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Roles of climate and agricultural practices in discharge changes in an agricultural watershed in Iowa

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ABSTRACT

River discharge represents a vital resource for many human activities. The improved understanding of the physical processes controlling its regime can lead to large economic and societal benefits, such as improved flood warning and mitigation, and improved water management during droughts. This is particularly true for the agricultural U.S. Midwest and Iowa more specifically. Iowa is relentlessly plagued by catastrophic flooding, with the spring and summer river floods of 1993, 2008, and 2013 and the drought of 2012 being the most recent widespread events affecting the state. These natural disasters also come with a very large price tag, both in terms of economic damage and fatalities.

During the 20th and 21st centuries, discharge over this area has been changing on a number of temporal scales, from annual to decadal. An outstanding question is related to the contribution of changes in the climate system and in land use/land cover and agricultural practices in explaining changes in discharge. We address this question by developing statistical models to describe the changes in different parts of the discharge distribution. We use rainfall and harvested corn and soybean acreage to explain the observed stream flow variability. We focus on the Raccoon River at Van Meter, which is a 9000-km^2 watershed with daily discharge measurements covering most of the 20th century up to the present. Our results indicate that rainfall variability is responsible for the majority of the changes observed in the discharge record, with changes in cultivated area affecting the discharge responses in different ways, depending on which part of the discharge distribution is considered. In particular, land use change exacerbates high discharge during heavy precipitation and low discharge during low precipitation.

1. Introduction

The examination of changes in discharge over the U.S. Midwest is a subject of intense scientific investigation because this area is plagued by a large number of hydrometeorological extremes, ranging from flooding to drought. The most recent examples are the flood events in 2011 and 2013, separated by the drought in 2012. Too much or too little water has profound societal and economic impacts in this highly agricultural region. During the 20th and 21st centuries, discharge over this area has been changing on a number of temporal scales, from annual to decadal (e.g., Hu et al., 1998; Mauget, 2003a,b). Improved understanding of the factors contributing to these changes will be highly beneficial for improving flood warning and mitigation, as well as water management during droughts.

A number of studies have examined historical discharge records over the U.S. Midwest trying to assess whether the stream flow changes where predominantly driven by changes in land use/land cover (LULC; mostly related to changes in agricultural practices), river engineering work (e.g., construction of dams), or climatic changes (e.g., Villarini et al., 2011). Among all these studies, different conclusions related to the main driver of change were reached depending on the research. Changnon and Kunkel (1995) examined 79 stream gage stations over the U.S. Midwest with daily data over the period 1921–1985. Their results suggest that flood magnitude tends to increase or decrease in a similar manner to heavy rainfall. On the other hand, Changnon and Demissie (1996) found that changes in LULC masked the effects that increasing precipitation would have in mean and peak discharge. Steffens and Franz (2012) examined changes in several discharge quantities for ten watersheds in Iowa covering a period up to the year 2002. While discharge increased, most of the changes were for low to moderate

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flow, rather than extremes, consistent with what found in other studies as well (e.g., Douglas et al., 2000; McCabe and Wolock, 2002; Lins and Slack, 1999, 2005). They also discuss the possible relationship between the increases in discharge and rainfall over the area. Novotny and Stefan (2007) analyzed the discharge records for 36 streamgage stations with records between 53 and 101 years and ending by the year 2002. They identified changes in all the flow quantities they examined, which they mostly related to variability in precipitation. Hirsch and Ryberg (2012) focused on the relation between flooding and global mean carbon dioxide concentration, without finding a strong relation between these two quantities over the central United States. Tomer and Schilling (2009) analyzed the discharge records in four watersheds in the U.S. Midwest and found that the role played by climate in describing the changes in discharge increased over time. Ryberg et al. (2013) and Frans et al. (2013) both indicated that climate change is the dominant factor in explaining changes in runoff over the U.S. Midwest.

While the aforementioned research identified climate as the main agent of change, other studies focused their attention to LULC changes. Gebert and Krug (1996) highlighted that just changes in rainfall could not explain the changes in flood peaks over the Driftless Area (southwestern Wisconsin). These results are similar to the findings in Potter (1991). For the same region, Juckem et al. (2008) concluded that climate acts in controlling the timing and direction of the changes, while changes in agricultural land management resulted in an amplification of the hydrologic response to both baseflow and stormflow. Zhang and Schilling (2006) found that most of the increases in the Mississippi River Basin since 1940s are largely driven by changes in baseflow, which they related to changes in land use (i.e., expansion of soybean cultivation). These conclusions are similar to what described in Schilling and Libra (2003), Schilling (2005), Raymond et al. (2008) and Schilling et al. (2010), to cite just a few. These large changes in agricultural practices were found to have large implications in the water balance of watersheds in the U.S. Midwest (e.g., Schilling et al., 2008). Xu et al. (2013) found that streamflow changes were more related to climate variability, while changes in baseflow were controlled by changes in LULC. By focusing on watersheds without trends in climate, however, Xu et al. (2013) found that LULC change were responsible for the increasing trends in stream flow and base flow, cautioning about the potential impact of biofuel production on hydrology.

