RUNOFF CHARACTERISTICS AND THE INFLUENCE OF LAND COVER IN DRYLANDS OF WESTERN TEXAS

A Dissertation

by

YUN HUANG

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

August 2006

Major Subject: Water Management and Hydrological Science

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Approved by:

Co-Chairs of Committee,	Bradford P. Wilcox
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ABSTRACT

Runoff Characteristics and the Influence of Land Cover in Drylands of Western Texas. (August 2006)

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In dryland regions, where water is a limited resource, land use/land cover has undergone and continues to undergo significant change mainly due to human activities. The nature of runoff from dryland regions and the influence of land use/land cover change are largely not quantified. The objective of this study is to examine runoff dynamics and the influence of land cover in drylands of western Texas across multiple spatial and temporal scales. The study consists of four major components: (1) an experimental study at Honey Creek upland catchment (19 ha) to assess vegetation treatment effects on runoff by hydrometric and isotopic methods; (2) a hydrochemical evaluation of hydrologic linkage between the upland and bottomland at the second-order Honey Creek watershed; (3) a detailed precipitation-streamflow analysis at North Concho River basin to assess long-term and large-scale precipitation-streamflow-vegetation dynamics; and (4) a comparison of streamflow in North, Middle, and South Concho River basins and a regional streamflow trend analysis for the entire western Texas. The study indicates runoff production in the drylands of

western Texas is dominated by a few large runoff-producing events. The small catchment experiment indicated that runoff increased about 40 mm per year when 60% of woody plants were removed. This effect may relate to the presence of a baseflow component, but was not verified in regional trend analysis for the Edwards Plateau region where most rivers are spring-fed. The decrease in streamflow in North Concho River basin after the 1950's is in large part related to the enhanced infiltration capacity from reduced grazing pressure and improved vegetation cover. Regional streamflow trend analysis suggests some headwater areas outside the Edwards Plateau region experienced patterns of streamflow change similar to those in North Concho River basin, although artificial impoundments complicated the analysis. The study has broader application in ecohydrological research beyond specific geographic areas and specific vegetation types when evaluating the impact of ecosystem structure change on hydrology and water resources.

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CHAPTER I

INTRODUCTION

Background

More than 47% of the Earth's land surface are drylands, which include hyperarid, arid, semiarid, and dry subhumid areas. Drylands provide habitat and source of livelihood for about a fifth of the world's populations (Middleton and Thomas, 1997). Runoff in dryland regions has been less studied and therefore poorly understood compared to regions that are more humid. The climate in the dryland regions is inherently of higher variability, which, in turn, affects timing of runoff production and subsequently our predictability of water availability. With the ever-increasing human population in dryland regions, land use/land cover change from human activities is ranked among one of the greatest influences to water cycle. Some examples of land use/land cover change include conversion of natural rangeland to agricultural land or pasture, increased woody plant cover, increased invasive species, and urban development. Some researchers believe that the global impact of land use/land cover change on hydrologic cycle may surpass that of recent climate change (Vorosmarty *et al.*, 2004). In dryland regions, land use/land cover change has been associated with water availability

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This dissertation follows the style of *Hydrological Processes.*

for societal use and ecosystem functioning (Jobbagy and Jackson, 2004; Scanlon *et al.*, 2005; Walker *et al.*, 1993). As water availability is increasingly becoming a concern, a comprehensive study of runoff characteristics and the influence of land use/land cover change in dryland regions is therefore imperative.

Land use/land cover in western Texas has changed dramatically since European settlement about 200 years ago. The vegetation communities have experienced two major transformations: (1) conversion of original prairie into agricultural land (mainly for grazing and farming) , and (2) woody plant encroachment primarily due to heavy grazing and reduced frequency of wild fire (Archer *et al.*, 2001; Van Auken, 2000). Those changes in vegetation communities are often associated with significant but not well-understood disturbances in hydrological and biogeochemical processes (Archer *et al.*, 2001). As a semiarid to arid region, competition for water between societal use and ecosystem functioning is intensifying in western Texas. Understanding the interactions between water cycle and land cover at various scales is needed for better resources management.

The most observable change in watershed water budget associated with changes in land use/land cover is change in runoff into the stream. The linkage between land cover and streamflow has long been a debate (Andreassian, 2004). In humid or Mediterranean climates, studies have shown increases in streamflow following the removal of woody plants (Bosch and Hewlett, 1982;

Zhang *et al.*, 2001a). Such increase has been attributed to the reduction of evapotranspiration (ET) with less woody plant cover. In most semiarid and arid regions, the result is much less certain (Wilcox, 2002). Huxman et al. (2005) has pointed out that demonstrated increase in streamflow through woody plant removal tend to be site-specific and influenced strongly by climate pattern.

Although paired watershed studies enabled us to draw a general conclusion, many uncertainties exist for evaluating the relationship of land cover and streamflow production. Most experiments are conducted in small-scale watersheds. Extrapolation into a larger scale is difficult as different processes dominate at different scales. Few studies have examined watershed runoff mechanisms, which relate closely to watershed streamflow potential and response to vegetation management strategies. Studies intended to verify using long-term streamflow record are difficult and scarce. For example, one difficulty is how to separate climate variation from anthropogenic effects. In sum, studies that link small catchment study to large regional assessment are critically lacking.

Research Questions

In this study, we center on the basic research questions: is there a detectable change in streamflow following change in woody plant cover in drylands of western Texas? If so, what is the magnitude and at what scale can it manifest itself? We approach this question using experimental watershed study, isotopic characterization of runoff mechanisms, hydrochemical analysis to identify linkage of water pools in a watershed system, and historical precipitation-streamflow analysis at various spatial scales. In the watershed experiment, the presence of a baseflow component is emphasized and a comparison is done with a previous study in the same region where baseflow tends to be absent. The hydrochemical investigation further evaluates how an upland catchment is hydrologically related to the bottomland stream. In order to extend this study to a larger temporal and spatial scale, historical Hydroclimatological records are evaluated. The detailed analysis on an individual basin serves the purpose of a cause-effect investigation while the regional assessment further validates the cause-effect study and reveals spatial pattern of runoff dynamics.

Organization of Study

Chapter II describes the watershed experiment and isotopic investigation of runoff mechanisms. Chapter III presents the hydrochemical analysis in order to explore the hydrologic linkage between the upland and bottomland. Chapter IV is a detailed analysis of long-term precipitation-streamflow record for an individual basin. Chapter V extends precipitation-streamflow analysis to the regional scale. Chapter VI provides summary and conclusions.

CHAPTER II

EXPERIMENTAL STUDY OF RUNOFF AND VEGETATION INFLUENCE IN A SPRING-FED CATCHMENT*

Introduction

The linkage between woody plant cover and streamflow has been widely studied, particularly in humid landscapes (Zhang *et al.*, 2001a). Increases in streamflow following removal of tree cover in many environments have been broadly documented (Bosch and Hewlett, 1982; Stednick, 1996). In semiarid regions, such relationship has also been observed. Examples include chaparral shrublands in Arizona and California (Hibbert, 1983), eucalyptus shrublands in Australia (Walker *et al.*, 1993), and grassland in South Africa (Van Lill *et al.*, 1980). Similarly, Baker (1984) demonstrated a small but significant increase in streamflow following juniper removal on Arizona rangelands where streamflow is a function of snowmelt. However, such relationship is not universally applied. In many dryland regions, little if any relationship has been found between woody plant cover and streamflow (Wilcox, 2002).

There are compelling reasons to better understand the linkage between woody plants and streamflow. Many grasslands and savannas have been or are

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now being converted to woodlands in a process described as woody plant encroachment (Archer, 1994; Van Auken, 2000). Some have suggested that woody plant encroachment is directly contributing to lower streamflow in many of these landscapes (Wright *et al.*, 1990). Presumably, the major mechanisms for the decrease in streamflow are increases in transpiration as well as interception loss.

Woody plants and Ashe juniper in particular in western Texas can modify the water budget, at least at the scale of an individual tree. What is less certain is what the effect may be on larger scales. An individual tree or shrub can modify the movement of water in their immediate vicinity, through a variety of mechanisms, including (1) changing the infiltration characteristics of the soil; (2) redistributing incident precipitation by interception and stemflow funneling; (3) using water in the process of transpiration; and (5) developing root system to distribute and access soil water. For example, it is well known that the soil infiltration rates are higher in the woody canopy area than in the adjacent intercanopy areas (Bergkamp, 1998; Joffre and Rambal, 1993; Pierson *et al.*, 1994; Schlesinger *et al.*, 1999; Seyfried, 1991). Hester et al. (1997) found significantly higher infiltration rates under Ashe juniper trees than in the intercanopy areas. Owens and Lyons (2004) indicates that an Ashe juniper in the Edwards plateau region can intercept from around 20-100% of incident precipitation and a dense stand of Ashe juniper could use as much as 400 mm of water per year through interception and transpiration.

These modifications at individual tree level may not always translate into larger scales. For example, Dugas et al. (1998) using the Bowen Ratio-energy balance method found that over the entire five-year study period, Ashe juniper removal had no statistically significant effect on daily evapotranspiration. Similarly, results from a 13-year watershed study indicated that Ashe juniper removal has little or no influence on streamflow from first order streams where springs are absent (Wilcox *et al.*, 2005). However, the authors put forth a hypothesis that shrub control effect on streamflow may be observed where springs are present. Such reasoning concurs with the hierarchical conceptual model developed by Huxman et al. (2005). The model suggests woody plant cover will have an influence on streamflow in semiarid landscapes only if streamflow has a baseflow component. Baseflow is defined here as the portion of runoff that cannot be attributed to an individual precipitation event while stormflow is that portion of runoff that can.

Springs are not a common feature on most arid and semiarid landscapes. Largely due to its unique karst limestone geology where the underlying rocks exhibit many solution-enlarged openings such as sinkholes, caves, or fissures, the Edwards Plateau (62,156 km^2) of central-west Texas is one of regions that boasts numerous spring-fed streams as well as productive groundwater aquifers. Meanwhile, Ashe juniper, which has a large capacity to intercept and transpire water (Owens and Ansley, 1997; Owens and Lyons, 2004), has significantly increased in density and coverage in the last century. Those two interesting interacting factors suggest that there may indeed be a strong linkage between woody plant cover and streamflow.

One study that has documented an increase in spring flow following juniper removal was carried out on a 3.2-ha (7.9 acres) catchment in the Seco Creek watershed: Wright (1996) reported that spring flow increased from 11.8 L/min to 14.3 L/min (equivalent to about 40 mm on an annual basis) following removal of Ashe juniper. Although this study is commonly cited as proof that shrub control leads to increases in runoff, a limitation of the report is that the methodologies, calculations, and assumptions used are not described.

Although anecdotal accounts of increasing or decreasing spring flow related to changes in woody plant cover are abundant, little data exists concerning the magnitude or timing of such effects. To explore this issue further, we use hydrometric and isotopic analysis to quantify runoff dynamics and to estimate changes in streamflow following removal of about 60% of the Ashe juniper on the catchment.

Study Area

Our study area is located within the Honey Creek State Natural Area that is run by the Texas Parks and Wildlife Division. The focus of our study is a small (19 ha) catchment in the eastern portion of the Edwards Plateau in South Central Texas of the United States (29˚50’ N, 98˚29’ W). The catchment drains into the middle section of Honey Creek, a tributary of the Guadalupe River

(Figure 1). The elevation of the watershed ranges from 369 to 393 m above msl, with gentle to steep topography. The stream is intermittently fed by a spring flow as well as episodic runoff from rainfall events. Long-term average precipitation is 909 mm per year, based on an analysis of records from nearby National Oceanic and Atmospheric Administration weather stations at Boerne, Spring Branch, and New Braunfels, from year 1956 to 2002. Using the Malmstrom method (Malmstrom, 1969), we estimate that annual potential evapotranspiration (PET) is around 1200 mm. Precipitation in this region has bimodal distribution, with the first peak occurring around May to June and the second peak around September to October. The soils in this upland watershed belong to Brackett-Rock outcrop-Comfort complex. The surface layer is gravelly clay loam or extremely stony clay about 10 to 15 cm deep, intricately mixed with limestone outcrop. The subsoils extend to a depth of up to 50 cm (U.S. Department of Agriculture, 1984). As part of the Texas Parks and Wildlife Department's Honey Creek State Natural Area, access to this area is strictly restricted, so the disturbance of vegetation and soil is minimal.

Common woody species in this catchment include Ashe juniper, live oak (*Quercus virginiana*), vasey shin oak (*Q. pungens* var. *vaseyana*), and redberry juniper (*J. pinchotti*). The herbaceous vegetation includes a variety of forbs and a mixture of short and mid-height grasses with indiangrass (*Sorghastrum nutans*), little bluestem (*Schizachyrium* and *Andropogon* spp.), and switchgrass (*Panicum virgatum*) dominating.

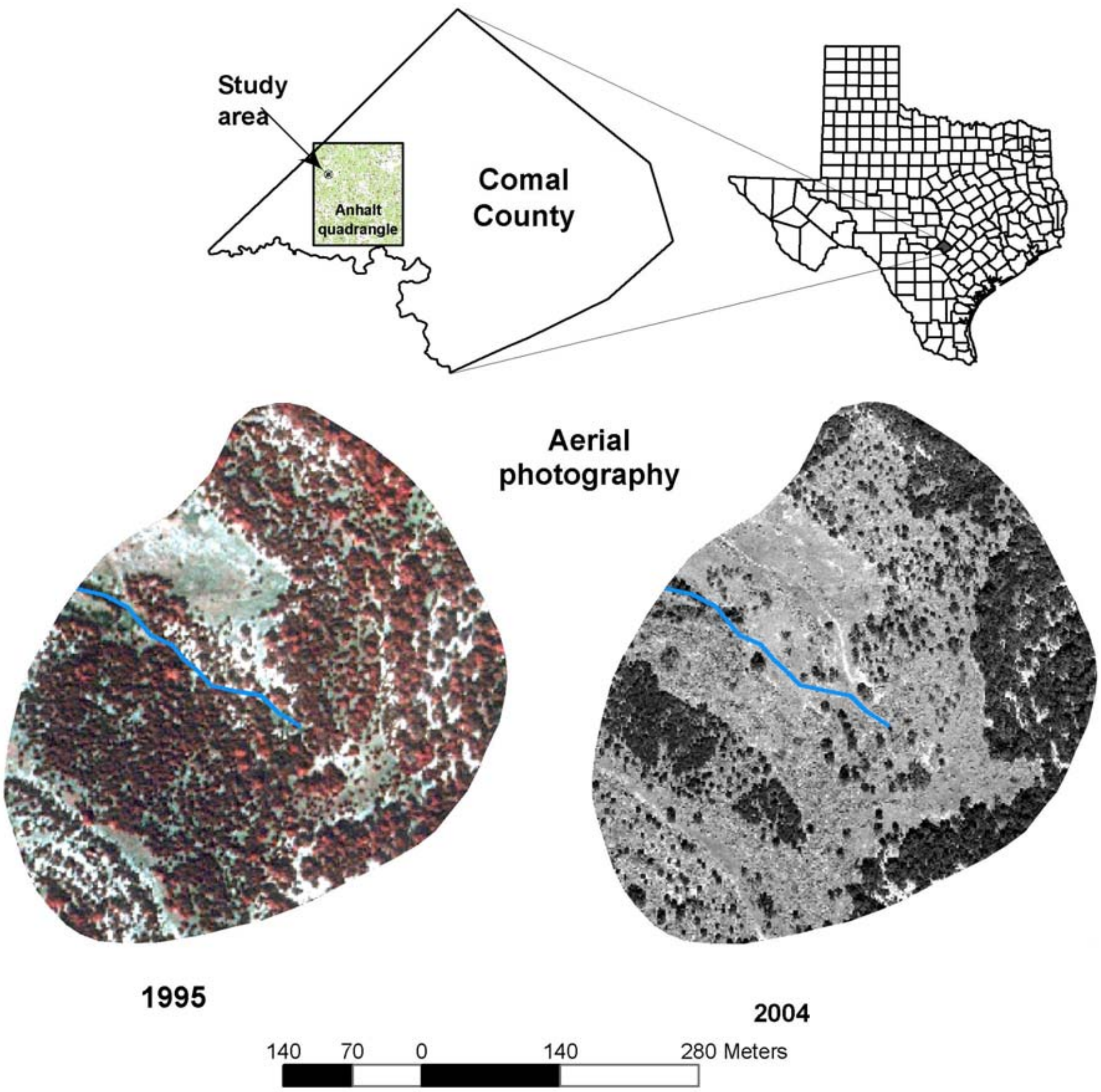

Figure 1. Location of the Honey Creek catchment study area within the Honey Creek State Natural Area. The green lines on the two images indicate the location of the main stream channel (the flume is located at the west end). The 1995 image (Texas Natural Resources Information System) shows the catchment before treatment and the 2004 image (P-2 Energy Solutions) shows it after treatment. Both are at a 1-m resolution.

Methods

Instrumentation and vegetation treatment

In May 1999, the Honey Creek catchment was instrumented with a 0.6-m (2-ft) H-flume (Plasti-Fab, Tualatin, Oregon) and a Campbell automated weather station, to record hourly streamflow and climate data. A Druck PDCR1830 pressure transducer was installed in the stilling well for the stage readings. The upstream drainage area of the catchment is about 19 ha, and its outlet is at an elevation of about 369 m above msl. Data collection began in late August of 1999 and continued for the next four years.

Before treatment, this catchment was about 90% woodland, dominated by Ashe juniper interspersed with live oak. In the summer of 2001, following two years of data collection, 60% of the catchment was cleared of Ashe juniper. Woody plants were left intact along the ridge top, on steep slopes, and along banks immediately adjacent to the stream channel. Selective cutting was done on the north and southwest hillslopes. The trees were removed by hydraulic shears attached to a small front-end loader, then piled in strips parallel to the slope. After treatment, the catchment was about 30% woodland, 20% mixed oak savanna, and 45% grasslands (Figure 1).

Data collection and datasets

A careful evaluation of discharge records indicated occasional abrupt increases in discharge in the absence of precipitation. We attributed these increases to instrument "drift" in the pressure transducer that recorded depth of water in the flume. On the assumption that the calibration slope of the pressure transducer did not change, we corrected the discharge records by deducting the additional amount from the recorded stream-depth data set. When our corrected data set was compared with a set of manual measurements taken in the later part of the study, the match was good (Figure 2).

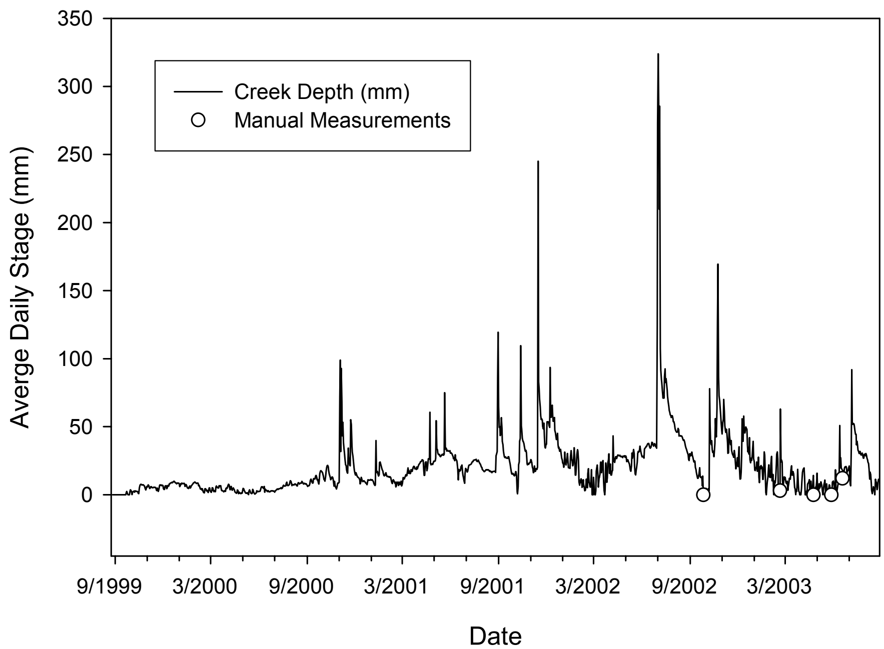

Figure 2. Daily mean stream depths, as corrected, compared with depths of manual measurements.

In the entire four years data set, information for two days is missing: 30-31 August 2002. The daily runoff values of those two days were fitted using average values of 29 August and 1 September 2002. Daily precipitation values were fitted using precipitation record of two nearby stations, Spring Branch and Boerne, both of which are maintained by NOAA. Part of the rainfall record, from 16 December 2002 to 7 February 2004, was checked against independent measurements by another research party (Keith Owens, Personal communication, 2004) in an adjacent location. The correlation of those two measurements has slope 0.99, and the coefficient of determination is 0.92 on hourly-based data. Correspondence was also checked by visual inspection of two time series plots. All checks indicate strong agreement of two data sets.

Event-based regression

In this study, we assess the influence of woody plant cover using a single-watershed approach, which has been used in many studies (Chang and Sayok, 1990; Potts, 1984; Trimble *et al.*, 1987). A paired or multiple watershed approach is preferable but was not feasible in this study, primarily because there were no other comparable catchments within the Honey Creek State Natural Area with springs supplemented streamflow. Reviews of paired basin experiments can be found in Bosch and Hewlett (1982) and Robinson (2003).

Common analysis methods for single watershed study include double-mass analysis (Potts, 1984), presentation of runoff/precipitation ratio (Pitt *et al.*, 1978), developing hydroclimatic calibration equation (Chang and Sayok, 1990), and regression analysis (Trimble *et al.*, 1987). In this study, we develop an event-based regression model to detect any change in streamflow following the treatment. Such event-based regression model is especially suited for situation when short time observation data are available.

In using an event-based regression model, we identified 80 storm events in the entire study period, with 43 in pre-treatment period and 37 in post-treatment period. On and off daily rain are considered continuous and grouped as one storm event unless they are five days apart. For example, daily rainfall amount series (in mm) 16, 0, 22, 41, 0, 0, 0, 10 are grouped as one event since "no-rain-days" were three in that series, while the series 19, 27, 0, 0, 0, 0, 0, 0, 5, 37 is grouped as two separated events since "no-rain-days" were six in the series. Runoff for the storm event is the sum of daily value from the first day of the storm until the first day of the next storm. The choice of five-day interval represents a balance of the storm characteristics and limited residual effects from this event to next event.

Both rainfall and runoff data were transformed using natural logarithmic model. Test statistics indicated that transformed data met the regression assumptions including homoscedasticity and gave the best distribution of data points along the entire range of the regression. Analysis of covariance (ANCOVA) model with simple linear regressions for pre-treatment period and post-treatment period is shown in formula (1).

$$\log_e Y_i = b_{0i} + b_1 \log_e X_i + \varepsilon \qquad (1)$$

where Y_i and X_i represent the runoff and rainfall on the per-event basis in the i^{th} treatment period. All statistical tests were performed at significance level of 0.1. Bias correction in retransformation to the original scale was carried out using Duan's smearing estimate (Duan, 1983). Data from the first nine month of the first observation year (late August 1999 to late August 2000) were not included in the regression analysis because the first six month was extremely dry; and data from an enormous rainfall event in late June to early July 2002 were excluded as well, to avoid the high leveraging effect such a large runoff-producing event would have.

Baseflow analysis

Baseflow provides a more consistent supply for aquatic productivity and human consumption. Increases in baseflow also reflect direct influence of evapotranspiration reduction following the removal of woody plants, if such reduction is significant. In other words, the reduced evapotranspiration following woody plant removal should be reflected in higher baseflow rather than stormflow. Changes in stormflow, either increases or decreases are likely a reflection in infiltration characteristics of the catchment that have resulted from the treatment itself. For this reason, it is useful and important to separate baseflow from stormflow. Baseflow separation was accomplished using an automated baseflow filter (Arnold and Allen, 1999; Arnold *et al.*, 1995).

