HYDROLOGIC RESPONSES TO CLIMATE, WATER

USE, LAND SURFACE TRANSFORMATION, AND

SURFACE WATER IMPOUNDMENT IN AN

IRRIGATION INTENSIVE WATERSHED

By

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Abstract:Climatic variability and land surface change have a wide range of often difficult to parse out effects on streamflow. 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 for the time period from 1950 through 2010 for an irrigation intensive agricultural watershed in the Southern Great Plains, USA.

Increase of surface impounding structures is a unique feature in land surface transformation for the Southern Great Plains. In the United States the highest density of farm ponds is in the Southern Great Plains and specifically in the state of Oklahoma. These represent a significant form of anthropogenic alteration to the landscape. Despite the vast proliferation of these small reservoirs in the state, very few studies have evaluated the ecosystem services and the effects of these water bodies on the hydrologic cycle.We quantified surface water storage in Oklahoma using remote sensing techniques. We qualitatively assess the potential effects of small reservoirs such as farm ponds, stock ponds, animal and industrial waste lagoons, and small flood control reservoirs on streamflow.

For the study period, we found ageneral trend of increases in grass and woody cover, rapid increase in urban area and surface impoundment. The atmosphere demand (ET_0) has trended downward due largely to increase in relative humidity and no trend in temperature change. We found that streamflow was most sensitive to changes in precipitation when annual water consumption for irrigation was high between 1965 and 1984 and was less responsive to precipitation variability since 1985. The changes in the total area of agricultural land and the encroachment of woody species into grassland have been negatively correlated with streamflow over the past 30 years when groundwater pumping has been relatively constant. We found a strong linear correlation between the logs of reservoir capacity and water surface area at multiple spatial scales - state, watershed and county, suggesting a potential in rapid assessment of surface water storage in impounding structures using remote sensing data for this region.

For a watershed with heavy anthropogenic alteration, there is a need to consider drivers aside from the traditional climatic ones and thus, water use, land use and land cover change can all be included in a holistic adaptation and mitigation strategy.

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CHAPTER I

STREAMFLOW RESPONSES TO CLIMATE, WATER USE AND LAND SURFACE TRANSFORMATION IN AN IRRIGATION INTENSIVE WATERSHED

1. Introduction

Partitioning climate from anthropogenic induced alteration to the hydrological regime, especially streamflow, is a major challenge for environmental flow 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, untangling the climate variability and anthropogenic change and their interaction on streamflow is pivotal to water resource planning and instream flow management under increasing climate variability (Chahine, 1992).

Compensative water input through withdrawing groundwater characterizes crop production in a water-limited ecosystem. 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, especially when this added water cycle, on an annual basis, is sufficiently large compared to streamflow in an alluvial aquifer dominated watershed such as the Cimarron-Skeleton watershed in the Southern Great Plains.

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 use since the turn of the twentieth century. The Cimarron-Skeleton watershed is underlain primarily by the Cimarron Alluvial and Terrace aquifer which consists of shallow, quaternary and tertiary alluvial terrace deposits. The deposits on the river's Southwestern side are considered poor for groundwater, 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 in this system (Heeren *et al.*, 2013). As a result, this alluvial aquifer dominated watershed has been turned into a very productive agricultural region with substantial groundwater pumping to support row crop production. However, a recent study reported a downward trend in total annual streamflow and increase in zero flow time for the upper reach of this watershed despite an overall upward trend in precipitation over the last six decades (Esralew and Lewis, 2010), potentially associated with declines of fish communities, and especially pelagic spawning minnows, including the federally listed Arkansas River shiner (Pigg, 1991; Wilde, 2002). This divergence of precipitation and streamflow trends suggests the increasing role of anthropogenic induced changes on streamflow responses.

Anthropogenic induced changes including a gradual but steady conversion of cropland back to range use was a general trend for this watershed (Boren *et al.*, 1997). The existing rangelands along with those newly abandoned or retired croplands have undergone a rapid increase in woody plant encroachment by Eastern redcedar (*Juniperusvirginiana*) and riparian gallery forest expansion since 1980s (Wine *et al.,* 2012b) and is transforming the non-cultivated land surface into a woody state (Van Auken, 2009). In addition, increase in urban area is a common trend for many watersheds in the southern Great Plains. Finally, the southern Great Plains including this watershed has been in the center of a rapid increase in impoundment and flood control structure construction in the last 60 years as a result of the low relief and dust bowl (Vance *et al.*, 2010). All those anthropogenic changes are intertwined with complicated feedback mechanisms on the hydrological system (Mahmood *et al.*, 2004; McPherson *et al.*, 2004; Adegoke *et al.*, 2007; DeAngelis *et al.*, 2010; Fall *et al.*, 2010), making it difficult to untangle the effect from climate and anthropogenic induced change on streamflow.

The elasticity of streamflow to climate 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 (potential evapotranspiration) (Sankarasubramanian *et al.*, 2001). Knowing the contribution of climatic forcing on streamflow variation, we are then able to compute a time series of streamflow sensitivity to anthropogenic activities as a whole and identify periods (or phases) when anthropogenic activities have augmented or reduced streamflow. This is essential to compare and contrast a range of hydrological metrics important to environmental flow management such as high flow frequency, low pulse counts, and base flow index for a given period of substantial anthropogenic activity.

In the south-central Great Plains of USA, as in many semi-arid regions of the world, a highly variable climate and an increasing demand of water resources for multiple uses made both the natural and production systems very vulnerable to climate extremes.

Untangling the climate variability and anthropogenic change and their effect on streamflow regime are fundamental in forming our climatic adaptation strategies and empowering managers to effectively adapt our production systems to increasing climate variability while sustaining our natural ecosystems.

2. Materials and Methods

2.1. Site - Cimarron-Skeleton Watershed

The Cimarron-Skeleton watershed is located in North Central Oklahoma (Fig.1) with a drainage area of 8275 sq kilometer. Adding the contribution area from the inflow gage station(Waynoka Station in Waynoka, Oklahoma, USGS ID -07185000), the total drainage area between the inflow and outflow gauge station (Guthrie Station in Guthrie, Oklahoma, USGS ID- 07160000) is 10,805 sq kilometer. This watershed has a low relief with a standard elevation deviation of 37.6 m. The precipitation declines from east (Guthrie Station, 915 mm) towards west (Waynoka Station, 690 mm).

2.2. Data Collection

2.2.1 Streamflow and Climate Data

Daily streamflow data in Waynoka Station and Guthrie Station dating from 1948 through 2010 were collected from the USGS National Water Information System. Streamflow exiting the watershed downstream of Guthrie was estimated using 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 stream gage near Lovell, OK, on Skeleton Creek (USGS #07160500) as a baseline. This is considered 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 gage is 1.02. Estimated flow at the confluence was then added to the recorded flow at Guthrie to get the total outflow for the watershed. Daily climate data were gathered for years 1950 through 2010 from the National Climate Data Center (NCDC) for twenty-five weather stations which are centrally distributed representing the temperature and precipitation gradient (Fig. 1).

The NCDC data were used to calculate mean reference evapotranspiration for the contribution 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, 2005).

Water-use and groundwater storage data compiled at 5-year increments from 1950-2005 for the Cimarron-Skeleton watershed and part of the Cimarron-Eagle Chief watershed (Fig. 1) were estimated from data obtained from the Aggregate Water Use Data System (AWUDS) of the USGS (U.S. Geological Survey 2012a), and data used to compile Tortorelli (2009). Major water-use categories included in this compilation include self-supplied irrigation from groundwater and from surface water, water withdrawal for domestic and industrial use. 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. 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 not computed by HUC watersheds, only by counties, so cannot be directly compared to previously compiled water-use data.

2.2.2. Land Use and Land Cover Data

For land cover prior to 1975, aerial photographs were obtained from Edmon Low Library at Oklahoma State University (OSU), the Oklahoma Department of Libraries (ODL), and the Oklahoma Corporation Commission (OCC), digitized by scanning at 800 dpi, and georeferenced against National Aerial Imagery Program (NAIP) imagery (NRCS Geospatial Data Gateway). The images were mosaicked using Mosaic Tool Pro in ERDAS. 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. 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).

Landsat imagery was obtained from USGS global visualization viewer every 10 years 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 (ERDAS Imagine 2011), clipped in ERDAS Imagine 2011 using watershed shapefiles of the 2 HUC-8 units that comprise the basin (National Hydrography Dataset).

2.3 Data Analysis and Statistics

In this study, we first estimate the effect of climate change on streamflow using the method of climate elasticity of streamflow proposed by Schaake and Waggoner (1990). The climate elasticity of streamflow(equation 1) 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). Then the land surface change elasticity of streamflow was estimated and stepwise analysis was used to quantitatively attribute the effect of conversion of cropland, urbanization, woody encroachment, impoundments and groundwater withdrawal on streamflow for the two periods between 1950 and 2012 andbetween 1980 and 2010 (when water use was more constant).

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

Trend of precipitation, ET_0, and streamflow were tested using Mann-Kendall seasonal trend analysis method(Mann, 1945; Kendall, 1948). Where a significant trend exists, change point analysis was used to detect the year when significant changes occurred (Taylor, 2000). After determining which time periods were significantly different to each other, changes in streamflow regime between the different time periods were determined using the Indicators of Hydrologic Analysis (IHA ver. 7.1) software package (Richter *et al.*, 1996). IHA produces results on 34 ecologically relevant flow components. There are five critical components of the flow regime that regulate ecological processes in river ecosystems: magnitude, frequency, duration, timing and rate of change of hydrologic conditions(Poff and Ward, 1989; Walker *et al.*, 1995; Richter *et al.*, 1996). We report here the results for these components in the Cimarron-Eagle Chief watershed. Relative contributions of climate and anthropogenic induced changes to streamflow were analyzed using linear model:

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

whereΔQ_t is change in annual streamflow, ΔP_t and ΔET_0 are changes in annual precipitation and potential evapotranspiration and the error term can be interpreted as the non-climatic, or anthropogenic, effects.

Kendall's tau test was used to determine which anthropogenic variables were significantlyassociated withstreamflow for the entire study period and the period without excessive water use.

3. Results

3.1 Streamflow Variation

The results of our linear regression model found that only about half of the observed streamflow variability could be accounted for by climatic factors (R^2=0.5178). Annual flows for the inflow into the study area are historically lower with a range of 4.1×10^7 to 9.9×10^8 m^3 yr^{-1}. Since the 1980s, this discharge range is narrowed by nearly half with the maximum annual flow never exceeding 6.6×10^6 $m^3 yr^{-1}$. IHA analysis found that during this time period, monthly maximum flows at Waynoka decreased in frequency and the water delivered during these flows was decreased by nearly half from just over 3000

m^3s^{-1} to around 1500 m^3s^{-1}. Also, the duration of high flow events decreased from 4 to just 2 days. The average count of monthly minimum flows at this station remained the same over the study period. However, the duration of minimum flows increased after the 1980s. The frequency of zero flow days decreased from an average of 30 per year to 19 after 1983 while base flow increased steadily.

Annual discharge at the outflow point of the Cimarron-Skeleton watershed showed considerable variation over a large range between 1.0×10^8 and 30.5×10^8 m^3yr^{-1} (Fig. 2). Mann-Kendall trend test showed that annual flows trended upwards at Guthrie Station ($p <0.02$) and at the confluence of Skeleton Creek and the Cimarron ($p < 0.02$). Areal precipitation in the watershed and contributing area trended upwards ($p < 0.02$) over the entire study period.

Change point analysis showed a new, higher mean annual streamflow occurred at the downstream gage beginning 1983 and continued through 2010. During this period, high flow pulses (streamflow ≥ 10% above the mean) decreased while the volume of water delivered during high flow events increased. Similarly, low flow frequency (streamflow ≤ 10% below the mean) also decreased while baseflow increased (Fig. 3).

