STREAMFLOW RELATIONS WITH INCREASING RIPARIAN WOODY COVER IN NORTH-CENTRAL OKLAHOMA

By

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STREAMFLOW RELATIONS WITH INCREASING RIPARIAN WOODY COVER IN NORTH-CENTRAL OKLAHOMA

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CHAPTER I

INTRODUCTION AND LITERATURE REVIEW

Synopsis

The rangeland water budget is driven by pulsed, limited precipitation input. Precipitation that is not intercepted by plant canopies or litter is then available to increase soil water storage, recharge groundwater, or run off. Woody plant encroachment is a process affecting rangelands worldwide in which trees invade chronically overgrazed grasslands in which fire is rare or absent. Based on the traits of trees they may have the potential to increase evapotranspiration when trees colonize grassland. These traits include a high capacity to intercept rainfall as well as the ability to extract water from the soil at low water potentials, and draw water from deeper in the soil profile relative to grasses. In addition, increasing tree cover influences soil hydraulic properties by increasing the soil's infiltration capacity by as much as a factor of eight. Greater infiltration of rainfall into the soil under forest cover, relative to grassland increases recharge of soil and perched aquifers. Though the aforementioned factors control runoff at the field scale, runoff at the watershed scale will also be controlled by the extent of woody cover and its distribution (i.e., riparian vs. upland). Therefore the objectives of this research are to determine how long-term changes in woody cover are related to trends in streamflow, and its components, stormflow and baseflow, at the watershed scale.

Rangeland water cycle

Familiarity with the nature and extent of rangelands and the components of the rangeland water budget is a necessary precursor to the following discussion of the effects of woody plants on streamflow. Rangelands are open areas used for grazing animals and account for about 40% of the global land area (Bailey, 1996). Vegetation on rangelands can include only herbaceous species or a patchwork of herbaceous and woody species. On rangelands precipitation is described as pulsed because it is low relative to evaporative demand and as a result evapotranspiration is limited by water availability for much of each year. This contrasts with humid environments where precipitation is more plentiful and evapotranspiration is limited primarily by energy available to overcome the latent heat of vaporization. In the Great Plains precipitation is concentrated in the spring and summer and is determined in part by the surface temperature of the Pacific Ocean (Schubert et al., 2004). Precipitation inputs are balanced by the sum of evapotranspiration, streamflow, and soil water and groundwater recharge during a given time step.

Evapotranspiration is the sum of evaporation from plant canopies, leaf litter, and the soil surface, together with transpiration. In rangelands evapotranspiration is the largest component in the water budget, after precipitation. Water availability, canopy cover, leaf litter, evaporative demand, vegetation effective rooting depth, and growing season of vegetation interact to control evapotranspiration. Sequentially, interception is the first process influencing the fate of precipitation. Precipitation is either intercepted by plant canopies or leaf litter or flows to the ground as stem flow or throughfall. The proportion of precipitation intercepted during a given storm depends on the storm size, storm intensity, and interception capacity of the vegetation (Gash, 1979; Thurow et al., 1987). During large, intense storms, a smaller proportion of the storm is intercepted, whereas during small or low intensity storms less or no precipitation reaches the ground (Couturier and Ripley, 1973; Thurow et al., 1987). Annual precipitation interception usually ranges from 20-40% in rangelands (Skau, 1964; Wilcox et al., 2003b; Young et al., 1984).

Effective precipitation is the fraction of precipitation that reaches the soil surface. Effective precipitation can contribute to streamflow, increase soil water or groundwater storage, evaporate, or be transpired.

Soil water evaporation is lowest in soils with high leaf litter and vegetation canopy cover (Allen et al., 1998; Saugier and Katerji, 1991; Walsh and Voigt, 1977). Transpiration is potentially high among tree species that can transpire on any warm day, access soil water located deep in the soil profile (Jackson et al., 1999), transpire groundwater (Horton et al., 2003; Snyder and Williams, 2000), or absorb water at low soil water potentials (Bihmidine et al., 2010; Lassoie et al., 1983). In water-limited systems evapotranspiration nearly equals precipitation on an annual basis (Phillips, 1994; Reynolds et al., 2000; Sala et al., 1992), whereas in energy-limited mesic systems, evapotranspiration is nearly equal to potential evapotranspiration (Likens et al., 1970). Potential evaporation is the evaporation that would occur from a given land cover type if water were not limiting.

Streamflow in rangelands usually accounts for less than 20% of precipitation and can be composed of three components—overland flow, shallow lateral subsurface flow, and groundwater (Wilcox et al., 2003b). Overland flow from rangelands occurs in rapid response to storms (Chang, 2006), ceases soon after the storm ends, is largely independent of evapotranspiration (Wilcox et al., 2010), and is a major contributor to total streamflow (Reid et al., 1999). Infiltration excess (Hortonian) overland flow occurs when the rainfall intensity exceeds the infiltration capacity of the soil (Horton, 1933), the maximum rate at which a soil in a given condition will absorb water. Saturation excess (Hewlettian) overland flow occurs when soils are saturated (Hewlett and Helvey, 1970). Hortonian overland flow is controlled by precipitation characteristics, soil infiltration capacity, and surface roughness (Descheemaeker et al., 2006). In rangelands Hortonian overland flow is lowest in shrublands or grasslands with highly porous soils, high leaf litter cover and low grazing rates (Berg et al., 1988; Wilcox et al., 2006a). Hortonian overland flow is highest on degraded and compacted sites with low leaf litter cover or high grazing rates

(Bartley et al., 2010). Grazing can increase runoff by compacting the topsoil and removing plant biomass. Hewlettian overland flow can occur when soils are frozen (Wilcox et al., 2003a), when there are shallow layers of low permeability (Walter et al., 2003; Wilcox et al., 1997), or as variable source area flow adjacent to a stream channel (Germer et al., 2010). Quickflow or stormflow is often assumed to be an indicator of overland flow. Such an assumption is not strictly correct because automated methods to separate baseflows from stormflow simply operate by removing high frequency signals from a streamflow time series (Arnold and Allen, 1999; Arnold et al., 1995). In regions where rapid subsurface flows can occur (Turton et al., 1992) there is no way to determine what component of a hydrograph consists of overland flow versus rapid subsurface flow and after using a hydrograph separation algorithm these two terms must be combined together and referred to as stormflow.

Shallow lateral subsurface flow occurs less rapidly than overland flow and may continue after overland flow has ceased. Subsurface flow is controlled by the amount of water held in the soil preceding a storm, by the presence of macropores, and by effective precipitation (Turton et al., 1992; Wilcox et al., 1997). Subsurface flow can be generated either through the soil matrix or as macropore flow that bypasses the soil matrix (Newman et al., 1998).

Groundwater can contribute to streamflow if the groundwater level is higher than the level of the stream channel. Groundwater recharge is typically low in rangelands whose soils have large storage capacities (Sandvig and Phillips, 2006; Scanlon et al., 2006; Scanlon et al., 2005; Seyfried et al., 2005; Seyfried and Wilcox, 2006; Wilcox et al., 2003b; Wilcox et al., 2006a). However, substantial groundwater recharge of 41 mm yr^{-1} has been reported for the Central Oklahoma aquifer (Runkle et al., 1997). Where groundwater recharge does occur it can be influenced by vegetation type (Peck and Williamson, 1987; Sandvig and Phillips, 2006). The effective rooting depth of plants represents an important factor determining the amount of water that can be stored in the root zone. Therefore vegetation change can alter the potential for the soil to store incident precipitation, thereby altering the probability of a deep drainage event (Seyfried and Wilcox, 2006). The greatest potential for deep drainage is in course-textured soils (Gee et al., 1994).

Historical context of changes in tree distribution and abundance

One cyclic factor affecting the distribution of plant species is that the earth's orbit has become more circular over the course of millennia, changing the timing and distribution of incoming solar radiation (Imbrie and Imbrie, 1980). These cyclic changes in the distribution and timing of incoming solar radiation have influenced the Earth's climate over the past 420 millennia (Petit et al., 1999). Earth's changing climate over the course of hundreds of millennia has caused macro-scale migration of species (Delcourt et al., 1982). During the Holocene North American species have migrated northward in response to higher temperatures driven by increases in atmospheric CO_2 (Van Auken, 2009). However, in the last 160 years unprecedented changes in many plant communities have occurred (Pimm et al., 1995). In Oklahoma increases in basal area and tree density of deciduous trees (*Quercus stellata* and *Quercus marilandica*) have been observed as well as increases in *Juniperus virginiana* (DeSantis et al., 2010; DeSantis et al., 2011).

These trends may result from a combination of forestation of areas that historically had a more frequent fire return interval and colonization of abandoned farmland (DeSantis et al., 2011). Since the 1950's cropland has decreased throughout most of the conterminous United States (Brown et al., 2005) and increasing forest cover has been observed throughout this region (Houghton, 2003). Riparian forest cover also has grown as greater awareness of the benefits of riparian forestation has spread in recent decades (Jones et al., 2010; Manoukian and Marlow, 2002).

Riparian gallery forests are present in lowlands and streambeds in otherwise grassland landscapes in the central U.S. (Abrams, 1996; Danner and Knapp, 2001). Riparian gallery forest expansion has been documented extensively in Konza Prairie, Kansas (Abrams and Knapp, 1986;

Bragg et al., 1993; Loehle et al., 1996). At that site increases in oaks, eastern redbud, and red hackberry were observed from 1859-1978 after fire frequency declined with European settlement (Abrams, 1986). Another study at Konza Prairie uncovered similar results that gallery forest area increased from 157 ha in 1939 to 241 ha in 1985 throughout a 3487 ha study area (Knight et al., 1994). Additional work in the Flint Hills of Kansas used historical aerial photography to uncover a 40% increase in woody cover concentrated on lower slopes from 1937-1969 (Bragg and Hulbert, 1976). Field observations revealed the presence of American elm, redcedar, and chinquapin oak.