Isotope analysis

Natural stable isotope tracers have been widely used to clarify runoff generation in various environments (Kendall and McDonnell, 1998). One method that has proved very useful—particularly in humid landscapes—is hydrograph separation. This method is based on the fact that individual precipitation events (event water) often exhibit a ratio of naturally occurring isotopes, such as oxygen-18 and deuterium, different from that of groundwater and soil water—the sources of pre-event water (Buttle, 1994).

Monitoring of naturally occurring isotopes in precipitation and streamflow did not begin until after the vegetation treatment. In 2003 and 2004, baseflow was sampled for ^{18}O analysis at intervals ranging from weekly to monthly, to characterize its temporal variation—including differences in isotopic composition at different flow rates. Concurrently, aggregate samples of precipitation for the same time period were sampled from a bucket collector (similar to that used by Newman et al. (1998) to prevent evaporation). An ISCO® automatic sampler coupled with a flow meter was used for more detailed sampling during four distinct storm events. Samples were taken at intervals of 20, 30, and 40 minutes, and more frequently during the rising limb of the hydrograph and during peak flows. All samples were refrigerated in sealed, full bottles until analyzed.

Hydrograph separations were done for two of the four events: one on 20 February 2003 (22 samples) and one on 27 June 2004 (26 samples). For both of these, the separations yielded clearly distinguishable $\delta^{18}O$ signatures for the event vs the pre-event water. The $\delta^{18}O$ isotope values were measured by the standard CO_2-water equilibrator, interfaced with a Prism II isotope ratio mass spectrometer, at the University of Texas (Austin) and are expressed in terms of

V-SMOW (Vienna Standard Mean Ocean Water) (Coplen, 1988). The analytical precision of the $\delta^{18}O$ measurements is 0.14‰ at a 95% confidence level, based on analyses of laboratory standards and duplicate samples.

Hydrograph separation into event and pre-event components is based on the following mass balance and mixing equations (Buttle, 1994):

$$Q_t = Q_p + Q_e \qquad (2)$$

$$C_tQ_t = C_pQ_p + C_eQ_e \qquad (3)$$

$$f = (C_t - C_e) / (C_p - C_e) \qquad (4)$$

where Q_t is the total streamflow during an event; Q_p and Q_e are contributions from pre-event and event water; C_t, C_p, and C_e are the isotopic compositions of streamflow, pre-event water, and event water, respectively; and f is the contribution of pre-event water to total streamflow.

Runoff Dynamics

The comparison of annual precipitation and runoff shown in Table 1 is based on the monitoring year (late August–late August) instead of the calendar year. The average annual precipitation was 832 mm, the minimum recorded being 433 mm and the maximum 1,270 mm. The average annual runoff was 180 mm (minimum of 16 mm and maximum of 431 mm), or about 22% of precipitation on average (varying from 4% to 34%, depending on the year). Baseflow made up about 50% of total runoff.

Table 1. Summary of annual hydrologic data for Honey Creek upland catchment.

Treatment period	Duration	Precipitation (mm)	Runoff (mm)	Baseflow (mm)	Maximum daily runoff (mm)	Runoff ratio	T (˚C)
Pre	9/99 to 8/00	433	16	12	0.1	0.04	20.5
	9/00 to 8/01	852	121	67	11.3	0.14	19.0
Post	9/01 to 8/02[a]	1270	431	177	53.1	0.34	19.2
	9/02 to 8/03	774	150	85	14.3	0.19	18.8

[a] When the largest event was excluded, total runoff and baseflow for this record year were 171 and 83 mm, respectively.

Higher amounts of stormflow resulted in proportionally higher runoff. In 1999, the first year of the study, maximum daily runoff was only 0.1 mm (Table 1). In contrast, on 1 July 2002, 53 mm of runoff was measured—the largest amount recorded for a single day. It was produced by an extreme flood event that began on 29 June 2002 and continued on and off for about 20 days, ending on 15 July 2002. Total precipitation during this period was 546 mm, of which 482 mm fell in the first week (Figure 3). The flume was overtopped during the flood peak, causing runoff to be underestimated. Over the 20 days, storm runoff was at least 260 mm, which accounted for 60% of the runoff in that year and 47% of the precipitation measured during this flood event. The elevated baseflow lasted more than 16 days after the storm had ended.

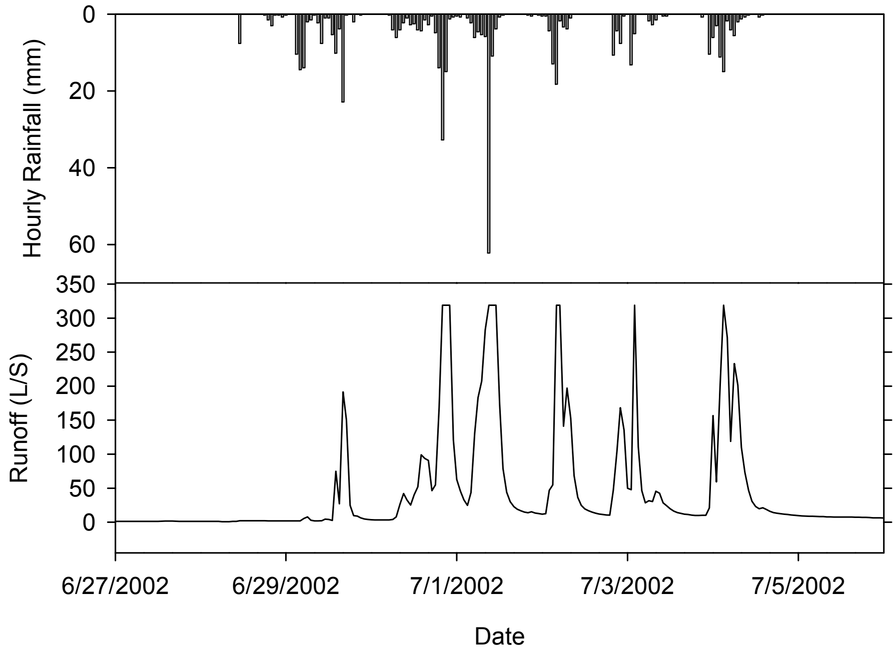

Figure 3. Hourly hydrograph of the largest precipitation event (June–July 2002) recorded during the 4-year study.

As shown in Figure 4, large runoff events accounted for most of the runoff. Top 5% of runoff events contributed to half of total runoff. Top 20% of runoff events accounted for 80% of total runoff. Small precipitation events generate only a small amount of runoff. Even if we exclude the largest event of June 2002, similar analysis indicates that half of runoff comes from top 10% of runoff events.

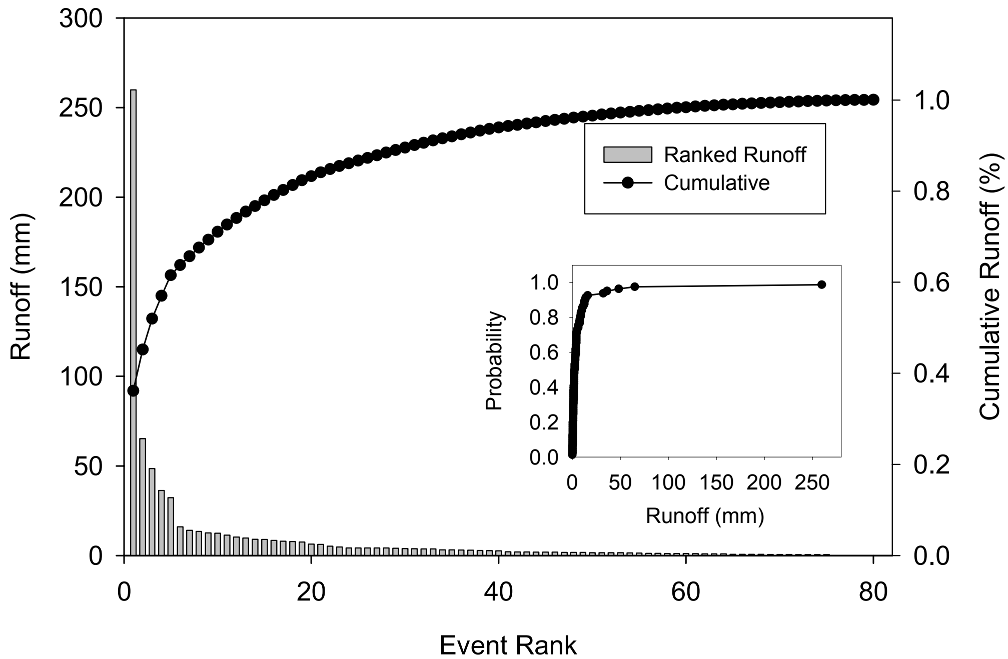

Figure 4. Runoff events distribution during the study period (August 1999–August 2003). The events are ranked by magnitude.

Components of runoff

Figure 5 illustrates the isotopic composition of the runoff, as measured from baseflow (pre-event water) and precipitation (event water) samples collected over an 18-month period. The isotopic composition of the rainfall was highly variable and exhibited little seasonal trend. Precipitation $\delta^{18}O$ values ranged from –1.41 to –7.14‰, with a mean of –4.05‰ and a coefficient of variation of 40%. This little seasonal trend is consistent with findings from isotope analysis of precipitation samples collected weekly at the National Atmospheric Deposition Program (NADP) sites (Welker, 2000).

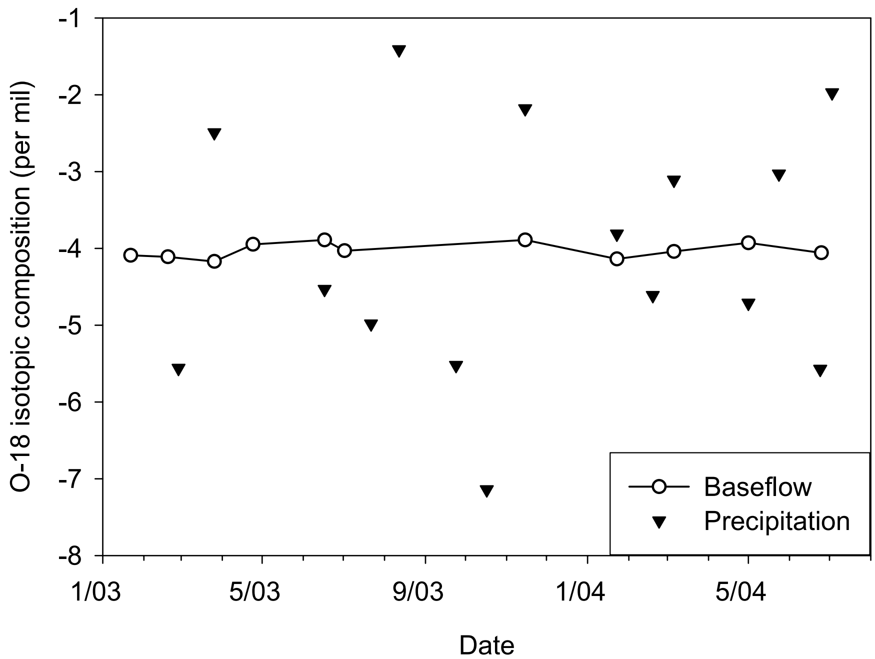

Figure 5. Time series of the ^{18}O isotopic compositions of baseflow and precipitation at the study area. Most samples were collected roughly at monthly intervals.

Baseflow isotopic composition was very consistent throughout the sampling period, especially considering that the samples were taken under different flow rates. The $\delta^{18}O$ values ranged from –3.82 to –4.17‰, with a mean of –4.00‰ and a coefficient of variation of 2.7%. As shown in Figure 5, this composition approximates the mean value for precipitation. For hydrograph separation, this consistency allows us to assume that the isotopic composition of a baseflow sample taken before a storm event will be representative of the isotopic composition of pre-event water throughout the event.

As mentioned above, hydrograph separations were done for two storm events. The findings were as follows:

Winter storm (20 February 2003): The baseflow sample used was collected one day before this storm. Precipitation during the two months preceding the storm event had totaled 55 mm – 42 mm between 20 December 2002 and 20 January 2003; and 13 mm between 20 January and 20 February. The total rainfall for the storm was 48 mm over 15 hours, and the highest intensity was 19 mm/hr. The runoff response was rapid, and the peak rate measured was 133 L/s (Figure 6a). Pre-event water contributed only about 41% of peak flow, but accounted for about 46% of hydrograph volume. In this region, storms of this magnitude occur with a frequency of just under once per year.

Summer storm (27 June 2004): Precipitation during the two months preceding this storm event had totaled 271 mm – 228 mm between 27 April and 27 May 2004; and 43 mm between 27 May and 27 June. The total rainfall for the storm was 45 mm, the bulk of which fell within 4 hours. The highest intensity was 27 mm/hr, and the peak runoff rate was 118 L/s. Only 20% of total flow at the runoff peak consisted of pre-event water. Volumetrically, pre-event water formed about 16% of the event hydrograph (Figure 6b).

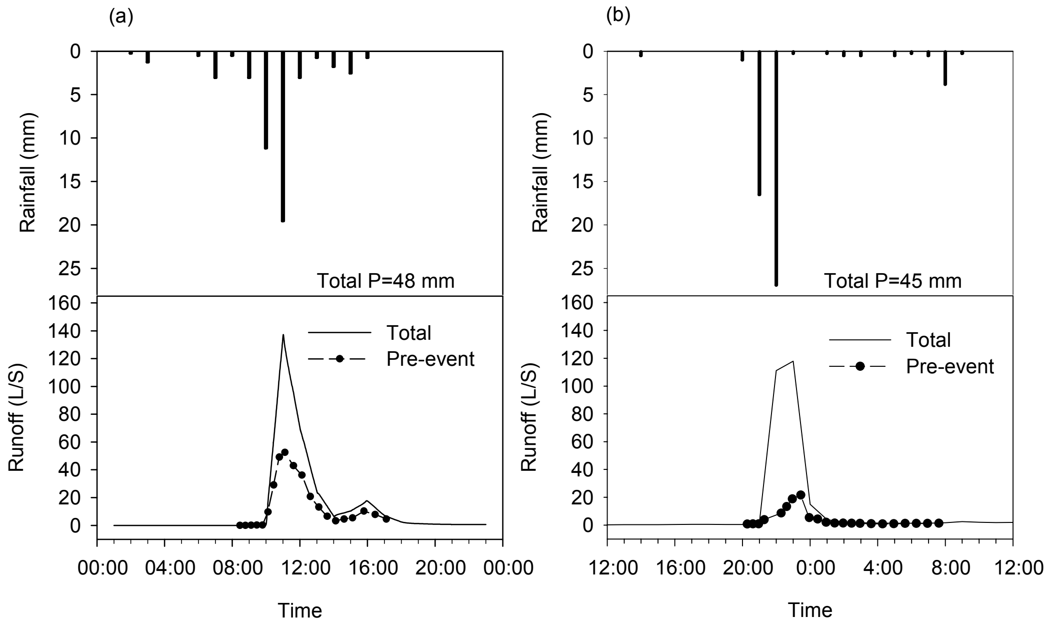

Figure 6. O-18 isotope hydrograph separation. (a) a winter event (20 February 2003) and (b) a summer event (27 June 2004).

Influence of Woody Plants

Regression and baseflow analysis

The event-based regression analysis (Figure 7) indicates that the slope in pre-treatment period was not significantly different from that in post-treatment period (p=0.64). The subsequent Tukey-Kramer (Kramer, 1956) test indicates significant difference in covariate adjusted streamflow between those two periods (p=0.04). On the per event basis, the adjusted treatment means for pre-treatment period and post-treatment period are 5.5 mm and 8.8 mm, respectively, indicating a 60% increase in streamflow after treatment.

To evaluate potential seasonal differences, we did event-based regression analysis separately for summer events and non-summer events—the rationale being that high-intensity, short-duration rainfall is more common in the summer. The Tukey-Kramer test did not detect significant difference for the summer events (p=0.61), but were significant (p=0.02) for non-summer events. On the basis of these regression relationships, we anticipate that removal of juniper will increase streamflow at this site by around 46 mm annually, representing about 5% of precipitation.

In the baseflow analysis, the values were reported using the fractions from the second backward pass of the filter. Forty-seven percent of total runoff in the study period is classified as baseflow (Table 1). In the year with above average precipitation, direct runoff is proportionally higher. When using the same period as in treatment effect analysis above and excluding the largest event, baseflow accounted for 55% of total runoff in the pre-treatment period, while 53% in the post-treatment period. In another word, baseflow increased proportionally following treatment, the direct runoff increase is slightly higher though.

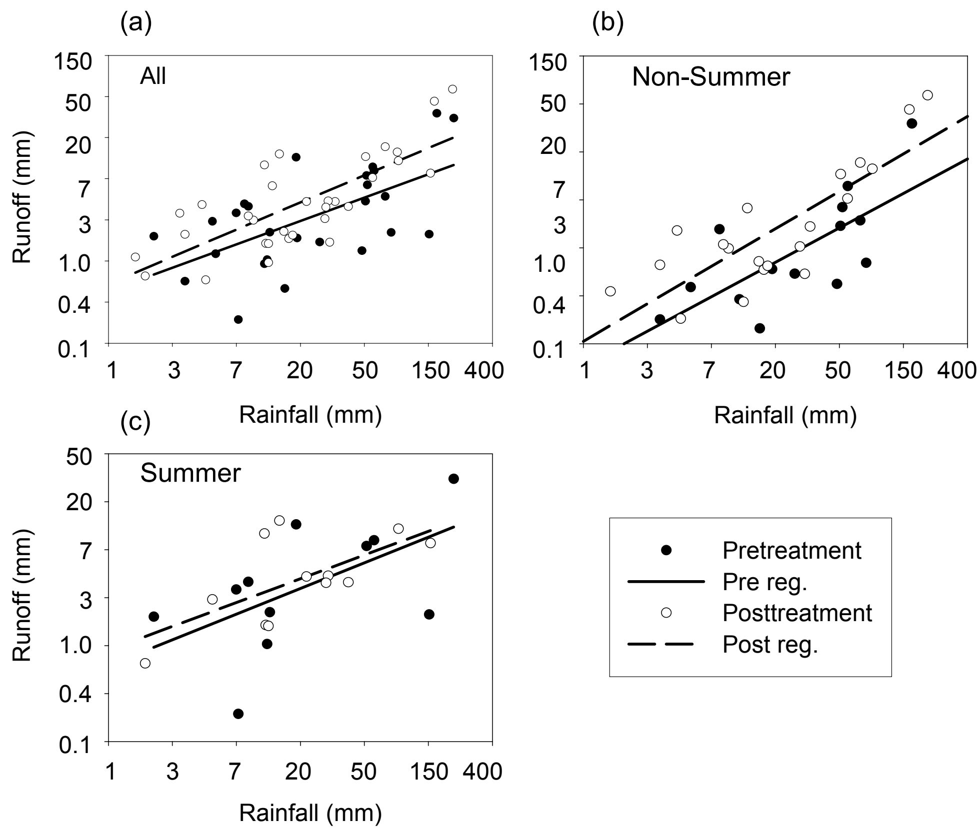

Figure 7. Event-based regression plot of runoff amount versus rainfall amount. The plots are in natural log scale. (a) 3 1/4 years of data (the largest event of the post-treatment period was not included); (b) non-summer events (events occurring between October and April); and (c) summer events (events occurring between May and September).

Discussion

We found that at our study site, runoff contributed significantly to the water budget – ranging from as little as 4% to as much as 34% and averaging about 22% over four years of observation. The baseflow to stormflow ratio was about 50/50.

The hydrograph separation analyses provided important clues concerning the relative importance of soil water/groundwater during stormflow events. The analysis of the winter storm described above indicates that for storms of longer duration and lower intensity, pre-event water makes up at least 50% of the runoff. Although Buttle (1994) emphasized that one must exercise caution in using hydrograph separation for determining source areas, it is likely that at our site the pre-event water and the spring flow have the same source area. This being the case, estimates of pre-event water provide at least a lower limit for contributions from the spring during storm runoff. For the summer (higher intensity) storm, pre-event water was lower, but still accounted for 25% of the runoff.

A few other hydrograph separation studies have been conducted in water limited environments – the majority in locations having Mediterranean or otherwise winter-dominated moisture regimes. Most of these studies found that pre-event waters dominate storm runoff. Nolan and Hill (1990), working on a 10.6-km^2 chaparral watershed in California where annual precipitation varied from 400 to 800 mm (depending on elevation), reported that pre-event water accounted for more than 57% of storm runoff. Neal et al. (1992), working in two oak-forest locations in Catalonia, Spain (with annual precipitation of 870 and 658 mm), reported that storm runoff was mostly pre-event water. Similarly, Taha et al. (1997) reported that storm hydrographs for an oak-forest catchment in the south of France consisted of up to 80% pre-event subsurface water. Sandstrom

(1996), in a study of forested and degraded catchments in semiarid tropical Tanzania, found that contributions from a soil's saturated zone made up only 25% of the total discharge (the main mechanisms of runoff generation at this site were overland flow and throughflow; rainfall occurs primarily during winter and averages 807 mm/yr).

Our results here show both similarities to and differences from those of an earlier study by Wilcox et al. (2005), on the Annandale Ranch in the western part of the Edwards Plateau. They examined streamflow–woody plant cover relationships by monitoring first-order catchments without springs. One similarity is that for both types of systems – first-order catchments with springs and those without – the bulk of the runoff is generated by a few large, flood-producing precipitation events. A difference is that runoff/precipitation ratios from spring-fed catchments are higher than those from catchments without springs. For example, runoff at the Annandale Ranch accounted for less than 5% of the precipitation. Another difference is that Wilcox et al. (2005) observed that in the absence of spring flow and major surface disturbance, changes in woody plant cover had a minimal effect on streamflow. In contrast, the Honey Creek catchment study suggests that where springs are present, streamflow in first-order catchments can be augmented through woody plant removal. Following the removal of approximately 60% of the Ashe juniper in the catchment, streamflow increased – though most significantly only for non-summer events.

Our results, augmented by the hydrograph separation analyses, are consistent with the hypothesis that the decrease in evaporative demand brought about by woody plant removal increases the contribution from groundwater or spring flow. An alternative hypothesis is that surface disturbances created during wood plant removal facilitate greater surface runoff/overland flow, and thus higher streamflow. But if this were a contributing mechanism, we would expect to see higher streamflow during summer events, which we did not.

These findings are important because they corroborate as well as constrain the numerous but poorly documented accounts of enhanced spring or seep flow following reduction of Ashe juniper. The only other work reporting an increase in spring flow following partial removal of Ashe juniper is an unpublished study by Wright (1996), who reported increases in flow of about 40 mm/yr, or 5% of annual precipitation. However, the work of Dugas et al. (1998) on evapotranspiration yielded some relevant data: their finding that evapotranspiration rates were about 40 mm/yr less for sites cleared of Ashe juniper is consistent with our observation that streamflow increased by approximately 46 mm/yr.

From overall water budget in our study, about half runoff came from baseflow. Such dichotomy suggested equal importance of surface runoff and shallow subsurface runoff in this region. Changes in baseflow following forest treatment have been reported in some literature. Some studies have shown that runoff peaks from major storms in a clear-cut watershed are not significantly increased (Harr *et al.*, 1982; Wright *et al.*, 1990). Keppler and Ziemer (1990) found that relative increase in runoff following logging were greater for the summer low-flow period than for annual flows through the experiment at Caspar Creek in northwestern California, the United States. In our study, the relative increase in baseflow was also high, indicating possible fundamental changes in soil water storage.

Conclusions

Runoff from this spring-fed catchment contributed about 22% of water budget on average over four years of observation. The baseflow to stormflow ratio was about 50/50. Half of total runoff was contributed by 5% of runoff events. The isotope analysis indicates about 40% of pre-event water in winter runoff production and 16% in summer storm. The vegetation treatment effect were significant for the non-summer events, but not detectable for the summer events. On the annual basis, the increase in runoff due to vegetation treatment is about 46 mm.

On the basis of our study results and those of related work, we estimate that in the Edwards Plateau region, reduction of woody plant cover can increase streamflow and/or groundwater recharge at the first order catchment scale by about 5% of annual precipitation for average or above average years. Many questions remain however. For example, how long will these increases persist following treatment? How variable are results with climate and location? And finally, to what extent do these results scale up? These questions can only be answered from larger scale and longer duration studies.

