A Conceptual Model of Groundwater Flow in the Pecos Valley and Edwards-Trinity (Plateau) Regional Aquifers

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Texas Water Development Board
August 2022

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

The conceptual model for the Pecos Valley and Edwards-Trinity (Plateau) regional aquifers includes the Pecos Valley Aquifer, the Edwards-Trinity (Plateau) Aquifer, a small portions of the southern tip of the Ogallala Aquifer, the San Antonio and the Barton Springs segments of Edwards (Balcones Fault Zone) Aquifer, and the Southern portion of the Trinity Aquifer. A conceptual model is a generalized representation of a groundwater flow system based on hydrogeologic information (Anderson and Woessner, 1992), and is a keystone to building a reliable groundwater availability model by consolidating real-world data. This report discusses geologic, hydrologic, and hydrogeologic information of the study area and presents the conceptual model developed based on that information.

The current modeling effort primarily focuses on the Pecos Valley Aquifer and Edwards-Trinity (Plateau) Aquifer. While other aquifers in the study area will be included in the model, it is only with the goal of helping better define the boundary conditions of the primary modeling targets. Note that the current model does not have an objective to update the models of the Trinity Aquifer or the Edwards (Balcones Fault Zone) aquifers, as these will be updated in later TWDB modeling efforts. This report is intended to be an update of the previous TWDB model of the Pecos Valley and Edwards-Trinity (Plateau) Aquifers (Anaya and Jones, 2009). Including these other non-primary aquifers in the current model is one of the major updates from previous work and will improve our understanding of the interconnected flow between the aquifers in this region. The aquifers in the study area occupy 49,000 square miles of West and Central Texas and supply springflow and baseflow to numerous intermittent and perennial streams. Also, these aquifers are the primary source of freshwater for irrigation, livestock, manufacturing, mining, municipal, and domestic use in the region. In recent decades, the water availability of these aquifers has been a challenge as droughts decrease recharge to the aquifer and result in an increase in groundwater pumping. To better estimate the groundwater availability and provide a tool for regional water planning in this region, the Texas Water Development Board (TWDB) is developing a revised and updated groundwater availability model for these aquifers as part of the Groundwater Modeling Program. For the first phase of the model development, we have updated the conceptual model that describes the aquifer flow system and summarizes the hydrogeologic system. This report documents the conceptual model development work for the Pecos Valley Aquifer and the Edwards-Trinity (Plateau) Aquifer regional model. The second phase of the process will be to build and calibrate a numerical groundwater model based on this conceptual model.

Most of the study area is a plateau (Figure ES-1). The elevation of the study area is highest in the northwest and slopes gradually to the southeast. The greatest relief occurs on the west margin of the study area along the Trans-Pecos Basin and Range of West Texas and the Eastern Sierra Madre Mountains in Mexico and on the southeast margin along the Balcones Fault Zone (Lindgren and others, 2004). Most streams in the study area are intermittent or ephemeral. Perennial streams are more common on the northern, eastern,

and southern margins of the Edwards Plateau along the spring-fed headwater tributaries (Anaya and Jones, 2009). Climate, surface geology, topographic slope, soil, and vegetation cover all affect recharge in the study area. Average annual precipitation in the study area decreases from 34 inches (east) to 12 inches (west). Average annual temperature increases from 60 degrees Fahrenheit in the north to 70 degrees Fahrenheit in the south. Land use change determines the water consumption, and the most prominent urbanization happens in the eastern part of the study area (San Antonio and Austin), where the Edwards (Balcones Fault Zone) Aquifer occurs. The Edwards Plateau and Hill Country areas have poor soil development, while the Pecos Valley and Edwards (Balcones Fault Zone) areas have slightly better.

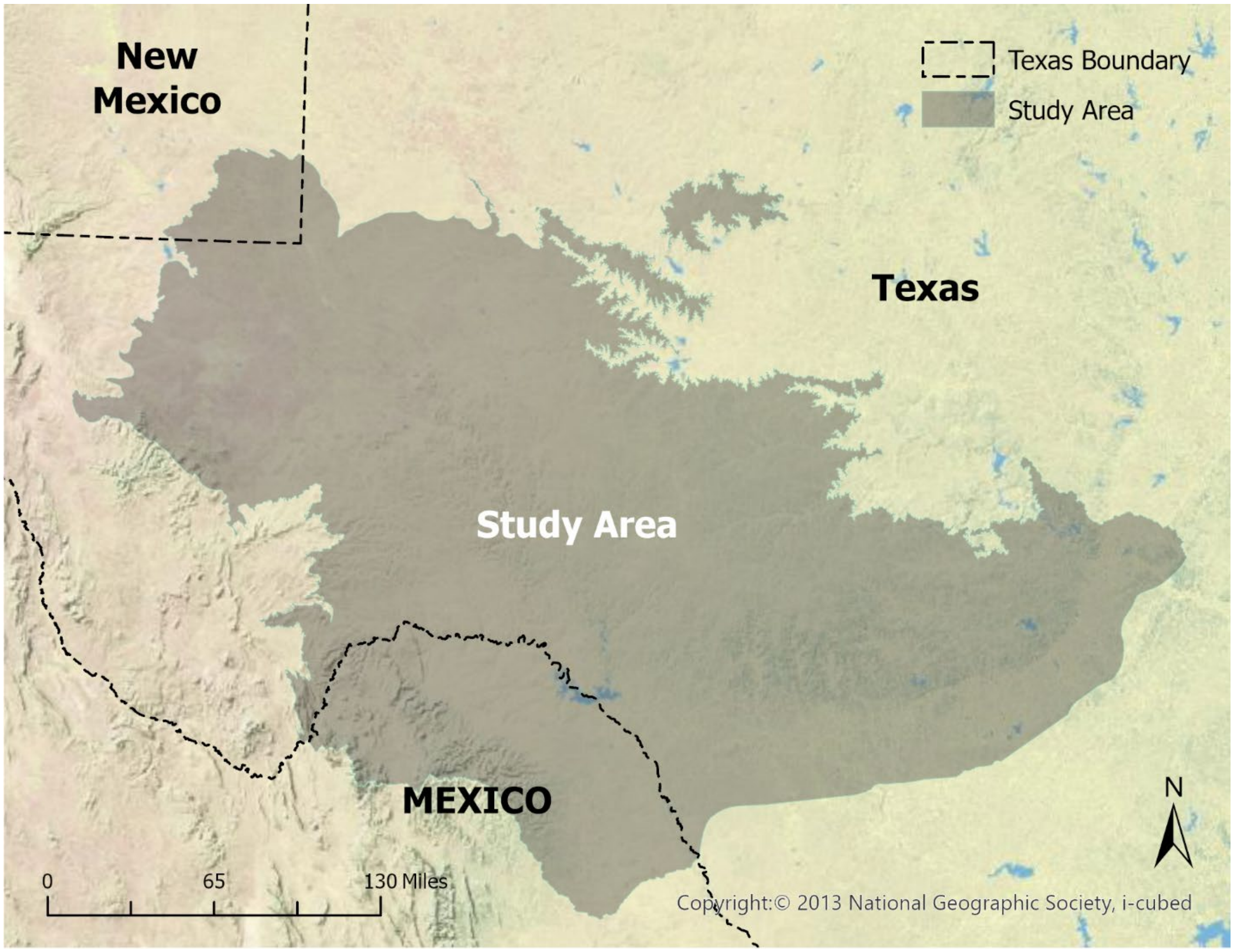


Figure ES-1. Map of study area.

The Edwards-Trinity aquifer system includes the Edwards-Trinity (Plateau), Edwards (Balcones Fault Zone), and the Trinity aquifers within the study area. The Edwards-Trinity aquifer system consists of Lower Cretaceous shallow marine rock sediments belonging to the Lower Washita, Fredericksburg, and Trinity groups. The Trinity Group sediments form the bottom unit of the Edwards-Trinity aquifer system. The Lower Washita and

Fredericksburg sediments form the Edwards Group on the top of the Trinity Group or the top unit of the Edwards-Trinity aquifer system. The Pecos Valley Aquifer consists of Cenozoic terrigenous rock sediments.

For modeling purposes, we have condensed the geology of the study area into three simplified layers. The top layer (Layer 1) represents younger units that overlie the Edwards and Trinity hydrostratigraphic units and includes the Pecos Valley Aquifer and other shallow units. The middle layer (Layer 2) represents the Edwards hydrostratigraphic unit and consists of the Edwards (Balcones Fault Zone) Aquifer and the Edwards portion of the Edwards-Trinity (Plateau) Aquifer. The bottom layer (Layer 3) represents the Trinity hydrostratigraphic unit (the southern portion of the Trinity Aquifer and the Trinity portion of the Edwards-Trinity (Plateau) Aquifer).

We compiled and analyzed well data, including water level data and aquifer test information, to determine the regional groundwater flow patterns and aquifer characteristics. The water level analysis shows that groundwater flows from northwest to southeast and generally follows the regional topography. Potentiometric surfaces were created with water level contours for 1950, 1980, 2000, and 2015, in addition to several hydrographs, to show water level changes over time. We also compared water levels from paired wells (neighboring wells drilled to different formations) to show potential vertical connections between hydrostratigraphic units. Aquifer tests provided information about the capacity of groundwater flow, referred to as storage and transmissivity. We compiled data from long-term and short-term aquifer tests to calculate the hydraulic conductivity, which measures the ease of groundwater flow through an aquifer. The median hydraulic conductivity of each region will be used as an initial calibration value for the numerical model. The median value of the hydraulic conductivity was 6.0 and 4.0 feet per day for the Pecos Valley Aquifer north and south of the Pecos River, respectively, and 4.1 feet per day for the Edwards hydrostratigraphic unit. For the Trinity hydrostratigraphic unit, the median hydraulic conductivity is 7.0 feet per day in the Northern Plateau region (where Glen Rose Formation is absent), 1.6 feet per day in the Southern Plateau region (where Glen Rose Formation is present), and 0.2 feet per day in the Hill Country and Balcones Fault Zone regions. During the calibration process of the model, these initial values will be adjusted within reasonable bounds to coincide with lithology standards. The storativity, which shows the availability of aquifer water storage, varies from 1.8×10^{-4} to 7.5×10^{-4} across the study area.

The water quality analysis of the Pecos Valley and Edwards-Trinity (Plateua) regional aquifers examined the salinity, relative age, recharge condition, and general groundwater flow direction in the study area. In terms of salinity, the Pecos River defines the groundwater quality divide in the Pecos Valley Aquifer, with fresh groundwater occuring north of the Pecos River, and slight to very saline groundwater occuring south of the Pecos River. In the Edwards-Trinity (Plateau) Aquifer, most groundwater is fresh. Only the western portion of the aquifer contains saline groundwater due to the interaction of underlying saline aquifers. In the Hill Country portion of the Trinity Aquifer, groundwater is fresh to moderately saline, and the salinity varies by depth rather than spatial location. In the Edwards (Balcones Fault Zone) Aquifer, groundwater is fresh, with very saline groundwater occurring in the down-dip portion of the units beyond the official boundary of the aquifer. From the groundwater isotopic composition analysis, we were able to identify the general locations where recharge occurs and the relative ages of groundwater. In general, the Edwards (Balcones Fault Zone) Aquifer and the Hill Country portion of Trinity Aquifer, both located in the eastern portion of the study area, undergo frequent recharge events and have relatively younger aged groundwater than the groundwater in the west, such as the Pecos Valley Aquifer.

Two studies are underway to develop the recharge and discharge analyses for the current conceptual model. These studies are estimating the recharge with consideration of surface water-groundwater interaction and developing a method for estimating pumping discharge from the Pecos Valley and Edwards-Trinity (Plateau) regional aquifers. The conceptualization of recharge to and discharge from aquifers in the study area for this model will be based on the findings from those two studies.

Figure ES-2 shows a block diagram of the proposed numerical groundwater model design based on the conceptual model presented in this report. This diagram is meant to represent the simplified layers and boundary conditions to be implemented in the numerical groundwater model. Please review this report in its entirety for further details into the data analysis and decision-making used to develop this simplified model.

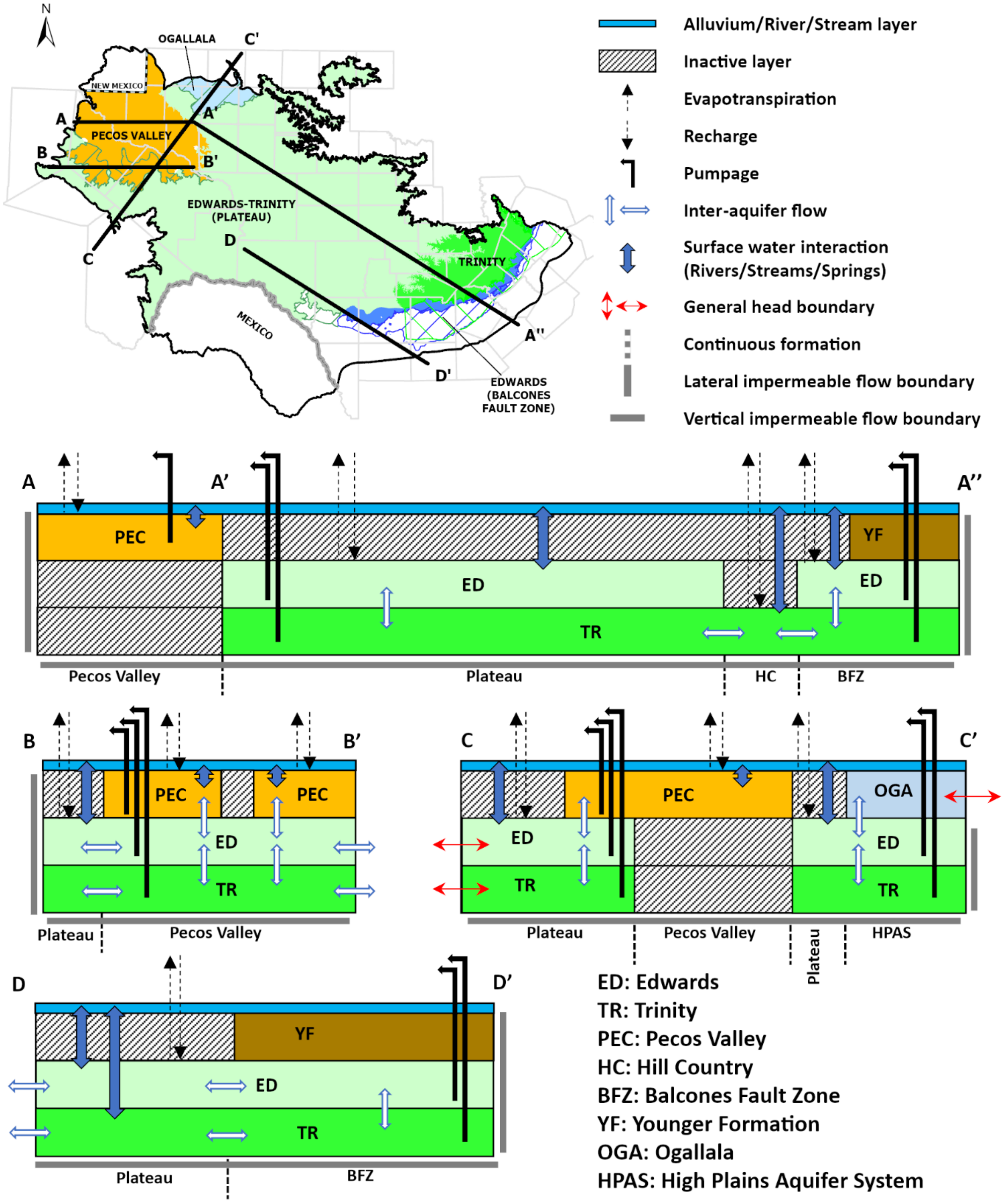


Figure ES-2. Block diagram of the conceptual model of study area.

INTRODUCTION

A groundwater conceptual model is a simplified representation of a complex real-world aquifer system. It provides the foundation for developing a numerical groundwater availability model that simulates and estimates the groundwater flow and volume within an aquifer. The current study develops the conceptual model for the Pecos Valley and Edwards-Trinity (Plateau) regional aquifers and will later be used to develop the numerical groundwater availability model of the study area.

The study area includes five major aquifers in West and Central Texas: the Pecos Valley Aquifer, the Ogallala Aquifer, the Edwards-Trinity (Plateau) Aquifer, the San Antonio and the Barton Springs segments of the Edwards (Balcones Fault Zone) Aquifer, and the Southern portion of the Trinity Aquifer. This report primarily focuses on the Pecos Valley Aquifer and Edwards-Trinity (Plateau) Aquifer. Even though they are not the focus of this modeling effort, this report also includes some analysis on the other aquifers, including the Trinity Aquifer and the Edwards (Balcones Fault Zone) Aquifer, that fall within the study area boundaries. These aquifers will be included in the eventual numerical model to help better define boundary conditions for the Pecos Valley Aquifer and Edwards-Trinity (Plateau) Aquifer. Previous models in the study area had smaller extents or did not fully model the interconnection between aquifers, so the inclusion of these additional aquifers represents a major update to the modeling of groundwater flow in the region.

The aquifers in the study area are the primary source of freshwater for irrigation, livestock, manufacturing, mining, municipal, and domestic use in the region. These aquifers also supply springflow and baseflow to numerous intermittent and perennial streams. Baseflow is streamflow without contributions from rainfall events. This semiarid/arid region already experiences extreme variations in precipitation, which will likely be exacerbated by future climate variability. As droughts decrease recharge to and increase pumping demands from these aquifers, groundwater levels, flows in springs and streams in a region containing several rapidly expanding population centers will likely become issues of public concern.

To better understand groundwater flow and provide a tool for regional water planning in this region, the Texas Water Development Board (TWDB) is revising and updating the groundwater availability model for these aquifers as part of the Groundwater Modeling Program. Historically, the TWDB published models for the Pecos Valley and the Edwards-Trinity (Plateau) Aquifers (Anaya and Jones, 2009; Hutchison and others, 2011), for the Hill Country portion of the Trinity Aquifer (Jones and others, 2011), and for the San Antonio and the Barton Springs segments of the Edwards (Balcones Fault Zone) Aquifer (Scanlon and other, 2001; Lindgren and others, 2004; Hutchison and Hill, 2011). The goal of the Groundwater Modeling Program is to provide a tool to estimate groundwater availability for the citizens of Texas by producing standardized and publicly available groundwater flow models with data and documentation (TWDB, 2013). A groundwater availability model is a quantitative tool to estimate the amount of water available in an aquifer by implementing simplified real-world geologic and hydrogeologic conditions into a computer program. Also, it is possible to evaluate the effect of pumping, drought, and different water management scenarios on the groundwater flow system in the study area on a regional scale. To construct the groundwater availability model, a conceptual model must first be developed that describes the aquifer flow system and organizes the hydrogeologic data that controls groundwater flow. The conceptual model includes: 1) introduction of the study area, 2) review of previous studies, and 3) hydrogeologic setting in the study area.

This conceptual model report is organized into several sections that describe the various components of conceptual models. First, Section 2 addresses the physical features that can impact aquifer conditions, such as topography, surface geology, stream locations, soil development, land cover and landuse, vegetation, climate, and the geologic history of the study area. Then, Section 3 describes the previous studies conducted for the current study area. Section 4 presents the hydrologic setting, or the characteristics that impact groundwater behavior and flow, based on data collected and analyzed for this report. The hydrologic setting section covers the hydrostratigraphy and structural framework of the aquifer, groundwater levels, groundwater flow directions, recharge to and discharge from the aquifer, surface water, evapotranspiration, hydraulic properties, and water quality. Section 5 introduces the conceptual model developed based on information presented in previous sections (Section 2 through 4). Finally, Section 6 includes brief introductions of ongoing studies related with the current study area and suggestions to improve the model, if possible, in the next update.

2 STUDY AREA

The study area covers over 49,000 square miles of West and Central Texas from 97°W to 105°W in longitude and between 28°N to 33°N in latitude (Figure 2.0-1). This region includes five major Texas aquifers, from southeast to northwest: the San Antonio and Barton Springs segments of the Edwards (Balcones Fault Zone) Aquifer, the Southern portion of the Trinity Aquifer, the Edwards-Trinity (Plateau) Aquifer, the Ogallala Aquifer, and the Pecos Valley Aquifer (Figure 2.0-2). The Edwards-Trinity (Plateau) Aquifer occupies much of the study area, encompassing about 35,000 square miles. The southern portion of the Trinity Aquifer and the Pecos Valley Aquifer each cover nearly 7,000 square miles, the Edwards (Balcones Fault Zone) Aquifer covers an area of 3,500 square miles and the Ogallala Aquifer covers an area of 1,100 square miles. For the current study, the Pecos Valley Aquifer and Edwards-Trinity (Plateau) Aquifer are the primary interest of the groundwater availability model and the rest of the aquifers will define the boundary conditions of the model.

The northern boundary of the study area coincides with the northern extent of the Pecos Valley Aquifer, the Edwards-Trinity (Plateau) Aquifer, and the Hill Country portion of the Trinity Aquifer. Along the northeastern boundary in Burnet County, we extended the study area beyond the previous TWDB model (Anaya and Jones, 2009) to include the surface water divide between the Brazos and the Colorado River basins. Along the southeastern boundary, we extended the study area to incorporate the San Antonio and the Barton Springs segments of Edwards (Balcones Fault Zone) Aquifer and the confined part of the Trinity Aquifer. This is a major update from the previous TWDB model (Anaya and Jones, 2009) meant to help account for flow between the Edwards-Trinity (Plateau) Aquifer and the Edwards (Balcones Fault Zone) Aquifer and to incorporate and extend westward to the Rio Grande the confined parts of the Trinity Aquifer in the study area. In this region, the study area boundary coincides with the boundary of a U.S. Geological Survey model that simulates the water quality of the San Antonio and Barton Springs segments of the Edwards (Balcones Fault Zone) Aquifer (Brakefield and others, 2015). The southeastern boundary continues southwest to the the surface water divide in the Sierra Madre Oriental in Mexico, southwest of the Rio Grande. This portion of Mexico was included in the study area to better account for potential groundwater flow towards the Rio Grande, as described in Boghici (2002). The western boundary of the study area coincides with the western boundaries of the Edwards-Trinity (Plateau) and Pecos Valley aquifers. In New Mexico, the western boundary coincides with the watershed boundary, as defined by National Hydrography Dataset 12-digit hydrologic unit (HUC) codes.

Figure 2.0-1. Location of study area.

Figure 2.0-2 shows cities in the study area with a population higher than 10,000 based on the 2010 Census. As shown, most of the study area is rural and over 70 percent of the region's cities have a population of less than 50,000 (white dots in the figure). However, rapid urbanization is occurring along the Interstate-35 corridor between San Antonio and Austin, with each of those metropolitan areas supporting a population of over 750,000 people and still growing. Population growth is highest in the southeastern portion of the study area, where these rapidly growing urban centers overlap the Hill Country portion of the Trinity Aquifer and the Edwards (Balcones Fault Zone) Aquifer.

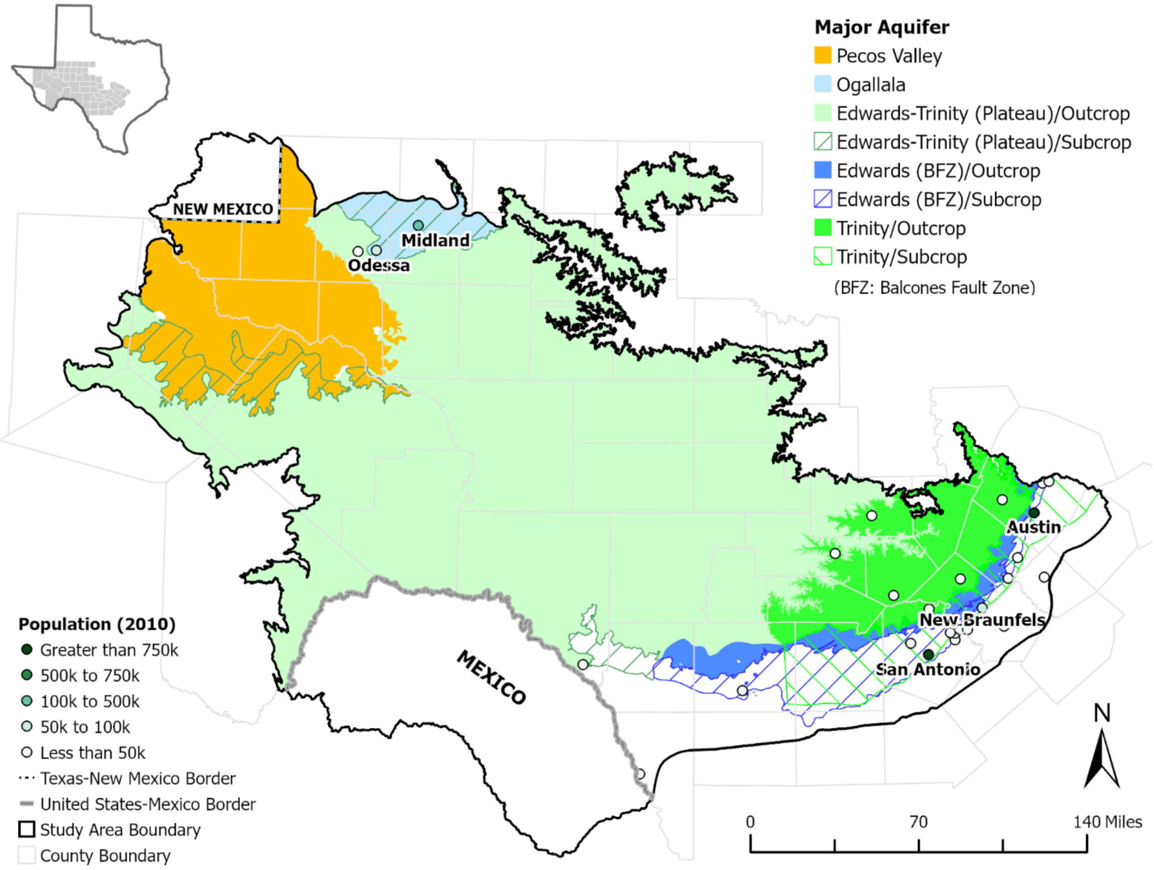


Figure 2.0-2. Major aquifers in Texas and major cities with population over 10,000 within the study area.

There are several administrative divisions in Texas for water resources planning and management. Figure 2.0-3 shows the regional water planning groups in the study area. Regional water planning groups develop a regional water plan for each planning area by identifying water needs and recommending water management strategies to meet future water needs. These regional plans are the basis for the Texas State Water Plan. The study area intersects seven regional water planning groups: Far West Texas (Region E), Region F, Region G, Plateau (Region J), Lower Colorado (Region K), South Central Texas (Region L), and Rio Grande (Region M). Of these, Regions F, J, and L cover the majority of the study area. Groundwater management areas were created based on Texas Water Code 35.001 to conserve, preserve, protect, recharge, and prevent the waste of groundwater resources. The study area includes nine groundwater management areas (2, 3, 4, 7, 8, 9, 10, 12, and 13) (Figure 2.0-4), and four of them (3, 7, 9, and 10) cover the majority of the study area. The most localized government unit for groundwater management is the groundwater conservation district, and there are 43 groundwater conservation districts within the study area (Figure 2.0-5).

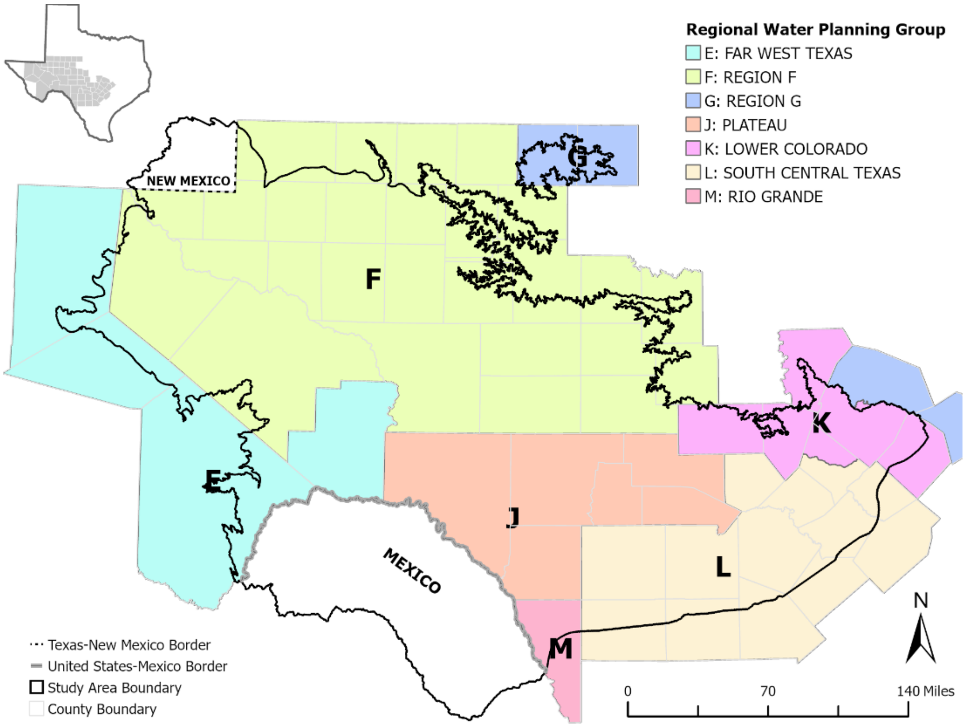


Figure 2.0-3. Regional water planning groups (RWPG) in the study area.

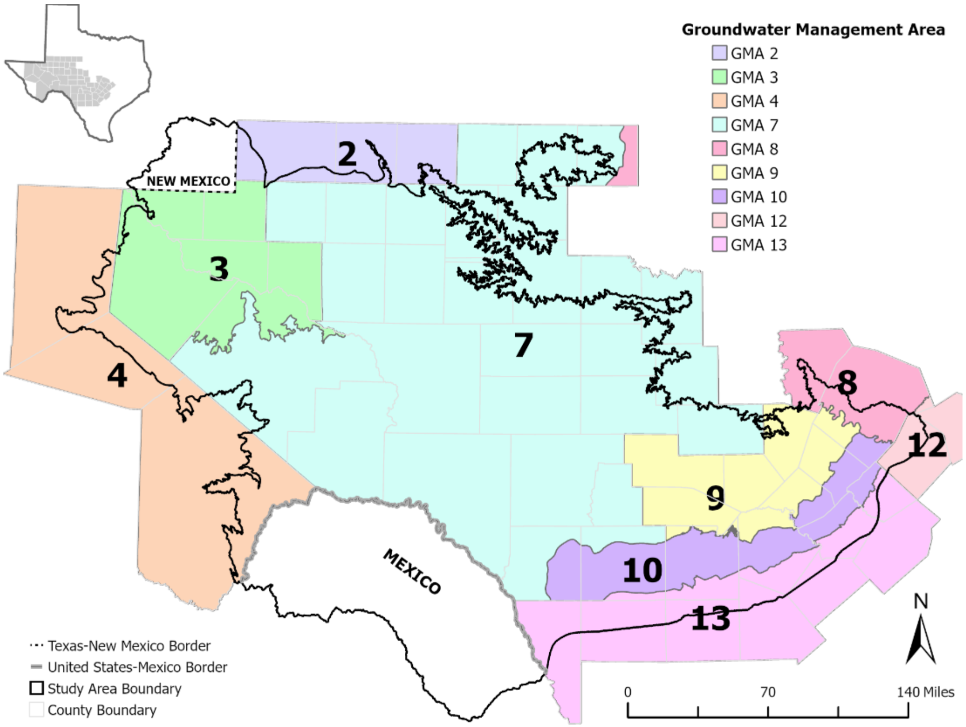


Figure 2.0-4. Groundwater management areas (GMAs) in the study area.

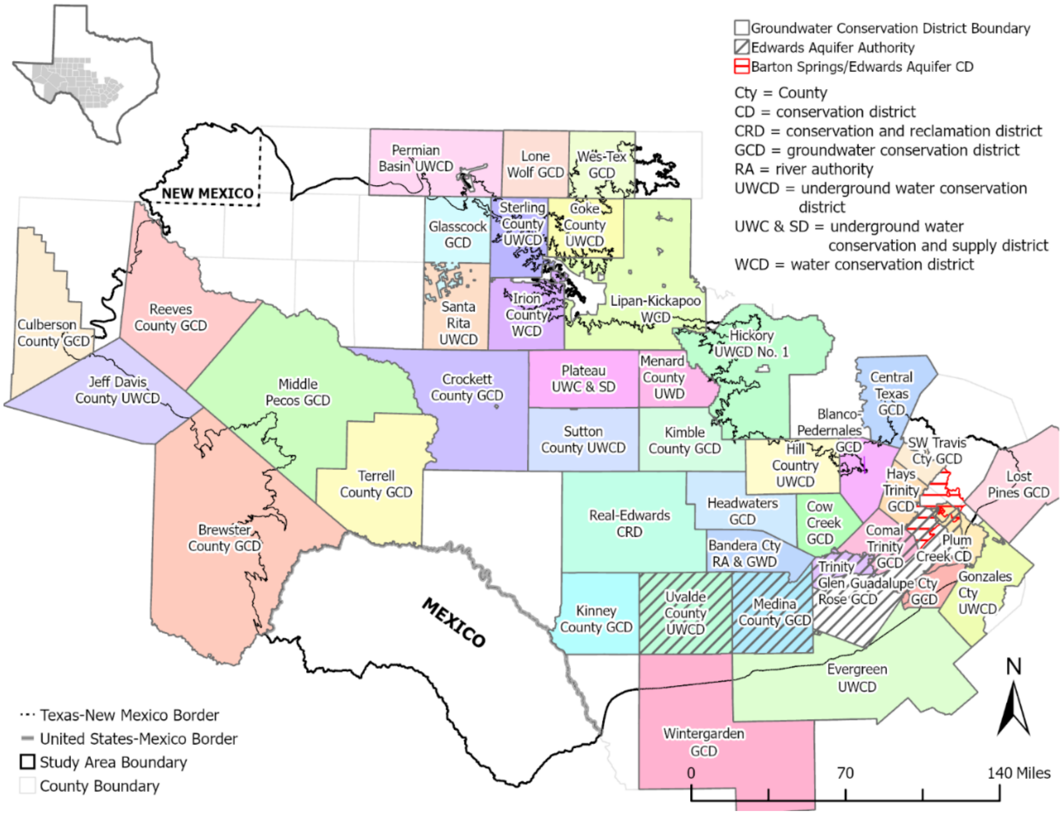


Figure 2.0-5. Groundwater conservation districts (GCDs) in the study area (As of July 2019).

2.1 Physiography

The term physiography is a contraction of the words "physical geography" and refers to the natural features of a landscape or geomorphology, as shaped by the local climate and underlying geology. Surface drainage (streams), soil development, vegetation, and land use can also influence the physical characteristics of a region. A physiographic province defines a geographic region with similar physiography. Figure 2.1-1 shows the landform and physiographic provinces and sub-provinces in the study area. The study area intersects the Edwards Plateau, High Plains, Gulf Coastal Plains, and Basin and Range physiographic provinces (Figure 2.1-2), as defined by Wermund (1996).

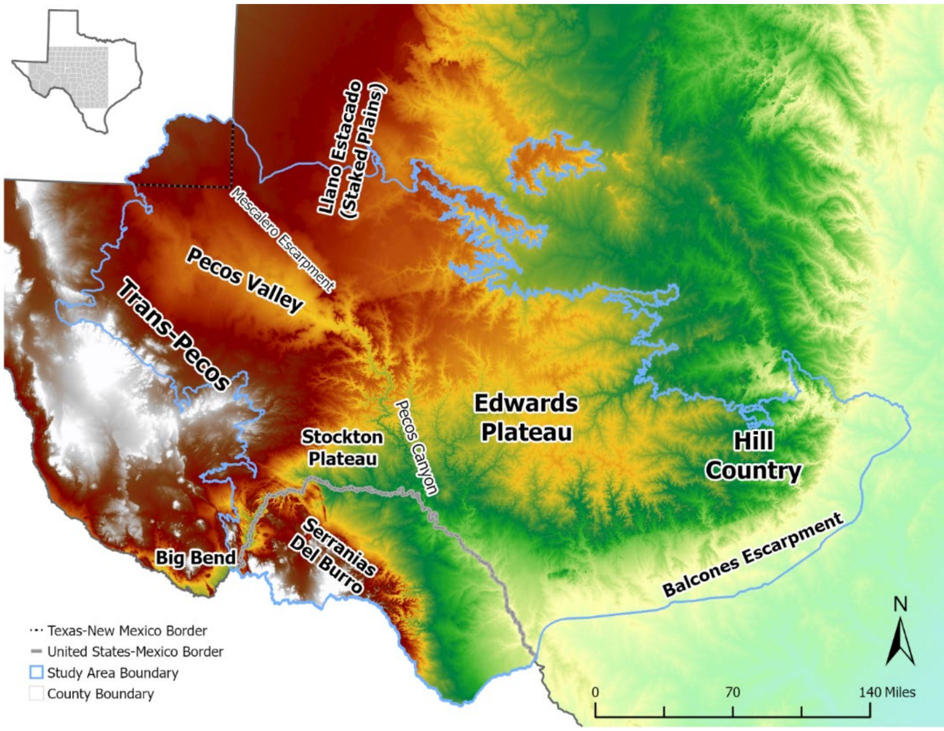


Figure 2.1-1. Landforms of study area with adjacent landscape (U.S. Geological Survey, 2014).

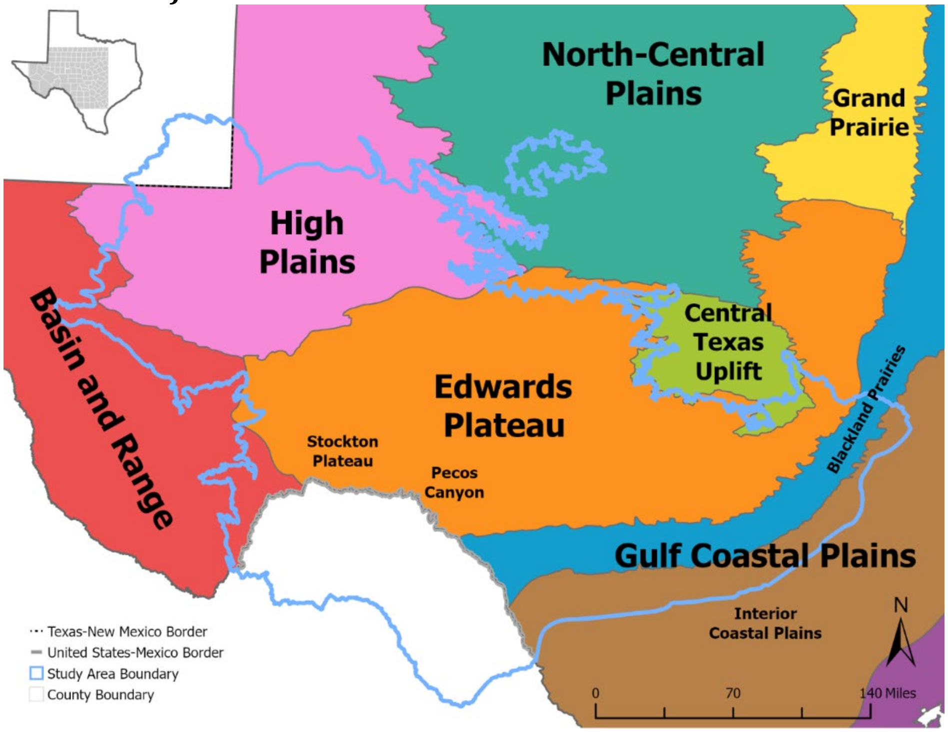


Figure 2.1-2. Physiographic provinces and sub-provinces of study area with (Wermund, 1996).

The Edwards Plateau province includes the extents of the Edwards-Trinity (Plateau) Aquifer and Hill Country portion of the Trinity Aquifer. This is the dominant physiographic province in the region, covering about two-thirds of the study area. In the southwest, the Edwards Plateau province includes the Stockton Plateau, a dry, high-elevation area, the Pecos Canyon, which has steep-walled canyons, and the Pecos River and its tributaries. A thick layer of Cretaceous limestone caps much of the Edwards Plateau province and forms a suitable environment for karst features. The Edwards Plateau province has experienced erosion since ancient Cretaceous seas retreated to the current Gulf of Mexico. The Balcones Fault Zone exists in the region of the Balcones Escarpment that separates the Gulf Coastal Plains and Edwards Plateau provinces along the southeastern margin of the Edwards Plateau province.

The Southern High Plains, a sub-province of the High Plains physiographic province, includes the Pecos Valley and Llano Estacado regions. The Llano Estacado section of the Southern High Plains is a flat area with many playa lakes and ends against the Mescalero Escarpment. On the south side of the Mescalero Escarpment, the Pecos Valley section of the Southern High Plains consists of a thick accumulation of alluvium capping the underlying Cretaceous and Paleozoic rocks. The Pecos River flows from northwest to southeast along the Pecos Valley. To the northeast, the Pecos Valley section slopes gently towards the Mescalero Escarpment. To the southwest, the Pecos Valley section slopes steeply towards the mountains of the Trans-Pecos section of the Basin and Range physiographic province.

The Basin and Range physiographic province occurs along the western boundary of the study area. It stretches from the south High Plains toward the United States and Mexico border. This area contains the highest elevations in Texas and has eight mountain peaks higher than 8,000 feet elevation. These mountain ranges are north-south oriented with complex folding and faulting. The province contains a large number of volcanic rocks due to a history of volcanic activity. Volcanic rocks of the Davis Mountains overlie a small portion of the Edwards-Trinity (Plateau) Aquifer in the study area.

The Gulf Coastal Plains province includes the southern extent of the Edwards (Balcones Fault Zone) Aquifer. The Balcones Fault Zone area contains a system of northeast to southwest oriented faults along the southeast side of the study area. As a result of faulting along the Balcones Fault Zone, the Balcones Escarpment formed, resulting in an elevated Hill Country juxtaposed against the low-lying Gulf Coastal Plains. An abrupt increase of elevation at the Balcones Escarpment affects regional weather (Caran and Baker, 1986) and stream drainage patterns. Caves and sinkholes are common in the exposed Cretaceous limestone on the elevated Balcones Escarpment (Maclay, 1995).

Figure 2.1-3 shows the geologic ages of surface rocks of the study area. Most of the study area exhibits post-Cretaceous rock units on the surface. In the western part of the study area, Quaternary, the younger unit, covers the top surface and creates the Pecos Valley Aquifer and the Edwards-Trinity (Plateau) Aquifer caps. The Cretaceous rock is on the surface of the central part of the study area. It extends from the down streams of the Pecos

Valley to the Edwards (Balcones Fault Zone) region, and its coverage is like the Edwards Plateau province in Figure 2.1-2. On the eastern boundary of the study area, Quaternary and Tertiary aged materials are present on the top surface and cap the Edwards (Balcones Fault Zone) Aquifer.

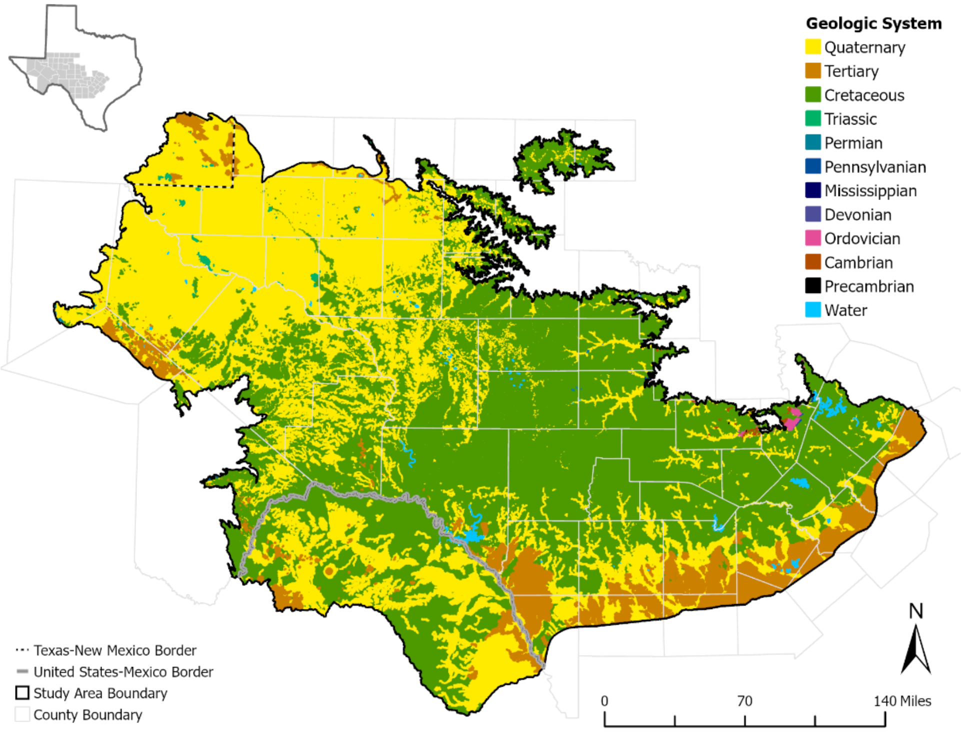


Figure 2.1-3. Geologic ages of the surface rocks in the study area (Bureau of Economic Geology, 2014).

2.1.1 Topography and Land surface elevation

Topography (or land surface elevation) can affect several aspects of groundwater behavior. The steepness of the land surface can determine the degree to which precipitation runs off into surface drainages versus percolating to recharge groundwater. Groundwater elevation in unconfined aquifers is typically assumed to be a subdued replica of land surface elevation, so topography can also help approximate groundwater levels. Figure 2.1-4 shows land surface elevation inside of the study area. The landform of the Edwards Plateau can be described as a tableland, and the elevation gradually declines from the northwest to the southeast until the Balcones Fault Zone. Then, elevation suddenly drops a hundred to several hundred feet at the Balcones Escarpment (Lindgren and others, 2004). Another steep elevation change occurs on the margin of the Basin and Range physiographic province in the west and along the Eastern Sierra Madre Mountains in Mexico. Here, the elevation drops over 4,000 feet from the mountains to the plateau over only 20 miles.

In the context of regional groundwater modeling, steep elevation changes can introduce an error for calculating water budgets in the numerical groundwater model unless the model grid optimization refines the grid. However, the model grid optimization increases the computational cost tremendously. During model construction, we will consider either excluding these areas from the model or smoothing the land surface elevation by refining the model grid in these areas. This can be a reasonable approach if no significant groundwater flow is expected in these areas or if including these areas significantly worsens groundwater flow results elsewhere.

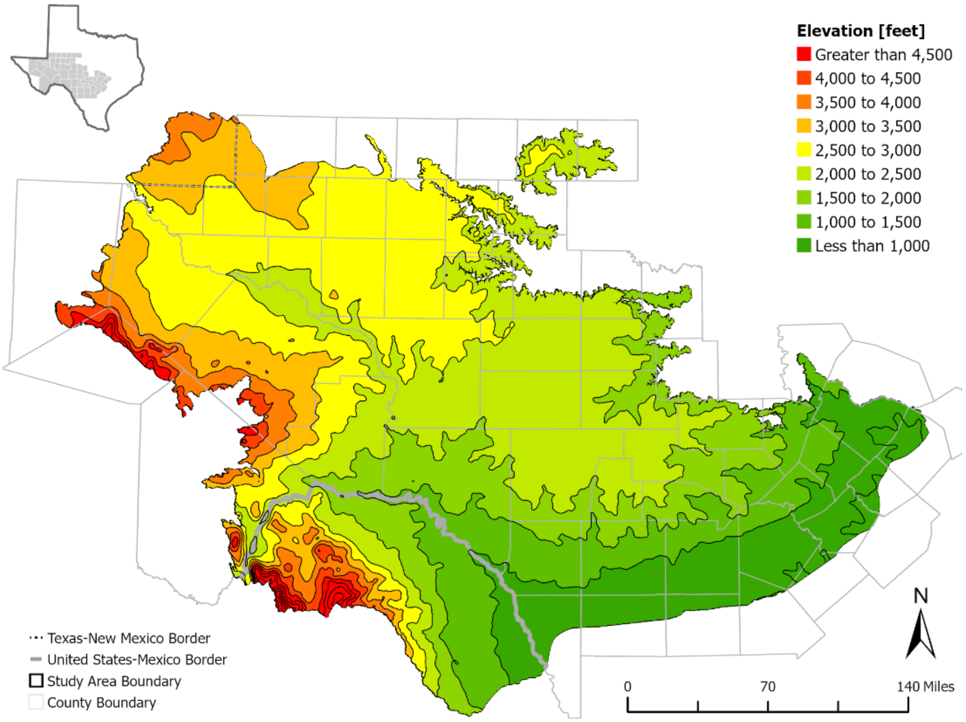


Figure 2.1-4. Land surface elevation (U.S. Geological Survey, 2014).

2.1.2 Surface drainage

The distribution of surface drainage can affect several aspects of groundwater behavior. Erosion from streams can remove sediments of permeable aquifer material, altering the direction of groundwater flow. Where streams intersect the groundwater table, they supply locations for discharge from the aquifer. Where a stream is above the groundwater table but connected through permeable sediments, it can provide locations of recharge to the aquifer. Figure 2.1-5 shows the surface drainage within the study area. The Edwards Plateau area has high stream density with well-developed stream channels, but very few perennial streams flow year-round. Most streams are intermittent or ephemeral and only flow during or shortly after precipitation events. Perennial streams are more common on the northern, eastern, and southern margins of the Edwards Plateau along the spring-fed headwater tributaries (Anaya and Jones, 2009). Higher average annual precipitation (Walker, 1979) and the discharge of the Edwards-Trinity (Plateau) Aquifer from springs at the southern and southeastern margin of Edwards Plateau likely contribute to this higher perennial stream coverage. As streams cross the Balcones Fault Zone they can often percolate down along the many faults in this area, disrupting flow along small tributaries. Besides the Pecos River, streams in the Pecos Valley are typically intermittent or ephemeral due to geologic characteristics and dry climate conditions. Streams are especially poorly developed north of the Pecos River, where the alluvium is overlain by windblown sand deposited in dunes. Precipitation quickly infiltrates into the dune sand without runoff, preventing the formation of streams (Garza and Wesselman, 1959; Ogilbee and others, 1962; Jones 2001, 2004).

2.1.3 Soil Development

Soil development, especially soil thickness and soil type, can also affect groundwater conditions. Thin soils or soils with low permeability can reduce how much precipitation percolates down to recharge groundwater. Soil types also control the amount and type of vegetation that can grow in a region, which in turn affects how much water is lost to evapotranspiration rather than recharging groundwater. Soil development in the Edwards Plateau and Hill Country is generally poor, with shallow soils and limited vegetation types, but is slightly better in the Pecos Valley and Balcones Fault Zone (Figure 2.1-6). Most of the Edwards Plateau and Hill Country areas have less than 1 foot of soil thickness, while the Pecos Valley and Edwards Balcones Fault Zone areas have 2 to 5 feet of soil cover.

Soil available water storage refers to the quantity of water that the soil can store. This parameter is important as it helps farmers choose which crops to plant and how to design irrigation systems. Soil available water storage in the study area ranges from 0.25 to 12 inches in the top 150 centimeters (about 5 feet) of soil (Figure 2.1-7).

The soils in the Edwards Plateau and Hill Country are typically Mollisols (Figure 2.1-8) that drain quickly and develop under subhumid to semiarid climates (U.S. Department of Agriculture, 1999). Aridisols occur from the northwestern Edwards Plateau across the Pecos Valley. Aridisols develop under arid conditions and contain sandy and loamy soils with limited soil moisture availability to sustain plant growth (U.S. Department of Agriculture, 1999). Vertisols and Alfisols cover most of the Edwards (Balcones Fault Zone) Aquifer. Those soils are generally silty to clayey loams with a brownish color and have a fair soil moisture regime (Baker and others, 1986; U.S. Department of Agriculture,1999).

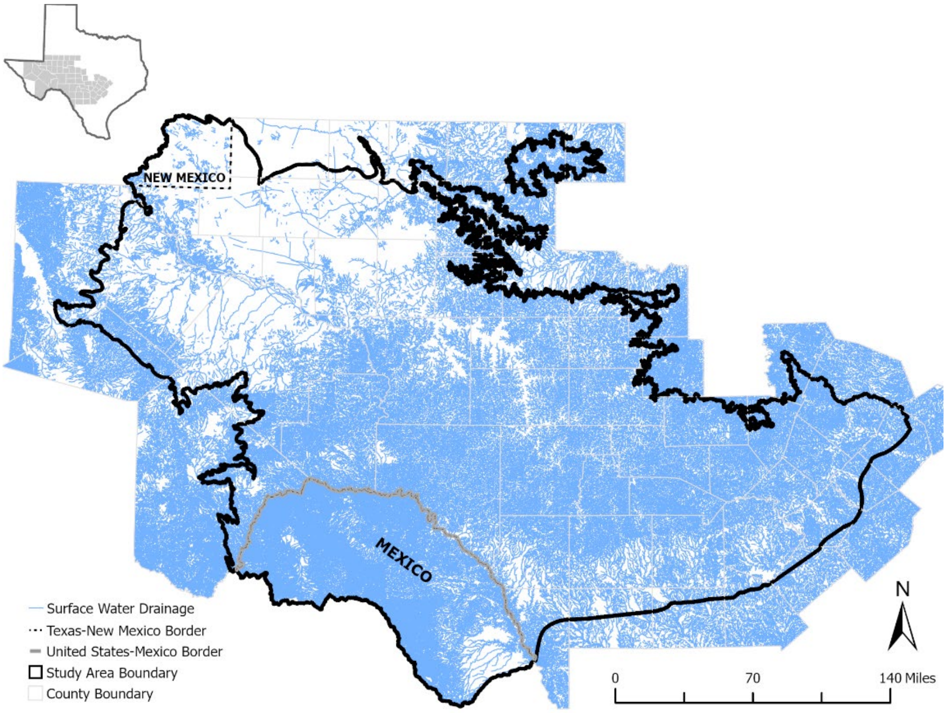


Figure 2.1-5. Surface water drainage in the study area (U.S. Geological Survey, 2021a).

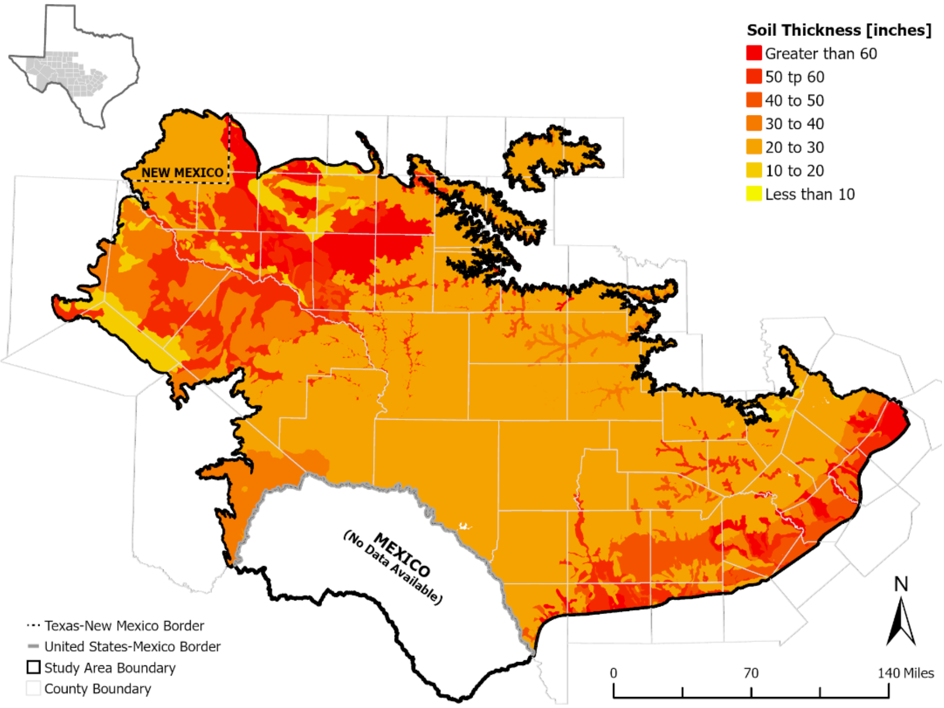


Figure 2.1-6. Soil thickness as an indication of soil development (Natural Resources Convervation Service, 2016).

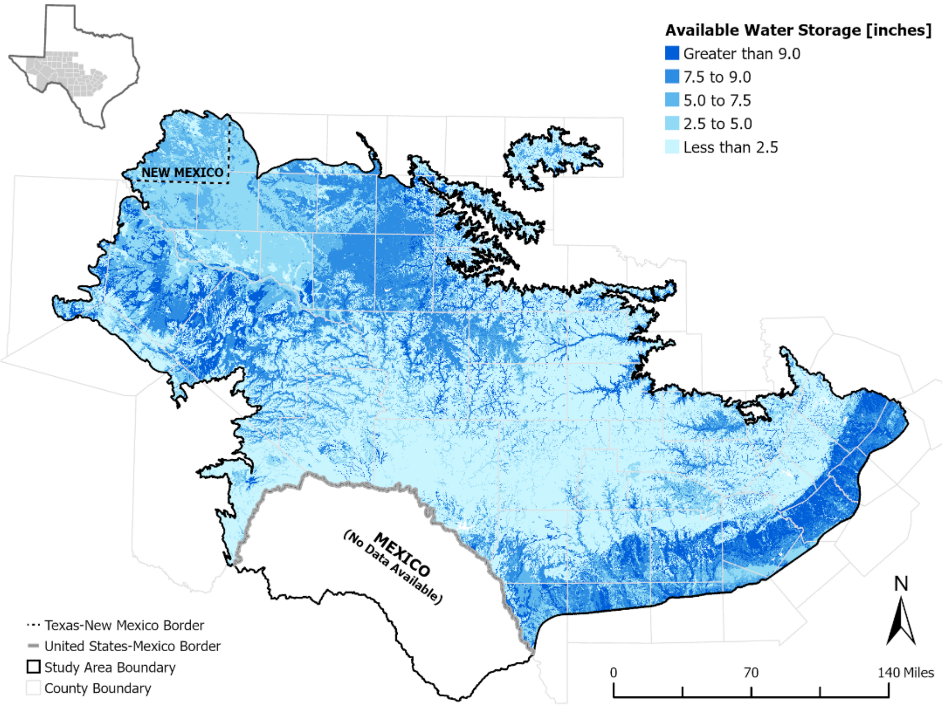


Figure 2.1-7. Soil available water storage in study area (Natural Resources Convervation Service, 2016).

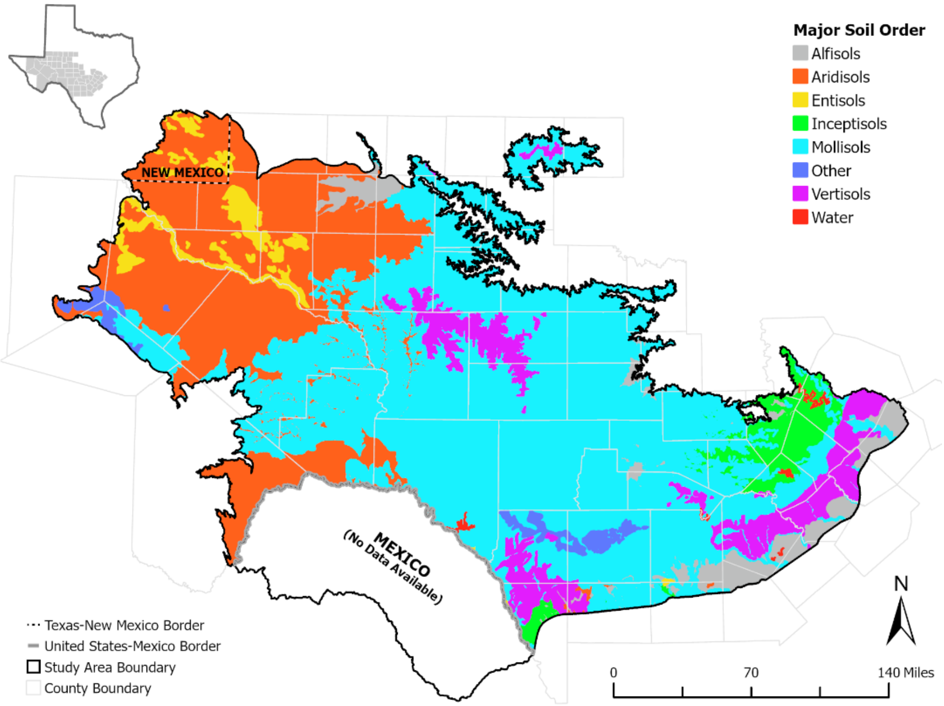


Figure 2.1-8. Soil order types (Natural Resources Convervation Service, 2016).

2.1.4 Vegetation and Land Use

Like soil development, vegetation and land use have a significant impact on recharge to the aquifer. The amount and type of vegetation affects how much water is lost to evapotranspiration rather than recharging groundwater. Figure 2.1-9 shows the vegetation types regrouped into the general categories from the ecological maps of Texas Parks and Wildlife (Elliott and others, 2014). The western and central Edwards Plateau and the Pecos region can be classified as mosaics of semi-open grassland, grassland-shrubland, or shrubland (Riskind and Diamond, 1988). Mid- and short-grass species dominate here along with woody vegetation such as juniper, white shin oak, plateau live oak, and mesquite (Riskind and Diamond, 1988; Anaya and Jones, 2009; Elliott and others, 2014). The eastern Edwards Plateau, the Hill Country area, is dominated primarily by forest and woodland vegetation. Species such as Texas Oak, Plateau Live Oak, Ashe Juniper, and Texas Ash occur with higher density than they do in the central Edwards Plateau (Riskind and Diamond, 1988; Elliott and others, 2014). In recent years, it was observed that urban development in the Balcones Fault Zone has been replacing natural vegetation types primarily consisting of grassland and shrubland.