As indicated by this brief overview, changes in climate and LULC are identified as the main drivers for the changes in discharge over the U.S. Midwest, even though their relative contribution differs from study to study. Some of these differences are related to the different quantities analyzed (e.g., annual maximum peak discharge, monthly runoff, stormflow and baseflow), to discharge records located in different parts of the U.S. Midwest, and different methodological approaches (e.g., using statistical models and tests, hydrologic models). As discussed in Merz et al. (2012), the issue of attribution of changes in the discharge records requires "more efforts and scientific rigour." Here, we focus on a watershed in Iowa, the Raccoon River at Van Meter, for which the U.S. Geological Survey (USGS) has been collecting daily data since the early 20th century. Rather than focusing on a particular summary statistic of the discharge distribution (e.g., median flow, annual maximum), we examine changes in all the quantiles. This work considers the effects of changes in rainfall and agricultural practices and their relative contributions to the observed changes in the discharge distribution.

This paper is organized as follows. In Section 2 we describe the area of interest, the data used, and the statistical framework for the attribution of the changes in discharge. Section 3 describes the results of our analyses, followed by summary and conclusions, which are presented in Section 4.

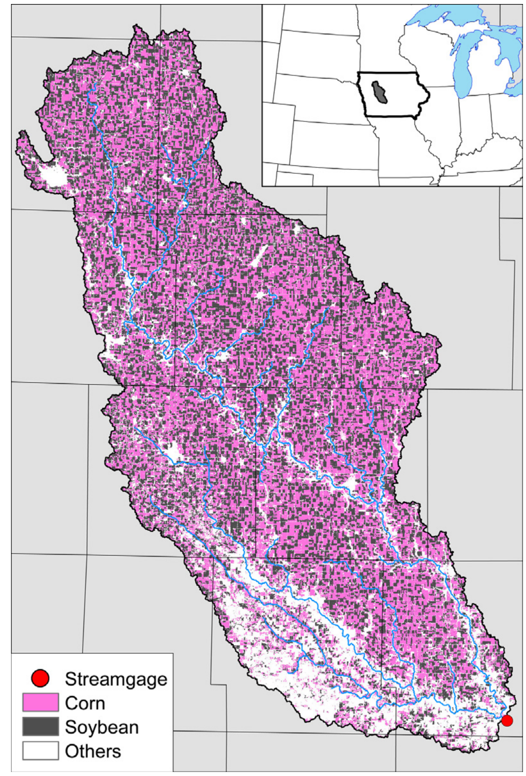

Fig. 1. Map showing the basin boundaries of the Raccoon River at van Meter (USGS 05484500). The land cover refers to the year 2002 and highlights that most of the watershed is cultivated with corn and soybean. Inset map: Location of the study area within the continental United States.

2. Data and methodology

2.1. Study area and covariates

This study focuses on the statistical modeling of the discharge record for the Raccoon River at Van Meter (USGS 05484500) in Iowa (Fig. 1). It has a drainage area of approximately 3441 mi^2 (8912 km^2) and daily discharge data have been collected from 1915 to the present. Based on the metadata from the USGS, there is no indication of river regulation by dam, water withdrawal for irrigation purposes, or significant urbanization. We focus on the period 1927–2012 because of the availability of agriculture-related data during this period. The record collected at this stream gage station exhibits large variations over the study period, with the 1940s and the years after 1970 with larger discharge (figure not shown), consistent with what documented by Ryberg et al. (2013) both in terms of precipitation and runoff. Given this daily average discharge record, we compute all the quantiles from $Q_{0.00}$ (yearly minimum daily discharge) to $Q_{1.00}$ (yearly maximum daily discharge) with a step of 0.05 for each calendar year (i.e., if the interest is in describing the temporal changes in the $Q_{0.50}$, from the daily data we compute the median for 1927, 1928, . . .). This is similar to the approach by Lins and Slack (1999, 2005). By creating these time series, we examine the role played by rainfall and agricultural practices in controlling the inter-annual variability in different parts of the discharge distribution.

Rainfall is used to assess the climate impacts on the changes in discharge over time. The rainfall data are created by means of the Parameter-elevation Regression on Independent Slopes Model (PRISM) climate mapping system (Daly et al., 2004). Rainfall information is available at the monthly scale over the continental United States, with a spatial resolution of about 4 km. This product represents the official climatological data for the U.S. Department

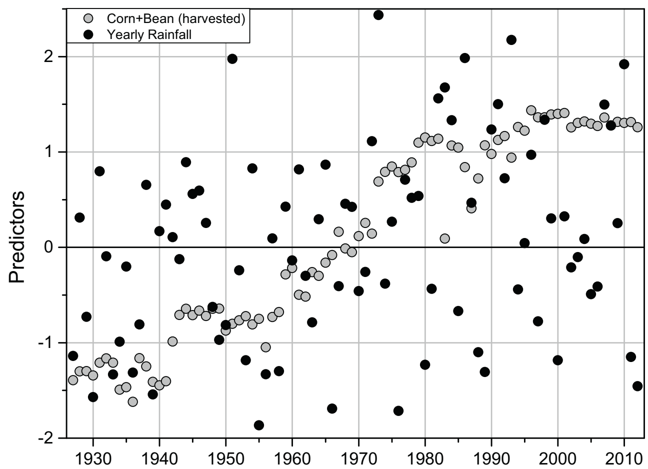

Fig. 2. Time series of the standardized anomalies of the two predictors (yearly rainfall, and corn and soybean harvested area) used in the statistical modeling of discharge. The standardized anomalies are computed with respect to the period 1927–2005.

of Agriculture (USDA; http://www.prism.oregonstate.edu/). We aggregate the rainfall data to the watershed level, and create basin-averaged monthly rainfall time series. The monthly rainfall is then aggregated at the yearly scale, which showed a higher Kendall's tau correlation with discharge than rainfall aggregated over the June–August or April–September periods.

