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Climate, water use, and land surface transformation in an irrigation intensive watershed—Streamflow responses from 1950 through 2010

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ABSTRACT

Climatic variability and land surface change have a wide range of effects on streamflow and are often difficult to separate. We analyzed long-term records of climate, land use and land cover, and re-constructed the water budget based on precipitation, groundwater levels, and water use from 1950 through 2010 in the Cimarron–Skeleton watershed and a portion of the Cimarron–Eagle Chief watershed in Oklahoma, an irrigation-intensive agricultural watershed in the Southern Great Plains, USA. Our results show that intensive irrigation through alluvial aquifer withdrawal modifies climatic feedback and alters streamflow response to precipitation. Increase in consumptive water use was associated with decreases in annual streamflow, while returning croplands to non-irrigated grasslands was associated with increases in streamflow. Along with groundwater withdrawal, anthropogenic-induced factors and activities contributed nearly half to the observed variability of annual streamflow. Streamflow was more responsive to precipitation during the period of intensive irrigation between 1965 and 1984 than the period of relatively lower water use between 1985 and 2010. The Cimarron River is transitioning from a historically flashy river to one that is more stable with a lower frequency of both high and low flow pulses, a higher baseflow, and an increased median flow due in part to the return of cropland to grassland. These results demonstrated the interrelationship among climate, land use, groundwater withdrawal and streamflow regime and the potential to design agricultural production systems and adjust irrigation to mitigate impact of increasing climate variability on streamflow in irrigation intensive agricultural watershed.

1. Introduction

Partitioning natural climate variation from anthropogenic-induced alteration to the hydrologic regime is a major challenge for water resource management in a human-dominated landscape (Matthews and Marsh-Matthews, 2003; Ellis et al., 2006). Anthropogenic activities can mimic, exacerbate, counteract, or mask the effects of climate on streamflow (Jones et al., 2012). Consequently, separating the effects of climate variability and anthropogenic change on streamflow is vital for water resource planning and environmental flow management under increasing climate variability (Chahine, 1992).

Intensive irrigation is an anthropogenic alteration that has been found to significantly alter climate in many areas (Sacks et al., 2009) although the feedback mechanisms involving atmospheric conditions and antecedent soil moisture that control evapotranspiration and runoff have not been thoroughly studied. Compensative water input through withdrawing groundwater characterizes crop production in water-limited ecosystems. From a water budget perspective, irrigation is a timed precipitation event cycled through surface water and groundwater exchange. It is unknown whether this added pathway of the water cycle increases or decreases streamflow response to natural inputs in precipitation. This topic is especially important when this added water cycle is sufficiently large compared to streamflow in alluvial aquifer dominated watersheds, such as the Cimarron–Skeleton watershed and lower portion

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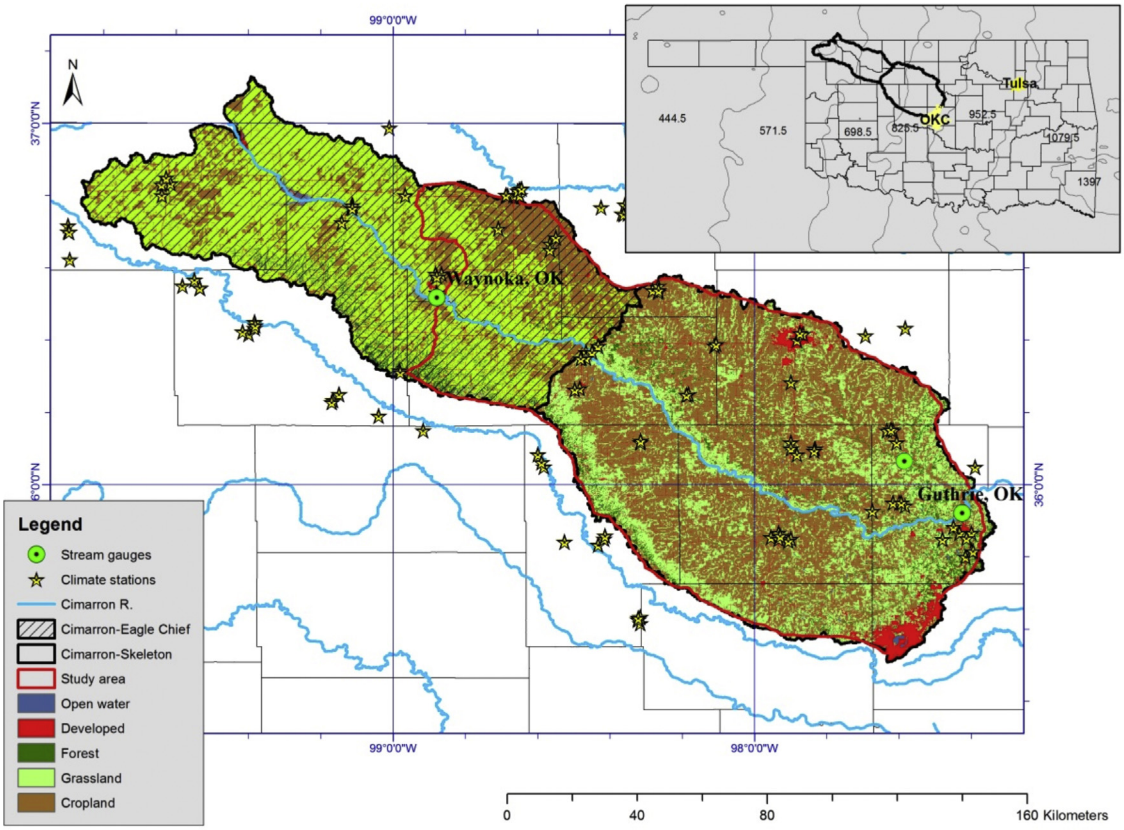

