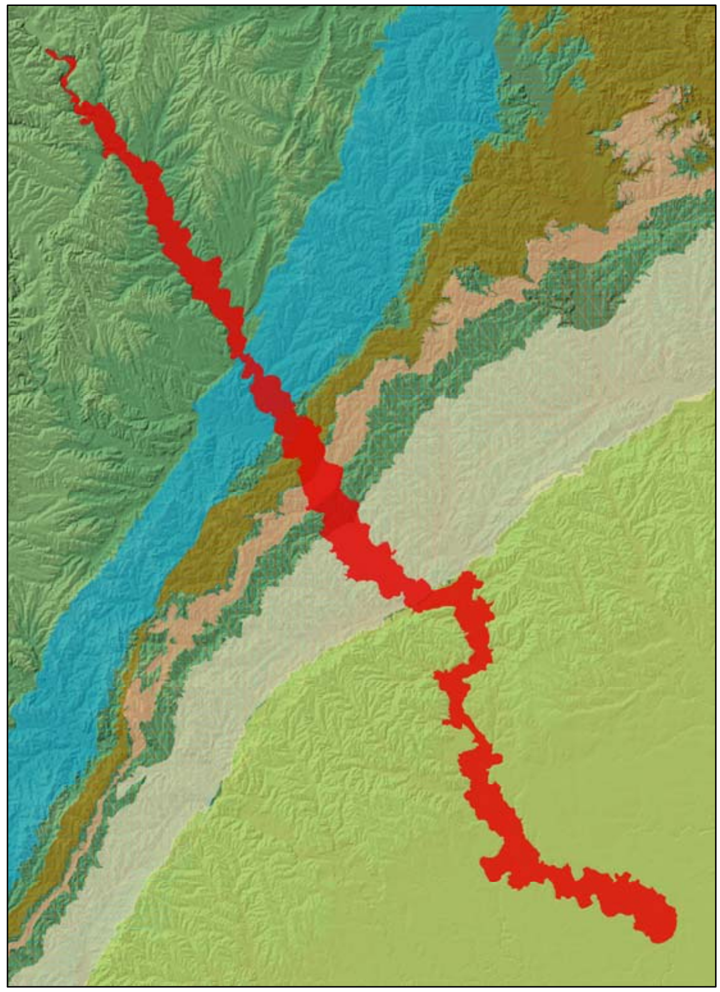
Final Conceptual Model Report for the Brazos River Alluvium Aquifer Groundwater Availability Model



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Texas Water Development Board

March 2016

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Geoscientist and Engineer Seals

This report documents the work of the following Licensed Texas Geoscientists and Licensed Texas Professional Engineers:

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Mr. Ewing was the Project Manager for this work and was responsible for oversight on the project.

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Executive Summary

This report documents the development of a conceptual model for the Brazos River Alluvium Aquifer. The Brazos River Alluvium Aquifer, a minor aquifer in Texas, consists of the alluvial floodplain and connected terrace deposits of the Brazos River from Whitney Dam to Fort Bend County. The Brazos River Alluvium Aquifer transverses portions of Bosque, Hill, McLennan, Falls, Milam, Robertson, Burleson, Brazos, Washington, Grimes, Austin, Waller, and Fort Bend counties. The physiography and climate, geology, previous studies, hydrostratigraphy, hydrostratigraphic framework, water levels, recharge, surface water interaction, hydraulic properties, discharge, and water quality for the Brazos River Alluvium Aquifer are documented in this report.

Sediment deposition related to the Brazos River includes both floodplain and terrace alluvial deposits. The deposits consist of typical alluvial sediments, including gravel, fine to coarse sand, silt, and clay, in lenses that pinch out or grade both laterally and vertically. In general, the deposits are coarser at the base and fine upward. The sequence of finer upper deposits transitioning to coarser lower deposits is consistent throughout the aquifer. However, due to pinching out and interfingering, the grain size and relative position of individual constituents in the sequence vary from place to place. The transition from one type of material to another, both laterally and vertically, can be either sharp and distinct or gradual. Groundwater in the Brazos River Alluvium Aquifer is predominately under unconfined conditions. In areas where clay lenses overlie lenses of sand or gravel, locally confined conditions may exist. The structural base of the Brazos River Alluvium Aquifer was based primarily on the work of Shah and others (2007a). Aquifer thickness ranges between a few feet at its edges to a maximum of 127 feet in Grimes County. The average thickness of the alluvium is 51 feet.

Historical water levels have fluctuated but remained generally stable in the long term, with the exception of the last several years where declines have been observed in some counties. Water levels generally dip toward the Brazos River locally and follow the regional downward trend in topography from the northwest towards the Gulf of Mexico. Target water levels and hydrographs have been identified that can be used in the calibration of the numerical model of the Brazos River Alluvium Aquifer.

Recharge to both the Brazos River Alluvium Aquifer and the outcrops of the formations underlying the aquifer in the study area has been estimated based on previous studies and base flow analyses as part of this study. Within the study area, pre-development recharge is estimated to be approximately 40,000 acre-feet per year in the Brazos River Alluvium Aquifer and approximately 710,000 acre-feet per year in the outcrops of the underlying formations. Post-development recharge is estimated to be approximately 50,000 acre-feet per year in the Brazos Alluvium Aquifer in 2012.

The interaction between the Brazos River Alluvium Aquifer and surface water bodies, including the Brazos River, its tributaries, reservoirs, and oxbow lakes have been evaluated. Gain/loss studies have been evaluated to describe the gains and losses between the Brazos River and its tributaries and the groundwater system at snap-shots in time. Long-term estimates of the contribution of the groundwater system to the base flow in the Brazos River and its tributaries has also been evaluated through hydrograph separation analyses.

Long-duration aquifer pumping tests to estimate hydraulic properties are lacking in the Brazos River Alluvium Aquifer. A theoretical relationship between transmissivity and specific capacity was used to estimate hydraulic properties at 575 wells where short-duration specific capacity measurement were available. Horizontal hydraulic conductivities range from 0.26 to 890 feet per day, with a geometric mean and median value of 59 and 83 feet per day, respectively.

Groundwater production from the Brazos River Alluvium Aquifer is used primarily for irrigation purposes, with smaller quantities used for rural domestic, livestock, and municipal purposes. Pumping estimates were based on the TWDB water use survey data, metered and voluntary production rates reported by Groundwater Conservation Districts, and historical reports.

Water quality in the Brazos River Alluvium Aquifer was evaluated with respect to total dissolved solids, sulfate, chloride, fluoride, nitrate, arsenic, irrigation salinity hazard, and sodium hazard. Groundwater in the aquifer is very hard and mostly fresh with some slightly saline areas. Total dissolved solids concentration exceeds the secondary maximum contaminant level of 500 milligrams per liter in approximately 92 percent of the groundwater sampled from Brazos River Alluvium Aquifer wells. Sixteen percent of groundwater samples from Brazos River Alluvium Aquifer wells exceed this level for sulfate and 18 percent exceed this level for chloride. Less than 1 percent of the groundwater samples from Brazos River Alluvium Aquifer wells have a chloride concentration greater than the level potentially dangerous for crops. No maximum contaminant levels for fluoride are exceeded in the aquifer. The primary maximum contaminant level for nitrate is exceeded in 13 percent of the groundwater samples from Brazos River Alluvium Aquifer wells. The maximum concentration level for arsenic is exceeded in 7 percent of the groundwater samples from Brazos River Alluvium Aquifer wells. Of the wells in the Brazos River Alluvium Aquifer with chemical analyses, groundwater samples from 96 percent exhibit a high salinity hazard and 81 percent exhibit a very high salinity hazard. In the Brazos River Alluvium Aquifer, none of the sampled wells has groundwater that falls into the high category but 1 percent of the sampled wells has groundwater with a very high sodium hazard.

The purpose of this report is to provide a conceptual understanding, based on available data, of the hydrogeologic processes and properties governing groundwater flow in the Brazos River Alluvium Aquifer. This conceptual model is prerequisite to constructing a numerical groundwater availability model for the aquifer. This report and associated geodatabase provides a documented, publicly-available, resource for use by state planners, Regional Water Planning Groups, Groundwater Conservation Districts, Groundwater Management Areas, and other interested stakeholders.

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1.0 Introduction

The Texas Water Development Board (TWDB) has identified the major and minor aquifers in Texas on the basis of regional extent and amount of water produced. The major and minor aquifers are shown in Figures 1.0.1 and 1.0.2, respectively. General discussion of the major and minor aquifers is given in George and others (2011). Aquifers that supply large quantities of water over large areas of the state are defined as major aquifers and those that supply relatively small quantities of water over large areas of the state or supply large quantities of water over small areas of the state are defined as minor aquifers.

This report is the first of two reports describing the groundwater availability model for the Brazos River Alluvium Aquifer, a minor aquifer in Texas. This report documents development of the conceptual model for the aquifer, which is a compilation of data and data analyses that provides understanding of the movement of groundwater in the aquifer. The conceptual model provides the information necessary to develop a numerical model of the aquifer, which will be documented in a companion model report.

The Brazos River Alluvium Aquifer consists of the floodplain deposits and hydraulically connected terrace deposits of the Brazos River in southeast Texas. Sediments comprising these deposits range from clay to large cobbles and occur in lenses that grade both laterally and vertically. The transition from one type of material to another, both laterally and vertically, can be either sharp and distinct or gradual. The Brazos River Alluvium Aquifer is unconfined with potentially locally confined conditions where clay lenses overlie lenses of sand or gravel. From northwest to southeast, the aquifer overlies the Carrizo-Wilcox, Queen City, Sparta, Yegua-Jackson, and Gulf Coast aquifers. The shallow portions of these aquifers are assumed to be hydraulically connected to the Brazos River Alluvium Aquifer since they are conceptualized to regionally discharge to the Brazos River.

The State Water Plan (TWDB, 2012a) projects that annual groundwater supplies (i.e., groundwater available through existing infrastructure) in the Brazos River Alluvium Aquifer will decrease by 1 percent from 2010 to 2060 (39,198 to 38,783 acre-feet per year). Groundwater pumped from the aquifer is used predominately for irrigation purposes. Total pumping from the aquifer is estimated to have increased by approximately 275 percent between 1950 and 2012 (37,097 to 138,890 acre-feet per year). This indicates that recent pumping is significantly higher than projected supplies in the 2012 State Water Plan. Groundwater in the Brazos River Alluvium Aquifer is fresh to slightly saline.

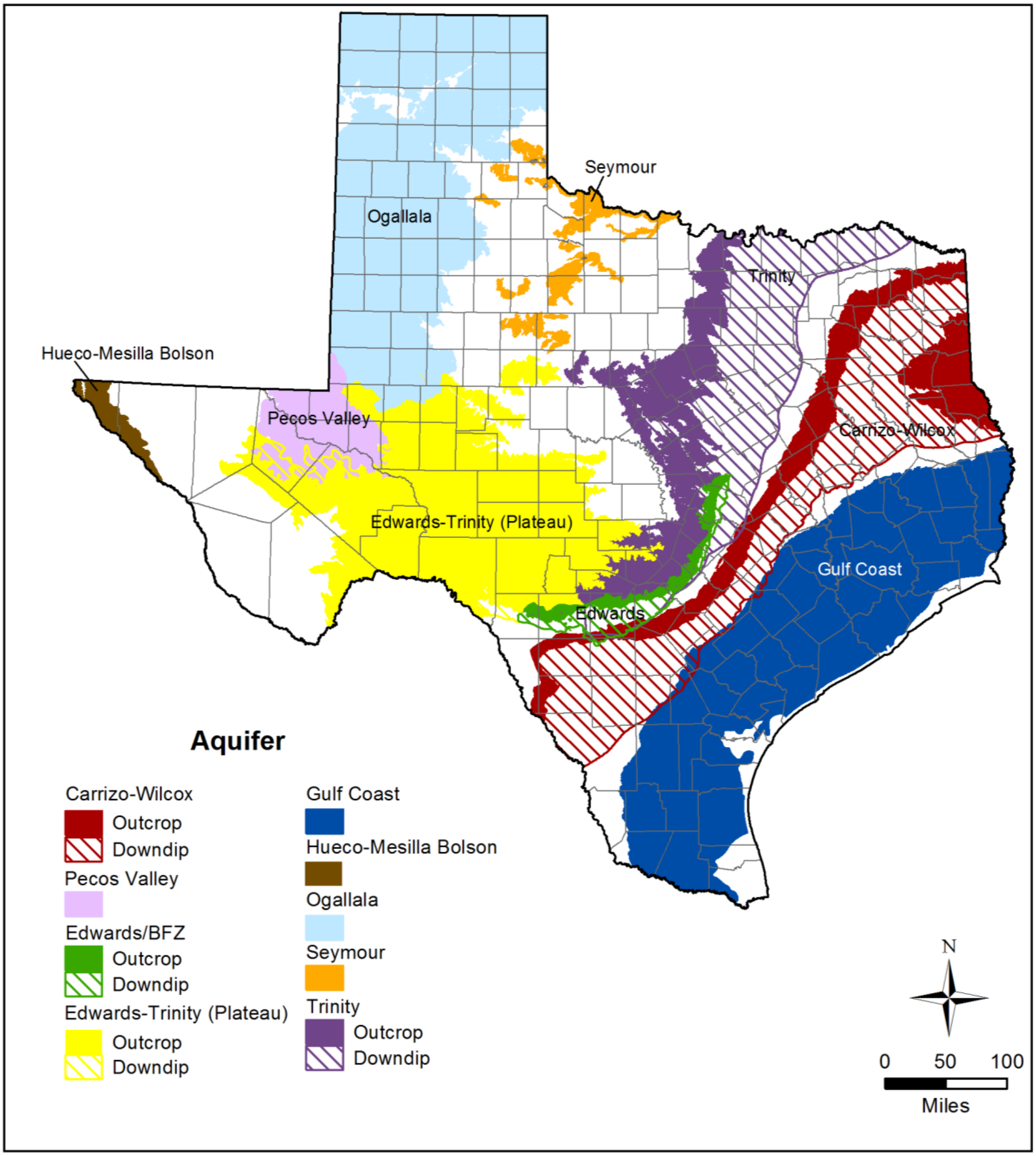
The Texas Water Code codified the requirement for generation of a State Water Plan that allows for the development, management, and conservation of water resources and the preparation and response to drought, while maintaining sufficient water available for the citizens of Texas (TWDB, 2012a). Senate Bill 1 and subsequent legislation directed the TWDB to coordinate regional water planning with a process based upon public participation. Also, as a result of Senate Bill 1, the approach to water planning in the state of Texas has shifted from a water-demand based allocation approach to an availability-based approach.

Groundwater models provide a tool to estimate groundwater availability for various water use strategies and to determine the cumulative effects of increased water use and drought. A groundwater model is a numerical representation of the aquifer system capable of simulating historical conditions and predicting future aquifer conditions. Inherent to the groundwater model are a set of equations that are developed and applied to describe the primary or dominant physical processes considered to be controlling groundwater flow in the aquifer system. Groundwater models are essential for performing complex analyses and making informed predictions and related decisions (Anderson and Woessner, 1992).

Development of groundwater availability models for the major and minor Texas aquifers is integral to the state water planning process. The purpose of the TWDB groundwater availability model program is to provide tools that can be used to develop reliable and timely information on groundwater availability for the citizens of Texas and to ensure adequate supplies or recognize inadequate supplies over a 50-year planning period. The groundwater availability models also serve as an integral part of the process of determining modeled available groundwater based on desired future conditions, as required by House Bill 1763 (79^{th} Legislative Session). The Brazos River Alluvium Aquifer groundwater availability model will, thus, serve as a tool for groundwater planning in the state.

The Brazos River Alluvium Aquifer groundwater availability model will be developed using a modeling protocol that is standard to the groundwater modeling industry. This protocol includes: (1) the development of a conceptual model for groundwater flow in the aquifer, including defining physical limits and properties, (2) model design, (3) model calibration, (4) sensitivity analysis, and (5) reporting. The conceptual model, which is documented in this report, is a description of the physical processes governing groundwater flow in the aquifer system. Available data and reports for the model area were reviewed in the conceptual model development stage. Model design, model calibration, and sensitivity analysis are aspects of the numerical model, which will be documented in a subsequent report.

This report on the conceptual model for the Brazos River Alluvium Aquifer consists of eight sections. Section 2.0 is a discussion of the study area including physiography, climate, and geology. Previous investigations are discussed in Section 3.0. The hydrologic setting, including hydrostratigraphy, hydrostratigraphic framework, water-levels and regional groundwater flow, recharge, interaction with surface water bodies, hydraulic properties, discharge, and water quality, is given in Section 4.0. Section 5.0 presents the conceptual model of groundwater flow in the aquifer. Future improvements, acknowledgments, and references are given in Sections 6.0, 7.0, and 8.0, respectively.



Edwards/BFZ = Edwards (Balcones Fault Zone) Aquifer

Figure 1.0.1 Locations of major aquifers in Texas (TWDB, 2006a).

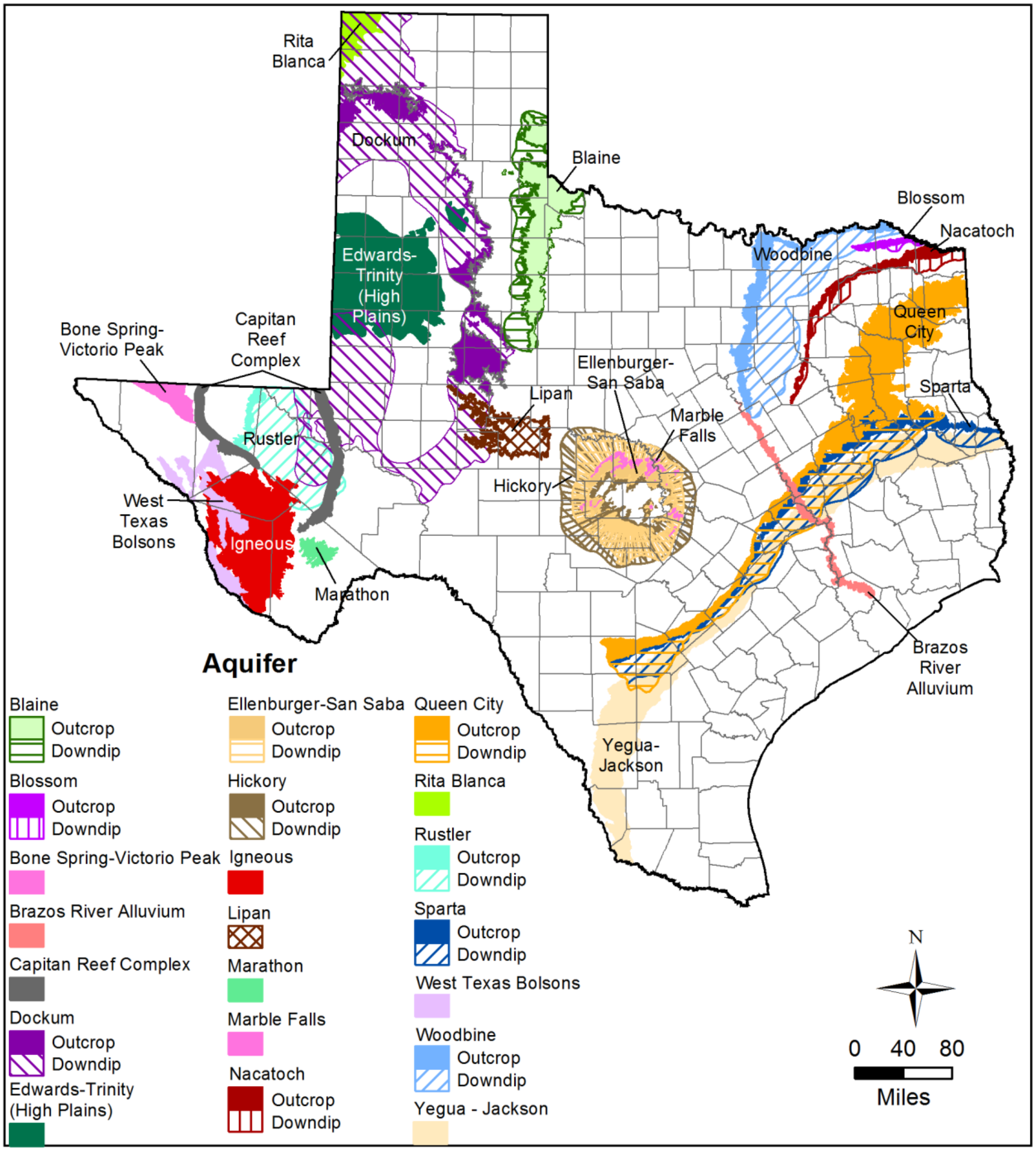


Figure 1.0.2 Locations of minor aquifers in Texas (TWDB, 2006b).

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2.0 Study Area

The Brazos River Alluvium Aquifer consists predominantly of Quaternary-age alluvium and connected terrace deposits flanking 350-river miles of the Brazos River in Texas from Whitney Dam in southern Hill and Bosque counties to Fort Bend County. The aquifer is up to 7 miles wide and has an area of 1,053 square miles (George and others, 2011).

The location of the active model boundary for the Brazos River Alluvium Aquifer groundwater availability model is shown relative to the state of Texas in Figure 2.0.1. The active model area is shown in Figures 2.0.2a and 2.0.2b, for the northern and southern portions of the aquifer, respectively. Groundwater model boundaries are typically defined on the basis of surface or groundwater hydrologic boundaries. The current model's lateral boundaries generally correspond to the boundaries of the Brazos River Basin as given by TWDB (2002). In the south, where the Brazos River Basin narrows, however, the model boundary was extended westward to the western boundary of the Brazos-Colorado River Basin, as given by TWDB (2002), and eastward to the eastern boundaries of the San Jacinto River Basin subwatersheds listed in Table 2.0.1. These latter subwatersheds are defined in the Watershed Boundary Dataset of the United States Department of Agriculture (2014a). The northern and southern boundaries of the model coincide with the northern and southern extent of the Brazos River Alluvium Aquifer and roughly parallel the direction of shallow groundwater flow towards the Brazos River. All or parts of 33 counties are included in the active model area, 13 of which intersect the Brazos River Alluvium Aquifer.

In order to show the entire aquifer in a single figure at a scale large enough to view detailed information, the majority of the figures in this report do not extend to the active model boundary. Rather, information is shown in a smaller study area (see Figure 2.0.1). The lateral boundaries for the active model area extend a large distance from the aquifer in order to capture hydrologic boundaries. However, the relevant information for this conceptual model report is that pertaining to the Brazos River Alluvium Aquifer and not information at large distances from the aquifer. Use of this smaller study area for display purposes does not compromise development of the conceptual model of the Brazos River Alluvium Aquifer.

Figure 2.0.3 shows the cities, towns, and major roadways in the study area. The only major city located on the Brazos River Alluvium Aquifer is the city of Waco in McLennan County. In addition, several towns are located on or partially on the aquifer. The locations of major rivers, lakes, and reservoirs in the study area are shown in Figure 2.0.4. The portion of the Brazos River overlying the Brazos River Alluvium Aquifer is a perennial river, as it tends to gain water from the underlying aquifer. Several reservoirs are located near the Brazos River Alluvium Aquifer, including Lake Whitney, Lake Waco, Lake Creek Lake, and Smithers Lake.

Figures 2.0.5 and 2.0.6 show the surface outcrop and downdip subcrop of the major and minor aquifers in the study area, respectively. Major aquifers that underlie the Brazos River Alluvium Aquifer are the Carrizo-Wilcox, Trinity, and Gulf Coast aquifers. The Trinity Aquifer is at such depth beneath the Brazos River Alluvium Aquifer that it is not likely to interact with the alluvium. Although the Edwards Balcones Fault Zone Aquifer lies within the study area, it does not underlie or interact with the Brazos River Alluvium Aquifer. Minor aquifers that underlie the Brazos River Alluvium Aquifer include the Queen City, Sparta, and Yegua-Jackson aquifers. Although the Woodbine Aquifer does outcrop near the northeastern boundary of the Brazos River Alluvium Aquifer, examination of the surface geology (Bureau of Economic Geology, 1970) indicates that the Brazos River Alluvium Aquifer does not actually contact the surface expression of the Woodbine Formation. Therefore, the Woodbine Aquifer is not thought to interact with the Brazos River Alluvium Aquifer.

The Brazos River Alluvium Aquifer is located within two Texas Regional Water Planning Areas (Figure 2.0.7). The northern portion of the aquifer is in the Brazos G Regional Water Planning Area (Region G) and the southern portion is in the Region H Regional Water Planning Area. Portions of the aquifer are located in six groundwater conservation districts and one subsidence district (Figure 2.0.8). From north to south, these are the Prairielands, Middle Trinity, Southern Trinity, Brazos Valley, Post Oak Savannah, and Bluebonnet Groundwater Conservation Districts and the Fort Bend Subsidence District. The Brazos River Alluvium Aquifer intersects portions of Groundwater Management Areas 8, 12 and 14 (Figure 2.0.9). The majority of the aquifer is located in the Brazos River Authority (Figure 2.0.10).

Since the Brazos River Alluvium Aquifer follows the Brazos River, the majority of the aquifer falls within the Brazos River Basin (Figure 2.0.11). At the southern end, a small portion of the aquifer is located in the San Jacinto-Brazos River Basin.

Table 2.0.1 Subwatersheds used to define the eastern boundary for the southern portion of the Brazos River Alluvium Aquifer groundwater availability model (United States Department of Agriculture, 2014a).

Watershed 12 Digit Hydrologic Unit Code	Watershed Name
120401040703	Lower Greens Bayou
120401040606	Middle Greens Bayou
120401040605	Upper Greens Bayou
120401040603	Headwaters Greens Bayou
120401020107	Marshall Lake-Cypress Creek
120401020212	Willow Creek
120401020212	Dry Creek-Spring Creek
120401010308	Landrum Creek-Lake Creek
120401010305	Kidhaw Branch-Lake Creek
120401010303	Flagtail Creek-Lake Creek
120401040705	Vince Bayou-Buffalo Bayou

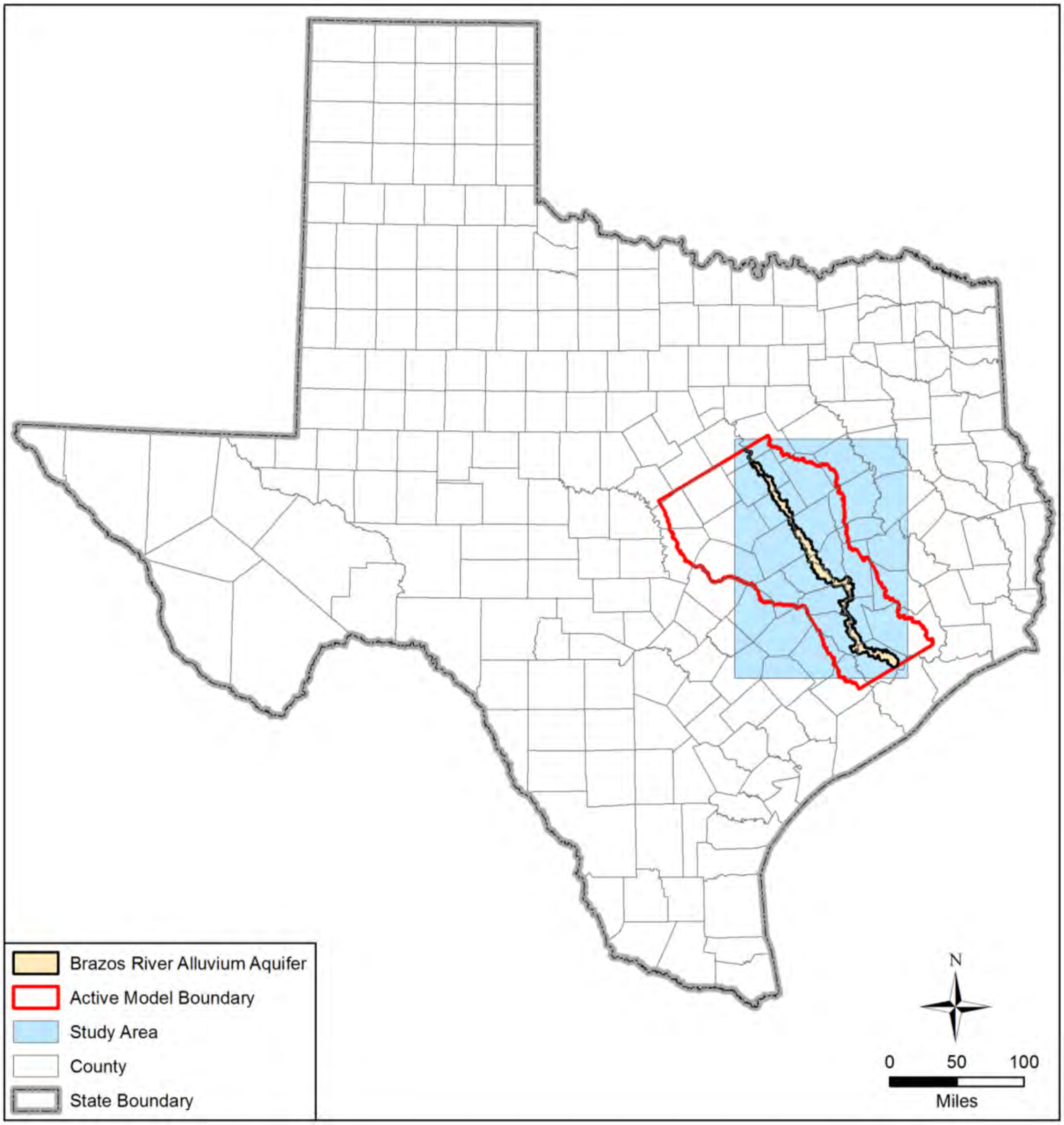


Figure 2.0.1 Active model boundary and study area for the Brazos River Alluvium Aquifer groundwater availability model.

