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Key Points:

- Increased precipitation is the main driver of increased streamflow
- Agricultural land use and land cover changes had minimal impacts on streamflow
- Incorrect assumptions in previous studies minimized precipitation impacts

Supporting Information:

- Supporting Information S1

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Climate and agricultural land use change impacts on streamflow in the upper midwestern United States

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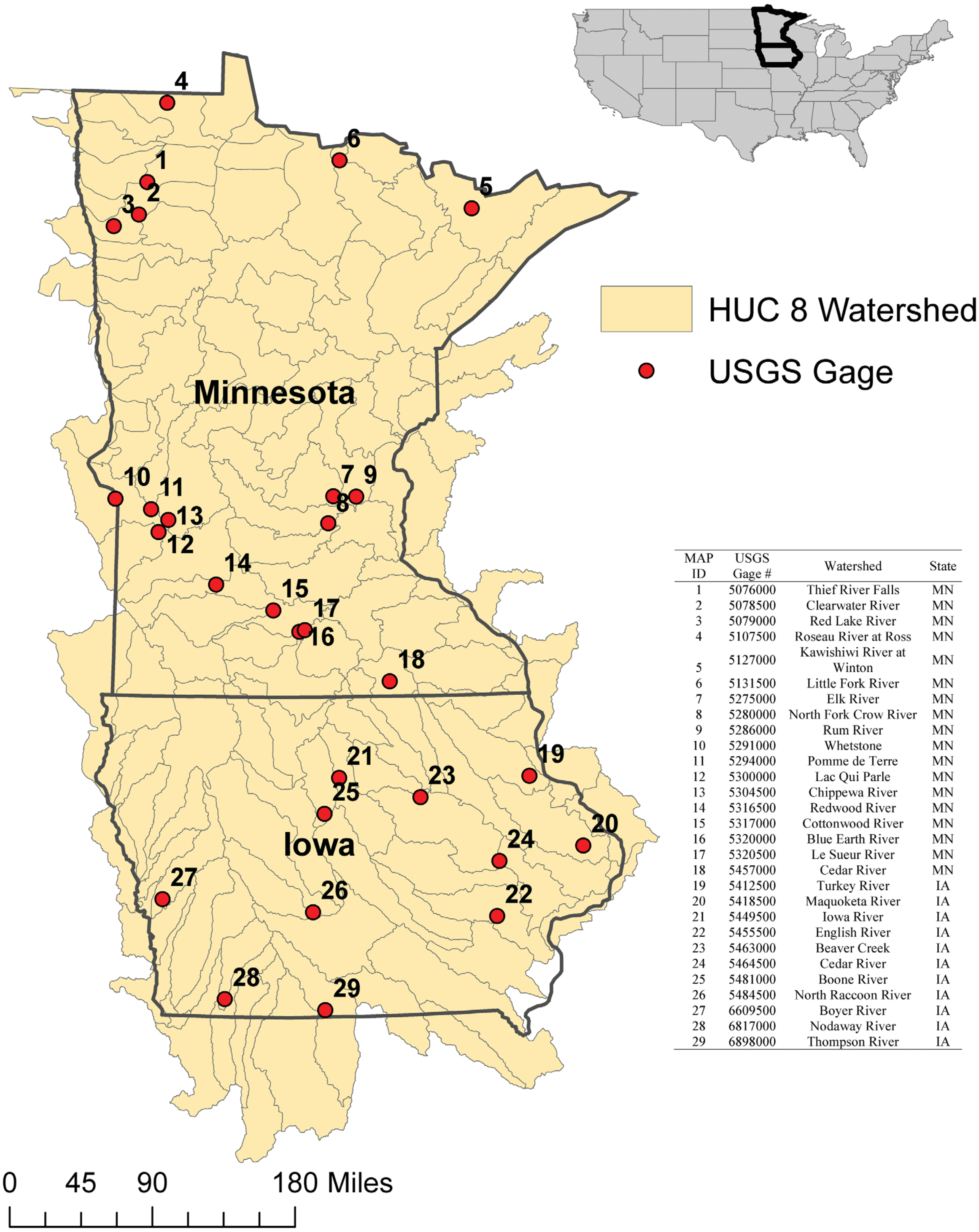
Abstract Increased streamflow and its associated impacts on water quality have frequently been linked to changes in land use and land cover (LULC) such as tile drainage, cultivation of prairies, and increased adoption of soybeans (*Glycine max*) in modern day cropping systems. This study evaluated the relative importance of changes in precipitation and LULC on streamflow in 29 Hydrologic Unit Code 008 watersheds in the upper midwestern United States. The evaluation was done by statistically testing the changes in slope and intercept of the relationships between ln(annual streamflow) versus annual precipitation for the periods prior to 1975 (prechange period) and after 1976 (postchange period). A significant shift either in slope or intercept of these relationships was assumed to be an indication of LULC changes whereas a lack of significant shift suggested a single relationship driven by precipitation. All 29 watersheds showed no statistical difference in slope or intercept of the relationships between the two periods. However, a simpler model that kept the slope constant for the two periods showed a slight upward shift in the intercept value for 10 watersheds in the postchange period. A comparison of 5 year moving averages also revealed that the increased streamflows in the postchange period are mainly due to an increase in precipitation. Minimal or the lack of LULC change impact on streamflow results from comparable evapotranspiration in the two time periods. We also show how incorrect assumptions in previously published studies minimized precipitation change impacts and heightened the LULC change impacts on streamflows.

1. Introduction

Increased streamflow and its associated impacts on water quality have frequently been linked to land use and land cover (LULC) changes such as tile drainage, cultivation of prairies, and increased adoption of soybeans (*Glycine max*) in modern day cropping systems in the upper midwestern United States (Figure 1) [*Schilling et al*., 2008; *Raymond et al*., 2008; *Wang and Hejazi*, 2011; *Schottler et al*., 2014]. On the other hand, several studies focused on climatic variation have also shown that alterations in river hydrology are primarily driven by increased precipitation in recent years [*Karl and Knight*, 1998; *Lins and Slack*, 1999; *Novotny and Stefan*, 2007; *Frans et al*., 2013]. Using the concepts of water and energy efficiency on four watersheds, *Tomer and Schilling* [2009] concluded that climate change has been the larger of two drivers (climate change and land use change) for increased streamflows in the midwestern United States. Recently, *Ryberg et al*. [2014] showed that changes in precipitation and potential evapotranspiration explained the multidecadal variability in streamflow, but precipitation was the dominant driver of the two.

Past analyses showing agricultural impacts on river hydrology [*Schilling*, 2003; *Schilling and Libra*, 2003; *Schilling* et al., 2008; *Zhang and Schilling*, 2006] are strictly based on empirical approaches that fail to account for the underlying principles of soil water storage, water infiltration, and surface runoff. For example, *Schilling and Libra* [2003] assumed a linear relationship between streamflow and precipitation, and in turn they used the changes in slope of this relationship (runoff ratio) as an indication of changes in LULC. However, it is well established that the relationship between streamflow and precipitation is nonlinear and the ratio of runoff to precipitation (runoff ratio) increases with an increase in precipitation [*Garbrecht et al*., 2004]. The nonlinearity in this relationship results from the nonlinearity in underlying infiltration and runoff processes; the former decreasing with time, precipitation, or soil wetness, and the latter increasing with time, precipitation, or soil wetness [*Kostiakov*, 1932; *Horton*, 1940; *USDA Soil Conservation Service*, 1957]. Recently, *Schottler et al*. [2014] showed that runoff ratios from 1975 to 2009 were higher than those for the 1940–1974 period and they attributed these changes primarily to agricultural modifications of the landscape. The authors



MAP ID	USGS Gage #	Watershed	State
1	5076000	Thief River Falls	MN
2	5078500	Clearwater River	MN
3	5079000	Red Lake River	MN
4	5107500	Roseau River at Ross	MN
5	5127000	Kawishiwi River at Winton	MN
6	5131500	Little Fork River	MN
7	5275000	Elk River	MN
8	5280000	North Fork Crow River	MN
9	5286000	Rum River	MN
10	5291000	Whetstone	MN
11	5294000	Pomme de Terre	MN
12	5300000	Lac Qui Parle	MN
13	5304500	Chippewa River	MN
14	5316500	Redwood River	MN
15	5317000	Cottonwood River	MN
16	5320000	Blue Earth River	MN
17	5320500	Le Sueur River	MN
18	5457000	Cedar River	MN
19	5412500	Turkey River	IA
20	5418500	Maquoketa River	IA
21	5449500	Iowa River	IA
22	5455500	English River	IA
23	5463000	Beaver Creek	IA
24	5464500	Cedar River	IA
25	5481000	Boone River	IA
26	5484500	North Raccoon River	IA
27	6609500	Boyer River	IA
28	6817000	Nodaway River	IA
29	6898000	Thompson River	IA

Figure 1. Map showing HUC 008 watersheds in the upper midwestern United States that were analyzed in this study.

failed to recognize that the changes in runoff ratios could be due to increased soil wetness from increased precipitation and in turn much higher runoff.

