Journal of Hydrology 387 (2010) 343–345

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Technical note

Quantifying the effect of land use land cover change on increasing discharge in the Upper Mississippi River

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ARTICLE INFO

Article history:
Received 26 January 2010
Received in revised form 12 April 2010
Accepted 19 April 2010

This manuscript was handled by K. Georgakakos, Editor-in-Chief, with the assistance of V. Lakshmi, Associate Editor

Keywords:
Land cover land use change
Mississippi River
Row crop
Streamflow
Agricultural hydrology

SUMMARY

There is convincing evidence that land use/land cover (LULC) change has contributed to increasing discharge in the Upper Mississippi River Basin (UMRB) but key details remain unresolved. In this study, we extend our previous work (Zhang and Schilling, 2006) to quantify how much of the increasing discharge was due to LULC change. We examined daily streamflow for the 1890–2003 period from the US Geological Survey stream gage at Keokuk, Iowa and compiled county agricultural statistics for soybean production in the watershed above the gage to quantify how much of the change in the relation of discharge to precipitation was due to increased soybean cultivation. By allowing the slope of the discharge–precipitation relationship to be a function of the area of the UMRB planted in soybean, we determined that increasing soybean acreage increased the slope of q_t–P_t by 32%. With row crop expansion anticipated from ethanol production, increasing agricultural production is expected to result in increased water yield and nutrient export. Results provide important benchmarks for assessing the significance of LULC change on the regional water and climate patterns in the UMRB.

1. Introduction

Discharge has been increasing in the Mississippi River more than increasing precipitation alone can explain (Raymond et al., 2008; Zhang and Schilling, 2006). Changes in agricultural management have been invoked to explain the residual difference. Raymond et al. (2008) argued that changing agricultural practices have led to a 50 $km^3\,yr^{-1}$ increase in water flux from the Mississippi River from a pre- to post-disturbance period (before and after 1940). Zhang and Schilling (2006) concluded that increasing discharge since the 1940s was mainly due to an increase in baseflow resulting from land cover land use (LULC) change from perennial vegetation to seasonal cropping systems. Specifically, LULC change involved rapid expansion of soybean cultivation that occurred in the Mississippi River basin during the middle of the 20th century (343% increase from 1950 to 1992; Donner et. al., 2003). Much of the soybean increase was concentrated in the Upper Mississippi River Basin (UMRB) (Fig. 1). Accompanying the expansion of total row crop area (combined maize and soybean in crop rotation), was increased fertilizer application in the UMRB, that together transformed the nitrogen cycle in the Mississippi River basin (Donner, 2004). With increased water and nitrogen flux, it was no surprise when recent assessment suggests that the UMRB now contributes about 43% of total nitrogen to the Gulf of Mexico despite representing only about 15% of the land area (USEPA, 2007).

Despite the convergence of understanding that (1) discharge has increased in the UMRB; and (2) LULC change contributed substantially to increasing discharge, the effect of LULC on increasing streamflow has not been quantified. A key question to address is how much of the increase in discharge was attributable to LULC change, specifically, the large increase in soybean cultivation that occurred in the UMRB? Although Zhang and Schilling (2006) correlated increasing baseflow in the Upper Mississippi River to increasing soybean acreage, correlation does not address causation. Thus, the objective of this study was to extend previous work and specifically quantify the effect.

It is important to quantify the magnitude of the LULC effect on increasing discharge in the UMRB because of anticipated change in the Corn-Belt region associated with growing biomass energy crops for ethanol production. In the near term, corn acreage is expected to increase and offset acreage devoted to soybean and other crops, including grasslands enrolled in the Conservation Reserve Program (Tokgoz et al., 2007). Beyond the next decade, another shift in LULC may occur when production of ethanol from cellulosic biomass becomes commercialized and energy crops become viable such switchgrass (Sanderson et al., 2006) or Miscanthus (Heaton et al., 2008). Improved understanding and quantification of the

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doi:10.1016/j.jhydrol.2010.04.019

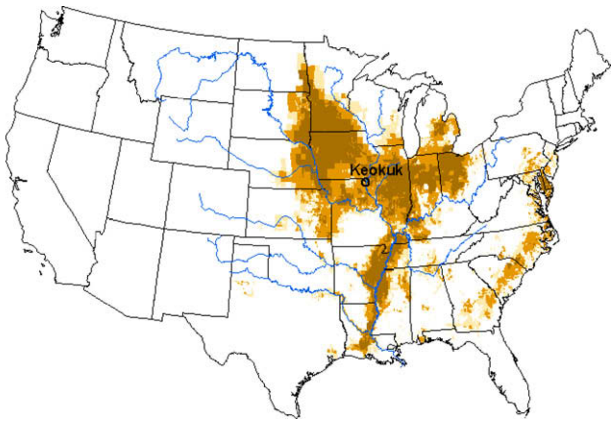

Fig. 1. Change in the fractional area of soybean from 1950 to 1992. The fraction represents the percent of each 5′ × 5′ grid cell covered by soybean. The four scales are used: white (fraction <2%), light brown (2–5%), brown (5–15%), dark brown (>15%). Also shown in the figure is the location of Keokuk gauging station at Mississippi River. (for interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

