HOW THICKETIZATION WITHIN THE POST-OAK SAVANNAH ECOREGION AFFECTS BASEFLOW AND GROUNDWATER THROUGHOUT THE CARRIZO-WILCOX AQUIFER

by

Margaret Anne Cross

A professional paper submitted in partial fulfillment
of the requirements for the degree

of

Master of Science

in

Land Resources and Environmental Sciences

MONTANA STATE UNIVERSITY
Bozeman, Montana

April 2023

DEDICATION

I would like to dedicate my work to my parents, Tom and Joanne Cross. Their continued support and encouragement have been an incredible blessing throughout my entire academic career.

ACKNOWLEDGEMENTS

I would like to thank Dr. Sam Carlson for teaching me and guiding me throughout this entire process. The valuable time he invested and his continued interest in this project provided me with the drive and passion necessary to complete this project.

I would like to thank all my professors in the Land Resources and Environmental Sciences M.S. program. Each class left me wanting to specialize in a new part of environmental science. I am truly grateful for such a positive experience.

Additionally, I would like to thank Robert A. Rivera for building me a strong personal computer, allowing me to utilize the softwares in this study to their maximum potential.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

Availability of surface and groundwater in the Post-Oak Savannah ecoregion of Texas is critical for local agriculture, municipal use, and energy production. However, woody-plant encroachment or 'thicketization' in this region is suspected to be a source of reduced groundwater recharge to the Carrizo-Wilcox Aquifer and may also affect local baseflow volumes. To test this hypothesis, I examined the changes in woody landcover in Texas watersheds since the 1950s using U.S. Geological Survey (USGS) Historical Topographic Maps and the National Land Cover Dataset (NLCD) to compare any changes to local baseflow volumes (90% flow duration) and zero-flow exceedance percentages (percentage of time streamflow exceeds zero-flow) from USGS streamflow data across the Carrizo-Wilcox Aquifer. I discovered substantial evidence suggesting a positive correlation ($p = 0.0133$) between thicketization and baseflow within the dataset, with a 2% increase in baseflow anomaly for every 1% increase in wooded area density anomaly. I also found that increased baseflow reflects an increase in depth to groundwater table ($p = 0.005$). These results suggest that thicketization increases local baseflow volumes, resulting in a lower the groundwater table. Although I hypothesized thicketization reduced baseflow and reduced groundwater recharge, the data suggest that there is a strong relationship between wooded landcover and local baseflow affecting groundwater recharge. Further research has the potential to reveal the mechanism behind thicketization's effect on baseflow's contribution to groundwater recharge.

CHAPTER ONE

INTRODUCTION

The Carrizo-Wilcox Aquifer is an essential source of groundwater for industry, irrigation, and municipalities across the State of Texas, and the spread of thicketization in overlaying ecoregions may contribute to reduced groundwater recharge rates. Thicketization is the process of woody plant encroachment into former grasslands (Archer et al. 2017; Basant et al. 2023). A landcover shift to increased woody landcover may affect low-flow conditions such as baseflow and zero-flow exceedance because of varying responses to precipitation events and climate contributing to streamflow. Investigation into thicketization's effect on low-flow conditions may also reveal an additional effect on groundwater percolation and recharge. Dense canopies intercept precipitation before it has the chance to infiltrate the ground (Archer et al. 2017). More extensive root systems can also capture additional precipitation that has already saturated the ground, reducing the amount of water capable of reaching the groundwater table. Baseflow is a major contributor to groundwater recharge (Schilling et al. 2021). Landcover change may have an indirect effect on depth to groundwater, alongside the direct effect of extensive groundwater withdrawal.

Texas groundwater laws are particularly unrestrictive due to the Rule of Capture law governing private property owners. This law allows property owners to withdraw any available groundwater from their land, even at the expense of neighboring groundwater wells. The law is also referred to as the 'law of the biggest pump'; if property owners can reach the groundwater, it can be used. Texas has used the Rule of Capture ever since the 1904 Texas Supreme Court case, referencing English common law's *damnum absque injuria* (Potter 2004). This Rule claims that groundwater abstraction, or groundwater withdrawal, at the cost of draining a neighboring well is within the bounds of the law, as it is a damage without injury.

There have been attempts to mitigate the extent of unlimited groundwater abstraction through regulations during drought seasons and the creation of Groundwater Conservation Districts (GCDs). There are 98 GCDs in the state of Texas, covering about 70% of the state. Despite their prevalence, it is still difficult to monitor and regulate groundwater abstraction. The attempts made by the state legislature to limit withdrawals often result in litigation, with courts ruling in favor of fewer restrictions for property owners (Supreme Court of Texas 2012). Loose groundwater laws are particularly detrimental where industry is prevalent. The Carrizo-Wilcox Aquifer supports huge industries like oil and gas within the Eagle Ford Shale as well as agriculture (Brien 2021).

The Carrizo-Wilcox Aquifer is one of the major aquifers in Texas, reaching from the borders in Mexico to Louisiana. This aquifer contains around 28,500 km^2 of outcrop or unconfined aquifer, which is the shallowest region of the aquifer. The aquifer outcrop is more connected to surface conditions, where rain and baseflow infiltrate into the aquifer and where groundwater discharges into streamflow (Ikard et al. 2018; Young et al. 2017). There is just under 65,000 km^2 of subsurface or confined aquifer. The aquifer is composed of mostly sand and various concentrations of saline groundwater (Boghici 2009). Depth to groundwater refers to the distance from the land surface to the groundwater table. Groundwater recharge reduces the depth to groundwater, while groundwater withdrawal increases the depth to groundwater.

Groundwater abstraction began within the Carrizo-Wilcox Aquifer in Dimmit County in the early 20^{th} century for irrigation purposes (Huang 2012). By the 1930s, the aquifer was being used for municipalities and industry. Contemporary irrigation represents the largest sector responsible for groundwater abstraction in the aquifer; however, population booms in the state have caused municipal water usage to rival irrigation demands (Young et al. 2018). Increasing water demands bring up the concern of water availability, especially in locations on the aquifer that experience reduced surface flows caused by drought and climate change (Melo and Wendland 2017; Miller et al. 2021). Texans are highly dependent upon groundwater because of the limited surface flow regimes, making conservation of groundwater extremely salient.

Streams that recharge aquifers with surface-flow leaching through the riverbed's hyporheic zone are considered losing streams (Ikard 2021; Wahl and Wahl 1995). Streams that receive groundwater discharge through the hyporheic zone are considered gaining streams. The streams with highest risk of reduced flows are in the southern portion of the aquifer, where pumping is the greatest, and recharge and streamflow are the lowest (Huang 2012). Recharge is an estimated 0.25 cm per year in the southern-most reaches of the aquifer and about 15 cm annually in the northeastern aquifer (Scanlon 2002). The variation in recharge rates reflects regional precipitation patterns, surface flow regimes, and geology. The Nueces and Frio Rivers are two major rivers that support the southern portion of the aquifer. Historically, these streams were likely gaining, perennial streams. However, these rivers' flow regimes have been affected by decreased spring-water input because of abstraction, drought, and climate change; they are now intermittent streams, more dependent on rainwater (Bureau of Economic Geology 2011). Several other streams flowing through the aquifer outcrop have shifted from gaining streamflow to losing throughout the last century. Changes in woody landcover on the aquifer's outcrop may have an additional effect on rivers' connectivity to the groundwater table.

The Post-Oak Savannah Ecoregion encompasses a large portion of the aquifer's outcrop and subcrop (or confined aquifer). The Post-Oak Savannah was historically grasslands with scattered broad-leafed evergreens and deciduous trees, shaped by frequent fires and large-animal grazing. Colonialism left its mark on the ecoregion with fire suppression and agriculture, contributing to woody plant encroachment, or 'thicketization' (Schmidly 2002). A 1965 groundwater report for Leon County claimed that forested areas on aquifer outcrops reduce groundwater recharge rates (Peckham 1965). It also claimed that woody-plant removal in the outcrop would result in increased recharge.

High-density canopies within the aquifer's outcrop are thought to increase precipitation interception, thereby reducing aquifer recharge by precipitation (Basant et al. 2023). This has resulted in increased restoration efforts in the Post-Oak Savannah/Carrizo-Wilcox outcrop intersection (Texas A&M *ENRTA*). The goals of these projects include combatting thicketization, restoring historical conditions, and increasing precipitation percolation potential for groundwater recharge in wetlands. Wetlands are particularly responsive to localized groundwater pumping (Gilvear and Bradley 2009). Groundwater abstraction close to wetlands results in a higher potential for subsidence and reduced groundwater sources. This loss can be quantified by reduced wetland extents.

The surface and groundwater resources in this region have massive social, economic, and ecological significance, yet some factors affecting aquifer recharge remain poorly understood. Despite suggestions that thicketization and forest cover change may impact water resources, the specific impact of thicketization on the water resources of this region remains unclear. To improve our understanding of factors affecting baseflow conditions and aquifer recharge, my study examines changes in woody landcover density, changes with local low-flow conditions, and changes in groundwater levels, across a set of watersheds.

I hypothesize that woody landcover exerts a substantial influence on baseflows due to increased precipitation interception by the canopy and root zone and reduced runoff generation. I also expect that increased baseflow will increase aquifer recharge rates and will therefore be associated with a decrease in depth to groundwater. A strong relationship between woody plant density and baseflow is assumed to indicate an additional effect on recharge, especially in areas above the aquifer outcrop. If baseflow is found to be influenced by woody landcover, mitigation of thicketization may improve groundwater recharge in aquifer outcrop regions.

CHAPTER 2

METHODS AND STUDY AREA

Methods

I compiled data representing woody cover, baseflow volumes, and groundwater depths for multiple time periods across 10 watersheds located within or bordering the Carrizo-Wilcox Aquifer. I created a dataset for each watershed describing the change in these metrics across multiple time periods within the last century. For each time period, I calculated the difference (anomaly) between each of these metrics and the average values for that metric at that site. I examined relationships between these anomalies to identify potential associations between thicketization, baseflow and zero-flow exceedance, and depth to groundwater.

I began compiling the dataset by identifying USGS Streamflow gauges and associated watersheds within and surrounding the Carrizo-Wilcox Aquifer region (Figure 1). Watersheds covered by one to three different USGS Historical Topographic Maps representing different time periods and with available streamflow data that overlaps with the time periods of the topographic maps were included in the analysis.

The 10 different watersheds analyzed are located across the entire breadth of the Carrizo-Wilcox Aquifer (Figure 1). Four of the analyzed watersheds are located within the more rainy and forested eastern part of the aquifer, and four watersheds are located within the Post-Oak Savannah region of the central aquifer. The remaining two watersheds are in the southern portion of the aquifer, within the semi-arid South Texas Plains ecoregion. Individual watersheds are explored further below. The watershed boundaries are only used when analyzing landcover.

