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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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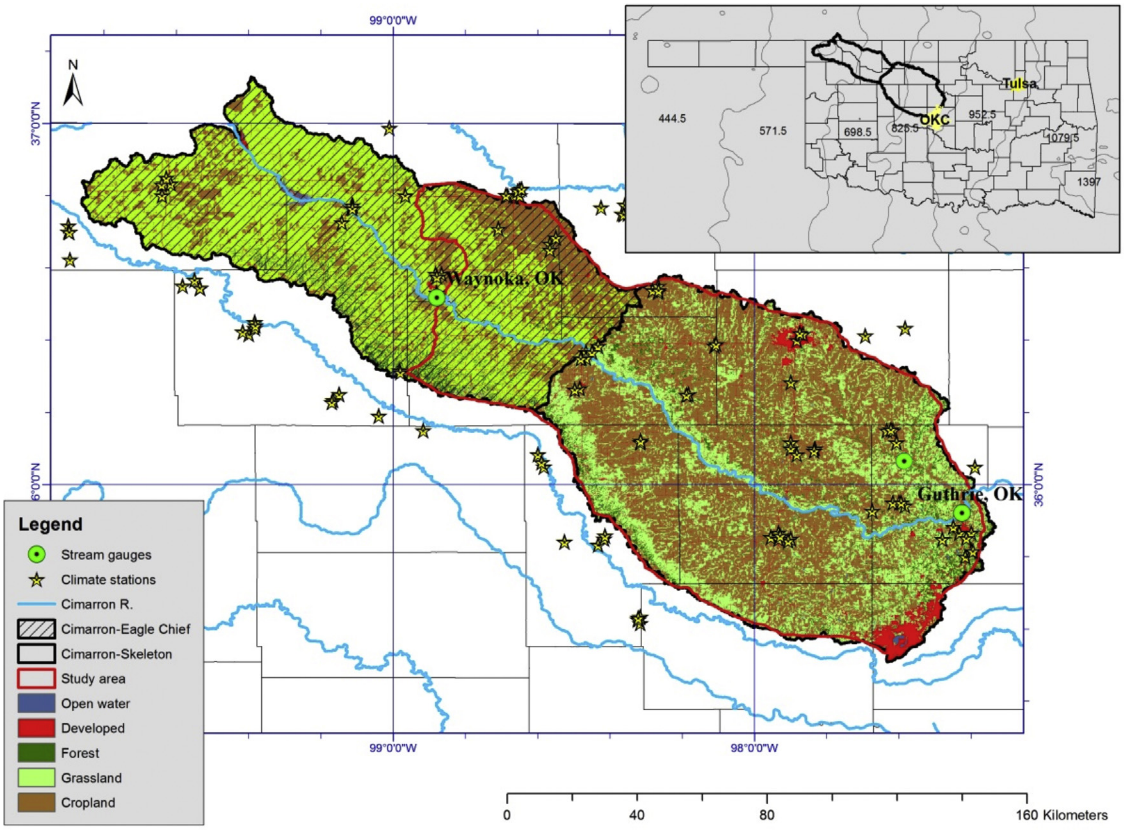

Fig. 1. Land use and land cover types, distribution of weather stations and gaging stations for the contribution area for the Guthrie gaging station (Cimarron–Skeleton watershed and a part of Cimarron–Eagle Chief watersheds). Inset: Precipitation isohyetal map over Oklahoma geographic map with bold line 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 extremes. Determining the effects of climate variability and anthropogenic changes on the streamflow regime is fundamental for forming climate-change adaptation strategies and empowering managers to effectively adapt agricultural production systems to increasing climate variability while sustaining natural ecosystems.

2. Materials and methods

2.1. Site—Cimarron–Skeleton and Cimarron–Eagle Chief watersheds

The Cimarron–Skeleton watershed is located in North Central Oklahoma (Fig. 1), with a drainage area of 8275 km^2. Adding the contribution area from the U.S. Geological Survey (USGS) gaging station (Cimarron River near Waynoka, Oklahoma, 07158000) in the Cimarron–Eagle Chief watershed, the total drainage area between the inflow and outflow USGS gaging station (Cimarron River near Guthrie, Oklahoma, 07160000) is 10,805 km^2. The Cimarron–Skeleton watershed has a low relief with a standard elevation deviation of 37.6 m and a long-term average precipitation that declines from east (Guthrie Gaging Station, 915 mm) to west (Waynoka Gaging Station, 690 mm).

