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Twentieth century agricultural drainage creates more erosive rivers

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Abstract:

Rivers in watersheds dominated by agriculture throughout the US are impaired by excess sediment, a significant portion of which comes from non-field, near-channel sources. Both land-use and climate have been implicated in altering river flows and thereby increasing stream-channel erosion and sediment loading. In the wetland-rich landscapes of the upper Mississippi basin, 20th century crop conversions have led to an intensification of artificial drainage, which is now a critical component of modern agriculture. At the same time, much of the region has experienced increased annual rainfall. Uncertainty in separating these drivers of streamflow fuels debate between agricultural and environmental interests on responsibility and solutions for excess riverine sediment. To disentangle the effects of climate and land-use, we compared changes in precipitation, crop conversions, and extent of drained depressional area in 21 Minnesota watersheds over the past 70 years. Watersheds with large land-use changes had increases in seasonal and annual water yields of >50% since 1940. On average, changes in precipitation and crop evapotranspiration explained less than one-half of the increase, with the remainder highly correlated with artificial drainage and loss of depressional areas. Rivers with increased flow have experienced channel widening of 10–40% highlighting a source of sediment seldom addressed by agricultural best management practices.

Supporting information may be found in the online version of this article.

KEY WORDS artificial drainage; agricultural hydrology; streamflow; crop conversion; channel widening; sediment

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INTRODUCTION

Rivers in intensively row-cropped watersheds are often impaired by excessive sediment loads (Payne, 1994; Thoma *et al*., 2005; Engstrom *et al*., 2009; Lenhart *et al*., 2010; US EPA, 2013), which degrade their habitat and recreational value and negatively impact downstream surface waters. In the latter half of the 20[th] century, cropping patterns in the USA and especially the midwestern corn belt underwent major changes (USDA, 2011). One of the most dramatic shifts was the conversion of small grains and forage crops to soybeans (Figure 1). Over this same period, both river flows and sediment loading from agricultural watersheds increased markedly (Zhang and Schilling, 2006; Novotny and Stefan, 2007; Raymond *et al*., 2008; Schilling *et al*., 2008; Engstrom *et al*., 2009; Lenhart *et al*., 2011). While the conversion to row-crop agriculture certainly increased the amount of sediment eroded from fields, and thus it is tempting to implicate row-cropping in general as the source of increased suspended sediment, several studies have shown that non-field, near-channel sources such as streambanks, bluffs, and ravines currently contribute the majority of sediment in many agricultural watersheds (Sekely *et al*., 2002; Thoma *et al*., 2005; Wilson *et al*., 2008; Juracek and Ziegler, 2009; Schottler *et al*., 2010; Zaimes and Schultz, 2012). Sediment cores from Lake Pepin, a natural impoundment on the Mississippi River, show that not only have sediment accumulation rates increased nearly tenfold since the onset of modern agriculture, but also that the relative contribution from non-field sources has increased, especially in the past few decades (Schottler *et al*., 2010; Belmont *et al*., 2011). The increasing dominance of near-channel erosion sources and the need to target effective management strategies to reduce sediment loads raise the question: have rivers in agricultural watersheds become more erosive, and if so, why?

Understanding increases in river flows over the latter half of the 20th century is confounded by multiple possible causes. Higher flows have been correlated to increased precipitation (Novotny and Stefan, 2007; Johnson *et al*., 2009; Nangia *et al*., 2010); however, other critical factors are coincident and cannot be neglected. In particular, 20[th]-century crop conversions are relevant to watershed

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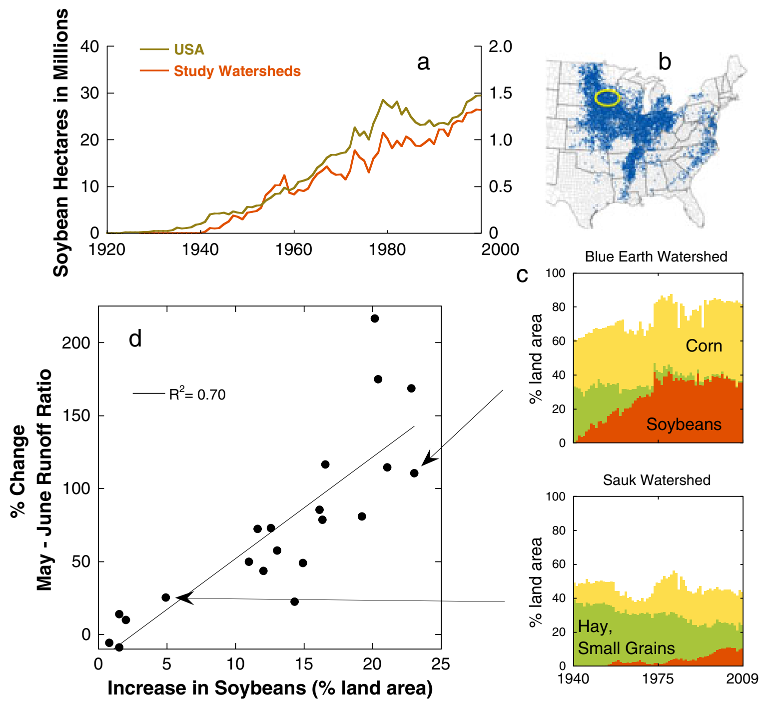