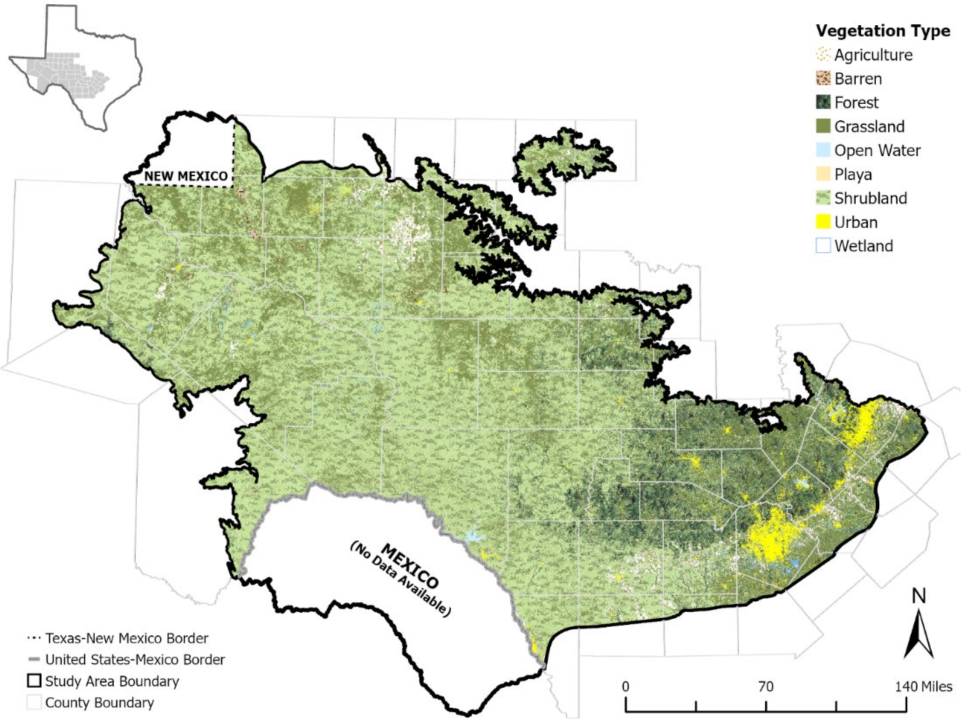


Figure 2.1-9. Vegetation types (modified from Elliott and others, 2014).

Land use can impact how much water runs off to surface drainages versus percolating down to recharge groundwater. Land use changing from natural vegetation to more paved and impermeable urban areas can both decrease groundwater recharge and increase surface runoff, leading to soil erosion and flooding. Figure 2.1-10 shows where land use in the region changed to urban use from other use types between 2001 and 2019. The change was mapped using land-cover datasets from the National Land Cover Database (https://www.mrlc.gov/data). Many spots on the northwestern Edwards Plateau and the Balcones Fault Zone areas show conversion to urban land use. The most prominent urbanization has happened in the San Antonio and Austin areas over the Edwards (Balcones Fault Zone) Aquifer.

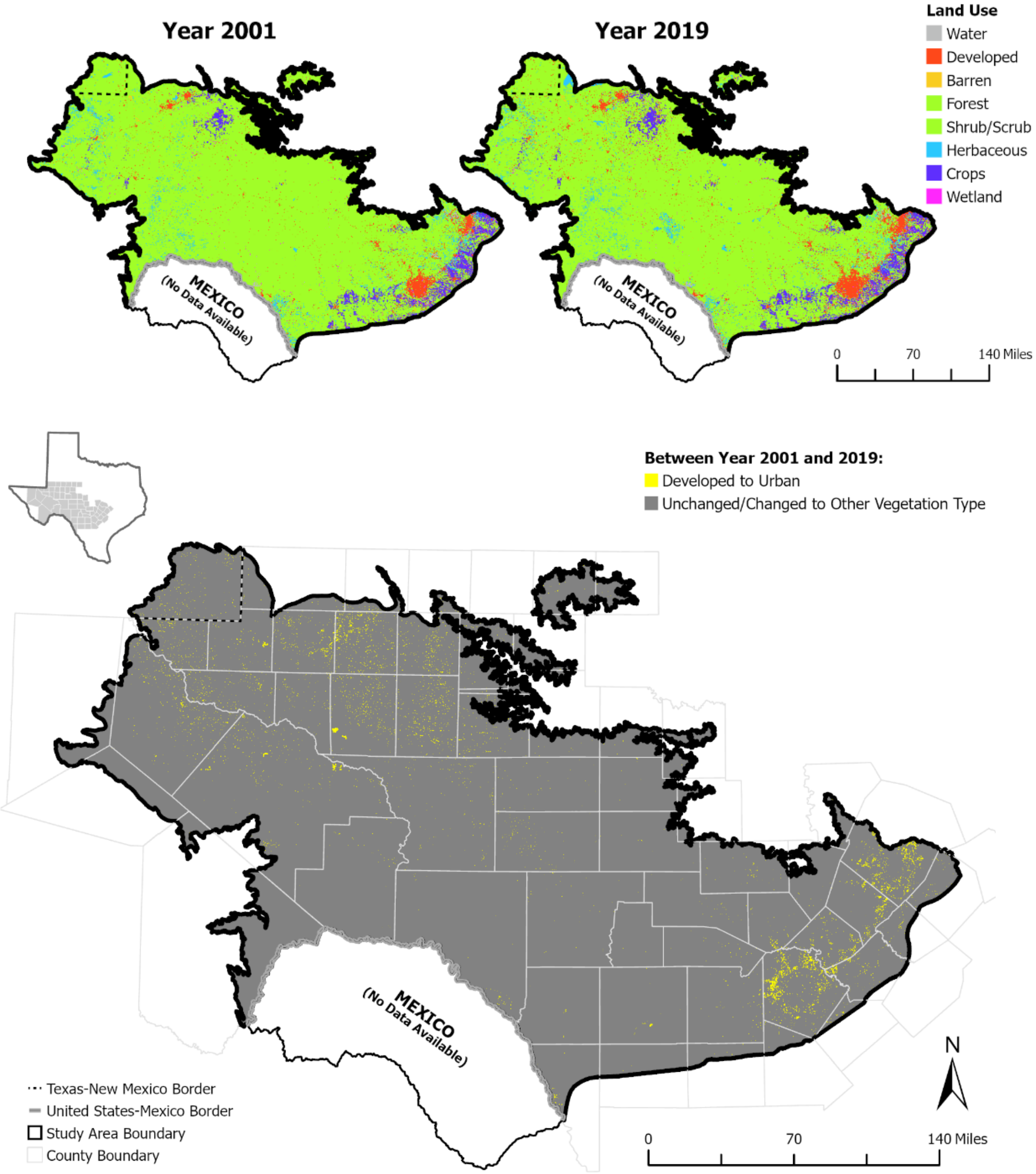


Figure 2.1-10. Land use in year 2001 (top left) and year 2019 (top right) and Land use change from 2001 to 2019 (bottom) (National Land Cover Database, 2021).

2.2 Climate

Climate is an essential consideration in water resources management because it determines the amount and distribution of precipitation, evaporation, and drought conditions, all of which can affect surface water flow and groundwater availability. Climate refers to spatial and temporal statistical interpretations of precipitation, temperature, evaporation, and drought observations. Most of the study area can be classified as a subtropical climate, characterized by hot summers and mild winters (Figure 2.2-1). The eastern study area, closest to the Gulf of Mexico, has the highest humidity and is classified as subhumid. Humidity drops with distance from the Gulf of Mexico, so that the central and western section of the study area is steppe (semi-arid to arid), and the Pecos Valley and Trans-Pecos regions are arid (Bomar, 1983; Larkin and Bomar, 1983). A small portion of the study area in the Llano Estacado region, is described as a continental-steppe climate in Larkin and Bomar (1983), rather than subtropical climate. The continental-steppe climate type is characterized by extreme temperature ranges, low humidity, and minimal rainfall.

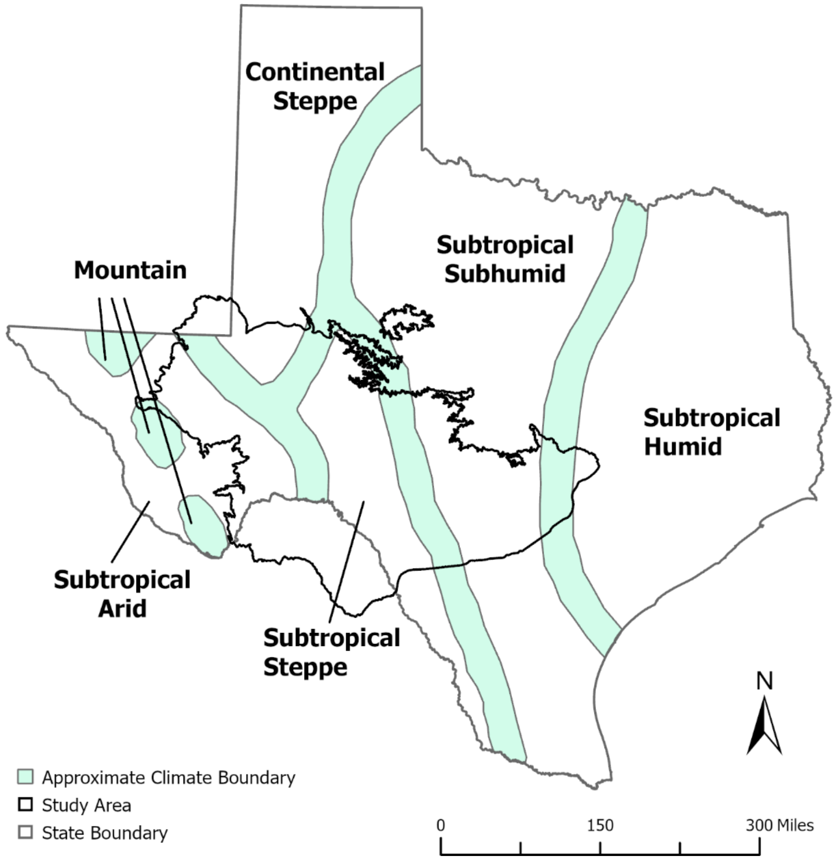


Figure 2.2-1. Climate classifications for Texas (from Larkin and Bomar, 1983).

The study area intersects six climate divisions, as defined by the National Climatic Data Center (NCDC, 2021). Divisions 5 (Trans-Pecos), 6 (Edwards Plateau), and 7 (Post Oak Savanna) cover most of the study area, while Divisions 1 (High Plains), 2 (Low Rolling Plains), and 9 (Southern) cover only a small section of the study area (Figure 2.2-2). The following sections discuss the climate conditions for these divisions.

Figure 2.2-3 shows the monthly average precipitation and temperature measured at 14 weather stations across the study area. This figure includes at least one station from each climate division. Each station had a minimum of 50 years of measurements although the measurement years vary for each station. Precipitation (blue bars in figure) follows one of two distinct annual precipitation patterns depending on the location of the stations. Precipitation in the eastern two-thirds of the study area is higher, with an average of 1 to 5 inches per month, and peaks twice, once in early summer and once in fall. Precipitation at western stations is lower, about 0 to 2 inches per month of precipitation, and only peaks once in late summer or early fall during monsoon season. The precipitation pattern is related to the distance from the Gulf of Mexico, with rain decreasing from east to west. The annual temperature pattern is similar at all 14 stations, with highest temperatures in the summer and lowest temperatures in the winter. Generally, monthly average temperatures are hotter in the southern section of the study area and decrease moving north. The hottest monthly average temperature (83 degrees Fahrenheit) was calculated for August at the Eagle Pass 3N station in Maverick County (Climate Division 9), and the lowest monthly average temperature (43 degrees Fahrenheit) was calculated for January at the Roscoe station in Sterling County (Climate Division 6).

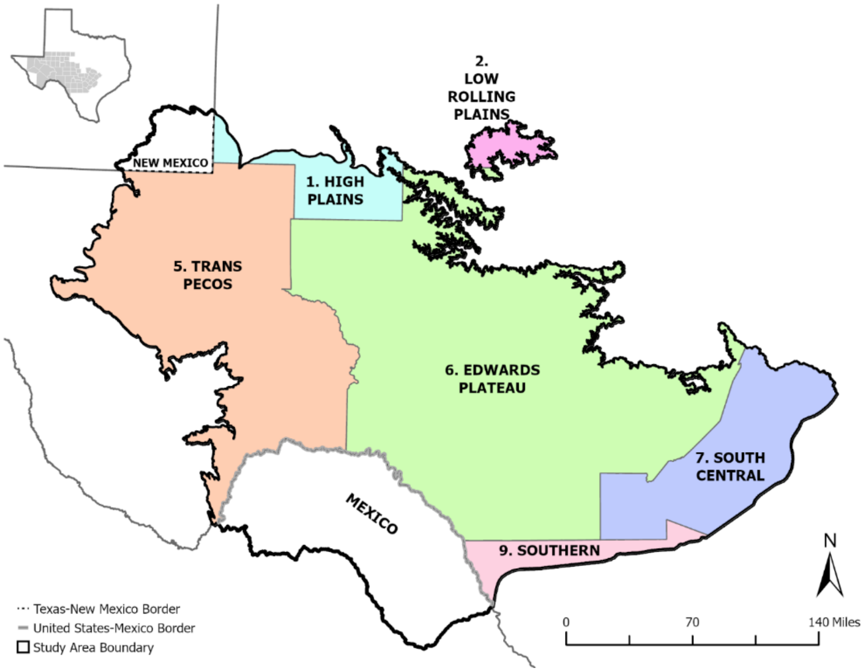


Figure 2.2-2. Climate division for Texas (National Climate Data Center, 2021).

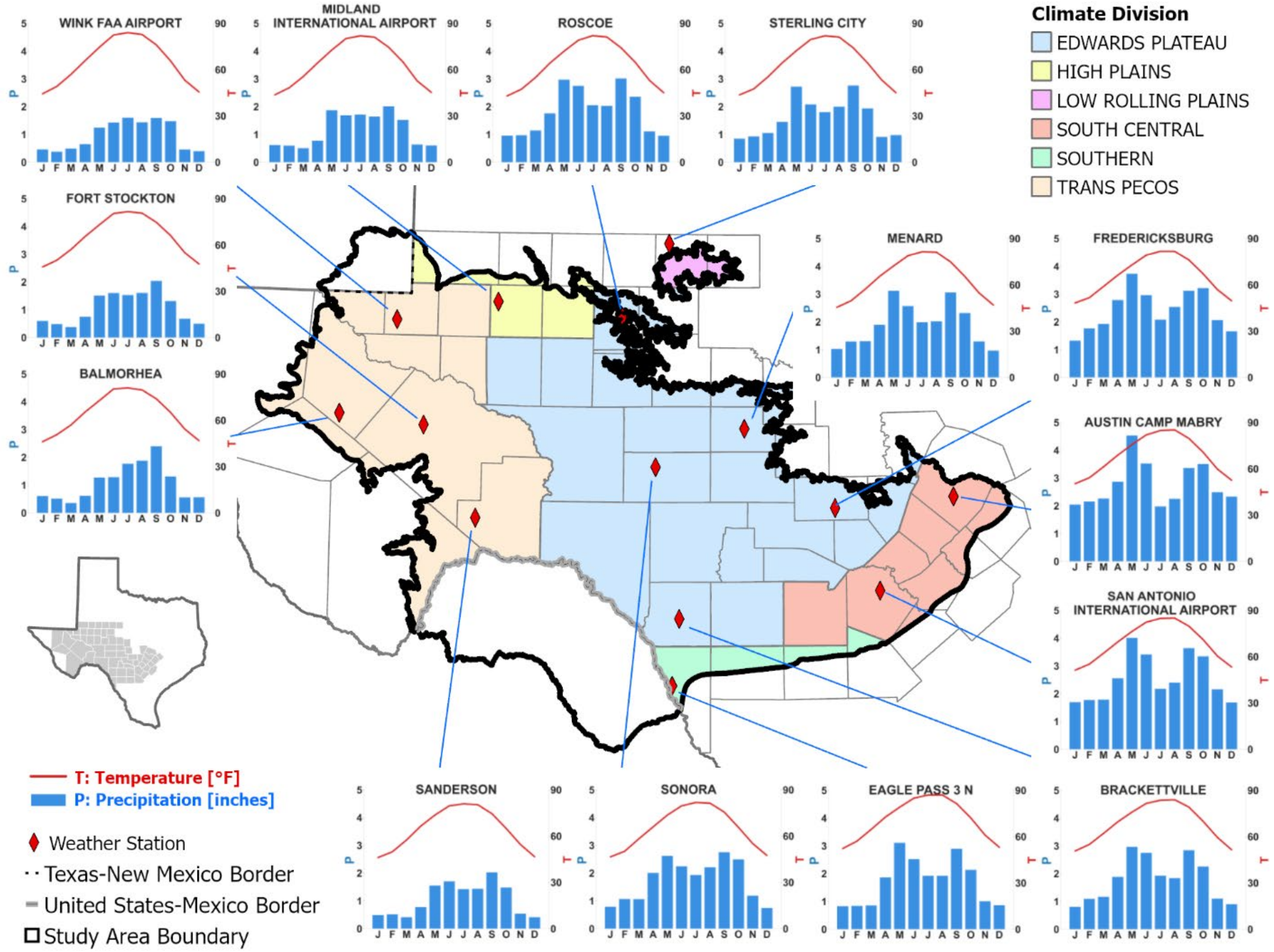


Figure 2.2-3. Monthly precipitation and temperature at weather station (National Climate Data Center, 2021).

2.2.1 Precipitation

Precipitation refers to the water falling to the ground as rain and snow. Figure 2.2-4 shows the contour map of average annual precipitation created using PRISM (PRISM, 2021) data from 1900 to 2019. As shown, precipitation decreases from 34 inches per year to 12 inches per year westward from the Gulf of Mexico. This pattern is consistent with the trends observed at individual stations, shown in Figure 2.2-3.. The difference in precipitation patterns between the eastern and western regions is likely due to differences in precipitation development. In general, precipitation in the eastern part of the study area occurs when humid air from the Gulf Coast meets cold air from the north, whereas precipitation in the western part is dominated by sporadic thunderstorms occurring during the summer period.

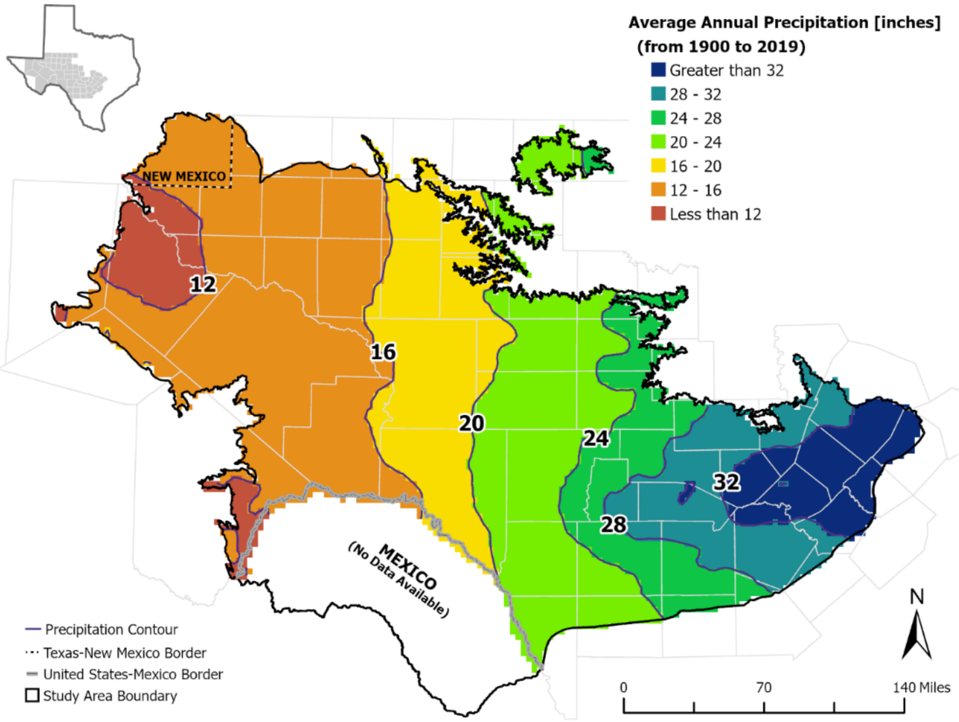


Figure 2.2-4. Average annual precipitation from 1900 to 2019 (PRISM, 2021).

2.2.2 Temperature

Figure 2.2-5 shows a contour map of the annual mean temperature in degrees Fahrenheit created using PRISM (PRISM, 2021) data from 1900 to 2019. Overall, temperatures in the southern portion of the study area are about 10 degrees Fahrenheit higher than in the northern area. The mean annual temperature in the northern portion of the study area is around 60 degrees Fahrenheit and gradually increases to 70 degrees Fahrenheit toward the south. Variations in the temperature map follow topographic trends. For instance, the downstream area of the Pecos River valley has a slightly higher average temperature than the surrounding area due to the lower elevations in the valley. The lowest mean annual temperature in the study area is in the mountains of the Trans-Pecos region in the west.

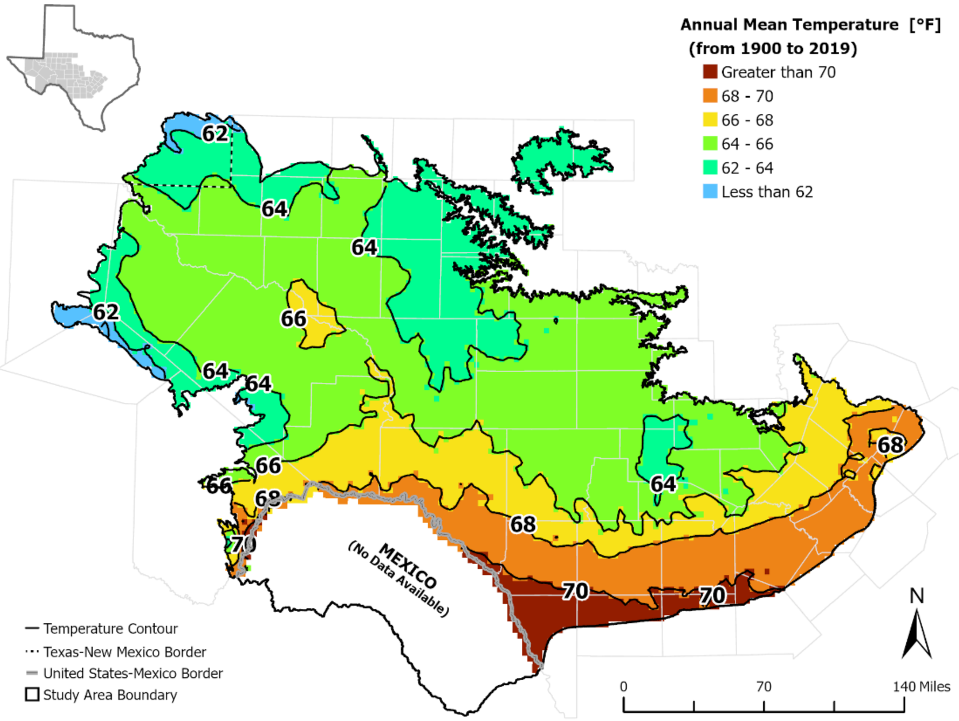


Figure 2.2-5. Annual mean temperatures for the study area from 1900 to 2019 (PRISM, 2021).

2.2.3 Evaporation

Evaporation is the amount of water that escapes from the Earth's surface due to the heat of solar energy. It is critical to know evaporation since it determines how much precipitation remains to either run off to surface water or percolate down to recharge groundwater. However, it is highly challenging to measure evaporation directly from the surface soil. The typical estimation method is based on lake evaporation data. TWDB provides the lake evaporation data based on one-degree latitude by one-degree longitude quadrangles for the entire state of Texas (TWDB, 2021a). Figure 2.2-6 shows a contour map created using the TWDB lake evaporation data by quadrangle for the 30 years from 1971 to 2000. The evaporation estimates range from 52 to 72 inches per year over the study area. Generally, evaporation rates are higher in the central Edwards Plateau area and get lower towards the mountains in the west or towards the Hill Country area in the east.

Another method for estimating evaporation is using a model. This approach helps to utilize other data, such as climate data, which have a more extended measurement history with higher spatial density. Narasimhan and others (2005) modeled evaporation data using limited climate data, including maximum, minimum, and dew point temperatures from 1971 to 2000. Figure 2.2-7 shows a contour map created using the evaporation data from Narasimhan and others (2005). These modeled evaporation trends are similar to the measured evaporation trends shown previously in Figure 2.2-6. The modeled evaporation values range from 48 to 82 inches per year, with the highest evaporation values in the Edwards Plateau region and lower towards the mountains in the west and towards the Hill Country area in the east.

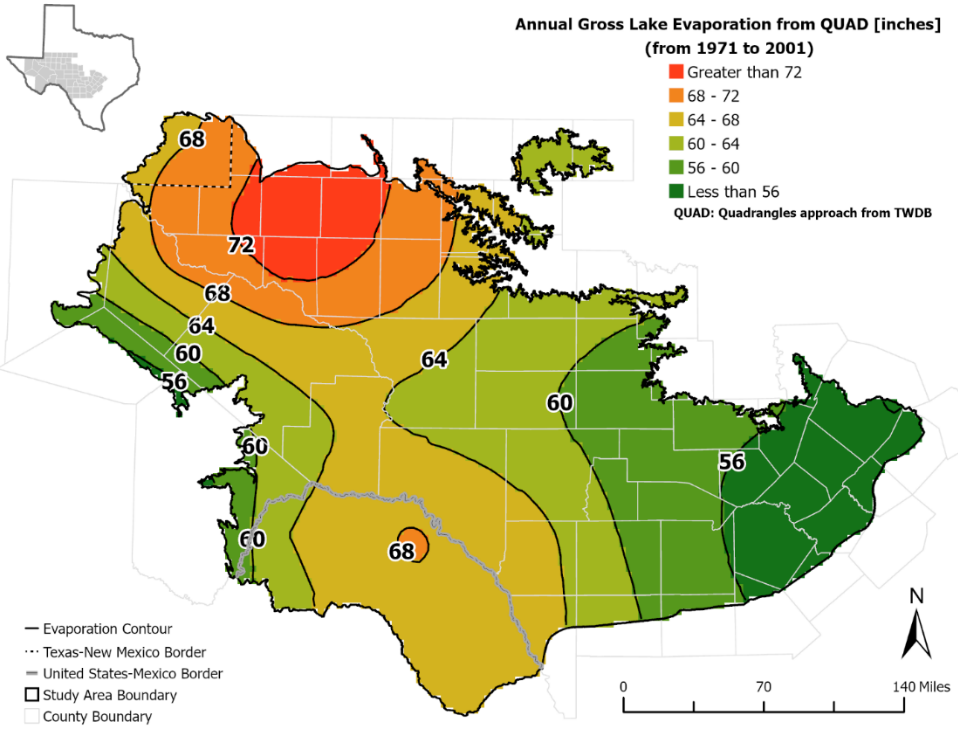


Figure 2.2-6. Gross lake evaporation for the study area from TWDB Quad approach from 1971 to 2001 (TWDB, 2021a).

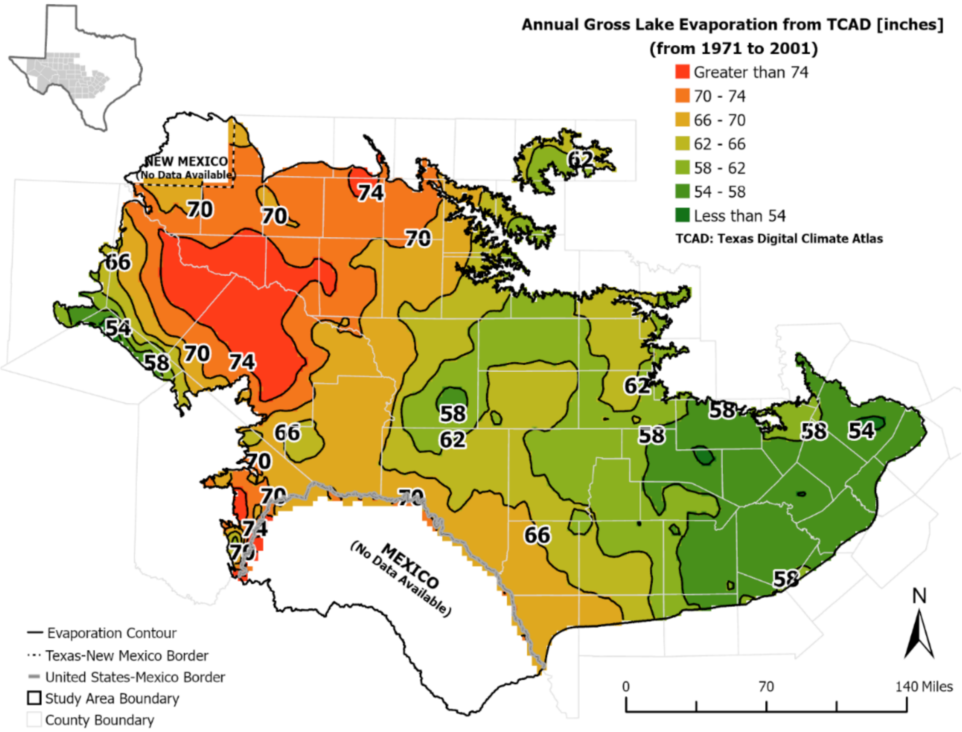


Figure 2.2-7. Gross lake evaporation for the study area from Texas Digital Climate Atlas from 1971 to 2001 (Narasimhan and others, 2005).

2.2.4 Drought Index (Palmer Hydrologic Drought Index)

The Palmer Hydrologic Drought Index is a scaled value used to represent abnormally wet, average, and abnormally dry conditions. Drought conditions can have a profound impact on groundwater resources. Lower precipitation and higher temperatures reduce the amount of water available to recharge the aquifer. In addition, as the severity of drought increases, surface water availability decreases, typically resulting in increased groundwater extraction. Thus, drought conditions not only reduce recharge of the groundwater but increases the amount of groundwater pumped for use.

Figure 2.2-8 and Figure 2.2-9 show the annual precipitation (top) and the Palmer Hydrologic drought indices (bottom) from 1895 to 2020 for climate divisions 5, 6, 7 and 9 (National Oceanic and Atmospheric Administration, 2021). A positive drought index indicates wetter than normal conditions and vice versa. The most severe drought (the drought of record), with respect to duration and intensity, occurred between 1950 and 1957 (Bradley and Malstaff, 2004). The most recent severe drought happened between 2011 and 2014. The comparison of temporal trends in the precipitation graphs versus the drought index graphs, shows a clear positive correlation between the drought index and precipitation. One of the purposes of regional groundwater modeling is to help better plan for droughts in Texas. During construction of the regional groundwater model, we will consider how best to implement drought conditions in the historical time period and in future simulations in order to best estimate the effects of droughts on groundwater resources.

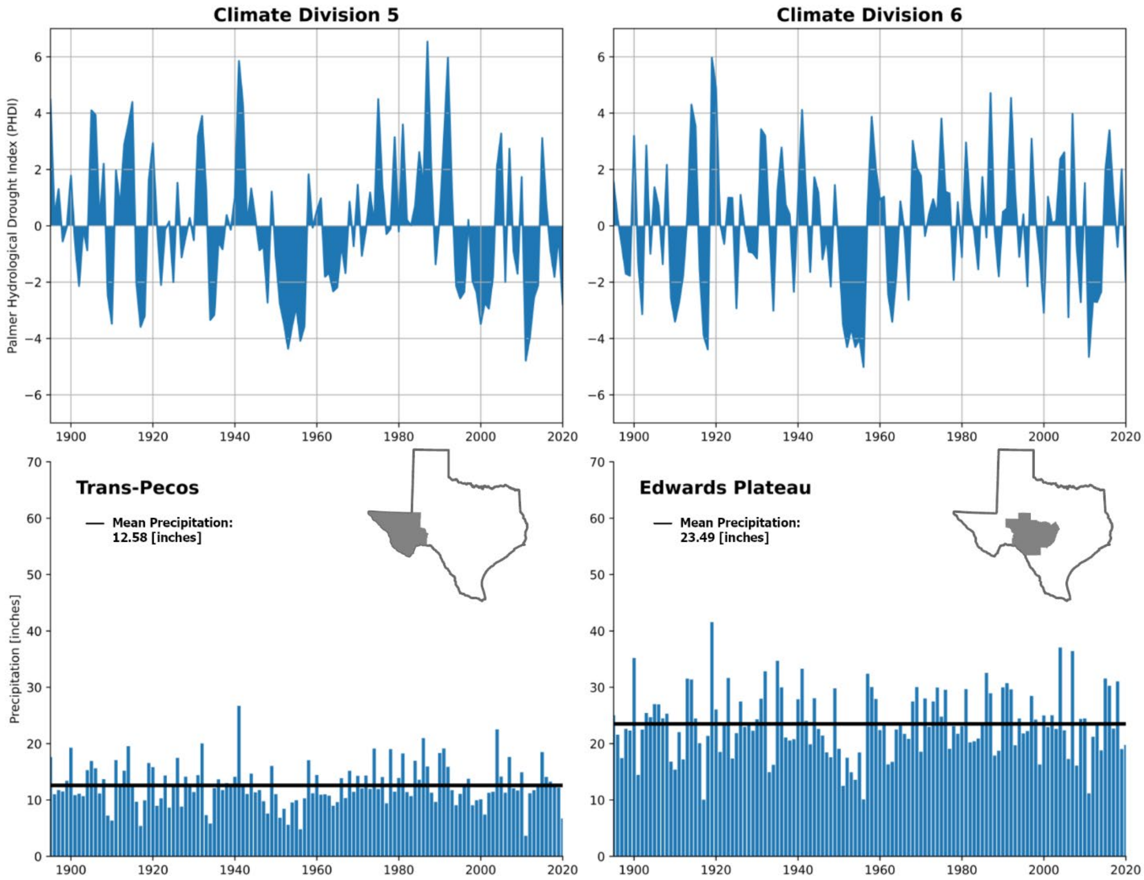


Figure 2.2-8. Annual Palmer Hydrological Drought Index (PHDI) and annual precipitation at Climate Division 5 and 6 for the period of 1895 to 2020. Black bar in the precipitation bar chart shows mean precipitation over the period (National Oceanic and Atmospheric Administration, 2021).

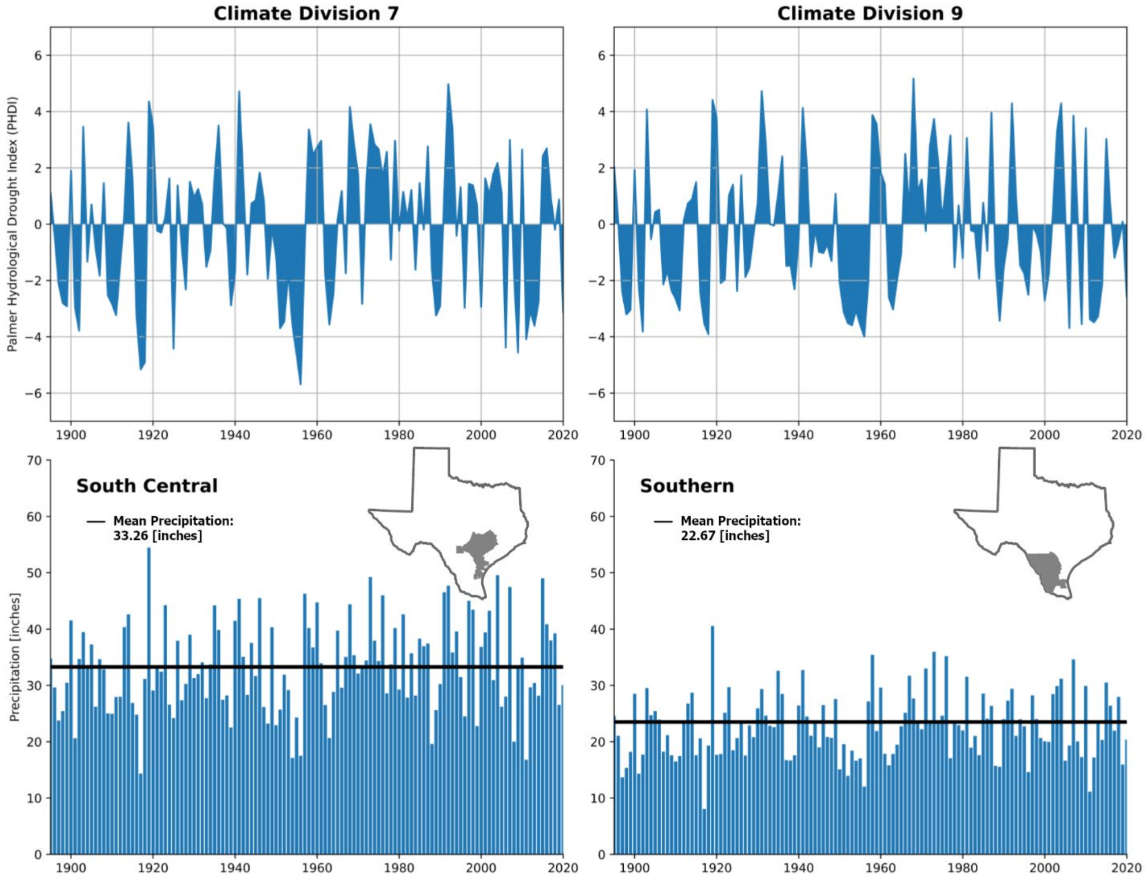


Figure 2.2-9. Annual Palmer Hydrological Drought Index (PHDI) and annual precipitation at Climate Division 7 and 9 for the period of 1895 to 2020. Black bar in the precipitation bar chart shows mean precipitation over the period (National Oceanic and Atmospheric Administration, 2021).

2.3 Geologic Setting

The current study area encompasses the entirety of the Pecos Valley Aquifer and the Edwards-Trinity aquifer system, which includes the Edwards-Trinity (Plateau) and Edwards (Balcones Fault Zone) aquifers as well as the Southern portion of the Trinity Aquifer. This section briefly summarizes the geologic history relevant to the component units of these aquifers.

The Edwards-Trinity aquifer system consists of Early Cretaceous shallow marine rock sediments belonging to the Lower Washita, Fredericksburg, and Trinity groups. The Lower Washita and Fredericksburg sediments form the Edwards Group, the top unit of the Edwards-Trinity aquifer system. The Trinity Group sediments form the bottom unit of the Edwards-Trinity aquifer system. In the eastern third of the study area (Central Edwards Plateau and Balcones Fault Zone), these Cretaceous units rest on top of Early to Late Paleozoic sediments. In the western portion of the study area, the Cretaceous units rest on

Triassic units (including the Dockum Aquifer) and Permian units (including the Rustler and Capitan Reef Complex aquifers). The unconformity, a contact between rock units representing a break in the time record, between the Cretaceous Edwards-Trinity aquifer system and underlying pre-Cretaceous units indicates a major shift in the geologic evolution of the study area. The gap between Late Triassic and Early Cretaceous rocks spans about 60 million years and was characterized by crustal warping and erosion (Barker and Ardis, 1992; Barker and other 1994). In general, the thin to medium-bedded Cretaceous strata of the Edwards-Trinity aquifer system are nearly flat-lying and typically dip southeastward on top of Triassic and Paleozoic units which generally dip westward. The Pecos Valley Aquifer consists of Cenozoic terrigenous rock sediments (Anaya and Jones, 2009) and overlies a portion of the Cretaceous Edwards-Trinity (Plateau) Aquifer. Where the Edwards-Trinity (Plateau) Aquifer is not present, the Pecos Valley Aquifer overlies Triassic units (including the Dockum Aquifer) and Permian units (including the Rustler and Capitan Reef Complex aquifers).

2.3.1 Pre-Cretaceous Period

In the context of the current study, the Pre-Cretaceous period refers to the the older units underlying the Pecos Valley Aquifer and the Edwards-Trinity aquifer system. During the Paleozoic Era, the geologic history of west-central Texas was dominated by activity related to the Ouachita geosyncline. The Ouachita geosyncline enters Texas from southeastern Oklahoma and extends around the southeastern and southern margins of the Llano uplift, then curves westward against the south edge of the Devils River uplifts and continues to the southeastern and eastern margins of the Marathon-Solitario uplifts (Barker and Ardis, 1992). Fine-grained materials were deposited in the foreland area until Late Permian time. The thickness of the deposits was more than 20,000 feet (Barker and Ardis, 1992). Intermittent periods of tectonic uplift and volcanic activity occurred along the cratonic margins of the geosyncline creating a subsiding trough (Barker and Ardis, 1996). The Ouachita orogeny climaxed between Late Pennsylvanian and Early Permian, with significant uplifting, thrust faulting, and intensive folding. Various degrees of metamorphism occurred in the interior sediments of the geosyncline. A very complex structure of foreland facies created petroleum traps and some of the world's most productive oil and gas reservoirs (Barker and Ardis, 1996). The Permian basin developed in west Texas as the Ouachita orogeny progressively phased out. During the middle to end of Late Permian, the Permian Basin repeatedly connected to the open ocean until the end of the Paleozoic, when the sea withdrew as West Texas was uplifted (Barker and Ardis, 1996).

The end of the Ouachita orogeny was followed by long periods of nondeposition, crustal warping, and erosion of the Paleozoic sediment during the Early and Middle Triassic (Baker and Ardis, 1996). Uplifting of the Llano area and the erosion of the central basin continued. Deposition of eroded materials from Paleozoic rocks in the low-lying fluvial, deltaic, and lacustrine environments formed the Dockum Group (McGowen and others, 1979). During the Jurassic, the landscape of the study area was tilted toward the southeast, and the surface drainage was reversed from northwestward flow toward the inland sea to southeastward flow toward the Cretaceous sea (Sellards, 1933). The Ouachita Mountains began to erode across central Texas and the Gulf of Mexico started to open.

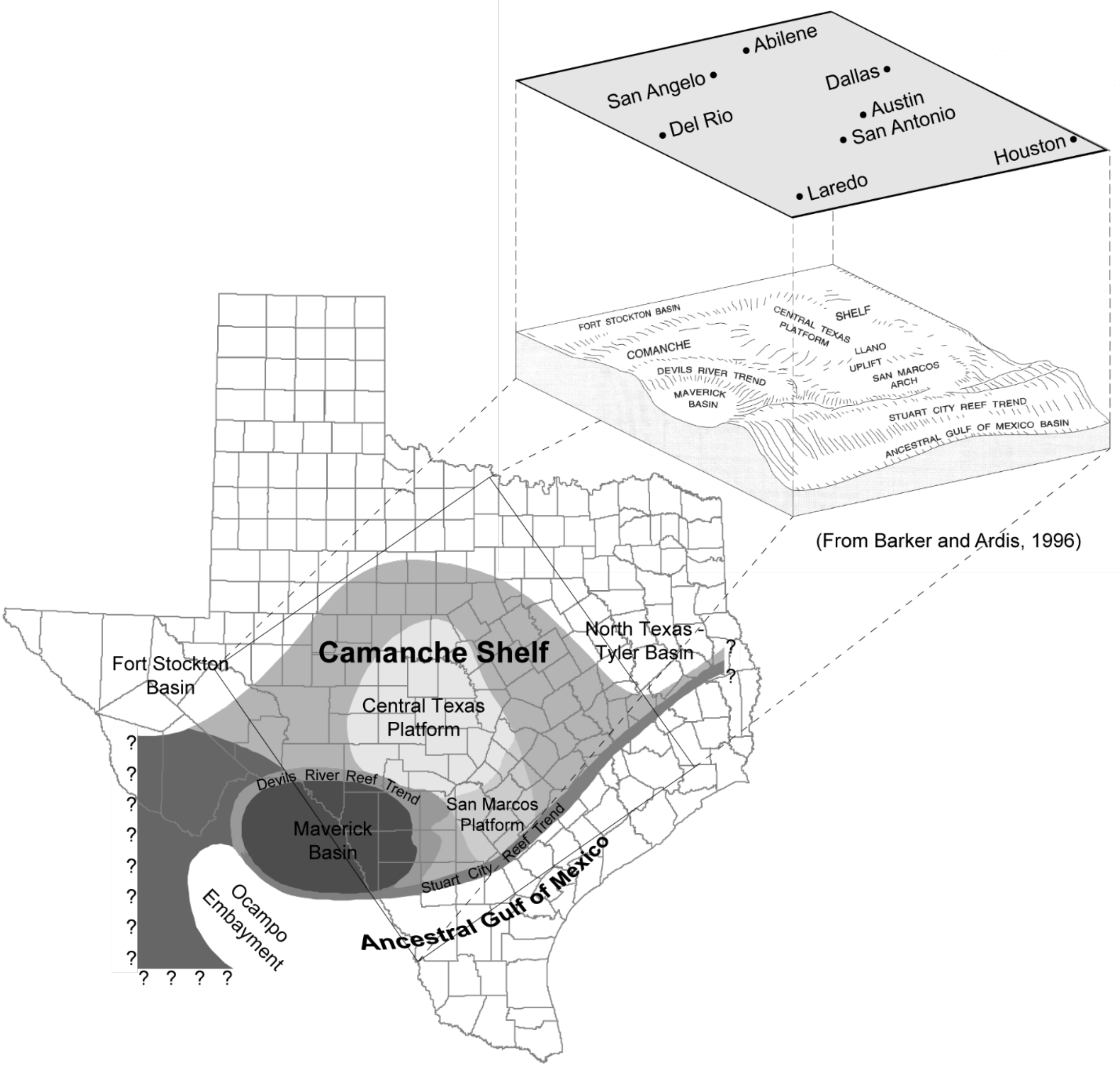
2.3.2 Cretaceous Period

In the context of the current study, the Cretaceous period refers to the age of the units of the Edwards-Trinity aquifer system. The development of the Gulf of Mexico continued into the Cretaceous Period (Wood and Walper, 1974). The Cretaceous seas advanced from the southeast and began to form a broad continental shelf known as the Comanche Shelf (Figure 2.3-1). During the Trinitian time, the Llano Uplift provided a prominent structural shelf for the deposition of Trinity Group sediments. The Trinity rock record indicates that three shoreline advance and retreat cycles occurred during deposition of Trinity Group sediments (Barker and Ardis, 1996). Trinity rocks have a wedge-like shape from less than 150 ft thick near the Llano uplift to more than 1,000 ft thick in the Balcones Fault Zone (Barker and Ardis, 1996). The southeast section of the Llano Uplift, the current Hill Country area, experienced several depositional periods with the transgressions and regressions of the Cretaceous seas. The basal Cretaceous sand was deposited as braided stream deposits on top of the pre-Cretaceous rocks in the western section of the Llano Uplift (Barker and Ardis 1992). The Glen Rose Limestone accumulated to the southwest and south of the Llano Uplift. Due to the significant subsidence rate during the middle to late Trinitian time, the Glen Rose Limestone is more than three times thicker in southern Kinney County as it is in central Sutton County (Barker and Ardis 1996). The sea withdrew further down south and east during the late Trinitian. The southwestern part of Glen Rose Limestone was replaced by the Maxon Sandstone (King, 1980). The shoreline receded continually slightly to the north of the Balcones Fault Zone at the end of Trinitian time.

In early Fredericksburgian time (the age of the Edwards Group), the Stuart City Reef Trend began to form from and extended from northern Mexico across nearly 500 miles of southeastern Texas. The reef sheltered depositional environments on the Comanche Shelf from storm waves and deep ocean currents (Barker and Ardis 1996). Figure 2.3-1 shows other structural elements around the Comanche Shelf that controlled depositional environments:

- The Central Texas Platform that was an elongated mound on the Comanche Shelf which extended from the Austin and San Antonio areas northwest to the San Angelo area;
- The San Marcos Platform that extended southeast of the Llano Uplift to the Stuart City Reef Trend;
- The Maverick basin that was a semicircular depression along the southern margin of the Comanche shelf straddling the Texas – Mexico border;
- The Devils River Reef Trend that developed around the eastern, northern, and western rim of the Maverick basin and surrounded the Maverick basin; and
- The Fort Stockton basin which extended from northern Mexico across the northwestern part of the Comanche shelf.

Those structural elements helped isolate the Comanche Shelf from open seas. Various formations were deposited depending on the relative sea levels and climatic conditions. Before the deposition of the Upper Cretaceous, much of the Central Texas Platform was subaerially exposed (Figure 2.3-2) and both erosion and karstification of the Lower Cretaceous carbonate sediments occurred, likely the origin of many of the caverns in today's Edwards Plateau area (Barker and Ardis, 1996). During the Late Cretaceous, deposition and subaerial erosion repeatedly occurred, forming the Del Rio Clay, Buda Limestone, Boquillas Formation, and Austin Group sediments over the study area.



(From Barker and Ardis, 1996)

Figure 2.3-1. Paleogeographic elements affecting the depositional environments of the Edwards Group sediments (from Anaya and Jones, 2009).

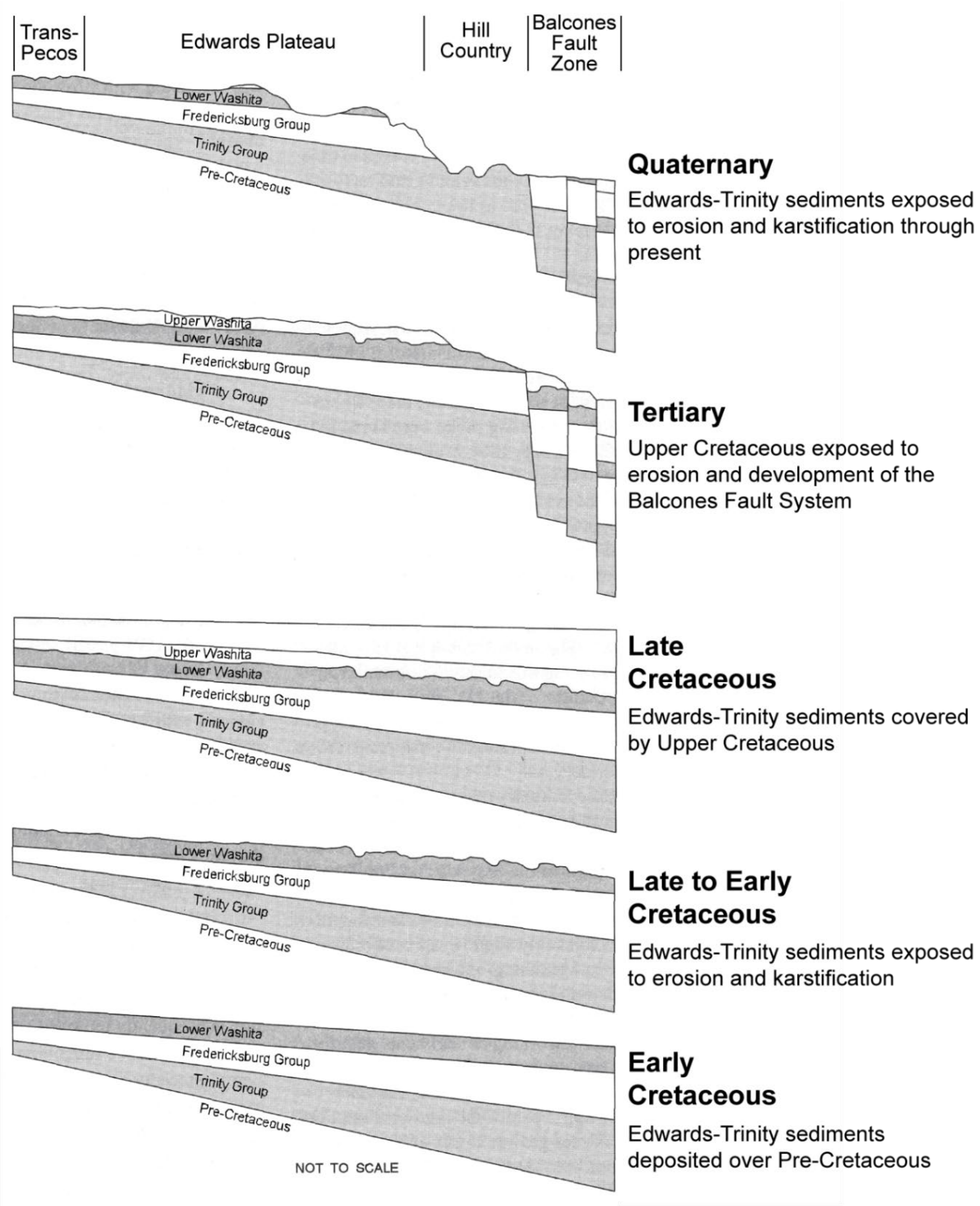


Figure 2.3-2. Evolutionary development of the Edwards-Trinity (Plateau) and Edwards (Balcones Fault Zone) aquifers system (modified from Barker and Ardis, 1996).

2.3.3 Post-Cretaceous Period

In the context of the current study, the Post-Cretaceous period refers to the ages of the Pecos Valley Aquifer and the younger units overlying the Edwards-Trinity aquifer system. The post-Cretaceous geologic history is dominated by uplift and erosion over west-central Texas and deposition and subsidence in the Gulf of Mexico. As the Laramide orogenic cycle began, Paleozoic sediments in the Delaware basin were uplifted, Upper Permian deposits were dissolved and deformed, and the overlying Triassic and Cretaceous sediments collapsed and eroded (Barker and Ardis, 1996; Anaya and Jones 2009). During the Tertiary and Quaternary, more than 1,500 feet of talus and alluvial fill accumulated in troughs in the current day Pecos Valley Aquifer (previously, Cenozoic Pecos Alluvium), and the Basin and Range tectonic cycle enhanced the deposition. On the southeastern side of the study area, sediments accumulated in the Gulf of Mexico and increased the tensile stress along the ancient hinge-line of the Ouachita Fold Belt. The Balcones Fault Zone formed afterwards, with mostly down-to-the-southeast normal faults. The vertical displacement across the Balcones Fault zone is about 900 to 1,200 feet (Barker and Ardis 1996). The Balcones Fault Zone's stair-stepped shape down toward the Texas Gulf Coast significantly impacted surface and subsurface hydrogeologic feature development. Groundwater flow speed, direction and volume, spring location, and stream movement and discharge were all influenced by the disrupted lateral continuity of Cretaceous strata.

3 PREVIOUS WORK

Numerous studies have been conducted for the study area, and there are many reports published accordingly. The study topics include geology (Fisher and Rodda, 1969; Smith, 1974), hydrogeology (Barker and others 1994; Barker and Ardis, 1996; Kuniansky and Ardis, 2004), ecology (Elliott and others, 2014), springs (Brune, 1975; 1981), climate (Larkin and Bomar, 1983), and well records.

Over the study area, the Texas Department of Water Resources conducted a regional groundwater study to discuss the Trans-Pecos (Rees and Buckner, 1980) and the Edwards Plateau (Walker, 1979). The TWDB published reports that describe groundwater resources for the Edwards (Balcones Fault Zone) (Klemt and others 1975) and the current Pecos Valley Aquifer (Ashworth, 1990).

In the late 1970s, the U.S. Geological Survey began the Regional Aquifer Systems Analysis (RASA) program to improve the hydrogeologic information of the major aquifer systems in the United States. A study covering the Edwards-Trinity (Plateau) Aquifer system and adjacent hydraulically connected units was completed under this program. Multiple comprehensive reports were published, including Barker and others (1994) and Barker and Ardis (1992; 1996), which describe the geologic history and hydrogeologic framework of the Edwards-Trinity aquifer system, and Kuniansky and Ardis (2004), which describes the hydrogeology, groundwater use, and groundwater flow in the study area.

Several numerical models have been developed, along with hydrogeological studies, to understand the groundwater flow systems better. The U.S. Geological Survey developed finite-element groundwater flow models for the Edwards-Trinity Aquifer system with a single layer (Kuniansky and Holligan, 1994) and multiple layers (Kuniansky, 1994; 1995). The single-layered model assumed a greatly simplified aquifer system and only simulated major springs in the study area. Kuniansky and Ardis (2004) developed two finite-element groundwater flow models with two different scales. The larger-scale model was a two-dimensional, single-layer model to simulate the entire Edwards-Trinity Aquifer system. The small-scale model was a three-dimensional, multilayer model. The smaller-scale model simulates a relatively localized area known for complex flow patterns: the Hill Country area and Balcones Fault Zone as well as part of the Edwards Plateau.

The TWDB and its subcontractors have produced several groundwater availability models in the study area as part the TWDB Groundwater Modeling Program. The TWDB developed two finite-difference numerical groundwater flow models to simulate three-dimensional steady-state and transient flow for the Edwards-Trinity (Plateau) and Pecos Valley Aquifer (Anaya and Jones, 2009) and the Hill Country portion of the Trinity Aquifer (Jones and others, 2011). Later, Hutchison and others (2011a) updated the model from Anaya and Jones (2009) by improving the calibration with model layer reduction and input parameters adjustment. Toll and others (2018) updated the conceptual model for the Hill Country portion of the Trinity Aquifer. For the Edwards (Balcones Fault Zone) Aquifer, Lindgren and others (2004) and Scanlon and others (2001) developed the models for the San Antonio and the Barton Springs segments, respectively. The Barton Springs segment of the Edwards (Balcones Fault Zone) Aquifer model was updated by Hutchison and Hill (2011) by re-calibrating to an extended period that included the historic drought-of-record.

In recent years, several studies updated these previous models or developed new models for relatively localized regions or specific purposes. A groundwater model was developed for the Pecos River watershed (Green and others, 2016) and coupled surface-water/groundwater model for the Devils River watershed (Toll and others, 2017), with a focus on surface water/groundwater interaction. For Kinney County and Val Verde County, two local groundwater models were created to fill a gap between other regional groundwater models (Hutchison and others, 2011b; Hutchison and Burton, 2014). In the Pecos County region, Bumgarner and others (2012) created a conceptual model while Clark and others (2014) created a numerical model of the Edwards-Trinity (Plateau) Aquifer. In the San Antonio segment of the Edwards (Balcones Fault Zone) Aquifer, several studies have updated the TWDB groundwater availability model to better simulate the conduit flow (Lindgren, 2006) or to assess the uncertainty from variable climate conditions (Brakefield and others, 2015; Foster and others, 2021). Fratesi and others (2015) developed an independent model for the San Antonio segment of the Edwards (Balcones Fault Zone) Aquifer and compared the prediction simulation with the TWDB groundwater availability model (Lindgren and others, 2004).

In the Hill Country and adjacent areas, many studies focused on geologic and hydrogeologic conditions. Smith and others (2018) and Watson and others (2018) discussed the karst geologic characteristics of the Trinity Group. The U.S. Geological Survey published several maps and reports regarding the geologic framework and hydrogeologic conditions at the county scale (Clark and Morris, 2011, 2015, 2017; Clark and others, 2016a, 2016b, 2018, 2020). Several studies discussed hydrogeologic features, cross-formational flow, and surface-water/groundwater interaction of this region including Wong and others, (2014), Hunt and others (2017), Smith and others (2018), Watson and others (2018), Martin and others (2019). Hydrogeologic atlases of the Hill Country portion of the Trinity Aquifer and the southwest Travis County were completed by Wierman and others (2010) and Hunt and others (2020), respectively. These hydrogeologic atlases compiled existing data, newly collected data, and identified data gaps within the study area.

Several reports provide water quality data, water quality analysis, or water budget analysis. Ashworth (2010) discussed aquifer data analysis (including water chemistry) in Edwards, Kinney, and Val Verde counties, whileKreitler and others (2013) examined the hydrochemical and isotope data analysis in Groundwater Management Areas 3 and 7. Water quality analysis studies on the San Antonio segment of the Edwards Aquifer were completed by Opsahl and others (2018, 2020). Green and Bertetti (2012) presented a quantitative water budget analysis as an alternative to the regional model to construct the desired future condition of eight counties in Southwest Texas.

Recently, Sharp and others (2019) published a memoir about the Edwards Aquifer that includes discussions on the history, characteristics, environment, biology, and ecology of the aquifer and identified emerging issues which threaten these water resources.

4 HYDROLOGIC SETTING

The hydrologic setting describes the aquifer characteristics and groundwater conditions that contribute to the groundwater hydrology of the aquifer system. Elements of the hydrologic setting include the layering of the geologic units comprising the aquifer system (hydrostratigraphy), groundwater levels and regional groundwater flow patterns, physical characteristics of the aquifer that impact groundwater flow (hydraulic properties), inflows to and outflows from the groundwater system, and groundwater chemistry (quality). Inflows include recharge from precipitation and leakage from surface water features such as streams, rivers, and reservoirs. Outflows include discharge to springs and surface water features, water loss from evapotranspiration, and groundwater pumping.

4.1 Hydrostratigraphy and Hydrostratigraphic Framework

Stratigraphy refers to the vertical and lateral organization of the geologic units, typically based on a hierarchical classification system of stratigraphic units. Stratigraphic units represent simplified groupings of geologic units and are typically chosen by correlating lithostratigraphic units (groups with similar rock characteristics) with chronostratigraphic units (groups with similar rock ages) and/or geochronologic units (groups with similar geologic time). Figure 4.1-1 provides a stratigraphic column, or a simplified representation of the geology, for the study area.

Hydrostratigraphy refers to the further organization of these geologic units into groups based on similar aquifer characteristics. We have condensed the stratigraphic units in Figure 4.1-1 into three simplified hydrostratigraphic units based on similar aquifer characteristics. The top hydrostratigraphic unit represents younger units that overlie the Edwards and Trinity hydrostratigraphic units and includes the Pecos Valley Aquifer and other shallow units. The middle hydrostratigraphic unit represents the Edwards hydrostratigraphic unit and includes the Edwards (Balcones Fault Zone) Aquifer and the Edwards Group equivalent units of the Edwards-Trinity (Plateau) Aquifer. The bottom hydrostratigraphic unit represents the Trinity hydrostratigraphic unit and includes the Southern portion of the Trinity Aquifer and the Trinity Group equivalent units of the Edwards-Trinity (Plateau) Aquifer. These hydrostratigraphic units are complex and can represent different geologic formations and aquifers depending on their location within the study area. To simplify our hydrostratigraphic discussion, we have split the study area into distinct geographic regions, as shown in Figure 4.1-2. The following sections provide individual hydrostratigraphic descriptions for each of these regions. For each region, we provide a stratigraphic column, with geologic units grouped into their corresponding hydrostratigraphic units.

