CHARACTERIZING STREAM-AQUIFER INTERACTIONS IN THE PEDERNALES WATERSHED IN CENTRAL TEXAS

by

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ABSTRACT

Understanding the nature of stream-aquifer interaction is important for understanding the degree of hydraulic connection between streams and adjacent aquifers within any given watershed. Such information is necessary before the effects of groundwater pumping on streamflow, or the effects of surface-water runoff on aquifer recharge, can be assessed. Traditional techniques to analyze stream-aquifer interaction are based on digital groundwater flow models; however, aquifer parameters for model calibrations are generally unavailable or difficult and costly to obtain. Recession curve analysis is an alternative approach to determining stream-aquifer interaction Basic assumptions in recession curve analysis include: (1) no regulation on the stream, (2) stream fully penetrates the aquifer, (3) the watershed is underlined by impermeable rocks, (3) aquifer systems have uniform hydraulic conductivity and transmissivity, (4) aquifer that sustains stream flow is a one-dimensional flow regime (neglects vertical interaction with deeper aquifers), and (5) watershed has uniform storage and recharge. This study sought to investigate changes in precipitation, streamflow, baseflow, and hydrologic properties of the Pedernales watershed in central Texas, as well as identify the primary aquifer contributing flow to the Pedernales River between 1940 and 2014. The USGS Ground Water Tool Box RECESS program was used to extract meaningful segments of streamflow recession and the slope (K) of such segments (recession curve index, RCI). Man-Kendall Monotonic trend (MK) tests were used to assess changes in climatologic and hydrologic conditions during the study period. The results of annual trend analysis of precipitation, streamflow, baseflow and RCI showed no significant changes over the study period. Values of the stream-aquifer property T/a^2S (where T is the transmissivity of the aquifer, a is the average distance between the stream and watershed divide, and S is the storativity of the aquifer was estimated as 0.0403/d and the watershed K value was 23.15 days/log cycle. It is concluded that the Hensel Sand (rock formation) of Cretaceous age is the primary source of baseflow to the Pedernales River above the Johnson City gage. Results of this study are relevant to water resource management in the study area to satisfy the needs of a growing population while maintaining the ecological integrity of the stream-aquifer system. The approach used in this study is transferable to other watersheds as method requires only streamflow hydrograph and recession analysis.

1. INTRODUCTION

Information concerning stream-aquifer interactions is critical to properly manage the hydrologic impact of rivers and groundwater use (Bevans 1986). Over the past few decades, water demands have accelerated due to expansion and intensification of agriculture and growth of urban areas to meet the demands of an increasing global population (Scanlona 2012). Methods of hydrological investigation for stream-aquifer interactions have long been established. Traditional techniques include digital ground-water flow models for simulating stream-aquifer interactions (Bevans 1986). Aquifer parameters used for model calibrations, however, are commonly unavailable or difficult and costly to obtain (Bevans 1986, Toebes and Strang 1964). In addition, highly parametrized, physical-based hydrologic models may be no more effective for explaining the relation between rainfall and watershed runoff than simpler models (Bevans 1986). An alternative approach to characterizing stream-aquifer interaction is using recession curve analysis (Bevans 1986). Following Boussinesq (1877), several studies (Rorabaugh 1964, Bevans 1986, Rutledge and Daniel 1994, and Rutledge and Mesko 1996) have investigated baseflow recession and estimated stream-aquifer interactions.

Recession curve analysis focuses on specific parts of the streamflow runoff hydrograph following the peak discharge after a precipitation event during dry periods (Berhail, et.al, 2012). The slope of the base-flow recession curve (K) on a semi-logarithmic plot is related to the product of aquifer diffusivity and $1/a^2$ (T/a^2S), where:

T = aquifer transmissivity,

a = distance between the stream and watershed divide, and

S = aquifer specific yield of the aquifer (Bevans 1986).

Recession curve analysis can help determine whether groundwater contributions to streamflow originate from a one-dimensional or multi-dimensional aquifer system. In addition, T/a^2S can be used to estimate volumes of groundwater storage, recharge and discharge from recharge occurrences as well as estimate the rates of evapotranspiration in a watershed, valuable parameters to manage the hydrologic impact of rivers and groundwater use on stream-aquifer interactions (Bevans 1986). The Pedernales River watershed is one of many watersheds in central Texas experiencing such increases in water demand (Poor, 2002.) However, the hydrological conditions that influence various aspects of Pedernales River are not fully understood (Bolfing and Haggerty 2014). Although stream-aquifer interaction occurs, it is unclear whether baseflow to the stream is from a one-dimensional or multi-dimensional groundwater-flow regime. A previous study (Zappitello 2016) indicated that streamflow in the Pedernales River is derived from multiple aquifers including the Edwards-Trinity Aquifer, the Marble Falls Aquifer, and the Ellenburger-San Saba Aquifer. However, (Holland and Hughes 1964) indicated that baseflow to the Pedernales River results most importantly from the Hensel Member of the Travis Peak Formation.

The purpose of this study is to characterize stream-aquifer interactions in Pedernales River watershed using recession curve analysis of streamflow records. The principal objectives are: (1) investigate changes in precipitation patterns, (2) examine changes in streamflow patterns, (3) determine watershed parameters K and T/a^2S and investigate changes in K over the course of 75 years, and (4) explore to what extent baseflow in the Pedernales River originates as groundwater seepage from a one-dimensional aquifer system.

2. STUDY AREA

2.1 Physical setting, Climate and Hydrology of Pedernales River Watershed

The Pedernales River watershed is within the subtropical karst Edwards Plateau ecoregion of Texas (Blum and Valastro 1989). The watershed area is approximately 2334 km^2 and is primarily located within Blanco and Gillespie counties but also includes small portions of Travis, Kimble, Kerrville, Kendal, Hays, and Burnet counties (LCRA 2002, Blum and Valastro 1989). Mean monthly temperatures near Fredericksburg range from a low of 9^o C in January to a high of 28^o C in August (Blum and Valastro 1989).The Pedernales River is a bedload-dominated stream system that traverses 1540 km and flows eastward through the watershed starting from the headwaters at 613 m msl to 213 m msl and flows into Lake Travis at the Colorado River confluence (Blum and Valastro 1989). The Pedernales River watershed has an annual average precipitation of 747mm near the western end at Fredericksburg to 864mm on the eastern end at Johnson City during 1939-1993 (LCRA 2002). Although the river is a gaining river system for the most part, small quantities of water are lost in areas of faulting and jointing, these minor stream-channel losses are not lost from the watershed (Holland and Hughes 1964). Additional water losses in the system are attributed to evaporation and transpiration (Holland and Hughes 1964). The Pedernales River has negligible dams or diversions, thus making it an ideal watershed in which to examine the relationship between rainfall and outflow processes using recession curve analysis.

2.2 Land use

The Pedernales watershed is covered predominantly by (roughly 70 percent) live oak, ash juniper and mesquite vegetation. Less than 30 percent is open/brush rangeland and agricultural lands (LCRA 2002). Land use in the watershed is primarily rangeland for livestock, (i.e., cattle, sheep and goats) and cropland oriented to livestock feeding areas along the streams. The watershed has been also subjected during the past few decades to brush managements to increase water yield to Lake Travis. Urban land use is limited to mostly Fredericksburg and Johnson City, covers roughly 1percent of the watershed area (Blum and Valastro 1989)

2.3 Geology

The exposed rocks of the Pedernales River watershed range from Precambrian to Mesozoic age. On the western portions of the watershed and at higher elevation, the watershed is dominantly covered by the limestone of Early Cretaceous age covers approximately 38 percent of the area presented in Figure 1. The Edwards group comprises, Segovia and Fort Terrett and Segovia formations. Segovia and Fort Terrett have three distinct layers the upper, middle and lower, that alternate between limestone and dolomite. The Segovia member is approximately 52 m to 91m in thickness and thickens southward. The Fort Terrett member is approximately 46 m to 70 m in thickness and thickens southward. Precipitation absorbed on the Edwards outcrop is lost mostly by evapotranspiration but small quantities infiltrated into the water table and appears in spring and seeps at the base of the formations (Holland and Hughes 1964). However, none of the spring discharges large amounts of water (Mount 1963)..

Under the Edwards is the Glen Rose Limestone formation of Early Cretaceous age. The southeastern portion of the study area is covered dominantly by outcrops of Glen Rose Limestone and accounts for 26.4 percent of the area presented in Figure 1. The formation is composed of thin-bedded limestone, dolomite and marl is stair step topography. The Glen Rose is divided into upper and lower layers by the Corbula Bed. The upper layer is approximately 67 m in thickness and the lower layer is 49m in thickness including the top of Courbula Bed. The Glen Rose formation is approximately 116 m in total thickness and feathers out towards the Llano Uplift. The outcrop of the upper Glen Rose member has not been eroded away much and constitutes 26 percent of the area while the he lower Glen Rose is only exposed in small portion of the study and makes up 0.4 percent of the study area. The Glen Rose formation is relatively impermeable layer and yields small quantities of water to seepage areas along the stream banks (Holland and Hughes 1964).

Under the Glen Rose Limestone is the Hensel member of the Travis Peak Formation. The Hensel formation is composed of poorly sorted sand, silt, clay and conglomerate. The upper part is generally finer grained sand and the lower part contains conglomerate and angular coarse sand (Mount 1963). Limestone beds occur in the subsurface of the Hensel (Mount 1963). The thickness of the Hensel member is approximately 67 m thick but varies considerably because of the uneven deposit on erosional surface (Mount 1963).. The central part of the study watershed is dominantly covered by outcrops of the Hensel member at lower elevation and accounts for 20 percent of the area presented in Figure 1. The Hensel member is highly permeable and captures a high percentage of precipitation that falls on the outcrop (Holland and Hughes 1964).

