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Relative importance of climate and land surface changes on hydrologic changes in the US Midwest since the 1930s: Implications for biofuel production

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SUMMARY

The US Midwest is an important area of first generation biofuels, accounting for 80–90% of US corn and soybean production (2009–2011). However, there are potential adverse impacts of biofuel production on water resources in this area. The objective of this study was to assess potential impacts of biofuel production on water resources by exploring relationships between hydrologic changes and climate and land surface changes based on long-term (~1930s–2010) stream gage and climate data from 55 unregulated watersheds in the US Midwest. Long-term trends in climate (precipitation and potential evapotranspiration) and flow were evaluated. Sensitivity of changes in annual streamflow and baseflow to climate was evaluated using climate elasticity (sensitivity) and the residuals were attributed to land surface changes. Results show that streamflow increased significantly ($p < 0.05$) in 35% (19/55) of watersheds (median 2.4 ± 0.3 mm/year), baseflow increased in 58% of watersheds (median 1.1 ± 0.4 mm/year), and baseflow index (baseflow/streamflow, BFI) increased in 42% of watersheds (median 0.2 ± 0.1%/year). Overall, climatic variability contributed more than land surface change to streamflow change (61 ± 19% vs. 40 ± 18%), while land surface change contributed much more to baseflow (74 ± 10% vs. 27 ± 10%; 2.7 times higher) and to BFI (119 ± 14% vs. 27 ± 18%; 4.4 times higher) than climate change. Watersheds (25/55, 45%) with no significant trend in climate but with significant flow trends provide direct evidence that the Midwest land surface change (cropping system and related land management) significantly impacted flow processes. Restricting analysis to these watersheds shows that land surface change contributed 2.0 times more than climate variability/change to streamflow change, 3.2 times more to baseflow change, and 7.7 times more to BFI change. The importance of past land surface changes on hydrology suggests that any future land surface changes, such as biofuel expansion or changing biofuel feedstocks, should consider impacts on the hydrology.

1. Introduction

The US Midwest is a hotspot for biofuel production based principally on using annual crops of corn and soybeans as an energy source (Mehaffey et al., 2012; Robertson et al., 2011; Scheffran and BenDor, 2009; Secchi et al., 2011). Currently, ~50% of the corn grown in the US is used for ethanol production.[1] Biofuel demands are resulting in rising commodity prices and economic pressures for increasing crop production (Secchi et al., 2011). Land cover devoted to crop production is expanding as perennial grasslands, forest, and pastures are being replaced by annual corn and soybean rotations in Midwest (Schilling et al., 2010).

There is growing concern about potential adverse impacts of first generation biofuel production on water resources, including effects on water quantity and water quality (NRC, 2007). However, against a backdrop of climate variability and increasing precipitation trends in the Midwest (Pryor et al., 2009), quantifying the potential impacts of first generation biofuels remains a challenge. Many different approaches have been used to assess effects of past and projected future biofuel production on water resources, including inverse analysis of streamflow trends to assess contributions from climate variability/change and land use change related to biofuel production (Donner et al., 2004; Novotny and Stefan, 2007; Zhang and Schilling, 2006). However, findings from various studies differ: some studies concluded that land surface change

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played a dominant role in this hydrologic change (Schilling, 2005; Zhang and Schilling, 2006), while others held the view that climate change was more important (Novotny and Stefan, 2007; Qian et al., 2007; Tomer and Schilling, 2009; Walter et al., 2004). Moreover, previous studies are mostly qualitative analysis. It is imperative to quantify the relative contribution of changes in land surface and climate to hydrologic changes (Renner and Bernhofer, 2012; Wang and Hejazi, 2011), particularly to different components of the hydrologic cycle (streamflow, baseflow, and BFI). Although physically based hydrologic models (Schilling et al., 2008; Wu and Liu, 2012) can quantitatively separate the contribution of changes in land surface and climate to hydrologic change, these models suffer from being parameter and structure dependent, and it is difficult to apply them to a large number of watersheds simultaneously. Conceptual and empirical methods (e.g., trend analysis, and climate elasticity) are promising in separating the contributions of changes in land surface and climate to hydrologic changes at large scales (Wang and Hejazi, 2011; Zheng et al., 2009). Trends in streamflow have been evaluated in many previous studies across the US. Lins et al. (1999) found that streamflow increases (1944–1993) were dominant in annual minimum (Q_0) to median (Q_{50}) flows and least in maximum flows (Q_{100}), particularly in the Midwest and northeast. McCabe and Wolock (2002) noted a step increase in streamflow in the eastern US around the 1970s which they attributed to a change in precipitation. Other studies evaluated trends in precipitation in the US positive. Precipitation trends within the last century were noted by Pryor et al. (2009) with the largest increases in the Central US (up to 4% per decade in individual stations). Increases in precipitation by up to 15% in the US Midwest within the past 50 years (1958–2008) are related primarily to increases in extreme precipitation (top 1% of all daily events) totaling 31% (Karl et al., 2009). Land use change has also been implicated in streamflow changes. Zhang and Schilling (2006) attributed larger increases in baseflow (by 28–134% for the period of 1940s–2003) relative to streamflow (9–102%) to reductions in evapotranspiration (ET) associated with changes from perennial crops to annual crops, particularly soybeans (443% increases in cultivation area for the period of 1940s–2003) in the Upper Mississippi River states of Iowa, Minnesota and Wisconsin. Because many of the previous studies focused on climate or land use change separately, it is important to consider both and assess their relative contribution to hydrologic change. In addition, the large increases in baseflow in Upper Mississippi River Basin found by Zhang and Schilling (2006) demonstrate that flow partition (baseflow and BFI) is worthwhile studying too.

As suggested by previous studies (Zheng et al., 2009), streamflow (Q) and changes in streamflow (ΔQ) can be considered as a function (f) of changes in climate (denoted as C, including P and ET_P) and/or in land surface (LS):

$$Q = f(P, ET_P, LS) \quad \Delta Q = \Delta Q_C + \Delta Q_{LS} = f'_P \Delta P + f'_{ET_P} \Delta ET_P + f'_{LS} \Delta ET_{LS} \tag{1}$$

where P is precipitation, ET_P is potential evapotranspiration, Δ represents changes, and $f'_P = \partial Q/\partial P$, $f'_{ET_P} = \partial Q/\partial ET_P$, and $f'_{LS} = \partial Q/\partial ET_{LS}$ (Zheng et al., 2009). The term climate change in this context refers to anthropogenic climate change and/or to climate variability. The general term land surface change is used instead of land use/land cover (LULC) change to include changes in land management, such as changes in tillage, terracing, and tiling. Measured streamflow gage data are generally used to represent ΔQ, and ΔQ_C (climate change induced streamflow change) is often calculated using climate elasticity, allowing ΔQ_{LS} to be calculated as a residual term.

Climate elasticity of streamflow refers to the sensitivity of streamflow change to climate change (Schaake, 1990). Specifically speaking, climate elasticity (ε) is the proportional change in streamflow (Q) relative to a proportional change in a climate parameter, e.g., P or ET_P (Kochendorfer and Hubbart, 2010). The precipitation elasticity of streamflow (ε_P) and ET_P elasticity of streamflow (ε_{ET_P}) are defined as follows (Zheng et al., 2009):

$$\varepsilon_P = \frac{dQ/Q}{dP/P} = \frac{dQP}{dPQ}; \quad \varepsilon_{ET_P} = \frac{dQ/Q}{dET_P/ET_P} = \frac{dQET_P}{dET_PQ};$$
$$\Delta Q_C = \left(\frac{\varepsilon_P \Delta P}{P} + \frac{\varepsilon_{ET_P} \Delta ET_P}{ET_P}\right) Q \tag{2}$$

Sensitivity of streamflow to climate change (climate elasticity) can also be evaluated using the Budyko hypothesis (BH) which is based on an annual water balance and assumes changes in water storage are negligible (Zheng et al., 2009):

$$Q = P - ET_a \tag{3}$$

The Budyko hypothesis assumes that actual evapotranspiration (ET_a) is a function (F) of the aridity index ($\varphi = ET_P/P$) resulting in $ET_a = PF(\varphi)$ (Budyko, 1974). When the aridity index value is <1 ($P > ET_P$), energy supply limits ET whereas aridity index values >1 represent regions where water supply limits ET. The precipitation elasticity of streamflow using the BH is as follows (Zheng et al., 2009):

$$\varepsilon_P = 1 + \frac{\varphi F'(\varphi)}{1 - F(\varphi)} \quad \varepsilon_P + \varepsilon_{ET_P} = 1 \tag{4}$$

A number of functions have been used to describe $F(\varphi)$ (Zhang et al., 2001). The limits of $F(\varphi)$ for a humid climate approach 0 with φ approaching 0 and for an arid climate approach 1 with φ approaching ∞.