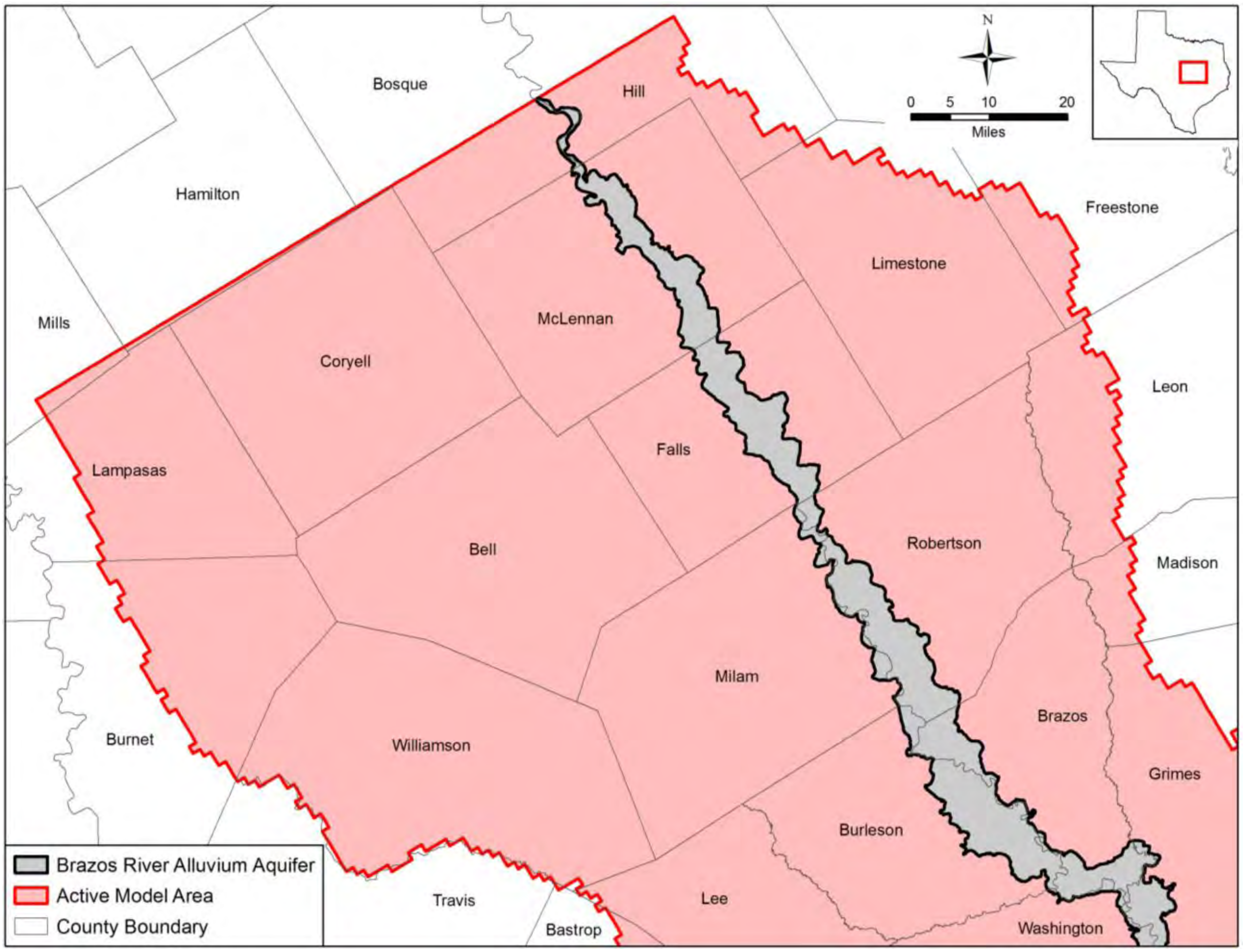


Figure 2.0.2a Northern portion of the active model area for the Brazos River Alluvium Aquifer groundwater availability model.

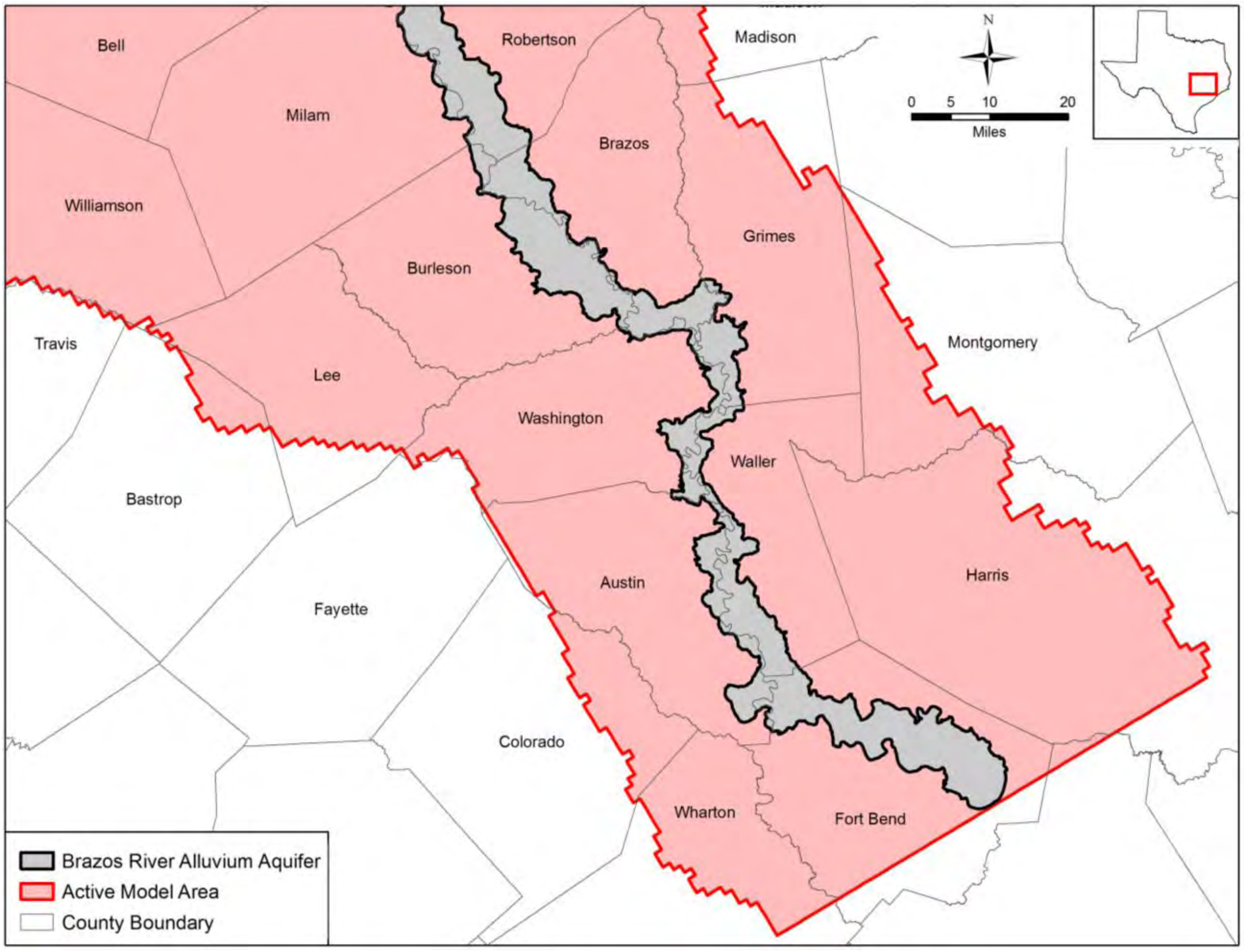


Figure 2.0.2b Southern portion of the active model area for the Brazos River Alluvium Aquifer groundwater availability model.

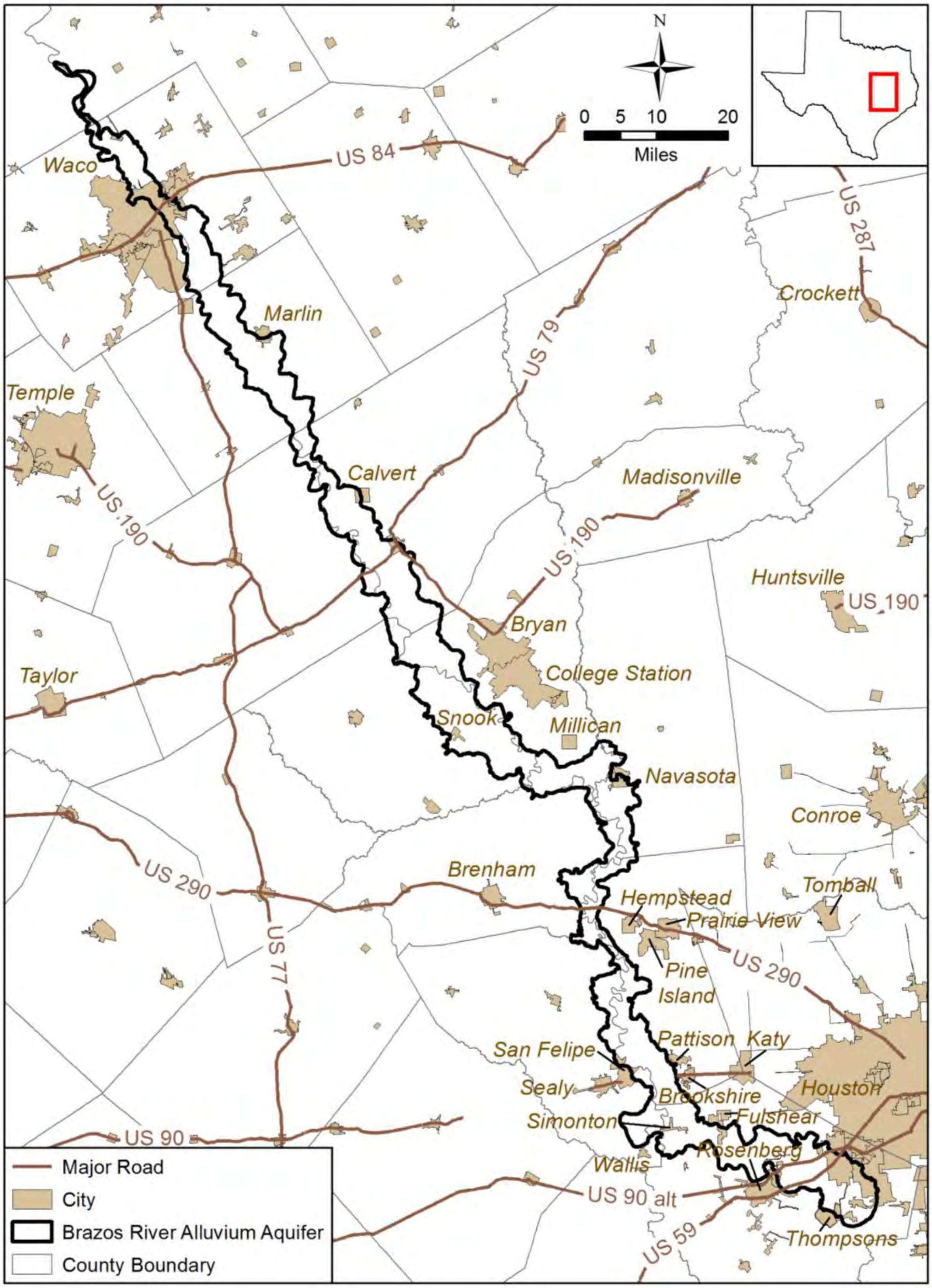


Figure 2.0.3 Cities, towns, and major roadways in the study area.

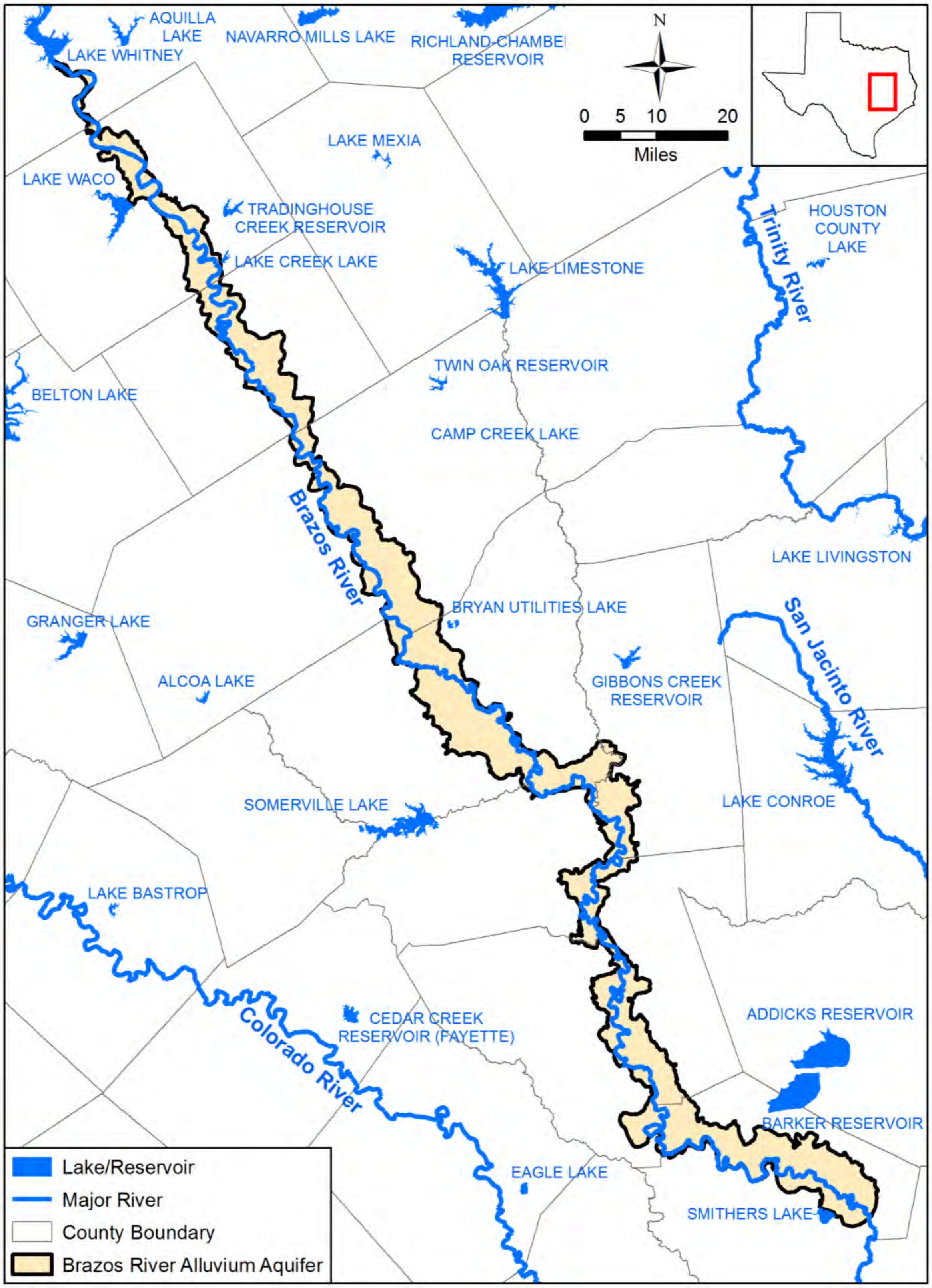
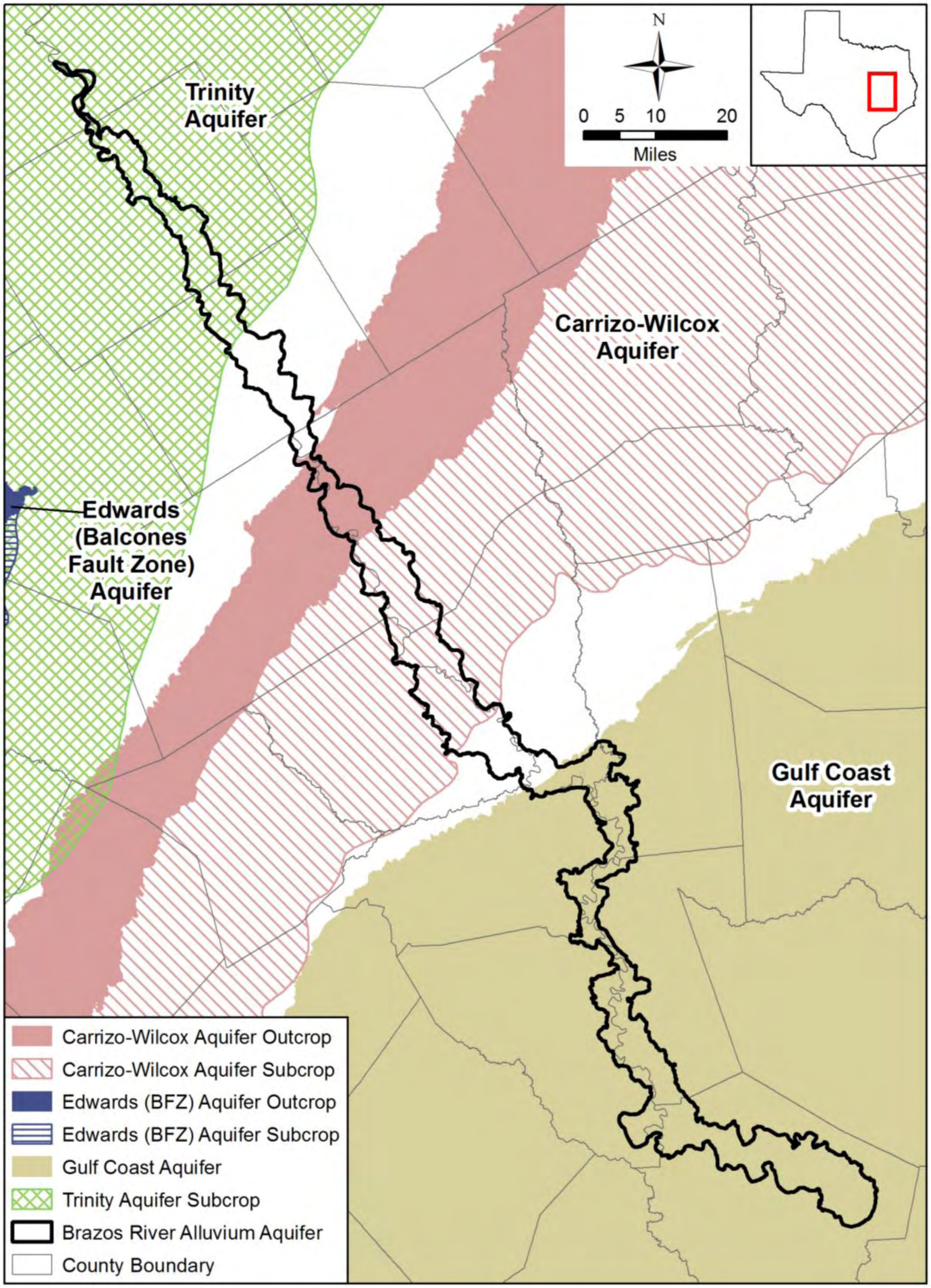


Figure 2.0.4 Major rivers, lakes, and reservoirs in the study area (TWDB, 2009; 2014a)



BFZ = Balcones Fault Zone

Figure 2.0.5 Major aquifers in the study area (TWDB, 2006a).

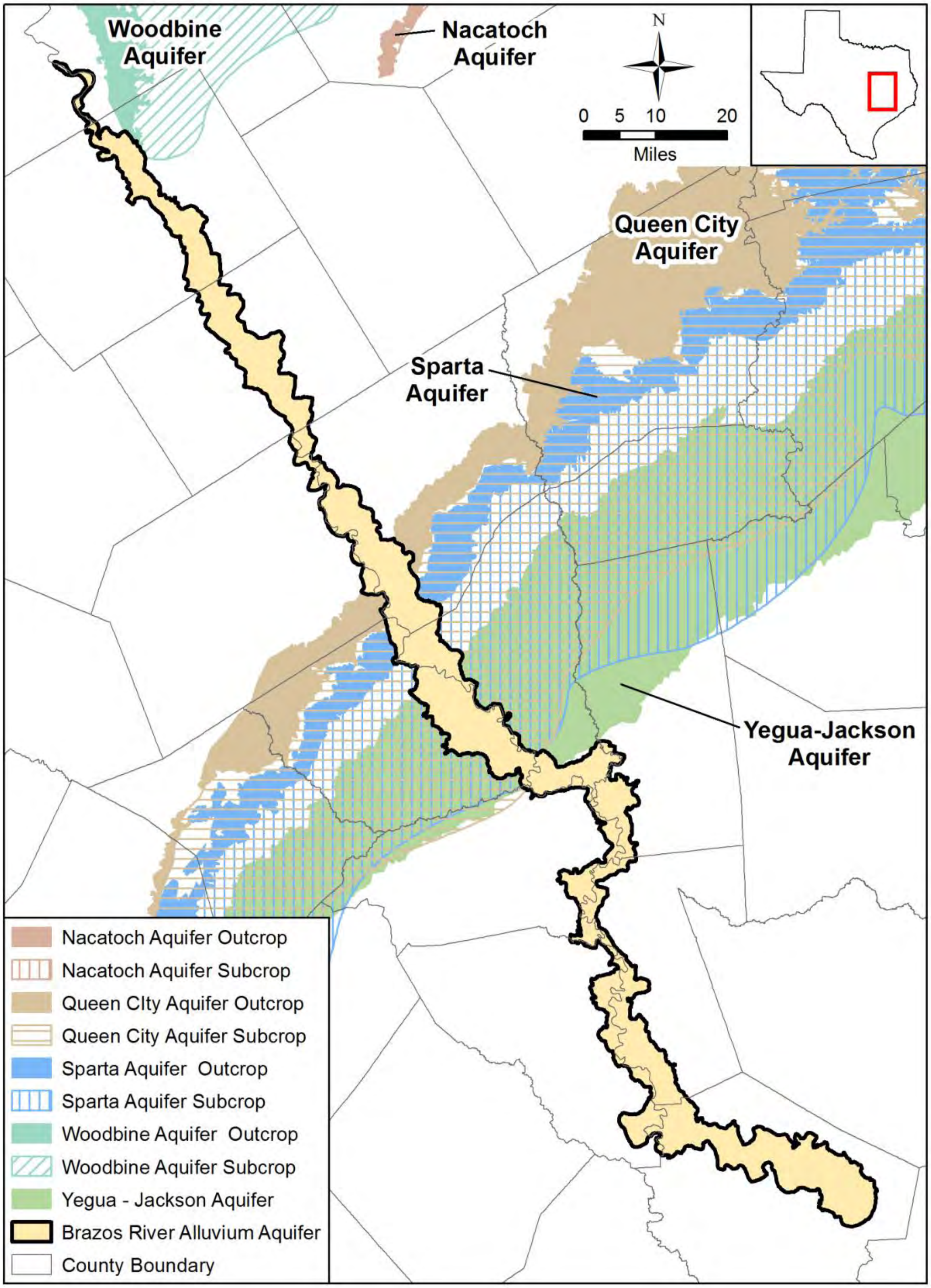


Figure 2.0.6 Minor aquifers in the study area (TWDB, 2006b).

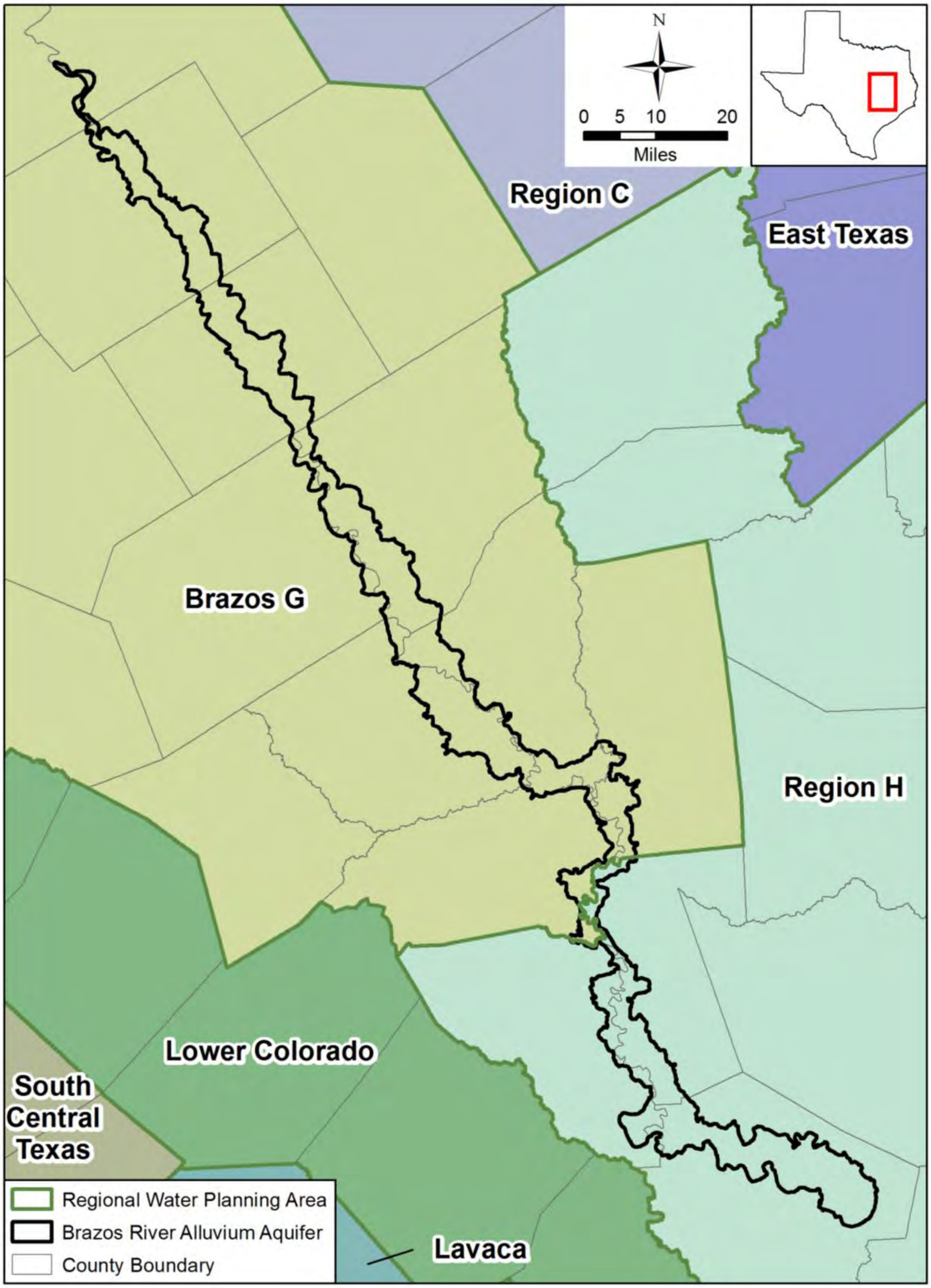


Figure 2.0.7 Regional water planning areas in the study area (TWDB, 2014b).