Under the subsurface of the Hensel sand is the Ellenburger group (Mount 1963). and small outcrop of the Ellenburger group is present in the study area consisting of two formations the Gorman and Tanyard. Outcrop of the Ellenburger is approximately 2 percent in the study area presented in Figure1.Water in the Ellenburger occurs in solution formed openings and are generally under artesian conditions (Mount 1963).

Below the Ellenburger group is Moore Hollow group, which consists of five different members: The San Saba, Point Peak, Morgan Creek Limestone, Welge Sandstone and Lion Mountain, and Cap Mountain. Outcrops of the Moor Hollow Group make up approximately 7 percent of the study area presented in Figure1. Below the Moore Hollow Group is the Hickory Sandstone. The Hickory Sandstone is present at various depth below the Cretaceous because of faulting displacement. Movement of water in the Hickory takes place in a very complicated matter due to numerous faulting, presented in Figure2, and thus water is not obtained from outcrop areas but is derived by downward vertical leakage from overlying water-baring Stata, specifically the Edwards group (Mount 1963). Outcrops of rocks from Precambrian make up approximately 1 percent of the study area presented in Figure 1. The Pedernales river channel is alluvium bedrock from floodplain deposit of recent Holocene and makes up 4 percent of the study area presented in Figure 1.

2.4 Aquifers

Based on the distribution of hydrogeological properties, there are four aquifers within the study are, the Edwards-Trinity, the Ellenburger-San Saba, the Welge-Lion Mountain, and the Hickory Aquifers (Shi et al, 2016). The Edwards-Trinity aquifer comprises the Edwards Group, the Glen Rose Limeston, and the Hensel Sand and lumped together as a single aquifer presented in Table (Shi et al, 2016). The Edwards-Trinity aquifer overlies the Ellenburger-San Saba. There is Mississippian and Devonian rocks undivided confining layer between Edwards-Trinity and Ellenburger-San Saba. The Ellenburger-San Saba aquifers consists of the Honeycut, Gorman, Tanyard formation and San Saba members and are lumped together as a single aquifer presented in Table 1(Shi et al, 2016). The Ellenburger-San Saba Aquifer overlies Welge-Lion Mountain

Aquifer and there is a confining layer that consists of the Point Peak and Morgan Creek members presented in Table 1 (Shi, Boghici and Kohlrenken). The Welge-Lion Mountain Aquifers consists of Welge Sandstone and Lion Mountain members and are lumped together as a single aquifer presented in Table 1(Shi et al, 2016). The Welge-Lion Mountain Aquifers over lies the Hickory Aquifer and Cap Mountain member is a confining layer between the two aquifer presented Table 1(Shi et al, 2016).

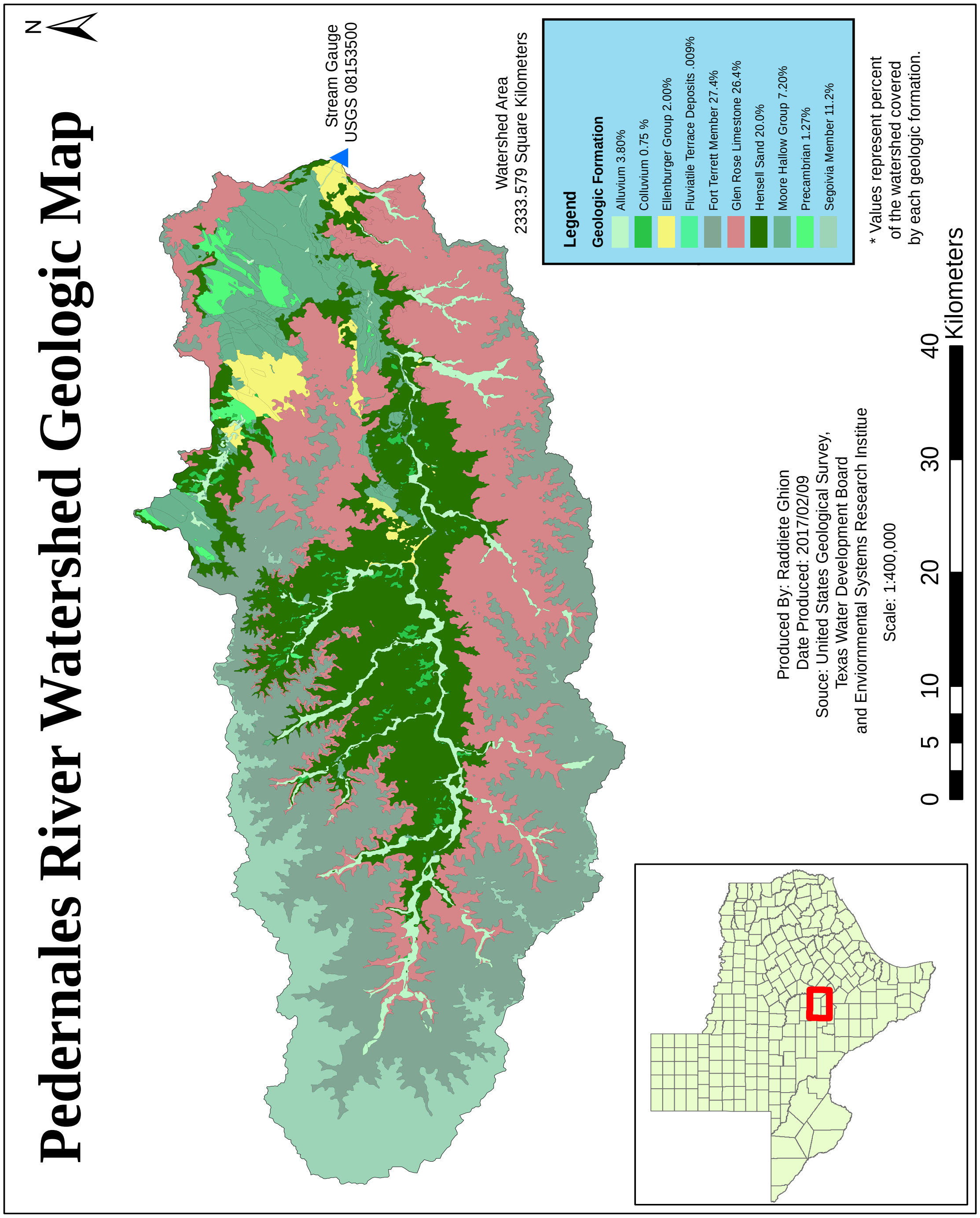


Figure 1. *Geological Map of Study area*

Table 1. *Stratigraphy and hydrogeological classification of geologic units in study area (adapted from Barker et al. 1994; Preston et al. 1996),*

Geologic Unit					Hydrogeologic Unit
Era	**System**	**Group**	**Formation**	**Member or Unit**	
Cenozoic	Quaternary	Pleistocene - Recent floodplain (alluvium & fluviatile terrace) deposits			Localized alluvial aquifers
Mesozoic	Cretaceous	Edwards Group	Segovia Formation	Undivided	Edwards Trinity aquifer: Edwards (Plateau) aquifer
			Fort Terrett Formation		
		Trinity Group	Glen Rose Limestone	Upper member	Edwards Trinity aquifer: Trinity aquifer: Upper Trinity aquifer
				Lower member	Middle Trinity aquifer
			Travis Peak Equivalent: Hensel Sand	Undivided	
			Travis Peak Equivalent: Cow Creek Limestone		
			Travis Peak Equivalent: Hammett Shale	Undivided	Confining Unit
			Travis Peak Equivalent: Sycamore Sand	Undivided	Lower Trinity aquifer
Paleozoic	Pennsylvanian	Canyon Group	Undivided	Undivided	Confining Unit
		Strawn Group			
		Bend Group	Smithwick Shale		
			Marble Falls Limestone	Undivided	Marble Falls aquifer
	Mississippian and Devonian	Undivided			Confining Unit
	Ordovician	Ellenburger Group	Honeycut Formation	Undivided	Ellenburger-San Saba aquifer
			Gorman Formation		
			Tanyard Formation	Staendebach Member	
				Threadgill Member	
	Cambrian	Moore Hollow Group	Wilberns Formation	San Saba Member	
				Point Peak Member	Confining Unit
				Morgan Creek Limestone Member	
				Welge Sandstone Member	Welge-Lion Mountain aquifer
			Riley Formation	Lion Mountain Sandstone Member	
				Cap Mountain Limestone Member	Confining Unit
				Hickory Sandstone Member	Hickory aquifer