The watershed landcover and discharge data were compared to changes in depth to groundwater from nearby Texas Water Development Board (TWDB) groundwater wells. I plotted the locations of all monitored TWDB groundwater wells within the Carrizo-Wilcox Aquifer, preferentially selecting the wells near streamflow gauges. These wells are used exclusively for monitoring; there is no groundwater withdrawal at these sites. They are automated and record the depth to groundwater from land surface. I found that these groundwater wells were the most limited among my dataset; most watershed analysis was applied to the nearest well regardless of how long the well has been operational. The wells were most often outside the watershed boundary.

In my analysis, woody landcover encompasses both forests and shrub/brushwood. Wooded area density calculations were completed using the geographic information system (GIS) application, QGIS. I used National Land Cover Dataset (NLCD) landcover data from 2001 and 2019 (Dewitz and USGS 2021). I am particularly interested in the presence and change of woody areas within the aquifer's watersheds; therefore, I isolated the pixels in the NLCD rasters representing any forested areas (evergreen, mixed, and deciduous) and shrub/scrub areas.

I used a similar method for analyzing USGS Historical Topographic Maps to separate forested areas marked on the maps (USGS and Esri 2014). I used the QGIS raster calculator to identify and isolate the green-colored forest regions in the map to create a raster that exclusively recognized the woody landcover. The topographic maps that I found generally ranged from the late-1950s to mid-1980s. My goal was to use at least two topographic maps covering the designated watershed area and preferably more than 10 years apart. For each watershed, I was able to include one to three topographic maps and two NLCD rasters. The goal for each dataset was to represent about 65 years of data. This approach enabled me to compare historical woody landcover to low-flow regimes.

I defined baseflow as 90% flow duration of stream discharge. Baseflow represents streamflow outside of the influence of precipitation events and is closely related to groundwater discharge into streams. There are many ways to calculate baseflow (Tenalem et al. 2019); however, using a consistent percentile of a stream's flow duration curve provided me with a simple and repeatable baseflow definition. I created flow duration curves based around the years the topographic maps were published, with the goal of getting five years of baseflow data before and after the maps' publication. If I found that there was still a recording of 0 cubic feet per second (cfs) at 90% flow duration, then I instead recorded the percent of time the stream exceeded 0 cfs, or 'zero-flow exceedance.'

The resulting datasets included wooded area density, baseflow (or low-flow description), and mean depth to groundwater each site. Wooded area density is used to describe the presence or absence of thicketization within the watershed of interest. I calculated wooded area density as the ratio of the number of pixels within the topographic map or NLCD raster representing wooded areas to the total number of pixels in each analysis area. Baseflow is the selected description of discharge to emphasize changes in low-flows. In the case of ephemeral or temporal streams, the percentage of streamflow exceedance over 0 cfs was used to describe the low-flow regimes. Mean depth to groundwater was chosen to reflect the general status of the aquifer during each compared era. Change in depth to groundwater between each compared era will reflect rapid or gradual trends in groundwater table fluctuations.

The entire dataset was organized by watersheds to make localized (or watershed-specific) calculations of change in wooded area density, change in low-flows, and change in the depth to groundwater. The data were compiled into a Microsoft Excel spreadsheet and described the individual watersheds, ecoregion, USGS streamflow gauge, wooded area density (NLCD forested and shrub/scrub land cover), baseflow (90% flow duration), mean depth to groundwater, and the year that the analysis is describing (Table A1). I then calculated comparisons between these data points on the basis of 'anomaly,' or deviance from the mean for each variable at each site. Anomaly enables the comparison of variables between sites. An anomaly of 100% indicates no deviance from the mean; greater indicates an increase from the mean and lesser implies a decrease from the mean. These anomalies were calculated in R Studio at the watershed-level and then plotted amongst the other watershed-specific anomalies across the aquifer. I calculated anomaly for wooded area density separately for the different data sources; historical topographic maps' anomaly is independent of the NLCD's anomaly calculation. The resulting scatter plots include the anomalies for wooded area density and baseflow; wooded area density and zero-flow exceedance; NLCD wooded area density and depth to groundwater; baseflow and depth to groundwater; and zero-flow exceedance and depth to groundwater.

Study Area

The dataset under analysis is spread throughout the entire Carrizo-Wilcox Aquifer (Figure 1). Each of the streamflow stations within the aquifer were analyzed and used based on data availability. The aquifer stretches across several different ecoregions. I considered the watershed located within the Post-Oak Savannah ecoregion if any part of the watershed is within that ecoregion's boundary.

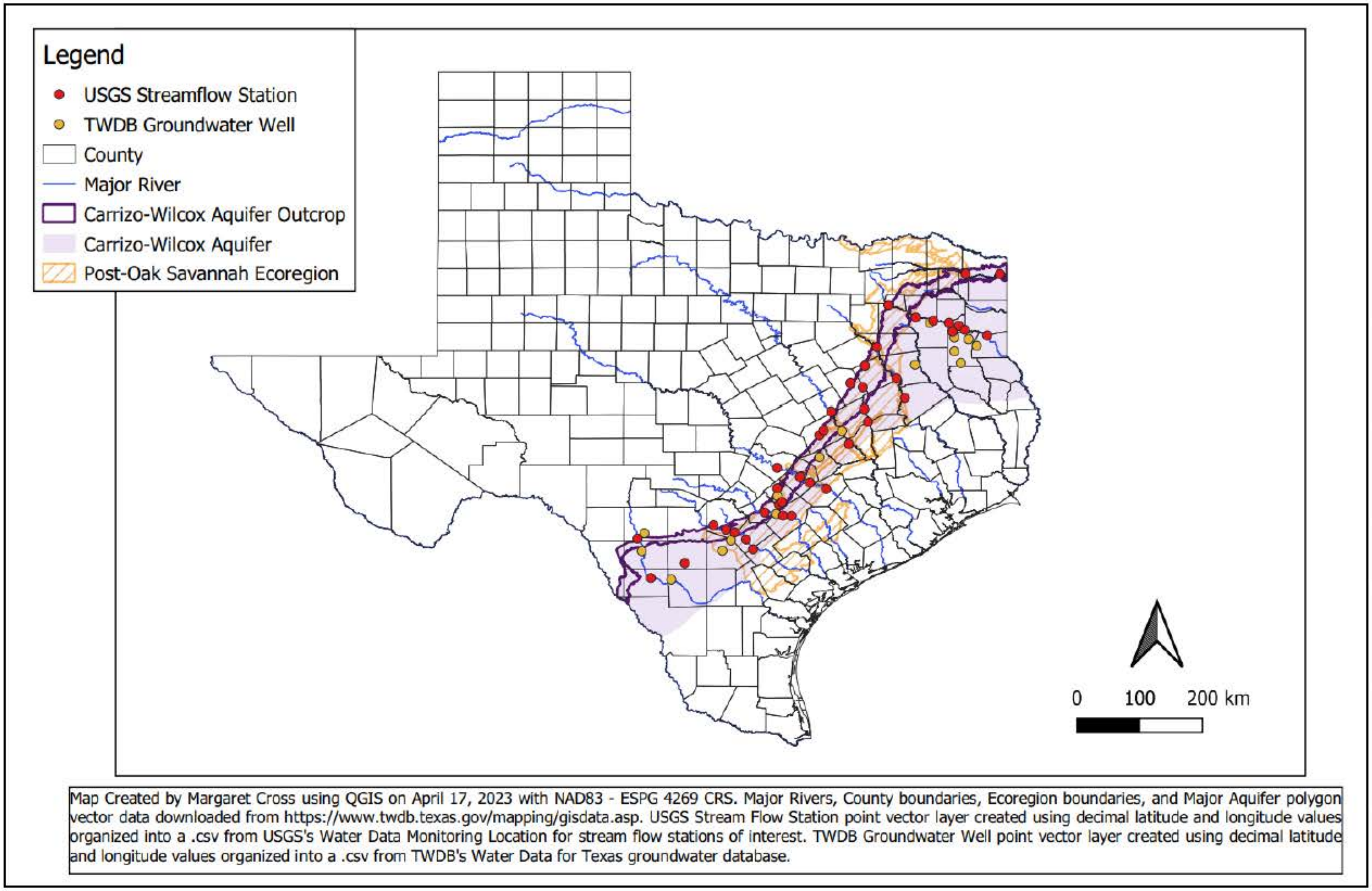


Figure 1. Map of Carrizo-Wilcox Aquifer and Post-Oak Savannah ecoregion.

<u>Gandia Branch- Sabine River Sub-watershed</u>

Gandia Branch (HUC: 120100020706) is the east-most watershed in the dataset (Figure 2). It is in the Piney Woods ecoregion; a temperate evergreen forest region overlaying Texas, Oklahoma, Arkansas, and Louisiana. The watershed lies on the confined portion of the Carrizo-Wilcox Aquifer. I used two topographic maps that cover the sub-watershed from 1956 and 1983. From 1956 to 2019, wooded area density decreased by 20%. I assigned *Sabine River near Beckville, TX* as the streamflow gauge for Gandia Branch, and I used baseflow data beginning in 1950. The groundwater well I used for this catchment is in Rusk County (Well # 3543906), with data beginning in August of 2011. The groundwater data only enabled one mean depth to groundwater point, and therefore I was unable to include it in the groundwater anomaly calculations.

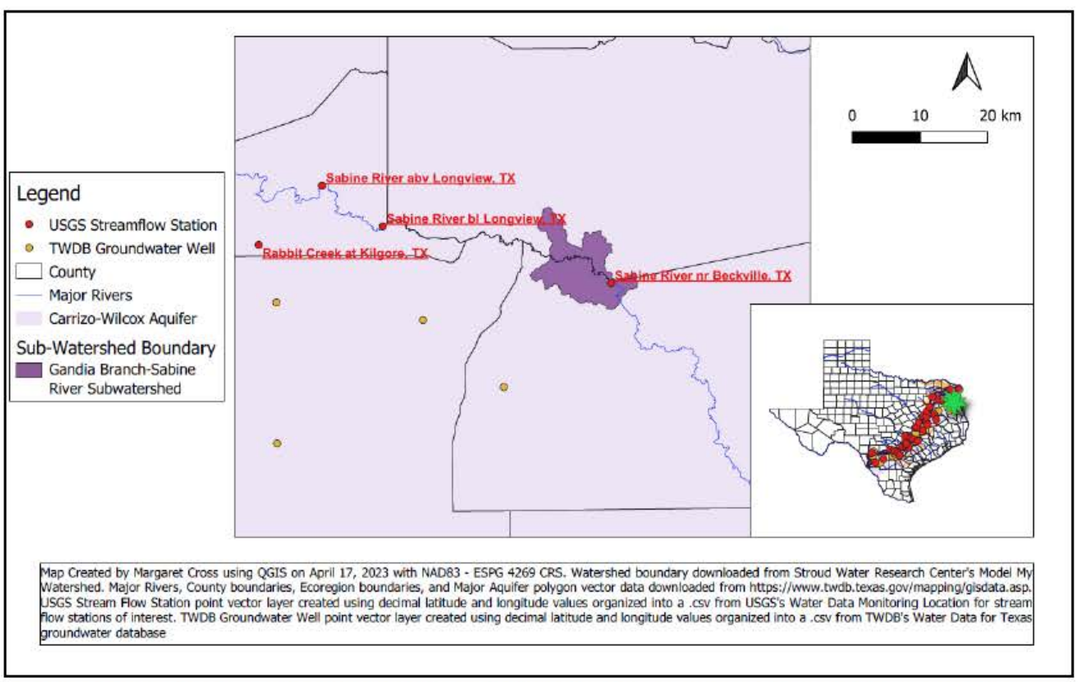


Figure 2. Map of Gandia Branch- Sabine River Sub-watershed in the northeastern part of the Carrizo-Wilcox Aquifer.