Though gallery forests have not been widely studied in Oklahoma, more attention has been given to woody plant encroachment. Woody plant encroachment is a process by which native trees or shrubs increase in abundance in grasslands at the expense of herbaceous species (Van Auken, 2000). The woody encroachers do not themselves drive encroachment, but rather represent a symptom of other biotic and abiotic changes (Van Auken, 2009). Understanding woody encroachment is important because this process is estimated to occur over 220-330 million ha in the conterminous United States (Houghton et al., 1999; Pacala et al., 2001). Woody encroachment can occur rapidly. For example, in the Flint Hills of east-central Kansas, eastern redcedar (*Juniperus virginiana*) encroachment converted tallgrass prairie to closed-canopy woodland in 40 years (Briggs et al., 2002). In tallgrass prairie of Kansas and Oklahoma, eastern redcedar has encroached rapidly into upland and lowland environments without regard to soil type or depth (Engle and Kulbeth, 1992; Knapp et al., 2008b; Starks et al., 2011). By 2013 eastern redcedar encroachment is predicted to exceed 3.5 million hectares in Oklahoma (Starks et al., 2011).

In grasslands worldwide numerous interacting anthropogenic factors have caused woody plant encroachment (Archer et al., 1995; Van Auken, 2009). Livestock overgrazing and fire exclusion are decisive factors that interact to favor woody encroachment (Bahre and Shelton, 1993). Livestock overgrazing reduces the vigor of palatable herbaceous plants and reduces their aboveground biomass. Less vigorous herbaceous species compete less effectively with woody species and less aboveground herbaceous biomass prevents fires that could otherwise destroy fire intolerant woody seedlings (Arend, 1950; Humphrey, 1958; Roques et al., 2001). Fragmentation of grasslands by roads and fire suppression reduce the frequency of fires, thereby favoring woody encroachment.

Though it is widely accepted that unrelieved high grazing rates and reduced fire frequency cause woody encroachment, a preponderance of the evidence does not support a causal relationship between climate change and woody encroachment. Increasing atmospheric CO_2 concentrations appear to facilitate and accelerate woody encroachment (Davis et al., 2007; Morgan et al., 2007). However, woody encroachment began prior to substantial increases in atmospheric CO_2 concentrations. Thus increasing atmospheric CO_2 concentrations can only be considered a background factor to woody encroachment, not a primary cause (Archer et al., 1995). Similarly, because changes in climate were small when woody encroachment commenced, this factor should not be considered a primary cause (Archer et al., 1995), though climate change is clearly a component of the backdrop of present-day woody encroachment.

Seed dispersal and herbivory also moderate the rate of woody plant encroachment. Livestock effectively disperse seeds of woody plants thereby enabling encroachment of woody plants well beyond the canopies of existing trees (Brown and Archer, 1999). Animals can affect the process of woody plant encroachment not only by dispersing seeds, but also by inhibiting woody plant establishment. Animal species that require unobstructed open spaces girdle woody seedlings. Specifically black tailed prairie dogs (*Cynomys ludovicianus*) were found to destroy honey mesquite (*Proposis glandulosa*) within two days of when they were planted near a prairie dog colony (Weltzin et al., 1997). Thus complex biotic and abiotic factors vary in both space and time, interacting to influence woody encroachment.

Streamflow and forestation

For over a century watershed managers have examined the effects of woody plants on streamflow (Stednick, 1996; Wilcox, 2010). In water-limited systems plants are of primary importance in controlling deep seepage (Scanlon et al., 1997). Many studies have found lower streamflow from forested relative to grassland watersheds (Bosch and Hewlett, 1982; Hibbert, 1983; Stednick, 1996; Thurow et al., 2000; Zou et al., 2010), though streamflow augmentation due to tree or shrub removal usually lasts no longer than a decade if woody vegetation is allowed to return (Hornbeck et al., 1993). Streamflow increases associated with woody plant removal occur in the form of increased baseflow during the growing season if soils are shallow (Hornbeck et al., 1993), but can extend into the dormant season if soils are deep (Miller et al., 1988). At Hubbard Brook in the White Mountains of New Hampshire, water yields decreased relative to pre-harvest levels several years after timber harvest when forests began to regenerate with trees having lower stomatal resistance than those that were harvested (Hornbeck et al., 1997). However, higher streamflow correlated with woody encroachment has also been reported (Wilcox and Huang, 2010). Others have found that after shrub removal herbaceous biomass increases rapidly, compensating for reduced evapotranspiration by woody plants and as a result there is little or no increase in streamflow (Carlson et al., 1990; Dugas and Mayeux, 1991; Weltz and Blackburn, 1995; Wilcox et al., 2010; Wright et al., 1976).

Climatic, hydrologic, edaphic, and geologic constraints largely determine the degree to which forestation might affect streamflow (Wilcox, 2002). Potential may exist for woody plants to reduce streamflow in areas where precipitation is greater than 500 mm, precipitation falls during a season of low evaporative demand, and subsurface flow is an important streamflow generation process (Hibbert, 1983; Huxman et al., 2005). In geology, such as karst, that allows for rapid drainage of water below plants' root zones streamflow may be affected by vegetation (Gregory et al., 2009). However, there is little potential to increase streamflow by converting woody plants to grasses in areas where infiltration excess overland flow is the primary streamflow generation process because in these dry areas most incident precipitation evaporates irrespective of vegetation cover (Wilcox et al., 2003c). To understand the potential effects of forestation on streamflow and associated uncertainties, we must understand how incident precipitation is partitioned in grassland and encroached systems. During a precipitation event, interception of incident precipitation by plant canopies and leaf litter is sequentially the first process that can affect the fate of precipitation.

In rangelands interception is an important process because it can reduce effective precipitation considerably. For example, Ashe juniper canopy in the Edwards Plateau of Texas were found to intercept 35% of rainfall and their leaf litter intercepted an additional 5%, reducing effective precipitation under these trees to 60% (Owens et al., 2006). However, precipitation interception is a more complex process in grasslands where canopy characteristics can vary greatly throughout the season (Gilliam et al., 1987). For instance, burned tallgrass prairie in the northeast Kansas foothills intercepted 19% of annual precipitation, whereas unburned tallgrass prairie at the same site intercepted 38% of precipitation (Gilliam et al., 1987). The fraction of precipitation not lost to interception then determines how much streamflow and increase in soil water storage will occur.

Baseflow is a secondary streamflow generation process in central Oklahoma, contributing a smaller proportion of total streamflow than stormflow. Baseflow is made up exclusively of subsurface and groundwater flow. The amount of baseflow that occurs depends largely on the initial water storage in the soil profile and how much water infiltrates into the soil. For example, modeling in the Blue River Basin in Oklahoma determined that after the deeper part of the soil profile dries down during the summer, streamflow is considerably lower than would be expected from a wet soil profile (Gourley and Vieux, 2006).Woody plants potentially affect these properties because they can transpire for more of the year relative to grasses (Eggemeyer et al., 2006; Lassoie et al., 1983; Ormsbee et al., 1976), can access water deeper in the soil profile (Asner et al., 2004; Eggemeyer et al., 2009), substantially reduce effective precipitation (Skau, 1964), and can extract water from lower soil water potentials (Seyfried et al., 2005). Thus, it seems plausible that increasing woody cover might have the potential to reduce streamflow during wet years.

Trees can also indirectly influence streamflow through their effects on soil hydraulic properties, particularly the soil's infiltration capacity. Relative to grassland soil, surficial forest soils have lower bulk density and as much as eight times higher infiltration capacity (Price et al., 2010). As a result conversion of grassland to forest increases recharge to groundwater and perched aquifers, thereby augmenting low flows during the dry season (Chandler, 2006).

Climate is important in controlling the threshold of woody plant cover change necessary to elicit a hydrologic response (Stednick, 1996; Zou et al., 2010). For example, in a semiarid shrubland in the Rolling Plains of Texas variation in shrub cover had no effect on streamflow because evapotranspiration accounted for over 99% of precipitation (Wilcox et al., 2006a). In contrast, in the Ouachita Mountains where precipitation averages 1317 mm, clearing 50% of the forest generated up to 558 mm of increased water yield (Miller et al., 1988).

Effects of scale

Measurement scale greatly affects the observed effects of woody encroachment on streamflow (Wilcox et al., 2006b). Under conifers, soils often become water repellent when they dry (Lebron et al., 2007; Madsen et al., 2008; Robinson et al., 2010), though much remains unknown about the temporal stability of soil water repellency (Doerr and Moody, 2004). Water repellent soils have lower infiltration capacity and hydraulic conductivities relative to wettable soils (Burch et al., 1989; Van Dam et al., 1990). At a square meter scale lower infiltration and hydraulic conductivity have caused as much as 35 times more runoff as would have occurred from wettable soils (Doerr et al., 2003). Thus under juniper trees high micro-plot runoff can be expected when soils are dry, assuming the rainfall event exceeds the canopy and litter interception capacity. Soil water repellency and high point-scale runoff might also be expected from prairie vegetation after fires of moderate intensity coat soil particles with hydrophobic substances (Glenn and Finley, 2010; Letey, 2001).

How far water travels over hydrophobic soils and the degree to which soil water repellency affects field-scale runoff are determined by the density of macropores, cracks, or hydrophilic patches in the landscape (Doerr et al., 2003). In juniper woodlands leaf litter retards the flow of water, which may then infiltrate rapidly via macropore flow. As a result, juniper woodlands do not substantially increase field-scale runoff even when soils are dry and hydrophobic at the point scale (Pierson et al., 2010). Furthermore, small-scale increases in runoff in general may not be realized at larger scales due to transmission losses (Wilcox et al., 2006b). Transmission losses occur when raindrops initially contact a substrate with low infiltration capacity, then run off and infiltrate in an area with greater infiltration or storage capacity. Such features that promote infiltration of runoff can include areas with high surface roughness, hydrophilic soil, or riparian aquifers.

The effects of forestation on a watershed scale are more complex than at plot or field scales because numerous land-uses and land-covers may be present in a single watershed and each may affect streamflow uniquely (Jang et al., 2010). These may include cropped fields, livestock grazing, roads, and urban development. Within each of these categories great variation can exist in the form of different crops, management practices, grazing rates, road characteristics, and density of development. Amidst this great variability some minimum threshold of encroachment must occur for it to be detectable at the watershed scale.