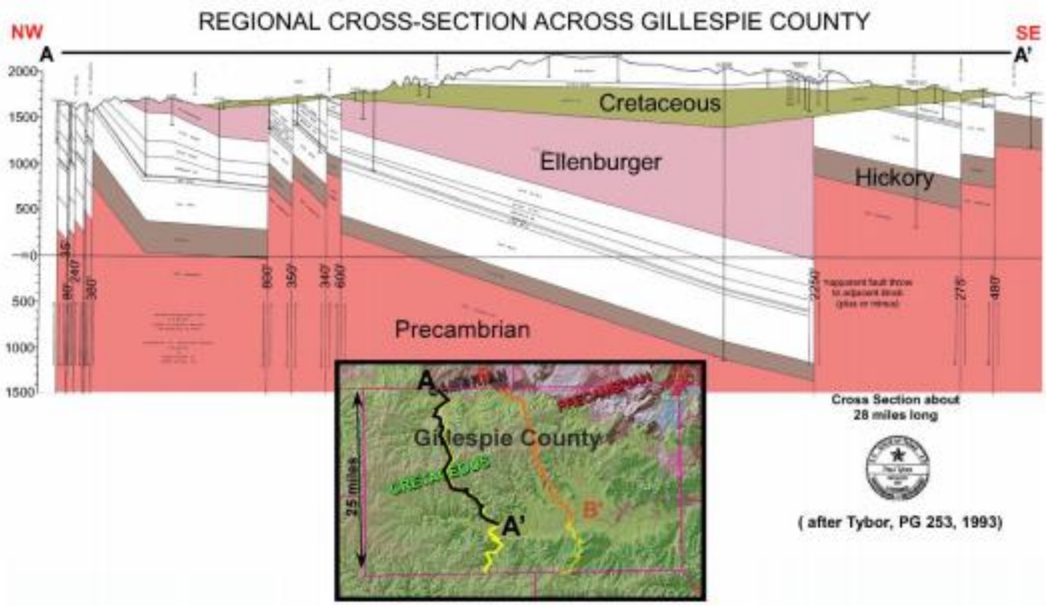


Figure 2. *Distribution of faults along a cross section in Gillespie County (Shi et al, 2016).*

3. METHODOLOGY

Stream-aquifer interactions for the Pedernales River watershed was elucidated by building on previous research (Bevans 1986, Chen and Lee 2003, Shi et al., 2016) and applying a combination of hydrological tools. The U.S. Geological Survey (USGS) Ground Water tool box was used to extract the recession curve index (RCI) for the watershed, which was used to further investigate and test the assumptions of recession curve analysis. RCI is a sample distribution that consists of slope K for each recession curve segment used in this study. A variety of different data sets were collected for this study to characterize stream-aquifer interactions.

3.1 Data collection

3.1.1 Precipitation

Daily precipitation data was collected from the Climate Data Online of the National Oceanic and Atmospheric Admiration (NOAA) database. The city of Fredericksburg was considered the center of the watershed for this study. The selected weather station, Fredericksburg TX, is located at 522.7 m msl, 38° 28′ 33″ latitude, and 98° 86′ 67″ longitude and was obtained from https://www.ncdc.noaa.gov/cdo-web/ database. Precipitation data for the period 1940 to 2014 was selected for this study.

3.1.2 Streamflow

Daily streamflow data was collected from the U.S. Geological Survey (USGS) database. The watershed outlet point considered for this study was located at Johnson City. The streamflow gage is located at 334 m msl, 30° 17′ 30″ latitude, and 98° 23′ 57″. Streamflow data for the period 1940 to 2014 was selected for this study.

3.1.3 Recession Curve Index (RCI)

The RCI for the Pedernales River watershed was obtained using the USGS Groundwater Tool Box (GWTB). The GWTB is a graphical and mapping interface for hydrological data analysis. The software, available at http://water.usgs.gov/ogw/gwtoolbox/, is an open-source Microsoft Windows computing environment. The GWTB allows for the retrieval of hydrologic daily time series data for streamflow from the USGS National Water Information System. It contains the RECESS program which was used to extract RCI K from streamflow data for the period of 1940 to 2014.

3.2 Precipitation, Streamflow, and Baseflow Analysis

The Man Kendell (MK) and Kendall Rank correlation test are both widely used in analyzing climatologic and hydrologic data (Karmeshu 2012). The advantages of using theses test is that one they both allow to test non parametric data and two, they have low sensitivity to abrupt breaks due to inhomogeneous time series (Karmeshu 2012). MK trend analysis was used to investigate change in annual and seasonal total precipitation patterns using the statistical program R. Mean annual and seasonal streamflow trend was investigated using non-parametric MK analysis. Annual and seasonal correlation between precipitation and streamflow was also investigated using Kendall Rank correlation analysis. Annual baseflow was determined using a 7-day moving average technique applied to daily streamflow from 1940 to 2014. Minimum annual values were obtained for each year. Annual baseflow trend was investigated using Man-Kendell trend test.

3.3 Recession Curve Analysis

3.3.1 Theoretical Development

Rudabaugh (1964) developed a theoretical model to characterize groundwater discharge to a stream (equation 1), assuming the watershed has uniform, homogenous, isotropic characteristics, such as constant hydraulic conductivity, specific yield, and aquifer thickness.

$$\frac{T}{S_y} = \frac{0.933a^2 \log(h_1 / h_2)}{(t_2 - t_1)} \qquad (1)$$

WhereT = transmissivity of the aquifer in meters squared per day; S_y = specific yield of the aquifer, dimensionless; a = half-width of the aquifer in meter; h_1 =is the initial water level in meter at time t_1 in days, h_2 = water level, in meters at time t_2 in days. This equation is applicable after the stream flow recession is well established, during which time ground water head is stable, following critical time critical time ($t_{c.}$) (equation 2).

$$t_c = \frac{0.2a^2 Sy}{T} \qquad (2)$$

Rorabaugh lumped T/S and a into a single parameter derived from equation 1 as:

$$\frac{T}{a^2Sy} = \frac{0.933\, log(h1/h2)}{\mathrm{t2-t1}} \qquad (3)$$

Where T/a^2s, in d^{-1}, is a constant representing base-flow recession in the basin.

Further, if the base flow recession curve is evaluated after t_c to determine the time required for flow to decrease by one log cycle, equation (3) can be reduced to

$$\frac{T}{a^2Sy} = \frac{0.933}{\Delta\mathrm{t/log\ cycle}} \qquad (4)$$

Application of equations (3) and (4) to estimate the stream-aquifer properties t_c and T/a^2s does not require the determination of a. Thus, the assumptions necessary to apply these equations are considerably simplified from equation (1). The assumptions are virtually met if the slope of baseflow (K) on a semi log plot is a straight line after critical time (t_c).

Once the assumptions were met and the stream-aquifer properties were determined using the recession-curve-displacement method, watershed storage and ground water recharge were estimated. Rorabaugh (1964) integrated equation (3) with respect to time to compute the volume of ground water remaining in storage on one side of the watershed (V) in equation 5.

$$\mathrm{V} = q(\frac{4a^2Sy}{\pi^2T}) \qquad (5)$$

Equation (5) was modified to estimate the total ground water remaining in storage (V) at critical time (t_c) on both sides of the stream in equation 6.

$$V = Q\ t_c(\frac{0.933a^2Sy/T}{2.3206}) \qquad (6)$$

Equation (6) is applied to a single recession slope, and volume of ground water remaining in storage from all previous periods of recharge is computed. Methods are available to remove the groundwater remaining in storage from previous recharge events (Bevans 1986).

Integrating the principles of superposition, Rorabaugh (1964) has shown that the total ground water discharge to the stream at time t_c fallowing a streamflow peak is equal to about one-half of the total volume of water that recharges the adjacent ground-water system (Chen and Lee 2003). Thus, the total recharge (R) was calculated by the fallowing equation.

$$\mathrm{R} = \frac{2(Q_2 - Q_1)\mathrm{K}}{2.3206} \times \frac{86400s}{1d} \qquad (7)$$

3.3.2 Filtering RCI

The RECESS program required watershed boundary map and discharge data from which the data for analysis was selected. Once the watershed was determined, discharge data was added to the program. The RECESS analysis requires two user inputs: the period of interest and a minimum flow recession length in days, which are dependent on watershed size. The selected period was from 1940-2014. Minimum flow recession length estimated from the literature for a watershed with an area between 740 km^2 and 3800 km^2 is about 7-days minimum (Shaw and Riha 2012). Recession periods, in days, are identified as a recession segment, when precipitation equals zero and streamflow is decreasing. For each year from1940-2014, a distribution of RCI was generated using the RECESS program for all recession events during that year. The recession segments that were constantly decreasing and did not have repeating values and linear, were selected. Each recession segment selected was crossed referenced using precipitation data and linearity was eyeballed from the graphical output of the RECESS program. Recession segments that had repeated values were associated with precipitation events in other parts of the watershed not captured by the precipitation gage at Fredericksburg, or input from irrigation and WWTP systems, were omitted from the analysis. Not all years had the same number of recession events so sample sizes were not identical for all the years. Some years did not have any recession events that met the requirement.