Other studies have used modeling to evaluate impacts of climate and land use change on water quantity and quality. Schilling et al. (2008) used the Soil and Water Assessment Tool (SWAT) model to evaluate various biofuel scenarios, including expansion of corn in the Raccoon River watershed in Iowa. Results show that increased annual corn production decreased ET and increased water yield, leaching nutrients, and eroding sediments. Donner et al. (2004) used the Integrated Biosphere Simulator (IBIS) terrestrial ecosystem model and the HYDRA aquatic transport model to simulate changes in nitrate export from 1960 to 1994 in response to expansion of corn and soybean production, increased fertilizer application, and increased streamflow.

The objective of this study was to assess relative impacts of climate and land surface changes on hydrology using climate elasticity in the US Midwest. This study builds on previous studies by considering not only streamflow but also baseflow in a large number of watersheds (55) that cover a wide range of climate, soil, and vegetation types across four states in the Midwest from Iowa to Ohio (Fig. 1). If land surface changes have had large scale impacts on water flow in the past, then future changes in land surface related to biofuel expansion and feedstock types need to consider potential hydrologic impacts.

2. Materials and methods

2.1. Study area

Four states (Iowa, Illinois, Indiana, and Ohio), accounting for 45% of US corn production and 43% of US soybean production from 2009 through 2011 (NRCS, 2012), is the most productive region for first generation biofuels in the US Midwest, and therefore was selected for this study. The original land cover was mostly prairies and forests that were converted to cropland over time. Cropland area in the Midwest increased from ~5% in 1850 to ~50% by 1880, and peaked at ~80% in the late 1900s (Fig. S1) (Bonan, 2001).

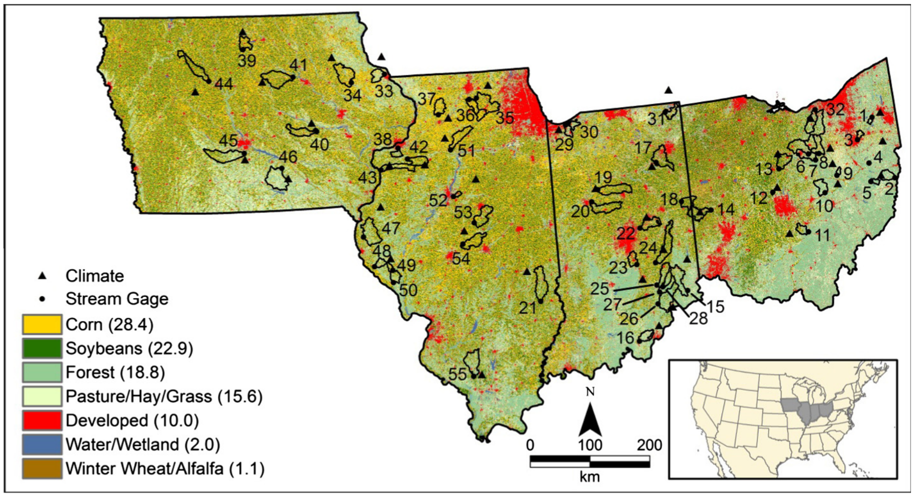

Fig. 1. Spatial distribution of land use/cover (USDA Crop Data Layer for 2010), USGS stream gage stations and contributing watersheds for the 55 gages (ID for each gage station refers to Table S1) considered in this study. Note: the number in bracket is the area percentage for each type of land use/cover.

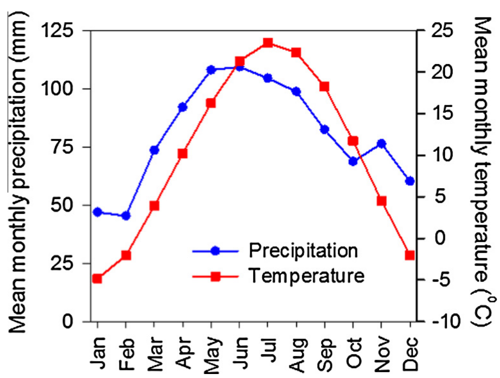

Fig. 2. Seasonal change in precipitation and temperature based on PRISM (PRISM, 2012) data (1971–2000).

Mean annual precipitation (1971–2000) across the region is 966 mm, ranging from 624 mm in the west to 1260 mm in the southeast (PRISM, 2012). Precipitation is slightly higher in summer, with 63% in April through September (Fig. 2). Mean annual temperature (1971–2000) is ~10.3 °C (50.5 °F), ranging from 6.8 °C (44.2 °F) in the northwest to 14.3 °C (57.7 °F) in the southeast.

Current land use is dominated by cropland, which averages 54% in the four states, ranging from 36% to 65% in individual states (Fig. 1). The dominant crops are corn (28% of total area) and soybeans (23%), followed by pasture/hay/grass (14%) (USDA Crop Data Layer for 2010; Fig. 1). Forest occupies 19% of the land area and ~10% of the area has been developed. Soils range from 0% to 74% clay content based on STATSGO data. Mean clay content in the 55 watersheds analysed in this study ranges from 20% to 40% (mean 29%) (Fig. S2).

2.2. Data sources

Streamflow records were obtained from the National Water Information System (NWIS) maintained by the US Geological Survey (USGS, 2012). The gage stations (Table S1 of Supplementary Information) were selected based on two criteria. First, drainage areas less than 1100 km^2 were selected to limit impacts of flow regulation on stream discharge (Santhi et al., 2008). No dams were located in the selected watersheds based on the Global Reservoir and Dam database (Lehner et al., 2011). To limit the effects of urban areas, watersheds with developed areas ⩾30% based on National Land Cover Data 2001 (NLCD2001; Homer et al., 2007) were also excluded. Secondly, we considered only those watersheds with at least 30 years of continuous flow data beginning in the 1930s or 1940s. Note that water year (October 1st to the following September 30th) was used for climate and flow variables in this study.

In total, 55 gage stations with drainage areas ranging from 57 to 1026 km^2 (mean 489 km^2) were evaluated in this study (Fig. 1), 24% of which belong to Hydro-Climatic Data Network (HCDN). Cropland accounted for most of the watershed areas (55 ± 27%), followed by forest land (20 ± 18%), and pastureland (12 ± 10%) (NLCD, 2001). Climate data (monthly precipitation and temperature) were acquired from US Historical Climatology Network (USHCN) (1895–2011) (Menne et al., 2012). Because of the small size of the watersheds used in this study, the closest USHCN station was used to represent climate data in each watershed (Figs. 1 and S3). Monthly potential evaporation (ET_P) was obtained from the University of East Anglia Climatic Research Unit (CRU, 2008). Potential evaporation was calculated using the FAO (Food and Agricultural Organization) grass reference evapotranspiration equation (Ekström et al., 2007), which is based on Allen et al. (1994). It is a variant of the Penman Monteith method using the gridded daily mean temperature, monthly average daily minimum temperature, monthly average daily maximum temperature, vapor pressure and cloud cover.

Statistical data on land use/land cover and soil erosion from 1982 to 2007 for the four states were obtained from the Natural Resources Inventory (NRI) (USDA, 2009). Harvested major crop areas were obtained from National Agricultural Statistics Service (USDA–NASS, 2012). Usual planting and harvesting dates for major crops were obtained from USDA agriculture handbook (USDA–NASS, 1997).

2.3. Methods

BFI software (Wahl and Wahl, 2006) was used for hydrograph separation (separating streamflow into surface runoff and baseflow). With this software, Wolock (2003) estimated BFI values for the conterminous United States using streamflow records of 8249 selected stream gages. Santhi et al. (2008) obtained a similar result with a recursive digital filter method. Following Wolock (2003), default values for the two parameters ($n = 5$ and $f = 0.9$)

in BFI software were used in this study. In addition to streamflow and baseflow, BFI (baseflow index, ratio of baseflow to streamflow, ranging from 0 to 1) was also estimated because BFI reflects the relative changes in baseflow and streamflow.

Temporal trends in climate parameters (P, ET_P) and flow (Q, Q_{bf}, BFI) parameters were evaluated for the entire record using non-parametric Mann Kendall test (Burkey, 2011) with a significance level (p) of 0.05. If a serial correlation in a time series data was found, trend-free pre-whitening (TFPW) method (Ahani et al., 2012; Yue and Pilon, 2003) was used before conducting the Mann Kendall test.