3.2 *Long Term Trends of Climatic Drivers – Precipitation, Temperature, VPD,* ET_0

The 60-year mean precipitation was 797 mm $yr^{-1}$with a change in the mean occurring in 1983 (733 $mmyr^{-1}$from 1950 to 1983 and 869 mm $yr^{-1}$from 1984 to 2010). Mean areal temperature for the years 1940-2010 was 15.7 °C +/- 0.4 °C and remained fairly static over the study period (Fig. 4).

An increasing trend in relative humidity occurred throughout the study period with the exception of a brief, three percent decrease between 1963 and 1968. There were shifts in mean RH in 1958, 1963, 1968 and 1982. A concomitant decline in vapor pressure deficit, or atmospheric demand was mirrored by an increase in humidity. Reference evapotranspiration (ET_0) over the 60-year period significantly declined ($p = 0.003$) (Fig. 4). Based on change point analysis, mean ET_0 changed twice over the 60-year period, from 1737 mm yr^{-1} through much of the 1950s, 1633 mm yr^{-1}until the early 1980s, and 1585 mm yr^{-1}from 1983 to 2010.

3.3 Consumptive WaterUse and Groundwater Storage

Consumptive water use in the watershed was around 10 million m^{3}yr^{-1}between 1950 and 1960. From 1965, water consumption increased rapidly, peaked at nearly 40 million m^{3}yr^{-1}in 1975, and decreased afterward. Consumptive water use was relatively stable (mean= 18 million m^{3}yr^{-1}) from the mid-1980s through the end of the study period (Fig. 5).

Groundwater storage in the Lower Cimarron-Skeleton watershed had a sharp decline in 1955 and a sharp increase in 1958. Since the 1960s, groundwater levels therefore groundwater storage in the watershed showed no discernible trends. Mean annual change in storage was 7.2×10^7 m^3. Thefairly large standard deviation of65×10^7 m^{3}yr^{-1}implies that the lack of a significant trend does not indicate a steady, stabilized groundwater storage pattern

3.4 Precipitation, ET_0 and Anthropogenic Elasticity to Streamflow and Climate and Anthropogenic Interaction

Streamflowwas positively correlated with precipitation and precipitation elasticity of streamflow was elevated in the 1970s and peaked in the early 1980s (Fig. 4). Similarly, potential ET elasticity of streamflow was elevated during the same period but in an opposite direction. Streamflow sensitivity to precipitation and ET_0 were relatively stabilized since 1980. As the residual of climate contribution, anthropogenic elasticity of streamflow was positive until 1983 when it turned generally negative but at a lesser magnitude along with a substantial reduction in the total consumptive water use.

3.5 Land Surface Change and Responses of Streamflowto Land Surface Change

Cropland declined from 66% in 1950 to 49% in 2010. The lost cropland was replaced by other land cover classes, predominantly by rangeland, though urban area had the fastest rate of increase moving from less than 1% of the watershed in 1950 to nearly 8% by 2010. Grasslands increased steadily alongside declining croplands until 2000 when grassland was encroached by woody plants. Surface water increased steadily, though still onlyaccounting for less than 1% of the land cover of the entire watershed in 2010.

For the period between 1950 to 2010, in addition to climate factors, there were strong positive correlations between streamflow and four of the land cover classes; grassland ($p = 0.0003$), urban area ($p = 0.0005$), forest ($p = 0.002$), and surface area of open water ($p = 0.0014$). There was a significant negative correlation between streamflow and percentage of crop cover ($p = 0.0019$)(Table 1). For the period between 1980 and 2010, only increase in grassland cover percentage and relative humidity were positively correlated to streamflow increase ($p = 0.0199$ and $p = 0.0366$, respectively) and streamflow was negatively correlated to increasing consumptive water use ($p = 0.0023$).

4. Discussions

Our results show that only 51% of observed streamflow variability for the studied period hasresulted from climatic factors, suggesting changes on the landscape due to anthropogenic causes play an equally important role in streamflow variability. It seems almost counter intuitive that streams would respond to precipitation more positively when the climate is relatively dry as we reported in this study. For an irrigation intensive watershed located in an area with hot summers and limited precipitation such as the Cimarron-Skeleton watershed, our study shows that substantial amounts of water are 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. In areas that are predominately cropland, we can expect increase in surface runoff when storm events do occur.

Our results showed an increasing trend in relative humidity coinciding with increased irrigation in the 1970s and an increase in precipitation in the 1980s and 1990s. Although atmospheric demand decreases as a result of higher humidity, it is not necessarily true to assume that the actual evapotranspiration decreases as well. In fact, compensative water from irrigation may make any increase in atmospheric demand more effective in evaporating soil moisture. This effectiveness is reflected by the observed increase in ET_0 elasticity during the years of heavy irrigation. When irrigation is stabilized starting from the 1980s, the increase in ET_0 started to have less of an impact on streamflow decrease.

Intensive irrigation has been found in many areas to significantly alter climate (Sacks *et al.*, 2009). However, the feedback mechanism of irrigation and resultant change in atmospheric condition, antecedent soil moisture conditions that controlled both the actual evapotranspiration and runoff at watershed scale have not been thoroughly studied in the Southern Great Plain region.

In the North Canadian River of NW Oklahoma, groundwater pumping was found to be responsible for a 47% loss of streamflow as a combined result of reduced baseflow to streams and increased stream leakage into the aquifer (Zume and Tarhule, 2008). In contrast to this, our results found that mean annual streamflowmore than doubled between the first 30 year period (1950-1980) and the second (1980-2010). This occurred concomitant with increases in peak flow velocities, andbaseflow. Groundwater in our study area comes primarily from the Cimarron alluvial and terrace aquifer. There is a rapid exchange between alluvial aquifer and surface water. As a result,irrigation acts as a controlled rainfall event and enhancesthe localized water cycle in the watershed. This added pathway of the water cycle when large enough compared to streamflow could have contributed to observed increase in total flow in our study.Excessive pumping of groundwater for irrigation and other purposes was reported to sustain streamflow at levels that exceed natural flows (Kendy and Bredehoeft, 2006).

In addition to irrigation, there are a variety of land use changes that can affect streamflow in a watershed. The combination of agricultural land retirement, fire suppression and urbanization has helped to fuel rapid woody expansion into riparian zones (mostly *J. virginiana*and *Tamarix spp.)*(Van Auken, 2009; Wine *et al.*, 2012a). Increases to impervious surface as a result of urbanization increases runoff volume and velocity but decrease flow duration, infiltration and baseflow(Hollis, 1975; Rose and Peters, 2001).

Streamflow along with groundwater recharge and water withdrawalsis the residual term between precipitation input and evapotranspiration (ET) output for a given watershed or region. Increase or decrease in precipitation trend projected for a given watershed or region from climate projection has been used as proxy of potential streamflow response (Miller *et al.*, 2003; Qi *et al.*, 2009)explicitly or implicitly. However, factors aside from precipitation can modify or even change this precipitation and streamflow relationship. Increased climate variability and anthropogenically induced changes to the landscape have substantially altered hydrological systems and imposed great pressure in water resources and environmental management globally. The specific effects and the extent of those effects vary for a given watershed and from region to region. A small watershed study in Iowa found discharge in midwestern watersheds had increased since 1970 without an increase in precipitation (Tomer and Schilling, 2009). In the Upper Mississippi River Basin, rural land use changessuch as soil and water conservation programs, and crop conversion from corn to soybeans have been attributed to declines in streamflow despite increased precipitation (Kochendorfer and Hubbart, 2010).In Canada, increase in temperature has resulted earlier snowmelts and decreased mean streamflows for most months (Zhang *et al.*, 2001). Because each area is affected differently by changes in climate and land use, there is no single generalization to be presented as panacea to this global phenomenon.

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 (IPCC 2007).

Increase in intensity will augment stormflow, potentially at a cost tobaseflow and groundwater recharge. Decrease in precipitation frequency will lead to increased drought and subsequent groundwater pumping. Both trends tend to deplete groundwater reserves. This could be of great consequence in this portion of the basin where the majority of agriculture in the Lower Cimarron takes place and the majority of the basin's population resides. Groundwater use regulations, urban growth regulations and vegetation management are all possible management techniques that might be able to ensure sufficient water resources availability in a future that will likely be hotter and drier.

CHAPTER II

LAND SURFACE TRANSFORMATION - IMPOUNDMENT AND ITSECOHYDROLOGICAL IMPACT IN OKLAHOMA

1. Background and Extended Literature Review

The construction of dams and other hydraulic structures is, therefore, one of the oldest branches of engineering (Baxter 1977). One purpose of building dams is to reduce annual variations in water level, making the floodplain habitable throughout the year and allowing its ecosystem to become more mature; or, more commonly perhaps, causing it to be replaced by a different ecosystem maintained in a state of immaturity throughagriculture.

Humans greatly impact the hydrologic cycle around the world both intentionally and unintentionally (Oleson*et al*.; Lins and Slack, 1999; Barnett *et al*., 2008). Dams reduce peak flows (Magilligan and Nislow, 2005), increase drawdown time, and decrease annual flood volume (Singer, 2007). Dams decrease flow variability in watersheds (Lajoie et al., 2007), which can be critical for downstream ecosystems (Isik et al., 2008). It is estimated that artificial impoundments permanently contain approximately one year’s worth of runoff from the North American continent (Smith et al., 2002). Water impounded in reservoirs since the early twentieth century is by far the largest anthropogenic hydrological change in terms of the mass involved. This mass redistribution contributes to geodynamic changes in the Earth's rotation and gravitational field that have been closely monitored by modern space geodetic techniques (Chao, 1995).

Presently, most reservoir studies focus largely on the results of major engineering projects. Smaller impoundments, such as farm ponds, have largely been ignored and the studies that do exist are primarily geared towards fisheries production and management. Globally, the cumulative volume of the millions of small reservoirs such as farm ponds, rice paddies, stock ponds, animal waste lagoons, industrial ponds, and small flood control structures may approach that of the larger, documented reservoirs. The total water impounded by reservoirs in any size range appears to be equal to that in any other size range, and this becomes apparent when viewed on a logarithmic scale (Sahagian 2000).

The term pond is semantically difficult to define and usage of the word varies in a colloquial sense from region to region. For the purposes of this study we use the definition by Willis et al. (2010) who define a pond as a small water body up to 40 ha in surface area. The term ‘reservoir’, unless specifically denoted as being a small reservoir, will be applied for constructed lakes.Three major types of constructed ponds are defined: (1) embankment, (2) excavated, and (3) levee(Lusk et al. 2012). Most ponds in the United States are embankment ponds (Bennett, 1971), built with a small dam placed between two hills to inundate a larger, upstream area.Or, in flatter areas, the dam ispushed up to a higher elevation than the lowest point on the landscape. Excavated ponds are simply dug out of the ground and often filled by seepage from groundwater, runoff from the watershed, or pumped in. A major concern with excavated ponds that are connected to groundwater is the potential of contaminating groundwater sources with pollutants in surface runoff that makes it way to the pond. Finally, the least common type of pond is the levee pond,which is typically excavated to a shallow depth, rectangular in shape, and surrounded by levees on all sides. Levee ponds have no watershed aside from the inside of the levee walls and can only be filled by direct precipitation and pumping..

Ponds, small reservoirs and small impoundments provide many uses including water for drinking, irrigation, stock watering, fish production, wildlife habitat, recreation and aesthetic purposes. A conservative estimate places the number of ponds in the United States at approximately 2.6 million, representing approximately 20% of the water storage in the United States (Smith et al., 2002). However, this number is likely much larger and growing all the time. Between 1998 and 2004 the total surface area of freshwater ponds in the U.S. increased by 12% (Dahl, 2005) and gained an additional 3% from 2004 to 2009 (Dahl, 2011).