CHAPTER III

HYDROCHEMICAL EVIDENCES OF STORAGE AND FLUX BETWEEN UPLAND AND BOTTOMLAND

Introduction

Subsurface flow is often assumed to be unimportant as a runoff-generation mechanism in semiarid landscapes, and for this reason has been relatively little investigated. But not only has subsurface flow been documented in these regions, it may occur more often than previously thought (Beven 2001). For example, shallow subsurface flow is important in semiarid ponderosa pine forests of New Mexico (Newman *et al.*, 1998; Wilcox *et al.*, 1997). Its most obvious indicator is the presence of seeps, springs, and/or flowing streams. When springs are found in a semiarid setting, they typically are associated with a relatively permeable underlying rock (either fractured or weathered by dissolution).

The extensive karst highland in Central Texas known as the Edwards Plateau is a prominent example of a semiarid-climate region that supports perennial rivers, extensive groundwater aquifers, and numerous springs—primarily because the soils are very shallow (and thus have little water-storage capacity), while at the same time much of the limestone and dolomite parent material is relatively permeable. As is typical of karst landscapes, the coupling between surface water and groundwater on the Edwards Plateau is extremely close: the regionally important Edwards Aquifer is recharged primarily by streamflow originating from the Plateau (Maclay, 1995). However, little is known about the hydrologic connection between upland and bottomland in this environment other than surface runoff connection. Seeking such information is important in many ways. For example, in estimating recharge to the Edwards Aquifer, how much is due to stream transmission losses and how much comes directly from the upland surfaces are essentially unknown. For another example, in evaluating how change in vegetation could alter local and regional hydrology, which one should we target, riparian vegetation or upland vegetation, if vegetation treatment could enhance streamflow.

Tracer or hydrochemical studies are preferred choice to study the hydrologic connection between upland and bottomland where physical measurements are often hard to obtain. One tool that is increasingly being adopted in hydrological research is long-term monitoring of isotope behavior in hydrological pools (Dewalle *et al.*, 1997; Soulsby *et al.*, 2000; Unnikrishna *et al.*, 2002; Vitvar *et al.*, 2002). Such long-term monitoring data can be used to examine intra- and inter-annual variability in hydrological processes, to analyze water mixing behavior or flow patterns in complicated hydrological systems, and to estimate water residence times in major hydrological stores (Maloszewski *et al.*, 1992; McGuire *et al.*, 2002; Winston and Criss, 2004). The temperature and chemical parameters of water can be also used to elucidate sources or pathways of the flow. Shuster and White (1971) classified springs into conduit type and diffuse type based on seasonal temperature variation; Newman et al. (1997) used stable isotope and other chemical tracers to estimate near-surface water fluxes in northern New Mexico.

The objective of this study is to evaluate the hydrologic connection between upland and bottomland, and the storage behavior in the Edwards Plateau region by monitoring streamwater chemistry for an upland catchment and a bottomland creek to which the upland catchment contributes runoff.

Study Site

Honey Creek, a tributary of the Guadalupe River, is located in western Comal County in the eastern portion of the Edwards Plateau (Figure 8). It is a perennial stream fed by active springs as well as episodic runoff from rainfall events. Long-term average precipitation in the Honey Creek watershed is about 900 mm/yr and is bimodally distributed, the first peak occurring around May and the second around September. Potential evapotranspiration (PET) averages 1200 mm, and the long-term annual average temperature is about 20˚C (Larkin and Bomar, 1983). The predominant geologic unit in this area is Glenn Rose Limestone. Along with Hensel Sand, this limestone forms the Trinity Aquifer

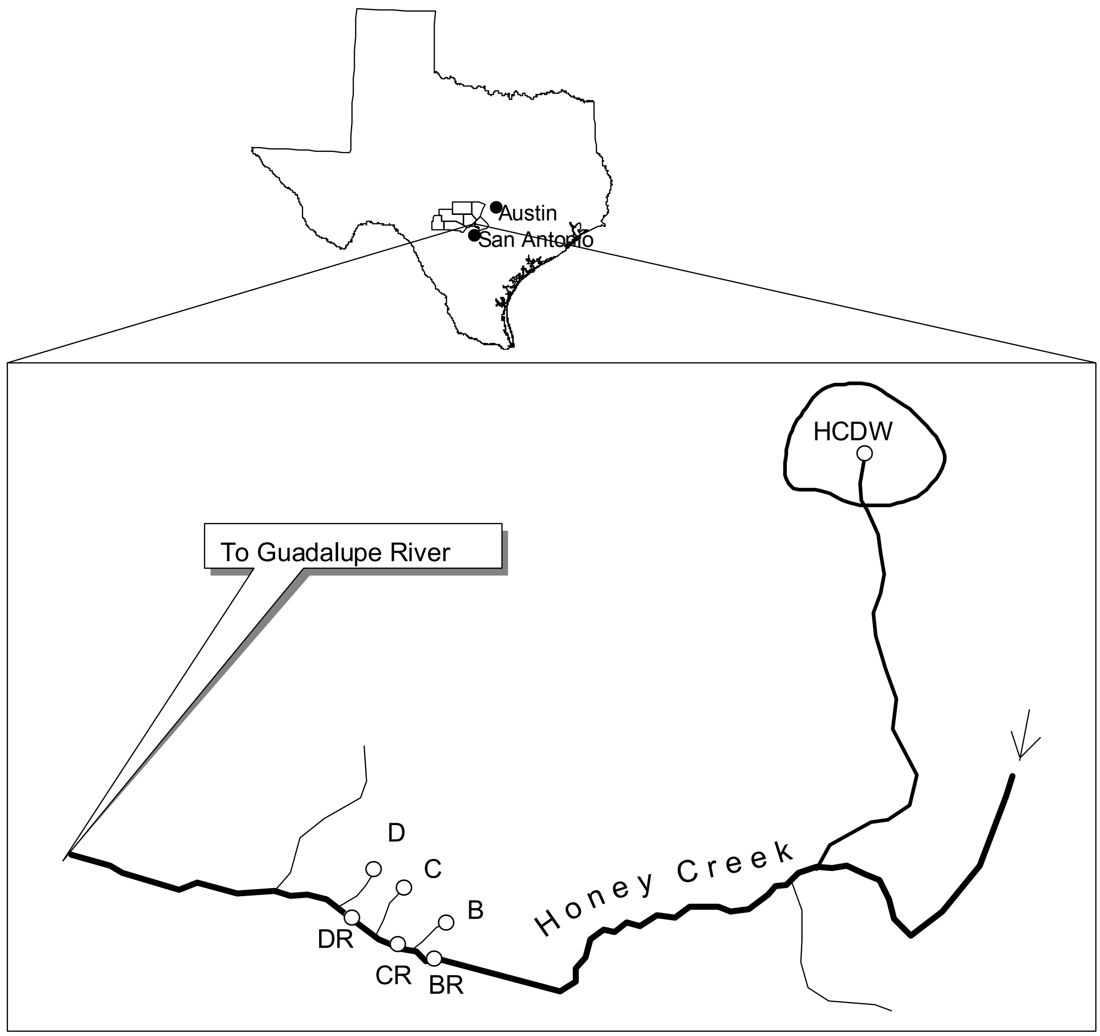

Figure 8. Diagram of the sampling locations in Honey Creek watershed system. B, C, and D are spring locations. B = Bravo, C = Cotton, and D = Delta. BR, CR, and DR are creek sampling locations, upstream of each spring location. HCDW = Honey Creek upland catchment, where the seeps are sampled.

(Ashworth, 1983). Our study area is within the Trinity Aquifer's recharge zone. Because part of Trinity Aquifer contributes recharge to the Edwards Aquifer via inter-formational flow, the area is therefore also considered part of the Edwards Aquifer contributing zone as well (Mace *et al.*, 2000).

The soils of the Honey Creek watershed are classified as the Anhalt, Denton, Doss, Eckrant, and Comfort soil series. They range from shallow (less than 20 cm deep) to moderately deep (70–130 cm). Limestone beds outcrop on sideslopes and backslopes of upland areas (U.S. Department of Agriculture, 1984).

Common woody species in the upland area include Ashe juniper, live oak (*Quercus virginiana*), vasey shin oak (*Q. pungens* var. *vaseyana*), and redberry juniper (*J. pinchotti*). Further down into the canyon of the creek itself, there is an increased presence of cedar elm (*Ulmus crassifolia*) and old-growth junipers. Along the creek, Bald Cypress (*Taxodium distichum*) growth is noteworthy.

Methods

Selected physical and chemical attributes, including ^{18}O isotopic composition, were determined at a bottomland site and an upland site (Figure 8), as follows**:**

(1) Bottomland sampling site includes three major springs that discharge into Honey Creek along the east bank of the creek and the creek itself. The three major springs are labeled as the Bravo, Cotton, and Delta springs. The

largest spring in the upstream of the Bravo spring feeding the creek could not be sampled because of restricted access of private land. The maximum difference in elevation among the discharge points of the three springs sampled is about 3 m. For a given spring, the sampling point could vary as much as 1 m in elevation because of seasonal variations in flow rate. Honey Creek itself was sampled at three locations, one upstream of each of the sampled spring location.

(2) Upland seeps within the Honey Creek upland catchment were sampled along the channel of the catchment. The difference in elevation between these upland seeps and the sampled springs along the bottomland creek is approximately 50 m.

Sampling at all locations took place at an interval of approximately one month, by the grab method. A Hanna® portable meter was used to measure temperature, pH, and electrical conductivity in the field. The probe was immersed in the running water at the sampling location and the reading was taken after stabilization. The meter was calibrated in the lab before each field session. A water sample was taken at the same time at each location. All samples were then refrigerated in sealed, full bottles until isotopic analysis.

Baseflow residence time is evaluated using Frederickson and Criss (1999) linear reservoir model. According to this model, the isotopic variation of baseflow is explained by a simple exponential weighting of the preexisting rainfall events, with more recent rains having a greater proportional influences than earlier rainfall events.

$$\delta^{18}O_{flow} = \Sigma\delta_i P_i \exp(-t_i/\tau) \,/\, \Sigma P_i \exp(-t_i/\tau) \qquad (5)$$

where δ_i and P_i are the isotopic composition and amount of rainfall for a given event. t_i is the time interval between the storm and the baseflow sample, exp(x) is the exponential function and τ is the residence time. Equation (5) is evaluated for estimated values of τ until the calculated curve from the precipitation measurements converges on the actual values measured in the baseflow.

Results

The mean temperature, pH, electrical conductivity, and ^{18}O isotopic composition of water from the three locations sampled are summarized in Figure 9. All the measurements are tabulated in Appendix A (Table A-1 to A-7). Water from the springs exhibited a very steady temperature year-round, whereas that from the seeps showed the highest seasonal temperature variation. Water from the creek and water from the seeps both displayed an annual cold–warm cycle.

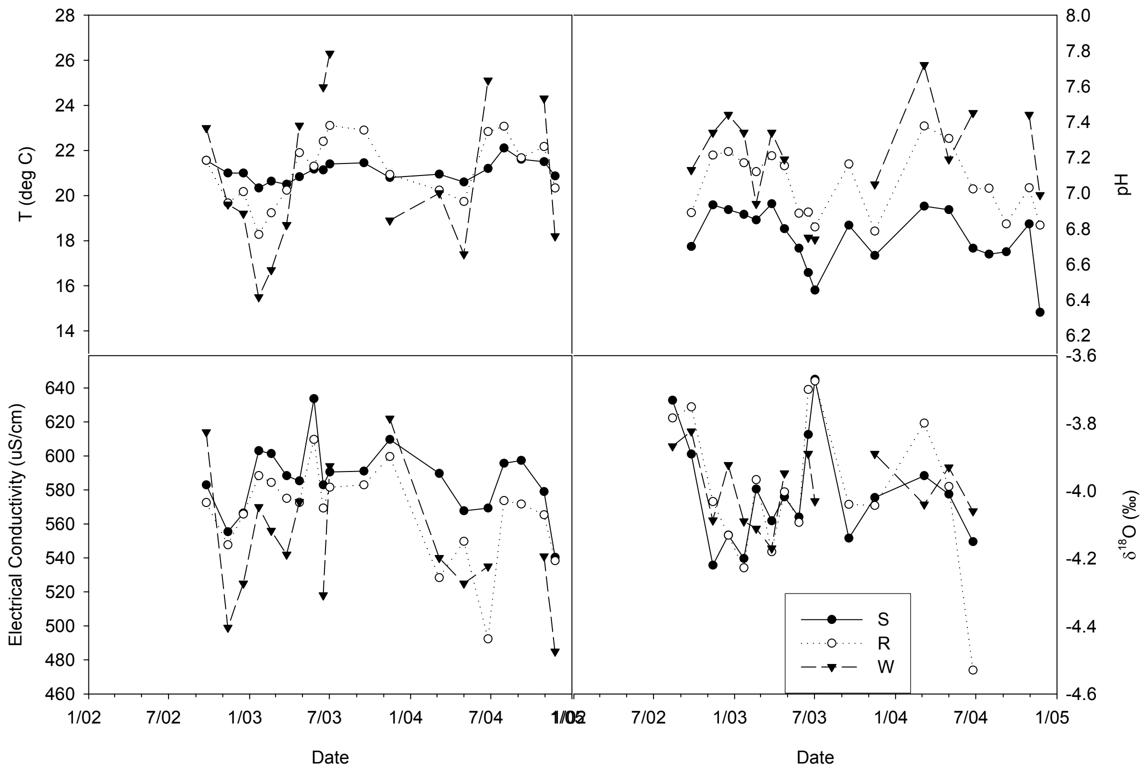

Figure 9. Average pH, electrical conductivity, temperature, and $\delta^{18}O$ for all the sampling locations. They are: three springs (S) feeding the creek, three sampling location of the creek (R), and the seeps from the upland catchment (W).

The overall mean temperatures of the water samples from the springs, the creek, and the seeps are summarized in Table 2. The mean temperatures are not significantly different when one considers the variability observed in the temperatures of the seep water and the creek water – all are close to the long-term average annual air temperature. For the spring water, this also indicates that the circulation depth of the associated groundwater source is limited.

Table 2. Group means of pH, electrical conductivity, temperature, and $\delta^{18}O$ of water samples from the springs, the creek, and the seeps for the sampling period at Honey Creek watershed.

	T (°C)	pH	EC (µS/cm)	$\delta^{18}O$ (‰)
The springs	21.1	6.75	586	-4.02
The creek	21.3	7.04	571	-3.99
The seeps	20.7	7.20	549	-4.00

Note: the mean $\delta^{18}O$ of precipitation is -4.05‰

Field observations showed clearly that the spring flows are highly variable seasonally: much reduced (or even absent at the higher discharge points) during dry months, and quite abundant during wet months. Steady temperature and variable discharge of the springs indicate that there is a fast component of recharge to these springs and the mixing in the groundwater storage is very efficient. Lag time between the time of significant precipitation until initial hydrograph response of the springs is generally within 24 hours from our field observations.

Electrical conductivity and pH show similar temporal trends among three locations. However, seep waters generally have higher pH than the creek waters, while the spring flows have the lowest pH values. The electrical conductivity, on the other hand, is higher for the spring flows than for the creek waters, while the seep waters are generally the lowest. In contrast, virtually no difference was observed in the temporal trend of ^{18}O isotopic composition among those three groups, and the differences between them are small for any given sampling event.

Further comparisons between the water from the springs and the seeps are illustrated in Figure 10. Both classes have undergone a varied degree of underground processes. Within-group variation of all the parameters is very small for the spring samples, indicating the three springs are very likely coming from the same water source. This water source is chemically different from water source of the upland seeps.

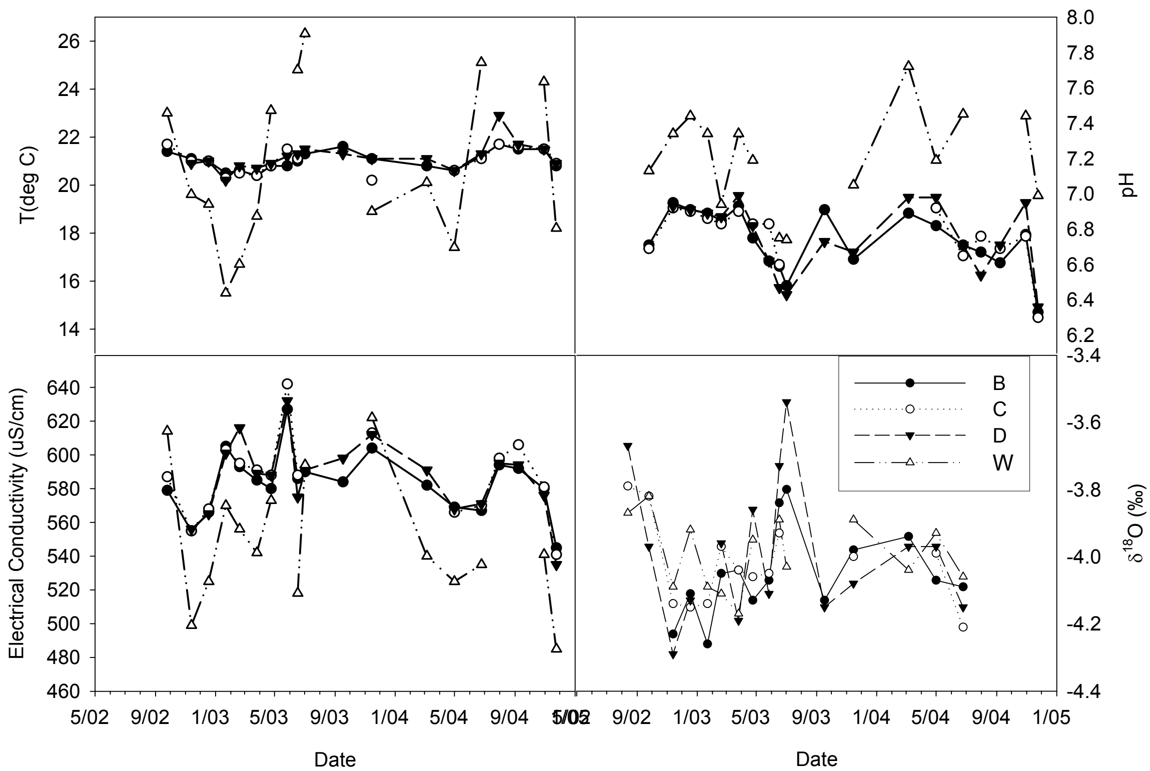

Figure 10. Hydrochemical parameters (pH, Electrical conductivity, temperature, and $\delta^{18}O$) from springs along the bottomland creek and seeps from upland catchment. B=Bravo spring, C=Cotton spring, D=Delta spring, and W =seeps.

We use seven baseflow samples in a period of about eight months to evaluate residence time of baseflow at Honey Creek upland catchment. A residence time of 20 days gives the best estimate according to standard deviation of the error. However, deviations for the first three samples between the measured and the calculated baseflow $\delta^{18}O$ values are large (Figure 11), reflecting the inaccuracy of model assumptions and model representation.

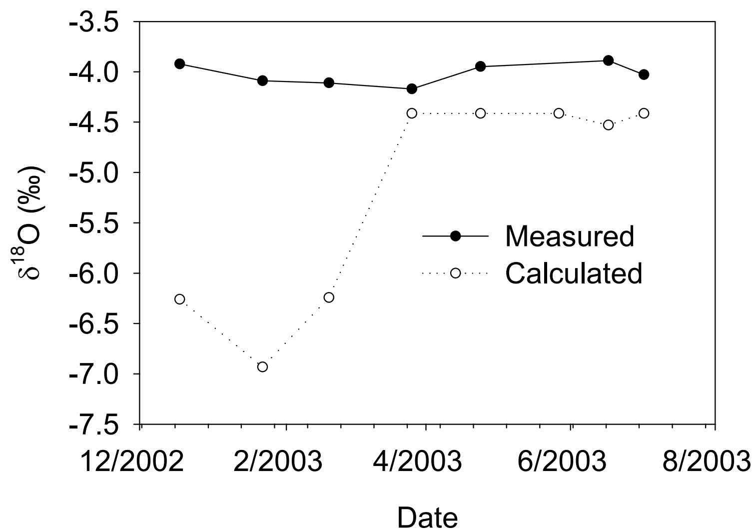

Figure 11. Measured baseflow $\delta^{18}O$ values vs time for the Honey Creek upland catchment compared to the calculated $\delta^{18}O$ values using Frederickson and Criss (1999) method. Large deviations exist for the first three samples.

Discussion

Stream chemistry

Water temperatures are influenced both by the ambient air temperature and by the temperature of the media with which the water is in contact (Mazor, 1991). The temperature of seep water and creek water is highly variable and exhibit an annual cycle, this can be explained by the fact that the temperature of near-surface water tends to re-equilibrate with the ambient air temperature and the temperature of the precipitation inputs.

The creek water can be generally considered as a mixing of seeps (plus surface runoff during storm events) and springs. Therefore, most of its measurements fall between those two. The pH of the seep waters is always higher than that of the spring flows, while the EC is always lower than that of the spring flows. The downgradient increase in calcium, bicarbonate, and TDS has been observed by Davis and Brook (1981) in a karst basin in Tennessee and by Troester and White (1986) in Puerto Rico. However, they observed concurrent increase in pH values downgradient as CO_2 being consumed by increased calcium concentration. The pH of a water body is controlled by carbonate equilibrium, but it may be influenced by recharge water as well as physiological processes, such as uptake and release of CO_2 (Finlay, 2003; Stumm and Morgan, 1996). The higher pH from upland seep water indicates the water has been in close contact with calcium material before it exits.

While other water chemistry parameters may exhibit large difference, O-18 isotopic composition showed only minor difference within measurements of the three springs or among the mean values of spring flows, seep water, and the creek water during sampling period (Figure 9&10). This is important in at least two ways: first, while the creek water can be seen as a mixing of the seeps and the springs, it has experienced higher degree of evaporation than any of the end members due to its surface exposure. Seep water, on the other hand, shows slightly higher evaporation effect than spring waters. Secondly, the evaporation and infiltration processes after the storm event have minimal effect on the seep water isotopic composition. In other words, seep water comes from the water that has not been exposed to high evaporation or mixing with isotopically different water pool during infiltration process.

Root zone moisture reservoir

Relatively steady baseflow isotopic composition leads us to the question of how the soil water connects with the seep water isotopically. Soil water sampling was not part of this project. However, a concurrent study at Honey Creek State Natural Area by McCole (2004) indicates the O-18 isotopic composition of soil water is highly variable temporally and spatially. Such variation has been observed in many landscapes (for example, Cramer *et al.*, 1999; Newman *et al.*, 1997; Zencich *et al.*, 2002).

The isotopic connection of the seep water and soil water is complicated by the dynamic nature of the evaporation front (Figure 12). While a continuum of the isotopic values is generally observed along a vertical profile, the relative steady isotopic signature of the seep water from this upland catchment suggests that the seep water comes from a moisture source loosely connected with the soil water. The soil is shallow, less than one meter in depth in most cases and has very limited water holding capacity (U.S. Department of Agriculture, 1984). The rooting depth, on the other hand, is far below the soil layer. We speculate that this moisture reservoir is closely related to the woody plant root development and term it root zone reservoir. Based on the physiography and plant community characteristics, it may have regional extent and a storage capacity at least as important as soil water.

Explicit identification of this moisture reservoir is important. Further characterization cannot start without realizing its identity. If validated, a series of questions can be asked: what is the dominant mechanism that regulates this reservoir? How this layer affects evaporation and recharge processes? What is the dynamic of root water uptake and reservoir development?