Climate elasticity (ε) of flow variables (Q, Q_{bf}, BFI) to climate variables (P, ET_P) was evaluated using the elasticity approach. Rearranging the climate elasticity equation (Eq. (2)) as follows according to Zheng et al. (2009) shows that ε can be considered a linear regression coefficient between $\Delta X_i/\bar{X}$ representing climate parameters (P, ET_P) and $\Delta Q_i/\bar{Q}$ representing flow variables (Q, Q_{bf}, BFI):

$$\frac{\Delta Q_i}{\bar{Q}} = \varepsilon_X \Delta X_i/\bar{X} \tag{5}$$

The elasticity of flow (Q) to climate parameters (X) can then be calculated using a least squares estimator (Zheng et al., 2009):

$$\varepsilon = \frac{\bar{X}}{\bar{Q}} \frac{\sum(X_i - \bar{X})(Q_i - \bar{Q})}{\sum(X_i - \bar{X})^2} = \rho_{XQ} C_Q / C_X \tag{6}$$

where ρ_{XQ} is the correlation coefficient between X and Q and C_Q and C_X are coefficients of variation of X and Q, respectively. To evaluate individual contributions of climate and land surface changes on flow conditions, the following steps were performed:

(1) Based on the observed datasets for the entire period of record and Eq. (6), climate elasticity (ε) with respect to P and ET_P was calculated for streamflow, baseflow, and BFI.
(2) The Pettitt's test (Pettitt, 1979) in the MeteoLab software (Cofiño et al., 2004) was used to detect the turning year for each climatic (P, ET_P) and hydrologic (Q, Q_{bf}, and BFI) variable. The turning year refers to a turning point in time series data, before and after which the mean values of the dataset in the two sub-periods differ from each other. Turning year (point) is widely used in hydrologic studies (Bassiouni and Oki, 2012; Gao et al., 2011) because it helps to infer factor(s) controlling hydrologic change. Because many more watersheds (46 of 55) show a significant ($p < 0.05$, Pettitt's test) turning year in baseflow relative to other variables, the turning year for baseflow was used for all variables (Table S2). The period before the turning year is referred to as the pre-change period, and that after the turning year as the post-change period.
(3) Based on Eq. (5), climate-induced (P or ET_P) flow change (ΔQ^c) of the post-change period relative to the pre-change period was calculated as follows:

$$\Delta Q^c = \varepsilon \frac{\Delta X}{\bar{X}_1} \bar{Q}_1 \tag{7}$$

where ΔX represents change in climatic factor (P or ET_P) from pre-change to post-change period, $\bar{X}_1$ and $\bar{Q}_1$ represent long term means of climate (P, ET_P) and flow parameters (Q, Q_{bf}, or BFI) for the pre-change period, respectively. Note that the sum of the P-induced and ET_P-induced flow change (Eq. (2)) was used as the climate-induced flow change in this study.

(1) Flow changes induced by land surface changes (ΔQ^{LS}) were then calculated by subtracting the climate-induced flow change (ΔQ^c) from the total observed flow change (ΔQ).
(2) The relative change in climate and land surface-induced changes in flow was computed:

$$C = 100(\Delta Q^c/\Delta Q)LS = 100(\Delta Q^{LS}/\Delta Q) \tag{8}$$

Note that the study by Zheng et al. (2009) applied this method to streamflow only; however, we also applied it to baseflow and BFI in this study, because previous studies demonstrated that expansion of row crops (corn and soybean) not only increased streamflow but also baseflow in the Midwest (Zhang and Schilling, 2006).

The Budyko approach was also used to segregate the climate and land surface impacts on streamflow, however, the Budyko approach cannot be applied to baseflow. The following steps were followed based on the work of Wang and Hejazi (2011):

(1) Mean annual ET_a was calculated for pre-change and post-change periods by subtracting Q from P for these periods ($P–Q = ET_a$).
(2) The following single parameter Budyko curve (Zhang et al., (2001)) was calibrated to the pre-change period for each watershed:

$$\frac{ET_a}{P} = \frac{1 + \omega \frac{ET_P}{P}}{1 + \omega \frac{ET_P}{P} + \left(\frac{ET_P}{P}\right)^{-1}} \tag{9}$$

where ET_P is potential ET, and ω is an empirical coefficient used to relate the effects of vegetation and soil texture to the evaporation process. Larger ω represents more water evaporated to the atmosphere.

(1) The calibrated curve from the pre-change period was used to calculate the theoretical evaporation ratio (ET'_{a2}/P_2) corresponding to the observed aridity index (ET_{P2}/P_2) for the post-change period. The difference between the theoretical flow ($P_2 - ET'_{a2}$) and the observed flow (Q_2) is attributed to land surface change (ΔQ^{LS}).
(2) The climate change contribution to streamflow change (ΔQ^c) was computed by subtracting the land surface induced change (ΔQ^{LS}) from total streamflow change (ΔQ).
(3) The relative change in climate and land surface induced changes in flow was computed according to Eq. (8).

Watershed boundaries were extracted based on USGS gage locations with NHDPlus tool (NHDPlus, 2012). Least squares linear fitting and parameter optimization were conducted with MATLAB R2011a. Spatial analysis was conducted with ArcGIS 10. Because of the non-normal distribution of most variables in this study, tabulated statistical descriptions of these variables are based on a non-parametric approach (Ziegler et al., 2004) that uses (1) median rather than mean value to reflect the central tendency of certain populations (gages), and (2) median absolute deviation (MAD) rather than standard deviation to reflect the degree of dispersion of certain populations (gages). MAD is calculated as follows:

$$\mathrm{MAD} = \mathrm{Median}\ |\mathrm{x_i} - \mathrm{M}| \quad i = 1, 2, 3, \ldots, n \tag{10}$$

where M is the median of n values of x.

3. Results

3.1. Climate and hydrology

Across the 55 watersheds, mean annual precipitation (MAP) ranges from 765 to 1163 mm (median: 936 mm; record length for each watershed is provided in Table S2) and decreases from east and south to west and north. Mean annual potential evaporation is higher than MAP, ranging from 881 to 1111 mm (median: 952 mm) decreasing from south to north. There is a wide range in mean annual streamflow (129–451 mm, median: 309 mm), decreasing from east to west. Baseflow is much lower than

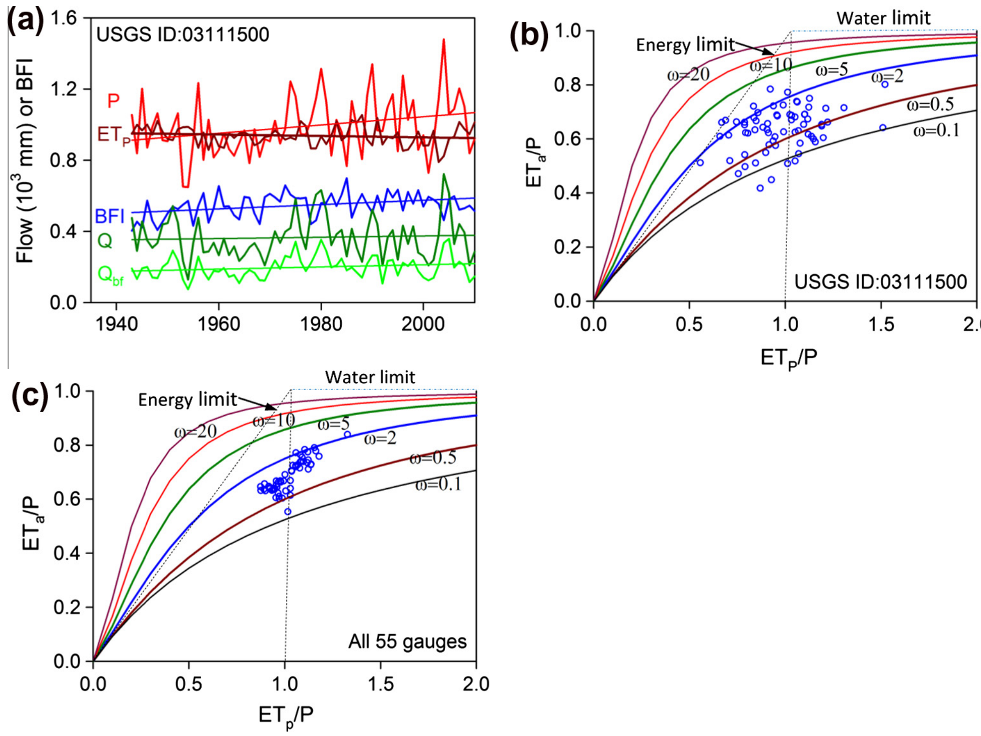

Fig. 3. (a) An example (USGS gage ID: 03111500) of hydrologic and climatic change trends for a single watershed; (b) an example of the relationship between aridity index (ET_P/P) and evaporation ratio ($ET_a/P = (P–Q)/P$) (inter-annual variability) for this watershed; and (c) relationship between aridity index and evaporation ratio for all gages (watersheds, long-term mean). Note: Q, streamflow; Q_{bf}, baseflow; BFI, baseflow index; P, precipitation; ET_P, potential evapotranspiration; ET_a, actual evapotranspiration; ω, parameter in Eq. (9).

streamflow, ranging from 24 to 233 mm (median: 103 mm). Mean annual BFI ranges from 0.10 to 0.67 (median: 0.34). Neither baseflow nor BFI shows any distinct spatial patterns.