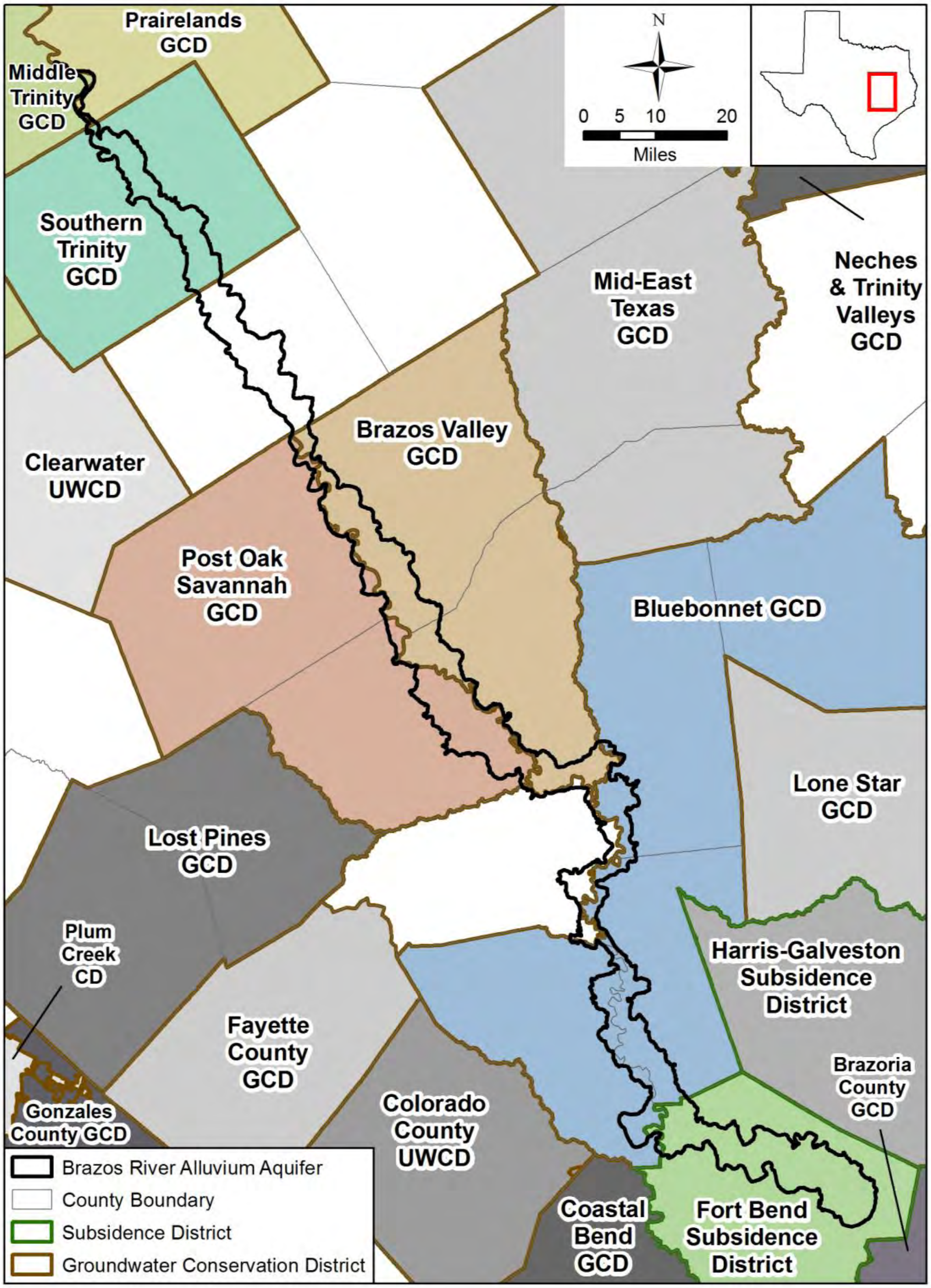


Figure 2.0.8 Groundwater conservation districts and subsidence districts in the study area (TWDB, 2014c). Abbreviation key: GCD = groundwater conservation district, CD = conservation district, UWCD = underground water conservation district

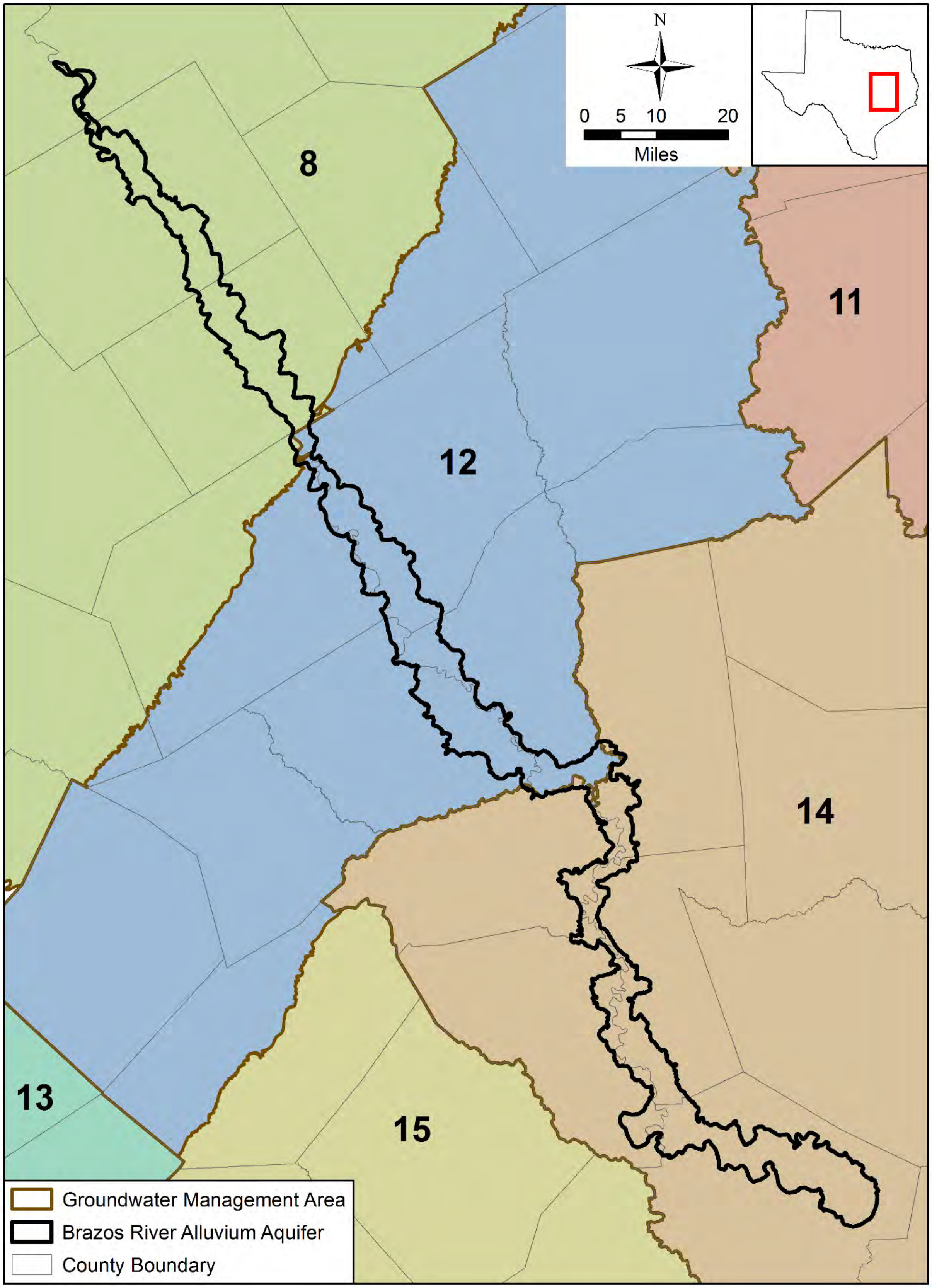


Figure 2.0.9 Groundwater management areas in the study area (TWDB, 2011).

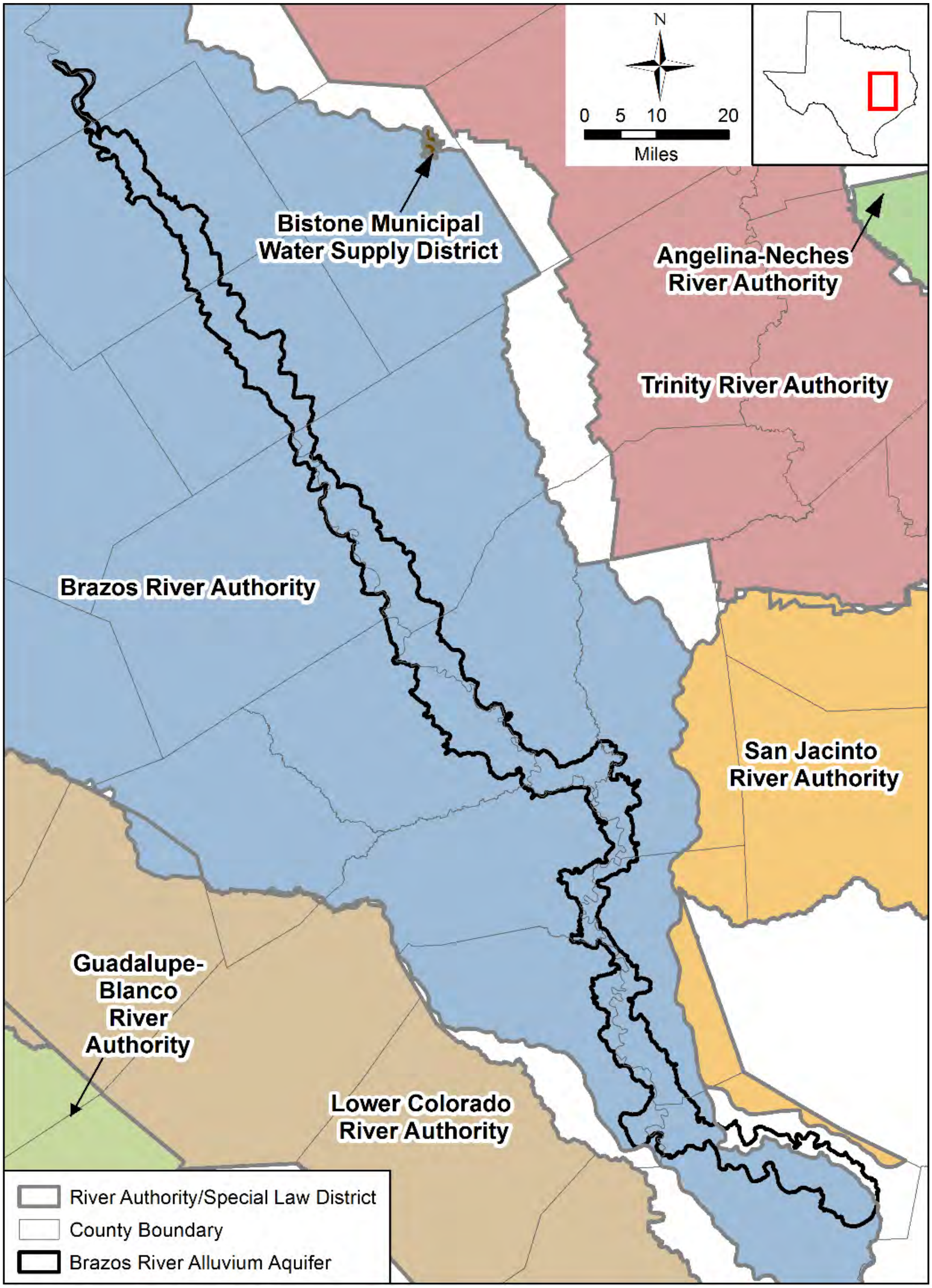


Figure 2.0.10 River authorities and special law districts in the study area (TWDB, 2014d).

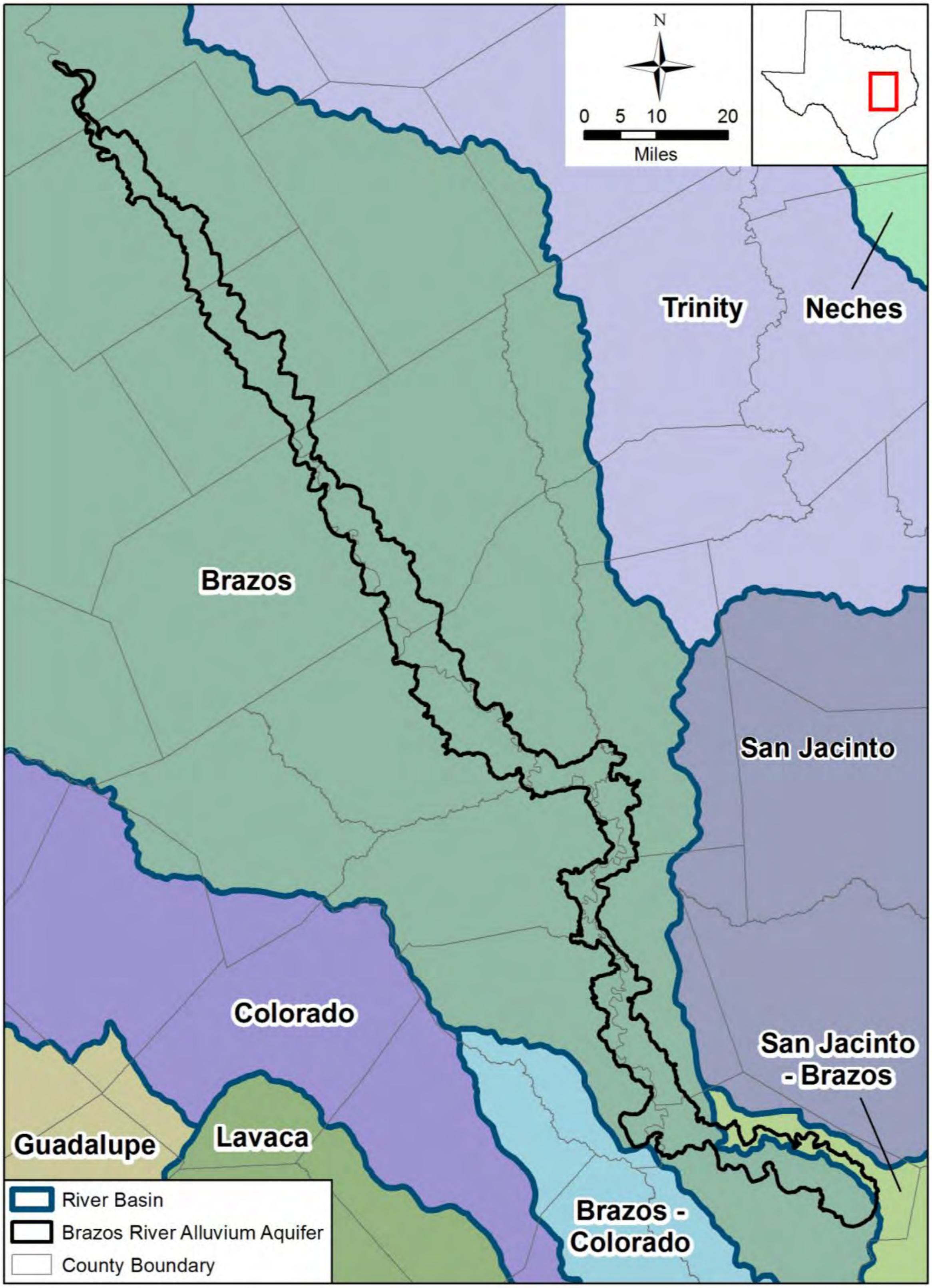


Figure 2.0.11 Major river basins and sub-basins in the study area (TWDB, 2002).

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2.1 Physiography and Climate

The Brazos River Alluvium Aquifer largely falls in the West Gulf Coast Plain section of the Coastal Plain Province of the Atlantic Plain Physiographic Division as mapped by Fenneman and Johnson (1946) (Figure 2.1.1). Note that on this figure the physiographic divisions are indicated by color and are shown in the legend, sections are indicated by fill, and section names are posted. The West Gulf Coast Plain section is characterized as a young coastal plain that grades inland to become a mature coastal plain (Fenneman, 1938). A small northern portion of the aquifer falls in the Central Texas section of the Great Plains Province of the Interior Plains Physiographic Division as mapped by Fenneman and Johnson (1946). This section is a mature plateau in the late stages of erosion that marks the transition between the lowlands in the east and north and younger plateaus to the west and south (Fenneman, 1931).

Figure 2.1.2 shows the Level III Ecological Regions in the study area as defined by the United States Environmental Protection Agency (2011). Ecological regions (also referred to as ecoregions) refer to areas exhibiting a distinct ecosystem type. The conterminous United States is divided into Level III Ecoregions based on factors such as vegetation, climate, hydrology, geology, and physiography. The northernmost portion of the Brazos River Alluvium Aquifer falls in the Cross Timbers Ecoregion, which consists predominately of native “cross-timbers” vegetation and is used mostly for pastureland and rangeland due to its general unsuitability for crops. This ecoregion corresponds roughly to the Central Texas Physiographic section defined by Fenneman and Johnson (1946) as discussed above. Towards the south, the ecoregion classification alternates between Texas Blackland Prairies and East Central Texas Plains until transitioning into the Western Gulf Coastal Plains. The Texas Blackland Prairies Ecoregion is generally characterized by natural prairie vegetation with sections converted to cropland, pasture, and forage production. The East Central Texas Plains ecoregion consists mostly of post oak savanna vegetation with a dense, underlying clay pan that limits conversion to cropland. The Western Gulf Coastal Plains ecoregion, a flat region more conducive to agriculture, has natural vegetation that ranges from grassland to forest or savanna-type further inland.

Figure 2.1.3 provides a topographic map of the study area based on the 10-meter (32.8-foot) digital elevation model (DEM) (United States Geological Survey, 2014a). The aquifer falls in the low-lying and relatively flat floodplain of the Brazos River. The surface elevation of the

Brazos River Alluvium Aquifer decreases from a high of about 588 feet above mean sea level in the northwest to a low of 17 feet above mean sea level in the southeast.

Surface soil was evaluated based on data from the SSURGO database (United States Department of Agriculture, 2014b) within the boundary of the Brazos River Alluvium Aquifer and from the lower-resolution STATSGO2 database (United States Department of Agriculture, 2006) for areas within the active model area outside the aquifer. These databases include data on soils to a depth up to about 6 to 7 feet below the surface. One of the physical properties of the soils estimated in the database is saturated hydraulic conductivity. The databases provide a spatial coverage of delineated areas, called map units, of soils with similar properties. For each of these map units, there can be up to six soil components, including an estimate of what fraction of the map unit is comprised of each component. In addition, each component can have up to four soil horizons, or layers of soil that share common physical characteristics. Each horizon of each component will generally have an associated estimate of saturated hydraulic conductivity, as well as the thickness of that particular horizon.

To develop an integrated estimate of infiltration capacity, an effective saturated hydraulic conductivity value for each component was calculated using the thickness-weighted harmonic mean of the horizons comprising that component:

$$Component\ K_{eff} = \frac{\sum b_i}{\sum \frac{b_i}{K_i}} \tag{2.1.1}$$

where:

K_{eff} = the effective saturated hydraulic conductivity of the component,
b_i = the thickness of each horizon, and
K_i = the saturated hydraulic conductivity of each horizon.

This method was chosen as it favors the lowest hydraulic conductivity layer, which exerts the most control on infiltration. Based on these component values, an estimate of saturated hydraulic conductivity for each map unit was calculated using an area-weighted, geometric average of the effective saturated hydraulic conductivity value of the components comprising that map unit:

$$Map\ Unit\ K_{eff} = \sum m_i \times K_i \tag{2.1.2}$$

where:

K_{eff} = the effective saturated hydraulic conductivity of the map unit,

m_i = the percentage of map unit area comprised by each component, and

K_i = the effective saturated hydraulic conductivity of each component.

Figure 2.1.4 shows the effective saturated hydraulic conductivity of map units for the surface soils in the vicinity of the Brazos River Alluvium Aquifer.

The climate in the study area is classified predominantly as Subtropical Humid, as defined by Larkin and Bomar (1983) (Figure 2.1.5). This is a type of Modified Marine climate caused by the onshore flow of air from the Gulf of Mexico that loses moisture content as it travels east to west across the state. The Subtropical Humid climate is characterized by warm summers and has a high moisture content since it is close to the coast. The northwest portion of the study area falls in the transition zone between the Subtropical Humid and Subtropical Subhumid climates. This transition marks a shift to slightly drier conditions as air moves further inland from the coast. The Subtropical Subhumid climate is characterized by hot summers and dry winters (Larkin and Bomar, 1983). Figure 2.1.5 also shows the climatic divisions in the study area as defined by the National Climatic Data Center Climate Divisional Dataset for long-term analyses of drought, temperature, and precipitation (National Oceanic and Atmospheric Administration, 2014a). The average monthly Palmer Drought Severity Index values for each division for the time period from 1895 to mid-2014 are depicted in Figure 2.1.5. All climatic divisions fall in the normal category, which is defined as the range from 0 to 0.5.

The Parameter-elevation Regressions on Independent Slopes Model (PRISM) temperature and precipitation datasets developed and presented online by the PRISM Climate Group at Oregon State University provides a distribution of average annual temperature and precipitation based on the period from 1981 to 2010 (PRISM Climate Group, 2013). Figures 2.1.6 and 2.17 show the average annual temperature and average annual precipitation in the study area, respectively. Across the Brazos River Alluvium Aquifer, the average annual temperature ranges from a high of 70 degrees Fahrenheit in the southeast to a low of 66 degrees Fahrenheit in the northwest, and the average annual precipitation ranges from a low of about 35 inches in the northwest to a high of about 50 inches in the southeast.

Climate monitoring data are available for 281 National Climatic Data Center Cooperative Observer Network stations in the study area from as early as the late 1800s through the present (National Oceanic and Atmospheric Administration, 2010) (Figure 2.1.8). Measurements at most stations did not begin until the 1940s. In general, precipitation measurements are not continuous on a month-by-month or year-by-year basis at these stations. Examples of historical variation in annual precipitation at select gages in the study area are shown in Figure 2.1.9 (National Oceanic and Atmospheric Administration, 2014b). Most of these examples are from the 15 Cooperative Observer Network stations located within the extent of the Brazos River Alluvium Aquifer. On this figure, the blue lines represent annual precipitation, and the red dashed lines correspond to the mean annual precipitation for the period of record. A discontinuity in the blue line indicates a year with fewer than 12 months of data available.

Figure 2.1.10 shows the long-term average monthly variation in precipitation at select sites (National Oceanic and Atmospheric Administration, 2014b). The period for the long-term average monthly data is 1931 to 2014 for gage 418491, 1932 to 2014 for gage 415611, 1931 to 2014 for gage 418728, 1931 to 2003 for gage 418160, and 1949 to 2014 for gage 419715. At all stations, precipitation peaks twice a year: in late spring and again in the fall. This figure shows slight differences in average monthly precipitation between the southern and northern portions of the Brazos River Alluvium Aquifer. The first precipitation peak occurs in May for all stations. However, the second precipitation peak occurs slightly later at the two northern stations (October) compared to earlier at the two southern stations (September). In addition, the precipitation peaks are much more pronounced at the northern stations due to low precipitation throughout the rest of the year.

Average annual lake evaporation in the study area ranges from a high of 59 inches per year in the north to a low of 46 inches per year in the southeast (TWDB, 2013) (Figure 2.1.11). Annual evaporation rates generally exceed the average annual rainfall (see Figure 2.1.7) in all portions of the Brazos River Alluvium Aquifer except in the southeast. Monthly variations in lake surface evaporation are shown in Figure 2.1.12 for five locations in the study area (TWDB, 2013). These values represent the average of the monthly lake surface evaporation data from January 1954 through December 2013. Monthly lake evaporation peaks in July for all locations, with the highest evaporation peaks occurring in the west.

Evapotranspiration is the combined process of soil water evaporation near land surface and the uptake in the root zone and subsequent transpiration of water by vegetation. For the purposes of groundwater modeling, two types of evapotranspiration are distinguished: vadose zone evapotranspiration and groundwater evapotranspiration. Evapotranspiration in the vadose zone captures infiltrating water before it reaches the water table. Groundwater evapotranspiration is plant uptake or surface evaporation of groundwater at the water table. Groundwater evapotranspiration is the focus here since it is the type implemented in groundwater models. Vadose zone evapotranspiration is accounted for in recharge estimates.

Groundwater evapotranspiration occurs primarily in riparian buffer zones adjacent to streams (Scanlon and others, 2005) and typically has limited influence on most regional groundwater models. However, since the entire extent of the Brazos River Alluvium Aquifer falls very near the Brazos River and, with the exception of developed areas, has significant vegetative cover consisting of both cropland and natural vegetation, groundwater evapotranspiration may be a large portion of the water budget for this aquifer. The United States Fish and Wildlife Service (2014) provides spatial coverage of riparian zones in Texas. Currently, however, this coverage is limited to west Texas, so it does not provide any information for the study area. For the conceptualization of the Brazos River Alluvium Aquifer, areas adjacent to streams are assumed to be the locations of riparian zones.

Scanlon and others (2005) summarize the conceptual approach to implementing groundwater evapotranspiration in groundwater models. In general, if water tables are very near the surface, evapotranspiration will be close to the potential evapotranspiration, assuming there is some type of vegetative cover. However, outside of riparian zones, the water table generally is not at land surface but rather lies some distance below the land surface. If the rooting depth of vegetation is known, then the areas where the water table is high enough to be available for evapotranspiration can be identified. When the water table is below land surface but still within the main vegetation root zone, evapotranspiration will occur at the unhindered vegetative evapotranspiration rate, estimated as (Scanlon and others, 2005):

$$ETV_{max} = PET \bullet K_c \tag{2.1.3}$$

where:

ETV_{max} = the unhindered vegetative evapotranspiration rate,

PET = potential evapotranspiration, and

K_c = vegetation coefficient.

Equation 2.1.3 requires estimates of potential evapotranspiration and vegetation coefficients for the Brazos River Alluvium Aquifer. In addition, vegetative rooting depth is needed to determine whether the water table lies within the root zone and evapotranspiration occurs at the unhindered vegetative evapotranspiration rate. The following explains how potential evapotranspiration, vegetation coefficients, and rooting depth were estimated for the Brazos River Alluvium Aquifer.

Borelli and others (1998) provide an estimate of long-term potential evapotranspiration in Texas, based on the Penman-Monteith method. In the vicinity of the Brazos River Alluvium Aquifer, long-term average potential evapotranspiration ranges from about 56 to 62 inches per year (Figure 2.1.13). Although evapotranspiration varies considerably with seasons, it does not vary significantly on an average annual basis.

