Quantitative assessment of climate variability and land surface change on streamflow decrease in the Upper Cimarron River

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Number of students supported by the project

Student Status	Number	Disciplines
Undergraduate	1	Engineering
M.S.	1	NREM
Ph.D.	0	
Post Doc	0	
Total	2	

Contents

Problem and Research Objectives

Problem statement

A recent report by Oklahoma Water Resource Board and USGS highlighted the apparent downward trend in long-term streamflow of rivers in northwest and north-central Oklahoma such as the North Canadian River and the Cimarron River (Esralew and Lewis 2008). For example, the 10-year average discharge rate for the Cimarron River since the 1970s is nearly half of that measured in the 1940s and 1950s (**Fig. 1**). Similar downward trends exist for several other rivers in this region.

Continued reduction in river flows could impose profound social, economic and ecological impacts in the northwest and central Oklahoma region. Namely, the North Canadian River provides more than half of the water supply to the City of Oklahoma. The Cimarron River is an important habitat for many fish species including the federally threatened Arkansas River shiner *Notropis girardi* (a priority species identified in the Oklahoma Comprehensive Wildlife Conservation Strategy and the Great Plains Landscape Conservation Cooperative Action Plan).

Despite its importance, streamflow accounts for only a small component of the water budget for semiarid regions (Wilcox 2002), usually less than 10% of precipitation. An increase in precipitation is positively related to total streamflow, in general, but this relation is not linear and depends on climate condition and land surface characteristics (Yang and Yang 2011). This relation varies with time even for the same river basin due to land cover change and human activities (Zheng et al. 2009). Therefore quantifying weighted precipitation (Esralew and Lewis 2008, Wine and Zou 2011) may not completely reveal interactions and feedbacks among climate, land use/land cover changes, and human activities.

Climate variability, including changes in precipitation regime, temperature, vapor pressure, and wind speed, can cause changes in streamflow directly or indirectly (Dam 1999). Land use and land cover change, on the other hand, are believed to affect infiltration and evapotranspiration, which consequently causes changes in groundwater levels and streamflow (Zhang et al. 2001).

Climate elasticity of streamflow proposed by Schaake (Schaake 1990) is an effective indicator identifying the sensitivity of streamflow to climate change (Dooge 1992, Dooge et al. 1999, Sankarasubramanian et al. 2001). After climate elasticity is defined, theoretically, the land surface change elasticity of streamflow can be estimated. Then one can compare the land surface elasticity index to change of land uses, woody cover change (data extracted from the historic aerial images), and groundwater withdrawal data to evaluate the relative effects components other than climate on streamflow.

Scope and objectives

This is a one year, collaborative research project involving faculty and students from Oklahoma State University and a USGS Oklahoma Water Science Center scientist. Originally, we proposed to focus on the upper Cimarron River from the Waynoka USGS Station (36°31'02", Longitude 98°52'45") to the Dover station (Latitude 35°57'06", Longitude 97°54'51"). We later decided to expend the contribution area to Guthrie to utilize the longer streamflow records. The contribution area includes the entire Lower Cimarron-Skeleton Watershed (HUC11050002) which has a contribution area of 8,375.26 square kilometers or 3233.68 square miles (U.S. Environmental Protection Agency, 2012).

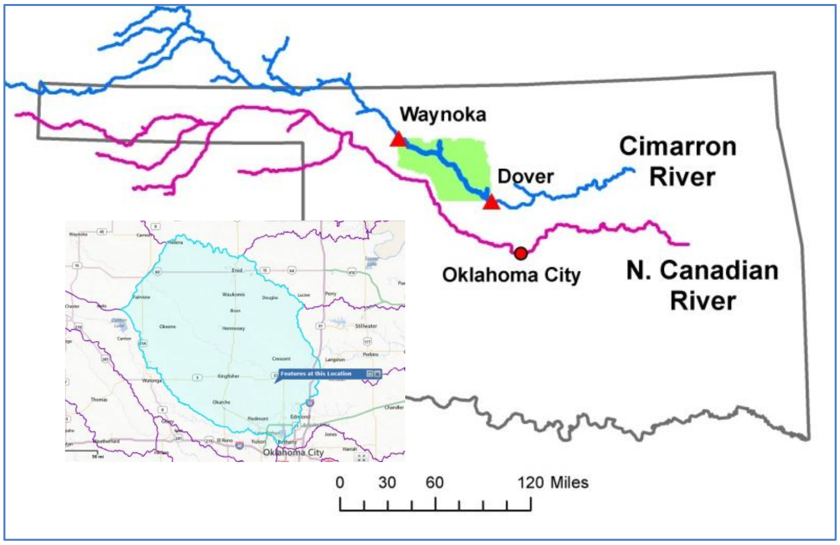


Fig. 1: Map showing location of the proposed study area between Waynoka and Dover in north-central Oklahoma and revised are from Waynoka to Guthrie (inset).

The overarching goal of this project is to quantitatively assess the effects of climate change, land surface change, and human activities on long-term streamflow characteristics of the upper Cimarron River. The area along the upper Cimarron River has a diverse land use history and pattern and is experiencing a rapid increase in woody vegetation cover (both riparian and upland) and increases in groundwater withdrawals from alluvial aquifers. Specific project objectives include:

Objective 1: Archive and digitize multi-temporal aerial photos from the 1930s to the 2010s and produce a time series of land use and land cover change history for the studied area; quantify and archive the long-term trends of climate variability, groundwater levels, and water withdrawals during the study period.

Objective 2: Quantify the effects of climate related change on streamflow and groundwater trends and understand the contribution of non-climatic factors including land use, woody plant encroachment, and groundwater withdrawal on streamflow and groundwater levels.

Objective 3: Apply stepwise regression to determine which variables (land use change, encroachment of woody plants (primarily eastern redcedar) and change in surface storage such as reservoir construction are significant predictors of land surface change elasticity index, therefore streamflow trends.

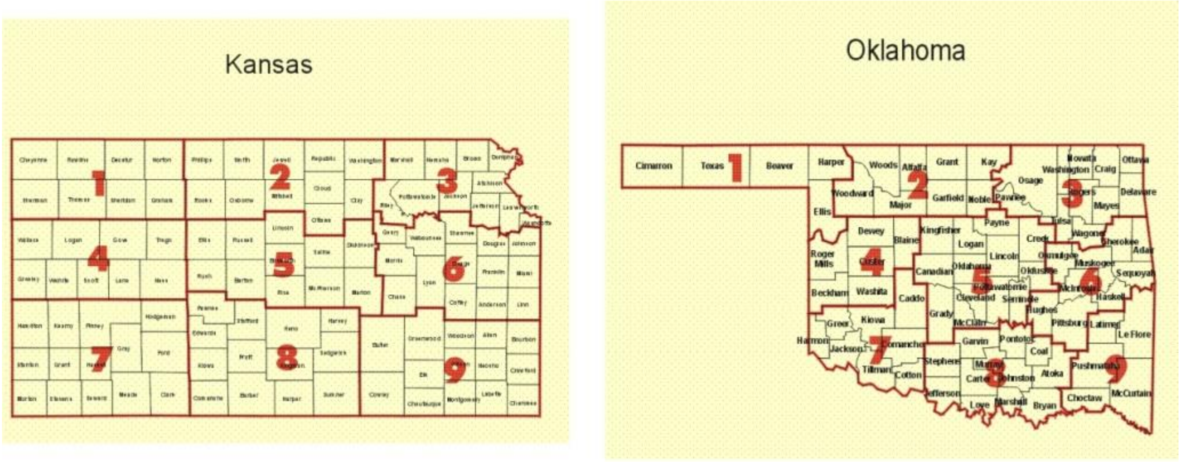
Methods and Procedures

Climate variability and hydrological cycle trends

Two streamflow-gaging stations (Cimarron River near Waynoka, Oklahoma, #070185000; and Cimarron River near Guthrie, Oklahoma, #071860000) and contributing areas upstream of those stations comprise the study area of this paper. Types of data collected to determine climate variability and trends in hydrologic cycle components in the watersheds in this study area included annual precipitation and mean annual air temperature, estimated consumptive water use, streamflow and contributing areas (areas from which runoff is likely to flow to streams), and groundwater levels.