Another series of studies [*Wang and Hejazi*, 2011; *Schottler et al.*, 2014; *Xu et al.*, 2013] used Budyko's curves [*Budyko*, 1958] to analyze precipitation and human impacts (tile drainage and cropping system) on streamflow. The underlying premise of these analyses is that (1) the ratio of mean annual evapotranspiration (ET) to mean annual precipitation (ET/PPT; evaporation index) is controlled by the ratio of mean annual potential ET (PET) to mean annual precipitation (PET/PPT; dryness index), (2) this relationship is unique for a given climate and landscape condition, and (3) any shift away from this relationship is an indication of changes in hydrology from anthropogenic factors such as tile drainage and cropping system. Thus, if climate change (dryness index) was the main driver then the only change would be in the evaporation index, but the relationship between evaporation index and dryness index would remain the same (prechange Budyko curve). However, if there is change in LULC then the relationship between evaporation index and dryness index will also shift. Using these concepts, *Wang and Hejazi* [2011] developed a decomposition method to estimate human impacts on river flows. The method used the prechange Budyko's curve along with the difference in the mean values of evaporation indices in prechange and postchange periods to estimate human impacts. Although conceptually sound, these studies presumed prechange and postchange Budyko's curves were different without running any statistical tests and thus may have inadvertently characterized the annual climatic variability as human impacts. Another source of error in this [*Wang and Hejazi*, 2011] and other similar analyses [*Xu et al*., 2013; *Schottler et al*., 2014] is the use of arithmetic means for pre and postchange periods even after they show that Budyko's curve is an exponential function.

Another study that used a similar approach of comparing changes in streamflow at mean precipitation between the prechange and the postchange periods [*Raymond et al*., 2008] also overlooked the differences in precipitation over time. These authors empirically related the differences in streamflow at mean precipitation to percent area under cropland for various watersheds and implied that their relationship shows that streamflow differences are due to changes in land cover such as adoption of soybeans in the cropping system. The above empirical relationship presumed that cropland changes are the main driver of streamflow changes.

The finding that adoption of soybeans has resulted in increased streamflow originates primarily from publications by *Schilling* and colleagues. It is based on two observations: (1) an empirical relationship relating base flow in the Mississippi River at Keokuk, IA to fractional area under soybean [*Zhang and Schilling*, 2006], and (2) an ET analysis that showed a decrease in the ratio of annual ET/PPT over time [*Schilling et al*., 2008]. For the latter observation, the authors argued that since precipitation has not statistically changed over time, the decrease in the ratio of ET/PPT was due to a decrease in ET. The underlying premise was that soybeans are planted a bit later in the spring in the postchange period as compared to small grains that were planted earlier in the prechange period and this resulted in lower ET losses and thus greater streamflow. These authors also reasoned that the area currently under soybean was once under perennial crops, such as hay and alfalfa, and thus had higher ET in the past than in modern cropping systems. However, an analysis by *Baker et al*. [2012] showed that ET has remained relatively unchanged for many watersheds in the Upper Mississippi River Basin (UMRB) since 1960. Thus, this raises the question: why is ET constant over time even though there have been substantial changes in the landscape including tile drainage, drainage of wetlands, cultivation of prairies, and adoption of different crops in the cropping system?

The objectives of this study were (1) to evaluate the relative importance of changes in precipitation and LULC on streamflow in HUC 8 (Hydrologic Unit Code 008) watersheds of the upper midwestern United States (Figure 1), and (2) to identify factors for nearly constant ET in the postchange period relative to the prechange period. For the second objective, we test the hypothesis that prechange period cropping systems (primarily small grains with lower ET) in combination with a large number of wetlands resulted in similar evapotranspiration losses as the postchange period cropping systems (predominantly row crops such as corn (*Zea mays*) and soybeans with higher ET) and fewer remaining wetlands.

2. Methods

Streamflow in this paper is presented as an equivalent water depth or area weighted volume (volume of water/watershed area). In the literature, streamflow has also been characterized by other nomenclature such as stream discharge [*Schilling and Libra*, 2003], runoff depth [*Frans et al*., 2013], and water yield [*Schottler et al*., 2014]. Streamflow data used in this study were taken from the U.S. Geological Survey (USGS) (http://waterdata.usgs.gov/nwis). All flow data were converted to equivalent water depth using the USGS listed contributing area above the gauge. For most streams, the starting date for the flow data varied but the end date used in this study was always the same, i.e., 2009.

The annual precipitation data for Minnesota watersheds were acquired from the Minnesota State Climatology Office (G. Spoden, personal communication, 2009). The State Climatology office created the data by summing daily observations from the High Spatial Density Precipitation (HSDP) network into monthly precipitation totals for various weather monitoring stations. The network encompasses over 1400 locations (http://climate.umn.edu/gridded_data/precip/monthly/explain_grids.htm) in Minnesota which includes the National Weather Service monitoring locations (about 200) plus additional observations from local volunteers. These monthly values were then interpolated to regularly spaced 10 km grid nodes using a "kriging" technique and a semivariogram relationship. Precipitation for a given watershed was then calculated by overlaying the outline of the watershed boundary on the 10 km grid nodes and taking the average of all grid node values within the polygon. This averaging process was completed via the Surfer program [*Keckler*, 1994] and additional software developed by the State Climatology Office.

Annual precipitation data for Iowa watersheds were downloaded from the *PRISM Climate Group* [2009] database managed by Oregon State University (http://www.prism.oregonstate.edu/). This database is only based on the National Weather Service monitoring locations. We used the PRISM database for Iowa because HSDP network data were not available. Annual precipitation estimates in the PRISM database are calculated using techniques similar to those used by the Minnesota State Climatology Office. To address the concerns of using different precipitation databases for Minnesota and Iowa, we also ran statistical tests on ln(streamflow) versus precipitation relationships for the Blue Earth River watershed in Minnesota with both databases. To show temporal changes in precipitation for various watersheds in Iowa and Minnesota, we also calculated (1) the trend in annual precipitation using the Mann-Kendall nonparametric test [*XLSTAT*, 2015] and (2) mean annual precipitation for three 30 year periods varying from 1920 to 1949, 1950 to 1979, and 1980 to 2009.

Land use and land cover (cropping system) changes in the upper midwestern United States evolved over time as the European immigrants moved to the territories starting around 1838 in Iowa and 1849 in Minnesota. Since the earliest river flow records analyzed in this study only go back to early 1903, the major changes since that period involved (1) setting up of drainage ditches and some installation of surface inlets and subsurface clay and cement tiles starting in the early 1900s, (2) adoption of soybeans in the cropping system starting around the 1940s, and (3) adoption of plastic drain tile starting in the mid-1970s. There are no records on the temporal changes in tile drainage in the upper midwestern United States.

In this study, we selected 1975 as the breakpoint between the prechange and postchange periods primarily because of (1) the widespread adoption of plastic drain tile in the mid-1970s which has been viewed by many as the major cause of increased river flows [*Schilling and Libra*, 2003; *Raymond et al*., 2008; *Wang and Hejazi*, 2011; *Xu et al*., 2013; *Schottler et al*., 2014], and (2) the area under soybean production appears to be stable starting in the mid-1970s. Although plastic drain tiles started being manufactured in 1967 in the United States, initially there was some reluctance in its adoption out of concerns that it may not withstand the soil freezing pressure in winter. Adoption of plastic drain tile involved both the drainage of new lands as well as replacement of older clay and cement tiles that had degraded over time or had filled with sediments. The use of 1975 as a breakpoint in this study is consistent with the observations of changing trends in river flows in the midwestern United States [*Tomer and Schilling*, 2009; *Xu et al*., 2013] as well as breakpoint years used in other studies. For example, *Wang and Hejazi* [2011] used 1970 as the breakpoint year whereas *Schottler et al*. [2014] used 1974. *Raymond et al*. [2008] used the flow data prior to 1966 for the prechange period and after 1987 for the postchange period.