2.2. Data collection

2.2.1. Streamflow and climate data

Mean daily streamflow data collected at the Waynoka and Guthrie gaging stations from 1948 through 2010 were retrieved from the USGS National Water Information System (U.S. Geological Survey, 2014). Because the Guthrie gaging station is upstream of the mouth of Skeleton Creek at the Cimarron River, streamflow exiting the watershed downstream of Guthrie was estimated with the drainage area ratio method (Ries and Friesz, 2000; Perry et al., 2004; Risley et al., 2008; Esralew and Smith, 2009), using records from the gaging station at Skeleton Creek near Lovell, Oklahoma (USGS ID-07160500). This approach is a reliable method if the ratio between the drainage areas of the gaged and ungaged sites is between 0.5 and 1.5 (Risley et al., 2008). The drainage area ratio between the ungaged pour point of Skeleton Creek into the Cimarron and the Lovell gaging station is 1.02. Estimated flow at the confluence was then added to the recorded streamflow measured at the Guthrie gaging station to get the total outflow for the study area. Daily climate data were gathered for the years 1950 through 2010 from the National Climate Data Center (NCDC) for fifty-three weather stations, twenty-five of which were continuously collecting data for the entire study period and are centrally distributed representing the temperature and precipitation gradient (Fig. 1).

The NCDC data were used to calculate mean reference evapotranspiration (ET$_0$) for the study area using the FAO-56 Penman–Monteith method (Allen et al., 1998). Missing humidity and radiation data were derived using empirical methods outlined by the ASCE Standardized Reference Evapotranspiration Equation (Allen et al., 2005).

Water-use and groundwater storage data, compiled at 5-year increments from 1950 and 2005 for the study area (Fig. 1), were estimated from data obtained from the USGS Aggregate Water Use Data System (AWUDS) (U.S. Geological Survey, 2012a,b), and from data used for water-use statistics throughout Oklahoma (Tortorelli, 2009). Major water-use categories included irrigation, domestic, and industrial from groundwater and surface water withdrawals. Water-use data prior to 1985 were estimated by developing coefficients for major water-use categories in Tortorelli (2009) relative to 1985 water-use data available from AWUDS. Consumptive water use (CWU) is an estimate of the portion of water withdrawn from aquifers and streams that is evaporated to the atmosphere or removed from the areas of withdrawal in commercial and industrial products. Annual water use data were calculated by using linear interpolation based on the 5-year data. For the 2010 USGS National water-use compilation, water use in Oklahoma was computed by county, and could not be compared to previously compiled water-use data that was computed by 4-digit hydrologic unit; as a result of this we had to extrapolate annual water use for the years 2006 through 2010.

2.2.2. Groundwater and change in groundwater level

Groundwater levels, measured annually in fifty-one selected wells (approximately one well for every 212 km^2 of the study area) by staff of the USGS or the Oklahoma Water Resources Board during the late winter (time of minimum irrigation pumpage), were obtained from U.S. Geological Survey (2012b). Water levels in some wells were sampled more than once per year, but to avoid overweighting data from such wells, the earliest water-level measurement made in each well completed in a known aquifer in these watersheds was compiled for each year. More than 90 percent of the wells in this area with available water-level measurements were completed in the Cimarron Terrace or alluvial aquifers, rather than in underlying bedrock aquifers of Permian age. Only water levels from wells completed in the younger unconsolidated aquifers were summarized for this paper as those wells generally were shallow, unconfined, likely to respond quickly to precipitation, and likely to be in hydraulic connection with the Cimarron River or its tributaries.

2.2.3. Land use and land cover data

Land use and land cover data in the study area between 1950 and 1975 were determined from aerial photographs obtained from Edmon Low Library at Oklahoma State University, the Oklahoma Department of Libraries, and the Oklahoma Corporation Commission. The aerial photographs were digitized by scanning at 800 dpi and georeferenced to National Aerial Imagery Program (NAIP) imagery obtained through the U.S. Department of Agriculture's Geospatial Data Gateway (NRCS, 2010). The images were mosaicked using Mosaic Tool Pro in ERDAS (Leica Geosystems, 2013). NAIP imagery was used to ground truth the data and to provide a baseline for the coarser resolution Landsat images. Each image was classified into land cover classes using the Image Classification toolbar in ArcMap 10 (ESRI, 2011). Images were iteratively selected using training data and previewed using the interactive supervised classification function. When a reasonable binary image was obtained, the training samples were processed and made into binary maps using the maximum likelihood classification tool. Training samples consisted of open water, forested, herbaceous-grass, herbaceous-crop, and urban/developed areas. Linear interpolation was used to fill tree cover values and land use for years in which aerial photography had not been classified (Lambin and Strahlers, 1994; Hasse and Lathrop, 2003; Latifovic et al., 2004).

Post-1975, Landsat imagery was obtained from USGS global visualization viewer at five year increments (i.e., 1975, 1980, 1985, . . ., 2010) for both the winter and summer (Multispectral Scanner for 1975 and 1980, Thematic Mapper for 1985–2010). These images were mosaicked together into color-averaged images using Mosaic Tool Pro (Leica Geosystems, 2013), clipped in ERDAS Imagine 2013 using 8-digit hydrologic units (U.S. Geological Survey, 2011).