Town of Grand Saline- Sabine River Watershed

Town of Grand Saline watershed (HUC: 1201000106) straddles the Post-Oak Savannah and Piney Woods ecoregions and is located on the aquifer outcrop (Figure 3). *Sabine River near Mineola, TX* is the streamflow gauge within this watershed, and I examined baseflow data dating back to 1948. I was able to find three topographic maps covering the boundaries of the watershed, ranging from 1956 to 1991. From 1956 to 2019, wooded area density increased by 11%. The groundwater well I used for the Grand Saline watershed is from Smith County (Well # 3430907), with data dating back to early 1993.

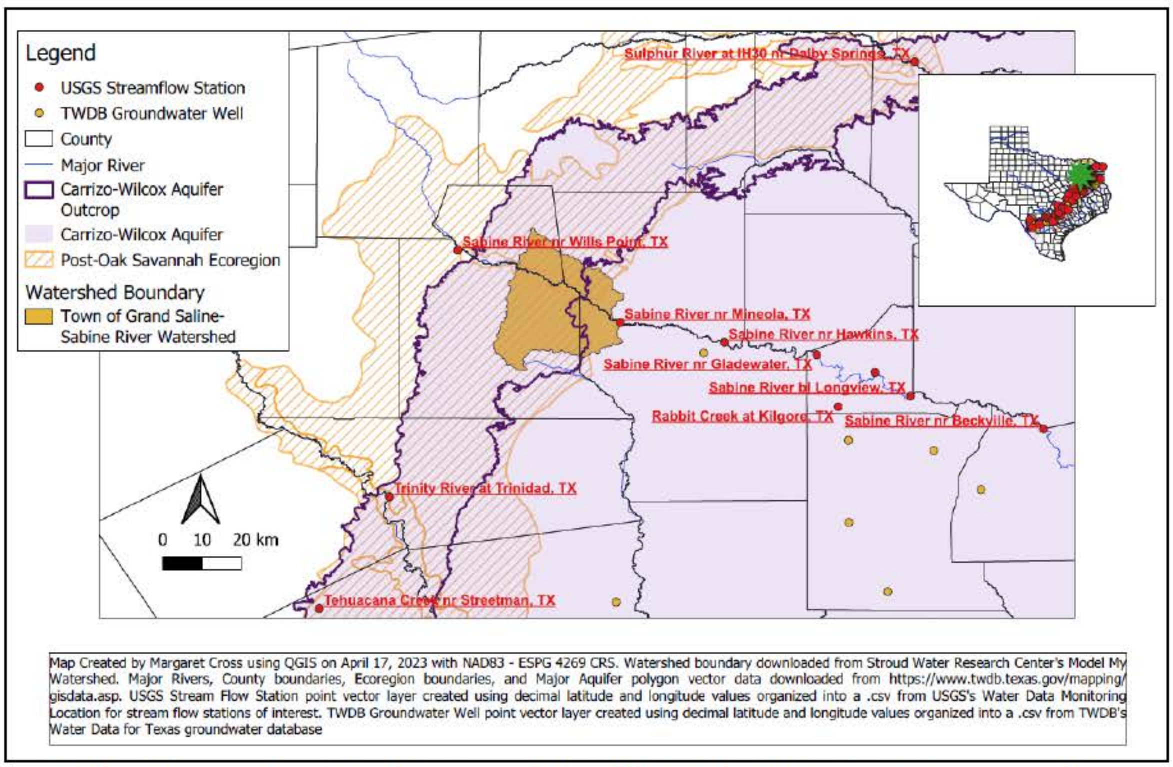


Figure 3. Map of Town of Grand Saline- Sabine River Watershed in the northeastern Carrizo-Wilcox Aquifer.

Trinidad Lake- Trinity River Sub-watershed

The Trinidad Lake sub-watershed (HUC: 120301050504) is in the Post-Oak Savannah ecoregion and the aquifer's outcrop (Figure 4). I used topographic maps from 1958 and 1985. From 1958 to 2019, wooded area density decreased by 22%. The streamflow gauge I used was *Trinity River at Trinidad, TX*, which has discharge data dating back to 1964. Because the streamflow data begins after the first topographic map, I used streamflow data from 1964-1970 to represent the baseflow-regime surrounding the 1958 topographic map. Groundwater data were accessed from the Anderson County well (Well # 3813106). The depth to groundwater readings began in 2015, limiting my groundwater data to one point and no anomaly calculation.

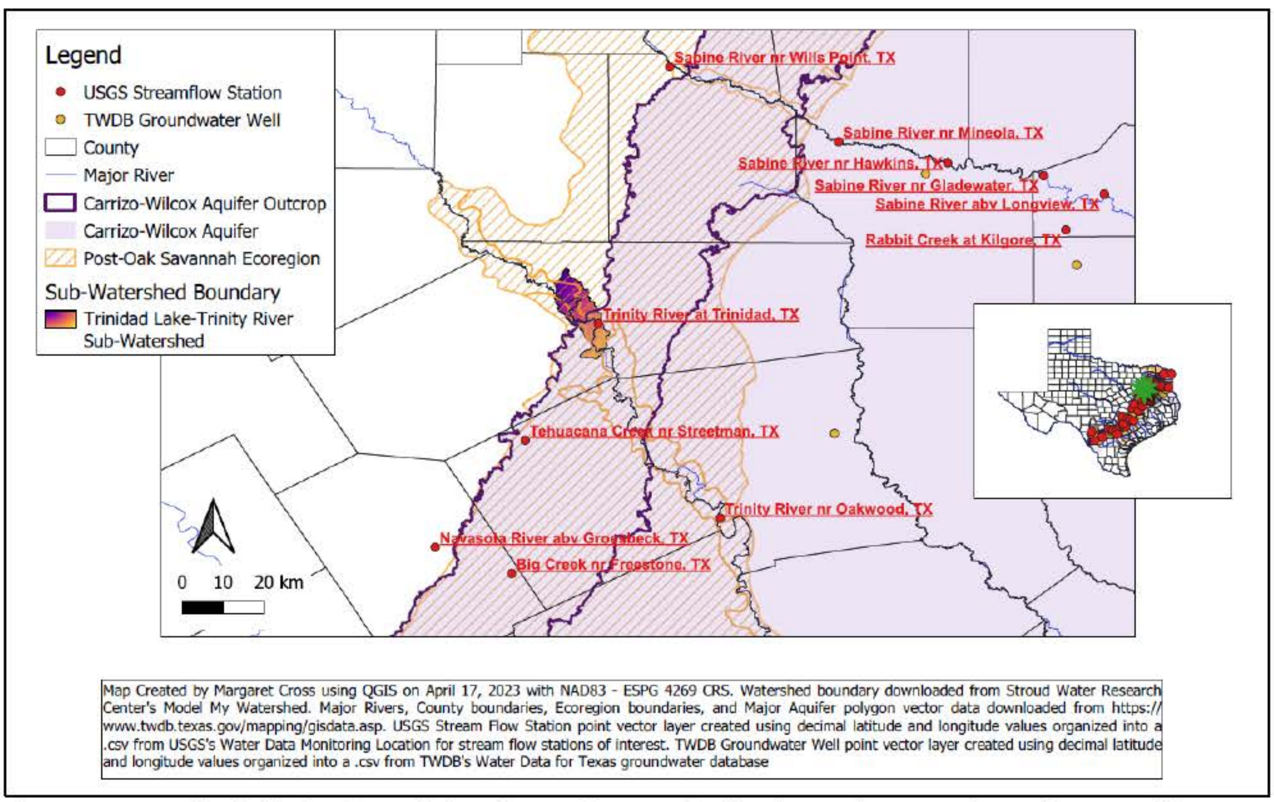
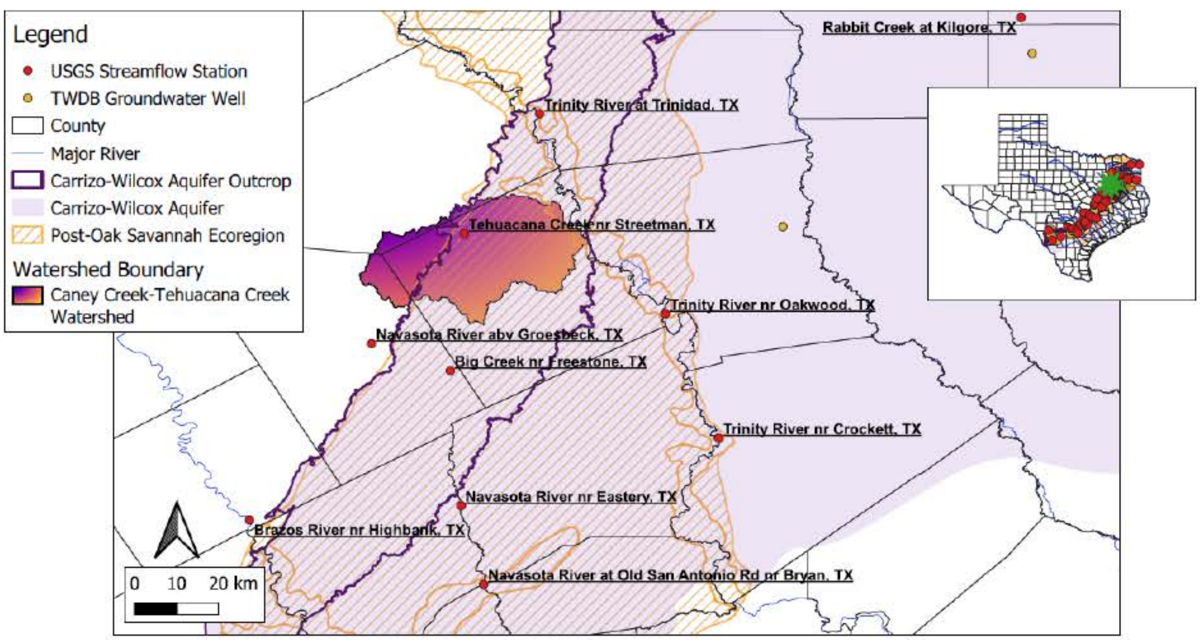


Figure 4. Map of Trinidad Lake- Trinity River Sub-watershed in the northern Carrizo-Wilcox Aquifer.

