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Increasing streamflow and baseflow in Mississippi River since the 1940 s: Effect of land use change

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Abstract

A trend of increasing streamflow has been observed in the Mississippi River (MR) basin since the 1940 s as a result of increased precipitation. Herein we show that increasing MR flow is mainly in its baseflow as a result of land use change and accompanying agricultural activities that occurred in the MR basin during the last 60 years. Agricultural land use change in the MR basin has affected the basin-scale hydrology: more precipitation is being routed into streams as baseflow than stormflow since 1940 s. We explain that the conversion of perennial vegetation to seasonal row crops, especially soybeans, in the basin since 1940 s may have reduced evapotranspiration, increased groundwater recharge, and thus increased baseflow and streamflow. This explanation is supported with a data analysis of the annually and monthly flow rates at various river stations in the MR basin. Results from this study will help to direct our effort in managing land use and in reducing nutrient levels in MR and other major rivers since nutrient concentrations and loads carried by storm water and baseflow are different.

Keywords: Streamflow; Baseflow; Land use change; Mississippi River

1. Introduction

Streamflow (Q) is composed of stormflow (SW) and baseflow (BF). The former is mainly surface runoff and the latter is groundwater discharge to a stream. SW is the major portion of streamflow that occurs right after a rainfall event and during a raining season whereas BF is the main source of stream water between rainfall events and during dry periods. Streamflow and the relative proportion of SW and BF in Q vary with time and are affected by climate, mainly precipitation, and watershed characteristics, and by human activities, e.g. changes in land use. Trends in Q in various river basins and regions have been studied to evaluate climate changes and greenhouse warming (e.g. Greenpeace International, 1995; Lins and Slack, 1999; Peterson et al., 2002) and, to a lesser extent, to assess the impacts of human activities (Copeland et al., 1996). Increasing streamflow in many rivers was attributed to increasing precipitation, which in turn was attributed to increased CO_2 and other greenhouse gases in the atmosphere (Houghton et al., 1996; IPCC, 2001).

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Increasing streamflow trends are particularly noticeable in the Mississippi River (MR) basin (Lins and Slack, 1999; Raymond and Cole, 2003). For example, annual discharge from four gauging stations operated by the US Geological Survey (USGS) along the MR at Clinton, IA, St Louis, MO, Memphis, TN, and Vicksburg, MS (Stations 1–4 in Fig. 1) show a statistically significant increase ($p<0.05$) (Fig. 2 and Table 1) from 1940 to 2003. The increase of 0.79–1.07 mm per year or 31–41% increase in Q during the last 46–63 years at these four stations has been explained by changing precipitation, which also increased during the same time period in the MR basin (IPCC, 2001). However, in other large basins of the United States with varying precipitation patterns, increasing streamflow trends were not observed. Annual streamflow in the Columbia River in the northwest United States, Rio Grande River in the southwest, Savannah River in the southeast, and Susquehanna River in the northeast (Fig. 1) showed no trend during the 1940–2003 period (Table 1).

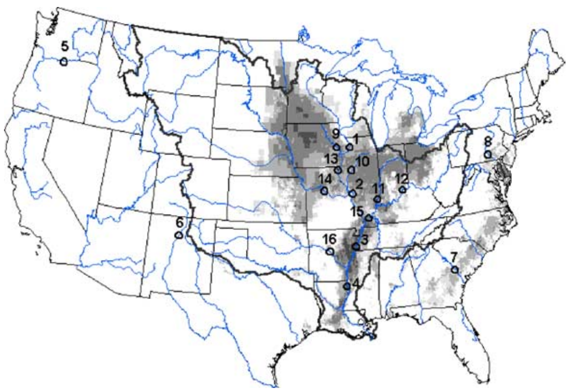

Fig. 1. Change in the fractional area of soybean from 1950 to 1992. The fraction represents the percent of each $5' \times 5'$ grid cell covered by soybean. The five gray scales are used: white (fraction $<2\%$), light gray (2–5%), gray (5–15%), dark gray (15–30%), and heavy dark gray ($>35\%$). Also shown in the figure is the Mississippi River basin and major rivers in the USA and 16 USGS gauging stations studied in this paper. The gauging stations are numbered as: 1. MR at Clinton, IA; 2. MR at St Louis, MO; 3. MR at Memphis, TN; 4. MR at Vicksburg, MS; 5. Columbia River at Dalles, WA; 6. Rio Grande River at San Felipe, NM; 7. Savannah River at Augusta, GA; 8. Sesquehanna River at Harrisburg, PA; 9. Cedar River at Cedar Rapids; 10. Illinois River at Kingston Mines, IL; 11. Wabash River at Carmel, IL; 12. Ohio River at Louisville, KY; 13. MR at Keokuk, IA; 14. Missouri River at Boonville, MO; 15. Ohio River at Metropolis, IL; 16. Arkansas River at Murry Dam, AR.

One factor unique to the MR basin is widespread agricultural land use. Overall land use in the MR basin consists of about 58% cropland, with lesser amounts of woodland (18%), range and barren land (21%), wetlands and water (2.4%), and urban land (0.6%) (Goolsby, 2000). However, most of the cropland is concentrated in the upper MR basin which is noted to contain the highest percentage of total land in agriculture (corn and soybeans) in the US (Keeney and Muller, 2000). Given the amount of land in cropland in the MR basin, it is evident that land use must be considered with precipitation to understand the changes in watershed hydrology that have occurred in the MR during the last 60 years.