3.3.3 Determining Watershed K, RCI Trend analysis, t_c and T/a^2s_y

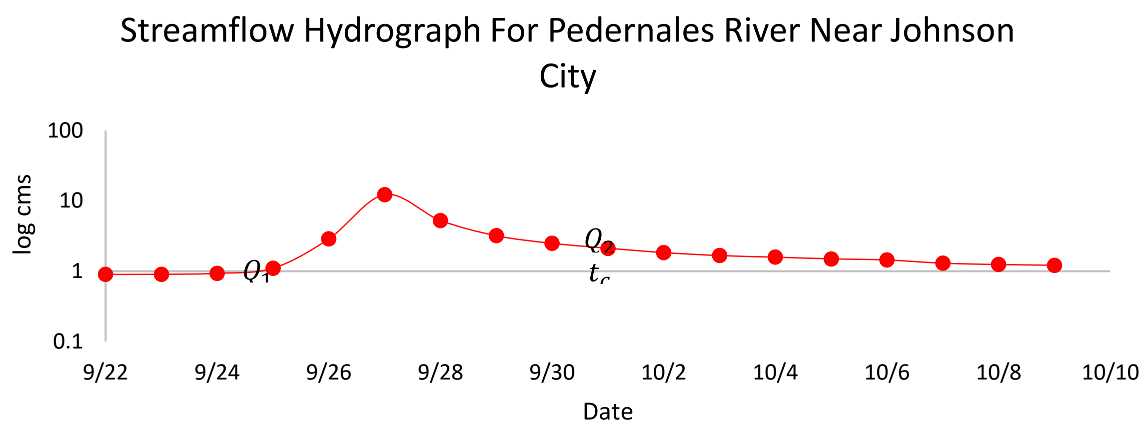
The Sample RCI was not normally distributed and had several breaks in the time series; the MK test was applied to a total of 37 annual median RCI values to assess whether there was an increasing or decreasing trend in RCI values across the study period in the Pedernales River watershed. A MK trend test was also applied to a total of 57 recession segments categorized into seasons to assess whether there was an increasing or decreasing trend in RCI values across the study period for each season. Using Palmers Drought Severity Index (PDSI) obtained from NOAA for the Edwards Plateau, filtered RCI values were categorized in to wet, normal and dry periods. A preliminary analysis was done using MK trend tests to explore whether there are trends during wet, normal and dry periods. K was estimated as the median value from the final filtered RCI sample recession segments for the period of study, which accounted for a total 57 segments. Once median K was estimated, 10 recession segments were sampled from the streamflow record. Using the 10 recession segment samples, median K values from the final 57 segments, annual median K, seasonal K, and PDSI conditions K, a total of nine baseflow slope K values were analyzed to assess the if recession curve analysis assumptions for a one dimensional aquifer (**Table 2.6**.) were met. The recession curve analysis assumptions were tested using Excel. This was done by plotting the median K on a semi-logarithmic graph versus days. Value of t_c was determined using equation (2). Each sampled recession segment was adjusted using t_c and plotted on the semi-logarithmic graph. The recession curve analysis assumptions are met when the sampled recession segment are linear after time t_c and decrease at the same rate as the median K or are within a narrow range of baseflow slope K (Bevans 1986) (not shown). The perimeter T/a^2s was estimated using equation (4) once the assumptions were met.

3.3.4 Developing a master recession curve

Using the 10 samples of recession segments a master recession curve (MRC) plot was developed using the matching strip method as described by Tallaksen (1995) and Rutledge and Mesko (1996). An MRC is a graph of flow on a logarithmic scale and is generally related to the aquafer capacity to yield water as baseflow to a stream during days with no precipitation input. From a hydrological perspective, the most important features of an MRC are the inclination and shape (Rutledge and Mesko 1996). The inclination is determined as the median value of the RCI and shape is a second order polynomial equation expression for time as a function of LogQ in the following equation

$$t=A(LogQ^2) + B(LogQ) + C \qquad (8)$$

3.3.5 Estimating Groundwater Recharge and Storage from a Single Occurrence



Procedure: Estimating Groundwater Recharge

1. Determine Recession Curve K, (Median value of Recession Curve index) K = (23.15 d/log cycle) (d=days)
2. Compute Critical time, t_c (0.2144 × K, or 4.96d)
3. Extrapolate pre-event recession to Q1 (0.906 m^3/s)
4. Extrapolate post-event recession, (locate 4.96 days after peak) Q2 (2.124 m^3/s)
5. Compute total recharge, R=$\frac{2(Q_2-Q_1)K}{2.3206} \times \frac{86400s}{1d}$

   = ((2*(2.124-0.906)*(23.15))/2.3026)*86400=2,116,038m^3

Procedure: Estimating Groundwater Storage

1. The slope of recession Curve K has been determined previously to be 23.15 d/log cycle
2. Compute total storage S= $\frac{Q_{tc}(0.933a^2 \text{ s/T})}{2.3206} \times \frac{86400s}{1d}$
3. $0.933a^2\ S_y$/T=23.15 d
4. Critical time, t_c (0.2144 × K, or 4.96d)
5. Extrapolate the declining limb of hydrograph 4.96 d after peak of recharge event
6. Determine Base flow at t_c = Q_2 (2.124 m^3/s) from figure x
7. Insert the determined values form equation on line 2 to compute the volume of ground water remaining in storage at time = t_c
8. S= ((2.124 m^3/s *23.15d)/2.3206)*86400= 1,830,707.5 m^3

Figure 3. *Recharge event*

3.3.6 Determining Hydraulic Diffusivity

The hydraulic diffusivity of the aquifer can be determined by the fallowing rearrangement of equation (4): where K is change in days per log cycle

$$\frac{T}{S_y} = \frac{0.933a^2}{\mathrm{K}} \qquad (9)$$

The average distance from the stream to the ground-water divide, *a*, was estimated using ArcGIS. The study area watershed boundary shape file was obtained from Texas Natural Resources Information System (TINRIS) and the Pedernales River shape file was obtained from Texas Water Development Board. The river shape file layer was turned into a raster layered file and then converted to points using 1 m resolution. A total of 165904 points were generated. The watershed boundary was split in two polylines, upper and lower boundary. Using the Near tool, for each point the nearest distance to watershed polyline was calculated for both upper and lower boundary polylines. The average distance from the river layer was then determined for all the points for both boundary polylines. The average distance from the stream to the ground-water divide, *a*, was determined to be 10695.3 $m^{2.}$ Using equation (8), median K value and a were plugged in to estimate hydraulic diffusivity as:

$$\frac{T}{S_y} = \frac{0.933(10695.3)^2}{23.15} = 4.6 \text{ X } 10^6 \text{ m}^2\text{/day}$$

4. RESULTS AND DISCUSSION

4.1 Results

4.1.1 Statistical Analysis of precipitation, streamflow and baseflow changes

Results of a Shapiro-Wilk normality test and qqnorm plots (not shown) revealed that annual and seasonal precipitation and streamflow in the Pedernales Watershed are not normally distributed, as well as annual baseflow. This means that the Man Kendall Monotonic trend (MK) and Kendall Rank Correlation (KR) test are warranted. MK trend and KR correlation test are statistical tests widely used to analyze trends and relationships in climatological and hydrological data. There are two advantages of using MK test. First, the test has low sensitivity to abrupt breaks due to heterogeneous time series. Second, it is a non-parametric test and does not require the data to be normally distributed (Karmeshu 2012). KR correlation like MK trend test also does not require the data to be normally distributed and measures the strength of dependence between two variables.

4.1.2 MK trend test of precipitation changes

MK trend in annual precipitation. Calculated values by the Mk test algorithm for annual total precipitation showed no trend across study years for the Fredericksburg weather station, as shown in **Figure 4(a)** and **Table 2.1**. The value of MK τ for annual precipitation series was -0.007, showing a slightly decreasing trend across the years but not statistically significant. **Table 2.3** shows the mean, minimum and maximum annual precipitation values over the 75year period. The linear trend applied to the non-parametric precipitation data in **Figure 4(a)** showed an increasing slope of 0.2391 mm/year and intercept value of 751.7 mm, which represents the mean value for the study period.

MK trend test of sessional precipitation. **Figure 4(b-e)** and **Table 2.1**. demonstrates the results of MK test for seasonal precipitation. There was no significant trend across the study years. The calculated values of MK tau (τ) for winter, summer and fall precipitation series was 0.042, 0.009 and 0.029 and showed a slightly increasing trend across the years but are not statistically significant. The value of MK τ for spring precipitation series was -0.029, shows a slight decrease in trend across the years but was also not statistically significant. Linear trend analysis of seasonal precipitation data **Figure 4(b, d, & e)** showed an increasing slope of 0.1464, 0.0222 and

0.1435 mm/month for winter, summer and fall with intercept of 43.7, 67.7 and 58.3. mm which also corresponds to the seasonal monthly mean value for the study period. The linear trend applied to the spring precipitation data in **Figure 4(c)** shows a decreasing slope of -0.0648 mm/month and intercept value of 81.3 mm which also corresponds to the spring monthly mean value of the study period. **Table 2.3** shows the mean, minimum and maximum precipitation value for each season over the 75year study period.

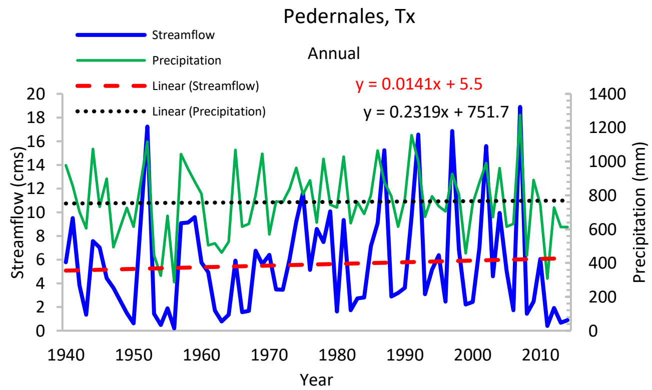
4.1.3 MK trend test of streamflow changes

MK trend test in annual streamflow. Calculated values by the Mk test algorithm for annual mean streamflow showed no trend across the study period, as shown in **Figure 4(a)** and **Table 2.1**. for the Johnson city weather station. The value of MK τ for annual mean streamflow series was 0.054 and showed a slightly increase trend across the years but was not statistically significant. **Table 2.3** shows the mean, minimum and maximum annual streamflow value over the 75year period. Linear trend analysis of streamflow data (**Figure 4a)** showed an increasing slope of 0.0141 cms/year and intercept value of 5.5 cms, which corresponds to the mean value for the study period.