2.3. Data analysis and statistics

In this study, we first estimated the effect of climate change on streamflow using the method of climate elasticity (Schaake, 1990). Climate elasticity of streamflow is defined by the proportional change in streamflow divided by the proportional change in a climatic variable such as precipitation or potential evapotranspiration (Zheng et al., 2009) with the equation:

$$\epsilon' = \text{median}\left(\frac{\left(Q_i - \bar{Q}\right)/\bar{Q}}{\left(X_i - \bar{X}\right)/\bar{X}}\right) \quad (1)$$

where ϵ' is the nonparametric estimator of climate elasticity of streamflow, Q_i and X_i are annual streamflow and the climatic variable (e.g., precipitation) with respect to long-term average of streamflow ($\bar{Q}$) and climate factors ($\bar{X}$), respectively. Subsequently, the land-surface change elasticity of streamflow was estimated using the error term from Eq. (2), ϵ_t, and stepwise analysis was used to quantitatively attribute the effect of conversion of cropland, urbanization, woody encroachment, impoundments, and groundwater withdrawal on streamflow for two periods, between 1950 and 2010, and between 1980 and 2010 (when water use was less excessive).

Trends in precipitation, ET_0, and streamflow were tested using the Mann–Kendall seasonal trend analysis method (Mann, 1945; Kendall, 1948). Where a significant trend was determined, change point analysis was used to detect the year when significant changes occurred at the Guthrie gaging station (Taylor, 2000). After determining which time periods showed significant differences, changes in streamflow regime between the time periods were determined using the Indicators of Hydrologic Analysis (IHA ver. 7.1) (Richter et al., 1996). IHA produces results on 34 ecologically relevant flow components relative to magnitude, frequency, duration, timing and rate of change of hydrologic conditions (Poff and Ward, 1989; Richter et al., 1996). The output produced by IHA includes the range of variability for monthly median flows, minimum and maximum flows for 1, 3, 7, 30, and 90 day intervals, the date of minimum and maximum flows, baseflow index (BFI), zero flow days, the duration and count of high flow and low flow pulses, rise rates, fall rates, and number of reversals. Relative contributions of climate and anthropogenic induced changes to streamflow were analyzed using a linear model:

$$\Delta Q_t = \beta_t \Delta P_t + \beta_{ET_0} \Delta ET_0 + \epsilon_t \quad (2)$$

where ΔQ_t is change in annual streamflow, ΔP_t and ΔET_0 are changes in annual precipitation and reference evapotranspiration, β and the error term, ϵ_t, can be interpreted as non-climatic, or anthropogenic, effects. Kendall's tau test was used to determine which anthropogenic variables were significantly associated with streamflow for the entire study period (1950–2010) and the period without excessive water use (1980–2010).

3. Results

3.1. Streamflow trends

Total annual inflow into the study area, calculated from streamflow measured at the Waynoka gaging station ranged from 4.1×10^7 to 9.9×10^8 m^3 yr^{-1} (Fig. 2). Since the 1980s, this range narrowed by nearly half with the maximum annual inflow never exceeding 6.6×10^6 m^3 yr^{-1}. Total annual outflow from the study area varied considerably from 1.0×10^8 to 30.5×10^8 m^3 yr^{-1} (Fig. 2). The Mann–Kendall trend test indicates annual flows increased at the Guthrie gaging station ($p < 0.02$) and at the confluence of Skeleton Creek and the Cimarron River ($p < 0.02$) beginning in 1983.

Change point analysis indicates that mean annual streamflow increased at the Guthrie gaging station beginning in 1983. By determining 1983 as the change point and considering this as the post-impact era in IHA, we found that the frequency of high flow events (streamflow ≥ 10% above the mean) decreased while streamflow and the duration of the events increased after 1983 (Fig. 3). The Range of Variability Approach (RVA) with IHA as described by Richter et al. (1996) weighs pre-impact streamflow variation against post-impact variations and allows for comparisons of change pre- and post-impact. Similarly, low-flow frequency also decreased whereas baseflow increased. Monthly median streamflow measured at the Guthrie gaging station also increased after 1983 for every month except July. The categories analyzed with IHA that display the greatest range of variability (≥67th percentile of pre-1983 values) were monthly median flows, minimum flows (for 1-day, 3-day, 7-day, 30-day, and 90-day intervals), maximum flows (for 30-day, and 90-day intervals), rise rate, and the duration of high flow events.

