INCREASED PRECIPITATION AS THE MAIN DRIVER OF INCREASED STREAMFLOW IN TILE-DRAINED WATERSHEDS OF THE UPPER MIDWESTERN U.S.

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ABSTRACT. *Recent increased streamflow (Q) and its associated impacts on water quality have frequently been linked to land use and land cover (LULC) changes such as increased tile drainage, cultivation of prairies, and adoption of soybean (*Glycine max*) in modern-day cropping systems. However, many previous studies have assumed minimal to no change in precipitation during their study period. A recent analysis of streamflow records from 29 HUC 8 (Hydrologic Unit Code 008) watersheds in Iowa and Minnesota showed that increased precipitation instead of LULC change was the main driver of increased streamflow. The analysis was done through hierarchical regression of annual streamflow as a function of annual precipitation for the periods prior to 1975 (pre-change period) and after 1976 (post-change period). A statistical shift in annual relationship from the pre- to post-change period was assumed to be an indication of LULC changes, whereas a lack of statistical shift suggested no change in the relationship and higher flows were mainly driven by increased precipitation. In this article, we further show that annual streamflow and annual baseflow were influenced not only by the current year's precipitation but also by precipitation in the preceding one to two years, and this effect was manifested through increased or decreased stored soil water. The present analysis was done using backward stepwise hierarchical regression with the natural log of annual streamflow as the predictor variable and three to five years of precipitation, the area under soybean production, a group variable simulating pre- and post-change periods, and its interaction terms with precipitation and soybean area as the explanatory variables. This analysis also showed that precipitation was the main driver of annual streamflow or baseflow; however, for some rivers, the area under soybean production and group differences were also significant variables, although at a much smaller confidence level. Annual streamflow testing was done for the Blue Earth River, Redwood River, Cottonwood River, and Whetstone River watersheds in Minnesota and the Maquoketa River and Raccoon River watersheds in Iowa. Annual baseflow testing was done only on the Redwood River and Raccoon River watersheds. Using similar backward stepwise regressions, the analysis showed that changes in Ln(monthly streamflow) were linked to stored soil water through the preceding months' and years' precipitation. On a daily scale, comparison of slopes of the hydrograph's rising limb for two large precipitation events in 1957 (pre-change period) and 1993 (post-change period) showed less watershed connectivity due to LULC changes such as drainage, a finding that is contrary to what has been suggested in the literature. A similar comparison of the falling limb slopes for a given streamflow condition showed similar slope values in pre-change (1947) and post-change (1991) periods, thus suggesting no changes in storage capacity of the watershed as a result of LULC changes. Further comparisons of high-level streamflows ($Q > 100\ m^3\ s^{-1}$) as a function of average daily storm precipitation showed no effect of drainage between the pre- and post-change periods. A statistical analysis of the relationship between the falling limb slopes as a function of streamflow for low ($dQ/dt < -5\ m^3\ s^{-1}\ d^{-1}$) and medium ($dQ/dt$ varying from -2 to -5 $m^3\ s^{-1}\ d^{-1}$) slopes also showed no discernable change in the retentive capacity of the Redwood River watershed between the pre- and post-change periods. The above evaluations at three temporal scales further supported our previous conclusion that increased precipitation in recent years is the main driver of the increased streamflow in tile-drained watersheds of the upper Midwestern U.S., and the impacts of LULC change on streamflow characteristics were minimal. We conclude that any comparison of daily, monthly, or annual streamflow and baseflow to evaluate LULC change impacts must be done at comparable stored soil water conditions or with accounting of precipitation from previous days, months, and years.*

Keywords. *Baseflow, Hydrograph, Land use land cover, Precipitation, Streamflow, Tile drainage.*

Land use and land cover (LULC) changes have been suggested to play a dominant role in recent increases in streamflow (*Q*) and/or baseflow (Q_b) in the upper Midwestern U.S. (Schilling, 2005;

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Zhang and Schilling, 2006; Schilling et al., 2008; Schottler et al., 2014; Foufoula-Georgiou et al., 2015). The LULC changes include increased tile drainage, cultivation of prairies, and adoption of soybean (*Glycine max*) in modern-day cropping systems. However, a recent analysis of streamflow records from 29 HUC 8 (Hydrologic Unit Code 008) watersheds in Iowa and Minnesota showed that climate change (increased precipitation) rather than LULC change was the major driver of increased annual streamflow in the upper Midwestern U.S. (Gupta et al., 2015, 2016a, 2016b, 2016c, 2016d, 2016e). The analysis was done through hierarchical regression analysis of annual streamflow as a function of annual precipitation for the periods prior to 1975 (pre-change period) and after 1976 (post-change period). A statistical shift in annual relationships from the pre- to post-change period was assumed to be an indication of LULC changes as well as differences in stored soil water (soil wetness), timing and intensity of storms, differences in crop growth stage, and their interactions between the two periods. On the other hand, a lack of statistical shift suggested no change in the relationship and higher annual flows were mainly driven by higher precipitation. This was further tested by plotting the five-year moving average of streamflows as a function of average precipitation. The moving averages partially smoothed out inter-annual stored soil water differences in each period. Five-year moving average relationships showed that higher streamflows in recent periods were associated with higher precipitation. The findings from both of these analyses were consistent with conclusions reached by other investigators using different methods of analysis (Lins and Slack, 1999; Novotny and Stefan, 2007; Frans et al., 2013; Ryberg et al., 2014; Hoogestraat and Stamm, 2015). However, some of the previous studies, including Gupta et al. (2015), overlooked or did not explicitly account for the effects of stored soil water from previous daily, monthly, and annual precipitation events on annual streamflow or baseflow. In some cases, there was also no accounting of changes in cropping area on annual streamflow or baseflow between the post- and pre-change periods.

Questions have also been raised about the role of LULC changes in increased daily, monthly, and seasonal streamflow in recent years. For example, Zhang and Schilling (2006) analyzed monthly streamflow and baseflow from 1940 to 2003 in the Mississippi River at Keokuk, Iowa, and concluded that trends in increased streamflow were due to increased baseflow, which they attributed to land use changes associated with expansion of the area under soybean production. However, no consideration was given to previous months' and years' precipitation and their effects on stored soil water and in turn on baseflow. Furthermore, it was assumed that precipitation was similar between the pre- and post-change periods. Foufoula-Georgiou et al. (2015) compared daily hydrographs of the Redwood River in southwestern Minnesota for two similar precipitation years (1971 and 2002) and suggested that increased daily streamflow in 2002 was due to the presence of tile drainage and adoption of soybean in the landscape. However, Foufoula-Georgiou et al. (2015) overlooked the role of stored soil water in comparing daily hydrographs between these two years (Gupta et al., 2016e). In further analysis of bi-monthly streamflows, Foufoula-Georgiou et al. (2015) concluded that increased streamflow from May-June was primarily due to land use changes (adoption of soybean and tile drainage) because there was not much difference in May-June precipitation distributions before and after adoption of the above LULC changes. Similar to their daily comparisons between 2002 and 1971, Foufoula-Georgiou et al. (2015) also overlooked the increased November-December precipitation in recent years and the role it played in increased stored soil water in spring and in turn on May-June streamflow in the post-change period (Gupta et al., 2016d, 2016e).

The first objective of this research was to highlight the importance of stored soil water on annual and monthly streamflow and annual baseflow in subsurface tile-drained watersheds of the upper Midwestern U.S. The importance of stored soil water is shown through (1) comparisons of individual annual streamflows for similar precipitation years in the pre- and post-change periods, (2) comparison of plant-available soil water distribution among years with similar or dissimilar precipitations, and (3) the use of previous years' and previous months' precipitation in hierarchical regression analysis. The p-values of various variables in the final regression were then used to assess their relative importance in explaining the variability in streamflow or baseflow.

Limited research has been reported on the effects of precipitation and LULC changes (e.g., drainage, cropping system) on daily streamflows in the Upper Midwestern U.S. Many factors affect daily streamflow. These factors include not only the amount and intensity of precipitation on a given day but also the precipitation on several previous days, months, and even years. All these factors affect stored soil water and in turn the timing and amount of runoff. There are also issues of vegetation type, stage of growth, changes in land management practices, and their interactions with changing climate.

Woodward and Nagler (1929) conducted one of the earliest studies to characterize drainage impacts on daily streamflow during flood periods in two Iowa rivers at four locations. Through a comparison of the maximum 24 h rate of discharge (slope of the rising limb) as a function of average daily storm precipitation between the pre-drainage (1903-1906) and post-drainage (1918-1923) periods, these authors showed no effect of drainage, including subsurface tile drainage, open ditches, and straightening of stream channels, on daily flood levels in the Des Moines River at Keosauqua, Des Moines, and Fort Dodge, Iowa, and the Iowa River at Iowa City, Iowa. Similarly, through a comparison of the relationships for decrease rate of discharge after flood levels (slope of the falling limb) as a function of river discharge for days with no subsequent precipitation, they concluded that there was no change in the storage capacity of the watersheds as a result of drainage enterprises between the pre- and post-drainage periods. In other tests, Woodward and Nagler (1929) also compared the monthly runoff in these rivers at a given level of monthly precipitation and found no difference between the pre- and post-drainage periods for three groups of months (February-March, April, and May with some data from June-September). These authors noted that if there were any differences in monthly runoff, then these streams had greater quantities of flow during flood months of 1903-1906 (pre-drainage) than the post-drainage months of 1918-1923. They also noted that some of the differences between the pre- and post-drainage comparisons were likely due to the location of the storm on the watershed, i.e., if the storm was located near the outlet, there was greater runoff than if the storm occurred in the upper part of the watershed.

Foufoula-Georgiou et al. (2015) used a similar approach as that of Woodward and Nagler (1929) in assessing the effects of land use (drainage and adoption of soybeans) on daily streamflow in the Redwood River during May-June. These authors plotted the slope of the rising limb of the hydrograph (dQ^+/dt) to previous day precipitation (P_t) between the pre-change (1944-1975) and post-change (1976-2007) periods. Similar to Woodward and Nagler (1929), the underlying premise of the Foufoula-Georgiou et al. (2015) analysis was that a faster rise in the slope of streamflow at a given daily precipitation level between the pre- and post-change periods is an indication of increased surface hydrologic connectivity from installation of ditches and surface inlets, i.e., a rapid conversion of daily precipitation to daily streamflow. However, from the scatter plot of positive slopes of daily streamflow as a function of the previous day's precipitation (fig. 6a in Foufoula-Georgiou et al., 2015), LULC change impact between the pre- and post-change periods cannot be discerned. This may be partially because the differences in stored soil water were also imbedded in the slope values at less than flood conditions. Using nonparametric Coupla analysis, Foufoula-Georgiou et al. (2015) concluded that "the rate of increase in streamflow has become more closely coupled to previous day precipitation across a range of quantiles, especially the medium (0.2-0.6) quantiles for both variables." In their analysis, these authors assumed that the daily slope of the rising limb was exclusively related to the previous day's precipitation and that there was no carryover effect of higher precipitation from previous precipitation events (on daily, monthly, or annual scales). Similar to the Woodward and Nagler (1929) analysis on decreasing rates of river runoff after high water levels, Foufoula-Georgiou et al. (2015) also plotted the absolute value of the negative slope (falling limb of the hydrograph) of daily streamflow with no precipitation on the previous day ($|dQ^-/dt|\ P_t = 0$) as a function of daily streamflow. The premise of this relationship was to see if the storage-discharge relationship changed due to tile drainage. Again using non-parametric Coupla analysis, these authors concluded that the Coupla of the falling limb did not show as significant a change in its dependence with the magnitude of streamflow between the two periods, and more likely this dependence may have weakened in the post-change period, possibly due to artificial drainage.