To examine the impact of LULC changes, we use data related to harvested corn and soybean acreage (see also Tomer and Schilling (2009)) available from the National Agricultural Statistics Services (NASS) database from USDA to construct time series for the watershed. The NASS data are available at the county level. We assume that farmed area is uniformly distributed across each county, and use the proportion of the counties contained within the watershed to construct watershed level LULC data. Because this variable is measured in acres, we construct the watershed acres by multiplying the county level acres by the proportion of the county in the watershed.

Because of the largely different scales of variation between these two predictors, we standardize them by removing the mean and dividing by the standard deviation computed over the 1927–2005 period. Fig. 2 shows the time series of the standardized anomalies for these two predictors. Yearly rainfall exhibits a large degree of variability from one year to the next, much more marked than for harvested corn and soybean area. We can also identify a shift in the mean of the rainfall record around 1970; application of the Pettitt test (Pettitt, 1979) identifies an abrupt change in the mean in 1967, significant at the 10% level. The presence of a step change in rainfall and discharge was also discussed in Juckem et al. (2008) and McCabe and Wolock (2002), among others. The pattern exhibited by the agricultural predictor is different. Beside the aforementioned lack of variability, the changes over time in this covariate can be described by a sigmoidal function. There are three main regions, from 1927 to the 1940s, then a sharp increase roughly until late 1970s/early 1980s, and then another plateau.

2.2. Statistical modeling

Let Q_i indicate the predictand. In this study, it represents the time series of quantiles of the discharge distribution, from annual minimum ($Q_{0.00}$) to annual maximum ($Q_{1.00}$) daily average discharge, with a step of 0.05 (i.e., if the interest is in describing the temporal changes in the $Q_{0.50}$, from the daily data we compute the median for 1927, 1928, ...; this time series will represent the quantity to be modeled). Focusing on a specific quantile, we can model Q_i by means of a gamma distribution (as parameterized in the Generalized Additive Models for Location, Scale and Shape (GAMLSS); Rigby and Stasinopoulos, 2005)

$$f_{Q_i}(q_i|\mu_i,\sigma_i)=\frac{1}{\left(\sigma_i^2\mu_i\right)^{1/\sigma_i^2}}\frac{q_i^{(1/\sigma_i^2)-1}\exp\left[-q_i/\left(\sigma_i^2\mu_i\right)\right]}{\Gamma\left(1/\sigma_i^2\right)} \tag{1}$$

The location parameter μ_i and the scale parameter σ_i are allowed to vary over time as a linear function of predictors $x_1, x_2, \ldots x_n$ using a logarithmic link function. As mentioned before, we will consider two predictors, yearly rainfall (x_r) and harvested corn and soybean acreage (x_a) to reflect the effects of climate and agricultural practices and LULC changes. We include an interaction term in order to quantify the effects of agricultural practice on changes in discharge. Agricultural land does not, by itself, impact discharge but may interact with precipitation to change the distribution of discharge. The dependence of the parameters on the covariates can be written as:

$$\begin{aligned}\mu_{it}&=\log\left(\alpha_{0i}+\alpha_{1i}x_{rt}+\alpha_{2i}x_{rt}\cdot x_{at}\right)\\ \sigma_{it}&=\log\left(\beta_{0i}+\beta_{1i}x_{rt}+\beta_{2i}x_{rt}\cdot x_{at}\right)\end{aligned} \tag{2}$$

The parameters μ_i and σ_i are strictly positive and the logarithmic link function ensures that this condition is met. The expected value of Q_i is equal to μ_i and the variance is equal to $\mu_i^2\sigma_i^2$.

The gamma distribution was selected because it is continuous, only defined over the positive axis and very flexible (it can describe data that are from highly positively skewed to almost symmetric). Even though more complex non-linear dependencies between the parameters and predictors could have been considered, as shown later, the gamma distribution with the location and scale parameters linearly dependent on x_a and x_r is able to well describe the changes over time in the discharge quantiles (see also Schilling et al. (2010)). It is worth clarifying that both of the predictors are enforced in Eq. (2), regardless of whether their coefficients are significantly different from zero. This approach is similar to what presented in Schilling et al. (2010) for the Mississippi River at Keokuk with some key differences. First of all, they focus only on the logarithm of annually aggregated discharge while we consider a number of different discharge quantiles without transformation; they analyzed the period 1938–2003 and excluded 1977 (considered to be an outlier) while we modeled the entire record from 1927 to 2012.