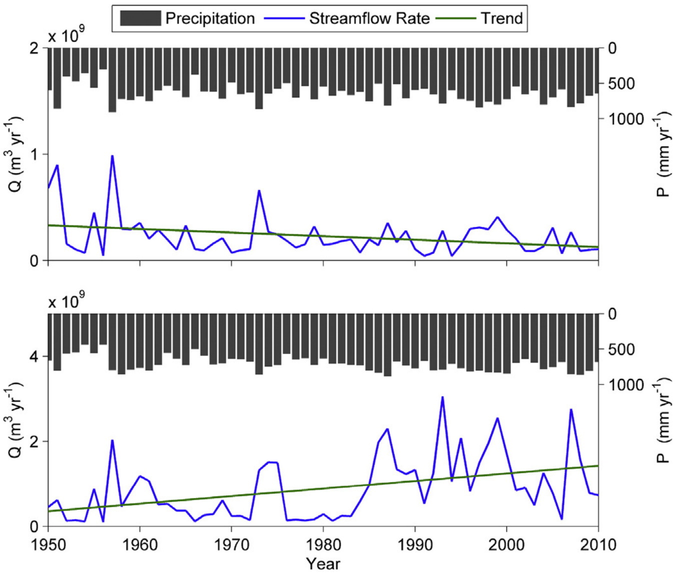

Fig. 2. Annual precipitation for Eagle Chief watershed and annual streamflow at Waynoka, OK (A) and annual precipitation for Cimarron Skeleton watershed and annual streamflow at the confluence of Skeleton Creek and the Cimarron River (B) from 1950 through 2010. The trend line is based on Mann–Kendall trend analysis.

3.2. Long term trends of climatic drivers—temperature, precipitation, evapotranspiration, and relative humidity

The 60-year mean precipitation was 797 mm yr^{-1} for the study area, with a change in the mean occurring in 1983 (733 mm yr^{-1} from 1950 to 1983 and 869 mm yr^{-1} from 1984 to 2010). Based on change point analysis, mean potential evapotranspiration (ET_0) changed twice over the 60-year period, decreasing from 1737 mm yr^{-1} through much of the 1950s to 1633 mm yr^{-1} through the early 1980s, and decreasing again to 1585 mm yr^{-1} through 2010 (Fig. 4A). There also were shifts in mean percentage of relative humidity (RH) in 1958, 1963, and 1968, with the period from 1982 to 2010 having the highest RH of 53 percent (Fig. 4B), while temperature remained fairly static around a mean of 15.7 °C ± 0.4 °C (Fig. 4C).

3.3. Groundwater storage and consumptive water use (CWU)

Between 1950 and 1960, the groundwater level fluctuated substantially, with a decrease of 2.18 m occurring in 1955 but a 4.46 m increase in 1958 (Fig. 5). Since the 1960s, groundwater levels stabilized with no discernible trends. CWU in the watershed was about 10×10^6 m^3 yr^{-1} between 1950 and 1960 (Fig. 6). Beginning in 1965, CWU increased rapidly, peaked at about 40×10^6 m^3 yr^{-1} in 1975, and then decreased. CWU was relatively stable (mean of 18×10^6 m^3 yr^{-1}) from the mid-1980s through 2010.

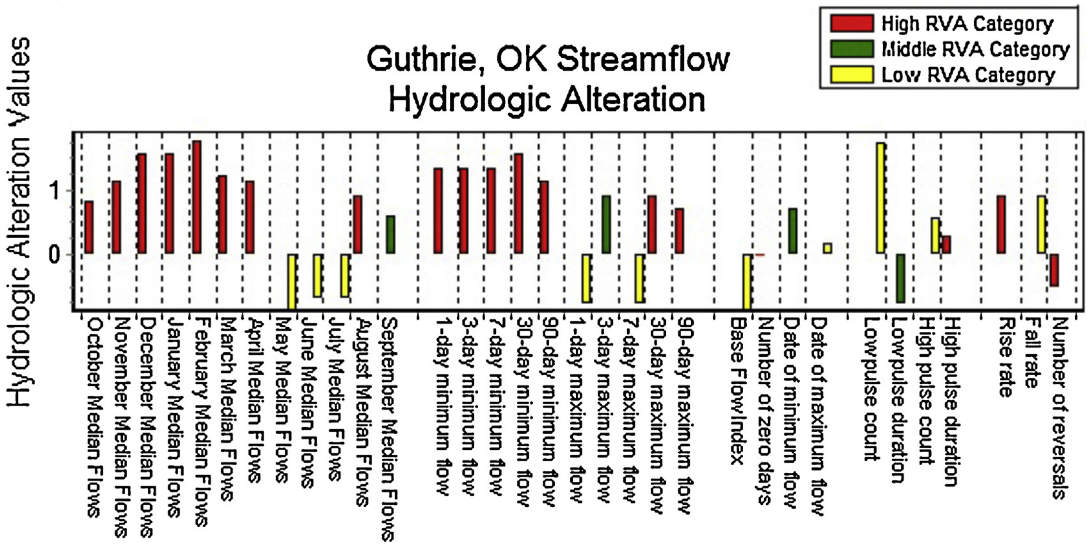

Fig. 3. Results of IHA analysis showing range of variability (RVA) for major ecological indicators for the Guthrie, OK gaging station. Categories that display a high RVA are in red, medium in green, and low in yellow. Positive RVA values indicate an increase in frequency for that category from the 1983 change point while negative values indicate a decrease. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