Figure 1. (a) Twentieth century increase in soybean acreage in the USA and for the combined 21 watersheds evaluated in this study. (b) Soybean growing region of the USA; yellow circle encompasses the 21 study watersheds. (c) Exemplary watersheds illustrating different levels of crop conversion among watersheds. (d) Relationship between the conversion to soybeans and the change in May–June runoff ratio. The conversion to soybeans subsumes multiple factors affecting hydrology. Change over time is expressed as the difference between the median values of the two time periods: 1940–1974 and 1975–2009

hydrology, not only because they can induce significant changes in seasonal evapotranspirative (ET) potential from the landscape (Zhang and Schilling, 2006; Schilling *et al*., 2008), but also because the conversion is often accompanied by an increase in artificial drainage (Sugg, 2007; Schilling and Helmers, 2008; Blann *et al*., 2009). In the midwestern USA, Wang and Hejazi (2011) recently estimated that human activities contributed more to increased flow than climate and showed that the increases were correlated with the area of watershed in cropland. Similarly, Schilling *et al*. (2008) concluded that crop conversion, especially to soybeans, was linked to increases in flow. However, the specific effects of artificial drainage as contributors to increased streamflow are not well understood. Given the extent of past wetland drainage and current intensification of subsurface drainage (Sugg, 2007; Blann *et al*., 2009), artificial drainage networks in total have the potential to alter water budgets and river flows on a watershed scale and must be quantified before management strategies can be fully developed.

In this study, we compare changes in hydrology for 21 southern Minnesota watersheds and show that artificial drainage is a major driver of increased river flow, exceeding the effects of precipitation and crop conversion. Rivers with altered hydrology also exhibit significant channel widening since the mid-20th century, supporting the hypothesis that agricultural land-use changes have created more erosive rivers.

METHODS

Precipitation

Spatial patterns of precipitation can vary considerably over a watershed such that using a single precipitation monitoring station to represent an entire watershed may introduce significant uncertainty. Moreover, every precipitation station has periods when no data were collected. To better account for spatial variation and to create a complete precipitation record, daily data from multiple precipitation stations were interpolated using the ordinary kriging methodology to produce daily area-weighted precipitation depths for each watershed. In all, 59 precipitation stations from the National Weather Service Cooperative Observer Program were used for the interpolation. Climate data were downloaded from the Utah State University Climate Center website (USU, 2010). The interpolation was conducted using PCP_SWAT (Zhang and Srinivasan, 2009), an ArcGIS 9.2 extension written for the SWAT hydrologic model (Arnold *et al*., 1998). Daily interpolated precipitation values were summed on a monthly and annual basis for the period 1940 to 2009.

Water yield and runoff ratio

Daily flow (m^3/day) records for the period 1940 to 2009 at the study watershed outlets were obtained from the USGS daily flow data website (USGS, 2010). Data gaps of days to months exist for some study watersheds.

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Gaps were evaluated on a monthly basis, and only months that possessed at least 25 valid flow days were used in the study. Total monthly flow for each year was calculated by multiplying the mean of the valid daily flows by the number of days in the month. Data were aggregated into bi-monthly (May–June, July–August, September–October) and annual time periods. The bi-monthly flow aggregates were chosen because May and June together comprise an important focal period for examining the ET effects from cropping changes. Consistent with the May–June focus, the annual dataset ran from the previous year's July to the current year's June. Water yield for each watershed was calculated by dividing flow by the respective watershed area. This normalization to watershed area allows direct water balance comparison to precipitation and ET. Runoff ratio, which is the proportionality between flow and precipitation in a watershed, is water yield divided by precipitation. While water yield and runoff ratio encompasses inputs to the river from both overland flow and infiltration, the contribution from each is not explicitly defined, or necessary for this study.

Trend analysis

Most time-series data in this study were found to have non-normal distributions. Therefore, trends were evaluated using non-parametric methods exclusively. The data set was split into two equal time periods: 1940 to 1974 and 1975 to 2009, and the Mann–Whitney U test (also known as the 'Wilcoxon-rank-sum test') was used to evaluate differences (Table S1). All analyses were conducted with the R statistical software using the R function *stats*:*wilcox.test* (R Development Team, 2010). This method, comparing two time periods, is similar to the approach used by others (Lenhart *et al*., 2011; Wang and Hejazi, 2011) and is less sensitive to end points when estimating magnitude of change. Kendall–Tau analysis of the continuous record gave similar results, confirming the watersheds with significant trends.

Potential evapotranspiration (PET)

PET was calculated using specific crop coefficients as defined by the Food and Agriculture Organization of the United Nations (FAO, 1998), the areal proportion of each crop, and an estimate of daily reference ET (RET). RET, calculated using the equation of Hargreaves and Samani (1985), was downloaded from the Utah State University climate datasets (USU, 2010). PET was calculated by multiplying RET by crop or vegetation coefficients using the FAO method (FAO, 1998),

$$PET = RET \times fc_i \times A_i \tag{1}$$

where fc_i is the mean monthly crop coefficient for crop(i), and A_i is the areal proportion of that crop in a particular watershed in given year.

Crop types were summarized into five classes: corn, soybeans, small grains (composed of barley, flax, oats, rye, and wheat), alfalfa hay, and non-agricultural (composed of all remaining land uses). Daily watershed PET was estimated using the following steps: (1) mean monthly crop coefficients were calculated for the five crop classes according to FAO growth curves, (2) daily aggregate crop coefficients were determined by multiplying each monthly crop-class coefficient by the corresponding areal proportion of each yearly crop class, and (3) PET was calculated by multiplying aggregate crop coefficients by daily RET. Because crop distributions have changed over time (e.g. less small grains, more soybeans), PET was evaluated on a yearly basis.

Several important assumptions were required to implement this PET calculation approach: (1) FAO crop growth curves (i.e. days to maturity, harvest, senescence, etc.) were the same regardless of watershed, (2) planting dates for corn, soybeans, and all other crop classes were Apr 25, May 10, and Apr 1, respectively, regardless of year or watershed, (3) the non-agricultural crop-class coefficient was the mean of FAO warm- and cool-season grass crop coefficients.