The second objective of this research was to use Woodward and Nagler (1929) type analysis for flood events and evaluate if the slopes of the hydrograph's rising limb at large precipitation events and the slopes of the hydrograph's falling limb at similar streamflow show any difference as a result of LULC changes resulting from tile drainage between the pre- and post-change periods. In this study, we assumed that an increase in the slope of the rising limb of the daily hydrograph is an indication of increased watershed connectivity, and a decrease in the slope of the falling limb is an indication of decreased storage capacity in the watershed, both from drainage activities. High precipitation events (flood events) were selected to compare the slopes of the rising limb to minimize the differences in soil wetness conditions between the two periods.

Methods

The primary focus of this analysis was on the Redwood River (USGS gauge 05316500) in southwestern Minnesota (fig. 1). However, precipitation and LULC change impacts on streamflow at annual scale were also evaluated for five other rivers: the Blue Earth River (gauge 05320000), Cottonwood River (gauge 05317000), and Whetstone River (gauge 05291000) in Minnesota and the Maquoketa River (gauge 05418500) and North Raccoon River (gauge 05484500) in Iowa. In addition, precipitation and LULC change impacts were also evaluated on annual baseflow of the Redwood River and Raccoon River. All six watersheds are medium (1,030 km^2) to large (8,912 km^2) agricultural watersheds with relatively small urban areas and thus minimal impact of changes in impervious surfaces on streamflow or baseflow. For example, the area of four major towns (Marshall, Redwood Falls, Tyler, and Vesta) in the Redwood River watershed equaled 46 km^2, compared to a total watershed area of 1,629 km^2 (Wikipedia, 2017). Furthermore, not all of the town area is impervious surfaces.

Streamflow data for all watersheds were taken from the U.S. Geological Survey (http://waterdata.usgs.gov/nwis) and converted to equivalent water depth using the contributing area above the gauge. Annual and monthly precipitation data for the Minnesota watersheds were acquired from the Minnesota State Climatologist Office (G. Spoden and P. Boulay, personal communication, 2016), whereas annual and monthly precipitation data for the Iowa watersheds were downloaded from the PRISM Climate Group database (http://www.prism.oregonstate.edu). Daily precipitation records for the Redwood River watershed were downloaded from the Minnesota Department of Natural Resources (MnDNR, 2017) website, maintained by the State Climatologist Office. Daily precipitation values in May-June from three sites (Tyler, Marshall, and Vesta) across the Redwood River watershed (fig. 1) were averaged to get a daily precipitation for the watershed. These average daily precipitation values were then used with the slope of daily hydrographs in May-June to assess drainage impacts between the pre- and post-change periods. Marshall is in the middle of the Redwood River watershed and about 33 and 31 km from Tyler and Vesta, respectively (fig. 1). Data on crop area in the various watersheds were downloaded from the USDA National Agricultural Statistics Service (NASS) database (http://quickstats.nass.usda.gov). Additional details about these databases and how these data were processed for statistical analysis have been reported by Gupta et al. (2015).

Plant-available soil water data reported in this article were taken from the historical records at the University of Minnesota Southwest Research and Outreach Center at Lamberton, Minnesota, which lies in the center of the Cottonwood River watershed south of the Redwood River wa-

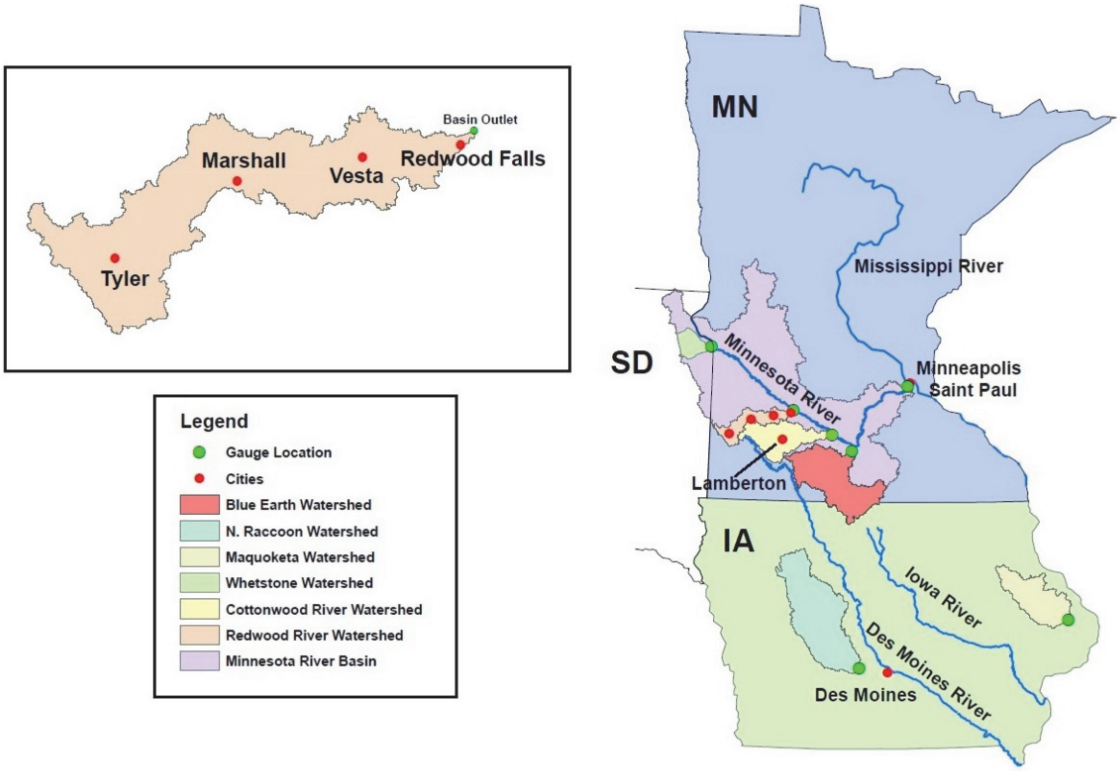


Figure 1. Map of Minnesota (MN) and Iowa (IA) showing the HUC 008 watersheds analyzed in this study. The inset map shows the locations of Tyler, Marshall, and Vesta within the Redwood River watershed in southwestern Minnesota. Daily precipitation for the Redwood River watershed was taken as the average daily precipitation from these three sites. The gauge for the Blue Earth River watershed represents the combined flow from the Blue Earth River and the Watonwan River. The Whetstone River watershed is located in South Dakota (SD) but empties into the Minnesota River.

tershed (fig. 1). Details on the data collection methods were reported by Baker et al. (1979). Briefly, the water content measurements were taken on a Webster silty clay loam (Typic Haplaquoll) under continuous corn (*Zea mays* L.) using the gravimetric method. Measurements were made on a monthly and a bi-weekly basis before and after 1970, respectively. Each measurement is an average of five borings prior to 1994 and six borings after 1994 at each sampling site (Lee Klossner, personal communication, 2017). The depth increments were 15 cm apart from 0 to 61 cm depth and 30 cm apart from 61 to 152 cm depth. Baker et al. (1979) reported 53.3 and 28.4 cm of water retention in the top 152 cm of the profile at field capacity and wilting point water contents, respectively. This is equivalent to 24.9 cm of potential plant-available water in the top 152 cm of the soil profile.

The effects of precipitation and LULC change on annual streamflow were tested using multiple regression analysis. The predicted variable was the natural log of annual streamflow, whereas the explanatory variables were the current year's precipitation, previous years' precipitation, and area under soybean production. For the Blue Earth River, Redwood River, Cottonwood River, and Whetstone River in Minnesota, this analysis was done using the current year and four previous years' precipitation data, whereas for the Maquoketa River and North Raccoon River in Iowa, the analysis was done using the current year and two previous years' precipitation data. Similar to the Gupta et al. (2015) analysis, the data were divided into two periods: before 1975 (pre-change) and after 1976 (post-change). The selection of 1975 as the breakpoint year between the pre- and post-change periods was because of widespread adoption of plastic drain tile starting in the mid-1970s. This adoption involved both the drainage of new lands as well as replacement of older clay and cement tiles that had degraded or had filled with sediments. Although the manufacturing of plastic drain tile began in 1967 in the U.S. (Fouss, 1974), there was some initial reluctance to its adoption due to concerns that it might not withstand soil freezing pressure in winter (Don Gass, tile layer since 1940, Slayton, Minn., personal communication, 2010). The use of plastic drain tile became common, especially in the Upper Midwestern U.S., only in the mid-1970s (Don Gass, personal communication, 2010). The use of 1975 as a breakpoint year is consistent with the observation of changing trends in river flows in the Midwestern U.S., as well as the breakpoint years used in other studies. For example, Wang and Hejazi (2011) and Schottler et al. (2014) used 1970 and 1974, respectively, as breakpoint years.

Differences in streamflow and baseflow between the pre- and post-change periods (groups) were evaluated using a hierarchical regression approach (Kleinbaum and Kupper, 1978) relating the natural logarithm of streamflow or baseflow to annual precipitation in a given year (P_1), a group variable (I) representing a time period (prior to 1975 or after 1975), an interaction term of a given year's precipitation with the group variable ($P_1 \times I$), annual precipitation from one year prior (P_2) and its interaction term with the group variable ($P_2 \times I$), annual precipitation from two years prior (P_3) and the corresponding interaction terms ($P_3 \times I$), and so on for up to five years (Minnesota) and three years (Iowa), plus the soybean area (S_b) and its interaction term with the group variable ($S_b \times$ I) (eq. 1):

$$\begin{aligned}\text{Ln}(\text{streamflow}) = {} & \beta_0 + \beta_1 P_1 + \beta_2 I + \beta_3 P_1 I \\ & + \text{K} + \beta_{10} P_5 + \beta_{11} P_5 I \\ & + \beta_{12} S_b + \beta_{13} S_b I\end{aligned} \tag{1}$$

where β_0 to β_{13} are the regression coefficients, and group variable I has a value of 1 for the pre-change period (prior to 1975) and 0 for the post-change period (after 1975). The coefficients β_2, β_4, etc., in equation 1 define the change in the intercept (β_0), whereas coefficients β_3, β_5, etc., define the change in the slope (β_1) of the line from the addition of previous years' precipitation and soybean area. The approach used in the final selection of the regression equation was a backward stepwise approach in which the variable with the highest p-value greater than $\alpha = 0.05$ (least significant) was taken out of the regression at each step. In the final regression, only variables that met the criteria $\alpha \leq 0.05$ were retained. Because the combination of explanatory variables at the start of the regression analysis may influence the selection of final variables in the regression, we also ran a sensitivity analysis with several combinations of various previous years' precipitation (5, 4, 3, or 2 years of precipitation data for Minnesota rivers and 3 or 2 years of precipitation data for Iowa rivers) plus the area under soybean production. Because the choice of the α value may also influence the selection of variables in the final regression, we also ran a sensitivity analysis using $\alpha > 0.1$ as the criterion for taking a variable out of the regression at each step.