2.1. Testing the Shifts in Streamflow Versus Precipitation Relationships

The relative importance of changes in precipitation and LULC on streamflow tested in this study is based on the principle enumerated by *Raymond et al*. [2008], which states that a shift in streamflow over time is a reflection of changes in both precipitation and LULC (Figure 2). Thus, if the streamflow versus precipitation records for the two periods (prechange and postchange periods) are superimposed, and there is a statistically significant upward or downward shift in the postchange period relationship (higher or lower flows at a given precipitation level), it would suggest flow alterations were mainly caused by human activities such as altered LULC, presence of dams and levees, increased impervious surfaces, etc. (Figure 2a). On the other hand, if the relationship between streamflow and precipitation for the prechange and the postchange

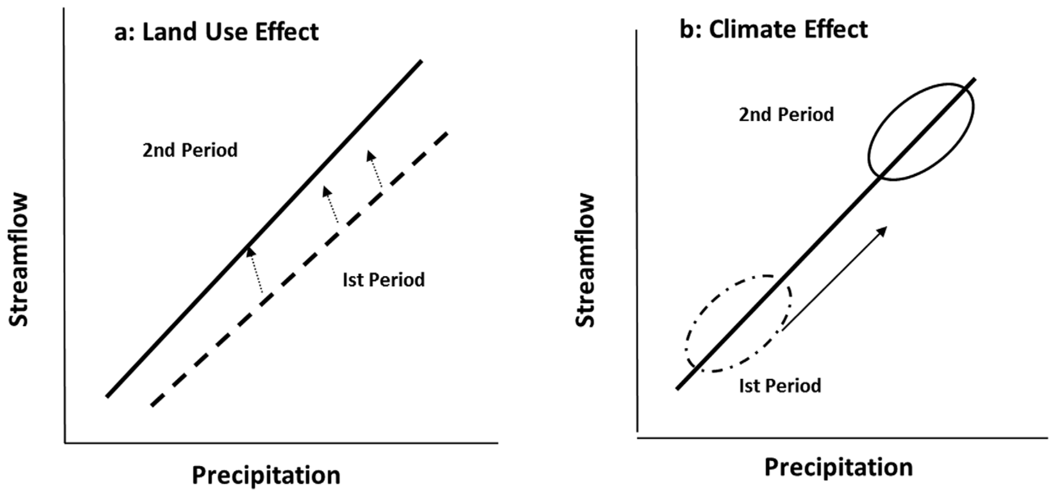


Figure 2. Hypothetical relationships between streamflow versus precipitation. In Figure 1a, the upward shift in the relationship suggests that the relationship between precipitation and flow has changed as a result of changes in land use land cover including tile drainage, wetland drainage, cultivation of prairies, and adoption of soybeans in the cropping system. On the other hand, Figure 1b suggests that the relationship between streamflow versus precipitation is the same but the streamflow data are clustered at lower precipitation levels in the first period and moves upward to higher-precipitation levels in the second period. (Figures adopted from *Raymond et al*., [2008].)

periods remain statistically similar (Figure 2b), it would suggest that the streamflow-precipitation relationship has not changed and precipitation is the main driver of changing streamflow.

Differences in streamflow versus precipitation relationships between the prechange and postchange periods (groups) were evaluated using analysis of variance (ANOVA) in a multiple regression approach relating the natural logarithm of streamflow (ln(streamflow)) to precipitation, a group variable (*I*) and an interaction term of precipitation and the group variable [*Kleinbaum and Kupper*, 1978].

$$\ln(Streamflow_{all}) = \beta_0 + \beta_1 \ X \ Precipitation_{all} + \beta_2 \ X \ I + \beta_3 \ X \ Precipitation \ X \ I \tag{1}$$

where β_0, β_1, β_2, and β_3 are the regression coefficients and *I* has a value of 1 for the first (prechange) period and 0 for the second (postchange) period. The coefficients β_2 and β_3 in equation (1), respectively, define the change in the intercept (β_0) and the slope (β_1) of the line from addition of prechange data in the above regression. The subscript "all" refers to the total record in the database. ANOVA gives the probability of various regression coefficients being statistically significant at the 95% level. If β_2 and β_3 values were not statistically significant at the 95% level then the above data were tested against a simpler model of the form:

$$\ln(Streamflow_{all}) = \beta_4 + \beta_5 \ X \ Precipitation_{all} + \beta_6 \ X \ I \tag{2}$$

where β_4, β_5, and β_6 are the regression coefficients. The above model assumes a constant slope of the ln(steamflow) versus precipitation relationship for both periods but tests if there is any statistical shift in the intercept value upon addition of data from the first period. If β_6 is significant then it suggests the two data sets (pre and postchange) have different intercepts. However, if β_6 is not significant then the next simpler model (equation (3)) is fitted that describes the relationship between ln(streamflow) versus precipitation for both periods.

$$\ln(Streamflow_{all}) = \beta_7 + \beta_8 \ X \ Precipitation_{all} \tag{3}$$

where β_7 and β_8 are the intercept and slope, respectively, of the regression relationship describing the total record. This statistical testing was done using the Excel data analysis tool [*Microsoft Office*, 2009]. Basically, the above analysis (equations (1)–(3)) checks if the relationship between streamflow versus precipitation for the prechange and postchange periods is better represented by one (driven by climate) or two (also affected by LULC changes) relationships. The above analysis assumes (1) normal distribution of residuals, and (2) homogeneity of variances. Natural log transformed streamflow data approximated a normal distribution, according to the Shapiro-Wilk test. Homogeneity of variances was confirmed by plots of residuals on the predicted values, which showed that the residuals were uniformly distributed around the zero line.

Since streamflow versus precipitation follows an exponential or a power function relationship [*Garbrecht et al*., 2004], initially both functions were tested on a few watersheds but there were minimal differences in the F statistics between these functions. To be consistent with the physics of water flow into the soil (infiltration) or at the soil surface (runoff), we chose an exponential function for the regression relationship of streamflow on precipitation. This is also consistent with the normality test for the log-linear relationship of streamflow versus precipitation in this and the *Schilling and Libra* [2003] study.

Two sets of analyses were performed with the available streamflow and precipitation records: (1) using all available complete flow records, and (2) using flow records with a starting date of 1940 or the next date after 1940 when flow records were available. For several gauging stations, some streamflow records were missing (Tables S1 and S2). Five year moving averages of streamflow and precipitation were calculated for all periods except when there were missing records.

The relative importance of changes in precipitation and LULC on streamflow was tested for 11 HUC 8 watersheds in Iowa (Table S1) and 18 HUC 8 watersheds in Minnesota (Table S2). All watersheds analyzed in this study are relatively small (899–13,649 km^2) rural watersheds and thus the effect of impervious surfaces is limited. Furthermore, there are no dams or levees in these watersheds and thus precipitation and LULC are the two main drivers of streamflow.

In this paper, we highlight our analysis of streamflow and precipitation data for two watersheds: the North Raccoon River watershed in North Central Iowa and the Blue Earth River watershed in South Central Minnesota. We chose these watersheds to provide a comparison of our results with earlier analyses by *Schilling et al*. [2008] for the North Raccoon River watershed and *Schottler et al*. [2014] for the Blue Earth River watershed. Both watersheds are located in an area that was glaciated by the Des Moines lobe during the Wisconsin glaciation approximately 11,000–85,000 years ago. The parent material in these watersheds predominantly consists of fine-textured, carbonate-rich buff colored glacial tills that were heavily packed during the last glaciation. High densities at greater depths in these landscapes often lead to perched water table conditions, especially during early spring. Farmers in the area have mitigated these conditions through installation of subsurface tile drains. Much of the area covered by the Des Moines lobe is also known as the Prairie Pothole region of the Upper Midwest. The area has many shallow surface depressions that have been drained through subsurface tile drainage or through installation of surface inlets that connect the soil surface to subsurface tile lines.

In addition to a detailed discussion on the results for the North Raccoon River and the Blue Earth River watersheds, a brief discussion covering the results of our analysis for the Little Fork River watershed in Northern Minnesota is also included. The Little Fork River watershed has limited agriculture (<3% area in crops and pastures), soils are formed in outwash sediments or in glacial drift overlying outwash, and there is no tile drainage.

2.2. Testing of Budyko Concepts

For the Blue Earth River watershed, we also tested the concepts of *Wang and Hejazi* [2011] using *Fu* [1981] functional form (equation (4)) for Budyko's curve.

$$\frac{ET}{PPT} = 1 + \frac{E_{pan}}{PPT} - \left[1 + \left(\frac{E_{pan}}{PPT}\right)^{w}\right]^{\frac{1}{w}} \qquad (4)$$

where w is the best fit coefficient. Instead of the potential evaporation or potential evapotranspiration in Budyko's curve, we used the pan evaporation (E_{pan}) data in equation (4). Also, rather than comparing the mean values of the streamflow for the two periods, we compared the exponent (w) of equation (4) for the two curves (prechange and postchange periods). The pan evaporation data were obtained from the University of Minnesota Southern Research and Outreach Center at Waseca, MN, about 80 km east of the Blue Earth River watershed. Since pan evaporation data were only available from 1964 to 2008, our comparisons are for 1964–1975 and 1976–2008.

The *Fu* [1981] function was fitted using an iterative process, and "w" was estimated by minimizing the average difference (d) and the standard deviation (s_d) of the difference between the fitted $(ET/PPT)_p$ and the measured $(ET/PPT)_m$ values.

$$d=\frac{1}{N}\sum\left(\left(\frac{ET}{PPT}\right)_p-\left(\frac{ET}{PPT}\right)_m\right) \tag{5}$$

$$s_D=\left[\frac{\sum\left(\left(\frac{ET}{PPT}\right)_p-\left(\frac{ET}{PPT}\right)_m\right)^2-Nd^2}{N-1}\right]^{0.5} \tag{6}$$

where N is the number of observations.