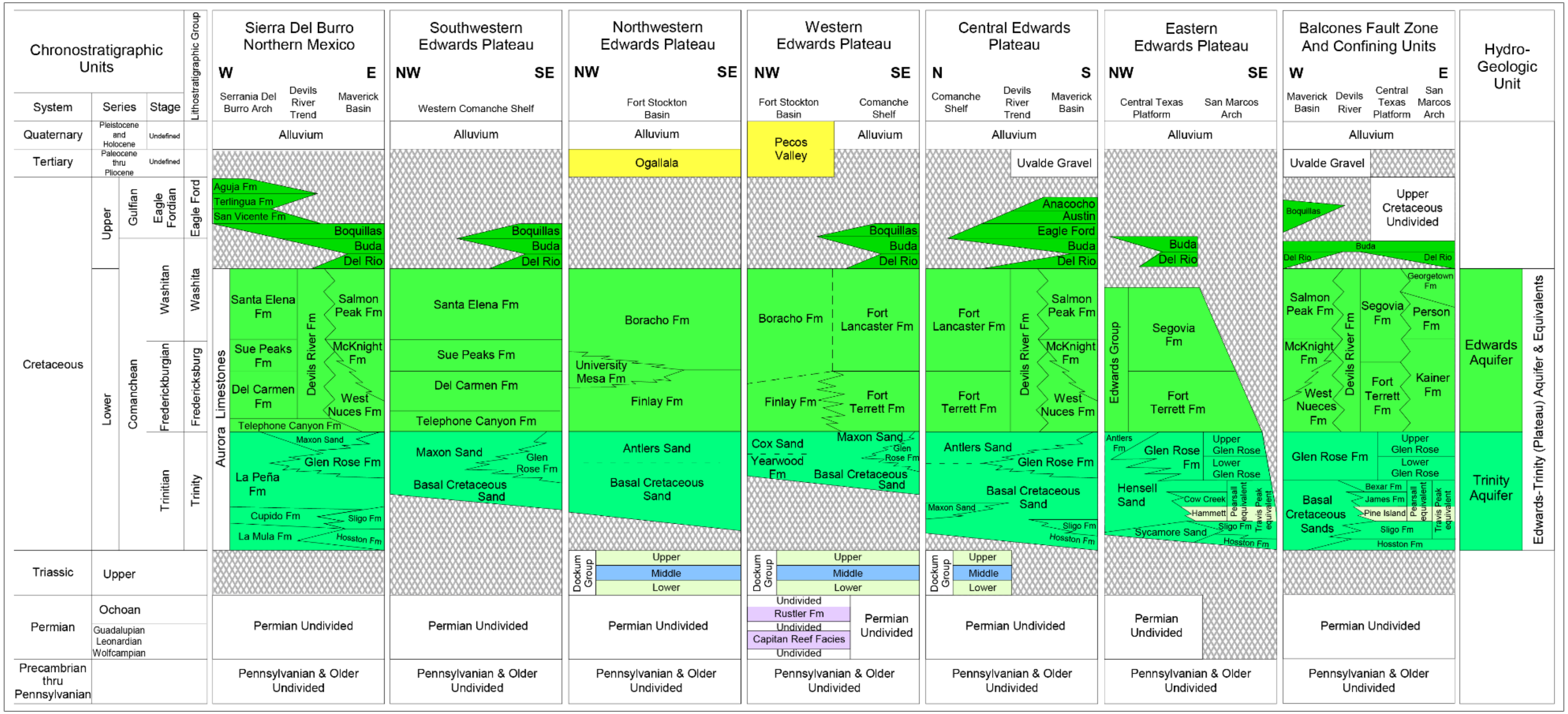


Figure 4.1-1. Stratigraphic correlation chart for the Edwards-Trinity (Plateau) and Pecos Valley aquifers regional Groundwater Availabilty Model.

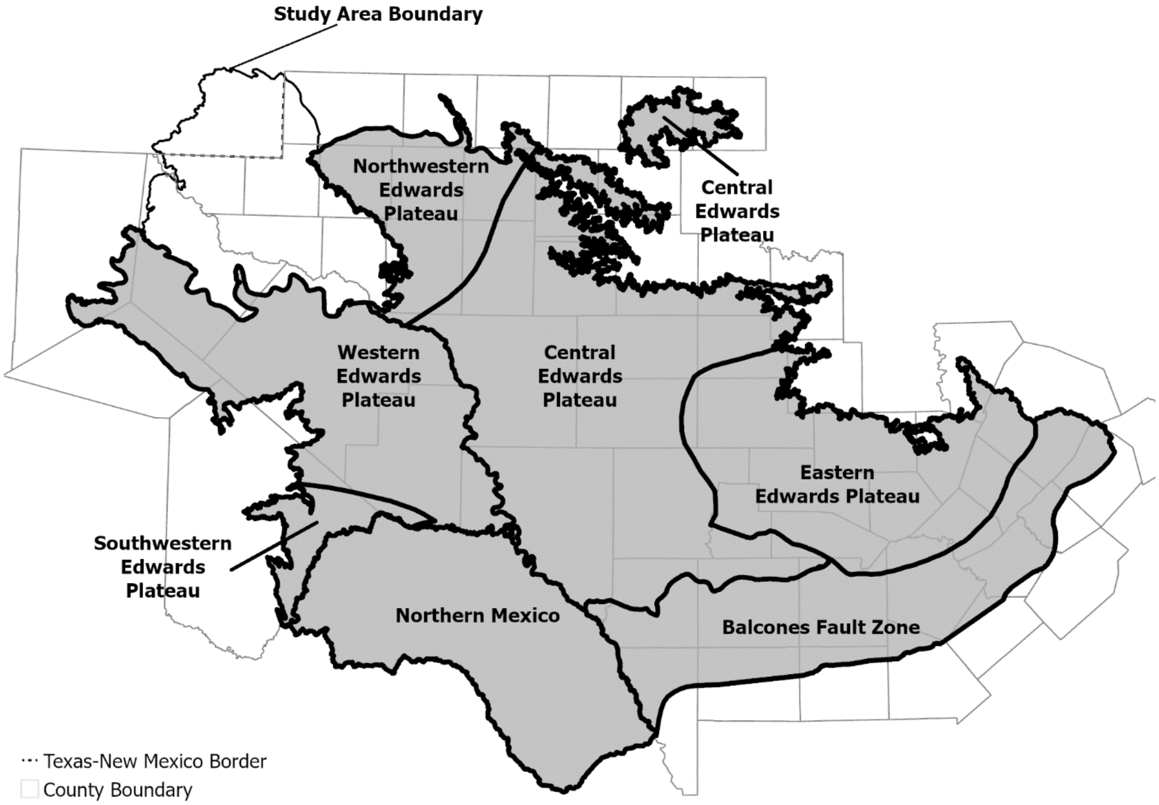


Figure 4.1-2. Stratigraphic regions delineated for the Edwards-Trinity (Plateau) and Pecos Valley aquifers regional Groundwater Availabilty Model.

4.1.1 Balcones Fault Zone and Younger Confining Units

In the Balcones Fault Zone, all three hydrostratigraphic units are present (Figure 4.1-3). The youngest hydrostratigraphic unit represents Late Washita to Gulfian sediments, including the Del Rio Clay, Buda Limestone, and Boquillas Formation. These units create a confining unit over about 70 percent of the Balcones Fault Zone (Barker and others, 1994). In the southeastern section of this region, where these Upper Cretaceous units dip down into the subcrop, the youngest hydrostratigraphic unit also includes any overlying units from the top of the Upper Cretaceous to land surface, such as the Eagle Ford, Austin, Taylor, and Navarro groups (shown in the stratigraphic column as Upper Cretaceous undivided).

The Edwards hydrostratigraphic unit represents the Edwards (Balcones Fault Zone) Aquifer and equivalent downdip units in the east and the Edwards portion of the Edwards-Trinity (Plateau) Aquifer in the west. This includes the lower part of the Washita Group and the entire Fredericksburg Group. In the northeastern Balcones Fault Zone (San Marcos Arch area), the Edwards hydrostratigraphic unit comprises the Kainer and the Person formations overlain by the Georgetown Formation. West of the San Marcos Arch, the

Segovia and Fort Terrett formations comprise the Edwards hydrostratigraphic unit. In the western Balcones Fault Zone (Devils River Trend area), the Edwards hydrostratigraphic unit represents the Devils River Formation. In the southwestern Balcones Fault Zone (Maverick Basin area), the Edwards hydrostratigraphic unit comprises the West Nueces, McKnight, and Salmon Peak formations.

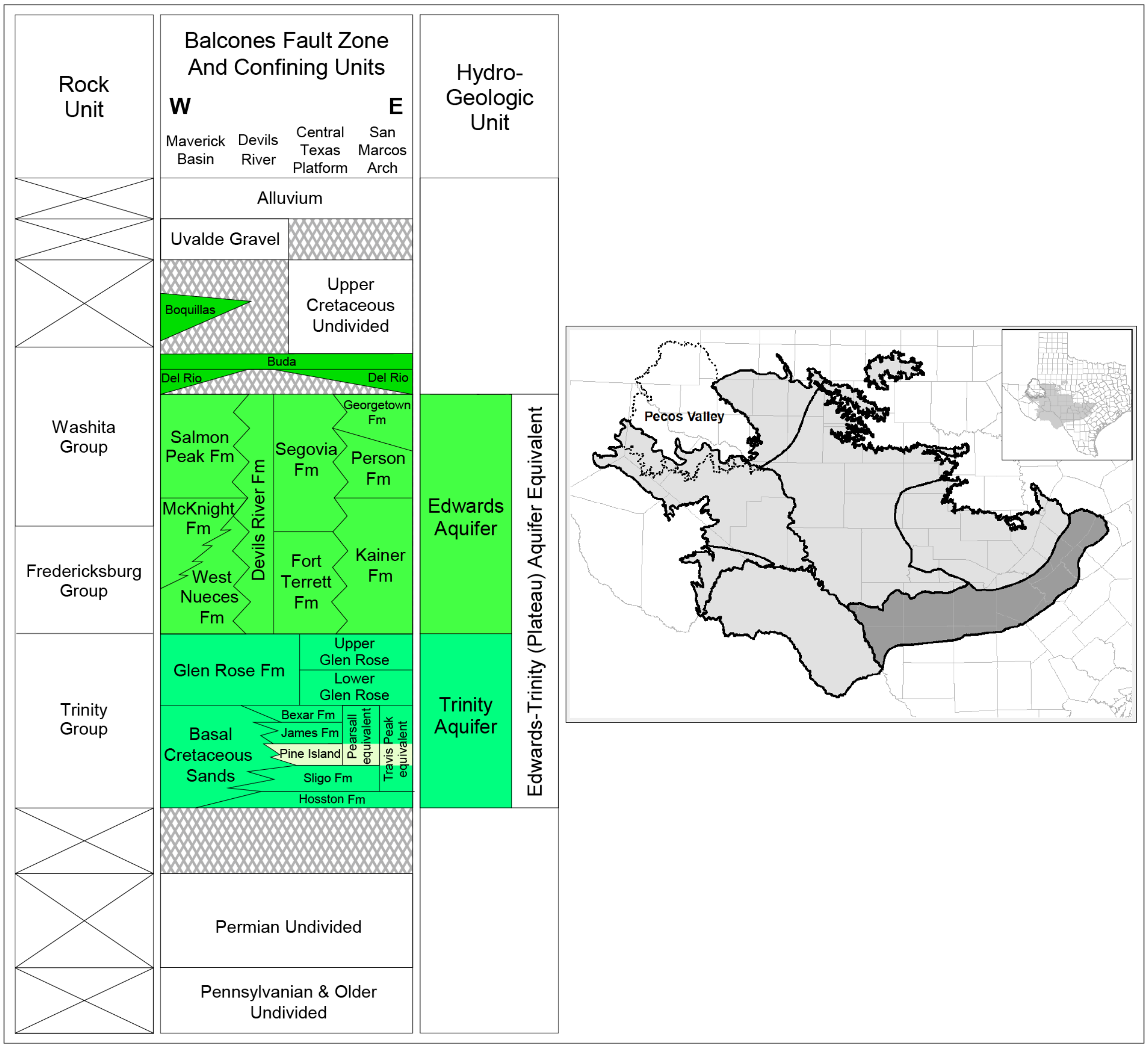


Figure 4.1-3. Hydrostratigraphy for the Balcones Fault Zone and younger confining units region.

The Trinity hydrostratigraphic unit represents the subcrop of the Hill Country portion of the Trinity Aquifer and equivalent downdip units in the east and the subcrop of the Trinity portion of the Edwards-Trinity (Plateau) Aquifer in the west. In the eastern section of the Balcones Fault Zone region, the Hosston and Sligo formations comprise the lower member of Trinity hydrostratigraphic unit. The Pearsall Formation, which contains the Pine Island Shale, James Formation, and Bexar Shale members, overlies the Sligo Formation and extends to the south-central part of the Edwards Plateau. The Pine Island Shale Member stretches eastward from the Balcones Fault Zone and is a persistent Lower Cretaceous unit in east Texas (Barker and others, 1994). The Bexar Shale Member is present between the James Formation and the Glen Rose Limestone in the Balcones Fault Zone (Barker and others, 1994). The Pearsall Formation and the underlying Sligo and Hosston formations grade into undifferentiated basal Cretaceous sands towards the Maverick Basin in the west. The Glen Rose Limestone overlies the Pearsall Formation in the east and the undifferentiated basal Cretaceous sands in the west. The base of the Edwards-Trinity aquifer system in the Balcones Fault Zone generally descends steeply towards the Gulf of Mexico.

In this region, the Edwards hydrostratigraphic unit is the major water-producing unit, as the Edwards (Balcones Fault Zone) Aquifer is one of the most productive aquifers in the world (Barker and Ardis, 1996). The Trinity hydrostratigraphic unit also produces water, but is deeper, less permeable and more saline than the overlying Edwards unit. Based on multiport wells south of Austin, Texas, Smith and Hunt (2020) found some connectivity between the Edwards hydrostratigraphic and the upper portion of the Trinity hydrostratigraphic unit, but little to no connection between the Edwards and lower units of the Trinity hydrostratigraphic unit. Relatively impermeable Paleozoic rocks underlie the Trinity hydrostratigraphic unit, precluding significant hydraulic connection between the Trinity unit and underlying units. It should be noted that this region is highly faulted, which can greatly alter the direction of or impede groundwater flow. The vertical fault displacement in the Cretaceous rocks ranges typically from 900 feet in Austin to 1,200 feet in San Antonio. The displacement within the overlying pre-Cretaceous rocks is unknown (Barker and Ardis, 1992).

4.1.2 Eastern Edwards Plateau (Hill Country and Llano Uplift)

In the Eastern Edwards Plateau region, only the bottom two hydrostratigraphic units are present (Figure 4.1-4). In the western portion of this region, the Upper Cretaceous sediments such as the Del Rio Clay and the Buda Limestone occur but are thin, discontinuous, and largely unsaturated, and therefore not considered a separate hydrostratigraphic unit in this region. The Edwards hydrostratigraphic unit represents the Edwards units of the Edwards-Trinity (Plateau) Aquifer, comprising the Fort Terret and the Segovia Formation of the Fredericksburg and Washita Group, respectively. The boundary between the Edwards-Trinity (Plateau) Aquifer and the Hill Country portion of the Trinity Aquifer marks where erosion removed most of the Fredericksburg and Washita groups and younger units in the Hill Country. East of this boundary, the remaining non-eroded portions of the Edwards units cap the higher ridges of the Hill Country, but since these are thin, discontinuous, and largely unsaturated, we do not include these discontinuous pieces overlying the Trinity Aquifer into the Edwards hydrostratigraphic unit extent.

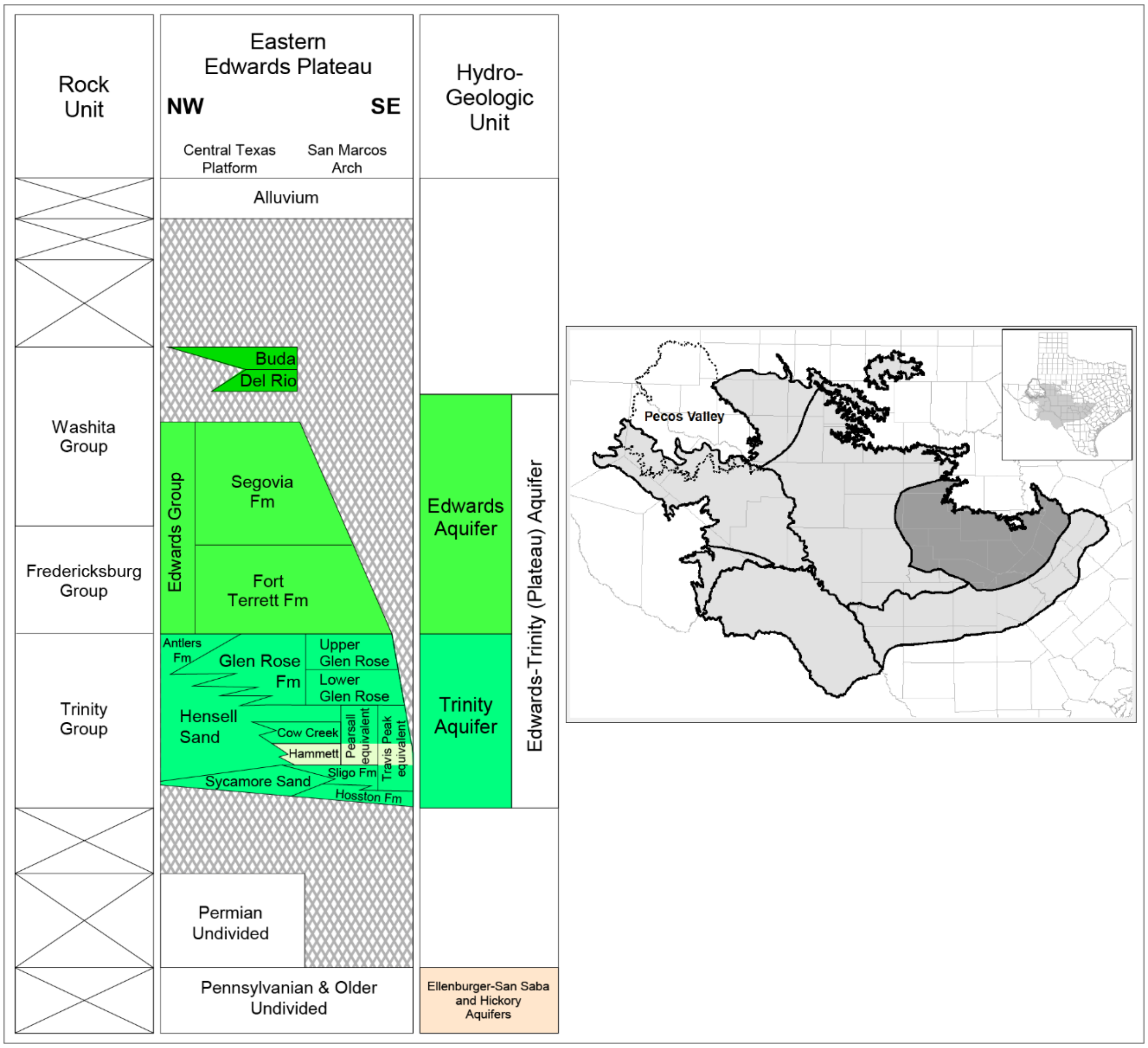


Figure 4.1-4. Hydrostratigraphy for the Eastern Edwards Plateau and Hill Country region.

The Trinity hydrostratigraphic unit can be subdivided into the Lower, Middle, and Upper Trinity productive subunits on the southeastern side of this region (Ashworth, 1983). The Lower Trinity productive unit consists of the Hosston Formation and Sycamore Sand and overlying Sligo Formation. The Lower Trinity unit extends northward from the Balcones Fault Zone. The Hammett Shale is a confining (impermeable) unit between the Lower and Middle Trinity units that separates the vertical flow between these two Trinity subunits. The Middle Trinity subunit comprises the Cow Creek Limestone, Hensell Sand, and the lower member of Glen Rose Limestone. The Upper Trinity subunit consists of the upper member of the Glen Rose Limestone (Ashworth, 1983; Mace and others, 2000). Unlike the

Balcones Fault Zone region, the Glen Rose Limestone in the southeastern portion of this region, is separated into upper and lower members by hydraulically tight sediments (Barker and others, 1994). As the Trinity Group extends west and northwest away from the Hill Country region, some formations start to pinch out. Unlike the Hill Country region, the separation between the Upper, Middle, and Lower Trinity subunits is less clear. The units of the Middle and Lower Trinity pinch out and grade into the Hensell Sand and Antlers Sand formations. The differentiation of the Lower and Upper Glen Rose formations also disappears as these blend into undifferentiated Glen Rose Formation further to the west and northwest.

In the Hill Country portion of this region, the Middle Trinity subunit of the Trinity hydrostratigraphic unit is generally the major water-producing unit, with smaller amounts produced from the Upper and Lower Trinity subunits. However, for the purposes of this study, we combined the Upper, Middle, and Lower Trinity into one Trinity hydrostratigraphic unit which presumes hydraulic connection between all component units. In the rest of the region, the major water-producing unit is the Edwards-Trinity (Plateau) Aquifer, a combination of the Edwards and Trinity hydrostratigraphic units. Since these two hydrostratigraphic units comprise one aquifer in this region, we assume hydraulic connection between them.

In most of this region, underlying Paleozoic rocks provide a relatively impermeable boundary at the base of the Trinity hydrostratigraphic unit (Barker and Ardis, 1992), so hydraulic connection is unlikely between the Trinity unit and underlying units. The exception is along the northeastern margin of this region, where several minor aquifers of the Llano Uplift, including the Precambrian Hickory Aquifer, and the Paleozoic Ellenburger-San Saba and Marble Falls aquifers, underlie and are likely hydraulically connected to the Trinity hydrostratigraphic unit. However, the study assumes cross-formational flow with these aquifers is likely minor.

4.1.3 Central Edwards Plateau (Plateau)

In the Central Plateau region, all three hydrostratigraphic units are present (Figure 4.1-5). The younger hydrostratigraphic unit is only present in the very southeastern section of this region in Val Verde and Kinney counties along the Devils River Trend and Maverick Basin. Here, it represents Late Washita to Gulfian sediments, including the Del Rio Clay, Buda Limestone, Eagle Ford Group, Austin Group, and Anacocho Limestone. In general, these Upper Cretaceous rocks act as confining units to the Edwards hydrostratigraphic unit of the Edwards-Trinity (Plateau) Aquifer. While Upper Washita sediments such as the Del Rio Clay and the Buda Limestone occur elsewhere in the region, they are thin, discontinuous, and largely unsaturated, and therefore not considered a part of the confining hydrostratigraphic unit in this study.

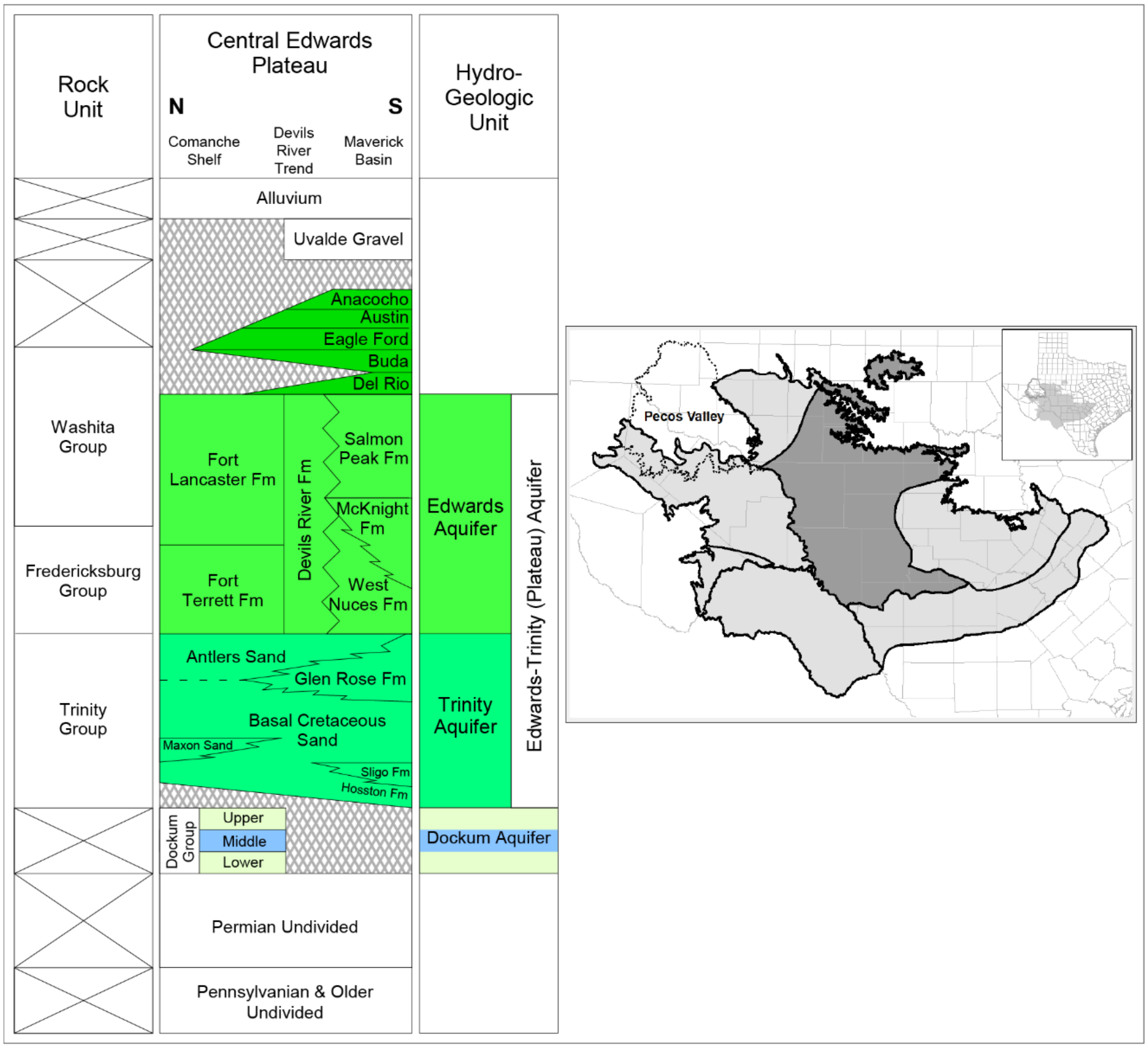


Figure 4.1-5. Hydrostratigraphy for the central Edwards Plateau region.

The Edwards hydrostratigraphic unit represents different formations of the Fredericksburg and Lower Washita groups depending on the location. In the Maverick Basin, this includes the West Nueces Formation (Fredericksburg), the McKnight Formation (Fredericksburg and Lower Washita), and the Salmon Peak Formation (Lower Washita). Within the Devils River Reef Trend, this includes the Devils River Formation (Fredericksburg and Lower Washita). On the Comanche Shelf, this includes the Fort Terrett Formation (Fredericksburg) and the Fort Lancaster Formation (Fredericksburg and Lower Washita). Rose (1972) refers to these combined units as the Edwards Group Limestones.

The Trinity hydrostratigraphic unit represents Trinity Group rocks, including a portion of the Sligo and Hosston formations, undifferentiated basal Cretaceous sands, the Glen Rose Limestone, the Maxon Sandstone and the Antlers Sand. The Sligo and Hosston formations pinch out in the south and grade into undifferentiated basal Cretaceous sands. The undifferentiated basal Cretaceous sands and the Maxon Sandstone are sometimes indistinguishable and are laterally equivalent to the Antlers Sand in the northern plateau (Anaya and Jones, 2009).

In this region, the major water-producing unit is the Edwards-Trinity (Plateau) Aquifer, a combination of the Edwards and Trinity hydrostratigraphic units. Since these two hydrostratigraphic units have a hydraulic connection, we comprise these units into one aquifer in this region for this study. Where present, the younger Upper Cretaceous hydrostratigraphic unit acts as confining unit for the Edwards hydrostratigraphic unit. Underlying Paleozoic rocks provide a relatively impermeable layer at the base of the Trinity hydrostratigraphic unit in the central section of the Edwards Plateau (Barker and Ardis, 1992), so hydraulic connection is unlikely between the Trinity unit and underlying units. In the northern section of this region, the Trinity hydrostratigraphic unit overlies the Late Triassic Dockum Group, including the Santa Rosa, Tecovas, Trujillo, and Cooper Canyon formations. The Dockum Aquifer and the Trinity hydrostratigraphic unit have insignificant hydraulic connection except where the Trinity Group directly overlies the Santa Rosa Formation (Walker, 1979).

4.1.4 Northwestern Edwards Plateau (Llano Estacado)

In the Llano Estacado of the Northwestern Edwards Plateau region, all three hydrostratigraphic units are present (Figure 4.1-6.). The younger hydrostratigraphic unit represents the Late Tertiary Ogallala Formation, or Ogallala Aquifer. This formation overlies the Edwards hydrostratigraphic unit and portions of the Trinity hydrostratigraphic unit where Edwards Group sediments have been eroded away.

The Edwards hydrostratigraphic unit represents the Finlay Formation (Fredericksburg), University Mesa Formation (Fredericksburg), and Boracho Formation (Fredericksburg and Washita). These units comprise the Edwards portion of the Edwards-Trinity (Plateau) Aquifer. In certain portions of this region, the Edwards Group rocks have been eroded away along old stream drainages, or paleochannels.

The Trinity hydrostratigraphic unit represents undifferentiated basal Cretaceous sands and the Antlers Sand of the Trinity Group, collectively referred to as the Trinity Sand. These units comprise the Trinity portion of the Edwards-Trinity (Plateau) Aquifer.

The major water-producing unit in this region is the Ogallala Aquifer, followed by the Edwards-Trinity (Plateau) Aquifer, a combination of the Edwards and Trinity hydrostratigraphic units. Since the Edwards and Trinity hydrostratigraphic units comprise one aquifer in this region, we assume hydraulic connection between the two hydrostratigraphic units. We also assume hydraulic connection between the Ogallala Aquifer and underlying Edwards and Trinity hydrostratigraphic units (Anaya and Jones, 2009). The Late Triassic Dockum Group, including the Santa Rosa, Tecovas, Trujillo, and Cooper Canyon formations, underlies the Trinity hydrostratigraphic unit in this region. The

Dockum Aquifer and the Trinity hydrostratigraphic unit have an insignificant hydraulic connection except where the Trinity Group directly overlies the Santa Rosa Formation (Walker, 1979).

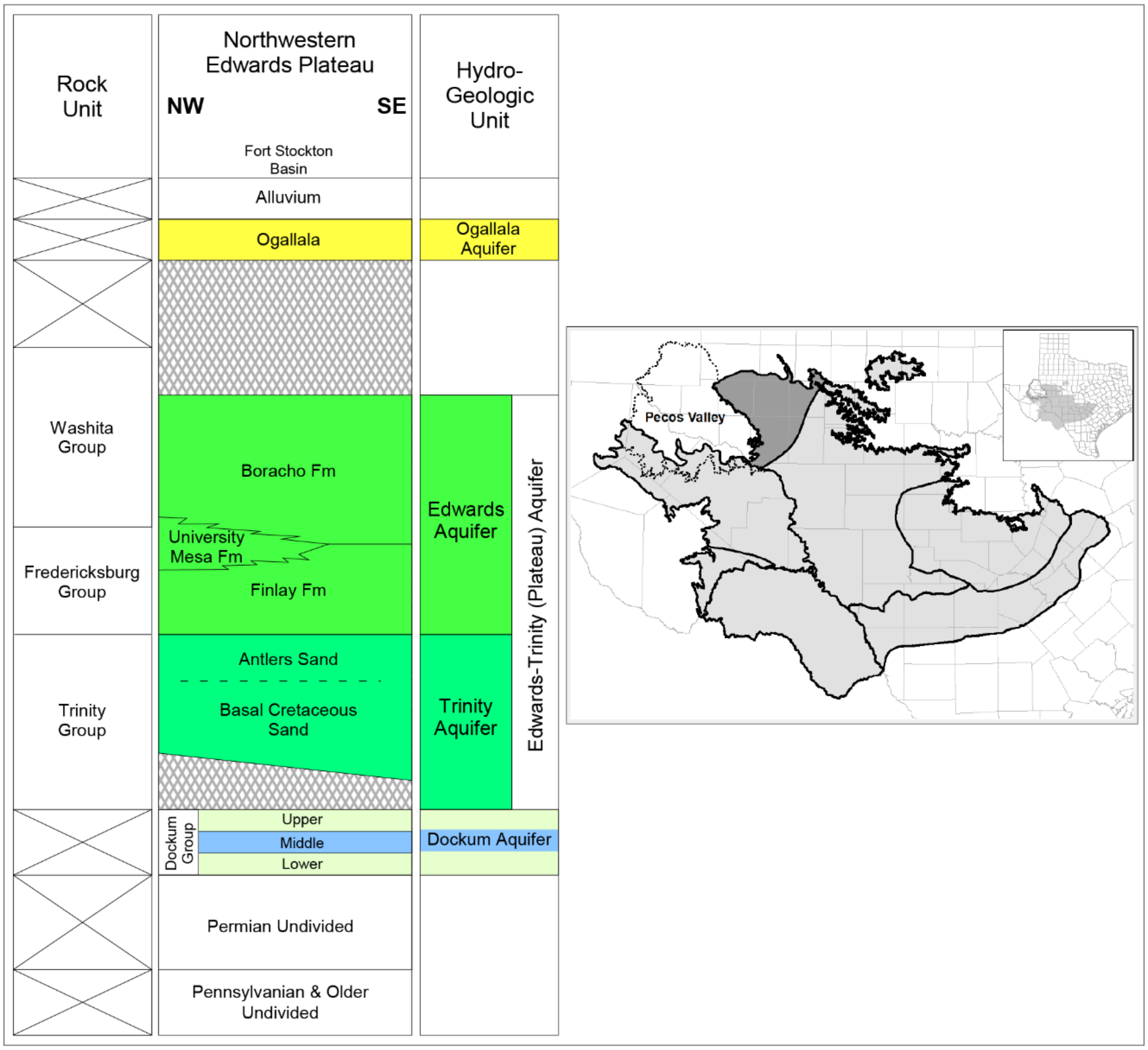


Figure 4.1-6. Hydrostratigraphy for the northwestern Edwards Plateau and Llano Estacado region.

4.1.5 Western Edwards Plateau (Trans-Pecos)

In the Trans-Pecos region, all three hydrostratigraphic units are present (Figure 4.1-7.). The younger hydrostratigraphic unit represents the Pecos Valley Aquifer. The Pecos Valley Aquifer consists of Tertiary and Quaternary age sediments that accumulated in the Pecos Valley, including the Tahoka, the Gatuna, the Judkins, and the Monahans formations. These units comprise a variety of discontinuous alluvium, lacustrine, eolian, and valley fill deposits, but act as one hydrostratigraphic unit despite their different origins and ages

(Anaya and Jones, 2009). The Pecos Valley Aquifer is only present in the northeastern section of this region. Elsewhere, the Del Rio Clay, Buda Limestone and the Boquillas Formation of the Upper Cretaceous do exist but are thin, discontinuous, and largely unsaturated. We do not consider them part of this hydrostratigraphic unit for this study.

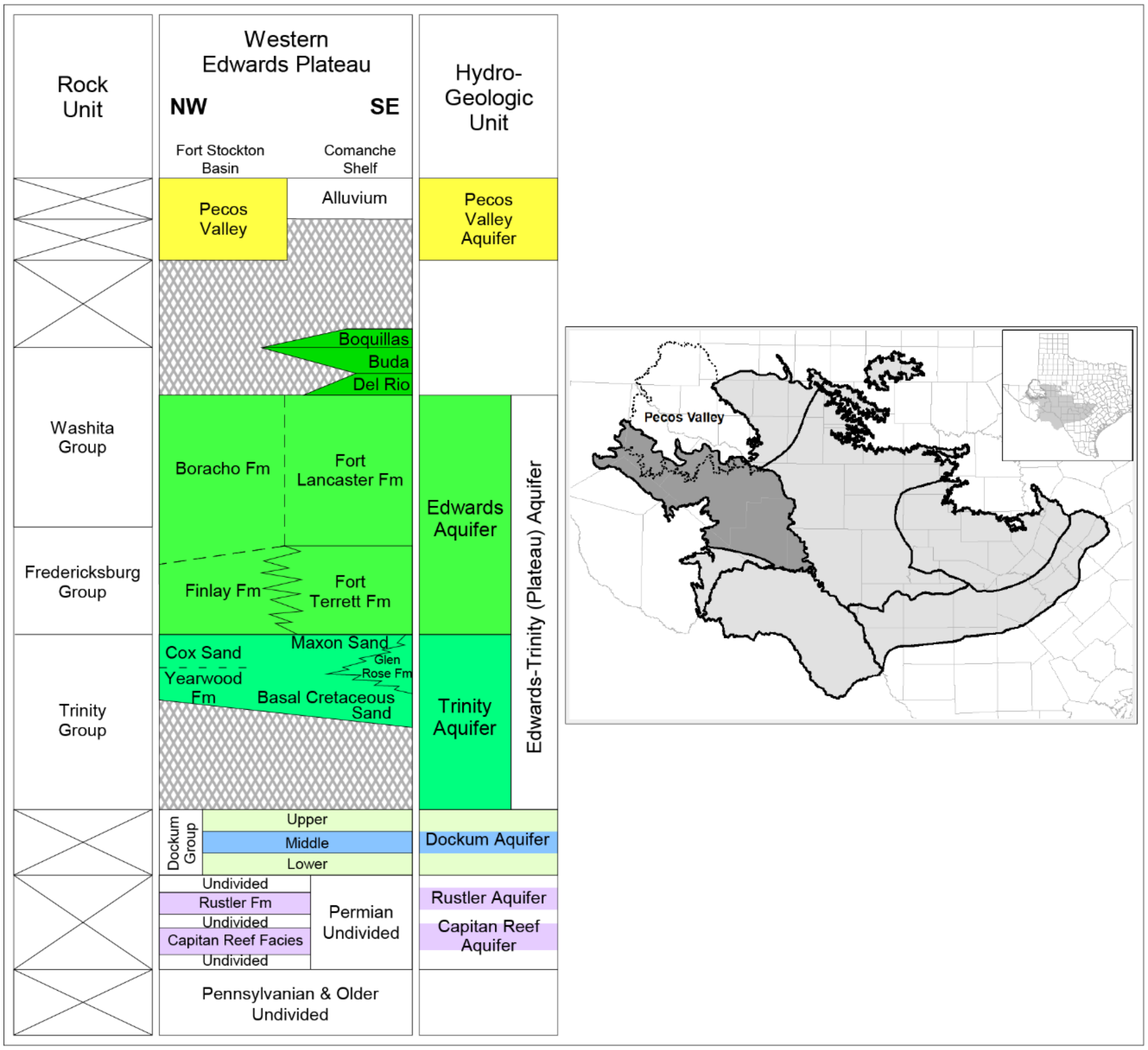


Figure 4.1-7. Hydrostratigraphy for the western Edwards Plateau and Trans-Pecos region.

The Edwards hydrostratigraphic unit represents the Fort Terrett, Fort Lancaster Finlay, and Boracho formations of the Edwards Group. The Fort Terrett Formation and the Fort Lancaster Formation formed within the Comanche Shelf environment, and the Finlay Formation and the Boracho Formation formed within the Fort Stockton Basin depositional environment. Locally, these four units, in a group, are referred to as Edwards Group Limestone, and they compose the Edwards portion of the Edwards-Trinity (Plateau) Aquifer.

The Trinity hydrostratigraphic unit represents Trinity Group rocks, including undifferentiated basal Cretaceous sands, the Glen Rose Formation, and the Maxon Sandstone. In the far northwestern Trans-Pecos region, this unit also includes the Yearwood Formation and the Cox Sandstone of the Trinity Group. Together, these units form the Trinity portion of the Edwards-Trinity (Plateau) Aquifer.

In this region, the Pecos Valley Aquifer is the major water-producing unit, followed by the Edwards-Trinity (Plateau) Aquifer, a combination of the Edwards and Trinity hydrostratigraphic units. Since the Edwards and Trinity hydrostratigraphic units comprise one aquifer in this region, we assume hydraulic connection between the two hydrostratigraphic units. At its southern edge, the Pecos Valley Aquifer overlies and is in hydraulic connection with the Edwards hydrostratigraphic unit. Elsewhere, it overlies the Triassic Dockum Aquifer and the Permian Capitan Reef Complex and Rustler aquifers. The difference in permeability between these units makes hydraulic connection unlikely. The Trinity hydrostratigraphic unit also overlies the Permian Capitan Reef Complex and Rustler aquifers and the Triassic Dockum Aquifer. Anaya and Jones (2009) assumed no significant hydraulic connection with these underlying units. However, Walker (1979) notes that the Dockum Aquifer and the Trinity hydrostratigraphic unit can be hydraulically connected where the Trinity Group directly overlies the Santa Rosa Formation of the Dockum Group (Walker, 1979).

4.1.6 Southwestern Edwards Plateau

In the Big Bend area of the Southwestern Edwards Plateau region, only the bottom two hydrostratigraphic units are present (Figure 4.1-8.). The Upper Cretaceous sediments, such as the Del Rio Clay, the Buda Limestone, and the Boquillas Formation are present but are discontinuous and largely unsaturated, so we do not consider them to be a separate hydrostratigraphic unit in this region.

The Edwards hydrostratigraphic unit represents the Telephone Canyon Formation (Fredericksburg), the Del Carmen Formation (Fredericksburg), Sue Peaks Formation (Frederickburg and Washita) and Santa Elena Formation (Lower Washita). Together, these units form the Edwards portion of the Edwards-Trinity (Plateau) Aquifer.

The Trinity hydrostratigraphic unit represents the Trinity Group rocks, including undifferentiated basal Cretaceous sands, Glen Rose Formation, and Maxon Sandstone. The

Glen Rose Formation pinches out in the southern portion of the region. Together, these units form the Trinity portion of the Edwards-Trinity (Plateau) Aquifer.

In this region, the major water-producing unit is the Edwards-Trinity (Plateau) Aquifer, a combination of the Edwards and Trinity hydrostratigraphic units. Since these two hydrostratigraphic units comprise one aquifer in this region, we assume hydraulic connection between them. The underlying Paleozoic rocks provide a relatively impermeable base for the Trinity hydrostratigraphic unit (Barker and Ardis, 1992), making hydraulic connection unlikely between the Trinity and underlying units.

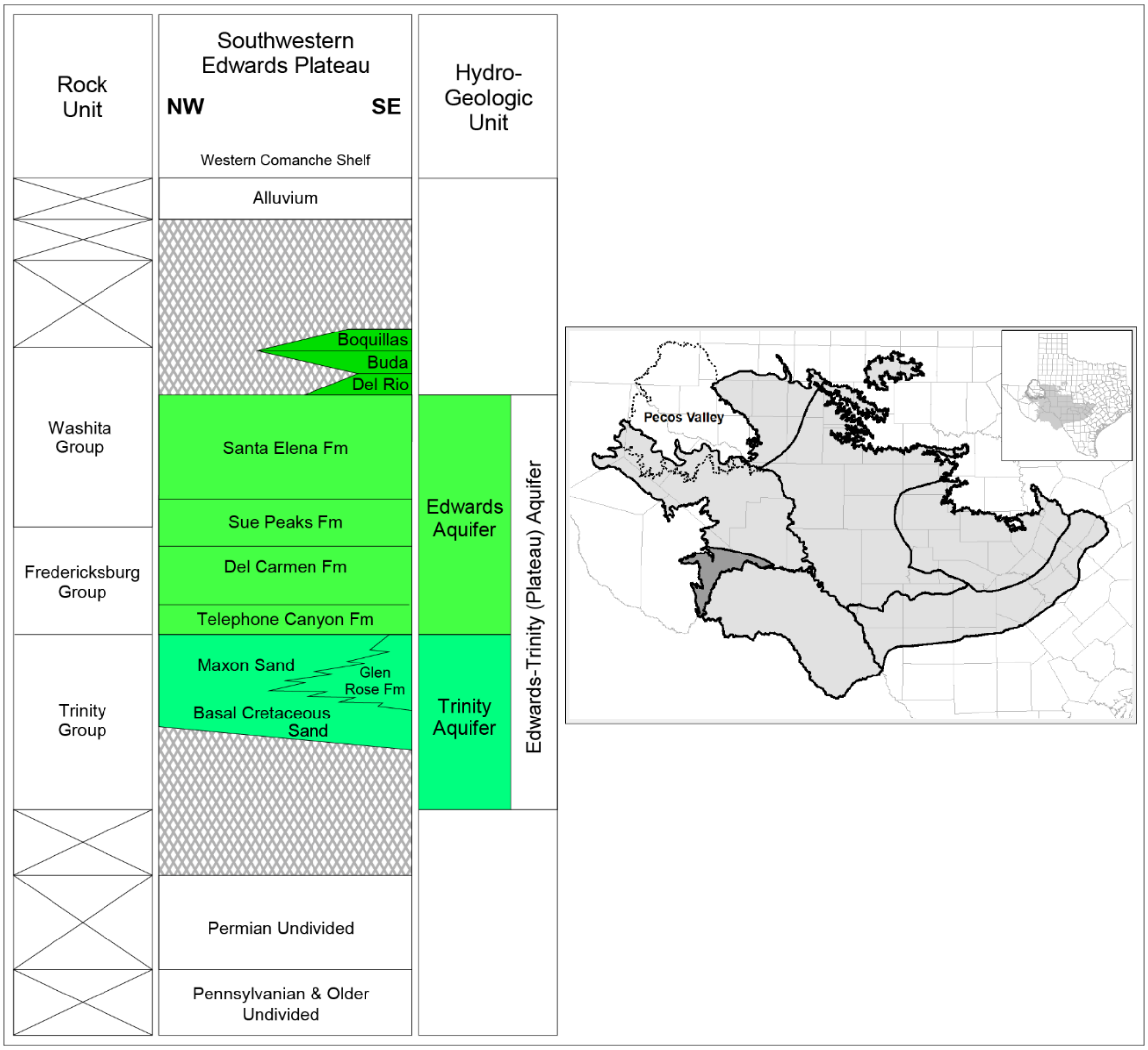


Figure 4.1-8. Hydrostratigraphy for the southewestern Edwards Plateau and Big Bend region.

4.1.7 Transboundary Edwards Plateau (Mexico)

In the Transboundary Edwards Plateau region, all three hydrostratigraphic units are present (Figure 4.1-9..) The geology is similar to the Central Edwards Plateau and Balcones regions, but with slightly different geologic names in Mexico. The younger hydrostratigraphic unit represents Upper Cretaceous ("Cretácico superior") units in the southeastern portion of the region, including the Del Rio Clay, Buda Limestone, and Boquillas Formation in the southeastern portion of the region, the San Vicente, Terlingua, and Aguja formations in the western portion of the region. In the southeastern section of this region, where these Upper Cretaceous units dip down into the subcrop, the youngest hydrostratigraphic unit also includes any overlying units from the top of the Upper Cretaceous to land surface, such as the Eagle Ford, Austin, Taylor, and Navarro groups (not shown in the stratigraphic column). Together, these act as a confining unit for the underlying Edwards hydrostratigraphic unit. In the west, Upper Cretaceous units can exist in isolated pods, but since these pieces are disconnected and largely unsaturated, we do not include them in the confining younger hydrostratigraphic unit.

The Edwards hydrostratigraphic unit represents Edwards facies similar to the Central Edwards Plateau region and the southwestern Edwards Plateau region. In the Maverick Basin area, this includes the West Nueces Formation (Fredericksburg), the McKnight Formation (Fredericksburg and Lower Washita), and the Salmon Peak Formation (Lower Washita). Within the Devils River Reef Trend, this includes the Devils River Formation (Fredericksburg and Lower Washita). In the Serrania Del Burro Arch area, this also includes the Telephone Canyon Formation (Fredericksburg), the Del Carmen Formation (Fredericksburg), the Sue Peaks Formation (upper Fredericksburg and Lower Washita) and Santa Elena Formation (Washita).

The Trinity hydrostratigraphic unit represents the Hosston Formation and its Mexican equivalent the La Mula Formation, the Sligo Formation and its Mexican equivalent the Cupido Formation, and the La Peña Formation (equivalent to the Pearsall Formation in Texas). The Glen Rose Limestone and overlying Maxon Sand are present in the Maverick Basin section in the east but grade into the La Peña Formation towards the west.

There is little available information about hydrogeology, water production and aquifer use in Mexico, so we assume it is similar to the Central Edwards Plateau region across the border. In this case, the younger hydrostratigraphic unit is assumed to act as a confining unit where it is present. Hydraulic connection between the Edwards and Trinity hydrostratigraphic units is also assumed. Underlying Paleozoic rocks provide a relatively impermeable base for the Trinity hydrostratigraphic unit, making hydraulic connection unlikely between the Trinity and underlying units.

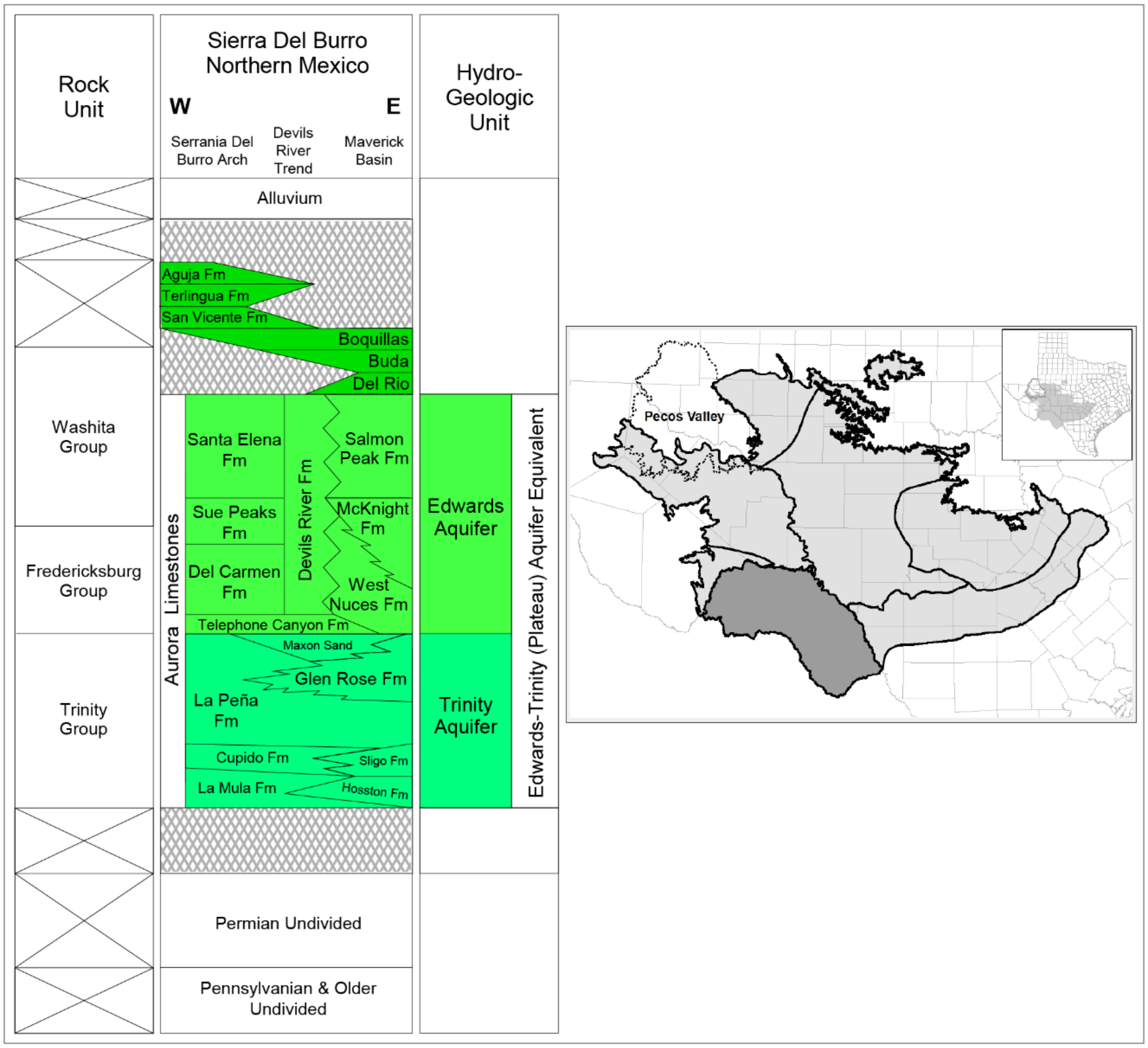


Figure 4.1-9. Hydrostratigraphy for the transboundary Edwards Plateau equivalent units within Mexico region.

4.2 Structural Framework

We have condensed the geology discussed in the previous section into three simplified layers. The following subsections discuss how we defined these layers, created elevation surfaces, and calculated thicknesses.

4.2.1 Pecos Valley Aquifer and other shallow units

The top layer (Layer 1) represents different geologic formations in different areas of the study area. In the northwestern portion of the study area, Layer 1 represents the Pecos Valley Aquifer and the Ogallala Aquifer. In the southeastern portion of the study area, Layer 1 represents younger shallow geologic formations that overlie the Edwards and Trinity formations and is conceptualized to act as a confining unit. Layer 1 does not exist in the rest of the study area, as these areas correspond either with outcrops where older rocks like the Edwards or Trinity formations are at land surface or with areas where overlying shallow formations are not conceptualized to act as a confining unit.

The top of Layer 1 is equivalent to land surface as defined by the National Elevation Dataset (U.S. Geological Survey, 2014) 30-meter resolution Digital Elevation Model (Figure 4.2-1). In the area corresponding to the spatial extent of the Pecos Valley Aquifer, the bottom of Layer 1 (Figure 4.2-2) is based on the Pecos Valley Aquifer surfaces created by the TWDB's Brackish Resources Aquifer Characterization System (BRACS) program (Meyer and others, 2012). The bottom of Layer 1 in this area is equal to the Meyers and others (2012) Pecos Valley Aquifer thickness raster subtracted from the top of Layer 1 (land surface). Any gaps were filled between the official extents of the Pecos Valley and Edwards-Trinity (Plateau) aquifers by extrapolating the Meyer and others (2012) surface using the *Topo to Raster* tool in ArcGIS Pro.

In the area corresponding to the spatial extent of the Ogallala Aquifer, the bottom of Layer 1 (Figure 4.2-2) is based on the Ogallala surfaces created as part of the High Plains Aquifer System Groundwater Availability Model (Deeds and others, 2015). The bottom of Layer 1 in this area is equal to the Deeds and others (2015) Ogallala thickness raster subtracted from the top of Layer 1 (land surface).

In the southeastern portion of the study area, Layer 1 represents Upper Cretaceous and other younger units such as the Del Rio Clay, Buda Limestone, Eagle Ford Group, Austin Group, and Anacocho Limestone that overlie the Edwards and Trinity hydrostratigraphic units. These units were conceptualized to potentially act as a confining unit for the underlying Edwards and Trinity hydrostratigraphic units. In Texas, Layer 1 extends from the southern edge of the Edwards (Balcones Fault Zone) Aquifer outcrop and the Edwards-Trinity (Plateau) Aquifer outcrop to the southeastern boundary of the study area. In Mexico, Layer 1 extends from the approximate western edge of the Upper Cretaceous outcrop provided by the Instituto Nacional de Estadistica y Geografia geologic maps (1982a; 1982b; 1982c; 1982d) to the southeastern boundary of the study area. The bottom of Layer 1 (Figure 4.2-2) in the southeastern portion of the study area is equivalent to the top of Layer 2, as defined in the following section.

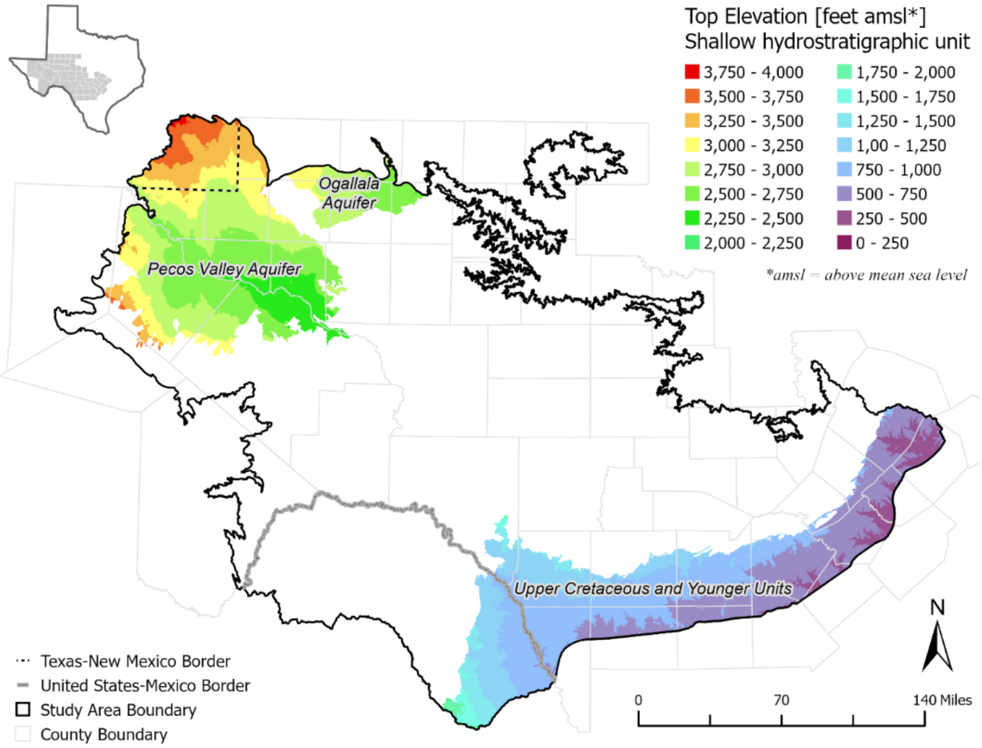


Figure 4.2-1. Elevation of the top of the shallow hydrostratigraphic unit (Layer 1).

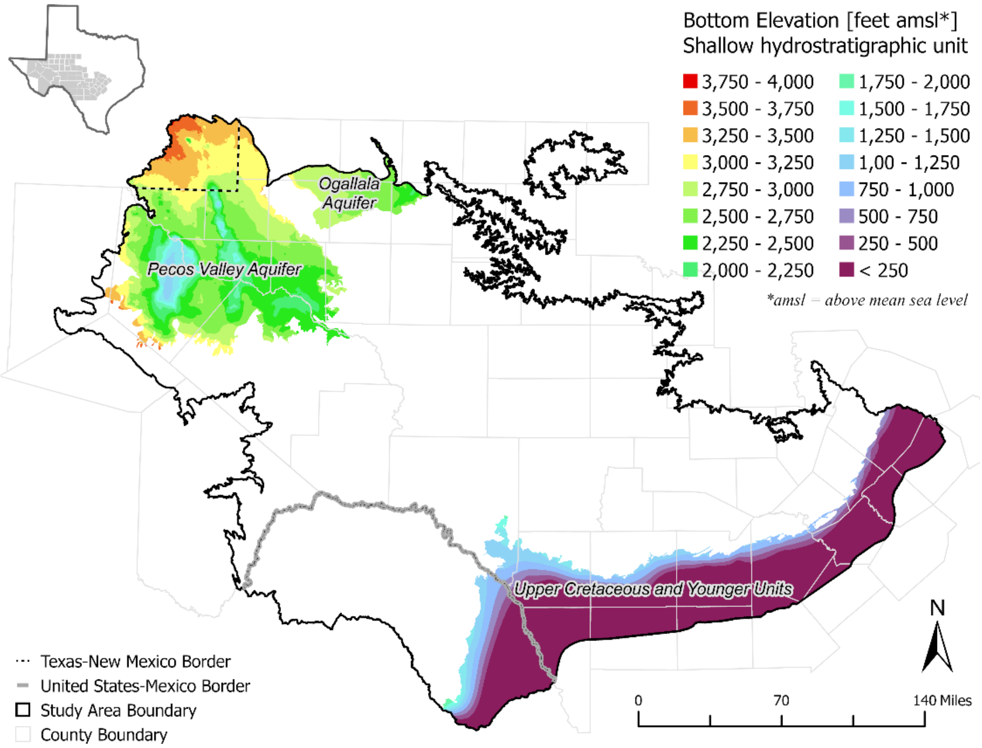


Figure 4.2-2. Elevation of the bottom of the shallow hydrostratigraphic unit (Layer 1).

Thickness

Figure 4.2-3 shows the thickness of Layer 1. In the area representing the Pecos Valley and Ogallala Aquifers, the thickness is equivalent to the thickness rasters in the source datasets described above. In the subcrop area in the southeastern portion of the study area, the thickness is equal to the top of Layer 2 (defined in Section 4.2.2 following section) subtracted from the top of Layer 1 (land surface).

In the portion of Layer 1 representing the Pecos Valley Aquifer, the median thickness is 119 feet. The largest thickness values (over 1,500 feet) occur in the center of two basins known as the Pecos Trough in Pecos and Loving counties and the Monument Draw Trough in Winkler and Ward counties. The smallest thickness values (near zero) occur along the edges of the aquifer and along a ridge of Dockum Formation that separates the Pecos and Monument Draw troughs. In the portion of Layer 1 representing the Ogallala Aquifer, thickness ranges from near zero to over 400 feet, with a median thickness of about 100 feet. In the portion of Layer 1 representing Upper Cretaceous and younger units, thickness ranges from near zero to over 4,500 feet with a median thickness of about 1,400 feet. Thickness increases consistently with distance from the boundary with the Edwards hydrostratigraphic unit towards the southeast boundary of the study area.

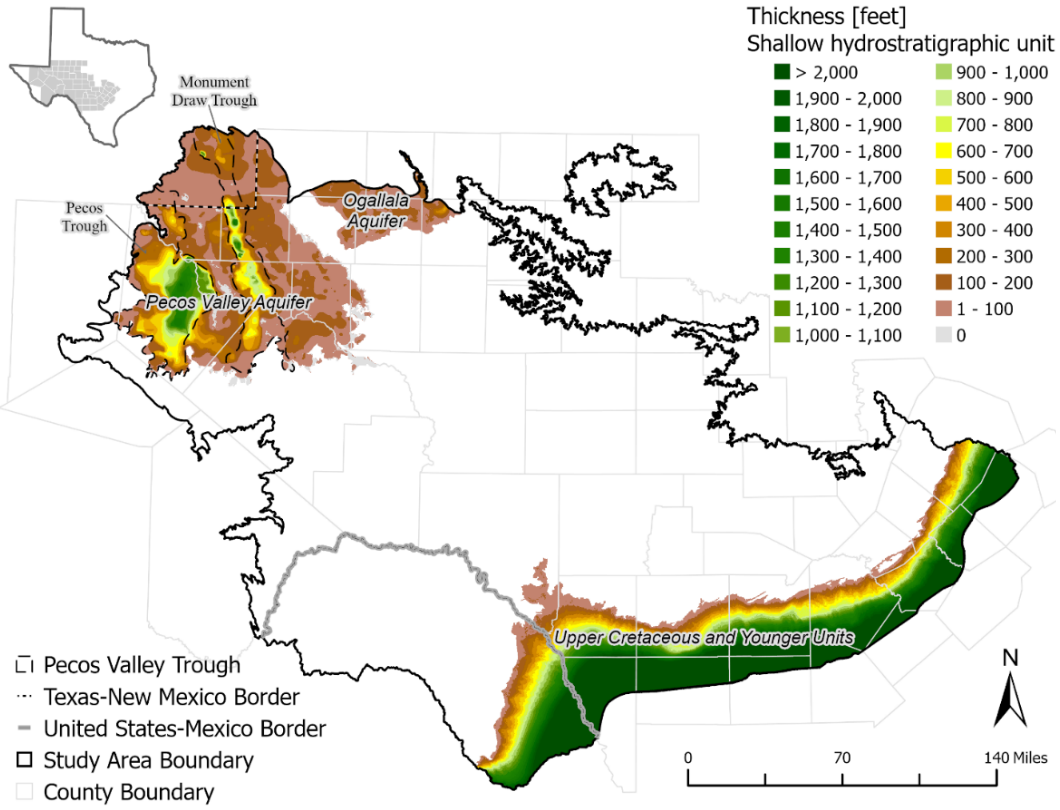


Figure 4.2-3. Thickness of the shallow hydrostratigraphic unit (Layer 1).