We assess the quality of the fit of the models for all the quantiles by examining the model's residuals. These residuals should be independent and identically distributed white noise if the model is able to describe all the systematic information in the data. This is accomplished by computing the first four moments of the residuals, their Filliben correlation coefficient (Filliben, 1975), and through visual examination of residual plots, in particular quantile–quantile (qq)-plots and worm plots (van Buuren and Fredriks, 2001). The Filliben correlation coefficient represents the correlation coefficient between the order statistics of the residuals and those of a standard normal distribution. Worm plots represent detrended forms of qq-plots, in which a flat worm supports the choice of the selected model; they display the differences between the empirical and theoretical quantiles on the vertical axis against the theoretical quantiles on the horizontal axis. Because of sampling variability, in particular for the high and low quantiles, the points should be within the 95% confidence intervals. For more information about model selection and fitting, the interested reader is pointed to Stasinopoulos and Rigby (2007). All the calculations are performed in `R` (R Development Core Team, 2012) using the freely available `gamlss` package (Stasinopoulos et al., 2007).

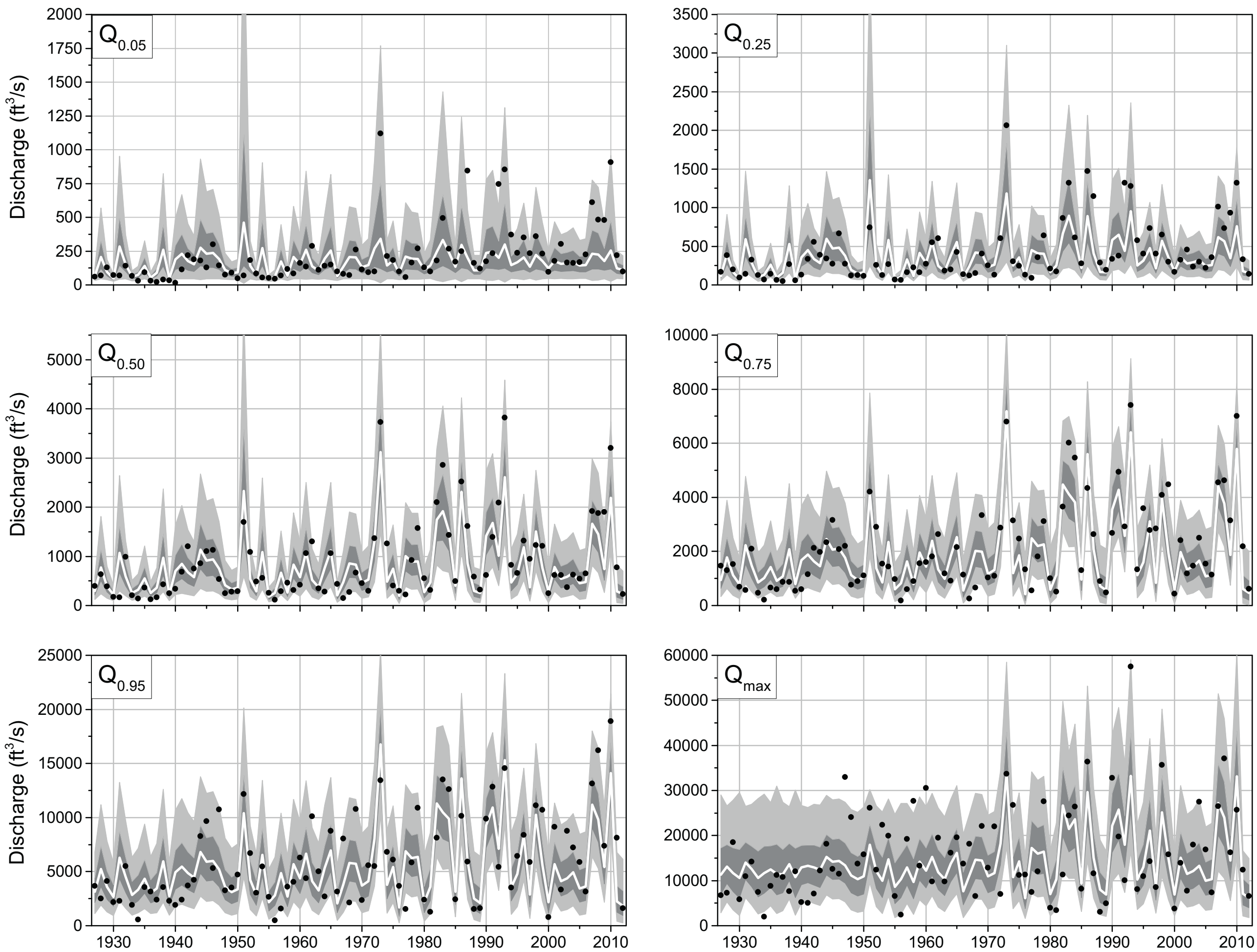

Fig. 3. Results of the statistical modeling of different discharge quantiles over time using yearly rainfall and total harvested corn and soybean area as predictors. The parameters of the gamma distribution depend linearly on the predictors (via a logarithmic link function). The white line represents the median (50th percentile), the dark grey region the area between the 25th and 75th percentiles, while the light grey region the area between the 5th and 95th percentiles.