2.3. ET Calculations

For the second objective, ET was calculated as the difference between precipitation (PPT) and streamflow (Q), assuming (1) a negligible change in soil water storage (ΔS) over long time periods, and (2) no difference in deep percolation (D) between the prechange and postchange periods [*Schilling et al*., 2008; *Baker et al*., 2012].

$$ET=PPT-Q-\Delta S-D \tag{7}$$

Since most of the tile drained watersheds are underlain by compacted fine textured tills that retard water flow and lead to the presence of a perched water table, our assumption of deep percolation being nearly the same for the two periods should not cause much error in the water budget. *Tomer and Schilling* [2009] cited low (60 mm yr^{-1}) vertical ground water velocities in glacial aquitards underlain with pre-Illinoian till as the reason for minimal errors in ET calculations from assuming similar deep percolation between the prechange and postchange periods. Water storage monitoring studies with the GRACE (Gravity Recovery and Climate Experiment, a joint U.S.-German satellite mission) satellite also show very little change in groundwater storage in Iowa and parts of southern and western Minnesota (current study areas) between 2003 and 2012 [*Famiglietti and Rodell*, 2013]. Senior author of this paper has also run a double ring infiltrometer test on a buried till in the Blue Earth River watershed and found no measureable vertical water movement over several hours. High bulk densities in tills is another indicator of the tight packing of particles that results in smaller pores and thus negligible water movement through the tills. In a 69 m deep core from the Le Sueur River watershed in Southern Minnesota, *Grundtner et al*. [2014] reported bulk density as high as 2.18 Mg m^{-3}. The depth weighted average bulk densities were 1.9 Mg m^{-3} in the top 20 m, 2.1 Mg m^{-3} from 20 to 40 m depth, and 1.9 Mg m^{-3} from 40 to 69 m depth. The presence of a perched water table (the reason for installing drain tiles) further indicates very small downward percolation losses most of which end up as interflow or groundwater seepage to streams.

We also estimated ET for continuous corn, corn after soybean, soybean after corn, CRP, and alfalfa at Lamberton, MN, using 1988–1993 precipitation, tile flow, and available soil moisture data in *Randall et al*. [1997]. These ET estimates are based on the water balance approach and are equal to precipitation minus the sum of tile flow and change in soil water storage. Since soil water storage at the end of 1987 was not reported, we assumed stored available water in 1987 was the same as in 1988 and thus there was no change in soil water storage in 1988. Considering 1987 and 1988 were severe drought years, this assumption should not result in any major error in ET estimates. Since these experimental plots are flat and the authors did not report any runoff losses, we assumed runoff losses were minimal from all five cropping systems. In addition to the above ET estimates, we also compiled the published ET values for various crops, potholes/wetlands, and lakes in the midwestern United States and Alberta, Canada. All of these ET estimates are reported in the supporting information.

2.4. Agricultural Statistics

Since it has also been suggested that the adoption of soybeans in cropping systems occurred primarily on lands that were under pastures or alfalfa, and this conversion reduced ET and in turn increased streamflow [*Schilling et al*., 2008; *Baker et al*., 2012], we also analyzed the historic distribution of crop land, as well as yields of hay and alfalfa in the Blue Earth River watershed using the National Agricultural Statistics Service (NASS) database (http://quickstats.nass.usda.gov/). NASS surveys are reported on a county-wide basis. To estimate annual distribution of land cover in the Blue Earth River watershed, county-wide statistics in a given year were weighted by the area that each county occupied within the watershed.

Table 1. Probability Values of Various Regression Coefficients (β_2, β_3, and β_6) Relating ln(Streamflow) Versus Precipitation in Two Hierarchical Models (Model 1 and Model 2) and the Mean ± Standard Error of the Regression Coefficients (β_7 and β_8) in Third Model (Model 3) for Various HUC 008 Watersheds in Iowa[a]

	Model 1[b]		Model 2[c]		Model 3[d]	
	β_2	β_3	β_6		β_7	β_8
Watersheds	*p* values			Record Years	Mean ± Standard Error	
Beaver Creek	0.48	0.67	0.10	1946–2009	2.08 + 0.37	0.0037 + 0.0004
Boone River	0.69	0.88	0.14	1941–2009	1.85 + 0.34	0.0040 + 0.0004
Boyer River	0.27	0.15	0.11	1919–2009	2.29 + 0.28	0.0032 + 0.0004
Cedar River	0.96	0.56	0.003[e]	1903–1975	3.10 + 0.31	0.0024 + 0.0004
				1976–2009	3.07 + 0.36	0.0027 + 0.0004
English River	0.76	0.75	0.98	1940–2009	2.19 + 0.29	0.0034 + 0.0003
Iowa River	0.22	0.37	0.05[e]	1941–1975	1.79 ± 0.0.56	0.0039 ± 0.0007
				1978–2009	2.70 + 0.48	0.0031 + 0.0005
Maquoketa River	0.81	0.99	0.18	1914–2009	3.50 + 0.18	0.0022 + 0.0002
Nodaway River	0.54	0.39	0.25	1937–2009	2.06 + 0.29	0.0035 + 0.0004
North Raccoon River	0.30	0.17	0.09	1916–2009	2.22 ± 0.28	0.0034 ± 0.0004
Thompson River	0.43	0.57	0.22	1919–2009	1.79 + 0.32	0.0035 + 0.0004
Turkey River	0.59	0.48	0.31	1920–2009	2.95 + 0.21	0.0028 + 0.0003

[a] In this analysis, the breakpoint year for all these watersheds was 1975.
[b] $\ln(Stream\ flow_{all}) = \beta_0 + \beta_1\ x\ Precipitation_{all} + \beta_2\ x\ I(First\ Period) + \beta_3 x\ Precipitation\ x\ I(First\ Period)$.
[c] $\ln(Stream\ flow_{all}) = \beta_4 + \beta_5\ x\ Precipitation_{all} + \beta_6\ x\ I(First\ Period)$.
[d] $\ln(Stream\ flow_{record\ years}) = \beta_7 + \beta_8\ x\ Precipitation_{record\ years}$.
[e] Intercept significantly different at 5% level.

3. Results and Discussion

3.1. Testing of Climate Versus LULC Change Impacts on Streamflow

In Tables 1 and 2 are listed the probability values of various regression coefficients (β_2, β_3, and β_6) in two hierarchical models (equations (1) and (2)) and the mean ± standard error of the regression coefficients (β_7 and β_8) in the third model (equation (3)) for various HUC 008 watersheds in Iowa and Minnesota, respectively. The probability values for β_2 and β_3 clearly show that the slope and intercept of the line relating ln(streamflow) versus precipitation are statistically similar between the first period and the second period. This was true for all the watersheds analyzed in this study both in Iowa and Minnesota. Additional analysis with the next simpler model (equation (2)) shows that 9 out of 11 watersheds in Iowa (Table 1) and 10 out of 18 watersheds in Minnesota (Table 2) had no significant shift in the intercept value (β_6) between the two periods. This suggests that 19 of the watersheds have a unique relationship between ln(streamflow) and precipitation for the total period under consideration and there was no effect of land use changes on the streamflow versus precipitation relationship. In other words, precipitation was the sole driver of streamflow for these watersheds.

The significant differences in the intercept (β_6) in model 2 for the two watersheds in Iowa and eight watersheds in Minnesota suggests that there was some shift in the relationship between ln(streamflow) and precipitation when data for the first period was included with the second period. This shift was primarily because some of the variability in the slope between the two periods shifted to its corresponding intercepts when the slope was kept constant in model 2. For these watersheds, the next simpler model (equation (3)) was applied and Tables 2 and 3 give the regression coefficient values for two separate functions corresponding to each time period.

Figures 3 and 4 show examples of the relationships between streamflow and precipitation when intercept values in model 2 were the same (North Raccoon River Watershed, IA, and Blue Earth River Watershed, MN) or different (Iowa River, IA, and Cottonwood River, MN) between the two periods. Also, plotted in Figures 3 and 4 are the 5 year moving averages of streamflow versus precipitation for these four watersheds. Five year moving average plots for all four watersheds (Figures 3c, 3d, 4c, and 4d) clearly show that data are clustered around low-precipitation levels in the prechange period (<1975) and then move to higher-precipitation levels in the postchange period (>1976). This suggests that even though model 2 shows some land use change effects on streamflow (a slight upward shift in the intercept value) for the Iowa River (Figure 3b) and the Cottonwood River (Figure 4b) watersheds, precipitation is still the main driver of

Table 2. Probability Values of Various Regression Coefficients (β_2, β_3, and β_6) Relating ln(Streamflow) Versus Precipitation in Two Hierarchical Models (Model 1 and Model 2) and the Mean ± Standard Error of the Regression Coefficients (β_7 and β_8) in the Third Model (Model 3) for Various HUC 008 Watersheds in Minnesota[a]