At smaller watershed scales within the upper MR basin, the relation of agricultural land use change to changing streamflow patterns has been documented. In Iowa, for example, long-term trends in annual flow characteristics were evaluated for 11 gauging stations by Schilling and Libra (2003). In nearly all watersheds evaluated, annual minimum streamflow, annual baseflow, and annual fraction of streamflow as baseflow showed statistically significant increases over time. The relation of baseflow to row cropland use was evaluated for these 11 Iowa rivers and their watersheds for their period of streamflow record (58–73 year period) by Schilling (2004). Results indicated increasing baseflow in Iowa's rivers is significantly related to increasing row crop intensity. In south-western Wisconsin, several studies have shown decreased flood peaks and increased baseflow due to improved land management and change in land use (Potter, 1991; Gebert and Krug, 1996; Knox, 2001).

In this paper, we examine the role that land use change occurring in the MR basin during the last 60 years has had an increasing streamflow in the MR. We hypothesize that agricultural land use change in the MR basin has resulted in more precipitation being routed into streams as baseflow than stormflow since 1940 and that increasing MR streamflow is primarily in baseflow of the river. We explain that the conversion of perennial vegetation to seasonal row crops, especially soybeans in the basin since the 1940 s, may have had significant impacts on basin-scale hydrology and the composition of the river flow. Our study will help to direct efforts in managing land use to reduce nutrient export in the MR and other

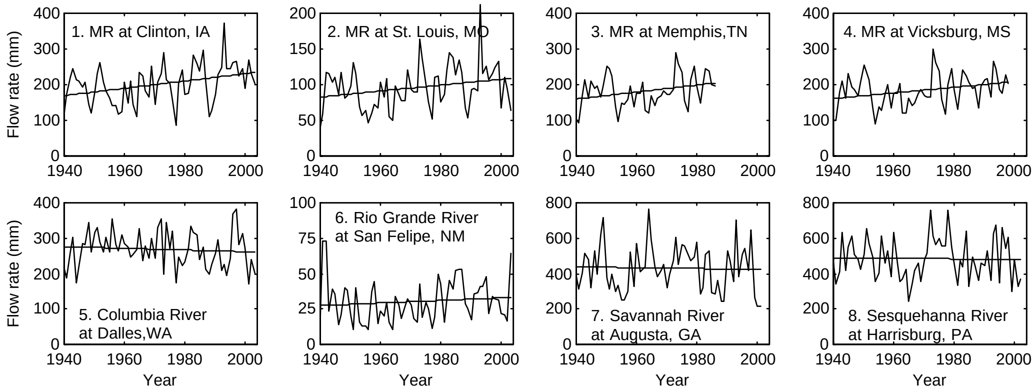

Fig. 2. Annual streamflow from 1940 to 2003 at the four USGS gauging stations 1–4 along Mississippi River and at the four stations 5–8 in four regions of the USA (Columbia River in the northwest, Rio Grande River in the southwest, Savannah River in the southeast, and Susquehanna River in the northeast). Some data for late years are missing at some stations. The streamflow is presented in millimeter or the annual discharge volume divided by the drainage area. The straight lines are fitted to the observed data by the least square (see Fig. 1 for the locations of the stations).

major rivers since nutrient concentrations and loads carried by storm water and baseflow are different.

2. Land use change in the MR basin: expansion of soybean cultivation

In North America, different vegetation types have been cleared for cultivation during the last century, with savannas/grasslands/steppes and forests/woodlands undergoing the most extensive conversion (Ramankutty and Foley, 1999). High-resolution datasets of the area of the three primary seasonal crops, maize, soybean and wheat cultivation in the United States for 1950, 1970 and 1992 indicate the rapid expansion of soybean cultivation (Donner, 2003). "As the total planted area of maize and wheat decreased with total cropland area from 1950 to 1992, by 33,661 km^2 (10%) and 23,224 km^2 (7%), respectively, there was a 343% increase (186,830 km^2) in the planted area of soybeans" (p. 345, Donner, 2003). The total area for soybean production increased by 17.7% in 42 years from 54,339 km^2 in 1950 to 241,169 km^2 in 1992 (Fig. 1). It is evident in Fig. 1 that the large increase in soybean fractional area occurred in the Upper MR basin and that little change is seen in other regions in the USA except for a narrow region along the Atlantic coast. Increase of soybean cultivation in the upper MR basin states of Iowa (IA), Minnesota (MN), and Wisconsin (WI) in the last 60 years is particularly pronounced (Fig. 3). The area of IA, MN, and MI comprises 11.4% of the total area of the MR basin. Soybean expansion in these three states increased more than 1000%, from 1,947,000 acres in 1940 to 19,500,000 acres (USDA, 2004). Most land for soybeans came out of previously untilled land (pastures) or other sod-based crops (i.e. oats, alfalfa, and hay) (Jackson, 2002; Schilling and Libra, 2003). The balance of sod versus annual crops was about 50-50 through the 1950 s (Jackson, 2002).

Table 1
Summary of slopes, standard error and *p*-values for regression lines of annual discharge versus time at the gauging stations 1–8 in various regions of the United States

Gauging station	*N*	Slope (mm/yr)	*p*-Value
1. MR at Clinton, IA	63	1.07 ± 0.34	0.003
2. MR at St Louis, MO	63	0.48 ± 0.20	0.022
3. MR at Memphis, TN	46	0.98 ± 0.47	0.041
4. MR at Vicksburg, MS	58	0.79 ± 0.33	0.020
5. Columbia River at Dalles, WA	63	-0.24 ± 0.34	0.484
6. Rio Grande River at San Felipe, NM	63	0.09 ± 0.10	0.370
7. Savannah River at Augusta, GA	61	-0.25 ± 0.93	0.793
8. Sesquehanna River at Harrisburg, PA	62	-0.11 ± 0.81	0.897

The locations of these stations are shown in Fig. 1.