3. Results

The attribution of the changes in discharge in terms of climate and LULC changes is evaluated using the statistical framework presented in the previous section. Fig. 3 shows the results of the modeling of different quantiles (from low to high) in terms of the two predictors. These models are able to describe very well the temporal variability exhibited by the discharge quantiles, capturing well both the periods of high and low values. Moreover, while the median of the fitted models is able to reproduce the observational records well, the area within the 5th and 95th percentiles is also generally rather narrow around it, indicating that the possible range of values around our best estimate (the median) is limited and well constrained by the model. This provides supporting evidence of the fact that these models are able to capture the signal contained in the discharge records. We have also performed an extensive evaluation of the goodness-of-fit of each of these models. We have examined the statistical properties of the residuals, both in terms of their statistical moments (Table 1) and visual examination of residual plots (Fig. 4). The four moments of the residuals as well as their Filliben correlation coefficient indicate that they can be described by a standard Gaussian distribution. Moreover, the shape of the "worm" in the worm plots is rather flat providing supporting evidence of the goodness of fit of our model. Based on all these diagnostics, the analyses of the residuals support the goodness of these models.

The examination of the dependence of the two parameters of the gamma distribution on the predictors for different discharge quantiles allows the examination of what controls the changes in magnitude and variability (Fig. 5). The intercept α_0 of the location parameter increases monotonically for increasing quantiles as expected, given that the expected value of the gamma distribution is equal to the parameter μ. On the other hand, the intercept parameter β_0 for the scale parameter does not present strong dependence on the quantile of the discharge distribution, with a tendency towards smaller values for increasing quantiles. The dependence

Table 1
Summary of the first four moments of the residuals and their Filliben correlation coefficient for the modeling of different discharge quantiles.

Quantile	Mean	Variance	Skewness	Kurtosis	Filliben
0.00	0.00	1.01	0.16	3.28	0.997
0.05	0.00	1.01	−0.07	2.92	0.998
0.10	−0.01	1.00	0.04	2.91	0.995
0.15	0.00	1.01	0.14	3.09	0.994
0.20	0.00	1.01	0.14	2.87	0.995
0.25	0.00	1.01	0.13	2.77	0.995
0.30	0.00	1.01	0.14	2.57	0.996
0.35	0.00	1.01	0.03	2.42	0.996
0.40	0.00	1.01	0.01	2.39	0.996
0.45	0.00	1.01	−0.02	2.37	0.996
0.50	0.00	1.02	−0.13	2.40	0.995
0.55	0.01	1.02	−0.27	2.56	0.993
0.60	0.01	1.03	−0.30	2.69	0.993
0.65	0.02	1.04	−0.39	2.77	0.990
0.70	0.02	1.04	−0.51	2.92	0.989
0.75	0.01	1.03	−0.48	3.04	0.991
0.80	0.01	1.03	−0.51	3.06	0.989
0.85	0.01	1.02	−0.52	3.06	0.989
0.90	0.01	1.02	−0.43	3.04	0.992
0.95	0.01	1.02	−0.45	2.99	0.992
1.00	0.00	1.01	0.01	2.32	0.995