The above regression analysis assumes (1) normal distribution of residuals and (2) homogeneity of variances. The 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. Durban-Watson statistics were also run on the regression residuals to ensure that there was no serial correlation from the inclusion of previous years' precipitation data in the regression.

Similar to the analysis on effects of current and previous years' precipitation and the area under soybean production on annual streamflow, regression analysis was also run to assess the effects of previous months' and previous years' precipitation and the area under soybean production on monthly streamflow for the Redwood River. However, no evaluation was made between the pre- and post-change periods. In this analysis, the predicted variable was the natural log of streamflow in a given month, whereas the explanatory variables were the previous year's precipitation, precipitation in a given month, precipitation in previous months, and area under soybean production in that year (eq. 2):

$$\begin{aligned}\text{Ln}(\text{SF}_{\text{GivenMonth}}) = {} & \beta_0 + \beta_1 P_{\text{PrevYear}} + \beta_2 S_b \\ & + \beta_3 P_M + \beta_4 P_{M-1} + \beta_5 P_{M-2} \\ & + \text{K} + \beta_{M-N} P_{M-N}\end{aligned} \tag{2}$$

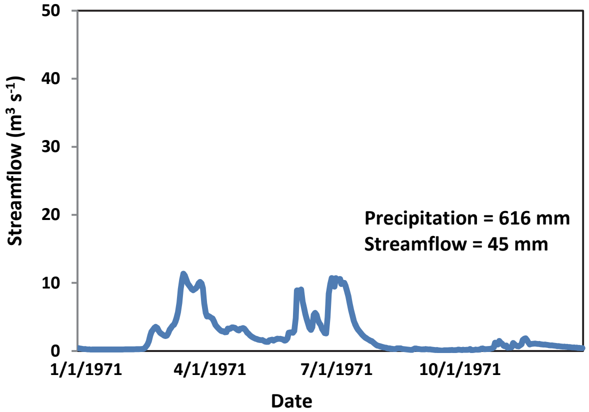
where $\text{SF}_{\text{GivenMonth}}$ is the streamflow in any given month, P_{PrevYear} is the precipitation in the previous year, S_b is the area under soybean production in the current year, P_M is the precipitation in a given month, $P_{M\text{-}1}$ is the precipitation in the month before, and $P_{M\text{-}N}$ is the precipitation in the Nth previous month. Depending on the given month, N could vary from 2 (February) to 11 (November). In other words, the regression analysis for streamflow in March had $M = 3$ and $N = 2$ (January and February). Similarly, the regression analysis for December ($M = 12$) had $N = 11$ (January through November).

The hierarchical regression approach was also used in testing the differences in high-level streamflows ($Q >$ 100 $\text{m}^3\ \text{s}^{-1}$) as well as the slope of the falling limb of daily hydrographs in May-June between the pre- and post-change periods. The slope of the daily hydrograph (dQ/dt) was defined as the difference in streamflows (Q) between the two dates $(Q_{t+1} - Q_t)/\Delta t$. The slope was recorded corresponding to precipitation on the previous day (P_t) or corresponding to average daily storm precipitation up to that day. Average daily storm precipitation was calculated by averaging the precipitation for all days prior to time t until there was a day with no precipitation (Woodward and Nagler, 1929). For the data reported in this article, the number of days in the daily storm varied from 1 to 13. Following the Foufoula-Georgiou et al. (2015) procedures, the slope data corresponding to $dQ^+/dt < 0.08\ \text{m}^3\ \text{s}^{-1}\ \text{d}^{-1}$ ($0.20\ \text{m}^3\ \text{s}^{-1}\ \text{d}^{-1}$) and $|dQ^-/dt| < 0.06\ \text{m}^3\ \text{s}^{-1}\ \text{d}^{-1}$ ($0.11\ \text{m}^3\ \text{s}^{-1}\ \text{d}^{-1}$) were excluded from the database for the pre-change (post-change) periods. Statistical testing in this study was done either with the R statistical package (R Core Team, 2016) or Excel data analysis tool (Microsoft Office 2009, Microsoft Corp., Redmond, Wash.).

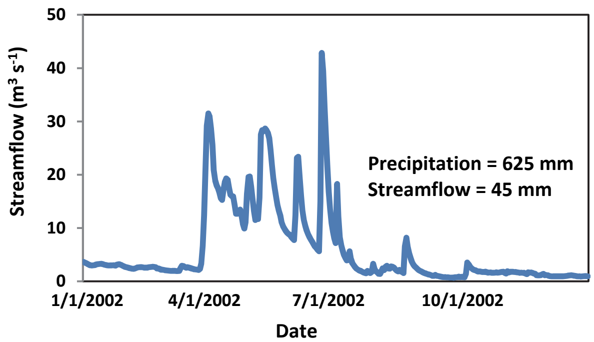
RESULTS AND DISCUSSION

ANNUAL STREAMFLOW

A comparison of daily streamflow hydrographs for 1971 and 2002 for the Redwood River in southwestern Minnesota is shown in figure 2. Although 1971 and 2002 had similar annual precipitation, annual streamflow for the Redwood River was 2.6 times (71 mm) higher in 2002 than in 1971 (table 1). Foufoula-Georgiou et al. (2015) attributed the differences in daily hydrographs and annual streamflows between these two years to increased area under tile drainage as well as increased area under soybean production, which replaced small grains in 2002 relative to 1971. The respective soybean and small grain areas were 36.9% and 1.6% of the total watershed area in 2002, compared to 15.8% and 9.0% in 1971. However, comparisons of annual precipitation for the four years prior to 1971 and 2002 showed large differences in temporal distribution between the two periods (table 1). For example, precipitation was 116 mm higher in 2001 (821 mm) than in 1970 (705 mm). Similarly, precipitation was 103 mm higher in 2000 (703 mm) than in 1969 (600 mm). Cumulatively, there was an additional 219 mm precipitation in the two years prior to 2002 relative to 1971. Some of the water from this additional precipitation was in the soil profile as stored soil water both above the drain tile (discussed later; fig. 3a) and probably below the tile at the start of 2002 and thus likely increased daily streamflow



(a) 1971

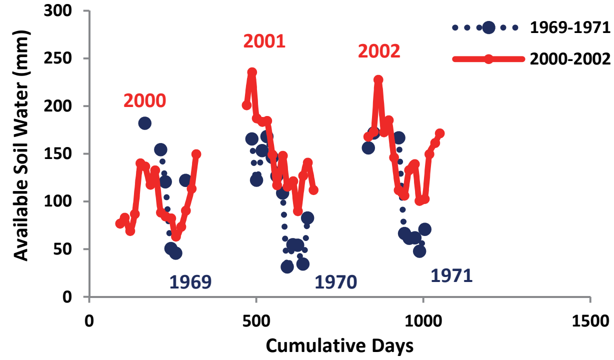


(b) 2002

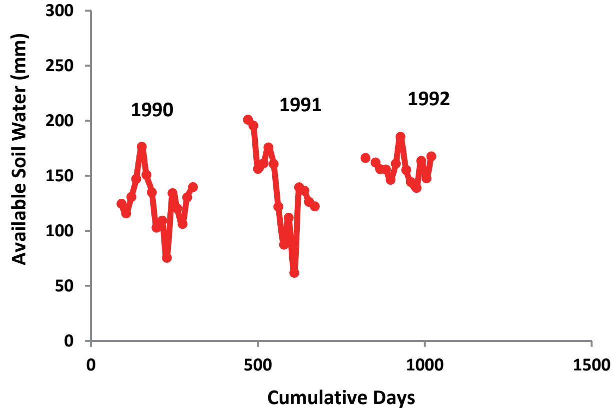
Figure 2. Comparison of daily streamflow hydrographs for the Redwood River in Minnesota for (a) 1971 and (b) 2002. Both years had similar annual precipitation, but 2.6 times greater annual streamflow was observed in 2002.

Table 1. Selected annual precipitation and streamflow for the Redwood River near Redwood Falls, Minnesota (USGS Gauge No. 05316500).

Year	Precipitation (mm)	Streamflow (mm)
1953	767	78
1954	542	41
1955	504	12
1956	629	13
1957	864	140
1967	491	40
1968	876	43
1969	600	182
1970	705	49
1971	616	45
1976	340	16
1977	923	44
1987	541	56
1988	476	23
1989	515	29
1990	666	35
1991	855	125
1992	665	99
1998	673	100
1999	557	96
2000	703	40
2001	821	210
2002	625	116



(a)



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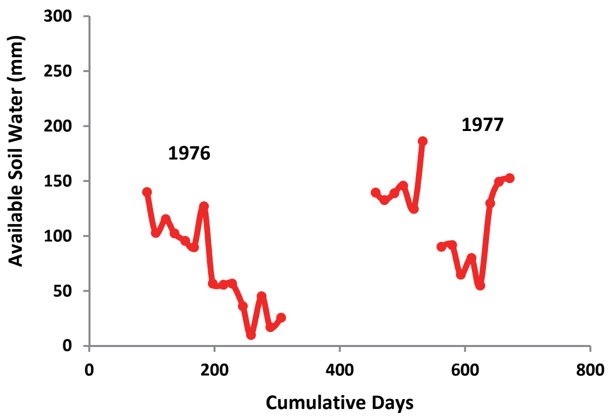


(c)

Figure 3. Comparisons of plant-available soil water in 1.5 m soil profile (a) for 1969 vs. 2000, 1970 vs. 2001, and 1971 vs. 2002; (b) among 1990, 1991, and 1992; and (c) for 1976 vs. 1977 at Lamberton, Minnesota, in the Cottonwood River watershed neighboring the Redwood River watershed. In (a), day 1 starts on 1 January 1969 for 1969-1971 data and on 1 January 2000 for 2000-2002 data. In (b), day 1 starts on 1 January 1990. In (c), day 1 starts on 1 January 1976.

through reduced fillable soil porosity, resulting in more overland flow and higher baseflow. Hoogestraat and Stamm (2015) showed upward trends in groundwater levels in eastern South Dakota bordering Minnesota from 1985-2014, thus supporting the above assertion of increased stored soil water below the tile depth from increased precipitation in the post-change period.