Precipitation and temperature

Because the contributing areas to the streamflow-gaging stations on the Cimarron River near Waynoka and near Guthrie, Oklahoma span approximately equal areas in several climate divisions in parts of Oklahoma, Kansas, and Colorado (**Fig**. 1), the averages of mean annual precipitation and mean annual air temperature data collected by the National Weather Service in five-year increments from 1950 through 2005 in those climate divisions (National Oceanic and Atmospheric Administration, 2012a) were used to represent mean annual precipitation and temperature in those contributing areas. Mean annual precipitation and air temperature data from Oklahoma Climate Division 2, and Kansas Climate Divisions 7 and 8 (**Fig. 2A**) were used to represent annual precipitation and air temperature for the contributing area of the streamflow-gaging station near Waynoka, Oklahoma. For the contributing area to the streamflow-gaging station near Guthrie, Oklahoma, averages of climate data from those climate divisions plus climate data from Oklahoma Climate Division 5 (**Fig. 2B**) were used to represent mean annual precipitation and mean annual air temperature.



Images from National Weather Service (2012)

Fig. 2: Climate Division maps for Kansas and Oklahoma showing contribution area for Waynoka and Guthrie gauge stations.

Water consumption

Water-use data compiled at 5-year increments from 1950-2005 for parts of 8-digit hydrologic unit code watersheds in contributing areas of these streamflow-gaging stations (**Fig.** 2) were estimated from data obtained from the Aggregate Water Use Data System (AWUDS) of the USGS (U.S. Geological Survey 2012a), water-use data supplied by the USGS Kansas Water Science Center (written commun. Joan Kenny, U.S. Geological Survey, 2012), and data used to compile Tortorelli (2009). Major water-use categories included in this compilation included: domestic use from public water supplies, domestic self-supplied, self-supplied irrigation from groundwater, self-supplied irrigation from surface water, self-supplied groundwater for livestock, self-supplied surface water for livestock, industrial self-supplied groundwater, industrial self-supplied surface water, industrial from public water supplies, commercial from public water supplies, and self-supplied withdrawals of freshwater for mining. The AWUDs system contains water-use data compiled every five years from watersheds from 1985, 1990, and 1995. For 2000 and 2005, commercial and domestic water obtained from public-water supply systems in Kansas were not available, so data from 1995 were substituted for those missing data. For 2005, water-use data were not compiled by watershed in Kansas, so the remaining water-use categories were carried over from 2000 data. Water-use data for four watersheds (hydrologic unit codes 11040006, 11040007, 11040008, 11050001, and 11050002) were scaled to the approximate proportions of contributing areas in those watersheds to total land area (33, 50, 90, 100, and 95 percent, respectively). Water-use data from prior to 1985 were estimated by developing coefficients for major water-use categories in Tortorelli (2009) relative to 1985 water-use data available in the AWUDS system. Consumptive water use 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. Estimates of consumptive water use were made by multiplying industrial and commercial water withdrawals by 7 percent, domestic water withdrawals by 30 percent, and irrigation and livestock water withdrawals by 100 percent. Water-use data from 1950-2005 were obtained from data used to compile Tortorelli (2009). For the 2010 USGS National water-use compilation, water use in Oklahoma and Kansas was not computed by HUC watersheds, only by counties, so could not be compared to previously compiled water-use data without substantial recomputation..

Streamflow

To investigate long-term trends in streamflow in this area, mean annual streamflow data collected at two streamflow-gaging stations operated by the USGS from 1950-2005 (Cimarron River near Waynoka, Oklahoma; and Cimarron River near Guthrie, Oklahoma) were compiled from U.S. Geological Survey (2012b). Those streamflow-gaging stations have the longest periods of data collection (record) and are on the primary river draining the study area. Contributing drainage areas for the streamflow-gaging stations near Waynoka and near Guthrie were determined to occur in parts of four 8-digit hydrologic unit code watersheds (11040006, 11040007, 11040008, 11050001, and 11050002) having contributing drainage areas of 4,594 and 8,154 square miles, respectively, based on geographic information system coverages developed for the Oklahoma Streamstats

Program (U.S. Geological Survey, 2012c). To investigate trends in the portions of streamflow represented by baseflow (primarily groundwater seepage) and runoff (primarily overland flow from precipitation) the BFI (Baseflow Index) program (Wahl and Wahl, 2012) was used to estimate components of daily streamflow, which were summarized to mean annual baseflow and runoff at those stations.

Groundwater

Groundwater levels, annually measured in selected wells 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 tributaries of that river.

As one of the primary purposes of this paper is to investigate relations between land-surface changes and water resources, a simple model was developed to estimate hydrologic cycle components, including those likely to be affected by land-surface changes, for the study area in 5-year increments from 1950-2005. The conceptual hydrologic cycle model (Fig. 3) incorporates existing meteorologic and hydrologic data to estimate an annual residual term for every fifth year that is likely to be associated with evapotranspiration of natural plants and non-irrigated crops, which can be substantially affected by land-surface changes.

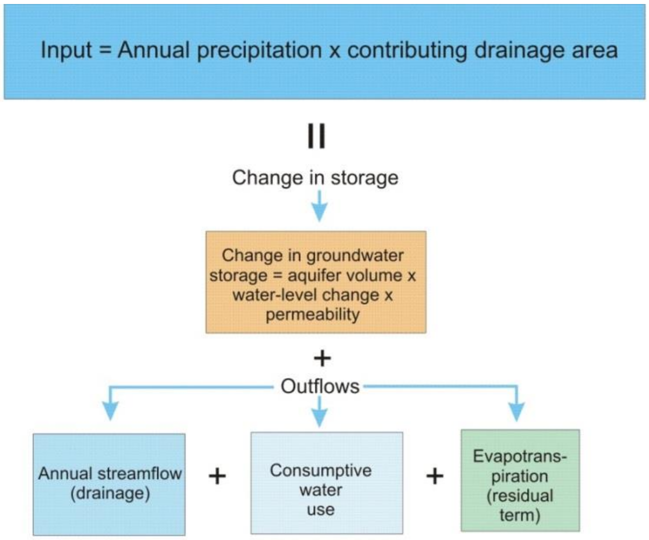


Fig. 3. Conceptual model used to summarize trends in available hydrologic data and evapotranspiration for the study watersheds