Land cover and crop distribution were used to determine appropriate vegetative coefficient values. Figure 2.1.14 shows the land cover distribution on the Brazos River Alluvium Aquifer as given in the 2013 Cropland Data Layer (United States Department of Agriculture, 2014c). In this figure, all crops are grouped into the general category "cropland." The distribution of individual crops is shown in Figure 2.1.15. A large percentage (33 percent) of the land on the Brazos River Alluvium Aquifer is cropland. Therefore, the distribution not only of cropland as a whole but of different crop types was investigated. Figure 2.1.16 illustrates the overall distribution of land use types as well as the break-down of cropland by individual crop types.

Table 2.1.1 gives the typical crop coefficient and rooting depth for the crop types on the Brazos River Alluvium Aquifer. The crop coefficients from Borelli and others (1998) represent Texas-specific peak season values under moderate wind conditions for a grass reference crop in a humid environment. Moderate wind is defined as a mean wind run (total distance wind traveled over a specified time) of less than or equal to 250 miles per day. "Humid" means minimum relative humidity greater than or equal to 70 percent (Borelli and others, 1998). The rooting depths in Table 2.1.1 are sourced from Allen and others (1998) and are global estimates, not Texas specific.

Table 2.1.2 provides typical values for vegetative coefficients and rooting depths for Texas land cover types (other than cropland) from Scanlon and others (2005). They report vegetative coefficients calculated using the historical average monthly temperatures of Del Rio, Austin, El Paso, and Amarillo, Texas. Of these cities, the study area is most climatically similar to Austin, Texas. Therefore, the vegetative coefficients for land use on the Brazos River Alluvium Aquifer were assumed to be the same as the values reported for that city. Scanlon and others (2005) cite several different sources for rooting depth. The ones assumed here are the values for Texas-specific species from Canadell and others (1996) for mesquite and loblolly pine and Texas measurements from Schenk and Jackson (2002) for grasslands.

Table 2.1.1 Crop coefficients (Borelli and others, 1998) and rooting depths (Allen and others, 1998) for common crops in the study area.

Crop	Crop Coefficient	Rooting Depth (feet)
Corn	1.05	3.3 to 5.6
Cotton	1.05	3.3 to 5.6
Non-Alfalfa Hay[1]	1.05	3.3 to 4.9
Winter Wheat	1.05	4.9 to 5.9
Sorghum	1.00	3.3 to 6.6
Oats	1.05	3.3 to 4.9

[1] Assumed to be barley/oats

Table 2.1.2 Typical vegetative coefficients and rooting depths for land cover types (Scanlon and others, 2005).

Vegetation Type	Assumed Land Use Category	Vegetative Coefficient	Rooting Depth (feet)
Wetlands	Wetlands	0.77	[1]
Ranchland: warm grasses	Grassland/pasture	0.7	2.0 to 3.0
Mesquite	Deciduous Forest	0.54	6.9 to 48.9
Pine	Evergreen Forest	0.53	6.9 to 3.1

[1] no value reported

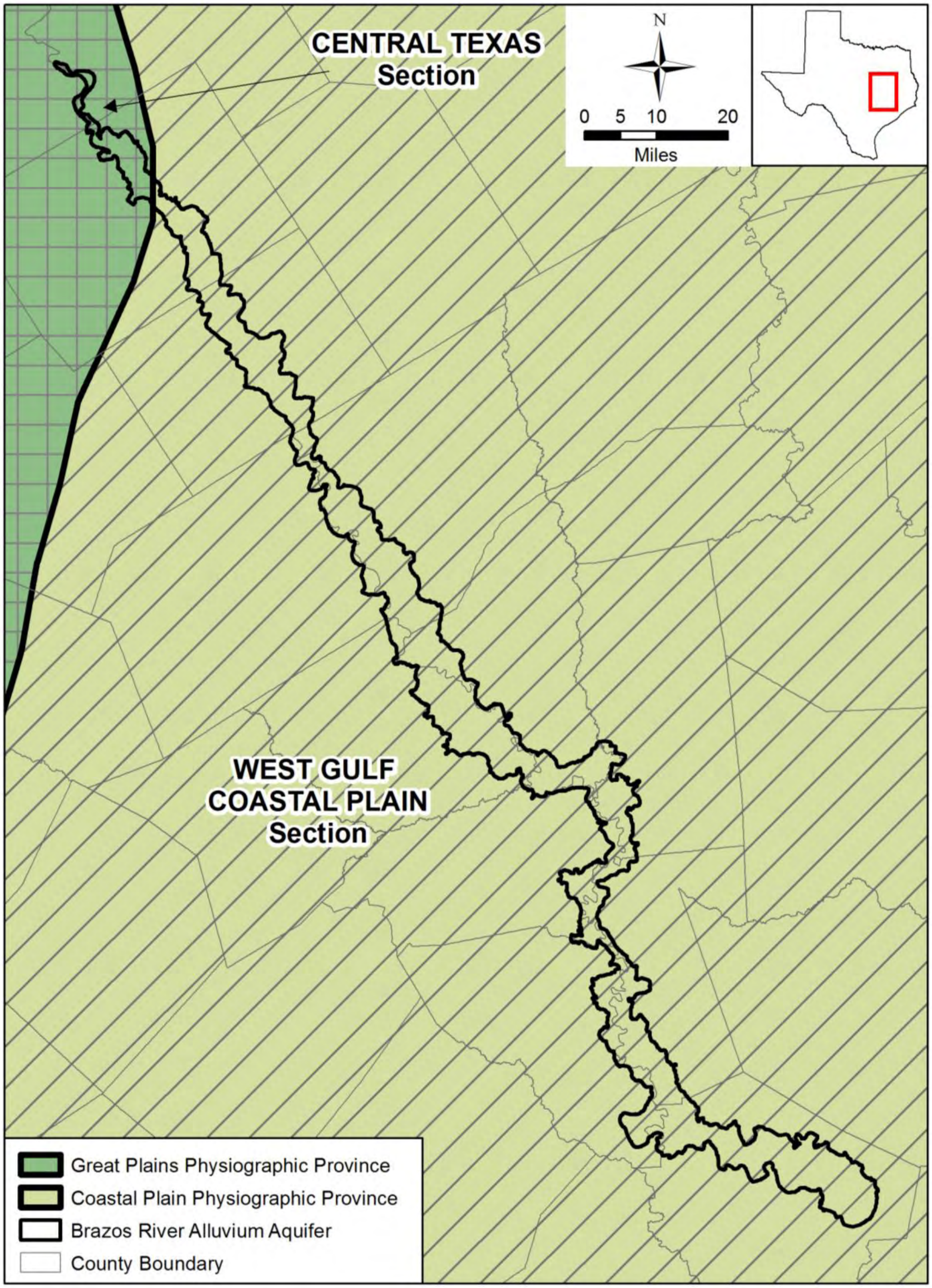


Figure 2.1.1 Physiographic provinces in the study area (Fenneman and Johnson, 1946).

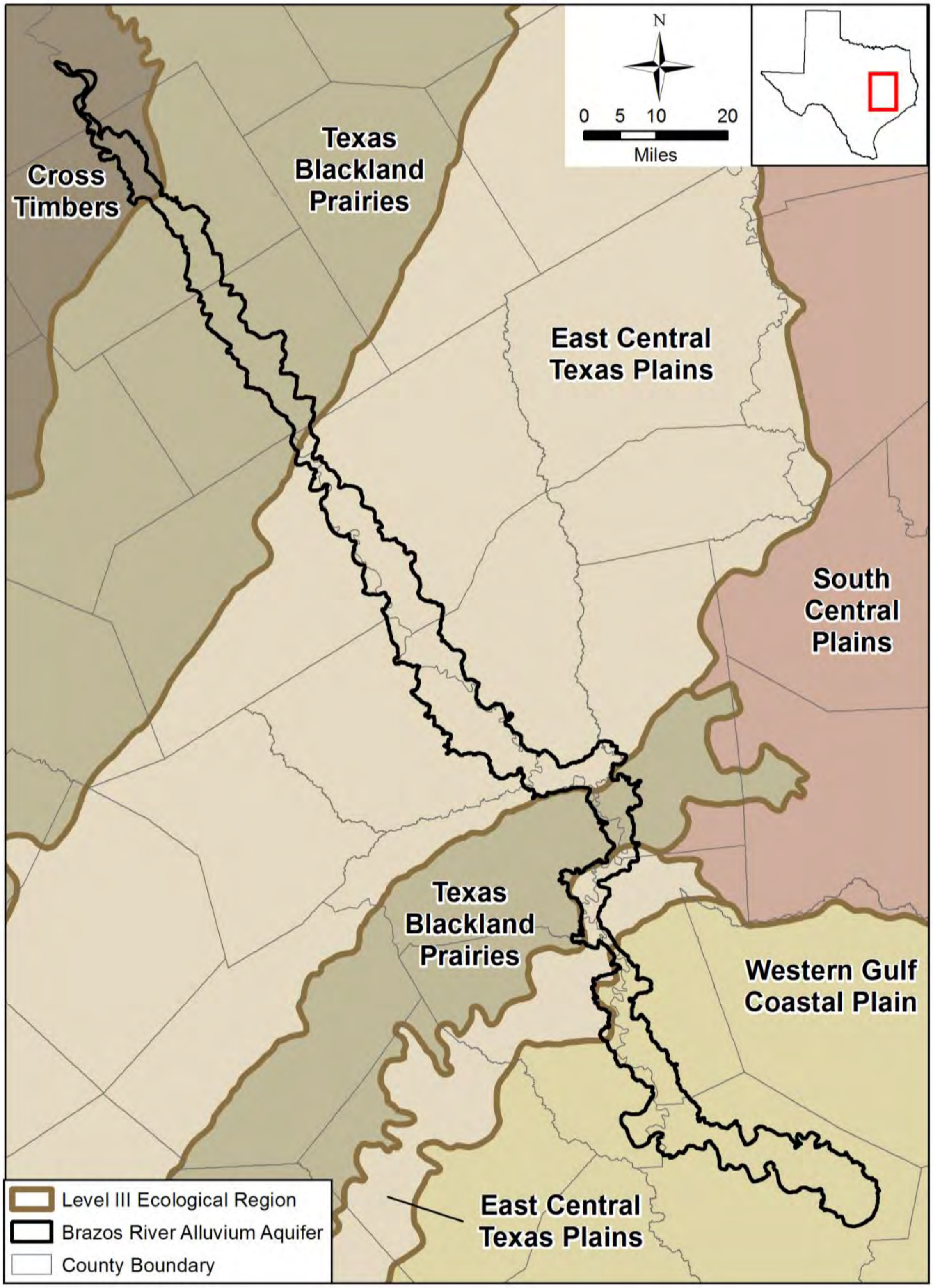


Figure 2.1.2 Level III ecological regions in the study area (United States Environmental Protection Agency, 2011).

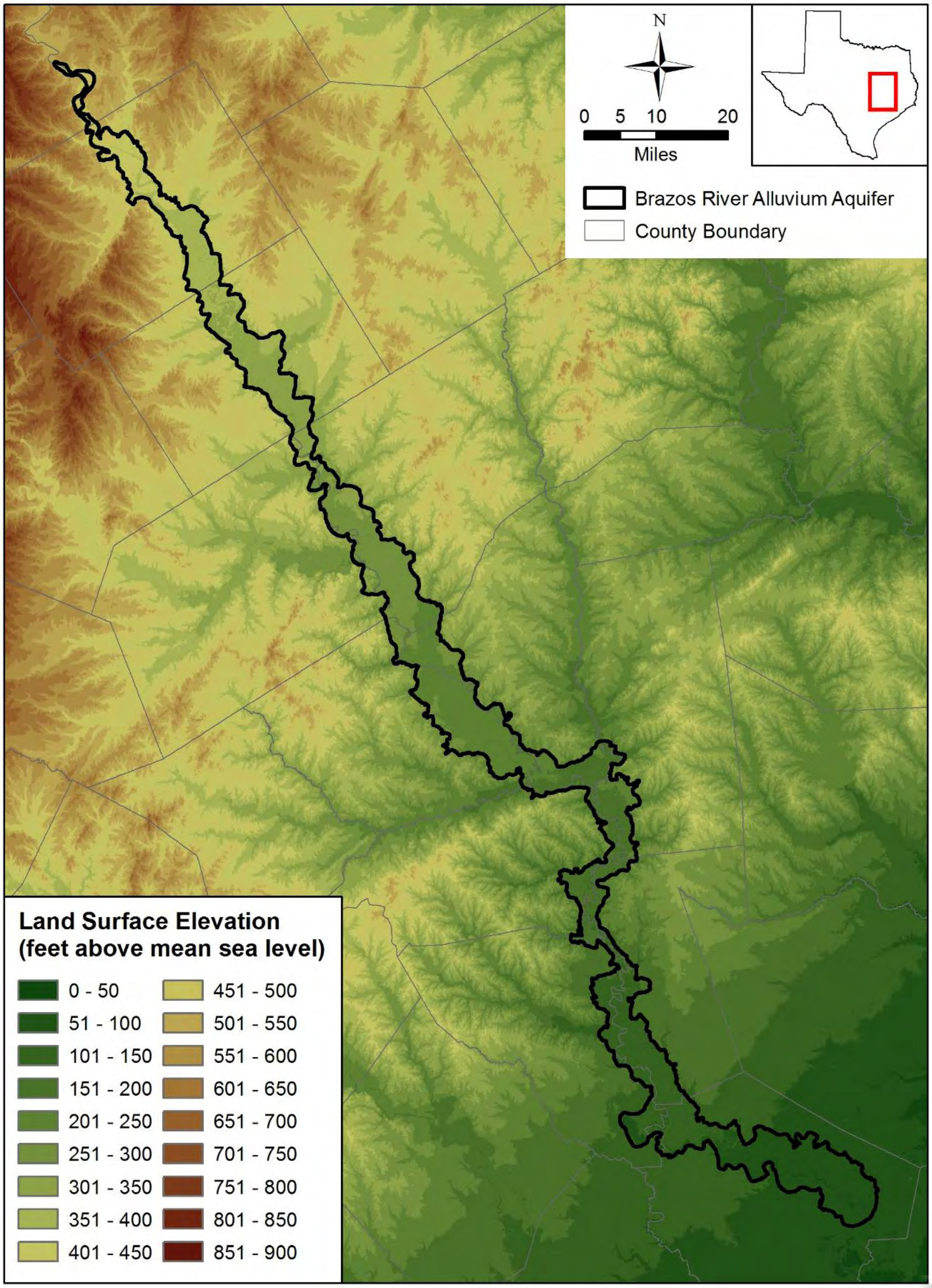


Figure 2.1.3 Elevation (in feet above NAD 88 datum) for the study area (United States Geological Survey, 2014a).

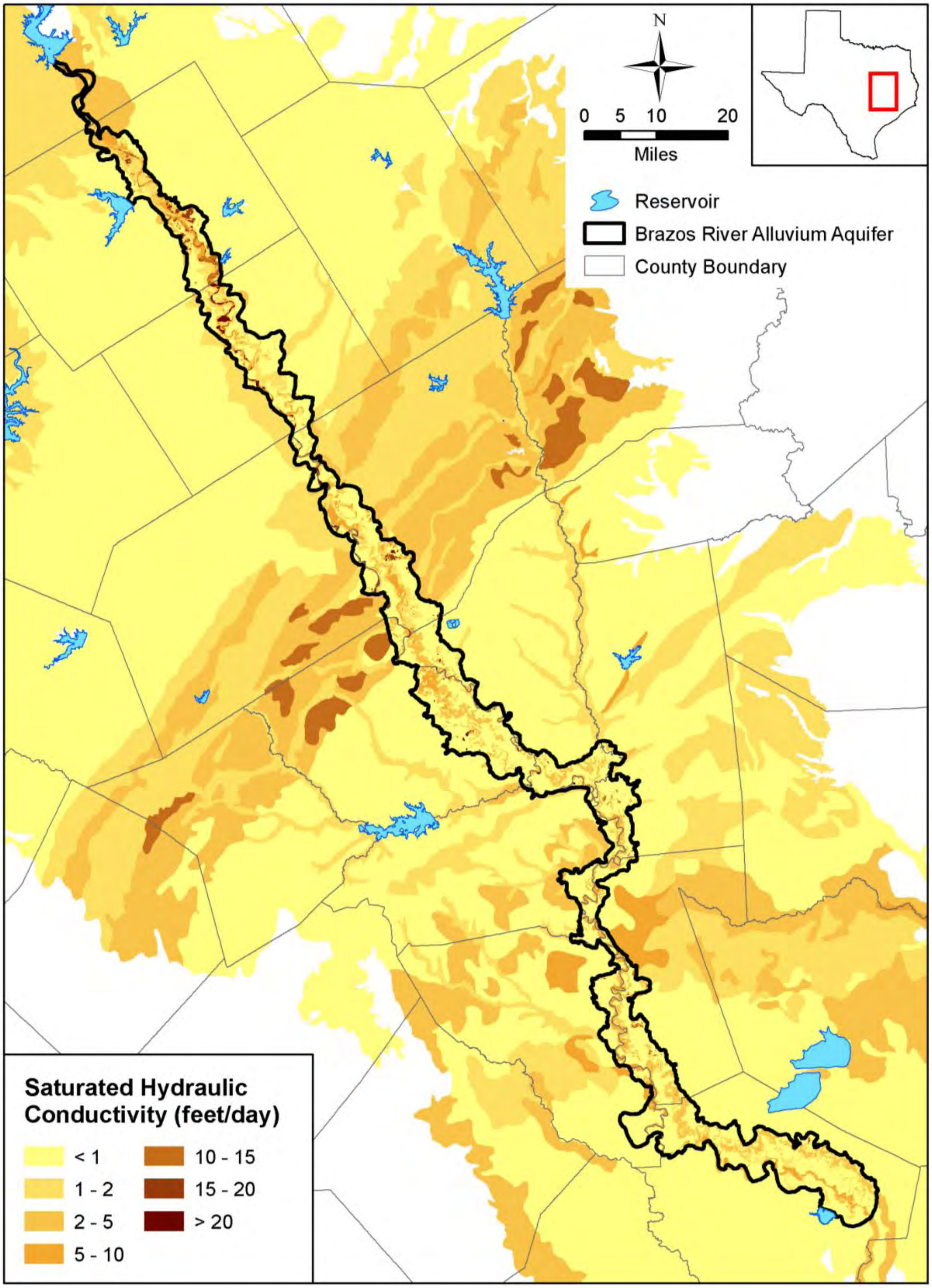
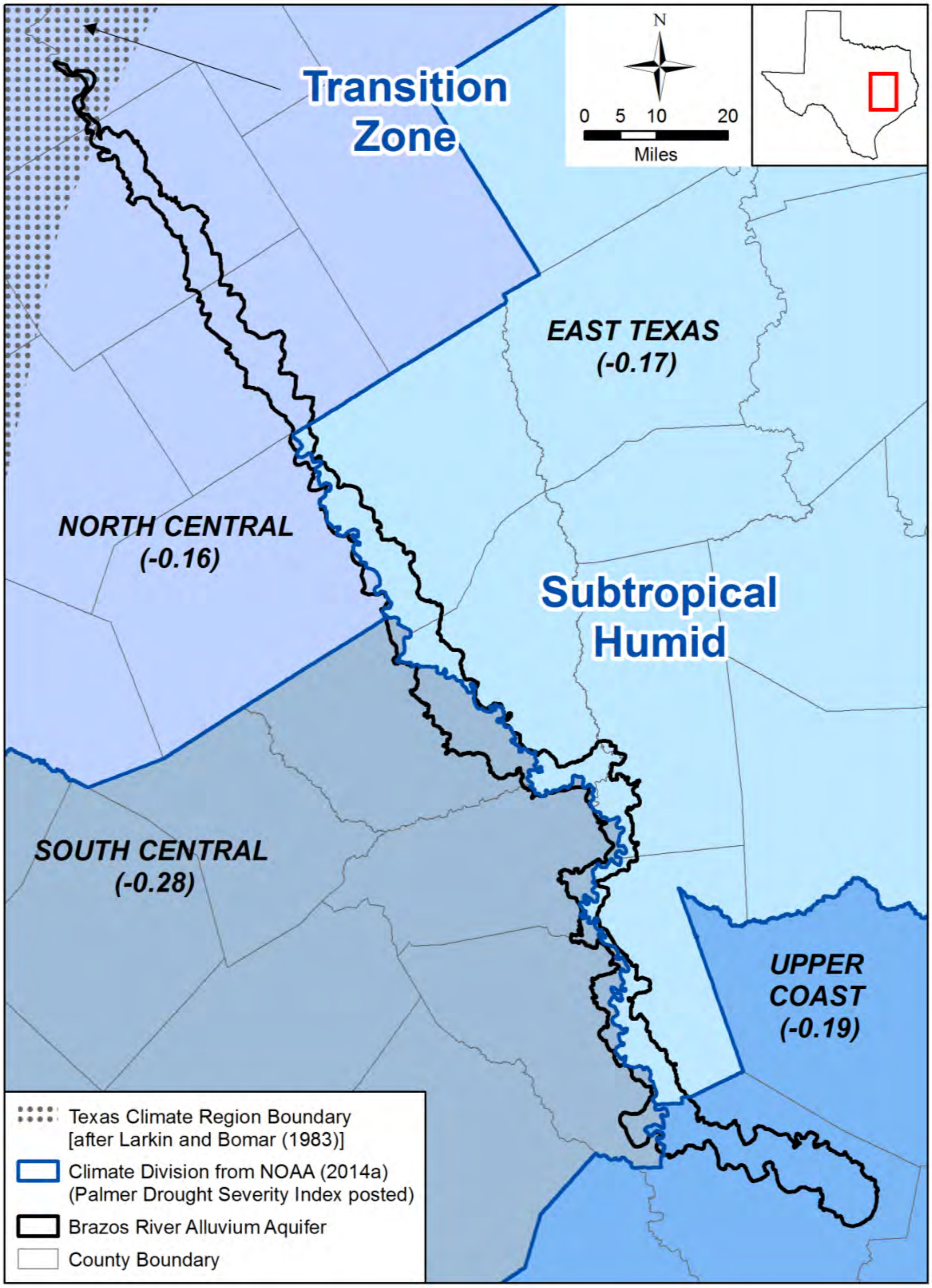


Figure 2.1.4 Average saturated hydraulic conductivity of surface soil in the vicinity of the Brazos River Alluvium Aquifer (United States Department of Agriculture, 2006; United States Department of Agriculture, 2014b).



NOAA = National Oceanic and Atmosphere Administration

Figure 2.1.5 Climate divisions in the study area (Larkin and Bomar, 1983; National Oceanic and Atmospheric Administration, 2014a).

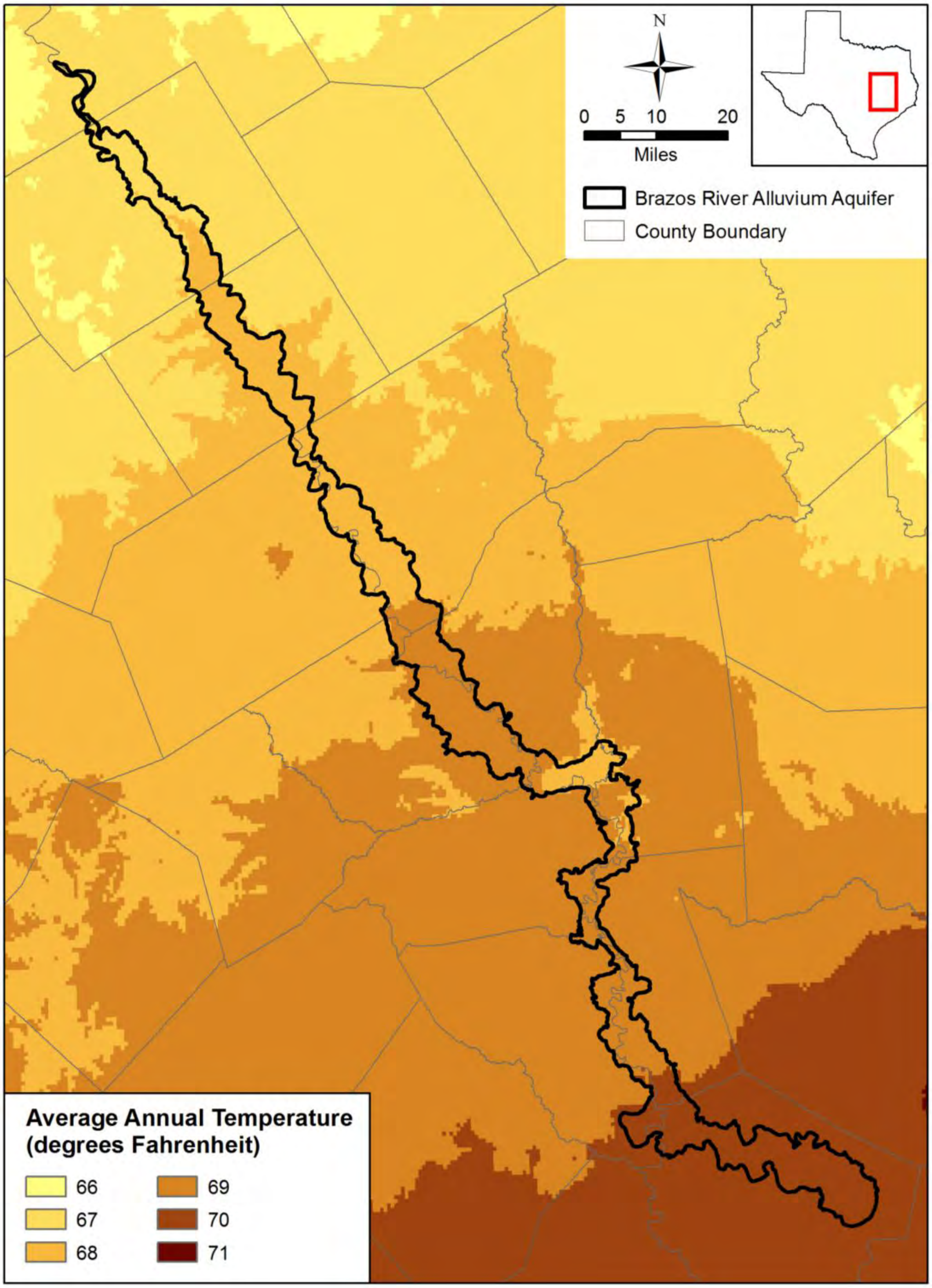


Figure 2.1.6 Average annual air temperature (in degrees Fahrenheit) in the study area for the time period 1981 to 2010 (PRISM Climate Group, 2013).