	Model 1[b]		Model 2[c]		Model 3[d]	
	β_2	β_3	β_6		β_7	β_8
Watersheds	p Values			Record Years	Mean ± Standard Error	
Blue Earth River	0.83	0.64	0.14	1940–2009	1.88 ± 0.44	0.0038 ± 0.0006
Cedar River	0.80	0.44	0.004[e]	1945–1975	3.29 ± 0.41	0.0022 ± 0.0005
				1976–2009	3.14 ± 0.41	0.0028 ± 0.0005
Chippewa River	0.13	0.42	9.02E-05[e]	1938–1975	1.17 ± 0.69	0.0038 ± 0.0011
				1976–2009	2.52 ± 0.56	0.0028 ± 0.0008
Clearwater River	0.43	0.48	0.53	1940–2009	2.57 ± 0.35	0.003 ± 0.0006
Cottonwood River	0.87	0.77	0.02[e]	1936–1975	1.91 ± 0.58	0.0034 ± 0.0009
				1976–2009	2.04 ± 0.58	0.0038 ± 0.0008
Elk River	0.38	0.47	0.35	1935–2009	3.49 ± 0.21	0.0020 ± 0.0003
Kawishiwi River at Winton	0.96	0.73	0.04[e]	1924–1975	4.35 ± 0.29	0.0018 ± 0.0004
				1976–2009	4.38 ± 0.29	0.0016 ± 0.0004
Lac Qui Parle	0.79	0.84	0.02[e]	1935–1975	0.77 ± 0.71	0.0043 ± 0.0011
				1976–2009	1.03 ± 0.66	0.0047 ± 0.0010
Le Sueur River	0.98	0.78	0.08	1940–2009	1.65 ± 0.44	0.0042 ± 0.0006
Little Fork River	0.19	0.13	0.24	1912–2009	3.51 ± 0.18	0.0027 ± 0.0003
North Fork Crow River	0.50	0.87	0.01[e]	1935–1975	1.79 ± 0.68	0.0035 ± 0.001
				1976–2009	2.35 ± 0.49	0.0033 ± 0.0006
Pomme de Terre	0.66	0.97	0.01[e]	1936–1975	1.63 ± 0.55	0.0031 ± 0.0009
				1976–2009	2.01 ± 0.66	0.0031 ± 0.0010
Red Lake River at Crookston	0.51	0.63	0.27	1902–2009	2.26 ± 0.40	0.0034 ± 0.0007
Redwood River	0.45	0.88	0.002[e]	1937–1975	1.44 ± 0.71	0.0037 ± 0.0011
				1976–2009	2.1 ± 0.52	0.0035 ± 0.0007
Roseau River at Ross	0.97	0.91	0.45	1929–2009	1.54 ± 0.37	0.0050 ± 0.0007
Rum River	0.29	0.37	0.36	1934–2009	3.25 ± 0.28	0.0024 ± 0.0004
Thief River Falls	0.44	0.50	0.57	1920–2009	0.33 ± 0.73	0.0059 ± 0.0013
Whetstone	0.34	0.54	0.10	1932–2009	0.61 ± 0.48	0.0050 ± 0.0008

[a]In this analysis, the breakpoint year for all these watersheds was 1975.
[b]$\ln(Stream\ flow_{all}) = \beta_0 + \beta_1\ x\ Precipitation_{all} + \beta_2\ x\ I(First\ Period) + \beta_3 x\ Precipitation * I(First\ Period)$.
[c]$\ln(Stream\ flow_{all}) = \beta_4 + \beta_5\ x\ Precipitation_{all} + \beta_6\ x\ I(First\ Period)$.
[d]$\ln(Stream\ flow_{record\ years}) = \beta_7 + \beta_8\ x\ Precipitation_{record\ years}$.
[e]Intercept significantly different at 5% level.

streamflow and higher flows in the second period are mainly due to increased precipitation in that period. This is contrary to the findings of *Schilling* [2003, 2005], *Schilling and Libra* [2003], *Schilling et al*. [2008, 2010], and *Zhang and Schilling* [2006] who concluded that higher annual streamflows in the North Raccoon River watershed in Iowa in recent years were mainly due to LULC changes, specifically the adoption of soybeans in the cropping system.

All 29 watersheds tested in this study displayed trends in 5 year moving averages similar to Figures 3c, 3d, 4c, and 4d, thus suggesting that increased precipitation in the second period is the dominating factor for

Table 3. Probability Values of Various Regression Coefficients (β_2, β_3, and β_6) Relating ln(Streamflow) Versus Precipitation in Two Hierarchical Models (Model 1 and Model 2) and the Mean ± Standard Error of the Regression Coefficients (β_7 and β_8) in the Third Model (Model 3) at Four Different Breakpoint Years for the North Raccoon River Watershed in Iowa

	Model 1[a]		Model 2[b]		Model 3[c]	
	β_2	β_3	β_6		β_7	β_8
Breakpoint Year	p Values			Record Years	Mean ± Standard Error	
1975	0.30	0.17	0.09	1916–2009	2.22 ± 0.28	0.0034 ± 0.0004
1965	0.43	0.24	0.04	1916–1965	2.61 ± 0.38	0.0028 ± 0.0005
				1966–2009	2.01 ± 0.42	0.0038 ± 0.0005
1955	0.23	0.14	0.13	1916–2009	2.22 ± 0.28	0.0034 ± 0.0004
1945	0.52	0.31	0.02	1916–1945	2.73 ± 0.62	0.0025 ± 0.0008
				1946–2009	2.28 ± 0.31	0.0034 ± 0.0004

[a]$\ln(Stream\ flow_{all}) = \beta_0 + \beta_1\ x\ Precipitation_{all} + \beta_2\ x\ I(First\ Period) + \beta_3\ x\ Precipitation\ x\ I(First\ Period)$.
[b]$\ln(Stream\ flow_{all}) = \beta_4 + \beta_5\ x\ Precipitation_{all} + \beta_6\ x\ I(First\ Period)$.
[c]$\ln(Stream\ flow_{record\ years}) = \beta_7 + \beta_8\ x\ Precipitation_{record\ years}$.

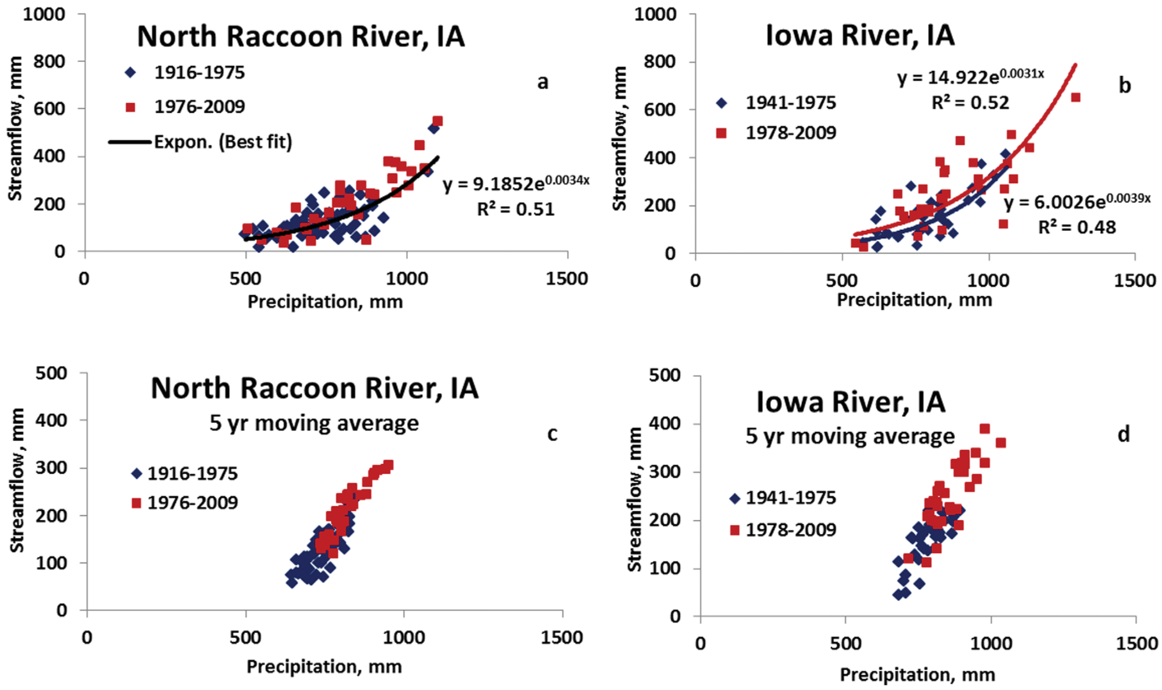


Figure 3. Plots of annual and 5 year moving average of streamflow versus precipitation for the North Raccoon River (Figures 3a and 3c) and Iowa River (Figures 3b and 3d) watersheds in Iowa.

increased streamflows in the upper midwestern United States. This is consistent with the increase in 30 year normal precipitation shown in Figures S1and S2 for the period 1920–2009 for Iowa and Minnesota, respectively. It is also in line with the linear trends in annual precipitation for the upper midwestern United States over the twentieth century using Kendall tau statistics and the bootstrapping of the ordinary least square regression residuals [*Pryor et al*., 2009]. Although for the short time frame used in this study some watersheds did not show a significant trend (Sen's slope) using the Mann-Kendall test (Tables S3 and S4), there is definitely higher precipitation in the second than the first period (data not included). For the North Raccoon River and the Iowa River watersheds, there was an average gain of 75 and 83 mm yr^{-1} between the two periods, respectively. Comparatively, for the Blue Earth River and the Cottonwood River watersheds in Minnesota, the precipitation increased by 50 and 60 mm yr^{-1}between the two periods, respectively. These increases are also consistent with the recent National Climate Assessment showing >15% increase in precipitation amounts from 1991–2011 relative to 1901–1960 in the upper midwestern United States [*Melillo et al*., 2014]. At some locations in the Upper Midwest such as Waseca, MN, annual precipitation has increased as much as 200 mm yr^{-1} in recent years (1978–2007) compared to 1921–1950 (M. Seeley, University of Minnesota, Personal Communication, 2013).