4.2.2 Edwards hydrostratigraphic unit

The middle layer (Layer 2) represents the Edwards hydrostratigraphic unit. In the southeastern portion of the study area, Layer 2 represents the Edwards (Balcones Fault Zone) Aquifer and equivalent downdip units. In the remainder of the study area, the layer represents the Edwards hydrostratigraphic unit within the Edwards-Trinity (Plateau) Aquifer in Texas and the equivalent units in Mexico.

Extent of Outcrop

In the area corresponding to the Edwards (Balcones Fault Zone) Aquifer, the outcrop of Layer 2 coincides with the extent of the Edwards (Balcones Fault Zone) Aquifer outcrop. In the remainder of the study area in Texas, the outcrop of Layer 2 is equivalent to the Edwards-Trinity (Plateau) Aquifer outcrop except where Layer 2 does not exist (where Layer 3 outcrops instead, as defined in Section 4.2.3). In the portion of the study area within Mexico, the outcrop of Layer 2 is equivalent to the extent of the study area except where Layer 2 does not exist (where Layer 3 outcrops instead, as defined in Section 4.2.3). Figure 4.2-4 shows the comparison between the surface geology and the simplified extent of the Edwards hydrostratigraphic unit outcrop.

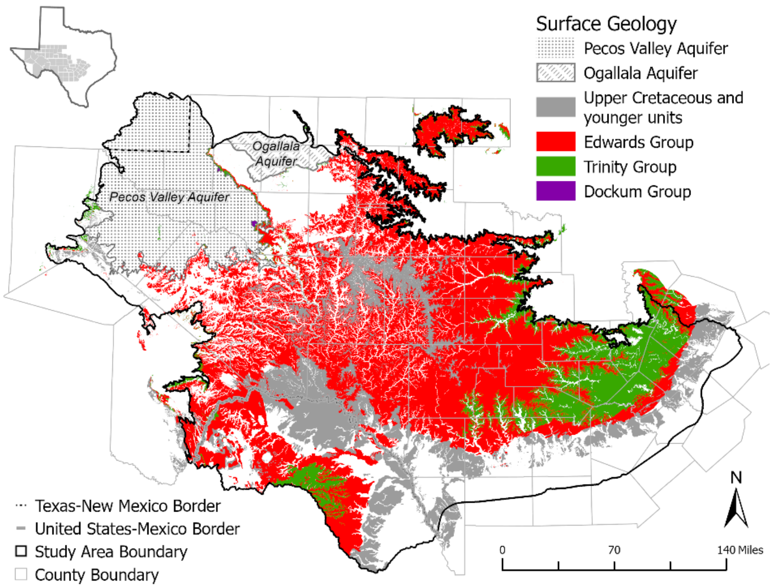
Within the extent of the Edwards-Trinity (Plateau) Aquifer, several Upper Cretaceous units exist as erosional remnants capping formations of the Edwards and Trinity Groups. Since these remnants are discontinuous, thin, and largely unsaturated, we did not include these formations as a separate layer but combined them into the simplified Layer 2. For this reason, please note that the *Edwards* hydrostratigraphic unit (Layer 2) referred to in this report can actually include some *non-Edwards* geologic units, as shown in Figure 4.2-4. This is consistent with the current mapping of the Edwards-Trinity (Plateau) Aquifer as well as with the approach used in the previous groundwater availability model (Anaya and Jones, 2009). In Mexico, all units were included from the top of the Edwards Group geologic units to land surface into Layer 2. As in Texas, this includes several Upper Cretaceous ("Cretácico superior") outcrops that exist as erosional remnants capping Edwards and Trinity units but also includes several large alluvial units. We considered this an acceptable simplification for the current analysis, as the study does not intend to use this model to provide comprehensive groundwater flow information in Mexico. However, readers interested in groundwater flow conditions in Mexico should be aware of these simplifications and interpret the current analysis accordingly.

Extent of Subcrop

In the area underneath the Pecos Valley Aquifer, the extent of the Layer 2 subcrop is equivalent to the extent of the Edwards-Trinity (Plateau) Aquifer created by the TWDB's Brackish Resources Aquifer Characterization System program (Meyer and others, 2012), though we did remove some discontinuous remnants or "islands". Please note that while this extent does not coincide with the official extent of the subcrop of the Edwards-Trinity (Plateau) Aquifer (see Figure 4.2-4), it does represent the most up-to-date TWDB interpretation of the extent of this unit.

In the area underneath the Ogallala Aquifer, the extent of the Layer 2 subcrop is equivalent to the extent of the Ogallala Aquifer. In the southeastern section of the model, the extent of the Layer 2 subcrop coincides with the extent of Layer 1 as described in the previous section.

(A)



(B)

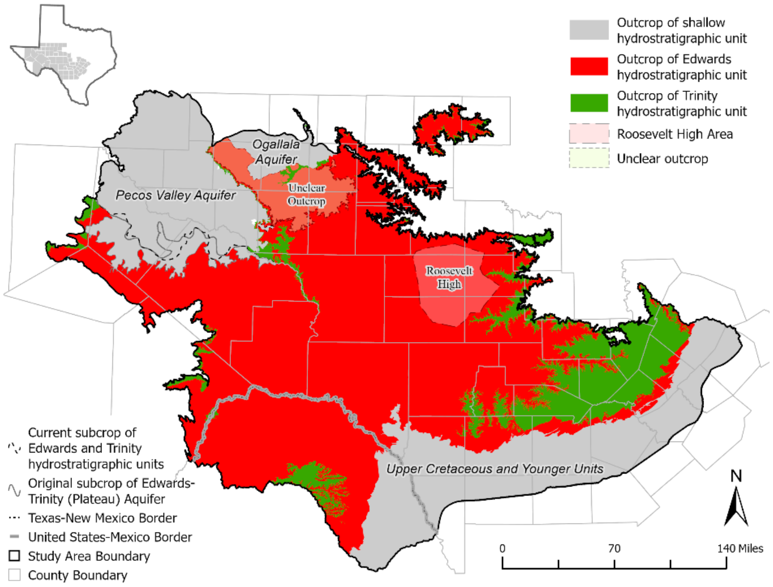


Figure 4.2-4. (A) Surface geology and (B) extents of corresponding hydrostratigraphic units.

Top Elevation

Figure 4.2-5 provides the top elevation of Layer 2. In the outcrop area of Layer 2, the top of Layer 2 is equivalent to land surface as defined by the National Elevation Dataset 30-meter resolution Digital Elevation Model. In the subcrop areas underlying the Pecos Valley and Ogallala aquifers, the top of Layer 2 is equivalent to the bottom of Layer 1, as defined in the previous section. These surfaces are represented by contour lines in Figure 4.2-5. In the subcrop area in the southeastern portion of the study area, we compiled a set of control points for the top of Layer 2, shown as dark gray dots (*Edwards Top Control Point*) in Figure 4.2-5. The Layer 2 top control points include:

- Stratigraphic picks representing the top of the Georgetown Formation from the Barton Springs Edwards Aquifer Conservation District, (Barton Springs/Edwards Aquifer Conservation District, 2020);
- Contours representing the top of the Georgetown Formation, derived from a United States Geological Survey model of the Edwards Aquifer (Brakefield and others, 2015); and
- Stratigraphic picks representing either the top of the Georgetown Formation or the bottom of the Del Rio Clay from the TWDB Brackish Resources Aquifer Characterization System database (TWDB, 2021b).

Additional control points were also used to enforce boundaries, provide control in areas of sparse to no data, and to smooth the transitions at boundaries between the outcrop at land surface and the interpolated subcrop surface. These boundary control points, shown as white squares (*Boundary Control Point*) in Figure 4.2-5, include:

- Points along the southern boundary of the Edwards (Balcones Fault Zone) Aquifer outcrop with an elevation equal to the National Elevation Dataset 30-meter resolution Digital Elevation Model (to avoid elevation jumps at the edge of the outcrop); and
- Contours representing the depositional shape of Buda Limestone in Mexico, georeferenced from Smith and others (2000) and set equal to estimated elevation values for the top of Layer 2 (to enforce drainage to the Rio Grande from Layer 2 in Mexico).

The Layer 2 control points and the boundary control points were interpolated using the *Topo To Raster* tool in ArcGIS Pro. Faults are from the TWDB Brackish Resources Aquifer Characterization System map of the Hill Country portion of the Trinity Aquifer (Robinson and others, in review) and implemented as “Cliffs” in the interpolation tool. The final Layer 2 surface is equivalent to this interpolated surface, with the following corrections to avoid inversions: in the outcrop, the Layer 2 surface is corrected to the National Elevation Dataset 30-meter resolution Digital Elevation Model values; in the subcrop under the Pecos Valley and Ogallala aquifers, the Layer 2 surface is corrected to the values of the bottom of Layer 1 (defined in Section 4.2.1).

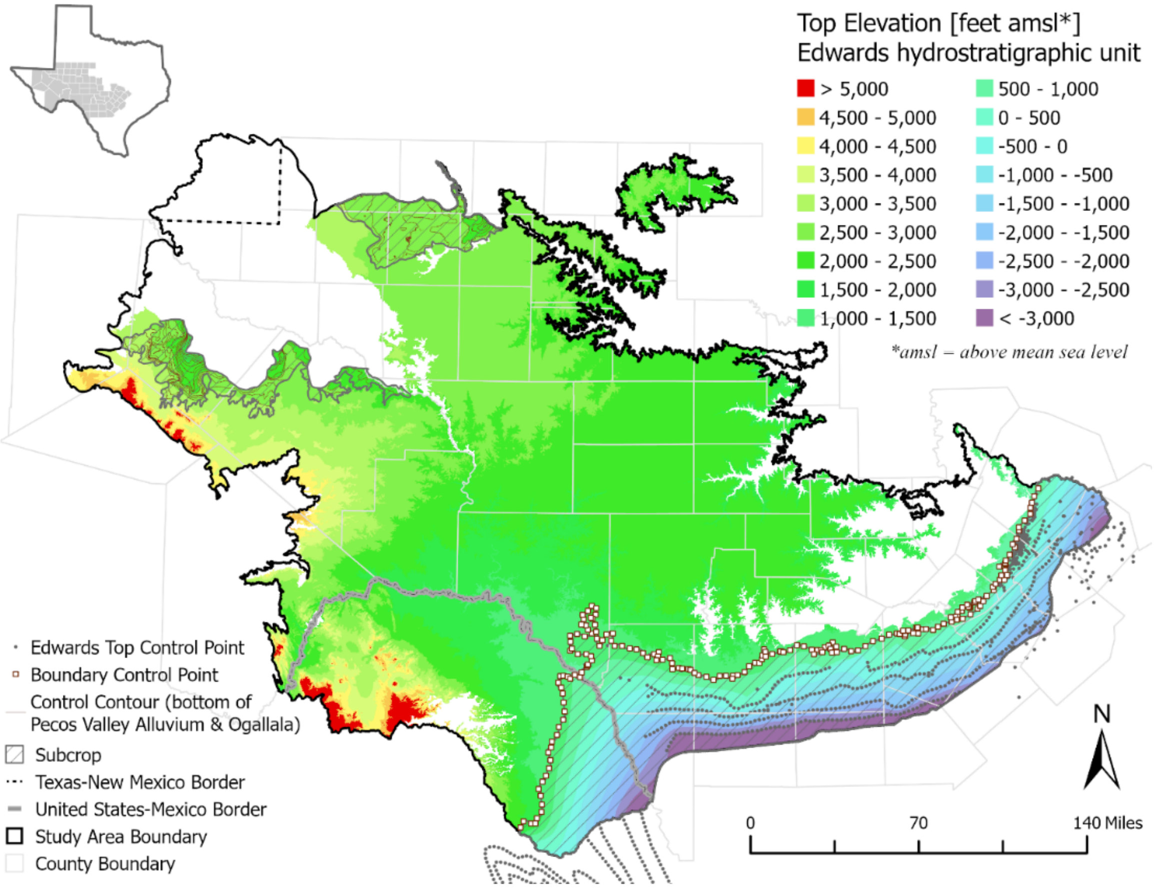


Figure 4.2-5. Elevation of the top of the Edwards hydrostratigraphic unit (Layer 2).

Thickness

Figure 4.2-6 shows the thickness of Layer 2. Thickness was calculated by subtracting the top of Layer 3 (defined in Section 4.2.3) from the top of Layer 2. In the portion of Layer 2 representing the Edwards-Trinity (Plateau) Aquifer and equivalent units in Mexico, thickness ranges from near zero to over 5,500 feet with a median thickness of 346 feet. The thickest portions correspond to mountainous areas along the western boundary of the study area and in Mexico. Combining overlying sediments into Layer 2 resulted in large thickness values in these areas. The thickness also consistently increases downdip from the Rio Grande towards the southernmost boundary of the study area in Mexico. In the subcrop underneath the Ogallala Aquifer, there is a section of zero thickness that we assumed represents an area where the Edwards hydrostratigraphic unit has been eroded away. In the portion of Layer 2 representing the Edwards (Balcones Fault Zone) Aquifer, thickness ranges from near zero to over 1,800 feet with a median thickness of 610 feet. Due to the highly faulted nature of this region, there is not a consistent trend downdip from the outcrop towards the southeast boundary of the study area.

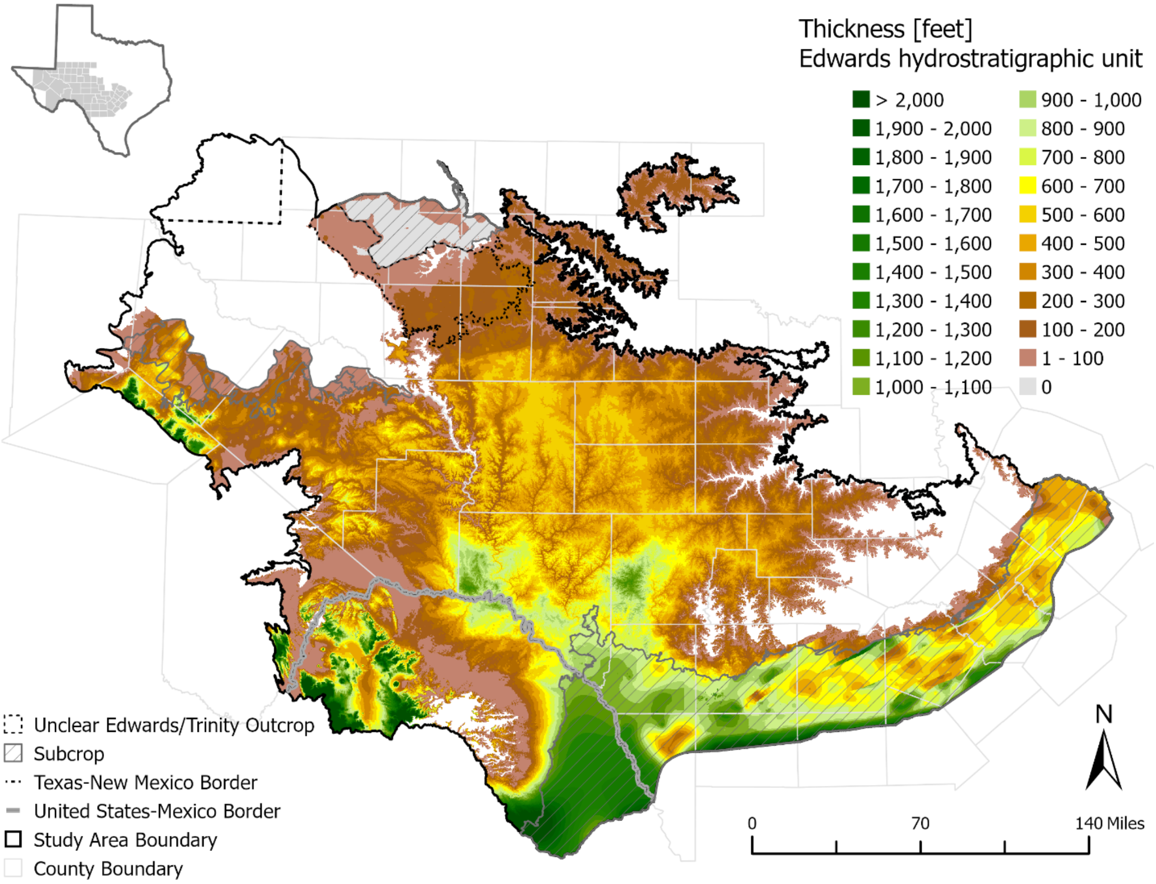


Figure 4.2-6. Thickness of the Edwards hydrostratigraphic unit (Layer 2).

4.2.3 Trinity hydrostratigraphic unit

The bottom layer (Layer 3) represents the Trinity hydrostratigraphic unit. In the eastern portion of the study area, Layer 3 represents the Hill Country portion of the Trinity Aquifer and equivalent downdip units. In the remainder of the study area, the layer represents the Trinity hydrostratigraphic unit within the Edwards-Trinity (Plateau) Aquifer in Texas and the equivalent units in Mexico.

Extent of outcrop

In the area corresponding to the Hill Country portion of the Trinity Aquifer, the extent of the Layer 3 outcrop is equivalent to the outcrop of the Hill Country portion of the Trinity Aquifer. In the remainder of the study area in Texas, the extent of the Layer 3 outcrop is equivalent to the extent of the Trinity surface outcrops in the Geologic Atlas of Texas. In Mexico, the extent of the Layer 3 outcrop is equivalent to the extent of the Glen Rose Formation outcrop, georeferenced from Smith (1970). Figure 4.2-4 shows the comparison between the surface geology and the simplified extent of the Trinity hydrostratigraphic unit outcrop.

Extent of Subcrop

The extent of the Layer 3 subcrop is equivalent to the extent of Layer 2. The exception is a small area in eastern Schleicher, western Menard, northeastern Sutton, and northwestern Kimble counties, where the Layer 3 does not exist. These gaps are consistent with gaps in the "Roosevelt High" area of the Trinity hydrostratigraphic unit in Anaya and Jones (2009). In this area, a Permian ridge creates a localized structural high that creates an extremely thin or nonexistent Trinity hydrostratigraphic unit. Figure 4.2-4(B) shows this area as a dashed line.

Top Elevation

Figure 4.2-7 provides the top elevation of Layer 3. In the outcrop area, the top of Layer 3 is equivalent to land surface as defined by the National Elevation Dataset 30-meter resolution Digital Elevation Model. In the subcrop area elsewhere in the study area, we compiled a set of control points for the top of Layer 3, shown as dark gray dots (*Trinity Top Control Point*) in Figure 4.2-7. The Layer 3 top control points include:

- Stratigraphic picks representing the top of the Trinity Group, from the Barton Springs Edwards Aquifer Conservation District, (Barton Springs/Edwards Aquifer Conservation District, 2020);
- Stratigraphic picks representing the top of the Glen Rose Formation, from the Hill Country Underground Water Conservation District, (Hill Country Underground Water Conservation District, 2020);
- Stratigraphic picks representing the top of the Trinity Group, from the TWDB Brackish Resources Aquifer Characterization System database (TWDB, 2021b);
- Stratigraphic picks representing the top of the "Trinity layer" from the U.S. Geological Survey model of the Edwards-Trinity Aquifer in Pecos County (Bumgarner and others, 2012);
- Stratigraphic picks representing the top of the Trinity group, from TWDB Brackish Resources Aquifer Characterization System project mapping the Hill Country portion of the Trinity Aquifer (Robinson and others, in review);
- Stratigraphic picks representing the top of the Trinity Group, from Walker (1979);
- Contours representing "the top of the Trinity strata and base of Fredericksburg strata," georeferenced from Barker and Ardis (1996); and
- Contours representing the land surface elevation in the outcrop of the Glen Rose Formation in Mexico, georeferenced from Smith (1970).

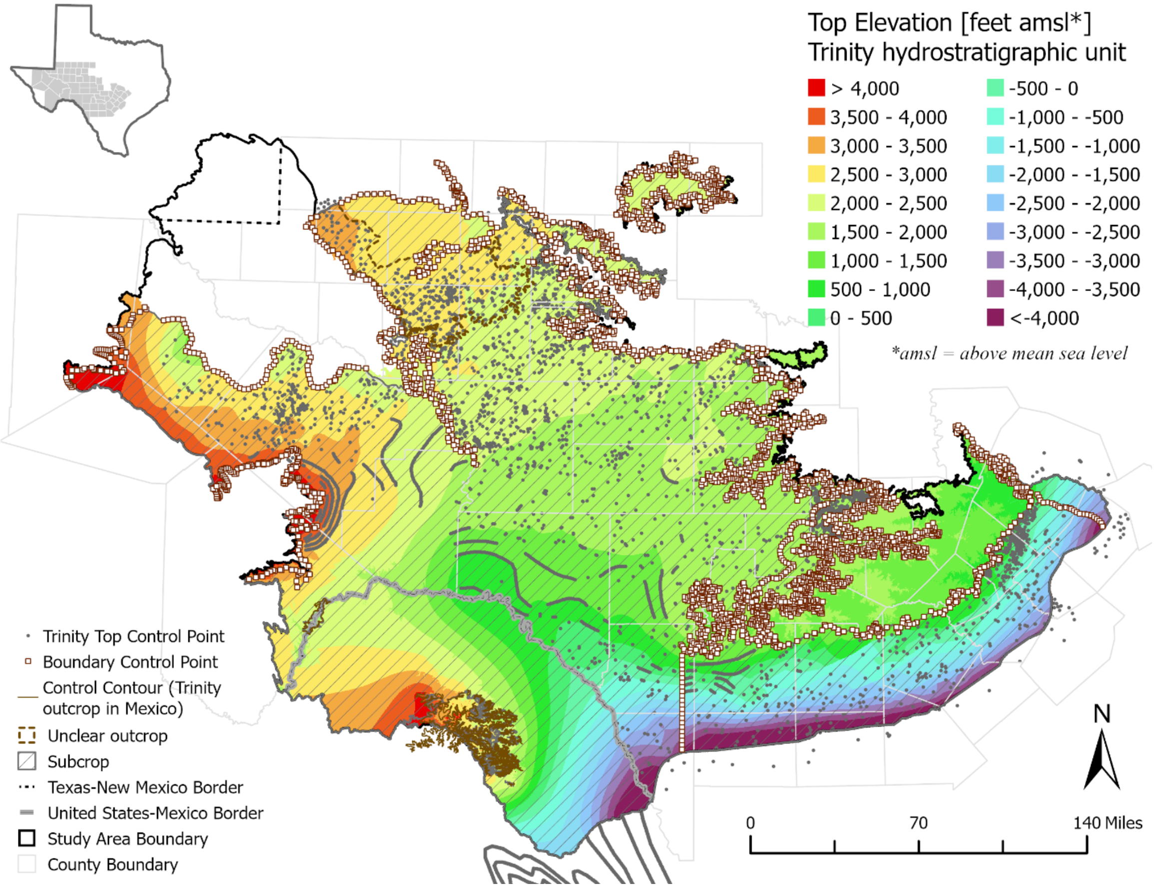


Figure 4.2-7 Elevation of the top of the Trinity hydrostratigraphic unit (Layer 3).

Additional control points were also used to enforce boundaries, provide control in areas of sparse to no data, and to smooth the transitions at boundaries between different regions. These boundary control points, shown as white squares (*Boundary Control Point*) in Figure 4.2-7, include:

- Points along the northern boundary of the Edwards-Trinity (Plateau) Aquifer subcrop under the Pecos Valley Aquifer, set equal to 10 feet below the bottom elevation of Layer 1 (to enforce a pinch-out at the aquifer boundary);
- Points along the northern boundary of the Edwards-Trinity (Plateau) Aquifer subcrop under the Ogallala Aquifer, set equal to 10 feet below the bottom elevation of Layer 1 (to enforce a pinch-out at the aquifer boundary);
- Points along the boundary between the outcrop of Layer 2 and the outcrop of Layer 3 and between the outcrop of Layer 1 (in the Ogallala Aquifer area) and the outcrop of Layer 3, set to the National Elevation Dataset 30-meter resolution Digital Elevation Model (to smooth the transition from outcrop to subcrop);
- Points along the western boundary corresponding to outcrops of older Pennsylvanian and Permian-age units, as defined by the Geologic Atlas of Texas, set

equal to 10 feet below the National Elevation Dataset 30-meter resolution Digital Elevation Model (to enforce a pinch-out at the aquifer boundary);

- Points along the Robinson and others (in review) boundary of the Hill Country portion of the Trinity Aquifer (to smooth the transition between Plateau and Hill Country region); and
- Contours representing the depositional shape of Buda Limestone in Mexico, georeferenced from Smith and others (2000) and set equal to estimated elevation values for the top of Layer 3 (to enforce drainage to the Rio Grande from Layer 3 in Mexico).

The Layer 3 top control points and the boundary control points were interpolated using the *Topo To Raster* tool in ArcGIS Pro. Faults are from the TWDB Brackish Resources Aquifer Characterization System map of the Hill Country portion of the Trinity Aquifer (Robinson and others, in review) and implemented as "Cliffs" in the interpolation tool. The final Layer 3 top surface is equivalent to this interpolated surface, with the following corrections to avoid inversions. In the outcrop, the surface is corrected to the values of the National Elevation Dataset 30-meter resolution Digital Elevation Model. In the area corresponding to the Robinson and others (in review) extent, the surface is corrected to the topmost elevation of all combined Trinity subunit surfaces provided in that report.

In the majority of the study area, if the top of Layer 3 was higher than Layer 2, we corrected these inversions by assigning them a value of 10 feet below the top elevation of Layer 2. However, as shown by the Trinity outcrop along the southern edge of the Ogallala Aquifer, there are areas where streams have eroded the Edwards hydrostratigraphic unit away, exposing the Trinity hydrostratigraphic unit. In these areas, enforcing a minimum Edwards thickness is inappropriate. Unfortunately, the surface geology in this area is unhelpful for distinguishing eroded areas since the Edwards-Trinity (Plateau) Aquifer is covered by either the Ogallala Aquifer or thin eolian sediments just south of the Ogallala Aquifer. This area has been marked with a dotted line in Figure 4.2-6. Since it is unclear whether this area represents an outcrop of the Edwards or the Trinity hydrostratigraphic unit, Layer 3 inversions with Layer 2 were not corrected by enforcing a minimum thickness in this area. Instead, it was assumed that these inversions represented areas where the Edwards hydrostratigraphic unit was eroded away, so a thickness of zero was used.

Bottom Elevation

Figure 4.2-8 provides the bottom elevation of Layer 3. We compiled a set of control points for the bottom of Layer 3, shown as dark gray dots (*Trinity Bottom Control Point*) in Figure 4.2-8. The Layer 3 bottom control points include:

- Stratigraphic picks representing the base of the Trinity Group, from the Barton Springs Edwards Aquifer Conservation District, (Barton Springs/Edwards Aquifer Conservation District, 2020);

- Stratigraphic picks representing the base of the Trinity Group, from the TWDB Brackish Resources Aquifer Characterization System database (TWDB, 2021b);
- Stratigraphic picks representing the base of the "Trinity layer" from the U.S. Geological Survey model of the Edwards-Trinity Aquifer in Pecos County (Bumgarner and others, 2012);
- Stratigraphic picks representing the top of the Lipan Aquifer below the Edwards-Trinity (Plateau) Aquifer, from TWDB Brackish Resources Aquifer Characterization System project mapping the Lipan Aquifer (Robinson and others, 2018);
- Stratigraphic picks representing the base of the Trinity Group, from the TWDB Brackish Resources Aquifer Characterization System mapping project for the Hill Country portion of the Trinity Aquifer (Robinson and others, in review);
- Stratigraphic picks representing the bottom of the Edwards-Trinity (Plateau) Aquifer, from the groundwater availability model for the High Plains Aquifer System (Deeds and others, 2015);
- Stratigraphic picks representing the base of "Cretaceous aquifers," from the groundwater availability model for the minor aquifers of the Llano Uplift region (Shi and others, 2016); and
- Contours representing "base of the Edwards-Trinity Aquifer," georeferenced from Barker and Ardis (1992).

Additional control points were used to enforce boundaries, provide control in areas of sparse to no data, and to smooth the transitions at boundaries between different regions. These boundary control points, shown as white squares (*Boundary Control Point*) in Figure 4.2-8, include:

- Points along the northern boundary of the Edwards-Trinity (Plateau) Aquifer subcrop under the Pecos Valley Aquifer, set equal to 20 feet below the bottom elevation of Layer 1 (to enforce a pinch-out at the aquifer boundary);
- Points along the northern boundary of the Edwards-Trinity (Plateau) Aquifer subcrop under the Ogallala Aquifer, set equal to 20 feet below the bottom elevation of Layer 1 (to enforce a pinch-out at the aquifer boundary);
- Points along the western boundary corresponding to outcrops of older Pennsylvanian and Permian-age units, as mapped by the Geologic Atlas of Texas, set equal to 20 feet below the National Elevation Dataset 30-meter resolution Digital Elevation Model (to enforce a pinch-out at the aquifer boundary);
- Points along the Robinson and others (in review) boundary of the Hill Country portion of the Trinity Aquifer (to smooth the transition between Plateau and Hill Country region);
- Contours representing the depositional shape of Buda Limestone in Mexico, georeferenced from Smith and others (2000) and set equal to estimated elevation values for the bottom of Layer 3 (to enforce drainage to the Rio Grande from Layer 3 in Mexico); and

- Contours representing the land surface elevation in the outcrop of the Glen Rose Formation in Mexico minus 1,500 feet, georeferenced from Smith (1970) (to enforce a reasonable thickness at the model's southern boundary).

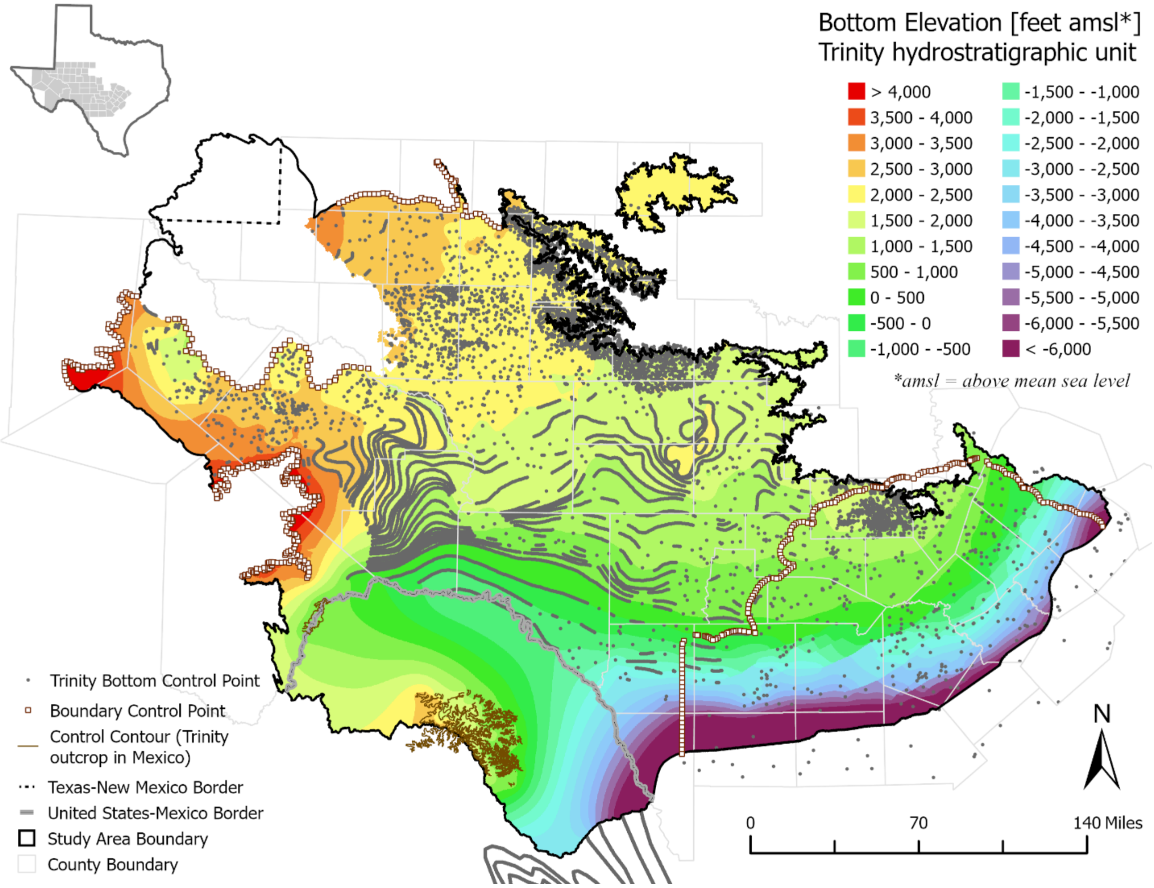


Figure 4.2-8. Elevation of the bottom of the Trinity hydrostratigraphic unit (Layer 3).

The Layer 3 bottom control points and the boundary control points were interpolated using the *Topo To Raster* tool in ArcGIS Pro. Faults are from the TWDB Brackish Resources Aquifer Characterization System map of the Hill Country portion of the Trinity Aquifer (Robinson and others, in review) and implemented as "Cliffs" in the interpolation tool. The final Layer 3 bottom surface is equivalent to this interpolated surface, with the following corrections to avoid inversions. In the area corresponding to the Robinson and others (in review) extent, the Layer 3 bottom surface is corrected to the base of Trinity raster from that report.

In the majority of the study area, if the bottom of Layer 3 was higher than the top of Layer 3, we corrected these inversions by assigning them a value of 10 feet below the top elevation of Layer 3. However, as noted earlier, the Trinity hydrostratigraphic unit is extremely thin to nonexistent in the "Roosevelt High" area in the central Plateau region.

Enforcing a minimum Trinity thickness in that area is not reasonable. We have marked this area with a dashed line in Figure 4.2-9. In this area, inversions were not corrected by enforcing a minimum thickness between the bottom and top of Layer 3. Instead, we assumed that these inversions represented areas where the Trinity hydrostratigraphic unit was absent and enforced a thickness of zero.

Thickness

Figure 4.2-9 shows the thickness of Layer 3. The thickness is equivalent to the bottom surface of Layer 3 subtracted from the top surface of Layer 3. In the portion of Layer 3 representing the Edwards-Trinity (Plateau) Aquifer and equivalent units in Mexico, the thickness ranges from near zero to over 4,700 feet with a median thickness of about 450 feet. Thickness generally increases from north to south. In the portion of Layer 3 representing the outcrop of the Hill Country portion of the Trinity Aquifer, thickness ranges from near zero to over 2,500 feet with a median thickness of about 730 feet. The thinnest sections correspond with eroded river valleys. In the portion of Layer 3 representing the subcrop of the Southern portion of the Trinity Aquifer, thickness ranges from about 75 feet to over 4,200 feet with a median thickness of about 2,040 feet. Thickness generally increases consistently with distance from the outcrop towards the southeastern boundary of the current model, with some variation in this trend due to faulting.

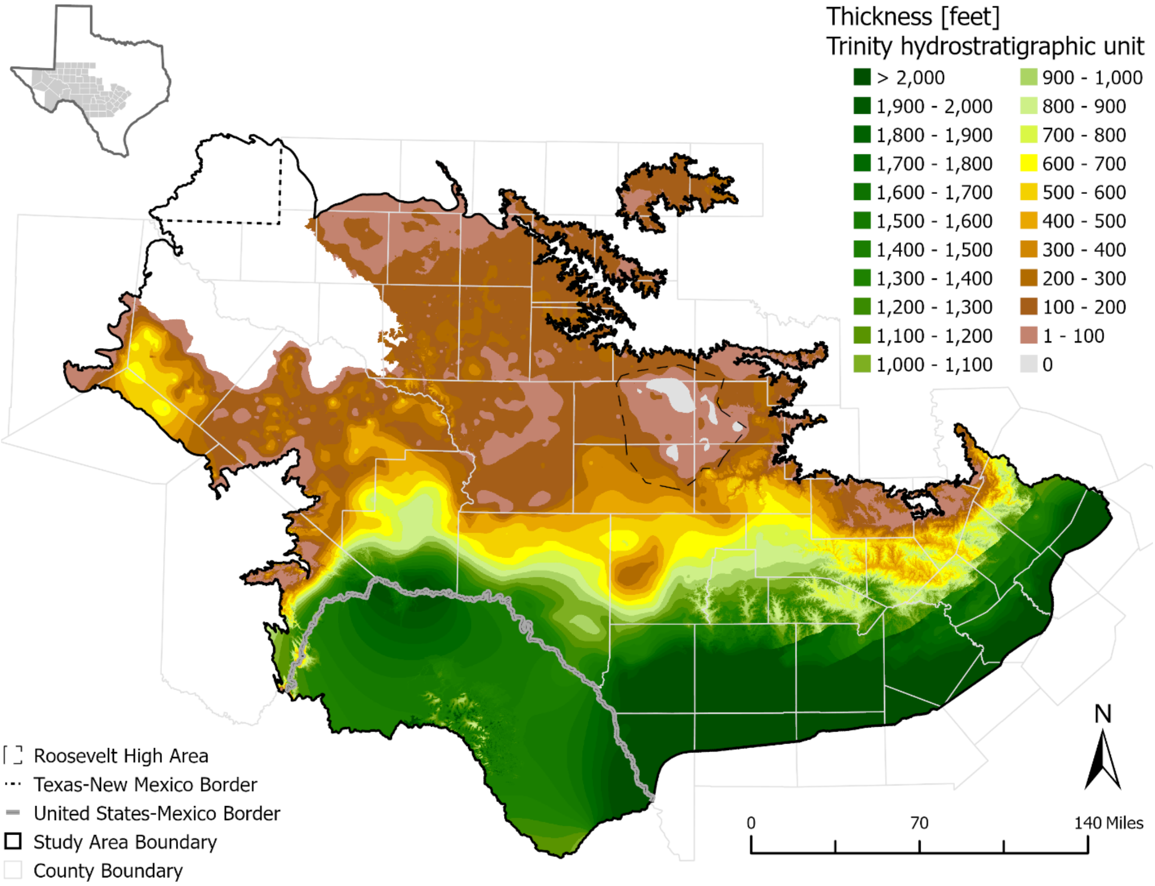


Figure 4.2-9. Thickness of the Trinity hydrostratigraphic unit (Layer 3).

4.2.4 Discussion

The surfaces described in the previous sections are meant to provide a structural framework for a regional groundwater model. Assumptions and simplifications were made while creating these surfaces, based on the goals of this proposed groundwater model. The primary focus of the proposed groundwater model is groundwater flow in the Pecos Valley and Edwards-Trinity (Plateau) aquifers. Therefore, the surfaces in those areas are the least simplified and closest to actual geology. To a lesser extent, the proposed groundwater model will include groundwater flow in the Southern portion of the Trinity Aquifer and the Edwards (Balcones Fault Zone) Aquifer. However, the focus in these areas will be groundwater communication between these units and the Edwards-Trinity (Plateau) Aquifer. For this reason, there were some significant simplifications made to these units. Most notably, we have combined the component units of the Southern portion of the Trinity Aquifer (Upper, Middle, and Lower Trinity) into one unit.

It is not the intention of this study to model groundwater flow conditions in younger units like the Ogallala Aquifer, Upper Cretaceous units, alluvial units, or the Carrizo-Wilcox Aquifer. Therefore, we drastically simplified the surfaces of these units and only include them in the context of “placeholder” units. For readers interested in groundwater flow conditions in these other aquifers, other TWDB groundwater availability models focused on those particular aquifers are recommended.

As noted previously, the interpretation of the Edwards and Trinity hydrostratigraphic units in Mexico were simplified as it is not the intention to use this model to provide comprehensive groundwater flow information in Mexico. We only include this region to account for additional flow to the Rio Grande and recharge to underlying aquifers. It is not recommended the current study to readers interested in groundwater flow conditions in Mexico.

The TWDB Brackish Resources Aquifer Characterization System team is concurrently working on an updated map of the Edwards-Trinity (Plateau) Aquifer. However, this data is still in preliminary stages and could not be incorporated into the current study. If additional data are available in time for the numerical model, we will consider updating our surfaces to incorporate new findings from that project.

4.3 Water Levels and Regional Groundwater Flow

Spatial and temporal trends in groundwater levels can help determine historical behavior of regional groundwater flow and cross-formational flow across the study area. This section discusses the sources of water-level data, estimates of historical groundwater-level contours, and analysis of cross-formational flow. We present the results of analysis by hydrostratigraphic unit (as defined in Section 4.1). The younger hydrostratigraphic unit (Layer 1), represents the Pecos Valley Aquifer, Ogallala Aquifer, and Upper Cretaceous confining units. The Edwards hydrostratigraphic unit (Layer 2) represents the Edwards (Balcones Fault Zone) Aquifer and the Edwards units within the Edwards-Trinity (Plateau) Aquifer. The Trinity hydrostratigraphic unit (Layer 3) represents the Hill Country portion of the Trinity Aquifer,the Trinity Aquifer below the Edwards (Balcones Fault Zone) Aquifer, and the Trinity units of the Edwards-Trinity (Plateau) Aquifer.

4.3.1 Assignment of hydrostratigraphic units to wells

We assigned wells to hydrostratigraphic units based on the structural framework developed in Section 4.2 and well construction information. We used well depth and screen information to determine aquifer assignments, according to the process summarized in Figure 4.3-1. Data sources for wells often use different nomenclature even for the same formations and aquifers, the standardization was necessary. In addition, the structural framework developed for this report is different from the structural framework used in previous studies of the Edwards-Trinity regional aquifer system and possibly has different aquifer surfaces used in those reports. For this reason, water-level elevations data were re-analyzed if wells had depth, screen, or open interval information available.

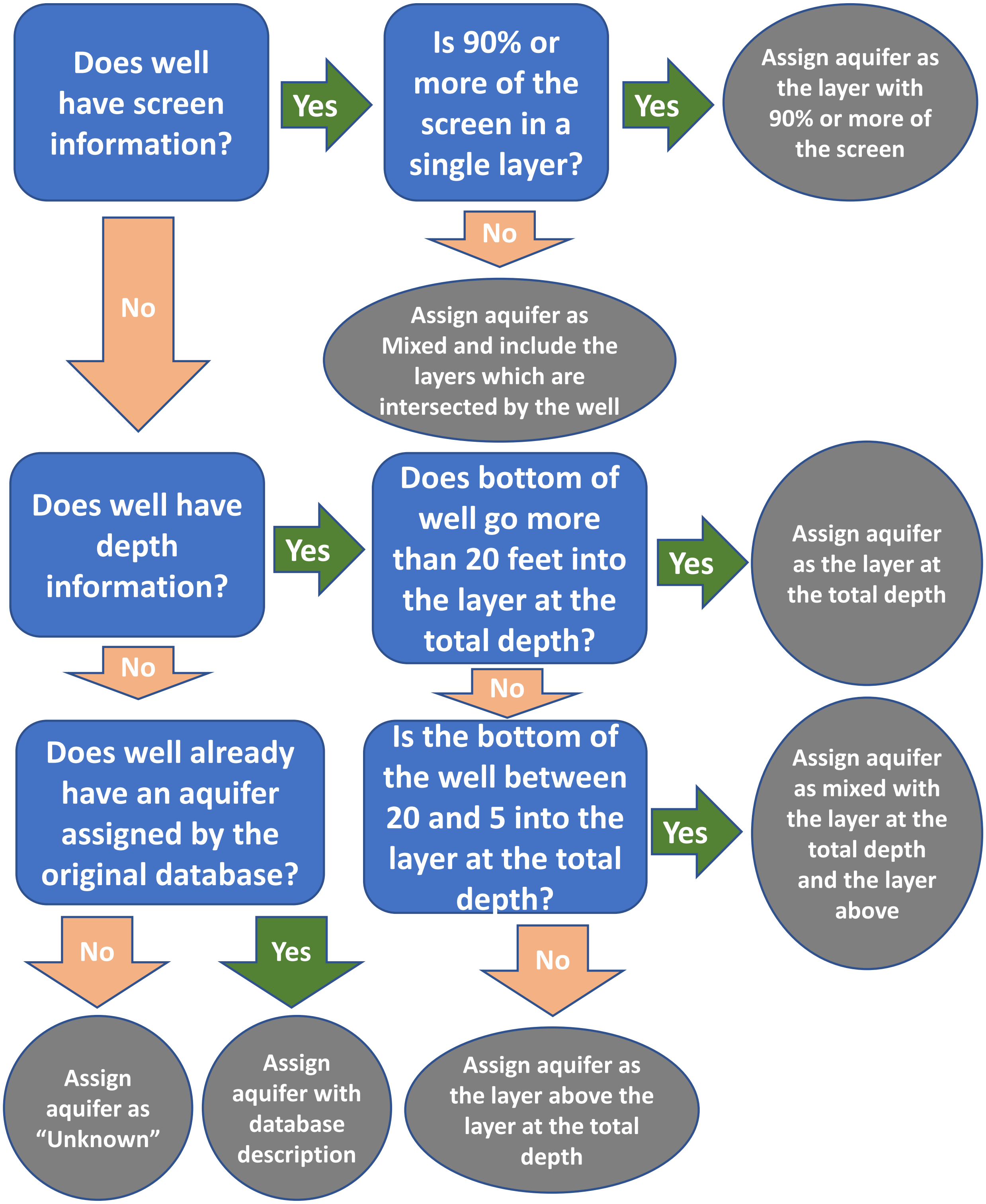


Figure 4.3-1. Aquifer assignment decision flow chart to determine which aquifer was contributing water levels to a well.

4.3.2 Water level data collection and analysis

Multiple sources for water level data were queried in the current study area. Data sources for water level measurements included:

- The "WaterLevelsMajor", "WaterLevelsMinor", "WaterLevelsCombination" and "WaterLevelsOtherUnassigned" tables in the TWDB groundwater database (TWDB, 2021c);
- The "*WellLevels*" table in the TWDB submitted drillers' report database (TWDB, 2021d);
- The "*tblBRACS_SWL*" table in the TWDB Brackish Resources Aquifer Characterization System database (TWDB, 2021b);
- The U. S. Geological Survey National Water Information System *"Historical Data"*, *"Field Measurements"*, and *"Daily Data"* databases (U.S. Geological Survey, 2021b)
- The database for the conceptual model for the Hill Country portion of the Trinity Aquifer (Toll and others, 2018);
- Water level data submitted by Barton Springs/Edwards Aquifer Conservation District (Barton Springs/Edwards Aquifer Conservation District, 2020);
- Water levels collected from groundwater resource maps in Mexico (Instituto Nacional de Estadistica y Geografia, 1982c; 1982d);
- Open data from Conagua Comision Nacional del Agua Data Abiertos (Conagua, 2021);
- The Public Water Supply database (Texas Commission of Environmental Quality, 2021); and
- Water levels used in previous models (Brakefield and others, 2015; Clark and others, 2014).

These datasets were compiled into one water level database for the current study. We only included water levels from the TWDB Groundwater Database which were assigned a "Publishable" status. There were many duplicate data points between the various data sources. The TWDB Groundwater Database was the primary source if there were conflicts or information discrepancies for the same well between different data sources. The compiled database contains sufficient information to support both the creation of the potentiometric surface maps and hydrographs shown in this report, as well as tasks that might require additional filtering in the future, such as the selection of calibration targets in the future numerical groundwater model. We also divided water level measurements into two seasons, either "Summer" or "Winter". The "Summer" is for water levels measured between the beginning of March and the end of October and "Winter" is for the measurement between the beginning of November to the end of February. In the interest of preserving all data that might be useful for developing the numerical groundwater model, the compiled database includes water levels that are not used in the analyses described below.

Potentiometric surfaces and water level elevation contours were created in all three hydrostratigraphic units for the years 1950, 1980, 2000, and 2015. We utilized the *Topo To Raster* tool in ESRI ArcMap to interpolate water level elevation data. We only used "Winter" water levels as we assumed these best represented static aquifer conditions with minimal influence from agricultural pumping. The average of the winter water levels from November 1945 through February 1955 represents the 1950 average water level surface for each hydrostratigraphic unit. As in the previous groundwater availability model of the Edwards-Trinity (Plateau) and Pecos Valley Aquifer model (Anaya and Jones, 2009), it was assumed that the year 1980 approximately represents steady-state conditions for the current study area. The average of the winter water levels from November 1975 through February 1985 represents the 1980 average water level surface for each hydrostratigraphic unit. The average of the winter water levels from November 1997 through February 2003 represents the 2000 average water level surface for each hydrostratigraphic unit . The average of the winter water levels from November 2013 to February 2017 represents the 2015 average water level surface for each hydrostratigraphic unit. We used a larger time span to average water levels in the 1950 and 1980 water level analysis to fill in some of the spatial gaps due to fewer water level measurements available for those time periods. There were enough data points available for the later water level analyses where a time span of only four winter cycles can improve spatial coverage for the 2000 and 2015 water level analyses. It should be noted that our interpolation method extends the potentiometric surface maps and contours beyond the control points to cover the entire study area for each hydrostratigraphic unit. As such, the areas closest to observed water level control points have less uncertainty and are more reliable than the areas far from the observed water level control points. Due to the difference in the spatial distribution of observed water level control points for each year, locations of less uncertainty vary by year and hydrostratigraphic unit.

Hydrographs show water level variations at a specific location through time. They are helpful for illustrating water level trends at the location of the well and surrounding area and for identifying erroneous measurements that don't represent static regional aquifer conditions—a spike caused by nearby pumping, for example. We generated representative hydrographs for each hydrostratigraphic unit using average winter water levels by year. Only the hydrographs which had a long enough history and high enough measurement frequency were considered as representative of regional water level trends.

4.3.3 Pecos Valley Aquifer and other shallow units water levels, regional flow, and trends

The Pecos Valley Aquifer, in the northwestern portion of the study area, consists of many layers of sand, silt and some coarse grained materials which accumulated during the Quaternary and Tertiary periods. These layers are exposed at the surface and the aquifer is entirely unconfined. The Pecos River divides the aquifer into two regions. Aeolian soils dominate the region north of the river while alluvium sediments dominate the region south of the river. The aquifer is thickest along two major troughs, the Monument Draw Trough and the Pecos Trough, north and south of the river, respectively.

Figure 4.3-2 through Figure 4.3-5 provide the interpolated water levels in the Pecos Valley hydrostratigraphic unit for the years 1950, 1980, 2000, and 2015 and Figure 4.3-6 provides representative hydrographs. In general, the regional groundwater flow pattern is from northwest to southeast following topography but is also strongly influenced by the Pecos River, with groundwater flowing toward the river on a local scale. High pumping rates in condensed areas can cause isolated water level drops, which are called cones of depression. Figure 4.3-3 shows cones of depression in the Pecos Trough in Reeves County and the Monument Draw Trough in Pecos County which were observed from 1960 (Jones, 2001; 2004; 2008). As of 2015, measured water levels range from a maximum of approximately 3,620 feet above mean sea level in the northernmost part of the aquifer in New Mexico to a minimum of approximately 2,290 feet above mean sea level at the intersection of Reeves, Pecos, and Ward counties (Figure 4.3-5). Hydrographs shown in Figure 4.3-6, display both shared and unique trends within the Pecos Valley Aquifer. Shared trends can be seen south of the Pecos River in Figure 4.3-6(A, F, and H) where water levels decline between the late 1950s to around the 1970s and then begin to rise sometime between the late 1960s to the late 1970s. These water-level fluctuations reflect irrigation pumping patterns in the Pecos Trough portion of the Pecos Valley Aquifer which peaked in the 1970s. On the north and west sides of the Pecos Valley Aquifer, Figure 4.3-6(C) shows that water levels remain steady or as Figure 4.3-6(B, D, and E) shows that water levels maintain a slow and steady decline. Figure 4.3-6(G) shows a steady water level from the 1960s to the mid-1970s followed by a sharp decline in the late 1970s to mid-1980s and then followed by steady water levels from the late 1980s until the late 2010s. Water level fluctuations tend to be greater south of the Pecos River and within the Pecos Trough. Water levels north of the Pecos River tend to have smaller fluctuations and are more stable as shown in Figure 4.3-6(B and C).

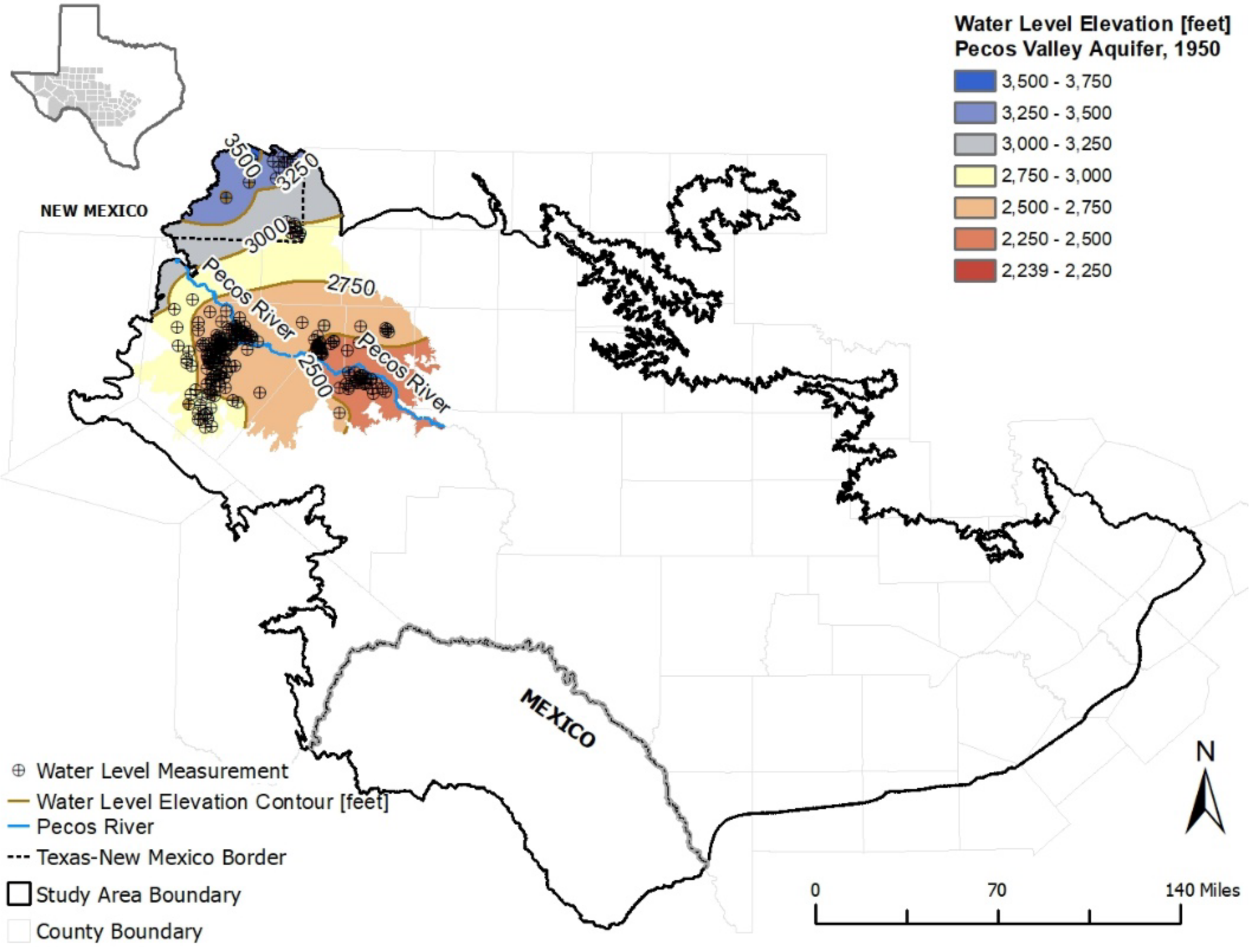


Figure 4.3-2. Interpolated potentiometric surface with contours of the Pecos Valley Aquifer for the year 1950. All elevations are reported in feet above mean sea level.

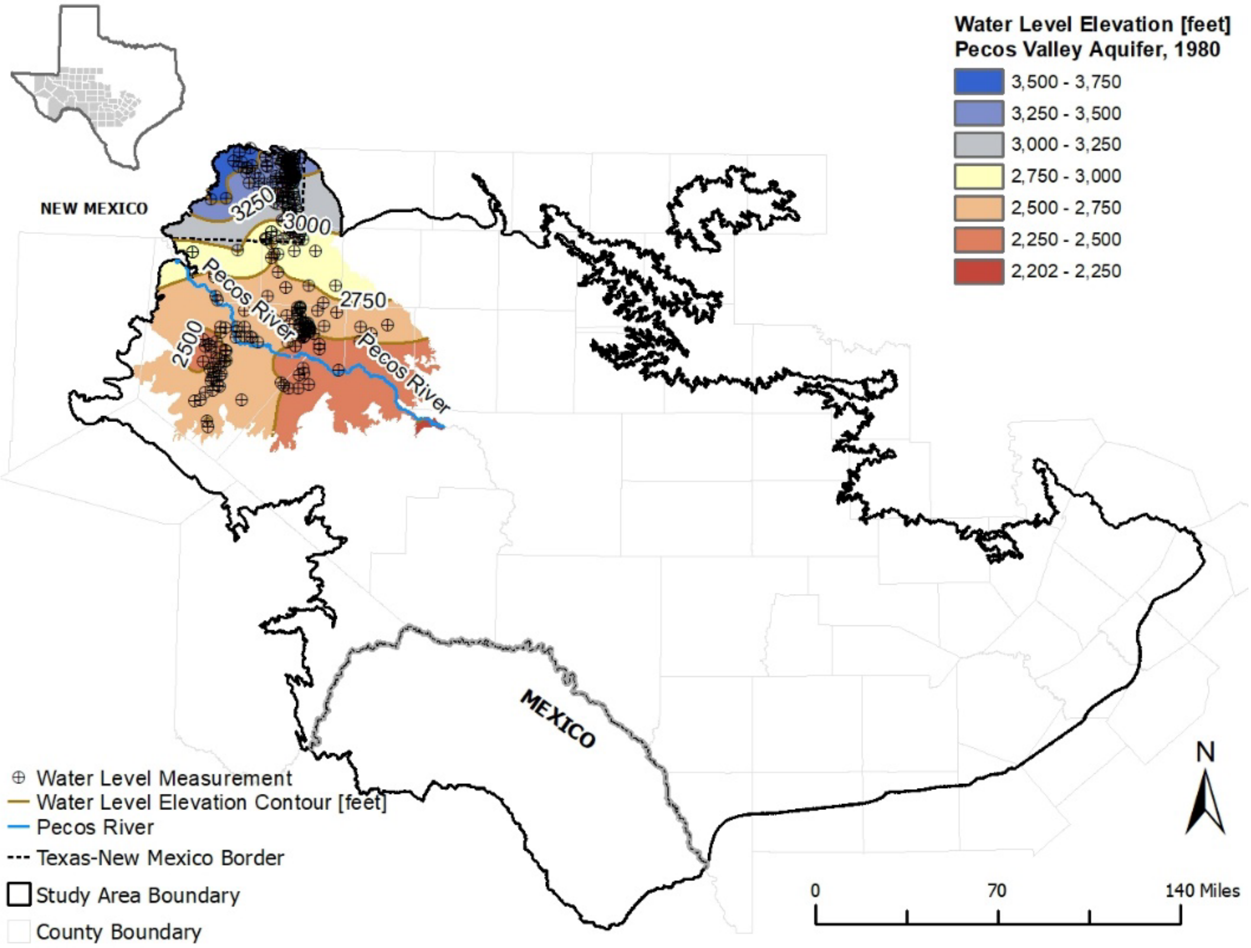


Figure 4.3-3. Interpolated potentiometric surface with contours of the Pecos Valley Aquifer for the year 1980. All elevations are reported in feet above mean sea level.

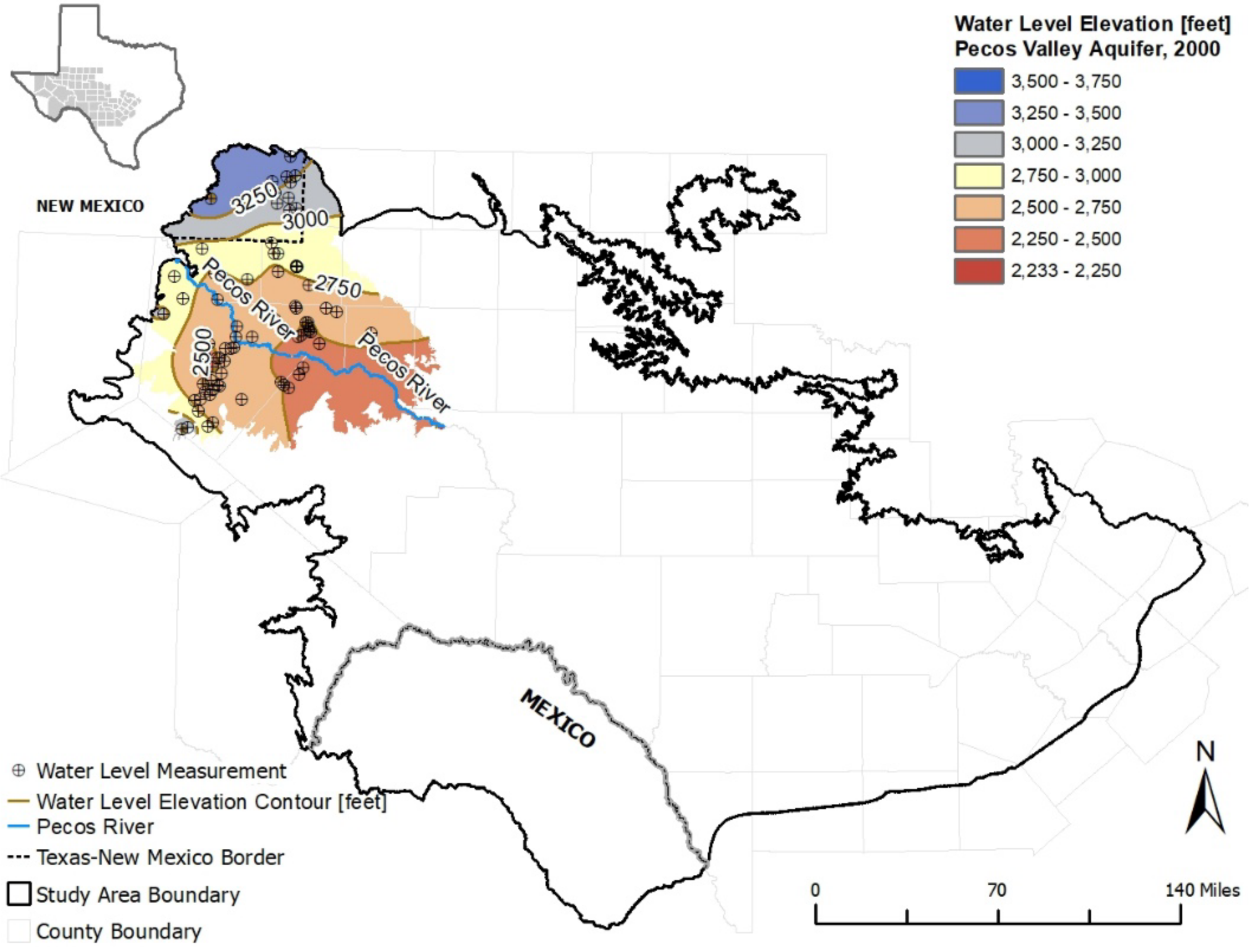


Figure 4.3-4. Interpolated potentiometric surface with contours of the Pecos Valley Aquifer for the year 2000. All elevations are reported in feet above mean sea level.

