Wetlands			*<0.0001*	*<0.0001*	*<0.0001*	*0.01*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*0.00*	*<0.0001*	*<0.0001*	*<0.0001*

(P1): Percent changes in actual evapotranspiration.
(P2): Percent changes in soil water content.
(P3): Percent changes in water percolation.
(P4): Percent changes in surface runoff contribution to streamflow.
(P5): Percent changes in groundwater contribution to streamflow.
(P6): Percent changes in water yield.
(P7): Percent changes in lateral flow contribution to streamflow.

(D1): Differences in actual evapotranspiration (mm).
(D2): Differences in soil water content (mm).
(D3): Differences in water percolation (mm).
(D4): Differences in surface runoff contribution to streamflow. (mm)
(D5): Differences in groundwater contribution to streamflow (mm).
(D6): Differences in water yield (mm).
(D7): Differences in lateral flow contribution to streamflow (mm).

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Table 7. Watershed-level impacts of land use changes (mid-1800 versus current).

Watershed (HUC)	State	Percent Change Evapotranspiration	Percent Change Recharge	Percent Change Surface Runoff	Percent Change Baseflow	Percent Change Water Yield
040302	WI	11.82	−21.41	−22.80	−22.33	−21.53
040301& 040400	WI	5.97	−36.99	17.48	−35.69	−6.89
070700	WI	4.13	−22.82	11.47	−21.98	−2.87
070900	WI	16.51	−51.50	38.46	−50.11	8.06
040801	MI	8.49	−29.17	58.98	−28.82	−7.27
040802	MI	5.69	−38.46	65.29	−37.15	−7.95
040900	MI	−5.50	−37.21	84.13	−35.27	24.60
040500	MI	10.57	−39.76	93.92	−38.72	−3.95

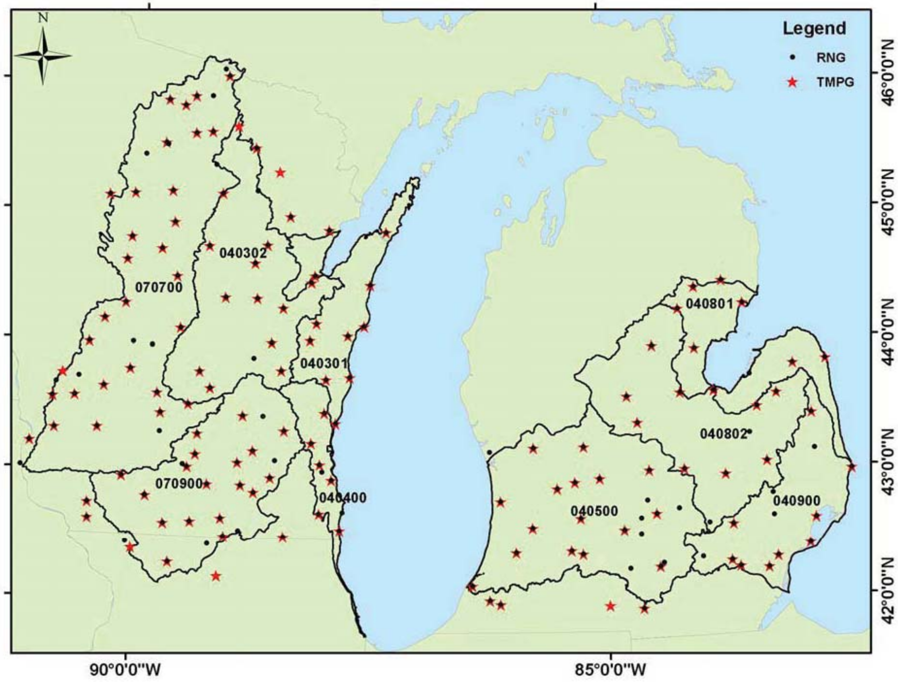

Fig. 1. Study area. RNG (precipitation gauging stations) and TMPG (temperature gauging stations).