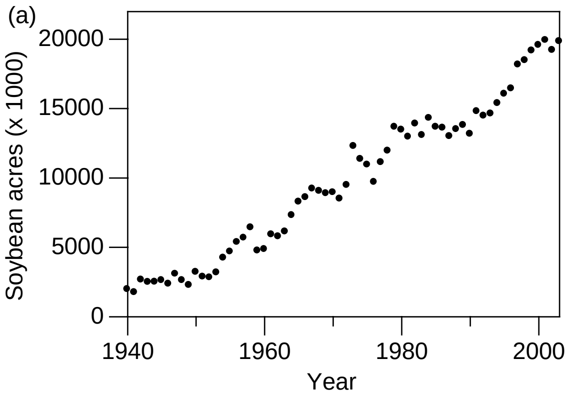

Fig. 3. Increase of soybean cultivation in Iowa (IA), Minnesota (MN), and Wisconsin (WI) from 1940 to 2003 (in thousands of acres).

In modern cropping systems with the expansion of fertilizers, soybeans are rotated annually with corn production. The two crops are often grouped together and designated as row crop. Hence, for all practical purposes, expansion of soybean cultivation in the MR basin is really the expansion of total land use for annual row crop production.

Accompanying the expansion of annual row crops, soil conservation practices began to be implemented by the US Soil Conservation Service after the 1930 s and 1940 s (Trimble and Lund, 1982; Johnson, 1991). Practices such as terraces, conservation tillage, and contour cropping, were installed to decrease soil erosion during storm events. These land use practices would also serve to increase water infiltration on row croplands since runoff is slowed or captured by the conservation practices. In turn, greater infiltration would increase groundwater levels and contribute to higher baseflow in streams. Effects of conservation practices on watershed hydrology have been observed in Midwestern row cropping systems. Gebert and Krug (1996) examined annual flood peak and the annual seven-day low flow records at 12 Wisconsin stream gauging stations and found that annual low flows increased and annual flood peaks decreased in many agriculture-dominated watersheds between about 1930 and 1991. In Iowa, an increase in baseflow and decrease in stormflow was measured in four small watersheds (<150 acres) in the loess hills of western Iowa over a 30-year period (Kramer et al., 1999). In these steeply sloping watersheds, hydrologic changes resulting from conservation tillage on highly erodible lands reduced sediment discharge from storm events and provided increased infiltration of precipitation and groundwater discharge to streams.

3. Effects of land use change on MR hydrology: increasing baseflow since 1940 s

Based on the above observations, we hypothesize that the changes in land use, particularly increased soybean production and accompanying soil conservation practices in the MR basin, have resulted in more groundwater recharge during the last 60 years. Consider the water balance for a large watershed (Gupta, 1989)

$$P - \mathrm{ET} - Q = \Delta S \tag{1}$$

where P is precipitation, ET is evapotranspiration, Q is streamflow out of the basin, and ΔS is the change in water storage in the basin. Eq. (1) does not take into consideration the pumpage or any other type of anthropogenic withdrawal because these withdrawals are negligible. According to Milly (2005) who estimated the major components of the water balance of the MR from 1949 to 1997, removal of groundwater in the basin is only 2 mm/year or 0.23% of the mean precipitation (835 mm/year). Over a long period of time (≥ 1 year), water storage stays more or less the same, i.e. $\Delta S \approx 0$ and thus $P = \mathrm{ET} + Q$. Comparing a basin covered by seasonal row crops to one covered by perennial vegetation (e.g. perennial crops, grasses or forest) under the same precipitation, one has $\mathrm{ET_S} + QS = \mathrm{ET_P} + Q_p$ where the subscript S stands for a basin covered by seasonal crops and P stands for perennial vegetation. Annual ET losses from a basin with seasonal row crops are generally smaller than ET losses from a basin with perennial vegetation because perennial vegetation transpires throughout the spring summer and fall, whereas seasonal crops, such as corn and soybeans, do not transpire until mid-growing season (Schilling and Libra, 2003; Dinnes, 2004). For example, single crop ET coefficients (K_c) reported by the United Nations (FAO, 1998) for various vegetation types vary substantially. Initial, mid-season, and late-season K_c

values for trees (0.50, 1.10, 0.65), rotational pasture (0.40, 1.50, 0.85) and fallow grass (0.85, 0.90, 0.90) show much greater ET in initial and late growing seasons compared to field corn (0.00, 1.20, 0.35) and soybeans (0.00, 1.15, 0.5). In a field study, Brye et al. (2000) compared the hydrologic budgets of restored native prairie and cultivated corn ecosystems and found that perennial grass maintained greater water content in the soil profile, had greater ET, and significantly less drainage through the soil profile. In Iowa, Dinnes (2004) compared the water demand of various cool and warm season annual and perennial vegetation types and found that perennial cool and warm season vegetation had an annual water demand 8–15% greater than warm season annual crops. A mix of cool and warm season perennial vegetation had an annual water demand 72% greater than warm season annual crops alone (Dinnes, 2004). Thus, we have $ET_S < ET_P$ and thus $Q_S > Q_P$. In other words, changing land cover from perennial vegetation to seasonal row crops would result in an increase in streamflow.

The increased cropland in the MR basin affected not only the amount of streamflow but also the proportion of stormflow and baseflow in the river. With less annual ET occurring in seasonally cropped fields (i.e. $ET_S < ET_P$) infiltrating water would be more available for groundwater recharge. Consider the water balance for the groundwater system under a watershed

$$R - BF = \Delta S_G \tag{2}$$

where R is the net recharge to groundwater, i.e. the recharge minus ET, BF is the baseflow, and ΔS_G is the change in groundwater storage in the watershed. Over a long period of time (≥ 1 year), $\Delta S_G \approx 0$ and thus $R = BF$. Comparing an aquifer system under a basin covered by seasonal row crops to one covered by perennial vegetation, we have $R_S > R_P$, and thus $BF_S > BF_P$. In other words, changing land cover from perennial vegetation to seasonal row crops would result in an increase in baseflow. In order to verify the above analysis, we selected four gauging stations in the Upper MR region (Cedar River, Illinois River, Wabash River, and Ohio River) (Stations 9–12 in Fig. 1) where largest increases in soybean cultivation have occurred, mainly in the states of Iowa, Illinois, Indiana, and Ohio and estimated their baseflow. The total soybean cultivation area for these four states increased 443% from 6,920,000 acres in 1940 to 30,650,000 acres in 2003 (USDA, 2004). Like the MR flow, annual streamflow at these four stations showed an increasing trend from 1940 to 2003 (upper row in Fig. 4). The streamflow in Cedar, Illinois, Wabash, and Ohio River at these four stations increased by 102, 46, 35, and 9.2%, respectively,