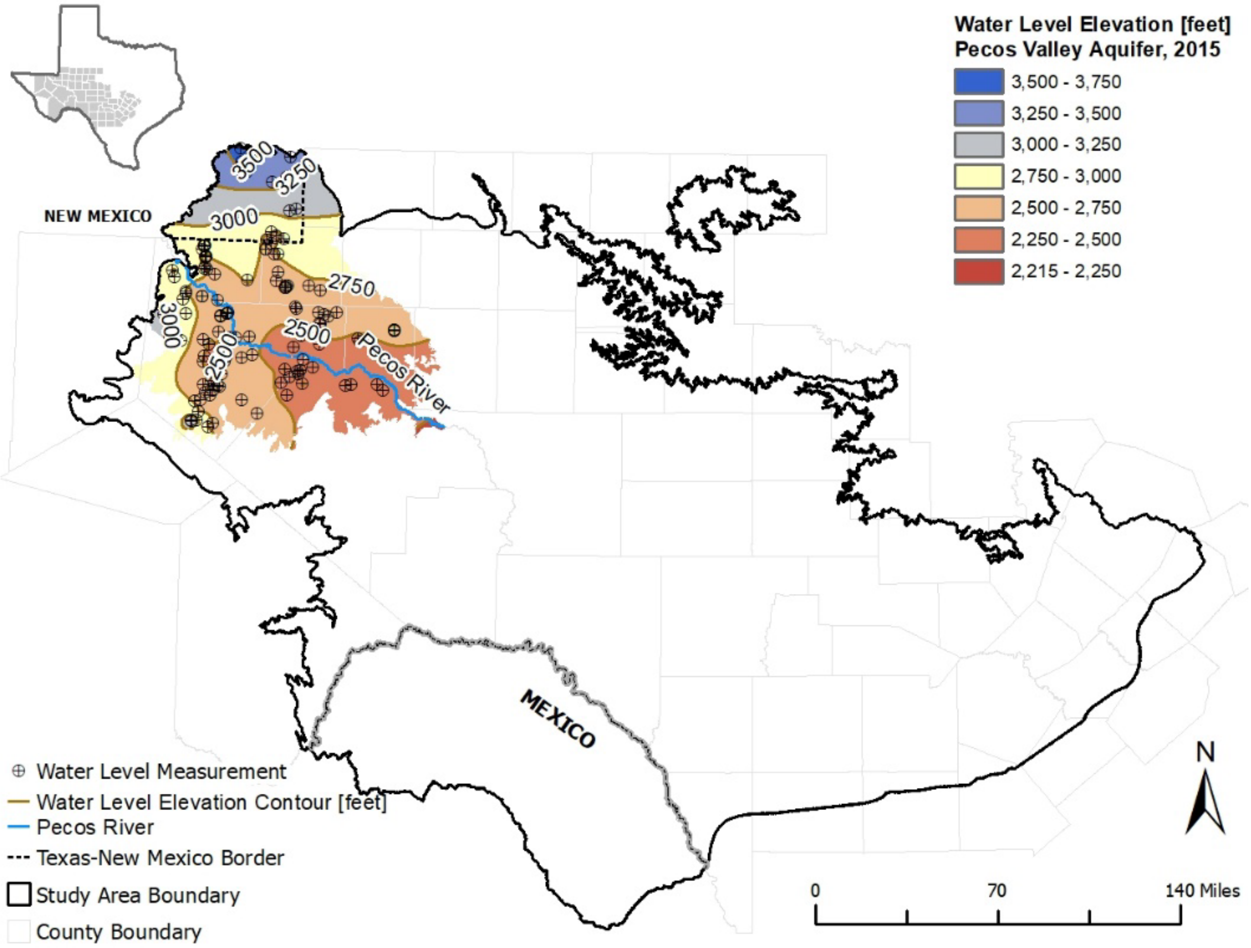


Figure 4.3-5. Interpolated potentiometric surface with contours of the Pecos Valley Aquifer for the year 2015. All elevations are reported in feet above mean sea level.

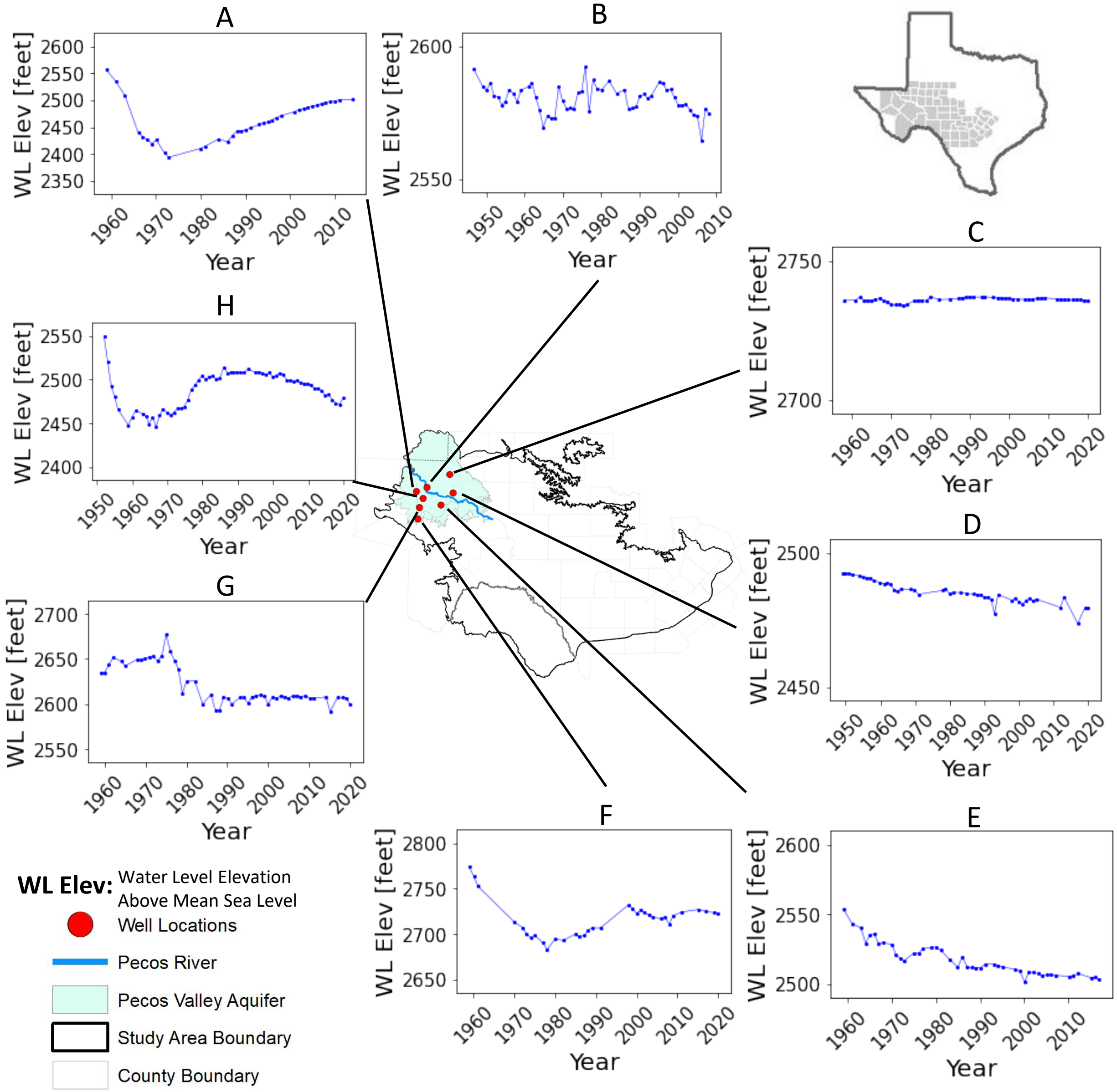


Figure 4.3-6. Representative hydrographs of the Pecos Valley Aquifer. All elevations are reported in feet above mean sea level. The Pecos Valley Aquifer is displayed as light green.

4.3.4 Edwards hydrostratigraphic unit water levels, regional flow, and trends

The Edwards hydrostratigraphic unit is exposed at surface throughout the Edwards Plateau region and largely unconfined with the exception of small areas where it underlies the Pecos Valley and Ogallala aquifers. The Edwards hydostratigraphic unit can be dry along the western and northwestern margins of the study area (Anaya and Jones, 2009). In the Balcones Fault Zone in the southeastern portion of the study area, the Edwards hydrostratigraphic unit is unconfined in the outcrop but confined downdip, where it underlies less permeable and continuous Upper Cretaceous units. When aquifers are confined by rock units which restrict flow upwards, they can become pressurized and contain water levels above the physical location of the aquifer. These portions are called artesian and can even have water levels which rise above the land surface. Water level measurements in the confined downdip Edwards Aquifer along the Balcones Fault Zone are artesian and several wells from the TWDB Groundwater Database record water levels above land surface.

Figure 4.3-7 through Figure 4.3-10 display the interpolated water levels in the Edwards hydrostratigraphic unit for the years 1950, 1980, 2000, and 2015 and Figure 4.3-11 provides representative hydrographs. In general, the regional groundwater flow pattern tends to follow the regional topography shaped by rivers and streams, especially the Pecos River and Rio Grande. In the Balcones Fault Zone, faults can also influence groundwater flow patterns (Hunt and Others, 2015). According to hydrographs and the interpolated potentiometric surfaces, water levels in the Edwards hydrostratigraphic unit have been mostly stable since the 1950s across the entire study area with some declines and rebounds in the west. As of 2015, water levels range from a maximum of approximately 3,480 feet above mean sea level in Jeff Davis County on the west side of the study area to a minimum of approximately 430 feet above mean sea level in central Travis County on the east side of the study area (Figure 4.3-10). Hydrographs tend to show the stability, but with significant fluctuations, of the Edwards hydrostratigraphic unit. In the Balcones Fault Zone, Figure 4.3-11(D and E) show large fluctuations on a small time scale but have a long term stable water level. In the eastern and central Edwards Plateau, Figure 4.3-11(C, F, and H) show similar trends to the hydrographs in the Balcones Fault Zone with stable long term trends but have smaller fluctuations. In the western and northern portions of the study area, Figure 4.3-11(A and B) shows large declines between the 1950s and 1960s but then recoveries beginning in the 1970s. A hydrograph in Val Verde County, Figure 4.3-11(G), shows a sharp rise in water levels in the late 1960 followed by stable water levels from the mid-1970s to the early 1990s before water levels declined into the 2000s. The Edwards hydrostratigraphic unit has a large recharge zone across the study area and is a karst aquifer with many dissolution features which allow for high rates of groundwater recharge. We assume that these characteristics help the Edwards hydrostratigraphic unit to maintain the relatively stable water levels displayed in the hydrographs.

The potentiometric surface map for the year 2015 (Figure 4.3-10) shows a groundwater divide in Kinney County approximately coinciding with the boundary between the Edwards

(Balcones Fault Zone) Aquifer and the Edwards-Trinity Aquifer. A groundwater divide represents a change in groundwater flow so that the direction of flow is different on either side of this feature.

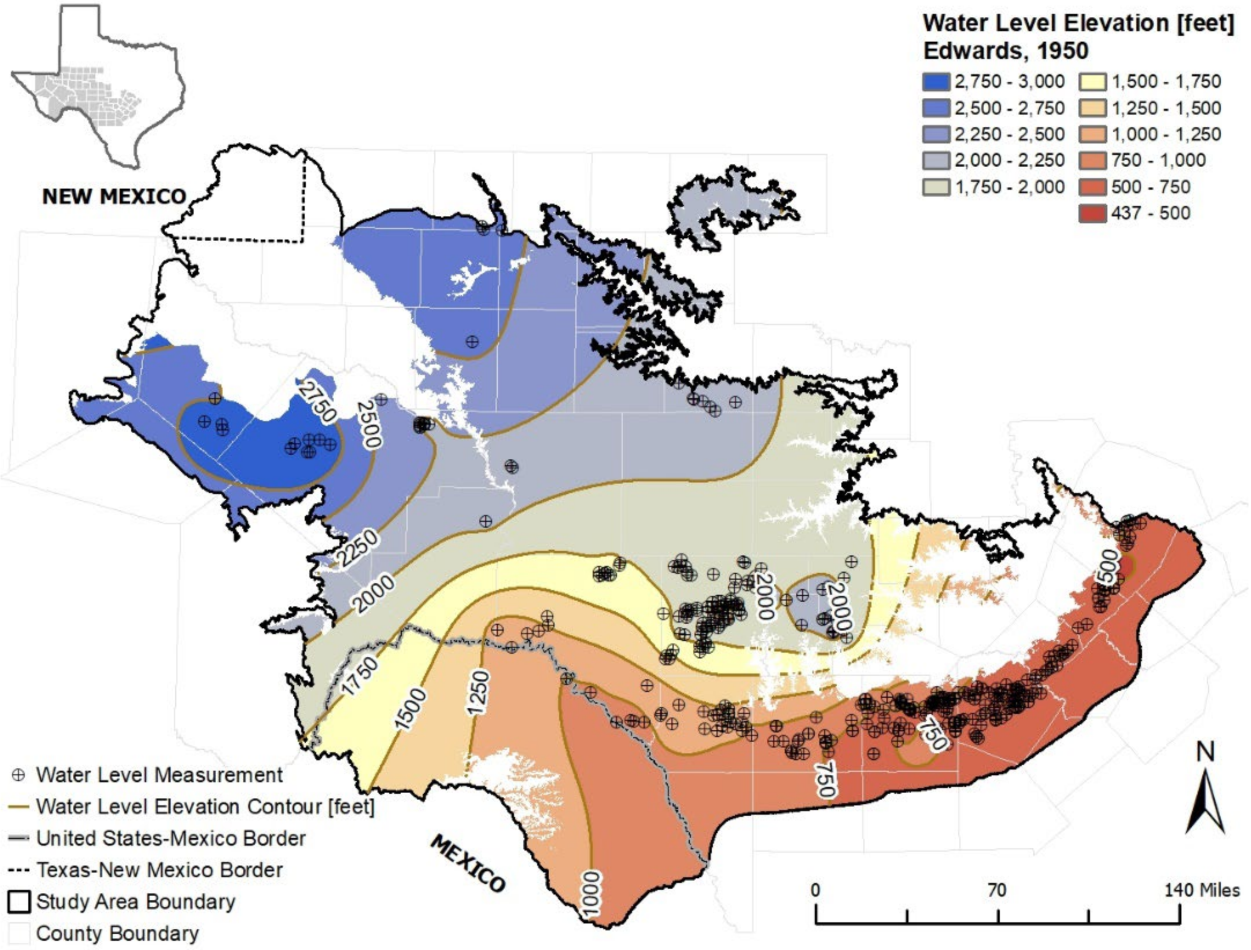


Figure 4.3-7. Interpolated potentiometric surface with contours of the Edwards hydrostratigraphic unit for the year 1950. All elevations are reported in feet above mean sea level.

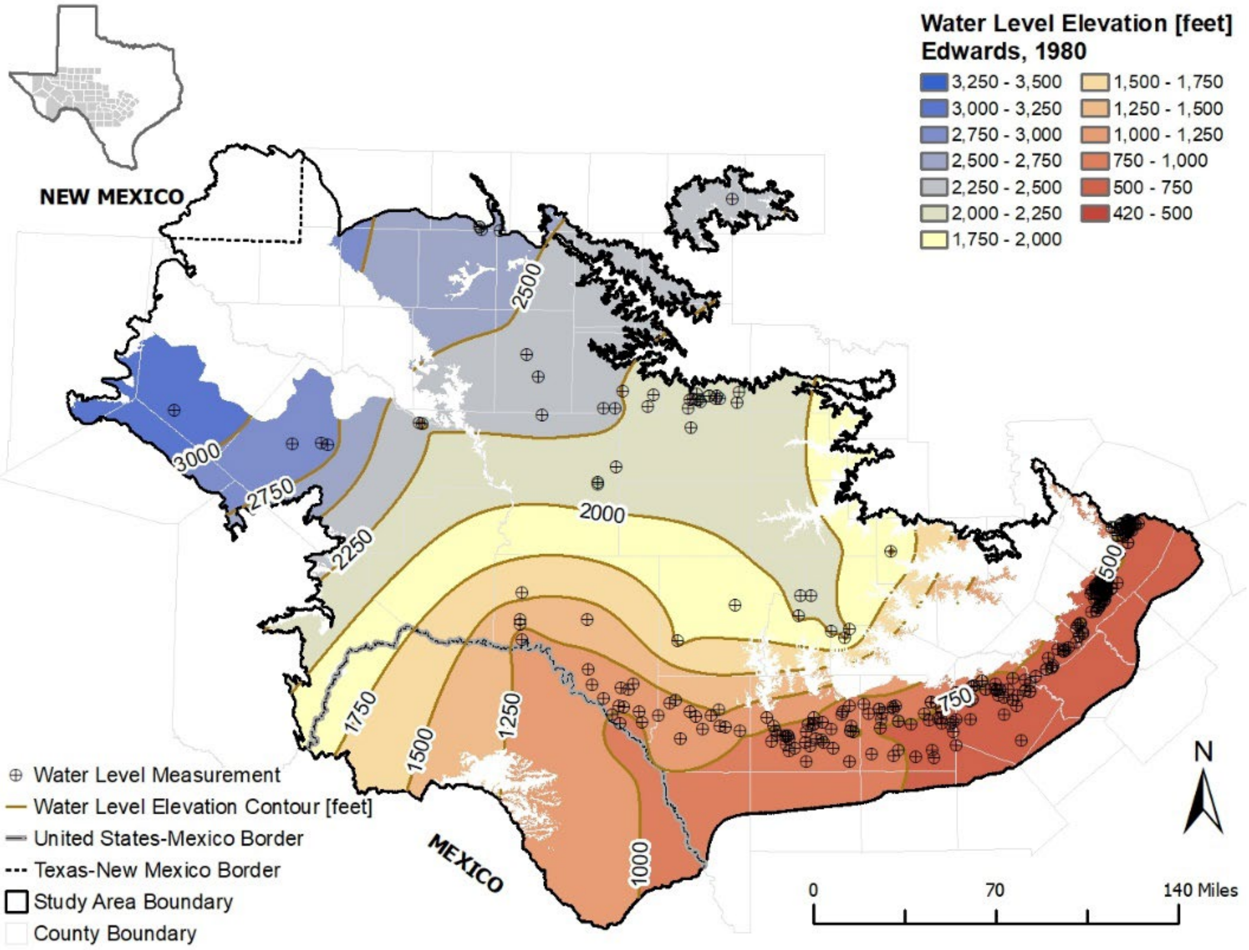


Figure 4.3-8. Interpolated potentiometric surface with contours of the Edwards hydrostratigraphic unit for the year 1980. All elevations are reported in feet above mean sea level.

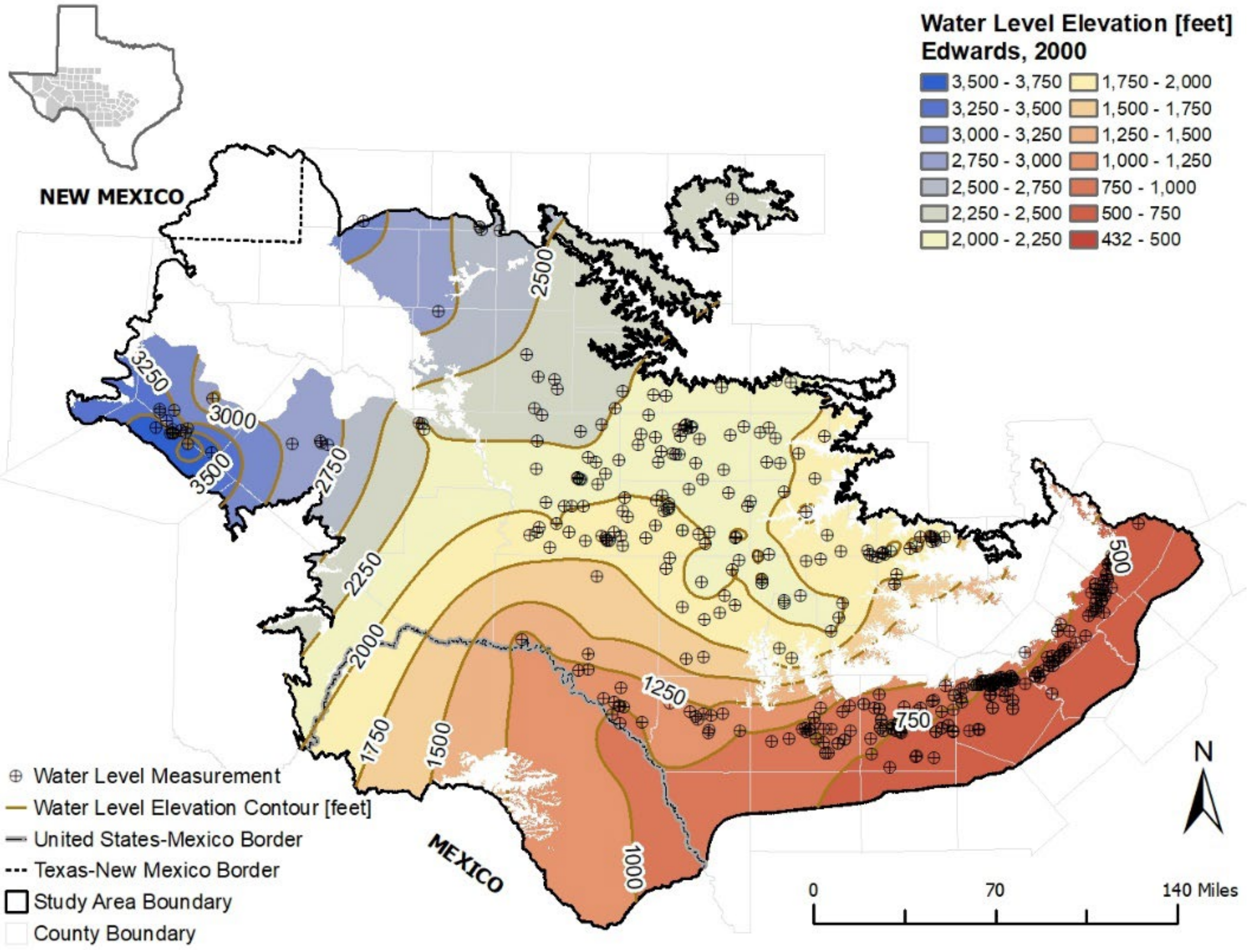


Figure 4.3-9. Interpolated potentiometric surface with contours of the Edwards hydrostratigraphic unit for the year 2000. All elevations are reported in feet above mean sea level.

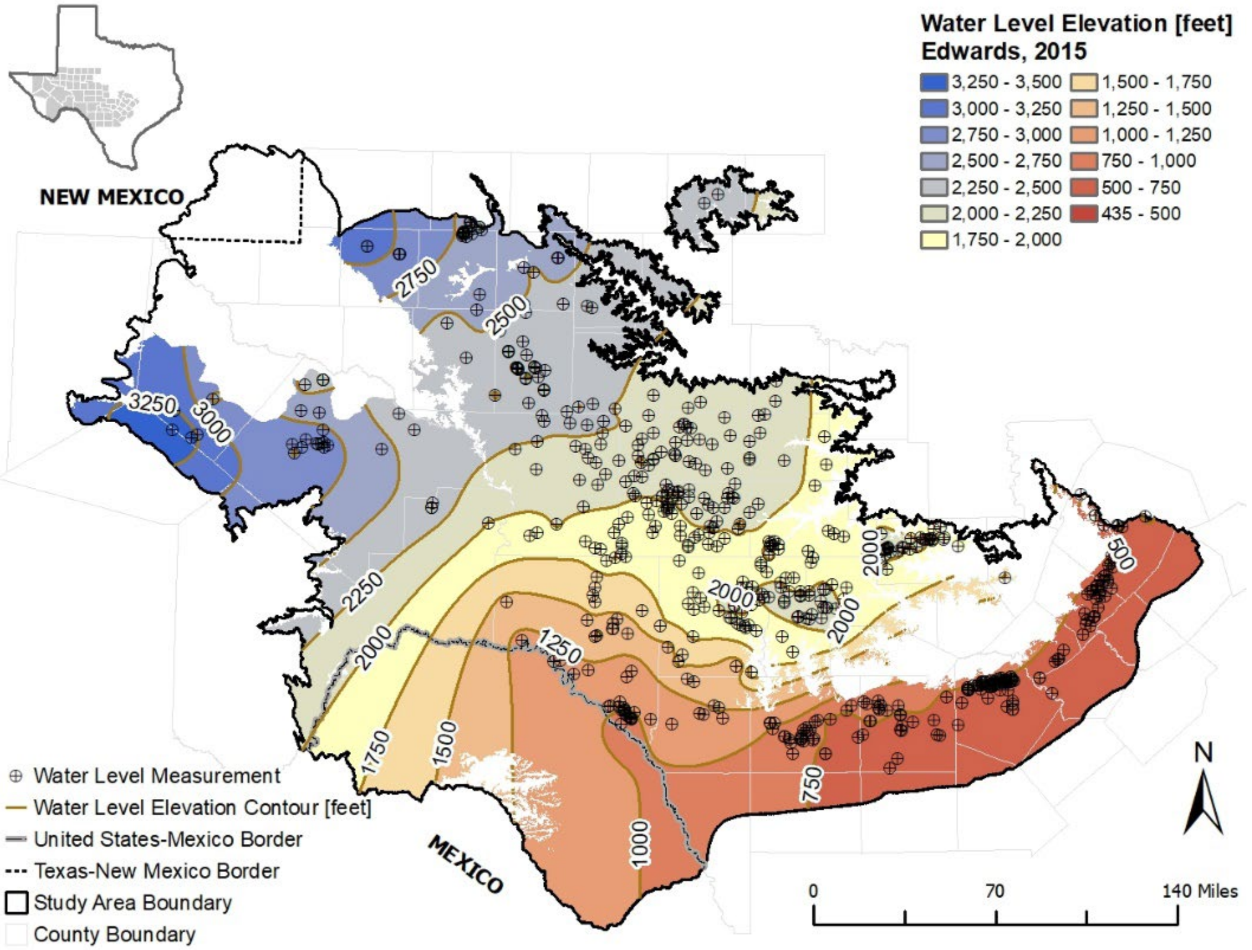


Figure 4.3-10. Interpolated potentiometric surface with contours of the Edwards hydrostratigraphic unit for the year 2015. All elevations are reported in feet above mean sea level.

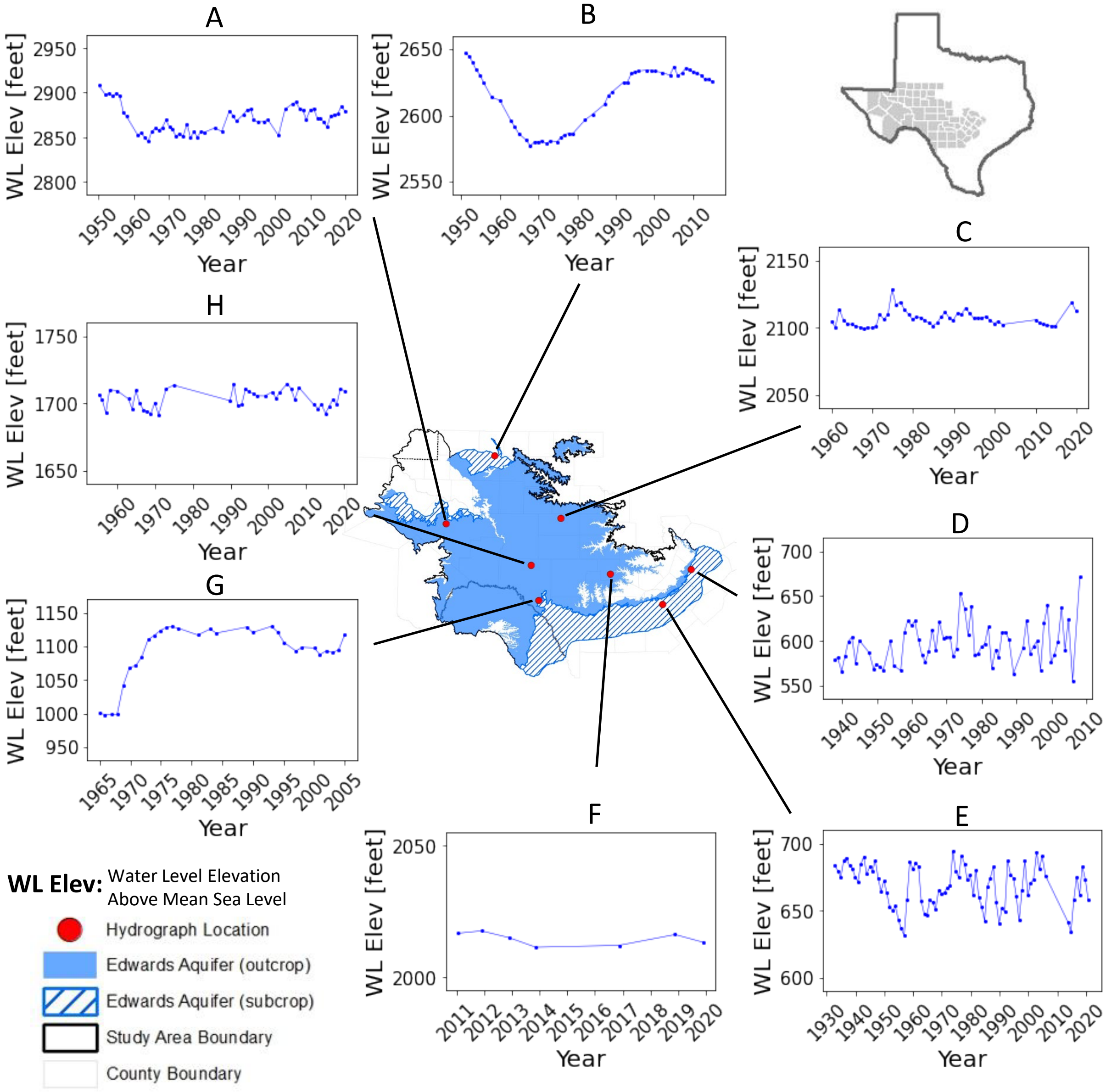


Figure 4.3-11. Representative hydrographs of the Edwards hydrostratigraphic unit. All elevations are reported in feet above mean sea level. The unconfined portion of the Edwards hydrostratigraphic unit is displayed in solid blue and the confined portion of the Edwards hydrostratigraphic unit is displayed in blue hatch pattern.

4.3.5 Trinity hydrostratigraphic unit water levels, regional flow, and trends

The Trinity hydrostratigraphic unit covers the largest portion of the study area. The majority of the Trinity hydrostratigraphic unit underlies the Edwards hydrostratigraphic unit and exists in the subcrop. The exception occurs in the Hill Country area, where the Edwards has been eroded away, leaving the Trinity exposed in the outcrop (see Figure 2.0-2). Where the Edwards hydrostratigraphic unit exists, the relatively impermeable sediments of the overlying basal member of the Edwards Group act as a confining or semi-confining unit to the Trinity hydrostratigraphic unit (Anaya and Jones, 2009). Otherwise, the Trinity hydrostratigraphic unit is unconfined where it crops out at the surface.

Figure 4.3-12 through Figure 4.3-15 provide the interpolated water levels in the Trinity hydrostratigraphic unit for the years 1950, 1980, 2000, and 2015 and Figure 4.3-16 provides representative hydrographs. In general, the regional groundwater flow pattern tends to follow the regional topography, which is shaped by rivers and streams. The Trinity groundwater flow patterns follow trends similar to those of the overlying Edwards hydrostratigraphic unit. According to the hydrographs and potentiometric surface maps, both regional groundwater trends and individual water levels in the Trinity hydrostratigraphic unit have fluctuated since the 1950s. As of 2015, measured water levels range from a maximum of around 3,430 feet above mean sea level in the far western portion of the study area in Jeff Davis County to a minimum of about 210 feet above mean sea level in the center of Travis County on the far east side of the study area (Figure 4.3-15). Figure 4.3-16(A, C, E, and H) shows that water levels in the Trinity hydrostratigraphic unit appear to have remained constant or slightly risen near the Pecos Valley Aquifer and eastward across the Edwards Plateau, even with one well within the heavily-developed area around San Antonio in Bexar County. However, in Figure 4.3-16(B, D, F, and G) water levels have fallen in the Hill Country area, from Real County to the Hays-Travis County boundary, as well as in the northernmost Edwards Plateau in Glasscock County. The declines in the Trinity hydrostratigraphic unit appear to be more recent, mostly after the 1980s. Some water level declines have been gradual and consistent since the 1950s while others were sudden but have since leveled out. The hydrographs show that there have been periods of water level decline followed by water level rise in Pecos County in the western portion of the study area. Local trends in water level hydrographs do not always match the regional groundwater trends seen in the water level maps.

The groundwater divide in the Trinity hydrostratigraphic unit occurs in the same area as the divide between the Edwards (Balcones Fault Zone) Aquifer and the Edwards-Trinity (Plateau) Aquifer. The potentiometric surface for the year 2015 shows a ridge of higher groundwater levels in Kinney County, which could indicate a groundwater divide.

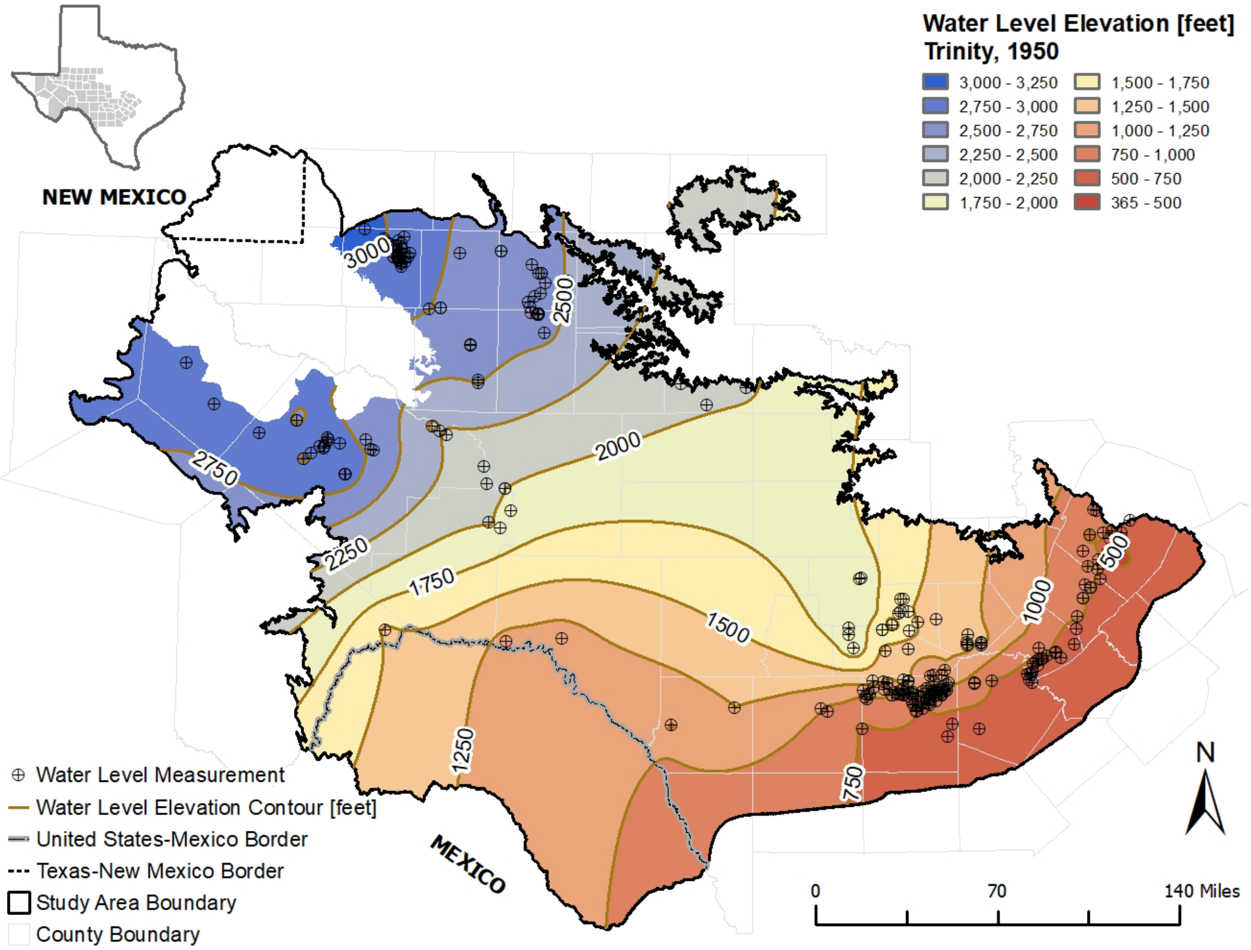


Figure 4.3-12. Interpolated potentiometric surface with contours of the Trinity hydrostratigraphic unit for the year 1950. All elevations are reported in feet above mean sea level.

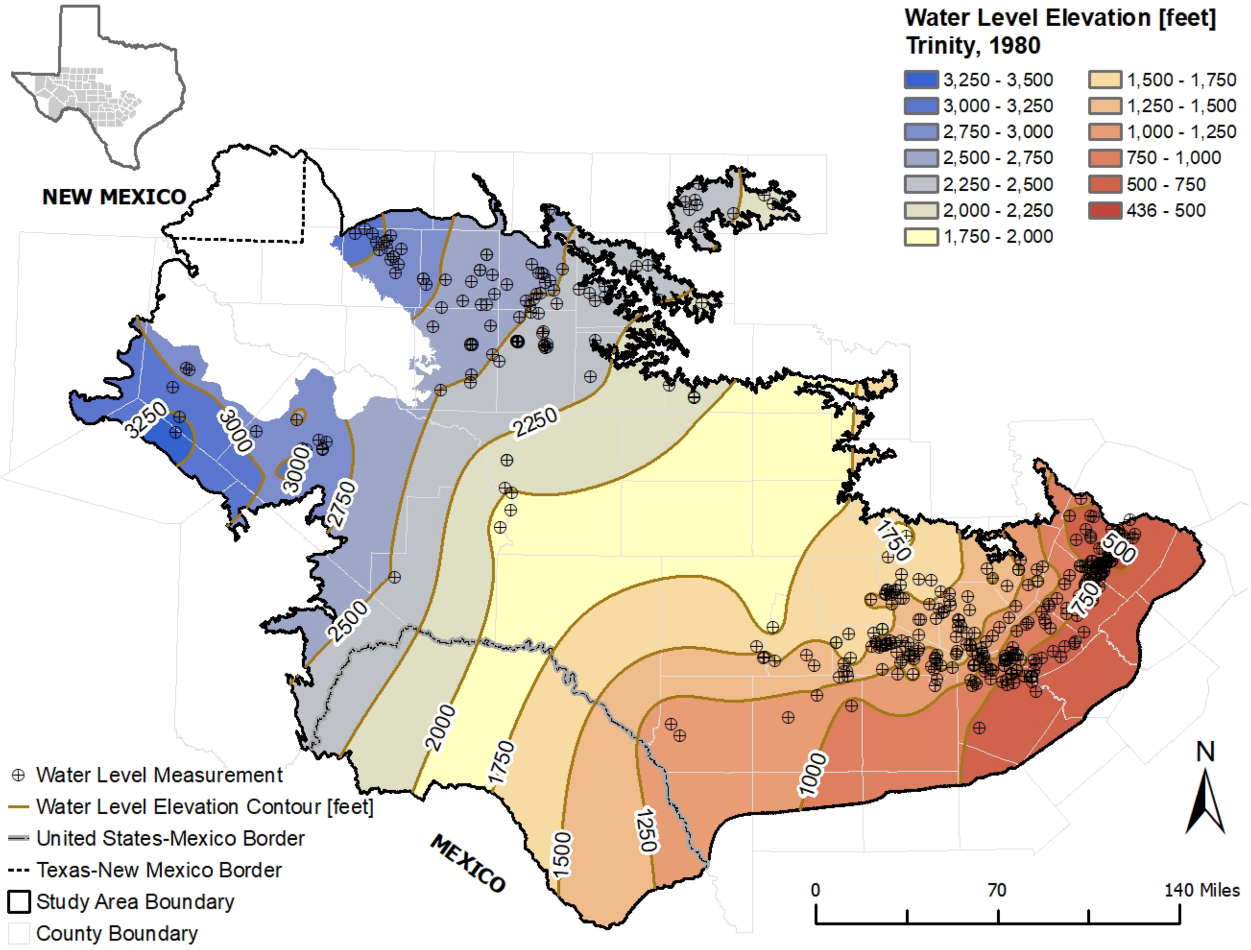


Figure 4.3-13. Interpolated potentiometric surface with contours of the Trinity hydrostratigraphic unit for the year 1980. All elevations are reported in feet above mean sea level.

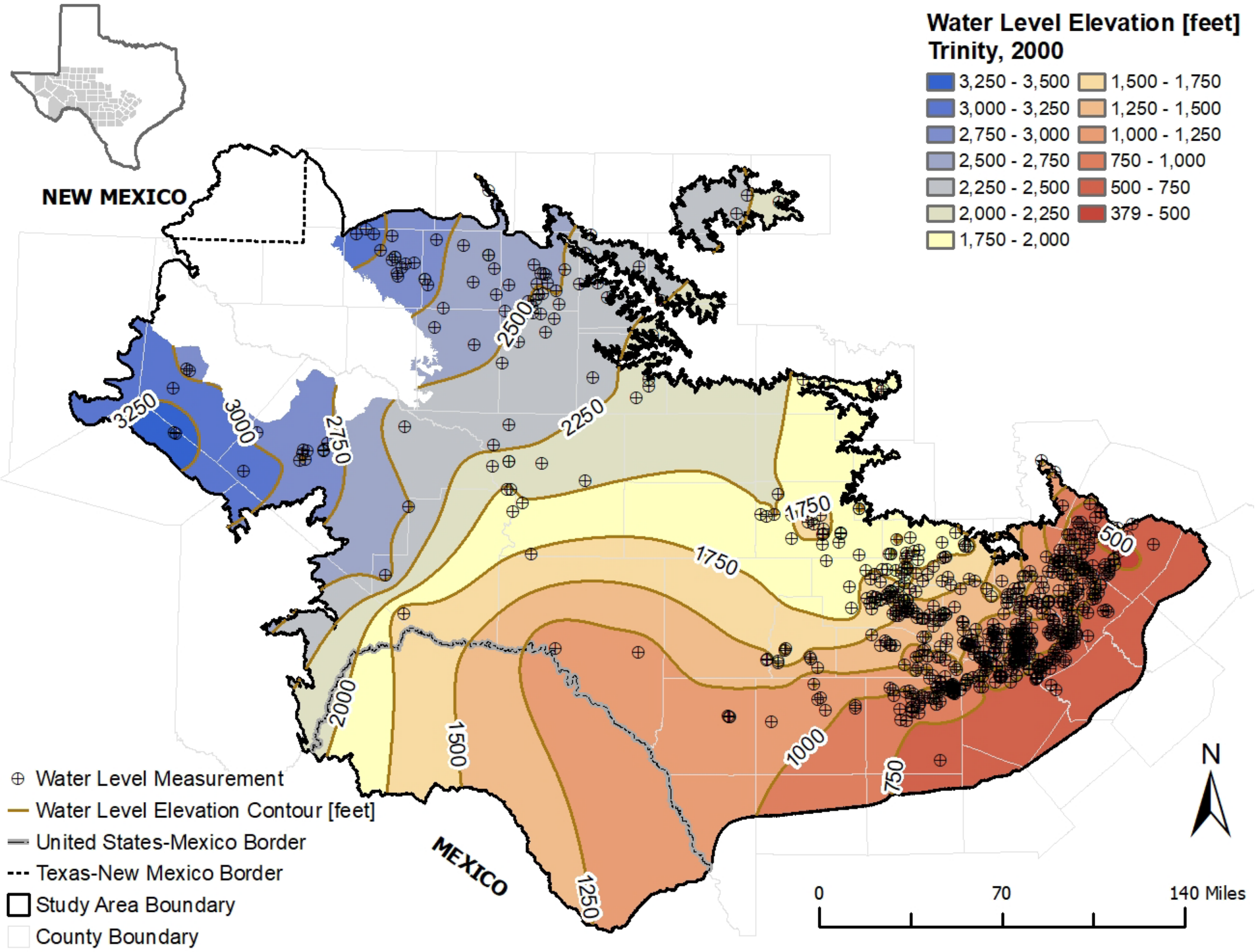


Figure 4.3-14. Interpolated potentiometric surface with contours of the Trinity hydrostratigraphic unit for the year 2000. All elevations are reported in feet above mean sea level.

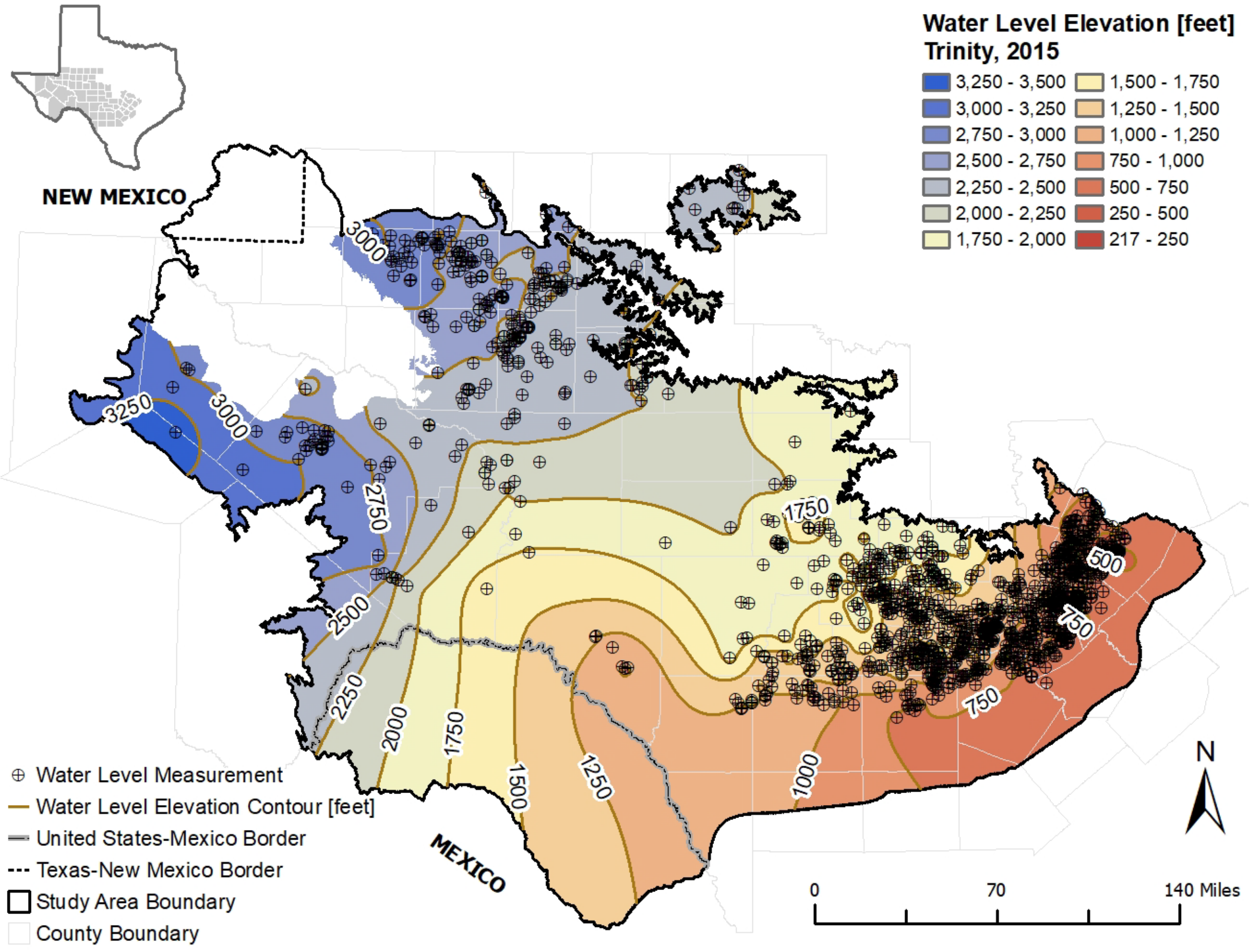


Figure 4.3-15. Interpolated potentiometric surface with contours of the Trinity hydrostratigraphic unit for the year 2015. All elevations are reported in feet above mean sea level.

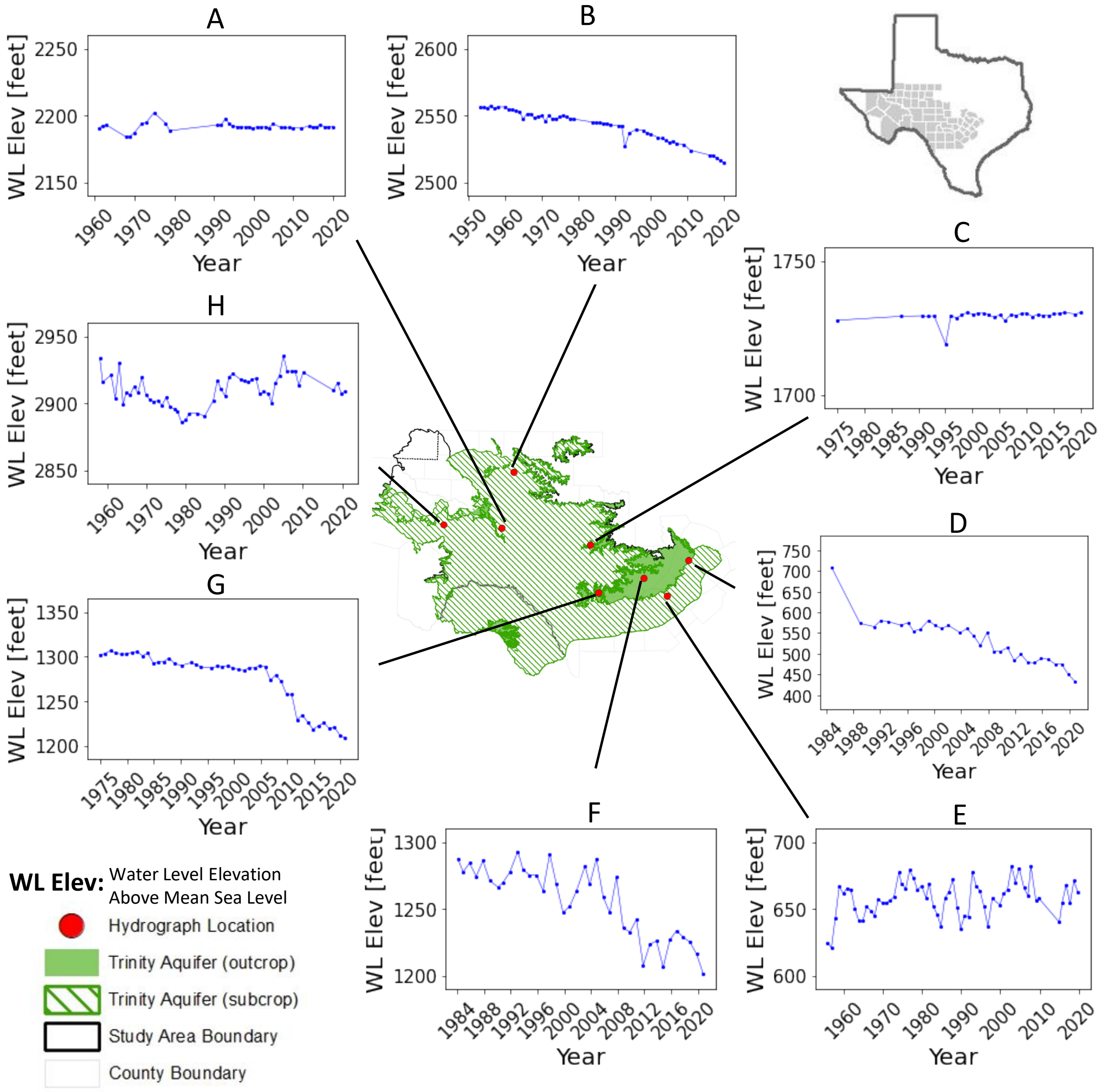


Figure 4.3-16. Representative hydrographs of the Trinity hydrostratigraphic unit. All elevations are reported in feet above mean sea level. The unconfined portion of the Trinity hydrostratigraphic unit is displayed in solid green and the confined portion of the Trinity hydrostratigraphic unit is displayed in green hatch pattern.

4.3.6 Regional groundwater flow paths

Figure 4.3-17 shows the schematic regional groundwater flow paths in the study area. In the Pecos Valley Aquifer, groundwater generally flows towards the Pecos River. In the Trans-Pecos region in the west, groundwater in the Edwards and Trinity hydrostratigraphic units flows toward the Pecos River and the Rio Grande, with potentiometric maps suggesting a steep gradient towards these surface water drainages. In the Central Edwards Plateau region, groundwater generally flows from northwest to southeast towards the Edwards Balcones Fault Zone. A regional groundwater divide in this area, coinciding with the surface water divide, separates groundwater flow toward the Colorado River in the north and toward the Pecos River and the Rio Grande in the south. A groundwater divide near Kerr and Real counties separates groundwater flow toward the Rio Grande in the south and groundwater flow toward the Balcones Fault Zone and into the Guadalupe, San Antonio, and Nueces river basins (Anaya and Jones 2009). This groundwater divide represents the boundary between the Edwards-Trinity (Plateau) Aquifer and the Hill Country portion of the Trinity Aquifer. As groundwater flows into the Balcones Fault Zone, groundwater flow direction shifts toward the northeast in response to faults in the area that block southeastward groundwater flow path. In general, the flow path in this region is parallel to the strike of the fault zone.

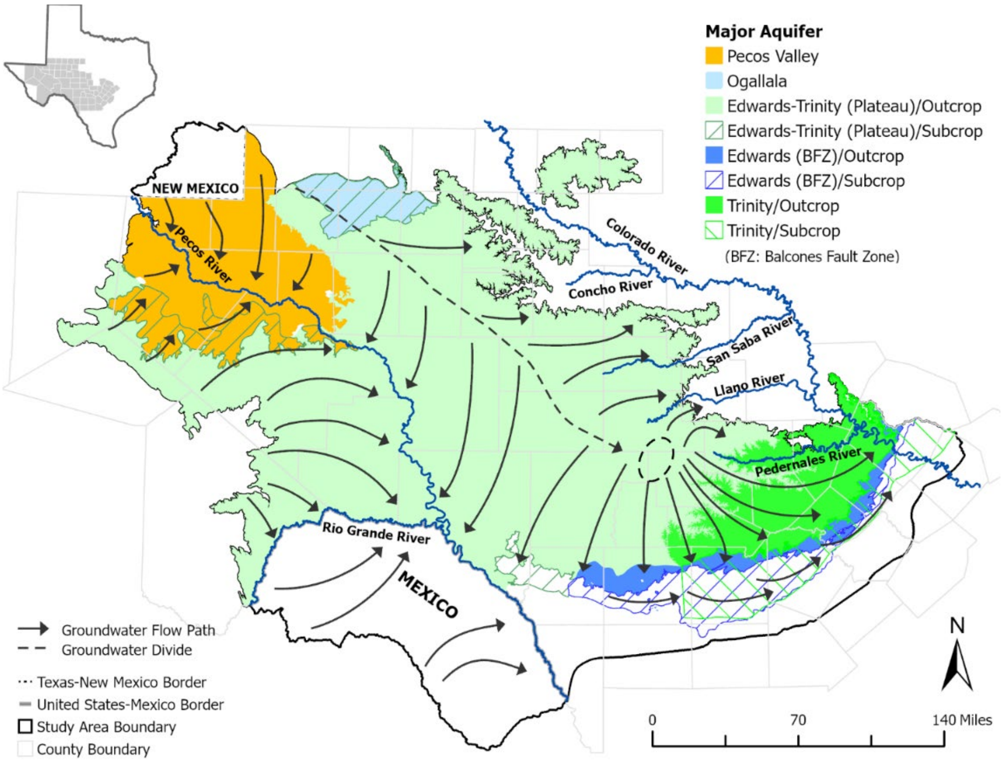


Figure 4.3-17. Generalized regional groundwater flow path for the Pecos Valley and Edwards-Trinity (Plateau) Region (modified from Anaya and Jones, 2009; Edwards Aquifer Authority, 2021).

4.3.7 Cross-formational flow

We analyzed cross-formational flow using hydrographs of neighboring well pairs completed in different hydrostratigraphic units. Figure 4.3-18 shows representative hydrograph comparisons for well pairs located within one mile of each other. In general, overlap in water levels or similar parallel trends between the paired hydrographs is assumed to indicate possible connection between hydrostratigraphic units while separation and lack of similar trends indicates that the hydrostratigraphic units are not locally connected. Figure 4.3-18 (A and B) shows that cross-formational flow might occur between the Trinity hydrostratigraphic unit and the underlying Pre-Cretaceous rocks (Paleozoic) in the northern and central portions of the Edwards Plateau in Reagan and Kerr counties. In Figure 4.3-18 (A), water levels overlap and have similar temporal trends, indicating a strong connection. The water levels do not overlap in Figure 4.3-18 (B), but they do rise and fall parallel to each other over the same time frame indicating some connection between these two units. This connection is less clear in the east, as shown in Figure 4.3-18 (C), where the Trinity and the underlying Pre-Cretaceous rocks (Paleozoic) in Blanco County do briefly overlap but do not have similar water level trends, indicating little to no connection.

The Edwards and the Trinity Hydrostratigraphic units appear to be connected in the Balcones Fault Zone based on the overlapping water levels with similar temporal trends from a well pair in Travis County, shown in Figure 4.3-18 (D). This strong connection is consistent with the findings of Smith and Hunt (2020) which found that the top portion of the Trinity hydrostratigraphic unit in Hays and Travis counties is connected to the Edwards hydrostratigraphic unit while the lower portions of the Trinity hydrostratigraphic unit are disconnected from the Edwards hydrostratigraphic unit. Smith and Hunt (2020) also conclude that, locally, lateral flow is much greater than cross-formational flow between the Edwards and Trinity hydrostratigraphic units in the highly faulted and karst Balcones Fault Zone. Unlike the Balcones Fault Zone, the connection between the Edwards and Trinity hydrostratigraphic units is not as strong in the Edwards-Trinity (Plateau) region. Figure 4.3-18 (F) shows water levels for these units in Kerr County that do not overlap and do not seem to share common trends over time. However, the cross-formational connection reappears further west in Pecos County, where the water levels of the Edwards and Trinity hydrostratigraphic units overlap and indicate strong connection, as shown in Figure 4.3-18 (G).

Figure 4.3-18 (E) shows the comparison between the overlying Upper Cretaceous confining units and the Edwards hydrostratigraphic unit in the Balcones Fault Zone. These do not appear to be connected, as the water levels do not overlap and do not show similar temporal trends. Figure 4.3-18 (H) shows that the Pecos Valley Aquifer and the underlying Pre-Cretaceous rocks (lower Mesozoic to Paleozoic rocks) appear to be connected because of overlapping water levels and similar temporal trends.