Inter-annual variability in precipitation is closely related to variability in flow (streamflow, baseflow, and BFI; correlation coefficients listed in Table S2). Temporal variability in a typical watershed is shown in Fig. 3a. Peaks and troughs in precipitation generally coincide with those in streamflow and baseflow, but appear opposite to (or are lag correlated with) those of BFI. Across the 55 watersheds, precipitation is significantly ($p < 0.05$) correlated with streamflow ($R = 0.26–0.85$; median 0.71) and baseflow ($R = 0.21–0.79$; median 0.55).

3.2. Climatic and hydrologic changes

Overall, 38% of watersheds (21/55) show a significant trend in climate (i.e., P and/or ET_P; $p < 0.05$). A significant positive trend in P is found in 22% of the watersheds (2.40 ± 0.39 mm/year, median ± MAD across 12 gages, see Table 1), whereas 78% do not show any significant change (Table 1). Most (78%) watersheds do not show any significant trend in ET_P; 22% show a decreasing trend (−1.17 ± 0.24 mm/year). The aridity index (ET_P/P) ranges from 0.87 to 1.33 across the 55 watersheds. In other words, the humidity index (P/ET_P) ranges from 0.75 to 1.15. According to the definition of UNEP (1997), this is a humid area with humidity index within the range of 0.75–1.25. About 35% of watersheds show a significant increasing trend in streamflow (Q) (2.35 ± 0.28 mm/year) (Table 1). A larger fraction of watersheds (58%) shows a significant increasing trend in baseflow (Q_{bf}; 1.06 ± 0.37 mm/year) than streamflow. About 42% of watersheds show a significant trend in BFI (0.16 ± 0.06%/year). Interestingly, there are many watersheds (45%) with no significant climate trend but with a significant trend in flow characteristics (streamflow, baseflow, or BFI) (Table 2 and Fig. 4).

The median turning year among all gages is 1971 for P and 1959 for ET_P (Table S2). Comparison of climate data before and after the turning year suggests that P increased by ∼8 ± 3% (Table 2 and 888 ± 42 to 971 ± 33 mm) whereas ET_P decreased by only −2 ± 1% (955 ± 42 to 948 ± 36 mm). The median turning year for Q is 1969, for Q_{bf} is 1970, and for BFI is 1969. Increases in flow are much greater than those in climate parameters (P or ET_p) with streamflow increasing by 25 ± 10% (286 ± 71 mm to 343 ± 48 mm), baseflow by 41 ± 18% (68 ± 30 to 120 ± 36 mm), and BFI by 12 ± 10% (35 ± 10 to 38 ± 11%). Restricting analysis to watersheds with no significant trend in climate parameters but with a significant trend in flow (25/55; Table 2) shows much larger increases in flow (streamflow: 53 ± 14%, baseflow: 64 ± 23%, and BFI: 23 ± 11%).

3.3. Land surface changes

In the Midwest, prairies and forest land were rapidly converted to croplands after the 1850s (Bonan, 2001) and cropland area continued to expand through the early half of the 20th century (Fig. S1). Throughout the four-state region, small grain crops (wheat and oats) and hay decreased from the 1920s to ∼1970s to 1980s, while corn and particularly soybeans increased (Fig. 5). Cropping systems converted from a mixture of crops (e.g., oats, wheat, hay and corn) to a predominantly corn and soybean rotation. The rate of cropland expansion slowed during the latter half of the 20th century, and land cover has not changed much since the early 1980s (Table S3). Since 1982, the proportions of cropland and pastureland decreased slightly while that of developed land and forest slightly increased. Land management practices (e.g. terraces, conservation tillage, farm ponds, and soil drainage improvement) have changed substantially in this area (Donner et al., 2004;

Table 1
Mann–Kendall analysis of long-term trends in climatic (P, ET_P) and hydrologic parameters (Q, Q_{bf}, BFI) based on 55 watersheds (record lengths are provided in Table S2).

Variables	Positive trend			Negative trend			No trend	
	N	Frequency (%)	Rate (mm/year)	N	Frequency (%)	Rate (mm/year)	N	Frequency (%)
P	12	22	2.40 ± 0.39	0	0		43	78
ET_P	0	0		12	22	−1.17 ± 0.24	43	78
Q	19	35	2.35 ± 0.28	0	0		36	65
Q_{bf}	32	58	1.06 ± 0.37	0	0		23	42
BFI	23	42	0.16 ± 0.06 (%/year)	0	0		32	58

Note that median ± one MAD (median absolute deviation) was used (see Section 2); P, precipitation; ET_P, potential evapotranspiration; Q, streamflow; Q_{bf}, baseflow; BFI, baseflow index; rate, linear regression slope; N, number of watersheds (gages); frequency, N/55.

Table 2
Climatic and hydrologic conditions before (pre-change) and after (post-change) the turning year (refer to Table S2), and the relative contribution of climate and land surface change to hydrologic change.

	N	Pre-change	Post-change	Relative change (%)	Actual value		Absolute value	
					LS (%)	C (%)	LS (%)	C (%)
All watersheds								
P (mm/year)	55	888 ± 42	971 ± 33	8 ± 3				
ET_P (mm/year)	55	955 ± 42	548 ± 36	-2 ± 1				
Q (mm/year)	55	286 ± 71	343 ± 48	25 ± 10	39 ± 19	61 ± 19	40 ± 18	61 ± 19
Q_{bf} (mm/year)	55	68 ± 30	120 ± 36	41 ± 18	74 ± 10	26 ± 10	74 ± 10	27 ± 10
BFI (%/year)	55	35 ± 10	38 ± 11	12 ± 10	117 ± 17	−17 ± 17	119 ± 14	27 ± 18
Watersheds with no significant climate change but with significant flow change (N = 25)								
With significant Q (mm/year) change	12	203 ± 35	318 ± 46	53 ± 14	67 ± 5	33 ± 5	67 ± 5	33 ± 5
With significant Q_{bf} (mm/year) change	20	66 ± 20	126 ± 41	64 ± 23	76 ± 5	24 ± 5	76 ± 5	24 ± 5
With significant BFI (%/year) change	15	26 ± 12	35 ± 10	23 ± 11	115 ± 9	−15 ± 9	115 ± 9	15 ± 9

Note that median ± one MAD (median absolute deviation) was used (see Section 2); P, precipitation; ET_P, potential evapotranspiration; Q, streamflow; Q_{bf}, baseflow; BFI, baseflow index; LS, land surface change-induced percentage change; C, climate-induced percentage change; N, number of watersheds (gages).

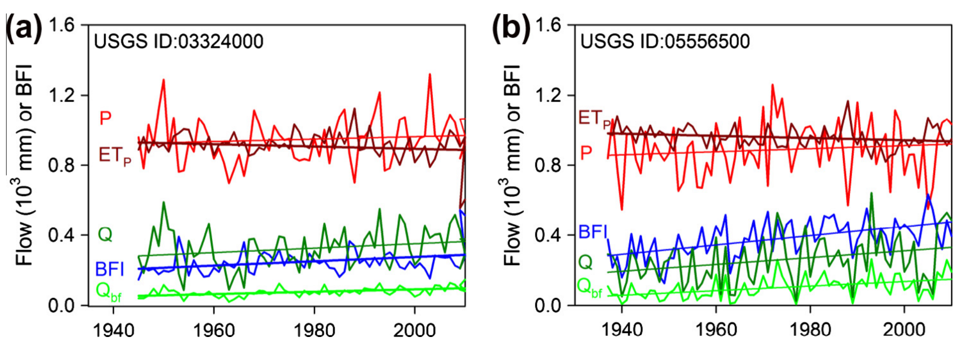

Fig. 4. Examples of watersheds with no significant trend in climate but with significant trends in hydrology (03324000: P and ET_P, $p > 0.05$; Q, $p > 0.05$; Q_{bf}, $p < 0.05$; BFI, $p > 0.05$. 05556500: P and ET_P, $p > 0.05$; Q, $p < 0.05$; Q_{bf}, $p < 0.001$; BFI, $p < 0.001$). Note: P, precipitation; ET_P, potential evapotranspiration; Q, streamflow; Q_{bf}, baseflow; BFI, baseflow index.

Mehaffey et al., 2012; Secchi et al., 2011; Smith et al., 2008; Tomer et al., 2005; Tuttle, 2003).