historical effects of LULC change on discharge in the UMRB will assist in predicting future consequences. While changes in discharge in the future will affect nutrient delivery to the Gulf of Mexico (Raymond et al., 2008; Turner and Rabalais, 1991), LULC changes may also affect climate and weather patterns in the US Corn-Belt region (Carleton et al., 2008) and play a key role in various climate change assessments (Jha et al., 2004; Feddema et al., 2005; Barnes and Roy, 2008).

2. Data

Daily streamflow for the 1890–2003 period from the US Geological Survey stream gage on the Mississippi River at Keokuk, Iowa (Lat 40°23′37″, Long 91°22′27″) was used in this study (Fig. 1). The drainage area of 308,210 km^2 includes portions of four states (Minnesota, Wisconsin, Iowa and Illinois) in the Corn-Belt region of the US for our analysis, daily discharge was summed to annual values. Since discharge (Q) is log-normally distributed, our analyses evaluated the logarithmically transformed river flow, i.e., $q_t = \log Q_t$. Annual precipitation from 12 weather stations in the region was obtained from the National Oceanic Atmospheric Administration ftp site (ftp://ftp.ncdc.noaa.gov/pub/data/cirs/drd964x.pcpst.txt) and averaged together for the analysis. Available precipitation information began in 1895, so the effective period of hydrologic analysis was from 1895 to 2003. Precipitation was divided by discharge to evaluate changes in the q_t–P_t relationship in this study (Fig. 2).

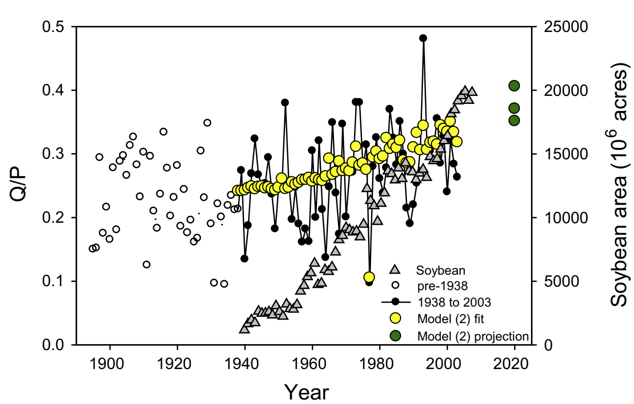

Fig. 2. The relation of discharge (Q) to precipitation (P) for the Mississippi River at Keokuk gauging station from 1890 to 2003. Also shown is the total area of soybean cultivation in Iowa, Wisconsin, and Minnesota from 1938 to 2003 (gray triangles) in million acres. Model (2) simulation results are shown as are three future LULC projections for year 2020.

Annual county agricultural statistics for the period from 1927 to 2003 were obtained from the National Agricultural Statistics Service database (NASS, 2003). The number of acres planted in soybean in the UMRB drainage area above Keokuk, Iowa was summed on an annual basis. The area of soybean cultivation increased more than 1000% from 1938 to 2003 (Fig. 2).

3. Analyses and results

We selected the year 1938 as the starting year for the analysis since this year represented the first reported planting of soybeans in the NASS database. The threshold year of 1938 is consistent with previous work that has assumed a start date of hydrologic changes occurring around 1940–1941 (Raymond et al., 2008; Zhang and Schilling, 2006; Lins and Slack, 1999; McCabe and Wolock, 2002).

To address our objective, we considered a model that allowed the slope of the q_t–P_t relationship to be a function of the area of planted soybean, A_t:

$$q_t = \lambda_0 + \lambda_P P_t + s(A_t)P_t + \lambda_D D_t + \varepsilon_t \tag{1}$$

where the slope of P_t equals $\lambda_P + s(A_t)$, i.e. it varies with the area of planted soybean possibly nonlinearly; $s(A_t)$ is a smooth function that has zero mean over the data, and the error terms are assumed to be uncorrelated over time (justification of the white-noise assumption is provided below). The sum, $\lambda_P + s(A_t)$, is the varying rate of change of P_t per unit change in q_t. Analysis suggested that 1977 (drought year) was an additive outlier so a dummy variable ($D_{t,}$) was included in the model, where D_t, equals 1 in 1977 and 0 otherwise. Model (1) is a variant of the Generalized Additive Model (GAM) (Green and Silverman, 1994; Wood and Augustin, 2002; Wood, 2006). We estimated this model using the GAM function of the mgcv library of R. The smooth function $s(A_t)$ can be non-parametrically estimated via a penalized least-squares approach which determines the smoothness of the function estimate. In particular, it is found that the penalized least-squares estimate of $s(A_t)$ is essentially a straight line. Substituting $\lambda_P + s(A_t) = \lambda_P + \lambda_{A,P}A_t$ into model (1), we get