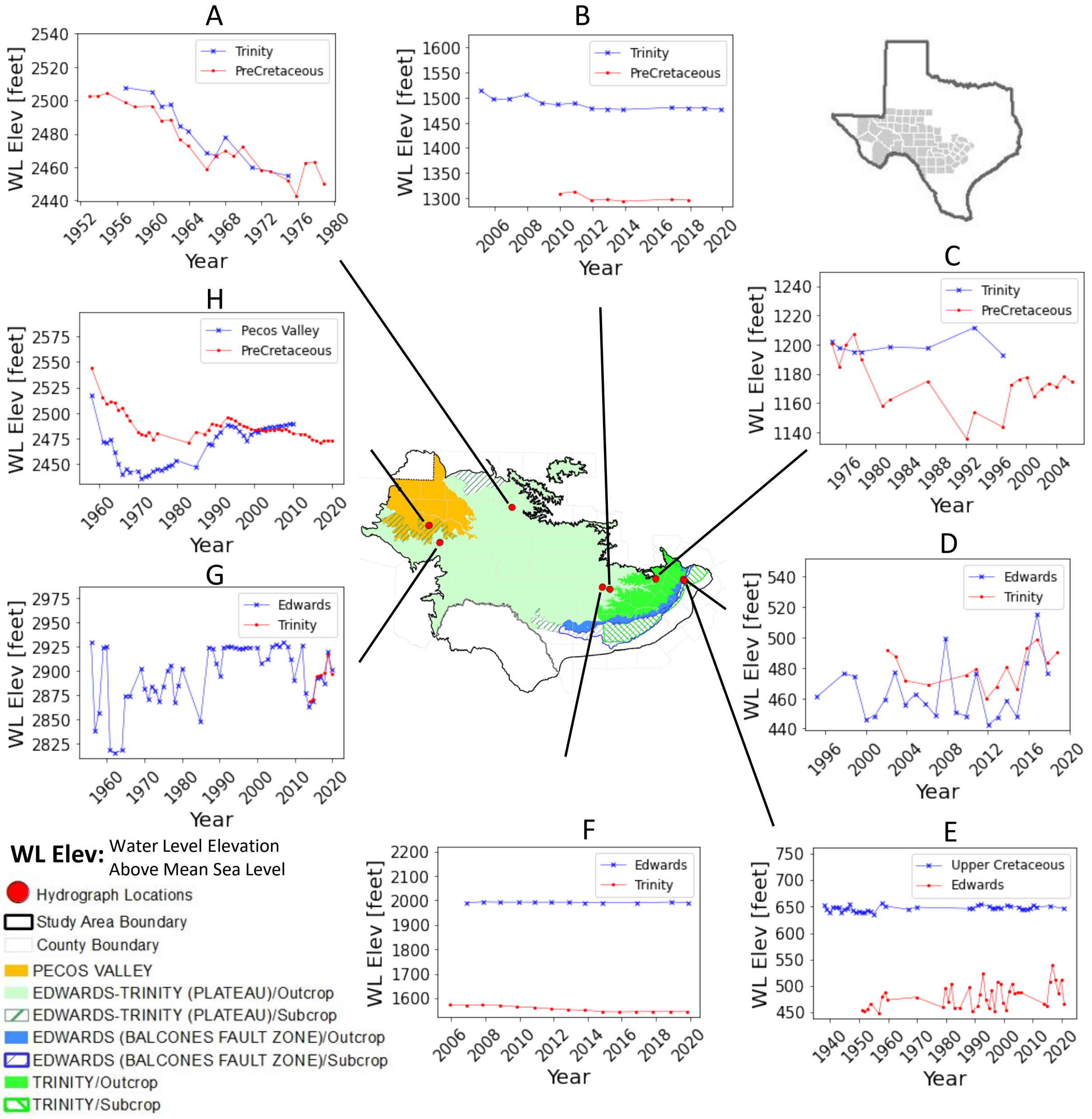


Figure 4.3-18. Selected hydrographs showing water level trends between different hydrostratigraphic units across the study area. All elevations are reported in feet above mean sea level. The Pecos Valley Aquifer is displayed as solid orange, the Edwards-Trinity Plateau Aquifer is displayed as light green, the Trinity Aquifer is displayed as lime green, and the Edwards (Balcones Fault Zone) Aquifer is displayed as blue.

4.4 Recharge

Groundwater recharge is the hydrologic process by which water travels downwards, reaches the water table, and becomes part of the groundwater flow system (Anderson and Woessner, 1992). It is the only natural hydrologic process that can increase the amount of groundwater. Potential sources for recharge include infiltration of precipitation, return flow from irrigation, and leakage from surface water. Factors that influence recharge include the amount and frequency of rainfall, topography, land use and vegetation type, outcrop extent, and the infiltration characteristics of both the upper soil layer and the aquifer (McLaurin, 1988).

However, measuring the amount of recharge to the aquifer directly is not available. Instead, it must be estimated using other measurable parameters. For instance, the sum of runoff, plant uptake, and evaporation from measured precipitation can be subtracted to calculate the infiltration from precipitation (or irrigation return flow). Streamflow analysis can also be used to estimate the recharge to the groundwater from streams.

A TWDB subcontractor (WSP USA) is concurrently developing recharge estimates for the Pecos Valley and Edwards-Trinity (Plateau) regional aquifers model study area based on several estimation methods. The draft report will be publicly available at the same time as the current report. That report will provide final recharge estimates and discuss the various approaches and techniques used to convert measurable data into recharge values in the study area. The recharge distribution in the final numerical groundwater model will be based on the findings of this study.

4.5 Rivers, Streams, Springs, and Lakes

Interaction between surface water and groundwater occurs in areas where surface water is in contact with the outcrop of aquifer rock units. Depending on the flow direction, these interactions can create surface water features including rivers, streams, springs, and lakes, or recharge the aquifer. The aquifer's water level relative to the surface elevation determines the direction of flow between the aquifer and the surface water bodies. In the study area, surface water features occur in the northern, eastern, and southern margins of the Edwards Plateau. Figure 4.5-1 and Figure 4.5-2 show the location of surface water features with river basins and major aquifers in the study area.

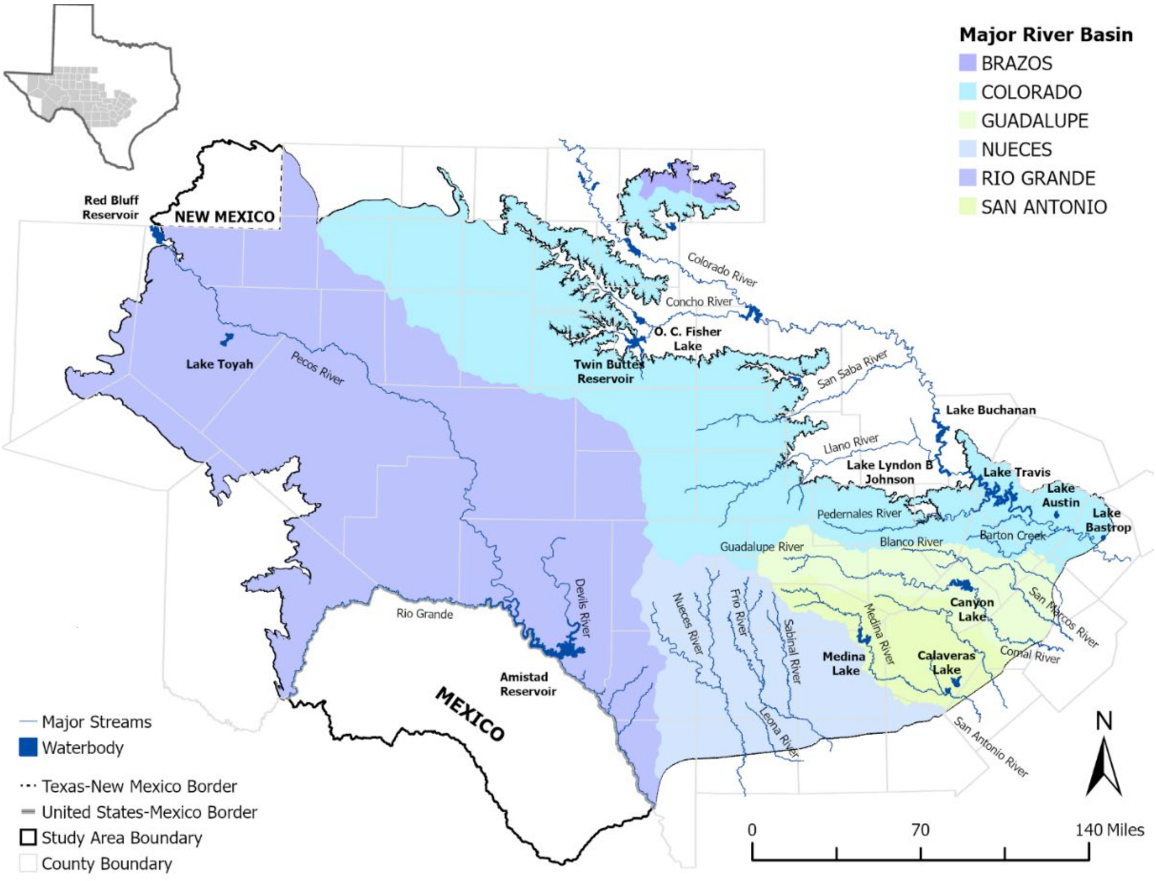


Figure 4.5-1. Major streams and drainage basins of the study area.

Figure 4.5-1 shows river basin, rivers, and reservoirs in the study area. There are six major river basins within the study area: the Brazos, Colorado, Guadalupe, Nueces, Rio Grande, and San Antonio river basins. Although the Brazos River does not flow within the study area, the Brazos River Basin intersects the northern tip of the study area in Nolan and Taylor counties. The major rivers generally flow from northwest to southeast following topography toward the Gulf of Mexico. The Pecos River and Devils River are major tributaries to the Rio Grande and drain the southwestern part of the study area, intersecting the outcrop of the Edwards-Trinity (Plateau) Aquifer. The Pecos River also intersects the Pecos Valley Aquifer in its upstream reaches. The Nueces, Frio, Sabinal, Medina, Guadalupe, and Blanco rivers are located in the southeastern river basins and drain the southeastern and southern portions of the plateau, intersecting the outcrops of the Hill Country portion of the Trinity Aquifer and the Edwards (Balcones Fault Zone) Aquifer. The Concho, San Saba, Llano, and Pedernales rivers are the tributary streams of the Colorado River and drain the northeastern part of Edwards Plateau, intersecting the outcrops of the Edwards-Trinity (Plateau) Aquifer in the west and the Hill Country portion of the Trinity Aquifer in the east.

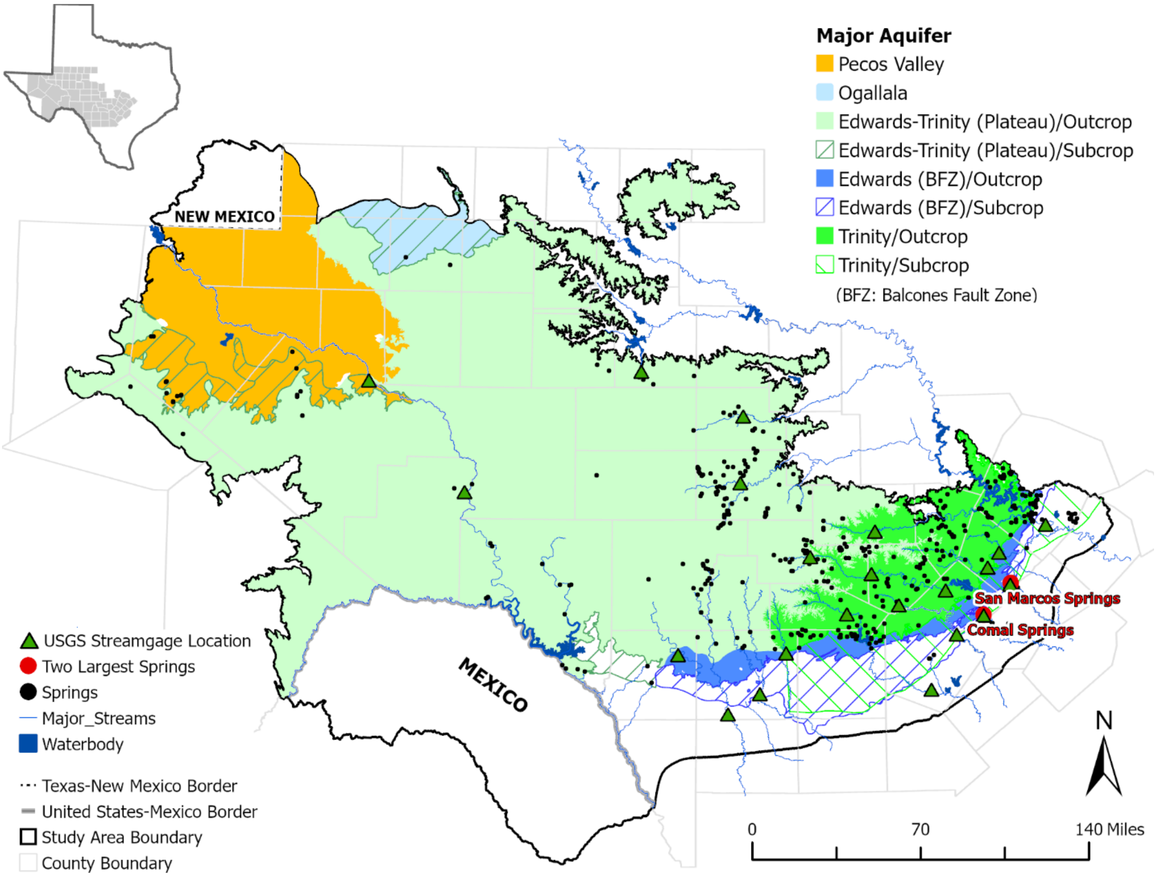


Figure 4.5-2. Stream gage and spring locations in the study area.

Building a dam creates reservoirs and the pressure head generated by the reservoir can artificially sustain groundwater levels higher than the regional aquifer. Weinberg and French (2018) reported higher groundwater level near the Amistad Reservoir along the Rio Grande in Val Verde County than the regional aquifer system. We will consider the potential effects of nearby reservoirs when choosing water level measurements to use during model calibration. Other noteworthy water bodies in the study area include Red Bluff Reservoir just west of the study area on the Pecos River in Loving County, Medina Lake on the Medina River in Medina County, Canyon Lake on the Guadalupe River in Comal County, and Lake Travis and Lake Austin both on the Colorado River in Travis County.

Springs represent locations where groundwater discharges from the aquifer to surface water. As such, springs with significant flow will be implemented in the numerical model, as possible and appropriate, to help better model groundwater/surface water interaction. Figure 4.5-2 shows springs within the study area. In the Edwards-Trinity (Plateau) Aquifer area, most springs fall along major streamlines in the south and southeast portion of the aquifer, although some springs also occur in the Trans-Pecos region. Within the Edwards (Balcones Fault Zone) Aquifer area, larger springs occur at the northern side of the aquifer, where the groundwater flows along fault lines and discharges when the water level is higher than the ground surface.

The two largest springs in the study area are in the Edwards (Balcones Fault Zone) area. Figure 4.5-3 shows the monthly discharge from Comal Springs and San Marcos Springs. From the 1930s to the present day, Comal Springs has discharged a monthly average of about 300 cubic feet per second. The significant drop observed during the several month period during the 1950s drought of record represents the only time that the springs ceased to flow. San Marcos Spring has produced a monthly average flow of about 175 cubic feet per second since the 1950s and has never ceased flowing.

Table 4.5-1 includes other significant springs in the study area. Within the Edwards (Balcones Fault Zones) Aquifer extent, these include Barton Springs in Travis County, San Felipe Springs in Val Verde County, Las Moras Springs in Kinney County, and San Antonio Springs in Bexar County. Barton Springs and San Felipe Springs have a monthly flow average higher than 60 cubic feet per second, while Las Moras Springs and San Antonio Springs have lower flow volumes (around 20 cubic feet per second). In addition, San Antonio Springs flows only in the wet season (data not shown).

In the Edwards-Trinity (Plateau) Aquifer extent, significant springs include San Solomon Springs and Giffin Springs in Reeves County, Phantom Lake Spring in Jeff Davis County, and Comanche Springs in Pecos County. When flowing, San Solomon Springs and Comanche Springs produce more than 25 cubic feet per second on average. Giffin Springs has relatively low rates (around 4 cubic feet per second), and Phantom Lake Spring has intermediate flow rates (around 12 cubic feet per second).

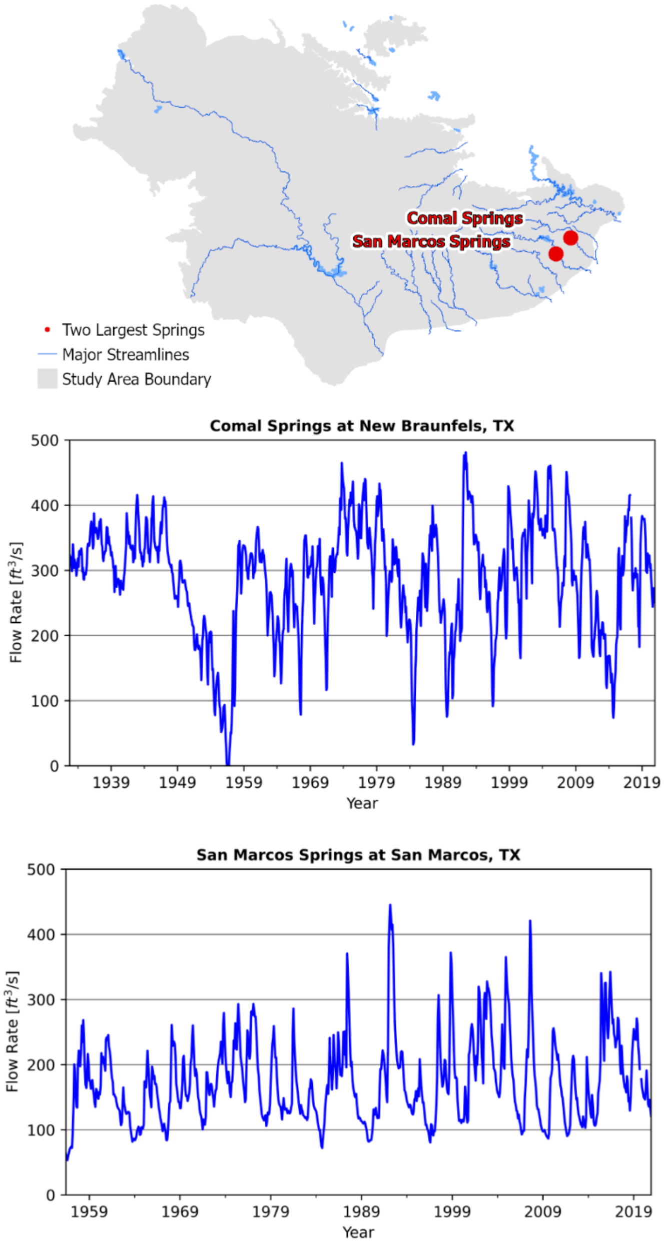


Figure 4.5-3. Hydrographs for the two largest springs (Comal Springs and San Marcos Springs) in the study area.

Table 4.5-1. List of Springs in each aquifer of the study area with the monthly average flow and county location.

Aquifer	Spring Name	Monthly average springflow (cubic feet per second)	County
Edwards (Balcones Fault Zone)	Barton Springs	64.7	Travis
	San Felipe Springs	100.5	Val Verde
	Las Moras Springs	20.7	Kinney
	San Antonio Springs	19.4	Bexar
Edwards-Trinity (Plateau)	San Solomon Springs	32.8	Reeves
	Giffin Spring	4.1	
	Phantom Lake Spring	12.4	Jeff Davis
	Comanche Springs	25.4	Pecos

Since springs are a strong indicator of groundwater availability and aquifer health, recently there has been increasing interest in the springs of the current study area. In 2020, the TWDB initiated the Springs Monitoring Program as part of the TWDB Groundwater Monitoring program. This effort aims to consistently collect discharge and water quality data at springs where data was previously only collected sporadically, often on a case-by-case basis. Springs were chosen for initial monitoring based on factors including cultural significance and sensitivity due to aquifer decline or the presence of endangered species. Most of the chosen springs discharge from the Edwards-Trinity (Plateau) Aquifer or the Hill Country portion of the Trinity Aquifer within the current study area. In the western portion of the study area, a recent study by the Meadows Center for Water and the Environment at Texas State University (Mace and others, 2020) focused on Comanche Springs, once the largest springs in West Texas. Comanche Springs stopped flowing in the 1960s due to significant groundwater pumping, but recently it has begun flowing again in winter months when the aquifer has rebounded from irrigation. Follow-up efforts, including the establishment of a water-market (Texas Water Trade) continue to focus on restoring perpetual flow at Comanche Springs. Since these efforts are still brand new, the current model will not be able to fully incorporate results generated by either the new TWDB program or the Comanche Springs program. However, these efforts do highlight the importance of springflow in the current study area.

Figure 4.5-2 also presents the U.S. Geological Survey streamflow gages in the study area. Figure 4.5-4. shows the streamflow hydrographs of the major streams in the study area.

These hydrographs represent a subset of streamflow gages with a long period of measurement, in locations likely to represent the aquifer behavior. The graphs present the monthly flow rate in cubic feet per second from 1980 to the most recent measurement date measured at the stream gage stations. Breaks in the graphs represent times when no measurements are available for that gage. The U.S. Geological Survey calculated monthly flow rate by averaging their higher frequency measurement data. Spikes in the hydrograph represent stormflow events. If the hydrograph remains constantly above zero, this indicates perennial, or yearlong, flow conditions. If the hydrograph has periods where flow is zero, this indicates intermittent flow conditions.

Streamflow hydrographs can be used as calibration targets to constrain surface water-groundwater interaction in a regional groundwater model. In addition, analyses of streamflow hydrographs can provide estimates of flow from the aquifer to the stream, and vice versa. These analyses separate hydrographs into the portions contributed by surface runoff versus baseflow and the portion that contributes to groundwater recharge in a basin.

A TWDB subcontractor (WSP USA) is concurrently developing baseflow and recharge estimates for the Pecos Valley and Edwards-Trinity (Plateau) regional aquifers model study area, based on several hydrograph separation techniques. The draft report will be publicly available at the same time as the current report. That report will provide final baseflow estimates for streams and rivers in the study area. The implementation of surface water – groundwater interaction in the final numerical groundwater model will be based on the findings of this study.

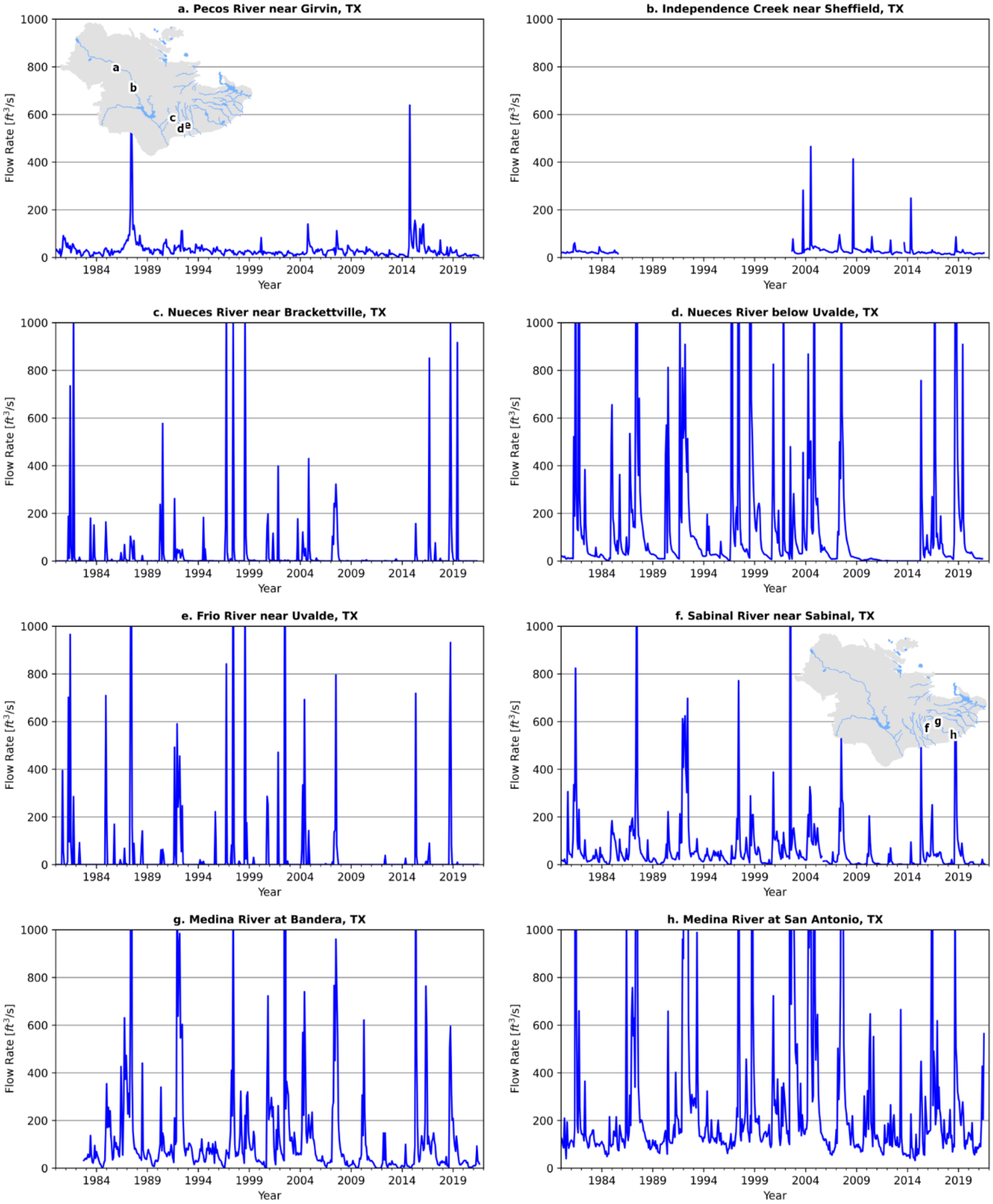
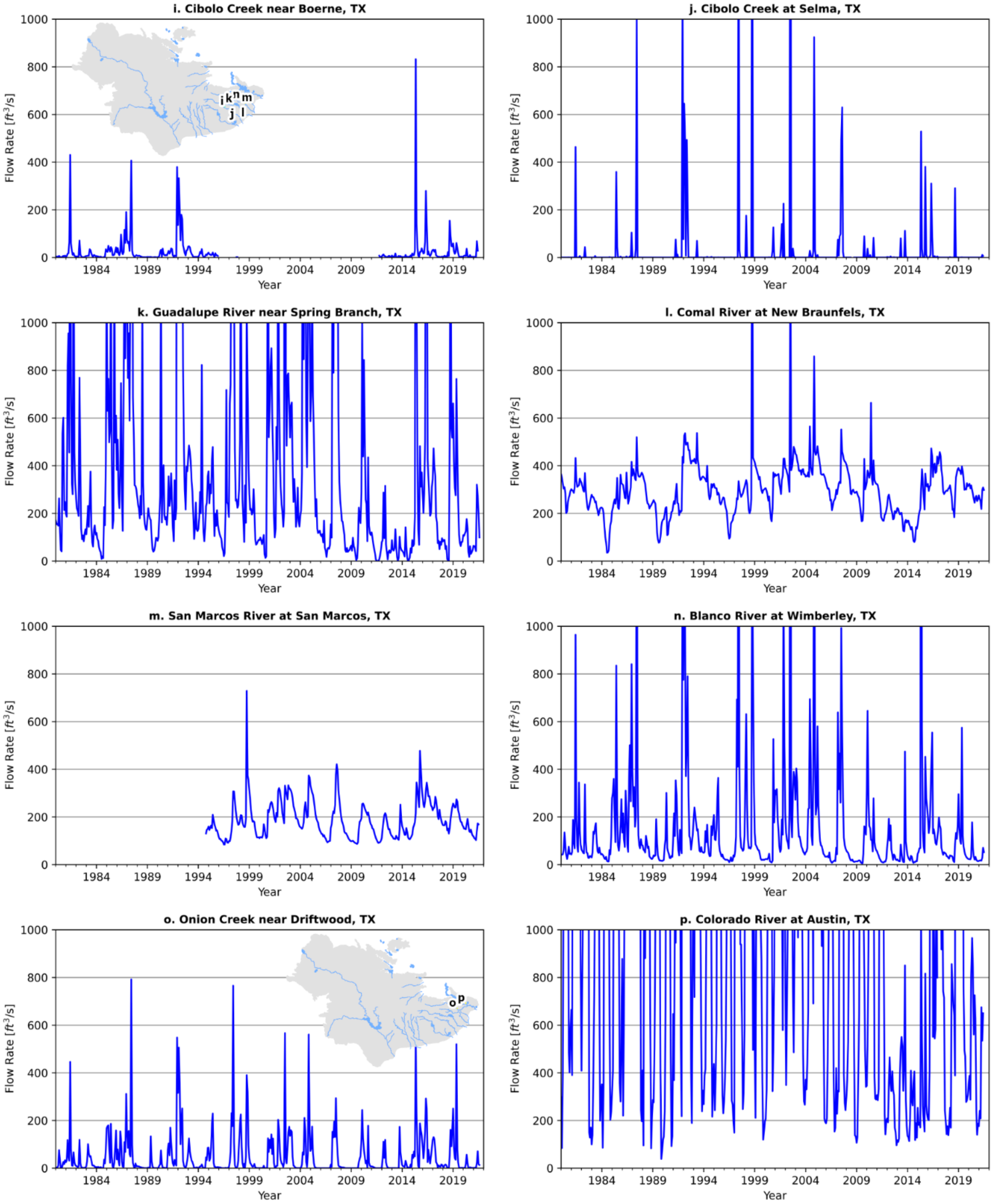


Figure 4.5-4. Streamflow hydrographs for major streams over the study area.



i. Cibolo Creek near Boerne, TX

j. Cibolo Creek at Selma, TX

k. Guadalupe River near Spring Branch, TX

l. Comal River at New Braunfels, TX

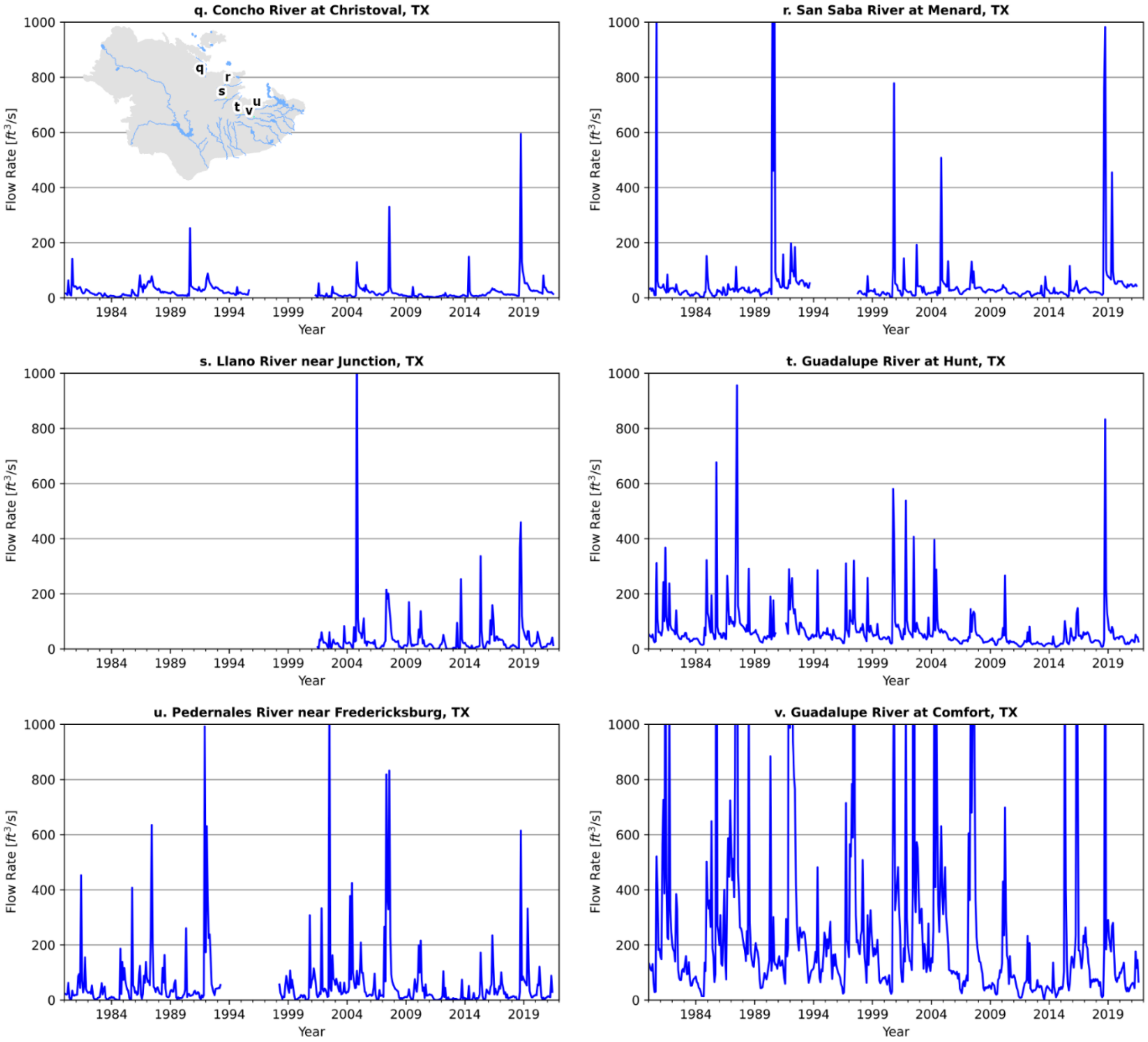
m. San Marcos River at San Marcos, TX

n. Blanco River at Wimberley, TX

o. Onion Creek near Driftwood, TX

p. Colorado River at Austin, TX

Figure 4.5-4 (continued)



q. Concho River at Christoval, TX

r. San Saba River at Menard, TX

s. Llano River near Junction, TX

t. Guadalupe River at Hunt, TX

u. Pedernales River near Fredericksburg, TX

v. Guadalupe River at Comfort, TX

Figure 4.5-4 (continued)

4.6 Hydraulic Properties

The ability of an aquifer to transmit groundwater is influenced by aquifer lithology, fracturing, karstification, structural deformation, and proximity to surface water bodies. Several hydraulic parameters are used to describe aquifer properties, including hydraulic conductivity, transmissivity, specific yield, storativity, and specific capacity. Each of these terms is briefly described below.

Hydraulic Conductivity (K) is a parameter representing how easily groundwater can flow through an aquifer. A higher hydraulic conductivity value means that the groundwater can flow through the aquifer more easily than an aquifer with lower hydraulic conductivity. Hydraulic conductivity may be expressed in feet per day.

Transmissivity (T) is the product of the hydraulic conductivity and the saturated aquifer thickness. Transmissivity is a measure of groundwater flow through the saturated thickness of an aquifer. An aquifer with a higher transmissivity tends to transmit more water than an aquifer with lower transmissivity. Transmissivity may be expressed in square feet per day.

Specific Yield (Sy), also called drainable porosity, is the volume of water released per unit volume of aquifer under the force of gravity. It approximates the effective porosity when the voids in the aquifer are large and well connected. For aquifers with finer materials, the specific yield is usually less than the effective porosity. Specific yield is unitless.

Storativity (S), also called the storage coefficient, is the volume of water released per unit area of aquifer when the water level in the aquifer is lowered by a unit of length. In a confined (or artesian) aquifer, storativity can be used to calculate aquifer specific storage by dividing the aquifer thickness. In an unconfined (water table) aquifer, storativity is essentially equal to the specific yield. The storativity of a confined aquifer is often lower than the specific yield of an unconfined aquifer; given both aquifers contain the same materials. As a result, for the same aquifer, the outcrop area yields more water than downdip portion with the same head loss or drawdown. Storativity is dimensionless. In a confined (or artesian) aquifer, storativity can be used to calculate aquifer specific storage by dividing the aquifer thickness. Specific storage is expressed as one over length such as 1/foot or foot^{-1}.

Specific Capacity (*S_c*), the discharge of a well divided by the drawdown, is a measure of well yield. Specific capacity depends on aquifer properties, well construction, and pumping rate. Specific capacity increases with increasing aquifer transmissivity and well diameter. Well specific capacity is often hindered by poor well design and construction as well as increasing pumping rate, which reduces well efficiency. Specific capacity may be expressed in gallons per minute per foot of drawdown in the well.

Aquifer hydraulic properties are important parameters typically adjusted during model calibration. For this reason, we focused on determining appropriate initial values and ranges of hydraulic properties for use in the model calibration process. Values for hydraulic properties were calculated based on observed data and also compiled values provided in previous studies. The following subsections discuss the data, calculations, and analysis of hydraulic properties for the Pecos Valley Aquifer, the Edwards hydrostratigraphic unit of the Edwards-Trinity (Plateau) Aquifer and the Edwards (Balcones Fault Zone) Aquifer, and the Trinity hydrostratigraphic unit of the Edwards-Trinity (Plateau) Aquifer, the Hill Country portion of the Trinity Aquifer, and the Balcones Falut Zone portion of the Trinity Aquifer within the study area.

4.6.1 Data Sources for Transmissivity Measurements

Aquifer performance tests provide field measurements of transmissivity and storage. Multi-hour to multi-day aquifer pumping tests provide the most reliable estimates of aquifer properties for regional groundwater models as these long tests have a large radius of influence and thus can provide information for a large portion of the aquifer. Unfortunately, conducting and analyzing the results of long-term aquifer tests is expensive and labor-intensive, so long-term aquifer tests are fairly uncommon. Multiple sources for long-term pump test data were queried in the current study area. Data sources for point measurements included:

- TWDB compilations of pumping test analyses (Myers, 1969; Christian and Wuerch, 2012);
- A compilation of pumping tests from county groundwater availability studies (Daniel B. Stephens and Associates, 2006);
- Pumping test data from groundwater conservation districts in the study area, including a compilation of aquifer tests from Barton Springs Edwards Aquifer Conservation District (Hunt and others, 2010) and individual records received and compiled by Toll and others (2018);
- Aquifer pump test data included in the TWDB Brackish Resources Aquifer Characterization System database (TWDB, 2021b);
- The source geodatabase for the Edwards-Trinity (Plateau) Aquifer groundwater availability model (Anaya and Jones, 2009);
- Aquifer pump test data included in the "*Remarks*" section of the TWDB Groundwater Database (TWDB, 2021c); and
- Scanned well documents available from the TWDB Groundwater Data Viewer accessible at https://www3.twdb.texas.gov/apps/WaterDataInteractive/GroundWaterDataViewer.

Two TWDB publications (Myers, 1969; Christian and Wuerch, 2012) provide compilations and analyses of aquifer test data contained in TWDB records. The current study area includes 103 tests from the Myers (1969) dataset and 52 tests from the Christian and Wuerch (2012) dataset.

Daniel B. Stephens and Associates (2006) provides a compilation of pumping tests conducted during the development of housing subdivisions, mostly from counties that require Groundwater Availability Studies as part of the subdivision platting process. This dataset included 10 counties that fall wholly or partially within the current study area, so we were able to use 57 aquifer tests from this dataset.

A Barton Springs Edwards Aquifer Conservation District report (Hunt and others, 2010) provides a compilation of aquifer test data in Hays and Trinity counties, collected from County Water Availability Studies, district hydrogeologic reports, and the TWDB Groundwater Database. After removing tests that are duplicates of previously mentioned datasets, we included 60 tests from this dataset. During the development of the Hill Country portion of the Trinity Aquifer conceptual model (Toll and others, 2018), Barton Springs Edwards Aquifer Conservation District and Blanco-Pedernales Groundwater Conservation District provided several recent documents for individual aquifer tests. We included 23 of these aquifer tests, which are available in the source geodatabase for Toll and others (2018).

The TWDB Brackish Resources Aquifer Characterization System database (TWDB, 2021b) contains aquifer test data collected as part of various TWDB brackish resources reports. Many of these are duplicates of other data sources, particularly Myers (1969) and Christian and Wuerch (2012). After removing duplicates, we included 49 tests from this dataset.

The Edwards-Trinity (Plateau) Aquifer Groundwater Availability Model (Anaya and Jones, 2009) database provides a compilation of aquifer test data from various sources. The majority of these wells are duplicates of wells in the Christian and Wuerch (2012) dataset, which was in progress at the time of that model's publication. After removing duplicates, we included 19 values from the Anaya and Jones (2009) dataset.

The "*Remarks*" field in the "*WellMain*" table of the TWDB Groundwater Database (TWDB, 2021c) includes text containing aquifer test data for several wells. We included 4 wells from this dataset. The "*OtherDataAvailable*" field of the TWDB Groundwater Database "*WellMain*" table also indicates when additional scanned well documents are available for a particular well. We filtered this for wells marked as having "Aquifer Test" data available. Many of these wells are already included in other data sources, including Myers (1969) and Christian and Wuerch (2012). After removing duplicates, we digitized available aquifer test data from the "Scanned Documents" accessible by State Well Number from the interactive interface of the TWDB Groundwater Database at https://www3.twdb.texas.gov/apps/WaterDataInteractive/GroundWaterDataViewer. We included 35 tests from this dataset. Because digitizing scanned documents is a labor-intensive process, focus was given only on areas with few to no aquifer tests available from other datasets and did not include all wells flagged as having available "Aquifer Test" data.

It should also be noted that some wells flagged as having available “Aquifer Test” data are mismarked or have illegible scans, so we did not include these tests in our hydraulic properties database.

We assigned these wells to the current report’s hydrostratigraphic units based on their well depth and screen information, according to the methodology described in Section 4.3.1. In the interest of preserving as much long-term aquifer test data as possible, the aquifer assignment provided in the source dataset for wells with no screen or well depth information available were used. This allowed the study to include several additional wells from the Myers (1969), Christian and Wuerch (2012), Daniel B. Stephens and Associates (2006), and Anaya and Jones (2009) datasets.

The left-hand side of Figure 4.6-1 shows the spatial distribution of transmissivity values from long-term aquifer tests by hydrostratigraphic unit. As shown, long-term aquifer tests are sparse in much of the study area. The hydraulic conductivity was calculated by dividing the transmissivity by the unit thickness at these locations. The left-hand side of Figure 4.6-2 shows the spatial distribution of hydraulic conductivity values from long-term aquifer tests by hydrostratigraphic unit. Table 4.6-1 provides the median transmissivity and hydraulic conductivity values from long-term aquifer tests for each hydrostratigraphic unit.

Table 4.6-1. Hydraulic Properties by Hydrostratigraphic Unit (values represent median of compiled measured values)

Hydrostratigraphic Unit	Transmissivity (square feet per day)			Hydraulic Conductivity (feet per day)			Storativity
	Long-term aquifer tests	Specific capacity tests	Combined long-term + specific capacity tests	Long-term aquifer tests	Specific capacity tests	Combined long-term + specific capacity tests	Long-term aquifer tests
Pecos Valley Alluvium	4,939	3,274	3,702	6.0	5.8	5.8	2.5×10^{-4}
North	4,545	3,293	3,309	8.1	5.9	6.0	3.0×10^{-4}
South	5,079	2,794	4,137	4.5	3.9	4.0	2.0×10^{-4}
Edwards	2,818	1,543	1,543	6.9	4.1	4.1	7.5×10^{-4}
Trinity	213	654	654	0.4	1.4	1.4	3.0×10^{-4}
North Plateau	325	1,037	973	1.8	7.2	7.0	6.0×10^{-4}
South Plateau	231	1,850	1,716	0.3	1.6	1.6	4.9×10^{-4}
Hill Country	164	135	135	0.2	0.2	0.2	1.8×10^{-4}

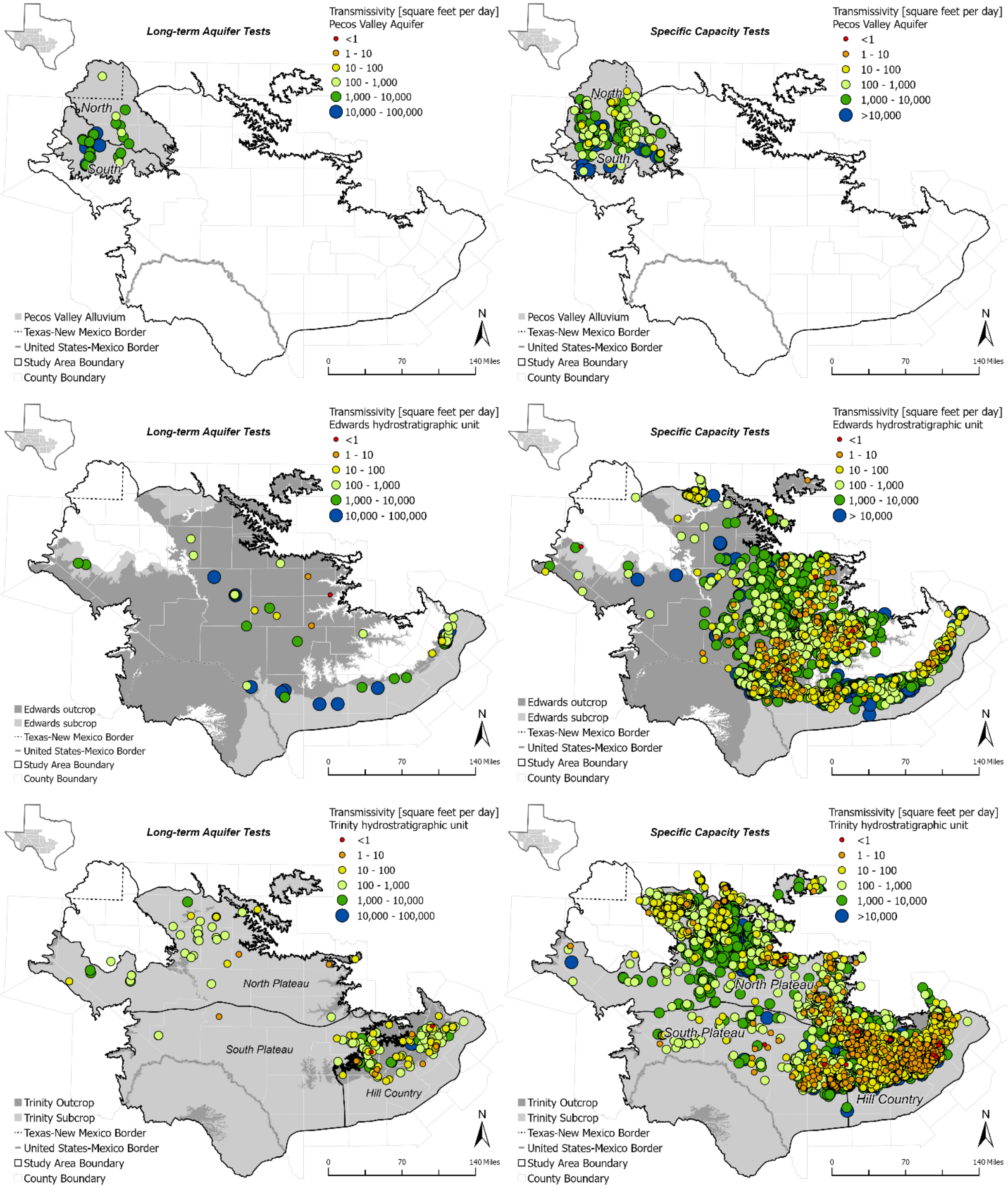


Figure 4.6-1. Transmissivity values by hydrostratigraphic unit estimated from long-term aquifer tests (left-hand side) and specific capacity tests (right-hand side).

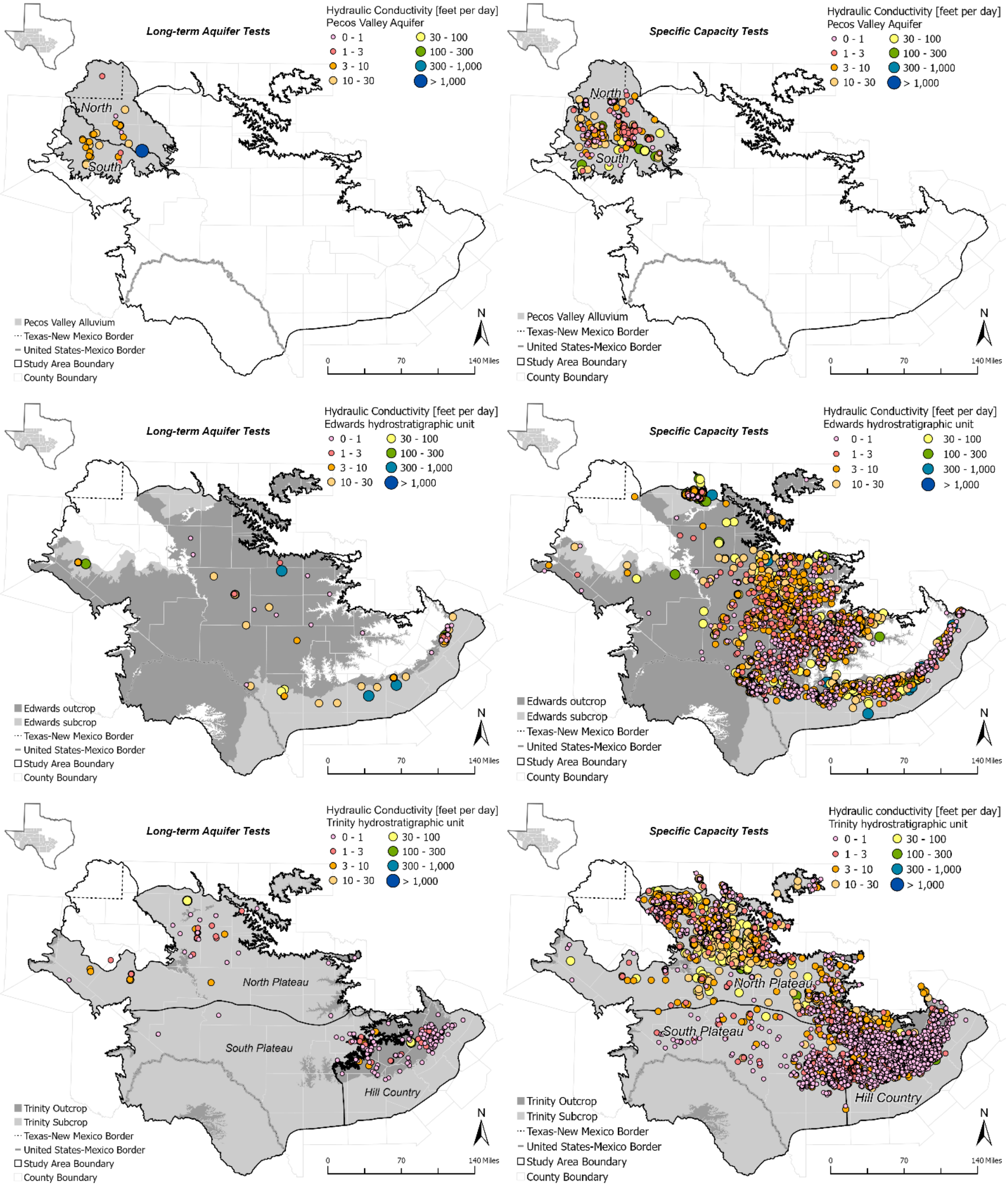


Figure 4.6-2. Hydraulic conductivity values by hydrostratigraphic unit estimated from long-term aquifer tests (left-hand side) and specific capacity tests (right-hand side).

4.6.2 Data Sources for Specific Capacity Tests

Conducting and analyzing the results of long-term aquifer tests is expensive and labor-intensive, so long-term aquifer tests are not well distributed throughout the study area. Specific capacity tests, on the other hand, are simple, short, and commonly available for most wells. Specific capacity, or the pumping rate divided by drawdown, is an important parameter for determining the expected performance of a drilled well. Specific capacity tests stress a smaller portion of the aquifer than long-term aquifer tests and represent near-well aquifer conditions. However, specific capacity tests are useful for filling gaps in areas where long-term aquifer tests are sparse. Multiple sources of specific capacity measurement data were queried in the current study area. Data sources for point measurements of specific capacity included:

- Drawdown, yield, and duration data for specific capacity tests from the "*WellTest*" table in the TWDB groundwater database (TWDB, 2021c);
- Specific capacity data from remarks in the "*WellMain*" table in the TWDB groundwater database (TWDB, 2021c);
- Drawdown, yield, and duration data for specific capacity tests from the "*WellTest*" table in the TWDB submitted drillers' report database (TWDB, 2021d); and
- Specific capacity and duration data for specific capacity tests from the "*tblBRACS_AquiferTestInformation*" table in the TWDB Brackish Resources Aquifer Characterization System database (TWDB, 2021b).

The "*WellTest*" table of the TWDB groundwater database (TWDB, 2021c) includes yield, drawdown, and duration data from specific capacity tests. We calculated specific capacity values by dividing yield by drawdown. Based on recommendations in Mace (2001), wells with a test type of "Bailed" and with a test duration of zero were ignored. Mace (2001) also noted that ignoring wells with zero reported drawdown can introduce a bias towards lower transmissivity values. For this reason, we assumed wells with zero reported drawdown to have a drawdown of 1 foot, a standard value used in previous reports mentioned in Mace (2001). This assumption allowed the study to calculate a specific capacity value for these wells instead of ignoring them. Altogether, we included 648 values from the "*WellTest*" table. The "*Remarks*" field in the "*WellMain*" table of the TWDB groundwater database (TWDB, 2021c) includes text containing specific capacity test results by well. We compiled the specific capacity and test duration values included in the text remarks. Based on recommendations in Mace (2001), wells with a test duration of zero were ignored. After removing duplicates from the "*WellTest*" table, we included 891 wells from this dataset.

The "*WellTest*" table in the TWDB submitted drillers' report database (TWDB, 2021d) includes a spreadsheet of yield, drawdown and duration data from specific capacity tests. This dataset has minor overlap with the TWDB groundwater database (TWDB, 2021c). After removing duplicates, we included 16,050 values from this dataset in the current study area. We used the same assumptions for calculating specific capacity values as we did for the "*WellTest*" table of the TWDB groundwater database (TWDB, 2021c).

The "*tblBRACS_AquiferTestInformation"* table in the TWDB Brackish Resources Aquifer Characterization System database (TWDB, 2021b) contains aquifer test data collected as part of various TWDB brackish resources reports. We compiled specific capacity and test duration values included in the spreadsheet. Based on recommendations in Mace (2001), wells with a test duration of zero were ignored. This database has significant overlap with other datasets, especially the TWDB groundwater database (TWDB, 2021c). After removing duplicates, we included 1,802 values from this dataset.

These wells were assigned to the current report's hydrostratigraphic units based on their well depth and screen information. Note that for brevity, "screen" in this analysis refers to both screened and open intervals. Wells without sufficient depth or screen information were ignored to satisfactorily assign them to the current report's hydrostratigraphic units.

4.6.3 Calculation of Transmissivity from Specific Capacity Tests

There are several methods available for estimating transmissivity using specific-capacity data. A commonly used analytical method from Driscoll (1986) uses a simplified version of the Cooper and Jacob (1946) equation and estimates transmissivity by multiplying specific capacity (in gallons per day per foot) by 2,000 in confined aquifers and by 1,500 in unconfined aquifers. This simplification makes assumptions that are not necessarily appropriate for this study area, so we did not use this method in the current analysis.

One empirical method described in Mace (2001) develops an aquifer-specific relationship between transmissivity and specific capacity using pairs of transmissivity and specific capacity measurements taken at the same wells. Mace (2001) provides a table of aquifer-specific empirical relationships that includes several Texas aquifers within the current study area. From the long-term aquifer test data, we compiled well pairs that had both a transmissivity value and specific capacity value reported and compared this data to the empirical relationships provided in Mace (2001). As shown in Figure 4.6-3, the Trinity well pairs from long-term aquifer test data most closely match the Mace (2001) relationship developed for the Glen Rose and Cow Creek formations while the Edwards well pairs most closely match the Mace (1997) relationship for the Edwards Aquifer.

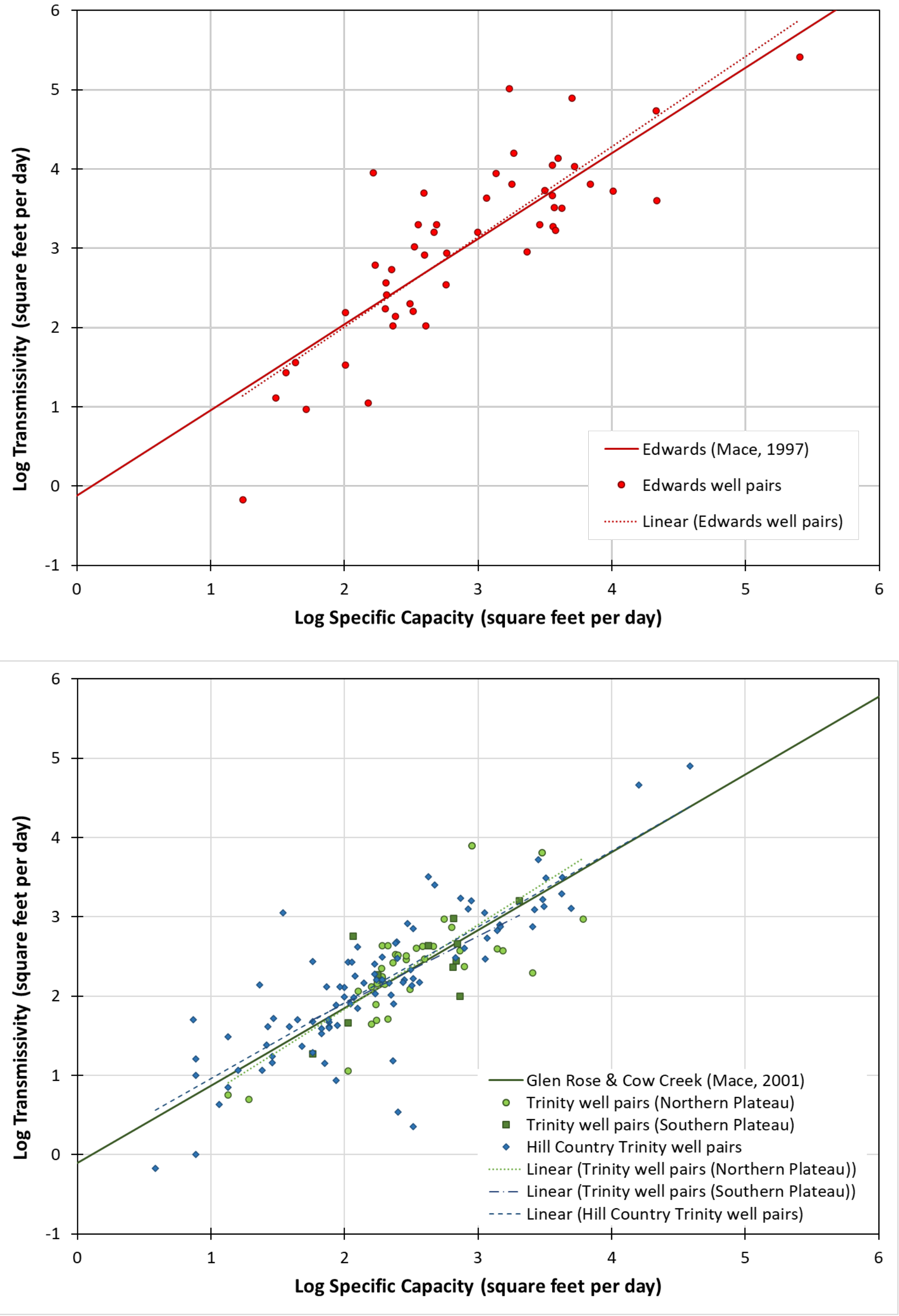


Figure 4.6-3. Comparison of transmissivity and specific capacity measurement pairs to aquifer-specific relationships in the literature.

Because the Edwards and Trinity well pairs closely matched the Mace (2001) empirical relationships, we used these relationships to calculate transmissivity from specific capacity for the Edwards and Trinity hydrostratigraphic units. However, the Pecos Valley Alluvium well pairs (data not shown) did not closely match any empirical relationships provided in Mace (2001). Since no relationships were established with confidence using empirical methods, an analytical method for calculating transmissivity values from specific-capacity data was used instead. According to Mace (2001), the preferred analytical approach for establishing a relationship between specific capacity and transmissivity is based on the Theis non-equilibrium equation (Theis and others, 1963):

$$S_c = \frac{4\pi T}{\left[\ln\left(\frac{2.25Tt}{r^2 S}\right)\right]} \qquad (Equation\ 4.1)$$

where:

S_c= specific capacity,
T = aquifer transmissivity,
t = pumping time,
r = well radius, and
S = aquifer storativity.

Since Equation 4.1 cannot be solved directly for transmissivity, Microsoft Excel was used to solve it iteratively, according to the method provided in Mace (2001). For wells with available screen information, we used the average screen radius. For wells with no screen information, we used an assumed well radius of 4 inches. This value is based on the average radius of wells assigned to the Edwards-Trinity Plateau in the TWDB groundwater database (TWDB, 2021c). The aquifer storativity for the calculation was assumed to be 1.0 x 10^{-4}, which is slightly low but reasonable based on measured storativity values (Section 4.6.6). Based on the recommendation from Mace (2001), the data was ignored where the specific capacity test type is “bailed” and where the pumping duration of the test is not recorded.

It should be noted that this dataset may contain wells whose screens do not cover a large percentage of the aquifer. For these “partially penetrating” wells, the transmissivity value calculated from Equation 4.1 will not be representative of the entire aquifer thickness (Mace, 2001). We did not attempt to correct for this through filtering or mathematical methods, as most wells in the dataset lacked sufficient screen information to confidently make these corrections.

The right-hand side of Figure 4.6-1 shows the spatial distribution of the transmissivity estimates derived from specific capacity data by hydrostratigraphic unit. The right-hand side of Figure 4.6-2 show the spatial distribution of hydraulic conductivity derived from specific capacity data by hydrostratigraphic unit. The hydraulic conductivity was calculated by dividing the transmissivity by the unit thickness at these locations. Table 4.6-1 summarizes the median transmissivity and hydraulic conductivity values calculated from specific capacity data for each hydrostratigraphic unit.

4.6.4 Transmissivity and Horizontal Hydraulic Conductivity Discussion

For this conceptual model, we focused on determining appropriate initial values and ranges of hydraulic properties for use in the model calibration process. As with all field data, the compiled hydraulic property measurements described above have some uncertainty. The assumptions in the methodology for assigning aquifers and calculating transmissivity from specific capacity introduce more uncertainty. Since interpolating over the current large study area might inadvertently emphasize misleading anomalies caused by these assumptions, we did not attempt to interpolate either the transmissivity or hydraulic conductivity distribution. Instead, the study depends on the calculated range and statistical distribution of these compiled values to determine representative hydraulic property values over the coarse of geologically similar spatial zones, as shown in Figure 4.6-1 and Figure 4.6-2. Table 4.6-1provides the median hydraulic property values calculated from the long-term aquifer tests and specific capacity tests as well as the median value of all tests combined. Figure 4.6-4 provides histograms of transmissivity values by hydrostratigraphic unit based on the combined data gathered from both long-term aquifer tests and specific capacity tests. Figure 4.6-5 provides histograms of hydraulic conductivity values by hydrostratigraphic unit.

Pecos Valley Aquifer

In the shallow hydrostratigraphic unit, we only considered hydraulic property data for the Pecos Valley Aquifer. In the Pecos Valley Aquifer, a median hydraulic conductivity of 5.8 feet per day was derived based on all well test data. The area north of the Pecos River has a slightly higher median hydraulic conductivity (5.9 feet per day) than the area south of the Pecos River (3.9 feet per day). During model calibration, it will be determined whether it makes sense to separate these areas into different zones. The previous TWDB groundwater availability model for the Edwards-Trinity (Plateau) Aquifer (Anaya and Jones, 2009) used a hydraulic conductivity value of 9 feet per day for the Pecos Valley Aquifer. An alternate version of this model using a different calibration method (Young and others, 2010) found a calibrated median hydraulic conductivity value of 7.1 feet per day.

The calculated hydraulic conductivity value for the Pecos Valley Aquifer is slightly lower than the values from previous models but seems reasonable as an initial value for calibration. Since the full aquifer thickness was used in the calculation of hydraulic conductivity rather than saturated thickness, it makes sense that the values skew lower. During calibration, we will consider increasing the hydraulic conductivity value to closer match the previous modeled values.