Yearly crop distributions were calculated using data from the National Agricultural Statistics Service (NASS, 2010) for the years 1940–2009. The overall cropping trend in the watersheds was the conversion of small grains, hay, and pasture to corn and soybeans (Figure 1). The approach outlined above was sensitive to this trend, and therefore a relatively large decrease in May–June PET (driven by conversion to soybeans) was predicted. Overall, the predicted May–June decrease was offset somewhat by a predicted July–August increase (due to peak corn and soybean FAO crop coefficients being greater than those in the small grain class), resulting in a small decrease in predicted annual PET. This decrease in PET is consistent with the work of Schilling (Zhang and Schilling, 2006; Schilling *et al*., 2008) conducted in agricultural watersheds of Iowa.

Cultivated land, poorly drained soils, and depressional areas

Current and historical cultivated land and crop type were determined from data compiled by the NASS (NASS, 2010; USDA, 2010) for the years 1940–2009. The crop data were compiled for all counties within the study area and intersected with the watershed boundaries using ArcGIS to determine the acres harvested of each crop in a watershed. Acreages of corn, soybeans, small grains, hay, alfalfa, pasture, and non-crop land were determined for each year. Median acreages for the two 35-year time periods (1940–1974 and 1975–2009) were used to assess and compare crop conversion in the different watersheds.

The extent and distribution of poorly drained soils were determined using the Soil Survey Geographic database (USDA, 2009). Seven classes of natural soil drainage are recognized in this database: excessively drained, somewhat excessively drained, well drained, moderately well drained, somewhat poorly drained, poorly drained, and very poorly drained. We extracted the poorly drained and very poorly drained classes to reflect the soils that would benefit from artificial drainage. The polygon input layers were clipped to the 21 watersheds using GIS software and intersected with cultivated lands to determine the amount of poorly drained, cultivated soils in each watershed.

Depressional areas were calculated based on data from the Minnesota Restorable Wetlands Inventory (RWI) created by the Restorable Wetlands Working Group (USFWS, 2011a), as well as data from the National Wetlands Inventory (USFWS, 2011b). These inventories used National Aerial Photography Program color infrared photographs (1:40 000 scale) viewed in stereo pairs at 5× magnification to delineate and digitize existing and drained depressional areas. The data, downloaded from the Ducks Unlimited website (USFWS, 2011a), were reviewed and found to contain duplicate entries within certain files for some counties. Staff at the Water Resources Center at MSU-Mankato manually removed the duplicate polygons to create a clean dataset. The RWI data for each county were then apportioned into the corresponding watershed.

Because the RWI database did not encompass all of our watersheds, we combined the available data from all watersheds to develop a landscape scale predictive relationship between poorly drained, cultivated soils, and drained depressions (Figure 2, $r^2 = 0.75$). We estimated the total amount of depressional area lost in each of the 21 watersheds by applying the total amount of poorly drained cultivated soils for a particular watershed to the regression in Figure 2.

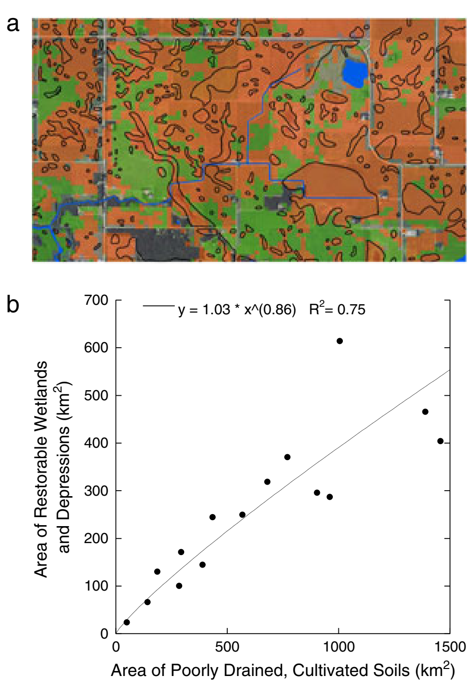

Figure 2. Predictive relationship between drained depressions and poorly drained cultivated soils for areas inventoried within the study watersheds. Upper image (a), from the Le Sueur watershed, shows cultivated soils (green), poorly drained cultivated soils (brown) drained depressions (black polygons) and existing wetlands (blue). In this example nearly all historic depressions/wetlands have been drained. Drained depression data were available for about 60% of the area in the 21 watersheds. The above regression (b) and the total amount of poorly drained cultivated soils in each watershed were used to estimate the total area of drained depressions

Apportionment of changes in water yield

Over the long-term (years to decades) changes in river flow can be expressed simply as a function of precipitation and ET (Wang and Hejazi, 2011)

$$\Delta Q = \Delta P - \Delta ET \tag{2}$$

where changes in mean annual water yield (ΔQ) and precipitation (ΔP) between the two periods (1940–1974 and 1975–2009) are measured values. Recognizing that there are multiple mechanisms for ET, this expression can be expanded to:

$$\Delta Q = \Delta P - \Delta ET_{climate} - \Delta ET_{crop} - \Delta ET_{other} \tag{3}$$