To construct the conceptual model of the hydrologic cycle, change in groundwater storage every five years was estimated from the change in the median depth to groundwater measured five years previously, multiplied by porosity of the alluvial and terrace aquifers, which was estimated to be 35 percent (Freeze and Cherry, 1979), multiplied by the surface areas of the alluvial and terrace aquifers upstream of each streamflow-gaging station (130 square miles for the contributing area upstream of the station near Waynoka, and 1,329 square miles for the contributing area upstream of the station near Guthrie, based on GIS coverages derived from Bingham and Moore (1975) and Morton (1980). Annual streamflows for each fifth year were based on the sums of mean annual baseflow and runoff at the streamflow-gaging stations on the Cimarron River near Waynoka and near Guthrie, Oklahoma. The residual amount, shown in the green box in **Fig. 3**, was assumed to represent evapotranspiration from non-irrigated crops, other plants, soils, and open-water surfaces for the contributing areas of each of those streamflow-gaging stations.

The Seasonal Kendall test (Kendall, 1938), with one test per year, was used to quantify trends of the hydrologic parameters for each fifth year from 1950-2005. Seasonal Kendall tests with p-values less than or equal to 0.05 were considered to indicate significant trends of meteorologic and hydrologic parameters with time.

Graphs and statistical computations were made using the statistical computer program TIBCO Spotfire S+ 8.1 for Windows (TIBCO Software, Inc., 2012). For some graphs, Loess trend lines were used to aid in visual analysis of trends. LOESS, or Locally Estimated Scatterplot Smoothing (also referred to as LOWESS or Locally WEighted Scatterplot Smoothing in other publications), is a nonparametric regression procedure that reduces the influence of outliers and displays a smooth or trend line for a range of data (Cleveland and Devlin, 1988; Helsel and Hirsch, 2002). Graphs were modified further using CorelDRAW X3 Graphing Suite software and Adobe Illustrator CS5 Version 15.0.2 software.

Land use and land cover change

Mapping land use and cover change

We archived and digitized the historical aerial photos and images taken around 1940s and 1960s for the study area and surrounding area. The majority of these historical aerial photos were provided by Oklahoma State University library, and the rest were provided by the Archives Division of the Oklahoma Department of Libraries, and the Oklahoma Corporation Commission. The scale of these photos ranges from 1:7,000 to 1:30,000, which is sufficient for observing individual tree canopies. These aerial photos were scanned at 800 dpi and geo-referenced for use in this project. Geo-referenced photos will be mosaiced and balanced by dodging, as described in Wine and Zou (2011).

A complete database of woody expansion and dynamics from 1975 to 2010 were developed from Landsat images. We will use most recent NAIP images as ground-truth data for defining Region-of-Interest (ROI) to support aerial photos and Landsat image classification and analysis. We propose to carry out the Classification And Regression Tree

(CART) method to process Landsat images to identify and document changes in spatial distribution of woody plants in the study area.

Nonparametric Estimator of Climate Elasticity and Land Surface Elasticity of Streamflow

The Cimarron River is one of a few Oklahoma rivers in which streamflow has not been largely regulated by hydro-power and other large diversion structures. For the drainage area of this study, there is some surface water withdrawal primarily for livestock and aquaculture (Tortorelli 2009), therefore the streamflow contributed from this drainage area (Q) can be computed based on streamflows measured at the two gaging stations and surface water withdrawals in this area. Assuming the streamflow and groundwater is completely linked and there is no observed change in groundwater level, the groundwater withdrawal was added to the streamflow to calculate the change. [Note – due to relatively stable ground water withdrawal since …, the absolute amount of groundwater withdrawal is not critical for analysis of climate and land surface elasticity). Then Q can be modeled as a function of climatic variables and catchment land surface characteristics of the drainage area:

$$Q = f\,(P, E_0, V), \tag{1}$$

where Q is streamflow contributed from this drainage area; P and E_0 are precipitation and potential evapotranspiration, respectively, representing dominant climate factors on the hydrological cycle; and V is a factor that represents the integrated effects of catchment land surface characteristics such as land use, cover change and human activities on streamflow. Using the following equation (1), changes in streamflow due to changing climate and catchment surface characteristics can be approximated as (Zheng et al. 2009):

$$\Delta Q = f'_P \Delta P + f'_{E0} \Delta \mathrm{E0} + f'_V \Delta V \tag{2}$$

where ΔQ, ΔP, ΔE_0, and ΔV are changes in streamflow, precipitation, potential evapotranspiration, and catchment surface characteristics, respectively, with $f'_P = \frac{\partial Q}{\partial P}$, $f'_{E0} = \frac{\partial \mathrm{Q}}{\partial \mathrm{E0}}$, and $f'_V = \frac{\partial Q}{\partial V}$. In terms of climate change, potential evapotranspiration instead of temperature is considered herein because potential evapotranspiration better represents the effects of climate change on water balance and because it integrates the effects of temperature, wind speed, solar radiation, sunshine duration and vapor pressure deficit.

Assuming that the land surface factors are independent of the climate factors, equation (2) can be rearranged as:

$$\Delta Q = \Delta Q_c + \Delta Q_v \tag{3a}$$
$$\Delta Q_c = f'_P \Delta P + f'_{E0} \Delta \mathrm{E0} \tag{3b}$$
$$\Delta Q_v = f'_V \Delta V \tag{3c}$$

Where ΔQ_c and ΔQ_v are changes in streamflow caused by climate change and land use and land cover change, respectively. In equation (3a), ΔQ can be estimated from observed streamflow records. If ΔQ_c is known, ΔQ_v can be calculated.

Climate elasticity of streamflow (ε), by definition, is the proportional change in streamflow (Q) divided by the proportional change in a climatic variable. The elasticity of streamflow to precipitation and potential evapotranspiration can be calculated as:

$$\varepsilon_P = \frac{\partial Q/Q}{\partial P/P} \tag{4}$$

$$\varepsilon_{E0} = \frac{\partial Q/Q}{\partial E0/E0} \tag{5}$$

Stepwise Regression

Stepwise regression was used to determine which variables were significant predictors of land surface change elasticity indices. Linear interpolation was used to fill tree cover values and land use and reservoir storage for years in which aerial photography had not been classified so that this variable could be used as a predictor in statistical analyses.

Principal Findings and Significance

Precipitation and air temperature

Mean annual precipitation in the contributing area to the streamflow-gaging stations near Waynoka and near Guthrie, Oklahoma, tended to increase from 1950 to 1960, decreased to 1975, increased to 2000, and decreased to 2005 (**Fig**. 4). Because much of the contributing area to the streamflow-gaging station near Guthrie, Oklahoma included the contributing area to the streamflow-gaging station near Waynoka, Oklahoma, mean annual precipitation trends for those areas were similar, though decreases in precipitation in Oklahoma Climate Division 5 in the 2000s tended to narrow the differences between precipitation in those two areas. Though indicating slight increases of mean annual precipitation with time in these contributing areas, the Seasonal Kendall test did not indicate significant upward trends in mean annual precipitation with time (Table 1).