Caney Creek- Tehuacana Creek Watershed

The Caney Creek watershed (HUC: 1203020101) is in the Post-Oak Savannah and Blackland Prairie ecoregions (Figure 5). It lies on the aquifer outcrop. I used one topographic map from 1985. From 1985 to 2019, wooded area density increased by 12%. I used the *Tehuacana Creek near Streetman, TX* streamflow gauge, and recorded 'zero-flow exceedance' as the discharge measure, as baseflow was 0 cfs at 10% exceedance for two flow duration curves. The closest groundwater well was the same well from Anderson County (Well # 3813106) in the Trinidad Lake watershed dataset.

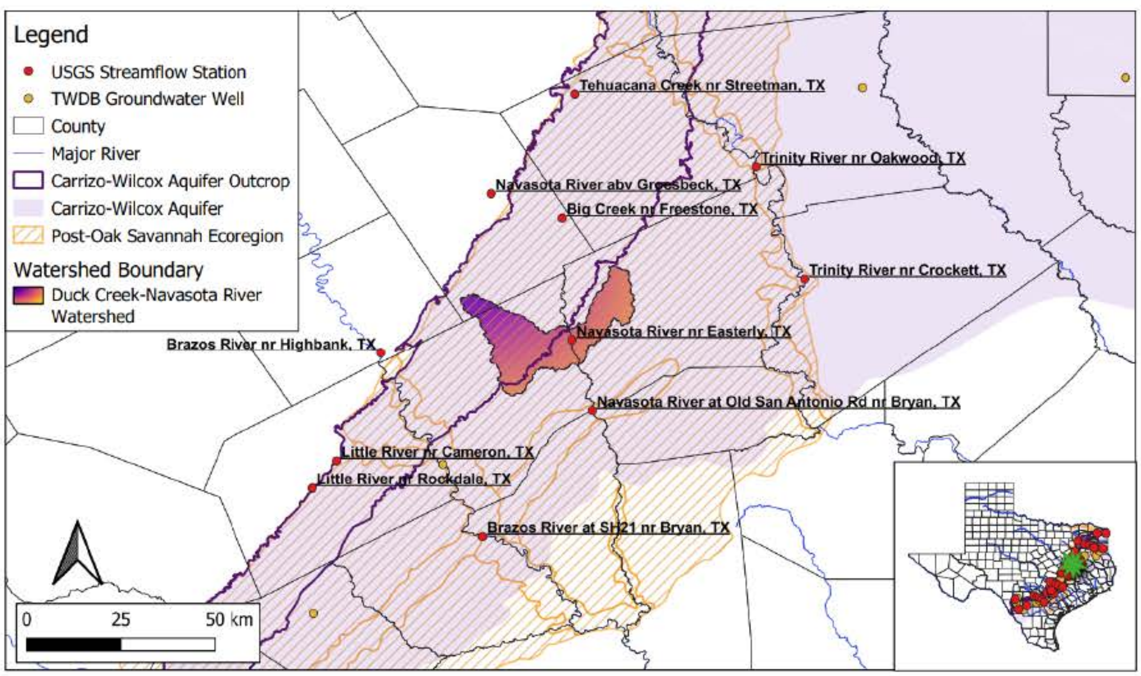


Map Created by Margaret Cross using QGIS on April 17, 2023 with NAD83 - ESPG 4269 CRS. Watershed boundary downloaded from Stroud Water Research Center's Model My Watershed. Major Rivers, County boundaries, Ecoregion boundaries, and Major Aquifer polygon vector data downloaded from https://www.twdb.texas.gov/mapping/gisdata.asp. USGS Stream Flow Station point vector layer created using decimal latitude and longitude values organized into a .csv from USGS's Water Data Monitoring Location for stream flow stations of interest. TWDB Groundwater Well point vector layer created using decimal latitude and longitude values organized into a .csv from TWDB's Water Data for Texas groundwater database

Figure 5. Map of Caney Creek- Tehuacana Creek Watershed in the northern Carrizo-Wilcox Aquifer.

Duck Creek- Navasota River Watershed

The Duck Creek watershed (HUC: 1207010304) is in the Post-Oak Savannah ecoregion as well as the aquifer outcrop (Figure 6). I used topographic maps from 1954 and 1985. From 1954 to 2019, wooded area density increased by 7%. I used surface flow data dating back to 1949 from the *Navasota River near Easterly, TX* gauge. The nearest TWDB groundwater well to the watershed is the Milam County well (Well # 5911621), which has groundwater data since 1995, allowing for two groundwater table datapoints and an anomaly calculation. There was a gap in groundwater data from 2000-2003.



Map Created by Margaret Cross using QGIS on April 17, 2023 with NAD83 - ESPG 4269 CRS. Watershed boundary downloaded from Stroud Water Research Center's Model My Watershed. Major Rivers, County boundaries, Ecoregion boundaries, and Major Aquifer polygon vector data downloaded from https://www.twdb.texas.gov/mapping/gisdata.asp. USGS Stream Flow Station point vector layer created using decimal latitude and longitude values organized into a .csv from USGS's Water Data Monitoring Location for stream flow stations of interest. TWDB Groundwater Well point vector layer created using decimal latitude and longitude values organized into a .csv from TWDB's Water Data for Texas groundwater database

Figure 6. Map of Duck Creek- Navasota River Watershed in the central Carrizo-Wilcox Aquifer.

Jordan Creek- Colorado River Sub-watershed

The Jordan Creek sub-watershed (HUC: 120903010701) is in the Post-Oak Savannah ecoregion and above the confined aquifer (Figure 7). This dataset had topographic maps from 1953 and 1985. From 1953 to 2019, wooded area density increased by 13%. I used the *Colorado River above La Grange, TX* streamflow gauge, where the discharge data began in 1988. This removed the possibility of comparing baseflow anomaly with the wooded area density anomaly from 1953. I used the Bastrop County groundwater well (Well # 5862208), which began recording in 2003.

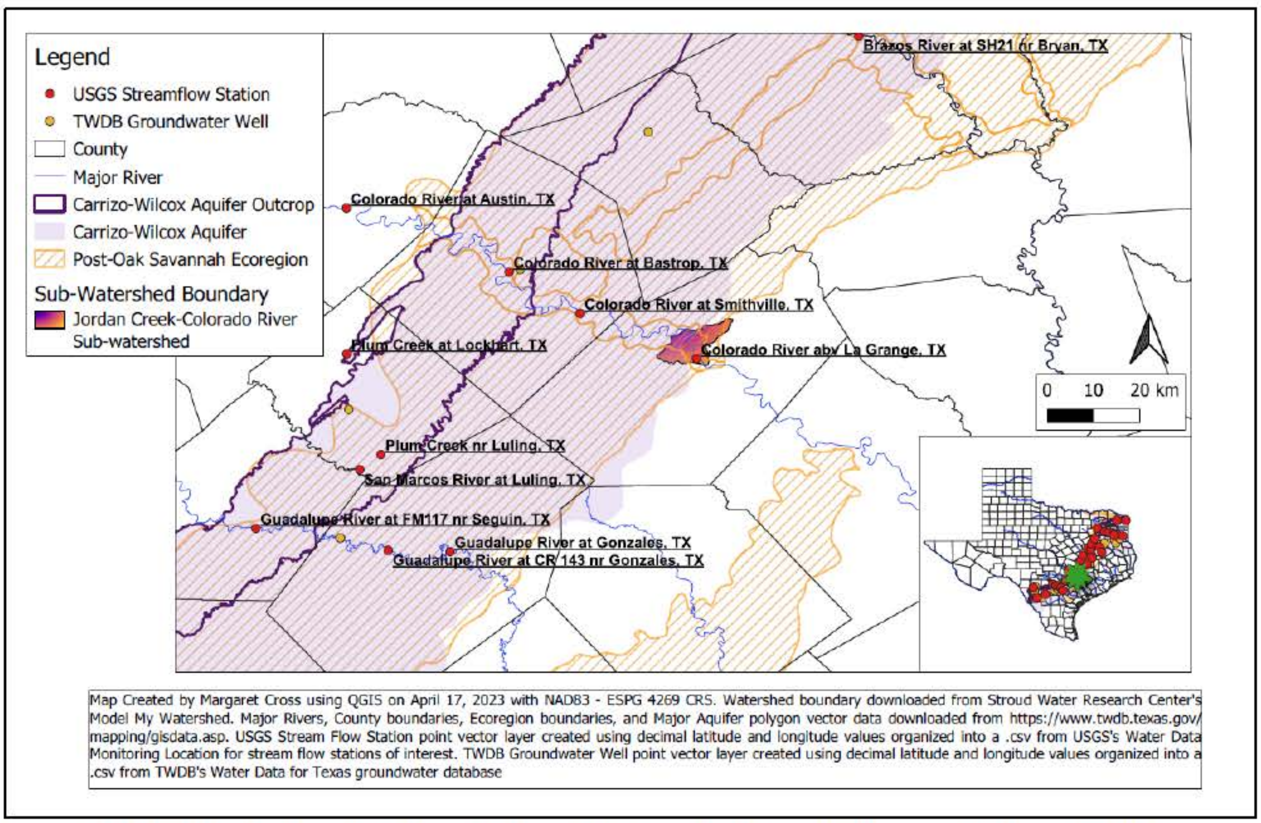
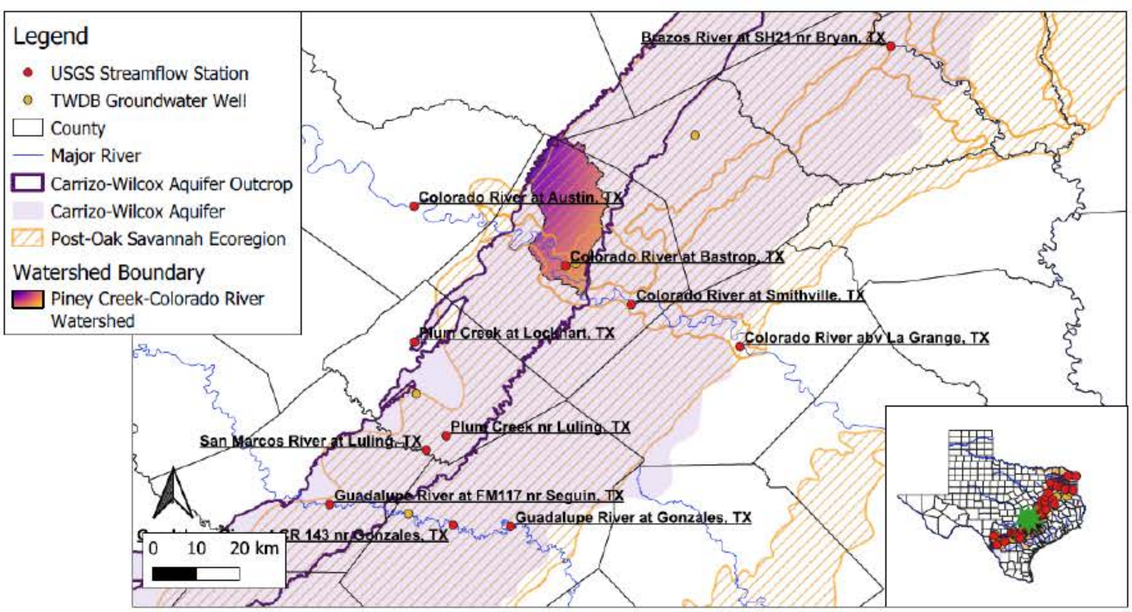


Figure 7. Map of Jordan Creek- Colorado River Sub-watershed in central Carrizo-Wilcox Aquifer.