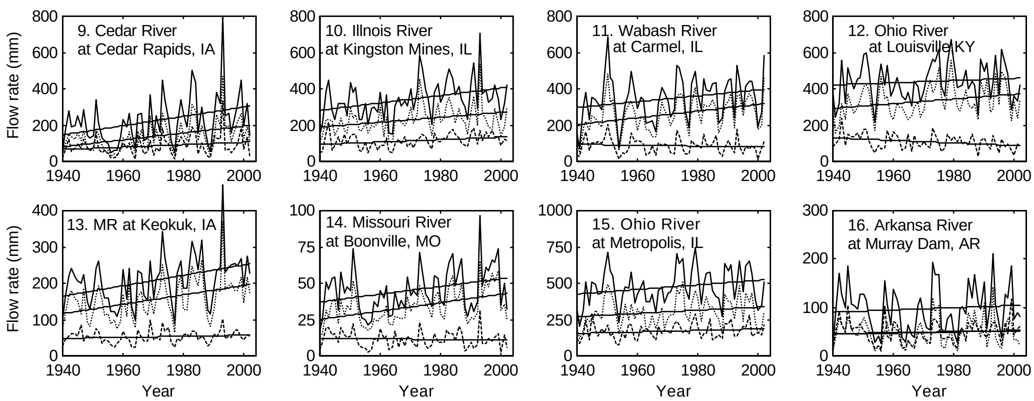

Fig. 4. Streamflow (solid curve), baseflow (dotted curve), and stormflow (dashed curve) from 1940 to 2003 at the four USGS gauging stations 9–12 in the upper Mississippi River basin where the largest change in soybean cover has occurred and at the four stations 13–16 in the Upper Mississippi and three major tributaries of Mississippi River (Missouri, Ohio, and Arkansas River). The streamflow is presented in millimeter or the annual discharge volume divided by the drainage area. The straight lines are fitted to the observed data by the least square (see Fig. 1 for the locations of the stations).

Table 2
Summary of slopes, standard error and *p*-values for regression lines of annual discharge, baseflow and stormflow versus time at the gauging stations 9–16 in various rivers

Gauging station	*n*	Annual discharge		Annual baseflow		Annual stormflow	
		Slope (mm/yr)	*p*-Value	Slope (mm/yr)	*p*-Value	Slope (mm/yr)	*p*-Value
9. Cedar River at Cedar Rapids, IA	63	2.37±0.83	0.006	1.75±0.50	0.001	0.62±0.36	0.090
10. Illinois River at Kingston Mines, IL	62	2.00±0.68	0.004	1.38±0.51	0.010	0.66±0.26	0.012
11. Wabash River at Carmel, IL	62	1.61±0.82	0.053	1.85±0.59	0.003	−0.24±0.29	0.409
12. Ohio River at Louisville, KY	62	0.60±0.70	0.391	1.30±0.57	0.027	−0.69±0.27	0.012
13. Mississippi River at Keokuk, IA	63	1.32±0.42	0.002	1.20±0.34	0.001	0.13±0.11	0.271
14. Missouri River at Boonville, MO	63	0.23±0.10	0.030	0.26±0.07	0.000	−0.03±0.04	0.402
15. Ohio River at Metropolis, IL	62	1.58±0.83	0.063	1.10±0.65	0.105	0.51±0.35	0.151
16. Arkansas River at Murray Dam, AR	62	0.23±0.33	0.485	0.11±0.20	0.584	00.12±0.16	0.461

The locations of these stations are shown in Fig. 1.

from 1940 to 2003 and all increasing trends were significant except for the Ohio River at Louisville (Table 2). Less change in *Q* at the Ohio River at Louisville is consistent with less conversion to seasonal row crops during the past 60 years in its drainage area (Fig. 1).

The daily river discharge at each of these four gauging stations was separated into SW and BF using a commonly used hydrograph separation program (Sloto and Crouse, 1996). The estimated BF (the dotted curves in upper row of Fig. 4) shows a consistent trend that is generally parallel to the streamflow trend but SW (the dashed curve) does not follow the streamflow trend. Regression analyses indicated a high degree of statistical significance in the BF trend in the Cedar, Illinois, Wabash and Ohio River (Table 2). The BF in Cedar, Illinois, Wabash, and Ohio River at the four locations increased by 134, 47, 59, and 28, respectively, from 1940 to 2003. The increase in stormflow is not significant in the Cedar and Wabash Rivers but is significant in the Illinois River and shows a significant decrease in the Ohio Rivers (Table 2). However, the slope of increased SW in the Illinois River is substantially less than the observed BF slope. These results indicate that the increasing streamflow in these rivers is mainly due to increased BF.

Furthermore, the increased BF is significantly related to increasing soybean acreage (Fig. 5). Regression of estimated BF in the MR at Keokuk, IA versus soybean fractional area in the Upper Mississippi River states of IA, MN and WI was highly significant ($p = 0.001$). The MR at Keokuk, IA station was selected for analysis because its drainage area comprises a large portion of the upper MR basin where the increase in soybean production occurred. The relation of baseflow to increased soybean production is consistent with trends observed in many interior Iowa rivers where regression of annual BF and BF percentage with annual row crop percentage for the 1940–2000 period was positive and highly significant ($p < 0.001$) (Schilling, 2004).