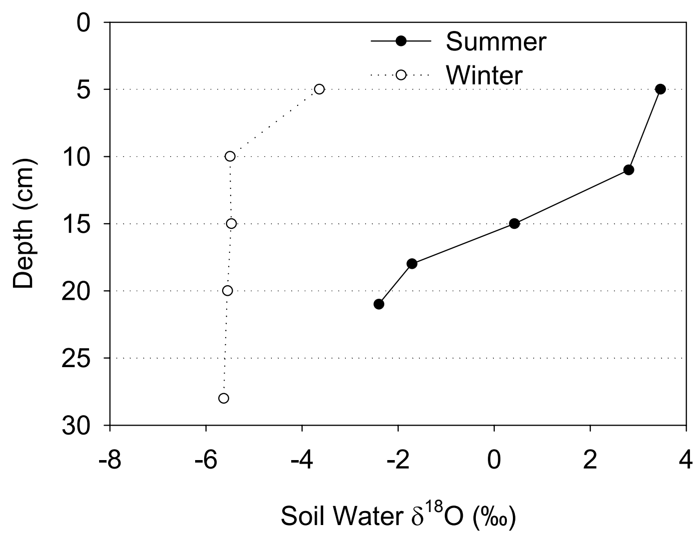

Figure 12. Change in soil water evaporation front at Honey Creek watershed in winter and summer time. The solid line indicates the sampling 4 m away from one Juniper canopy edge in summertime – August 2002. The dashed line represents sampling at the same location in wintertime – February 2003. Data from McCole (2004).

Conclusions

A fast recharge pathway to regional groundwater exists in this landscape. The recharge water is well mixed with existing groundwater before it exits as springs. This is suggested by fast discharge response and relative constant temperature of spring flows. While the temperature of the seep water equilibrates with the surface condition rapidly, higher pH values of the seep water indicate it may have been in close contact with calcium material before it exits. The residence time for the seep water from Honey Creek upland catchment is estimated to be around 20 days.

The isotopic composition of the seep water is minimally affected by the subsequent infiltration and evaporation processes following rainfall events. A root zone moisture reservoir below the soil layer but above the regional groundwater is suggested based on the site characteristics and isotope data. This layer of moisture storage is important in supporting the vegetation community in this landscape but was never explicitly identified.

CHAPTER IV

TRENDS AND DRIVERS OF LONG-TERM STREAMFLOW CHANGE IN NORTH CONCHO RIVER BASIN

Introduction

Land use is increasingly of global importance (Foley *et al.*, 2005). While many studies have quantified streamflow changes following land use conversion, careful evaluations of what drives the change have been lacking or limited by available data. Identifying what drives the change is essential for better resource management to minimize the negative environmental impacts of land use while maintain its economic and social benefits.

Common land uses include agricultural and pastoral use, forestry, and urban development. Conversion of one class to another inevitably brings changes to soil condition and vegetation composition and structure (cover, density, and type), depending on which an ecosystem functions. Land degradation may occur if effective ecosystem functions have been disrupted. Given time, land can be restored or recovered but probably cannot return to the state before the degradation (Briske *et al.*, 2003; van de Koppel *et al.*, 2002). In this sequence of change in states, the watershed system will be involved in hydrologic modification, adjusting each term in water budget.

The most noticeable change in hydrology following land cover change is in watershed runoff. Decades of research using mainly paired watershed experiments generally indicate that surface runoff would decrease following afforestation or reforestation (Bosch and Hewlett, 1982; Stednick, 1996; Van Lill *et al.*, 1980; Zhang *et al.*, 2001a). A more recent analysis (Jackson *et al.*, 2005) indicates plantations decreased streamflow by 227 millimeters per year globally (52%), with 13% of streams drying completely for at least 1 year. In drier regions (mean annual precipitation <1000 mm), afforestation was more likely to eliminate streamflow completely than in wetter regions. The decreased runoff has been attributed to increased evapotranspiration from woody plants.

The above analyses of land cover change on streamflow are based on data mostly from small scale experimental studies (usually area <10 km^2) where an abrupt change was enforced. It is logical to ask whether such strong effect can be observed in a larger spatial scale and often with much gradual change in vegetation cover. A large river basin (>1000 km^2), for example, often has a variety of land use classes, diversified vegetation, and a mosaic of development. The available observational studies of large scale river basins have painted very informative picture. By studying runoff responses following reforestation due to land use conversion from row crops to forest and pasture, Trimble (1987) indicated the annual discharge of 10 large basins decreased about 4 to 21%, with a larger reduction in dry years than in wet years. Increased ET and possibly reduced overland flow have been suggested as the mechanisms. Costa (2003) evaluated the conversion of cerrado covered land (dominantly closed shrubs) to crops and pastures and found higher discharge following the conversion, more evidently in the rainy season (28% increase) than in dry season. Reduced ET in dry season and reduced infiltration in wet season have been suggested as the main causes. When there is no change in land use, but with soil conservation practices, such as gully treatment and conservation tillage, a meso-scale study (Potter, 1991) indicated reduced flood peak and a shift in the partition of stormflow and baseflow, while the total runoff being roughly the same. The above studies are in the climatic region with annual precipitation greater than 1000 mm.

In drylands, even fewer cases are available. However, a recent large scale observational study tells the same story. Huang and Zhang (2004), working in the Loess Plateau of north China where annual precipitation is about 420 mm, suggested that soil conservation practices have reduced both surface runoff and baseflow. Those soil conservation practices include tree and grass plantation, terrace construction, and construction of gully erosion control dams. The authors attributed most of reduction to increased ET from plantation.

A few cases mentioned above, either in wetter regions or drier regions, and their explanations seem to conform to Zhang's model (Zhang *et al.*, 2001a) and agree with Jackson (2005) study. The observable effect in such a large scale and the causation of the effect renders much more implications: not only related to catchment water balance, but also to soil conservation practices, or even towards policy level decision-making about carbon sequestration (Jackson *et al.*, 2005). The strong implications call for the necessity to conduct further studies and to look carefully at the inconsistent pictures. Bruijnzeel (2004) reviewed a few cases that evaluate the hydrologic effect of medium or large scale tropical deforestation. Not only did he conclude that a consistent relationship could not be arrived because of mixed effects (positive or negative among cases), but also pointed out in a few cases possibly different interpretation of the causations where a positive effect was observed. In dryland regions, lack of large scale observational studies renders generalization hardly possible. Nevertheless, Huxman et al. (2005) has pointed out site-dependence of hydrological effects of increased woody plants in arid and semiarid landscape.

Not only is the hydrologic effect of land cover change in large scale basins inconsistent, but also the interpretation of what drives the change. In most studies, groundwater pumping has been ignored. Increased groundwater pumping, concomitant with increasing demand from agricultural and municipal water uses, has long been linked to decreased streamflow. Well known cases include the Edwards aquifer in south-central Texas where San Macros Springs and Comal Springs have been affected (U.S. Department of Agriculture, 1996); the groundwater pumping in the City of Albuquerque, New Mexico that has affected streamflow of Rio Grande River (DuMars and Minier, 2004); and numerous other accounts (Brune, 2002). Another commonly overlooked factor is grazing. In arid to semiarid regions, grazing is the single most extensive form of land use (Asner *et al.*, 2004). Overgrazing is believed to be one of major contributors to woody encroachment (Archer *et al.*, 2001; Van Auken, 2000) and soil erosion (Donkor *et al.*, 2002; Evans, 1998; Trimble and Mendel, 1995). The impact of grazing on ecosystems has been long studied. Most studies concentrate on the impact on soil and vegetation (for example, Hibbard *et al.*, 2003; Hill *et al.*, 1998; Neff *et al.*, 2005; Pietola *et al.*, 2005; Schlesinger *et al.*, 1990); runoff increase due to overgrazing has been observed in many landscapes as well (Blackburn *et al.*, 1982; Castillo *et al.*, 1997), including more than doubled runoff due to overgrazing while much lower runoff after a recovery (Heathwaite *et al.*, 1990; Pereira, 1979; Sartz and Tolsted, 1974). It has been generally recognized that heavy grazing causes reduced infiltration and increased sediment production in most grazing systems, while moderate and light grazing may have much less adverse hydrologic impacts and depend on site conditions (Gifford, 1978; Merzougui and Gifford, 1987; Warren *et al.*, 1986). While grazing land use in the United States has been declining slowly since 1980's (U.S. Department of Agriculture, 2004), the consequences of overgrazing in some areas are still reverberating.

In this study, we evaluate hydrologic responses to large scale land degradation and recovery in a semiarid river basin that has experienced intensive grazing. We analyzed long-term (77 years) precipitation and streamflow records. The objective is to understand runoff dynamics from this watershed, to assess the magnitude of change, and to explore the driving forces if the change is persistent.

Study Site

North Concho River basin is located in the west central Texas near San Angelo (Figure 13). The basin above Carlsbad is our focus in this study and it has a drainage area of about 3,279 km^2 based on U. S. Geological Survey (USGS) information system. The River heads out in northeastern Glasscock County southeastward and discharges into O. C. Fisher Reservoir. The basin is situated at the margins of the Edwards Plateau and the Llano Estacado or High Plains. Topographically, the area generally consists of broad valleys near the river and tributaries flanked by hills, buttes, and plateaus of Edwards Limestone (Upper Colorado River Authority, 1998). Annual mean precipitation in the nearby city of San Angelo is about 500 mm/yr, with the rainfall peaks in May and in September. The monthly mean temperature is 28°C in August and 6°C in January.

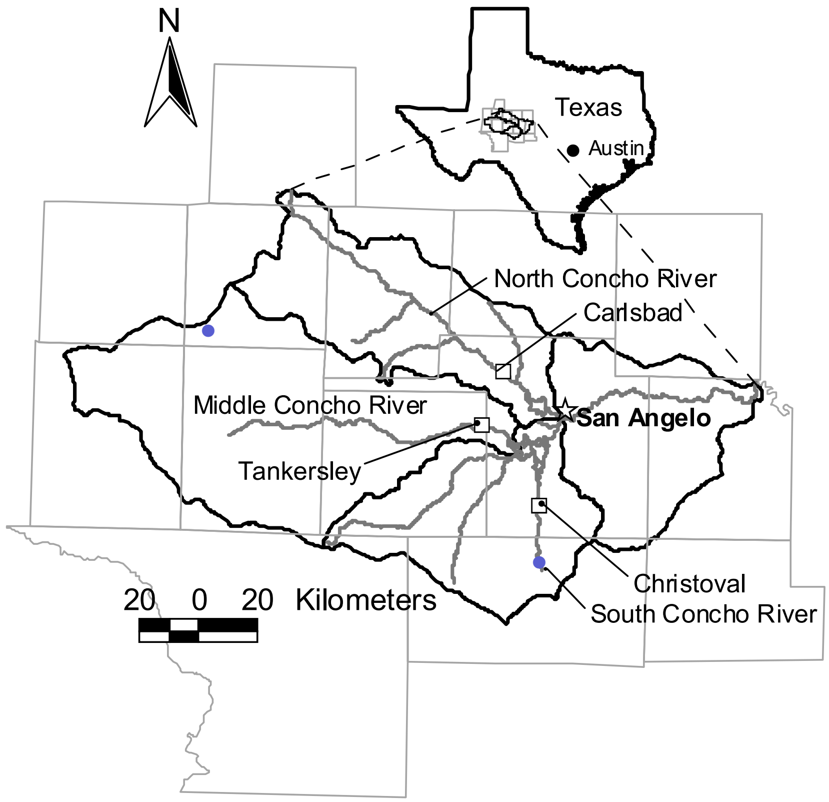

Figure 13. Site map of North, Middle and South Concho River basins in the west-central Texas. The location of USGS streamflow gauging stations at Carlsbad, Tankersley and Christoval in each basin is shown on map. The background is the map of county boundary.

Most of the land in the Concho River basin area, which includes North, Middle and South Concho River sub-basins, is used for ranching. Homesteading started around 1900. Total cropland in the basin was estimated to be not more than 3% of the total land area (Sauer, 1972) and has been relatively stable since then. Early accounts indicate the valley as open rangeland prior to the time of the settlement in 1860's (Maxwell, 1979; Sauer, 1972). Cattle and sheep grazing grew rapidly since the settlement. Figure 14 provides a general picture of relative grazing pressure in the basin (Smeins *et al.*, 1997). Possibly due to increased grazing and reduced frequency of wild fire (Archer, 1994; Van Auken, 2000), increased density of woody plants such as mesquite and juniper trees can be seen as early as 1880's. A classification of Landsat images of 1992 indicates about 40% of land in the North Concho River basin above Carlsbad was covered by heavy cedar, heavy brush (mainly mesquite), and moderate brush (Upper Colorado River Authority, 1998). Quantitative estimates for different periods for the basin are not available. However, another quantitative study (Asner *et al.*, 2003) of the nearby region indicates a net 30% woody plant cover increase from 1937 to 1999, including the areas that have been repeatedly undergone brush management. This study also points out topo-edaphic control in spatial pattern of woody plant increase: greatest in riparian corridors and shallow clay uplands and least on upland clay loams. Overgrazing since 1900's and the drought in 1950's seriously depleted herbaceous cover. However, reduced grazing pressure thereafter as well as soil and water conservation practices have improved land cover condition since 1970's (Sauer, 1972; Taylor and Kothmann, 1993).

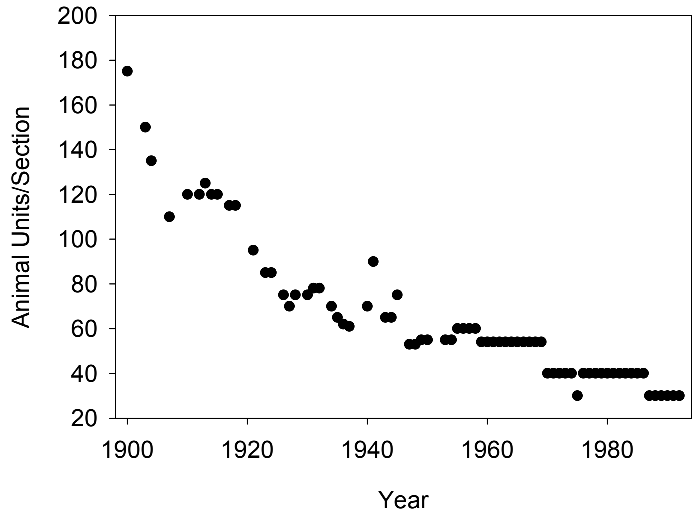

Figure 14. Change in stocking rate on the Sonora Research Station, about 150 km south of San Angelo, Texas. One hundred animal units per section translate into about 40 cows (200-250 sheep or goats) per km^2. Numbers are visual estimates from Figure 3 of Smeins (1997).

North Concho basin has been a focus in several studies. Sauer (1972) investigated the reasons for the unusually low runoff in the Concho River basin during the period 1962-68 and concluded it is mainly due to climate variation. In retrospective, his analysis was limited by the data available at that time. A modeling report (Upper Colorado River Authority, 1998) suggested that the increasing woody plant coverage depleted the alluvium aquifer and caused decreasing flow. By simulating woody plant removal, they were able to calculate how much streamflow could be restored. This report is often cited as a justification for a large restoration project that is going on in Concho River basin. Wilcox (2002), though, argues that limited chance of a successful streamflow restoration exists based on his observations and reasoning of high soil water deficit, Horton overland flow dominated runoff generation, and flashy runoff nature in the basin.

In summary, some observed evidences exist for the reduced streamflow and some explanations have been proposed. The questions remain: is there a persistent change in streamflow beyond climate variation? If so, what could be the driving forces?

Data and Methodology

Data

Daily discharge record from USGS gauging station along North Concho River at Carlsbad (08134000) is selected for analysis. Its completeness of the record and no regulation or diversion upstream make it a good candidate for analysis. The streamflow record from Carlsbad station goes back to 1924. In order to be compatible with the precipitation record, daily streamflow data from 1926 to 2002 are selected for analysis in this project.

Relatively complete record of daily precipitation in North Concho River basin goes back to 1926. Stations selected within and near the basin include Cope Ranch, Forsan, Funk Ranch, Garden City, Sterling City and Water Valley (Table 3). Precipitation data from each station were obtained from the National Oceanic and Atmospheric Administration (NOAA) database. Records from two or more nearby stations were combined to develop a continuous record when necessary. Thiessen polygon method was used to obtain spatial average precipitation series from the selected stations. Monthly and annual streamflow and precipitation data were synthesized from daily series.

Table 3. Rainfall stations used in North Concho River basin streamflow analysis.

Cope ranch	1-Mar-1948 to 31- Dec-2002	Combined record of three Cope Ranch stations
Forsan	1-Apr-1949 to 31-Dec-2002	
Funk Ranch	1-Mar-1948 to 31- Dec-2002	
Garden City	1-Jan-1926 to 31-Dec-2002	Garden City 1 E and Garden City 16 E Combined
Sterling City	1-Apr-1926 to 31-Dec-2002	Combined record of three stations in the vicinity of Sterling City
Water Valley	1-Apr-1949 to 31-Dec-2002	Water Valley 10 NNE and Water Valley 8 NE combined

Methodology

Directional change is evaluated by applying trend test on daily, monthly and annual streamflow and precipitation series using nonparametric Mann-Kendall test. For the daily series, incremental percentiles on annual basis will be used. Streamflow and precipitation of each month as well as annual mean (or total) are also subjected to trend test.

Mann-Kendall test was originally used by Mann (1945) and the test statistic distribution was derived subsequently by Kendall (1975). This test has been used widely in climatic and hydrologic research fields (Douglas *et al.*, 2000; Gan, 1998; Kahya and Kalayci, 2004; Lettenmaier *et al.*, 1994; Zhang *et al.*, 2001b). The magnitude of trend is estimated using a Sen slope estimation

(Sen, 1968). A two-tailed test at a significance level of 0.1 was used to evaluate whether the trend is significant.

While Mann-Kendall test does not require normality of distribution, presentation of autocorrelation in the data set violates independence assumption. In this case, the effective degree of freedom will be less than the number of observations. Consequently, spurious trend would appear if autocorrelation were not accounted for. In our data set, first order autocorrelation, if present, was removed by using the following Cochrane-Orcutt procedure (Cochrane and Orcutt, 1949):

$$Y_t' = Y_t - rY_{t-1} \qquad (6)$$

where Y_t' is the transformed time series values, Y_t is the original time series values, and r is the estimated serial correlation. The significance of first order autocorrelation was judged using Durbin-Watson statistics at 0.05 significance level (Bowerman and O'Connell, 1979). Trend analysis is performed on a transformed series if autocorrelation presents.

Baseflow is closely related to groundwater and soil water discharge. While percentiles provide an image of change in flow conditions, low flow percentiles do not necessarily illustrate the profiles of baseflow condition, especially in this arid watershed where daily flow variation is large. Baseflow separation techniques (Arnold and Allen, 1999; Arnold *et al.*, 1995), instead, is used to assess the change in baseflow. It is important to realize the baseflow definition has always been fuzzy and subsequently the separation would not be unique.

Most rainfall-runoff studies aggregate rainfall or runoff data into annual, monthly, weekly or daily time step for convenience. However, observations with predefined intervals are bound to cause information loss because natural events occur independently of the human unit for time. This is especially a problem in dryland environments, where precipitation and streamflow tend to be episodic. While annual aggregation is commonly used, it obscures many details of rainfall-runoff relationship. In addition to annual, monthly and daily data, we aggregate rainfall and runoff into natural events in this study. Daily rainfall is considered to belong to one event unless there are two no-rain days between. Such aggregation shows non-significant serial correlation between rainfall events (α=0.1). Runoff is aggregated from the beginning of the current rainfall event until the beginning of next rainfall event.

Results

Trend test in streamflow and precipitation parameters

The trend analysis (Table 4) indicates daily flow percentiles, from 50th percentile up to the maximum, all showed significant downward trend. The higher the percentile goes, the larger the degree of reduction. Percentiles less than 50th represent primarily dry streambed conditions and trend tests were not applicable. Monthly flows, except for January, also showed significant downward trend. May and April are the two months that exhibit most significant down trend. Annual mean flows display significant downward trend too. Over the course of 77 years, annual mean streamflow has reduced up to 7 mm based on Sen-slope estimation, an approximate 70% reduction off the starting amount.

Daily precipitation percentiles, showed significant increasing trend on 90th percentile and below. Percentiles from 95th up to maximum showed downward moving. However, this downward moving is not in a statistically significant manner, except for 98th percentile – which is significantly downward moving. On the other hand, no significant trend was detected on monthly precipitation for each month of the year. Annual total precipitation shows non-significant downward moving.

The analysis confirms change in streamflow and indicates that the change is consistent across low to high percentiles with higher percentile shows larger degree of reduction. Chang in precipitation is divided: there are enhancements in precipitation of low percentiles, but decreasing in high percentiles.

Annual and seasonal precipitation and streamflow

Annual basin-wide precipitation and streamflow for the entire study period (1926 to 2002) is shown in Figure 15. The annual mean precipitation is 486 mm. Year to year variation ranges from a minimum of 226 mm to a maximum of 950 mm. The annual mean streamflow is about 8 mm, with year to year variation ranging from 0 mm to 99 mm. The mean runoff ratio (streamflow/precipitation) for the entire study period is about 1.5%.

Table 4. Trend test on flow and precipitation variables for the North Concho River basin. Number of observations for each variable is 77.

Category	Variable	Trend	Sen slope
Daily flow percentile	25%	Decreasing	0
	75%	Decreasing	-1.05E-05
	90%	Decreasing	-8.78E-05
	98%	Decreasing	-1.02E-03
	Maximum	Decreasing	-2.24E-02
Monthly and annual flow	January	Insignificant	-6.47E-05
	February	Decreasing	-1.25E-03
	March	Decreasing	-6.17E-04
	April	Decreasing	-2.19E-03
	May	Decreasing	-6.33E-03
	June	Decreasing	-1.24E-03
	July	Decreasing	-9.90E-05
	August	Decreasing	-7.18E-05
	September	Decreasing	-8.37E-05
	October	Decreasing	-7.29E-05
	November	Decreasing	-2.22E-04
	December	Decreasing	-8.85E-04
	Annual mean	Decreasing	-7.14E-02
Daily precipitation percentile	80%	Increasing	0.006
	85%	Increasing	0.018
	90%	Increasing	0.024
	95%	Insignificant	-0.003
	98%	Decreasing	-0.047
	Maximum	Insignificant	-0.136
Monthly and annual precipitation	January	Insignificant	0.061
	February	Insignificant	0.058
	March	Insignificant	-0.011
	April	Insignificant	-0.074
	May	Insignificant	-0.092
	June	Insignificant	0.215
	July	Insignificant	-0.179
	August	Insignificant	0.132
	September	Insignificant	0.170
	October	Insignificant	-0.007
	November	Insignificant	0.075
	December	Insignificant	-0.120
	Annual mean	Insignificant	-0.139

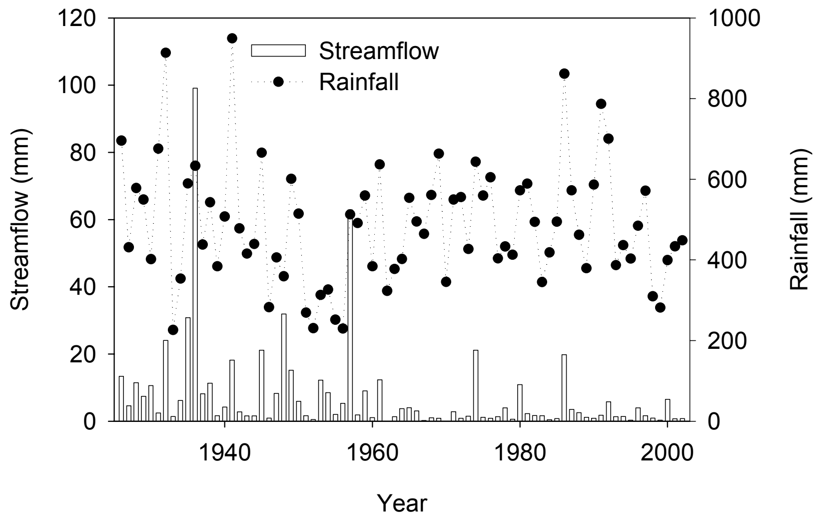

Figure 15. Annual total streamflow and precipitation at North Concho River basin from year 1926 to 2002. Basin-wide precipitation is obtained using Thiessen polygon method from five stations within and nearby the North Concho River basin. Annual streamflow data reflects USGS Carlsbad station (08134000) record.