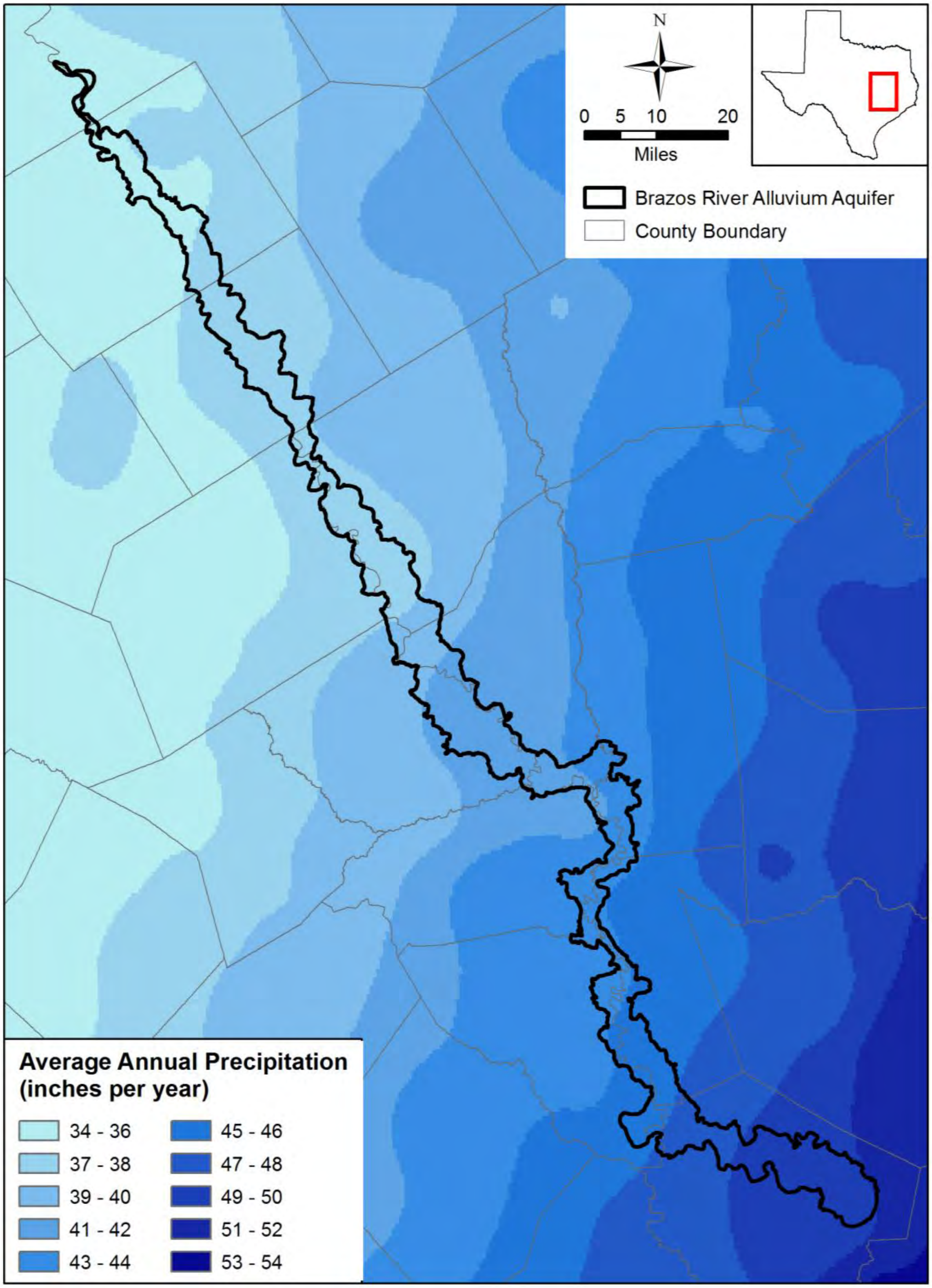


Figure 2.1.7 Average annual precipitation (in inches per year) in the study area for the time period 1981 to 2010 (PRISM Climate Group, 2013).

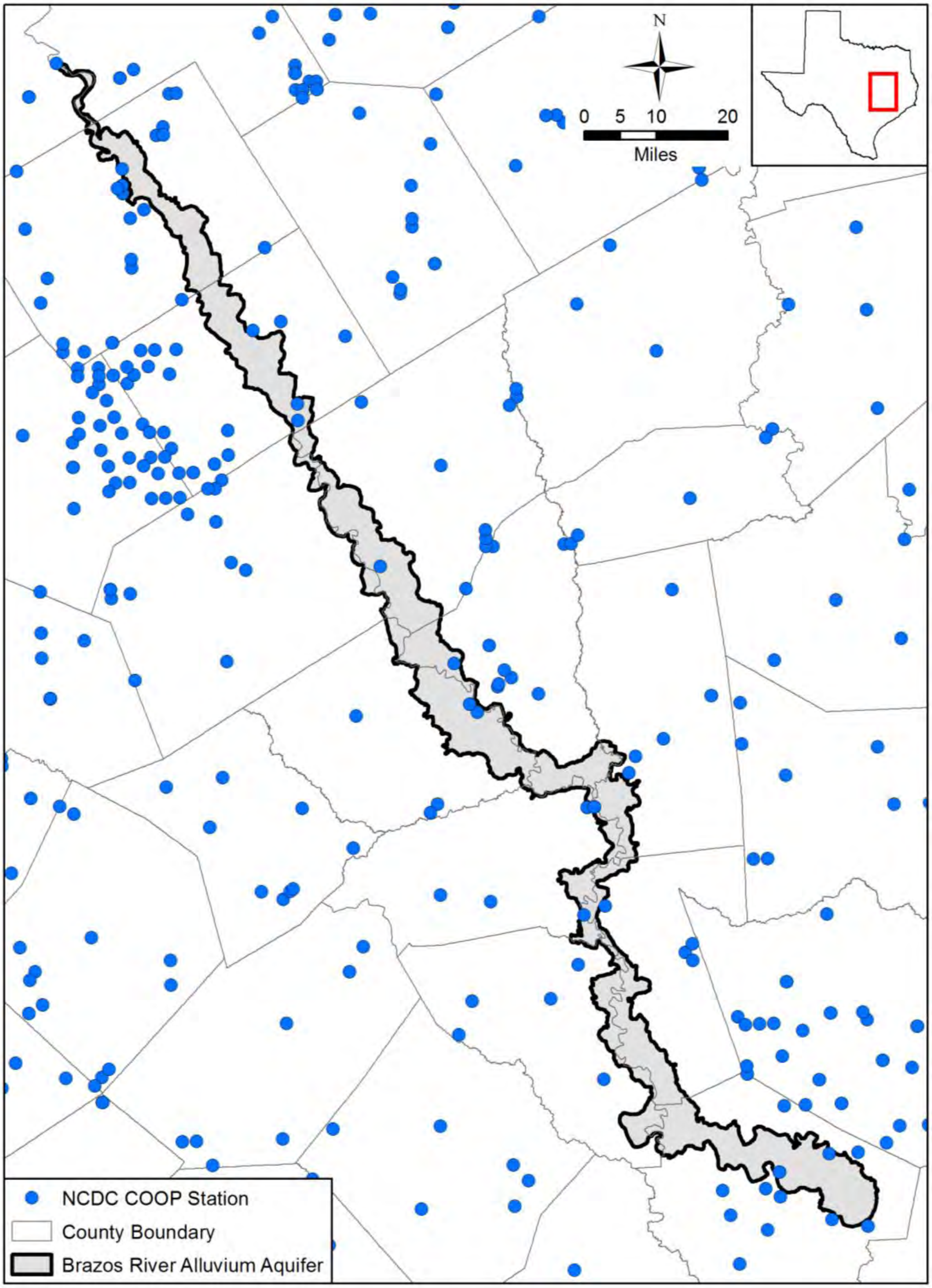


Figure 2.1.8 Location of precipitation gages in the study area (National Oceanic and Atmospheric Administration, 2010). Abbreviation key: NCDC = National Climatic Data Center; COOP = Cooperative Observer Network.

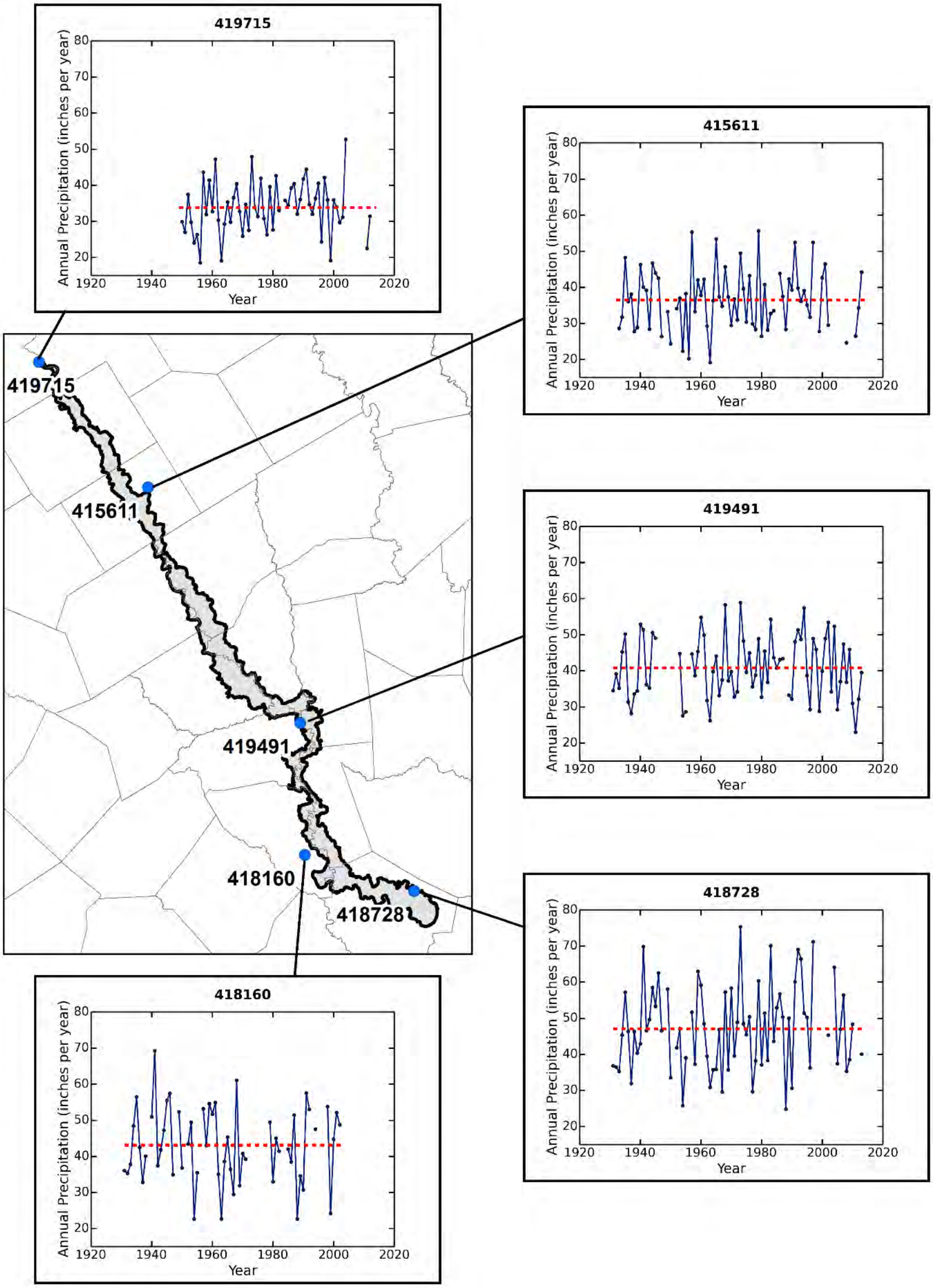


Figure 2.1.9 Select time series of annual precipitation (in inches per year) in the study area (National Oceanic and Atmospheric Administration, 2014b).

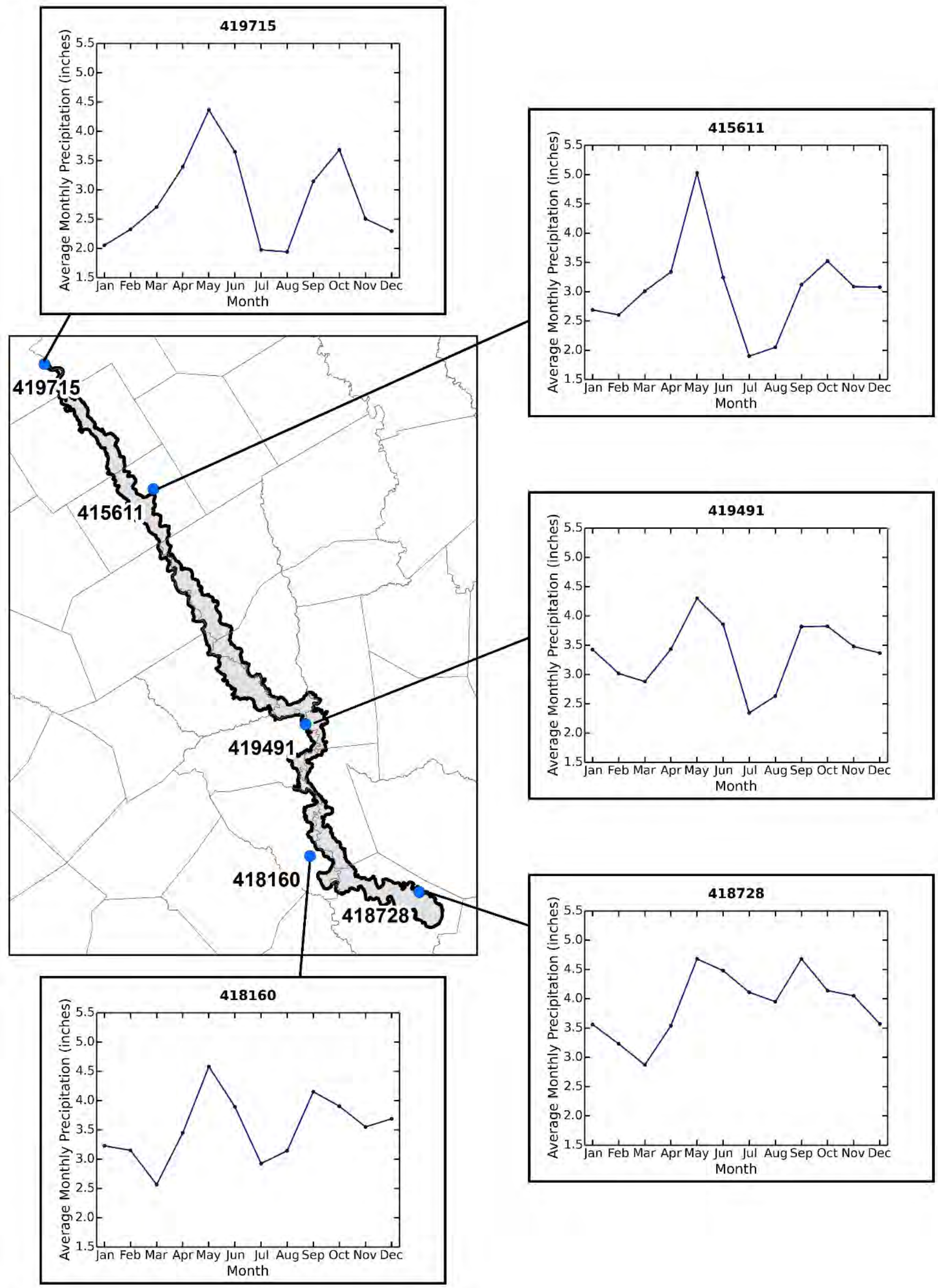


Figure 2.1.10 Select time series of mean monthly precipitation (in inches per month) in the study area (National Oceanic and Atmospheric Administration, 2014b).

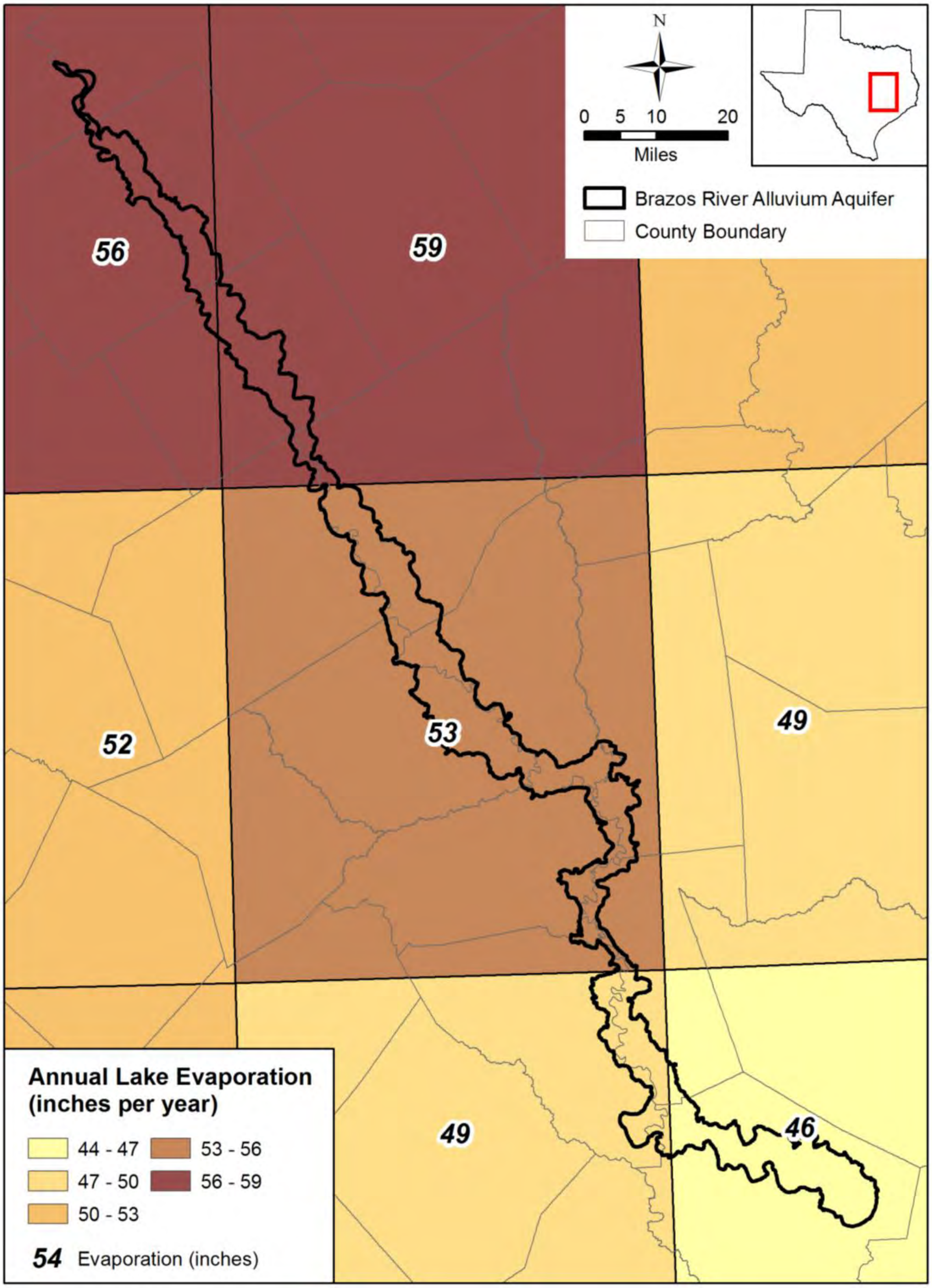


Figure 2.1.11 Average annual lake evaporation rate (in inches per year) in the study area (TWDB, 2013).

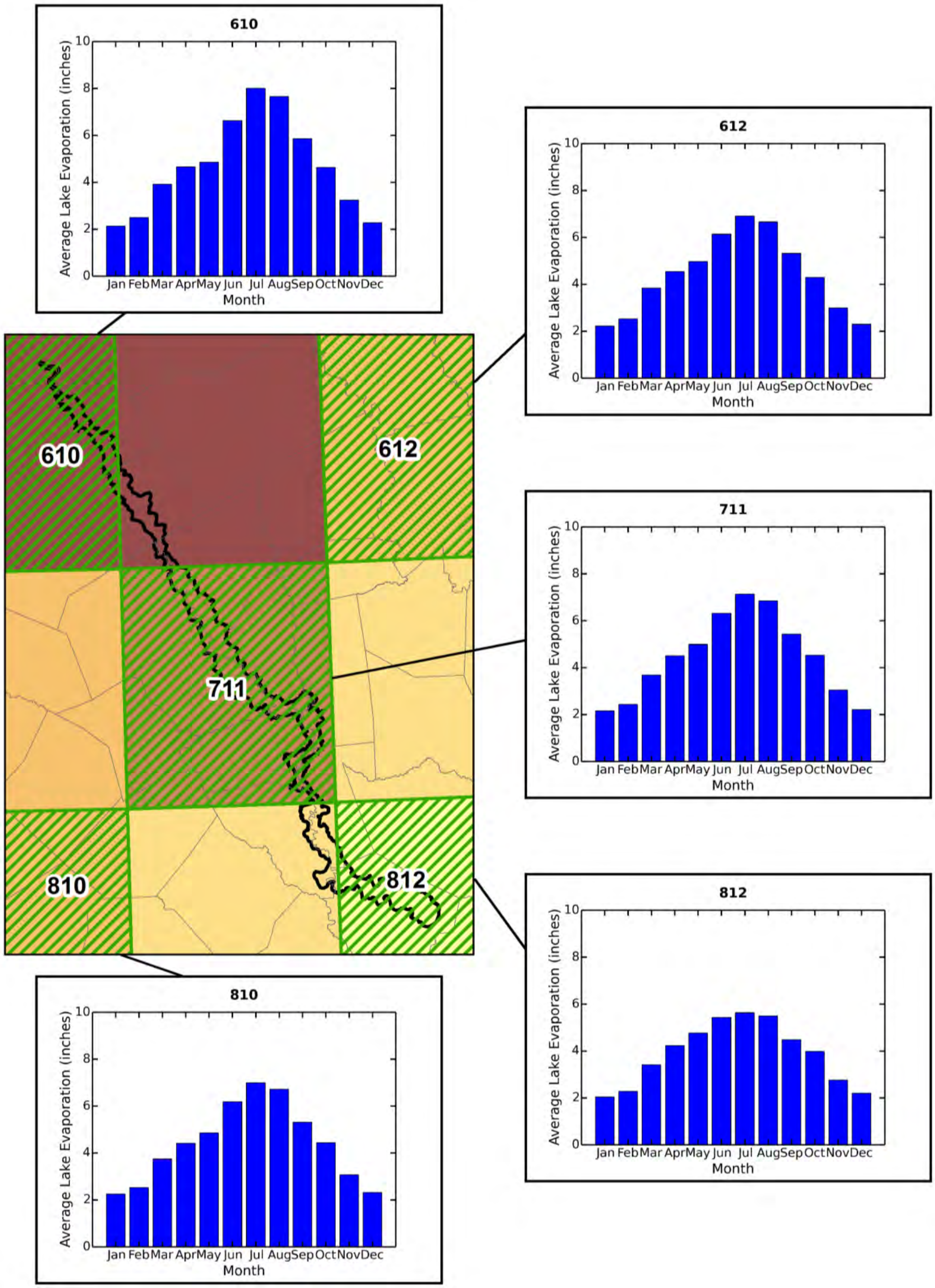


Figure 2.1.12 Average monthly lake evaporation rates (in inches) at select locations in the study area (TWDB, 2013).

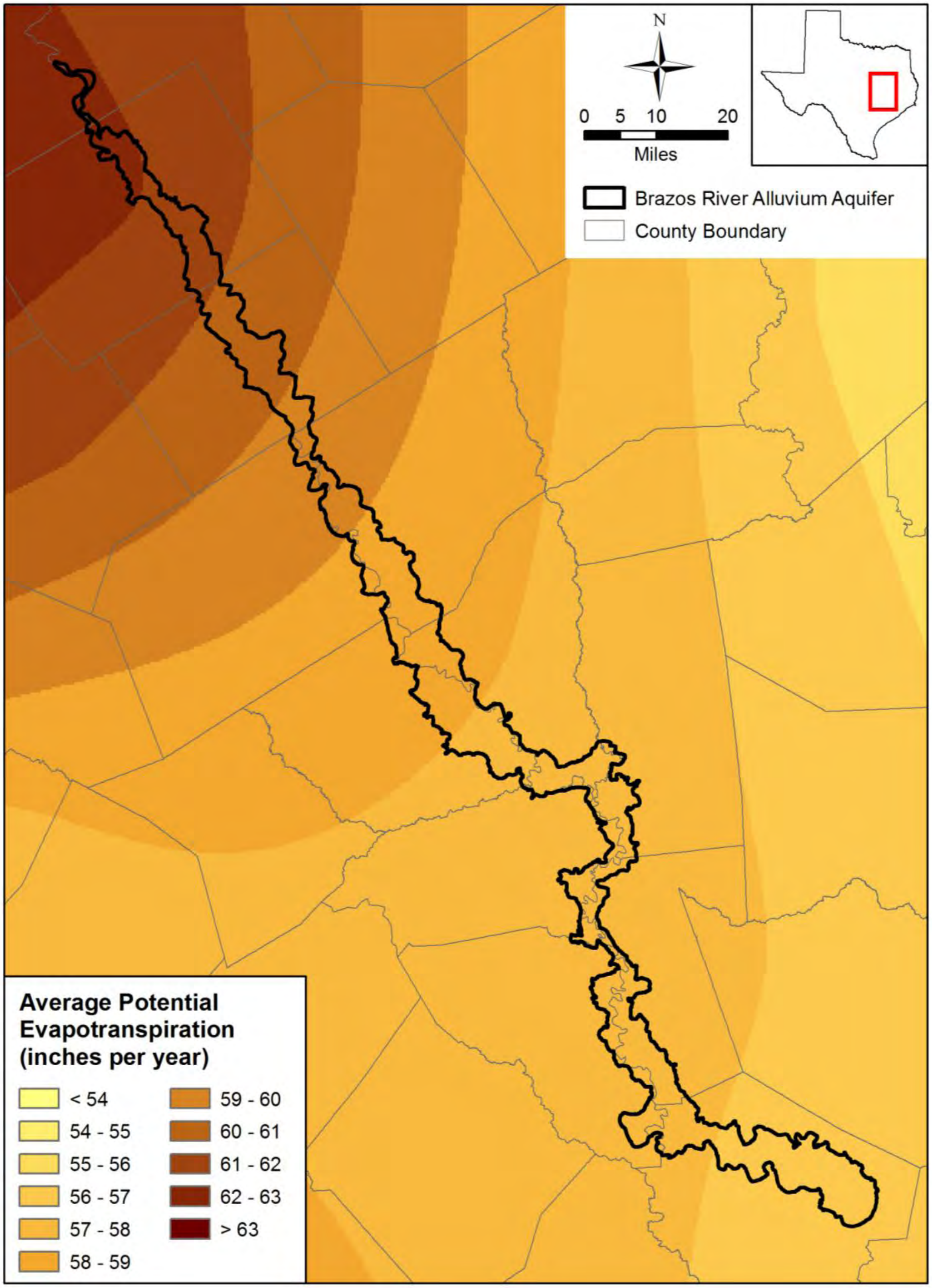


Figure 2.1.13 Average annual potential evapotranspiration in the study area (Borelli and others, 1998).