In addition to the potential effects of the extent of woody plant coverage on streamflow, the topographic position of vegetation may also influence evapotranspiration (Compaore et al., 2008), and by inference, streamflow. Whereas upland vegetation obtains most of its water directly from soil water, phreatophytic, woody riparian vegetation transpires groundwater when topsoils are dry (Scott et al., 2000), and may therefore have a greater potential to reduce streamflow than a similar area of woody upland vegetation (Dunford and Fletcher, 1947; Wilcox et al., 2006b). However, where overland flow passes through a woody riparian buffer, infiltration is increased (Hernandez-Santana et al., 2011; Schultz et al., 1995), increasing the potential for baseflow. Transpiration of riparian vegetation explains diurnal variation in streamflow in which baseflows are lowest during the afternoon and greatest at night (Gribovszki et al., 2008). Phreatophytic plants have the greatest potential to reduce baseflow on days with the most incoming solar radiation (Nyholm et al., 2003).

North-central Oklahoma

North-central Oklahoma is a relatively flat region whose upland geology consists primarily of shale and secondarily of limestone and sandstone formed 300 million years ago during the Late Pennsylvanian age (Stoeser, 2005). There are some discontinuous, narrow corridors of Holocene-age alluvium contiguous with riparian corridors of higher order streams in this region (Stoeser, 2005). Eastern redcedar encroachment into tallgrass prairie is a widely reported regional issue (Engle and Kulbeth, 1992; Linneman and Palmer, 2006; Palmer, 2007; Palmer and Rusch, 2001; Starks et al., 2011; Van Els et al., 2010). Understanding how woody encroachment affects streamflow in central Oklahoma is important because in this region users obtain water primarily from surface sources. For example, in Payne county, 80% of water was drawn from surface sources in 2005 (Tortorelli, 2009). From 1950-2005 Oklahoma's population grew by 50% and withdrawals for livestock and aquaculture, primarily from surface waters, have also increased along with withdrawals for thermoelectric power (Tortorelli, 2009). Concomitantly, the population served by surface water sources has increased (Tortorelli, 2009). Lakes McMurtry, Carl Blackwell, and Keystone are important water supply reservoirs for cities in this region. However, droughts occur regularly in this region, including from 1929-1941, 1952-1956, 1961-1972, 1976-1981, and 2002-2006 (Tortorelli, 2008).

Scope and objectives

In north-central Oklahoma demand for water resources is increasing, yet the effects of forestation of degraded grassland on streamflow are unknown. Field-scale runoff from agricultural operations has been quantified across Oklahoma (Berg et al., 1988; Sharpley and Smith, 1994; Smith et al., 1992; Smith et al., 1991) and the effects of forest harvesting in the Ouachita mountains have been examined (Miller et al., 1988). However, it is widely perceived that encroachment of woody species can threaten water supplies by increasing evapotranspiration, thereby reducing streamflow (Starks et al., 2011). It would seem that expanding riparian gallery forests could have a similar effect. This effect is likely minimal in western Oklahoma where almost all water evaporates due to high evaporative demand and low precipitation. Similarly, woody encroachment is not likely to greatly increase evapotranspiration in areas that are historically forested in eastern Oklahoma. However, less is known regarding the degree to which forestation affects streamflow in north-central Oklahoma, where precipitation is intermediate between eastern and western Oklahoma. Therefore, the goal of the present study is to determine the effects of forestation in north-central Oklahoma's grassland-forest ecotone on streamflow. Several objectives were conceived to fulfill this goal:

(1) Determine how woody cover has changed over time in a study area representative of north-central Oklahoma.

(2) Assess whether and to what degree changes in baseflow, stormflow, and streamflow are related to changes in woody cover.

Though it is widely assumed, both among Oklahoma residents and lawmakers, that woody encroachment reduces streamflow, this has never been demonstrated, and evidence on this topic is anecdotal. Furthermore, woody encroachment in Oklahoma is patchy at small scales. Even if woody encroachment reduces streamflow at small scales, it is unclear if present encroachment is extensive enough to reduce streamflow at the watershed scale. The watershed scale is an ideal scale at which to examine the effects of forestation on water yield because this scale is directly relevant to water supply. Examining the effects of forestation at the watershed scale integrates both the degree to which forestation reduces water yields along with the extent of forestation in the watershed. Finally, this study provides a valuable framework by which to couple historical aerial photographs and USGS stream gauge records to elucidate long-term drivers of streamflow.

CHAPTER II

MATERIALS AND METHODS

Synopsis

The 78 km^2 Council Creek watershed, located in Payne County, Oklahoma was chosen as the study site to assess changes in woody cover and streamflow because no major reservoirs were constructed during the study period in this watershed, historical aerial photography classification would be manageable over this area, adequate aerial photography was available for the study duration, and woody cover represents a substantial component of the watershed area. Aerial photography was georeferenced and classified using maximum likelihood classification. Then a process was developed to edit the initial classification to correct for spectral similarities between the forest cover and darkly colored agricultural fields. Aerial photographs from 1938, 1954, 1974, and 1995 were classified and woody cover during intervening years was estimated by linearly interpolating between the former years. Streamflow was separated into baseflow and stormflow using an automatic algorithm to remove the high frequency stormflow signals. Annual evapotranspiration was estimated as the complement of annual streamflow. Thornthwaite potential evapotranspiration was computed and precipitation data were obtained from Stillwater, Oklahoma's long-term climate station. Along with woody cover, these variables were used as covariates in stepwise regressions to determine which factors are related to changes in streamflow. Nonparametric Mann-Kendall tests were used to assess long-term hydrologic trends.

Study area

The study area is the Council Creek watershed (Fig. 1) located in Payne County in north-central Oklahoma, east of Stillwater (36° 10’ N, 96° 53’ W). Council Creek is a third order stream following the Horton (1945) classification system. Its watershed is 78 km^2 in area and includes 68 km of stream channel. The highest point in the watershed is 333 m above sea level and its mouth is at 255 m elevation. Beyond the mouth of Council Creek where the USGS gauge is located, the stream flows 19 km southeast where it empties into the Cimarron River. From the point where Council Creek empties into the Cimarron River, there are 116 km of stream channel before the Cimarron River empties into the Arkansas River within Keystone Lake. Keystone Lake is used for water supply, hydroelectric power, fishing, and other recreation. The Council Creek watershed contributes directly to these vital societal services and was selected to be representative of north-central Oklahoma. The topography of the watershed is typical of north-central Oklahoma in that it is relatively flat. From 1961-1990 the area-averaged precipitation in this watershed averaged 894 mm (Smith et al., 2010). Major soils in the watershed include Pulaski fine sandy loam, Grainola-Ashport-Mulhall complex, Zaneis-Huska complex, Grainola-Lucien complex, Renfrow loam, Mulhall loam, and Stephenville-Darnell. Land-cover in the watershed includes roads, developments, agricultural fields, grassland, deciduous trees, and areas encroached by eastern redcedar (*Juniperus virginiana*). This watershed was chosen because of its relatively long streamflow record, because encroachment in this watershed is representative of north-central Oklahoma, and because it has only a few small farm ponds and no major impoundments.

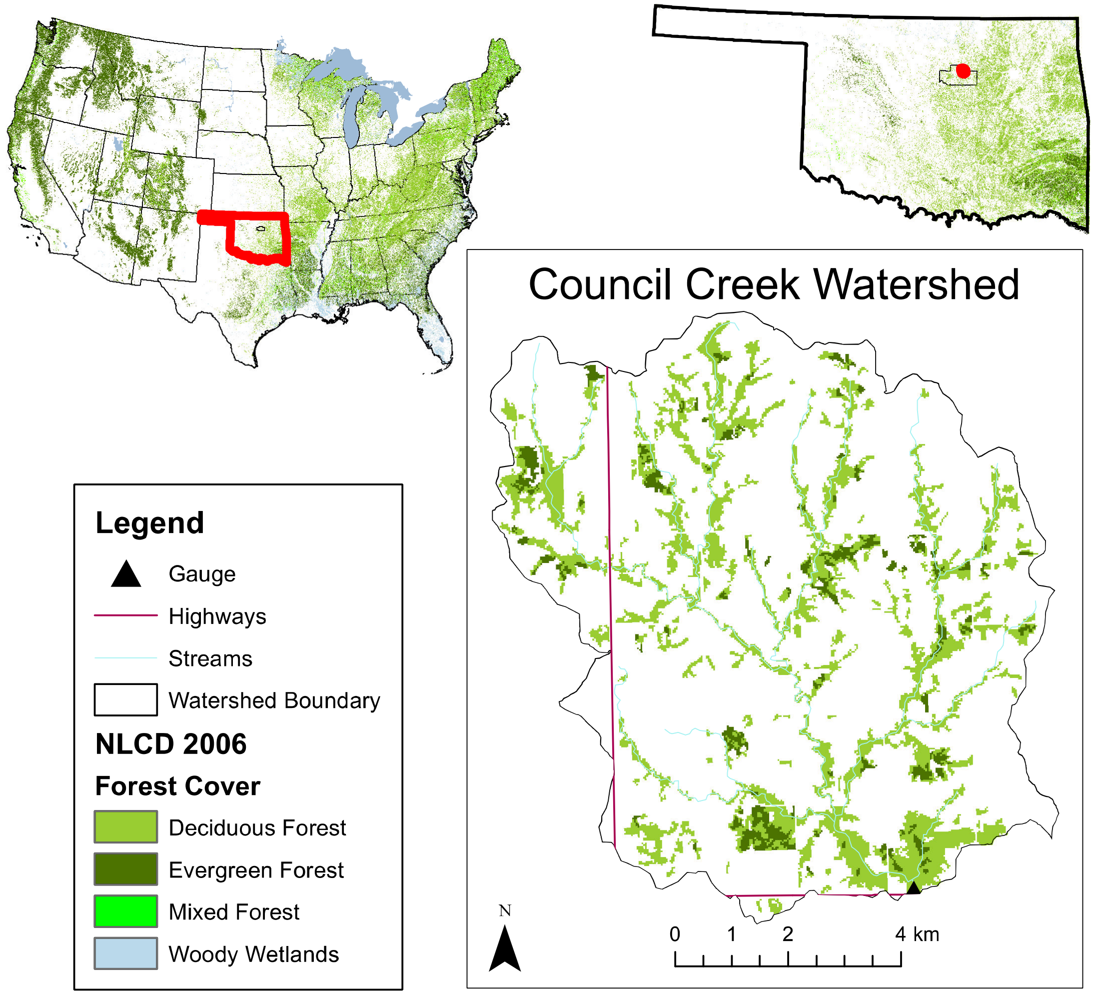

Figure 1. Maps of the distribution and abundance of woody cover in the United States, Oklahoma, and the Council Creek watershed.