Mean of the monthly runoff for the entire study period is plotted in Figure 16. May and September see high amount of rainfall and corresponding runoff. Seasonal runoff dynamics can be seen in Figure 17. As time traverses from winter to spring (from November to April), monthly runoff profile changes from sustained low runoff to increasingly higher amount of flow with greater variation. In the middle summer (July and August), runoff is flash – only responding to large precipitation events.

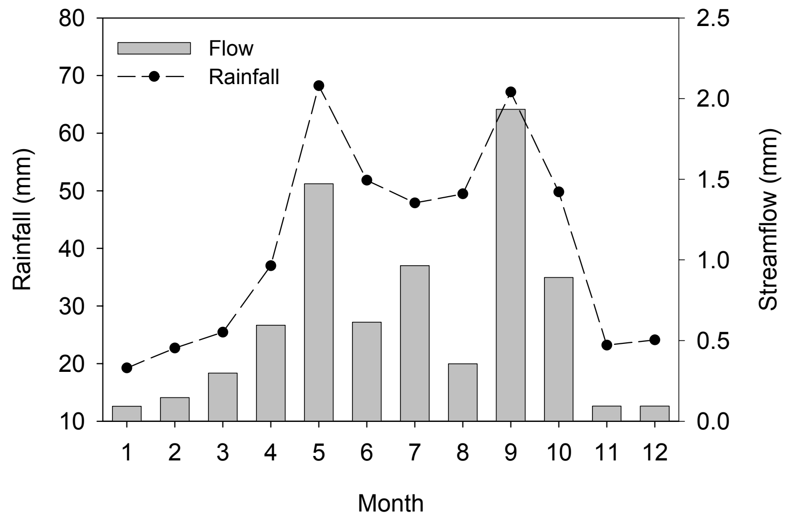

Figure 16. Mean of monthly rainfall and streamflow for the entire study period for the North Concho River basin (1926-2002).

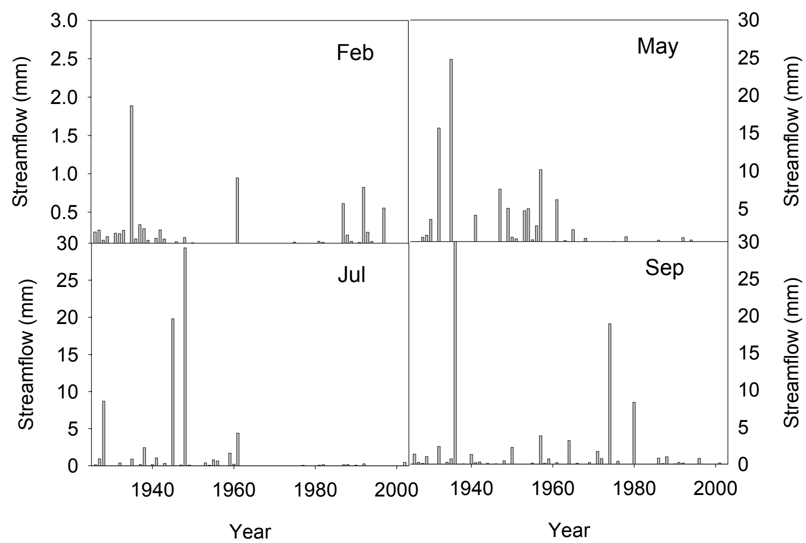

Figure 17. Seasonal streamflow at North Concho River basin from year 1926 to 2002. Feb graph represents general watershed flow condition in winter months (November to March), May graph spring rainy months (April to June), July graph middle summer months (July and August), and September graph fall rainy months (September and October). Scales are different. The large flooding event in September 1936 has been cut off due to the scale (The total is 96 mm). Data reflects USGS Carlsbad station (08134000) record.

Figure 18 illustrates how runoff events (defined in section 3) distribute in the study period. On average, there are 30 events per year. In the entire study period, the largest event accounts for 16% and the largest six events accounted for 38% of the total runoff. Each year, the largest event accounted for 9-100% of runoff in that year with an average of 65% and the largest six events accounted for 44-100% of the runoff in that year with an average of 92%. The dominance of large events in runoff production is quite apparent in this system.

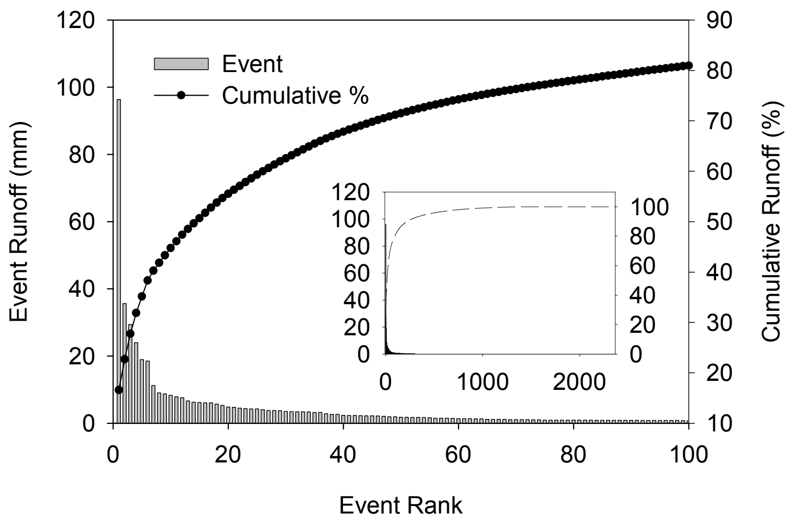

Figure 18. Event runoff ranks (from high to low) and percentage cumulative runoff from year 1926 to 2002. The larger graph plots only the largest 100 out of 2,342 rainfall-runoff events. The smaller graph, which is inside the larger one and bears the same XY titles, plot all the events in the study period.

Total baseflow contributes only 8% of total streamflow in the study period. Baseflow at the North Concho basin has been strongly affected by the drought in 1950's (Figure 19) while a decent recovery can be seen starting 1973. Baseflow in 80's and early 90's are comparable to pre-drought condition. Table 5 demonstrates 24-year mean of precipitation, streamflow and baseflow in periods A (1926-1949) and B (1974-1997). Those two periods were selected to better account for climate variability as well as drought effects in comparison. The long-term mean annual rainfall is very close between two periods. The percentage reduction in baseflow, which is 35%, is far less than the percentage reduction in streamflow, which is 73%.

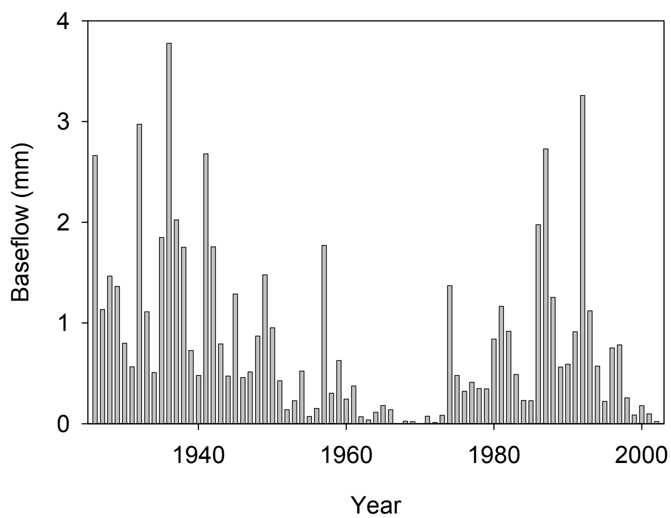

Figure 19. Annual mean baseflow from 1926 to 2002 at Carlsbad station in North Concho River basin. The separation was done with daily discharge series and the annual mean is aggregated from the daily series.

Table 5. Twenty-four years mean of annual rainfall and runoff in North Concho River basin in two periods.

Period	# of years	Rainfall (mm)	Streamflow (mm)	Baseflow (mm)	Runoff Ratio (%)
A (1926-49)	24	521	14.1	1.4	2.7
B (1974-97)	24	525	3.8	0.9	0.7
Change (%)	--	-0.7	73	36	--

Figure 20 shows 24-year mean of monthly rainfall and runoff in period A and B. The largest absolute reductions are in the months of September, July, May and April. However, the reduction in July probably can be partially explained by a reduction in rainfall. Considering one large flooding event in September 1936 (period A), the large reduction in September would be less prominent but it is still appreciably higher than in April.

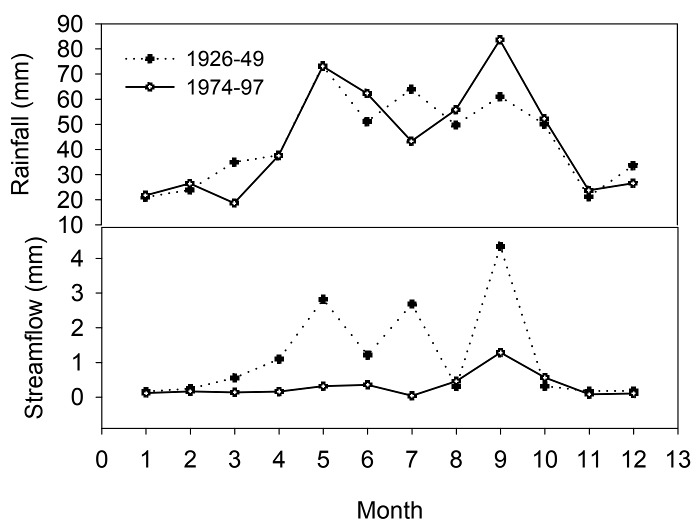

Figure 20. Twenty-four year mean of monthly rainfall and streamflow in the period 1926-49 and 1974-97.

Annual precipitation and streamflow for the two periods exhibit a very weak relationship (Pearson correlation r=0.34 for A and 0.58 for B). Such weak correlation at the annual level suggests runoff production is highly sensitive to watershed conditions and perhaps rainfall distribution, instead of merely annual amount of precipitation. This fact as well as the fact that majority of runoff was produced by a few events per year prompt us to explore an analysis at a finer time scale.

In order to examine what drives the runoff difference in the two comparison periods A and B, we sampled a group of largest 63 runoff-producing events (defined in section 3) from each period (Pearson correlation r=0.75 for A and 0.71 for B). The samples represent 87% and 80% of total runoff in period A and B, respectively. The total amounts of rainfall for two sampled groups are roughly equal and the difference in runoff between the samples represents 90% of runoff difference between two comparison periods. Scatterplot (Figure 21) of rainfall and streamflow for the sampled events indicates runoff is almost always higher in period A than in B. A two-way ANOVA is subsequently employed, considering the factors the amount of rainfall, the number of raining days for a given event (an indicator for rainfall intensity), and change in watershed conditions. As the detailed information of watershed conditions is not available, an average condition in two periods is used and represented as a categorical variable. The streamflow is transformed using natural logarithmic model (Figure 21). The model indicates change in watershed conditions contribute significantly to the variation of streamflow ($p<0.0001$). The model also points out the marginal significance of rainfall intensity ($p=0.085$) to the variation of streamflow. An analysis without the outlier (the 1936 flooding event) provides us similar conclusions.

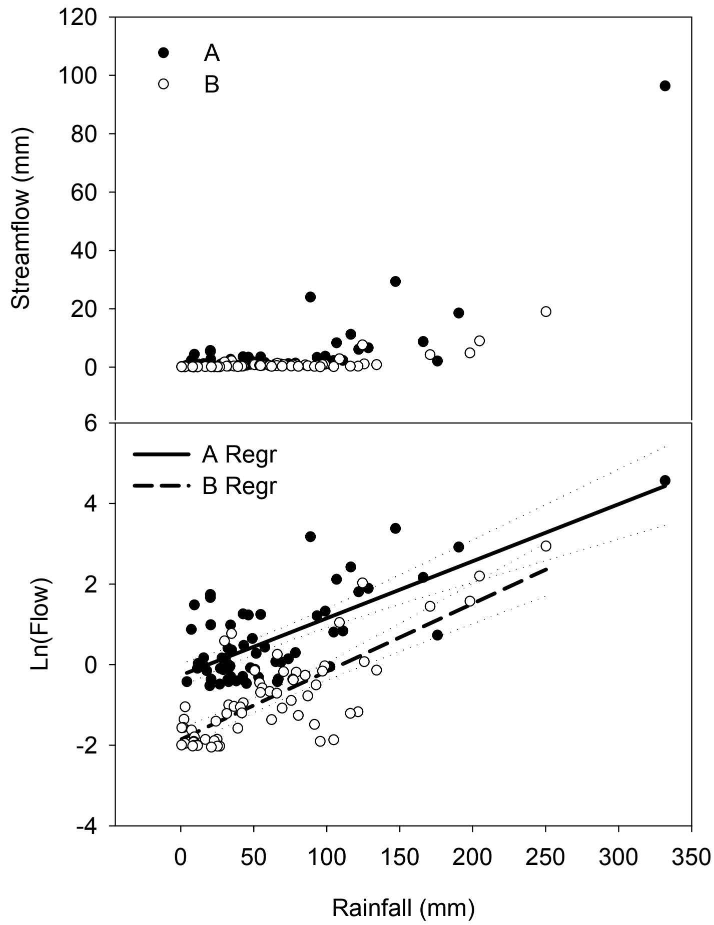

Figure 21. Largest 63 runoff-producing events in the two periods A (1926-1949) and B (1974-1997) in North Concho River basin. (a) Scatter plot and (b) Natural logarithmic transformed streamflow verses rainfall. Separate regression lines and 95% confidence intervals (dotted line) for A and B are shown.

No trend in monthly or annual precipitation was detected as mentioned above. The means of precipitation of the sampled events for those two periods are roughly the same and the variances are not significantly different (Table 6). The means and variances of the number of raining days per event, on the other hand, are significantly different between two periods. Also in Table 6 is the comparison of maximum daily rainfall during an event and they are significantly different between two periods. The model, however, indicates some contribution of rainfall intensity difference to the runoff.

Table 6. Independent two-sample test for null hypotheses of no difference in means (T-test) or variances (F-test) of two predictor variables between two periods A (1926-49) and B (1974-97) for North Concho River basin. Each observation corresponds to one event.

Variable	Rainfall amount			Number of raining days			Maximum daily rainfall		
Period	A	B	P-value	A	B	P-value	A	B	P-Value
# of obs.	63	63	--	63	63	--	63	63	--
Mean	61	62	0.95	4.1	7.2	0.0001	38	25	0.0051
Std Dev	55	54	0.83	3.1	4.4	0.0086	29	21	0.0128

Discussion

As has been demonstrated, change in watershed conditions is the main driver to the large reduction in runoff. In this watershed, change in watershed conditions has three major components: woody plant encroachment, improved land cover condition from reduced grazing (Figure 14) and better land management, and change in groundwater storage. Since baseflow is a tiny fraction of water budget and reduction in baseflow is quite small compared to total streamflow reduction, the increased ET from woody plants, if any, cannot account for greatly reduced streamflow – each year, majority of streamflow was produced by a few large events, further decoupling streamflow production with ET reduction.

Our observations have been consistent with the hypothesis that increased infiltration capacity is mainly responsible for decreased runoff. Surface runoff increased appreciably when the watershed was degraded due to overgrazing since 1900's but surface runoff decreased when the vegetation cover condition is getting better since 1970's. This hypothesis can explain the drastic changes in direct surface runoff from large storm events, which contribute majority of annual runoff.

Part of groundwater potentiometric surface data was analyzed. Data was obtained from Texas Water Development Board (2005). Lack of middle- to long-term fine resolution observations of basic groundwater level hinders a reliable and comprehensive analysis. Most wells have on average less than one observation per year, but could have many observations in some years. Analysis of 54 well hydrograph data enable us to hypothesize that the alluvium aquifer responds to the surface condition directly, while the deeper formations experience a lag effect and respond to the surface processes (such as recharge) in a complex way. The alluvium aquifer is likely to be refilled regularly following good precipitation. Although hydraulically connected, the deeper formations function independently to some degree. Figure 22 plots water level fluctuation in a well with relatively complete record. The well is located in Glasscock county and penetrates to the Antlers Sand formation (a formation underlying the Quaternary Alluvium and overlying the Triassic Dockum Group). The general decreasing trend in deeper aquifer water level suggests the groundwater storage has been significantly affected by groundwater pumping and 1950's drought. Continued pumping when recharge was hardly available drove the water level in deeper aquifers lower and lower. It is also important to notice that recharge did occur following good amount of rainfall. This well is far away from the stream channel so the recharge mechanism needs further exploration. It is likely that groundwater pumping partially contribute to the low flow as more recharge is allocated. This mechanism is complimentary to the mechanism of change in surface condition, as demonstrated by flashy nature of runoff production. The baseflow component of runoff may have stronger association with alluvium aquifer than with the deeper aquifers.

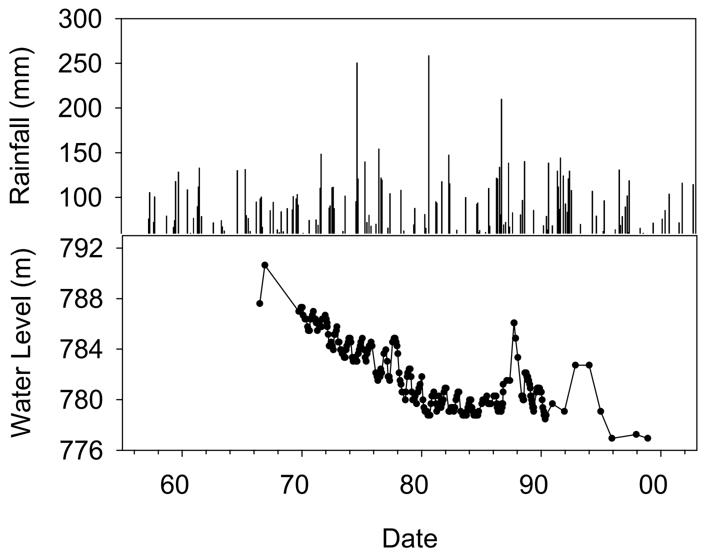

Figure 22. Monthly rainfall input and groundwater level fluctuation in a well (Lat/Long: 31.6977778/-101.6902778) that penetrating to the Antlers sand formation in Glasscock County, Texas. The well is within the boundary of Middle Concho River basin but it is close to the divide between the North and Middle Concho basin. Only months with rainfall greater than 60 mm are shown. The rainfall data is spatial averaged data in the North Concho River basin above Carlsbad streamflow gauging station. Well depth is about 50 m and the depth to water level is more than 35 m from the land surface during the period of measurements. An annual cycle, low in the summer (mostly July or August) and high in the winter (Mostly December), is associated with the general decreasing trend. The drops in water level are commonly seen in other wells in North Concho River basin, though each well may behave very differently.

Conclusions

Streamflow at Concho River basin has decreased about 70% over the last 80 year, especially after the drought about 50 years ago. We used event-based analysis to overcome the problem that the relationship between annual precipitation and runoff is weak. The analysis demonstrates that runoff was dominated by large runoff-producing events, either in any given year or in the entire period. The event-based regression analysis points to the change other than climate difference for the reduction of streamflow. The change of precipitation intensity has an effect, but to a much lesser degree. Our analysis supports the hypothesis that reduction in streamflow is mainly due to enhanced infiltration from more protective watershed conditions, including both woody and herbaceous cover. Groundwater pumping may contribute to the low flow, but it is complementary to the mechanism of change in watershed surface condition. The influence of increased woody plants is minimal.

Our study suggests the current hydrologic regime is similar to the pre-disturbance condition; despite there has been a significant increase in woody plant cover following the disturbances (overgrazing, drought, et al.). An ecological tradeoff may have occurred: the increase of woody plants is made at the expense of the loss of topsoil due to heavy grazing. This tradeoff modifies the partition of how vegetation access available surface and soil/ground water resources.

What has happened and is happening in Concho River basin provides excellent opportunities to test ecohydrological theories. This large scale observational study does not support the generalizations made from mostly small scale experiments. The conclusion would be stronger if carefully designed long-term monitoring of groundwater level dataset were available. Some questions remain. For example, is what happened in North Concho an isolated phenomena or it has much broader implications?

CHAPTER V

A REGIONAL ASSESSMENT OF STREAMFLOW CHANGE IN THE WAKE OF WOODY PLANT ENCROACHMENT

Introduction

Experimental studies of runoff responses to vegetation management enabled us to make a generalization that removing woody plant coverage would increase runoff from the watershed and vice versa (Bosch and Hewlett, 1982; Zhang *et al.*, 2001a). However, problems exist. First, the change of vegetation in experimental studies is often abrupt. In real world, vegetation change is a natural process and tends to be gradual – although slash and burn activities will create an abrupt change. Secondly, the experiments are often conducted in small catchments. Interpolation to large spatial scales of resolution is difficult. Observational case studies have supplemented this information. Depending on the availability of the site information, different approaches have been adopted in case studies. One approach is to conduct detailed historical precipitation-streamflow analysis (for example, Bewket and Sterk, 2005; Costa *et al.*, 2001; Xu, 2005). Another approach is to use rainfall-runoff models, i.e., to calibrate a rainfall-runoff model to baseline condition as a virtual control for changing condition (Cornish, 1993; Jakeman and Hornberger, 1993; Schreider *et al.*, 2002). While most studies using modeling approach reported satisfactory model performance and subsequent trend assessment, the conclusions are heavily dependent on model calibration. In addition, the baseline condition has to be clearly identifiable. Regardless of which approach being used, individual basin analysis may often invite the question: is this an isolated phenomena or it has regional implications?

An analysis of regional streamflow trend often provides clues as to regional effects of land use/land cover change. Although along a different track, scientists seeking evidence of climate change have utilized regional scale streamflow trend analysis (Burn and Hag Elnur, 2002; Kahya and Kalayci, 2004; Lettenmaier *et al.*, 1994; McCabe and Clark, 2005), as streamflow is often regarded as an integrated watershed response to climatic forcing. While important spatial patterns were revealed, the discrepancies are often attributed to unparallel of changes in streamflow and climatic variables (Lettenmaier *et al.*, 1994), or to different analytic methods involved (Douglas *et al.*, 2000). Those studies often choose target stations that experience minimal development or have stable land use conditions to minimize anthropogenic effects. Limitations of regional trend analysis exist. One limitation is that most climatic variations are often associated with land use/land cover changes, or even with watershed development downstream that affect underground flow processes. Another limitation is that only sparse stations are often included in the analysis and those stations may not be representative. For example, in Lettenmaier (1994) study, less than 20 stations were included for the entire Texas and most of them appear to be in the southeast Texas. Modeling approach has also been used for regional streamflow evaluation. A family of terrestrial ecosystem models (e.g. general circulation models) has been used to evaluate large scale runoff response from change in vegetation and climate (Arnell, 1999; Gordon *et al.*, 2004; Kiely, 1999). For example, Arnell (1999) examined changes in runoff produced by the general circulation model HadCM2 and HadCM3. He found that HadCM2 simulations yielded increases in runoff for the year 2050 compared with the baseline period of 1961–1990 over much of the United States while HadCM3 projected decreases in runoff, which he attributed to higher rates of evapotranspiration in the HadCM3 simulations. As another example, Gordon and Famiglietti (Gordon *et al.*, 2004) examined trends in runoff and actual evapotranspiration in selected 13 United States watersheds using four terrestrial ecosystem models. They found positive runoff trend in the majority of the watersheds examined. Because of the complexity of ecosystem interactions, the validity of the model outputs will be continuously checked and verified. In sum, regional streamflow trend analysis that incorporates as many stations as possible to evaluate spatial pattern of the changes is still desirable.

In this study, we extend North Concho study to the entire Concho River basin, which include North, Middle, and South Concho River basins. A comparison is made between those three. A further trend analysis of streamflow in the entire western Texas is made to further explore the inference drawn from the comparison of three basins. The objective of this study is to examine whether the North Concho model is extendable to other area and to identify regional spatial pattern of watershed runoff responses in the wake of increased woody plant coverage.

Study Site

The Concho River basin examined in this study includes North Concho River basin above Carlsbad, Middle Concho River basin above Tankersley, and South Concho River basin above Christoval. A USGS streamflow gauging station at each of the locations defines the watershed boundary. The drainage areas are 3,279, 5,398, 1,070 km^2 for the North, Middle, and South Concho River basins, respectively.