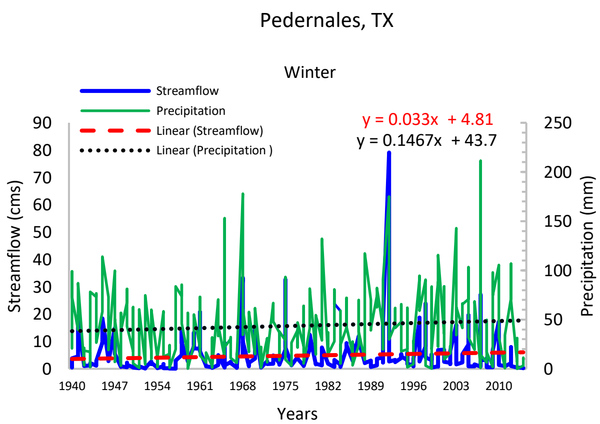
MK trend test of sessional streamflow. Results of the Mk trend test for winter mean streamflow showed a trend across the study period, as shown in **Figure 4(b)** and **Table 2.1**. The value of MK τ for winter streamflow series was 0.088, which showed a significant increasing trend across the study period. The value of MK τ shown in **Figure 4(e)** and **Table 2.1**. for fall mean monthly streamflow was 0.044 and showed an increasing trend across the years but was not significant. Results of Mk test for spring and summer mean monthly streamflow did not show any significant trend across the study period as shown in **Figure 4(c & d)** and **Table 2.1**. The value of MK τ for spring and summer were -0.017 and -0.024 and showed a slight decrease. The linear trend applied to the non-parametric streamflow data in **Figure 4(b-e)** showed an increasing slope for winter, spring, summer and fall with slopes values of 0.033, 0.0241, 0.0108 and 0.017 cms/month and intercept of 4.81, 8.1, 4.45 and 4.6 cms. **Table 2.3** shows the mean, minimum and maximum of seasonal mean streamflow value over the 75year period.

4.1.4 KR correlation between precipitation-streamflow.

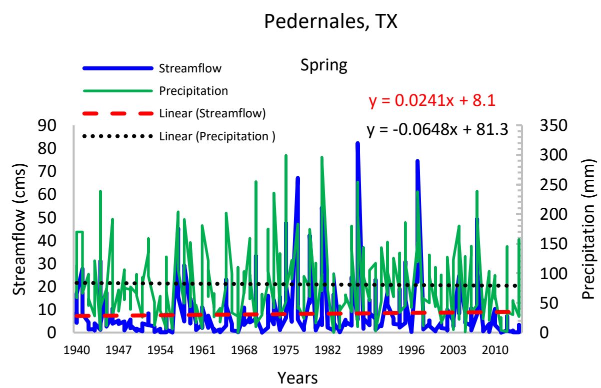
Table 2.2 shows the KR strength of the correlation between annual total precipitation and annual mean streamflow. The value of the KR correlation coefficient τ for precipitation and streamflow was 0.597, indicating a strong correlation between the two. Annual correlation between precipitation and streamflow was much higher than the seasonal correlation. The value of the KR correlation coefficient τ for winter, spring, summer, and fall precipitation and streamflow were 0.391, 0.492, 0.382 and0.429. The KR correlation coefficient for all the seasons indicated a moderate correlation between precipitation and streamflow in the Pedernales watershed.



(a)

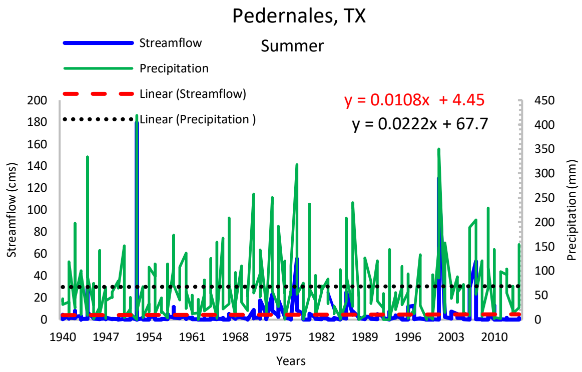


(b)

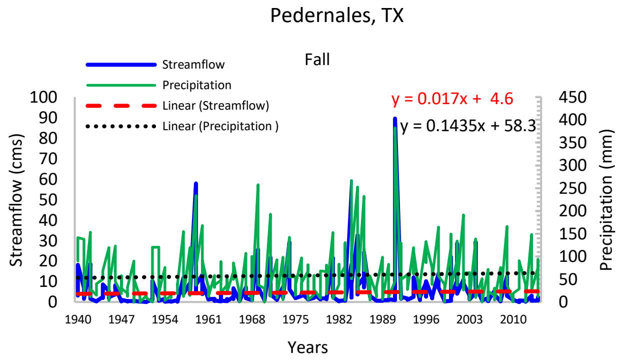


(c)

Figure 4. *Plots of Annual (a): winter (January-March) (b): spring (April-June) (c): summer (July-September) (d): and fall (October-December) (e) of the Pedernales Watershed precipitation and streamflow during 1940-2014. The two horizontal dashed lines correspond to the linear trend during the study period.*



(d)



(e)

Figure 4. Cont.

Table 2.1 *Man-Kendell Trend Analysis during 1940-2014 for Annual, winter (January-March), spring (April-June), summer (July-September), and fall (October-December) precipitation and streamflow.*

Mann-Kendall Monotonic Trend						
Variables	τ	S	Var(S)	α	p-value (two tailed test)	Test Interpretation
Precipitation Annual	-0.007	-18	44075.3	0.05	0.93546	Accept H0
Precipitation Winter	0.042	1051	1257074	0.05	0.34901	Accept H0
Precipitation Spring	-0.029	-742	1273964	0.05	0.5115	Accept H0
Precipitation Summer	0.009	214	1257061	0.05	0.84933	Accept H0
Precipitation Fall	0.029	738	1273921	0.05	0.51377	Accept H0
Streamflow Annual	0.054	149	47789.7	0.05	0.4984	Accept H0
Streamflow Winter	0.088	2199	1257116	0.05	0.049952	Reject H0
Streamflow Spring	-0.017	-439	1273997	0.05	0.69798	Accept H0
Streamflow Summer	-0.024	-611	1257024	0.05	0.58639	Accept H0
Streamflow Fall	0.044	1105	1273991	0.05	0.32802	Accept H0

Table 2.2. *Kendall Rank Correlation during 1940-2014 for Annual, winter (January-March), spring (April-June), summer (July-September), and fall (October-December) precipitation and streamflow.*

Kendall Rank Correlation						
Variables	τ	S	Var(S)	α	p-value (two tailed test)	Test Interpretation
Annual Precipitation vs Streamflow	0.597	15645	44073	0.05	2.2E-16	Reject H0
Winter Precipitation vs Streamflow	0.391	9764	1257065	0.05	2.2E-16	Reject H0
Spring Precipitation vs Streamflow	0.492	12397	1273961	0.05	2.2E-16	Reject H0
Summer Precipitation vs Streamflow	0.382	9515	1256960	0.05	2.2E-16	Reject H0
Fall Precipitation vs Streamflow	0.429	10789	1273912	0.05	2.2E-16	Reject H0

Table 2.3. *Statistical summary during 1940-2014 for Annual, winter (January-March), spring (April-June), summer (July-September), and fall (October-December) precipitation and streamflow.*

75 Year Statistics (mm)					75 Year Statistics (cms)				
Parameter	Time	Min	Max	Mean	Parameter	Time	Min	Max	Mean
Precipitation	Annual	287.02	1275.08	751.6	Streamflow	Annual	0.198218	18.89583	5.5
Precipitation	Winter	0	211.328	130.5	Streamflow	Winter	0.047572	79.11727	4.5
Precipitation	Spring	0	298.958	235.4	Streamflow	Spring	0.001699	82.26044	8.1
Precipitation	Summer	0	418.592	195	Streamflow	Summer	0	179.3023	4.5
Precipitation	Fall	0	382.27	168.7	Streamflow	Fall	0	89.50955	4.6

4.1.5 MK trend statistical analysis of baseflow

Annual baseflow in the Pedernales watershed, calculated using 7-day moving average of daily streamflow, showed no trend. Results of Mk trend test for baseflow is presented in **Table 2.4.** The value of MK τ for annual baseflow was -0.032 and showed a slightly decreasing trend but not statistically significant.

Table 2.4. *Man-Kendell Trend Analysis during 1940-2014 for Annual Baseflow*

Mann-Kendall Monotonic Trend						
Variables	(S)	Var(S)	alpha	Tau	p-value (two tailed test)	Test Interpretation
Baseflow	-90	47297	0.05	-0.032	0.68237	Accept H0

4.1.6 Statistical analysis and summary of RCI

Results of Shapiro-Wilk normality test and qqnorm plots (not shown) revealed that the annual RCI, seasonal RCI and RCI during PDSI conditions in the Pedernales Watershed are not normally distributed. The MK trend analysis for annual RCI showed no trend across study years (**Figure 5.** and **Table 2.5).** The value of MK τ for annual RCI series was 0.144 and showed a slightly increasing trend across the years but not statistically significant. **Table 2.6** shows the median, minimum and maximum values of the annual median RCI over the 75year period.