$$q_t = \lambda_0 + \lambda_P P_t + \lambda_{A,P} A_t P_t + \lambda_D D_t + \varepsilon_t \tag{2}$$

which has an interaction term A_tP_t in the model. Model estimates are provided in Table 1. Note that the estimate of $\lambda_{A,P}$ equals 5.79×10^{-7} and was significant, at 5% significance level, showing that the slope of the q_t–P_t relationship was significantly affected by the area of planted soybean. The area of planted soybean increased from virtually nil in late 1930s to nearly 20 million acres in 2003 (Fig. 2), According to Model (2), the slope of the q_t–P_t relationship in year t equaled $\lambda_P + s(A_t)$, and changed from 0.0359 in 1938 to 0.0474 by 2003 indicating a 32% change in slope.

We fitted model (2) with the error term following an AR(1) process, but the AR(1) coefficient was found to be insignificant, and thus justifies specifying the error term in Models (1) and (2) to be temporally uncorrelated. Note that Model (2) provides a good

Table 1
Estimates of model (2) fitted by the GAM function of the GNU software R. Coefficient estimates that are significant at 5% level are bold-faced.

	Intercept	Slope	Interaction (times 10^{-7})	Outlier	Noise variance
Model (2)	**15.8** (0.27)	**0.0359** (0.0083)	**5.79** (1.7)	−**1.06** (0.24)	0.0557

fit to the discharge-precipitation pattern ($R^2 = 46.3\%$), with the noise being independent and normally distributed with noise variance of 0.0557 (Table 1). Model diagnostics (unreported) confirm that the residuals are normally distributed and uncorrelated over time. The good fit of Model (2) is due, in part, because the model represents a continuous increase in the slope of the q_t–p_t relationship and not a step change as implied by other analytical models. Hence, Model (2) extends the analysis beyond simply indicating a change has occurred to providing a description of the mechanism that effected the change.

The 32% change estimated in this study is similar to the 30% increase in bicarbonate flux estimated for the Mississippi River due to mechanisms other than precipitation, such as recovery from acidification and anthropogenic alterations (Raymond et al., 2008). Raymond et al. (2008) listed several potential agricultural practices that might be altering discharge, including tile drainage, fertilizer use, irrigation, tillage practices, and changes in crop type, rotation and productivity. Of these practices, our results suggest that the ∼30% increase in water flux in the UMRB may be produced by LULC change alone.

With future LULC change on the horizon due to anticipated ethanol expansion, we used Model (2) to project changes in Mississippi River discharge with increasing soybean acreage. It should be noted that in this analysis we emphasize the increase in soybean acreage, it should be stressed that increasing soybean production is largely a surrogate measure of increasing row crop production since maize and soybean are annual crops that are often in rotation. In the next decade (by the year 2020) given average precipitation (31.5 in. or 800.1 mm; avg. 1980–2003) and soybean acreage expansion by 10%, 25% and 50%, the relation of q_t–P_t may be expected to increase to 0.35, 0.37 and 0.41, respectively (Fig. 2). This would represent a major increase in water yield from the UMRB and ultimately serve to increase pollutant export of nitrate, phosphorus and sediment. In the Raccoon River in west-central Iowa, model simulations of increasing corn acreage due to ethanol expansion from 2% to 18% suggested nitrate and phosphorus losses would increase to nearly 34 kg/ha and 1.5 kg/ha, respectively, and sediment loss would increase from 3.5 to more than 5 T/ha (Schilling et al., 2008). Overall, LULC change from increasing soybean (row crop) production in the UMRB affects the basin-scale water balance in many ways, and future work will consider how LULC changes have contributed to increasing discharge, changing seasonal and annual evapotranspiration patterns, increasing tile drainage, changing tillage practices, and modifying fertilizer and nutrient management (Raymond et al., 2008; Zhang and Schilling, 2006; Donner, 2004).

4. Summary and Conclusions

Statistical analysis of annual discharge and precipitation in the Mississippi River at Keokuk from 1895 to 2003 indicated that increasing soybean acreage in the UMRB increased the slope of q_t–P_t by 32%. This result is consistent with the work of Raymond et al. (2008) who suggested that LULC and management changes in the Mississippi River basin were more important than climate change to increases in river flux. Quantification of the magnitude of soybean influence on increasing streamflow is an important benchmark for assessing the significance of LULC change on the regional water and climate patterns in the UMRB. With future LULC changes anticipated from expanding ethanol production, historical effects provide a preview of future consequences that should be anticipated.

Acknowledgements

The work of KSC and YKZ was partly supported by the Obermann Center for Advanced Studies, the University of Iowa (IDRG 2004). Calvin Wolter plotted Fig. 1 with land cover data provided by Simon Donner.

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