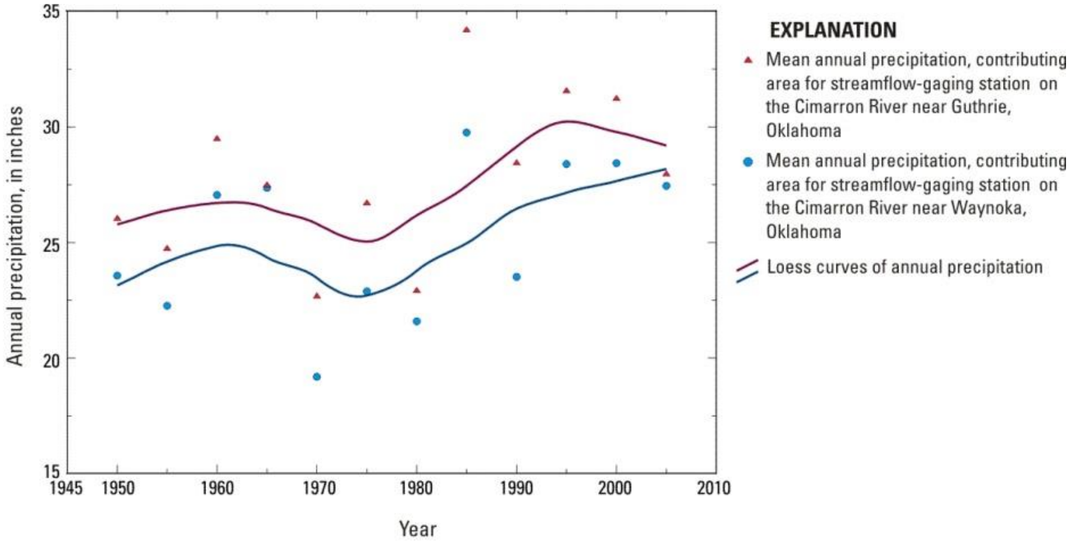


Fig. 4. Mean annual precipitation, in five-year increments for contributing areas for streamflow –gaging stations on the Cimarron River near Waynoka and near Guthrie, Oklahoma

Mean annual air temperature in the contributing area of the streamflow-gaging station near Waynoka generally was about 0.5 ^{0}C cooler than in the contributing area for the station near Guthrie (**Fig. 5**). In both areas, mean annual air temperatures increased by about 1.5 ^{0}C from 1950 to 2005, with the rate of warming increasing starting in 1990 (**Fig. 5**). Although there were general upward trends in mean annual air temperature during this period, the Seasonal Kendall test did not indicate significant increases in mean annual air temperature for these two areas during this period due to temperature increasing and decreasing notably between subsequent periods. Empirical relations between water evaporation, humidity, and air temperatures typical for this area indicate that an increase of air temperature of 1.5 ^{0}C would increase evaporation from a water surface by about 11 percent (The Engineering Toolbox, 2012), though relatively small parts of these contributing areas have free water surfaces subject to direct evaporation to the atmosphere.

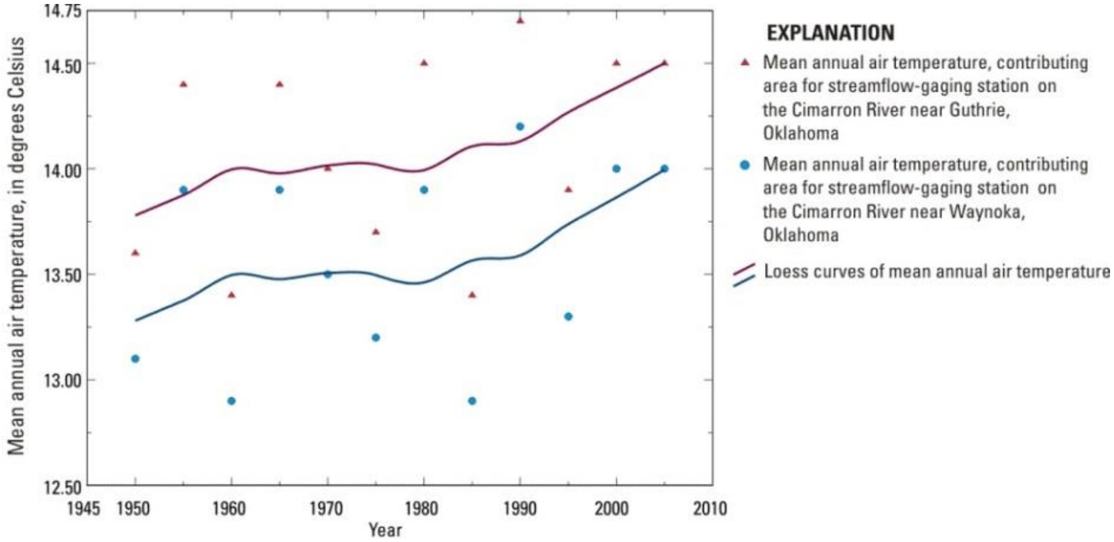


Fig. 5. Mean annual air temperature, in five-year increments for contributing areas for streamflow–gaging stations on the Cimarron River near Waynoka and near Guthrie, Oklahoma

Table 1. Seasonal Kendall tests for trend for meteorologic and hydrologic parameters for contributing areas of streamflow-gaging stations on the Cimarron River near Waynoka and near Guthrie, Oklahoma, 1950-2005.

[mgd, million gallons per day; *, not computed for 1980 because of lack of streamflow data; Waynoka, streamflow-gaging station Cimarron River near Waynoka, Oklahoma (07158000); Guthrie, streamflow-gaging station Cimarron River near Guthrie, Oklahoma (07160000), annual constituents analyzed at 5-year intervals]

Component	Contributing Area	Period	S-score	Z-score	P-value	Estimated trend equation[2]
Precipitation, in inches per year	Waynoka	1950-2005	22	1.44	0.150	Precipitation =23.3 + 0.0663*year
	Guthrie		20	1.30	0.193	Precipitation =25.31 + 0.0804*year
Mean annual air temperature, in degrees Celsius	Waynoka	1950-2005	21	1.39	0.164	Temperature=13.55+0.005*year
	Guthrie		21	1.39	0.164	Temperature=14.0+0.008*year
Consumptive water use, in mgd	Waynoka	1950-2005	17	1.10	0.271	Consumptive water use=238+3.03*year
	Guthrie		18	1.17	0.244	Consumptive water use=258+3.27*year
Mean annual streamflow, in mgd	Waynoka	1950-2010	-18	-1.17	0.244	Streamflow=286-3.30*year
	Guthrie[1]		15	1.090	0.276	Streamflow=604+8.04*year
Change in groundwater storage, in mgd	Waynoka	1950-2010	11	0.737	0.461	Groundwater storage=0+0*year
	Guthrie		6	0.343	0.732	Groundwater storage=-718.3+18.0*year
Evapotranspiration, in mgd[3]	Waynoka	1950-2005	16	1.03	0.304	Evapotranspiration=4488+19.1*year
	Guthrie		22	1.44	0.150	Evapotranspiration=7596+55.2*year

[1] No streamflow data for 1980 due to break in operation of this streamflow-gaging station.