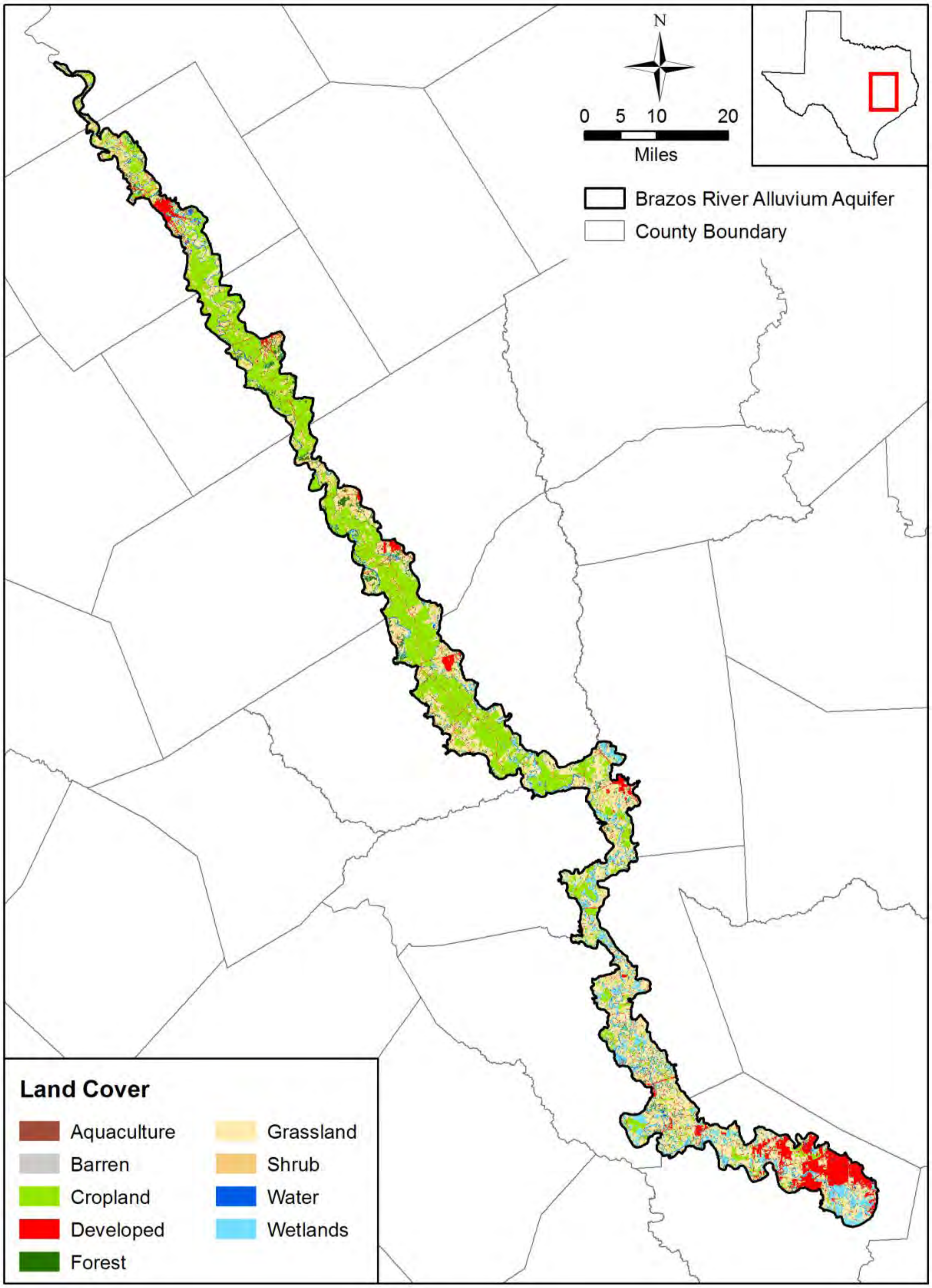


Figure 2.1.14 Land cover distribution on the Brazos River Alluvium Aquifer (United States Department of Agriculture, 2014c).

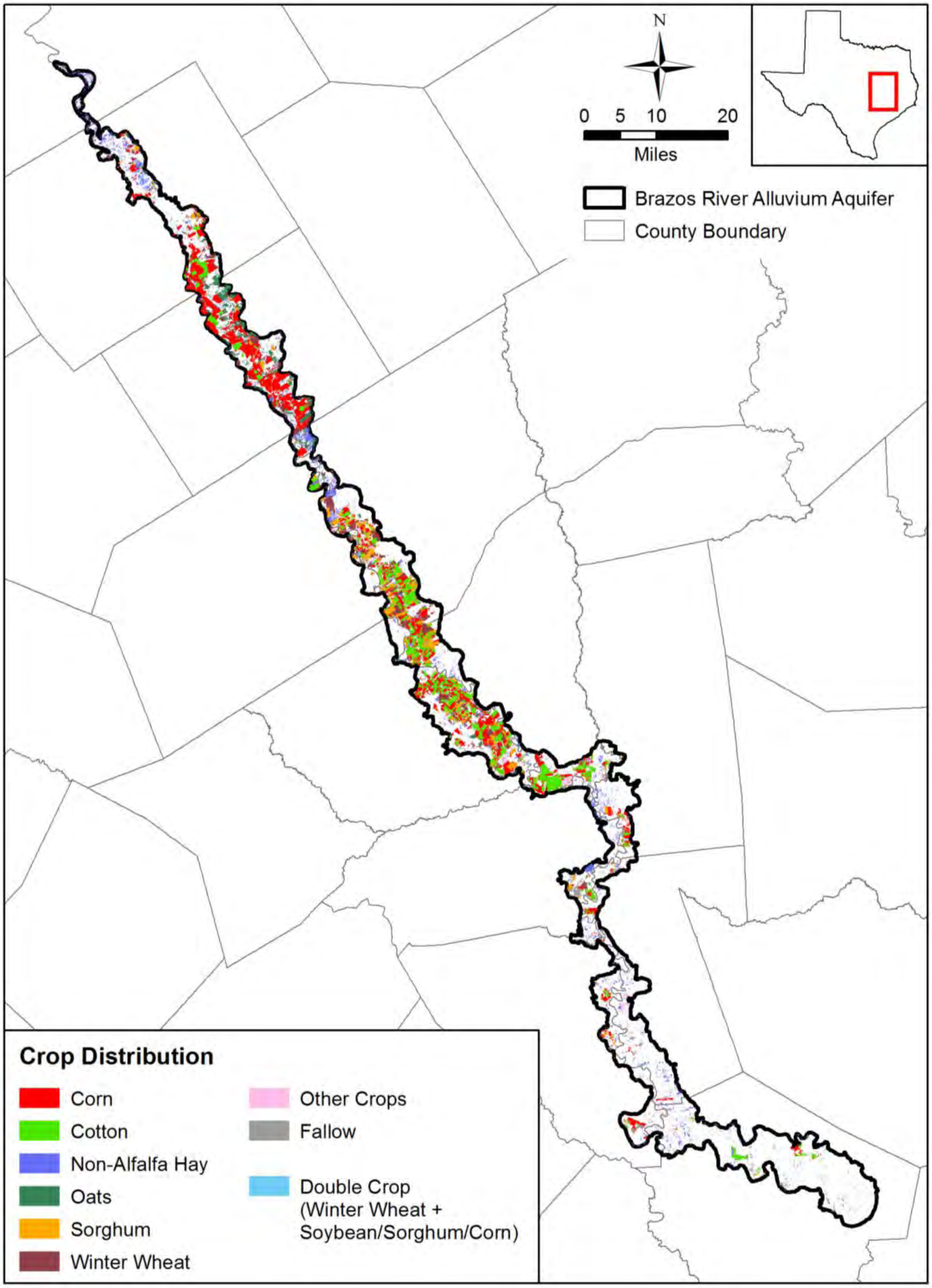


Figure 2.1.15 Crop distribution on the Brazos River Alluvium Aquifer (United States Department of Agriculture, 2014c).

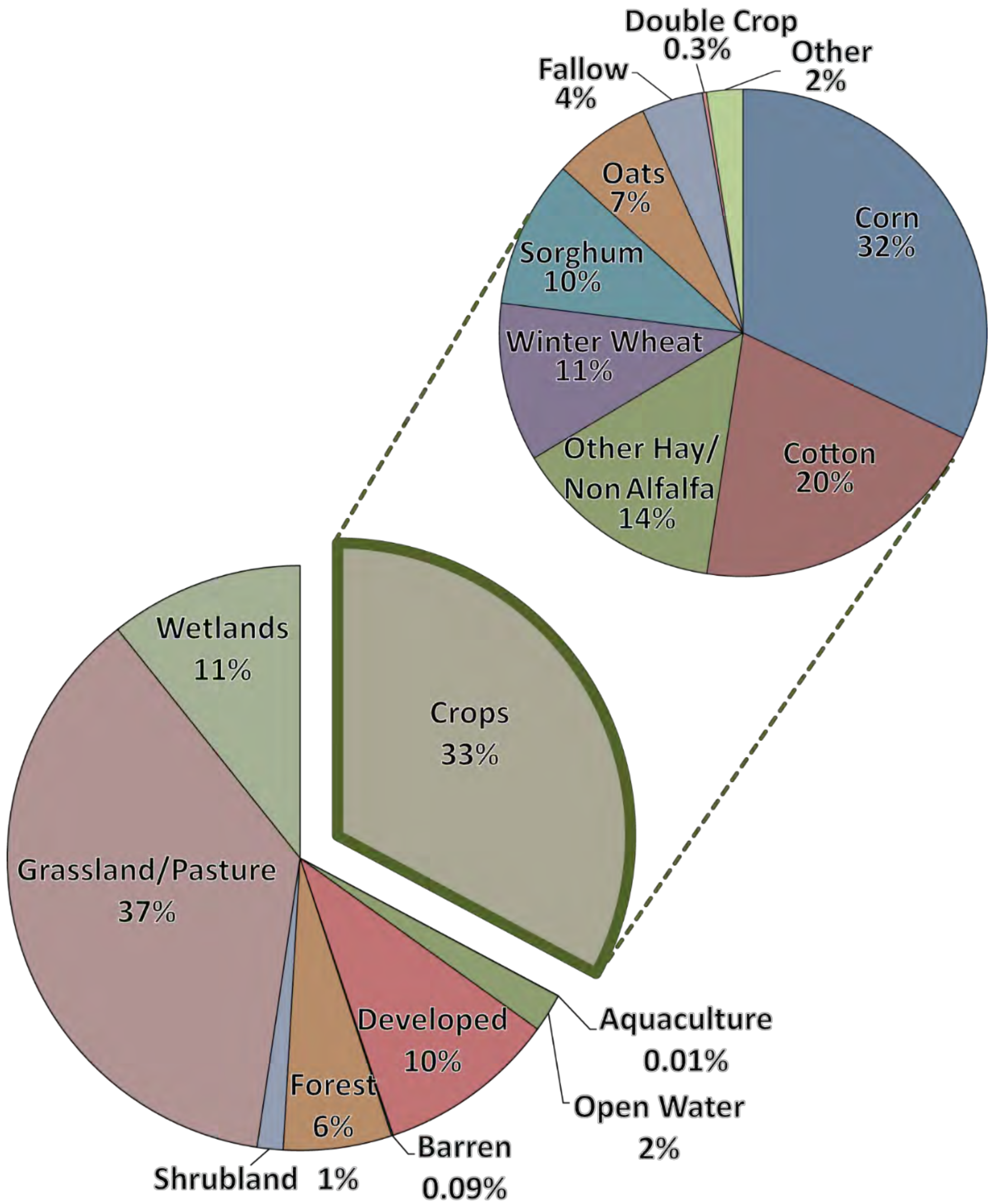


Figure 2.1.16 Division of land use type and crop type by total land area on the Brazos River Alluvium Aquifer.

2.2 Geology

The structural setting for the study area is shown in Figure 2.2.1. The fault traces were modified from Ewing (1990), and the other structural features were modified from Guevara and Garcia (1972), Galloway (1982), and Galloway and others (2000). Sediment deposition in the study area was focused in the Houston Embayment. There are several regional fault zones in the study area including the Wilcox Fault Zone, the Karnes/Milano/Mexia Fault Zone, and the Balcones Fault Zones (Ewing, 1990). The Wilcox Fault Zone is a series of growth faults caused by sediment progradation onto marine clays and resulting basinward slippage and subsidence. The Karnes/Milano/Mexia Fault Zone is a series of normal faults active throughout the Eocene. The Balcones Fault Zone is a series of normal faults formed at the perimeter of the Gulf Coast Basin.

The Brazos River Alluvium Aquifer consists of Quaternary-age water-bearing sediments in the floodplain and terrace deposits of the Brazos River in southeast Texas. The bedrock strata underlying the Brazos River Alluvium Aquifer are composed of consolidated and unconsolidated sedimentary rocks deposited under both marine and continental conditions (Cronin and Wilson, 1967). Some of these formations comprise major and minor aquifers as defined by the TWDB, including the Carrizo-Wilcox, Queen City, Sparta, Yegua-Jackson, and Gulf Coast aquifers. Formations lying between the aquifers are generally considered to be non-productive or to provide only very low water production. Brief descriptions of all underlying units are provided in Table 2.2.1. A simplified surface geology map based on Bureau of Economic Geology (2007) is shown in Figure 2.2.2. Cronin and Wilson (1967) provide three longitudinal cross-sections that illustrate the relationship between the Brazos River Alluvium Aquifer and the underlying formations. The locations of these cross-sections are shown in Figure 2.2.3, cross-sections A-A′ and B-B′ are shown in Figure 2.2.4a, and cross-section C-C′ is shown in Figure 2.2.4b. As shown in the cross-sections, all underlying formations generally dip southeast towards the Gulf of Mexico.

Since the lithology and structural features of the individual underlying formations are not particularly relevant for developing a conceptual model of groundwater flow in the Brazos River Alluvium Aquifer, the individual characteristics of these formations are not provided here. Details regarding the underlying aquifers can be found in their respective groundwater availability model reports, which are Dutton and others (2003) for the central Carrizo-Wilcox

Aquifer; Kelley and others (2004) for the Queen City, Sparta, and Carrizo-Wilcox aquifers; Deeds and others (2010) for the Yegua-Jackson Aquifer; and Kasmarek (2013) for the Gulf Coast Aquifer System.

The floodplain and terrace deposit sediments of the Brazos River can be divided into two distinct units. The following descriptions of these units are summarized from Cronin and Wilson (1967) unless another source is noted.

2.2.1 Terrace alluvium

"Terrace alluvium" refers to the Brazos River alluvial deposits that occur above the current floodplain of the Brazos River. These deposits consist of clay, silt, sand, and gravel and can be somewhat cemented in places. Older (higher) terrace deposits are often geologically and hydrologically separated from both the younger (lower) terrace deposits and the floodplain alluvium. They are often found as isolated bodies on hilltops or river-cut benches above the current floodplain. Therefore, even though some of the thicker terrace deposits can locally provide small amounts of water, the older terrace alluvium is not generally considered part of the Brazos River Alluvium Aquifer. Younger (lower) terrace deposits that are in hydraulic connection with the floodplain alluvium are part of the Brazos River Alluvium Aquifer since they are in direct hydraulic connection with the floodplain deposits.

Cronin and Wilson (1967) provide cross-valley profiles illustrating the deposition patterns of the Brazos River alluvial sediments. The locations of the profiles are shown in Figure 2.2.5 and the profiles are shown from north to south in Figures 2.2.6a, 2.2.6b, 2.2.6c, 2.2.6d, and 2.2.6e. These cross-valley profiles show widely varying deposition patterns for the terrace deposits. For instance, cross-valley profiles 2 and 5 (see Figures 2.2.6a and 2.2.6b, respectively) provide examples of completely isolated terrace deposits, cross-valley profiles 9 and 10 (see Figures 2.2.6c and 2.2.6d, respectively) show terrace deposits directly connected with floodplain deposits, and the terrace deposits shown in cross-valley profiles 3 and 4 (see Figures 2.2.6a and 2.2.6b, respectively) have an unclear, but probably non-zero, degree of connection with the floodplain alluvium.

2.2.2 Floodplain alluvium

"Floodplain alluvium" refers to the alluvial deposits underlying the Brazos River and its current floodplain. These sediments include sand, gravel, silt, and clay that occur in lenses that pinch out or grade both laterally and vertically. Deposition of these materials occurred either in stream channels or as a result of overbank flow in the floodplain. Gravel lenses are associated with stream channel deposition, whereas finer sediments are likely contributed by overbank flow. As a unit, the floodplain alluvium generally fines upward, with gravels or gravels mixed with sand at the bottom of the deposit and fine-grained material at the top. Clay is common in the fine-grained upper portion of the unit and can create local confining conditions (Shah and others, 2007a, 2009). The mineralogical composition of gravels shifts slightly from north to south, with gravels near Waco being predominately limestone and gravels downstream from Navasota predominately siliceous.

The floodplain alluvium generally appears to increase in thickness from north to south (see Figures 2.2.6a-e). Although the base of the alluvium is easy to distinguish from the underlying hard, compact bedrock in the north, it is difficult to distinguish in the south where it overlies other Quaternary-age alluvial sediments. Therefore, it is unclear whether the alluvium is actually thicker in the south or if the base is just less well defined. Cronin and Wilson (1967) note that cross-valley profile 15 (see Figure 2.2.6e) illustrates that it is not always possible to determine the contact between underlying formations and the floodplain alluvium in test holes in the southern portion of the Brazos River Alluvium Aquifer. Shah and others (2007a, 2009) also express concern about the accuracy of the aquifer base in the south, where alluvium overlies the lithologically similar Gulf Coast Aquifer System. This points out the uncertainty in the observed thickening of the Brazos River Alluvium Aquifer from north to south.

Table 2.2.1 Generalized stratigraphic description of geologic formations in the model area.

System	Series	Geologic Unit	Geologic Description[1]
Quaternary	Holocene	Alluvium	Floodplain and tributary alluvium, clay, sand, silt and gravel. Yields small to large quantities of water.
	Pleistocene	Fluvial terrace deposits	Clay, silt, sand, and gravel, somewhat cemented in places. Locally yields small quantities of water.
		Beaumont Formation	Clay, silt, sandy clay, and sand. Yields small to moderate quantities of water.
		Lissie Formation	Sand, clay, and gravel. Yields small to large quantities of water.
Tertiary	Pliocene	Willis Sand	Sand, gravel, clay, silt, and sandy clay. Yields small to large quantities of water.
	Miocene	Goliad Sand	Sand, clay, and sandy clay. Yields small to moderate quantities of water.
		Fleming Formation	Clay and sandstone.
		Oakville Sandstone	Sand, sandstone, and clay. Yields small to large quantities of water.
	Oligocene	Catahoula Sandstone	Sand, sandstone, clay, and tuff. Yields small to moderate quantities of water.
	Eocene	Jackson Group	Clay, sand, sandstone, and shale. Yields small to moderate quantities of water.
		Yegua Formation	Sand, shale, sandstone, and lignite. Yields small to moderate quantities of water.
		Cook Mountain Formation	Shale, clay, sandy shale, sand, and glauconite. Yields small quantities of water.
		Sparta Sand	Sand, clay, and shale. Yields small to moderate quantities of water.
		Weches Formation	Glauconitic, clay, and silt. Yields small quantities of water.
		Queen City Sand	Sand and clay. Yields small to moderate quantities of water.
		Reklaw Formation	Shale, sandy shale, sand, and some glauconite. Yields small quantities of water.
		Carrizo Sand	Sand, clay, and silt. Yields small quantities of water.
		Wilcox Group	Sand, clay, silt, and lignite. Yields small to large quantities of water.
	Paleocene	Midway Group	Glauconitic clay, silt, sandy clay, and sand. Yields small quantities of water.
Cretaceous	Gulfian	Navarro Group	Sandy marl, clay, and some sand. Yields small quantities of water.
		Taylor Marl	Marl, clay, chalk, and sand. Locally yields small quantities of water.
		Austin Chalk	Chalky and marly limestone. Yields small quantities of water.
		Eagle Ford Group	Shale, sandy shale, and thin beds of sandstone and limestone. Not known to yield water to wells in study area.
		Grayson Marl	Mostly marl with some thin interbeds of limestone near top.[2]
	Comanchean	Washita Group	Marl, clay, and limestone. Yields small quantities of water.
		Fredericksburg Group	Limestone, marl, and clay. Yields small quantities of water.

[1] from Cronin and Wilson (1967) unless noted otherwise; small quantities of water refers to less than 100 gallons per minute, moderate quantities of water refers to 100 to 1,000 gallons per minute, and large quantities of water refers to greater than 1,000 gallons per minute.

[2] from Stoeser and others (2007)

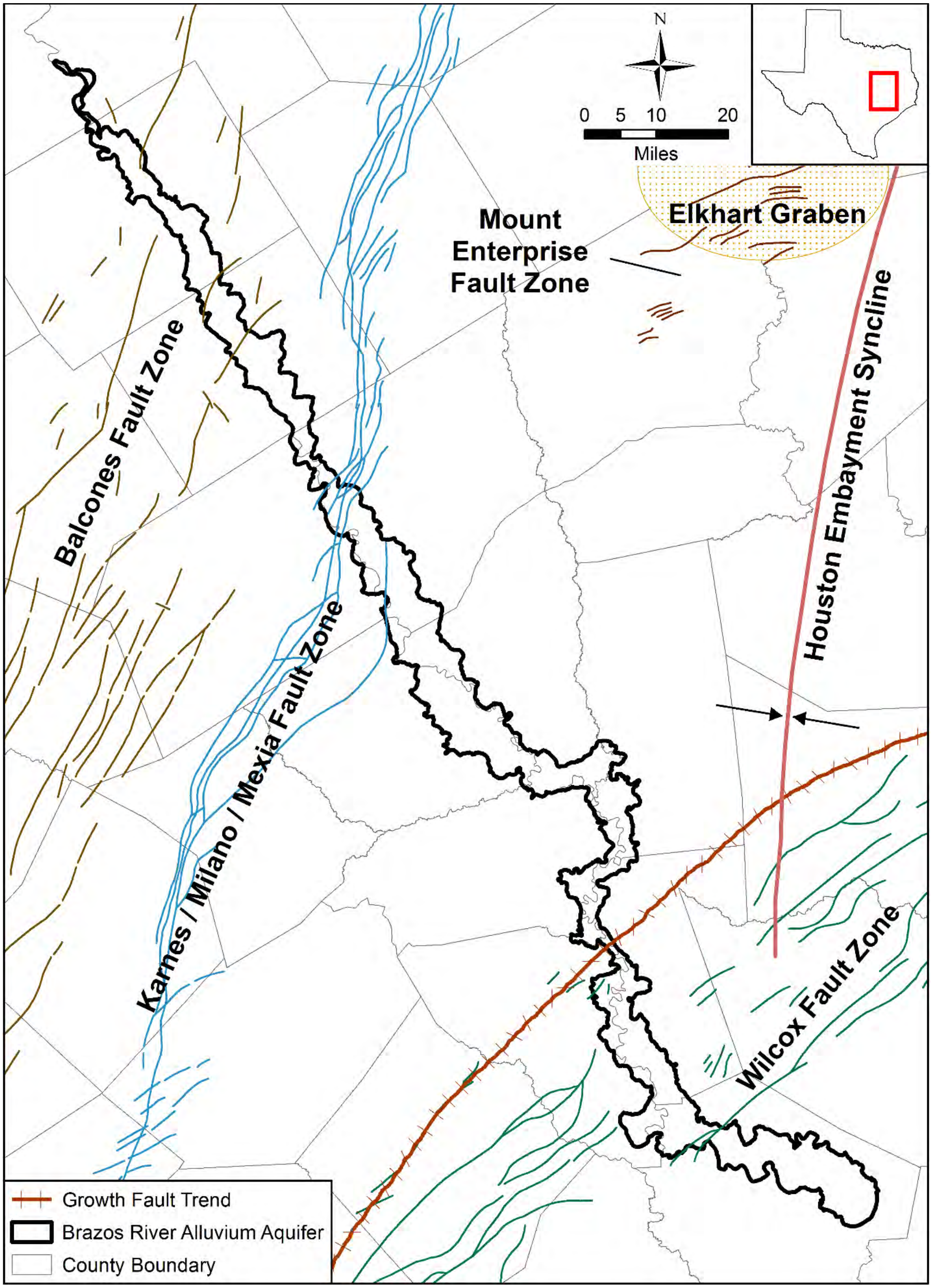
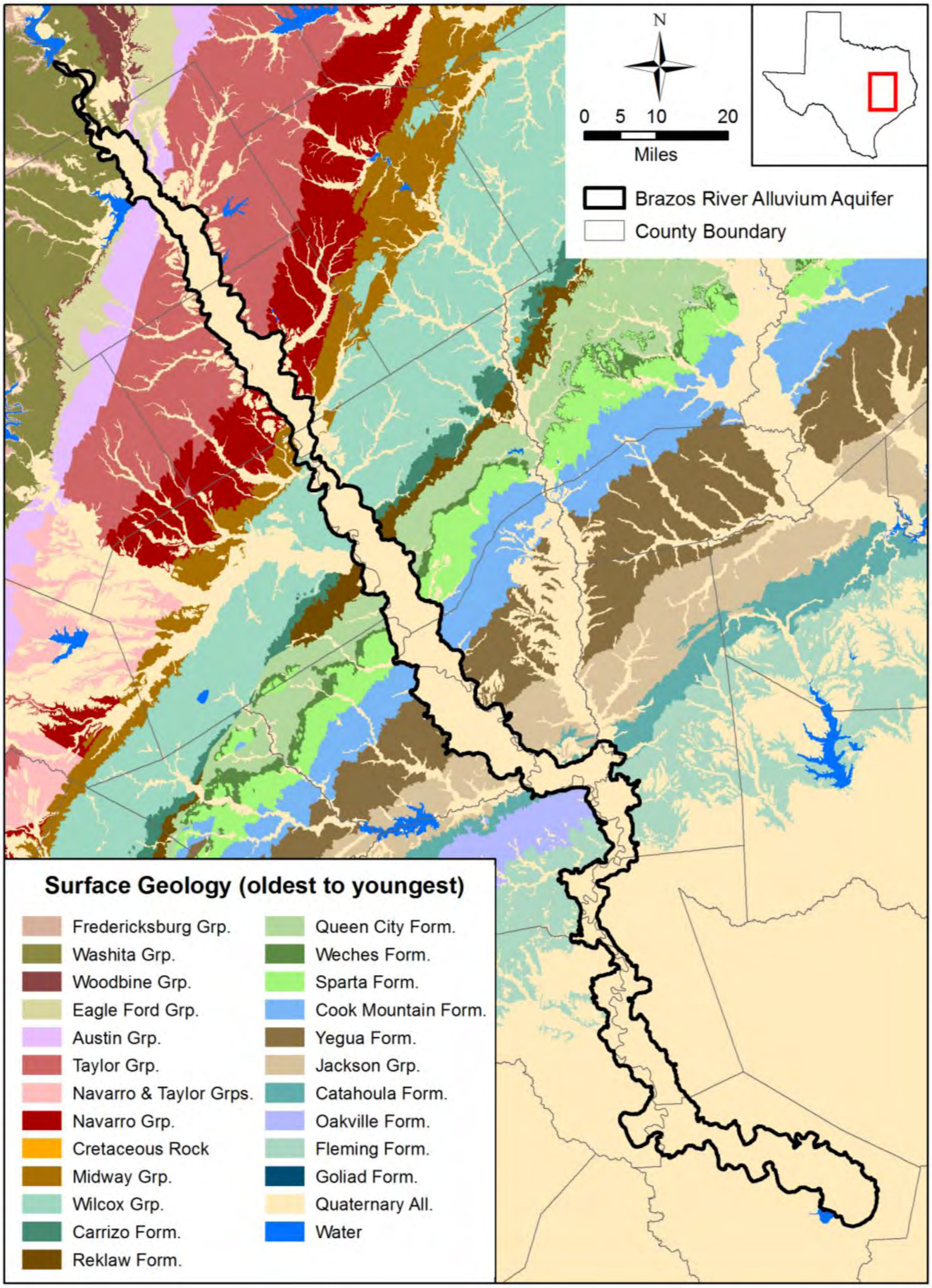


Figure 2.2.1 Major faults and structural features in the study area (modified from Ewing, 1990; Guevara and Garcia, 1972; Galloway, 1982; Galloway and others, 2000.



Grp. = Group Form. = Formation

Figure 2.2.2 Generalized surface geologic map in the study area (modified from Bureau of Economic Geology, 2007).