To determine if BF trends vary in the Mississippi River basin, we plotted the streamflow and estimated BF in the Upper Mississippi and three major tributaries of Mississippi River, i.e. Missouri, Ohio, and Arkansas River (lower row of Fig. 4). While precipitation increased slightly in these basins since

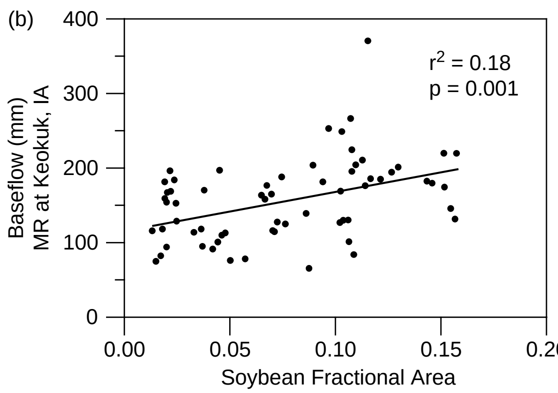

Fig. 5. Relation of soybean fractional area of IA, MN and WI with estimated BF in the MR at Keokuk, IA, 1940–2003.

1940 (<7.5%), streamflow and BF increased significantly in the Upper Mississippi and Missouri River basins ($p<0.05$, Table 2) and less significantly in the Ohio River ($p>0.05$). No significant trends in Q and BF were evident in the Arkansas River (Table 2). The streamflow increased by 51, 38, 24, and 9.3%, and the baseflow by 66, 65, 20, and 10.1%, respectively, at these four rivers from 1940 to 2003. The increases in Q and BF in the Upper Mississippi River at Keokuk, IA and in the Missouri River at Boonville, MO are larger than those in the Ohio River at Metropolis, IL and in Arkansas River at Murry Dam, AR. A greater proportion of the watersheds above the Keokuk and Boonville stations was converted to soybean areas than the Metropolis and Murry Dam drainage basins. The Arkansas River basin has had little increase in soybean production since 1950 (Fig. 1) and thus has had less increase in baseflow.

4. Changes in monthly streamflow, baseflow, and stormflow since 1940

Streamfow and baseflow vary significantly during a year due to seasonal weather changes and the seasonal variation in Q and BF should be affected by changes in land use. If increasing baseflow in the MR is the result of increasing annual vs. perennial vegetation, then seasonal variations in baseflow should correspond to differences in annual and perennial plant water demands. General patterns of water demand differ between annual and perennial plants and cool and warm season plants (Dinnes, 2004). Cool season plants, like perennial rye grass or annual oats, come out of dormancy in the spring after the soil thaws, go dormant in the heat of summer, and then become active again in the fall if not previously harvested. In contrast, the growing season of warm season crops like corn and soybeans, extend over the middle portion of the year and reach peak water demand in mid-summer (Dinnes, 2004). Considering that peak precipitation in the Upper MR basin occurs in spring and early summer, the water demand of annual row crops are not synchronous with peak rainfall periods and vulnerable leaching periods occur in the spring and fall (Dinnes et al., 2002; Power et al., 1998). Thus the conversion of perennial vegetation to annual row crops in the MR basin since 1940 s may have decreased ET and SR or SW, and increased R and BF, especially during the spring (March, April, and May) and late fall (October and November) when row crop fields are freshly plowed or fallow. It follows that baseflow increases in the MR should be greatest during these vulnerable leaching periods.

The monthly variations in Q and BF were examined for the MR at Keokuk, IA station. Based on the daily data, the estimated monthly baseflow in the MR at Keokuk is presented in Fig. 6 where the straight lines were fitted to show the long-term trends for each month in a year from 1940 to 2003. Similar to the long-term trends shown in Fig. 4, the estimated BF (the dotted curves in Fig. 6) for each month shows a consistent increasing trend that is generally parallel to the Q trend but SW (the dashed curve) does not follow the Q trend. Regression analyses indicated a higher degree of statistical significance in the BF trend for almost every month compared to Q and SW (Table 3). The monthly results indicate that the increasing streamflow in these rivers is a result of increased BF.

Based on the regression lines fitted to the data in Fig. 6, we calculated Q, BF, and SW of each month in1940 and 2003 (Fig. 7) in order to quantify the total changes that occurred during the last 63 years. Comparing Q, BF, and SW in 1940–2003, the amount of Q and BF significantly increased while SW changed comparatively little (Fig. 7). In both 1940 and 2003, the overall seasonal pattern of streamflow was evident, with greatest streamflow and baseflow occurring in the March to July period. It is evident that the largest increase in Q and BF occurred in May, since April exhibited highest Q in 1940, but May Q was highest in 2003 (Fig. 7).

The monthly changes in Q, BF, and SW from 1940 to 2003 at the Keokuk station are more clearly demonstrated in Fig. 8. Changes in Q and BF are large and all positive while the changes in SW are small and for some months (March, April, and June) are negative (Fig. 8). Large changes in BF occur in the spring, early summer, and late fall, as more precipitation was routed through groundwater. In April, for example, the change of BF (7.7 mm) is even larger than that in Q (5.8 mm), and the change in SW is negative (−1.9 mm) from 1940 to 2003. The largest increases in Q and BF (14.5 and 12.0 mm, respectively) are observed in May during this period (Fig. 8) because May is a month when abundant