Historically, studies on farm ponds have focused largely on fisheries production, capture of pollutants and pathogens, and various wildlife studies. Surprisingly, there have been few studies on farm pond hydrology. Such water features are often overlooked in hydrologic studies likely because the effect of a single pond on the water budget is negligible. However, in areas with high densities of ponds, the cumulative effect may be substantial. The purpose of this study is to provide a qualitative look at the effects of small reservoirs on hydrology and ecology, specifically for Oklahoma.

1.1 Hydrology

Some of the most dramatic effects of impoundments are the changesto the downstream flow regime. One purpose of building dams is to reduce annual variations in water level, making the floodplain habitable by humans throughout the year (Baxter, 1977). While post-impoundment impacts on Great Plains river ecosystems have been identified, few studies have examined specific impoundment-driven changes to the hydrologic regime of these ecosystems (Costigan and Daniels, 2012).

Impoundments reduce peak storm flows, alter hydrographs and interrupt natural streamflow patterns and processes (Vorosmarty and Sahagian, 2000). Additionally, impoundments increase surface water residence time and surface water area available for evaporative loss and basin runoff reduction. Van Liew (2003) found that flood retarding structures were responsible for a 3% decrease in annual streamflow in Southwestern Oklahoma and an increase in evaporation (Van Liew et al., 2003). Another study in Illinois found that the presence of small impoundments within the watershed had no effect on rainfall-runoff ratios (Longbucco, 2010). Alternatively, drainage through the reservoir bottommay contribute to groundwater or subsurface flow which may subsequently become streamflow (Tortorelli et al., 1985). However, few studies have examined seepage through pond bottoms. Ham (2005) found that these losses are minimal (< 3 mm/day) even in ponds without compacted clay liners due to the low hydraulic head pressure of these shallow water bodies.

Due to differences in pond densities, climatic regimes and land use factors, it is unlikely that any hydrologic study of small reservoirs can be applied across ecoregions or climatic zones. Because of this, it is necessary that hydrologic studies of small reservoirs be carried out for individual regions. Furthermore, to be of greater applicable use these studies should be done on a watershed scale.

Due to the small size and low surface area of farm ponds and small impoundments, it is often assumed that they make no significant contribution to the water budget. This may be true in regards to an individual impoundment. However, the cumulative hydrologic impact may be quite substantial (Graf 1999). For example, single stock pond study in the Flint Hills of Kansas found evaporation accounted for 64% of the total water loss annually, while seepage, cattle consumption, and transpiration accounted for 31%, 3%, and 2%, respectively (Duesterhaus 2008). In a semi-arid system in Kenya, farm pond water losses to evaporation and seepage accounted for 30-50% of total storage (Ngigi et al., 2005). A quick, ‘back of the envelope’ calculation that assumes Oklahoma ponds to have equal size, experience equal water losses as the one from the Kansas study, and applies the same water loss values to the current 316,000 ponds in the state, then evaporative water loss alone would be greater than 433 million m^3 on an annual basis.

1.2 Sedimentation

In large reservoirs sedimentation is a major problem that can lead to reductions in power production, the introduction of nutrients that lead to algae blooms, loss of recreational opportunities, lessened navigational possibilities, and often requires costly dredging to mitigate. Small reservoirs can retain up to 98% of all incoming sediments (Dendy and Champion, 1978) and can serve to keep sediments out of larger reservoirs, thus mitigating dredging costs.

By some estimates, small impoundments trap nearly half of all sediment runoff in the United States (Smith et al., 2002). In one sense this high trap efficiency has a negative impact on downstream biodiversity by changing the downstream biogeochemical regime (Baxter 1977). On the other hand, trapping these sediments may keep excess nutrients in check by sequestering harmful pollutants, bacteria and pathogens from runoff. In addition, farm ponds act as carbon sinks, thus mitigating the increase of carbon in the atmosphere (Callihan 2013). In areas that are historically lacking in surface water, the emplacement of farm ponds adds habitat connectivity for aquatic flora and fauna, and help provide migratory pathways that had not existed previously.

Series of small impoundments are efficient at trapping sediment and pollutant runoff from farming operations and can eliminate *Escherichia coli*(*E. coli)*runoff from cattle pastures into streams (Jackson and Pringle, 2010). However, it is logical to conclude that ponds as a water source are associated with heavily grazed pastures. For example, grazing occurs, in a large part, within 365 m of a water source (Gerrish and Davis, 1997). In effect, this reduction of *E. coli* runoff may simply be mitigating the problem created by the emplacement of the pond in the first place. Still, the ability of ponds to trap pollutants is beneficial in that those pollutants are kept from moving downstream.

With such a large amount of farm ponds on the landscape, especially in the Southern Great Plains, it is economically unfeasible to conduct traditional in-situ surveys for estimating the size, distribution and volume of more than a handful of these reservoirs. A simple model developed for use in Ghana (Liebe et al., 2005)for estimating reservoir volumes from surface area has been found to be a reliable method in Ghana, Zimbabwe, and Brazil (Liebe et al., 2005; Sawunyama et al., 2006; Rodrigues et al., 2012). Preliminary studies in Oklahoma suggest that this model provides reliable estimates in this region as well (Dale and Zou, 2012, 2013). Though sediment entering the lake contributes to the raise of the lake bottom elevation, aquatic plants slow inflow to the lake, trapping sediment. The end result being a lakeward movement of plants and concomitant reduction in lake surface area (Penfound, 1953).

1.3 Wildlife

Impoundments have been linked to declines in freshwater mussel species in Southeastern Oklahoma (Vaughn and Taylor 1999). However, farm ponds have also been found to increase freshwater biodiversity in agricultural landscapes (Céréghino et al., 2010). Farm ponds support increased turtle assemblages (Failey et al., 2007) and when properly managed help sustain amphibian populations (Knutson et al., 2004). Low head dams have also been observed to alter spatiotemporal patterns of fish assemblages (Gillette et al. 2005). The large scale, statewide construction of flood control dams has been attributed to an increase in both number and distribution of beaver (*Castorcanadensis*) populations in Oklahoma rivers (Reynolds 1977). Goddard and Board (1967) attributed the proliferation of farm ponds in Oklahoma to increased reproductive success of red-winged blackbirds (*Agelaiumphoeniceus*). Small impoundments also provide habitat for the Plains muskrat (*Ondatrazibethicus*), a species whose status in the region is questionable at best (Glass, 1952).

Nationally, in 2006, U.S. sportsmen spent in excess of 24 billion dollars on freshwater fishing trip and equipment costs (USDI 2007). In Oklahoma, other direct, economically tangible benefits include the leasing of farm ponds for oil and gas exploration, increased property value for homes with water features, and the sale of excavated soil from pond construction as fill.

Stocking ponds with fish for food, aesthetic, and sport purposes is common practice, not only in Oklahoma but world-wide. Common fish used for these purposes are carp, crappie, bluegill, and bass, among others. Carp are a good choice if manure is being used to promote fish production (Dor, 1980). However, the invasion of grass carp into U.S. waterways is an ecological concern that received wide attention. If stocking with carp or any non-native fish it is imperative that the farm pond not be hydrologically connected to any waterways. Pond owners also must be aware of interspecific interactions when stocking different fish species. It has been shown that the proportional stocking density of crappie populations is inversely proportional to that of largemouth bass in Oklahoma farm ponds (Boxrucker, 1987). A high number of largemouth bass will not be conducive to someone interested in also having a large crappie population. In addition, it has been found that depredation of bluegills by largemouth bass is higher at southern latitudes such as Oklahoma (Modde and Scalet, 1985). This should be taken into consideration by any pond owner trying to produce both types of fish.

1.4. Vegetation

Pond vegetation, when properly managed, can play an important role in the restoration of pond ecosystems. Excess pond vegetation encourages eutrophication and can lead to fish kills. A study in New York State found that *Chara vulgaris* increased water clarity, lessened phytoplankton growth, reduced wind caused turbidity and significantly lowered CO_2 readings within the pond (Crawford, 1979). Vegetation structure and pond surface area have been found to be important variables in pond usage by water birds (Froneman et al., 2001).

2. Introduction

The Dust Bowl of the 1930s brought about significant changes to the way hydrologic resources are managed in the Great Plains and led to the Federal Flood Control Act of 1944 (Public Law 78-534),which was further strengthened by the Watershed Protection and Flood Prevention Act (Public Law 83-566) in 1953. In Oklahoma, one of the main states affected by the Dust Bowl drought, small impoundments and reservoirs were constructed to control flood waters, trap sediment and supply water for farms, homes and industry. The first man-made lake was built in Oklahoma in 1894 (Harper and Stout, 1944). Between 1940 and 1944, 23,000 farm ponds existed (Harper and Stout, 1944). By 1950 the number of farm ponds and reservoirs had increased to 71,000 and 188, respectively(Harper and Stout, 1944; Penfound, 1953). By 1967 this number had more than doubled to 161,000 total ponds and reservoirs (Goddard and Board, 1967). Currently, these impoundments are mostly in the form of over 316,000 farm ponds and a total of 4925 reservoirs, of which 2351 are small watershed upstream flood control structures assisted by USDA NRCS and maintained by Oklahoma Conservation Commission (OCC) via land easements. The National Inventory of Dams (NID) maintained by the US Army Corps of Engineers (USACE) contains data on about 75,000 dams in the United States (Graf, 1999).

Willis and Neal (2012) define farm ponds/small impoundments as any man made water body under 40 ha in surface area and those greater than 40 ha aslarge impoundments or reservoirs. In the colloquial vernacular, these larger impoundments are often given the misnomer of ‘lake’, however, the state of Oklahoma has no natural lakes with the exception of oxbows and playas. Neither of these natural lake types shares the same hydrology of true lakes or man-made water bodies.

Currently, Oklahomais second only to Texas in the number of artificial impoundments,and subsequently, amount of shoreline in the continental United States, butpond density in Oklahoma (ponds/unit area) is the highest in the United States (Callihan 2013).

It has been reported that the Great Plains may be the first region in the United States to experience severe disruption to its hydrologic regime as a result of long-term climate change (Hurd et al., 1999). Already, there have been substantial losses to surface water as a result of extensive groundwater mining (Sophocleous, 2000). Streams and rivers of the Great Plains are particularly susceptible to downstream effects of reservoir emplacement because they are typically fine-grained alluvial systems without confining canyon walls (Graf, 2006). Indeed, regulated rivers in the Great Plains tend to have up to 91% active riparian and floodplain area than unregulated rivers within the same region (Williams, 1978).

One of the goals of this project was to quantify surface water storage in Oklahoma using simpleand easily employable remote sensing techniques. While there exists surface water resource inventories available from the Oklahoma Dam Inventory and the National Inventory of Dams, these only contain a small percentage of constructed lakes and ponds. The vast majority of impounded surface waters are privately held in rural areas and the data that is currently available is of little benefit to the individual pond owner.

A more specific objective of this project was to explore if any relationship existed between the surface area of farm ponds and other small reservoirs, and their volumes using available database resources. Because this data does not account for sedimentation it must be calibrated using remotely sensed bathymetric data. By determining the relationship between surface area and volume we can then apply it to surface areas obtained through satellite imagery and historic, aerial photos. Because surface water storage is a direct buffer to drought, such information will be important for land management, rural water management and agricultural planning.

Furthermore, there have been very few studies that have examined evaporation from lakes on a large scale. The author is only aware of one study done by Farnsworth and Thompson (1983) that looks at the statewide scale evaporation from Oklahoma reservoirs. This information will also further assist the research community to enhance regional hydrology models that in return may improve long term water planning and water resource management for the state.