3.4. Impacts of climate and land surface changes on hydrology

Precipitation elasticity of streamflow is 1.7 ± 0.3 and elasticity of baseflow is 1.4 ± 0.3 (Fig. 6). Therefore, a 10% increase in precipitation would result in a 17% increase in streamflow and 14% increase in baseflow. However, potential evaporation elasticities of streamflow and baseflow are both negative (−2.4 ± 0.9 and −2.2 ± 1.2), suggesting that a 10% increase in potential evaporation would result in a 24% decrease in streamflow and 22% decrease in baseflow. Precipitation elasticity of BFI is negative (−0.4 ± 0.2), but potential evaporation elasticity of BFI is positive (0.5 ± 0.3). Based on absolute values, climate elasticity of streamflow (1.7 ± 0.3 to P and 2.4 ± 0.9 to ET_P) is higher than that of baseflow (1.4 ± 0.3 to P and 2.2 ± 1.2 to ET_P) and of BFI (0.4 ± 0.2 to P and 0.5 ± 0.3 to ET_P). The annual evaporation ratio (ET_a/P) increases with the aridity index (ET_P/P) for each watershed, and this relationship follows a Budyko-type curve (Zhang et al., 2001) (e.g., Fig. 3b). Inter-gage variability of long term means also follows a Budyko-type curve but is more linear than the inter-annual variability within a watershed (Fig. 3b vs. c).

Two separation methods (climate elasticity and Budyko-type) produced similar results ($R^2 = 0.73$, Fig. 7), but the Budyko framework only applies to streamflow and cannot be applied to baseflow. This study therefore only presents the climate elasticity results. Considering all 55 watersheds, the land surface change contribution to hydrologic change is 39 ± 19% to streamflow, 74 ± 10% to baseflow, and 117 ± 17% to BFI, while the climate change contribution is 61 ± 19% to streamflow, 26 ± 10% to baseflow, and −17 ± 17% to BFI (Table 2). Both land surface and climate change provide a positive contribution to streamflow and baseflow, while climate change provides a negative contribution to

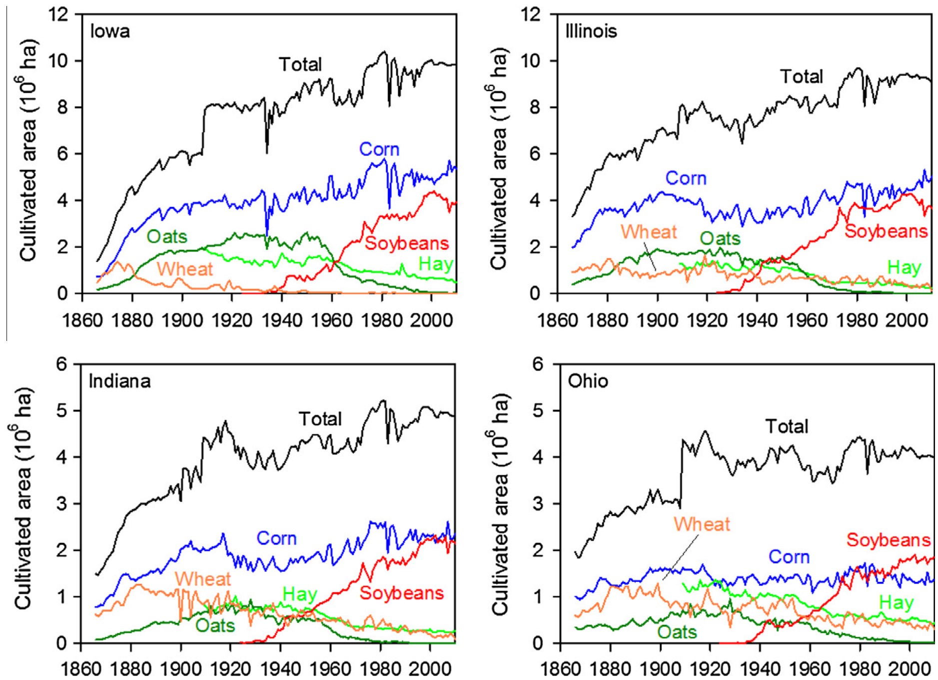

Fig. 5. Change in annual harvested crop areas in Iowa, Illinois, Indiana, and Ohio (USDA–NASS, 2012).

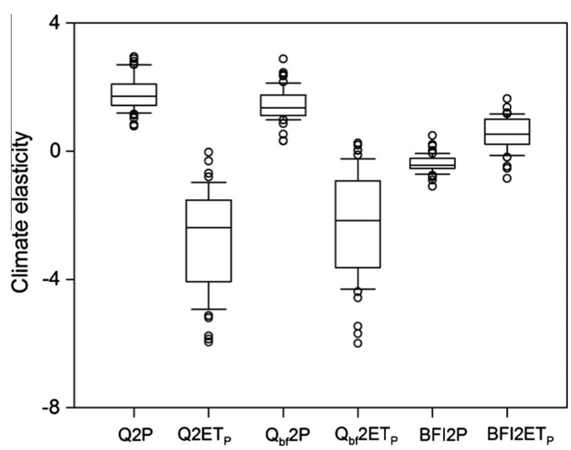

Fig. 6. Climate elasticity of streamflow, baseflow, and BFI. *Q2P*, precipitation elasticity of streamflow; *Q2ET$_P$*, potential evapotranspiration elasticity of streamflow; *Q_{bf}2P*, precipitation elasticity of baseflow; *Q_{bf}2ET$_P$*, potential evapotranspiration elasticity of baseflow; BFI2P, precipitation elasticity of baseflow index (BFI); BFI2ET$_P$, potential evapotranspiration elasticity of BFI.

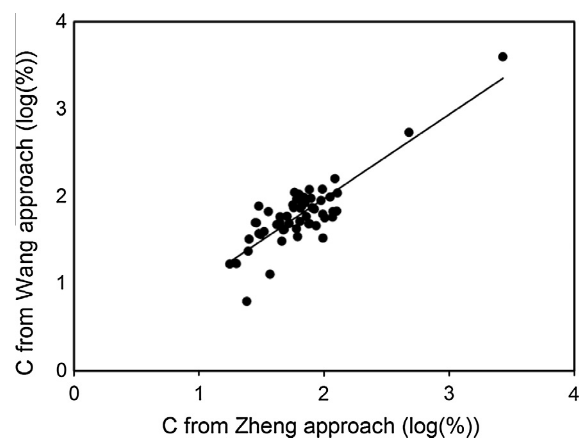

Fig. 7. Comparison between the result (absolute value of climate contribution, *C*, %) from Zheng approach (Zheng et al., 2009) and that from Wang approach (Wang and Hejazi, 2011) in separating land surface and climate contribution to hydrology change (for details, see Section 2). Note that the axes are log scaled.

BFI. Based on absolute values, climate provides higher contributions to streamflow change than land surface change but land surface change contributes more to baseflow than climate change (LS is 0.7 times C for streamflow, 2.7 times for baseflow, and 4.4 times for BFI) in this study area (Table 2). Limiting analysis to the specific watersheds (25/55) with no significant trends in climate but with significant trends in hydrology (change in either streamflow, baseflow, and/or BFI) shows that the contribution of land surface changes is 2.0 times that of climate change to streamflow, 3.2 times to baseflow, and 7.7 times to BFI (Table 2). On the one hand, this suggests that the separation method used in this study (climate elasticity) is reasonable because it reflects the reality for these specific watersheds where land surface impacts dominate; on the other hand, it also demonstrates that land surface change played a much greater role in controlling baseflow than climate change in this study area.

4. Discussion

4.1. Impacts of climate vs. land surface change on hydrology

Although several studies relate hydrologic change to land surface and/or climate change (Novotny and Stefan, 2007; Qian et al., 2007; Schilling, 2005; Walter et al., 2004; Zhang and Schilling, 2006), few quantitatively separate the contributions of the two factors (climate and land surface changes) in the agricultural Midwest. In addition, the climate elasticity approach has been applied to watersheds globally, but it is mainly applied to streamflow (runoff) only. Our study extends the application to other key hydrologic components, namely baseflow and BFI, and further provides a more reasonable approach to assess the validity of the separation method by applying it to specific watersheds with significant trends in flow variables rather than climate changes (Table 2 and Fig. 4). A total of 25 watersheds (45%) show no significant climate (P or ET_P) trends but show significant increases in flow (Table 2). These watersheds indicate the importance of land surface changes in regulating hydrologic processes. The parameter ω (1.2 ± 0.4) optimized for the Budyko curve (Eq. (9)) for the pre-change period is ~1.2 times that (1.0 ± 0.2) for the post-change period. This suggests that land surface characteristics in the post-change period have less ET_a/P than in the pre-change period. Baseflow increases are found in 58% of the watersheds (32/55). Cropland accounts for a larger proportion than any of the other land use/land cover types (forest, pasture, etc.), but the proportion appears to be only reduced slightly (Tables S1 and S3). Therefore, increases in baseflow and reductions in ET_a must be related to some other factors than land use/land cover change. Although there has been less change in land cover devoted to cropland within the past few decades (Rhemtulla et al., 2007), crop types (see Fig. 5) and land management practices (conservation measures and drainage improvements) have changed substantially (Donner et al., 2004; Mehaffey et al., 2012; Secchi et al., 2011; Smith et al., 2008; Tomer et al., 2005; Tuttle, 2003). Our results agree with those of previous research which shows that changes in crop types and related land management practices in the Midwest have greatly impacted hydrology over the 20th century (Schilling et al., 2010; Tomer et al., 2005; Tuttle, 2003; Zhang and Schilling, 2005). The land surface changes facilitated water infiltration into soil, reducing surface runoff and ET_a. Small grains (wheat and oats) as well as hay have been decreasing, while soybeans have been increasing since the 1930s and 1940s (Fig. 5). Soybeans and corn dominate since the 1970s and 1980s. Cropping systems have changed from a mixture of crops (wheat, oats, hay, and corn) to a corn and soybean dominated production system. Wheat (winter) is usually planted in fall or winter (Table S4), and the main growing season is in spring and fall. Oats (spring) are usually planted in April, and harvested in July or August with rapid growth in spring and early summer. Soybeans and corn are planted in late spring and early summer (April, May or June) with the main growing season in summer and are usually harvested in fall (September, October or November). The early mixture crop system is composed of crops with different growing seasons, similar to perennial crops that have a longer growing season.