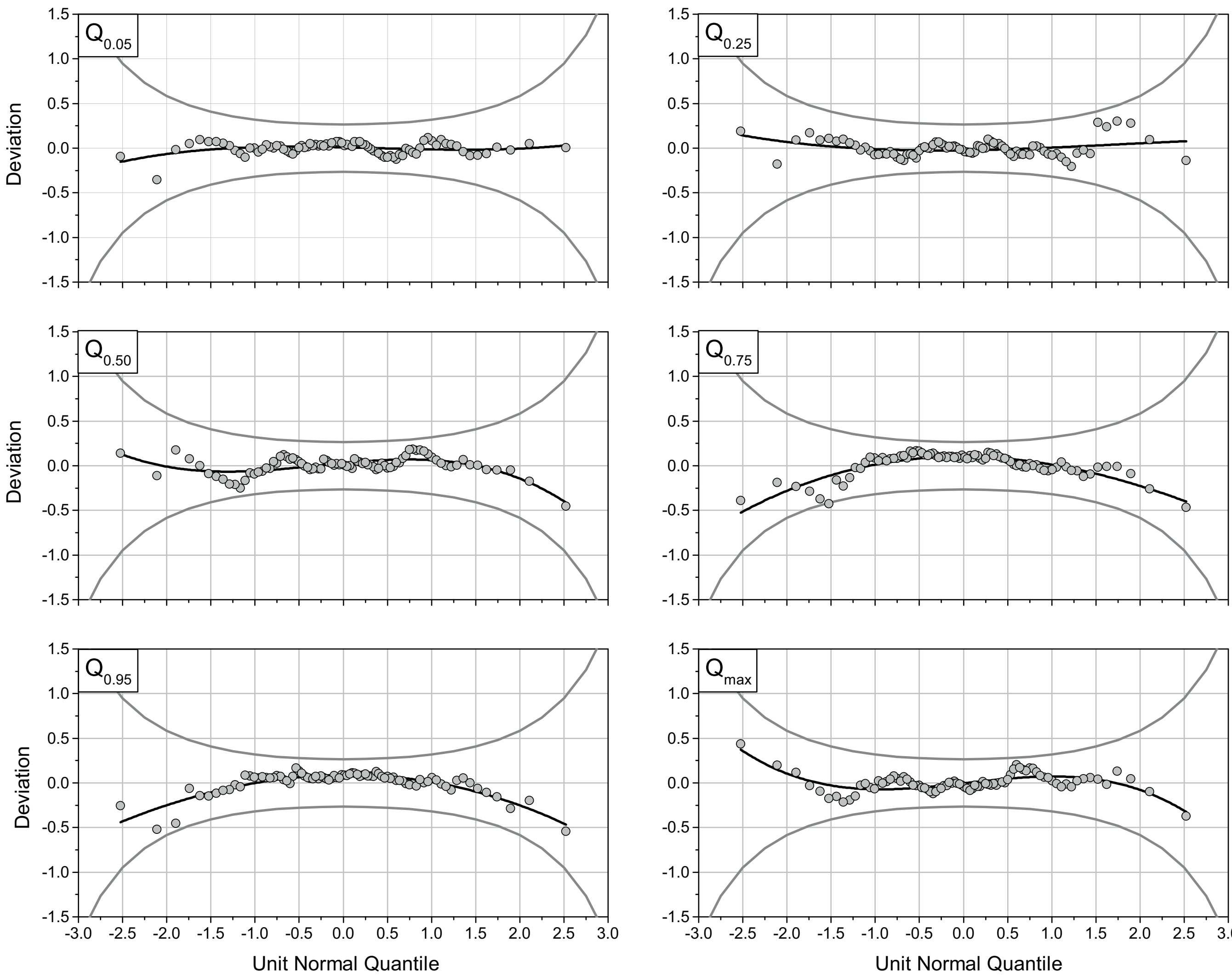

Fig. 4. Worm plots for the models in Fig. 3.

of the coefficients α_1 and α_2 on the discharge quantiles provides some interesting insight on the controls exerted by each predictor on the changes in discharge magnitudes. As expected, rainfall is a significant and positive predictor for all the quantiles. On the other hand, the impact of LULC exerted through the interaction term highlights a different behavior for different quantile levels. For the first tercile of the discharge distribution, α_2 is significant and negative, indicating a reduction in mean discharge at low flow associated with the expansion of corn and soybean area. On the other hand, despite the fact that the coefficient for the interaction term is not significant, it changes sign as we move towards the upper quantiles. This transition occurs around the median, suggesting that the observed changes in agricultural practices in this watershed had the effect of decreasing the average discharge for the lower half of the discharge distribution and increasing it for the upper half, once we control for rainfall. This is particularly true for the annual maximum peak discharge, for which increases in cultivated areas results in large increases in flooding.

To assess the role of agriculture on the relationship between discharge and rainfall across different quantiles, our first experiment considers the marginal effect of changes in rainfall on the expect discharge across all quantiles. We consider the marginal effects of a change in rainfall on the percentage change in mean discharge between the year 2012 and five difference reference years of agricultural extent: 1927 (first year in this study), 1938 (first year in Schilling et al., 2010), and 1950, 1970, and 1980 because they represent three different periods in the agricultural development of this basin. Similar to Schilling et al. (2010), we construct:

$$\frac{[\alpha_{1i} + \alpha_{2i}x_a(2012)] - [\alpha_{1i} + \alpha_{2i}x_a(t)]}{\alpha_{1i} + \alpha_{2i}x_a(t)} \quad (t = 1927, 1938, 1950, 1970, 1980) \tag{3}$$

Fig. 6 summarizes the results for the various quantiles based on Eq. (3). For the lower half of the discharge distribution, there is up to a 60% reduction in the relation between discharge and rainfall. These impacts are more significant for lower quantiles and when comparing the current discharge-rainfall relation with respect to the earlier part of the record (see for instance the results with respect to 1927 and 1980). Therefore, at low quantiles, we see a reduction in the average impact of rainfall on discharge. As we move towards the central part of the distribution, these changes tend to be smaller regardless of the period we are comparing the current conditions to. This is consistent with the results in Fig. 5(bottom-left panel), in which the estimated coefficient for the interaction term α_2 is shown to be close to zero, resulting in small differences in discharge response based on Eq. (3). The changes in discharge response will eventually increase as we consider larger quantiles. For quantiles larger than the median, increases in cultivated area result in an amplification of the average impact of rainfall on discharge. This is particularly true for the annual maximum peak discharge (Fig. 6, right panel). Based on these modeling results, the changes in agricultural practice lead to over a seven-fold increase in rainfall contribution to the average annual maximum discharge when we compare 2012 with 1927. This magnification progressively decreases as we move forward in time due to changes in agricultural production, with minimal differences over the past 30 years. Schilling et al. (2010) found a 30% change in the slope of the relation between rainfall and discharge. Our results indicate that the impact of agriculture is different and of opposite sign depending on the quantity of interest, whether low or high flow. In particular, it appears that the largest impact is for the annual maximum discharge.