Total evapotranspiration can change over time due to changes in precipitation, temperature, and radiation ($\Delta ET_{climate}$) or because of changes in vegetation due to crop conversions (ΔET_{crop}). ET_{other} represents changes to the water budget that are not captured in the estimation of $ET_{climate}$ or ET_{crop}. The watersheds in this study have negligible irrigated land and minimal population changes upstream of the monitoring stations (MPC, 2010), but many have extensive artificial drainage networks (Sugg, 2007). Thus, in the absence of any other drivers to ET, it is reasonable to hypothesize that ET_{other} is the result of drainage, such that

$$\Delta ET_{other} \cong \Delta ET_{drainage} \tag{4}$$

Changes in actual ET cannot be measured directly, but a relationship between calculated PET and measured water yield for the first time period can be developed and used to predict Q in the second period. The difference between the predicted and measured water yield in the second period is the change in water yield due to non-crop, non-climate factors. To evaluate the contributions of climate and crop ET to changes in flow, we first established and calibrated an empirical relationship of water yield to PET and precipitation (P) over the initial 35-year period (1940–1974) (see Figure 3 for example). This relationship is non-linear and can be expressed as a unique power function for each watershed:

$$Q = C \times (PET/P)^{-B} \tag{5}$$

where B and C are empirical calibration coefficients, and Q is the predicted annual water yield. Change in water yield due to crop conversion and changes in climate between the two time periods ($\Delta Q_{climate + crop}$) is estimated by solving Equation (5) using the mean PET/P ratio for each period and subtracting the two values (Equation (6)). To estimate a representative PET/P ratio for a 35-year period, mean PET/P is defined as cumulative PET divided by cumulative P for each time period.

$$\Delta Q_{climate+crop} = C \times \left((PET/P)^{-B}_{75-09} - (PET/P)^{-B}_{40-74} \right) \tag{6}$$

Overall, this method using a calibrated response to PET/P in one time period to apportion changes in a

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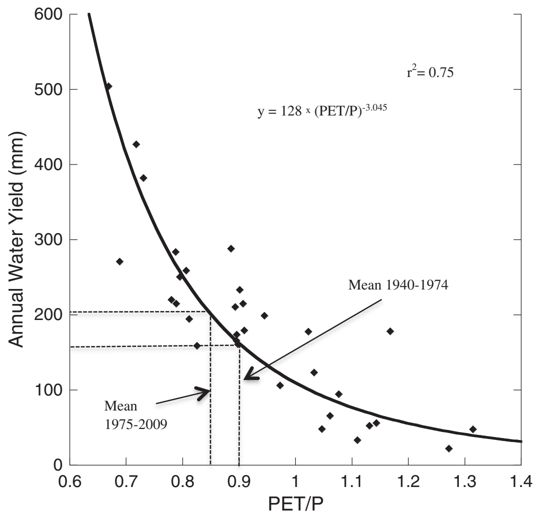

Figure 3. Calibration of the response of water yield to climate (precipitation), and cropping characteristics using annual values for the initial 35 year period (1940–1974): an example for the Blue Earth watershed. The mean PET/P ratio changed from 0.9 to 0.85 from the first period to the second (dashed lines). Applying this change in PET/P to the empirical relationship predicts a 33.5 mm increase in annual water yield in the second time period due climate and crop conversions combined

second time period is similar to that used by Wang and Hejazi (2011), but here directly relates PET and P to measured water yield.

The change described by Equation (6) can be further apportioned between climate and crop conversion using the relative changes in the variables used to calculate the PET:P ratio. The combined change in water yield ($\Delta Q_{\text{climate + crop}}$) predicted by changes in PET and P is proportional to changes in P, RET, and fc and can be partitioned between climate and crop by comparing the relative changes in the three variables (Equations (7) and (8))

$$\Delta Q_{crop} = \Delta Q_{climate+crop} \times [\%fc/(\%RET + \%P + \%fc)] \tag{7}$$

$$\Delta Q_{climate} = \Delta Q_{climate+crop} \times (\%RET + \%\,P)/(\%RET + \%P + \%fc)] \tag{8}$$

where %RET and %P are the relative changes in RET and P, respectively, between the two time periods. Because PET is RET multiplied by each areally weighted crop coefficient, the relative change in mean crop coefficient (%fc) is simply the mean PET:RET of period two divided by the mean PET:RET ratio of period one.

The change in water yield due to artificial drainage is then estimated by difference from the measured total change in water yield ($\Delta Q_{\text{measured}}$) between the two periods.

$$\Delta Q_{drainage} = \Delta Q_{measured} - \Delta Q_{climate} - \Delta Q_{crop} \tag{9}$$

Channel widening

Channel widening was estimated for six of the watersheds and also on the downstream Minnesota River. Channel width was measured by digitizing polygons representing the active channel, defined by vegetation boundaries, on historic and recent air photos. Polygons were approximately ten meander bends long and the area of each polygon was divided by polygon length to obtain a reach-average width. Measurements were made on a minimum of four and as many as 12 sets of air photos for each location (Table S2). Each location had a set of air photos dating back to 1937–1939, which provides the oldest channel width measurement used in this study. Channel widening was defined as the difference in mean width estimated from pre-1975 photos and post-1975 photos (Table S2). Multiple air photo sets were available between 2000 and 2010 for most locations, providing multiple constraints on modern channel widths as well as an estimate of uncertainty associated with bank classification. Typical channel widths for tributaries ranged from 30 to 60 m for tributary channels and 85 to 105 m for the mainstem Minnesota River. Typical reach lengths ranged from approximately 5 to 10 km.

RESULTS AND DISCUSSION

In over half of the watersheds, water yield (flow divided by watershed area) and runoff ratio (water yield normalized to precipitation) show large and significant increases in the spring (May–June), with much smaller changes in the fall (Sept–Oct) (Figure 4). By definition, changes in runoff ratio include changes in surface runoff and infiltration. In those watersheds with statistically significant trends, May–June water yields and runoff ratios have increased by 45–200% since the middle of the 20th century (Figures 1 and 4). This two-month increase in water yield accounts for about one-third of the total annual increase in water yield. Equally important is the observation that water yield and runoff ratio show no significant increases in about half of the watersheds (Figure 4). Given the close spatial proximity of the watersheds, the observation that only some show changes in hydrology suggests a local land-use effect rather than a regional rainfall driver.