3. Methods

Landsat MSS and TM imagery was obtained for the Cimarron-Skeleton watershed and contributing area for the period between 1975 and 2011. We estimated surface water area of major reservoirs and other small impoundments within the watershed using band 5 from Landsat 7 TM images taken during the winter leaf-off period to minimize canopy obstruction. The images were made into binary maps separating water and non-water pixels. These were verified against the original image for accuracy and fixed accordingly (Fig. 23).

After determining the locations of water bodies from Landsat imagery we were able to work backwards through historic, aerial photos dating back to the late 1940sto locate water bodies more easily in the grayscale images. This was done manually. The water pixels were counted in all images for both types to determine total surface area of open water for each year.

NID reservoir data were gathered from OWRB's Oklahoma Dam Inventory and an empirical model for volume estimation as described by (Liebe et al., 2005) was applied to all data in the NID to test for relationship between surface area and volume at three separate scales; Statewide, watershed (Lower Cimarron River basin) and county (Kingfisher County, OK).

$$V_{half\ pyramid} = \frac{1}{6} * SA * d \qquad (1)$$

Where V = volume of an object conforming to a half-pyramid; S = , A = surface area, and d = mean depth. A simple, linear regression between the log10 transforms of surface area and volume was carried out at the three different scales.This equation had the form of:

$$\log_{10} V = a \log_{10} SA + b \qquad (2)$$

In which V and SA represent volume, respectively, a is the slope of the line, and b is the intercept.

Because NID contains only data for the reservoirscapturing one moment in time, and sometimes from different surveying methods, bathymetric data available from OWRB for Oklahoma lakes were obtained to test for model accuracy. The bathymetric data was collected by OWRB through the use of side scanning sonar and was assumed to reflect the true water storage capacity. A few impoundments in this dataset returned impoundments that had decreased in surface area but increased in volume compared to the original structural values from NID. Since this case is unlikely, these impoundments were deemed to have inaccurate data. It is difficult to determine which survey method yielded the inaccurate result. Subsequently, those impoundments were removed from the analysis due to uncertainty.

The volume was then computed from the remotely sensed surface area data using the linear correlation derived from the model (eqn. 2).

Evaporation from small water bodies in the study was estimated by modifying long-term lake evaporation records from the National Oceanic and Atmospheric Administration (NOAA) (Farnsworth and Thompson, 1983) with a pan coefficient of 0.81 developed specifically for ponds (Boyd, 1985).

$$E_{pan} = \frac{E_{lake}}{0.7} \tag{2}$$

$$E_{pond} = 0.81 \times E_{pan} \tag{3}$$

4. Results

A strong linear relationship was found between log of reservoir capacity and water surface area for the NID data at all three scales; state, watershed and county (r^2=0.93, 0.90 & 0.87, respectively). Applying the same method to the remotely sensed data for the Cimarron-Skeleton watershedyielded a slightly stronger relationship between surface area and volume (r^2=0.91) than the NID database relationship, however the value still indicated a strong relationship (Fig. 7). The results of the model when tested against bathymetric data showed a closer relationship between the log transforms of surface area and volume (r^2=0.96) than the NID data. Analysis of residuals showed a fairly constant variability with very few outliers on both the NID and the bathymetric data. Deviation from the mean increases when reservoir size becomes very large (Fig. 7).

Analysis of the historic, aerial images revealed that the Cimarron-Skeleton watershed had an increase in surface area for surface water storage of 29.06% between 1950 and 2010.Applying the equation derived for estimating reservoir volume at the watershed level, we estimated the amount of water storage increased from 62.4 million m^3 to 80.1 million m^3 over the same time period,an increase of 28.3% increase in the total volume of surface water in the watershed. A large amount of this increase took place from the mid-1980s through the early 1990s.

By averaging the values from individual impoundments examined in Farnsworth's study we find that the average annual evaporation from any given reservoir in the state is 1940 $mmyr^{-1}$. The Farnsworth study had data collected from as early as 1917 and running up through 1979. More recent values from OWRB put a range on lake evaporation from 1219 mm annually in the eastern portion of the state to 1651 mm in the southwest. Despite being much lower than the numbers from the aforementioned study, these values still exceed precipitation values for those areas. While, those values are informative, they are for constructed lakes, not ponds. Weestimated the value for pan evaporation based on lake evaporation using the pan coefficient of 0.7 (equation 2, Snyder, 1992). After applying the pond pan evaporation coefficient of 0.81 to the pan evaporation values we estimated evaporation from a single pond (equation 3) to be from 1410 mm to 1910 mm yr^{-1}. Over the entire Lower Cimarron watershed we estimated evaporation to be between 110 million m^3 to 149 million m^3on average, annually, which is 176-186% of total storage being lost to evaporation annually.

5. Discussion

Due to the sparse amount of information available regarding farm ponds and other such small reservoirs, especially in regards to hydrology, much more research is needed to fully understand the effects these systems have on regional ecosystems.

Our study reported strong correlations between reservoir volume and water body surface area for three different regional scales. Because the outliers were clustered at the extreme low and high ends of reservoir area, this model is most useful for medium sized reservoirs.

Our study found total evaporative losses were nearly double that of total reservoir storage. These valueswere three times greater than those reported for ponds in the Flint Hills of Kansas (Callihan 2013). Land cover data we used was captured once per year and there can be major fluctuations in pond water storage depending on the time of year. Generally, ponds and reservoirs hold more water in the winter when irrigation, transpiration and evaporation are lower whereasthey may dry up completelyin the summer (Ferguson, 1952; Brown and Carpelan, 1971; Ong et al. 1997). Certainly, more in depth studies on pond evaporation will be needed that account for changes in water level and evaporation throughout a year to truly get a full picture of what is happening throughout the watershed.

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TABLES

Table 1: Correlation analysis between anthropogenic induced land surface change (cropland, grassland, urbanization, woody encroachment, impoundments) and streamflow for the period between 1950 and 2010 using Kendall's tau test. Correlations that display strong significance are shown in bold. *denotes significance of p < 0.05, ** for p < 0.01, *** for p < 0.001

	Q outflow	Temp	ET0	RH	Precip.	Consumption	GW Storage	Cropland	Grassland	Forest	Urban
Temp	-0.229*										
ET0	-0.5528**	0.6761***									
RH	0.5886****	-0.3101*	-0.8747***								
Precip.	0.6691***	-0.4017*	-0.7156***	0.6721***							
Consumption	-0.1924	-0.151	-0.0211	-0.0357	-0.0683						
GW Storage	0.0788	-0.0933	-0.1293	0.1719	0.3541***	-0.0575					
Cropland	-0.4437**	0.1661	0.3709**	-0.3513**	-0.4453***	0.0206*	0.053				
Grassland	0.4762***	-0.2078	-0.4282**	0.4338***	0.4463**	0.0737	-0.0541	-0.895***			
Forest	0.3344**	-0.1831	-0.3476***	0.2956**	0.4001**	0.145**	-0.0396	-0.9329***	0.7336***		
Urban	0.4133***	-0.1092	-0.2952**	0.2756**	0.4072***	-0.1541	-0.0513	-0.9726***	0.7829***	0.9171***	
Water	0.1215**	-0.0174	-0.0704**	0.0159	0.2047***	-0.0985	-0.0309	-0.642***	0.2429***	0.7788***	0.7648***

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. Correlations that display strong significance are shown in bold. *denotes significance of $p < 0.05$, ** for $p < 0.01$, *** for $p < 0.001$

	Q outflow	Temp	ET0	RH	Precip.	Consumption	GW Storage	Cropland	Grassland	Forest	Urban
Temp	-0.1054										
ET0	-0.1785	0.4366***									
RH	0.2645*	-0.0323	-0.5527***								
Precip.	0.5011***	-0.0882	-0.1613	0.2215							
Consumption	-0.3849*	0.1097	0.0968	-0.0022	-0.3677**						
GW Storage	0.0992	-0.0129	0.0949	-0.0345	0.2546*	-0.0777					
Cropland	-0.0968	-0.0237	-0.0452	0.1312	-0.1656	0.3161*	0.0518				
Grassland	0.2946*	-0.0366	0.0366	-0.0194	0.1312	-0.428***	-0.0647	-0.3806**			
Forest	0.0882	-0.0366	-0.0065	-0.1398	0.071	-0.3333**	-0.0604	-0.7935***	0.1742		
Urban	0.1022	0.0239	0.0544	-0.1413	0.1674	-0.3152*	-0.0523	-0.9892***	0.3805**	0.7805***	
Water	0.1381	0.0276	0.0552	-0.1427	0.1657	-0.3406*	-0.0346	-0.9344***	0.29*	0.7641***	0.9446***

Table 3.Table of changes in surface water supply for Upper Cimarron watershed (1975-2010).

	1975	**1980**	**1985**	**1990**	**1995**	**2000**	**2010**
Total Surface Area(10,000 m^2)	7559	7560	7560	7560	7563	9292	9725
Total Volume(1,000,000 m^3)	115134	115133	115157	115157	115158	115216	144982

FIGURES

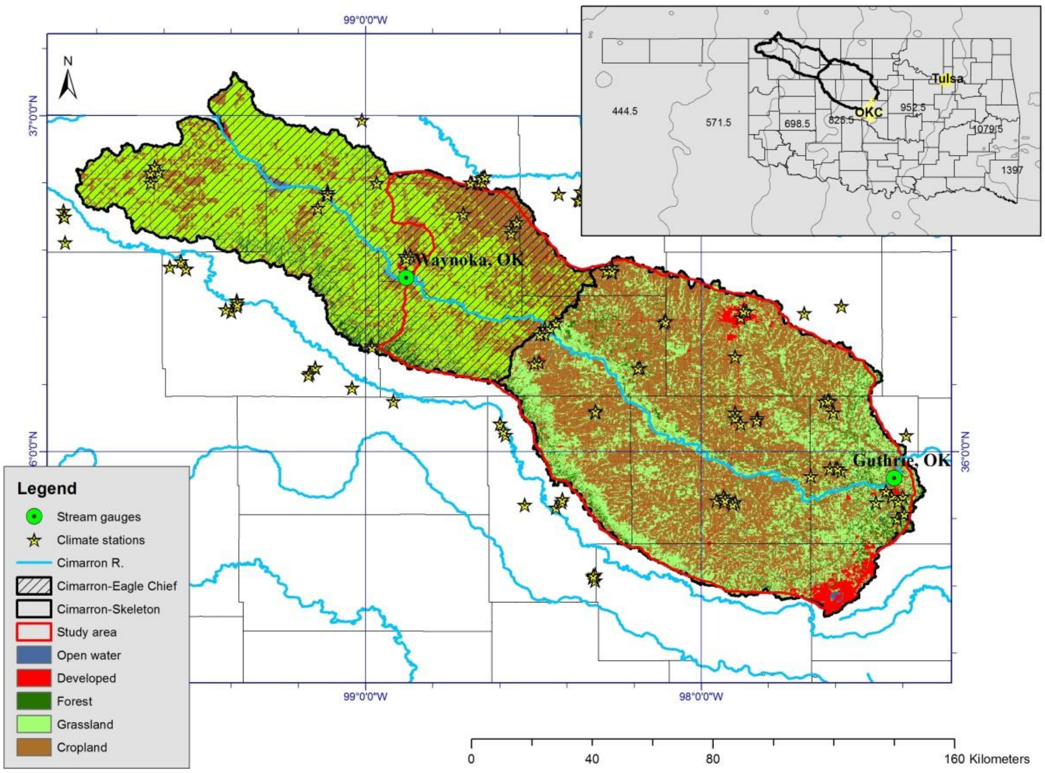

Fig. 1: Land use and land cover types, distribution of climate stations and stream gauges for the contribution area for Guthrie guage station (Cimarron-Skeleton watershed and a part of Cimarron-Eagle Chief watersheds). Inset: Precipitation isohyetal map over Oklahoma geographic map with bold line showing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

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 dotted line is trend line based on Mann-Kendall trend analysis.