Because of the proximity, there are many similarities among those three basins. Most notably are increased woody plant coverage in the last century, similar grazing trend and lack of major urban development. For example, 57% of land in Middle and South Concho River basin contributing area is covered by heavy cedar, heavy brush (mainly mesquite), and moderate brush based on a classification of 1999 Landsat images (Upper Colorado River Authority, 2000). That percentage for North Concho River basin was 40% based on a classification of Landsat images of 1992 (Upper Colorado River Authority, 1998). The valley of North Concho River basin is predominantly covered by mesquite trees while South Concho River basin is predominantly covered by juniper trees. Geologically, the Quaternary deposits are present in the stream valley and the Cretaceous limestones form the hills and sloped terrains. However, transitional changes in geological feature exist from the North to South Concho River basins. One noteworthy difference is that the South Concho River has much better contact with the Edwards group, which consists of limestone and dolomite. Soils in floodplain are similar for the three basins, which are characterized as deep, nearly level, calcareous soil. Adjacent to its floodplain, both North and Middle Concho have a belt of undivided Quaternary deposit, which consists of alluvial fan deposits, colluvium, and caliche layers (Barnes, 1976). However, this feature is lacking for South Concho River. Away from the floodplain, North and Middle Concho River are mainly surrounded by Kimbrogh-Mereta-Angelo association: very shallow, shallow, and deep, nearly level to sloping and undulating, calcareous soils on outwash plains. South Concho River, instead, is surrounded by Tarrant-Ector association: very shallow to shallow, undulating to hilly calcareous soils on limestone hills (U.S. Department of Agriculture, 1976).

The western Texas in this study is loosely defined by the drainage basins. It encompasses eight river basins: Canadian, Red, Brazos (upstream above Waco), Colorado (upstream above Austin), Guadalupe, San Antonio, and Rio Grande (Figure 23). The precipitation varies from 900 mm in the east to 200 mm in the west. Major urban developments include San Antonio, Austin, and El Paso.

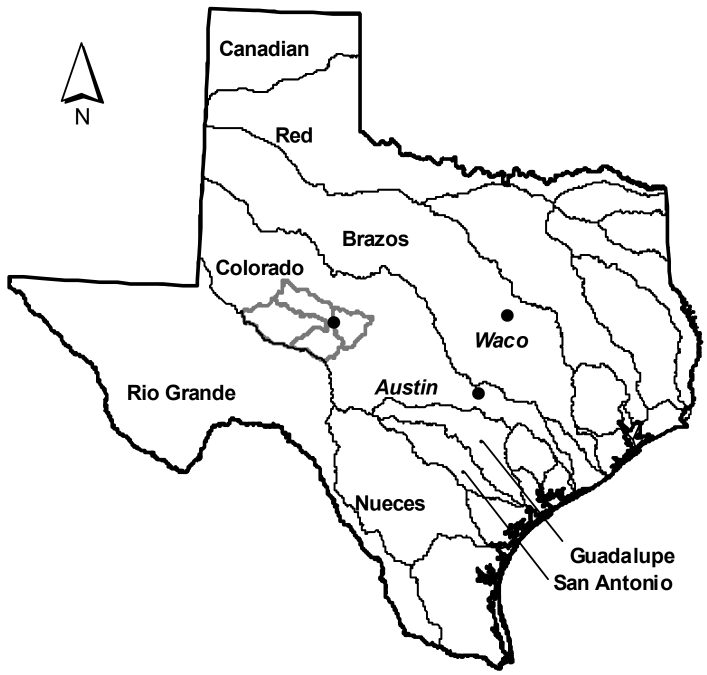

Figure 23. Map of the western Texas. The name of the major basins along with the two cities (Waco and Austin) are shown on the map. The slightly shaded boundary within the Colorado River basin shows the location of the North, Middle and South Concho River basin.

Data and Methodology

For the Concho River basin comparison, USGS streamflow records such as Carlsbad gauging station in North Concho, Tankersley station in Middle Concho, and Christoval station in South Concho are chosen for analysis. The common records span from 1 Mar 1930 to 30 September 1995. Due to changes in gauging location and establishment of diversion features along the river, adjustments were done to obtain complete and consistent streamflow record for each basin. The gauging station used to measure flows near Tankersley in the Middle Concho was moved towards more upstream above Tankersley on 1 April 1961. The near Tankersley record was converted to the upstream location by multiplying a ratio of the contributing areas. For the South Concho River basin, diversion from the South Concho Irrigation Company's irrigation canal was added to the measured streamflow values. For the precipitation data, relatively complete measurements within the Middle and South Concho basins did not start until 1940's. Mean monthly rainfall difference from 1941 to 2002 between South Concho and North Concho River basin is less than 2 mm, with standard deviation of 28 mm. Therefore, spatially averaged data from North Concho Basin study was used in long-term comparison.

For the regional streamflow analysis, all the USGS streamflow records across western Texas were examined. Comparisons were done among the stations with comparable and relatively complete record.

Nonparametric Mann-Kendall test is used to detect trend. A detailed description about this test can be found in Chapter III. Since the Sen slope estimation is dependent on the units of measurements, a normalized Sen slope estimation is proposed and used to facilitate trend comparison between basins. A normalized Sen slope is the Sen slope divided by the central tendency of the original dataset. In our study, median is used to represent the central tendency because most of the distributions are skewed due to the presence of extreme events.

Results

North, Middle and South Concho River Basin comparison

Comparison of annual streamflow and baseflow from three stations in Concho River basin can be found in Figure 24 and 25. The means of streamflow for the common period (1931 to 1994) are 8.1, 6.7, and 34.3 mm/year for North, Middle and South Concho River basins, respectively. The means of baseflow are 0.8, 1.3, and 20.7 mm/year, respectively. Although they are close to each other and subject to similar precipitation inputs, streamflow productions from North and Middle Concho are much less than in South Concho River basin. However, a positive gradient of baseflow production can be seen from the North to the South.

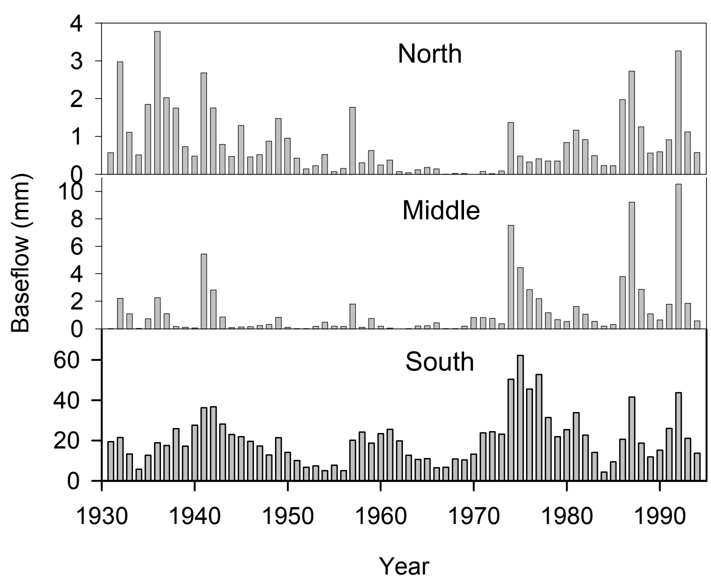

Figure 24. Annual mean baseflow in North (Carlsbad), Middle (Tankersley) and South (Christoval) Concho River basins. Scales are different for each plot.

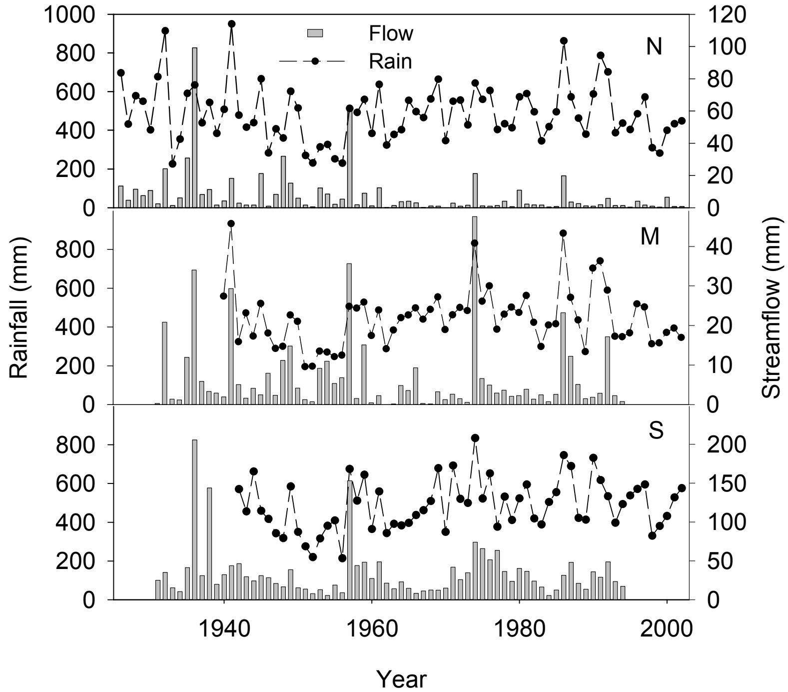

Figure 25. Annual total streamflow and precipitation in North, Middle and South Concho River basins. Basin-wide precipitation is obtained using Thiessen polygon method. Annual streamflow data reflects USGS Carlsbad, Tankersley and Christoval gauging station for North, Middle, and South Concho, respectively.

In order to better account for climate variability and drought effect, Table 7 provides a 18-year comparison between period A (1931 to 1949, excluding 1936 in which year an extreme flooding event occurred) and B (1977 to 1994). The comparison indicates significantly decreasing rate of reduction in streamflow from North to South Concho River basin. In contrast, baseflow component did not change parallel to the change of streamflow.

Table 7. Eighteen years mean of annual rainfall and runoff in North, Middle and South Concho River basins in periods A (1931-1949, excluding 1936) and B (1997-1994).

	North Concho			Middle Concho			South Concho		
Period	A	B	%	A	B	%	A	B	%
Rainfall (mm)	513	518	--	513	518	--	513	518	--
Streamflow (mm)	10.6	3.4	68	7.1	4.9	31	35.2	29.3	17
Baseflow (mm)	1.2	1.0	17	0.9	2.2	-144	21	24	-14
Runoff Ratio (%)	2.1	0.7	--	1.4	0.9	--	6.8	5.7	--

Comparison between those three basins indicates observations in North Concho River basin may not be fully extendable to other areas without considering additional factors. Streamflow in South Concho River basin is at least four times and baseflow 20 times higher than in North Concho River basin. While baseflow account for 16% of streamflow in North Concho River basin, it is 70% in South Concho River basin. We attribute this difference mainly to the South Concho River's better contact with the Edwards group – permeable limestone and dolomite. This geologic feature allows the South Concho River to exchange directly with regional groundwater of Edwards-Trinity aquifer.

The interaction between surface water and groundwater in South Concho River basin was investigated by evaluating 17 well hydrographs. Groundwater storage was affected by 1950's drought but was quickly recovered (Figure 26). Compare to the deep well in North Concho River basin study, the groundwater levels in this well respond very quickly to precipitation inputs and fluctuate in a smaller range. Annual cycle was lacking.

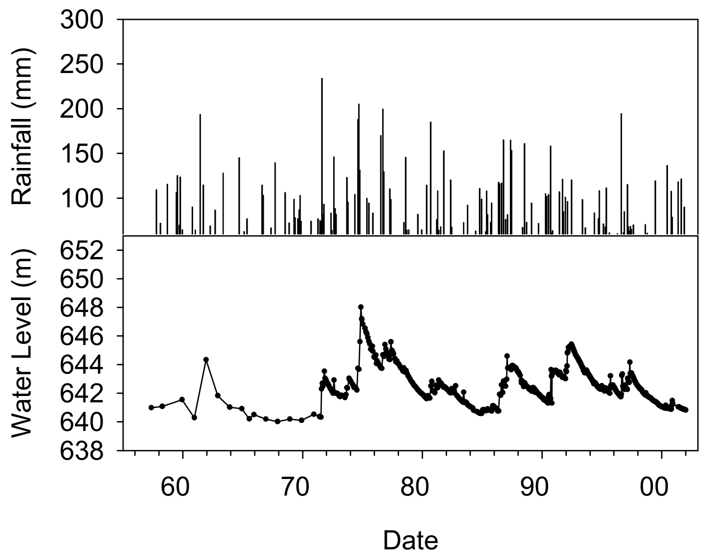

Figure 26. Monthly rainfall input and groundwater level fluctuation in a well (Lat/Long: 31.0075/-100.4963889) that penetrating to the Edwards and Associated Limestones formation in South Concho River basin. Only months with rainfall greater than 60 mm are shown. The rainfall data is spatial averaged data in the South Concho River basin above Christoval streamflow gauging station. Well depth is about 53 m and the depth to water level is more than 21 m from the land surface during the period of measurements. The well is located in Schleicher County, TX.

The comparison validates our conclusion from North Concho River basin study – it is the main change in soil infiltration capacity of the soil and/or groundwater storage that is mainly responsible for change in streamflow. Increased ET from increased coverage of woody plants, if any, seems to have small influence in streamflow. The combination of soil and geological conditions render streamflow in South Concho River much more resilient to surface disturbances (such as soil and vegetation changes).

The surface drainage in the Edwards Plateau region often has similar soil and geological conditions as in South Concho River basin. Do we see difference in streamflow responses in the Edwards Plateau area, which is dominated by karst terrain, and other regions? In order to evaluate this hypothesis, streamflow trend test is extended to the entire western Texas.

Spatial patterns of Western Texas streamflow change

We examined all the available USGS flow records across western Texas, about 393 stations in eight river basins. We took a detailed look at the stations with flow record that goes back to 1950 or earlier. We further removed stations with record length less than 30 years or canal stations (for diversion measurements). This leaves us a total of 72 stations. Trend test for those 72 stations is shown in Table 8 sorted by normalized Sen slope. In Canadian, Brazos (watershed upstream of Waco, TX), Colorado (watershed upstream of Austin, TX) and Rio Grande River basins, we see similar declining patterns in most headwater catchments. Such effects diminish as we move further downstream. However, few watersheds show decreasing flow as dramatic as in

North Concho; for those that do (such as Colorado River at Robert Lee of Texas, Canadian River near Canadian of Texas, or Colorado River near Ballinger of Texas), dam constructions confound the effects. In contrast, we rarely see any footprints in basins in the Edwards Plateau region, such as Guadalupe, San Antonio, and Nueces River basins. On the contrary, flows in some basins are increasing.

Table 8. Trend test on western Texas streamflow. The station name is a short name following the USGS gauging station naming convention. Length is the number of years of record for particular station. Table is sorted by normalized Sen Slope (Norm Sen). Area: drainage area in km2. The full station name and corresponding ID can be found in appendix B Table B-1.

ID	Station name	Length	Trend	Period	Norm Sen	Basin
1	Colorado Rv at Robert Lee	55	Decreasing	1924-2003	-0.11502	Colorado
2	Canadian Rv nr Canadian	63	Decreasing	1939-2003	-0.03568	Canadian
3	N Concho Rv nr Carlsbad	79	Decreasing	1925-2003	-0.03286	Colorado
4	Colorado Rv nr Ballinger	96	Decreasing	1908-2003	-0.03082	Colorado
5	Concho Rv at San Angelo	88	Decreasing	1916-2003	-0.02897	Colorado
6	N Concho Rv at Sterling City	45	Decreasing	1940-1984	-0.02363	Colorado
7	Colorado Rv at Colorado City	58	Decreasing	1924-2003	-0.02258	Colorado
8	Colorado Rv at Winchell	69	Decreasing	1924-2003	-0.02166	Colorado
9	Pecan Bayou at Brownwood	57	Decreasing	1924-1982	-0.01893	Colorado
10	Concho Rv at Paint Rock	88	Decreasing	1916-2003	-0.01782	Colorado
11	Salt Fk Brazos Rv nr Aspermont	65	Decreasing	1924-2003	-0.01727	Brazos
12	Canadian Rv nr Amarillo	65	Decreasing	1939-2003	-0.01612	Canadian
13	Clear Fk Brazos Rv at Nugent	79	Decreasing	1925-2003	-0.01586	Brazos
14	Pecos Rv nr Orla	66	Decreasing	1938-2003	-0.01554	Rio Grande
15	Devils Rv nr Juno	32	Decreasing	1926-1972	-0.01443	Rio Grande
16	Pecos Rv nr Girvin	64	Decreasing	1940-2003	-0.01296	Rio Grande
17	Nueces Rv nr Mathis	64	Decreasing	1940-2003	-0.01147	Nueces
18	Colorado Rv nr San Saba	84	Decreasing	1916-2003	-0.01044	Colorado
19	Brazos Rv nr Palo Pinto	79	Decreasing	1925-2003	-0.01001	Brazos
20	DMF Brazos Rv nr Aspermont	74	Decreasing	1924-2003	-0.00956	Brazos
21	Mid Concho Rv Tankersley	63	Insignificant	1931-1994	-0.00907	Colorado
22	Brazos Rv at Seymour	80	Decreasing	1924-2003	-0.00851	Brazos
23	Brazos Rv nr Glen Rose	80	Decreasing	1924-2003	-0.00812	Brazos
24	Brazos Rv nr South Bend	65	Decreasing	1939-2003	-0.00806	Brazos
25	Clear Fk Brazos Rv at Ft Griffin	79	Decreasing	1925-2003	-0.00796	Brazos
26	Nueces Rv nr Tilden	61	Insignificant	1943-2003	-0.00692	Nueces
27	Clear Fk Brazos Rv at Eliasville	47	Insignificant	1916-1981	-0.00603	Brazos
28	Brazos Rv nr Aquilla	65	Insignificant	1939-2003	-0.00517	Brazos
29	Colorado Rv at Austin	104	Decreasing	1899-2003	-0.00513	Colorado
30	San Saba Rv at San Saba	83	Decreasing	1916-2003	-0.00434	Colorado
31	Nueces Rv nr Three Rivers	88	Insignificant	1916-2003	-0.00419	Nueces
32	San Saba Rv at Menard	83	Insignificant	1916-2003	-0.00404	Colorado

Table 8. Continued,

ID	Station name	Length	Trend	Period	Norm Sen	Basin
33	Wichita Rv at Wichita Falls	65	Insignificant	1939-2003	-0.00383	Red
34	Nueces Rv at Cotulla	77	Insignificant	1927-2003	-0.00381	Nueces
35	Pinto Ck nr Del Rio	41	Insignificant	1929-1971	-0.00363	Rio Grande
36	Brazos Rv at Waco	104	Insignificant	1899-2003	-0.00351	Brazos
37	Elm Ck at Ballinger	71	Insignificant	1933-2003	-0.00349	Colorado
38	N Llano Rv nr Junction	63	Insignificant	1916-2003	-0.00251	Colorado
39	San Antonio Rv at San Antonio	68	Insignificant	1918-1996	-0.00202	San Antonio
40	Atascosa Rv at Whitsett	71	Insignificant	1933-2003	-0.00168	Nueces
41	S Concho Rv at Christoval	66	Insignificant	1931-2003	-0.00125	Colorado
42	Red River nr Denison	70	Insignificant	1924-2003	-0.00012	Red
43	Comal Spgs at New Braunfels	71	Insignificant	1933-2003	-0.00008	Guadalupe
44	Comal Rv at New Braunfels	71	Insignificant	1933-2003	0.00036	Guadalupe
45	Aquilla Ck nr Aquilla	62	Insignificant	1939-2000	0.00104	Brazos
46	N Tule Draw at Res nr Tulia	30	Insignificant	1941-1972	0.00110	Red
47	USIBW Alamito Ck nr Presidio	39	Insignificant	1932-1971	0.00140	Rio Grande
48	N Bosque Rv nr Clifton	80	Insignificant	1924-2003	0.00145	Brazos
49	Nueces Rv nr Asherton	64	Insignificant	1940-2003	0.00303	Nueces
50	Llano Rv nr Junction	83	Insignificant	1916-2003	0.00445	Colorado
51	Guadalupe Rv at Victoria	69	Insignificant	1935-2003	0.00476	Guadalupe
52	Red Rv nr Terral, OK	65	Insignificant	1939-2003	0.00512	Red
53	Cibolo Ck nr Falls City	73	Insignificant	1931-2003	0.00521	San Antonio
54	Plum Ck nr Luling	64	Insignificant	1931-2003	0.00579	Guadalupe
55	Llano Rv at Llano	63	Insignificant	1940-2003	0.00620	Colorado
56	Frio Rv nr Derby	88	Increasing	1916-2003	0.00655	Nueces
57	San Marcos Rv at Luling	64	Insignificant	1940-2003	0.00692	Guadalupe
58	Nueces Rv at Laguna	80	Increasing	1924-2003	0.00825	Nueces
59	Pedernales Rv nr Johnson City	64	Increasing	1940-2003	0.00890	Colorado
60	Blanco Rv at Wimberley	75	Increasing	1929-2003	0.00924	Guadalupe
61	Guadalupe Rv at New Braunfels	76	Increasing	1928-2003	0.00979	Guadalupe
62	Frio Rv at Concan	78	Increasing	1924-2003	0.01002	Nueces
63	Guadalupe Rv nr Spring Branch	81	Increasing	1923-2003	0.01069	Guadalupe
64	San Antonio Rv at Goliad	68	Increasing	1925-2003	0.01123	San Antonio
65	Cibolo Ck at Selma	57	Increasing	1947-2003	0.01175	San Antonio
66	San Antonio Rv nr Falls City	78	Increasing	1926-2003	0.01433	San Antonio
67	Guadalupe Rv at Comfort	64	Increasing	1940-2003	0.01535	Guadalupe
68	Sabinal Rv nr Sabinal	61	Increasing	1943-2003	0.01833	Nueces
69	Nueces Rv bl Uvalde	64	Increasing	1940-2003	0.02044	Nueces
70	Medina Rv at San Antonio	63	Increasing	1940-2003	0.02372	San Antonio
71	Medina Rv nr Pipe Creek	41	Increasing	1923-1981	0.02449	San Antonio
72	Johnson Ck nr Ingram	52	Increasing	1942-2003	0.02510	Guadalupe

Conclusions

Grazing trends and increased woody plant coverage have been common across western Texas and they generally follow a similar pattern as in Concho area. However, comparison between North, Middle, and South Concho indicates what was happening in North Concho River basin may not be fully extendable to other areas without considering additional factors that affect watershed runoff. The main difference between North and South Concho basin may have been different runoff mechanism as imposed by different soil and geological conditions. Further exploration of the entire western Texas streamflow trend validates such hypothesis. There is also a possibility that North Concho basin is closely tied to the headwater area of groundwater so it is sensitive to change.

Although more detailed hydrologic analysis is needed to evaluated the magnitude of change, similar footprints found in Canadian basin (such as Colorado River at Robert Lee of Texas, Canadian River near Canadian of Texas, or Colorado River near Ballinger of Texas) suggest what has happened in North Concho is not an isolated case.

CHAPTER VI

SUMMARY

Major Findings

This study uses a variety of approaches across multiple temporal and spatial scales to investigate the relationship of runoff and land cover in drylands of western Texas. The methods include field experimental study, tracer application, historical precipitation-streamflow analysis, and regional streamflow trend assessment. The spatial scales encompass small headwater catchment (19 ha), individual river basin, multiple river basins, and the entire western Texas.

Runoff in dryland regions is generally dominated by a few large runoff-producing events. In Honey Creek catchment, about half of total runoff comes from the largest four events during the four monitoring years. In North Concho River basin, the largest six events account for 38% of total runoff during 77 years monitoring. The noticeable difference is in baseflow component. While baseflow contributes to half of runoff in Honey Creek catchment, only 8% of runoff can be attributed to baseflow in North Concho River basin. However, the percentage is 19% and 60% for the Middle and South Concho River basin, respectively. This suggests strong control of geological settings on baseflow production.