Several studies have shown increasing regional precipitation trends and river discharge over the past century (Zhang and Schilling, 2006; Novotny and Stefan, 2007; Nangia *et al.*, 2010), but efforts to decouple rainfall from multiple land-use changes as drivers of hydrologic trends have been incomplete. For the watersheds in this study, annual precipitation over the two time periods increased by less than 15%, with the changes highly skewed by season (Figure 4). In particular, May–June precipitation has been constant or has decreased since 1940. The fact that the largest changes in water yield and runoff ratio occur during May–June, a period with no increase in precipitation (and more than a month after

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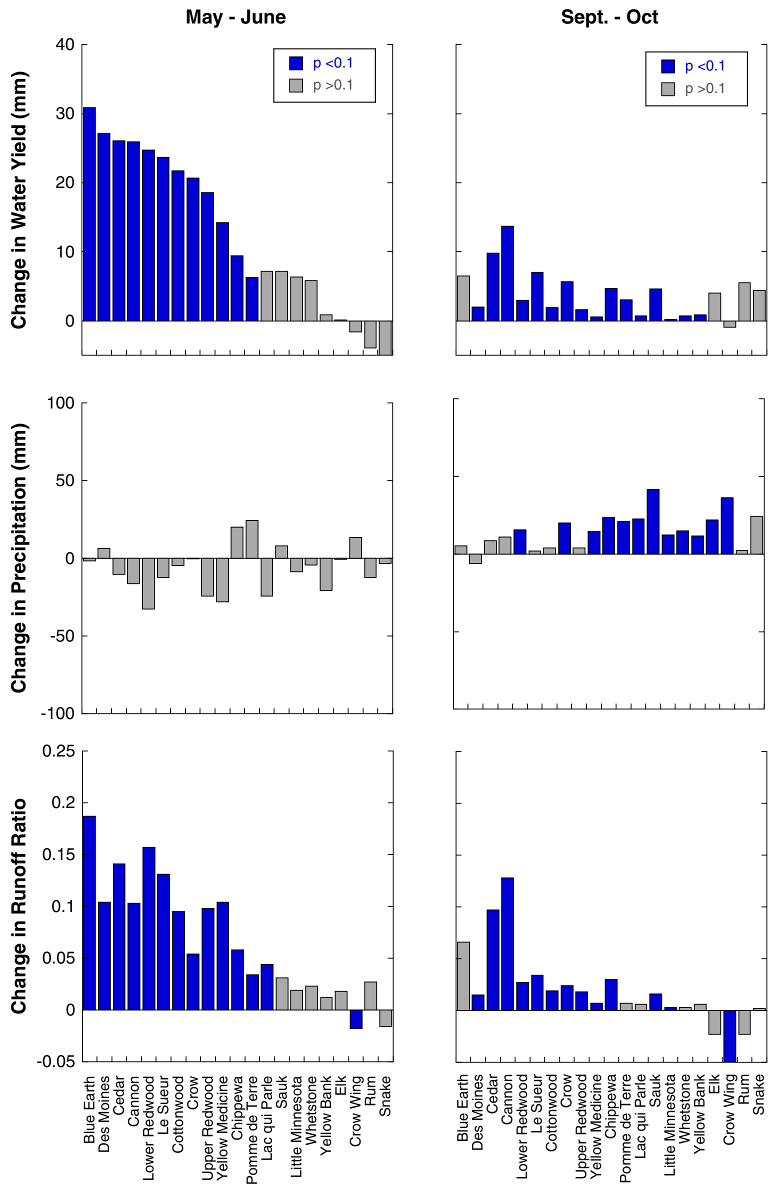

Figure 4. Seasonal changes in water yield (flow volume/watershed area), precipitation, and runoff ratio (water yield/precipitation) for 21 watersheds tributary to the Upper Mississippi River. Changes represent the difference between median values for two 35-year periods (1940–1974 and 1975–2009). Annual changes follow a similar pattern, with water yield and runoff ratios increasing by >50% in watersheds with significant trends

snowmelt), strongly implies that seasonal changes in river hydrology are not the result of increases in precipitation. Conversely, in the Sept–Oct period, when there is an increase in precipitation, water yields and runoff ratios show only small changes.

Our seasonal and multi-watershed comparisons (Figure 4) lead to several important conclusions: first, river flow during the early growing season has increased dramatically in certain watersheds, and second, the increase is not proportional to the seasonal changes in precipitation. Our calculations apportioning the changes in annual water budgets confirm that precipitation (climate) alone cannot account for the large increases in water yield observed in about half of the watersheds (Figure 5a). Comparison of land-use changes among the watersheds sheds light on why some and not others have experienced such large changes in hydrology.

The change in runoff ratio is highly correlated with the magnitude of mid-century crop conversion to soybeans in each watershed (Figure 1). Conversion to soybeans encompasses two important mechanistic drivers leading to more water entering the rivers – changes in crop ET, and reduction in ET from depressional areas owing to expansion of artificial drainage. Conversion to soybeans has largely displaced forage crops and small grains that actively grow early in the spring and reduce available soil moisture through ET. In contrast, soybeans do not begin consuming water through ET until nearly a month later because they are