Evidence of increased stored soil water in 2000-2002 relative to 1969-1971 is shown in a plot of the measured plant-available soil water at the Southwest Research and Outreach Center at Lamberton, Minnesota (fig. 3a). Lamberton lies near the center of the Cottonwood River watershed, a watershed neighboring the Redwood River watershed (fig. 1). The data in figure 3a show that 219 mm of additional precipitation in the previous two years (2000-2001) in the Redwood River watershed (266 mm at the experimental site in Lamberton, Minn.) resulted in higher stored soil water in 2001 and 2002 compared to 1970 and 1971. Because a large portion of streamflow is from baseflow (i.e., slow flow moving through the deep soil profile), a portion of the stored soil water from additional precipitation in previous years was likely present in the streamflow in subsequent years (Hoogestraat and Stamm (2015). Thus, the higher soil wetness from previous years' high precipitation in 2000 and 2001 likely resulted in more runoff to streams. For the Redwood River, baseflow represented an average of 71% of streamflow, with a standard deviation of 9%, from 1936 to 2009. The above analyses suggest that increased precipitation, not only in a given year but also in previous years, was important in determining the changes in daily (fig. 2) and annual (table 1) streamflows in the upper Midwestern U.S.

Hierarchical Regression Analysis of Annual Streamflow and Baseflow

Means and standard deviations of Q, P_1, P_2, P_3, P_4, P_5, and S_b for the Redwood River in the pre- and post-change periods are summarized in table 2. The mean and standard deviation of streamflow in the post-change period were each about double the value in the pre-change period. Not only were the means of P_1 through P_5 higher, there was also greater variability (standard deviations) associated with these values. The mean area under soybean production was much higher in the post-change period than in the pre-change period; however, a greater standard deviation was associated with the pre-change area under soybean production.

The p-values of five, four, three, or two years' precipitation plus the area under soybean production as explanatory variables of Ln(Q) for the Redwood River are listed in table 3. The corresponding R^2 values for these regressions were 0.67, 0.67, 0.66, and 0.65. Irrespective of the combination of variables in the regression at the start (table 3), the three significant variables in the final regression (eq. 3) for the Redwood River were P_1, P_2, and S_b:

$$\text{Ln}(Q) = -0.621 + 0.0040P_1 + 0.0030P_2 + 6.19\text{E-}06S_b \quad (3)$$

$$(R^2 = 0.63)$$

The corresponding p-values of these variables were 3.3E-11, 1.5E-07, and 0.036, respectively. Much lower p-values for precipitation relative to area under soybean production highlight the power of precipitation as the main variable in determining Ln(Q). An analysis similar to table 3 was also run for the other three rivers in Minnesota and the two rivers in Iowa. Again, irrespective of the starting variables in the regression, the significant variables in the final regression for a given river were the same.

The above regression (eq. 3) shows that streamflow in the Redwood River in any given year is influenced not only by the precipitation in that year but also by the precipitation in the previous year. This regression supports the conclusion drawn above in figure 2 that higher daily and annual flows in 2002 relative to 1971 were from additional precipitation received in previous years (2000-2001). The previous year precipitation effects were primarily due to increased stored soil water, not only in the soil above tile drains (fig. 3a) but also below tile drains to groundwater (Hoogestraat and Stamm, 2015; Schuh, 1999). The effect of increased stored water above the drains likely resulted in reduced fillable soil porosity and less time to ponding and thus increased overland flow to streams. Comparatively, the effect of increased stored water below the drains likely increased percolation and thus increased baseflow to streams. These effects of antecedent soil wetness on overland flow and deep percolation have been well documented in the literature both at plot scale (Mannering and Meyer, 1961; Moldenhauer and Kemper, 1969; Freebairn et al., 1989; Kemper and Bongert, 2012) and small catchment scale (Meyles et al., 2003, Peters et al., 2003; James and Roulet, 2009). These effects of antecedent moisture conditions have also been incorporated into various runoff simulating tools, such as the NRCS Curve Number method (SCS, 1972).

The presence of area under soybean production in the above regression (eq. 3) also suggests some significant effect

Table 2. Means and standard deviations of streamflow (Q), annual precipitation in current year (P_1), annual precipitation one year prior (P_2), annual precipitation two years prior (P_3), annual precipitation three years prior (P_4), annual precipitation four years prior (P_5), and annual area under soybean production (S_b) in the Redwood River watershed for the pre-change (1941-1975) and post-change (1976-2009) periods.

Period	Q (mm)	P_1 (mm)	P_2 (mm)	P_3 (mm)	P_4 (mm)	P_5 (mm)	S_b (ha)
1941-1975	61 (43)	626 (110)	628 (109)	632 (105)	634 (104)	632 (103)	19,364 (13,455)
1976-2009	121 (92)	683 (148)	681 (149)	675 (155)	669 (156)	672 (155)	59,913 (8,201)

Table 3. The p-values of precipitation in a given year (P_1), precipitation in the previous one to four years (P_2, P_3, P_4, and P_5), area under soybean (S_b) production, and their interaction with group (I) for explaining the variation in Ln(streamflow) at the start of the regression analysis for the Redwood River in southwestern Minnesota. Interaction (I) has a value of 1 for the first group, i.e., the pre-change period (1941-1975), and a value of 0 for the second group, i.e., the post-change period (1976-2009).[a]

I	P_1		P_2		P_3		P_4		P_5		S_b	
β_2	β_1	β_3	β_4	β_5	β_6	β_7	β_8	β_9	β_{10}	β_{11}	β_{12}	β_{13}
0.2	0.00001	0.81	0.0002	0.81	0.42	0.12	0.98	0.42	0.47	0.73	0.32	0.33
0.17	0.000006	0.67	0.0002	0.92	0.3	0.08	0.93	0.4			0.22	0.24
0.32	0.000002	0.73	0.0001	0.93	0.29	0.13					0.21	0.22
0.78	0.0000006	0.7	0.0002	0.67							0.1	0.13

[a] Ln(streamflow) = $\beta_0 + \beta_1P_1 + \beta_2I + \beta_3P_1I + \beta_4P_2 + \beta_5P_2I + ... + \beta_{10}P_5 + \beta_{11}P_5I + \beta_{12}S_b + \beta_{13}S_bI$.

of LULC change on Ln(Q) for the Redwood River. A comparison of the R^2 values of regressions with and without soybean area in equation 3 showed that area under soybean production explained a little over 3% of the variability in Ln(Q) for the Redwood River. This is also reflected in a much higher p-value ($p = 0.036$) for the area under soybean production relative to the p-values of precipitation (P_1 and P_2). In other words, the power of the LULC change (area under soybean production) to explain Ln(Q) variability was much weaker than that of precipitation. Schilling (2005) showed a similar p-value ($p = 0.03$) for the relationship between increase in baseflow and increase in row crop fraction for nine Iowa watersheds. A comparison of R^2 values from regressions with only P_1 or with P_1 and P_2 also showed that previous year precipitation (P_2) explained 24% of the variability in Ln(Q) for the Redwood River. The absence of a significant group term in equation 3 suggests no difference in the Ln(Q) relationship with P_1, P_2, and S_b between the pre-change (1941-1975) and post-change (1976-2009) periods for the Redwood River.

The above regression analysis was also run for the other three rivers in Minnesota and the two rivers in Iowa (table 4). The corresponding values of the regression coefficients and associated standard errors at $\alpha \le 0.05$ are given in table A1 in the Appendix. Again, the regression analysis for the rivers in Minnesota was run with five years of precipitation data plus soybean area as explanatory variables, whereas the regression analysis for the Iowa rivers was run with three years of precipitation and soybean area as explanatory variables. Only the Blue Earth River in Minnesota and the Maquoketa River in Iowa showed an effect of current and two previous years' precipitation on annual streamflow (table 4). For the other four rivers, precipitation effects were limited to the current year and one previous year precipitation. Except for the Raccoon River in Iowa, there was no significant presence of the group term or its interactions with precipitation (P_1, to P_5 or P_3) and the area under soybean production in the regression relationships. This suggests no difference in the relationship of Ln(Q) with significant variables between the two periods for the Blue Earth River, Cottonwood River, Redwood River, and Whetstone River in Minnesota and the Maquoketa River in Iowa. Only the North Raccoon River in Iowa showed a group effect, i.e., a separate relationship of Ln(Q) with significant variables between the two periods (table 4). The presence of a group effect in the Ln(Q) regression equations for the North Raccoon River could be due to different combinations of P_1 and P_2 between the two periods. The lower R^2 values of the Ln(Q) regression for the Whetstone River reflect greater variability in streamflow, which may be a result of greater variability in the timing and intensity of precipitation events relative to crop growth stage between various years. The timing and intensity effects of precipitation and their interactions with crop growth stage will likely be more dominating in (1) drier than wetter watersheds and (2) drier than wetter periods. Thus, because the Whetstone River watershed is in a drier region (South Dakota bordering southwestern Minnesota), it will be more susceptible to variation in the timing of precipitation events relative to crop growth stage than a watershed in southern or eastern Minnesota, which are wetter regions.

The relationships between annual streamflow and current year precipitation (P_1) and between the five-year moving averages of annual streamflow and P_1 are shown in figures 4a and 4b, respectively. Considering the water balance equation ($P_1 = ET + Q + \Delta S$), the scatter in the Q-P_1 relationship (fig. 4a) includes the annual variation in ET and the change in soil water storage (ΔS). Over a long period, we can assume that ΔS is negligible compared to the other terms in the water balance equation. Although five years is not a long period, averaging over time helps minimize the variation in ΔS between years and thus smooths the relationship between streamflow and precipitation (fig. 4b). The clustering of average streamflow at higher average precipitation levels in the post-change period for the Redwood River (fig. 4b) shows that increased streamflow in the post-change period was mainly due to higher precipitation. Plots of five-year moving averages of streamflow as a function of precipitation for the Blue Earth River, Cottonwood River, and Whetstone River in Minnesota and the Maquoketa River and North Raccoon River in Iowa were similar to those for the Redwood River (fig. A1 in the Appendix), i.e., increased streamflow in the post-change period was mainly driven by increased precipitation.