Since several published studies have reported their analyses using streamflow data starting in 1940, we also did a similar statistical analysis with models 1–3 using streamflow and precipitation records starting in 1940 (when available) and ending in 2009. For Iowa watersheds, there was no change in statistical trends from those shown in Table 1. Except for Lac Qui Parle watershed in Minnesota, there was also no change in statistical trends from those shown in Table 2 for Minnesota watersheds. For the Lac Qui Parle watershed, the intercept values in model 2 were not significantly different between the first and the second period.

Since precipitation databases were different for Iowa and Minnesota, a question also came up whether or not the precipitation databases make a difference in the statistical outcomes of the above analysis. To address this concern, we also ran the above analysis for the Blue Earth River watershed using the PRISM precipitation values. There was no difference in the statistical outcome from using the PRISM precipitation values relative to the precipitation values from HSDP network. The probability values for regression coefficients β_2, β_3, and β_6 using PRISM precipitation were 0.99, 0.83, and 0.16 whereas the mean ± standard error for β_7 and β_8 were 1.95 ± 0.44 and 0.0037 ± 0.0006, respectively. Comparatively, the probability values for regression coefficients β_2, β_3, and β_6 using HSDP network precipitation were 0.83, 0.64, and 0.14 and the

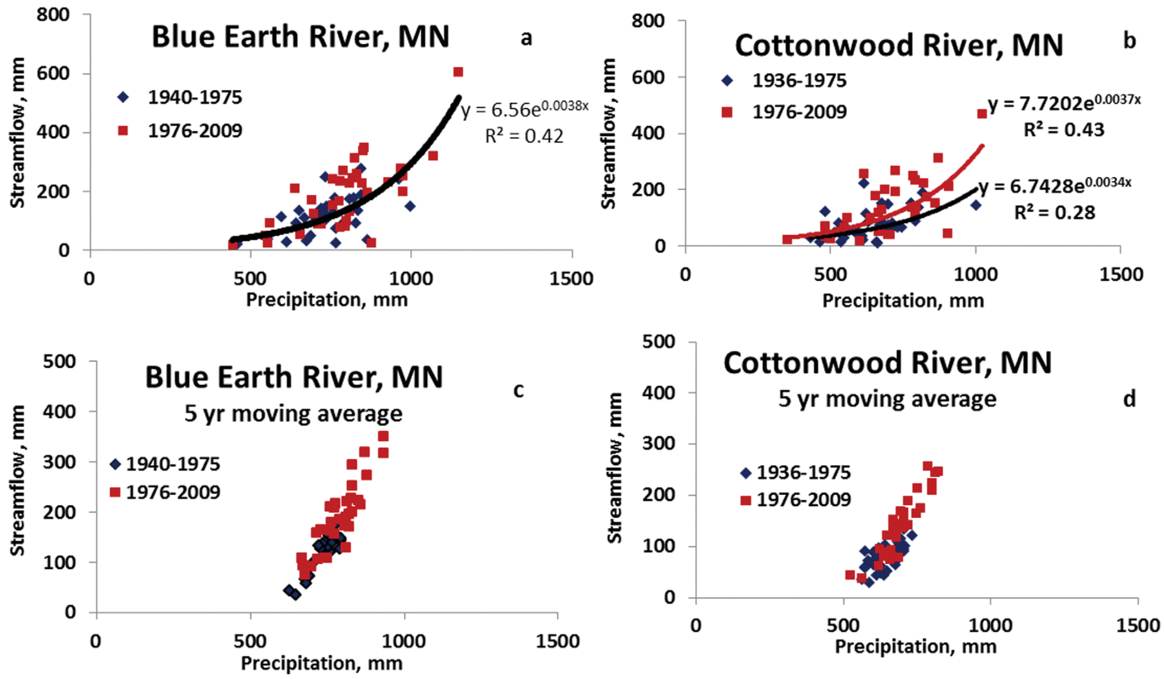


Figure 4. Plots of annual and 5 year moving average of streamflow versus precipitation for the Blue Earth River (Figures 4a and 4c) and Cottonwood River (Figures 4b and 4d) watersheds in Minnesota.

mean $\pm$ standard error for β_7 and β_8 were 1.88 $\pm$ 0.44 and 0.0038 $\pm$ 0.0006, respectively (Table 2). In both cases, precipitation was the sole driver of streamflow for this watershed.

Since we used 1975 as a breakpoint year between the two periods, we also ran a sensitivity analysis to see how statistical outcome changes in the above analysis as one varies the breakpoint year. For this sensitivity analysis, we used the data from the North Raccoon River watershed and fitted models 1–3 for breakpoint years of 1965, 1955, and 1945. Table 3 presents the probabilities of $\beta_{2,}$ β_3, and β_6 regression coefficients for models 1 and 2 and the mean $\pm$ standard error for β_7 and β_8 in model 3. Similar to the 1975 breakpoint year, there was no statistical difference in the slope and intercept of the ln(streamflow) versus precipitation relationship between the first and second period using model 1. However, when slope was kept constant for the two periods in model 2, the statistical differences in the intercept value depended upon the breakpoint year. Similar to the 1975 breakpoint year, the year 1955 also did not show any significant shift in the intercept values between the two periods. Comparatively, breakpoint years of 1965 and 1945 showed the intercepts in model 2 being different between the two periods. However, plots of 5 year moving averages of streamflow versus precipitation relationships for breakpoint years of 1965 and 1945 (Figure S3) showed that the upward shift in the relationship from prechange to postchange period was relatively small compared to an upward slide of the data cluster to higher-precipitation levels in the postchange period. This again supports the hypothesis that higher annual streamflows in recent periods are mainly due to higher precipitation, contrary to what has been suggested by *Schilling* [2003, 2005], *Schilling and Libra* [2003], *Schilling et al*. [2008, 2010], and *Zhang and Schilling* [2006]. As with many statistical analyses in which explanatory variable levels are not under control of the experimenter, relating streamflow to precipitation as was done in this study by itself does not suggest a cause and effect relationship.

3.2. Tests Using Budyko's Curves

The concept of Budyko's curves was tested on the Blue Earth River watershed. The plot of ET/PPT versus E_{pan}/PPT relationships for the Blue Earth River watershed showed much overlap in data points between the two periods (Figure S4). The best fit exponent (w) of equation (4) for all three periods (1964–2008, 1964–1975, and 1976–2008) was 3.025. The corresponding mean difference (d) and the standard deviation of the mean difference between the fitted and the measured ET/PPT values (s_d) were 0.039 $\pm$ 0.830, 0.016 $\pm$ 0.869, and 0.047 $\pm$ 0.832. The same best fit value of "w" for all three periods suggests that ET/PPT versus E_{pan}/PPT

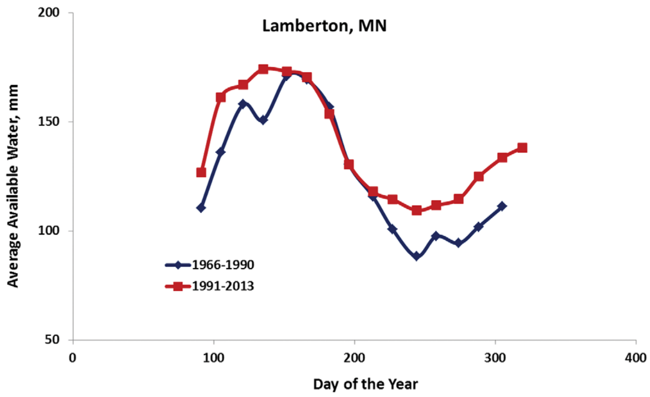


Figure 5. A comparison of average available soil water in 1.53 m of soil profile from 1991 to 2013 versus 1966 to 1990 under corn cropping system at Lamberton, MN.

relationships for the pre and postchange periods (1964–1975 and 1976–2008) were not statistically different than a single relationship for the whole period (1964–2008). This suggests that had *Wang and Hejazi* [2011] compared two curves (pre and postchange) rather than two mean ET/PPT values for their watersheds, they may have found that almost 100% of the change was due to increased precipitation (climate impact) and very little was due to changes in LULC (human impacts) for most watersheds.