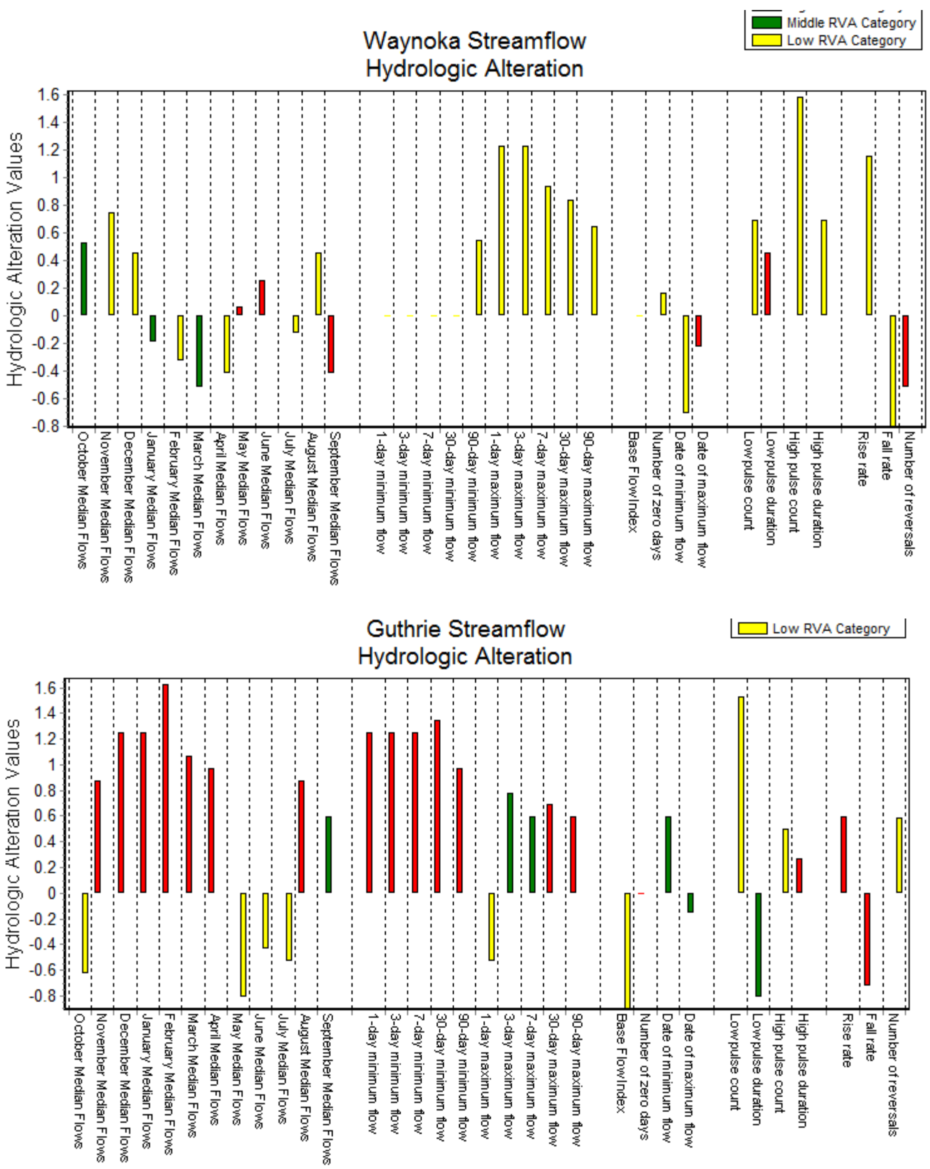

Fig. 3. Results of IHA analysis showing Range of Variability (RVA) for major ecological indicators for (A) Waynoka, OK gauge station and (B) Guthrie, OK.Categories that display a high RVA are in red, medium in green, and low in yellow. Positive RVA values indicate an increase in frequency for that category from the reference state while negative values indicate a decrease.

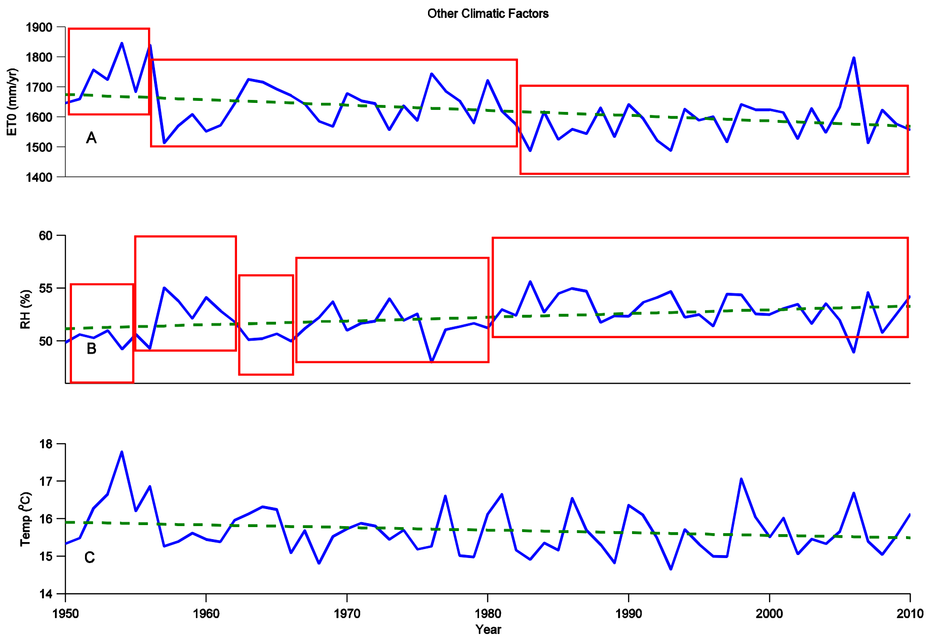

Fig. 4. Change in (A) annual mean temperature, (B) relative humidity and (C) potential evapotranspiration from 1950 through 2010 in the Cimarron-Skeleton watershed. Time periods with significant changes in annual mean values are highlighted by red boxes. There was no significant change in annual temperature.

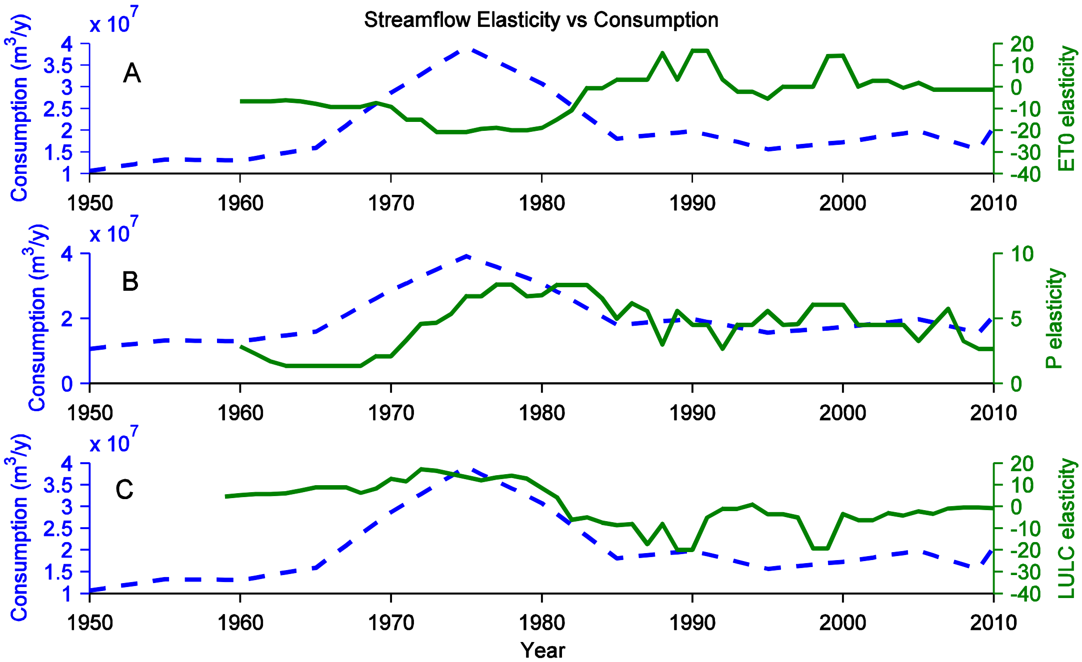

Fig.5: Changes in (A) reference evapotranspiration elasticity of streamflow, (B) precipitation elasticity of streamflow, and (C) anthropogenic elasticity of streamflow (bottom) against changes in the total consumptive water use for the entire contribution area from 1950 through 2010.

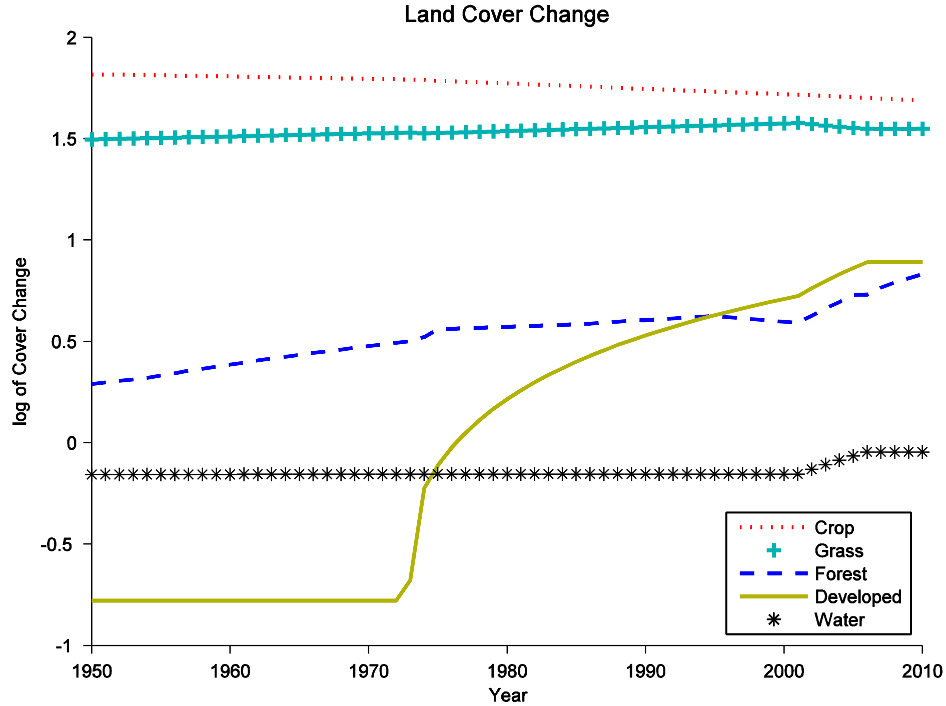

Fig. 6: Changes to major land cover types since 1950 in Cimarron-Skeleton watershed. Logarithmic (base 10) transform applied to variables for ease of visualization.