Our estimation strategy assumes that land use change only impacts discharge through its interaction with precipitation. As such, a second experiment considers

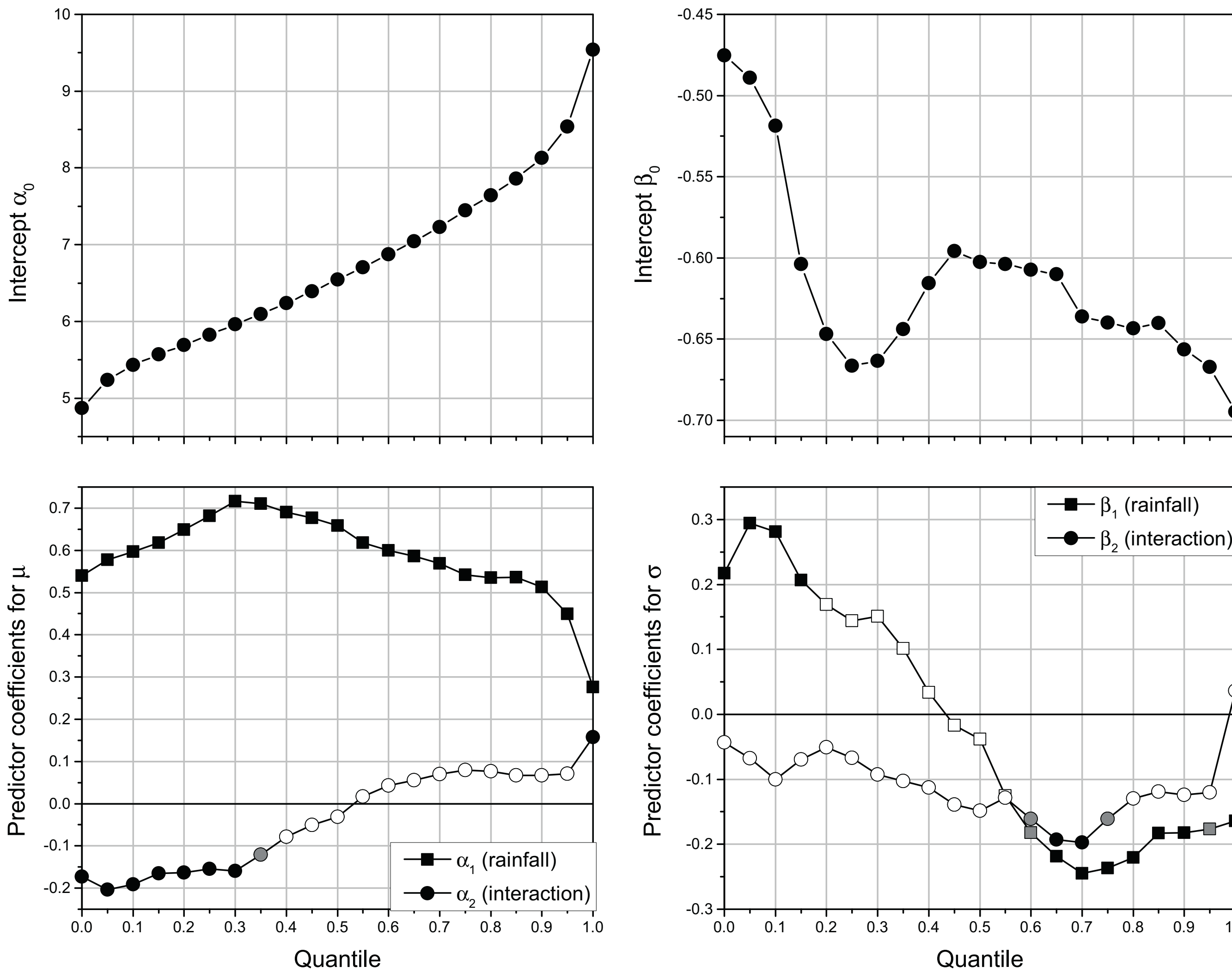

Fig. 5. Dependence of the parameters of the gamma models on the discharge quantiles. The dependence of the location μ and scale σ parameters are summarized in Eq. (2). The black (gray)-filled symbols indicate that the parameter is significant at the 5% (10%) level. The white symbols are for the case in which the parameter is not significant at the 10% level.

the impact of different agricultural practices on the entire distribution of discharges fixing rainfall at different levels within the data. Fig. 7(top panel) displays the distribution of discharge for agricultural practices in 1927, 1970 and 2012 given the rainfall that occurred in 1973, the wettest year based on our data. More specifically, we plot:

$$\mu_{it} = \log(\alpha_{0i} + \alpha_{1i}x_{r,1973} + \alpha_{2i}x_{r,1973} \cdot x_{at}) \tag{4}$$

with t equal to 1927, 1970, and 2012.

During times of heavy precipitation, increases in agricultural areas decreases discharge at the lower end of the discharge distribution. At the upper end of the distribution, increases in agricultural practices exacerbate the high flow, increasing the discharge by roughly 300% when we compare agricultural practices in 1927–2012. Fig. 7(bottom panel) performs the same experiment but considers rainfall conditions in 1955, the driest year in our dataset. In this case, we use the same formulation as in Eq. (4), with the only difference being that we use the rainfall value for 1955 ($x_{r,1955}$). During dry periods, increases in agricultural area increases (decreases) discharge at the low (high) end of the discharge distribution. The effects of agricultural practices are dependent not only on the amount of rainfall that occurs but also on where in the distribution of discharge we consider. There is not a monotonic relationship between agricultural practices and discharge.

While rainfall is a significant predictor for the μ parameter, this is not the case for the parameter σ, with the exception of low and high quantiles (Fig. 5, bottom-right panel). Moreover, the interaction term is not significant at the 5% level for the vast majority of the quantiles, suggesting that agriculture practice controls more the magnitude rather than the variability in discharge.