However, the corn and/or soybean system has a shorter growing season which is more limited to the summer. Previous studies show that the area of annual crops (corn and soybean) is a good predictor of baseflow and streamflow (Schilling, 2005; Schilling et al., 2010). However, we want to emphasize that the expansion of annual crops (corn and soybean) alone does not change the flow pattern, and they are simply an index that reflects changes in cropping systems and related land management practices (e.g., terraces, conservation tillage, farm ponds, and soil drainage improvement). As demonstrated by many studies, soil erosion and sediment transport decreased substantially due to conservation measures applied in this region (Knox, 2001; Rakovan and Renwick, 2011). USDA data also show that sheet and rill erosion in these four states decreased in the past few decades (Table S5) (USDA, 2009). Brutsaert (2010) found an increasing trend in baseflow in the Upper Mississippi and Ohio regions that could not be attributed solely to climate change but, most likely, reflects changes in land management practices (soil conservation practices) too. Kochendorfer and Hubbart (2010) also attributed increasing low flow to rising application of soil and water conservation in the Upper Mississippi River Basin.

Our finding that precipitation elasticity of streamflow is higher than that of baseflow (1.7 ± 0.3 vs. 1.4 ± 0.3) agrees with results from Harman et al. (2011) who show that precipitation elasticity of fast flow (2.4) is higher than that of slow flow (2.0) for watersheds in the US. Xu et al. (2012) also found surface runoff has a higher precipitation elasticity (3.47) than subsurface flow (2.59) for Australian watersheds. In contrast, Kochendorfer and Hubbart (2010) found mean-flow has a lower precipitation elasticity (2.36) than low-flow (3.16) and higher than peak-flow (1.89) for watersheds in the Upper Mississippi River Basin. The precipitation elasticity of streamflow (~2 in the Midwest), estimated by Sankarasubramanian et al. (2001), is slightly higher than the value of 1.7 from this study. Zheng's approach to calculate elasticities was already shown to produce lower values than Sankarasubramanian's method (Zheng et al., 2009). Our results for relationships between evaporation ratios (ET_a/P) and aridity index (ET_P/P) agree with those from another study based on MOPEX datasets (Sivapalan et al., 2011).

The turning years identified for precipitation, discharge, and baseflow are all around 1969–1971 (Table S2). Close agreement in turning years between P and Q suggests an important role of P in increasing Q. The high correlation coefficients between P and Q (Table S2) also demonstrate good correlations between interannual variations in P and in Q in our study. This finding is consistent with McCabe and Wolock (2002) who described a step increase in streamflow in the eastern US around the 1970s, but they attributed the increase in streamflow to a change in precipitation only. Our results show that change in hydrology was influenced by a combination of climate and land surface changes in this area. Climate change has a greater impact on streamflow than land surface change, whereas land surface change has a greater impact on baseflow than climate change (Table 2).

4.2. Implications for biofuels expansion

According to our results (Tables 1 and 2) together with previous research (Schilling et al., 2008; Zhang and Schilling, 2006), annual biofuel crops (corn and soybean) already significantly impacted the hydrologic cycle in the mid-20th century in US Midwest. However, unprecedented increases in biofuel production are ongoing in the US: thirteen billion gallons of ethanol are produced currently (2010), from <2 billion gallons (<0.06 billion tons) of ethanol to 13 billion gallons (0.41 billion tons) in 2001. A total of 189 ethanol plants were operational as of January 2010, with 15 more under construction (Renewable Fuels Association 2012). The Energy Independence and Security Act (EISA 2007) mandates 36 billion gallons (1.13 billion tons) of ethanol by 2022 with 15 billion gallons (0.47 billion tons) from corn. The remaining 21 billion gallons (0.66 billion tons) are expected to be derived from second generation technologies (e.g., cellulosic and lipid-based feedstocks). This mandate would result in expansion of the area planted with corn. However, we note that much of the large-scale land use change in the US Midwest occurred mostly throughout the mid to late 20th century; therefore expansion of first generation biofuel crops will likely include moving into marginal lands (Dominguez-Faus et al., 2009) or conversion of existing grasslands, pastures or alfalfa to annual crops. Donner and Kucharik (2008) suggested that expansion of ethanol production may not involve "new" cropland production but rather shifting land from soybean to corn or conversion of Conservation Reserve Program (CRP) grasslands to corn. In the Raccoon River watershed in west-central Iowa, conversion of CRP grasslands could result in a 2% increase in annual crop area, whereas conversion of all grasslands to annual crops could result in an 18% increase in corn area (Schilling et al., 2008).

Furthermore, once ethanol production from cellulosic biomass becomes commercialized and energy crops (e.g. miscanthus and switchgrass) become viable, there will be a shift in land use and land cover with more areas occupied by perennial grasses. This will be expected to have another significant impact on the hydrologic cycle. According to the study by Bernacchi et al. (2010), miscanthus and switchgrass have 55% and 25% higher cumulative ET than that of corn during the growing season, respectively. Based on a model simulation, VanLoocke et al. (2010) pointed out that large scale conversion of current land use to miscanthus in the Midwest could deplete soil moisture, and alter water yield. But model simulations in Midwest also showed that biome water use efficiency of two perennial crops (miscanthus and switchgrass) is higher than that of corn (VanLoocke et al., 2012). While our study explored water quantity impacts of conversion of perennial cropping patterns to annual crops and land management practices associated with biofuels (corn and soybeans), increased water yield has also resulted in large scale impacts on water quality by flushing nutrients into the Mississippi River and contributing to the Gulf of Mexico hypoxia (Helmers et al., 2007; NRC, 2007). Because nitrate-nitrogen is primarily delivered to streams with baseflow or tile drainage (Jaynes et al., 2001; Schilling, 2005), increasing baseflow delivery to streams through land use change increases nitrate losses. Furthermore, the amount of nitrogen exported from agricultural watersheds will increase with added fertilizer applied to newly converted corn ground (David et al., 2010; Raymond et al., 2012). Changes in hydrology associated with land use change will make nutrient reduction goals more difficult to achieve. Recent assessments suggest that a 45% reduction in nitrogen and phosphorus is required to reduce the size of the hypoxia zone in the Gulf of Mexico (USEPA, 2008). One study suggested that expansion of corn cultivation to meet ethanol demands may increase inorganic nitrogen delivery to the Gulf of Mexico by 10–18% (Donner and Kucharik, 2008). From the perspective of water quality protection, conversion from first generation biofuels (corn and soybeans) to second generation biofuels (perennial grasses such as switchgrass and miscanthus) should reduce water yield and improve water quality by decreasing nutrient loading to streams (McIsaac et al., 2010; Schilling et al., 2008; Smith et al., 2013; Wu and Liu, 2012). Although the Midwest is a humid area where water quantity issues are generally not as great as water quality concerns, widespread droughts also occur in this region such as the 2012 drought throughout the Midwest, limiting water availability.[2] McIsaac et al. (2010) reported that ET for miscanthus is ∼140 mm greater than that for switchgrass and 104 mm greater than that for corn–soybean rotation over a growing season. For perspective, the 104 mm increase in ET from miscanthus could cause a 32% decrease in stream discharge if planted throughout the central Illinois region. Hence, future land surface changes related to biofuels should seriously consider potential impacts on water resources, including effects on both water quantity and quality (NRC, 2007; Vanloocke et al., 2010).