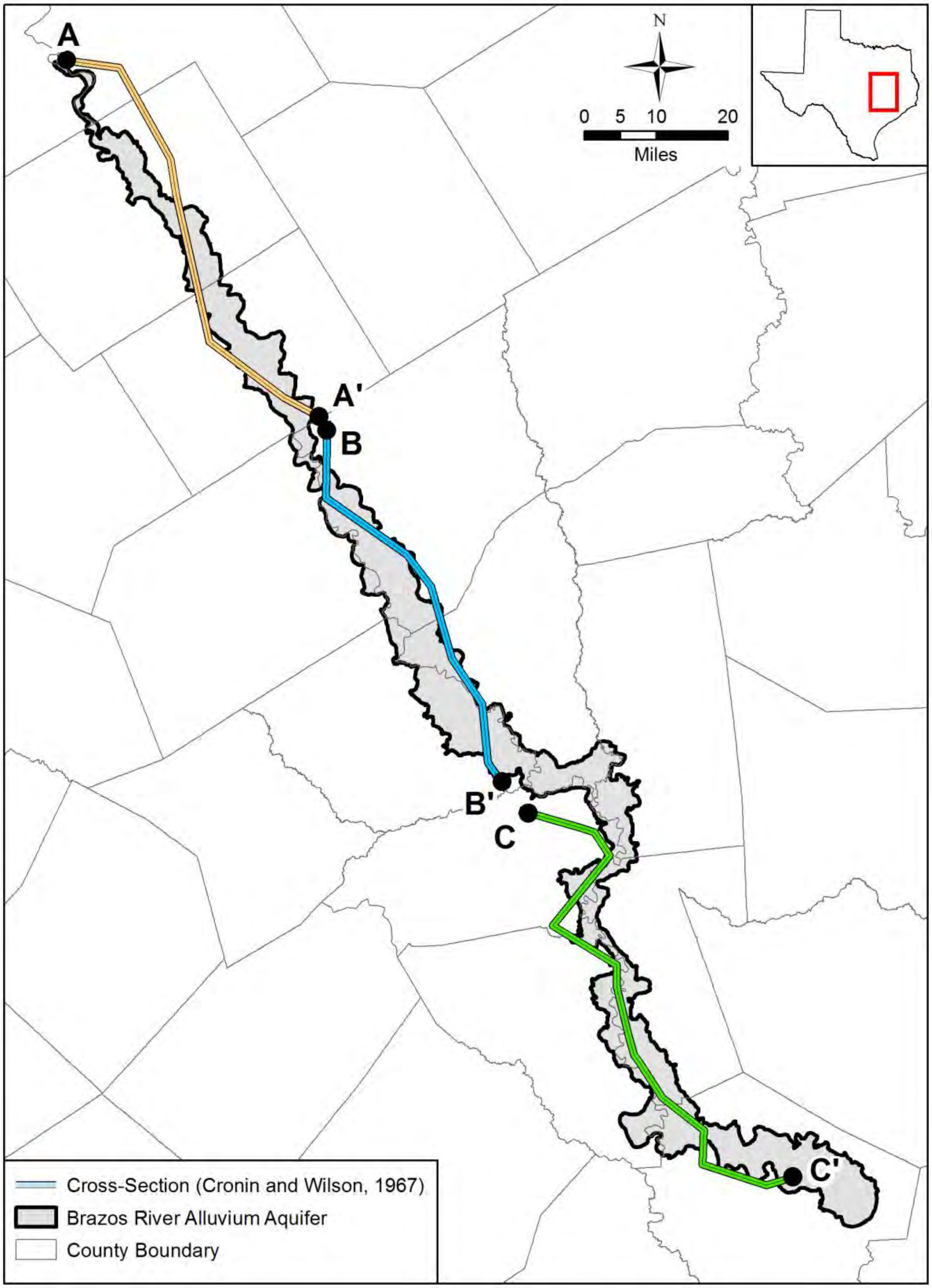


Figure 2.2.3 Location of longitudinal cross-sections of the Brazos River Alluvium Aquifer (after Cronin and Wilson, 1967).

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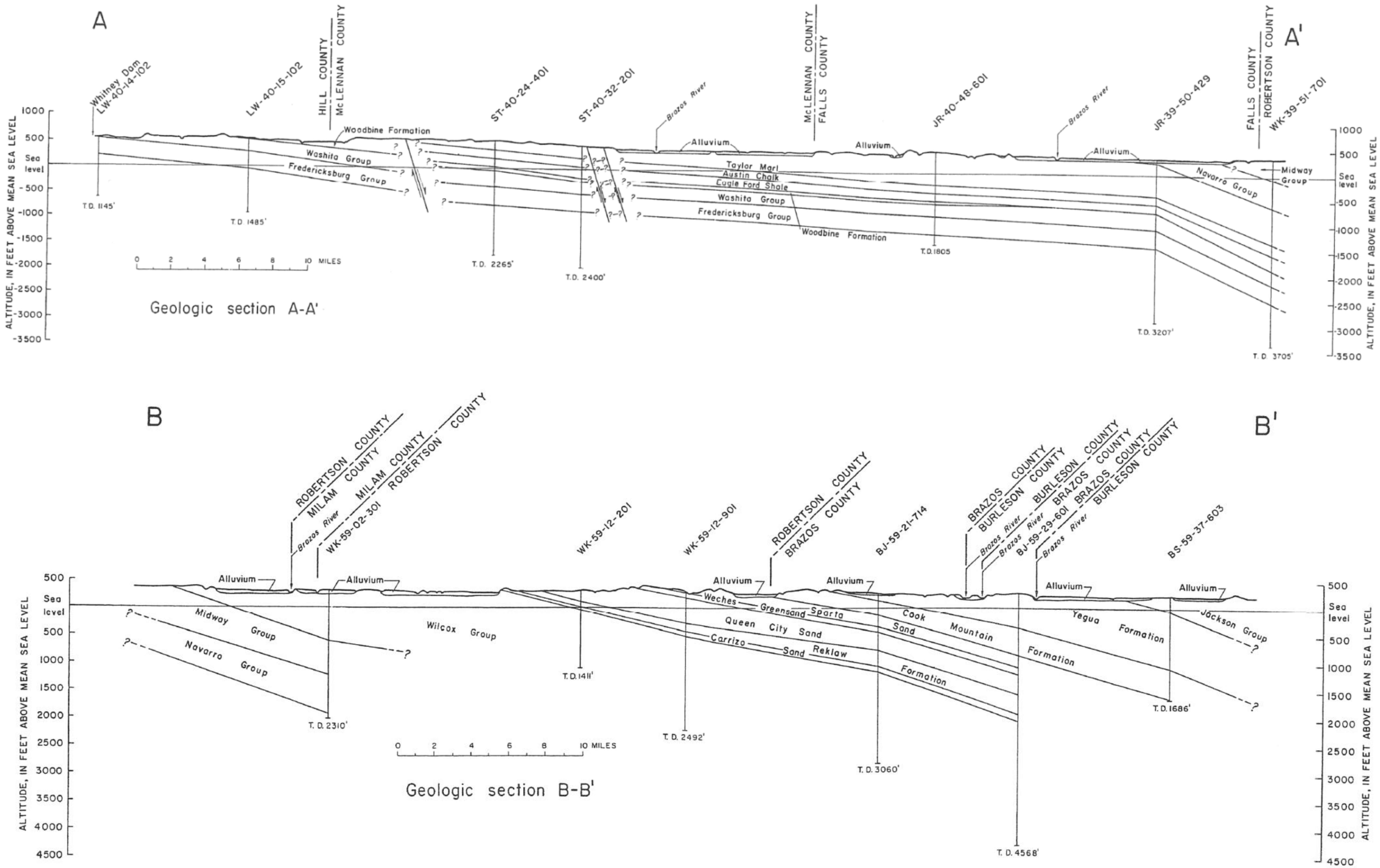

Figure 2.2.4a Cross-sections A-A' and B-B' from Cronin and Wilson (1967) (locations given in Figure 2.2.3).

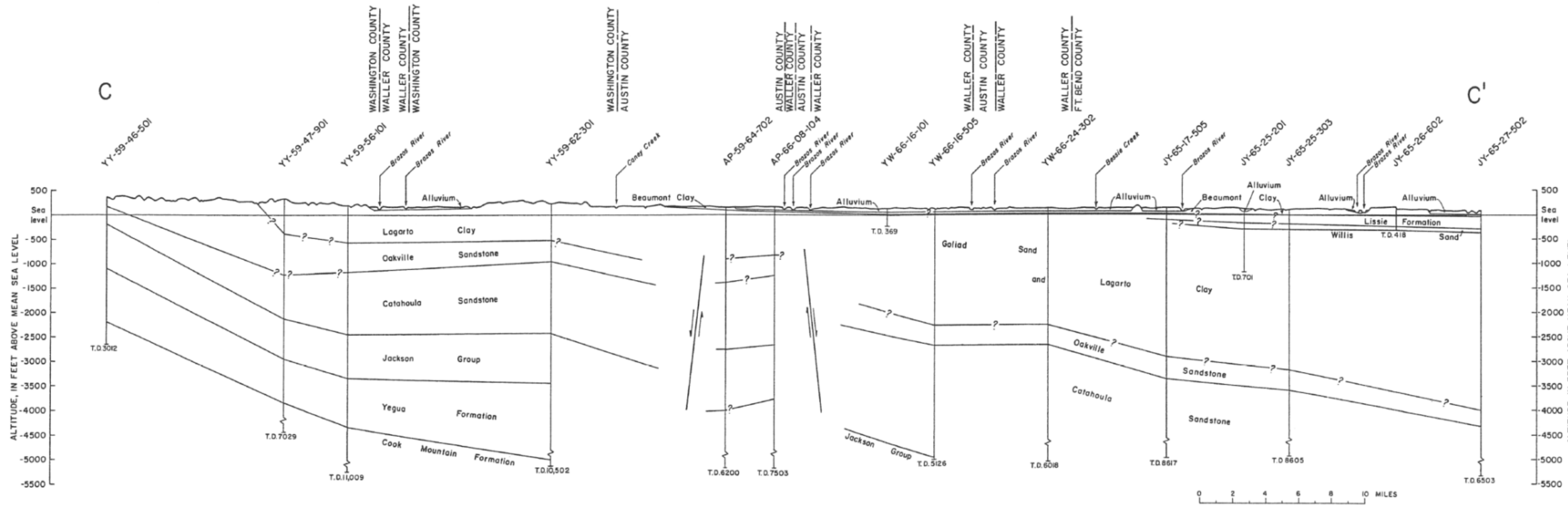

Figure 2.2.4b Cross-section C-C' from Cronin and Wilson (1967) (location given in Figure 2.2.3).

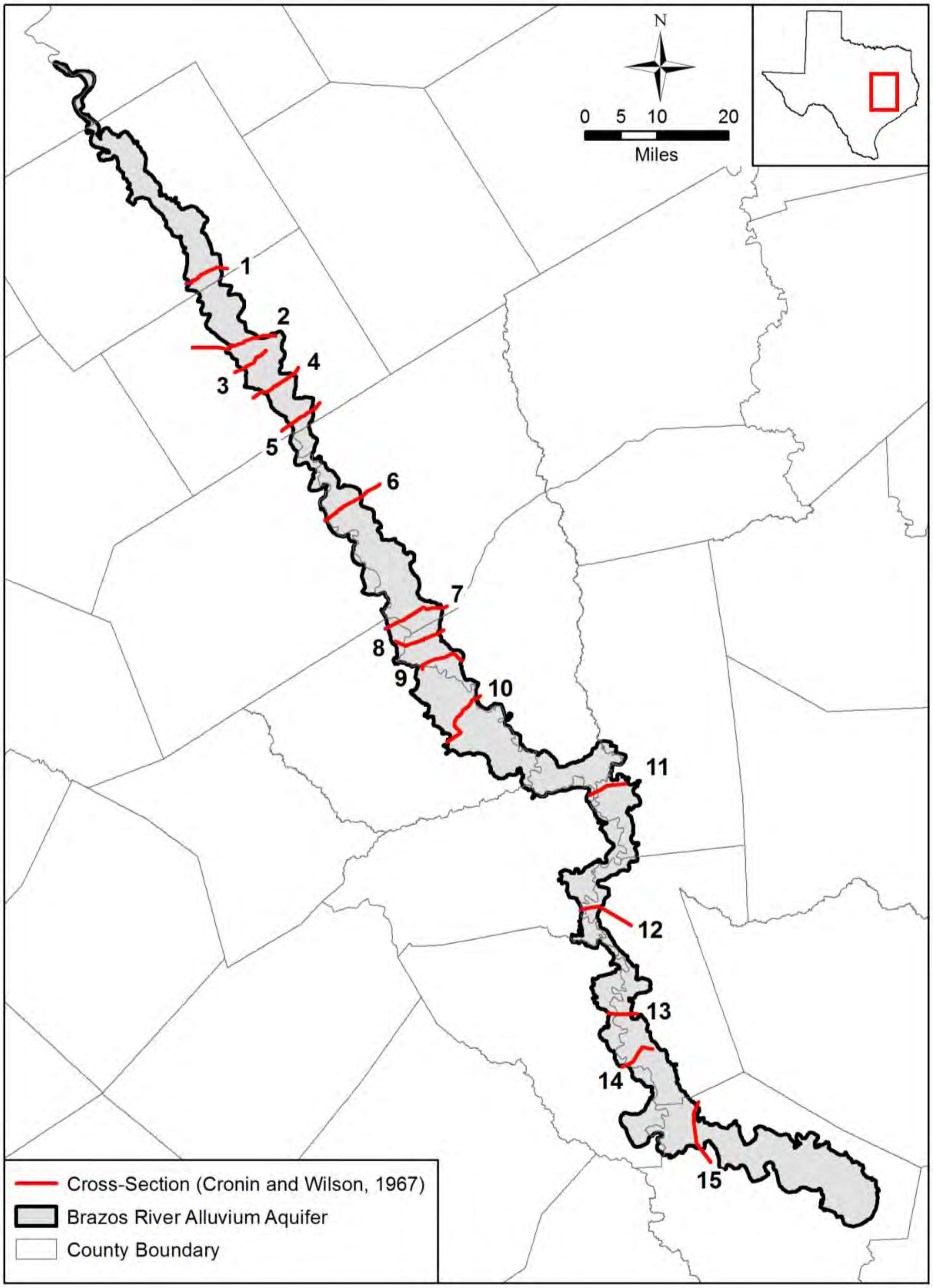

Figure 2.2.5 Location of cross-valley profiles (after Cronin and Wilson (1967).

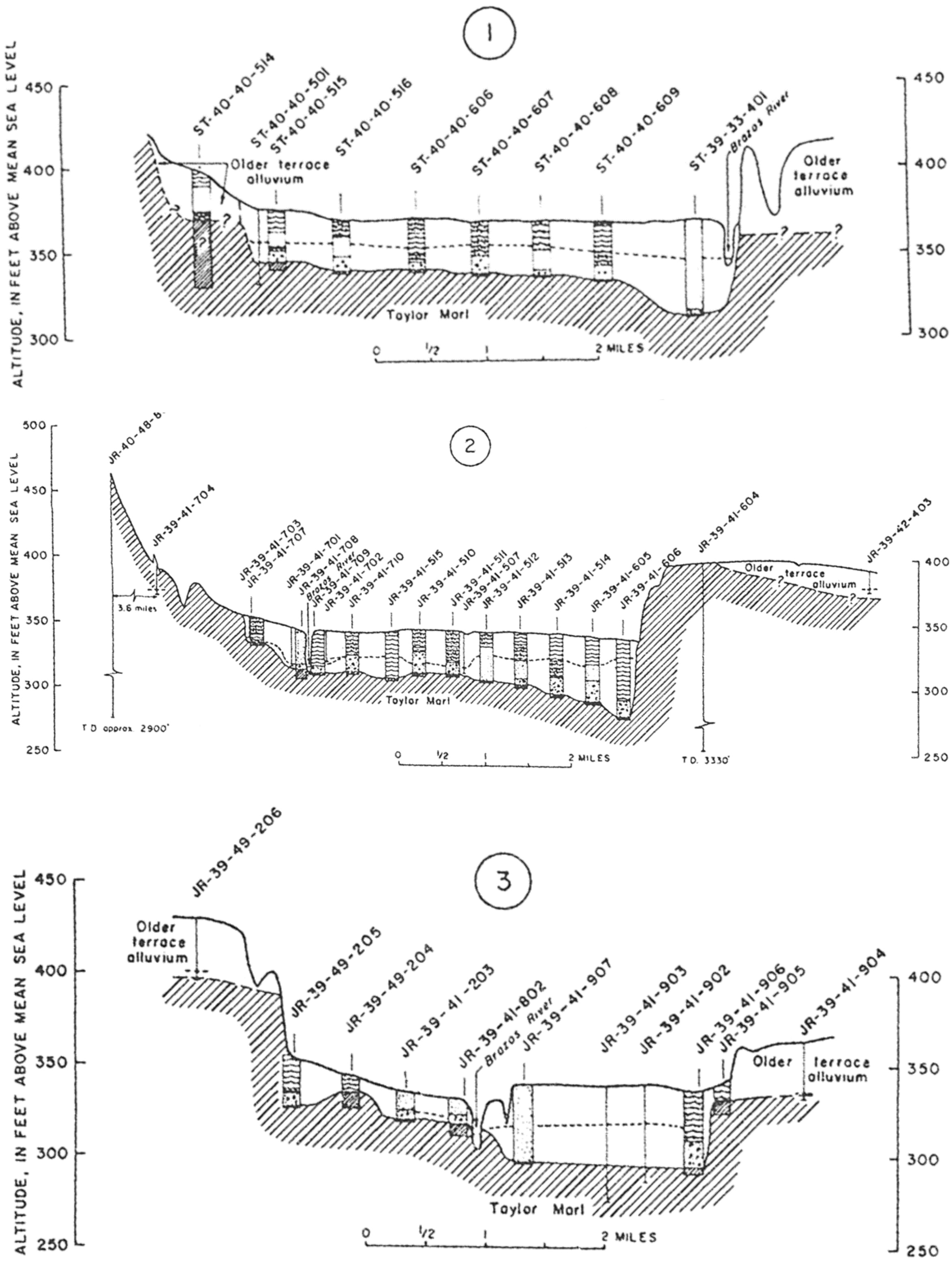

Figure 2.2.6a Cross-valley profiles 1 through 3 from Cronin and Wilson (1967) (locations given in Figure 2.2.5).

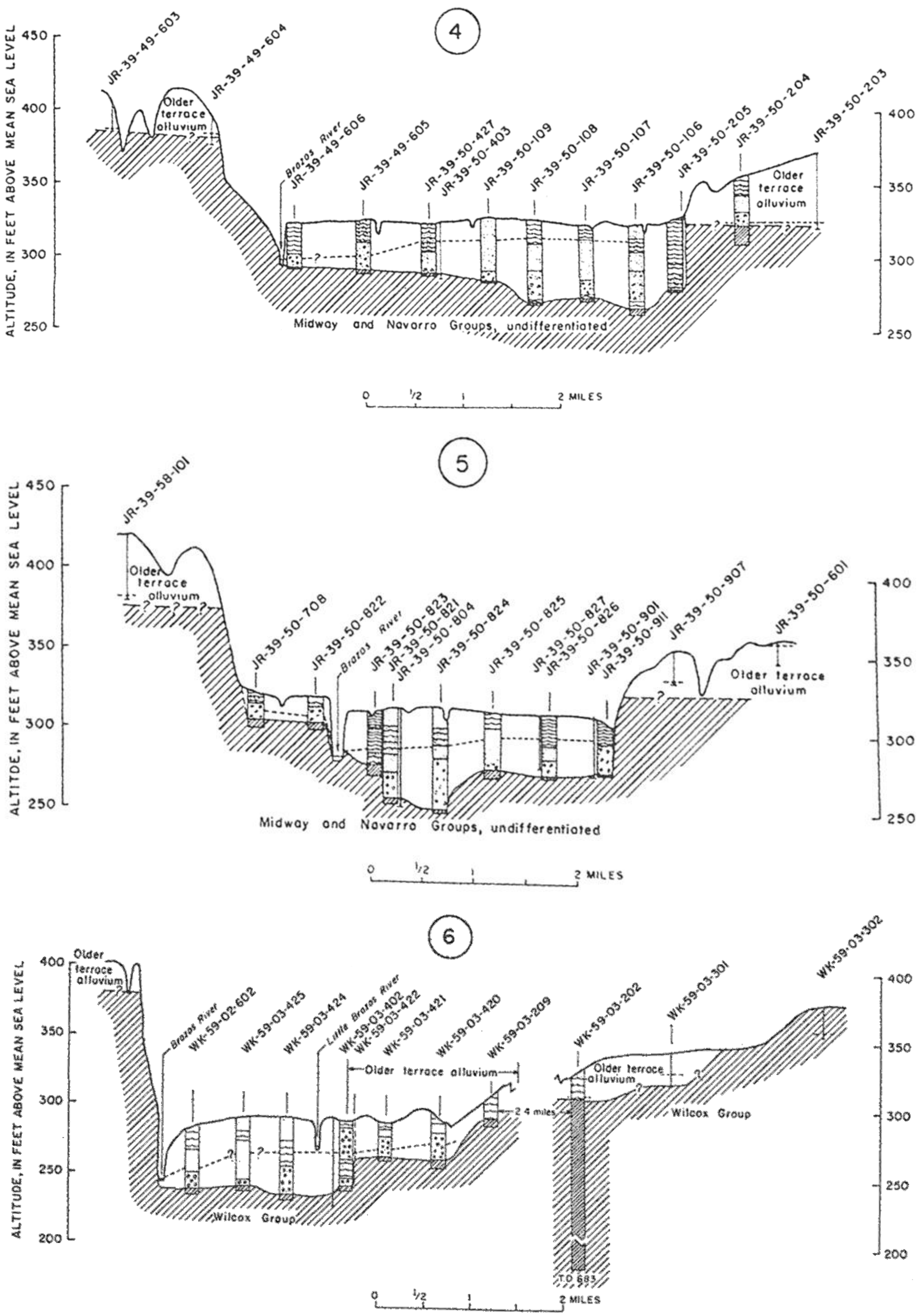

Figure 2.2.6b Cross-valley profiles 4 through 6 from Cronin and Wilson (1967) (locations given in Figure 2.2.5).

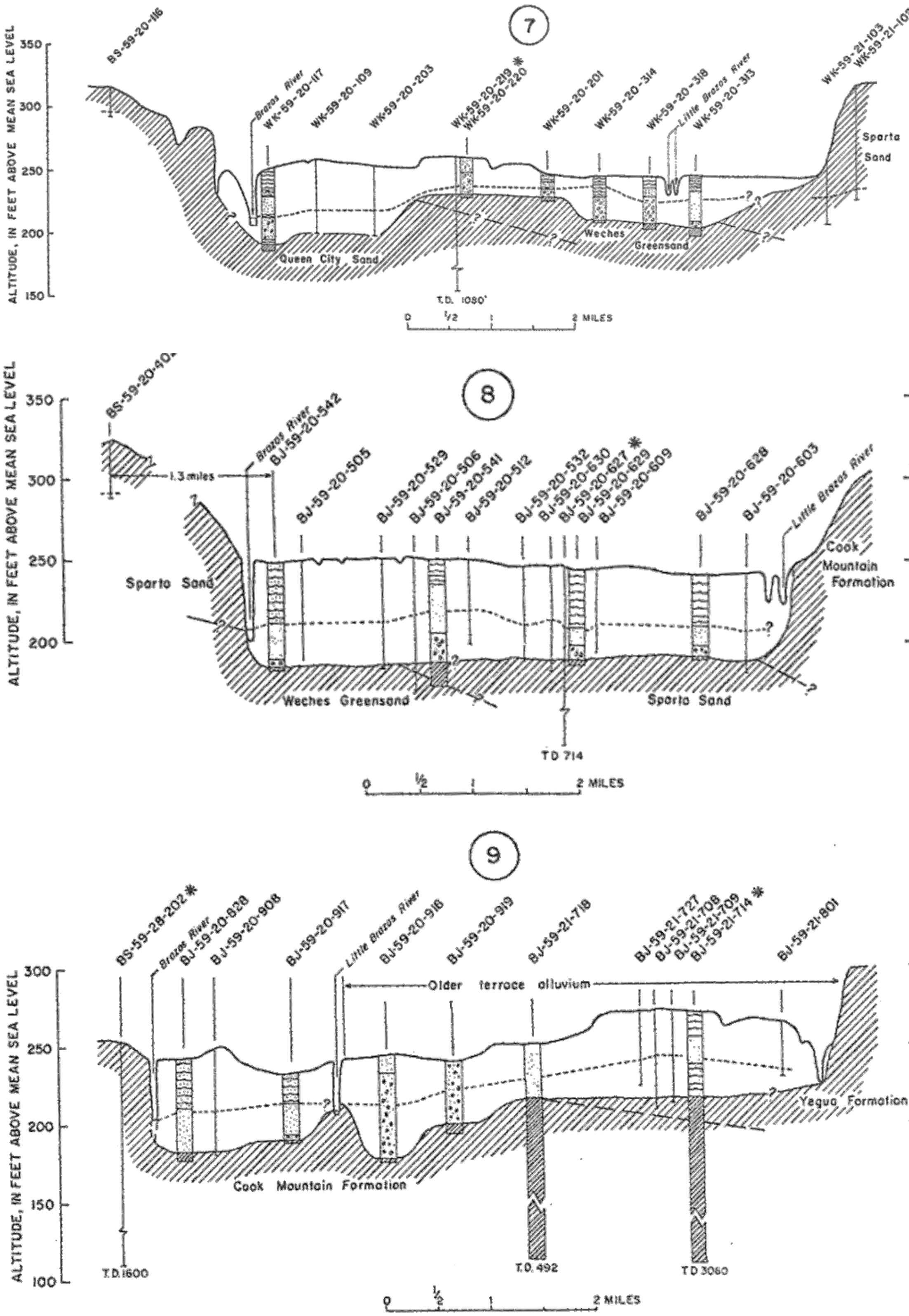

Figure 2.2.6c Cross-valley profiles 7 through 9 from Cronin and Wilson (1967) (locations given in Figure 2.2.5).

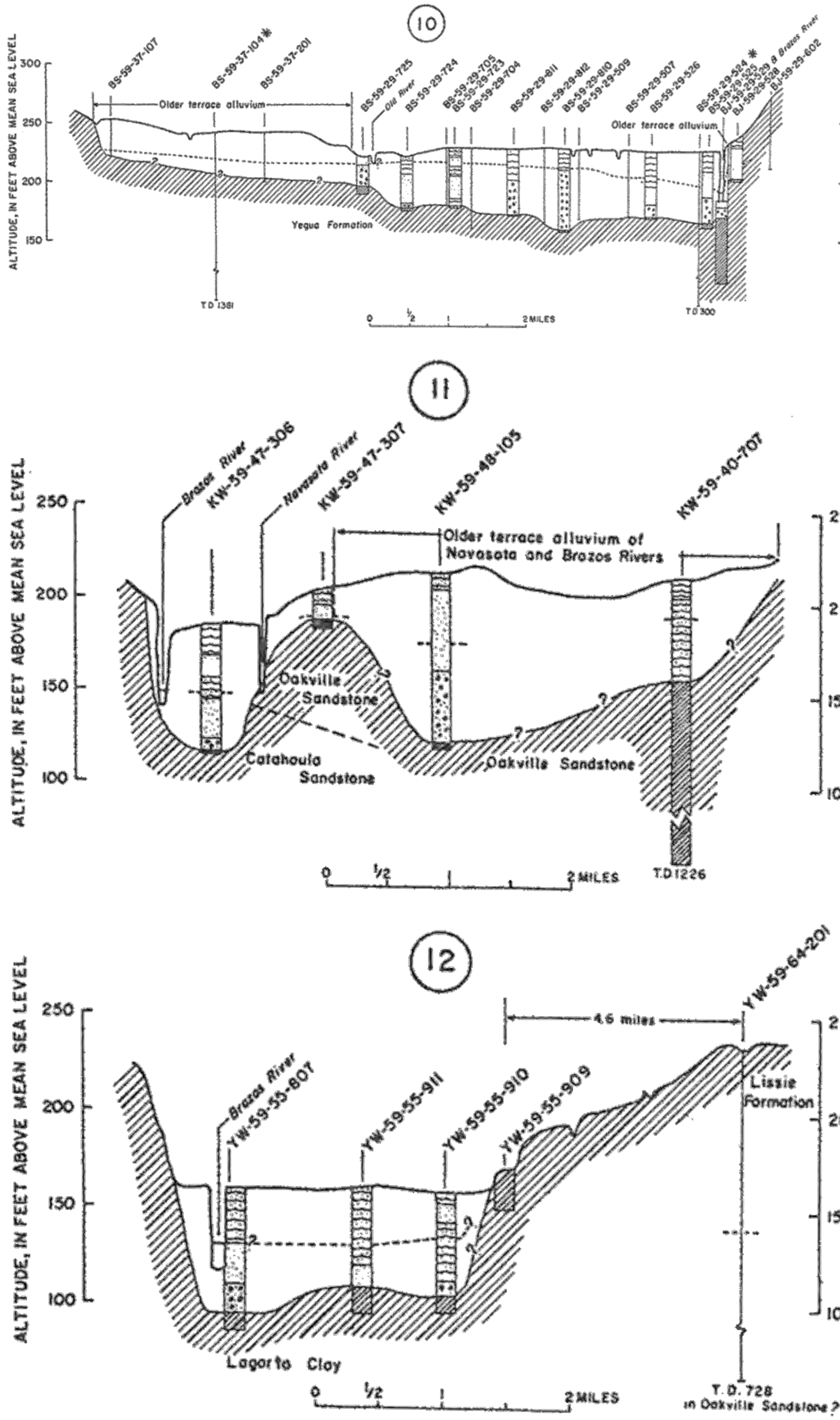

Figure 2.2.6d Cross-valley profiles 10 through 12 from Cronin and Wilson (1967) (locations given in Figure 2.2.5).