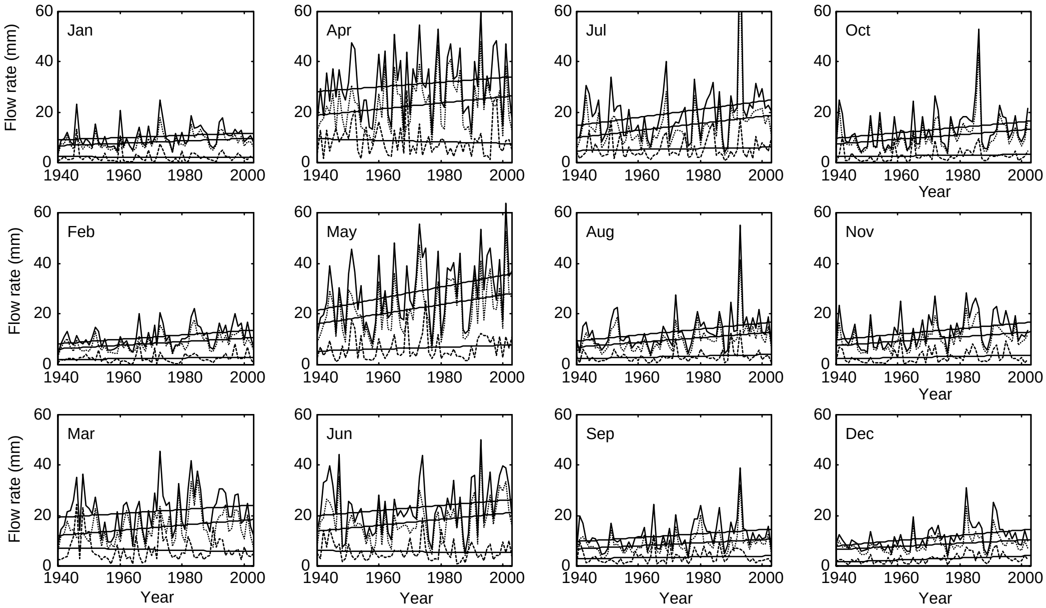

Fig. 6. Monthly streamflow (solid curve), baseflow (dotted curve), and stormflow (dashed curve) from 1940 to 2003 at the USGS gauging station at Keokuk, IA on Mississippi River. The streamflow is presented in millimeter or the monthly discharge volume divided by the drainage area. The straight lines are fitted to the observed data by the least square.

rainfall occurs on freshly plowed and newly planted cropped fields. ET would be at a minimum during this time. Less difference between 1940 and 2003 was noted in June when annual crops are transpiring at rates similar to perennial cool season vegetation. The late fall increase in Q and BF from 1940 to 2003 is consistent with greater leaching of water through fallow row crop fields. In general, the pattern of seasonal BF increases in the MR at Keokuk closely follows the periods of vulnerable leaching described by Dinnes et al. (2002) for Midwestern agricultural systems.

Table 3
Summary of slopes, standard error and p-values for regression lines of monthly discharge, baseflow and stormflow versus time at the MR at Keokuk gauging station ($n=63$)

Month	Annual discharge		Annual baseflow		Annual stormflow	
	Slope (mm/yr)	p-Value	Slope (mm/yr)	p-Value	Slope (mm/yr)	p-Value
Jan	0.00173±0.0012	0.143	0.00187±0.0073	0.013	−0.0001±0.0006	0.863
Feb	0.00338±0.0011	0.002	0.00275±0.0078	0.001	0.0006±0.0005	0.191
Mar	0.00310±0.0022	0.165	0.00404±0.0016	0.018	−0.0010±0.0013	0.458
Apr	0.00318±0.0032	0.263	0.00483±0.0026	0.072	−0.0012±0.0016	0.445
May	0.00905±0.0033	0.008	0.00752±0.0026	0.006	0.0015±0.0013	0.259
Jun	0.00405±0.0027	0.140	0.00457±0.0022	0.045	−0.0006±0.0010	0.566
Jul	0.00634±0.0032	0.056	0.00552±0.0026	0.037	0.0008±0.0011	0.438
Aug	0.00464±0.0019	0.018	0.00365±0.0014	0.014	0.0010±0.0006	0.114
Sep	0.00309±0.0016	0.050	0.00242±0.0012	0.043	0.0006±0.0007	0.335
Oct	0.00446±0.0021	0.036	0.00380±0.0016	0.022	0.0007±0.0007	0.318
Nov	0.00453±0.0016	0.006	0.00352±0.0011	0.003	0.0011±0.0007	0.110
Dec	0.00421±0.0012	0.001	0.00260±0.0009	0.005	0.0015±0.0004	0.001

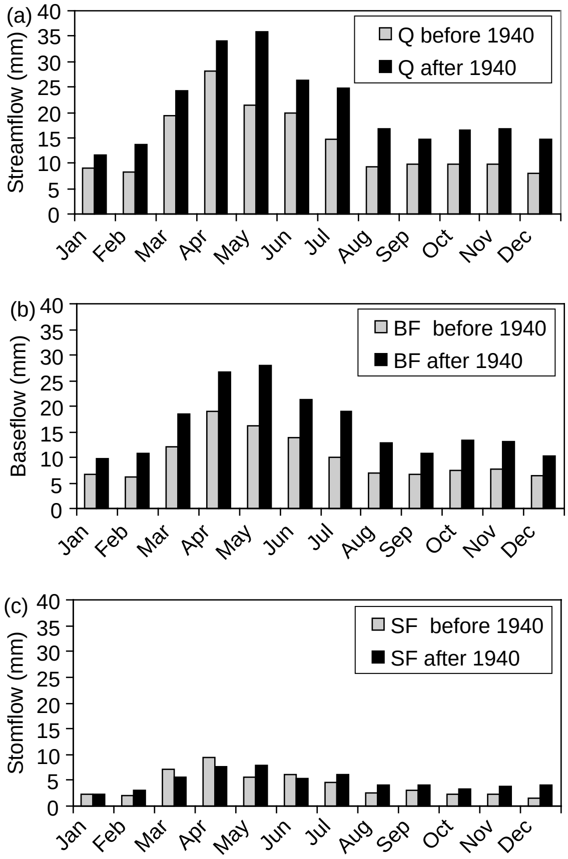

Fig. 7. Average monthly streamflow (a), baseflow (b) and stormflow (c) before 1940 (grey bars) and after 1940 (black bars) at the USGS gauging station at Keokuk, IA on Mississippi River.