A hierarchical regression analysis of the natural log of baseflow, Ln(Q_b), for the Redwood River in Minnesota and the North Raccoon River in Iowa showed the same significant variables (table 5) as in their respective streamflow analyses (table 4). The corresponding values of the regres-

Table 4. The p-values of precipitation in a given year (P_1), two previous years (P_2, P_3), and area under soybean production (S_b) for explaining the variation in Ln(streamflow) for four rivers in Minnesota and two rivers in Iowa.[a]

	State	River	Gauge No.	Area (km²)	Years of Record	p-Value β_1	β_2	β_3	β_4	R^2
$\alpha \le 0.05$	Minnesota	Blue Earth	5320000	6,242	1950-2009	3E-10	2E-09	0.012	0.034	0.73
		Cottonwood	5317000	3,367	1943-2002	9E-13	1E-09	-	-	0.69
		Redwood	5316500	1,629	1941-2009	3E-11	1E-07	-	0.036	0.63
		Whetstone	5291000	1,030	1936-2009	2E-08	2E-06	-	-	0.48
	Iowa	Maquoketa	5418500	4,022	1918-2009	<2E-16	1E-11	6E-04	-	0.77
		North Raccoon	5484500	8,912	1926-1975	7E-10	8E-09	-	-	0.68
					1976-2009	1E-09	0.0031	-	-	0.73
$\alpha \le 0.10$		Cottonwood	5317000	3,367	1943-1975	2E-05	0.0006	-	-	0.54
					1976-2002	6E-07	1E-05	-	0.08	0.80
		Whetstone	5291000	1,030	1936-1975	0.0004	0.0066	-	-	0.35
					1976-2009	7E-05	0.0002	-	-	0.56
		Maquoketa	5418500	4,022	1918-1975	1E-12	1E-08	0.02	-	0.73
					1976-2009	6E-11	0.0002	0.008	-	0.84

[a] $\mathrm{Ln(streamflow)} = \beta_0 + \beta_1 P_1 + \beta_2 P_2 + \beta_3 P_3 + \beta_4 S_b$.

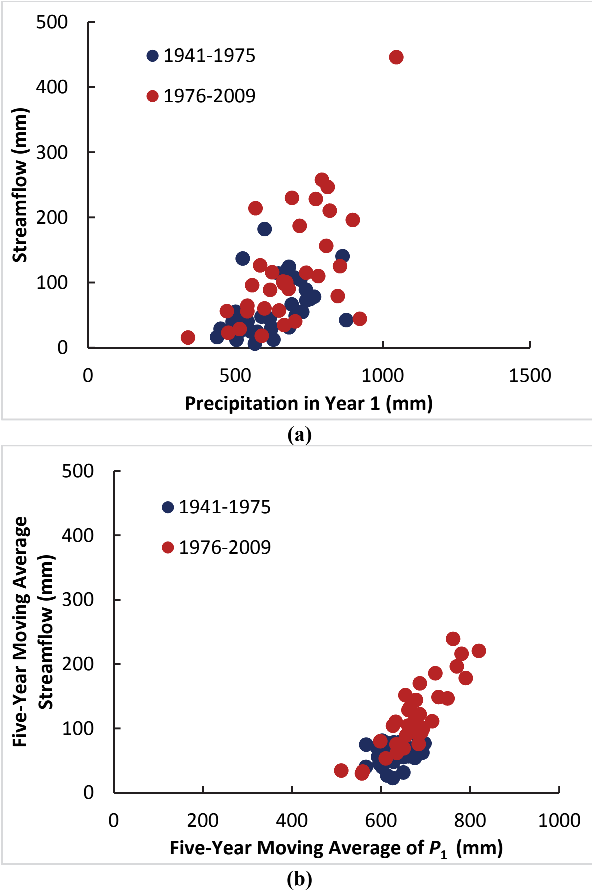


Figure 4. Relationships between (a) annual streamflow and first-year precipitation (P_1) and (b) five-year moving average streamflow and five-year moving average of first-year precipitation for the Redwood River in Minnesota.

sion coefficients and associated standard errors at $\alpha \leq 0.05$ are given in table A2 in the Appendix. The final baseflow regression for the Redwood River (eq. 4) was:

$$\mathrm{Ln}(Q_b) = -1.056 + 0.0037P_1 + 0.0033P_2 + 7.1\mathrm{E}\text{-}06S_b \quad (4)$$

$$(R^2 = 0.64)$$

A regression analysis similar to equation 4 but without soybean area resulted in an R^2 value of 0.60, thus suggesting that soybean area explained 3.3% of the variability in annual baseflow for the Redwood River. This low power for the area under soybean production is reflected in its higher p-value (p = 0.018) relative to the precipitation variables (p = 3E-10 for P_1 and p = 1E-08 for P_2) in the regression.

Sensitivity analyses on the choice of α (≤0.05 or ≤0.1) for keeping a variable in the stepwise streamflow regression showed no difference in the significant variables, in their p-values, nor in the R^2 value of the final regression for the Blue Earth River and Redwood River in Minnesota and the North Raccoon River in Iowa. However, use of $\alpha \leq 0.1$ caused the group term or its interaction with the P_1, P_2, or S_b terms to be significant for the Cottonwood River and Whetstone River in Minnesota and the Maquoketa River in Iowa, thus resulting in a different relationship for the pre-change and post-change periods (table 4). Similar divergence in relationships for the pre- and post-change periods occurred for Redwood River baseflow; however, the area under soybean production was not a significant variable for the pre-change period (table 5). Because 1941-1975 was a drier period relative to 1976-2009, the lower R^2 value for Redwood River baseflow in table 5 may also be a reflection of greater variability in the timing of precipitation events relative to crop growth stage. Irrespective of the significant probability criteria (α-value), the p-values in tables 4 and 5 showed that precipitation (P_1, P_2, and in some watersheds P_3) was much more powerful in explaining the variability in the natural log of streamflow and baseflow than the area under soybean production. For the six rivers discussed in this study (tables 4 and 5), the Durban-Watson test did not show a serial correlation in multiple regression tests using the annual data.

Carryover Precipitation Effects on Annual Streamflow

Another example of carryover precipitation effects on increased stored soil water was demonstrated in the comparison of streamflow between 1990 and 1992 (table 1). In both of these years, precipitation was about the same (666 mm vs. 665 mm), but streamflow was 64 mm (about three times) higher in 1992 than in 1990. Cropping system and length of drain tile in the basin were likely the same or similar from 1990 to 1992. The three-fold increase in streamflow in 1992 was mainly because there was 190 mm of additional precipitation in 1991 over the average for 1990 and 1992 (table 1). This increased precipitation in 1991 likely led to more stored soil water in 1992 (fig. 3b), which in turn increased the annual streamflow and baseflow, both through more percolation and overland flow.

Carryover precipitation or stored soil water effects on streamflow were also manifested when the previous years were drier than the current year. One such example is a comparison of streamflows in 1976 and 1977 (table 1). Precipitation was 2.7 times (583 mm) higher in 1977 than in 1976, but there was a small difference (28 mm) in streamflow between these two years. This minimal difference in streamflow between 1976 and 1977 was driven by a drought in 1976, which created substantial fillable soil storage both in the root zone (fig. 3c) and below to hold water from a very wet 1977. For example, available soil water on 1 November

Table 5. The p-values of precipitation in a given year (P_1), two prior years (P_2, P_3), and area under soybean production (S_b) for explaining the variation in Ln(baseflow) for the Redwood River in Minnesota and the North Raccoon River in Iowa.[a]

	State	River	Gauge No	Area (km²)	Years of Record	p-Value β1	β2	β3	β4	R^2
$\alpha \leq 0.05$	Minnesota	Redwood	5316500	1,629	1941-2009	3E-10	1E-08	-	0.0176	0.64
	Iowa	North Raccoon	5484500	8,912	1926-1975	2E-10	2E-11	-	-	0.74
					1976-2009	7E-09	0.0004	-	-	0.72
$\alpha \leq 0.10$		Redwood	5316500	1,629	1941-1976	0.0005	0.0011	-	-	0.42
					1976-2009	6E-07	9E-06	-	0.01	0.74

[a] $\mathrm{Ln(baseflow)} = \beta_0 + \beta_1 P_1 + \beta_2 P_2 + \beta_3 P_3 + \beta_4 S_b$.

1976 was only 26 mm, compared to 153 mm on 1 November 1977 (fig. 3c). This means that 127 mm of the water in the 152 cm of the soil profile never contributed to streamflow in 1977. Potentially, these soils can hold as much as 533 mm of non-drainable water (field capacity) in 152 cm of the soil profile (Baker et al., 1979). The extent of drain tile, as well as the distribution of crop acreage, was likely similar between 1976 and 1977. This example shows that the presence of drain tile by itself does not increase streamflow. Instead, the stored soil water or fillable soil water storage for subsequent precipitation events above and below the drain tile determines the magnitude of drainage and overland flow in response to precipitation. If precipitation in 1977 (923 mm) was the only factor affecting streamflow, and available water storage was not involved, then there would have been close to 150 mm of streamflow (best-fit curve) rather than 44 mm.

The above examples of individual year streamflow comparisons in table 1 show that the assumption of attributing annual streamflow to annual precipitation is not sufficient, and there are effects of previous year precipitation on stored soil water that influence a given year's streamflow. These examples also show that the presence of subsurface drain tile by itself does not take the water out of the landscape; instead, the stored soil water above the drain tiles determines whether or not drainage will occur from subsequent precipitation events.

Land Use and Land Cover Change Impacts on Annual Streamflow

The above examples also suggest the need to compare annual streamflows for years with similar annual precipitation, not only in a given year but also in previous years, when evaluating LULC effects on streamflow and baseflow between the pre- and post-change periods. This is mainly to ensure that the stored soil water conditions are similar. An example of such a comparison for the Redwood River in southwestern Minnesota is 1957 (pre-change) compared to 1991 (post-change). Annual precipitation amounts (864 mm in 1957 and 855 mm in 1991) were similar not only in these two years but also in the two or three prior years (table 1). Considering that the stored soil water was likely similar in 1957 and 1991, the comparison of annual streamflows showed similar values (140 mm vs. 125 mm) for these years. This similarity in annual streamflows, despite the likely significant increase in the extent of drain tile installation in the Redwood River watershed from 1957 to 1991 and that the soybean area was nearly 3 times greater in 1991 (61,361 ha; 37.7% of total area) than in 1957 (21,466 ha; 13.2% of total area), suggests a dominant effect of increased precipitation and minimal effects of LULC changes on annual streamflow. A minimal effect of increased area under soybean production on annual streamflow is also consistent with the above regression analysis (eq. 3), which showed that the area under soybean production explained only 3.3% of the variability in Ln(Q). The small difference (15 mm) in streamflow between 1991 and 1957 is likely a reflection of the natural variability in precipitation events (i.e., timing and intensity) relative to crop growth stage between the years.