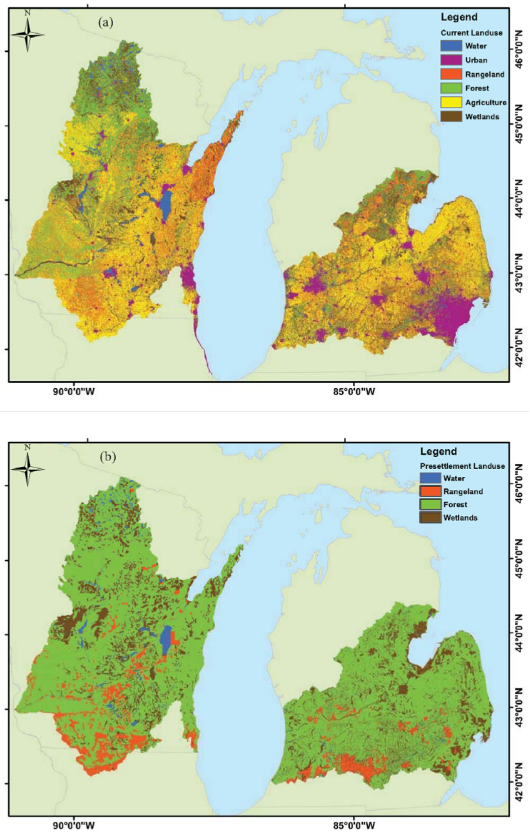

Fig. 2. **(a)** Current land use map, **(b)** Pre-settlement land use map.

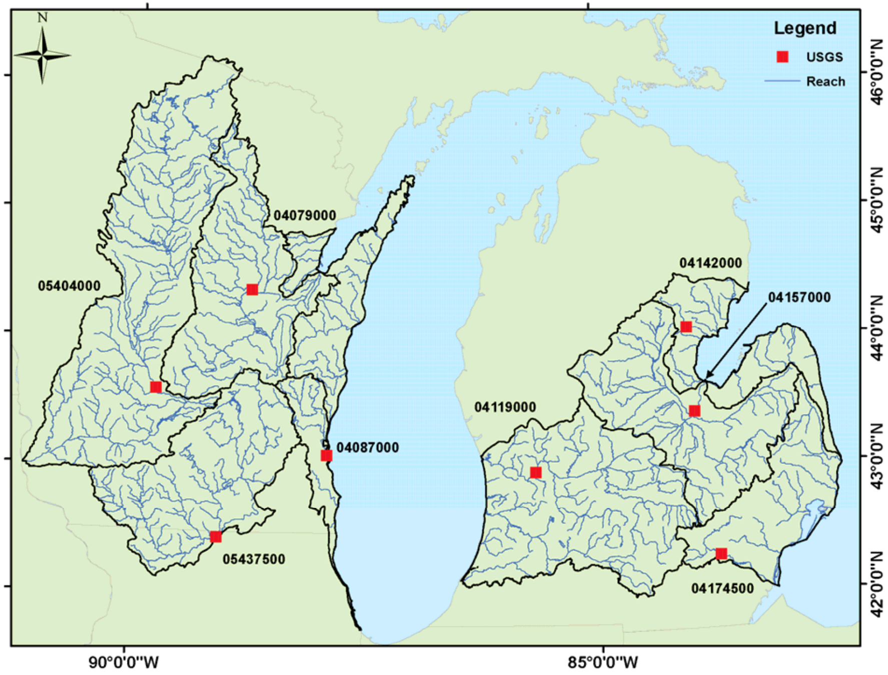

Fig. 3. USGS gauging stations.

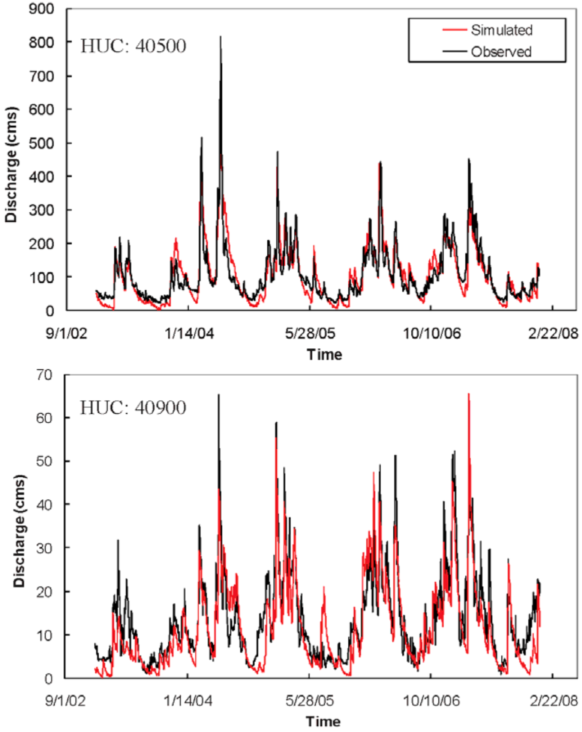

Fig. 4. Comparison between observed (USGS) and simulated streamflows for selected watersheds.