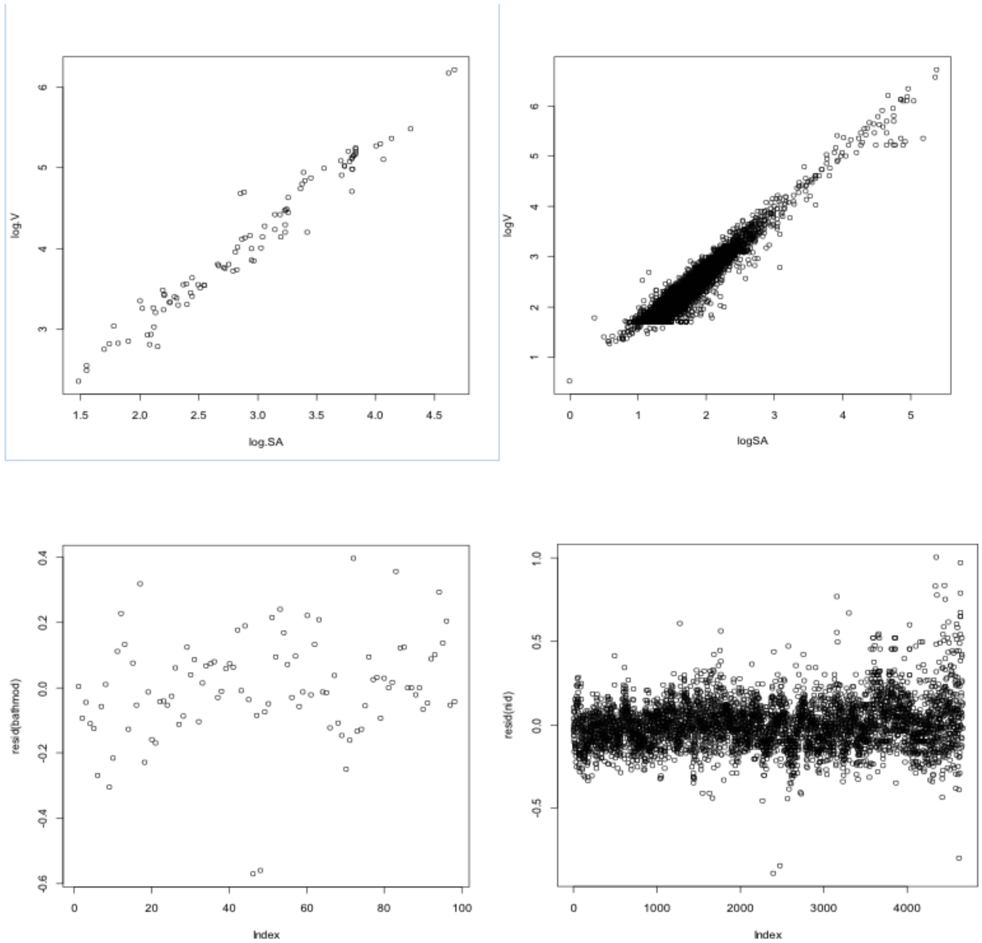

Fig. 7. Top left: surface area to volume relationship for bathymetric data. Bottom left: residuals from bathymetric data plot. Top right: surface area to volume relationship for all Oklahoma NID reservoirs. Bottom right: residuals from NID data plot.

APPENDICE

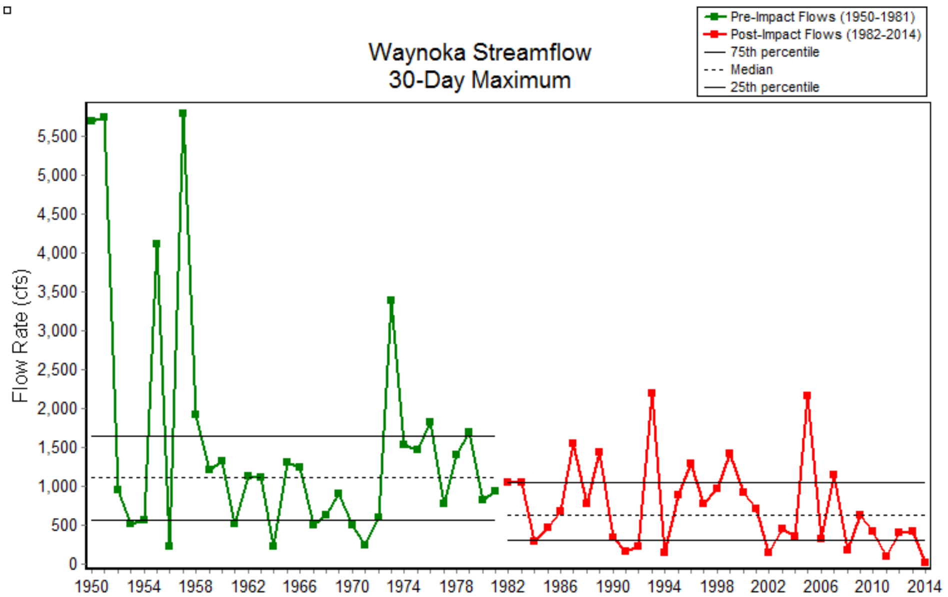

Fig.8. 30 day maximum streamflow for Waynoka, OK. Monthly maximum flows decreased between pre-impact and post-impact periods. The 25th percentile, median value and 75th percentile of flows all declined, with the new median being close to equal the 25th percentile values from the previous time period.

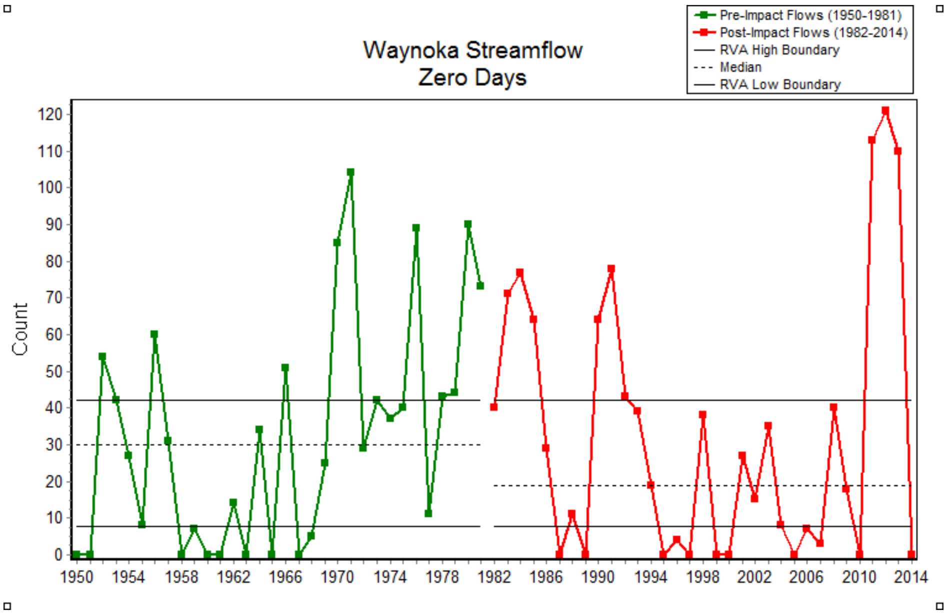

Fig. 9. Waynoka streamflow zero flow days. The median number of zero flow days at the Waynoka, OK gaging station decreased in the post-impact period. This decrease continued through 2010.

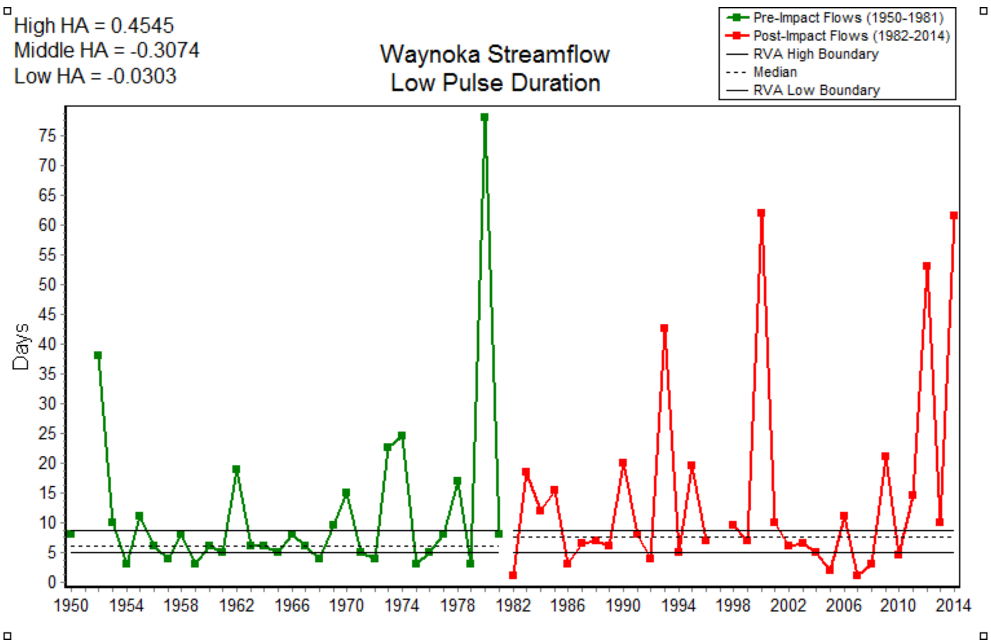

Fig.10. The low pulse duration at the Waynoka gage station slightly increased in the post impact time period.

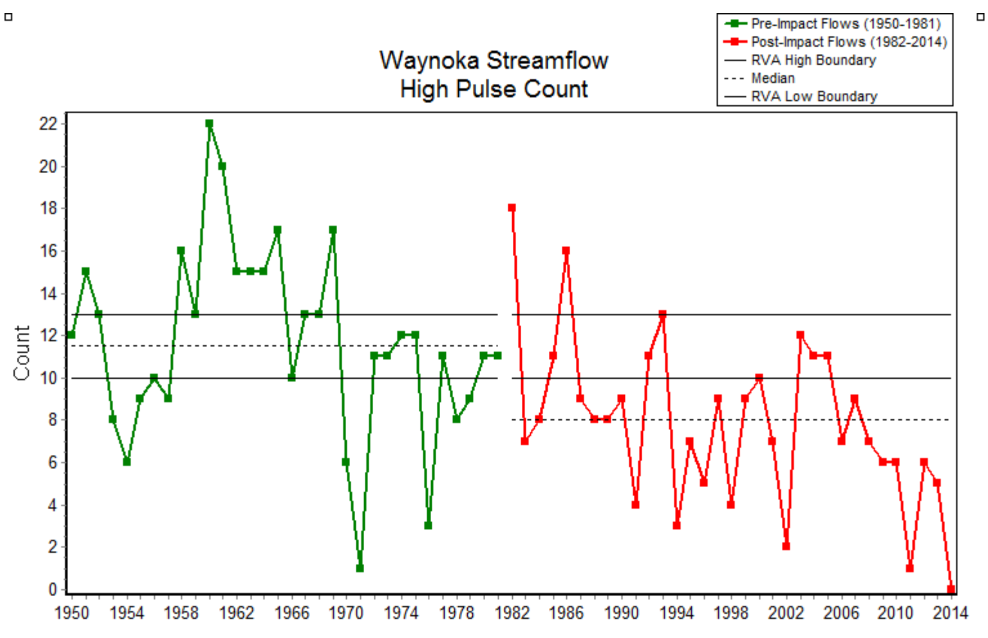

Fig.11. The high pulse count for Waynoka, OK has steadily decreased, with the median count of high flow pulses dropping from around 12 to 8 between pre and post impact time periods.