Annual median RCI values range from -5.687 to -73.074 with a median value of -28.248 for the study period. Linear trend analysis applied to the non-parametric annual median RCI data (**Figure 5)** showed an increasing slope of 0.1058 days/log cycle/year and had an intercept value of 32.18 days/log cycle.

4.1.7 Determining the slope of the base-flow recession curve

Using the median K values for total sample, 75-year annual median, seasonal, and PDSI conditions, a total of nine-baseflow slope K values were analyzed to assess whether the recession curve analysis assumptions for a one-dimensional aquifer (**Table 2.6**.) were met using 10 samples of recession events. PDSI normal condition and total sample K values were very close, 22.641 and 23.15 days/ log cycle. All the sampled events became linear after t_c (4.96 days) and receded at the same rate as the baseflow slope of 23.15 days/log cycle (**Figure 6)**. Baseflow slope K for total sample was chosen as the best fit for the Pedernales watershed because the 10 sample recession segments were within a narrow range as compared to the other 8 baseflow K values tested (not shown).

Table 2.5. *Man-Kendell Trend Analysis during 1940-2014 for annual, seasonal and PDSI dry, normal and wet conditions of Recession Curve Index K*

Mann-Kendall Monotonic Trend						
Variable	(S)	Var(S)	alpha	Tau	p-value (two tailed test)	Test Interpretation
Annual	230	21102.7	0.05	0.144	0.11493	Accept H0
Winter	6	65.33	0.05	0.214	0.53619	Accept H1
Spring	-85	3461.67	0.05	-0.183	0.1534	Accept H2
Summer	-5	408.33	0.05	-0.048	0.84309	Accept H3
Fall	-3	3.667	0.05	-1	0.29627	Accept H4
Dry	2	92	0.05	0.056	0.91697	Accept H0
Normal	16	589.33	0.05	0.118	0.53	Accept H0
Wet	-3	165	0.05	-0.055	0.8763	Accept H0

Table 2.6. *Statistical Summary of RCI K values during 1940-2014 for total sample, annual, seasonal, and PDSI dry, normal and wet conditions*

Variable	Min	Max	Median
Annual	-5.687	-73.074	28.248
Winter	-16.433	-68.185	42.066
Spring	-5.687	-73.074	-20.009
Summer	-3.41	-59.207	-16.744
Fall	-35.7	-44.343	-36.245
Dry	-6.309	-36.245	-11.772
Normal	-3.41	-73.074	-22.641
Wet	-7.486	-58.905	-40.026
Total	-3.41	-73.074	23.15

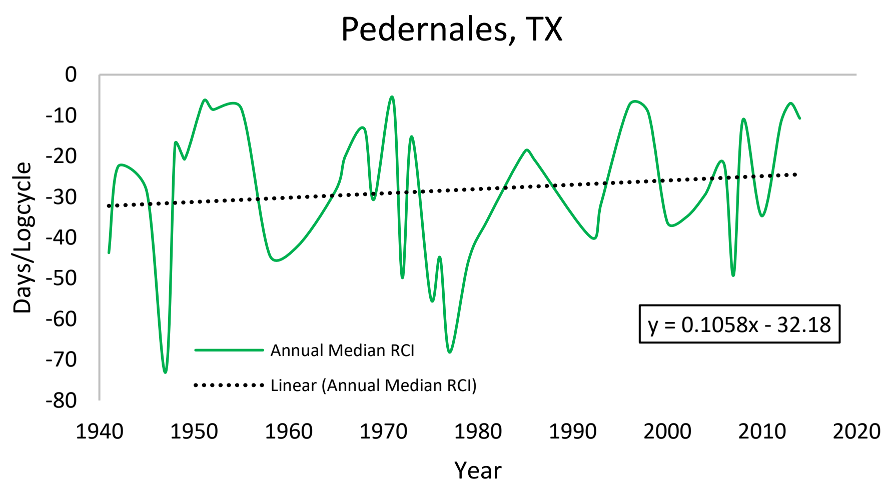


Figure 5. *Plot of Median Annual RCI value of the Pedernales Watershed during 1940-2014. The horizontal dashed line corresponds to the linear trend during the study periods.*

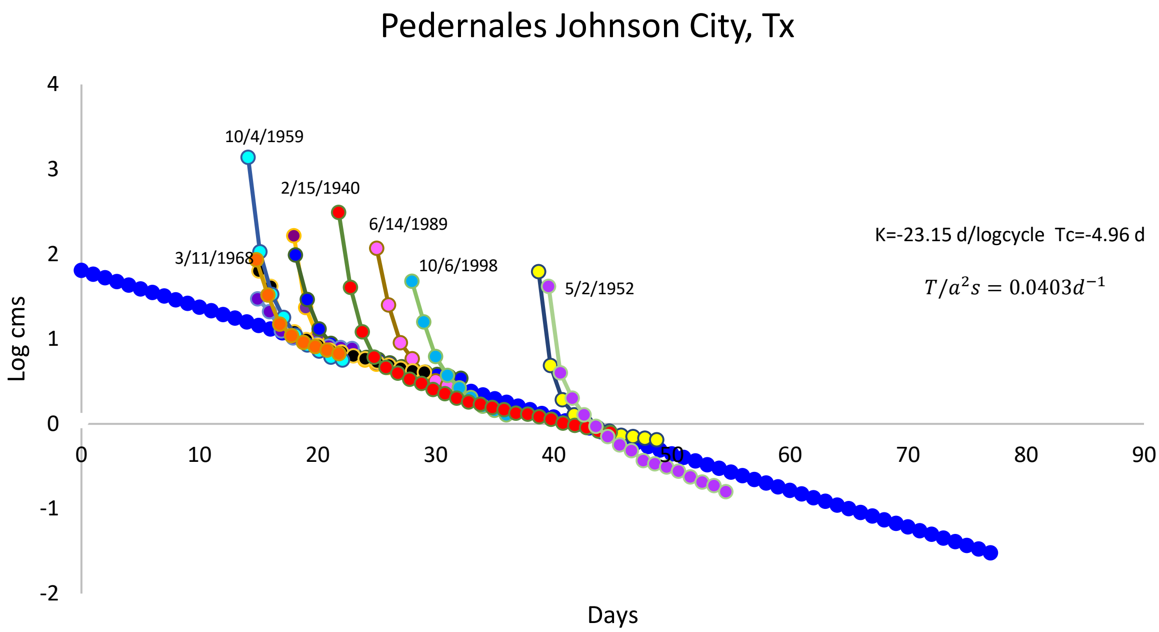


Figure 6. *Determination of the slope of base-flow recession curve for the Pedernales River near Johnson City, TX.*

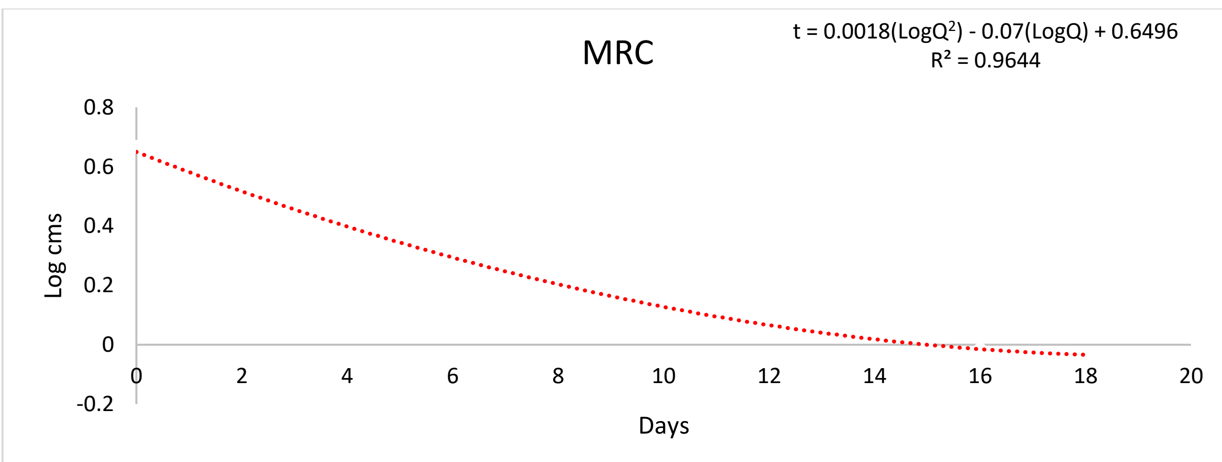


Figure 7. *Master Recession curve of ground-water discharge for the Pedernales River near Johnson City, TX*

Table 4.1 *Summary of Ground water recharge and storage*

Area: Hensel Formation m^2	Precipitation Total m	Precipitation m^3	Percent Recharge %	Percent Storage %
466715800	0.079502	37104839.53	5.702862556	4.933877961

4.1.8 Estimating ground water recharge and storage

Records of daily flow were used to estimate ground-water recharge and storage using recession curve displacement. MRC and RCI were used to represent streamflow recession. The Pedernales watershed commonly has frequent precipitation; therefore, the river draining the watershed does not have frequent or long ground-water recessions. After RCI was determined, ground-water recharge was estimated. The result for ground water recharge estimation using equation (7) for a single event in September 2016 was $2.12X10^6m^3$. Ground water storage was also computed for the same event using equation (6) and was estimated to be $1.832X10^6m^3$. The total ground water recharge from the single event was 5.7 %, shown in Table 4.1.