Finally, it needs to be pointed out that hydrology and water and energy balance of the MR basin have been extensively investigated in the Global Energy and Water Cycle Experiment's (GEWEX)

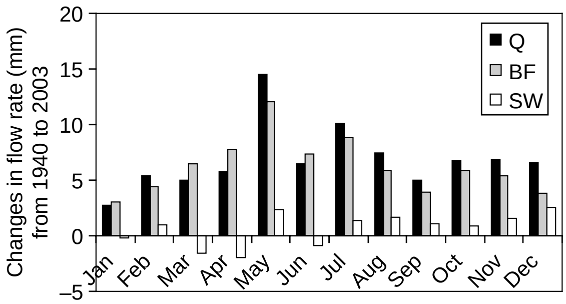

Fig. 8. Changes in the monthly streamflow (black bar), baseflow (grey bar), and stormflow (white bar) from 1940 to 2003 at the USGS gauging station at Keokuk, IA on Mississippi River.

Continental-Scale International Project (GCIP) started in 1995. Results from GCIP, covering observations, modeling, process studies, and water resources applications, were published in the special issues of the *Journal of Geophysical Research-Atmospheres* in 2003 (Robock, 2003). However, most GCIP studies were done for relatively short time periods, e.g. a few years. Moreover, there has been a lack of observed ET data with ET usually estimated as residuals of a water balance equation. In the most comprehensive report of GCIP (Roads et al., 2003) a water and energy synthesis (WEBS) of the MR basin was developed for the period of 1996–1999. In their study (Roads et al., 2003), the annual average evaporation was estimated by the difference between precipitation and runoff as well as from model simulations. As Roads et al. (2003) pointed out: "Observations cannot adequately characterize or "close" budgets since too many fundamental processes are missing… it did appear that we now qualitatively understand water and energy budgets of the Mississippi River Basin. However, there is still much quantitative uncertainty." We believe that evidence presented in this paper showing that increasing MR flow is mainly in its baseflow improves our understanding of MR hydrology and assists quantitative assessment of the main components of the MR basin water budget.

5. Conclusions

A trend of increasing streamflow was observed in the Mississippi River (MR) basin since 1940 s. While this trend has been noted elsewhere and ascribed to increasing precipitation occurring in the basin, herein, we observed that increasing MR flow from 1940 to 2003 was mainly due to an increase in baseflow. We posit that the baseflow increase was the result of land use change that occurred in the MR basin over the last 60 years during expansion of soybean cultivation. Conversion of perennial vegetation to seasonal row crops and accompanying agricultural activities that occurred in the MR basin since 1940 s decreased evapotranspiration and surface runoff, and increased groundwater recharge, baseflow, and thus streamflow. Our results are consistent with previous studies (Jordan et al., 1997; Lins and Slack, 1999; Schilling and Libra, 2003) that showed increasing minimum streamflow trends in the United States (Lins and Slack, 1999) and particularly in Iowa (Schilling and Libra, 2003). A close examination of daily stream flow for the past 60 years found that increasing trends were most prevalent in the annual minimum to median flows and least prevalent in the annual maximum flows (Lins and Slack, 1999).

The results from this study are important in efforts to reduce nutrient export in river water since nutrient concentrations and loads carried by storm water and baseflow are different. Studies show that nitrate concentrations increased and the concentration of organic N and C decreased as the proportion of cropland increased or as the proportion of baseflow increased (Jordan et al., 1997; Schilling and Libra, 2003) since nitrate is primarily delivered to streams with groundwater discharge (Hallberg, 1987; Schilling, 2002). Understanding of temporal changes and trends in streamflow and the proportion of stormflow and baseflow is critically important in directing efforts in managing land use, in improving agricultural practices, and in reducing nutrient levels in the Mississippi River and other major rivers in the United States and the world (Alexander et al., 2000; Goolsby, 2000; Peterson et al., 2001; McIsaac et al., 2002).

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References

Alexander, R.B., Smith, R.A., Schwarz, G.E., 2000. Effect of stream channel size on the delivery of nitrogen to the Gulf of Mexico. Nature 403, 758–761.

Brye, K.R., Norman, J.M., Bundy, L.G., Gower, S.T., 2000. Water budget evaluation of prairie and maize ecosystems. Soil Sci. Soc. Am. J. 64, 715–724.

Copeland, J.H., Pielke, R.A., Kittel, T.G., 1996. Potential climate impacts of vegetation changes: a regional modeling study. J. Geophys. Res. 101, 7409.

Dinnes, D.L., 2004. Assessments of Practices to Reduce Nitrogen and Phosphorus Nonpoint Source Pollution of Iowa's Surface Waters. Iowa Department of Natural Resources, Des Moines, Iowa.

Dinnes, D.L., Karlen, D.B., Jaynes, T.C., Kasper, J.L., Hatfield, T.S., Colvin, D., Cambardella, C.A., 2002. Nitrogen management strategies to reduce nitrate leaching in tile-drained Midwestern soils. Agron. J. 94, 153.

Donner, S., 2003. The impact of cropland cover on river nutrient levels in the Mississippi River Basin. Global Ecol. Biogeogr. 12, 341.

Food and Agriculture Organization of the United Nations (FAO), 1998. Crop Evapotranspiration, Guidelines for Computing Crop Water Requirements. FAO Irrigation and Drainage Paper 56. Food and Agriculture Organization of the United Nations, Rome, Italy.

Gebert, W.A., Krug, W.R., 1996. Streamflow trends in Wisconsin's driftless area. Water Resour. Bull. 32, 733.