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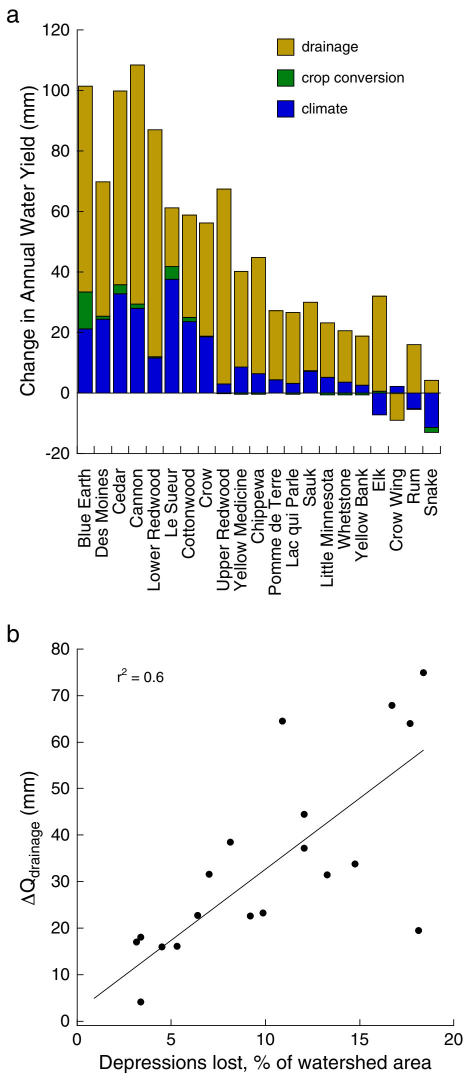

Figure 5. (a) Apportionment of changes in mean annual water yield for each watershed. In rivers with significant changes in flow, climate and crop conversions account for less than half of the total change in water yield. Excess water yield is the portion that cannot be attributed to changes in crop ET and climate and is hypothesized to result from artificial drainage ($\Delta Q_{drainage}$). (b) The increase in water yield attributed to drainage is strongly correlated with the loss of depressional areas, supporting the argument that the change in flow not accounted for by climate and crop conversion is a result of artificial drainage networks

planted in late spring. The conversion to soybeans thus changes the seasonal loss of upland ET, allowing a greater proportion of precipitation to enter the rivers.

Yields of corn and soybeans benefit greatly from enhanced subsurface drainage, and it is not surprising that 20th century drainage intensification is coincident with the crop conversion trends (Dahl and Allord, 1996; Kuehner, 2004; Blann *et al*., 2009). Artificial drainage, which includes ditching, subsurface tiling with and without surface inlets, and wetland drainage, affects water yield in two fundamental ways: by permanent decreases in residence time of water on the landscape (thereby reducing evaporative losses) and through continuous incremental installation of subsurface tile and the attendant one-time reduction in soil profile storage.

Although subsurface pattern tiling continues to be installed on the landscape, changes in storage are probably a minor component of long-term water budgets. For example, if subsurface tile were incrementally installed over 35 years, lowering the water table by a maximum of 1.25 m (the depth of tile installation) across a watershed with 50% poorly drained soils (an upper value for our watersheds, see USDA, 2009) and drainable porosity of 30%, this would produce an increase in annual water yield of only ~5 mm. This rough calculation is a maximum estimate and demonstrates that while changes in storage are not zero, they are small. For the purpose of this study, small changes in storage due to drainage are indistinguishable from the larger effect of evaporative losses due to artificial drainage and are thus combined into the single term, $\Delta ET_{drainage}$.

The larger impact of artificial drainage on the hydrologic budget is through reduction in ET losses from depressional areas (loss of residence time). These depressions range from former wetlands with significant residence time to extensive ephemeral ponded water in fields. In all cases, artificial drainage reduces the amount of time that water is on the landscape and can be lost to ET. Artificial drainage continues to be installed to enhance crop yields on these poorly drained areas, and while drainage installation databases are incomplete, in some of our watersheds, over 50% of the land is estimated to have some form of tile drainage (Sugg, 2007). Our estimates for the loss of depressional areas using the RWI datasets (USFWS, 2011a; USFWS, 2011b) show that watersheds with poorly drained soils and a high percentage of cultivated land have high losses of depressional areas. In these watersheds nearly all of the natural wetlands and depressional areas have been altered by drainage, representing a profound hydrologic modification of up to 20% of the total watershed area (Figure 5b).

The method used in this study to apportion increases in water yield shows that changes in precipitation (climate) and crop ET account for only a fraction of the total change in water yield (Figure 5a). In our study watersheds, PET/P changes by less 10% between 1940–1974 and 1975–2009, and this relatively small change in climate and crop conversion is simply not enough to account for a >50% increase in water yield. The surplus water yield is a consequence of other changes to ET, namely large reductions in depressional ET resulting from artificial drainage. While changes in annual water yield vary considerably among the 21 watersheds, on average, more than half of the change is attributable to drainage (Figure 5a). Three of our watersheds were also studied by Wang and Hejazi (2011) with comparable results, where less than half of the increase in water yield observed from 1948–2003 could be explained by climate alone. Our study offers additional insight into the non-climate drivers of change.

The total change in water yield not accounted for by changes in precipitation (climate) and crop conversion represents the excess water yield that must result from other

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drivers – specifically, artificial drainage, as we hypothesize above. This attribution is supported by the correlation of excess water yield with the estimated loss of wetlands and depressional area in each watershed ($r^2 = 0.6$; Figure 5b). This relationship strongly suggests that artificial drainage – the rapid removal of water from depressional areas, which significantly reduces depressional ET – is a major driver of increased river flow. This analysis cannot define which forms of artificial drainage or pathways are most important. What is clear is that precipitation that was once lost to ET is now being transported to the rivers.

Changes in streamflow can have important water-quality consequences such as increased river erosion, including stream-channel widening, resulting in greater sediment loading and increased river turbidity (Wolman and Miller, 1960; Doyle *et al*., 2005; Simon and Rinaldi, 2006). In this study, we quantified channel widening for several watersheds using historical aerial photography dating back to the late 1930s. For the six watersheds quantified, channel widening was related to the historic increase in water yield (Figure 6), which in turn is a function of crop conversion in general and artificial drainage in particular. Rivers that experienced only small changes in water yield have responded with similarly small changes in channel width, while those with large increases in water yield have increased their widths by 10–42%.