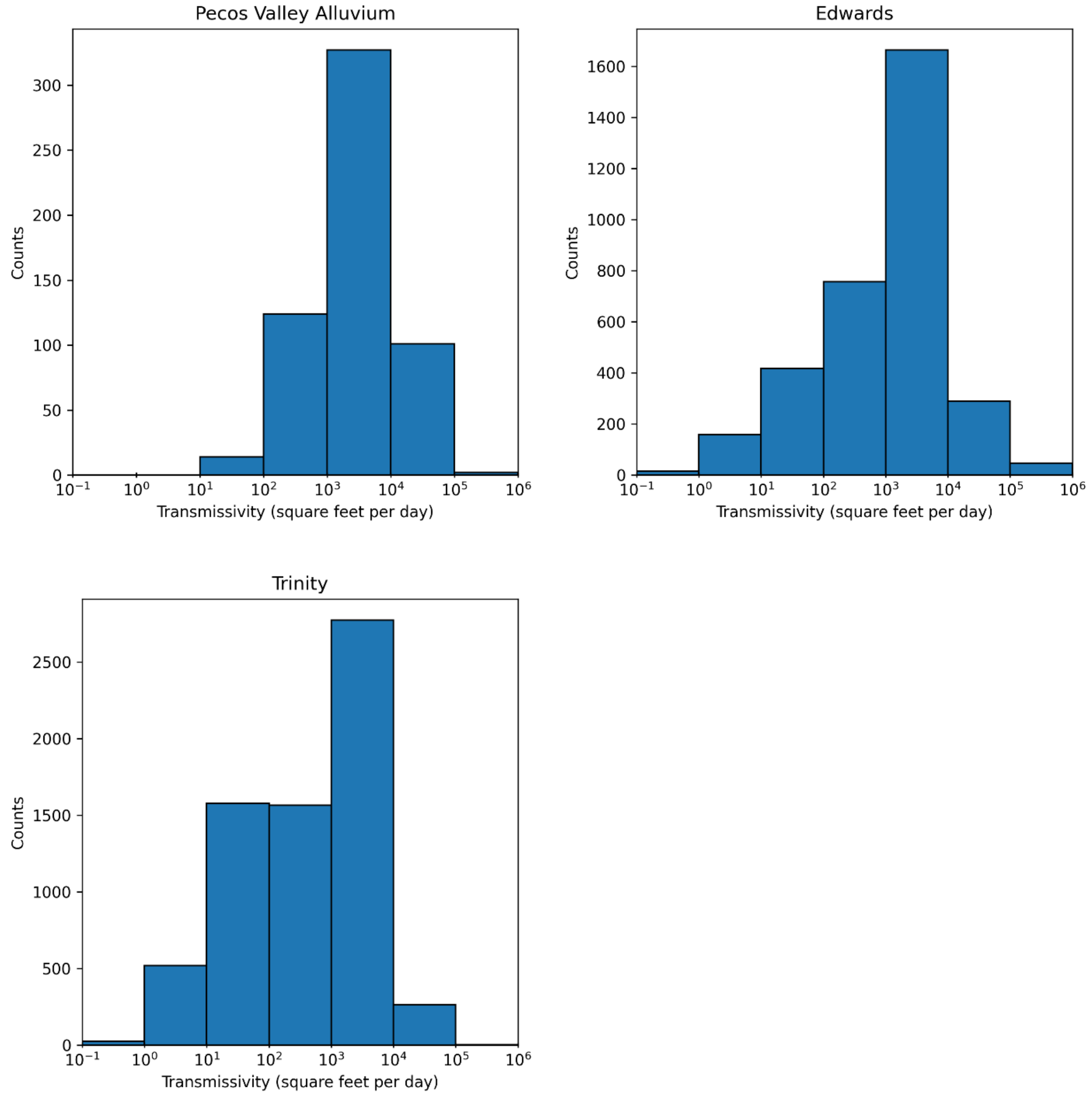


Figure 4.6-4. Histograms of Transmissivity estimates by hydrographic unit.

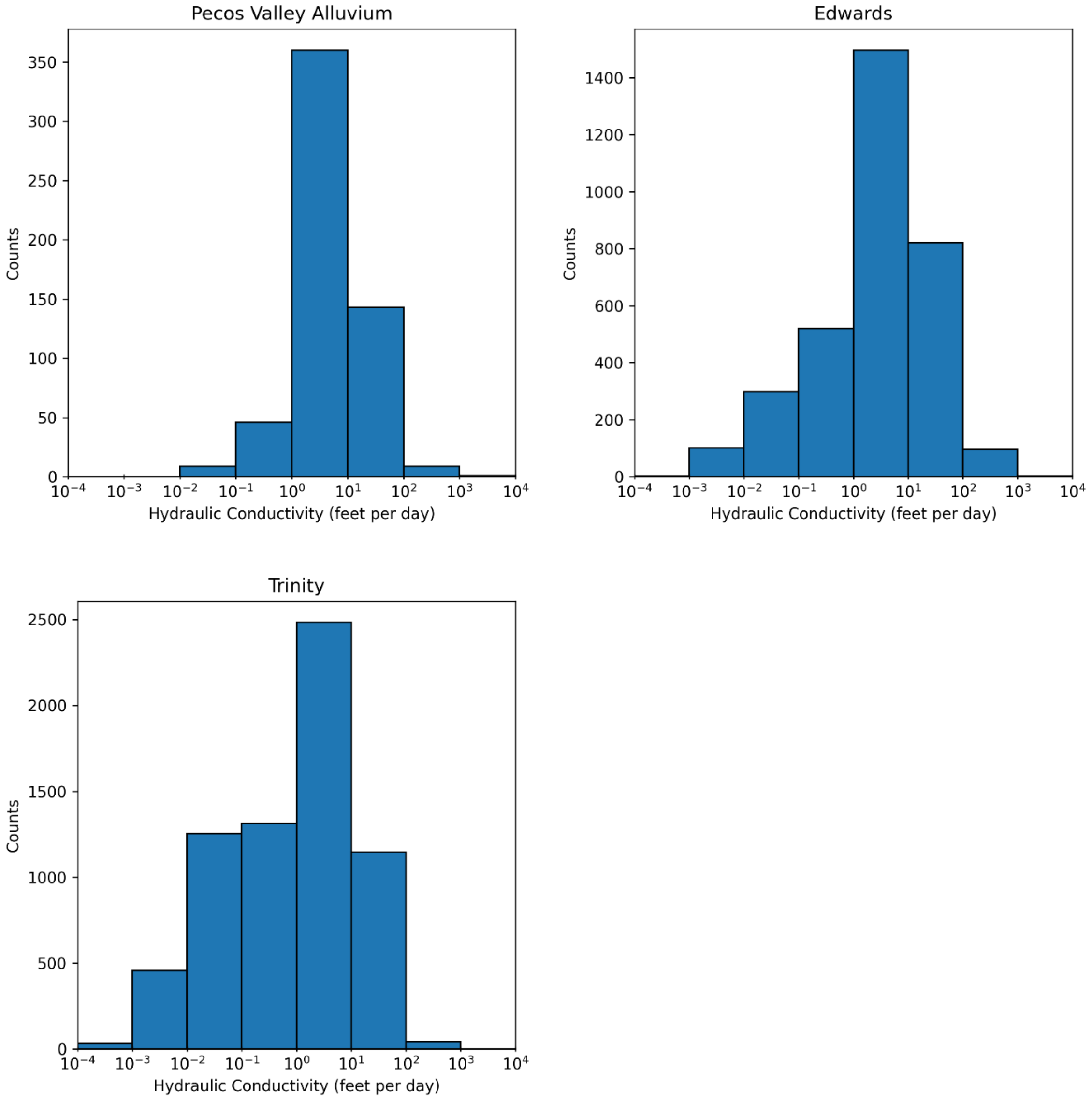


Figure 4.6-5. Histograms of hydraulic conductivity estimates by hydrographic unit.

Edwards hydrostratigraphic unit

In the Edwards hydrostratigraphic unit, a median hydraulic conductivity of 4.1 feet per day was derived based on all well data. The previous TWDB groundwater availability model for the Edwards-Trinity (Plateau) Aquifer (Anaya and Jones, 2009) used a hydraulic conductivity value of 6.65 feet per day for this unit. An alternate version of this model using a different calibration method (Young and others, 2010) found a calibrated median hydraulic conductivity value of 8 feet per day. The previous TWDB model for the Hill Country portion of the Trinity Aquifer (Jones and others, 2011) found a calibrated hydraulic conductivity value of 11 feet per day for the Edwards Group.

The calculated hydraulic conductivity value for the Edwards hydrostratigraphic unit is slightly lower than the values from previous models but generally seems reasonable as an initial value for calibration. The exception is in the highly-productive Edwards (Balcones Fault Zone) Aquifer, where this hydraulic conductivity value may be too low. During calibration, it will be determined whether it makes sense to either increase hydraulic conductivity or to separate this highly-faulted area into a different zone than the rest of the study area (where the Edwards hydrostratigraphic unit is largely intact). However, a compilation of aquifer tests in this region (Hunt and others, 2010) found a median Edwards hydraulic conductivity of 5.71 feet per day, which implies that the calculated value for this study may not be unreasonable. A model of the Edwards-Trinity aquifer system in the Hill Country area (Kuniansky and Ardis, 2004) also showed that the faults in this region can severely constrict flow perpendicular to the faults, which may also cause lower hydraulic conductivity values.

Trinity hydrostratigraphic unit

For discussion purposes, the Trinity hydrostratigraphic unit was split into several zones, labeled in Figure 4.6-1 and Figure 4.6-2. The “Hill Country” region refers to the area of the Trinity hydrostratigraphic unit representing the Hill Country portion of the Trinity Aquifer. The “North Plateau” region refers to those western portions of the Trinity hydrostratigraphic unit in the Edwards-Trinity (Plateau) Aquifer where the Glen Rose Formation is absent and the “South Plateau” region refers to where the Glen Rose Formation is present. This boundary of the Glen Rose Formation was georeferenced from Barker and others (1994). The “Nolan Island” region refers to the isolated portion of the Edwards-Trinity (Plateau) Aquifer occurring mostly in Nolan and Taylor counties. For this analysis, we have included this area into the “North Plateau” region, but during calibration, considerations will be made as to whether it makes sense to treat this area separately.

In the North Plateau region of the Trinity hydrostratigraphic unit, the median hydraulic conductivity derived from all well data is 7.0 feet per day. The previous TWDB groundwater availability model for the Edwards-Trinity (Plateau) Aquifer (Anaya and Jones, 2009) used a hydraulic conductivity value of 15 feet per day for this region. A re-calibrated version of the Edwards-Trinity (Plateau) Aquifer model (Young and others, 2010), found a calibrated median hydraulic conductivity value of 3.7 feet per day. The calculated hydraulic conductivity value for the North Plateau region of the Trinity hydrostratigraphic unit falls between the values from previous models and seems reasonable as an initial value for calibration.

In the South Plateau region of the Trinity hydrostratigraphic unit, the median hydraulic conductivity derived from compiled well data is 1.6 feet per day. The previous TWDB groundwater availability model for the Edwards-Trinity (Plateau) Aquifer (Anaya and Jones, 2009) used a hydraulic conductivity value of 2.5 feet per day for this region. An alternate version of this model using a different calibration method (Young and others, 2010) found a calibrated median hydraulic conductivity value of 2.1 feet per day. The calculated hydraulic conductivity value for the South Plateau region of the Trinity hydrostratigraphic unit is slightly lower than the values from previous models but seems reasonable as an initial value for calibration.

In the Hill Country region of the Trinity hydrostratigraphic unit, the median hydraulic conductivity derived from compiled well data is 0.2 feet per day. The previous TWDB groundwater availability model for the Edwards-Trinity (Plateau) Aquifer (Anaya and Jones, 2009) used a hydraulic conductivity value of 2.5 feet per day. An alternate version of this model using a different calibration method (Young and others, 2010) found a calibrated median hydraulic conductivity value of 2.1 feet per day. The calculated hydraulic conductivity value for the Hill Country region of the Trinity hydrostratigraphic unit in this study is lower than the values from previous models. Since the calculated value includes all subunits of the Trinity hydrostratigraphic unit, even the very low permeability portions, the lower calculated value might be over-representing lower permeability subunits. Since these subunits will not be implemented individually in the model, it may not be reasonable to use the lower value to represent the combined Trinity hydrostratigraphic unit in this area. During calibration of the numerical model, we will consider using higher values, more similar to past models, for hydraulic conductivity in this region.

4.6.5 Vertical Hydraulic Conductivity

In the context of regional groundwater planning, vertical hydraulic conductivity is largely considered for its impact on leakage between hydrostratigraphic units and into hydrostratigraphic units from springs and streams. A vertical leakage coefficient is the vertical hydraulic conductivity of a unit divided by the thickness of the unit. In most sedimentary aquifers, we assume that vertical hydraulic conductivity is lower than horizontal hydraulic conductivity. In other words, water flows more easily along the horizontal plane of the geologic layer than vertically through the layer. A common assumption is that horizontal hydraulic conductivity is 10 times greater than vertical hydraulic conductivity. However, the actual difference between vertical hydraulic conductivity and horizontal hydraulic conductivity, often expressed as a vertical anisotropy ratio, depends on local geologic conditions. In the Hill Country area, low-permeability confining units like the Hammett Shale, Bexar Shale, and the clays and marls of upper member of the Glen Rose Limestone create high vertical anisotropy ratios within the Trinity Aquifer. A study by W.E. Simpson Company and William F. Guyton Associates (1993) in northern Bexar County estimated vertical hydraulic conductivity in these confining units is only around 1.0×10^{-4} to 0.003 feet per day. These confining units are not present further west in the study area. So, as noted in Anaya and Jones (2009), the thinner, but more homogenous Trinity Sands in the northwest portion of the Edwards-Trinity (Plateau) Aquifer have less vertical anisotropy than the shale, sand, and limestone transgressive-regressive sequence in the Hill Country portion of the Trinity Aquifer. For this reason, we will consider the Hill Country region separately from the Plateau regions during calibration.

Since measured vertical hydraulic conductivity values are rare, vertical hydraulic conductivity is usually a calibrated model parameter. In fact, standard modeling procedures provided by Anderson and Woessner (1992) recommend using groundwater models for estimating vertical hydraulic conductivity at a regional scale. The previous TWDB model for the Edwards-Trinity (Plateau) Aquifer (Anaya and Jones, 2009) assumed an initial vertical hydraulic conductivity value equal to 10 percent of the horizontal hydraulic conductivity. Within the model layer representing the Edwards hydrostratigraphic unit, the calibrated vertical hydraulic conductivity value was 1.0×10^{-4} feet per day in areas overlying those portions of the Trinity hydrostratigraphic unit that represented the Glen Rose Formation and 1.0×10^{-5} feet per day in areas where Glen Rose Formation was absent. Within the model layers representing the Edwards and Trinity hydrostratigraphic units, little to no cross-formational flow was found to or from the underlying Dockum, Capitan Reef Complex, Rustler, and Hickory aquifers. The previous TWDB model for the Hill Country portion of the Trinity Aquifer (Jones and others, 2011) assumed an initial vertical hydraulic conductivity value equal to 10 percent of the horizontal hydraulic conductivity, with the and the vertical leakance ranging from 1.0×10^{-6} to 0.8 per day.

4.6.6 Storage Properties

Storativity, or storage coefficient, is the volume of water released per unit area of aquifer when the water level in the aquifer is lowered by one unit of length. In a confined (or artesian) aquifer, aquifer specific storage can be calculated by dividing storativity by the aquifer thickness. In an unconfined (water table) aquifer, storativity is essentially equal to the specific yield, or drainable porosity. The following sections discuss our estimates for these storage properties.

Storativity and Specific Storage Values

As with transmissivity, analyses of long-term pump tests provide the most reliable estimates for storativity. We queried multiple sources for long-term aquifer test data, as discussed in Section 4.6.1. The queries found 145 measurements of storativity values from long-term aquifer test data in the current study area. We ignored values marked as literature values since these were not calculated using aquifer test data or marked as unreliable or out-of-range. Table 4.6-1 provides the median values of measured storativity values by hydrostratigraphic unit. Figure 4.6-6 shows the spatial distribution of these point measurements by hydrostratigraphic unit. Figure 4.6-7 shows the histograms of storativity by hydrostratigraphic unit. The median storativity value is 2.5×10^{-4} for the Pecos Valley Aquifer, 7.5×10^{-4} for the Edwards hydrostratigraphic unit, and 3.0×10^{-4} for the Trinity hydrostratigraphic unit. Within the Trinity hydrostratigraphic unit, storativity is lower in the the Hill Country portion of the Trinity Aquifer (1.8×10^{-4}) than in the northern portion of the Edwards-Trinity Plateau (6.0×10^{-4}) and the southern portion of the Edwards-Trinity Plateau (4.9×10^{-4}).

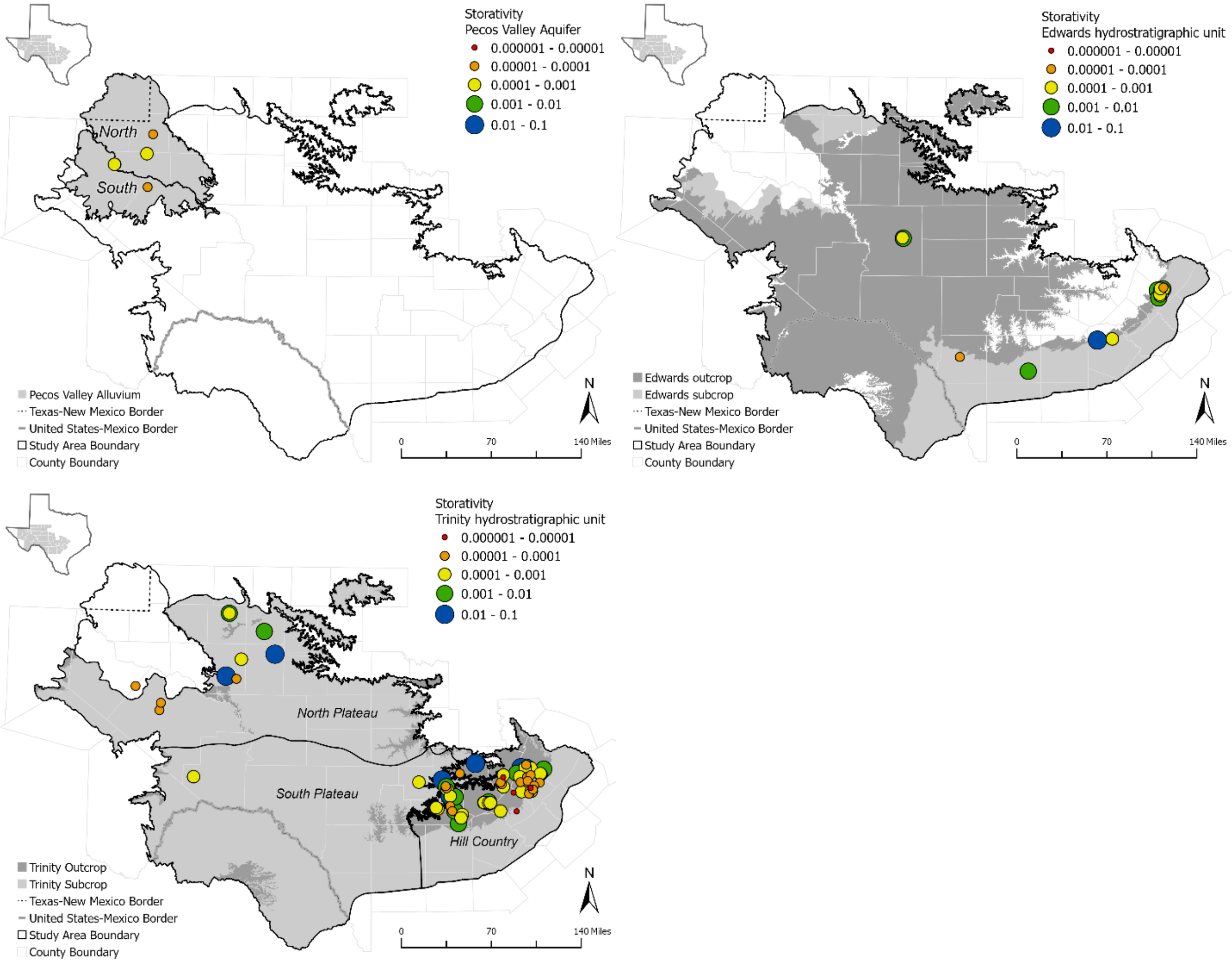


Figure 4.6-6. Measured storativity values derived from long-term aquifer tests by hydrostratigraphic unit.

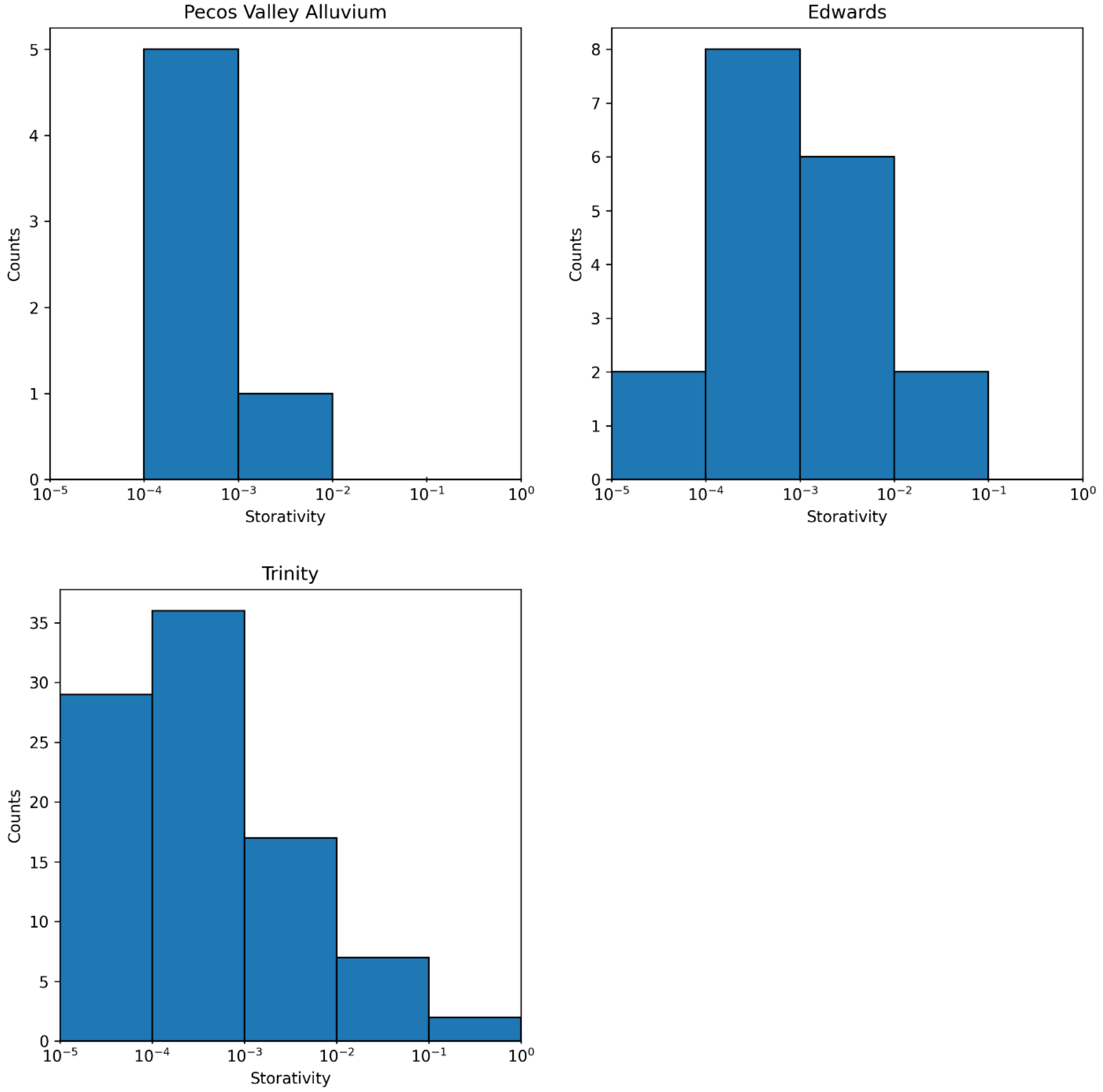


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Figure 4.6-7. Range of measured storativity values by hydrostratigraphic unit.

In addition to measured data, we also considered literature values for storage properties. Walker (1979) provides a compilation of aquifer tests for the “Lower Cretaceous Aquifer” in the Edwards-Trinity (Plateau) region. This dataset includes several wells falling within the current model’s Trinity hydrostratigraphic unit, including a Gillespie County well in the Hensell Formation with a storativity value of 7.0×10^{-5} and five Kerrville wells in the Hosston and Sligo formations with storativity values ranging from 2.0×10^{-5} to 5.0×10^{-5}. Ashworth (1983) compiled storativity values from Walker (1979) and an additional well completed in Cow Creek, Sligo and Hosston formations with a storage coefficient of 7.4×10^{-4}.

Specific storage refers to the storage coefficient divided by the thickness of the aquifer. In the previous TWDB groundwater availability model for the Edwards-Trinity (Plateau) Aquifer (Anaya and Jones, 2009), the calibrated specific storage value was 2.0×10^{-4} per foot for the modeled unit representing the current Pecos Valley Aquifer. For the modeled unit representing the current Edwards hydrostratigraphic unit, the calibrated specific storage value ranged from 5.0×10^{-7} to 5.0×10^{-6} per foot. For the modeled unit representing the current Trinity hydrostratigraphic unit, the calibrated specific storage value ranged from 1.0×10^{-7} to 1.0×10^{-5} per foot. An alternate version of this model using a different calibration method (Young and others, 2010) found that the calibrated median specific storage value was 4.1×10^{-5} per foot in the modeled unit representing the Pecos Valley Aquifer and 1.1×10^{-5} per foot in the modeled unit representing the current Edwards hydrostratigraphic unit. For the modeled unit representing the current Trinity hydrostratigraphic unit, the calibrated specific storage value was 9.2×10^{-6} per foot in the Southern Plateau and Hill Country regions, 9.4×10^{-6} per foot in the Northern Plateau region and 1.0×10^{-5} per foot in the Nolan Island region.

Specific Yield Values

As discussed earlier, the storativity is essentially equal to the specific yield for unconfined aquifers and tends to be higher in unconfined aquifers than in confined aquifers. The median storativity values in Table 4.6-1 seem lower than typical specific yield values and therefore likely represent confined storativity values rather than specific yield values. For comparison, representative specific yield values in the literature for unconsolidated gravels and sands similar to the Pecos Valley Aquifer range from 0.21 to 0.33 (Morris and Johnson, 1967) or from 0.19 to 0.22 (Heath,1983). These literature values are similar to the calibrated specific yield values in previous models. In the previous TWDB groundwater availability model for the Edwards-Trinity (Plateau) Aquifer (Anaya and Jones, 2009), the calibrated specific yield value was 0.2 for the modeled unit representing the current Pecos Valley Aquifer. An alternate version of this model using a different calibration method (Young and others, 2010) found that the calibrated median specific yield value was 0.1 in the modeled unit representing the current Pecos Valley Aquifer. Since the calculated storativity values are too low to consider them representative of unconfined specific yield in the Pecos Valley Aquifer, we will instead use a higher value during calibration, more similar to previous models and the literature values.

The specific yield of consolidated materials, like the limestone and sandstone present in the Edwards and Trinity hydrostratigraphic units, are typically lower than in unconsolidated materials like the alluvium of the Pecos Valley Aquifer. However, representative specific yield values for these materials in the literature are still much higher than the storativity values in Table 4.6-1. For instance, typical limestone values range from 0.14 (Morris and Johnson, 1967) to 0.18 (Heath, 1983) and sandstone ranges from 0.06 (Heath, 1983) to 0.27 (Morris and Johnson, 1967). In the previous TWDB groundwater availability model for the Edwards-Trinity (Plateau) Aquifer (Anaya and Jones, 2009), the calibrated specific yield value ranged from 5.0×10^{-4} to 0.05 for the modeled unit representing the current

Edwards hydrostratigraphic unit. For the modeled unit representing the current Trinity hydrostratigraphic unit, the calibrated specific yield value ranged from 0.003 to 0.03 throughout most of the Edwards-Trinity Plateau region, and down to 3.0×10^{-4} in the southern confined part of the Hill Country region. An alternate version of this model using a different calibration method (Young and others, 2010) found that the calibrated median specific yield value was 0.009 in the modeled unit representing the current Edwards hydrostratigraphic unit, and 0.08 in the modeled unit representing the current Trinity hydrostratigraphic unit. Since the calculated storativity values for this study are too low to consider them representative of unconfined specific yield in the Edwards and Trinity hydrostratigraphic units, we will instead use a higher value during calibration, more similar to previous models. As those models indicate that the Edwards and Trinity hydrostratigraphic units act as confined aquifers through much of their extent, specific yield will be a less important parameter for these units compared to the fully unconfined Pecos Valley Aquifer.

4.7 Discharge

Discharge is the process by which water leaves an aquifer. There are two types of discharge: natural and anthropogenic. The natural discharge process can include outflow to streams or springs, evapotranspiration, and cross-formational flow. Pumping from wells is an example of anthropogenic discharge from aquifers.

4.7.1 Natural Aquifer Discharge

Groundwater discharges naturally through springs or stream baseflow in areas where the water level intersects ground surface. As discussed in Section 4.5, discharge to springs and streams mostly occurs in the southern and southeastern portion of the study area, particularly in the Edwards Balcones Fault Zone area and along the eastern margin of the Edwards Plateau area. Detailed discussion about groundwater discharges to surface water bodies within the study area can be found in Section 4.5.

Natural groundwater discharge can also take the form of cross-formational flow between hydraulically contiguous major and minor aquifers of the Edwards-Trinity aquifer system. Cross-formational flow in the study area occurs between the Hill Country portion of the Trinity Aquifer and the Edwards (Balcones Fault Zone) Aquifer. However, the actual rate of cross-formational flow is difficult to measure. While several studies (Kuniansky and Holligan, 1994; Mace and others, 2000; Anaya and Jones, 2009) provide evidence for the existence of this cross-formation flow and provide estimates of the volume of flow, there is no consensus on the actual amount of flow. Another location for cross-formational flow is near the eastern flanks of the Trans-Pecos mountains, where some groundwater flows from the Edwards-Trinity (Plateau) Aquifer into the Pecos Valley Aquifer (Anaya and Jones, 2009).

Evapotranspiration refers to the net water extraction due to evaporation from bare soil, open water surfaces, and transpiration from plants. If the water table is shallow or phreatophytes are abundant, groundwater evapotranspiration can be significant for aquifers (Scanlon and others, 2005). Phreatophytes, which are deep-rooted and obtain most of their water from the saturated zone of an aquifer, occur along major stream valleys and can greatly increase evapotranspiration rates. Anaya and Jones (2009) noted that high evapotranspiration rates occur along the Pecos River in the Trans-Pecos region. Scanlon and others (2005) completed the evapotranspiration study over Texas as shown in Figure 4.7-1.

A TWDB subcontractor (WSP USA) is concurrently developing discharge estimates for the Pecos Valley and Edwards-Trinity (Plateau) regional aquifers model study area based on several estimation methods, including an evapotranspiration analysis based on remote-sensing and TexMesonet data. The draft report will be publicly available at the same time as the current report. That report will provide estimates for evapotranspiration values in the study area. The evapotranspiration rates in the final numerical groundwater model will be based on the findings of that study.

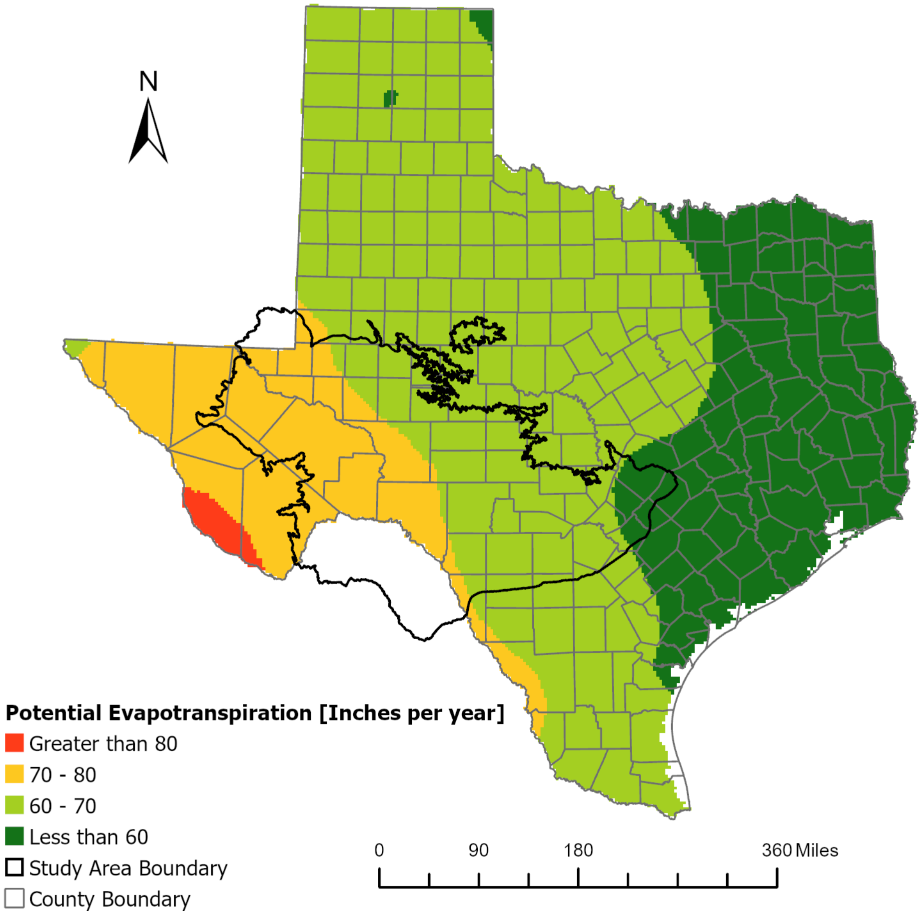

Figure 4.7-1. Potential Evapotranspiration for Texas (Scanlon and others, 2005).

4.7.2 Aquifer Discharge through Pumping

Pumping-or anthropogenic extraction of groundwater from an aquifer-often makes up a significant portion of groundwater discharge. Groundwater pumping in the study area provides water for irrigation, livestock, manufacturing, mining, municipal, and domestic use. TWDB collects pumping data from industrial and municipal users through the Water Use Survey, as mandated by the Texas Water Code. TWDB provides the compiled results by year and by county in the historical groundwater pumpage dataset. This dataset provides an invaluable starting point for developing a pumping dataset in the study area. However, this dataset requires substantial understanding to provide a complete picture of pumping in the study area. For instance, in addition to surveyed water use, this dataset contains the non-surveyed water use, which estimates the county-level water use based on the methodologies and assumptions developed by TWDB staff for the area where no water use survey data is collected. Understanding the assumptions and methodologies behind the data is essential. In addition, changes in data collection, survey distribution, and survey response rates can introduce inconsistencies or even data gaps to this dataset.

A TWDB subcontractor (LRE Water LLC.) is concurrently developing pumping estimates for the Pecos Valley and Edwards-Trinity (Plateau) regional aquifers model study area meant to fill the data gaps in the TWDB historical groundwater pumpage dataset. The draft report will be publicly available at the same time as the current report. That report will provide estimates for pumping values and spatial distribution of pumping in the study area. The pumping rates in the final numerical groundwater model will be based on the findings of this study.

4.8 Water Quality

We will be developing a regional groundwater flow model instead of a contaminant transport (water quality) model or a seawater intrusion model. As such, water quality variations will not be directly incorporated into the numerical model. However, water quality analysis can still provide insight into the overall conceptualization of groundwater flow in the study area. The following groundwater quality analysis was used to evaluate groundwater's salinity levels, recharge conditions, approximate and relative ages, and the general flow direction. We conducted the water quality analysis with the "*WaterQualityMajor*" table in the TWDB groundwater database (TWDB, 2021c). Water quality analysis includes 7,635 wells data from the Pecos Valley, Edwards-Trinity (Plateau), and Edwards (Balcones Fault Zone) aquifers and the Hill Country portion of the Trinity Aquifer (Figure 4.8-1). We used the aquifer classification assigned within the TWDB groundwater database since water quality analysis provides a general groundwater trend rather than the numerical model's specific data. This section discusses the major element and isotopic compositions of groundwater in the aquifers within our study area with implications for determination of groundwater flow through and recharge to the respective aquifers.

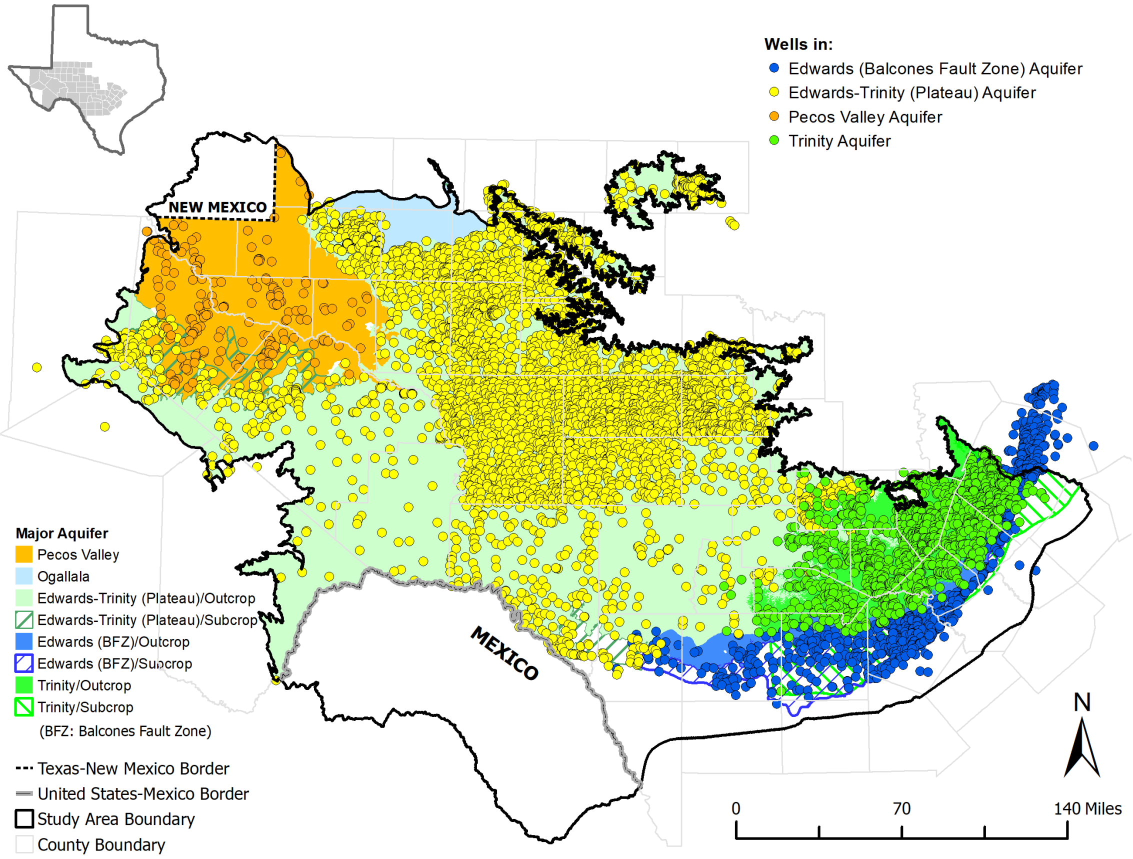

Figure 4.8-1. Location of Water Quality Samples (TWDB, 2021c).

4.8.1 Major Elements

Groundwater total dissolved solids and major elements concentrations can provide information about groundwater hydrology. In general, lower concentrations can represent areas with freshwater inflow- often recharge from precipitation- or areas where the groundwater has not extensively interacted with the rock formations of the aquifer due to either the young age of water or the insolubility of the aquifer matrix. Higher concentrations can indicate deeper areas with less recent recharge or areas where water has extensively interacted with the rock formations of the aquifer due to either the older age of the water or the solubility of the aquifer matrix. Areas of anomalously high salinity can also help pinpoint the locations of features like salt domes and evaporite beds or, near the coast, the extent of seawater intrusion. Some major elements are of concern due to their deleterious effects on human health and need to be measured against drinking water standards. In some parts of the study area, total dissolved solids and chloride and sulfate concentrations exceed applicable water quality standards. High concentrations of these constituents occur in the Pecos Valley and Trinity aquifers, north-central parts of the Edwards-Trinity (Plateau) Aquifer, and downdip portions of the Edwards (Balcones Fault Zone) Aquifer.

Figure 4.8-2 shows total dissolved solids in Pecos Valley Aquifer groundwater. Fresh groundwater—total dissolved solids less than 1,000 milligrams per liter—primarily occurs in the Monument Draw portion of the aquifer that extends through Winkler County and parts of Ward and Pecos counties (Jones, 2008). Fresh groundwater also occurs in parts of Crane and Reeves counties. Generally, most fresh groundwater in the aquifer occurs north of the Pecos River. Slightly to very saline groundwater—total dissolved solids of 1,000 milligrams per liter to less than 35,000 milligrams per liter—occurs throughout the remainder of the aquifer, especially south and west of the Pecos River. Jones (2008) attributes this moderate to very saline groundwater either to 1) the recharge of surface runoff derived from the evaporitic outcrops of the Rustler Formation west of the Pecos Valley Aquifer, or 2) upward influxes of saline groundwater from the underlying Rustler, Dockum and Capitan Reef Complex aquifers. While the bottom of the Pecos Valley Aquifer over these deeper aquifers is currently conceptualized as a no-flow boundary, the potential for upward flow based on these observed salinity fluxes will be considered during development of the numerical model, if appropriate.

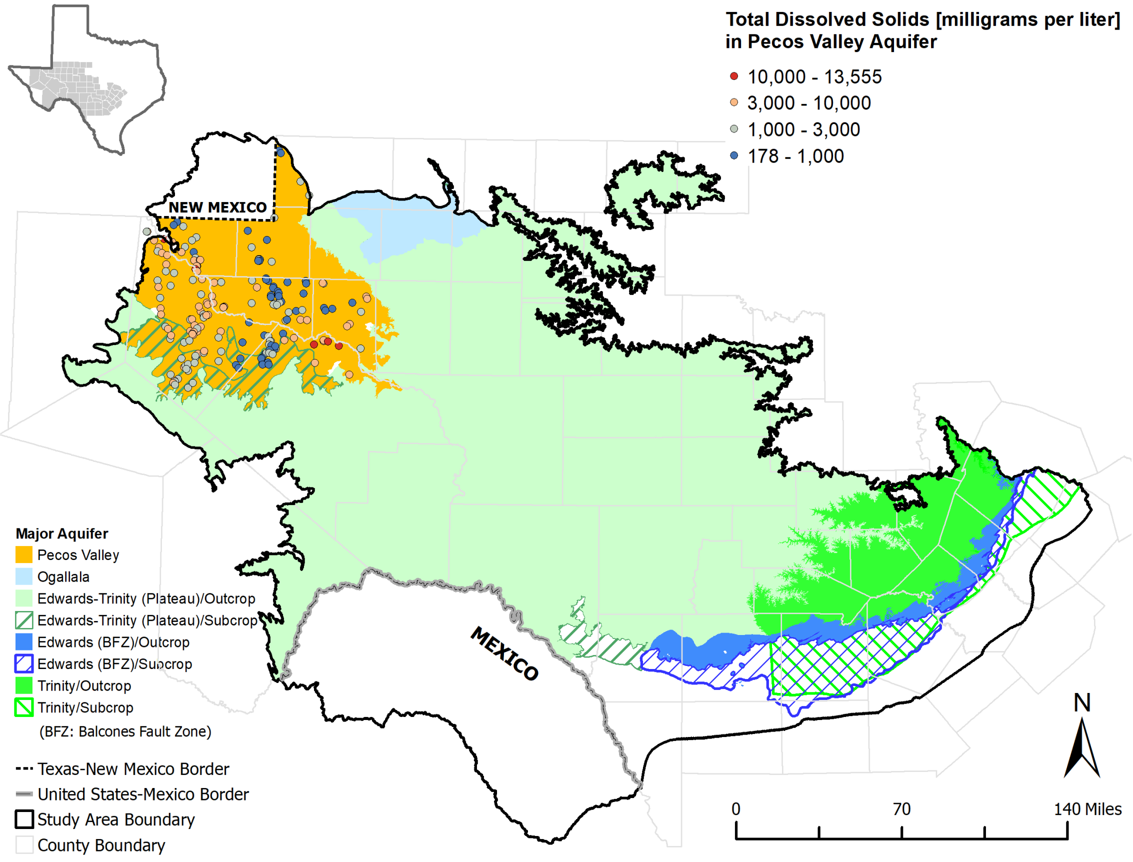

Figure 4.8-2. Map of average total dissolved solids (in milligrams per liter) for the Pecos Valley Aquifer (TWDB, 2021c).

In the Edwards-Trinity (Plateau) Aquifer, most groundwater is fresh (Figure 4.8-3). Slightly to very saline groundwater occurs mostly in the western half of the aquifer. The saline groundwater occurs along the boundary between the Edwards-Trinity (Plateau) and Pecos Valley aquifers where the two aquifers overlap and overlie saline aquifers such as the Rustler and Dockum aquifers. While the bottom of the Edwards-Trinity (Plateau) Aquifer over these deeper aquifers is currently conceptualized as a no-flow boundary, the potential for upward flow based on these observed salinity fluxes will be considered during development of the numerical model, if appropriate. Saline groundwater in the Edwards-Trinity (Plateau) Aquifer also occurs in the central portion of the aquifer, associated with the Antlers Sand and overlying Edwards Limestone (Nance, 2010).

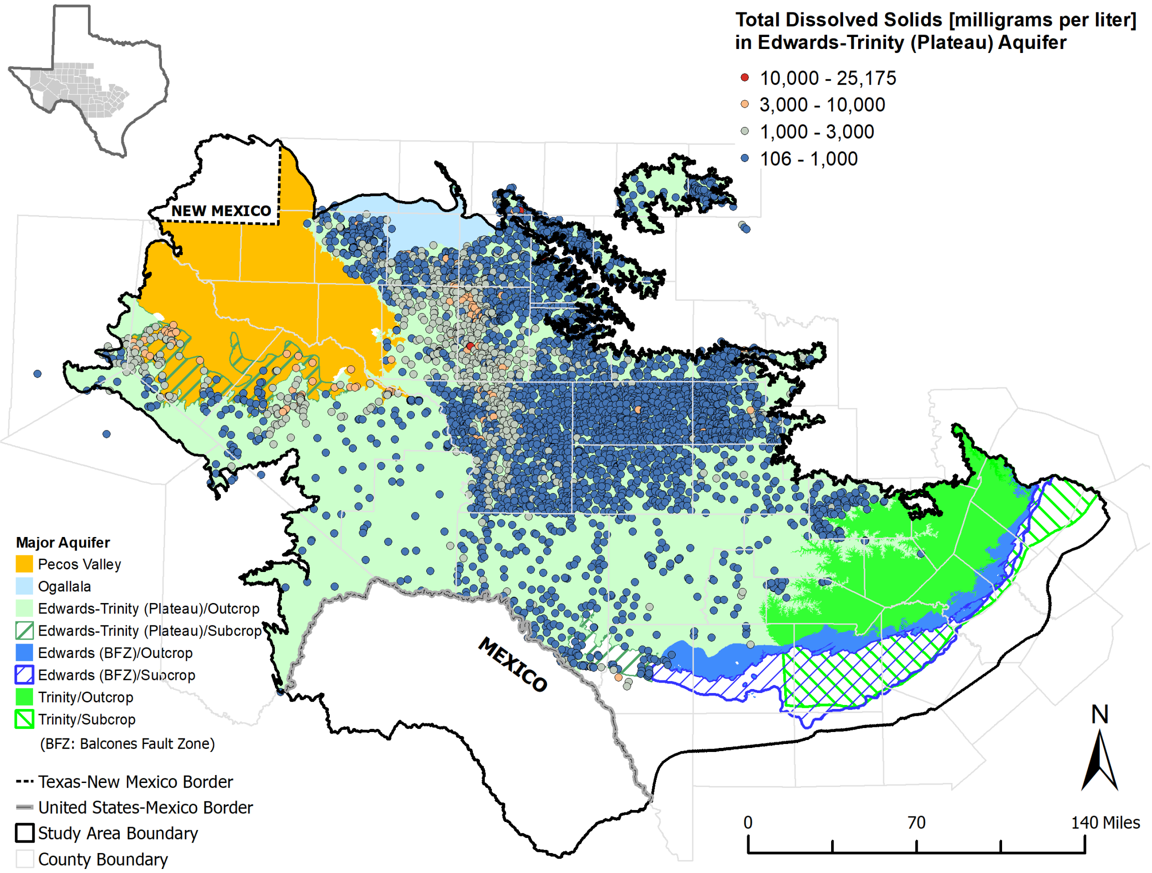

Figure 4.8-3. Map of average total dissolved solids (in milligrams per liter) for the Edwards-Trinity (Plateau) Aquifer (TWDB, 2021c).

In the Hill Country portion of the Trinity Aquifer, groundwater is fresh to moderately saline (Figure 4.8-4). There are no apparent spatial trends in the distribution of groundwater salinity. However, there is some vertical variation in groundwater salinity. In general, Trinity Aquifer groundwater is more saline in the upper member of the Glen Rose Formation (Upper Trinity) and in the Sligo and Hosston formations (Lower Trinity) than in the lower member of the Glen Rose Formation, Hensell Formation and Cow Creek Formation (Middle Trinity). However, these salinity differences have little impact on the current conceptualization of groundwater flow in this area as the numerical model will not distinguish between component formations of the Trinity Aquifer.

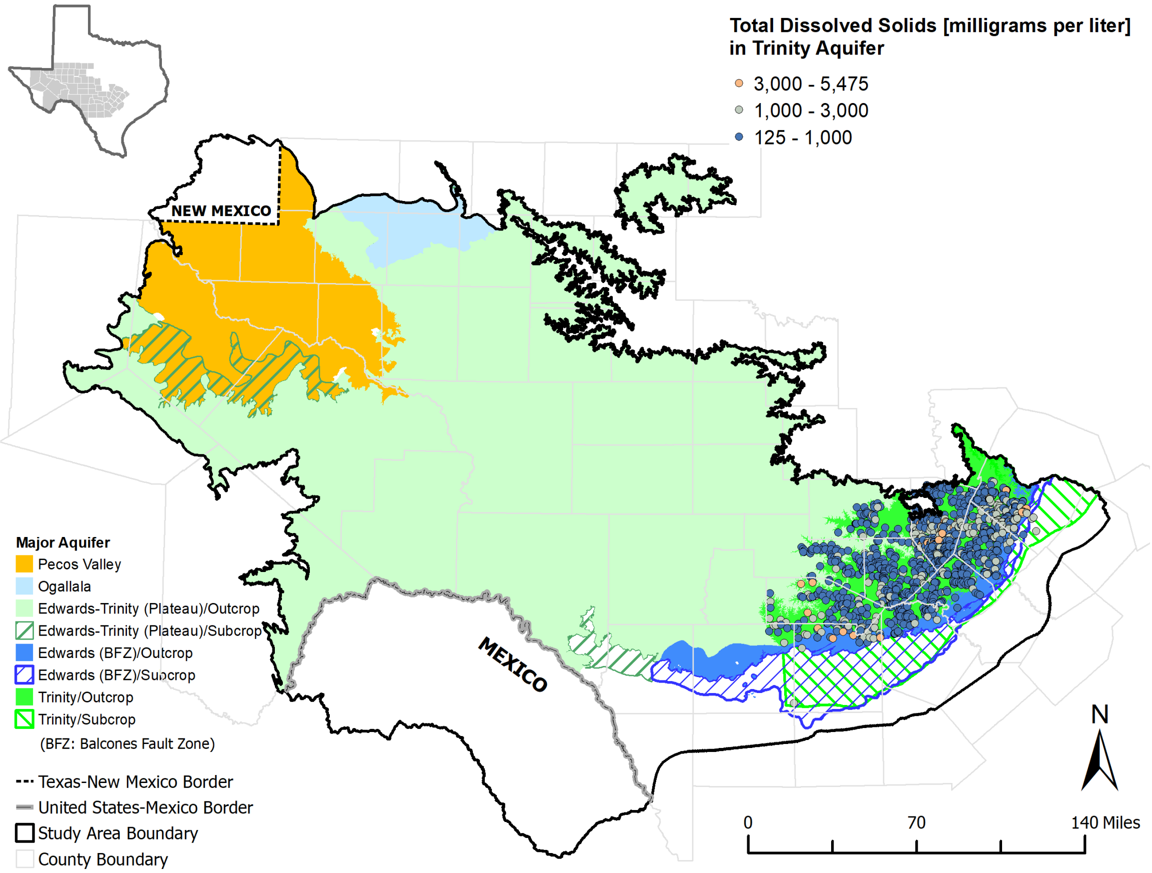

Figure 4.8-4. Map of average total dissolved solids (in milligrams per liter) for the Hill Country portion of the Trinity Aquifer (TWDB, 2021c).

In the Edwards (Balcones Fault Zone) Aquifer, groundwater is fresh to very saline (Figure 4.8-5). Groundwater is fresh throughout most of the aquifer. The slightly to very saline groundwater occurs in the down-dip portions of the aquifer beyond the official boundary of the aquifer, also called the “Bad Water Line”. As the current model is not intended to model groundwater availability in the Edwards (Balcones Fault Zone) Aquifer, with the Edwards Group included only to provide a boundary condition, the entirety of the Edwards Group will be included in the numerical model regardless of salinity.

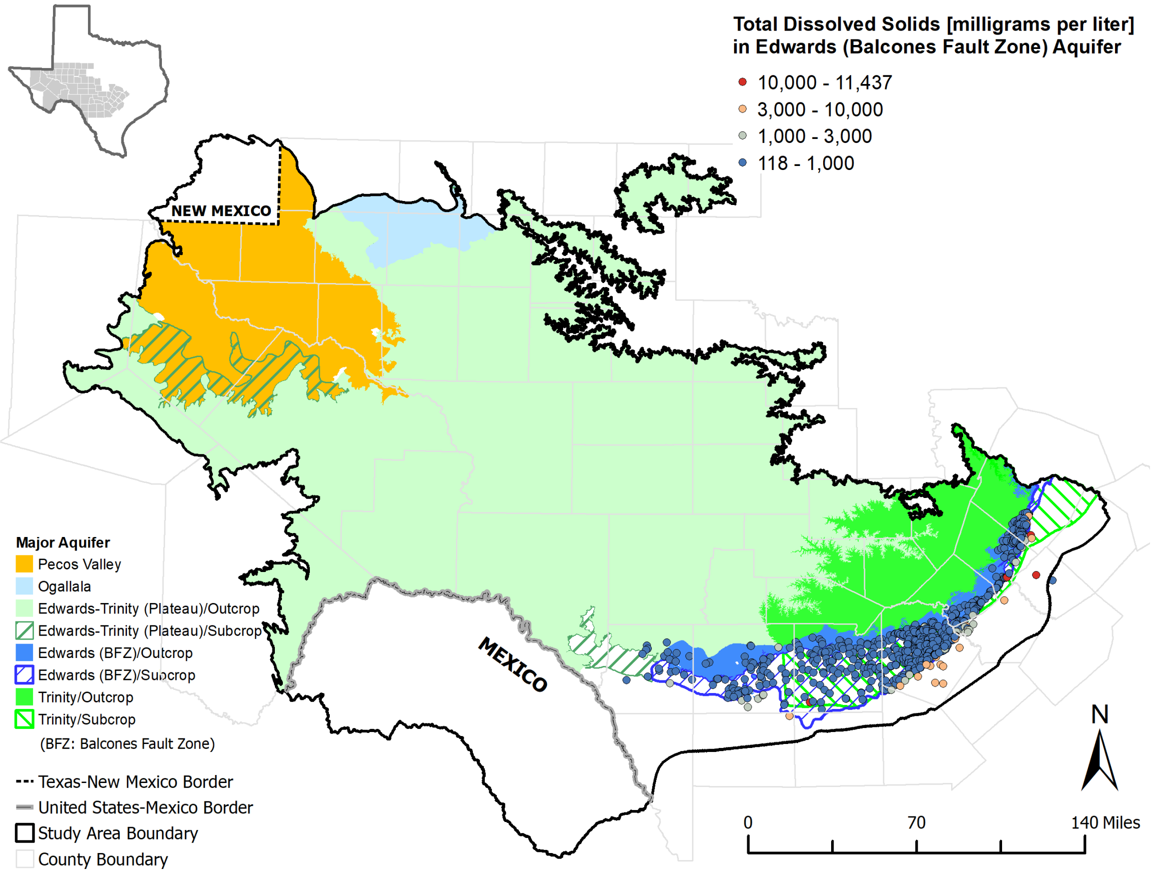

Figure 4.8-5. Map of average total dissolved solids (in milligrams per liter) for the Edwards (Balcones Fault Zone) Aquifer (TWDB, 2021c).

Groundwater within our study area displays a wide range of geochemical compositions (Figure 4.8-6). Groundwater compositions range from calcium-magnesium to sodium compositions and bicarbonate to sulfate and chloride compositions. These compositional differences represent the effects of varying geochemical processes that take place as the groundwater flows through and interacts with aquifer rock and mixes with groundwater inflows from surrounding stratigraphic units. These compositions indicate groundwater interaction with calcite, dolomite, halite, and gypsum—minerals that occur within the various aquifers and adjacent stratigraphic units. Groundwater interaction with dolomite and calcite produces calcium-magnesium-bicarbonate compositions, gypsum produces calcium-sulfate compositions, and upward migration of groundwater from deep evaporite units that contain halite produces sodium-chloride groundwater compositions. In the carbonate Edwards-Trinity (Plateau), Trinity, and Edwards (Balcones Fault Zone) aquifers, groundwater compositions change from calcium to calcium-magnesium and bicarbonate compositions in up-dip parts of the aquifer, becoming increasingly sodium-rich with depth. These changes in groundwater compositions tend to be accompanied by increases in total dissolved solids. The Pecos Valley Aquifer tends to have the lowest magnesium and bicarbonate groundwater compositions of all the aquifers in the study area.

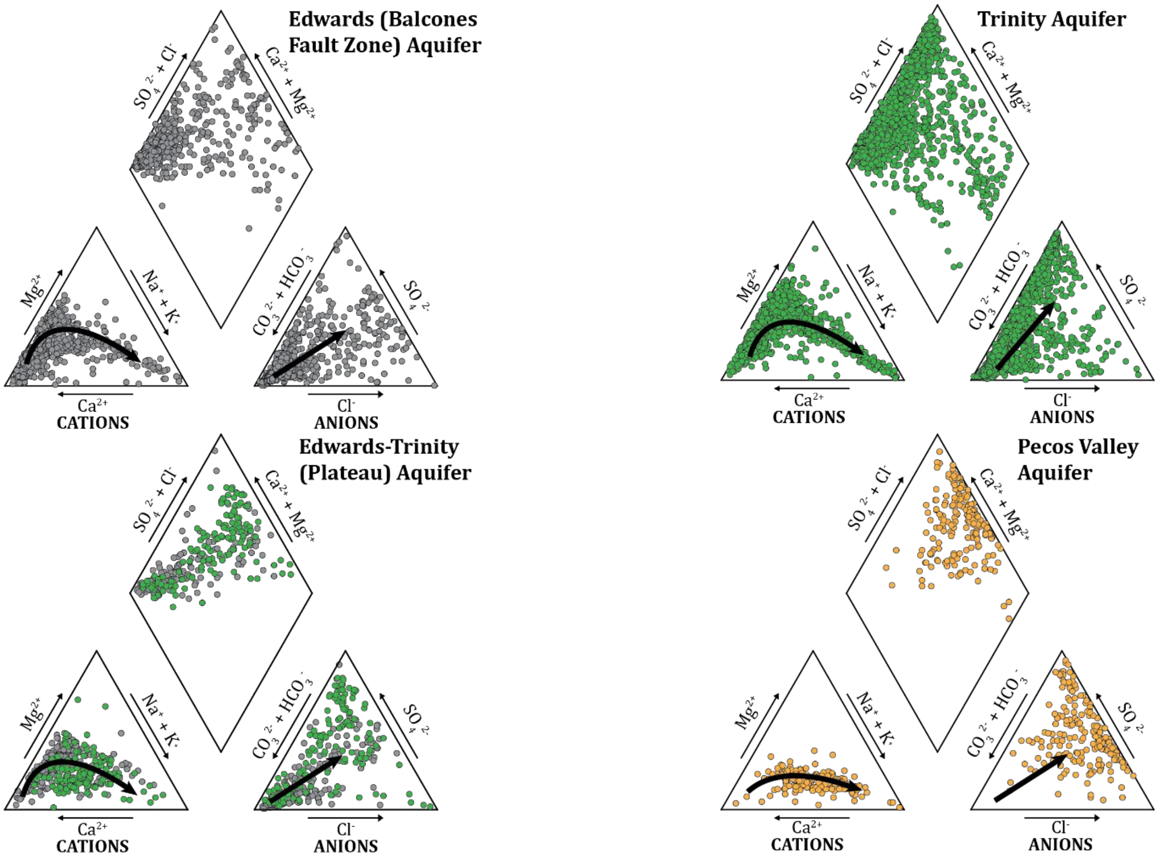

Figure 4.8-6. Piper diagrams showing the range of groundwater compositions in the Edwards (Balcones Fault Zone), Trinity, Edwards-Trinity (Plateau), and Pecos Valley aquifers. The arrows indicate compositional changes along flow paths.

The Barton Springs/Edwards Aquifer Conservation District drilled five Westbay Multiport wells located in Travis and Hays counties (Figure 4.8-7). These wells penetrate the Edwards (Balcones Fault Zone) and Trinity aquifers. Their multiple ports facilitate collection of groundwater samples from selected intervals in the respective aquifers and evaluation of geochemical variation along vertical transects through the adjacent aquifers. Figure 4.8-8 shows groundwater compositions in the Edwards (Balcones Fault Zone) Aquifer and Upper, Middle and Lower portions of the Trinity Aquifer in the Antioch, Driftwood, Ruby Ranch, West Travis County, and Saline Edwards multiport wells. These data sets show that groundwater from the Edwards (Balcones Fault Zone) and Trinity aquifers has a calcium-magnesium composition. Groundwater in the Lower Trinity unit tends to have more sodium, falling along a trend between calcium-magnesium and sodium compositions. Edwards (Balcones Fault Zone) Aquifer groundwater compositions are mostly bicarbonate but may overlap with the Trinity Aquifer compositions near contacts between the aquifers. The Trinity Aquifer groundwater has a wide range of compositions, mostly ranging from bicarbonate-sulfate to sulfate compositions. One of the multiport wells ("Saline Edwards") is located in the saline zone down-dip of the Edwards (Balcones Fault Zone) Aquifer. In this area, groundwater composition is sodium-chloride instead of the calcium-bicarbonate composition found in the freshwater portions of the aquifer.