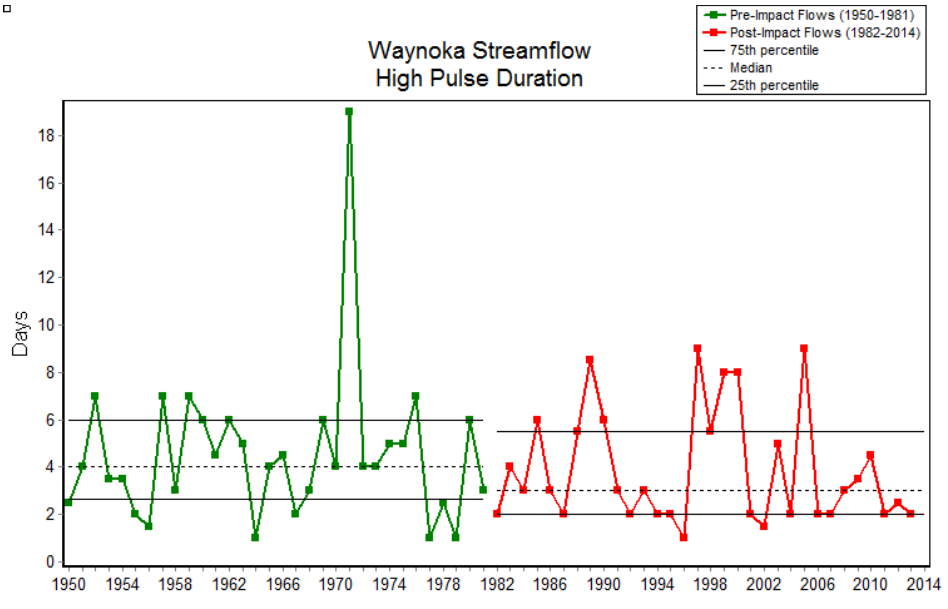

Fig.12. The median value for high pulse durations at the Wanoka, OK gauging station decreased from 4 to 2 days in the post-impact period. There were also slight decreases in the 75th and 25th percentile flows.

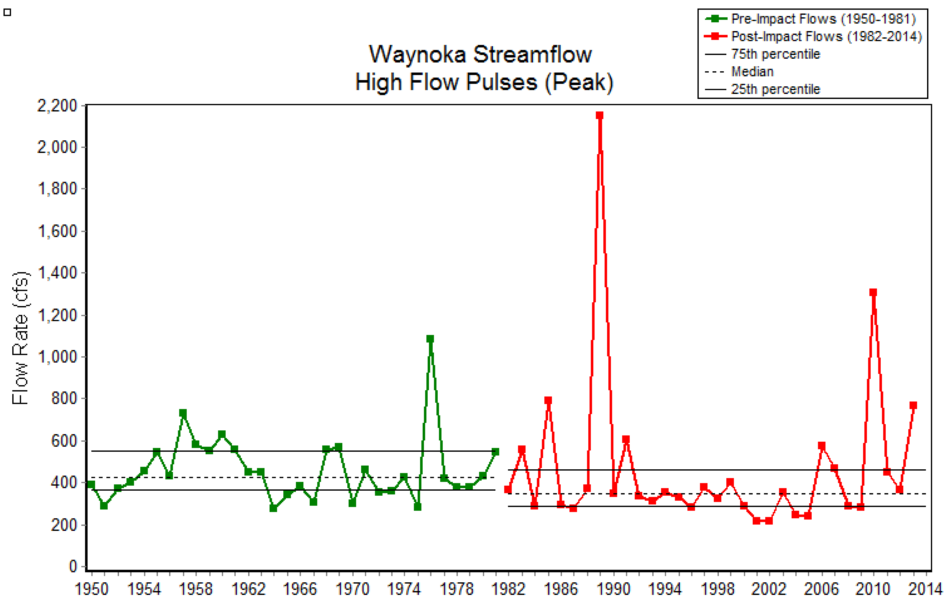

Fig.13. High flow pulses, or peak flows, decreased between pre and post-impact periods at the Waynoka, OK stream gauging station. However, this change was slight.

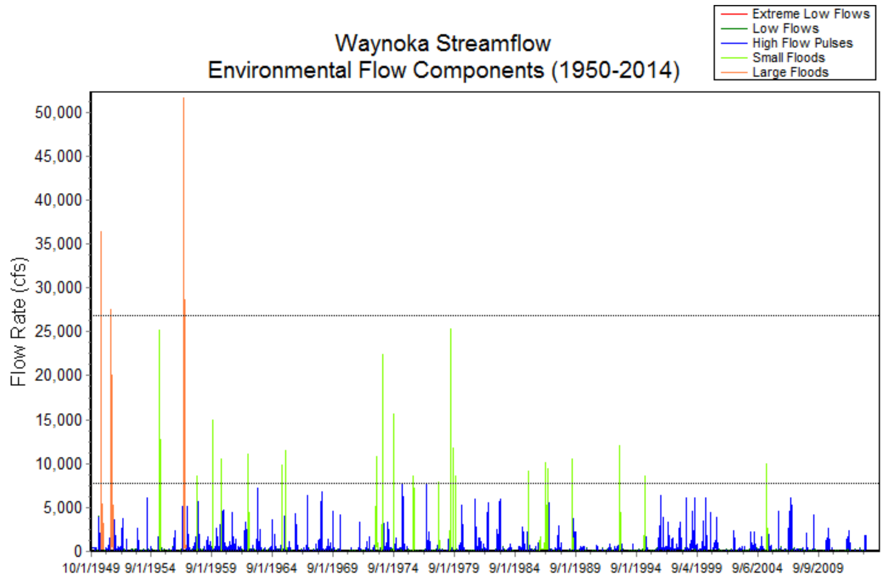

Fig.14.Environmental flow components have all decreased at the Waynoka station since 1950. The most noticeable decrease is in large floods, which stopped completely in the mid-1950s. Small floods have continued to occur but appear to have decreased in both frequency and volume at this site.

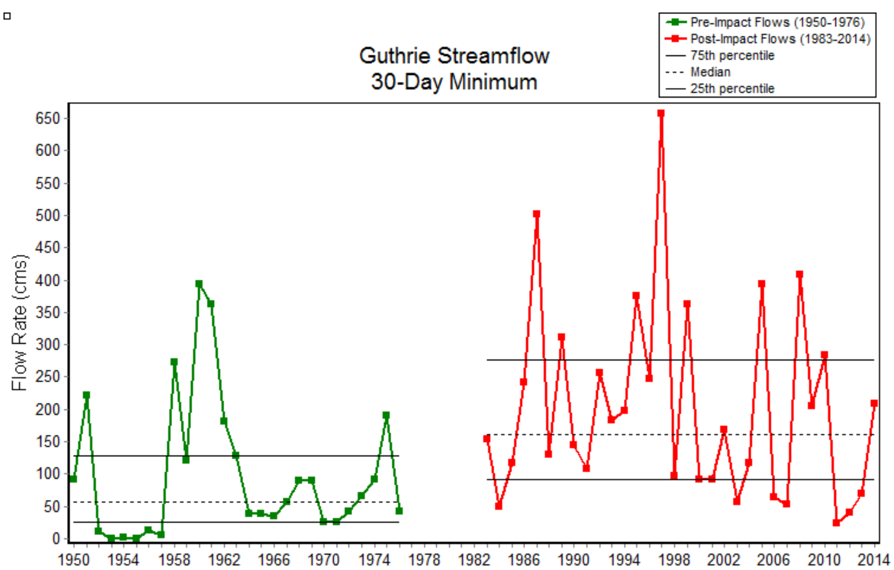

Fig.15. 30 day minimum streamflows have tripled in their volume of delivery since the early 1980s.

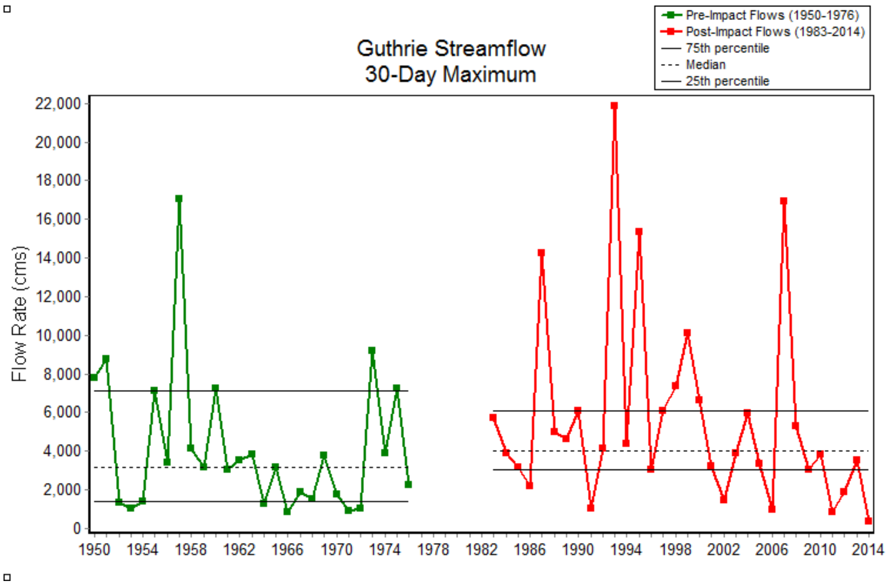

Fig.16. The median value for the 30 day maximum streamflow at Guthrie, OK increased during the post impact period. However, the range between the 25th and 75th percentile become noticeably more narrow than it had been during the pre-impact period.

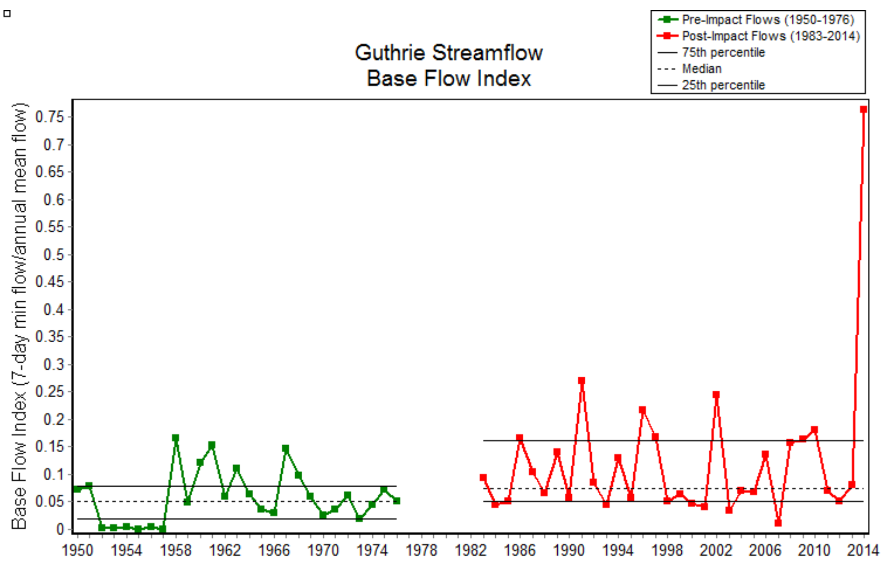

Fig.17. The base flow index (BFI) for the Guthrie, OK stream gauge slightly increased starting in the early 1980s. The 25th and 75th percentage of these values increased as well with the range between them becoming wider than in the previous time period.