Piney Creek- Colorado River Watershed

The Piney Creek watershed (HUC: 1209030102) is in the Post-Oak Savannah ecoregion and the aquifer outcrop (Figure 8). I used topographic maps from 1954 and 1985. From 1954 to 2019, wooded area density increased by 31%. I examined the *Colorado River at Bastrop, TX* streamflow gauge for baseflow data, which began daily measurements in March of 1960. The nearest well for Piney Creek is the same Bastrop County well (Well # 5862208) as the Jordan Creek sub-watershed. Piney Creek and Jordan Creek have the same depth to groundwater anomalies.



Map Created by Margaret Cross using QGIS on April 17, 2023 with NAD83 - ESPG 4269 CRS. Watershed boundary downloaded from Stroud Water Research Center's Model My Watershed. Major Rivers, County boundaries, Ecoregion boundaries, and Major Aquifer polygon vector data downloaded from https://www.twdb.texas.gov/mapping/gisdata.asp. USGS Stream Flow Station point vector layer created using decimal latitude and longitude values organized into a .csv from USGS's Water Data Monitoring Location for stream flow stations of interest. TWDB Groundwater Well point vector layer created using decimal latitude and longitude values organized into a .csv from TWDB's Water Data for Texas groundwater database

Figure 8. Map of Piney Creek- Colorado River Watershed in the central Carrizo-Wilcox Aquifer.

West Fork Plum Creek- Plum Creek Sub-watershed

The West Fork Plum Creek sub-watershed (HUC: 121002030409) is in the Post-Oak Savannah and Blackland Prairie ecosystems (Figure 9). It is also located on the aquifer outcrop. I used topographic maps from 1953 and 1985. From 1953 to 2019, wooded area density increased by 43%. I sourced discharge data since 1947 from the *Plum Creek near Luling, TX* streamflow gauge. The groundwater well I used for this sub-watershed was from Gonzales County (Well # 6727805). I decided to use the Gonzales County well instead of the Caldwell County well (located inside the West Fork Plum Creek sub-watershed) because it had more data. I still was only able to create one groundwater datapoint and therefore I could not calculate anomaly.

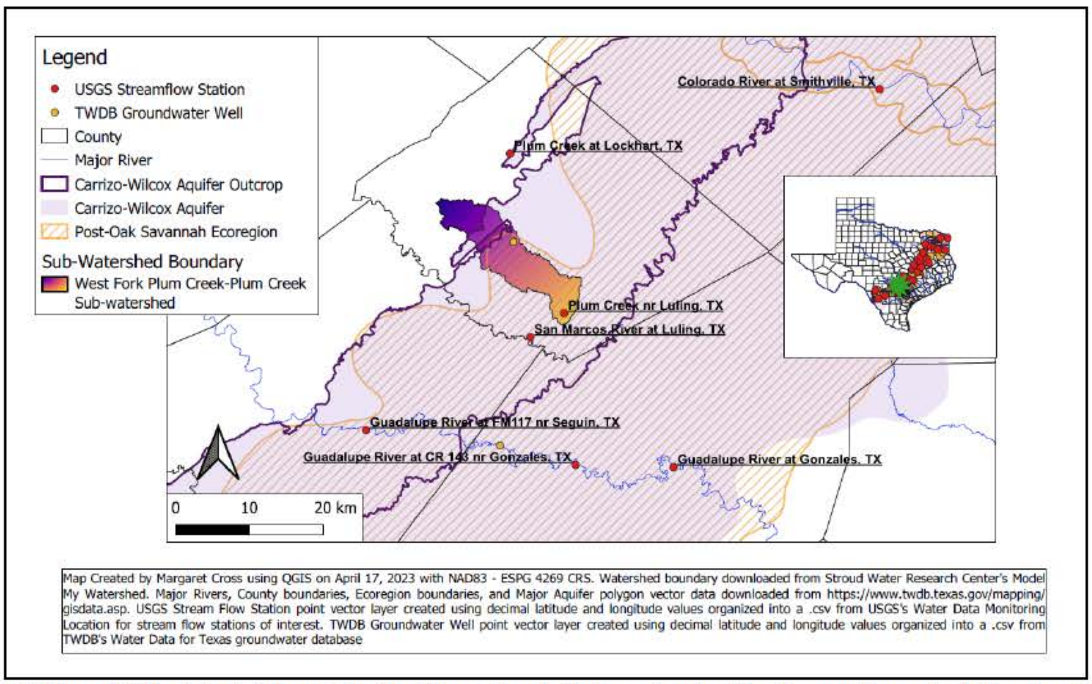


Figure 9. Map of West Fork Plum Creek- Plum Creek Sub-watershed in the south-central Carrizo-Wilcox Aquifer.

Town of Derby- Frio River Sub-watershed

The Town of Derby sub-watershed (HUC: 121101061205) is in the South Texas Plains ecoregion, also known as 'brush country' (Figure 10). Figure 10 includes the Crystal City 1955 USGS Historical Topographic Map raster layer. It is found above the confined aquifer. I found topographic maps from 1955, 1968, and 1976. From 1955 to 2019, wooded area density increased by 8%. I used the *Frio River near Derby, TX* discharge data dating back to 1950. This stream has zero-flows ranging from 7% to 71% of the time, based on the five created flow duration curves. I used the La Salle County groundwater well (Well # 7738103), which has groundwater data since November 2003.

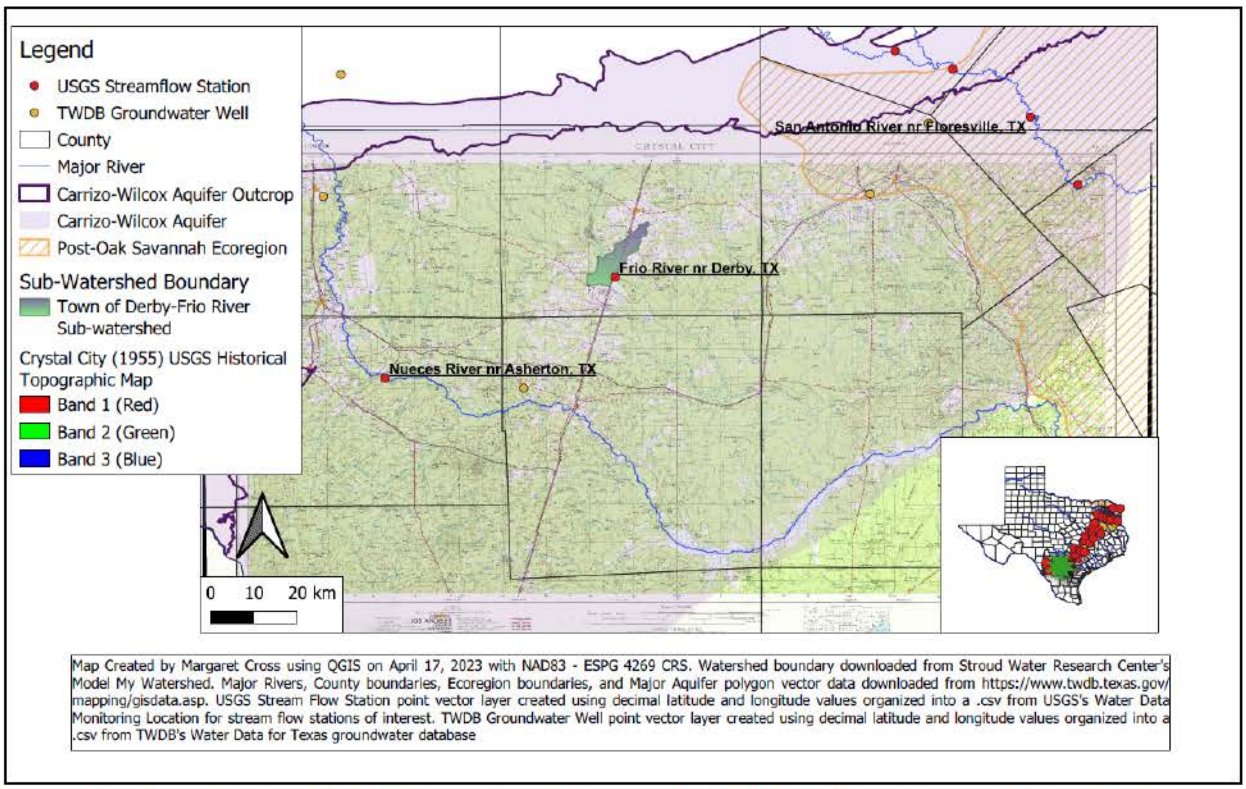
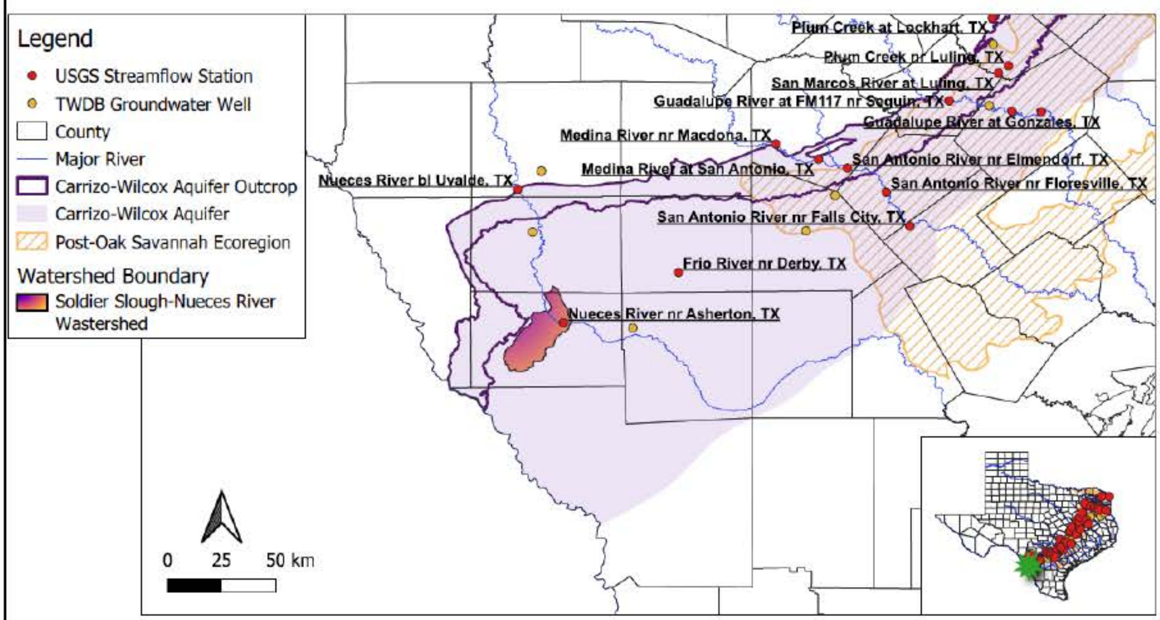


Figure 10. Map of Town of Derby- Frio River Sub-watershed in the southern Carrizo-Wilcox Aquifer.