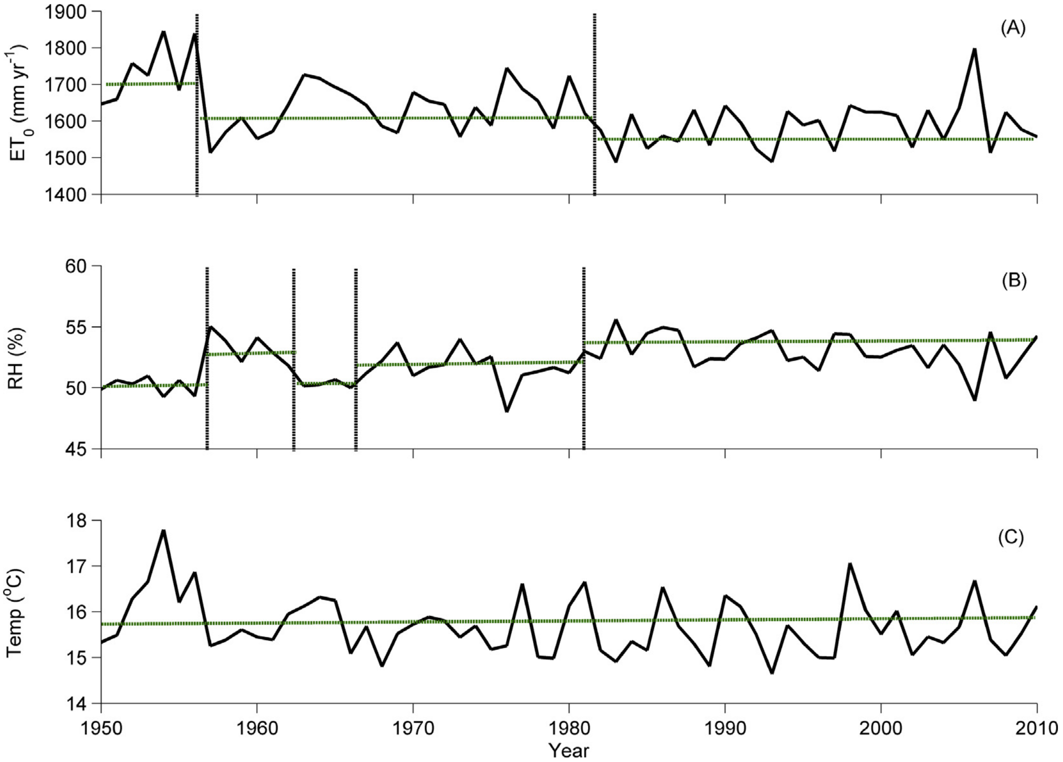

Fig. 4. Changes in (A) potential evapotranspiration, (B) relative humidity and (C) annual mean temperature from 1950 through 2010 in the study area. Time periods with significant changes in annual mean values are highlighted by boxes. There was no significant change in annual temperature.

3.4. Elasticity of streamflow

Elasticity of streamflow varied temporally and differentially according to measures of water availability (Fig. 6). Streamflow was negatively correlated with reference evapotranspiration and was most positively correlated (i.e., high ET_0 elasticity of streamflow) in the late 1970s through the early 1980s (Fig. 6A). In relation to water use, precipitation elasticity of streamflow increased beginning in the early 1970s (Fig. 6B). Streamflow sensitivity to ET_0 and precipitation were relatively stable from 1980s to 2010. As the residual of climate contribution, anthropogenic elasticity of streamflow (land use, land cover [LULC]; Fig. 6C) was positive until 1983 and then decreased concurrently alongside a reduction in the total consumptive water use.