[2] Years computed as sequential integers, with multiplier for year being divided by 5 to account for 5-year periods.

[3] Residual term that does not include evapotranspiration from irrigated cropland

Consumptive water use

Estimated consumptive water use in the two watersheds in the study area peaked in 1975, due to a peak in estimated crop irrigation. A peak in crop irrigation in the study area in 1975 was validated by increases in irrigated acreage numbers in the counties in those areas from U.S. Department of Agriculture census of agriculture from 1949 through 1978 with subsequent leveling off of irrigated acreages from 1982-2007, combined with relative lack of precipitation in between 1970 - 1975 (**Fig. 4**). Declines in consumptive water use from 1975-2005 may be related to wetter conditions leading to less water applied per irrigated acre and more efficient water use in households and commercial and industrial facilities.

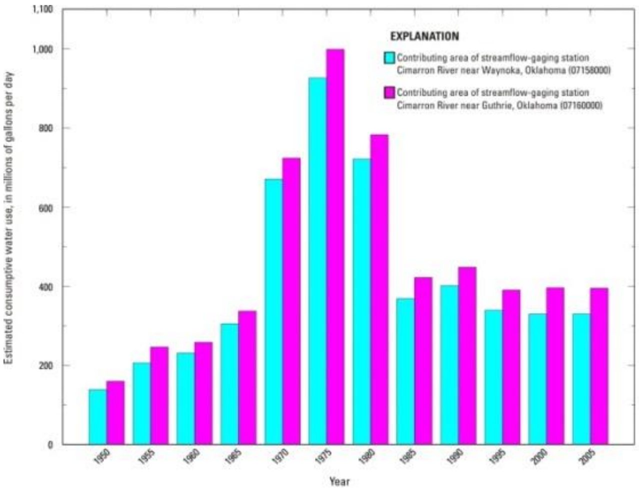


Fig. 6. Estimated consumptive water use in contribution areas upstream of streamflow-gaging stations on the Cimarron River near Waynoka and near Guthrie, Oklahoma.

Estimated consumptive water use generally was about 20 percent greater in the contributing area of the streamflow-gaging station near Guthrie than the contributing area to the station near Waynoka because of water use by additional people, livestock, irrigated agriculture, and commercial and industrial facilities in the area between those two stations. Estimated consumptive water use in both areas was dominated by irrigated agriculture in Kansas, which far exceeded additional water use by as many as 200,000 additional people in the area between the Waynoka and Guthrie gages, which is on the fringes of the Oklahoma City metropolitan area (written commun., R.L. Tortorelli, U.S. Geological Survey, 2005). The Seasonal Kendall test did not indicate significant increases in estimated consumptive water use in these areas over this period (**Table 1**).

Streamflow

From 1950 through 2005 at the streamflow-gaging station near Waynoka, Oklahoma, mean annual baseflow (comprised mostly of groundwater seepage) in the Cimarron River decreased from 170 cubic feet per second (cfs) to about 80 cfs through 1990 (**Fig. 7**). From 1990 through 2005 baseflow at that station increased to more than 100 cfs (**Fig. 7**), probably due to a combination of trends in precipitation and estimated consumptive water use over those periods (**Fig. 6,** and **Fig.** 8). Mean annual runoff (consisting primarily of overland flow after precipitation events) at that station had a similar pattern with time, though more accentuated, decreasing from 600 cfs in 1950 to about 150 cfs in the 1980s through the 1990s, and increasing to more than 200 cfs in 2005. The Seasonal Kendall test did not indicate significant upward or downward trends in mean annual streamflow at this station during this period (**Table 1**).

Downstream at the Cimarron River streamflow-gaging station near Guthrie, Oklahoma, baseflow generally increased from about 250 cfs in 1950 to about 500 cfs in 2005 (**Fig. 7**). Reasons for increasing baseflow at that station over that period may include increasing annual precipitation, particularly during the 1980s through early 1990s (**Fig. 4**), and decreases in consumptive water use since 1980 (**Fig. 6**).

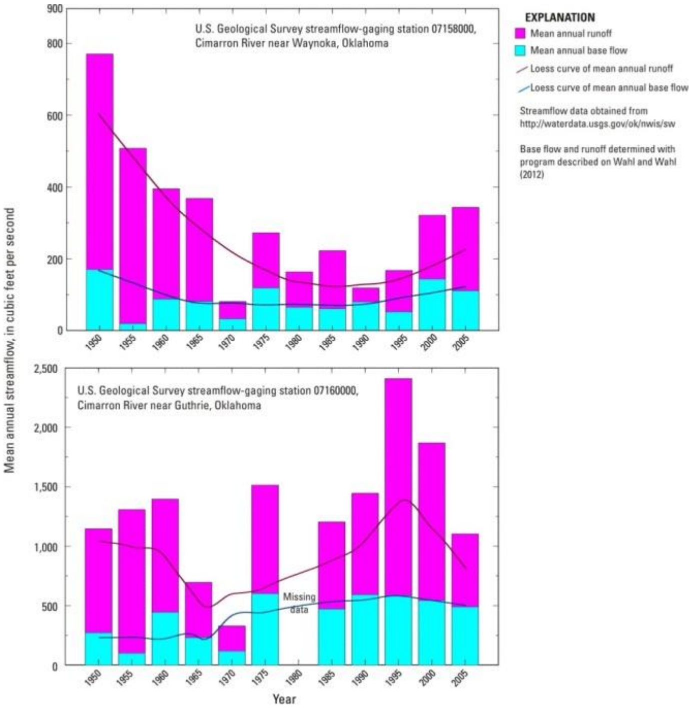


Fig.7. Mean annual base flow and runoff at two streamflowing-gaging stations on the Cimarron River, northwest Oklahoma (1950 -2005)

Groundwater storage

Changes in groundwater storage in aquifers can be estimated through periodic measurement of groundwater levels (depth to groundwater below land surface). In HUC watershed 11050001, in which the streamflow-gaging station near Waynoka, Oklahoma in located, water levels were measured at least annually in 4 to 14 wells completed in alluvial and terrace aquifers along the Cimarron River (**Fig. 8**). In HUC watershed 11050002, in which the streamflow-gaging station near Guthrie, Oklahoma is located, between 8 and 29 wells were measured at least annual for water levels from 1950 through 2005 (**Fig. 8**). As previously described for computation of hydrologic-cycle parameters, data collected at 5-year intervals were selected for analysis (**Fig. 7**). Because of lack of groundwater-level prior to 1975 for the HUC 1105002 watershed, groundwater levels in that watershed from 1950-70 were assumed to have remained constant at 1975 levels, based on relatively little change in annual precipitation for that period (**Fig. 6**).