Fig. 1. Land use and land cover types, distribution of weather stations and gaging stations for the contribution area for the Guthrie gaging station (Cimarron–Skeleton watershed and a part of Cimarron–Eagle Chief watersheds). Inset: Precipitation isohyetal map over Oklahoma geographic map with bold line showing the relative location of the study area.

of the Cimarron–Eagle Chief watershed in the Southern Great Plains (Fig. 1).

The Cimarron River is one of a few virtually free-flowing rivers in the southern Great Plains (Moody et al., 1986). Its contributing region has been under intensive agricultural production since the mid to late nineteenth century (Cunfer, 2005), especially after the Land Run of April 22, 1889. The Cimarron Terrace and Alluvial aquifer is used for irrigation in the Cimarron–Skeleton watershed and lower portion of the Cimarron–Eagle Chief watershed and consists of quaternary and tertiary-aged river alluvium and terrace deposits of varying thickness (Bingham and Bergman, 1980). The deposits on the river's southwestern side are thin and are poor for irrigation, however, the deposits on the northeastern side of the river are considered one of the best alluvial aquifers in the state (Ryder, 1996), with fast exchange between surface and groundwater (Heeren et al., 2013). As a result, this alluvial-aquifer dominated watershed has been turned into a very productive agricultural region with substantial groundwater withdrawal to support row crop production. However, a recent study reported a downward trend in total annual streamflow and an increase in zero-flow time for the upper reach of this watershed over the last six decades despite an upward trend in precipitation (Esralew and Lewis, 2010). This decline in streamflow is potentially associated with declines of fish communities, and especially pelagic spawning minnows, including the federally listed Arkansas River shiner (*Notropis girardi*; Pigg, 1991; Wilde, 2002). This divergence of trends between precipitation and streamflow indicates an increasing role of anthropogenic-induced changes on streamflow responses.

A gradual but steady conversion of cropland back to rangeland has been a general trend for this watershed (Boren et al., 1997). However, these range lands have also undergone a rapid increase in encroachment by Eastern redcedar (*Juniperus virginiana*) and riparian gallery forest expansion since the 1980s (Wine and Zou, 2012), which are transforming the land surface into a woody state (Van Auken, 2009). In addition, an increase in urban area is a common trend for many watersheds in the southern Great Plains. Finally, the southern Great Plains has seen a rapid increase in surface water storage and flood control structure construction in the last 60 years as a result of the low relief and the dust bowl (Vance et al., 2010) in part, and for other uses such as soil conservation and agricultural use. All of those anthropogenic changes are intertwined with complicated feedback mechanisms on the hydrologic system (Mahmood et al., 2004; McPherson et al., 2004; Adegoke et al., 2007; DeAngelis et al., 2010; Fall et al., 2010; Wine et al., 2012; Ge and Zou, 2013), making it difficult to discern the effects of climate and anthropogenic-induced changes on streamflow.

The climate elasticity of streamflow provides a measure of the sensitivity of streamflow to changes in climate forcing, usually by assessing the proportional change in streamflow against the proportional change in precipitation and atmospheric demand (Sankarasubramanian et al., 2001). Knowing the contribution of climatic forcing on streamflow variation, one can compute a time series of streamflow sensitivity to anthropogenic activities as a whole and identify periods (or phases) when anthropogenic activities have affected streamflow. Such computation is essential for comparing and contrasting a range of hydrological metrics (e.g., high-flow frequency, low-flow counts, and base-flow index) important to environmental-flow management.

In the southern Great Plains of the U.S., as in many semi-arid regions of the world, a highly variable climate and increasing demand of water resources for multiple uses have made both the natural and production systems highly vulnerable to climate