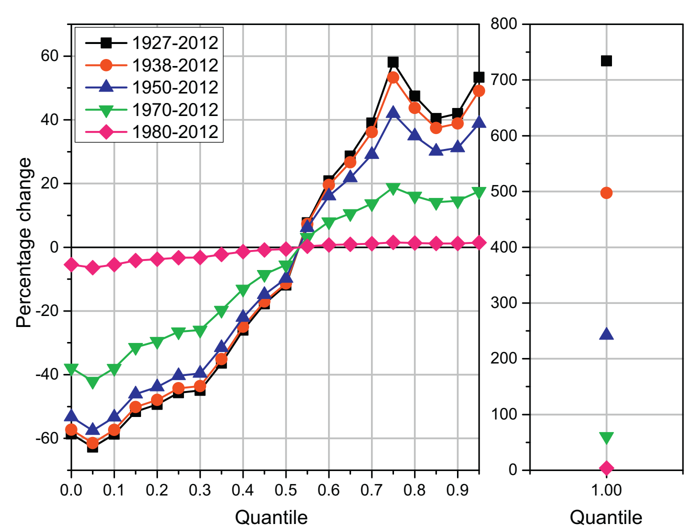

Fig. 6. Changes in the impact of cultivated area on the relation between rainfall and average discharge for different quantile levels between the year 2012 and five prior reference years (see legend) based on Eq. (3). The results in the right panel refer to the annual maximum peak discharge and are plotted separately from the other quantiles to increase readability.

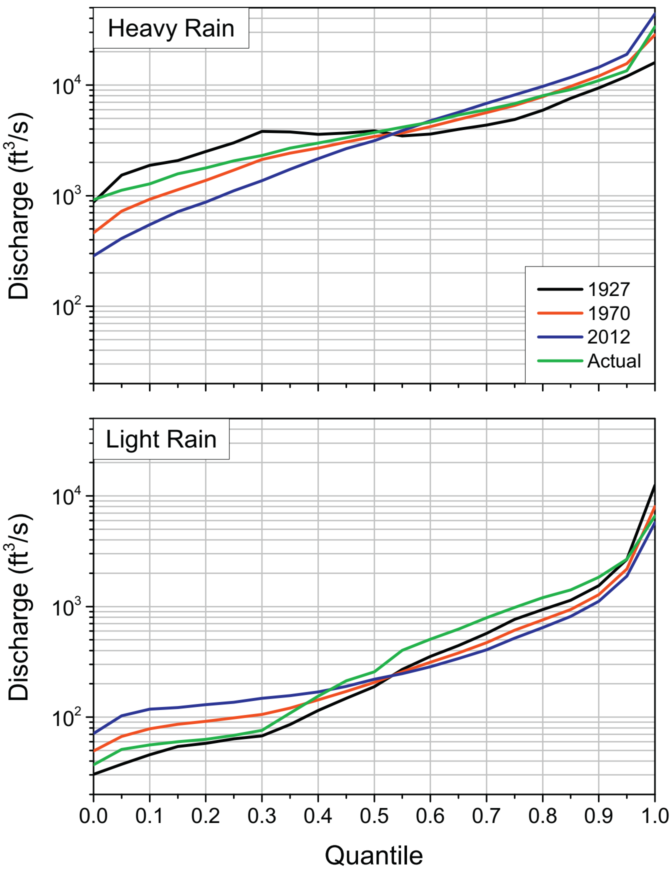

Fig. 7. Changes in the mean discharge of each quantile under two different precipitation regimes, heavy rain (1973) and light rain (1955), under various levels of agricultural practices. "Actual" refers to the discharge record observed in 1973 (top panel) and 1955 (bottom panel).

4. Conclusions

This study examined the role played by rainfall and changes in agricultural practice in explaining the observed changes in the discharge for the Raccoon River at Van Meter (Iowa) over the period 1927–2012. Rather than focusing on a specific quantile of the discharge distribution (e.g., annual maxima), we considered all the discharge quantiles from annual minima to maxima. In this way, we were able to assess whether the impact of climate and LULC changes was the same across the discharge distribution. To accomplish this task, we have developed a series of statistical models. More specifically, we fitted each discharge quantile record with a gamma distribution, the parameters of which were a function of one climate predictor (rainfall), and one covariate related to the interaction between rainfall and LULC. The models that we have developed using these two predictors were able to describe very well the variability exhibited by the observational discharge records at all quantiles. This was also supported by our examination of the goodness-of-fit of these models. Moreover, examination of the changes in the parameters of the gamma distribution indicated that agricultural practice exerts a negative feedback on the relation between rainfall and discharge at low quantiles and a positive one at high quantiles during periods of heavy rainfall, while the opposite holds during periods of light rainfall. On the other hand, if we do not consider different rainfall scenarios, we found that agricultural practices in this watershed had the effect of decreasing the average discharge for the lower half of the discharge distribution and increasing it for the upper half.

The implications of this work are twofold. First, in-stream flow may be an ecological concern during drought periods which is slightly mitigated by increases in agricultural acreage. The low flow scenarios would also have important implications when the river network is used for transportation of goods. But, as suggested by Schilling (2005), this may result in increases in nitrate concentrations in the stream. Second, flood conditions may be exacerbated by increases in agricultural production. This must all be balanced by the private concerns of increased revenue from agricultural production through increased cultivation.

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