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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.

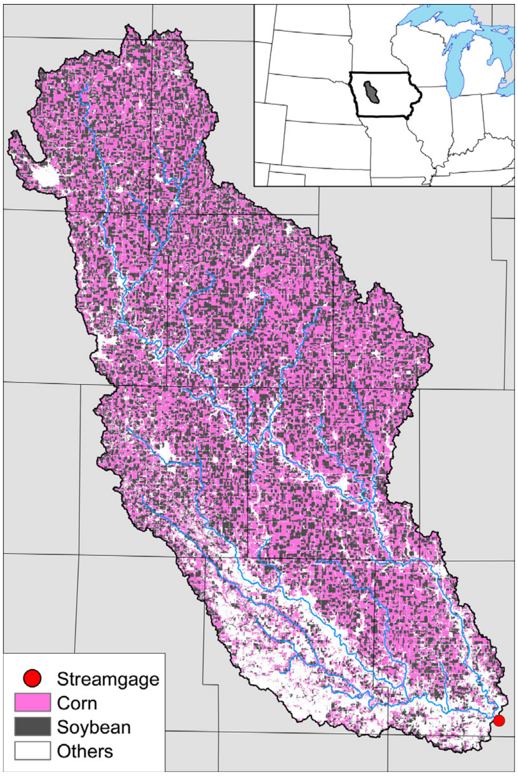

Fig. 1. Map showing the basin boundaries of the Raccoon River at van Meter (USGS 05484500). The land cover refers to the year 2002 and highlights that most of the watershed is cultivated with corn and soybean. Inset map: Location of the study area within the continental United States.

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