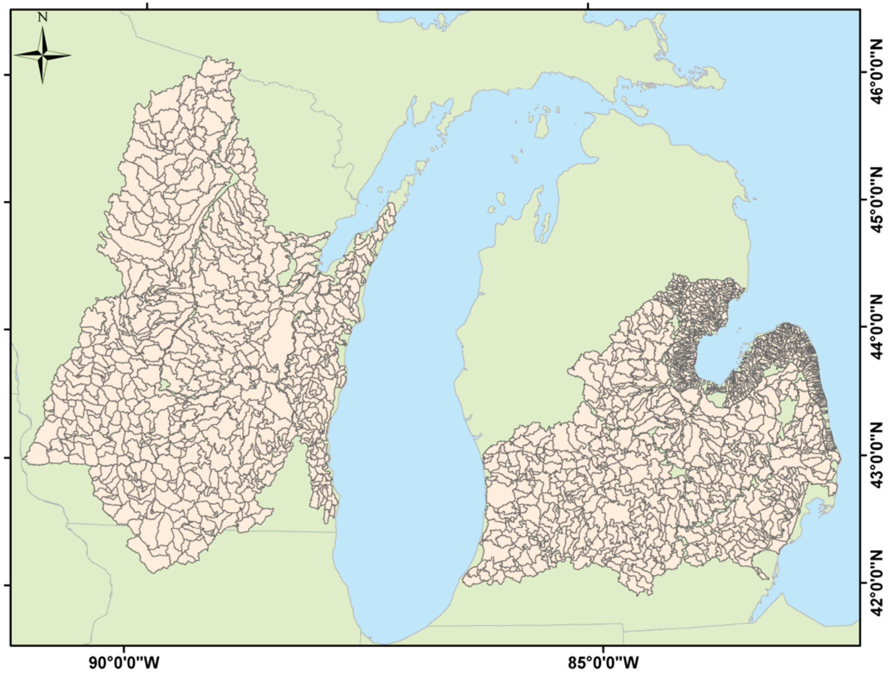

Fig. 5. Subbasin map.

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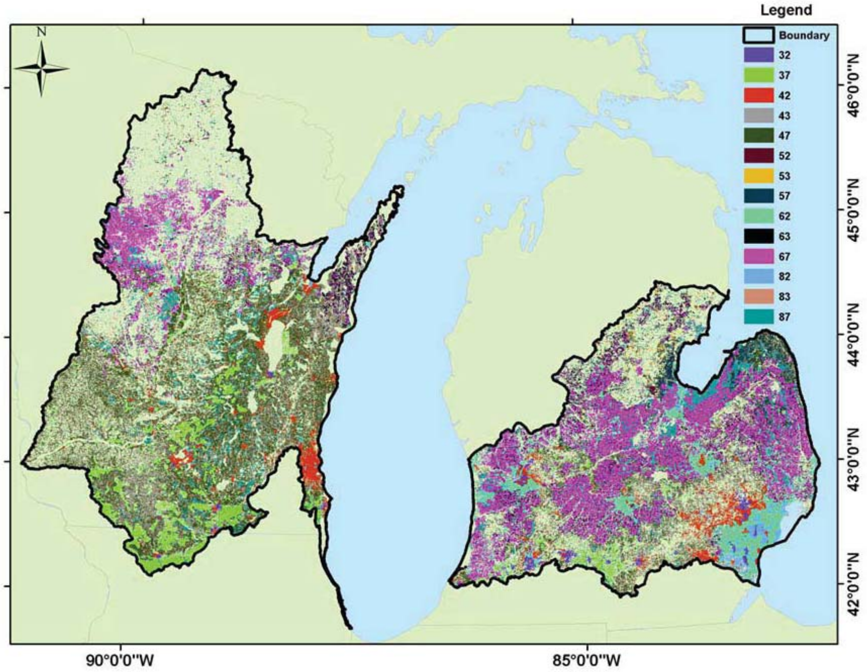