Aerial photography processing procedure

The Council Creek watershed was delineated using a 10-m resolution USGS digital elevation model (DEM). First, sinks (local depressions in the landscape) were filled using the Fill tool in ArcGIS 10's Hydrology toolset. Then, the direction of water flow was determined from each 10-m raster cell based on slopes determined from the DEM. The flow direction raster was then used as input for the Watershed tool, which determines the contributing area above a set of cells in a raster. In this case I used the Watershed tool to determine which cells in the raster contributed to streamflow measured at the USGS gauging station. The raster representing the Council Creek watershed was used to mask all aerial photo mosaics to the watershed area.

Aerial photographs obtained via USGS Earth Explorer (earthexplorer.usgs.gov) were used to determine change in woody cover because multispectral imagery was not available prior to 1972 and it seemed desirable to use a consistent image source for all image classification in this study. Road intersections on the aerial photographs were georeferenced as necessary using the georeferencing toolbar in ArcGIS 10 to a 1:12,000 scale June, 2010 USDA-FSA-APFO NAIP color orthophoto mosaic of Payne County with ±5 m horizontal accuracy obtained from the Oklahoma Geographic Information Council (ftp://ftp.okcc.state.ok.us/GIS/County/). Georeferencing was usually accurate to within ±10 m. In certain cases, slightly greater errors resulted because several roads were moved somewhat between the date of the early imagery and 2010. However, overall errors in georeferencing were small. Georeferenced aerial photographs were then mosaicked and balanced by dodging, a common photogrammetric process in which each pixel value is changed toward the mean color in a panchromatic raster mosaic. Images from February 1995 were obtained from the National Aerial Photography Program at a scale of 1:40,000. Imagery from February 1974 was obtained from the USGS at a scale of 1:24,000. Imagery from March 1954 was obtained from the Army Map Service at a scale of 1:64,600. Imagery from April 1938 was obtained from the USDA at a scale of 1:20,000 and scanned using an Epson Perfection 4490 at 1,200 dpi.

The greatest challenge in the present study as well as the greatest uncertainty involved classifying the historical aerial photography. One challenge was that the aerial photos were from three different months. In April of 1938 there was the potential that some deciduous trees could have started to leaf out, causing a potential inconsistency with the other photos, in which leaf out had not occurred. Therefore, throughout classifying the historical aerial photos I attempted to classify them on the basis of where I believed the canopy cover of the trees would be if they had leaves. Another issue was that some dark areas on photos were present that could not be identified as trees with a high degree of confidence. Features other than trees can appear dark on panchromatic aerial photographs, such as wet areas or fertilized vegetation. Thus only those areas that clearly appeared to be trees based on both their color and texture were classified as such. Though this clearly entails some inexactitude I am confident that any errors in this regard are small relative to the over threefold variation in woody canopy cover.

Maximum likelihood classification was used to determine which cells in each raster image represented forested and non-forested areas. This supervised classification procedure assumes that the pixel density values of each class are normally distributed. (Pixel density quantifies how dark or light a pixel is.) Tree-covered areas on each image were selected from several regions to ensure that the spectral signature of trees from all parts of the image would be captured. Then the spectral signatures of several background (non-forested) classes within the image were obtained. Based on these user-selected samples within each image, every cell of each raster image was classified.

However, it would be impractical to verify that classification of each pixel proceeded correctly. Therefore, the image was resampled to 10 m^2 pixels to reduce processing time; reclassified to only include the forested class; converted to features (polygons) for easier editing; and then simplified to preserve only contiguous 1,000 m^2 or greater areas classified as entirely forested. (A tolerance was set to allow forested patches within 10 m of one another to be considered contiguous.) Since this post classification process was repetitive, the “Classify Watershed” workflow was automated using Model Builder (Fig. 2).

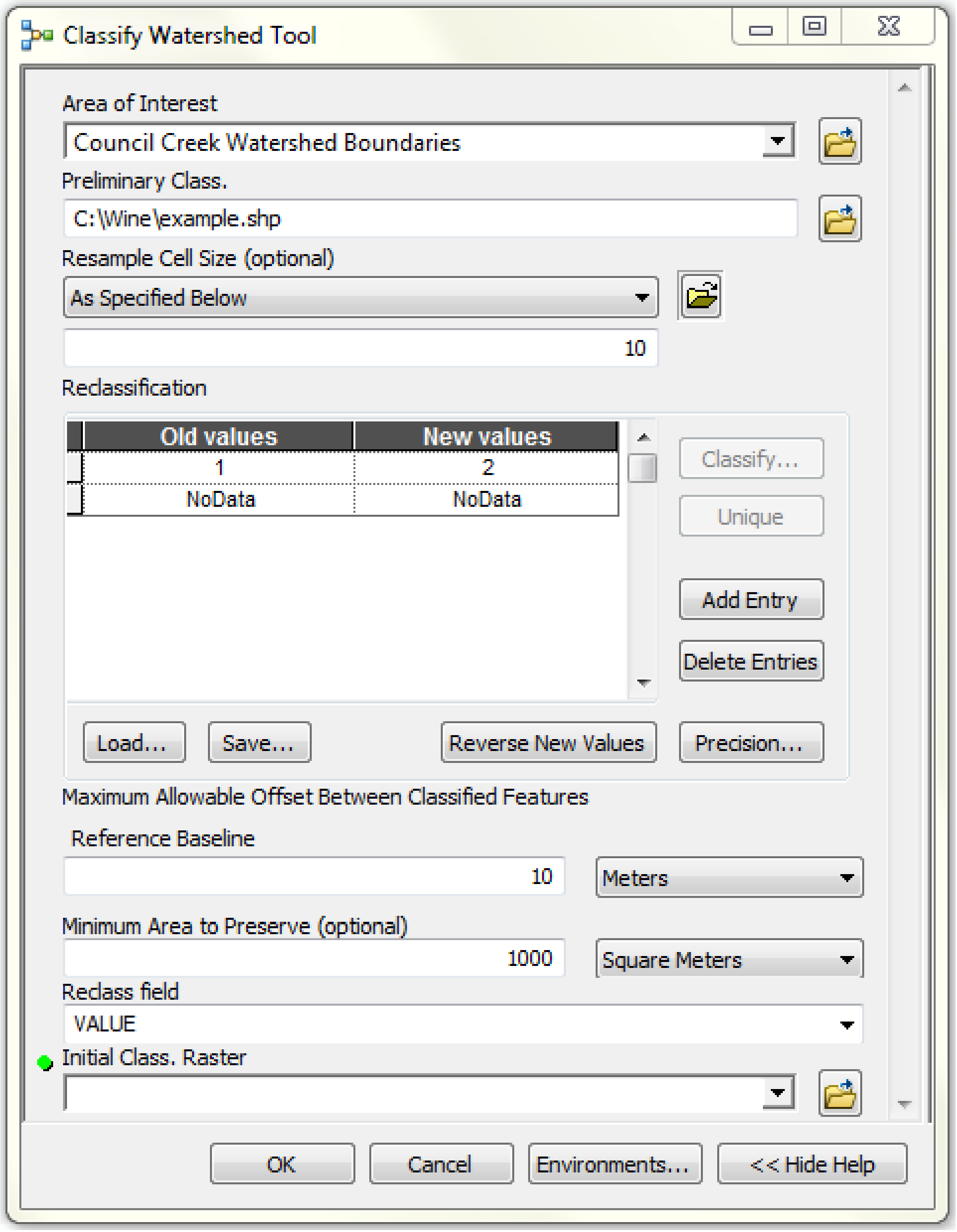

Figure 2. Example dialog box associated with the Classify Watershed tool developed to facilitate classification of the historical aerial photographs.

Once patches of forest of at least 1,000 m^2 (the minimum mapping unit) were converted to features, the individual features (forest patches) were edited until they satisfactorily represented all and only large forested patches. This manual correction was deemed necessary because the initial density-based classification method was prone to classifying dark-colored agricultural fields as forest and also classified some light-colored leaf-off deciduous trees as non-forest.

For the 1938 imagery several additional processing steps were necessary. The dodging procedure was ineffective in balancing the 1938 mosaic and the maximum likelihood classification was unable to classify the images from 1938. Dodging apparently failed because the image was scanned at 16-bit grayscale to preserve image quality and too many bins or pixel densities (tens of thousands) were created for each image with too few pixels assigned to each bin. To solve this problem each 1938 image was sliced into 255 bins of approximately equal area and thereafter classified. All geographic analyses were conducted in ArcGIS 10 (ESRI, Redlands, CA).

Hydrologic variables and statistical analysis

Climate data were obtained from the U.S. Historical Climatology Network's Stillwater, Oklahoma station (36.1175 N, 97.095 W). Potential evapotranspiration (PET) was calculated from monthly average temperature (Thornthwaite, 1948). Actual evapotranspiration (ET) was estimated as the complement of streamflow on an annual basis (Garbrecht et al., 2004). Daily streamflow was obtained from the USGS Council Creek gage and separated into stormflow and baseflow using an algorithm that assigns the high frequency signals associated with storms to stormflow and the remaining streamflow to baseflow (Arnold and Allen, 1999; Arnold et al., 1995). This gauge ceased to operate in mid-1993, so annual streamflow data were available only through 1992. Where necessary variables were appropriately transformed to centralize their distribution mode following Helsel and Hirsch (2002). Mann-Kendall trend tests were performed on the annual time series of each variable other than tree cover. Mann-Kendall tests are widely used in analyzing hydrologic time series because this nonparametric test is not sensitive to non-normally distributed data and is not unduly influenced by unusually large storms that occur infrequently. Stepwise regression was used to determine which variables were significant predictors of total streamflow, stormflow, and baseflow. Stepwise regression was chosen because it determines whether a response is related to a predictor independent of potentially confounding factors if these factors are included as covariates. Since only four aerial photos were classified during the study, linear interpolation was used to fill tree cover values for years in which aerial photography had not been classified so that this variable could be used as a predictor in statistical analyses. All statistical analyses were carried out in Minitab 16. An α value of 0.1 was used to determine statistical significance (Wilcox and Huang, 2010).