4.1.9 Determining the hydraulic diffusivity of the aquifer

The hydraulic diffusivity of the Edwards-Trinity aquifer in the Pedernales watershed was estimated using equation (9). The average watershed divide (*a*) was determined to be 10695.3 m in ArcGIS. Watershed divide value was used in equation (9) and hydraulic diffusivity was estimated to be $4.6 \text{ X } 10^6 \text{ m}^2$/day, which is the ratio of the transmissivity to the specific yield of the aquifer.

4.2. Discussion

4.2.1 Precipitation and streamflow analysis

Increases in global temperate have increased precipitation in many regions of Texas (Mishra and Singh 2010). However, we did not observe increases in precipitation in the Pedernales watershed on annual or a sessional monthly scale from 1940-2014. Annual precipitation varied widely during the study period with a minimum value of 287mm and a maximum 1275mm. Like precipitation, we did not find significant trends in streamflow pattern on an annual scale. Seasonal increases during winter were observed. Winter had the second highest streamflow rate compared with other seasons and experienced a significant increasing trend. Approximately

25percent of the Pedernales watershed had received brush removal treatment during the period of study (Table 1; appendix (LCRA 2002). Brush removal can increase recharge by modest amounts, depending on geological and soils characteristics of the area, and the degree of vegetation removal (Moore et al., 2012). As there no increase in precipitation was observed, the increased trend in streamflow during winter could have been associated with shrub removal. There was also a significant increase in groundwater usage from deeper artesian aquifers including the Marble Falls, Ellenburger-San Saba, Welge-Lion Mountain, and Hickory Aquifers. Return flow from irrigation water from these wells could also have led to an increase in streamflow (LCRA 2002). Correlation between precipitation and streamflow was high on an annual scale; this is more likely associated with smaller standard deviation between years than between months due to the binomial distribution of precipitation (not shown).

4.2.2 Recession curve analysis

In the original sample output from USGS Ground Water Tool box, before filtration, there was a total of 906 recession segments. The RCI for the recession segments ranged from -3.41 to -501.08 days/ log cycle. There are several reasons for the wide range in original RCI sample values. First, some of the recession segments contained days when there were precipitation events. The Ground Water Toolbox (GWTB) did not filter recession segment using precipitation data, that had to be cross-referenced with precipitation data manually. Second, there were some recession segments that did not decrease continually; additionally there were days when streamflow values repeated several days in a row. This is likely attributed to precipitation that was not captured at the Fredericksburg weather station or affluent release from WWTP and agriculture. Third, some of the segments contained days before the ground water head was stable, and received flow contribution from the surface and interflow (Toebes and Strang). After filtration, all the recession segments that met the recession curve analysis criteria were obtained, there were 57 recession segments identified as total sample K (Table1 in the Appendix).

Like precipitation and streamflow, the RCI for the Pedernales Watershed did not show changes across years. No change in annual median RCI values may indicate that there was no change in the stream aquifer properties across the study period that could be associated with land cover changes. There was a wide variation in the median RCI value for the 9 categories tested. During the winter, fall and PDSI wet condition, the median RCI values were approximately -42, -36 and

-40 days/ log cycle. This is most likely associated with one lower rate of evapotranspiration and higher antecedent moisture conditions (Aksoy et al., 2011; Kienzle, 2006; Wittenberg, 1994. Spring and PDSI normal conditions were approximately -20 and -22, which both are close to the total sample median RCI of -23. The lower rate of recession for spring may be associated with higher rate of evapotranspiration and increase in temperature. During normal condition, antecedent moisture is reduced compared to wet periods and may explain the lower rate of recession during normal condition. Summer and dry PDSI conditions were estimated when recession rates were at their lowest, which is highly associated with evapotranspiration, lower water table levels, and high temperatures, as well as low antecedent moisture conditions (Berhail, et.al, 2012). The median Annual RCI value was approximately -28 and is close to the total median RCI of -23. The median K value for the total sample of recession events for the study periods is a reasonable representation of the hydraulic properties of the watershed. Soil moisture conditions and water table levels change due to season and drought condition however, it is possible to use seasonal and drought condition K values to estimate ground water recharge, storage, and runoff using the associated median K values for the period of interest.

Figure 6 shows that the Pedernales river above the Johnson city gage maintains baseflow from a one-dimensional aquifer system. The one-dimensional aquifer that is feeding the Pedernales is the Edwards-Trinity aquifer but most directly associated with the Hansel formation of the Edwards-Trinity aquifer (Mount 1963, Holland and Hughes 1964). There are springs that originate from the Edwards formation of the Cretaceous Aquifer, however, given their distance from the main river channel, it is unlikely that these springs feed the Pedernales River (Mount 1963). An estimation of geological formation that contribute groundwater flow to the Pedernales river was produced in GIS based on literature and recession curve analysis, presented in **Figure 7**. A combination between the Hansel, Alluvium, and Colluvium sand formations makes up approximately 92percent of the contribution zone. The stream-aquifer property (T/a^2s) to estimate volumes of ground water storage, recharge and discharge from one or a series of recharge occurrences was 0.0403 d^{-1}, a constant that represents baseflow recession for the Pedernales watershed (Bevans 1986). To further emphasize that the Pedernales River above the Johnson City gage, maintains baseflow from a one-dimensional aquifer system, a master recession curve is presented in **Figure 7.** The MRC is slightly concave; this may occur for watersheds with large relief when ground-water levels decline and some stream segments go dry.

This will cause an increase in the distance from some points on the hydrologic divide to the nearest active stream segments. This will result in an increase in the average distance from the stream to the hydrologic divide *(a*). Concavity may be prevalent in the watershed due to the variation in *a* because of the reduction in specific yield as the water table recedes (Rutledge and Mesko 1996). Ground water flow from deeper aquifer contribute to the Pedernales river occurs downstream from Johnson city gauge and this is made clear from examining the gain loss study (**Figure 1 in** the appendix). There is significant increase in flow, almost double the flow, downstream from Johnson city gauge then from the upstream stream reach.

Based on groundwater recharge and storage calculation, approximately 87percent of ground water recharge is stored in the cretaceous aquifer. It is possible that the remainder of groundwater recharge events were lost to a deeper ground water flow system not connected to the shallow ground water table of the watershed (Chen and Lee 2003, Halford et al., 2006). Rate of ground water recharge was estimated to be 5.7% of the single precipitation. This supports the average ground water recharge rate in the Trinity Aquifer of the Hill Country conducted in previous study, including (Anaya, et.al, 2009). The hydraulic diffusivity for the Pedernales watershed is relatively high compared to previous studies (Bevans 1986, Chen and Lee 2003, Rutledge and Mesko 1996, Lamb et al, 1997). For example, (Rutledge and Mesko 1996) describe a watershed whose divide values were between 305 m to 610m and the estimated hydraulic diffusivity was 1858 m^2/day. The Pedernales watershed divide is 10695.3m. As equation (9) is a function of the watershed divide, this could explains the difference in hydraulic diffusivity for the Edwards-Trinity aquifer.