Figure 6 presents a strong relationship between changes in water quantity (water yield) and channel widening but does not describe which flow regimes have increased sufficiently to induce the channel instability. Examination of flow duration curves in watersheds with significant increases in annual water yield shows that nearly all flow regimes have increased since 1940 (Figure 7). The excess water yield is manifest not only as increases in baseflow as shown by studies in other agricultural watersheds (Zhang and Schilling, 2006; Schilling and Helmers, 2008) but also as increases in the duration of high flows.

Wolman and Miller (1960) first demonstrated that 90% of sediment removed from a watershed (i.e. 90% of geomorphic work) is transported in relatively high, but frequently occurring events, which are commonly, referred to as ‘effective’ or ‘channel forming’ discharge events. Figure 7 shows that the duration of these events has increased in the watersheds with significant increases in annual flow volume. Changes in channel morphology,

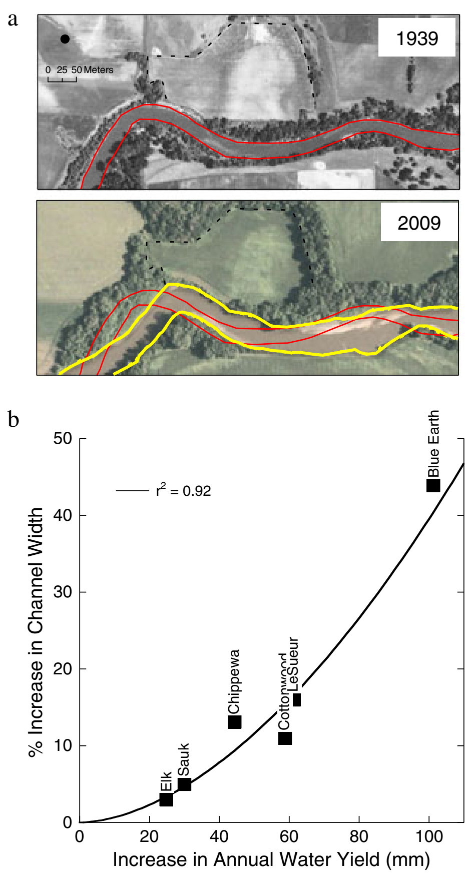

Figure 6. Channel widening related to increases in flow. (a) Photos show widening on the Blue Earth River. Red line is the bankfull width in 1939; yellow line is 2009. (b) Widening is the percent change in mean width between the two time periods (1940–1974 *vs* 1975–2009) and is strongly related to the increase in annual water yield. The four rivers with the greatest amount of widening are all tributaries to the Minnesota River, which has experienced a 33% (Table S2) increase in mean channel width over the same time period

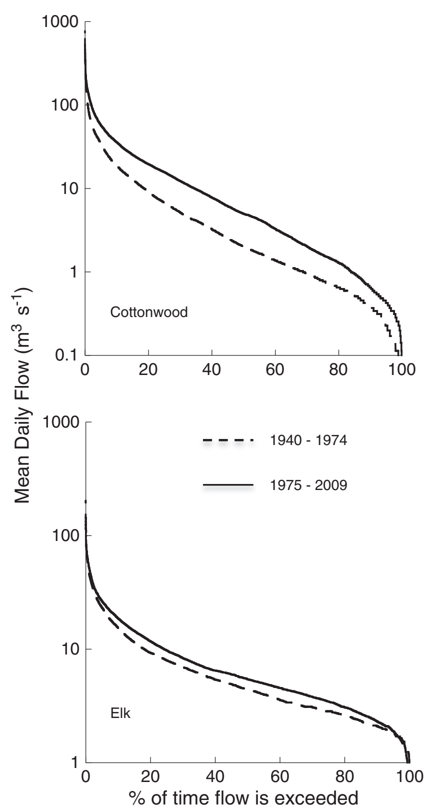

Figure 7. Representative flow duration curves for a river with channel widening (Cottonwood) and one without (Elk). High flows are toward the left and low flows toward the right. Rivers such as the Cottonwood, which had significant increases in total annual water yield, showed increases in nearly all flow regimes

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which are controlled by a variety of interrelated variables, including water discharge, slope, sediment supply, and vegetation, have been a foundational question in fluvial geomorphology for decades (Leopold and Maddock, 1953; Wolman and Miller, 1960; Nash, 1994; Goodwin, 2004; Klonsky and Vogel, 2011). Thus, the concomitant increases in channel width and duration of channel forming flows observed in this study offer a plausible but not exclusive explanation of how increased flow has induced erosion along the rivers.

The watersheds in this study are tributaries to the Mississippi River, and their integrated erosion history is recorded in the sediment stratigraphy of the downstream, natural impoundment, Lake Pepin. Radioisotope fingerprinting on sediment cores from Lake Pepin shows that non-field, near-channel inputs such as streambank erosion have increased dramatically over the past century (Engstrom *et al*., 2009; Schottler *et al*., 2010; Belmont, *et al*., 2011). Additionally, current measurements of sediment fluxes on several of the study watersheds and the Mississippi show that over 40% of the annual load is delivered in the months of May and June alone (MCES, 2010), which is consistent with the seasonal flow increases documented in this study (Figure 4). This observation and the trends in Lake Pepin not only provide supporting evidence for the linkages between increased flow and sediment from channel widening, but also demonstrate that the signature of this interaction is large enough to be detected in water quality measurements.