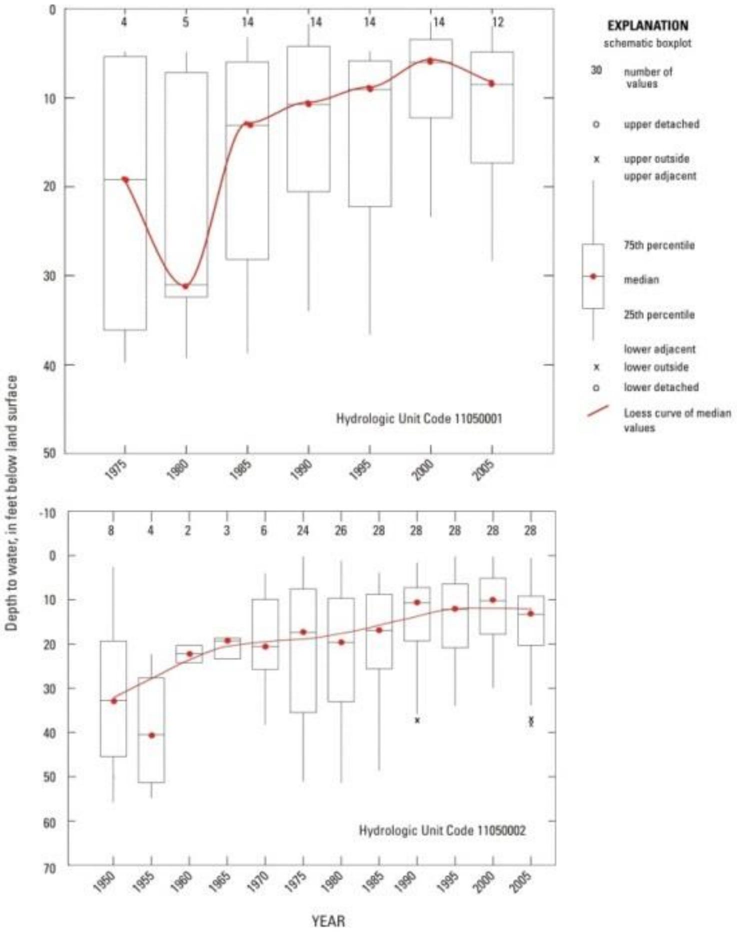


Fig. 8. Distribution of depths to groundwater in selected wells completed in alluvial and terrace aquifers of the Cimarron River in Hydrologic Unit Code watersheds 11050001 and 11050002, 1950 – 2005

For wells measured in the HUC 11050001 watershed, groundwater levels generally increased from 5 to more than 10 feet from 1975-2005, similar to the trend of increasing precipitation in that area for much of that period (**Fig. 6** and **Fig. 8**). Similarly, groundwater levels measured in the HUC 11050002 watershed increased by a median value of about 10 feet from 1975-2005, with a preceding increase of about 10 feet for the period 1950-75 (**Fig. 8**). Because the boxplots shown on **Fig. 8** represent varying numbers of different wells for successive measurement years, they may misrepresent or exaggerate water-level trends. Long-term water level measurements from selected individual wells (**Fig. 9**) also indicated that groundwater levels in alluvial and terrace aquifers of the Cimarron River in these watersheds tended to increase by at least a few feet from the mid- to late-20th century to 2005, indicating increases in groundwater stored in those aquifers during that period.

As with other hydrologic parameters, the Seasonal Kendall test did not indicate significant upward or downward trends in change in groundwater in storage in alluvial aquifers in either of these areas for this period (**Table 1**).

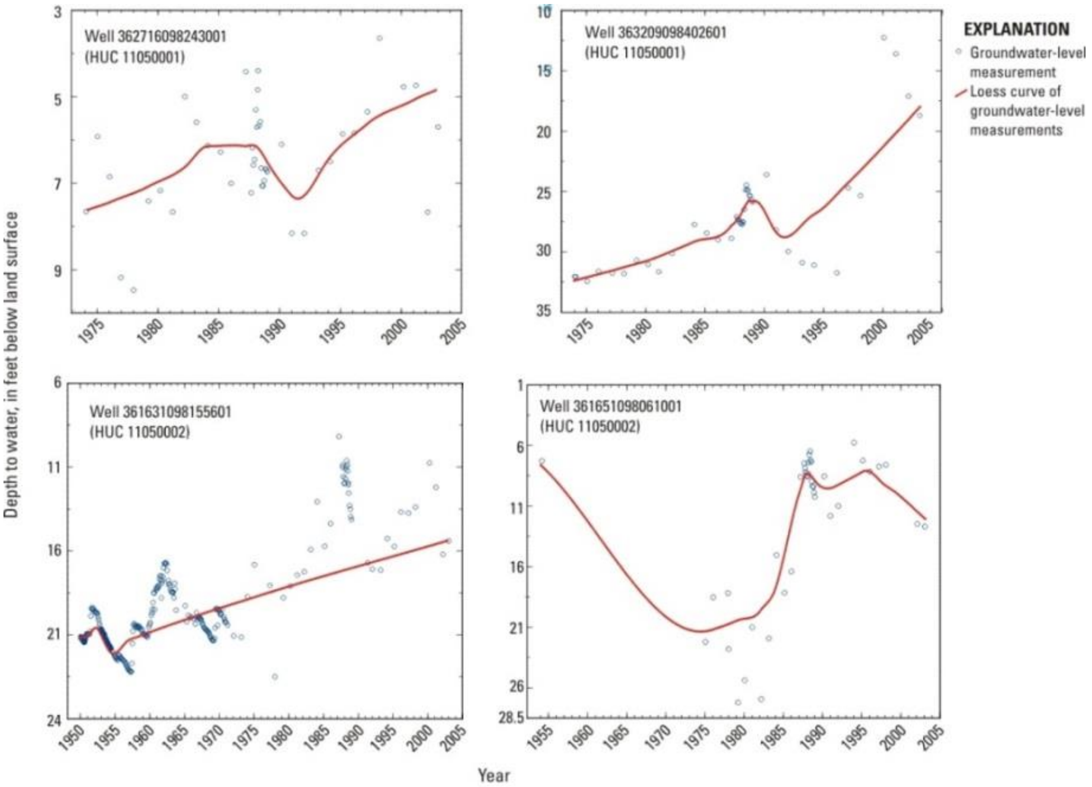


Fig.9. Depths to water in selected wells completed in alluvial and terrace aquifers of the Cimarron River in Hydrologic Unit Code watersheds 11050001 and 11050002, 1950 – 2005

Hydrologic cycle estimates

Estimated evapotranspiration, the residual of inputs, plus or minus change in storage, minus measured outputs of water from the contributing areas upstream of these streamflow-gaging stations, gradually increased for the contributing area upstream of the station near Waynoka, Oklahoma from 1950 to 2005 (**Fig. 10**). Estimated evapotranspiration increased from 1950 to 1990 in the contributing area upstream of the station near Guthrie, Oklahoma, but decreased from 1990-2010 in that area (**Fig. 10**). Decreases in estimated evapotranspiration since 1990 in the contributing area upstream of the station near Guthrie largely are attributable to decreases in annual precipitation in Climate Division 5 since 1990 (**Fig. 4**). The Seasonal Kendall test did not indicate significant upward or downward trends in estimated evapotranspiration in either of these contributing areas during this period (**Table 1**).