We also tested *Wang and Hejazi* [2011] technique as applied by *Schottler et al.* [2014] for the Blue Earth River watershed. The major differences between our application and that of *Schottler et al.* [2014] are in the use of potential ET and the comparison of curves instead of mean values for the two periods. *Schottler et al.* [2014] calculated PET by multiplying the estimated RET based on air temperatures and a crop coefficient representing the average cropping systems for the two time frames. In comparison, we used the measured annual pan evaporation (E_{pan}) as a surrogate of PET. The two periods in our analysis were 1964–1975 and 1976–2008, whereas the two periods in *Schottler et al.* [2014] were 1940–1974 and 1975–2009. Statistical analyses using equations (1)–(3) showed that there was no difference in the slope or the intercept value relating ln(streamflow) and E_{pan}/PPT for the two periods and the relationship can be represented by a single function (Figure S5). The probability values for regression coefficients β_2, β_3, and β_6 were 0.37, 0.44, and 0.40 whereas the mean $\pm$ standard error for β_7 and β_8 were 6.95 $\pm$ 0.28 and -1.48 ± 0.20, respectively. This further validates our earlier finding that changes in streamflow have mainly occurred due to changes in precipitation and not due to changes in cropping system or tile drainage as suggested by *Schilling et al.* [2008] and *Schottler et al.* [2014]. Had *Schottler et al.* [2014] tested the differences between the curves rather than the arithmetic means for the two periods, it is likely they would have found no significant difference in their relationship of annual water yield versus PET/PPT for the two periods. In their analysis, *Schottler et al.* [2014] also showed a much larger impact of drainage than climate (their Figure 5a), primarily because (1) they did not account for climatic variability (assumed the annual water yield versus PET/PPT relationships for pre and postchange periods were different), and (2) there are errors associated with the use of an arithmetic mean instead of a geometric mean for a nonlinear relationship of annual water yield versus PET/PPT [*Schottler et al.*, 2014, Figure 5a]. Furthermore, had they plotted five year moving average trends of their data, they would have found that the major factor controlling streamflow was precipitation and not tile drainage.

We also applied *Schottler et al.* [2014] analysis to the Little Fork River watershed in Northern Minnesota where there is limited agriculture (<3% of the area is in crops and pastures) and no tile drainage. The major difference in our approach to this watershed compared to that of *Schottler et al.* [2014] was the lack of accounting for differences in ET (vegetation differences) between the two periods. Since most of the watershed is wetland or forest and there has been little agricultural development, the assumption of similar ET for the two periods is reasonable. Calculations revealed a 139% increase in streamflow in this watershed due to tile drainage. This is contrary to the physical facts that there is limited agriculture and no agricultural tile drainage exists in this watershed. This further demonstrates that the approach employed by *Schottler et al.* [2014] along with *Wang and Hejazi* [2011] and *Xu et al.* [2013] in comparing mean values for the two periods fails to fully account for similarity in the streamflow versus precipitation relationships for the two periods, and in turn fails to tease out the true anthropogenic impacts. Using the approach developed in this study, we found no statistical difference in ln(streamflow) versus precipitation relationships between the two periods (1940–1975 versus 1976–2009) for the Little Fork River watershed (Table 2).

3.3. Test Using Raymond et al. [2008] Approach

As mentioned earlier, *Raymond et al.* [2008] empirically related changes in discharge for the two periods (<1966 and >1987) to land cover in various subwatersheds of the Mississippi River and found that change in discharge increased from about -0.02 m yr^{-1} at near zero percent cropland to 0.07 m yr^{-1} at about 95% cropland. These authors concluded that agricultural practices such as tile drainage, fertilizer use, irrigation, tillage practices and changes in crop type potentially led to this increase in discharge between the two periods. For both periods, discharge was estimated at the average precipitation for the complete record.

Following *Raymond et al*. [2008] procedure, we also calculated changes in discharge between the two periods (1940–1975 and 1976–2009) for the Little Fork River watershed in northern Minnesota and the Le Sueur watershed in south central Minnesota. The respective cropland area for these watersheds was <3% and 84%, respectively. The discharge for any given period was estimated from best fit exponential relationships for the two periods at an average precipitation over the whole period. The average precipitation from 1940 to 2009 for the Little Fork River and the Le Sueur River watersheds was 694 and 772 mm, respectively. Change in discharge between the two watersheds corresponded to -0.02 mm yr^{-1} for the Little Fork River watershed and 0.04 m yr^{-1} for the Le Sueur River watersheds; a trend similar to those given by *Raymond et al*. [2008] for subwatersheds of the Mississippi River. However, a closer examination showed that the differences in discharge were likely due to differences in precipitation. Difference in average precipitation between the two periods equaled 14 mm yr^{-1} (687 versus 701 mm) for the Little Fork River watershed and 42 mm yr^{-1} (750versus 792 mm) for the Le Sueur River watershed. Although *Raymond et al*. [2008] acknowledged trends in increased precipitation in the Mississippi River watershed, they did not explore if the increase in discharge was related to an increase in precipitation.

3.4. Seasonal Changes in River Flows

For various Minnesota watersheds, *Schottler et al*. [2014] also showed that streamflows and runoff ratios (streamflow/precipitation) are much higher in May–June compared to September–October, even though precipitation in recent years has decreased in May–June, and increased in September–October. These authors suggested that the dramatic increase in streamflow and runoff ratio early in the season (May–June) cannot be explained based on increased precipitation. They argued that drainage of depressions and adoption of soybeans must be the reasons for these dramatic changes early in the season. However, this reasoning neglected the role of soil recharge/soil storage on short time scales, i.e., increased precipitation in September–October has consequences on surface runoff the following May–June. This is apparent by following the schematic of seasonal changes in average available soil water in the Upper Midwest [*Baker et al*., 1979] (Figure S6). During the winter season, the soils in the area are frozen and thus there is minimal increase in soil water storage. With the onset of soil thawing and spring rains, there is a small increase in soil storage. Crops are planted in early spring (mid-April for corn and early May for soybeans) and thus soil water depletion starts. This depletion continues until mid-September when crops senesce, after which there is very little water loss due to ET. From crop planting to senescence is also called the "Grand Consumption" period [*Baker et al*., 1979]. After mid-September soil recharge starts again until the soils freeze in late December to early January. Since there is more precipitation occurring in September–October now than in the past, there will be an upward lift in the soil water storage curve starting in fall, i.e., there will be more water stored in the soil profile now than in the past. For watersheds with fine textured soils, increased soil water storage will be carried over to next spring which will result in more runoff, even if there is slightly less rainfall in May through June. This is primarily because wet soils have less infiltration capacity, which leads to more runoff.

Figure 5 shows an example of this behavior in terms of average available soil water (volumetric water content-permanent wilting point) under corn at Lamberton, MN for the periods 1966–1990 versus 1991–2013. Because of the increase in precipitation in September–October in recent years, there is greater soil available water that is carried to the following April–May in the years 1991–2013 relative to 1966–1990. On the other hand, for watersheds with coarse textured soils, increased precipitation in September through October will dissipate due to rapid water percolation thus leading to little change in soil water storage as well as spring runoff (streamflow).

In *Schottler et al*. [2014] study, many of the watersheds (Blue Earth, Redwood, Cottonwood) with large changes in river flows have fine textured soils; thus, increased soil water storage in September–October is reflected in higher flows in May–June even though there is less precipitation in May through June in post-change than prechange period. Comparatively, several of the watersheds (Elk River, Rum River and Snake River) experiencing no change or reduced river flows have coarse textured soils which are not retaining increased fall precipitation, thus leading to unchanged or decreased streamflow as a result of decreased May–June precipitation. Another reason for several watersheds in *Schottler et al*. [2014] study showing significant increases in May–June flow is their use of a lower confidence interval (90%) for testing statistical differences. In other words, the authors are ignoring higher levels of climatic variability and thus forcing more watersheds to show statistically significant increase in river flow in May through June now than in the past.

The above discussion also points out that comparison of changes in runoff ratios on a seasonal basis [*Schottler et al*., 2014] is not appropriate partially because (1) runoff in any given season depends on the soil wetness conditions at that time which in turn are controlled by precipitation and ET in previous months or seasons, and (2) runoff follows an exponential or a power function of soil wetness, and these ratios will be higher in the postchange period because of higher wetness (due to higher precipitation). *Schottler et al*. [2014] assumption that the relationship between runoff and precipitation is linear and thus the runoff ratio should not change with a change in precipitation is erroneous. It is well established that runoff increases exponentially with an increase in rainfall, resulting in an exponential increase in streamflow with an increase in rainfall [*Garbrecht et al*., 2004]. Similar to above observations about seasonal comparisons in *Schottler et al*. [2014], the comparison of monthly streamflow values [*Zhang and Schilling*, 2006] is also inappropriate because runoff in any given month depends upon soil wetness for that month which in turn is affected by precipitation and ET in previous months.