Fig. 6. Spatial variation of land use conversion from mid-1800 to current. (32) Rangeland to Urban; (37) Rangeland to Agriculture; (42) Deciduous Forest to Urban; (43) Deciduous Forest to Rangeland; (47) Deciduous Forest to Agriculture; (52) Evergreen Forest to Urban; (53) Evergreen Forest to Rangeland; (57) Evergreen Forest to Agriculture; (62) Mixed Forest to Urban; (63) Mixed Forest to Rangeland; (67) Mixed Forest to Agriculture; (82) Woody wetlands to Urban; (83) Woody wetlands to Rangeland; and (87) Woody Wetlands to Agriculture.

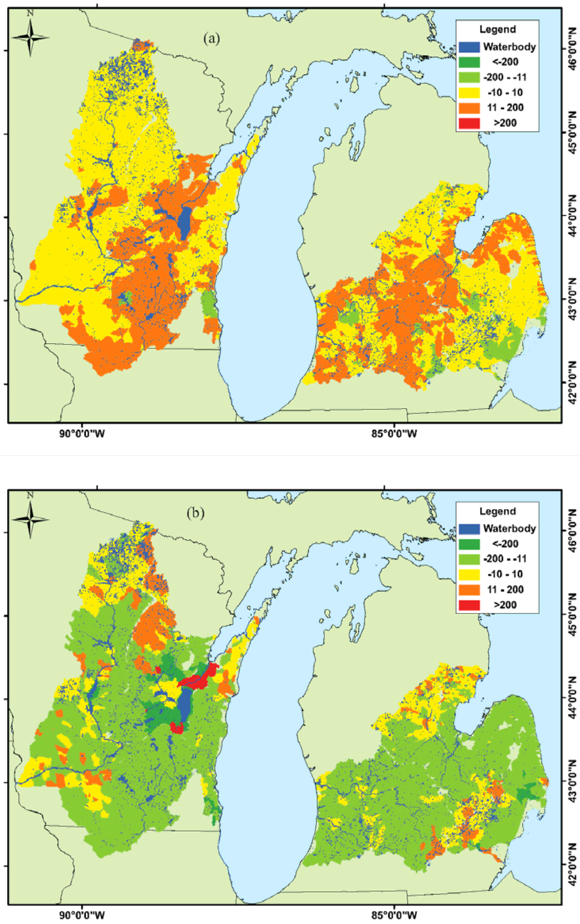

Fig. 7. Long-term average impacts of land use change at basin level **(a)** percent change in actual evapotranspiration; **(b)** percent change in recharge entering aquifers.

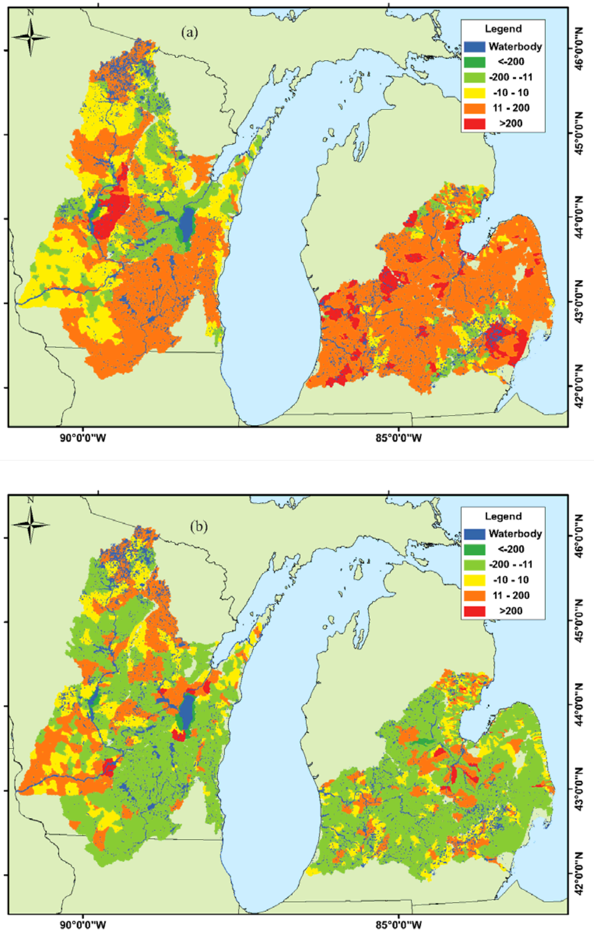

Fig. 8. **(a)** percent change in surface runoff; **(b)** percent change in lateral flow contribution to streamflow.