3.5. Land surface change

Land use and cover in the study area have changed since 1950 in response to changes in agricultural practices and urban growth, among other things (Fig. 7). The percent of cropland decreased from 66% in 1950 to 49% in 2010, and was replaced by other land cover classes, predominantly range land though urban area had the

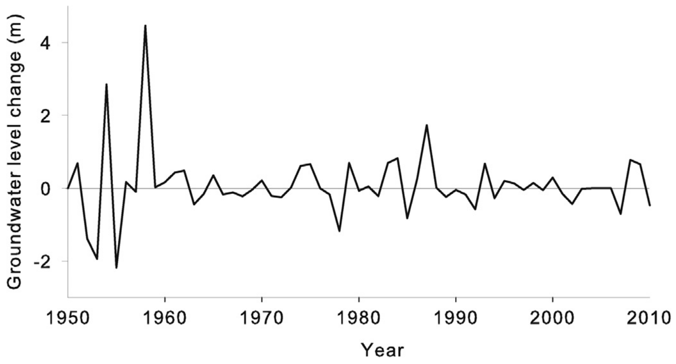

Fig. 5. Annual change in groundwater storage in the alluvial aquifer and terrace deposit between 1950 and 2010 in the study area.

fastest rate of increase (from <1% in 1950 to ∼8% in 2010). Grassland increased steadily until 2000 when encroachment of woody plants accelerated.

We calculated correlations between climate, land surface cover, and streamflow for the study area. For the entire period (1950–2010), there were significant positive correlations between streamflow and percentage of four land cover classes: grassland, developed areas, forest, and surface area of open water (Table 1). There also was a significant negative correlation between streamflow and percentage of crop cover from 1950 to 2010. For the period between 1980 and 2010, only the percentage of grassland and precipitation were positively correlated to streamflow, which was negatively correlated to CWU (Table 2).

4. Discussions

Our results show that only 52% of observed streamflow variability for the studied period was attributed to climatic factors, indicating that changes on the landscape due to anthropogenic causes (e.g., crop production through irrigation, urbanization) played an equally important role in streamflow variability. For an irrigation intensive watershed located in an area with hot summers and limited precipitation such as the study area, substantial amounts of water were being added into this system from groundwater pumping during times of below-average precipitation. As a result, an improvement in antecedent soil moisture was anticipated with cropland soils being wetter than surrounding non-irrigated land despite the dry climatic conditions affecting stream flow. Other studies in sub-humid watersheds have found that surface runoff is strongly controlled by antecedent soil moisture conditions (Western et al., 1998).

Streamflow, in relation to groundwater recharge and water withdrawals, is the residual term between precipitation input and evapotranspiration output for a given watershed. Though changes in precipitation for a given watershed have been used as a proxy of potential streamflow response in climate-change projections (Miller et al., 2003; Qi et al., 2009; Qiao et al., 2014), factors other than precipitation can modify this relationship. Climate variability and landscape changes can substantially alter hydrological systems and limit the amounts of available water and conditions of aquatic ecosystems. For example, a small watershed study in Iowa found that streamflow in Midwestern watersheds increased after increases in irrigation from groundwater beginning in 1970 without a change in precipitation (Tomer and Schilling, 2009). Conversely, in the Upper Mississippi River Basin, rural land use change largely in the form of water impoundment for soil and water conservation was attributed to declines in streamflow despite increased precipitation (Kochendorfer and Hubbart, 2010). In Canada, an increase in temperature resulted in earlier snowmelt and decreased mean streamflow for most months (Zhang et al., 2001). Thus, watershed-specific properties appear to affect precipitation–streamflow relationships such that no single generalization can be made for this global phenomenon.