CHAPTER III

RESULTS AND DISCUSSION

Synopsis

From 1938-1992 precipitation trended significantly upward driven by above average precipitation from 1980-1992. Baseflows, the ratio of baseflow to precipitation, the ratio of baseflow to total streamflow, the duration of streamflow, and evapotranspiration also trended upward over time. Woody cover increased from 5% in 1938 to 18% in 1992. However, eastern redcedar woodland never comprised more than 15% of woody cover and covered less than 2.6% of the watershed area in the 2006 National Land Cover Dataset. Canopy cover was directly and PET inversely related to the ratio of baseflow to streamflow. However, the present study does not prove that the trees themselves caused the observed increase in baseflows. Possible alternative explanations include landscape-wide hydrologic recovery from clean tillage and overgrazing, non-linear baseflow responses to increased precipitation, or changes in precipitation characteristics. The results fail to support the common assumption that woody cover reduces streamflow, particularly baseflows. Another common assumption is that woody cover along riparian corridors is particularly efficient in reducing streamflows. The present study fails to support this assumption as well since woody cover in the present study increased in abundance primarily along the riparian corridors, yet all measures of baseflow increased over time and streamflow did not change significantly. However, it is unknown how baseflow and total streamflow would have been affected had precipitation remained constant over the study period and not increased at the end, coincident with the increase in woody cover. The results indicate that there is no measurable tradeoff between water yields and forestation of riparian areas at 1992 levels of woody plant cover.

Results

From 1938-1995 precipitation averaged 850 mm (Table 1) and ranged from 424 mm in 1956 to 1572 mm in 1959 when Hurricane Debra doused north-central Oklahoma. During the study precipitation trended significantly upward (p = 0.021, Fig. 3), increasing at an average rate of 2.7 mm yr^{-1}. This trend was driven in part by above average precipitation of 955 mm from 1980-1992. During this period precipitation was 12% higher than average during the study. PET averaged 1171±12 mm, ranging from 1047 mm in 1961 to as high as 1422 mm during 1954, the second driest year of the study. There was no evidence of an upward trend in PET (p = 0.849). Evapotranspiration increased significantly during the study (p = 0.086), increasing at an average rate of 1.5 mm yr^{-1}. Precipitation was highest in May, June, and September whereas evaporative demand peaked from June through September (Figure 3). Median streamflow and baseflow peak in May at 11 mm and 3 mm, respectively.

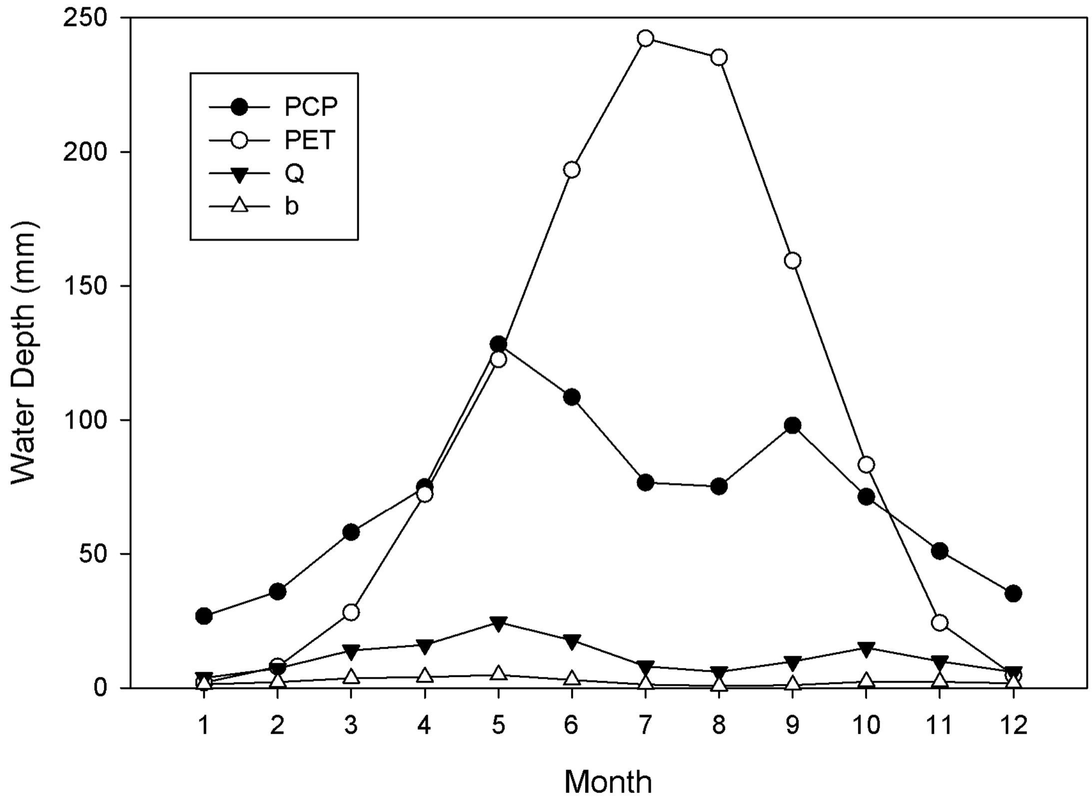

Figure 3. Mean precipitation (PCP), potential evapotranspiration (PET), streamflow (Q) and baseflow (b) by month in the Council Creek watershed, Payne County, Oklahoma (1938-1992).

Cover of the woody class increased from 5.0% of the Council Creek watershed in 1938 to 11.0% in 1954. Cover of the woody class then decreased slightly to 10.7% in 1974 before it increased to 19.2% in 1995 (Figs. 4-6). Thereafter cover increased to 26.2% as of July, 2010. From 1974 to 2010, canopy cover increased at an average annual rate of 0.4 percentage points of the watershed area, or 0.33 km^2. Increases in woody cover were most concentrated along riparian corridors (Fig. 7). According to the 2006 National Land Cover Dataset eastern redcedar trees comprised only 15% the total woody cover in the Council Creek watershed, despite their present rapid encroachment.

Streamflow averaged 143 mm and ranged from 4 mm in 1956 to 724 mm in 1959. From 1980-1992 annual streamflow averaged 195 mm, 36% higher than mean streamflow during the study period. Despite this substantial decadal increase in streamflow toward the end of the study the total variability in streamflow was high and no significant trends were observed in annual streamflow ($p > 0.129$) or stormflow ($p > 0.248$). On average Council Creek flowed for 264 days of the year, making it an intermittent stream. However, it became ephemeral during 1956 when it only flowed for 9 days. The stream has also flowed perennially during five of the years of the study, including 1992, a leap year, when it flowed for 366 days. The number of days that the stream flowed increased significantly over the course of the study ($p = 0.008$), an average increase of 1.8 days yr^{-1}. This increase was associated with an increase in the number of days the stream flowed from 1980-1992. During this period the stream flowed on average 307 days per year, 16% higher than the average from 1938-1992.

Table 1. Mean, median, first quartile, third quartile, and p-values from Mann-Kendall trend tests for annual hydrologic variables in the Council Creek watershed, Payne County, Oklahoma. Bold values are statistically significant ($\alpha = 0.1$). Negative signs indicate decreasing trends and positive p-values correspond to positive trends.

Variable	Mean	Median (Q1–Q3)	P-value
Precipitation (mm)	850	818 (711–950)	**0.021**
Potential Evapotranspiration (mm)	1170	1160 (1109–1216)	-0.151
Streamflow (mm)	143	110 (49–212)	0.129
Stormflow (mm)	114	90 (38–151)	0.248
Baseflow (mm)	30	21 (10–42)	**0.012**
Evapotranspiration (mm)	706	718 (621–772)	**0.086**
Baseflow / Streamflow (%)	20%	19 (15–24)	**0.001**
Streamflow / Precipitation (%)	15%	14 (7–20)	0.173
Flow Duration (Days)	264	275 (220–330)	**0.008**