The small scale watershed experiment conducted at Honey Creek upland catchment shows a signal of increased runoff (about 40 mm per year) following removal of about 60% of the Juniper trees. Such manifested effect may be related to the presence of spring flow or baseflow. The 20% runoff ratio in this catchment compares very favorably to other catchments where baseflow component is lacking. The isotope hydrograph separation suggests higher percentage of pre-event water contribution in a winter storm (40%) than in a summer storm (16%). Subsurface flow is very dynamic in this landscape.

Hydrochemical analysis indicates strong exchange of water fluxes between the upland catchment and the bottomland creek. The rapid recharge components could successfully bypass vadose zone and reach the groundwater table or bottomland stream channel. However, this direct relationship may not exist if it were not because of its karst geology. The isotope data for the seep water in the upland catchment points to the possibilities that woody plants have the abilities to develop a moisture reservoir. This moisture reservoir may provide sustainable moisture supply for the woody vegetation communities in this landscape.

Detailed analysis of North Concho River basin streamflow indicates a significant reduction in streamflow that is beyond climate variation but relates to the change in watershed conditions. The evidence is more consistent with the hypothesis that the reduced streamflow is a result of enhanced infiltration from better vegetation cover due to reduced grazing and better land management. Unsustainable groundwater use may also contribute to the low flow.

The comparison between North, Middle and South Concho Rive basins indicates the North Concho model may not be fully extendable to other areas without considering additional factors. Those additional factors may include soil and geological conditions that greatly influence watershed streamflow production, erosion potential and sensitivity of response to land management. The regional trend analysis confirmed the conclusion we drew in the North Concho study and revealed important spatial patterns. In the Edwards plateau region, which is dominated by karst geology, it is clear the response was not evident. In other regions, especially in the headwater areas, the decrease of streamflow is manifested. Among them, few basins show as dramatic a change in streamflow as the North Concho. Further studies considering dam effects on water balance could elucidate additional information.

Collectively, the cross-examination in this study indicates contradictory results on the surface. While the catchment study suggests a signal when baseflow is present, the regional assessment indicates no change of streamflow in the Edwards Plateau region, where most rivers have a spring flow component. One explanation is the influence of urbanization on the river flows in the Edwards Plateau region, which confounded the comparison. Another explanation is when we scale up and when the land cover change is gradual, the effect diminishes. Some headwater catchments showed responses to the change in watershed conditions. As indicated in the North Concho study, this may not be related to the vegetation change alone. Detailed study of those watersheds that exhibit some responses will reveal additional information.

Suggestions for Future Research

Carefully laid-out catchment studies have provided information otherwise not available. A robust conclusion requires longer calibration time as well as longer post-treatment monitoring, especially in dryland regions where climate variability is high. Isotope hydrograph separation can be improved by sampling rainfall sequentially (Weiler *et al.*, 2003).

As finer time scale precipitation and streamflow data is increasingly available, the investigation of rainfall-runoff relationship can be improved. For example, precipitation intensity can be explicitly incorporated into rainfall-runoff model. Rainfall-runoff events can be delineated more precisely.

The basic groundwater physical parameter, such as water level data, can complement many hydrologic studies. Those measurements have received little attention compared to surface-water monitoring network. In hydrologic studies, it is very likely surface water and groundwater problems are correlated. Currently, there is no other means to reproduce such information despite the advances in computer modeling, age dating and tracing in groundwater study.

As mentioned above, further study can be directed to analyze historical streamflow record. Flow diversion, dam, and urbanization can be factored into the model to evaluate the change (Burns *et al.*, 2005; Claessens *et al.*, 2006; Rose and Peters, 2001; Ye *et al.*, 2003). However, in doing this, the uncertainty should be explicitly specified.

Understanding the relationship between land cover and water cycle is the key to understanding the interaction between biosphere and hydrosphere, where ecohydrology is rooted. The scale dependence of hydrologic effects demands us to explicitly recognize and describe different watershed responses at different scale of observations. Process-based investigations at controllable scales and classification and pattern recognition at a scale when integrated variable is representative will advance our basic understanding of the relationship between land cover and water cycle.

REFERENCES

Andreassian V. 2004. Waters and forests: from historical controversy to scientific debate. *Journal of Hydrology* **291**: 1-27.

Archer S. 1994. Woody plant encroachment into southwestern grasslands and savannas: Rates, patterns and proximate causes. In *Ecological Implications of Livestock Herbivory in the West,* Vavra M, Laycock WA, Pieper RD (eds). Society for Range Management: Denver, CO; 13-68.

Archer S, Boutton TW, Hibbard KA. 2001. Trees in grasslands: Biogeochemical consequences of woody plant expansion. In *Global Biogeochemical Cycles in the Climate System*. Academic Press: Durham, NC; 115-138.

Arnell NW. 1999. Climate change and global water resources. *Global Environmental Change* **9**: S31– S49.

Arnold JG, Allen PM. 1999. Automated methods for estimating baseflow and ground water recharge from streamflow records. *Journal of the American Water Resources Association* **35**: 411-424.

Arnold JG, Allen PM, Muttiah R, Bernhardt G. 1995. Automated base flow separation and recession analysis techniques. *Ground Water* **33**: 1010-1018.

Ashworth JB. 1983. Ground-water availability of the lower cretaceous formations in the hill country of south-central Texas. Texas Department of Water Resources: Austin, TX.

Asner GP, Archer S, Hughes RF, Ansley RJ, Wessman CA. 2003. Net changes in regional woody vegetation cover and carbon storage in Texas Drylands, 1937-1999. *Global Change Biology* **9**: 316-335.

Asner GP, Elmore AJ, Olander LP, Martin RE, Harris AT. 2004. Grazing systems, ecosystem responses, and global change. *Annual Review of Environment and Resources* **29**: 261-299.

Baker MB. 1984. Changes in streamflow in an herbicide-treated pinyon-juniper watershed in Arizona. *Water Resources Research* **20**: 1639-1642.

Barnes VE. 1976. Geologic Atlas of Texas, Pecos Sheet. Bureau of Economic Geology, The University of Texas at Austin.

Bergkamp G. 1998. A hierarchical view of the interactions of runoff and infiltration with vegetation and microtopography in semiarid shrublands. *Catena* **33**: 201-220.

Bewket W, Sterk G. 2005. Dynamics in land cover and its effect on stream flow in the Chemoga watershed, Blue Nile basin, Ethiopia. *Hydrological Processes* **19**: 445-458.

Blackburn WH, Knight RW, Wood MK. 1982. Impact of grazing on watersheds: a state of knowledge. Texas Agricultural Experiment Station: College Station, TX;1-32.

Bosch JH, Hewlett JD. 1982. A review of catchment experiments to determine the effect of vegetation changes and water yield and evapotranspiration. *Journal of Hydrology* **55**: 3-23.

Bowerman BL, O'Connell RT. 1979. *Time Series and Forecasting: An Applied Approach*. Duxbury Press: North Scituate, MA.

Briske DD, Fuhlendorf SD, Smeins FE. 2003. Vegetation dynamics on rangelands: a critique of the current paradigms. *Journal of Applied Ecology* **40**: 601–614.

Bruijnzeel LA. 2004. Hydrological functions of tropical forests: not seeing the soil for the trees? *Agriculture Ecosystems & Environment* **104**: 185-228.

Brune G. 2002. *Springs of Texas*. Texas A&M University Press: College Station, TX; 590.

Burn DH, Hag Elnur MA. 2002. Detection of hydrologic trends and variability. *Journal of Hydrology* **255**: 107-122.

Burns D, Vitvar T, McDonnell J, Hassett J, Duncan J, Kendall C. 2005. Effects of suburban development on runoff generation in the Croton River basin, New York, USA. *Journal of Hydrology* **311**: 266-281.

Buttle JM. 1994. Isotope hydrograph separations and rapid delivery of pre-event water from drainage basins. *Progress in Physical Geography* **18**: 16-41.

Castillo VM, Martinezmena M, Albaladejo J. 1997. Runoff and soil loss response to vegetation removal in a semiarid environment. *Soil Science Society of America Journal* **61**: 1116-1121.

Chang M, Sayok AK. 1990. Hydrological responses to urbanization in forested La Nana Creek watershed, Nacogdoches, Texas. In *Tropical Hydrology and Caribbean Water Resources, Proceeding of American Water Resources Association*. Herndon, VA; 131-140.

Claessens L, Hopkinson C, Rastetter E, Vallino J. 2006. Effect of historical changes in land use and climate on the water budget of an urbanizing watershed. *Water Resources Research* **42**.

Cochrane D, Orcutt GH. 1949. Application of least squares relationships containing autocorrelated error terms. *Journal of the American Statistical Association* **44**: 32-61.

Coplen TB. 1988. Normalization of oxygen and hydrogen isotope data. *Chemical Geology* **72**: 293-297.

Cornish PM. 1993. The effects of logging and forest regeneration on water yields in a moist eucalypt forest in New South Wales, Australia. *Journal of Hydrology* **150**: 301-322.

Costa AA, Cotton WR, Walko RL, Pielke RA. 2001. Coupled ocean-cloud-resolving simulations of the air-sea interaction over the equatorial western Pacific. *Journal of the Atmospheric Sciences* **58**: 3357-3375.

Costa MH, Botta A, Cardille JA. 2003. Effects of large-scale changes in land cover on the discharge of the Tocantins River, Southeastern Amazonia. *Journal of Hydrology* **283**: 206-217.

Cramer VA, Thorburn PJ, Fraser GW. 1999. Transpiration and groundwater uptake from farm forest plots of Casuarina glauca and Eucalyptus camaldulensis in saline areas of southeast Queensland, Australia. *Agricultural Water Management* **39**: 187-204.

Davis JD, Brook GA. 1981. Hydrology and water chemistry of upper Sinking Cove, Franklin County, Tennessee. In *Proceedings of the 8th International Congress of Speleology,* Beck BF (ed). National Speleological Society: Huntsville, AL; 38-41.

Dewalle DR, Edwards PJ, Swistock BR, Aravena R, Drimmie RJ. 1997. Seasonal isotope hydrology of three Appalachian forest catchments. *Hydrological Processes* **11**: 1895-1906.

Donkor NT, Gedir JV, Hudson RJ, Bork EW, Chanasyk DS, Naeth MA. 2002. Impacts of grazing systems on soil compaction and pasture production in Alberta. *Canadian Journal of Soil Science* **82**: 1-8.

Douglas EM, Vogel RM, Kroll CN. 2000. Trends in floods and low flows in the United States: impact of spatial correlation. *Journal of Hydrology* **240**: 90-105.

Duan N. 1983. Smearing estimate: a nonparametric retransformation method. *Journal of the American Statistical Association* **73**: 605-610.

Dugas WA, Hicks RA, Wright P. 1998. Effect of removal of *Juniperus ashei* on evapotranspiration and runoff in the Seco Creek watershed. *Water Resources Research* **34**: 1499-1506.

DuMars CT, Minier JD. 2004. The evolution of groundwater rights and groundwater management in New Mexico and the western United States. *Hydrogeology Journal* **12**: 40-51.

Evans R. 1998. The erosional impacts of grazing animals. *Progress in Physical Geography* **22**: 251-268.

Finlay JC. 2003. Controls of streamwater dissolved inorganic carbon dynamics in a forested watershed. *Biogeochemistry* **62**: 231-252.

Foley JA, DeFries R, Asner GP, Barford C, Bonan G, Carpenter SR, Chapin FS, Coe MT, Daily GC, Gibbs HK, Helkowski JH, Holloway T, Howard EA, Kucharik CJ, Monfreda C, Patz JA, Prentice IC, Ramankutty N, Snyder PK. 2005. Global consequences of land use. *Science* **309**: 570-574.

Frederickson GC, Criss RE. 1999. Isotope hydrology and time constants of the unimpounded Meramec River basin, Missouri. *Chemical Geology* **157**: 303-317.

Gan TY. 1998. Hydroclimatic trends and possible climatic warming in the Canadian Prairies. *Water Resources Research* **34**: 3009-3015.

Gifford GF. 1978. Hydrologic impact of grazing on infiltration: a critical review. *Water Resources Research* **14**: 305-313.

Gordon WS, Famiglietti JS, Fowler NL, Kittel TGF, Hibbard KA. 2004. Validation of simulated runoff from six terrestrial ecosystem models: results from VEMAP. *Ecological Applications* **14**: 527-545.

Harr RD, Levno A, Mersereau R. 1982. Streamflow changes after logging 130-year-old Douglas Fir in two small watersheds. *Water Resources Research* **18**: 637-644.

Heathwaite AL, Burt TP, Trudgill S. 1990. The effect of land use on nitrogen, phosphorus and suspended sediment delivery to streams in a small catchment in southwest England. In *Vegetation and Erosion,* Thornes JB (ed). Wiley: Chichester, England; 161-177.

Hester JW, Thurow TL, Taylor CA. 1997. Hydrologic characteristics of vegetation types as affected by prescribed burning. *Journal of Range Management* **50**: 199-204.

Hibbard KA, Schimel DS, Archer S, Ojima DS, Parton W. 2003. Grassland to woodland transitions: integrating changes in landscape structure and biogeochemistry. *Ecological Applications* **13**: 911-926.

Hibbert AR. 1983. Water yield improvement potential by vegetation management on western rangelands. *Water Resources Bulletin* **19**: 375-381.

Hill J, Hostert P, Tsiourlis G, Kasapidis P, Udelhoven T, Diemer C. 1998. Monitoring 20 years of increased grazing impact on the Greek island of Crete with earth observation satellites. *Journal of Arid Environments* **39**: 165-178.

Huang MB, Zhang L. 2004. Hydrological responses to conservation practices in a catchment of the Loess Plateau, China. *Hydrological Processes* **18**: 1885-1898.

Huang Y, Wilcox BP, Stern L, Perotto H. 2006. Springs on rangelands: runoff dynamics and influence of woody plant cover. *Hydrological Processes* **20**: In press.

Huxman TE, Wilcox BP, Breshears DD, Scott RL, Snyder KA, Small EE, Hultine K, Pockman WT, Jackson RB. 2005. Ecohydrological implications of woody plant encroachment. *Ecology* **86**: 308-319.

Jackson RB, Jobbagy EG, Avissar R, Roy SB, Barrett DJ, Cook CW, Farley KA, le Maitre DC, McCarl BA, Murray BC. 2005. Trading water for carbon with biological sequestration. *Science* **310**: 1944-1947.

Jakeman AJ, Hornberger GM. 1993. How much complexity is warranted in a rainfall-runoff model. *Water Resources Research* **29**: 2637-2649.

Jobbagy EG, Jackson RB. 2004. Groundwater use and salinization with grassland afforestation. *Global Change Biology* **10**: 1299-1312.

Joffre R, Rambal S. 1993. How tree cover influences the water balance of Mediterranean rangelands. *Ecology* **74**: 570-582.

Kahya E, Kalayci S. 2004. Trend analysis of streamflow in Turkey. *Journal of Hydrology* **289**: 128-144.

Kendall C, McDonnell JJ. 1998. *Isotope Tracers in Catchment Hydrology*. Elsevier: Amsterdam, The Netherlands; 837.

Kendall MG. 1975. *Rank Correlation Methods*. Charles Griffin: London.

Keppler ET, Ziemer RR. 1990. Logging effects on streamflow: water yield and summer low flows at Caspar Creek in Northwestern California. *Water Resources Research* **26**: 1669-1679.

Kiely G. 1999. Climate change in Ireland from precipitation and streamflow observations. *Advances in Water Resources* **23**: 141-151.

Kramer CY. 1956. Extension of multiple range tests to group means with unequal numbers of replications. *Biometrics* **12**: 307 -310.

Larkin TJ, Bomar GW. 1983. Climatic Atlas of Texas. Texas Department of Water Resources;151.

Lettenmaier DP, Wood EF, Wallis JR. 1994. Hydro-Climatological trends in the continental United States, 1948-88. *Journal of Climate* **7**: 586-607.

Mace RE, Chowdhury AH, Anaya R, Way S-CT. 2000. Groundwater Availability of the Trinity Aquifer, Hill Country Area, Texas: Numerical Simulations through 2050. Texas Water Development Board: Austin.

Malmstrom VH. 1969. A new approach to the classification of climate. *Journal of Geography* **68**: 351-357.

Maloszewski P, Rauert W, Trimborn P, Herrmann A, Rau R. 1992. Isotope hydrological study of mean transit times in an alpine basin (Wimbachtal, Germany). *Journal of Hydrology* **140**: 343-360.

Mann HB. 1945. Non-parametric tests against trend. *Econometrica* **13**: 245-259.

Maxwell TC. 1979. Avifauna of the Concho valley of West-Central Texas with special reference to historical change In *Rangeland Ecology and Management*. Texas A&M University: College Station.

Mazor E. 1991. *Applied Chemical and Isotopic Groundwater Hydrology*. John Wiley & Sons: New York.

McCabe GJ, Clark MP. 2005. Trends and variability in snowmelt runoff in the western United States. *Journal of Hydrometeorology* **6**: 476-482.

McCole AA. 2004. Seasonal water usage by Juniperus ashei: assessment with stable isotopes of hydrogen and oxygen In *Department of Geosciences*. The University of Texas at Austin;97.

McGuire KJ, DeWalle DR, Gburek WJ. 2002. Evaluation of mean residence time in subsurface waters using oxygen-18 fluctuations during drought conditions in the mid-Appalachians. *Journal of Hydrology* **261**: 132-149.

Merzougui M, Gifford GF. 1987. Spatial variability of infiltration rates on a semiarid seeded rangeland. *Hydrological Sciences Journal-Journal des Sciences Hydrologiques* **32**: 243-250.

Middleton NJ, Thomas DSG. 1997. *World Atlas of Desertification*. Edward Arnold: London; 182.

Neal C, Neal M, Warrington A, Avila A, Pinol J, Roda F. 1992. Stable hydrogen and oxygen isotope studies of rainfall and streamwaters for two contrasting holm oak areas of Catalonia, northeastern Spain. *Journal of Hydrology* **140**: 163-178.

Neff JC, Reynolds RL, Belnap J, Lamothe P. 2005. Multi-decadal impacts of grazing on soil physical and biogeochemical properties in southeast Utah. *Ecological Applications* **15**: 87-95.

Newman BD, Campbell AR, Wilcox BP. 1997. Tracer-based studies of soil water movement in semi-arid forests of New Mexico. *Journal of Hydrology* **196**: 251-270.

Newman BD, Campbell AR, Wilcox BP. 1998. Lateral subsurface flow pathways in a semiarid ponderosa pine hillslope. *Water Resources Research* **34**: 3485-3496.

Nolan KM, Hill BR. 1990. Storm runoff generation in the Permanente Creek drainage basin, west central California: an example of flood-wave effects on runoff composition. *Journal of Hydrology* **113**: 343-367.

Owens KW, Ansley J. 1997. Ecophysiology and growth of Ashe and redberry juniper. In *Juniper Symposium,* Taylor CA (ed). Texas A&M University: San Angelo, TX; 19-31.

Owens KW, Lyons RK. 2004. Evaporation and interception water loss from juniper communities on the Edwards Aquifer Recharge area. Texas A&M University Systems;1-13.

Pereira HC. 1979. *Land Use and Water Resources in Temperate and Tropical Climates*. Cambridge University Press: London; 232.

Pierson FB, Blackburn WH, Vanvactor SS, Wood JC. 1994. Partitioning small scale spatial variability of runoff and erosion on sagebrush rangeland. *Water Resources Bulletin* **30**: 1081-1089.

Pietola L, Horn R, Yli-Halla M. 2005. Effects of trampling by cattle on the hydraulic and mechanical properties of soil. *Soil & Tillage Research* **82**: 99-108.

Pitt MD, Burgy RH, Heady HF. 1978. Influences of brush conversion and weather patterns on runoff from a northern California watershed. *Journal of Range Management* **31**: 23-27.

Potter KW. 1991. Hydrological impacts of changing land management proctices in a moderate-sized agricultural catchment. *Water Resources Research* **27**: 845-855.

Potts DF. 1984. Hydrologic impacts of large-scale mountain pine beetle (*Dendroctonus Ponderosa Hopkins*) epidemic. *Water Resources Bulletin* **20**: 373-377.

Robinson M, Cognard-Plancq A-L, Cosandey C, David J, Durand P, Fu¨hrer H-W, Hall R, Hendriques MO, Marc V, McCarthy R, McDonnell M, Martin C, Nisbet T, O'Dea P, Rodgers M, Zollner A. 2003. Studies of the impact of forests on peak flows and baseflows: a European perspective. *Forest Ecology & Management* **186**: 85-97.

Rose S, Peters NE. 2001. Effects of urbanization on streamflow in the Atlanta area (Georgia, USA): a comparative hydrological approach. *Hydrological Processes* **15**: 1441-1457.

Sandstrom K. 1996. Hydrochemical deciphering of streamflow generation in semi-arid East Africa. *Hydrological Processes* **10**: 703-720.

Sartz RS, Tolsted DN. 1974. Effect of grazing on runoff from two small watersheds in southwestern Wisconsin. *Water Resources Research* **10**: 354-356.

Sauer SP. 1972. Factors contributing to unusually low runoff during the period of 1962-68 in the Concho River Basin, Texas. United States Geological Survey;48.

Scanlon BR, Reedy RC, Stonestrom DA, Prudic DE, Dennehy KF. 2005. Impact of land use and land cover change on groundwater recharge and quality in the southwestern US. *Global Change Biology* **11**: 1577-1593.

Schlesinger WH, Abrahams AD, Parsons AJ, Wainwright J. 1999. Nutrient losses in runoff from grassland and shrubland habitats in Southern New Mexico: I. rainfall simulation experiments. *Biogeochemistry* **45**: 21-34.

Schlesinger WH, Reynolds JF, Cunningham GL, Huenneke LF, Jarrell WM, Virginia RA, Whitford WG. 1990. Biological feedbacks in global desertification. *Science* **247**: 1043-1048.

Schreider SY, Jakeman AJ, Letcher RA, Nathan RJ, Neal BP, Beavis SG. 2002. Detecting changes in streamflow response to changes in nonclimatic catchment conditions: farm dam development in the Murray-Darling basin, Australia. *Journal of Hydrology* **262**: 84-98.

Sen PK. 1968. Estimates of the regression coefficient based on Kendall's tau. *Journal of American Statistical Association* **39**: 1379-1389.

Seyfried MS. 1991. Infiltration patterns from simulated rainfall on a semiarid rangeland soil. *Soil Science Society of America Journal* **55**: 1726-1734.

Shuster ET, White WB. 1971. Seasonal fluctuations in the chemistry of limestone springs: a possible means for characterizing carbonate aquifers. *Journal of Hydrology* **14**: 93-128.

Smeins FE, Fuhlendorf SD, Taylor CA. 1997. Environmental and land use changes: a long-term perspective. In *Juniper Symposium*. Texas A&M University: San Angelo, TX; 1.3-1.21.

Soulsby C, Malcolm R, Helliwell R, Ferrier RC, Jenkins A. 2000. Isotope hydrology of the Allt a' Mharcaidh catchment, Cairngorms, Scotland: implications for hydrological pathways and residence times. *Hydrological Processes* **14**: 747-762.

Stednick JD. 1996. Monitoring the effects of timber harvest on annual water yield. *Journal of Hydrology* **176**: 79-95.

Stumm W, Morgan JJ. 1996. *Aquatic Chemistry*. Wiley: New York.

Taha A, Gresillon JM, Clothier BE. 1997. Modelling the link between hillslope water movement and stream flow: application to a small Mediterranean forest watershed. *Journal of Hydrology* **203**: 11-20.

Taylor CA, Jr., Kothmann MM. 1993. Managing stocking rates to achieve livestock production goals on the Edwards Plateau. In *Proceedings managing livestock stocking rates on rangeland,* Cox JR, Cadenhead JF (eds). Texas Agricultural Experiment Service: College Station, TX; 42-52.

Texas Water Development Board. 2005. Groundwater Database Reports, Accessed August 2005. http://www.twdb.state.tx.us/publications/reports/GroundWaterReports/GWDatabaseReports/GWdatabaserpt.htm.

Trimble SW, Mendel AC. 1995. The cow as a geomorphic agent - a critical review. *Geomorphology* **13**: 233-253.

Trimble SW, Weirich FH, Hoag BL. 1987. Reforestation and the reduction of water yield on the Southern Piedmont since circa 1940. *Water Resources Research* **23**: 425-437.