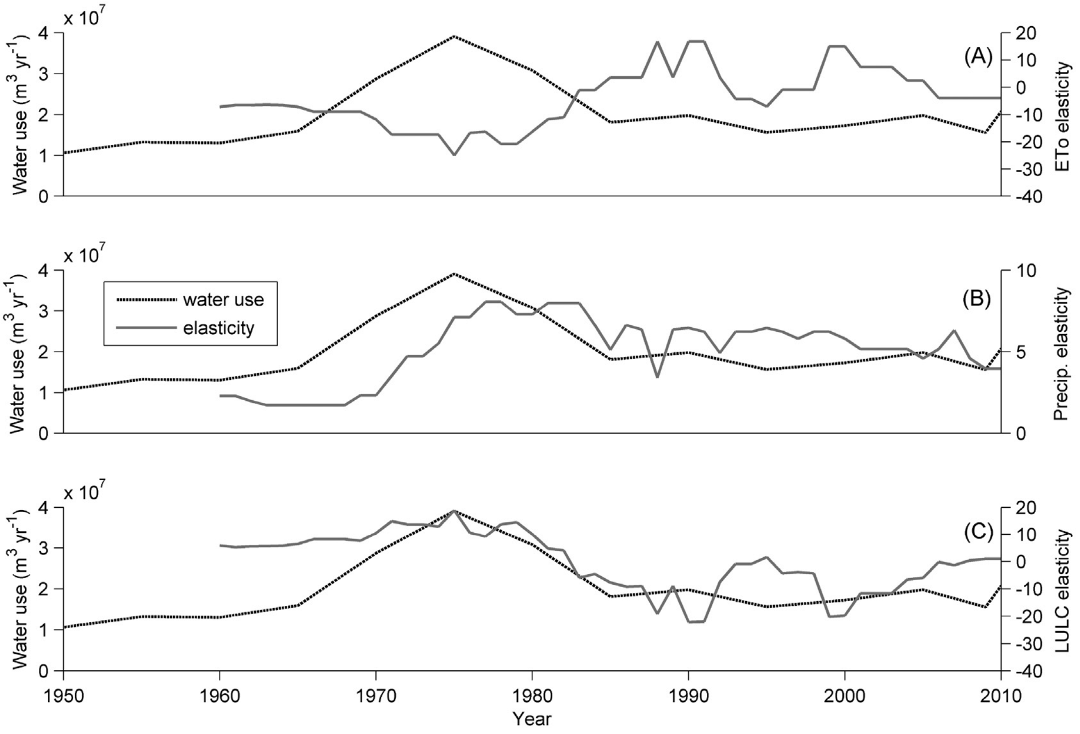

Fig. 6. Changes in precipitation elasticity of streamflow (A), reference evapotranspiration elasticity of streamflow (B), and anthropogenic elasticity of streamflow (C) against changes in the total consumptive water use for the entire study area from 1950 through 2010.

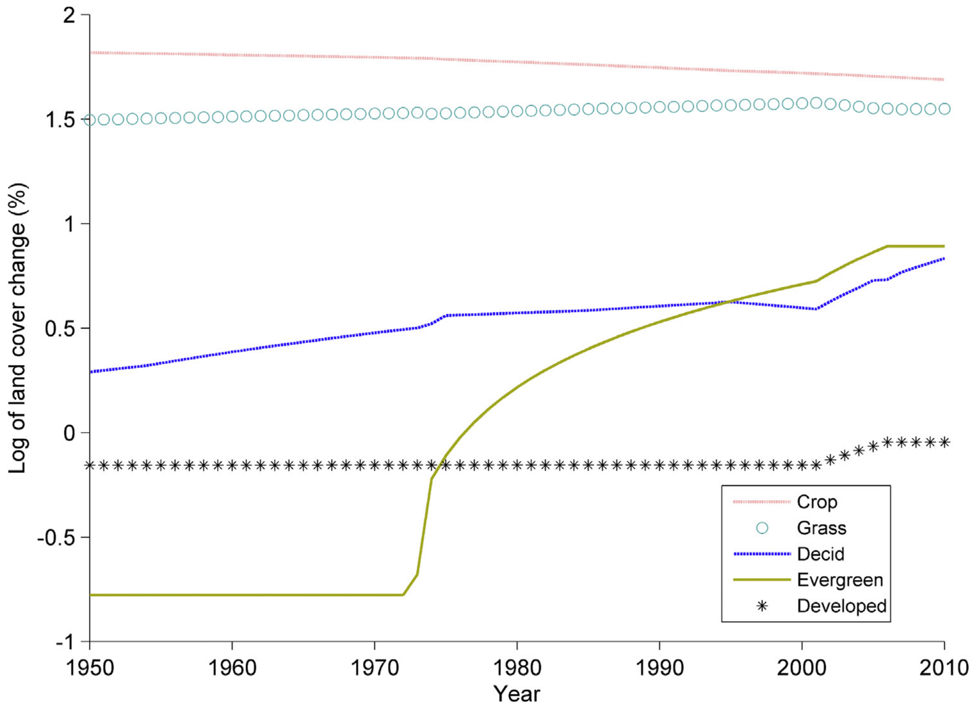

Fig. 7. Changes to major land cover types since 1950 in the study area. Logarithmic (base 10) transform applied to variables for ease of visualization.

Intensive irrigation in the study area appeared to significantly alter climate, which has been shown to occur in similar cases with larger scale studies (Sacks et al., 2009). We saw an increasing trend in relative humidity coincident with increased irrigation and precipitation. In this study, CWU from irrigation appeared to make atmospheric demand more effective in evaporating soil moisture as decreases in ET_0 elasticity of streamflow were evident during the years of intensive irrigation. When the amount of water used for irrigation stabilized beginning in the 1980s, streamflow reacted more strongly to coincident changes in ET_0. In another Oklahoma watershed (North Canadian River), groundwater pumping from the terrace and alluvial aquifer was responsible for a 47%

Table 1
Correlation analysis between anthropogenic induced percent of land surface change (cropland, grassland, urbanization, woody encroachment, water surface) and streamflow for the period between 1950 and 2010 using Kendall's tau test.