Goolsby, D.A., 2000. Mississippi Basin nitrogen flux believed to cause Gulf hypoxia: EOS. Am. Geophys. Union Trans. 81, 321.

Greenpeace International, 1995. Climate change and river flooding. Special Report.

Gupta, R.S., 1989. Hydrology and Hydraulic System. Prentice–Hall, Englewood Cliffs, NJ.

Hallberg, GR., 1987 In: D'Itri, F.M., Wolfson, L.G. (Eds.), Rural Ground Water Contamination. Lewis Publishers, Chelsea, Michigan.

Houghton, J.T., Meira Filho, L.G., Callander, B.A., Harris, N., Kattenberg, A., Maskell, K. (Eds.), 1996. Climate Change 1995: The Science of Climate Change. Cambridge University Press, Cambridge.

Intergovernmental Panel on Climate Change (IPCC), 2001. In: Houghton, J.T., et al. (Ed.), Climate change 2001: The Scientific Basis. Cambridge University Press, Cambridge.

Jackson, L.L., 2002. Restoring prairie processes to farmlands. In: Jackson, D.L., Jackson, L.L. (Eds.), The Farm and Natural Habitat. Island Press, Washington, DC.

Johnson, L.C., 1991. Soil Conservation in Wisconsin: Birth to Rebirth. Department of Soil Science, University of Wisconsin, Madison.

Jordan, T.E., Correll, D.L., Weller, D.E., 1997. Relating nutrient discharges from watersheds to land use and streamflow variability. Water Resour. Res. 33, 2579.

Keeney, D., Muller, M., 2000. Nitrogen and the Upper Mississippi River. Institute for Agriculture and Trade Policy, Minneapolis, Minnesoda.

Knox, L.C., 2001. Agricultural influence on landscape sensitivity in the Upper Mississippi River valley. Catena 42, 193–224.

Kramer, L.A., Burkart, M.A., Meek, D.W., Jaquis, R.J., James, D.E., 1999. Field-scale watershed evaluations in deep-loess soils: II. Hydrologic responses to different agricultural land management systems. J. Soil Water Conserv. 54, 705–710.

Lins, H.F., Slack, J.R., 1999. Streamflow trends in the United States. Geophys. Res. Lett. 26, 227.

McIsaac, G., David, M.B., Gertner, G.Z., Goolsby, D.A., 2002. Nitrate flux in the Mississippi river. Nature 414, 166.

Milly, P.C.D., 2005. Trends in the Water Budget of the Mississippi River Basin, 1949–1997. USGS Fact Sheet 2005–3020.

Peterson, B.J., Wollheim, W.M., Mulholland, P.J., Webster, J.R., Meyer, J.L., Tank, J.L., Martõ, E., Bowden, W.B., Valett, H.M., Hershey, A.E., McDowell, W.H., Dodds, W.K., Hamilton, S.K., Gregory, S., Morrall, D.D., 2001. Control of nitrogen export from watersheds by headwater streams. Science 292, 86.

Peterson, B.J., Holmes, R.M., McClelland, J.W., Vorosmarth, C.J., Lammers, R.B., Shiklomanov, A.I., Shiklomanov, I.A., Rahmstor, S., 2002. Increasing river discharge to the Arctic Ocean. Science 298, 2171.

Potter, K.W., 1991. Hydrological impacts of changing land management practices in a moderate-sized agricultural catchment. Water Resour. Res. 27, 845.

Power, J.F., Flowerday, A.D., Wiese, R.A., Watts, D.G., 1998. Agricultural Nitrogen Management to Protect Water Quality. Bulletin 4. USDA-CSREES-IDEA, Washington, DC.

Ramankutty, N., Foley, J.A., 1999. Estimating historical changes in global land cover: Croplands from 1700 to 1992. Global Biogeochem. Cycles 13, 997.

Raymond, P.A., Cole, J.J., 2003. Increase in the export of alkalinity from North America's largest river. Science 301, 88.

Roads, J.O., Lawford, R., Bainto, E., Berbery, E., Chen, S., Fekete, B., Gallo, K., Grundstein, A., Higgins, W., Kanamitsu, M., Krajewski, W., Lakshmi, V., Leathers, D., Lettenmaier, D., Luo, L., Maurer, E., Meyers, T., Miller, D., Mitchell, K., Mote, T., Pinker, R., Reichler, T., Robinson, D., Robock, A., Smith, J., Srinivasan, G., Verdin, K., Vinnikov, K., Vonder Haar, T., Vörösmarty, C., Williams, S., Yarosh, E., 2003. GCIP water and energy budget synthesis (WEBS). J. Geophys. Res. 108 (D16), 8609. doi:10.1029/2002JD002583.

Robock, A., 2003. Preface to special section: GEWEX Continental-Scale International Project (GCIP)-3. J. Geophys. Res. 108 (D16), 8605. doi:10.1029/2003JD003924.

Schilling, K.E., 2002. Chemical transport from paired agricultural and restored prairie watersheds. J. Environ. Qual. 31, 1846.

Schilling, K.E., 2004. Relation of baseflow to row crop intensity in Iowa. Agric. Ecosys. Environ. 105, 433.

Schilling, K.E., Libra, R.D., 2003. Increased baseflow in Iowa over the second half of the 20th century. J. Am. Water Res. Assoc. 39, 851.

Sloto, R.A., Crouse, M.Y., 1996. US Geological Survey Water Resources Investigation Report 96-4040. United States Geological Survey, Lemoyne, Pennsylvania.

Trimble, S.W., Lund, S.W., 1982. Soil conservation and the reduction of erosion and sedimentation in the Coon Creek basin, Wisconsin. US Geological Survey Professional Paper 1234.

US Department of Agriculture (USDA), 2004. National Agricultural Statistics Service. http://www.usda.gov/nass/.