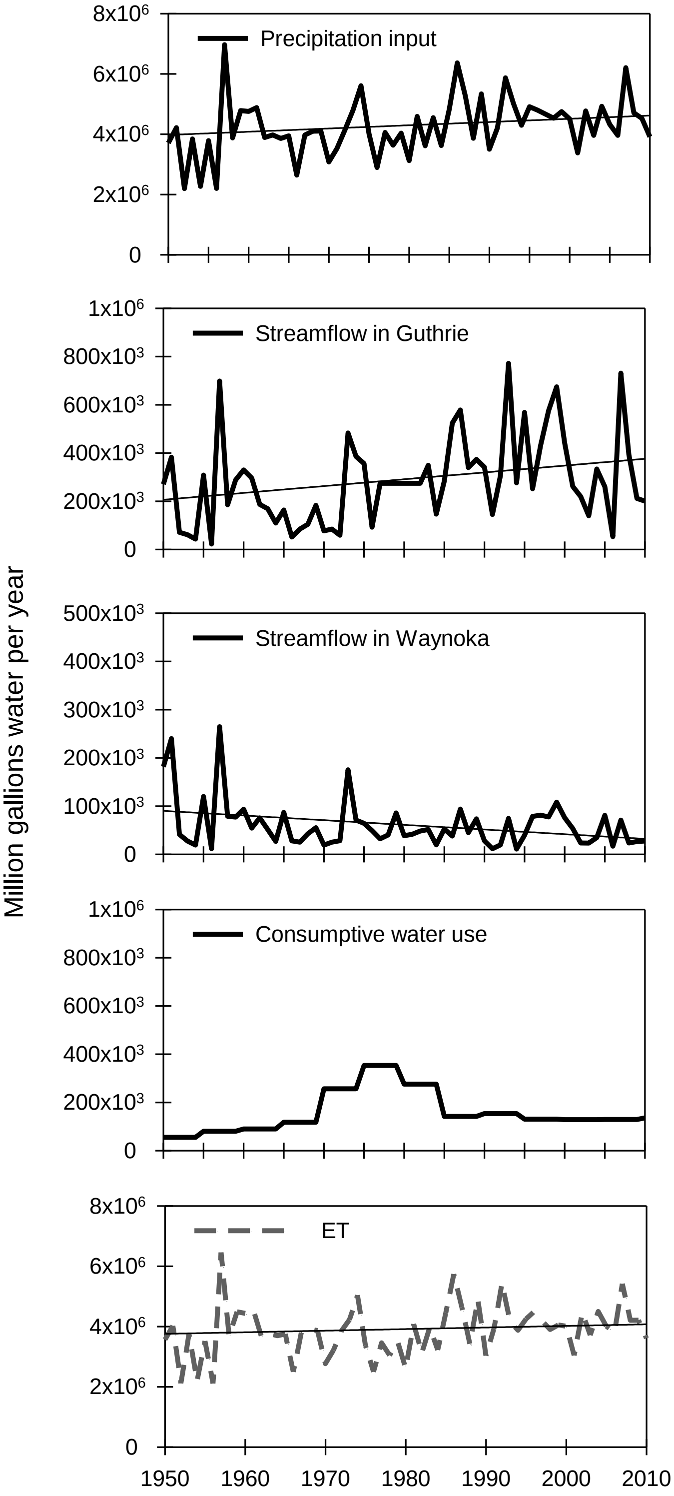


Fig. 10. Change in precipitation input, streamflows in Guthrie and Waynoka, Consumptive water use and estimated ET for the contribution area.

Land-surface change

Between 1975 and 2010 woody cover more than doubled in the contribution area to Cimarron River from Waynoka to Guthrie, from covering 2.7% of the total land area in 1975 to 5.7% in 2010 (approximately 477 sq kilometers or 118,000 acres). Of the total woody cover, approximately 88% consisted of evergreens.

Table 2. Change of woody and herbaceous land cover between 1975 and 2010

Year	Season	Trees % total land	Herb % total land	Total vegetation cover
1975	winter	3.63	72.58	76.20
1985	winter	3.49	69.12	72.61
1995	winter	3.29	62.56	65.86
2005	winter	4.05	69.63	73.68
2010	winter	5.42	72.61	78.03
1975	summer	2.71	78.10	80.81
1985	summer	3.84	74.38	78.21
1995	summer	4.22	67.32	71.54
2005	summer	4.58	73.20	77.77
2010	summer	5.66	69.93	75.59

Given the wide proliferation of the species in the state, the majority of these are likely to be eastern redcedar (*Juniperus virginiana*) and salt cedar (*Tamarix ra mosissima*). During the 35 years from 1975 to 2010, stands of these trees appear to have increased in density in the upper portion of the watershed while decreasing in the lower portion near Guthrie and Oklahoma City, OK. A substantial increase in woody cover along the river channel and riparian zone, particularly in the upper part of the river, was observed in 1995 vegetation distribution map. Expansion in the upland portion of the watershed became apparent in 2005 and 2010 vegetation distribution maps. Coincident with the increase in woody cover has been a 7% decrease in total herbaceous cover. A large portion of this reduction has been from retirement or abandonment of irrigated acreage, which has decreased by 9.2% since 1985 (**Fig. 11**).

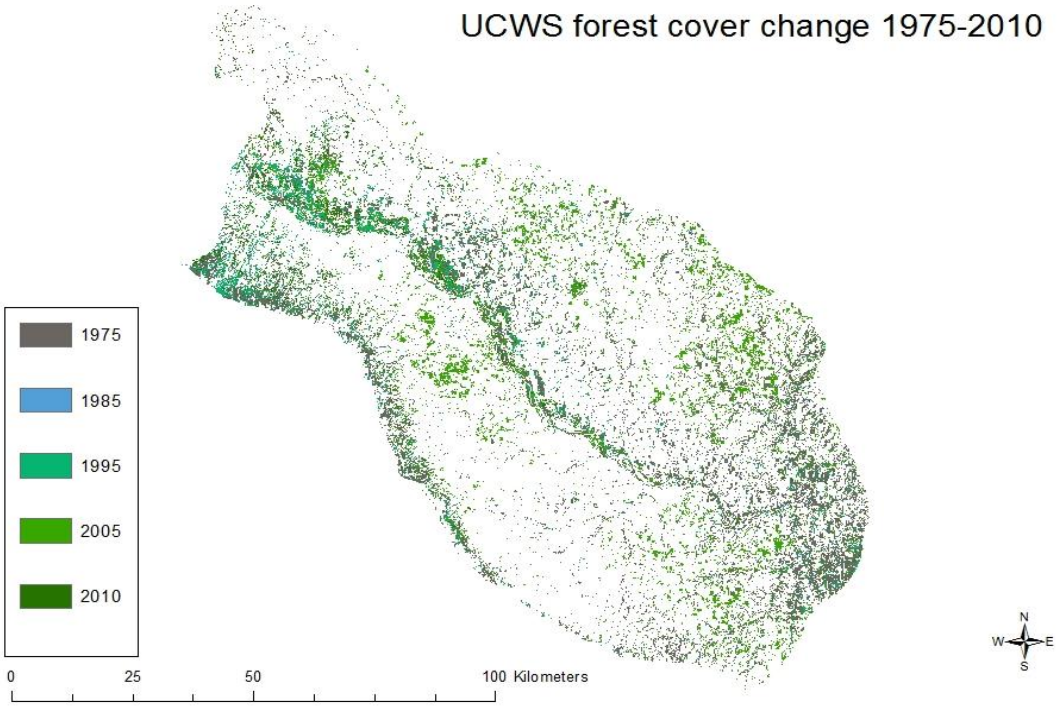


Fig. 11 Change in woody cover from 1975 to 2010 in the contribution area to Cimarron River between Waynoka and Guthrie

Climatic elasticity and vegetation impact

The calculation of climate elasticity and land surface elasticity of streamflow produced unsatisfactory results (not reported here). The main challenge in calculating climate elasticity was to precisely quantify change in streamflow ($\partial Q/Q$). In contrast to our original thoughts, we found that a substantial change (both increase and decrease) in groundwater storage during this period (**Fig. 8** and **Fig. 9**); this change has been estimated to be substantial in magnitude and its effect on streamflow is not well understood. In addition, consumptive water use might partially come from groundwater storage. A subtle error in streamflow change will affect $\partial Q/Q$ substantially, resulting unsatisfactory climate elasticity results.