Backward Stepwise Regression Analysis of Monthly Flow

The p-values of significant variables in the regression describing Ln(monthly Q) for the Redwood River from March to December are reported in table 6. The corresponding values of the regression coefficients and associated standard errors are given in table A3 in the Appendix. Except for March and April, the R^2 values of all the remaining monthly regressions were above 0.7 (table 6). For all months from March to November, previous year precipitation was a significant variable in explaining the natural log of monthly streamflow. The strength of the previous year's precipitation in explaining streamflow variability was large in May and decreased over time until November, after which it was not significant. Although the previous year's precipitation was a significant variable in March and April, its strength was not as high as in May. This may be because precipitation in March and April is not always in liquid form, and much of it quickly runs off due to variable frozen soil conditions. In other words, the contribution of precipitation to streamflow in these months is much more important than the precipitation from the previous year. The effect of previous year precipitation in November was relatively weak ($p = 0.01$), and there was no effect of previous year precipitation on streamflow in December. Considering the annual cycle, it is likely that the previous year's precipitation had drained out of the soil profile or was taken up by plants by November, resulting in a weak to no impact on November and December streamflows in this watershed.

Except for December, the precipitation in any given month was a significant variable in explaining the natural log of monthly streamflow (table 6). Although January precipitation was a significant variable in explaining streamflow in April, May, July, September, and November, its strength was relatively small ($p = 0.01$ to 0.00001) compared to some

Table 6. The p-values of precipitation in various months and in the previous year, along with area under soybean production (S_b), as significant variables explaining the variation in Ln(streamflow) for the Redwood River at Redwood Falls, Minnesota (gauge 05316500) from 1941-2009.[a]

Streamflow	Precipitation Month											Previous	S_b	
Month	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Year	Area	R^2
Mar.	-	-	0.04	-	-	-	-	-	-	-	-	2E-04	-	0.22
Apr.	4E-06	-	2E-04	2E-04	-	-	-	-	-	-	-	3E-05	-	0.54
May	1E-05	-	6E-05	7E-08	1E-08	-	-	-	-	-	-	2E-10	-	0.71
June	-	-	-	-	5E-10	<2E-16	-	-	-	-	-	1E-07	1E-08	0.8
July	3E-03	-	-	0.05	3E-04	6E-12	4E-07	-	-	-	-	7E-06	3E-03	0.76
Aug.	-	-	-	-	0.03	9E-08	9E-11	3E-06	-	-	-	2E-04	3E-05	0.75
Sept.	0.05	-	-	-	0.018	9E-08	2E-09	8E-09	5E-11	-	-	2E-04	1E-04	0.82
Oct.	-	-	0.01	-	-	9E-05	1E-08	5E-06	1E-11	7E-11	-	1E-03	6E-05	0.83
Nov.	0.01	-	-	-	0.01	1E-03	5E-06	6E-04	5E-07	4E-13	-	0.01	2E-06	0.81
Dec.	-	0.05	-	-	0.03	5E-04	1E-04	7E-04	2E-06	1E-09	1E-03	-	5E-10	0.81

[a] $\mathrm{Ln}(SF_{GivenMonth}) = \beta_0 + \beta_1 P_{Jan} + \beta_2 P_{Feb} + \beta_3 P_{Mar} + \beta_4 P_{Apr} + \beta_5 P_{May} + \ldots + \beta_{12} P_{Dec} + \beta_{13} P_{PrevYear} + \beta_{14} S_b$.

other variables in the regression (table 6). The exception was the month of April. For most months, the previous months' precipitation (going back two or more months) was a significant variable in explaining streamflow variability. Except for December streamflow, February precipitation was not a significant variable in predicting monthly streamflow. Precipitation in December was also not a significant variable because precipitation in December is most often in solid form (snow), stays in place, and does not contribute to streamflow until sometime in late winter or early spring. Typically, soils in Minnesota are frozen from December through March; however, the frozen period may extend by two weeks to a month on either end (Pokorny, 1993). In Iowa, the frozen period may be about two weeks shorter.

Soybean area was a significant variable in explaining monthly streamflow from June to December for the Redwood River (table 6). Furthermore, the strength of this variable ($p = 0.003$ to 5E-10) generally increased with time from July to December. The exception was September, when the p-value for soybean area, being significant, slightly decreased ($p = 0.0001$). Because soybean crops start senescing in mid-September and are often harvested by late October, evapotranspiration losses and their effect on stored soil water will be minimal from September onward. Thus, it is not apparent why the area under soybean production was a significant variable in streamflow regression from September through December. Overall, the monthly regression analysis also showed that precipitation was the main driver of change in monthly streamflow.

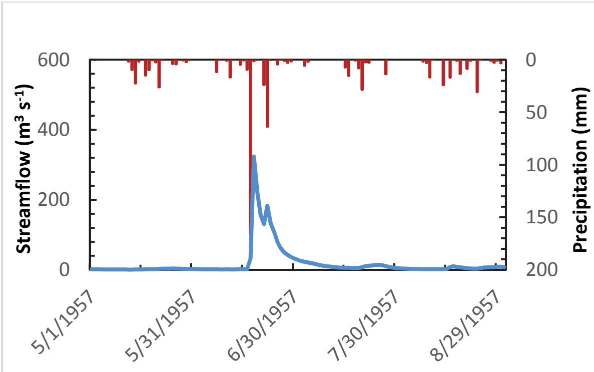
Daily Streamflow

In their analysis, Foufoula-Georgiou et al. (2015) assumed that the daily slope of the rising limb of the hydrograph was exclusively related to previous day precipitation and there was no carryover effect from prior precipitation events. Below, we show that this assumption does not hold, and the slope of the rising limb is influenced not only by the previous day precipitation but also by earlier precipitation events in the sequence. This effect of previous precipitation events is likely through changes in stored soil water even in tile-drained watersheds. Table 7 lists the daily precipitation, daily streamflow, and daily slope of the hydrograph for the Redwood River for 14 to 22 June 1993. The slopes of the rising limb were 83.7 $m^3 s^{-1} d^{-1}$ for daily rainfall of 23.9 mm on 16 June, 90.8 $m^3 s^{-1} d^{-1}$ for daily rainfall of 126.4 mm on 17 June, and 132.8 $m^3 s^{-1} d^{-1}$ for daily rainfall of 7.8 mm on 18 June. These calculations assume that each day's precipitation independently caused the increase in the slope of the rising limb. However, the higher slope of the rising limb on 18 June cannot be solely attributed to 7.8 mm precipitation and likely had some carryover effect from the 150 mm of rainfall on 16-17 June through increased stored soil water and in turn greater runoff on 18 June. Similarly, the data for 15 June show a rise in the slope of the hydrograph even when there was no precipitation. This raises the question: should the slope correspond to the previous day (t) or the present day (t+1)? Woodward and Nagler (1929) minimized this problem by using average daily precipitation over the storm period. They also minimized the differences in stored soil water between the pre- and post-change periods by analyzing the slopes of hydrographs when soils were saturated, i.e., flood conditions. Using a Woodward and Nagler (1929) type approach, we show that the slopes of the rising limb of the hydrograph at high precipitation levels (1957 and 1993) were higher in the pre-change period than in the post-change period, i.e., with less watershed connectivity due to LULC changes such as drainage, a finding that is contrary to what has been suggested in the literature. Similarly, comparing the slopes of the hydrograph's falling limb for similar-size precipitation (or streamflow) events in the pre-change (1947) and post-change (1991) periods or for two different groups of slopes, we show similar slope values, thus suggesting no change in storage capacity of the watershed as a result of LULC changes.

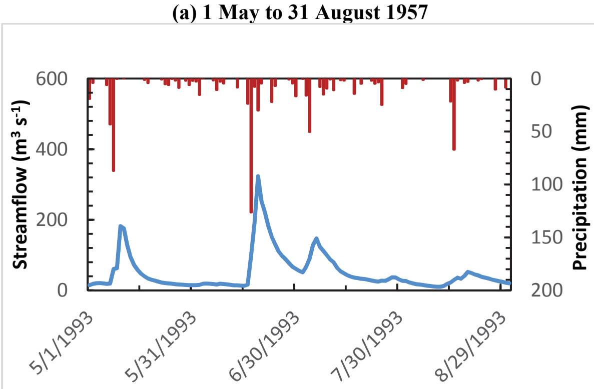
Table 7. Daily precipitation, streamflow, and slope of the rising and falling limbs of the Redwood River hydrograph for 14-22 June 1993.

Date	Precipitation (mm)	Streamflow ($m^3 s^{-1}$)	Slope of Rising and Falling Limbs ($m^3 s^{-1} d^{-1}$)
14 June	0	13.6	-0.6
15 June	0	13.0	3.2
16 June	23.9	16.2	83.7
17 June	126.4	99.9	90.8
18 June	7.8	190.7	132.8
19 June	30.1	323.5	-69
20 June	4.6	254.5	-32.9
21 June	0	221.6	-39.2
22 June	0	182.4	-31.2

As noted by Woodward and Nagler (1929), no two storms are the same. Thus, finding two similar periods, both with similar daily precipitation as well as similar initial soil wetness conditions in the pre- and post-change periods, is rather difficult. One of the ways to overcome these differences may be to select periods of maximum daily precipitation; hopefully, these high precipitation events will minimize the differences in soil wetness conditions between the two periods. Two examples of such high precipitation events in the pre- and post-change periods were storms on 17 June 1957 and 17 June 1993 (fig. 5). The corresponding precipitation of these two events was 166 and 126 mm. There were small precipitation events prior to both of these two events. The total precipitation of these small events was 15 mm on 14-16 June 1957 and 24 mm on 16 June 1993. The total precipitation in the corresponding prior years (1956 and 1992) was 660 and 745 mm, respectively. Precipitation for January through May was 111 mm for 1957, compared to 146 mm for 1993. These precipitation statistics suggest that June 1957 was relatively drier than June 1993, but the large precipitation event in 1957 likely minimized the soil wetness difference and its effect on streamflow. For the two events under discussion (17 June 1957 and 17 June 1993), the increase in the slope of the daily hydrographs occurred for two days in 1957 and for three days in 1993 (fig. 5). For these events, the highest slopes of the rising limb were 291 $m^3 s^{-1} d^{-1}$ on 17-18 June 1957 and 133 $m^3 s^{-1} d^{-1}$ on 18-19 June 1993. The slower rise in the hydrograph in the post-change period for a large spring precipitation event suggests less watershed connectivity from LULC changes (i.e., tile drainage and adoption of soybeans) in the post-change period. This is contrary to what has been suggested in the literature for LULC change impacts. Other possible reasons for the higher daily slope of the rising limb in the pre-change period may

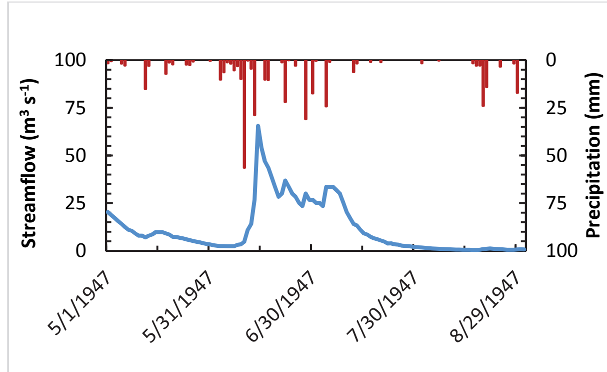


(a) 1 May to 31 August 1957

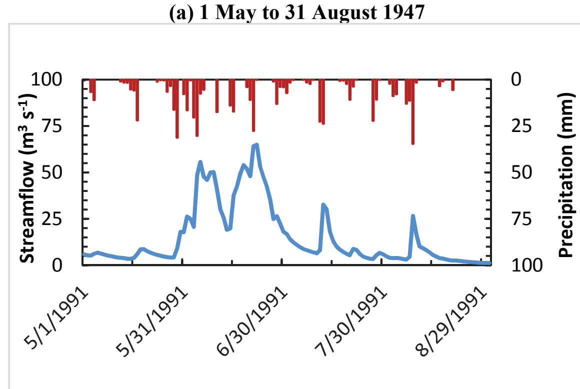


(b) 1 May to 31 July 1993

Figure 5. Comparison of daily hydrographs of the Redwood River, Minnesota, for large June events in the (a) pre-change (17 June 1957) and (b) post-change (17 June 1993) periods.