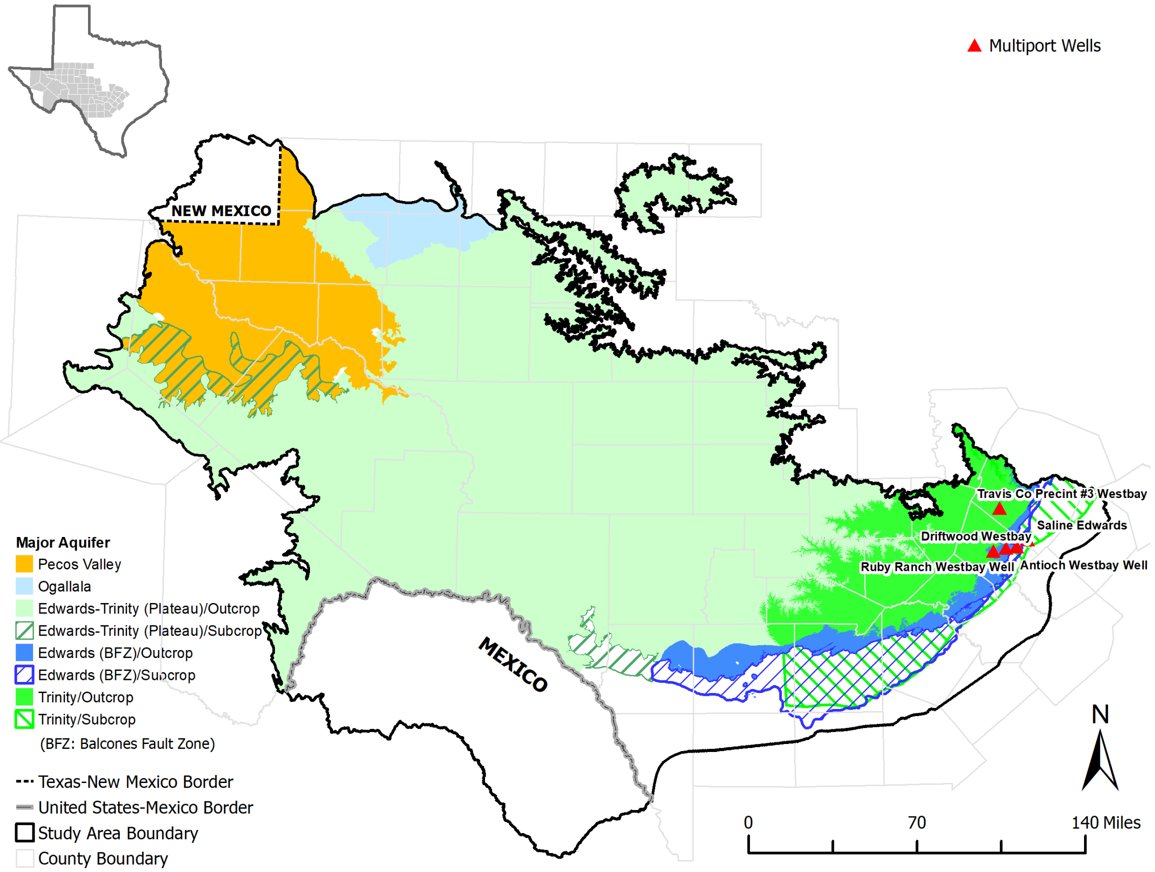

Figure 4.8-7. Locations of multi-port wells that penetrate the Edwards (Balcones Fault Zone) and Trinity aquifers.

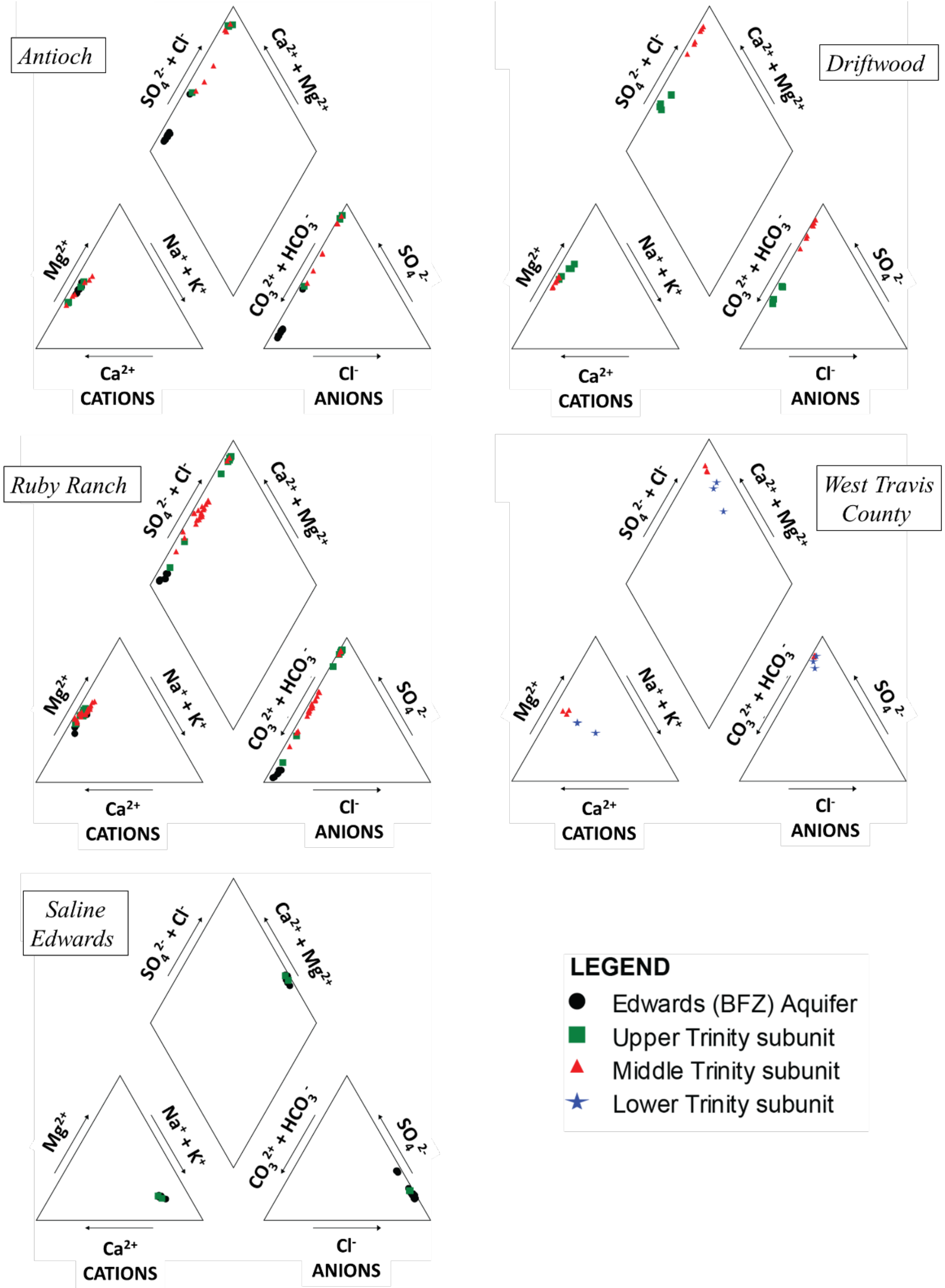

Figure 4.8-8. Piper diagrams showing the groundwater compositions measured in the Barton Springs and Edwards Aquifer Groundwater Conservation District multiport wells.

In general, these observed groundwater types are consistent with the compositions expected from groundwater interactions with dolomite and calcite (calcium-magnesium-bicarbonate) and gypsum (calcium-sulfate) in the shallower sections and with deep evaporite (sodium-chloride) in the deeper sections. The compositions of the Edwards (Balcones Fault Zone) and Trinity aquifer samples from the multiport wells are similar (calcium-magnesium). This suggests the potential for cross-formational flow between these two aquifers in this area, which is consistent with results from water level analyses (see Section 4.3.7).

4.8.2 Isotopes

Groundwater isotopic compositions can provide information about groundwater hydrology. Concentrations or ratios of different isotopes often change in response to processes such as evaporation, water-rock interaction, recharge processes, and the time elapsed since recharge.

Groundwater carbon-13 ($\delta^{13}C$) isotopic compositions represent the ratios of stable carbon isotopes—^{12}C and ^{13}C—in groundwater relative to the composition of the standard Peedee Belemnite calcite (Clark and Fritz, 1997). These isotope ratios are expressed as the relative difference in per mil, meaning parts per thousand. Groundwater carbon-13 isotopic compositions often reflect relative carbon inputs from interaction with soil and aquifer rock. Recently recharged groundwater near recharge zones tends to have more negative carbon-13 compositions reflecting recent contact with the soil. As the groundwater flows through the aquifer and away from the recharge zone, water-rock interaction results in the groundwater taking on more positive carbon-13 isotopic compositions, reflecting those of the aquifer rock. These trends are apparent in the aquifers of the Edwards-Trinity region where groundwater carbon-13 compositions vary from -20 indicative of soil to +10 indicative of limestone rock (Figure 4.8-9). Groundwater carbon-13 compositions of about -20 to -10 per mil indicate recent recharge while compositions of about 0 to +10 per mil indicate groundwater with long residence time in the aquifer.

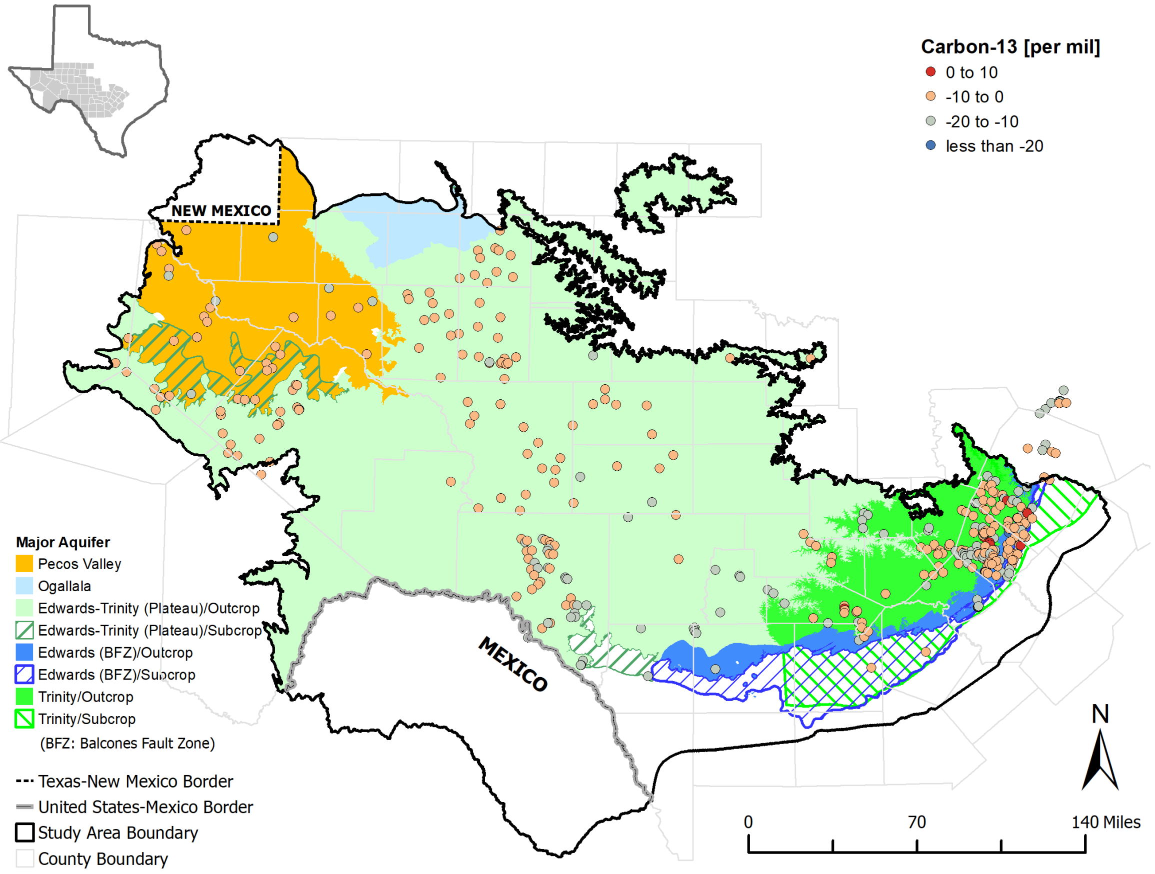

Figure 4.8-9. Groundwater Carbon-13 isotopes (in per mil) in the aquifers of the Edwards-Trinity region.

Carbon-14 is a radiogenic isotope that can help determine the relative age of groundwater. Carbon-14 measurements are expressed as a fraction of modern carbon. Without a continuous influx of carbon-14 from recharge, carbon-14 decays over time in an aquifer. As a result, groundwater carbon-14 activity is typically higher in shallower parts of an aquifer where recharge is occurring. In the study area, carbon-14 fractions range from 0 to about 1.1 and are highest within and immediately adjacent to aquifer outcrops where recharge occurs and lowest where there is no local recharge and almost all of the groundwater carbon-14 has decayed (Figure 4.8-10).

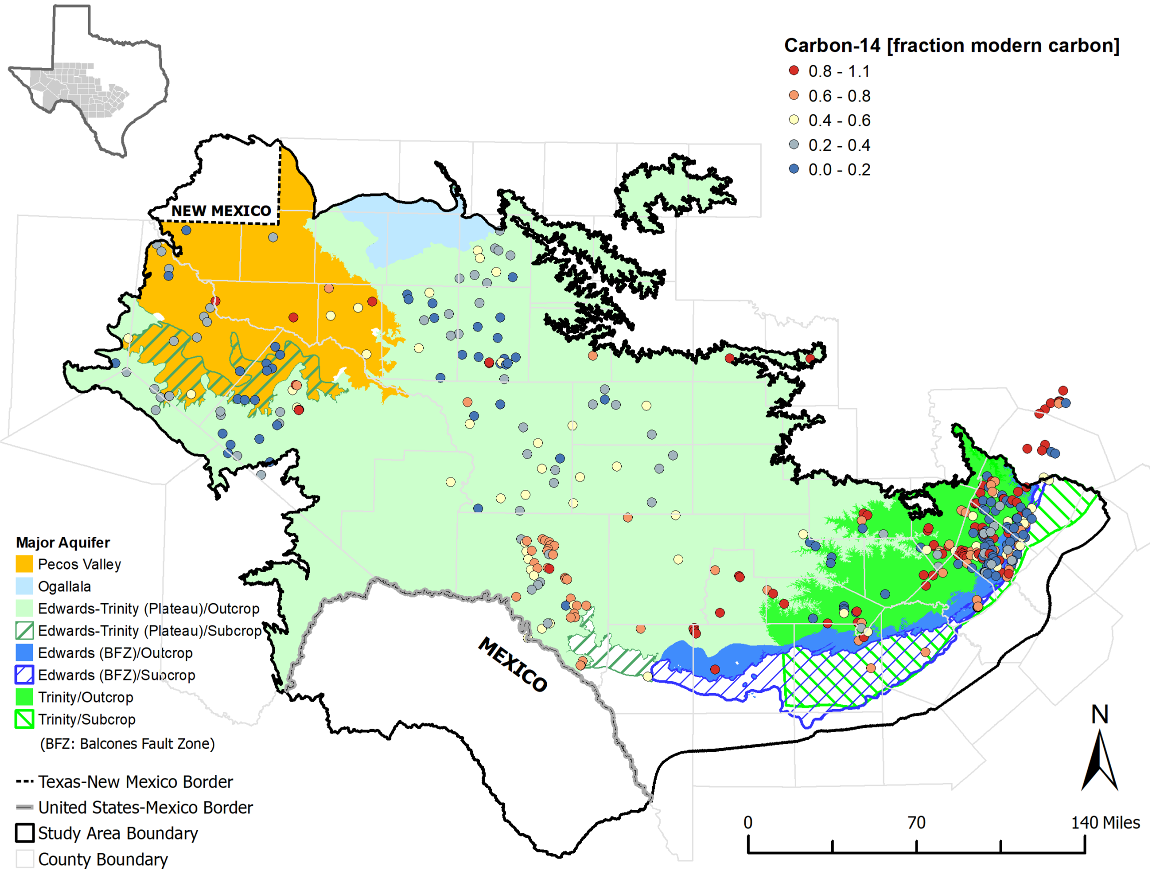

Figure 4.8-10. Groundwater Carbon-14 (in fraction modern carbon) in the aquifers of the Edwards-Trinity region.

Tritium, a radiogenic isotope of hydrogen, can also help determine the age of groundwater. Groundwater tritium behaves like carbon-14. The difference is that tritium has a faster decay rate with a half-life of 12.3 years compared to 5,730 years for carbon-14 (Clark and Fritz, 1997). High tritium activity indicates the most recent recharge. In the study area, the groundwater tritium activity ranges between 0 and 6 Tritium Units (one Tritium Unit = 3.22 picocuries) as shown in Figure 4.8-11. The highest groundwater tritium activity indicates recent recharge while tritium activity near or below detection indicates groundwater that is very old.

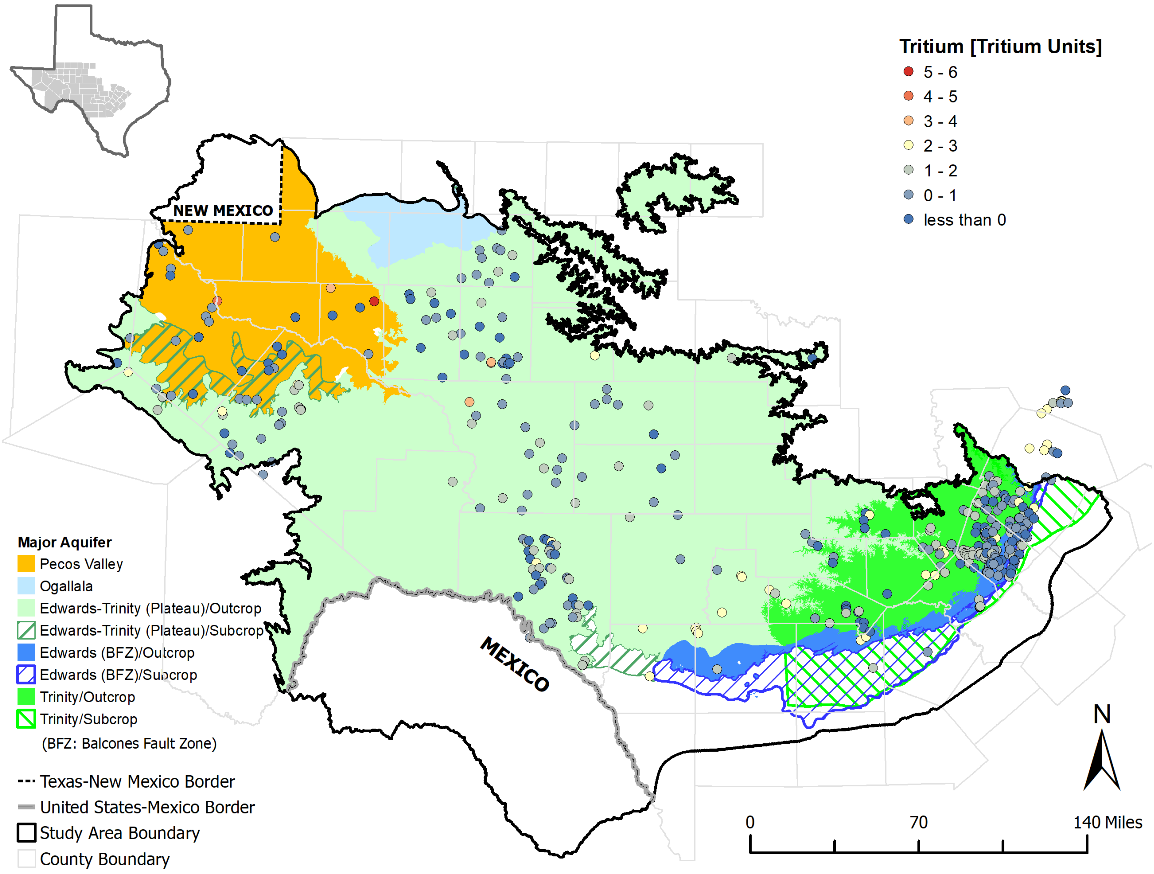

Figure 4.8-11. Groundwater tritium (in Tritium Units) in the aquifers of the Edwards-Trinity region.

Figure 4.8-12 and Figure 4.8-13 show the relationships between groundwater isotopic compositions in the respective aquifers within the study area. All the aquifers have the same range of carbon-14 compositions between 0 and 1.1 where close to 1.1 indicates recent recharge and 0 indicates groundwater that recharge more than 20,000 years ago (Figure 4.8-12). This range indicates that all of the aquifers in the study area are active, receiving modern recharge water. Because both carbon-14 and tritium undergo radioactive decay, both will decline over time. Recently recharged groundwater appears to the top-right of the graph and becomes progressively older to the bottom-left. Figure 4.8-13 shows the relationship between radioactive carbon-14 and stable carbon-13 isotopes and the arrow for the general compositional trend over time. As carbon-14 decreases due to decay, water-rock interaction gradually changes groundwater carbon-13 compositions from soil-influenced recharge water to rock-influenced ancient groundwater.

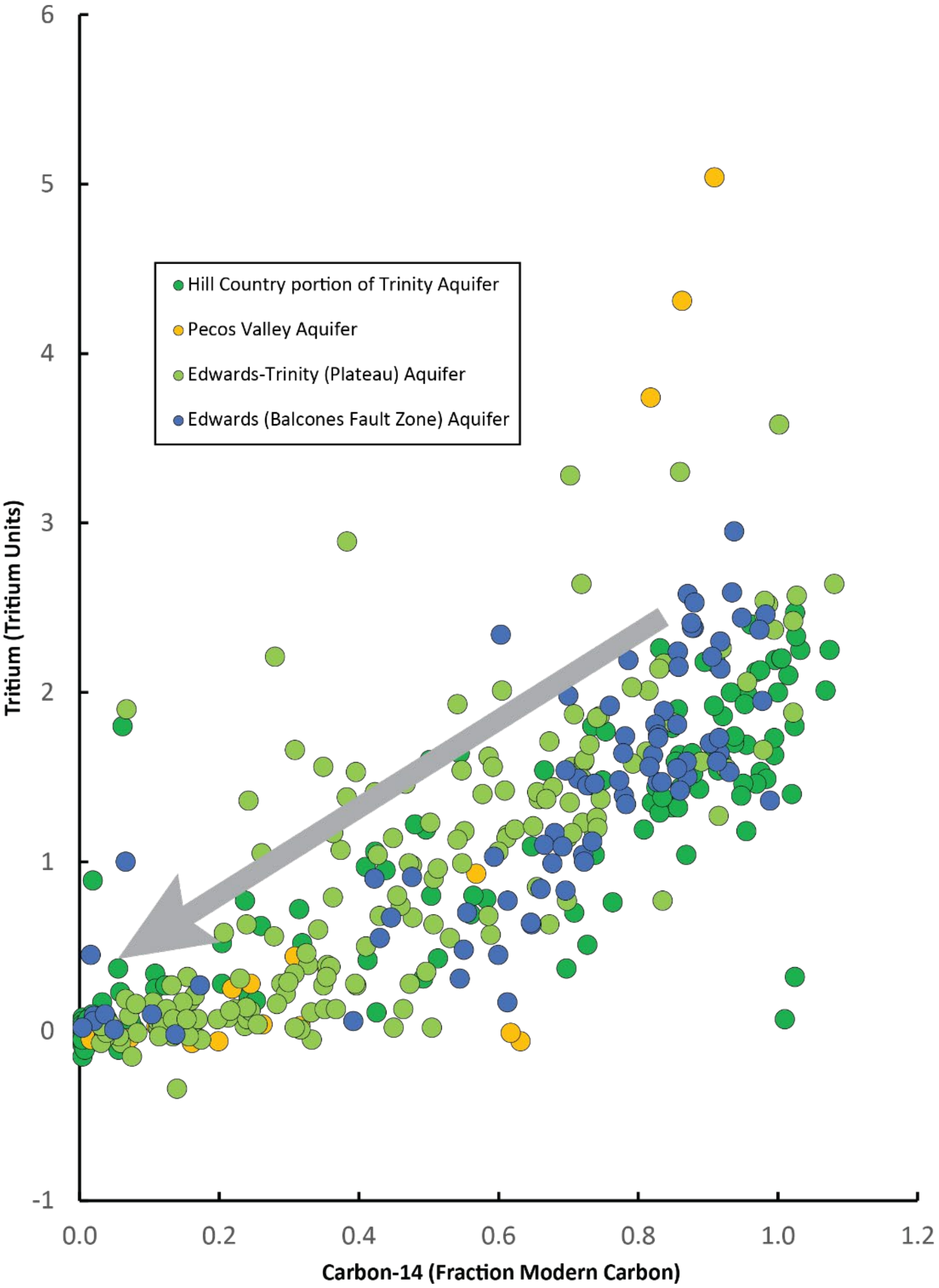

Figure 4.8-12. Groundwater tritium and carbon-14 isotopes in the aquifers of the Edwards-Trinity region. The arrow indicates the trend of groundwater compositions from younger to older groundwater.

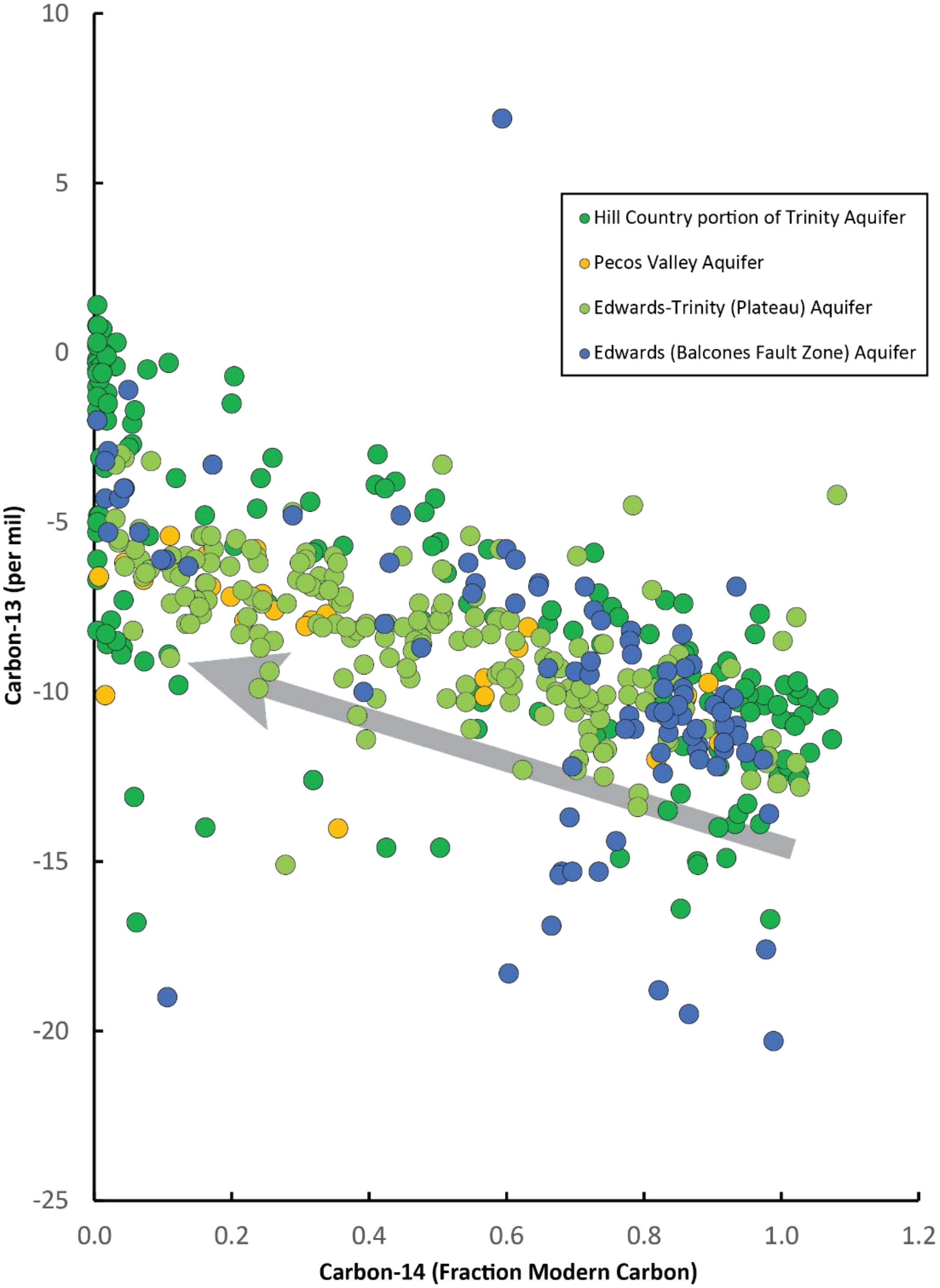

Figure 4.8-13. Groundwater carbon-13 and carbon-14 isotopes in the aquifers of the Edwards-Trinity region. The arrow indicates trends from younger to older groundwater compositions.

In general, this analysis of radiogenic isotopes supports our current conceptualization of recharge from recent precipitation over most of the study area. As expected, areas where the carbon-13, carbon-14, or tritium compositions indicate higher ages correspond to deeper portions of the aquifer that are not expected to be heavily influenced by recharge. Within the outcrop and near-crop areas where radiogenic isotopes indicate young groundwater ages from recent recharge, there is still some slight variation in calculated ages. The spatial distributions shown in Figure 4.8-9 through Figure 4.8-11 could thus be used to adjust recharge zoning in the numerical model, if necessary.

Figure 4.8-14 shows the groundwater carbon-14 and carbon-13 isotopes in the Edwards (Balcones Fault Zone) and Trinity aquifers measured at the Barton Springs/Edwards Aquifer Conservation District multiport wells. This evaluation shows the same general trends observed at the aquifer scale in Figure 4.8-13. The carbon isotopes in the multiport wells indicate that on average Edwards (Balcones Fault Zone) Aquifer groundwater is younger and more likely to have soil-influenced carbon-13 compositions than groundwater in the Trinity Aquifer. The groundwater compositions in the upper member of the Glen Rose Limestone (Upper Trinity) are similar to the oldest Edwards (Balcones Fault Zone) Aquifer groundwater. Groundwater compositions in the lower member of the Glen Rose Limestone, Hensell Sand, and Cow Creek Limestone (Middle Trinity) are older and more rock-influenced than the overlying hydrostratigraphic units. The oldest and most rock-influenced groundwater in the multiport wells occurs in the down-dip saline Edwards hydrostratigraphic unit, located beyond the “Bad Water Line” boundary of the Edwards (Balcones Fault Zone) Aquifer. This groundwater is ancient and highly saline—total dissolved solids are greater than 8,000 milligrams per liter, increasing with depth. The carbon-14 in the down-dip saline Edwards unit is below detection and therefore the groundwater is highly unlikely to have detectable tritium. The apparent groundwater age of this unit is greater than 45,000 years based on the half-life of carbon-14.

Groundwater stable hydrogen ($\delta^{2}H$) and oxygen ($\delta^{18}O$) isotopic compositions represent the ratios of stable hydrogen isotopes (H and ^{2}H) and stable oxygen isotopes (^{16}O and ^{18}O) in groundwater relative to the composition of Standard Mean Ocean Water (Clark and Fritz, 1997). These isotope ratios are expressed as the relative difference in per mil, meaning parts per thousand. Groundwater stable hydrogen and oxygen isotopic compositions reflect the composition of the precipitation that recharged the aquifer, which may vary spatially or temporally in response to factors such as elevation, temperature, and amount of precipitation (Dansgaard, 1964; Fontes and Olivry, 1977; Fontes, 1980; Gonfiantini, 1985; Scholl and others, 1996). Consequently, the hydrogen and oxygen isotopic compositions of groundwater can be used as an indicator of the conditions under which recharge to the aquifer occurred.

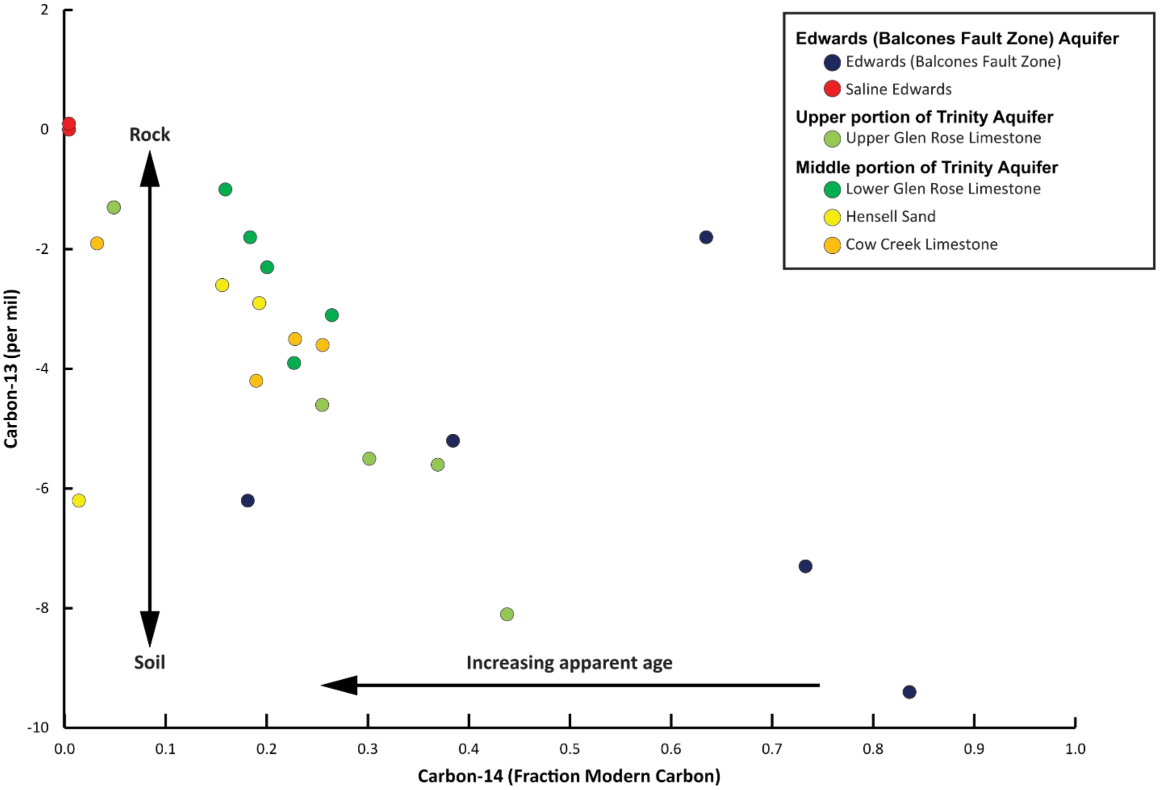

Figure 4.8-14. Groundwater carbon-13 and carbon-14 isotopes showing the range of groundwater compositions in the stratigraphic units of the Edwards (Balcones Fault Zone) Aquifer, and the Upper and Middle portions of the Trinity Aquifer in the Multiport Wells in the Barton Springs/Edwards Aquifer Conservation District.

Figure 4.8-15 and Figure 4.8-16 show groundwater hydrogen and oxygen isotopic compositions in the study area. Figure 4.8-15 show that the most negative groundwater oxygen isotopic compositions occur in the western parts of the study area and become progressively more positive towards the east, which reflects changes in precipitation isotopic composition across the study area. Figure 4.8-16 shows groundwater stable hydrogen and oxygen isotopic compositions relative to the Global Meteoric Water Line. Groundwater stable hydrogen and oxygen isotopic compositions in the study area lie in the ranges -73 to -13 per mil and -10 to -1 per mil, respectively. Stable hydrogen and oxygen isotope compositions generally lie along the Global Meteoric Water Line, which represents the average relationship between stable hydrogen and oxygen isotopic compositions in precipitation around the world (Craig, 1961). Hydrogen and oxygen isotopic compositions in the respective aquifers vary widely due to interannual or spatial variation of recharge conditions. Hydrogen and oxygen isotopic compositions in the Edwards (Balcones Fault Zone) and Trinity aquifers fall within a relatively narrow range of values compared to the Pecos Valley and Edwards-Trinity (Plateau) aquifers. The median hydrogen (-25.1 per mil) and oxygen (-4.3 per mil) isotopic compositions of groundwater in the Edwards (Balcones Fault Zone) and Trinity aquifers in the study area are almost identical and higher than the

Pecos Valley and Edwards-Trinity (Plateau) aquifers (inset graph in Figure 4.8-16). This trend can be attributed to climatic variation across the study area. The climate in the study area becomes progressively more arid from east to west. The result of this climatic trend is that overall stable hydrogen and oxygen isotopic compositions of recharging precipitation water would migrate down the Global Meteoric Water Line from east to west.

Surface evaporation from rivers and reservoirs, mixing with connate water/seawater, or extensive rock-water interaction can cause isotopic compositions to deviate from the Global Meteoric Water Line. However, since the hydrogen and oxygen isotopic composition of all aquifers in the study area closely match the Global Meteoric Water Line, this supports the current conceptualization that the majority of inflow to these aquifers is from modern precipitation.

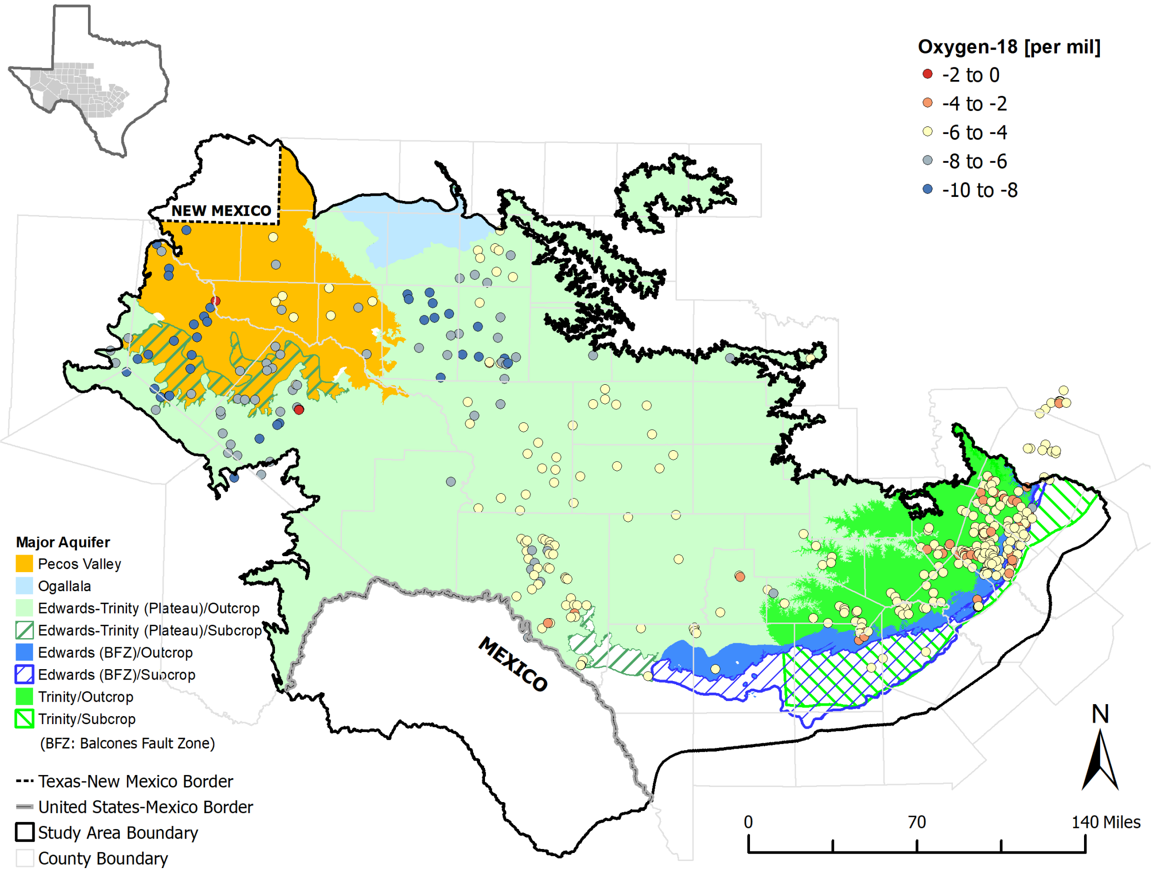

Figure 4.8-15. Groundwater stable oxygen isotopes ($\delta^{18}O$, in per mil) in the aquifers of the Edwards-Trinity region.

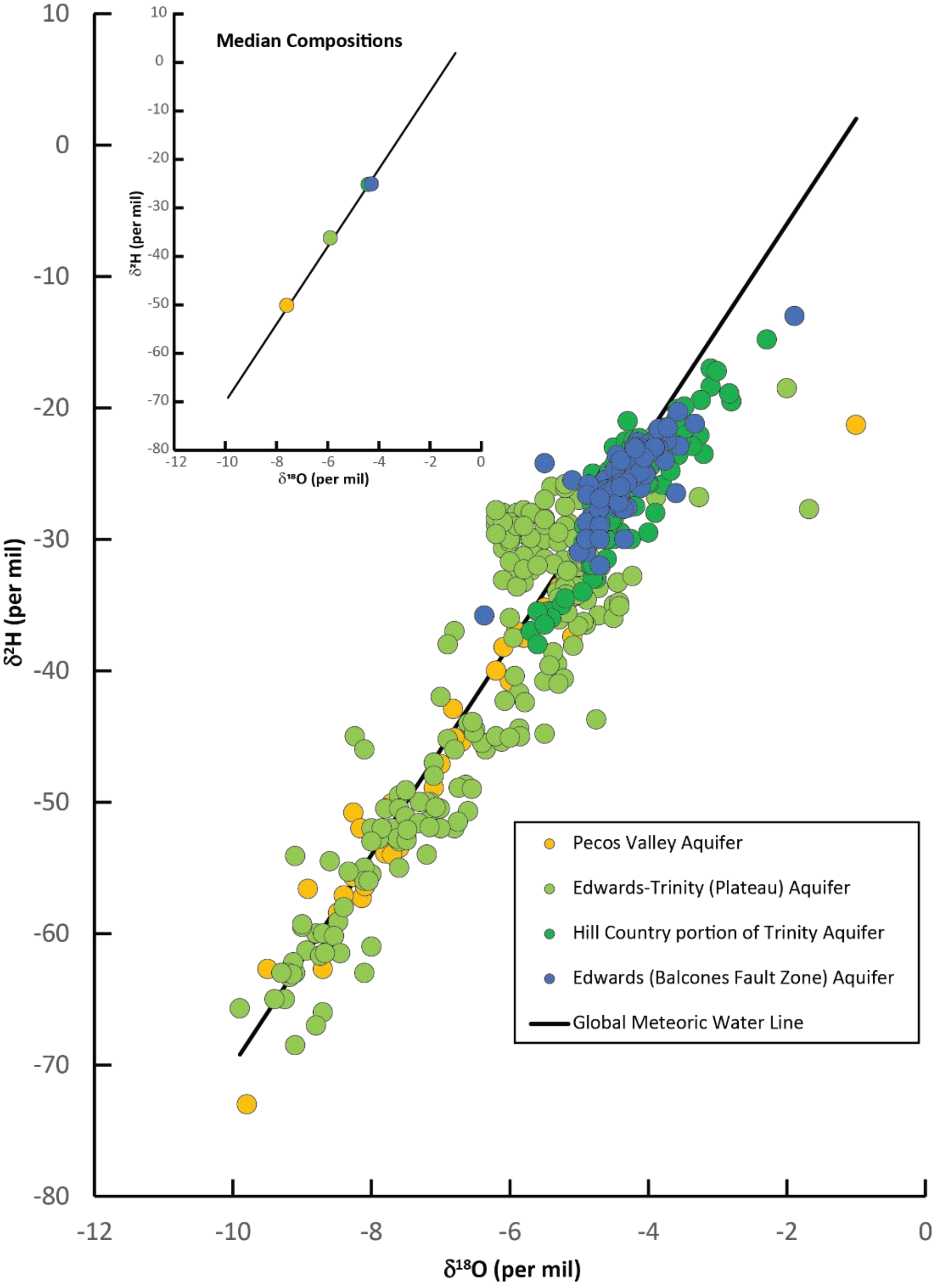

Figure 4.8-16. Groundwater stable oxygen isotopes (δ¹⁸O, in per mil) and stable hydrogen isotopes (δ²H, in per mil) in the aquifers of the Edwards-Trinity region. The inset graph shows the median values for each aquifer.

5 CONCEPTUAL MODEL

A conceptual model is a generalized representation of a groundwater flow system based on the hydrogeologic setting (Anderson and Woessner, 1992). The primary purpose of the conceptual model is to consolidate relevant real-world data into a simplified aquifer flow system that can be approximated using a mathematical groundwater model. In this report, we have developed a conceptual model by defining the hydrostratigraphic framework and aquifer boundaries, calculating approximate values for hydrologic parameters and climatic conditions, and identifying locations and pathways for discharge and recharge.

Figure 5.0-1 provides a summary of the conceptual model, represented as a simplified geologic cross-section with inflows and outflows marked with arrows. Figure 5.0-2 illustrates the conceptual model as a block diagram, meant to represent the aquifer system approximated by a numerical groundwater model. The structural framework for the Edwards-Trinity (Regional) aquifers system comprises three basic hydrostratigraphic units that represent: 1) the Pecos Valley Aquifer and other surficial younger units, 2) the units of the Edwards Group, and 3) the units of the Trinity Group (see discussion in Sections 4.1 and 4.2). For modeling purposes, we will add an additional layer on the top of these units to represent the river or stream channels in the study area. The extra layer does not have structural hydrogeologic meaning, but it simulates streamflow that overlies the aquifer system and has a hydraulic connection to the aquifer system. This additional layer is meant to improve the model simulation of surface water – groundwater interaction.

The first layer below the river layer, or the younger hydrostratigraphic unit (Layer 1 in Section 4.2), represents the Pecos Valley Aquifer and other younger units that overlie the Edwards and Trinity formations. The Pecos Valley Aquifer receives recharge from precipitation over the aquifer and cross-formational flow from the adjacent Edwards-Trinity (Plateau) Aquifer. Groundwater leaves the Pecos Valley Aquifer through evapotranspiration, as baseflow to the Pecos River, and by pumpage from irrigation wells. Evapotranspiration outflow also occurs around the riparian reaches of the Pecos River, where the water table is shallow.

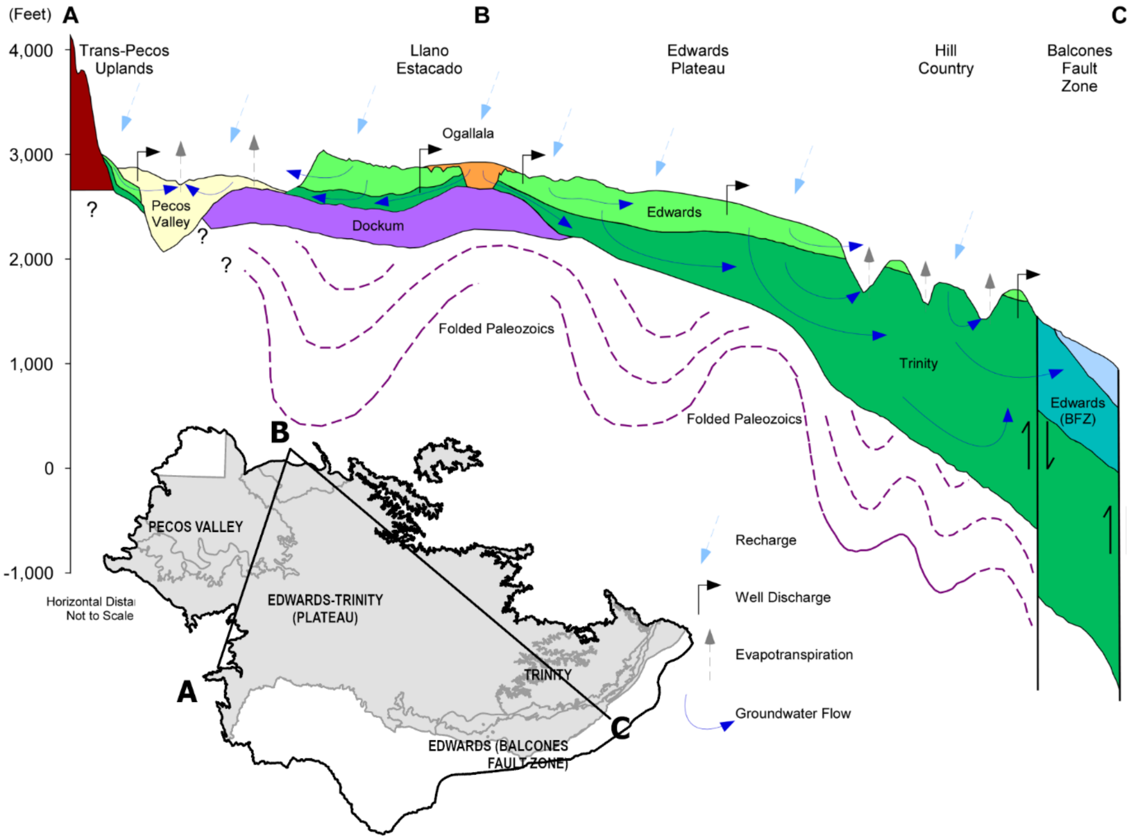

Figure 5.0-1. Conceptual model of the Edwards-Trinity (Plateau), Trinity (Hill Country), Edwards (Balcones Fault Zone) and Pecos Valley aquifers (modified from Anaya and Jones, 2009).

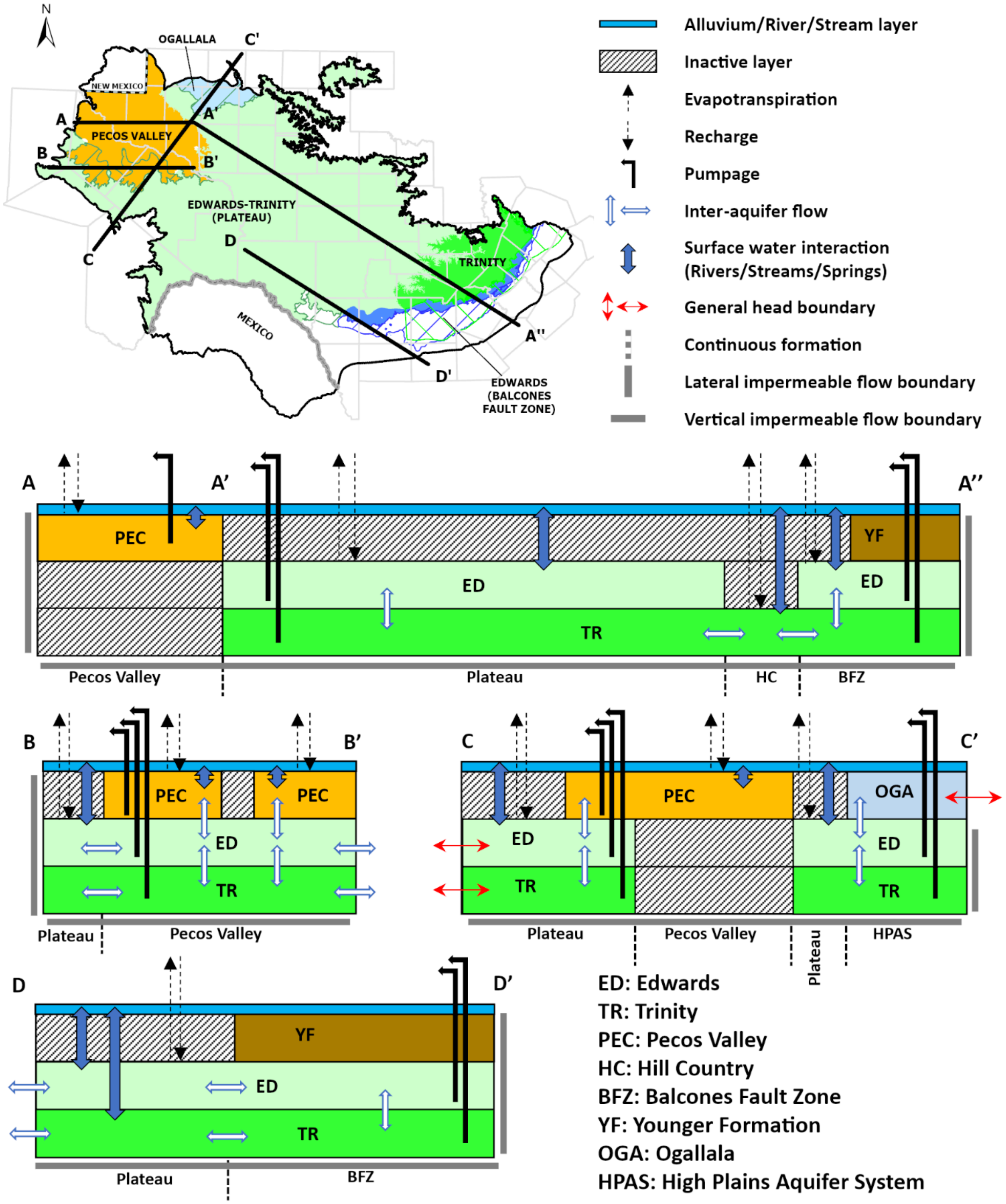

Figure 5.0-2. Block diagram of the Edwards-Trinity (Plateau), Trinity (Hill Country), Edwards (Balcones Fault Zone) and Pecos Valley aquifers.

The Edwards hydrostratigraphic unit (Layer 2 in Section 4.2), represents the Edwards (Balcones Fault Zone) Aquifer and the Edwards unit of the Edwards-Trinity (Plateau) Aquifer. Recharge from precipitation provides the primary inflow for the Edwards hydrostratigraphic unit. However, only a small amount (0 to 10 percent) of the annual precipitation actually recharges the aquifer, either directly through the aquifer outcrops or through the losing streams that overlie the aquifer outcrops. The rest of the precipitation leaves the study area by evapotranspiration or runoff and does not contribute to the aquifer's recharge. The previous TWDB model (Anaya and Jones, 2009) indicates that up to 10.9 percent of precipitation recharges the Edwards unit of the Edwards-Trinity (Plateau) aquifer. For the Edwards (Balcones Fault Zone) Aquifer, recharge from infiltration of rainfall was about 15 to 40 percent of total recharge (Scanlon and others, 2001; Maclay and Land, 1988). The Edwards hydrostratigraphic unit loses water through evapotranspiration, springs, streams, and pumpage. Evapotranspiration occurs where vegetation can tap into the water table, usually in riparian areas where the water table is shallow. Losses due to spring discharge and gaining streams occur at the south and southeastern margin of the Edwards Plateau, as discussed in Section 4.5. Losses from pumpage occur over the entire study area, but most aggressively in the eastern part of the study area, due to increasing demand from rapidly growing urban centers.

The Trinity hydrostratigraphic unit (Layer 3 in Section 4.2), represents the Hill Country portion of the Trinity Aquifer and the Trinity unit of the Edwards-Trinity (Plateau) Aquifer. The Trinity hydrostratigraphic unit has a restricted outcrop area, and as a result, recharge from precipitation is limited. Consequently, much of its recharge comes from the overlying Edwards hydrostratigraphic unit. Only the Hill Country area has exposed outcrops, and the previous study (Anaya and Jones, 2009) indicates about 4 to 6 percent of precipitation contributes to the recharge of the Trinity hydrostratigraphic unit in this area. Groundwater leaves the Trinity hydrostratigraphic unit through the springs and streams of the Hill Country and by pumping across the entire study area. Losses to gaining streams occur along the major streams in the Hill Country area.

Groundwater can move between the different layers as cross-formational flow. For example, at the boundary between the Edwards-Trinity (Plateau) and Edwards (Balcones Fault Zone), the Trinity hydrostratigraphic unit discharges groundwater to the Edwards hydrostratigraphic unit. In the west of the study area, both the Edwards and Trinity hydrostratigraphic units have a hydraulic connection to the Pecos Valley and Ogallala aquifers. But the amount of groundwater flow from the Ogallala Aquifer is relatively small, about 3,000 acre-feet per year (Blandford and Blazer, 2004; Deeds and Jigmond, 2015). Several underlying minor aquifers, including the Dockum, Capitan Reef Complex, Rustler, Hickory, Ellenburger-San Saba, Marble Falls, and Lipan aquifers, are hydraulically connected with the Edwards-Trinity (Plateau) Aquifer. However, we assume the groundwater flow between those aquifers is insignificant and did not implement in the conceptual model. While the Pecos Valley Aquifer is hydraulically connected to underlying minor aquifers, including the Dockum, Capitan Reef Complex, and Rustler aquifers, we assume the groundwater flow from those aquifers is insignificant and did not implement this flow in the conceptual model.

The current conceptual model incorporates several major updates compared to the previous TWDB groundwater availability model (Anaya and Jones, 2009). First, the extent of the model is much larger than the previous model and extends to the south and southeast to include northeastern Mexico and the Balcones Fault Zone. The portion in Mexico was included to improve our conceptualization of groundwater flow to the Rio Grande River while the Balcones Fault Zone region was included to better account for cross-formational flow between the Edwards-Trinity (Plateau) and Edwards (Balcones Fault Zone) aquifers, as well as the Hill Country portion of the Trinity Aquifer. Another update to the current model is the separation of the Pecos Valley Aquifer from the Edwards-Trinity (Plateau) Aquifer. The previous model conceptualized the Pecos Valley Aquifer blending into the Edwards hydrostratigraphic unit and modeled these two units as one contiguous layer. The current model separates these aquifers into two distinct layers with the aim to better understand the differences in groundwater flow as well as the connections between these two aquifers. Updates to modeling feature and software made since the previous model allow higher resolution and more detail near surface water features. With this in mind, the current conceptualization includes an additional layer for streams and rivers, which is intended to improve our understanding of surface water - groundwater interaction. Besides the updates described in the current report, the contracted studies for pumping estimates (LRE) and recharge analysis (WSP) in the study area represent major updates in their own right. These in-depth studies provide previously unavailable data on a regional scale for two parameters that have a significant impact on groundwater availability modeling. The results of these original studies will provide tremendous insight into developing the groundwater availability model of the Pecos Valley and Edwards-Trinity (Plateau) Regional Aquifers that was not available during the development of the previous model.

6 FUTURE IMPROVEMENTS

The structural framework is the foundation for developing the groundwater availability model. The current structural framework was created using the most current data available in the literature. The data collected from previous studies include the TWDB's Groundwater Availability Modeling Program (Walker, 1979; Anaya and Jones, 2009; Deed and others, 2015), the TWDB's Brackish Resources Aquifer Characterization System (BRACS) program (Meyer and others, 2012; Robinson and others, in review), the United States Geological Survey (Barker and Ardis, 1996; Bumgarner and others, 2012; Brakefield and others, 2015), and the Bureau of Economic Geology at the University of Texas, Austin (Smith, 1970; Smith and others, 2000). In addition, some groundwater conservation districts provided geologic data for the framework development.

There are currently two separate studies in development which will provide additional geologic data to improve the geologic framework in the future. The TWDB Brackish Resource Aquifer Characterization System is currently conducting a study of brackish groundwater in the Edwards-Trinity (Plateau) Aquifer. The study is reanalyzing geophysical logs and will develop a new framework of its own for the Edwards-Trinity (Plateau) which could fill data gaps for this conceptual model. The Texas Railroad Commission also recently presented preliminary results for a geologic study in Maverick County which could expand the freshwater extent of the Trinity Aquifer and provide insight into transboundary groundwater flow. If additional data is available in time for the numerical model, we will consider updating our framework and model extent to incorporate new findings from these projects.

Surface water and groundwater interactions have demanded more attention as climate uncertainty intensifies and population continues to grow. Accordingly, there is a greater need to implement more comprehensive modeling of surface water and groundwater interaction in groundwater availability models. The current software used in groundwater availability modeling is not optimized to simulate these interactions, particularly at the regional scale of the current model. It is costly to perform such comprehensive modeling at such a large scale. In addition to the lack of computing resources, insufficient data for calibrating the surface water and groundwater interactions presents a challenge for developing these models.

However, as computational resources increase and the software and computation techniques to solve these complex problems improves, a comprehensive model that simulates the entire hydrologic cycle could be possible at a reasonable cost in the future. TWDB is currently collecting field data and investigating surface water/groundwater interaction elswhere in the study area. These efforts include a study to establish quantitative relationships between groundwater elevations and river baseflow in the South Llano River basin and a study to collect spring/stream flow and produce a potentiometric map using LIDAR (Light Detection and Ranging) in Val Verde County. If additional data is available in time, we will consider incorporating new findings from these projects into the numerical model.

Independently of the TWDB GAM program, various stakeholders are developing a localized coupled surface water-groundwater model in the Hill Country portion of the Trinity Aquifer, but it is not scheduled to be completed in time to provide new insights for the current model. However, this study will be helpful for developing the localized model of the Hill Country portion of the Trinity Aquifer that TWDB plans to create as a future improvement to the current regional model.

Another method for addressing the limitations of regional scale groundwater modeling is to develop nested local scale models. The TWDB Groundwater Modeling Program plans to develop local scale models for the Hill Country portion of the Trinity Aquifer and the Edwards-Trinity (Plateau) Aquifer within “Nolan Island,” the isolated portion of the aquifer located in Nolan and Taylor counties. These localized models will improve simulations of smaller scale groundwater flow without the need for additional computing resources or new software. Importantly, the local scale model in the Hill Country portion of the Trinity Aquifer will implement subunits of the Trinity Aquifer, which will help identify, manage, and plan the available groundwater resources in that area.

New data for water levels, hydraulic properties, and other parameters are constantly being collected by TWDB and other stakeholders, including groundwater conservation districts. Of particular interest, the new TWDB springs monitoring program has begun providing additional data of surface water and groundwater interaction (aquifer discharges) through the springs in Texas. As new data could potentially improve on our current conceptualization, these findings will need to be incorporated into future work.

7 ACKNOWLEDGEMENTS

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