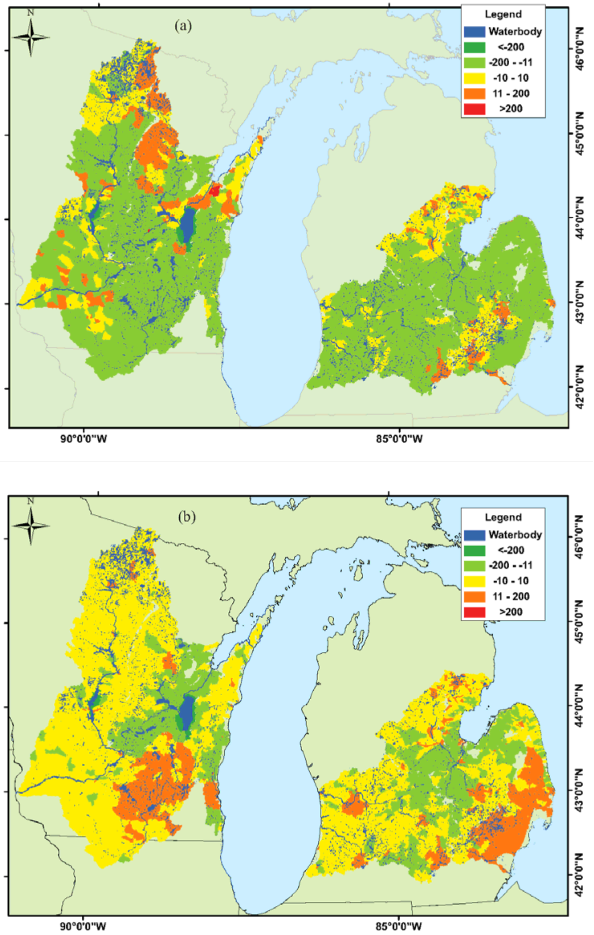

Fig. 9. **(a)** percent change in groundwater contribution to streamflow; and **(b)** percent change in water yield.

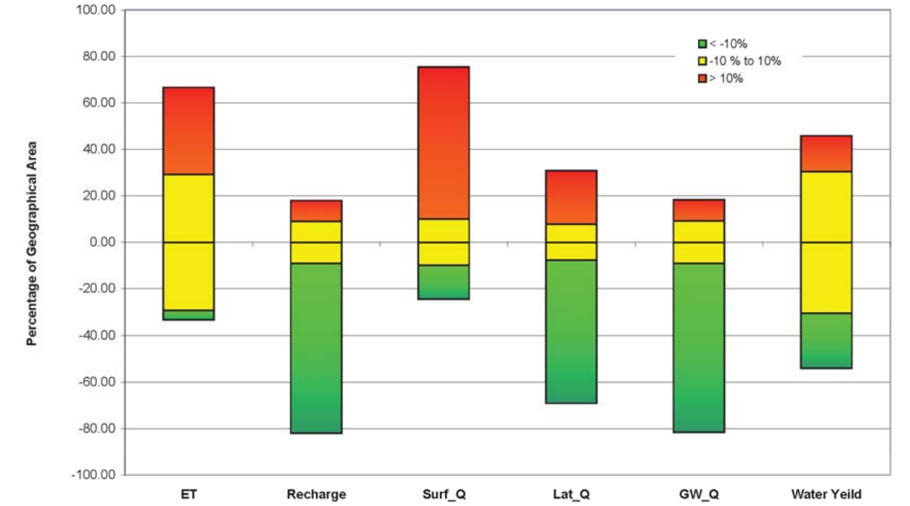

Fig. 10. Percentage of geographical area under positive high, modest, or negative high classes; (ET) percent change in actual evapotranspiration; (Recharge) percent change in recharge entering aquifers; (Surf_Q) percent change in overland flow contribution to streamflow; (Lat_Q) percent change in lateral flow contribution to streamflow; (GW_Q) percent change in baseflow contribution to streamflow; and (Water Yield) percent change in water yield.