Instead, we used linear and non-linear regression analysis. Regression analysis showed that precipitation in the contribution area strongly affected streamflow recorded in Guthrie gauge station. The streamflow decreased nearly linearly with increase in potential ET calculated based on mean monthly temperature and mean monthly precipitation using Thornthwaite monthly water balance model (http://wwwbrr.cr.usgs.gov/projects/SW_MoWS/Thornthwaite.html) for the contribution area (**Fig. 12**).

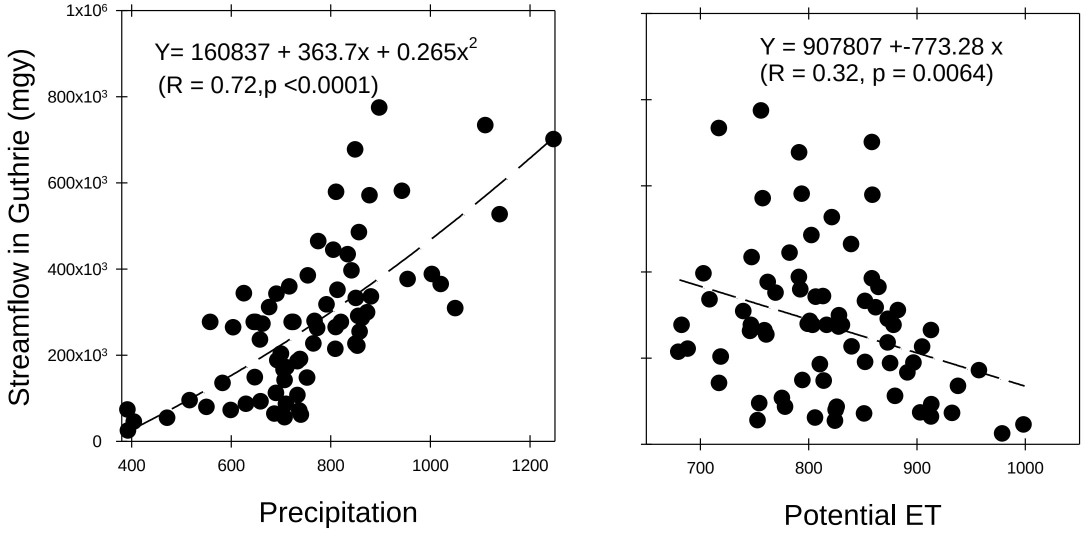


Fig. 12. Responses of streamflow in Guthrie Station to precipitation and potential ET of the contribution area.

There is an upward trend in ET/P with increase in tree cover in summer (**Fig. 13**) although the positive correlation is not statistically significant (p = 0.2067).

The increase in tree cover is relatively small compared with the contribution area percentage wise. However, the increased tree cover has mainly concentrated around the riparian zone and river channel. We found some positive relationship between ET/P and tree cover (in summer) although this relationship is not statistically significant.

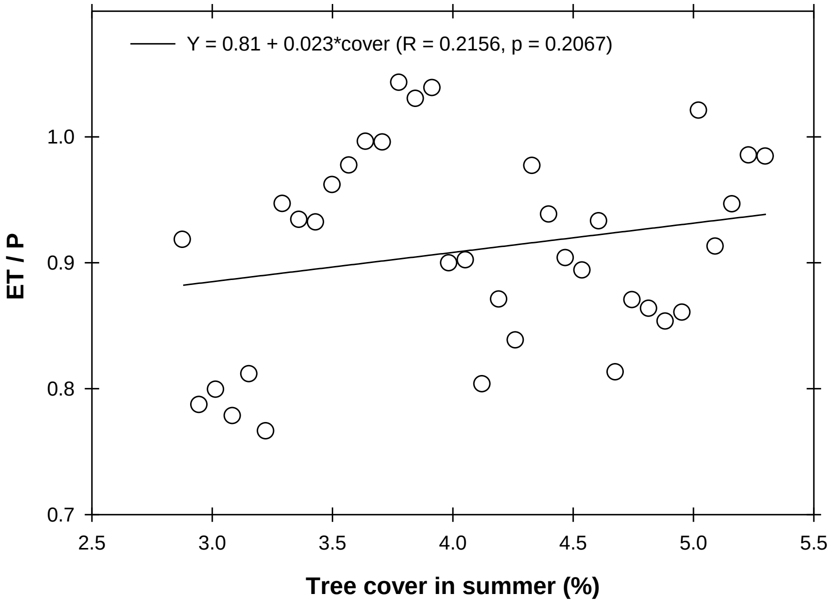


Fig. 13. Response of ET/P to increase in tree cover

Conclusion and Future Research

1. There were general upward trends in mean annual air temperature and mean annual precipitation during 1950 - 2005, but the Seasonal Kendall test did not indicate significant increases in either mean annual air temperature or mean annual precipitation during this period;
2. Consumptive water use in the contribution area peaked in 1975 and subsequently leveled off from 1982-2005;
3. Groundwater levels in alluvial and terrace aquifers in the contribution area tended to increase from the 1960s to 2005, indicating increases in groundwater stored in those aquifers during that period.
4. There was a general upward trend in streamflow for Guthrie gage station since 1970 to 2005. In contrast, there was a downward trend in streamflow for Waynoka station since 1950 although seasonal Kendall test did not indicate significant increases or decrease.
5. The magnitude of streamflow for Guthrie gage station was strongly, positively correlated with annual precipitation in the contribution area, but negatively correlated with potential ET.

6. Increase in tree cover has primarily concentrated in riparian zone and river channels. During 1975 to 2010, the tree cover has doubled from 2.7% to 5.7% (approximately 477 sq kilometers) primarily from increase in evergreen trees such as eastern redcedars.
7. There is an upward trend in ET/P with the increase in tree cover, suggesting increase of tree cover may have augmented the ET component and reduced streamflow or recharge component in the water budget.
8. Future research should focus on: 1. Quantify vegetation and land use change in riparian zone and alluvial area to investigate vegetation impact on water use and groundwater recharge; 2. Quantify change in impoundment in the contribution area, its history, its relative magnitude, and its potential impact on water budget calculation. 3. Improve potential ET estimation using Penman-monteith or other approaches with a daily step and re-evaluate the elasticity of streamflow to potential ET.

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