	Streamflow	ET_0	Precip.	CWU	Cropland	Grassland	Forest	Urban
ET_0	**−0.5528****							
Precip.	**0.6691*****	**−0.7156*****						
CWU	−0.1924	−0.0211	−0.0683					
Cropland	**−0.4437****	**0.3709****	**−0.4453*****	**0.0206***				
Grassland	**0.4762*****	**−0.4282****	**0.4463****	0.0737	**−0.895*****			
Forest	**0.3344****	**−0.3476*****	**0.4001****	**0.145****	**−0.9329*****	**0.7336*****		
Urban	**0.4133*****	**−0.2952****	**0.4072*****	−0.1541	**−0.9726*****	**0.7829*****	**0.9171*****	
Water	**0.1215****	**−0.0704****	**0.2047*****	−0.0985	**−0.642*****	**0.2429*****	**0.7788*****	**0.7648*****

Note: Correlations that display strong significance are shown in bold. ET_0—reference evapotranspiration; CWU—consumptive water use.
* For $p < 0.05$.
** For $p < 0.01$.
*** For $p < 0.001$.

Table 2
Correlation analysis between anthropogenic-induced land surface change (cropland, grassland, urbanization, woody encroachment, impoundments) and streamflow for the period between 1980 and 2010 using Kendall's tau test.

	Streamflow	ET0	Precip.	CWU	Cropland	Grassland	Forest	Urban
ET0	−0.1785							
Precip.	**0.5011*****	−0.1613						
CWU	−**0.3849***	0.0968	−**0.3677****					
Cropland	−0.0968	−0.0452	−0.1656	**0.3161***				
Grassland	**0.2946***	0.0366	0.1312	**−0.428*****	**−0.3806****			
Forest	0.0882	−0.0065	0.071	**−0.3333****	**−0.7935*****	0.1742		
Urban	0.1022	0.0544	0.1674	**−0.3152***	**−0.9892*****	**0.3805****	**0.7805*****	
Water	0.1381	0.0552	0.1657	**−0.3406***	**−0.9344*****	**0.2900***	**0.7641*****	**0.9446*****

Note: Correlations that display strong significance are shown in bold. ET_0—reference evapotranspiration; CWU—consumptive water use.
* For $p < 0.05$.
** For $p < 0.01$.
*** For $p < 0.001$.

loss of streamflow through a combination of reduced base flow and increased leakage into the aquifer (Zume and Tarhule, 2008). In contrast, while our results also show a negative relationship between streamflow and CWU, we found an overall increase in baseflow. Groundwater in the study area comes primarily from the Cimarron Terrace and Alluvial aquifer, which has a rapid exchange between groundwater and streams. This observation is not unique. For example, excessive pumping of groundwater was reported to sustain winter streamflow at levels exceeding natural flows in the Gallatin Valley, Montana (Kendy and Bredehoeft, 2006).

Many studies have shown that increases of impervious surfaces from urbanization make stream systems less stable by increasing runoff volume and velocity while decreasing flow duration, infiltration and baseflow (Hollis, 1975; Rose and Peters, 2001). However, our IHA analysis found that the Cimarron River at the lower portion of the study area has transitioned from a historically flashy river to a river that is more stable. There were a variety of land use and cover changes that appeared to affect streamflow in the study area (Wine and Zou, 2012 Zou et al., 2013). It remains a challenge to untangle how urbanization and associated increase in impervious surface area and inter-basin water transfer interact with irrigation water use and land use and vegetation changes to result in the observed streamflow regime for the lower Cimarron River.

Based on the prevailing climate change models, the precipitation regime in the Southern Great Plains is projected to increase in intensity and decrease in frequency (Shafer et al., 2014). Decrease in precipitation frequency will likely exacerbate drought conditions and increase groundwater pumping (Castle et al., 2014). This depletion of groundwater could be of great concern in the study area and the Lower Cimarron basin as a whole where the majority of cropland agriculture and population of the basin reside. Moreover, the consequences of the altered hydrologic regime could have cascading trophic effects that will extend beyond the direct influence of the river itself and be difficult to predict. Groundwater use regulations, urban growth regulations, and vegetation management are all possible management techniques that might be able to affect water resource availability in the future.

5. Conclusions

- Irrigation through groundwater pumping modifies climatic feedback and therefore affects the relation between streamflow and precipitation in an irrigation-intensive agricultural watershed. While this conclusion applies specifically to the area in this study, the results may be applicable to other watersheds with similar features and land use.
- Irrigation through withdrawing groundwater in highly permeable alluvial aquifer increases precipitation elasticity of streamflow and reference evapotranspiration elasticity of streamflow. However, an increase in irrigation is associated with a decrease in annual streamflow.
- Consumptive water use and land use and land cover change contributed up to 50% in streamflow variability for the irrigation intensive Cimarron–Skeleton watershed in the South-central Great Plains.
- Returning irrigated cropland to grassland was associated with increases in annual streamflow amounts.

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