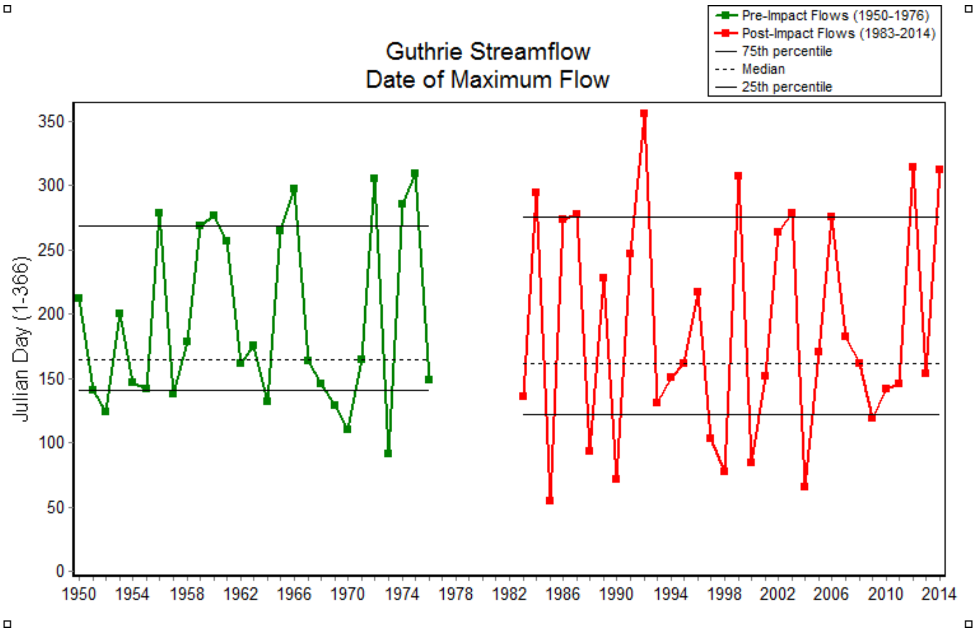

Fig.18. The date of minimum flow in Guthrie, OK has remained relatively stable over the study period.

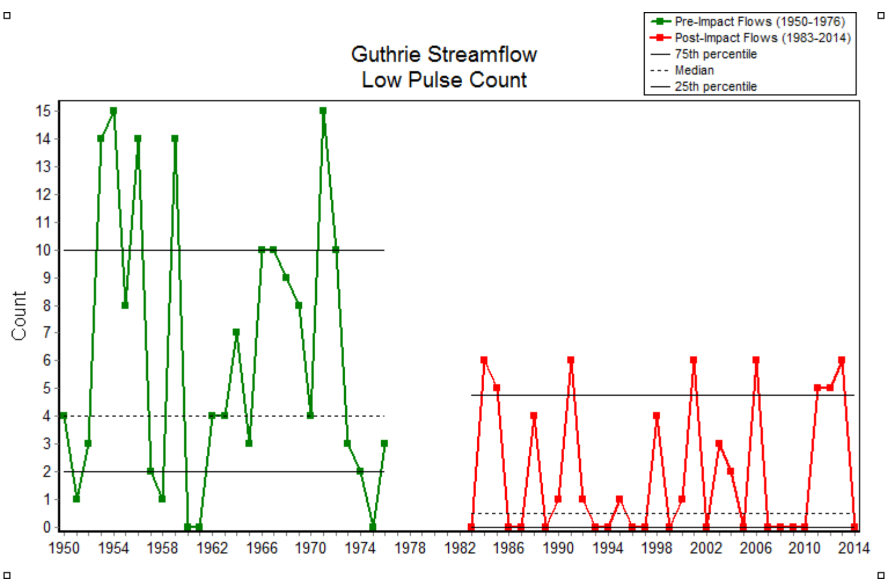

Fig.19. The median low pulse count for Guthrie, OK decreased to near zero in the post impact period. Also, the 75th percentile of low pulse counts decreased by half from the previous era.

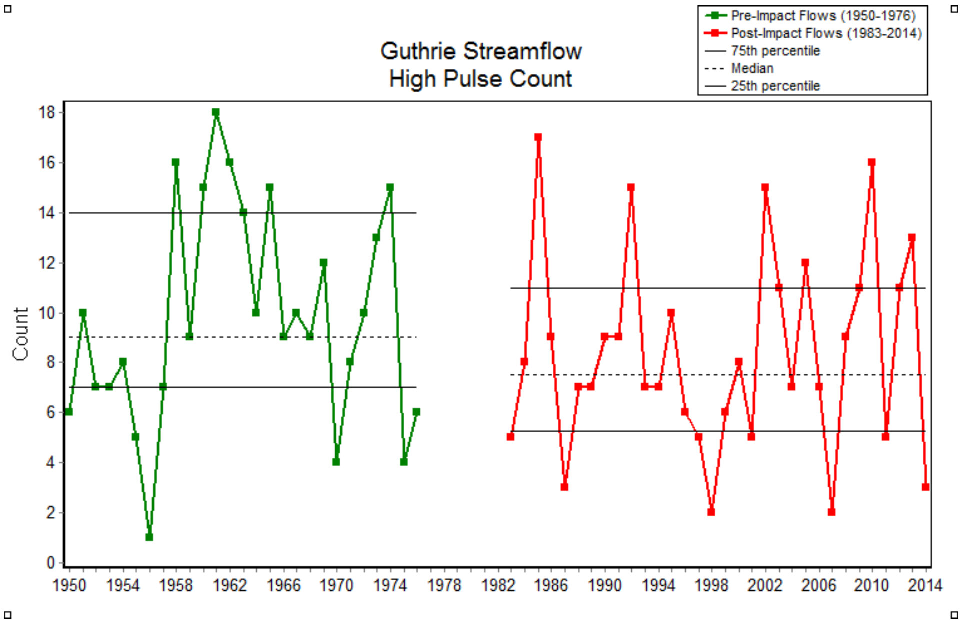

Fig.20. High pulse flow counts at the Guthrie stream gauge decreased slightly at the Guthrie gauge between pre and post-impact periods.

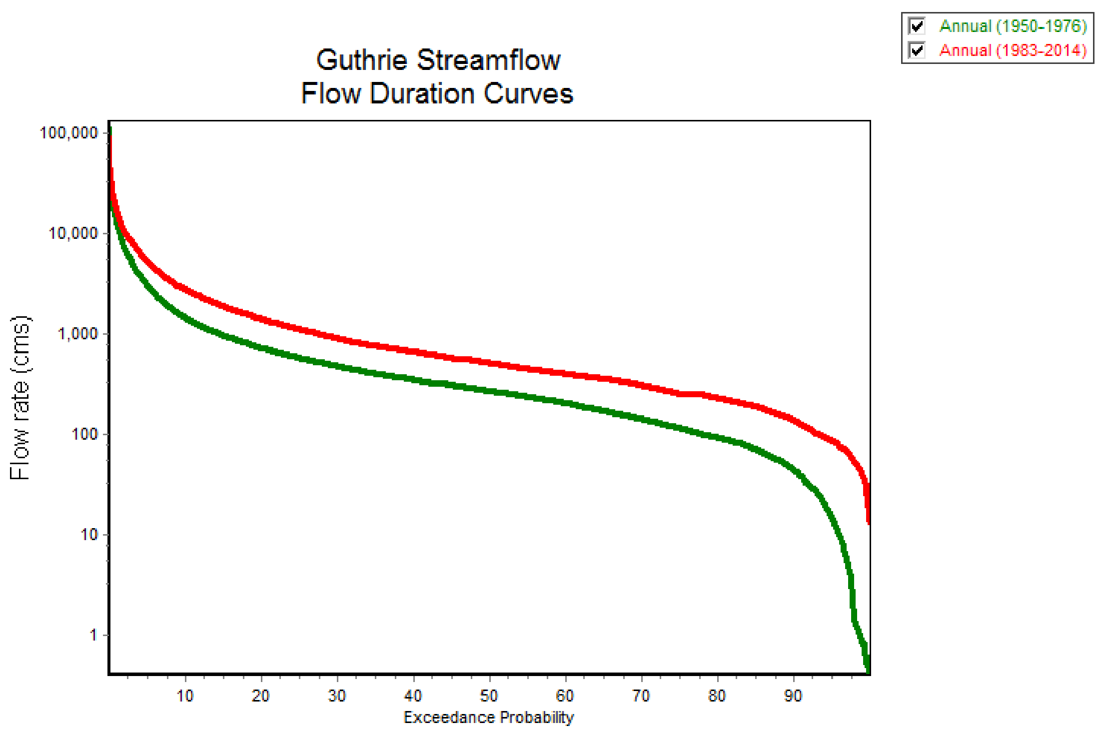

Fig.21.Flow Duration Curves for Guthrie, OK streamflow. There is a greater exceedance probability of higher streamflows in the post-impact period.

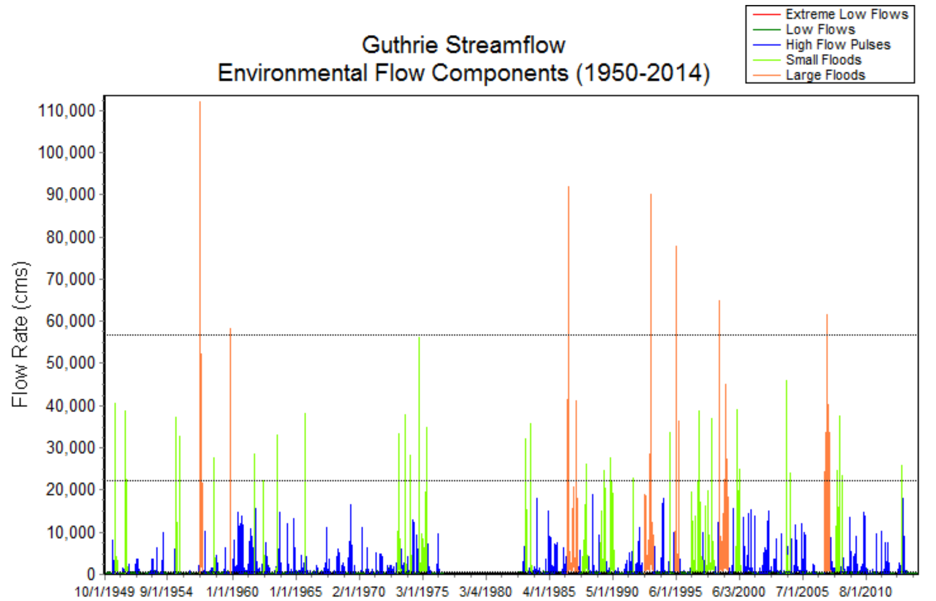

Fig. 22. Environmental flow components for Guthrie, OK gauge station. Most noticeable is that large floods have decreased in volume over the study period, as have high flow pulses.

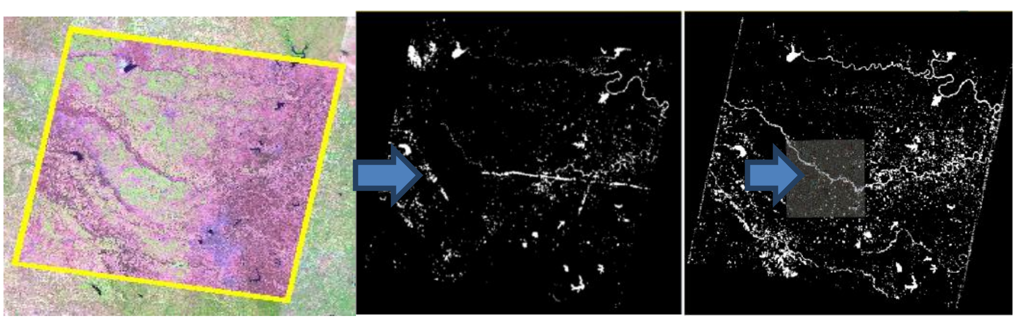

Fig. 23.Process of creating binary maps. First images are selected representing some area of interest. A model is used in GIS to display all pixels that represent water as '1' and all others as '2'. To check for accuracy, a high resolution NAIP image layer was added with high transparency.

VITA

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