4.3. Some limitations of this study

Our analysis and explanations in this study are based on statistical and empirical methods that have some limitations. The calculation of elasticity is based on annual datasets (current flow vs. current climate), and inter-annual water storage carryover effects and intra-annual climate change effects (e.g., climate extremes) were not accounted for (Istanbulluoglu et al., 2012). For example, we found that significant ($p < 0.05$) correlations of Q and Q_{bf} with P of the previous year exist, which might suggest that P of the previous year impacts flows of the current year. However, the correlation coefficient is 0.42 (both mean and median value, across the 55 gages) for Q_{bf} and P of the previous year, less than 0.55 (both mean and median) for Q_{bf} and P of the current year; correlation coefficients of Q and P of the previous year, 0.34 (mean) and 0.35 (median), are also less than that, 0.70 (mean) and 0.71 (median), of Q and P of the current year. This is similar to results from Xu et al. (2012) who also found that P of the previous year has some influence on flow but the influence of P of the current year still dominates on flow over the P of the previous year. Moreover, this study was designed to explore long-term impacts, and we separated the entire period (at least 30 years) into two sub-periods based on Pettitt's method (Pettitt, 1979). We first computed climate-induced flow change from the pre-period (multi-year mean) to the post-period (multi-year mean) based on climate elasticity, and then attributed the residual flow change to land surface (human activity) change. All of these analyses are based on two sub-periods, namely, relatively long term mean change, and therefore, the inter-annual water storage carryover effects and intra-annual change in climate should only play minor roles in our results. In addition, water year (October through following September) was used in this study that might also reduce some inter-annual water storage carryover effects.

However, we still noticed that there is a problem in attributing the residual flow change after removing climate-induced flow change to land surface (human activity) change, i.e., we neglected the interactions between climate and human activities. For example, irrigation may influence precipitation in some areas (Kustu et al., 2011); conversion of annual to perennial crops can enhance ET, which may in turn facilitates raining (Georgescu et al., 2011); ponding may increase both recharge and ET. However, process-based methods are required to decompose these types of interactions between human activity and climate. In addition, paired watersheds comparisons may provide another approach to isolate impacts of climate and land surface changes, but it is still difficult to identify a control watershed for a large number of watersheds because many factors (climate, soil, topography, land use/land cover, and land management) control hydrologic processes simultaneously.

5. Conclusions

Analysis of flow data in 55 watersheds in the US Midwest indicate that: 78% percent of watersheds do not show any significant trend in P, while the remaining 22% show a positive trend (2.40 ± 0.39 mm/year). Similarly, most (78%) watersheds do not show any significant trend in ET_P, whereas the remaining 22% show a decreasing trend (−1.17 ± 0.24 mm/year). Streamflow increased significantly in 35% of watersheds (2.35 ± 0.28 mm/year), baseflow increased in 58% of watersheds (1.06 ± 0.37 mm/year) and BFI increased in 42% of watersheds (0.16 ± 0.06%/year). Many (45%) watersheds do not show any significant climate trend but show a significant trend in flow characteristics (streamflow, baseflow, or BFI).

Climate elasticity of streamflow (absolute value: 1.7 ± 0.3 relative to P and 2.4 ± 0.9 relative to ET_P) is higher than that of baseflow (1.4 ± 0.3 to P and 2.2 ± 1.2 to ET_P) and of BFI (0.4 ± 0.2 to P and 0.5 ± 0.3 to ET_P). The turning years of P and flows are all around 1969–1971. Relative to the situation before the turning year, P increased by ∼8 ± 3% (888 ± 42 to 971 ± 33 mm) whereas ET_P changed by only −2 ± 1% (955 ± 42 to 948 ± 36 mm). Increases in flow are much higher than increase in P with increases of 25 ± 10% (286 ± 71 to 343 ± 48 mm) in streamflow, 41 ± 18% (68 ± 30 to 120 ± 36 mm) in baseflow, and 12 ± 10% (35 ± 10 to 38 ± 11%) in BFI.

Overall, climate change contributions were higher to streamflow change (61 ± 19% vs. 40 ± 18%) than land surface change contributions, while land surface change contributions were much higher to baseflow (74 ± 10% vs. 27 ± 10%; 2.7 times higher) and to BFI (119 ± 14% vs. 27 ± 18%; 4.4 times higher) than climate change contributions. Watersheds with no significant trend in climate but with significant flow trends provide direct evidence that the Midwest land surface changes (cropping system and related

[2] http://www.reuters.com/article/2012/07/11/us-usa-crops-idUSBRE86A0LL20120711.

land management) significantly impacted flow processes. Because of the significant relationship between land surface changes and hydrology, future land surface changes related to biofuel expansion and/or changing feedstocks should consider potential impacts on hydrology.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.jhydrol.2013.05.041.