(a) 1 May to 31 August 1947



(b) 1 May to 31 August 1991

Figure 6. Comparison of daily hydrographs of the Redwood River, Minnesota, showing similar slopes of the falling limb for similar flow conditions on (a) 14 June 1947 (pre-change period) and (b) 23 June 1991 (post-change period).

be (1) slightly higher precipitation in June 1957 (166 mm) than in June 1993 (126 mm) and/or (2) differences in precipitation intensity between the two events.

A similar comparison of the slopes of the falling limb on days with no precipitation was made between the pre-change (14 June 1947) and post-change (23 June 1991) periods (fig. 6). The selection of these dates was based on nearly similar precipitation one to two days before, i.e., 29 mm on 13 June 1947, 28 mm on 21 June, and 0.1 mm on 22 June 1991. Precipitation totaling 99 mm occurred over ten days prior to 13 June 1947. Comparatively, there was only 15 mm precipitation over two days prior to 21 June 1991. Cumulative precipitation from 1 January to 30 April was 166 mm in 1947 and 172 mm in 1991. Precipitation in previous years corresponded to 740 mm in 1946 and 695 mm in 1990. The falling limb of the hydrographs for these two precipitation events started on 14 June 1947 and on 22 June 1991 (fig. 6). The streamflows (54 $m^3\ s^{-1}$ vs. 53 $m^3\ s^{-1}$) and slopes of the falling limb (-11.4 $m^3\ s^{-1}\ d^{-1}$ vs. -11.9 $m^3\ s^{-1}\ d^{-1}$) for 14 June 1947 and 23 June 1991 were similar, thus suggesting similar retentive capacity in the pre- and post-change periods.

Because high water levels in a river are determined not only by the precipitation in the watershed on any given day but also by previous precipitation history (table 7), we used the Woodward and Nagler (1929) approach of averaging daily storm intensity and compared May-June high-level streamflows ($Q > 100\ m^3\ s^{-1}$) as a function of average storm intensity between the pre- and post-change periods (fig. 7). The reason for comparing high-level streamflows instead of the slope of the rising limb of the hydrograph, as in the

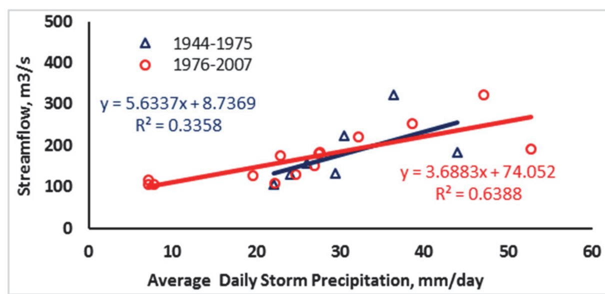
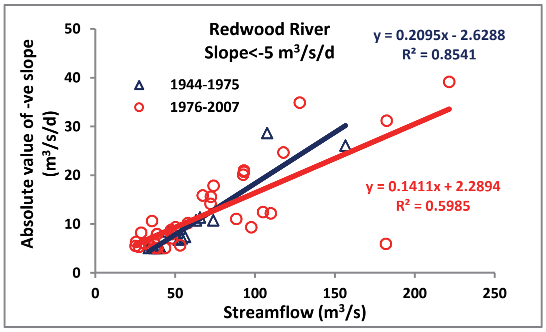
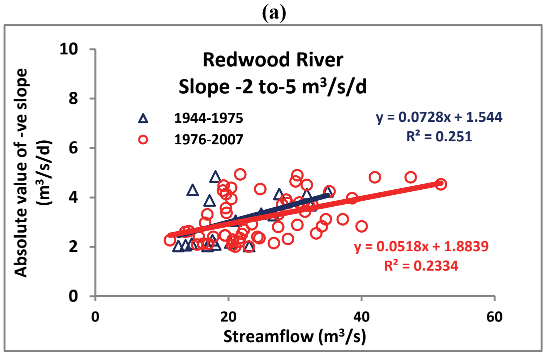


Figure 7. Comparison of high-level streamflows ($Q > 100\ m^3\ s^{-1}$) as a function of average daily storm precipitation for the pre-change and post-change periods in the Redwood River watershed.

Woodward and Nagler (1929) analysis, was due to the lack of enough high-precipitation events in the pre-change period. There was only one high-precipitation event in the pre-change period (17 June 1957) and four high-precipitation events in the post-change period (28 April to 7 May 1983, 14-22 June 1984, 5-9 May 1993, and 16-20 June 1993). The high-level streamflow data ($Q > 100\ m^3\ s^{-1}$) for the above dates resulted in six data points for the pre-change period (all occurring in June 1957) and 14 data points in the post-change period (mainly associated with the June 1993 event). Storm periods varied from one to seven days for the pre-change data points and from three to ten days for the post-change data points. There was no difference in high-level streamflows ($Q > 100\ m^3\ s^{-1}$) at a given average daily storm precipitation between the two periods (fig. 7), thus indicating no effect of drainage modifications on high-level stream-



(a)



(b)

Figure 8. Comparison of absolute values of the negative slope of daily hydrographs in May and June with no precipitation between the pre-change (1944-1975) and post-change (1976-2007) periods for Redwood River, Minnesota, for (a) all falling limb slopes less than -5 m^3 s^{-1} d^{-1} and (b) all falling limb slopes between -2 and -5 m^3 s^{-1} d^{-1}.

flows between the pre-drainage and post-drainage periods in the Redwood River watershed. This comparison also helps to demonstrate the value of averaging precipitation over the storm period rather than assigning increased streamflow to a given day's precipitation, as in table 7.

Similar to the Woodward and Nagler (1929) analysis for the falling limb of the hydrograph, we also found no statistical difference in the absolute slope of the falling limb as a function of streamflow between the two periods (fig. 8). The comparisons were for two groups of slopes: <-5 m^3 s^{-1} d^{-1} and -2 to -5 m^3 s^{-1} d^{-1}. This again suggests no difference in the retentive capacity of the Redwood River watershed between the pre- and post-change periods. This lack of difference in retentive capacity between the two periods may be due to balancing of the increased fillable soil porosity from tile drainage (Kemper and Bongert, 2012; Kemper et al., 2012) in the post-change period along with higher evapotranspiration (ET) resulting from replacement of small grains (ET ~350 mm), hay (ET ~250 mm), potholes and wetlands (ET ~0 to 800 mm), and cool-season prairies in the pre-change period with corn and soybean (ET ~500 to 650 mm) in the post-change period (Gupta et al., 2015).

Conclusions

Recent increased streamflow and its associated impacts on water quality have frequently been linked to LULC changes, such as increased tile drainage, cultivation of prairies, and adoption of soybean in modern-day cropping systems. Using backward stepwise regression analysis, we showed that recent increases in annual streamflow and baseflow in the upper Midwestern U.S. were mainly due to increased precipitation, not only in a given year but also during the preceding two to three years. This effect was mainly manifested through increased stored soil water, which likely increased both the baseflow and overland flow. For some watersheds, statistical analysis also showed some effect of area under soybean production on increased streamflow and baseflow, but the statistical confidence was much lower than that for annual precipitation, both for a given year's precipitation and for previous years' precipitation. For some watersheds, there were also some differences in the relationship of streamflow with precipitation between the pre- and post-change periods, but those differences were probably due to different combination sequences of annual precipitation (P_1, P_2, P_3) between the two periods.

Comparison of individual year precipitation and streamflow values also showed that the presence of subsurface drain tile by itself does not increase streamflow in tile-drained watersheds. Instead, the stored soil water, along with current year precipitation (i.e., the availability of water), determines how much water drains out of the landscape. Changes in monthly streamflow were also linked to stored soil water through the preceding months' and years' precipitation. The area under soybean production was also a significant variable for several months. However, its importance in September through December was not apparent, considering that soybean crops generally start senescing in September and are harvested by late October.

Comparisons of the slopes of the rising limb of daily hydrographs for large precipitation events in 1957 and 1993 showed less watershed connectivity due to LULC changes such as drainage, a finding that is contrary to what has been suggested in the literature. Comparisons of daily slopes of the hydrograph's falling limb for similar-size precipitation events in the pre-change (1947) and post-change (1991) periods showed similar slope values, thus suggesting no changes in storage capacity of the watershed as a result of LULC changes. Further comparisons of high-level streamflows (Q > 100 m^3 s^{-1}) as a function of average daily storm precipitation help to demonstrate the value of averaging precipitation over the storm period rather than assigning increased streamflow to a given day's precipitation. Comparison of daily slopes of the falling limb for low (dQ/dt < -5 m^3 s^{-1} d^{-1}) and medium (dQ/dt varying from -2 to -5 m^3 s^{-1} d^{-1}) slopes as a function of streamflow showed no discernable change in the retentive capacity of the Redwood River watershed between the pre- and post-change periods.

Considering the above evaluations at three temporal scales, we conclude that increased precipitation in recent years was the main driver of increased streamflow in tile-drained watersheds of the upper Midwestern U.S., and LULC change impacts on streamflow characteristics were minimal. The minimal impact of LULC changes on streamflow may be from balancing of ET between the pre- and post-drainage periods, i.e., lower ET crops (small grains, wild hay) plus shallow potholes and wetlands in the pre-change period (prior to 1975) versus higher ET crops (corn and soybeans) and more fillable soil porosity from wetland drainage in the post-drainage period (after 1975).