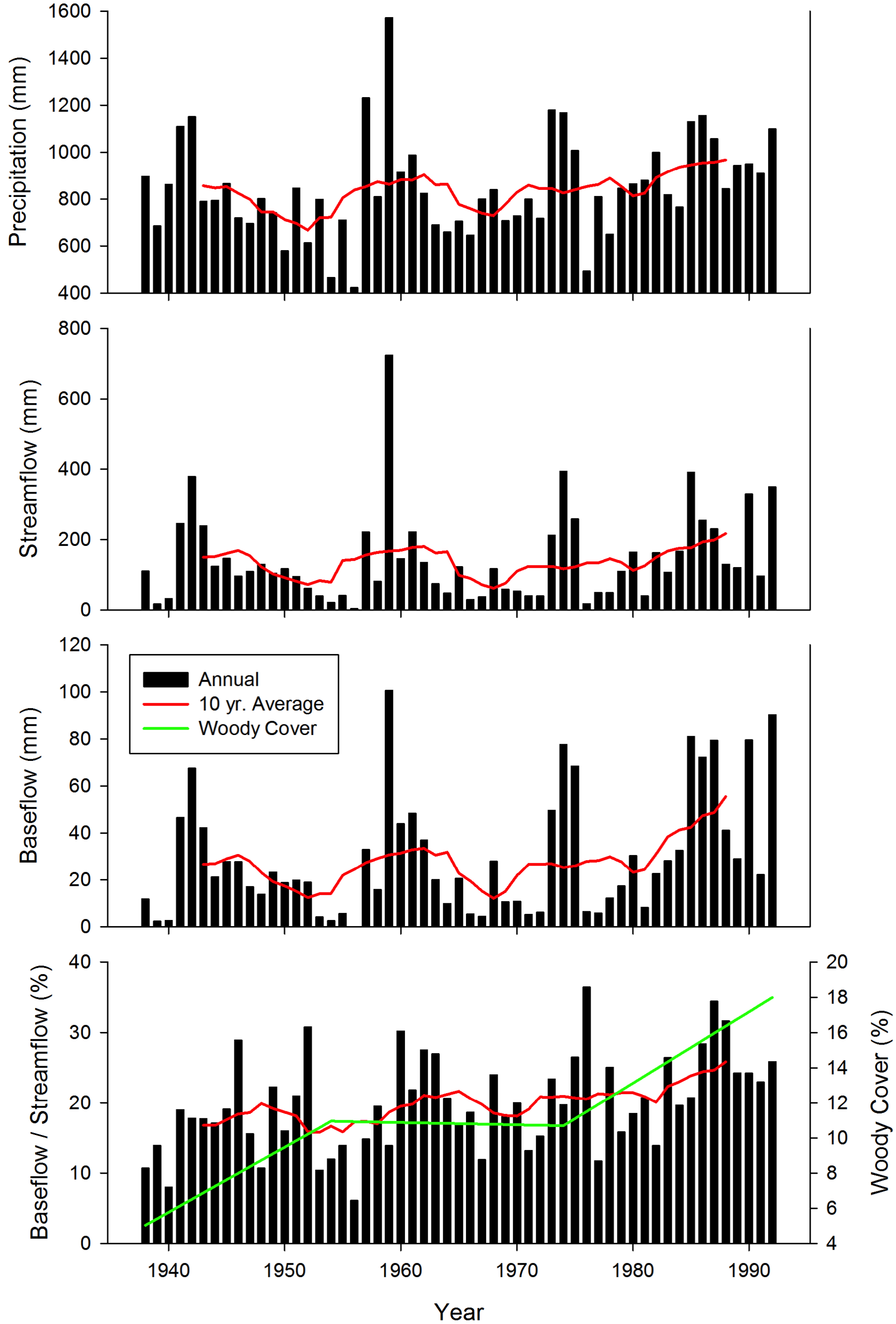

Figure 4. Annual precipitation, streamflow, baseflow, baseflow as a proportion of streamflow, and woody cover in the Council Creek watershed from 1938-1992.

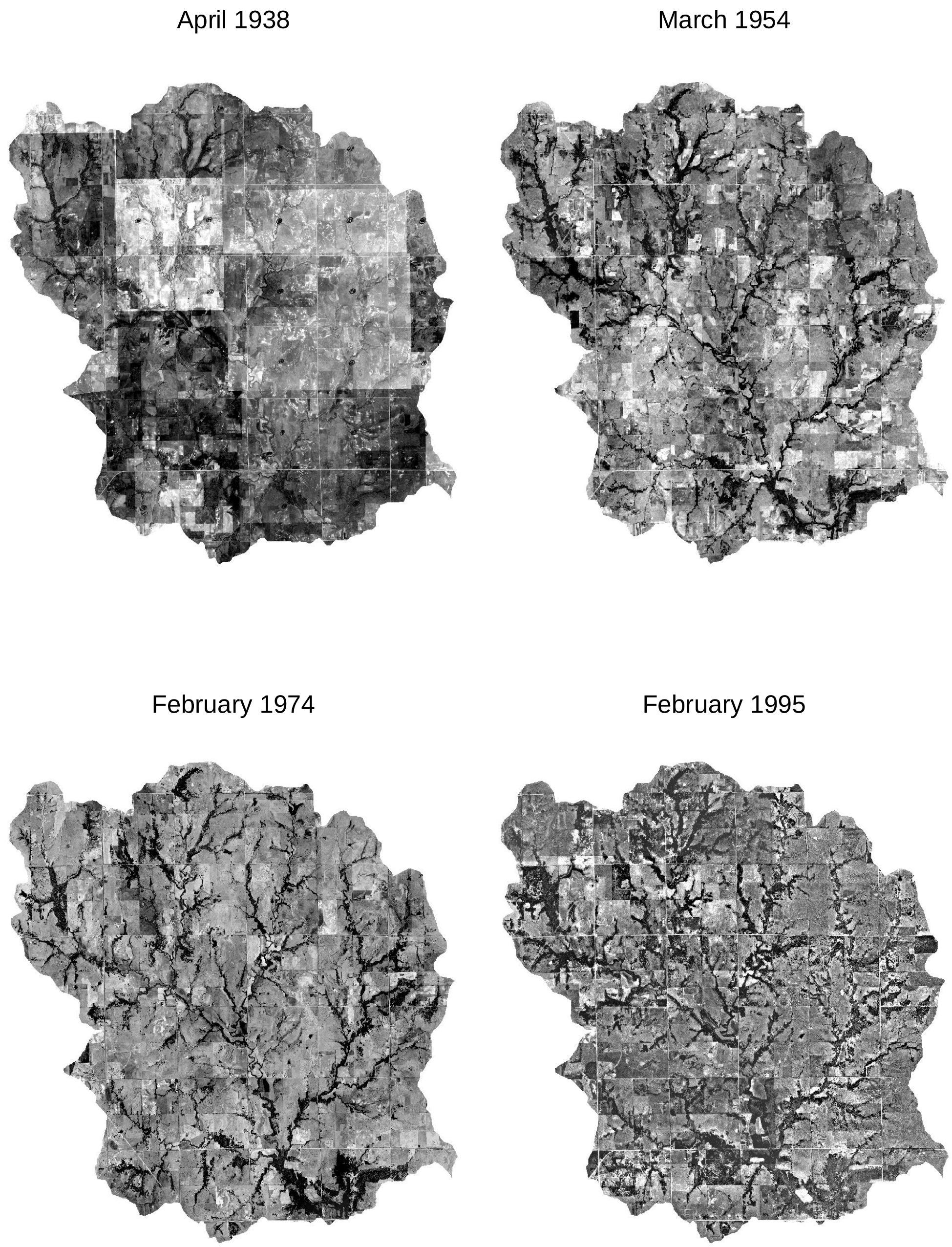

Figure 5. Georeferenced aerial photograph mosaics masked to the watershed boundaries of the Council Creek watershed, Payne County, Oklahoma.

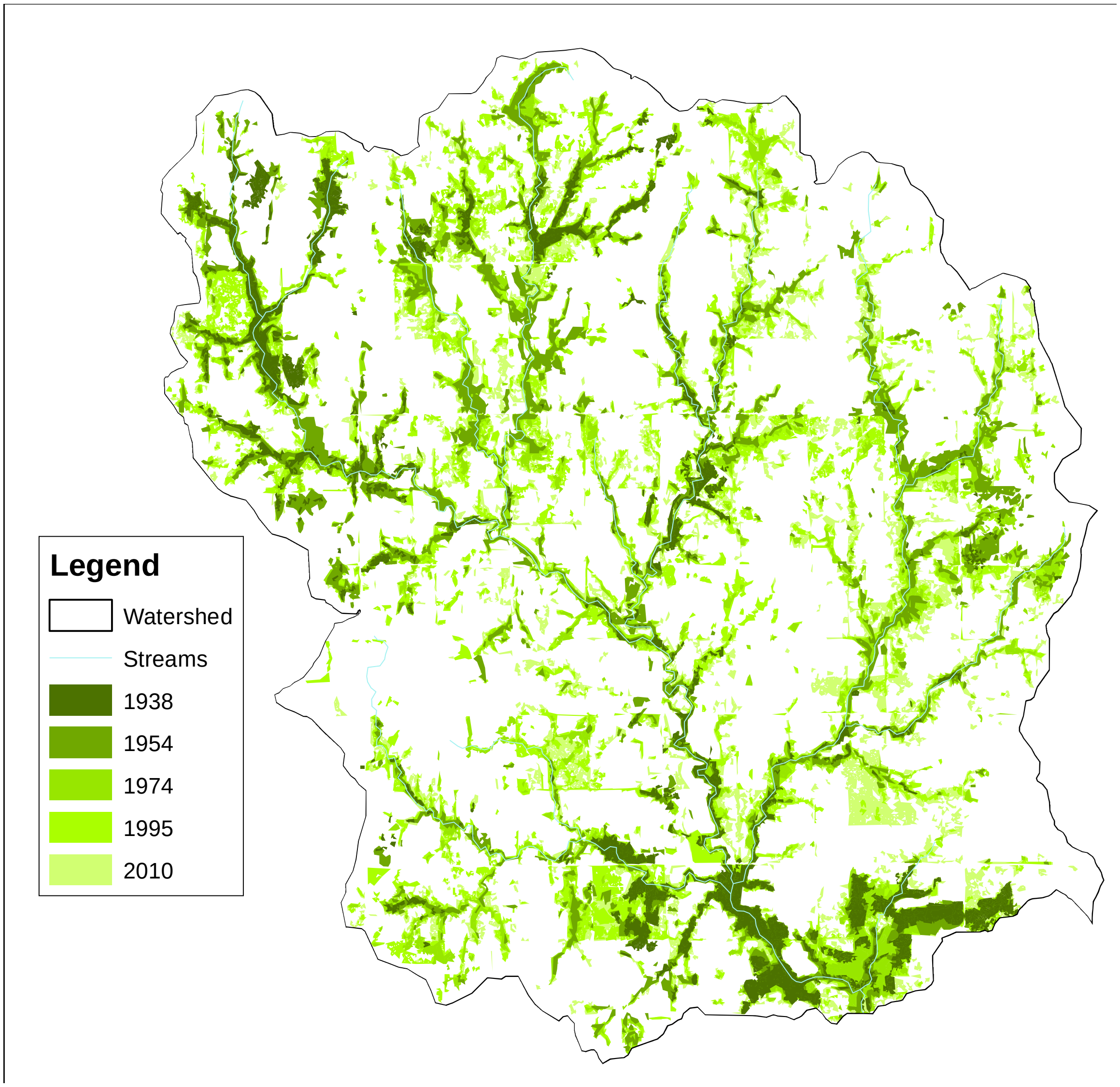

Figure 6. Changes in woody cover in the Council Creek watershed, Payne County, Oklahoma (1938-2010).