In the sense that increased flows have resulted in the carving of a wider channel, the rivers can be described as more erosive relative to past conditions. The term 'erosive' likewise applies to the notion that the rivers have simply eroded and transported more sediment. Based on the increasing non-field suspended sediment loads recorded in Lake Pepin, and the measured channel widening in this study, both connotations of 'more erosive rivers' are applicable to the watersheds in this study.

Because of the complexity and interrelated nature of variables controlling channel morphology, a comprehensive model for predicting changes in channel geometry as a function of a single boundary condition (e.g. discharge) remains elusive at present. However, channel widening is one of several modes of channel adjustment that would accommodate the observed increases in moderate to high flows, with other modes of adjustment being changes in channel depth, planform, and roughness (the latter two primarily affecting water velocity). Although it is not possible to determine the respective proportions of the increase in flows that has been accommodated by increases in channel depth, width, or water velocity, the notion that channel widening may be the dominant mechanism of adjustment is reasonable for the reasons explained below.

Changes in channel depth can occur as a result of bed scour or floodplain aggradation. However, Parker *et al*., 2007 showed that depth is a relatively insensitive mode of adjustment, varying little over a wide range of river types and sizes. Further, Belmont (2011) observed much variability, but little systematic change in depth over a distance of 80 km in two branches of the Le Sueur River, one of our 21 study watersheds. The surveyed 80-km reaches spanned the transition from low gradient (0.0004) channels to relatively high gradient (0.002) channels, above and below the prominent knick point that exists in all Minnesota tributary channel networks. On the scale of the channel networks considered here (fifth order, $>10^3$ km^2 drainage area), slope is also unlikely to change appreciably over the time period of a few decades. Thus, while we cannot negate the possibility that the observed changes in discharge have been partially accommodated by other modes of channel adjustment, the notion that changes in flow and channel width are causatively linked is consistent with basic geomorphic principles. The fact that the two are so strongly correlated in Figure 6 ($r^2 = 0.92$) suggests that channel widening may be the dominant mode of adjustment. This conclusion is consistent with the observation by Parker *et al*. (2007) that channel width increases significantly more than depth as a function of water discharge.

CONCLUSIONS AND IMPLICATIONS

The purpose of this study was to verify and elucidate the drivers of increased streamflow in a suite of 21 agricultural watersheds and determine if these hydrologic changes triggered an increase in erosion of near-channel sediment sources. Seasonal and annual water yield (flow) and runoff ratio were found to increase by >50% since 1940 in half of the watersheds, with no statistical change in the others. Using the first 35 years of the dataset (1940–1974) to calibrate the relationship between water yield and PET and precipitation, it was found that climate and crop conversion could explain less than half of the observed increase in river flow that occurred in the second period (1975–2009). Artificial drainage was identified as the largest driver of increased flow. The majority of the increase in flow was attributed to changes in water residence time on the landscape and subsequent reductions in ET resulting from installation of artificial drainage networks. This conclusion is supported by the strong correlation between the amount of wetland/depressional areas lost and increases in excess annual water yield in the 21 watersheds. The magnitude of change caused by artificial drainage deserves further scrutiny, but the link to increased flow follows a clear set of connections: (1) a principal purpose of artificial drainage is to facilitate agricultural production by reducing the amount of time water is ponded in fields; (2) quickly routing ponded water to rivers reduces the amount of time available for ET; (3) thus, the proportion of precipitation lost to ET is reduced and instead ends up as river flow.

The increase in flow is not inconsequential and was shown to be correlated to widening of the river channels over the past 70 years. Rivers that had significant increases

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in annual flow volume experienced channel widening of 10–40%, whereas rivers with no flow increase had no change in channel width. Flow duration curves showed that both baseflow and high flow events have increased in watersheds with increased annual flow volume, and it is likely that the increased duration of channel forming flows is responsible for the observed widening.

The results presented here highlight the role of artificial drainage in increasing streamflow, resulting in rivers that have carved wider channels. This set of observations leads to the conclusion that the installation of artificial drainage has created more erosive rivers. The sediment eroded during widening represents an increase in a major non-field source, which is consistent with the results from downstream sediment cores that show a large increase in the relative contribution of non-field sediment over the past century (Schottler *et al*., 2010; Belmont *et al*., 2011).

Increased flow and sediment loading from our study watersheds is a serious problem for the Minnesota and upper Mississippi rivers where such changes have been noted previously but lacked adequate explanation. Not only have sediment loads increased greatly since the onset of modern agriculture (Engstrom *et al*., 2009), but also over 50% of the present-day load is from non-field sources (Thoma *et al*., 2005; Johnson *et al*., 2009; Schottler *et al*., 2010). This study contributes to understanding why streamflows have increased and how this change resulted in increased non-field sediment contributions.

The findings presented in this study have implications for the entire intensively cultivated corn belt of the Midwest USA, where former wetland depressions have been drained, and in general wherever agricultural drainage has reduced water residence on the land surface. Twentieth century crop conversions and the attendant decreases in ET from depressional areas due to artificial drainage have combined to significantly alter watershed hydrology on a very large scale, resulting in more erosive rivers. While the widening we document cannot continue indefinitely, particularly if future increases in discharge are modest, chronically high discharges could result in essentially permanent increases in sediment supply at the toe of bluffs and high streambanks eroding through natural bank migration processes.

Apportionment of causes of changes in flow in this study and others tends to focus on annual measurements. The seasonal differences highlighted in Figure 4 deserve additional investigation, as the effects of climate versus land-use could be different at different times of the year. This point becomes especially salient as strategies to manage excess water and channel widening develop. Although the impact of agriculture on the world's rivers is highly variable (Walling and Fang, 2003), the results from this study offer an important lesson: crop conversions that require artificial drainage pose a risk to riverine water quality. Efforts to mitigate excessive sediment loads and turbidity must include strategies to manage watershed hydrology and reverse conditions contributing to higher river flows.

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