3.5. Cropping System and Drainage Impacts on Changes in Evapotranspiration

As stated earlier in the introduction, *Schilling et al*. [2008] have suggested that the introduction of soybeans into the cropping system replacing perennial crops such as hay and alfalfa has led to reduced ET and consequently increased streamflows in the upper midwestern United States. ET calculations using equation (7) showed that the annual ET for the North Raccoon River watershed has remained constant ($p = 0.61$) from 1916 to 2009 (Figure S7b). Furthermore, the decrease in the ratio of ET/PPT with time (Figure S7c) is not due to a decrease in ET from adoption of soybeans as suggested by *Schilling et al*. [2008], but is due to an increase in precipitation (Figure S7a). Average annual ET for the North Raccoon River watershed over the whole period (1916–2009) corresponded to 611 mm. The corresponding ET values for 1916–1975 and 1976–2009 were 613 and 608 mm, respectively. A similar analysis showed an average ET of 624 mm for the Maquoketa River watershed in Eastern Iowa from 1914 to 2009, and an average ET of 602 and 611 mm for the Le Sueur River and the Blue Earth River watersheds, respectively, in Southern Minnesota from 1940 to 2009. Except for some northern watersheds in Minnesota (Roseau River, Kawishiwi River, and Little Fork River) and Beaver Creek in Iowa, there was no statistical trend in ET values over time for Iowa and Minnesota watersheds analyzed in this study (Tables S3 and S4).

It was puzzling to see that in spite of LULC changes there was no significant temporal change in ET even for the North Raccoon River and the Maquoketa River watersheds, which have two of the longest streamflow records starting in the 1910s. Since ET losses from a watershed are a function of crops, wetlands, and lakes, and their corresponding areas, we searched the literature for ET values of various crops, potholes/wetlands, and lakes in the upper midwestern United States and how the area under various crops has changed for one of the watersheds in Minnesota. The analysis was undertaken to explore if the earlier crops of small grains with low ET in combination with wetlands resulted in similar evaporative losses as the present day row crops with higher ET and fewer remaining wetlands.

The literature survey on ET of row crops, hay and alfalfa summarized in the supporting information show that under rain-fed conditions of the upper midwestern United States, ET of row crops such as corn and soybean are a bit smaller than those of alfalfa, somewhat similar to those of natural grasses and hay, and much higher than those of small grain crops and flax. Average annual water loss from corn and soybean ranges between 550 and 650 mm. Comparatively, annual water loss from small grains and flax is less than 550 mm ($\sim$350 mm plus nongrowing season soil evaporation) and alfalfa is greater than 650 mm (581 mm plus nongrowing season soil evaporation). Evaporative losses from potholes, wetlands, and lakes in the upper midwestern United States (supporting information) vary from relatively small values ($<$134 mm due to drying out of small potholes) to about 700.

To understand the temporal distribution of various crops in the upper midwestern United States, we also examined NASS statistics for area under various crops in the Blue Earth River watershed from 1921 to 2009 (Figure 6b). The crops considered were barley, hay, alfalfa, oats, corn, soybeans and wheat. Hay

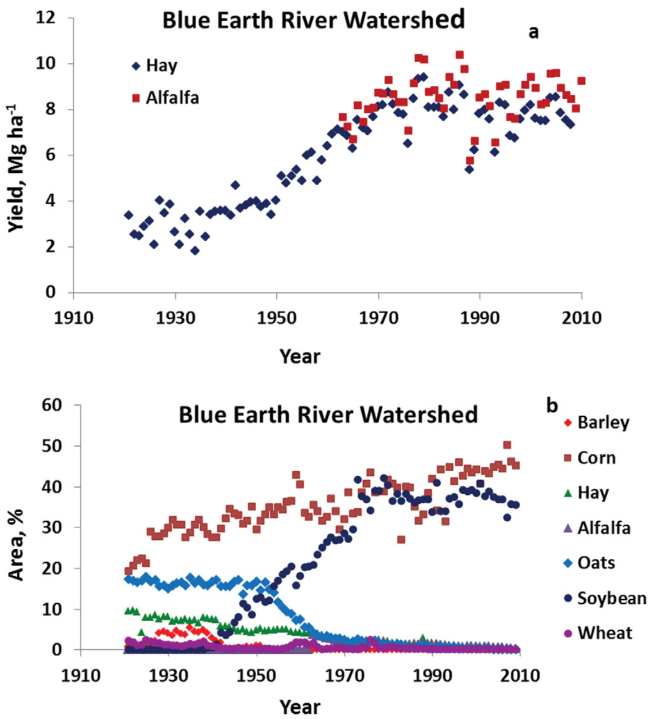


Figure 6. (a) Temporal variation in hay and alfalfa yields, and (b) area under various crops in the Blue Earth River Watershed, MN.

characterization in agricultural statistics includes wild hay, alfalfa, timothy grass and clover. In general, corn and soybean area increased whereas barley, oats, wheat, hay (including alfalfa) acreage decreased over time. Based on these crop statistics, soybean introduction in this watershed occurred in 1937. Going back to 1921, hay and oats represented less than 10% and 20% of the cropland area, respectively. On the other hand, alfalfa (part of the hay category) represented less than 4% of the cropland. Barley and wheat represented less than 5% and 3% of the cropland area, respectively. Area under corn was higher than any other crop in the landscape and varied from about 20% in 1921 to about 45% in 2009. Soybean area increased from about 0.1% in 1937 to a stable value of about 35% starting in 1974. Total cropland area in this watershed also increased from about 50% in 1921 to about 83% in 2009, which means not only did corn and soybeans replace oats, hay, alfalfa, and other small grain crops, but additional area (that may have been in prairies or in forest) was also brought under row crop cultivation between 1921 and 2009.

Considering that row crops such as corn and soybean (higher ET) replaced oats and hay (lower ET), one would expect greater ET losses from agricultural lands in postchange than prechange periods. On the other hand, since some of the wetlands and potholes (with slightly higher ET losses than the row crops) have been drained, there should be lower evaporative losses under current landscape conditions than in earlier times. Considering that many of the potholes and wetlands are shallow [*Kessler and Gupta*, 2015] and dry out during the growing season [*Shjeflo*, 1968], it appears that the net effect of replacing small grains, meadows, prairie grasses and shallow wetlands with row crops likely had a minimal impact on the water balance of tile drained watersheds in the Upper Midwest. This may be in part a reason for no statistical trend in annual ET since the early 1900s (Figure S7b). Another possible reason could be that there is a lower vapor pressure gradient between plants and atmosphere due to more rainfall. Pan evaporation data from St. Paul showed a slight decrease in evaporation over time (E_{Pan} (mm) $= -3.66$ year $+ 8221.1$; $p = 0.01$; year varying from 1972 to 2011) thus indicating reduced atmospheric demand for evaporation likely from reduced water vapor pressure deficit. However, there was no statistical trend in pan evaporation data from Waseca (E_{Pan} (mm) $= -1.29$ year $+ 3565.8$; $p = 0.23$; year varying from 1964 to 2008) even though it tended to decrease with time. The above discussion on ET losses thus negates the hypothesis suggested by several investigators [*Schilling et al.*, 2008; *Baker et al.*, 2012; *Schottler et al.*, 2014] that the adoption of soybean has increased streamflow because of its lower ET. As shown above, soybean ET is about the same as that of corn and native prairie grasses, and only slightly less than that of alfalfa.

4. Conclusions

Recently, several studies have associated LULC changes (tile drainage, cultivation of prairies, and adoption of soybeans) to higher streamflows in the upper midwestern United States. The above analysis shows that the recent higher streamflows for most watersheds in the Upper Midwest are mainly due to increased precipitation (additional 50–100 mm yr^{-1}), consistent with the principles of increased runoff at higher soil moisture conditions. The lack of impact on streamflow from changes in LULC in most watersheds may partially be due to nearly equivalent evapotranspiration (ET) in the prechange and post-change periods, i.e., higher ET from row crops on an expanded area (even with some loss of wetlands) in postchange period versus low ET from small grain areas (even with presence of some wetlands and native prairies) in the prechange period. Additional analysis of precipitation and LULC change impacts with published approaches such as the Budyko curve also showed that increased precipitation was the main driver of increased streamflows in the postchange period. The differing conclusions in the literature are the result of (1) the authors' presumption that streamflow versus precipitation relationships for the pre and postchange periods are different without running any statistical test, (2) ignoring the principles of runoff and infiltration and assuming streamflow is linearly related to precipitation, (3) comparison of arithmetic mean streamflows when streamflow versus precipitation relationships follow exponential or power functions, and (4) an emphasis on empirical relationships of some streamflow parameter versus area under row crops [*Schilling*, 2005] or soybeans [*Schilling et al*., 2010; *Zhang and Schilling*, 2006], or simply a display of temporal decrease in pasture and hay crops area and temporal increase in row crop area [*Baker et al*., 2012] as an indication of cause and effect.

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