Streamflow was composed primarily of stormflow, on average 114 mm. Though there were no trends in stormflow (p = 0.248), annual baseflow increased significantly over time (p = 0.012), at an average rate of 0.5 mm yr^{-1}. From 1980-1992 substantially higher median baseflows occurred primarily from February through May relative to pre-1980 flows. However, monthly baseflows trended up significantly during all months except June through September (Table 2). Over time baseflows accounted for a greater proportion of precipitation (p = 0.018) and total streamflow (p < 0.001).

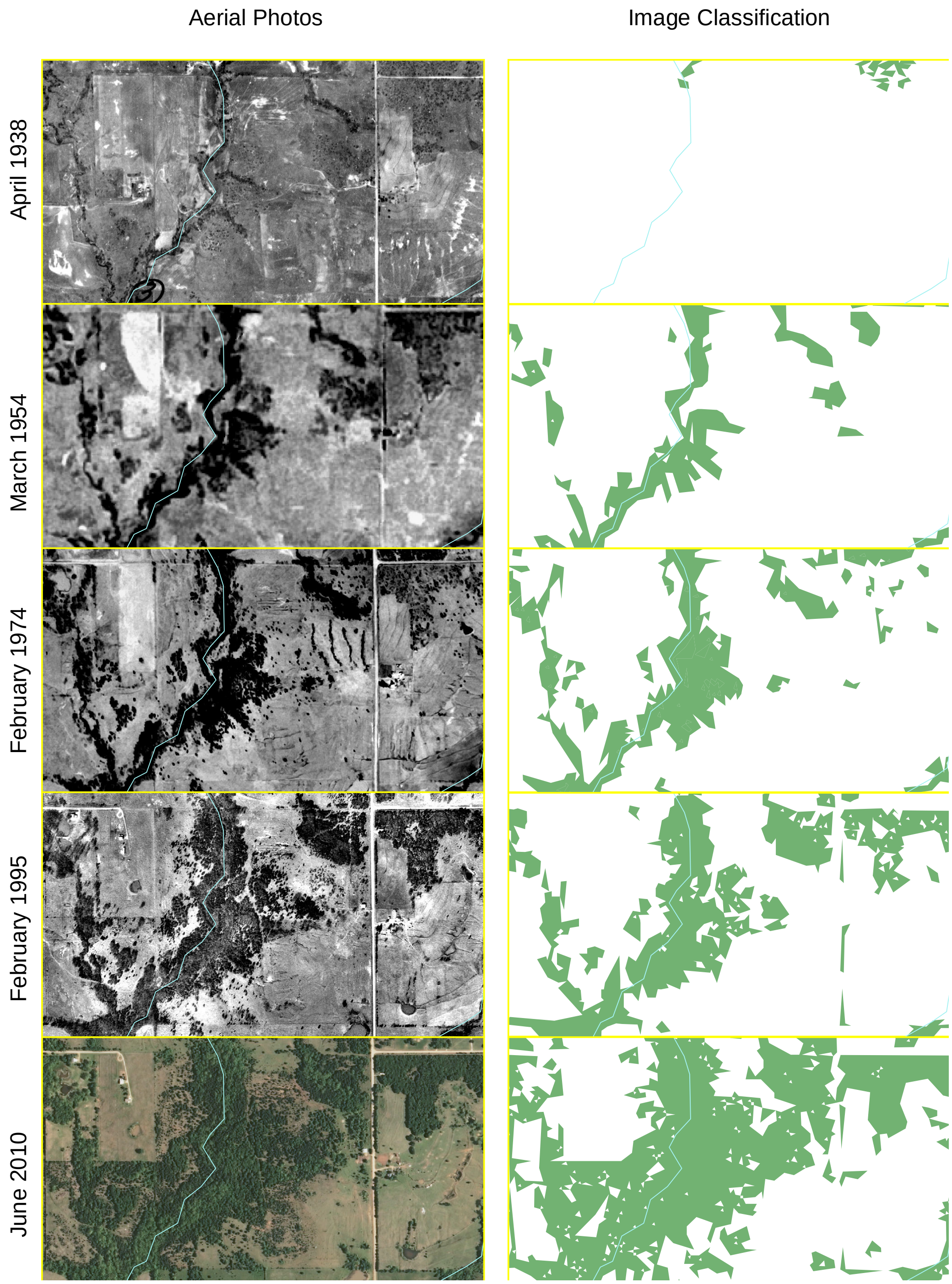

Figure 7. Chronosequence of woody encroachment in a riparian area representative of the Council Creek watershed.

Table 2. Results of Mann-Kendall trend tests on monthly baseflow from 1938-1992 in the Council Creek watershed, Payne County, Oklahoma. Bold values are statistically significant ($\alpha = 0.1$). Negative values indicate a decreasing trend.

Month	**P-value**
January	**0.001**
February	**<0.001**
March	**0.001**
April	**0.001**
May	**0.002**
June	0.222
July	0.319
August	0.360
September	-0.425
October	**0.065**
November	**0.009**
December	**0.006**

Table 3. Regression equations explaining variation in streamflow (Q), stormflow (q), baseflow (b), the proportion of streamflow that is baseflow (b/Q), and the duration of streamflow (Q_{DUR}). Predictor variables were potential evapotranspiration (PET), precipitation (PCP), and woody cover (C_W). All variables are expressed in mm except Q_{DUR}, which is expressed in days and C_W, which is expressed as percent.

Regression Equation	P-value	R^2
$LOG_{10}Q = 2.005 - 0.073\ PET^{1/3} + 0.088\ PCP^{1/2}$	<0.001	67.2%
$LOG_{10}q = -0.796 + 0.096\ PCP^{1/2}$	<0.001	66.1%
$b^{1/3} = -3.485 + 0.059\ C_W + 0.195\ PCP^{1/2}$	<0.001	61.3%
$b/Q = 75.80 + 0.8845\ C_W - 6.244\ PET^{1/3}$	0.001	21.1%
$Q_{DUR}^2 = 389224 + 2750\ C_W - 45449\ PET^{1/3} + 4678\ PCP^{1/2}$	<0.001	46.8%

Total streamflow was directly related to precipitation, but inversely related to PET ($p < 0.001$, Table 3). Precipitation explained 67% of the variation in streamflow and PET, an additional 1%. Stormflow was only related to precipitation ($p < 0.001$, $R^2 = 66\%$). Baseflow was related to precipitation and woody cover ($p < 0.001$). Precipitation explained 58% of the variation in baseflow and woody cover, an additional 3%. Canopy cover was related and PET inversely related to the ratio of baseflow to total streamflow ($p = 0.001$). Canopy cover explained 19% of the variability in this ratio and PET explained an additional 5%. The number of days that the stream flowed was related to precipitation and woody cover and inversely related to PET ($p <$

0.001). Precipitation explained 38% of the variability in flow duration; PET an additional 7%, and woody cover, 5%.

Discussion

Similar to the present study, increases in woody cover centered in riparian corridors were observed in Northern Texas (Asner et al., 2003). Increases in forest cover observed in the Southern Great Plains are part of a larger-scale reforestation in the Southern United States that started in the early 20th century after the intensive agriculture of the 19th century (Wear and Greis, 2002). In the present study, a slight reduction in tree cover between 1954 and 1974 may have resulted from a drought in Oklahoma from 1952-1956 that caused tree mortality (Rice and Penfound, 1959).

It has been widely believed that woody cover in rangeland reduces streamflow (Kreuter et al., 2004; Starks et al., 2011; Tennesen, 2008). The present study questions whether 1992 levels of woody cover in north-central Oklahoma, such as in the Council Creek watershed, are in fact producing the postulated reduction in streamflow. This study fails to uncover decreases in streamflow associated with increased tree cover. In 1956, the driest year on record, 99% of precipitation was lost to evaporation, assuming that ET is the complement of runoff. In this year baseflow was absent so vegetation management strategies intended to reduce evapotranspiration would have been ineffectual. In fact, to increase streamflow during the driest years, such as 1956, water-harvesting—practices that reduce infiltration and increase overland flow— would be necessary.

The present study finds that baseflows actually increased with forestation, similar to on the Edwards Plateau of Texas (Wilcox and Huang, 2010). However, encroachment in the Council Creek watershed is less extensive than on the Edwards Plateau. Accepting that infiltration is a prerequisite for baseflow and assuming that forestation of grassland improves the soil's infiltration capacity, less extensive forestation in the Council Creek watershed relative to on the Edwards Plateau provides a possible explanation for less dramatic increases in baseflow in the present study. Baseflows require permeable subsurface geology. Thus, lower baseflows in the present study may also reflect less permeable subsurface geology in the Council Creek watershed relative to the Edwards Plateau. Wilcox and Huang (2010) qualified the results of their study, noting that baseflows may only increase with hydrologic recovery in areas with similar geology to the Edwards Plateau. The present study indicates that hydrologic recovery may convey increased baseflows in non-karst geological settings as well, though the potential magnitude of baseflow increases in deeper, finer textured substrates is lower. In deep, fine textured soils there is less potential for changes in vegetation to influence baseflows because these soils can store more water than coarser substrates.

Modification of soil hydraulic properties may represent the physical mechanism causing higher baseflows with greater woody cover (Bruijnzeel, 2004). In the 1930's, much of the study site was degraded cropland. Hydraulic conductivity is lower and overland flow, higher on degraded, sparsely vegetated hillslopes relative to areas with intact vegetation cover (Moreno-de las Heras et al., 2010; Wilcox et al., 2003c). Other land-uses within the watershed such as agricultural fields or grazinglands tend to have lower macroporosity than forest soils (Neary et al., 2009). As a result higher infiltration rates have been reported as overgrazed lands revert to forest (Gilmour et al., 1987). Since baseflow is made up entirely of water that infiltrates into the soil, high infiltration is a prerequisite for high baseflows. From 1938-1992 Council Creek infiltration must have increased to a greater extent than evapotranspiration, thus creating the observed positive trend in baseflows.