Troester JW, White WB. 1986. Geochemical investigations of three tropical karst drainage basins in Puerto Rico. *Ground Water* **24**: 475-482.

U.S. Department of Agriculture. 1976. Soil Survey of Tom Green County, Texas.

U.S. Department of Agriculture. 1984. *Soil Survey of Comal and Hays Counties, Texas*.

U.S. Department of Agriculture. 1996. San Marcos and Comal Springs and Associated Ecosystems (Revised) Recovery Plan. USFWS (United States Fish and Wildlife Service) Austin Ecological Services Station: Austin, TX;120.

U.S. Department of Agriculture. 2004. National Resources Inventory 2002 Land Use. Natural Resources Conservation Service;4.

Unnikrishna PV, McDonnell JJ, Kendall C. 2002. Isotope variations in a Sierra Nevada snowpack and their relation to meltwater. *Journal of Hydrology* **260**: 38-57.

Upper Colorado River Authority. 1998. North Concho River Watershed: Brush Control Planning, Assessment and Feasibility Study. Upper Colorado River Authority: San Angelo, TX;66.

Upper Colorado River Authority. 2000. Concho River & Upper Colorado River Basins Brush Control Feasibility Study. Upper Colorado River Authority, Texas State Soil & Water Conservation Board, and Texas A&M University: San Angelo, TX;1-198.

Van Auken OW. 2000. Shrub invasions of North American semiarid grasslands. *Annual Review of Ecology & Systematics* **31**: 197-215.

van de Koppel J, Rietkerk M, van Langevelde F, Kumar L, Klausmeier C. 2002. Spatial heterogeneity and irreversible vegetation change in semiarid grazing systems. *The American Naturalist* **159**: 209-218.

Van Lill WS, Kruger FJ, Van Wyk DB. 1980. The effect of afforestation with Eucalyptus grandis Hill ex Maiden and Pinus patula Schlecht. et Cham. on streamflow from experimental catchments at Mokobulaan, Transvaal. *Journal of Hydrology* **48**: 107-118.

Vitvar T, Burns DA, Lawrence GB, McDonnell JJ, Wolock DM. 2002. Estimation of baseflow residence times in watersheds from the runoff hydrograph recession: method and application in the Neversink watershed, Catskill Mountains, New York. *Hydrological Processes* **16**: 1871-1877.

Vorosmarty C, Lettenmaier D, Leveque C, et al. 2004. Humans transforming the global water system. *EOS* **85**: 509-520.

Walker J, Bullen F, Williams BG. 1993. Ecohydrological changes in the Murray-Darling Basin. I. The number of trees cleared over two centuries. *Journal of Applied Ecology* **30**: 265-273.

Warren SD, Blackburn WH, Taylor CA. 1986. Effects of season and stage of rotation cycle on hydrologic condition of rangeland under intensive rotation grazing. *Journal of Range Management* **39**: 486-491.

Weiler M, McGlynn BL, McGuire KJ, McDonnell JJ. 2003. How does rainfall become runoff? A combined tracer and runoff transfer function approach. *Water Resources Research* **39**.

Welker JM. 2000. Isotopic (delta O-18) characteristics of weekly precipitation collected across the USA: an initial analysis with application to water source studies. *Hydrological Processes* **14**: 1449-1464.

Wilcox BP. 2002. Shrub control and streamflow on rangelands: a process-based viewpoint. *Journal of Range Management* **55**: 318-326.

Wilcox BP, Newman BD, Brandes D, Davenport DW, Reid K. 1997. Runoff from a semiarid ponderosa pine hillslope in New Mexico. *Water Resources Research* **33**: 2301-2314.

Wilcox BP, Owens MK, Knight RW, Lyons RK. 2005. Do woody plants affect streamflow on semiarid karst rangelands? *Ecological Applications* **15**: 127-136.

Winston WE, Criss RE. 2004. Dynamic hydrologic and geochemical response in a perennial karst spring. *Water Resources Research* **40**.

Wright KA, Sendek KH, Rice RM, Thomas RB. 1990. Logging effects on streamflow: storm runoff at Caspar Creek in Northwestern California. *Water Resources Research* **26**: 1657-1667.

Wright PN. 1996. Spring enhancement in the Seco Creek water quality demonstration project. United States Department of Agriculture: Hondo, TX.

Xu HX. 2005. Temporal variation of river flow renewability in the middle Yellow River and the influencing factors. *Hydrological Processes* **19**: 1871-1882.

Ye BS, Yang DQ, Kane DL. 2003. Changes in Lena River streamflow hydrology: Human impacts versus natural variations. *Water Resources Research* **39**.

Zencich SJ, Froend RH, Turner JV, Gailitis V. 2002. Influence of groundwater depth on the seasonal sources of water accessed by Banksia tree species on a shallow, sandy coastal aquifer. *Oecologia* **131**: 8-19.

Zhang L, Dawes WR, Walker GR. 2001a. Response of mean annual evapotranspiration to vegetation changes at catchment scale. *Water Resources Research* **37**: 701-708.

Zhang X, Harvey KD, Hogg WD, Yuzyk TR. 2001b. Trends in Canadian streamflow. *Water Resources Research* **37**: 987–998.

APPENDIX A

Table A-1. Hydrochemical measurements (EC=electrical conductivity in μS/cm, T=Temperature in °C, and O-18=$\delta^{18}O$ in ‰) at the Bravo spring along Honey Creek in Comal County, TX.

Date	Variable	Value	Variable	Value	Variable	Value	Variable	Value
9/25/2002	pH	6.71	EC	579	T	21.4	O-18	na
11/13/2002	pH	6.95	EC	555	T	21.1	O-18	-4.23
12/18/2002	pH	6.91	EC	566	T	21	O-18	-4.11
1/22/2003	pH	6.89	EC	605	T	20.5	O-18	-4.26
2/19/2003	pH	6.85	EC	593	T	20.6	O-18	-4.05
3/26/2003	pH	6.93	EC	585	T	20.4	O-18	-4.04
4/24/2003	pH	6.75	EC	580	T	20.8	O-18	-4.13
5/27/2003	pH	6.62	EC	627	T	20.8	O-18	-4.07
6/17/2003	pH	6.59	EC	586	T	21	O-18	-3.84
7/2/2003	pH	6.48	EC	590	T	21.3	O-18	-3.80
9/17/2003	pH	6.91	EC	584	T	21.6	O-18	-4.13
11/15/2003	pH	6.63	EC	604	T	21.1	O-18	-3.98
3/6/2004	pH	6.89	EC	582	T	20.8	O-18	-3.94
5/1/2004	pH	6.82	EC	569	T	20.6	O-18	-4.07
6/25/2004	pH	6.71	EC	567	T	21.2	O-18	-4.09
7/31/2004	pH	6.67	EC	594	T	21.7	O-18	na
9/8/2004	pH	6.61	EC	592	T	21.5	O-18	na
10/30/2004	pH	6.77	EC	580	T	21.5	O-18	na
11/24/2004	pH	6.33	EC	545	T	20.8	O-18	na

Table A-2. Hydrochemical measurements (EC=electrical conductivity in μS/cm, T=Temperature in °C, and O-18=$\delta^{18}O$ in ‰) at the Cotton spring along Honey Creek in Comal County, TX.

Date	Variable	Value	Variable	Value	Variable	Value	Variable	Value
8/13/2002	pH	na	EC	na	T	na	O-18	-3.79
9/25/2002	pH	6.69	EC	587	T	21.7	O-18	-3.82
11/13/2002	pH	6.92	EC	555	T	21	O-18	-4.14
12/18/2002	pH	6.9	EC	568	T	21	O-18	-4.15
1/22/2003	pH	6.86	EC	603	T	20.3	O-18	-4.14
2/19/2003	pH	6.83	EC	595	T	20.5	O-18	-3.97
3/26/2003	pH	6.9	EC	591	T	20.4	O-18	-4.04
4/24/2003	pH	6.83	EC	588	T	20.8	O-18	-4.06
5/27/2003	pH	6.83	EC	642	T	21.5	O-18	-4.05
6/17/2003	pH	6.6	EC	588	T	21.1	O-18	-3.93
7/2/2003	pH	na	EC	na	T	na	O-18	na
9/17/2003	pH	na	EC	na	T	na	O-18	na
11/15/2003	pH	na	EC	613	T	20.2	O-18	-4
3/6/2004	pH	6.91	EC	596	T	21.1	O-18	na
5/1/2004	pH	6.92	EC	566	T	20.6	O-18	-3.99
6/25/2004	pH	6.65	EC	570	T	21.1	O-18	-4.21
7/31/2004	pH	6.76	EC	598	T	21.7	O-18	na
9/8/2004	pH	6.69	EC	606	T	21.6	O-18	na
10/30/2004	pH	6.76	EC	581	T	21.5	O-18	na
11/24/2004	pH	6.3	EC	541	T	20.9	O-18	na

Table A-3. Hydrochemical measurements (EC=electrical conductivity in µS/cm, T=Temperature in °C, and O-18=$\delta^{18}O$ in ‰) at the Delta spring along Honey Creek in Comal County, TX.

Date	Variable	Value	Variable	Value	Variable	Value	Variable	Value
8/13/2002	pH	na	EC	na	T	na	O-18	-3.67
9/25/2002	pH	na	EC	na	T	na	O-18	-3.97
11/13/2002	pH	6.93	EC	556	T	20.9	O-18	-4.29
12/18/2002	pH	6.91	EC	565	T	21	O-18	-4.13
1/22/2003	pH	6.89	EC	601	T	20.2	O-18	na
2/19/2003	pH	6.87	EC	616	T	20.8	O-18	-3.96
3/26/2003	pH	6.99	EC	589	T	20.7	O-18	-4.19
4/24/2003	pH	6.82	EC	588	T	20.9	O-18	-3.86
5/27/2003	pH	6.62	EC	632	T	21.2	O-18	-4.11
6/17/2003	pH	6.47	EC	575	T	21.3	O-18	-3.73
7/2/2003	pH	6.43	EC	591	T	21.5	O-18	-3.54
9/17/2003	pH	6.73	EC	598	T	21.3	O-18	-4.15
11/15/2003	pH	6.67	EC	612	T	21.1	O-18	-4.08
3/6/2004	pH	6.98	EC	591	T	21.1	O-18	-3.97
5/1/2004	pH	6.98	EC	568	T	20.6	O-18	-3.97
6/25/2004	pH	6.71	EC	571	T	21.3	O-18	-4.15
7/31/2004	pH	6.54	EC	595	T	22.9	O-18	na
9/8/2004	pH	6.71	EC	594	T	21.7	O-18	na
10/30/2004	pH	6.95	EC	576	T	21.5	O-18	na
11/24/2004	pH	6.36	EC	535	T	20.9	O-18	na

Table A-4. Hydrochemical measurements (EC=electrical conductivity in μS/cm, T=Temperature in °C, and O-18=$\delta^{18}O$ in ‰) at the Honey Creek upland catchment in Honey Creek Natural Area in Comal County, TX.

Date	Variable	Value	Variable	Value	Variable	Value	Variable	Value
8/13/2002	pH	na	EC	na	T	na	O-18	-3.87
9/25/2002	pH	7.13	EC	614	T	23	O-18	-3.82
11/13/2002	pH	7.34	EC	499	T	19.6	O-18	-4.09
12/18/2002	pH	7.44	EC	525	T	19.2	O-18	-3.92
1/22/2003	pH	7.34	EC	570	T	15.5	O-18	-4.09
2/19/2003	pH	6.94	EC	556	T	16.7	O-18	-4.11
3/26/2003	pH	7.34	EC	542	T	18.7	O-18	-4.17
4/24/2003	pH	7.19	EC	573	T	23.1	O-18	-3.95
5/27/2003	pH	Dry	EC	Dry	T	Dry	O-18	Dry
6/17/2003	pH	6.75	EC	518	T	24.8	O-18	-3.89
7/2/2003	pH	6.74	EC	594	T	26.3	O-18	-4.03
9/17/2003	pH	Dry	EC	Dry	T	Dry	O-18	Dry
11/15/2003	pH	7.05	EC	622	T	18.9	O-18	-3.89
3/6/2004	pH	7.72	EC	540	T	20.1	O-18	-4.04
5/1/2004	pH	7.19	EC	525	T	17.4	O-18	-3.93
6/25/2004	pH	7.45	EC	535	T	25.1	O-18	-4.06
7/31/2004	pH	Dry	EC	Dry	T	Dry	O-18	na
9/8/2004	pH	Dry	EC	Dry	T	Dry	O-18	na
10/30/2004	pH	7.44	EC	541	T	24.3	O-18	na
11/24/2004	pH	6.99	EC	485	T	18.2	O-18	na

Table A-5. Hydrochemical measurements (EC=electrical conductivity in μS/cm, T=Temperature in °C, and O-18=$\delta^{18}O$ in ‰) of Honey Creek at the sampling point upstream of the Bravo spring in Comal County, TX.

Date	Variable	Value	Variable	Value	Variable	Value	Variable	Value
9/25/2002	pH	7.04	EC	566	T	21.5	O-18	na
11/13/2002	pH	7.54	EC	533	T	17.9	O-18	-3.97
12/18/2002	pH	7.56	EC	537	T	19.4	O-18	-4.10
1/22/2003	pH	7.48	EC	557	T	15.6	O-18	na
2/19/2003	pH	7.41	EC	538	T	17.6	O-18	-4.01
3/26/2003	pH	7.54	EC	534	T	20	O-18	-4.17
4/24/2003	pH	7.33	EC	545	T	21.9	O-18	-3.93
5/27/2003	pH	7	EC	582	T	21.4	O-18	-4.15
6/17/2003	pH	7.15	EC	541	T	23.2	O-18	-3.51
7/2/2003	pH	6.97	EC	564	T	23.7	O-18	-4.02
9/17/2003	pH	7.39	EC	560	T	23.6	O-18	-4.01
11/15/2003	pH	7.07	EC	580	T	20.8	O-18	-4.02
3/6/2004	pH	7.59	EC	478	T	18.8	O-18	-3.67
5/1/2004	pH	7.57	EC	534	T	19.3	O-18	-3.99
6/25/2004	pH	7.24	EC	416	T	23.6	O-18	-4.77
7/31/2004	pH	7.19	EC	550	T	24.7	O-18	na
9/8/2004	pH	6.98	EC	546	T	22.5	O-18	na
10/30/2004	pH	7.29	EC	544	T	22.8	O-18	na
11/24/2004	pH	6.9	EC	539	T	20.2	O-18	na

Table A-6. Hydrochemical measurements (EC=electrical conductivity in μS/cm, T=Temperature in °C, and O-18=$\delta^{18}O$ in ‰) of Honey Creek at the sampling point upstream of the Cotton spring in Comal County, TX.

Date	Variable	Value	Variable	Value	Variable	Value	Variable	Value
8/13/2002	pH	na	EC	na	T	na	O-18	-3.70
9/25/2002	pH	6.74	EC	579	T	21.6	O-18	-3.85
11/13/2002	pH	6.94	EC	557	T	20.8	O-18	na
12/18/2002	pH	7	EC	585	T	20.7	O-18	-4.18
1/22/2003	pH	6.89	EC	605	T	20.2	O-18	-4.17
2/19/2003	pH	6.87	EC	596	T	20.3	O-18	-4.07
3/26/2003	pH	6.94	EC	586	T	20.4	O-18	-4.19
4/24/2003	pH	7.03	EC	593	T	21.8	O-18	-3.97
5/27/2003	pH	6.73	EC	624	T	21.3	O-18	-4.02
6/17/2003	pH	6.72	EC	586	T	21.7	O-18	-3.81
7/2/2003	pH	na	EC	na	T	na	O-18	na
9/17/2003	pH	7.01	EC	595	T	22.7	O-18	-4.06
11/15/2003	pH	6.62	EC	611	T	21.2	O-18	-4.06
3/6/2004	pH	7.23	EC	549	T	20.8	O-18	na
5/1/2004	pH	7.14	EC	558	T	20	O-18	-3.96
6/25/2004	pH	6.92	EC	520	T	22.4	O-18	-4.42
7/31/2004	pH	6.94	EC	587	T	23.1	O-18	na
9/8/2004	pH	6.69	EC	583	T	21.8	O-18	na
10/30/2004	pH	6.87	EC	574	T	21.9	O-18	na
11/24/2004	pH	6.76	EC	538	T	20.4	O-18	na

Table A-7. Hydrochemical measurements (EC=electrical conductivity in µS/cm, T=Temperature in °C, and O-18=$\delta^{18}O$ in ‰) of Honey Creek at the sampling point upstream of the Delta spring in Comal County, TX.

Date	Variable	Value	Variable	Value	Variable	Value	Variable	Value
8/13/2002	pH	na	EC	na	T	na	O-18	-3.87
9/25/2002	pH	na	EC	na	T	na	O-18	-3.65
11/13/2002	pH	7.16	EC	553	T	20.3	O-18	-4.09
12/18/2002	pH	7.14	EC	575	T	20.4	O-18	-4.11
1/22/2003	pH	7.14	EC	603	T	19	O-18	-4.28
2/19/2003	pH	7.08	EC	619	T	19.8	O-18	-3.82
3/26/2003	pH	7.15	EC	605	T	20.3	O-18	na
4/24/2003	pH	7.1	EC	580	T	22	O-18	-4.11
5/27/2003	pH	6.93	EC	623	T	21.2	O-18	-4.11
6/17/2003	pH	6.81	EC	581	T	22.3	O-18	-3.78
7/2/2003	pH	6.65	EC	599	T	22.5	O-18	-3.33
9/17/2003	pH	7.09	EC	594	T	22.4	O-18	-4.05
11/15/2003	pH	6.67	EC	608	T	20.8	O-18	-4.05
3/6/2004	pH	7.31	EC	558	T	21.1	O-18	-3.93
5/1/2004	pH	7.21	EC	557	T	19.9	O-18	-4.01
6/25/2004	pH	6.91	EC	541	T	22.5	O-18	-4.40
7/31/2004	pH	6.95	EC	584	T	21.4	O-18	na
9/8/2004	pH	6.81	EC	586	T	20.7	O-18	na
10/30/2004	pH	6.93	EC	578	T	21.8	O-18	na
11/24/2004	pH	6.8	EC	538	T	20.4	O-18	na

APPENDIX B

Table B-1. Station information for trend test on western Texas streamflow. The name and site number of the stations follow the USGS gauging station naming convention. Area: drainage area in km^2.

ID	Site	Station name	Area	Basin
1	08124000	Colorado Rv at Robert Lee, TX	39645	Colorado
2	07228000	Canadian Rv nr Canadian, TX	59223	Canadian
3	08134000	N Concho Rv nr Carlsbad, TX	3279	Colorado
4	08126380	Colorado Rv nr Ballinger, TX	42367	Colorado
5	08136000	Concho Rv at San Angelo, TX	14354	Colorado
6	08133500	N Concho Rv at Sterling City, TX	1523	Colorado
7	08121000	Colorado Rv at Colorado City, TX	10272	Colorado
8	08138000	Colorado Rv at Winchell, TX	65214	Colorado
9	08143500	Pecan Bayou at Brownwood, TX	4299	Colorado
10	08136500	Concho Rv at Paint Rock, TX	17027	Colorado
11	08082000	Salt Fk Brazos Rv nr Aspermont, TX	13287	Brazos
12	07227500	Canadian Rv nr Amarillo, TX	50363	Canadian
13	08084000	Clear Fk Brazos Rv at Nugent, TX	5695	Brazos
14	08412500	Pecos Rv nr Orla, TX	54934	Rio Grande
15	08449000	Devils Rv nr Juno, TX	7071	Rio Grande
16	08446500	Pecos Rv nr Girvin, TX	76560	Rio Grande
17	08211000	Nueces Rv nr Mathis, TX	43149	Nueces
18	08147000	Colorado Rv nr San Saba, TX	80852	Colorado
19	08089000	Brazos Rv nr Palo Pinto, TX	61670	Brazos
20	08080500	DMF Brazos Rv nr Aspermont, TX	22782	Brazos
21	08128450	Mid Concho Rv Tankersley, TX	5398	Colorado
22	08082500	Brazos Rv at Seymour, TX	40243	Brazos
23	08091000	Brazos Rv nr Glen Rose, TX	66869	Brazos
24	08088000	Brazos Rv nr South Bend, TX	58723	Brazos
25	08085500	Clear Fk Brazos Rv at Ft Griffin, TX	10329	Brazos
26	08194500	Nueces Rv nr Tilden, TX	20961	Nueces
27	08087300	Clear Fk Brazos Rv at Eliasville, TX	14755	Brazos
28	08093100	Brazos Rv nr Aquilla, TX	70562	Brazos
29	08158000	Colorado Rv at Austin, TX	101033	Colorado
30	08146000	San Saba Rv at San Saba, TX	7889	Colorado
31	08210000	Nueces Rv nr Three Rivers, TX	39956	Nueces
32	08144500	San Saba Rv at Menard, TX	2940	Colorado
33	07312500	Wichita Rv at Wichita Falls, TX	8133	Red
34	08194000	Nueces Rv at Cotulla, TX	13393	Nueces
35	08455000	Pinto Ck nr Del Rio, TX	645	Rio Grande
36	08096500	Brazos Rv at Waco, TX	76558	Brazos
37	08127000	Elm Ck at Ballinger, TX	1166	Colorado
38	08148500	N Llano Rv nr Junction, TX	2367	Colorado
39	08178000	San Antonio Rv at San Antonio, TX	108	San Antonio
40	08208000	Atascosa Rv at Whitsett, TX	3033	Nueces
41	08128000	S Concho Rv at Christoval, TX	1070	Colorado
42	07331600	Red River at Denison Dam nr Denison, TX	102875	Red
43	08168710	Comal Spgs at New Braunfels, TX		Guadalupe
44	08169000	Comal Rv at New Braunfels, TX	337	Guadalupe
45	08093500	Aquilla Ck nr Aquilla, TX	798	Brazos
46	07298000	N Tule Draw at Res nr Tulia, TX	490	Red
47	08374000	USIBW Alamito Ck nr Presidio, TX	3885	Rio Grande
48	08095000	N Bosque Rv nr Clifton, TX	2507	Brazos
49	08193000	Nueces Rv nr Asherton, TX	10572	Nueces

Table B-1. Continued,

ID	Site	Station name	Area	Basin
50	08150000	Llano Rv nr Junction, TX	4802	Colorado
51	08176500	Guadalupe Rv at Victoria, TX	13463	Guadalupe
52	07315500	Red Rv nr Terral, OK	74393	Red
53	08186000	Cibolo Ck nr Falls City, TX	2142	San Antonio
54	08173000	Plum Ck nr Luling, TX	800	Guadalupe
55	08151500	Llano Rv at Llano, TX	10870	Colorado
56	08205500	Frio Rv nr Derby, TX	8881	Nueces
57	08172000	San Marcos Rv at Luling, TX	2170	Guadalupe
58	08190000	Nueces Rv at Laguna, TX	1909	Nueces
59	08153500	Pedernales Rv nr Johnson City, TX	2334	Colorado
60	08171000	Blanco Rv at Wimberley, TX	919	Guadalupe
61	08168500	Guadalupe Rv abv Comal Rv at New Braunfels, TX	3932	Guadalupe
62	08195000	Frio Rv at Concan, TX	1008	Nueces
63	08167500	Guadalupe Rv nr Spring Branch, TX	3406	Guadalupe
64	08188500	San Antonio Rv at Goliad, TX	10155	San Antonio
65	08185000	Cibolo Ck at Selma, TX	710	San Antonio
66	08183500	San Antonio Rv nr Falls City, TX	5473	San Antonio
67	08167000	Guadalupe Rv at Comfort, TX	2173	Guadalupe
68	08198000	Sabinal Rv nr Sabinal, TX	534	Nueces
69	08192000	Nueces Rv bl Uvalde, TX	4820	Nueces
70	08181500	Medina Rv at San Antonio, TX	3411	San Antonio
71	08179000	Medina Rv nr Pipe Creek, TX	1228	San Antonio
72	08166000	Johnson Ck nr Ingram, TX	295	Guadalupe

VITA

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