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APPENDIX

Table A1. Values of regression coefficients (standard errors in parentheses) relating Ln(streamflow) to precipitation in a given year (P_1), two previous years (P_2, P_3), and area under soybean production (S_b) for four rivers in Minnesota and two rivers in Iowa. These coefficient values correspond to the regression equations obtained using the backward stepwise approach with $\alpha \leq 0.05$.[a]

State	River	Gauge No.	Area (km^2)	Years of Record	Regression Coefficient (Standard Error)					R^2
					β_0	β_1	β_2	β_3	β_4	
Minnesota	Blue Earth	5320000	6,242	1950-2009	-0.86	3.3E-03	2.9E-03	1.1E-03	1.4E-06	0.73
					(0.50)	(4.3E-04)	(4.0E-04)	(4.1E-04)	(6.2E-07)	
	Cottonwood	5317000	3,367	1943-2002	-0.36	4.0E-03	3.1E-03	-	-	0.69
					(0.43)	(4.3E-04)	(4.3E-04)	-	-	
	Redwood	5316500	1,629	1941-2009	-0.62	4.0E-03	3.0E-03	-	6.2E-06	0.63
					(0.48)	(5.0E-04)	(5.0E-04)	-	(2.9E-06)	
	Whetstone	5291000	1,030	1936-2009	-0.95	4.2E-03	3.5E-03	-	-	0.48
					(0.58)	(6.6E-04)	(6.7E-04)	-	-	
Iowa	Maquoketa	5418500	4,022	1918-2009	2.02	2.1E-03	1.3E-03	5.9E-04	-	0.77
					(0.23)	(1.6E-04)	(1.6E-04)	(1.6E-04)		
	North Raccoon	5484500	8,912	1926-1975	0.40	3.0E-03	2.7E-03	-	-	0.68
					(0.43)	(3.9E-04)	(3.9E-04)	-	-	
				1976-2009	0.91	3.7E-03	1.4E-3	-	-	0.73
					(0.50)	(4.4E-04)	(4.4E-04)	-	-	

[a] $\text{Ln(streamflow)} = \beta_0 + \beta_1 P_1 + \beta_2 P_2 + \beta_3 P_3 + \beta_4 S_b$.

Table A2. Values of regression coefficients (standard errors in parentheses) relating Ln(baseflow) to precipitation in a given year (P_1), two previous years (P_2, P_3) and area under soybean production (S_b) for the Redwood River in Minnesota and for the North Raccoon River in Iowa. These coefficient values correspond to regression equations obtained using the backward stepwise approach with $\alpha \leq 0.05$.[a]

State	River	Gauge No.	Area (km^2)	Years of Record	Regression Coefficient (Standard Error)					R^2
					β_0	β_1	β_2	β_3	β_4	
Minnesota	Redwood	5316500	1,629	1941-2009	-1.06	3.7E-03	3.3E-03	-	7.1E-06	0.64
					(0.48)	(5.0E-04)	(5.1E-04)	-	(2.9E-06)	
Iowa	North Raccoon	5484500	8,912	1926-1975	-0.65	3.1E-03	3.3E-03	-	-	0.74
					(0.42)	(3.9E-04)	(3.8E-04)	-	-	
				1976-2009	0.45	3.5E-03	1.7E-03	-	-	0.72
					(0.50)	(4.4E-04)	(4.4E-04)	-	-	

[a] $\text{Ln(baseflow)} = \beta_0 + \beta_1 P_1 + \beta_2 P_2 + \beta_3 P_3 + \beta_4 S_b$.

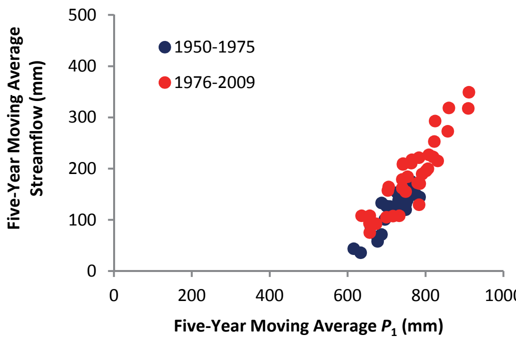
Table A3. Values of regression coefficients (standard errors in parentheses) relating Ln(monthly streamflow) to precipitation in various months and the previous year, along with soybean (S_b) area for the Redwood River at Redwood Falls, Minnesota (gauge 05316500) from 1941-2009. These coefficient values correspond to regression equations obtained using the backward stepwise approach with $\alpha \leq 0.05$.[a]

Streamflow Month	Intercept	Precipitation Month											Previous Year	S_b Area	R^2
		Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.			
Mar.	-1.30	-	-	1.3E-02	-	-	-	-	-	-	-	-	4.2E-03	-	0.22
	(0.77)			(6E-03)									(1E-03)		
Apr.	-1.91	4.3E-02	-	1.8E-02	1.2E-02	-	-	-	-	-	-	-	3.6E-03	-	0.54
	(0.63)	(9E-03)		(5E-03)	(3E-03)								(8E-04)		
May	-3.54	2.9E-02	-	1.4E-02	1.3E-02	1.2E-02		-	-	-	-	-	4.4E-03	-	0.71
	(0.49)	(6E-03)		(3E-03)	(2E-03)	(2E-03)							(6E-04)		
June	-3.57	-	-	-	-	1.2E-02	1.5E-02	-	-	-	-	-	3.3E-03	2.0E-05	0.80
	(0.43)					(2E-03)	(1E-03)						(5E-04)	(3E-06)	
July	-5.14	2.3E-02	-	-	5.4E-03	8.5E-03	1.4E-02	1.1E-02	-	-	-	-	3.3E-03	1.2E-05	0.76
	(0.56)	(7E-03)			(3E-03)	(2E-03)	(2E-03)	(2E-03)					(7E-04)	(4E-06)	
Aug.	-5.93	-	-	-	-	5.0E-03	1.0E-02	1.6E-02	1.2E-03	-	-	-	2.8E-03	1.8E-05	0.75
	(0.59)					(2E-03)	(2E-03)	(2E-03)	(2E-03)				(7E-04)	(4E-06)	

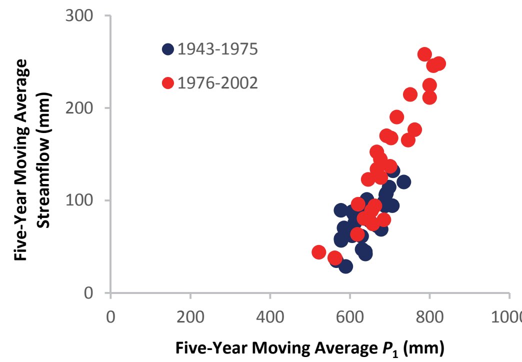
Table A3. Values of regression coefficients (standard errors in parentheses) relating Ln(monthly streamflow) to precipitation in various months and the previous year, along with soybean (S_b) area for the Redwood River at Redwood Falls, Minnesota (gauge 05316500) from 1941-2009. These coefficient values correspond to regression equations obtained using the backward stepwise approach with $\alpha \leq 0.05$.[a]

Streamflow		Precipitation Month											Previous	S_b	
Month	Intercept	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Year	Area	R^2
Sept.	-7.35	1.4E-02	-	-	-	5.0E-03	9.4E-03	1.3E-02	1.5E-02	1.7E-02	-	-	2.5E-03	1.5E-05	0.82
	(0.54)	(7E-03)				(2E-03)	(2E-03)	(2E-03)	(2E-03)	(2E-03)			(6E-04)	(4E-06)	
Oct.	-6.25	-	-	8.8E-03	-	-	5.9E-03	1.1E-02	1.0E-02	1.7E-02	1.6E-02	-	2.0E-03	1.5E-05	0.83
	(0.50)			(3E-03)			(1E-03)	(2E-03)	(2E-03)	(2E-03)	(2E-03)		(6E-04)	(3E-06)	
Nov.	-4.97	1.6E-02	-	-	-	4.7E-03	4.4E-03	8.0E-03	6.7E-03	1.0E-02	1.7E-02	-	1.4E-03	1.7E-05	0.81
	(0.48)	(6E-03)				(2E-03)	(1E-03)	(2E-03)	(2E-03)	(2E-03)	(2E-03)		(5E-04)	(3E-06)	
Dec.	-4.88	-	1.3E-02	-	-	3.9E-03	5.2E-03	6.9E-03	7.1E-03	1.0E-02	1.4E-02	9.4E-03	-	2.5E-05	0.81
	(0.36)		(7E-03)			(2E-03)	(1E-03)	(2E-03)	(2E-03)	(2E-03)	(2E-03)	(3E-03)		(3E-06)	

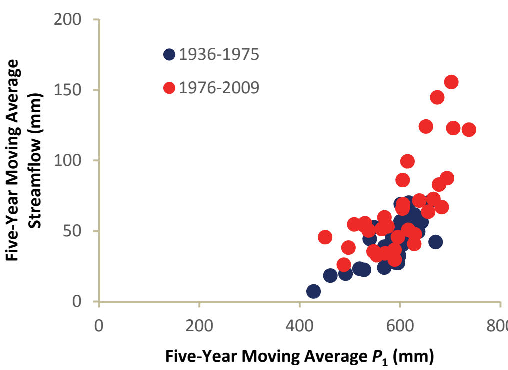
[a] $\mathrm{Ln}(SF_{GivenMonth}) = \beta_0 + \beta_1 P_{Jan} + \beta_2 P_{Feb} + \beta_3 P_{Mar} + \beta_4 P_{Apr} + \beta_5 P_{May} + \ldots + \beta_{12} P_{Dec} + \beta_{13} P_{PrevYear} + \beta_{14} S_b$.



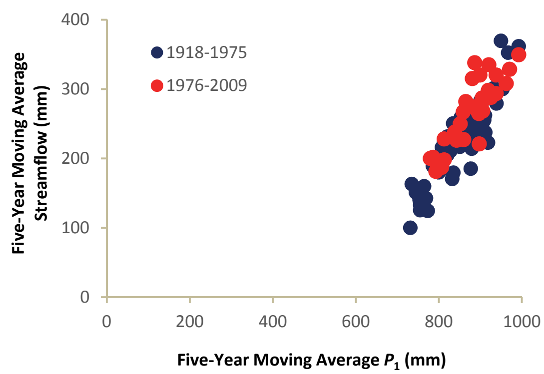
(a) Blue Earth River



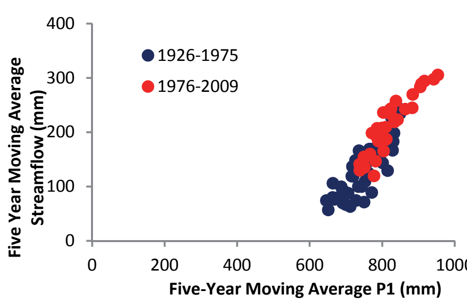
(b) Cottonwood River



(c) Whetstone River



(d) Maquoketa River



(e) North Raccoon River

Figure A1. Plots of five-year moving average of streamflow versus five-year moving average of precipitation for the (a) Blue Earth River, (b) Cottonwood River, and (c) Whetstone River in Minnesota and the (d) Maquoketa River and (e) North Raccoon River in Iowa. Because of missing values for 2003-2005, the Cottonwood River data are from 1943-2002.