From 1992-2010 woody cover increased by 8%. This higher level of cover may influence present-day streamflow and since the gauge ceased recording in 1992 it is impossible to determine at what point, if any, a reduction in total streamflow will occur. Such a reduction was observed when grazingland in central Texas converted to woodland (Wilcox et al., 2008). Though there are numerous benefits associated with augmenting baseflows, in water-limited regions, these benefits have historically been viewed as coming at the expense of reduced streamflows

(Calder, 2007). Benefits associated with increased baseflows include greater streamflow during the summer, healthier riparian zones, greater channel and bank stability, lower erosion and sediment transport, enhanced habitat for aquatic species, cooler stream temperatures, and more aesthetically appealing streams (Ponce and Lindquist, 1990). My results suggest that increases in woody cover, baseflow, and their aforementioned ecohydrologic benefits do not necessarily come at the cost of reduced streamflow.

It is a generally accepted precept that on watersheds where subsurface flow is an important streamflow generation process, the potential exists for increases in woody cover to diminish streamflow (Huxman et al., 2005; Wilcox, 2002). However, at the watershed scale the extent of woody cover change required to elicit a streamflow response has also been described as a threshold process (Lewis et al., 2000; Stednick, 1996). Lack of observed decreases of streamflow or its components may have resulted because the extent of forestation was insufficient to detect a reduction and because of the increasing trend in precipitation. In rangeland studies that have observed large streamflow changes with woody encroachment, the extent of encroachment was substantially greater than in the present study (Afinowicz et al., 2005; Wilcox et al., 2008). It is reasonable to anticipate that a high woody cover change threshold would be necessary to alter streamflow in Council Creek because evaporative demand is high relative to precipitation and the climate is continental. In climates in which precipitation and evaporative demand are out of phase, such as Mediterranean climates, changes in vegetation characteristics are more likely to influence streamflow. In contrast, in continental climates where precipitation and evaporative demand are more nearly in phase with one another, most precipitation that infiltrates into the soil ultimately evaporates, irrespective of plant characteristics.

Since this retrospective study indicates a weak correlation between woody cover and baseflow, but by its design cannot prove causation, it seems prudent to evaluate possible alternate explanations for increasing baseflows over time. Elevated precipitation from 1980-1992 near the Council Creek watershed was representative of the Central and Southern Great Plains (Garbrecht et al., 2004; Garbrecht and Rossel, 2002). These increases in precipitation in the Central and Southern Great Plains were observed to cause non-linear, exponential increases in streamflow (Garbrecht et al., 2004). Since peak woody cover coincided with elevated decadal precipitation, it is possible that observed increases in baseflows would have occurred without increases in tree cover, as a result of precipitation alone.

Precipitation characteristics, including the storm size distribution, also have changed over time. In central Oklahoma the average size of individual storms increased dramatically from 1950-1990 (Knapp et al., 2008a). Small, frequent storms wet the soil surface and can produce overland flow, but do not saturate deeper soil layers. Large less frequent storms—in which a greater depth of water is conveyed to the soil—are more likely to saturate the soil deeply. Since the water content of the deep soil is an important predictor of streamflow in central Oklahoma (Gourley and Vieux, 2006), it is reasonable to expect that an increase in the average size of a storm event would produce greater baseflows.

In addition to the potential confounding effects of precipitation on baseflows, changing land use can also affect baseflows (Dams et al., 2008). The Dust Bowl occurred in the 1930’s and spurred awareness of soil and water conservation practices. Thereafter, programs, such as the Conservation Reserve Program encouraged planting perennial grasses to replace former cropland (Dewald et al., 1985). In addition, cropland management practices in Oklahoma are sensitive to other economic incentives, such as commodity prices (Berg et al., 1988). On the historical aerial photos it is difficult to distinguish between specific non-forest land uses. Therefore, no attempt was made to quantify changes from cropland to grazingland or changes in grazing rate. Thus, woody cover may simply be a surrogate for wider land-use and soil hydraulic changes.

The effects of farm ponds and impoundments in the Council Creek watershed are also unknown. After floods vitiated agricultural lands during the late 1930’s and early 1940’s the Federal Flood Control Act of 1944 was passed authorizing pilot flood-control programs in the United States (Schoof et al., 1978). In 1953, the Watershed Protection and Flood Prevention Act directed government agencies to protect vulnerable areas from flooding (Van Liew et al., 2003). As a result, the USDA NRCS built 2,500 flood control structures in Oklahoma to reduce peak discharge. These flood retarding structures reduce storm flows and augment baseflows immediately following storms as impounded water pours over the spillway of dams (Van Liew et al., 2003). Thus increasing impoundments might explain the change in the ratio of baseflows to stormflows over time. In light of the great abundance of ponds, reservoirs, and flood control structures in Oklahoma, it is nearly impossible to find watersheds that are unaffected by dams. However, dams also reduce low flows by trapping baseflows from above the flood control structure (Van Liew et al., 2003). There are only a few small farm ponds and no major impoundments in the Council Creek. Thus, any changes in impoundments that may have occurred in the Council Creek watershed do not appear to drive observed baseflow trends since the number of days that the stream flowed increased and was correlated to increases in woody cover.

CHAPTER IV

CONCLUSIONS

Retrospective analysis of the Council Creek watershed provided useful information regarding trends in woody species and the nature of their association with the rangeland water cycle. First, a semi-automated supervised classification method was developed to assess woody cover changes using aerial photography throughout the entire watershed from 1938-1992. Then, stepwise regression and Mann-Kendall trend tests were used to assess hydrologic changes and to determine how observed hydrologic changes were related to measured changes in woody canopy cover.

Classification of woody cover on historical aerial photographs is a promising, affordable approach to determine large-scale, long-term changes in woody cover starting in the 1930's when the first organized aerial photography campaigns were carried out in the United States. The process developed for estimating woody cover was more laborious than necessary. Future studies should consider investing in object-recognition software as these products become more powerful. Furthermore, at the beginning of future studies an assessment should be made to determine to what degree historical woody cover increases were confined to the present extent of woody cover. If most historical woody cover is within the bounds of present-day woody cover classifications (available from sources such as the National Land Cover Dataset) then restricting classification to these areas could save valuable time.

As woody cover (composed primarily of deciduous trees) increased, baseflows increased significantly as a proportion of total streamflow, though total streamflow did not change significantly. Confounding factors within the Council Creek watershed and during the study period included increased precipitation toward the end of the study period when woody cover was highest, construction of impoundments, and potential land-use change within the non-forested areas of the watershed. Nonetheless, the present study failed to support two prevailing paradigms in range management. The first states that woody cover should reduce the subsurface component of streamflows. The second states that phreatophytic riparian vegetation should have a differential impact in reducing baseflows, relative to upland plants that cannot access water tables. In contrast, the present study suggests the hypothesis that forestation of riparian areas may have a differential effect on increasing baseflows. Increases of woody cover to 1992 levels showed no decrease in streamflow and only increases of baseflow, indicating no measurable reduction in water yields despite the ecological benefits of increased woody cover.

Further research is needed into the hydrologic effects of changing forest cover along Oklahoma's unique grassland-forest ecotone. Though the methods presented herein seem viable for watersheds that are nearly devoid of impoundments, these structures are especially common in the state of Oklahoma. Further application of aerial photography to assess drivers of change in streamflow in Oklahoma will require highly accurate reconstruction of streamflow components that have been altered by impoundments in most large gauged watersheds in Oklahoma.

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VITA

Michael Louis Wine

Candidate for the Degree of

Master of Science

Thesis: STREAMFLOW RELATIONS WITH INCREASING RIPARIAN WOODY COVER IN NORTH-CENTRAL OKLAHOMA

Major Field: Natural Resource Ecology and Management

Biographical:

Education:

Completed the requirements for the Master of Science in your Natural Resources Ecology and Management at Oklahoma State University, Stillwater, Oklahoma in July, 2011.

Completed the requirements for the Bachelor of Science in Natural Resources at Cornell University, Ithaca, NY in 2009.

Experience:

The author was born in Brooklyn, New York on October 21, 1986 and graduated from the Bronx High School of Science in 2004. Following the completion of his Bachelor of Science in Natural Resources from Cornell University in May of 2009, he enrolled as a Master of Science student in the Department of Natural Resource Ecology and Management. The author's obtained funding from Decagon Devices for an ongoing project. Funding for the author's project was provided through the Department.

Name: Michael L. Wine Date of Degree: July, 2011

Institution: Oklahoma State University Location: Stillwater, Oklahoma

Title of Study: STREAMFLOW RELATIONS WITH INCREASING RIPARIAN WOODY COVER IN NORTH-CENTRAL OKLAHOMA

Pages in Study: 47 Candidate for the Degree of Master of Science

Major Field: Natural Resources Ecology and Management

Scope and Method of Study:

The study was conducted in the Council Creek watershed in Payne County, Oklahoma using historical data from 1938-1992. Historical aerial photographs were obtained and georeferenced, masked, and mosaicked to the Council Creek watershed. A semi-automated processing procedure was developed using Model Builder in ArcGIS 10. Maximum likelihood classification, a supervised classification method, was used to initially classify each pixel within images of the watershed as either woody or as one of several background categories. The individual pixels were then processed using an algorithm to convert areas greater than 1,000 m^2 classified as woody to polygons. These polygons were then individually examined and areas that appeared to have been misclassified were corrected. Statistical methods were then used to determine which among potential evapotranspiration, woody cover, and precipitation best predicted changes in streamflow and its components.

Findings and Conclusions:

Significant increasing trends of precipitation, streamflow duration and baseflow were uncovered, though total streamflow did not change significantly. Woody cover increased from 5% in 1938 to 18% in 1992, driven primarily by increases in deciduous trees. Eastern redcedar canopy cover never comprised more that 15% of total woody cover. Baseflows were directly related to precipitation and woody cover. Precipitation explained 59% and woody cover explained an additional 4% of variability in baseflows. The correlation between woody cover and baseflows does not prove causation. Other possible causes include changes agricultural and grazing management strategies, changing storm characteristics, or a non-linear increase in streamflow associated with above average precipitation from 1980-1992. Notwithstanding ambiguity regarding the causes of increased baseflows, the study has implications for range management. There are numerous hydrologic benefits associated with wooded riparian areas and increased baseflows. Many of these benefits are assumed to come at the cost of reduced water yield. The present study indicates that low levels of woody cover may elicit ecohydrologic benefits without measurable reductions in water yield.

ADVISER’S APPROVAL: Chris B. Zou