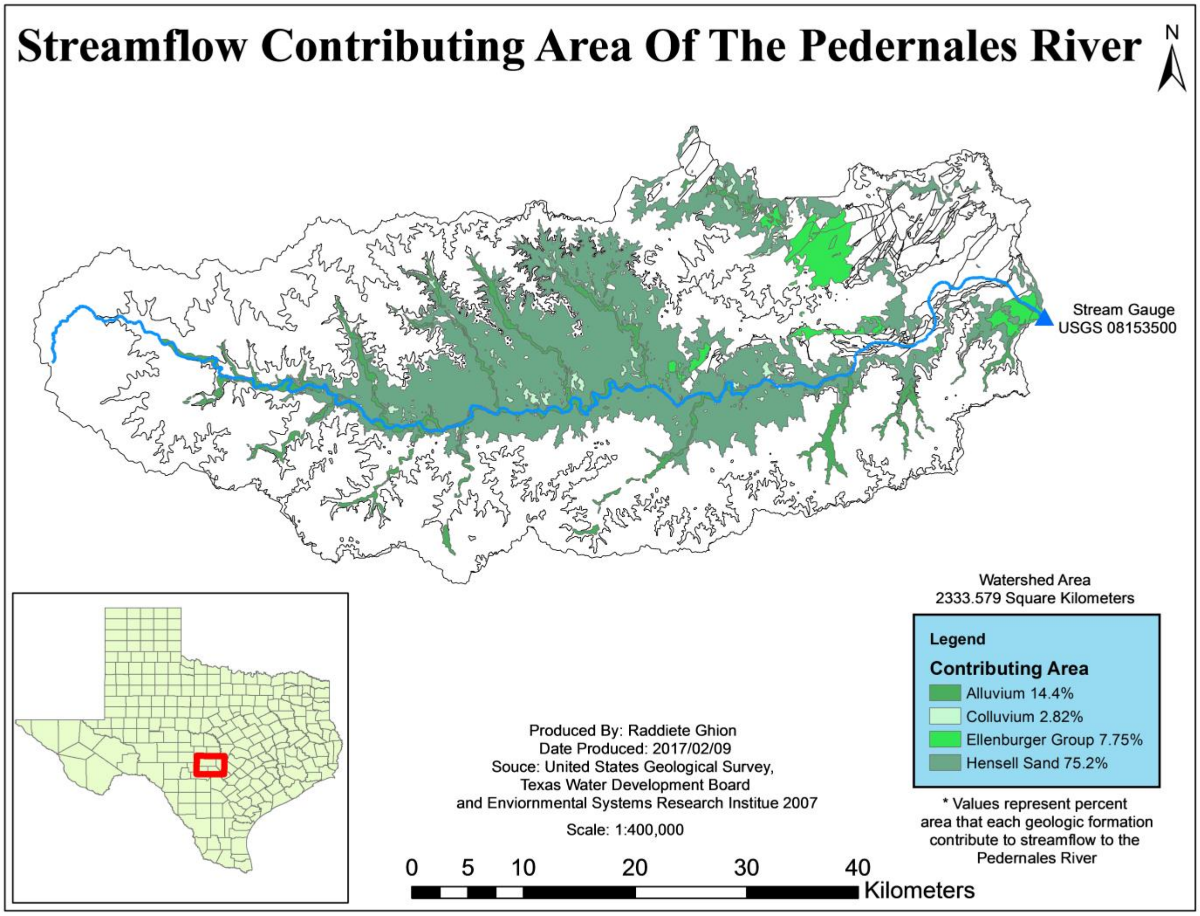


Figure 8. *Streamflow contribution zone in the Pedernales watershed.*

5. CONCLUSIONS

Information concerning stream-aquifer interaction is necessary to manage groundwater and river usage. Although digital models for determining stream-aquifer interactions exist, aquifer parameters used for model calibrations are generally unavailable, difficult and expensive to obtain (Bevans 1986). Recession curve analysis is a highly utilized tool in hydrological analysis and serves as an alternate or a supplemental approach to digital models. The concept is based on a lumped watershed parameter concept and should be applicable to a wide range of geological conditions and climatic settings (Kienzle, 2006). This methodology is readily transferable to other watersheds as it only requires simple recession and streamflow analysis. To apply this method to other watershed the fallowing criteria have to be considered: (a) streamflow record being investigated may not be regulated and, (b) the recession curve of the watershed linearity has to be confirmed.

The Pedernales river is a perennial stream but has run dry during years of precipitation below normal. From 1940 to 2014, the Pedernales river ceased flow across 17 years over a 75-year period. The river predominately maintains flows from precipitation events stored in a shallow aquifer system within the watershed divide (Mount, 1963). Annual trend analysis of precipitation and streamflow showed there was no statistically significant changes across the 75-year study period. As shown in this study, there is a great sessional variation in precipitation and streamflow patterns during the period of study. However, only streamflow during the winter season showed a significantly increasing trend. Possible causes for this trend could be brush removal in the watershed or affluent released from wells pumping from deeper artisanal ground water aquifers.

Analysis of precipitation and streamflow records have provided estimates of hydraulic properties of a shallow aquifer and quantified the median rate of ground water recession. There was a considerable variation in baseflow recession rate during the seasons and PDSI conditions. However, based on the theoretical development and assumptions used in this study, the median K value (-20.15 days/log cycle) for the total sample of recession curves segments was considered to be the best fit. The assumptions for baseflow to reach linearity at critical time tc tested for the derived K for each season and PDSI conditions were not met for all the categories. The rates of base flow after time tc did not decrease at the same rate as K. Based on the assumptions of recession curve analysis, it was determined that flow in Pedernales river is maintained primarily by a one dimensional aquifers system. Trend analysis of K values across the study period was insignificant. This indicates that there was no significant change in land cover in the watershed during the study period. K values ranged from -3.4 to -73.1 days/ log cycle, which is within the range found in previous studies (Rutledge and Mesko 1996). A large recession index is generally related to good potential for water storage because of the aquifer's larger specific yield. However, a large recession rate may also indicate a small transmissivity, and thus smaller water yield capacity for the aquifer. A median value of -20.15 days/ log cycle in the Pedernales watershed is relatively small compared to previous studies (Rutledge and Mesko 1996). The lithology contributing flow to the Pedernales river is that of the Hensel formation, which is typically a porous with relatively high hydraulic conductivity. This indicates that the specific yield of the aquifer is relatively small. For the purpose of this study, base-flow MRC represent the recession of streamflow. The shape of MRC can be related to variations in aquifer diffusivity with respect to variations in ground-water levels. The Pedernales watershed has high relief (613 m to 213 m msl) from headwater to outlet point. The MRC is concave, which can be characteristic of high relief and/or significant ground-water declines. Some streams run dry thus, potentially increasing in the average distance from the stream to the hydrological divide. Variations in recession characteristics, watershed relief, and precipitation explain the wide range in RCI values (Rutledge and Mesko 1996). The median watershed RCI may indicate the capacity of the aquifer to supply water (baseflow) to the stream, which depends on the specific yield of the aquifer. Ground water recharge and storage were estimated for one recharge event. There was a 13percent loss of recharge which was attributed to water percolating into a deeper ground water aquifer system. Aquifer diffusivity was estimated 4.6 X 10^6 m^2/day, which is the ratio of the transmissivity to the specific yeild s of the aquifer. The Pedernales watershed area is relatively large compared to previous studies (Bevans 1986, Chen and Lee 2003, Rutledge, and Mesko 1996, Lamb et al., 1997). The relatively large magnitude of aquifer diffusivity in the Pedernales watershed may be associated with the watershed divide length, which influences aquifer diffusivity.

APPENDIX

Table 1. *Pedernales Brush Removal Area*

Table P-2. Pedernales areas and water yield

Subbasin	Subbasin Total Area (acres)	Brush Removal Area (acres)	Fraction of Subbasin Containing Brush	Avg. Annual Water Yield (gallons)	Water Yield Per acre (gal/ac)
1	26,951	11,294	0.42	3509934604	310766
2	48,747	12,456	0.26	3830330157	307505
3	23,362	11,487	0.49	1173085471	102122
4	18,206	7,322	0.40	1203434375	164352
5	37,687	12,304	0.33	2613606806	212420
6	21,437	3,836	0.18	2078427110	541837
7	72,037	16,982	0.24	2142472557	126164
8	12,075	2,620	0.22	143029849	54591
9	9,397	1,983	0.21	969947825	489030
10	43,245	6,735	0.16	3499761808	519659
11	8,532	1,021	0.12	82369342	80663
12	32,645	10,810	0.33	3339561545	308919
13	12,319	2,284	0.19	45832580	20066
14	20,595	6,368	0.31	1120243861	175919
15	19,478	6,074	0.31	482484548	79440
16	29,202	6,743	0.23	224459965	33290
17	7,359	0	0.00	0	
18	5,272	1,432	0.27	552188395	385687
19	3,665	412	0.11	54225936	131751
20	24,943	3,774	0.15	2606809374	690679
21	4,661	0	0.00	0	
22	27,850	6,144	0.22	3290299232	535568
23	27,156	7,292	0.27	686889242	94197
24	26,025	5,497	0.21	1530495204	278402
25	17,631	4,026	0.23	803690121	199616
26	24,708	2,861	0.12	2113161	739
27	23,364	3,142	0.13	1352300667	430366
28	3,780	507	0.13	1858684	3669
29	23,396	5,569	0.24	1073272439	192729
30	12,893	3,171	0.25	476201733	150173
31	19,389	2,808	0.14	324609923	115592
32	18,093	2,478	0.14	1515842097	611720
33	13,794	1,866	0.14	300394705	160941
34	56,624	21,884	0.39	2445623566	111752
35	23,757	10,570	0.44	24635822	2331

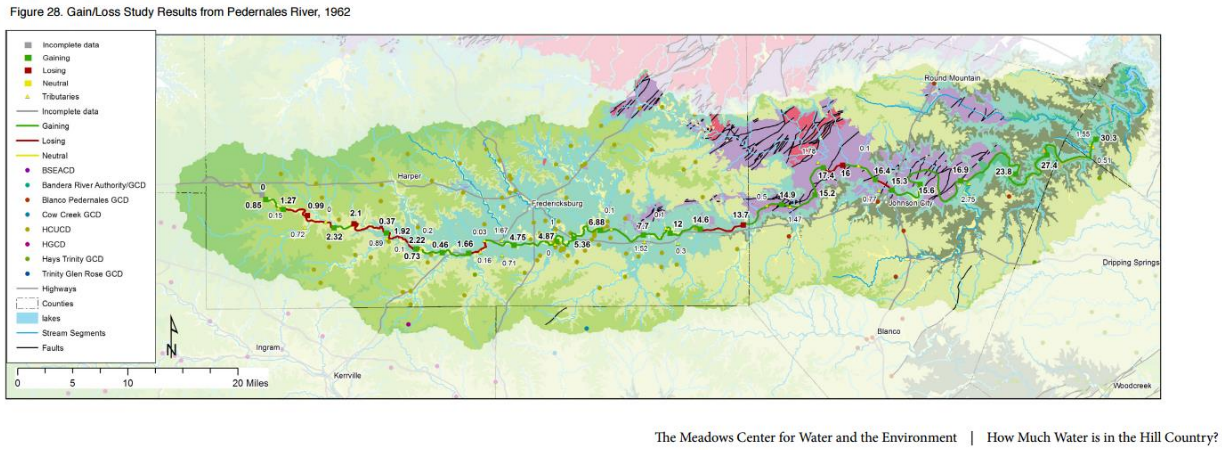


Figure 1. *Gain loss study results from Pedernales River, 1962 (Bolfing and Haggerty 2014).*

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