Soldier Slough- Nueces River Watershed

The Soldier Slough watershed (HUC: 1211010303) is in the South Texas Plains ecoregion, above the confined aquifer (Figure 11). I used topographic maps from 1968 and 1976. From 1968 to 2019, wooded area density increased by 19%. I analyzed the *Nueces River near Asherton, TX* discharge data beginning in the 1960 water year and recorded it in the form of 'zero-flow exceedance.' The nearest groundwater well was from Zavala County (Well # 7702509), which began recording measurements in 2002.



Map Created by Margaret Cross using QGIS on April 17, 2023 with NAD83 - ESPG 4269 CRS. Watershed boundary downloaded from Stroud Water Research Center's Model My Watershed. Major Rivers, County boundaries, Ecoregion boundaries, and Major Aquifer polygon vector data downloaded from https://www.twdb.texas.gov/mapping/gisdata.asp. USGS Stream Flow Station point vector layer created using decimal latitude and longitude values organized into a .csv from USGS's Water Data Monitoring Location for stream flow stations of interest. TWDB Groundwater Well point vector layer created using decimal latitude and longitude values organized into a .csv from TWDB's Water Data for Texas groundwater database

Figure 11. Map of Soldier Slough- Nueces River Watershed in the southern Carrizo-Wilcox Aquifer.

CHAPTER 3

RESULTS

I used 10 different watersheds and sub-watersheds within the Carrizo-Wilcox Aquifer (Table A1). Each watershed has three to five data entries representing different time periods; the variety was a result of data availability from USGS Historical Topographic Map Explorer, USGS streamflow data, and TWDB Water Data for Texas databases. The watersheds and streamflow gauges in Table A1 were arbitrarily colored by relative location; green indicating eastern aquifer, orange indicating central aquifer, and yellow indicating southern aquifer. Streams that had entries for 'zero-flow exceedance' contained at least one flow duration curve where the stream ran dry for greater than 10% of designated time period (typically 10 years).

The dataset includes a variety of shifting local woody landcover, low-flow, and groundwater regimes across the aquifer (Table A1). Of the seven watersheds with baseflow readings (all of which had increasing baseflow volumes), two of those watersheds saw a decrease in thicketization while five experienced an increase in thicketization. All three watersheds with zero-flow exceedance measurements experienced an increase in thicketization; two of those watersheds saw an increase in percentage of zero-flow measurements. Six watersheds compared landcover and discharge to groundwater table data. Half of the wells in the study experienced an increase in the depth to groundwater and one of them saw almost no change in more than 20 years of groundwater data. The well with minimal change in groundwater table saw an increase in both wooded area density and baseflow, and was located in the central Post-Oak Savannah (Duck Creek- Navasota River Watershed).

A scatterplot of the relationship between baseflow anomaly and wooded area density anomaly (Figure 12) reveals a positive correlation (i.e., higher baseflow anomalies associated with higher wooded area density anomalies). In contrast, I predicted that wooded area density would have a negative correlation with streamflow volumes. Although I hypothesized that thicketization would increase the interception of precipitation and thus lower baseflows and reduce aquifer recharge, these data suggest the opposite.

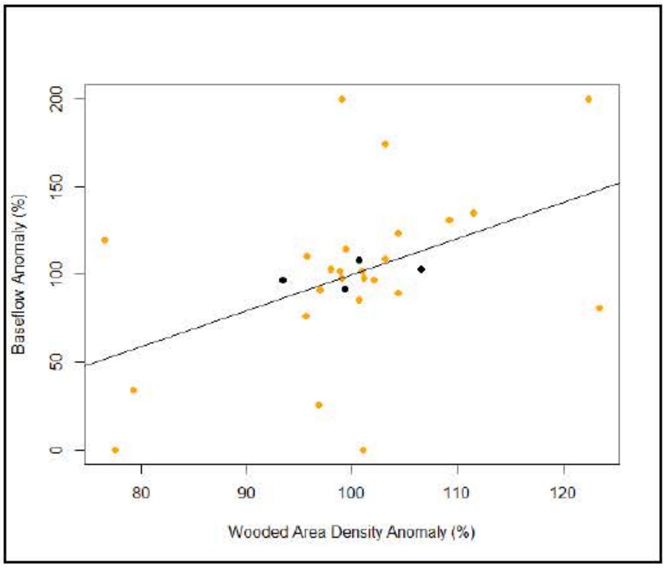


Figure 12. Baseflow anomaly plotted against wooded area density anomaly. Orange points indicate the watershed is in the Post-Oak Savannah Ecoregion. Black points indicate the watershed is outside of the Post-Oak Savannah Ecoregion. The trendline shows a 2% increase in baseflow anomaly per 1% increase in wooded area density anomaly ($p = 0.0133$).

The fitted linear trendline for this comparison provides high confidence for this positive relationship ($p = 0.0133$) and indicates that an increase of 2% in baseflow anomaly is associated with a 1% increase in wooded area density anomaly (Figure 12). The majority of the datapoints are concentrated around the trendline. Because wooded area density anomaly was calculated separately for historical topographic maps and NLCD datasets, there were often only two datapoints for the anomaly calculation. An anomaly calculation for a single site's topographic maps will contain one datapoint below the mean (100% anomaly) and one datapoint the same distance above the mean. This is reflected in the non-Post-Oak Savannah points (Figure 12).

There is no relationship (p = 0.277) between zero-flow exceedance anomaly and wooded area density anomaly at the aquifer-level (Figure 13). The plot shows very different patterns for the datapoints within and outside of the Post-Oak Savannah with the points in the Post-Oak Savannah ecoregion extending a much wider range in wooded area density than the points outside of the ecoregion. The datapoints from the Post-Oak Savannah ecoregion reflect very little fluctuation in zero-flow exceedance anomaly; this ecoregion has very few streams with a single 0 cfs baseflow value. The datapoints outside of the Post-Oak Savannah ecoregion have much greater variation in zero-flow exceedance and much less variation in wooded area density.

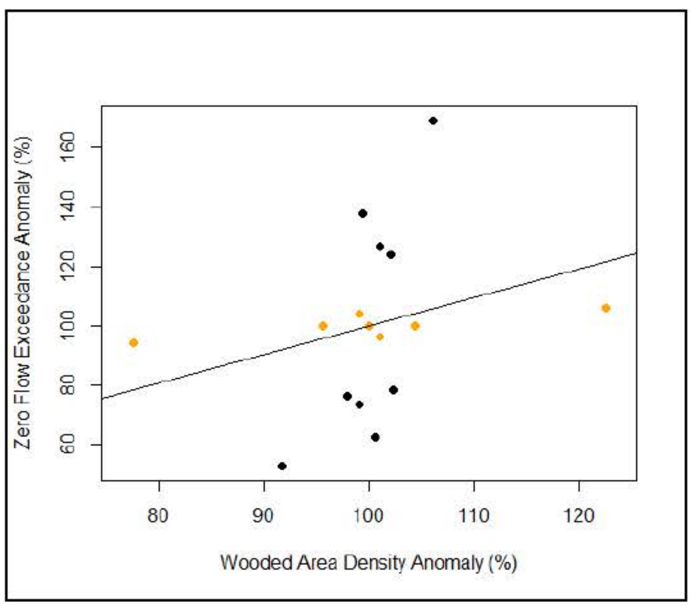


Figure 13. Zero-flow exceedance anomaly plotted against wooded area density anomaly. Orange points indicate the watershed is in the Post-Oak Savannah Ecoregion. Black points indicate the watershed is outside of the Post-Oak Savannah Ecoregion. There is minimal confidence (p = 0.277) in the trendline's representation of the dataset.

There is also no clear relationship (p = 0.671) between depth to groundwater anomaly and wooded area density anomaly (Figure 14). All datapoints are concentrated between 95-105% wooded area density anomaly. This pattern reflects minimal fluctuations in woody land cover among the available groundwater datapoints. The groundwater data were limited to 1995 or later, meaning that each of the wooded area density anomaly calculations were a part of the NLCD dataset.

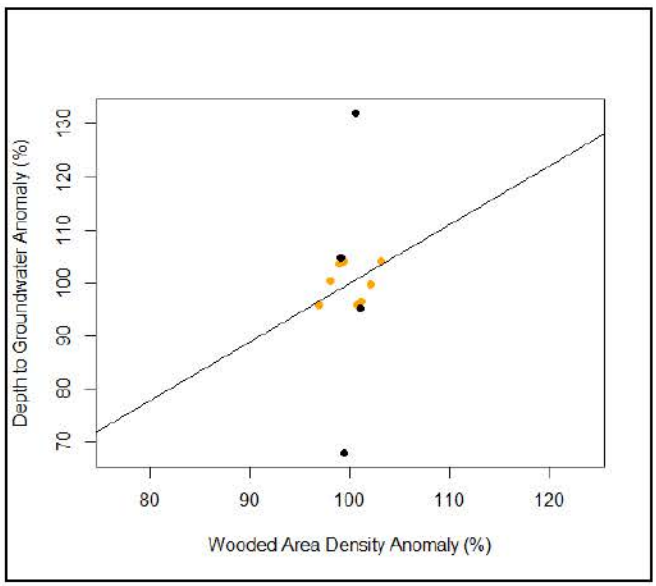


Figure 14. Depth to groundwater anomaly plotted against wooded area density anomaly. Orange points indicate the watershed is in the Post-Oak Savannah Ecoregion. Black points indicate the watershed is outside of the Post-Oak Savannah Ecoregion. There is little to no confidence (p = 0.671) in the trendline's representation of the dataset.