References

Ahani, H. et al., 2012. Non-parametric trend analysis of the aridity index for three large arid and semi-arid basins in Iran. Theor. Appl. Climatol.
Allen, R.G. et al., 1994. An update for the calculation of reference evapotranspiration. ICID J. 43, 35–92.
Bassiouni, M., Oki, D.S., 2012. Trends and shifts in streamflow in Hawai'i, 1913–2008. Hydrol Process 27, 1484–1500.
Bernacchi, C.J. et al., 2010. A comparison of canopy evapotranspiration for maize and two perennial grasses identified as potential bioenergy crops. Gcb Bioenergy 2, 157–168.
Bonan, G.B., 2001. Observational evidence for reduction of daily maximum temperature by croplands in the Midwest United States. J. Climate 14, 2430–2442.
Brutsaert, W., 2010. Annual drought flow and groundwater storage trends in the eastern half of the United States during the past two-third century. Theoret. Appl. Climatol. 100, 93–103.
Budyko, M.I. (Ed.), 1974. Climate and Life. Academic, San Diego, Calif.
Burkey, J., 2011. A non-parametric trend test including Sen's slope method using Mann-Kendall Tau-b technique. <http://www.mathworks.com/matlabcentral/fileexchange/11190-mann-kendall-tau-b-with-sens-method-enhanced>.
Cofiño, A.S. et al., 2004. MeteoLab, a Software Library for Matlab>= 5 Implementing Statistical and Data Mining Techniques for Meteorology. Applied Meteorology Group. Universidad de Cantabria.
CRU, 2008. University of East Anglia Climatic Research Unit (CRU). [Phil Jones, Ian Harris]. Time Series (TS) high resolution gridded datasets, [Internet]. NCAS British Atmospheric Data Centre, 2008, Date of citation. <http://www.badc.nerc.ac.uk/view/badc.nerc.ac.uk__ATOM__dataent_1256223773328276>.
David, M.B. et al., 2010. Sources of nitrate yields in the Mississippi River Basin. J. Environ. Qual. 39, 1657–1667.
Dominguez-Faus, R. et al., 2009. The water footprint of biofuels: a drink or drive issue? Environ. Sci. Technol. 43, 3005–3010.
Donner, S.D., Kucharik, C.J., 2008. Corn-based ethanol production compromises goal of reducing nitrogen export by the Mississippi River. Proc. Natl. Acad. Sci. USA 105, 4513–4518.
Donner, S.D. et al., 2004. Impact of changing land use practices on nitrate export by the Mississippi River. Glob. Biogeochem. Cy 18.
Ekström, M. et al., 2007. Regional climate model data used within the SWURVE project 1: projected changes in seasonal patterns and estimation of PET. Hydrol. Earth Syst. Sci. 11, 1069–1083.
Gao, P. et al., 2011. Changes in streamflow and sediment discharge and the response to human activities in the middle reaches of the Yellow River. Hydrol. Earth Syst. Sci. 15, 1–10.
Georgescu, M. et al., 2011. Direct climate effects of perennial bioenergy crops in the United States. Proc. Natl. Acad. Sci. USA 108, 4307–4312.
Harman, C.J. et al., 2011. Functional model of water balance variability at the catchment scale: 2. Elasticity of fast and slow runoff components to precipitation change in the continental United States. Water Resour. Res. 47.
Helmers, M.J. et al., 2007. Theme overview: agriculture and water quality in the cornbelt: overview of issues and approaches. Choices 22, 79–84.
Homer, C. et al., 2007. Completion of the 2001 national land cover database for the conterminous United States. Photogramm. Eng. Remote Sens. 73, 337–341.
Istanbulluoglu, E. et al., 2012. Interpretation of hydrologic trends from a water balance perspective: the role of groundwater storage in the Budyko hypothesis. Water Resour. Res. 48.
Jaynes, D.B. et al., 2001. Nitrate loss in subsurface drainage as affected by nitrogen fertilizer rate. J. Environ. Qual. 30, 1305–1314.
Karl, T.R. et al. (Eds.), 2009. Global Climate Change Impacts in the United States. Cambridge University Press.
Knox, J.C., 2001. Agricultural influence on landscape sensitivity in the Upper Mississippi River Valley. Catena 42, 193–224.
Kochendorfer, J.P., Hubbart, J.A., 2010. The roles of precipitation increases and rural land-use changes in streamflow trends in the Upper Mississippi River Basin. Earth Interact. 14.
Kustu, M.D. et al., 2011. Possible link between irrigation in the US high plains and increased summer streamflow in the Midwest. Water Resour. Res. 47.
Lehner, B., et al., 2011. Global Reservoir and Dam (GRanD) database. <http://www.gwsp.org/>, (verified 12.04.12).
Lins, H. et al., 1999. Streamflow trends in the united states. In: Linsley, R., Crawford N., (Eds.), Continuous Simulation Models in Urban Hydrology. Geophys. Res. Lett. 26, 227–230.
McCabe, G.J., Wolock, D.M., 2002. A step increase in streamflow in the conterminous United States. Geophys. Res. Lett. 29.
McIsaac, G.F. et al., 2010. Miscanthus and switchgrass production in central Illinois: impacts on hydrology and inorganic nitrogen leaching. J. Environ. Qual. 39, 1790–1799.
Mehaffey, M. et al., 2012. Midwest US landscape change to 2020 driven by biofuel mandates. Ecol. Appl. 22, 8–19.
Menne, M.J. et al., 2012. United States Historical Climatology Network (USHCN) Version 2 Serial Monthly Dataset. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, Tennessee.
NHDPlus, 2012. NHDPlus Basin Delineation Tool. <http://www.horizon-systems.com/nhdplus/tools.php>, (verified 12.04.12).
Novotny, E.V., Stefan, H.G., 2007. Stream flow in Minnesota: indicator of climate change. J. Hydrol. 334, 319–333.
NRC, 2007. Water Implications of Biofuels Production in the United States. National Research Council, pp. 1–4.
NRCS, 2012. National Soil Survey Center (NSSC). <http://www.nrcs.usda.gov/wps/portal/nrcs/main/national/nssc>, (verified 04.05.12).
Pettitt, A.N., 1979. A non-parametric approach to the change-point problem. J. Royal Statist. Soc. Ser. C (Appl. Statist.) 28, 126–135.
PRISM, 2012. PRISM Climate Group, Oregon State University. <http://www.prism.oregonstate.edu>, (verified 09.04.12).
Pryor, S.C. et al., 2009. How spatially coherent and statistically robust are temporal changes in extreme precipitation in the contiguous USA? Int. J. Climatol. 29, 31–45.
Qian, T. et al., 2007. Hydroclimatic trends in the Mississippi River basin from 1948 to 2004. J. Climate 20, 4599–4614.
Rakovan, M.T., Renwick, W.H., 2011. The role of sediment supply in channel instability and stream restoration. J. Soil Water Conserv. 66, 40–50.
Raymond, P.A. et al., 2012. The impact of fertilization and hydrology on nitrate fluxes from Mississippi watersheds. Curr. Opin. Environ. Sust. 4, 212–218.
Renner, M., Bernhofer, C., 2012. Applying simple water-energy balance frameworks to predict the climate sensitivity of streamflow over the continental United States. Hydrol. Earth Syst. Sci. 16, 2531–2546.
Rhemtulla, J.M. et al., 2007. Regional land-cover conversion in the US upper Midwest: magnitude of change and limited recovery (1850–1935–1993). Landscape Ecol. 22, 57–75.
Robertson, G.P. et al., 2011. The biogeochemistry of bioenergy landscapes: carbon, nitrogen, and water considerations. Ecol. Appl. 21, 1055–1067.
Sankarasubramanian, A. et al., 2001. Climate elasticity of streamflow in the United States. Water Resour. Res. 37, 1771–1781.
Santhi, C. et al., 2008. Regional estimation of base flow for the conterminous United States by hydrologic landscape regions. J. Hydrol. 351, 139–153.
Schaake, j., 1990. From climate to flow. In: Wagonner, P.E. (Ed.), Climate Change and US Water Resources. John Wiley, pp. 177–206.
Scheffran, J., BenDor, T., 2009. Bioenergy and land use: a spatial-agent dynamic model of energy crop production in Illinois. Int. J. Environ. Pollut. 39, 4–27.
Schilling, K.E., 2005. Relation of baseflow to row crop intensity in Iowa. Agric. Ecosyst. Environ. 105, 433–438.
Schilling, K.E. et al., 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.
Schilling, K.E. et al., 2010. Quantifying the effect of land use land cover change on increasing discharge in the Upper Mississippi River. J. Hydrol. 387, 343–345.
Secchi, S. et al., 2011. Land use change in a biofuels hotspot: the case of Iowa, USA. Biomass Bioenergy 35, 2391–2400.
Sivapalan, M. et al., 2011. Functional model of water balance variability at the catchment scale: 1. Evidence of hydrologic similarity and space-time symmetry. Water Resour. Res. 47.
Smith, D.R. et al., 2008. Nutrient losses from row crop agriculture in Indiana. J. Soil Water Conserv. 63, 396–409.
Smith, C.M. et al., 2013. Reduced nitrogen losses after conversion of row crop agriculture to perennial biofuel crops. J. Environ. Qual. 42, 219.
Tomer, M.D., Schilling, K.E., 2009. A simple approach to distinguish land-use and climate-change effects on watershed hydrology. J. Hydrol. 376, 24–33.
Tomer, M.D. et al., 2005. Agricultural practices influence flow regimes of headwater streams in Western Iowa. J. Environ. Qual. 34, 1547–1558.
Tuttle, R.W., 2003. Farm ponds. In: Stewart, B.A., Howell, T.A. (Eds.), Encyclopedia of Water Science. Marcel Dekker, Inc., pp. 278–281.

UNEP, 1997. World atlas of desertification 2ED. UNEP (United Nations Environment Programme), London.
USDA, 2009. Summary Report: 2007 National Resources Inventory, Natural Resources Conservation Service, Washington, DC, and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa, p. 123. <http://www.nrcs.usda.gov/technical/NRI/2007/2007_NRI_Summary.pdf>, (verfied 09.04.12).
USDA–NASS, 1997. Usual Planting and Harvesting Dates for US Field Crops. Agricultural Handbook.
USDA–NASS, 2012. NASS-National Agricultural Statistics Service. USDA–NASS, Washington, DC. <http://www.nass.usda.gov/Data_and_Statistics/Quick_Stats_1.0/>, (verified 09.04.12).
USEPA, 2008. Hypoxia in the Northern Gulf of Mexico. An Update by the EPA Science Advisory Board. United States Environmental Protection Agency (USEPA), Washington, DC.
USGS, 2012. USGS Surface-Water Daily Data for the Nation. <http://www.nwis.waterdata.usgs.gov/nwis/dv/?referred_module=sw>, (verified 09.04.12).
Vanloocke, A. et al., 2010. The impacts of Miscanthus x giganteus production on the Midwest US hydrologic cycle. Gcb Bioenergy 2, 180–191.
VanLoocke, A. et al., 2012. A regional comparison of water use efficiency for miscanthus, switchgrass and maize. Agric. Forest Meteorol. 164, 82–95.
Wahl, T.L., Wahl, K.L., 2006. A Computer Program for Determining an Index to Base Flow. <http://www.usbr.gov/pmts/hydraulics_lab/twahl/bfi/index.html>, (verified 09.04.12).
Walter, M.T. et al., 2004. Increasing evapotranspiration from the conterminous United States. J. Hydrometeorol. 5, 405–408.
Wang, D., Hejazi, M., 2011. Quantifying the relative contribution of the climate and direct human impacts on mean annual streamflow in the contiguous United States. Water Resour. Res. 47.
Wolock, D.M., 2003. Base-flow index grid for the conterminous United States. US Geological Survery Open-File, Report 03–263.
Wu, Y., Liu, S., 2012. Impacts of biofuels production alternatives on water quantity and quality in the Iowa River Basin. Biomass Bioenergy 36, 182–191.
Xu, X. et al., 2012. Assessing the impact of climate variability on catchment water balance and vegetation cover. Hydrol. Earth Syst. Sci. 16, 43–58.
Yue, S., Pilon, P., 2003. Canadian streamflow trend detection: impacts of serial and cross-correlation. Hydrol. Sci. J. des Sci. Hydrol. 48, 51–63.
Zhang, Y.K., Schilling, K., 2005. Temporal variations and scaling of streamflow and baseflow and their nitrate–nitrogen concentrations and loads. Adv. Water Resour. 28, 701–710.
Zhang, Y.K., Schilling, K.E., 2006. Increasing streamflow and baseflow in Mississippi River since the 1940s: effect of land use change. J. Hydrol. 324, 412–422.
Zhang, L. et al., 2001. Response of mean annual evapotranspiration to vegetation changes at catchment scale. Water Resour. Res. 37, 701–708.
Zheng, H. et al., 2009. Responses of streamflow to climate and land surface change in the headwaters of the Yellow River Basin. Water Resour. Res. 45.
Ziegler, A.D. et al., 2004. Hydrological consequences of landscape fragmentation in mountainous northern Vietnam: evidence of accelerated overland flow generation. J. Hydrol. 287, 124–146.