There is high confidence (p = 0.005) in the positive relationship between depth to groundwater anomaly and baseflow anomaly (Figure 15). All plotted points are in the Post-Oak Savannah, as the datapoints located outside of that ecoregion had zero-flow greater than 10% of the time. The fitted linear trendline shows a 0.34% increase in baseflow anomaly for every 1%

increase in depth to groundwater anomaly. However, this confidence is limited by the small dataset.

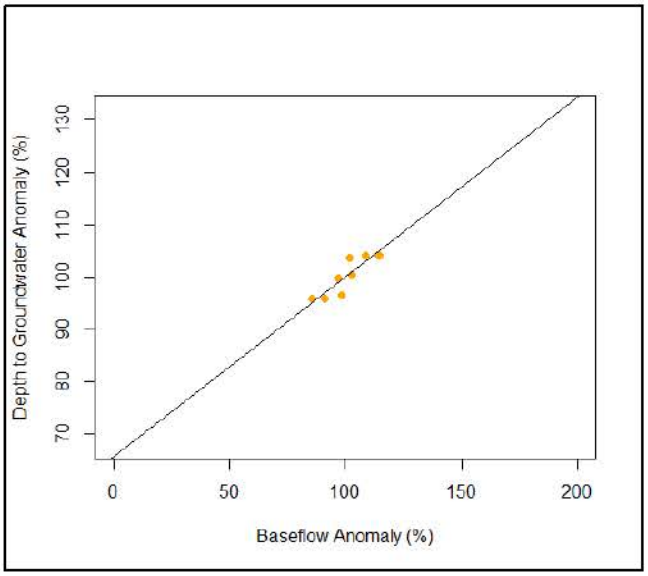


Figure 15. Depth to groundwater anomaly plotted against baseflow anomaly. Orange points indicate each watershed in this dataset are in the Post-Oak Savannah Ecoregion. There were no watersheds in this dataset outside of the Post-Oak Savannah. There is very high confidence (p = 0.005) in the trendline's representation of the relationship between the variables.

There is limited confidence (p = 0.1077) in the relationship between depth to groundwater anomaly and zero-flow exceedance anomaly (Figure 16). The fitted linear trendline suggests a 0.63% decrease in depth to groundwater anomaly for every 1% increase in zero-flow exceedance anomaly. Both watersheds in Figure 16 are within the semi-arid South Texas Plains ecoregion, where surface flows are limited, and groundwater recharge rates are the lowest in the aquifer.

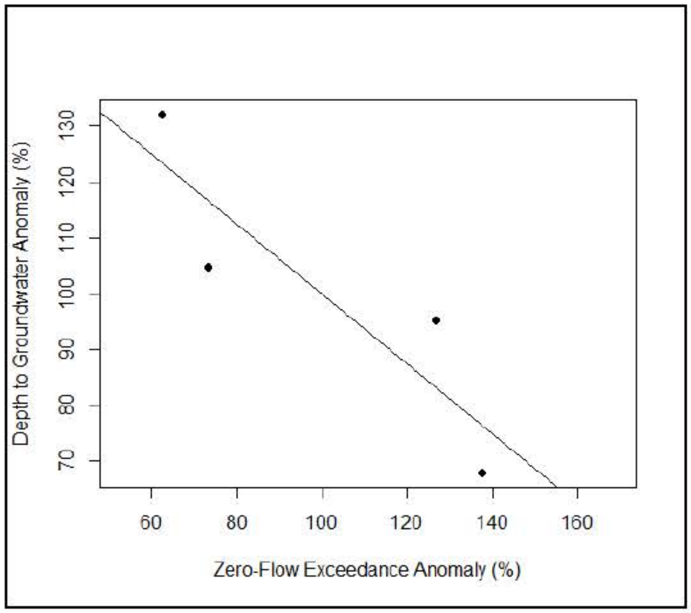


Figure 16. Depth to groundwater anomaly plotted against zero-flow exceedance anomaly. Black points indicate each watershed in this dataset are located outside of the Post-Oak Savannah Ecoregion. There is limited confidence (p=0.107) in the trendline's representation of the dataset.

CHAPTER 4

DISCUSSION

The data suggests a strong relationship between baseflow and wooded area density, regardless of ecoregion (Figure 12). There is a positive correlation between baseflow and wooded area density, unanticipated in my hypothesis. In retrospect, this relationship may reflect decadal climate conditions affecting both woody landcover and baseflows. Landcover changes like urbanization may also be affecting both woody landcover and flow regimes. It is possible that there is some truth in the original hypothesis, but these external variables potentially present a strong effect on the relationship, hiding the anticipated trends. Focusing on watersheds within stream-reaches that lose flow to groundwater, estimated with gradient self-potential logging (Ikard et al. 2021), would create a streamflow dataset with an identified relationship to groundwater recharge. The effect of local land use change (i.e., development and agricultural) on low-flows and groundwater levels across the aquifer could also be investigated utilizing the same methodology from this study.

The datapoints outside of the Post-Oak Savannah in Figure 13 show minimal correlation between zero-flow exceedance and wooded area density. These black datapoints are all from the South Texas Plains ecoregion. Within a slim range of wooded area density, the black points have a wide range of potential zero-flow exceedance. The limited range makes change in wooded area density within a watershed difficult to anticipate a resulting change in zero-flow exceedance. The orange points from the Post-Oak Savannah in Figure 13 reflect the minimal zero-flows experienced amongst a wide range of potential wooded area density changes. This also shows that zero-flow exceedance is a poor indicator for change wooded area density among the datapoints from in the Post-Oak Savannah.

The small variation of wooded area density anomaly and the much larger variation around the mean in depth to groundwater anomaly reflects a very weak relationship between groundwater and thicketization in this dataset (Figure 14). This makes it difficult to anticipate changes in depth to groundwater by exclusively observing change in woody landcover in a nearby watershed. The minimal correlation between changing woody land cover and the groundwater table was expected. The groundwater wells were often kilometers from the watersheds where woody area density calculated; fluctuations of groundwater within the aquifer are affected by slow-moving recharge and groundwater abstraction. There are many uncertainties in groundwater table analysis; change in wooded area density does not have a clear, immediate effect on the local groundwater table.

The positive relationship between baseflow and depth to groundwater was unexpected (Figure 15). I anticipated that increased baseflow would result in reduced depth to groundwater, indicated by a higher groundwater table. Figure 15 suggests that increased baseflow volumes correlate with a lower local groundwater table. Increased woody landcover density is positively correlated with baseflow; with further research, it may be possible to attribute a disconnect in baseflow contribution to the groundwater table due to thicketization. If this is true, then woody landcover mitigation across the Carrizo-Wilcox Aquifer outcrop may improve recharge rates.

The other low-flow graph compares zero-flow exceedance anomaly and depth to groundwater anomaly and is limited to four datapoints (Figure 16). A more robust dataset may result in a similar trend with higher confidence. The trend suggests that longer periods of zero-flow is reflected in a rise in groundwater table. This is another unanticipated result and may be a further reflection of outside factors affecting these results.

The findings in this study are in some cases limited by the scarcity of data. Most of the groundwater wells reported by the Texas Water Development Board (TWDB) within the Carrizo-Wilcox Aquifer date to the early 2000s, making direct comparisons between groundwater levels and the historical topographic maps an impossibility. Some of the watersheds in the dataset shared the same well data, as it was the closest monitored groundwater well to each site. In some cases, the groundwater well selected for a watershed was not the nearest TWDB-monitored well due to longer periods of recorded groundwater measurements. The addition of historical groundwater table data would have provided a more robust data set for woody landcover density and low-flow comparisons.

The methods I used to quantify woody landcover from the historical topographic maps relied on interpretation of the extent of green shaded areas. However, some maps contained regions of dotted-green shading, representing the extent of 'brushwood' or shrub land cover. I combined all forested, brushwood, and shrub/scrub types into a single 'wooded' category because of the complexity distinguishing these brushwood regions from forested areas and inconsistency in the categorization of 'brushwood' and 'shrub/scrub' versus forested land cover types between the USGS topo maps and the NLCD data. Using all 'wooded' landcover types instead of just forested reduces the error that would accumulate when using pixel density of historical topographic map imagery.

I also determined that topographic map derived densities were likely an underestimate of actual land cover relative to NLCD densities. Contour lines, labels, streams, and railroads drawn on the topographic map overlay the green-colored forests and shrub land cover. This resulted in reduced recognition by QGIS of the forested areas. This error is reflected in Figure 17, where 'False' represents the topographic maps and 'True' represents the 2001 and 2019 NCLD datasets. I calculated anomaly independently for the historical topographic maps and the NLCD datasets to minimize error due to using two different sources for landcover estimates.

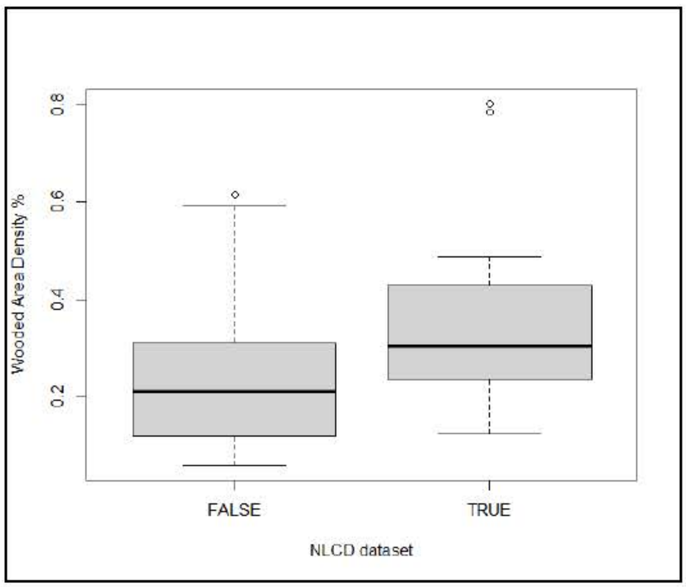


Figure 17. Boxplot of the recorded wooded area densities from the USGS Historical Topographic Maps ('False') and NLCD Land Cover ('True'). The second and third quartiles of USGS Historical Topographic Map wooded area density data percentages are lower than NLCD wooded area density data percentages.

Further information can be obtained from additional research focused on varying wetland extent as a result disconnection for groundwater sources due to local groundwater abstraction (Gilvear and Bradley 2009). Such a project could also examine varying woody-cover density to determine if there is a further effect on groundwater detachment. Wetlands were not delineated in the historical topographic maps, making long term examination of wetland extent an impossibility using my methods.

Applying my methods to other aquifers within and outside of Texas may reveal that the trend of thicketization affecting baseflow and the groundwater table is applicable to more than just the Carrizo-Wilcox Aquifer. It also provides the opportunity to include a more robust dataset for each variable. I recommend using smaller USGS Historical Topographic Maps to make isolating the green-colored forest designations more accurate. These methods may also be applied to other NLCD designated categories (i.e., Wetlands, Developed, Planted/Cultivated, etc.) to investigate their effects on local low-flow regimes and groundwater table.

CHAPTER 5

CONCLUSION

My project revealed a clear positive correlation between baseflow and woody landcover change, as well as between baseflow and depth to groundwater. Although these relationships contradict my predictions, they suggest that wood landcover may have a significant effect on the connection between surface and groundwater hydrology. This may be especially true in the Post-Oak Savannah ecoregion due to its historical condition as a grassland with only scattered evergreen and deciduous trees. Investigation into the mechanisms relating local climate, land use change, woody cover, baseflow generation, and aquifer recharge may explain the unexpected patterns found in my project. A deeper analysis into these factors could ultimately lead to an improved understanding and management of the valuable water resources in this region.

REFERENCES CITED

Archer, S.R., Anderson, E.M., Predick, K.I., Schwinning, S., Steidl, R.J., Woods, S.R., 2017. Woody Plant Encroachment: Causes and Consequences. *Rangeland Systems*, pp 25-84.

Shishir Basant, Bradford P. Wilcox, Chelsea Parada, Briana M. Wyatt, Brent D. Newman, 2023. Thicketized oak woodlands reduce groundwater recharge. *Science of The Total Environment*, vol 862, 160811, no. 0048-9697, https://doi.org/10.1016/j.scitotenv.2022.160811.

Boghici, R., 2009. Water Quality in the Carrizo-Wilcox Aquifer, 1990-2006. *Texas Water Development Board*, Report 372.

Brien, J., 2021. Impacts of Groundwater Pumping for Hydraulic Fracturing on Other Sector Wells in Aquifers Overlying the Eagle Ford Shale of Texas. Master's thesis, *Texas A&M University*. Available electronically from https : / /hdl .handle .net /1969 .1 /196116.

Bureau of Economic Geology, 2011. Carrizo-Wilcox Aquifer Study. *Texas Commission on Environmental Quality*, Final Contract Report.

Dewitz, J., and U.S. Geological Survey, 2021, National Land Cover Database (NLCD) 2019 Products (ver. 2.0, June 2021): U.S. Geological Survey data release, https://doi.org/10.5066/P9KZCM54.

Gilvear, D.J., and Bradley, C., 2009. Hydrological Dynamics II: Groundwater and hydrological connectivity. *The Wetlands Handbook*, 1st edition, Chapter 7.

Huang, Y., Scanlon, B.R., Nicot, J.P., et al., 2012. Sources of groundwater pumpage in a layered aquifer system in the Upper Gulf Coastal Plain, USA. *Hydrogeology Journal* 20(4):783-796. DOI: 10.1007/s10040-012-0846-2

Ikard, S.J. et al., 2018. New Insights on Scale-dependent Surface-groundwater Exchange from a Floating Self-potential Dipole. *Journal of Environmental and Engineering Geophysics*, iss. 23 no. 2, https://doi.org/10.2113/JEEG23.2.261

Ikard, S.J. et al., 2021. Gradient Self-Potential Logging in the Rio Grande to Identify Gaining and Losing Reaches across the Mesilla Valley. *Water* 13, no. 10: 1331. https://doi.org/10.3390/w13101331

Melo, D., and Wendland, E., 2017. Shallow aquifer response to climate change scenarios in a small catchment in the Guarani Aquifer outcrop zone. Anais da Academia Brasileria de Ciencias, Earth Sciences. https://doi.org/10.1590/0001-3765201720160264

Miller, K., Milman, A., Burson, M., Tracy, J., Kiparsky, M., 2021. Groundwater recharge for drought and endangered species protection: The H2Oaks Aquifer to aquifer transfer for storage and recovery, San Antonio, Texas. *Case Studies in the Environment* (2015). https://doi.org/10.1525/cse.2020.1118198

Peckham, R.C., 1965. Availability and Quality of Ground Water in Leon County, Texas. *Texas Water Commission*, Bulletin 6513. https://www.twdb.texas.gov/publications/reports/bulletins/doc/B6513/B6513.pdf

Potter, Harry Grant III, 2004. History and evolution of the rule of capture, *Texas Water Development Board*, Williams-Bailey Law Firm, LLC., ch.1. https://www.twdb.texas.gov/publications/reports/numbered_reports/doc/R361/1%20CH%20Potter.pdf

Scanlon, B.R. et al., 2002. Groundwater Recharge in Texas. *TWDB*. https://www.twdb.texas.gov/publications/reports/contracted_reports/doc/2000483340.pdf

Schiling, K.E. et al., 2021. Using baseflow to quantify diffuse groundwater recharge and drought at a regional scale. *Journal of Hydrology*, vol 602, 126765, ISSN 0022-1694. https://doi.org/10.1016/j.jhydrol.2021.126765.

Schmidly, D. J., 2002. Texas Natural History: A Century of Change. *Texas Tech University Press*, Lubbock, Texas. (pp 371-374).

Supreme Court of Texas, 2012. The EDWARDS AQUIFER AUTHORITY and The State of Texas, Petitioners, v. Burrell DAY and Joel McDaniel, Respondents. No. 08-0964. https://caselaw.findlaw.com/court/tx-supreme-court/1595644.html

Tenalem, A., et al., 2019. Comparison of Different Base Flow Separation Methods and Drought Vulnerability in a Rift Valley area. *Journal of Spatial Hydrology*: Vol. 15: No. 2, Article 2.

Texas A&M *ENRTA*. Post Oak Savanna restoration plan. https://enrta.tamu.edu/restoration/

Texas Water Development Board (TWDB). Automated Groundwater Level Wells, *Water Data for Texas*. https://www.waterdatafortexas.org/groundwater

USGS and Esri, 2014. USGS Historical Topographic Map Collection and Explorer. https://livingatlas.arcgis.com/topoexplorer/index.html

Wahl, K.L., Wahl, T.L., 1995. Determining the flow of comal springs at New Braunfels, Texas, in Proceedings of Texas Water '95. San Antonio, Texas: *American Society of Civil Engineers*, pp. 77–86.

Young, S., Jigmond, M., Jones, T., Ewing, T., 2018. Final Report: Groundwater availability model for the central portion of the Sparta, Queen City, and Carrizo-Wilcox Aquifers. *Texas Water Development Board*, Report.

Young, S., Jones, T., Jigmond, M., 2017. Final Report: Field Studies and Updates to the Central-Carrizo-Wilcox, Queen City, and Sparta GAM to Improve the Quantification of Surface Water-Groundwater Interaction in the Colorado River Basin. *TWDB*, *INTERA*. https://www.environmental-stewardship.org/wp-content/uploads/2019/06/BBASC1548301856_Final-Report.pdf

APPENDIX A

WATERSHED DATASET

Table A1. Wooded density, surface flow, and groundwater depth characteristics of all analyzed watersheds.

Watershed	Landcover Year	Wooded Density	Baseflow	0cfs Exceedance	Mean Depth to GW	Discharge Year Range
Gandia Branch- Sabine River Subwatershed	1956	0.5074833	64			1950-1960
Gandia Branch- Sabine River Subwatershed	1983	0.5789199	68			1978-1988
Gandia Branch- Sabine River Subwatershed	2001	0.3045377	113			1996-2006
Gandia Branch- Sabine River Subwatershed	2019	0.30852	134		173.86	2014-2023
Town of Grand Saline- Sabine River Watershed	1956	0.1313684	1.7			1948-1959
Town of Grand Saline- Sabine River Watershed	1985	0.1809548	6.6			1980-1990
Town of Grand Saline- Sabine River Watershed	1991	0.1847917	6.8			1985-1995
Town of Grand Saline- Sabine River Watershed	2001	0.2500489	11		405.9	1995-2005
Town of Grand Saline- Sabine River Watershed	2019	0.2445411	11.4		435.9	2015-2023
Trinidad Lake- Trinity River Subwatershed	1958	0.340724	416			1964-1970
Trinidad Lake- Trinity River Subwatershed	1985	0.211072	617			1980-1990
Trinidad Lake- Trinity River Subwatershed	2001	0.1252242	847			1995-2005
Trinidad Lake- Trinity River Subwatershed	2019	0.1229037	814		228.82	2015-2023
Caney Creek- Tehuacana Creek Watershed	1985	0.0943031	0	83%		1980-1990
Caney Creek- Tehuacana Creek Watershed	2001	0.21346813	0	89%		1995-2005
Caney Creek- Tehuacana Creek Watershed	2019	0.20930778	0.1	96%	228.82	2015-2023
Duck Creek- Navasota River Watershed	1954	0.2220763	0.5			1949-1959
Duck Creek- Navasota River Watershed	1985	0.2365113	3.4			1980-1990
Duck Creek- Navasota River Watershed	2001	0.3017335	9.81		46.5	1995-2005
Duck Creek- Navasota River Watershed	2019	0.2897134	10.4		46.8	2015-2023
Jordan Creek- Colorado River Subwatershed	1953	0.0993839				N/A
Jordan Creek- Colorado River Subwatershed	1985	0.1097574	273			1988-1992
Jordan Creek- Colorado River Subwatershed	2001	0.2436123	470		226.118	1995-2005
Jordan Creek- Colorado River Subwatershed	2019	0.228961	394		208.434	2015-2023
Piney Creek- Colorado River Watershed	1954	0.120198	170			1960-1964
Piney Creek- Colorado River Watershed	1985	0.131015	137			1980-1990
Piney Creek- Colorado River Watershed	2001	0.4264421	444		226.118	1995-2005
Piney Creek- Colorado River Watershed	2019	0.4316877	332		208.434	2015-2023
West Fork Plum Creek- Plum Creek Subwatershed	1953	0.05864977	0	89%		1947-1957
West Fork Plum Creek- Plum Creek Subwatershed	1985	0.09257402	2.2	100%		1980-1990
West Fork Plum Creek- Plum Creek Subwatershed	2001	0.44766245	4.23	100%		1995-2005
West Fork Plum Creek- Plum Creek Subwatershed	2019	0.48873185	6.88	100%	43.47	2015-2023
Town of Derby- Frio River Watershed	1955	0.2686311		29%		1950-1960
Town of Derby- Frio River Watershed	1968	0.2994605		43%		1962-1972
Town of Derby- Frio River Watershed	1976	0.3107671		93%		1970-1980
Town of Derby- Frio River Watershed	2001	0.34270186		86%	255.06	1995-2005
Town of Derby- Frio River Watershed	2019	0.34650935		39%	495.55	2015-2023
Soldier Slough- Nueces River Subwatershed	1968	0.5912321		48%		1960-1970
Soldier Slough- Nueces River Subwatershed	1976	0.6158934		78%		1970-1980
Soldier Slough- Nueces River Subwatershed	2001	0.8015572		76%	366.5	1995-2005
Soldier Slough- Nueces River Subwatershed	2019	0.7859599		44%	403.4	2015-2023