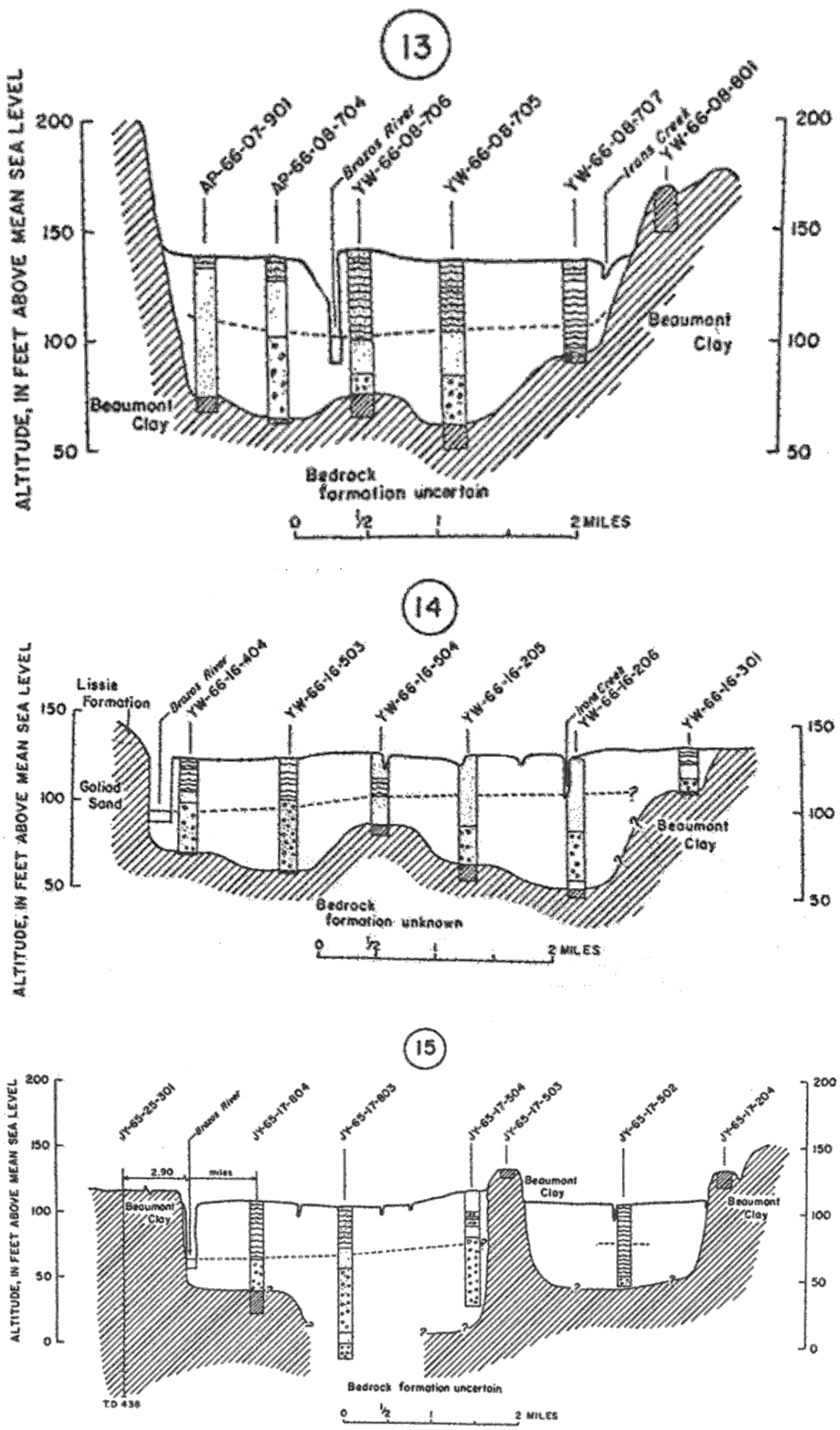

Figure 2.2.6e Cross-valley profiles 13 through 15 from Cronin and Wilson (1967) (locations given in Figure 2.2.5).

3.0 Previous Investigations

Several studies have been conducted on the Brazos River Alluvium Aquifer, but little information about the aquifer dates back prior to its development as a source for irrigation water in the 1950s. One modeling study has been conducted for a small portion of the Brazos River Alluvium Aquifer. In addition, several modeling studies of aquifers underlying the Brazos River Alluvium Aquifer have been conducted. The following discussion of previous investigations is divided into those related to hydrogeology and those related to numerical modeling.

3.1 Previous Hydrogeologic Investigations

The earliest published documentation of shallow wells in the vicinity of the Brazos River is found in Taylor (1907), which provides overviews of groundwater resources on a county-by-county basis for the Texas Coastal Plain. His report, however, is lacking specific information for the Brazos River Alluvium Aquifer. Early wells completed in the Brazos River Alluvium Aquifer were documented in several county-scale reports generally produced as part of Works Progress Administration projects between 1937 and 1943, consisting primarily of tabulated well records, drillers' logs, and water quality data (Texas Board of Water Engineers, 1937a, 1937b, 1937c, 1938, 1942, 1943a, 1943b; Livingston and Turner, 1939; Turner, 1939; Turner and Livingston, 1939). Post-development county-based investigations generally provide a narrative overview of the groundwater resources of their respective counties, including the Brazos River Alluvium Aquifer (Fluellen and Goines, 1952; Wilson, 1967; Sandeen, 1972; Wesselman, 1972; Baker and others, 1974; Follett, 1974; Thorkildsen, 1990). Later well inventories in Fort Bend and Waller counties are provided in Naftel and others (1976), Ratzlaff and others (1983), and Williams and others (1987). Well records and water resources reports for counties intersecting the Brazos River Alluvium Aquifer are summarized in Table 3.1.1.

Greater interest in the Brazos River Alluvium Aquifer as a source for water was instigated by the drought of the 1950s, when many irrigation wells were completed in the aquifer. This early development was documented by Hughes and Magee (1962). The Brazos River Alluvium Aquifer was discussed in some detail within the subsection "Quaternary Alluvium in the West Gulf Coastal Plain" of a broader report on the groundwater resources of the entire Brazos River Basin (Cronin and others, 1973). That subsection discusses groundwater recharge, movement, and discharge; water quality; groundwater development, utilization, and availability; and variations in water levels for the Brazos River Alluvium Aquifer from Whitney Dam northwest of Waco to near the Gulf of Mexico. Cronin and Wilson (1967) treated the Brazos River Alluvium Aquifer with greater detail in in their study of groundwater in the aquifer from Whitney Dam to the vicinity of Richmond, Texas, which remains the most comprehensive report on the aquifer to date. Cronin and Wilson (1967) discuss the geology, areal extent and depth variations, water quality, water-level variations and flow directions, interactions with surface water, interactions with underlying bedrock aquifers, recharge and discharge, irrigation within the floodplain, and general availability of groundwater in the Brazos River Alluvium Aquifer. They also present hydraulic property data for the Brazos River Alluvium Aquifer, including laboratory measurements of hydraulic conductivity and specific yield of samples of different sediment types collected during test drilling, transmissivity estimates from short-duration aquifer pumping tests, and 351 estimates of specific capacity of irrigation wells made in 1963 and 1964 (many of which were made on the same wells in both years). Using an empirical relationship, Cronin and Wilson (1967) estimated transmissivity from the specific capacity data.

Apart from the county-based investigations mentioned above, no published studies were conducted on the Brazos River Alluvium Aquifer in the 1970s and 1980s. Harlan (1990) conducted a study of the northwestern portion of the aquifer from Waco to Marlin. Several reports were generated discussing results of activities conducted at the Texas A&M Brazos River Hydrogeologic Field Site, which is located near the south bank of the Brazos River in Burleson County, near College Station. This site is situated atop an approximately 25-foot thick surficial clay layer and includes a large-diameter pumping well and several nests of wells completed at different vertical intervals within the aquifer. An overview of the Brazos River Hydrogeologic Field Site is given in Munster and others (1996), and site-scale aquifer characterization activities are reported in Wrobelski (1996). Field tests conducted using in-situ permeable flow sensors to compare variations in groundwater flow direction at two different depths with variations in the stage of the Brazos River are documented in Alden and Munster (1997a). Pumping tests and slug tests conducted at the Brazos River Hydrogeologic Field Site are discussed in Alden and Munster (1997b). The nested piezometers at the site were used to monitor agricultural chemical transport through the subsurface following surface application in Chakka and Munster (1997a) and atrazine transport through the unsaturated zone at the site was modeled by Chakka and

Munster (1997b). Shah and others (2007b) conducted a pilot study to define the extent of the surficial clay layer at the Brazos River Hydrogeologic Field Site using time-domain electromagnetic sounding and 2-dimensional direct current resistivity imaging to estimate hydraulic conductivity and moisture content of the aquifer material.

Studies on groundwater/surface water interactions that include the Brazos River Alluvium Aquifer were conducted by Chowdhury (2004) and Chowdhury and others (2010). Chowdhury (2004) collected water samples from three oxbow lakes in Burleson, Washington, and Waller counties and also from the Brazos River and wells completed in the Brazos River Alluvium Aquifer at locations near the lakes. Observed Brazos River Alluvium Aquifer gradients, known river-lake connectivity history, and chemical and isotopic analyses of these waters were used to infer the relationship between the aquifer and the Brazos River and the aquifer and the oxbow lakes. The study by Chowdhury (2004) was expanded upon in Chowdhury and others (2010), with somewhat more of a focus on groundwater, including water chemistry and isotopic sampling from wells completed in the underlying Queen City and Evangeline aquifers. Conclusions from both Chowdhury (2004) and Chowdhury and others (2010) are presented and discussed with respect to previous water quality investigations in Section 4.7.1.

Turco and others (2007) conducted base flow separation analyses on stream gage data for the years 1966 through 2005 from three stations located on the Brazos River and from gaging stations on seven tributaries. They also determined gaining/losing reaches along the Brazos River and several tributaries in March and August 2006. Increases in base flow to the Brazos River were observed in areas where it cuts across the outcrop areas of the Carrizo-Wilcox, Queen City, Sparta, and Yegua-Jackson aquifers, but no similar increase was observed in areas where the river crosses the Gulf Coast Aquifer outcrop area. Additional information regarding the Turco and others (2007) study is provided in Sections 4.4.1.1 and 4.4.1.2.

Geologic and hydrogeologic data for the Brazos River Alluvium Aquifer were compiled as a geodatabase in Shah and Houston (2007). Information on the compilation of this data set was reported in Shah and others (2007a, 2009). A detailed discussion of their development of the structure for the aquifer is provided in Section 4.1.2.1 and Section 4.5.1 and discusses the hydraulic property data they compiled.

Wong (2012) completed a study focusing on the northwestern portion of the Brazos River Alluvium Aquifer in portions of Bosque, Hill, McLennan, and Falls counties. Aquifer thickness was characterized on a relatively local scale using data from boreholes located on the Baylor University campus in Waco and compared to more regional-scale isopachs, indicating that much of the short-scale variation is not captured in regional surfaces. Well depth was considered to be a reasonable proxy for aquifer thickness when the alluvium is thin and underlain by a confining unit, as is the case in and near Waco. She noted, however, that well depth becomes less suitable for approximating aquifer thickness as the Brazos River Alluvium Aquifer thickens and the probability of any given well being fully penetrating declines. In contrast to the Trinity Aquifer in the area, Wong (2012) noted that water levels in the Brazos River Alluvium Aquifer have historically fluctuated rather than shown a steady decline.

Table 3.1.1 Summary of well records and water resources reports by county.

County	Records of Wells Report	Groundwater Resources Report	Citation
Austin	M008		TBWE (1938)
		R68	Wilson (1967
Brazos		R185	Follett (1974)
Burleson	M026		TBWE (1937a)
		R185	Follett (1974)
Fort Bend	M085		TBWE (1937b)
	M086		Livingston and Turner (1939)
		R155	Wessleman (1972)
	R201		Naftel and others (1976)
	R277		Ratzlaff and others (1983)
	R303		Williams and others (1987)
		R321	Thorkildsen (1990)
Grimes	M100		Turner (1939)
	M101		TBWE (1943a)
		R186	Baker and others (1974)
Milam	M188		TBWE (1937c)
Robertson	M232		TBWE (1942)
Waller	M289		Turner and Livingston (1939)
		B5208	Fluellen and Goines (1952)
		R68	Wilson (1967)
	R201		Naftel and others (1976)
	R277		Ratzlaff and others (1983)
	R303		Williams and others (1987)
Washington	M290		TBWE (1943b)
		R162	Sandeen (1972)

R = TWDB Numbered Report B = TWDB Bulletin M = TWDB Historical Groundwater Report
TBWE = Texas Board of Water Engineers

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3.2 Previous Numerical Models

Several numerical models have been constructed within the study area including one model of a small portion of the Brazos River Alluvium and three models of aquifers underlying the alluvium. The locations of the models are shown in Figure 3.2.1. A groundwater model for a central portion of the Brazos River Alluvium Aquifer in Milam, Robertson, Burleson, and Brazos counties was reported in O'Rourke (2006). The purpose of this model was to evaluate a proposed project where the Brazos River Alluvium Aquifer would be used to store excess water during high flows of the Brazos and Little Brazos rivers for later use during relatively low-flow periods. Cyclical storage/recovery on an annual basis was simulated for a 6-year period to evaluate long-term effects on water levels. The model used a single layer with a 500-foot grid size. Possible upward vertical leakage from underlying aquifers was acknowledged, but the base of the aquifer was modeled as a no-flow boundary due to the lack of reliable data to account for this.

Dutton and others (2003) constructed a model of the central Carrizo-Wilcox Aquifer. This model included an alluvium layer in the Colorado, Brazos, and Trinity River valleys, which included the Brazos River Alluvium Aquifer. The model of Dutton and others (2003) has been superseded by a model of the Queen City and Sparta aquifers by Kelley and others (2004), which includes the Carrizo-Wilcox Aquifer. Deeds and others (2010) constructed a model for the Yegua-Jackson Aquifer. Kasmarek and Robinson (2004) constructed a model for the northern Gulf Coast Aquifer System and Kasmarek (2013) provides an updated model. Apart from Dutton and others (2003), none of these models included a model layer for the Brazos River Alluvium Aquifer nor simulated the alluvium explicitly. Where these models outcrop, however, they do provide initial estimates of hydraulic properties, as discussed in Section 4.5.3, and recharge, as discussed in Section 4.3, for the formations underlying the Brazos River Alluvium Aquifer. The models may also provide information about the impacts of pumping within the underlying aquifers on the cross-formational flow to the Brazos River Alluvium Aquifer.

The United States Army Corps of Engineers constructed a river system model of the Brazos River Basin that extends from Possum Kingdom Reservoir to Richmond, Texas (Avance, 2015) (Figure 3.2.2). This model contains 12 reservoirs, nine of which are operated by the United

States Army Corps of Engineers and three that are controlled by the Brazos River Authority (Table 3.2.1).

The model was built in RiverWare (Zagona and others, 2001) and is a daily time step model that runs for 71 years, from 1939 to 2009. River objects in the model are used to route flows throughout the system. They are also used to add additional streamflow into the model in headwater basins and along major rivers where there is local inflow from smaller tributaries. River objects can also be used to simulate withdrawals, however, no river withdrawals are simulated in this model. The United States Army Corps of Engineers is chiefly concerned with flood control operations, and river withdrawals have little impact on the analysis of flood events.

Reservoirs in the model are simulated using both physical and operational constraints. Physical constraints include spillway and outlet ratings that limit the amount of water that can actually be released. Operational constraints include rules that establish desired pool elevations, flood control and water quality releases, hydropower requirements, and water supply obligations. Water withdrawals that occur directly from reservoirs are simulated in the model with no return flows.

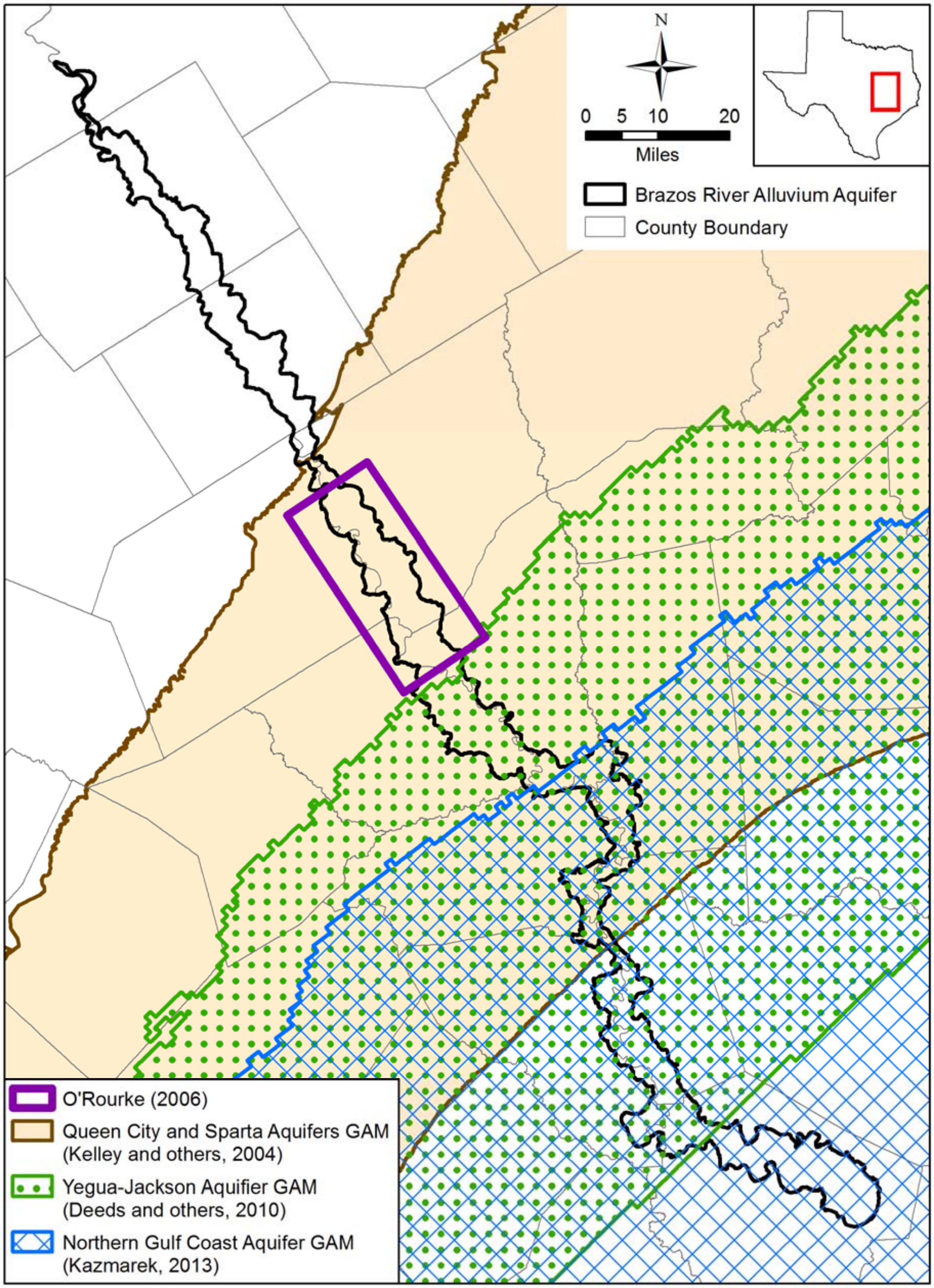
During the model run, it is assumed that the reservoirs are in place for the entire simulation. In reality, several of the reservoirs were not constructed until well after the start of the simulation. This assumption was made in order to test the response of current reservoirs to past flood events. However, this means results in the model output may not match measured streamflow gage data during periods when reservoirs were not operational. This difference can be demonstrated by comparing the simulated results for the river object located on the Brazos River near Bryan, Texas in the model to the actual streamflow measurements from its real counterpart, gaging station 08109000 on the Brazos River near Bryan, as given in the United States Geological Survey National Water Information System database (United States Geological Survey, 2014b). Figure 3.2.3 shows the location of the gage and nearby reservoirs, labeled with the year they were created. The oldest reservoirs in the gage vicinity are Lake Whitney and Lake Belton, which were created in 1951 and 1954, respectively. Plots comparing the simulated flow at the river object from the RiverWare model and the measured flow at gage 08109000 are presented in Figure 3.2.4. The uppermost plot shows the entire period of overlapping data. Note that the plot does not extend to the end of the model run in 2009 because gage 08109000 actually stopped recording on September 30, 1993. This plot shows a large difference in measured versus modeled peak flows prior to approximately 1969, due to the model including reservoirs that had not actually been built yet. The middle and lower plots only show the earliest overlapping records, providing more detail for the pre-1950s time period before any reservoir had been built. In the middle plot, measured streamflow peaks are clearly much larger than the simulated peaks, because the reservoirs in the model provide a damping effect that did not yet exist in reality. The lower plot only shows flows less than 2,000 cubic-feet per second in order to emphasize the differences during low flow events. In this case, the simulated streamflow is higher than the measured streamflow. This difference is largely because the model simulates a 200 cubic feet per second minimum water quality release from Lake Whitney, which again, did not yet exist in reality.

Despite these differences, the RiverWare model is quite effective at simulating surface water conditions in the Brazos River Basin. Although the model does not include any surface water - groundwater interaction, the model is still helpful for conceptualizing the river flow system in the current Brazos River Alluvium Aquifer model.

Table 3.2.1 Reservoirs simulated in the United States Army Corps of Engineers Brazos River Basin RiverWare model.

Lake Name	Controlling Authority	Year Created[1]	Latitude[1] (decimal degrees)	Longitude[1] (decimal degrees)	Conservation Capacity[2] (acre-feet)
Granbury	Brazos River Authority	1969	32.3733	-97.6883	125,756
Limestone	Brazos River Authority	1978	31.3250	-96.3200	208,014
Possum Kingdom	Brazos River Authority	1941	32.8700	-98.4250	523,873
Aquilla	United States Army Corps of Engineers	1983	31.9133	-97.2083	43,243
Belton	United States Army Corps of Engineers	1954	31.0833	-97.4833	435,225
Georgetown	United States Army Corps of Engineers	1980	30.6750	-97.7250	36,823
Granger	United States Army Corps of Engineers	1980	30.7033	-97.3000	50,779
Proctor	United States Army Corps of Engineers	1963	31.9717	-98.4767	55,457
Somerville	United States Army Corps of Engineers	1967	30.3167	-96.5167	147,104
Stillhouse Hollow	United States Army Corps of Engineers	1968	31.0167	-97.5167	227,771
Waco	United States Army Corps of Engineers	1964	31.6013	-97.1936	189,418
Whitney	United States Army Corps of Engineers	1951	31.8124	-97.2978	553,344

[1] From United States Geological Survey (2014c)
[2] From TWDB (2014a)



GAM = groundwater availability model

Figure 3.2.1 Previous model boundaries in the study area.

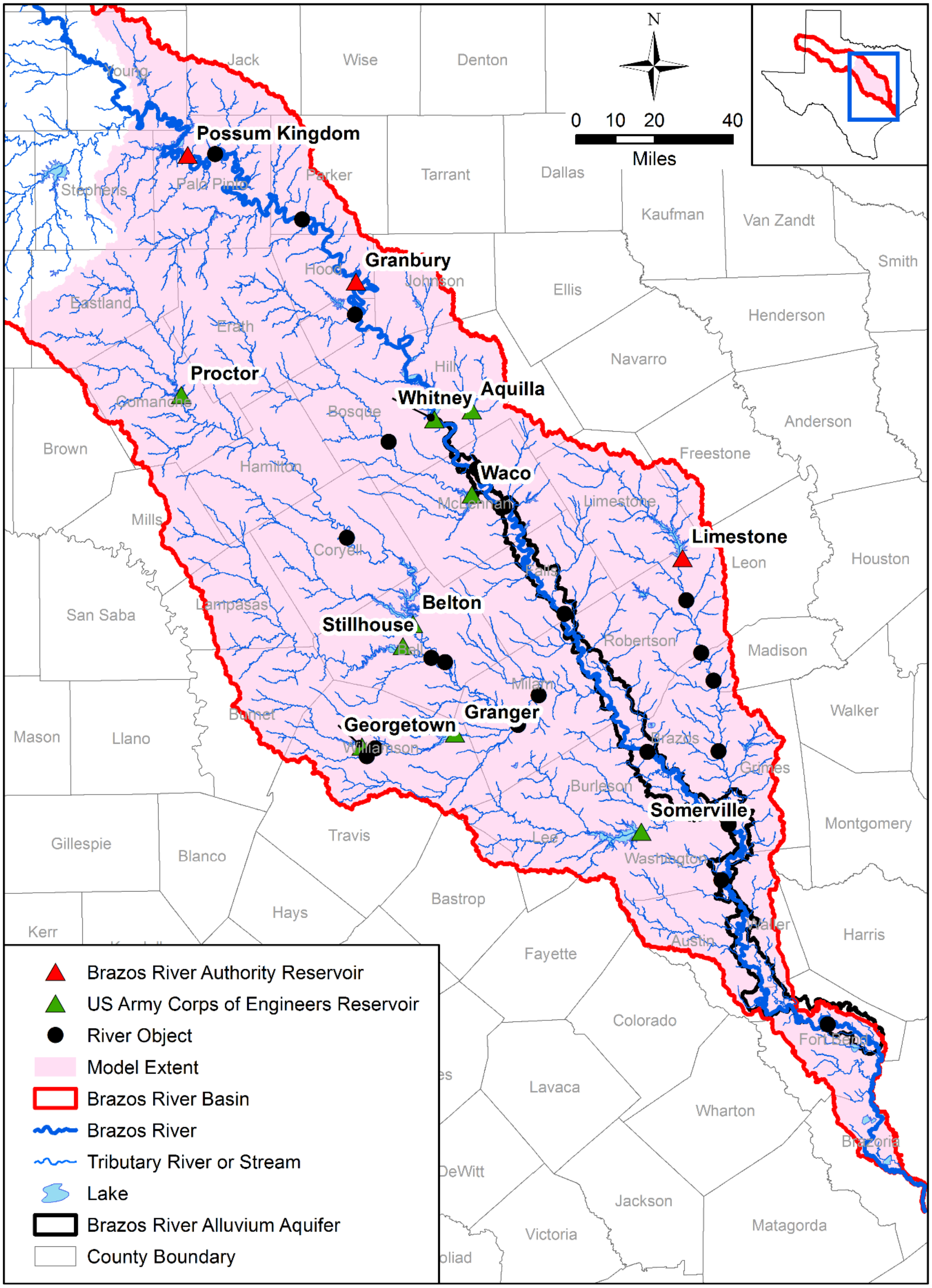


Figure 3.2.2 Location of simulated objects in the United States Army Corps of Engineers Brazos River Basin RiverWare model.

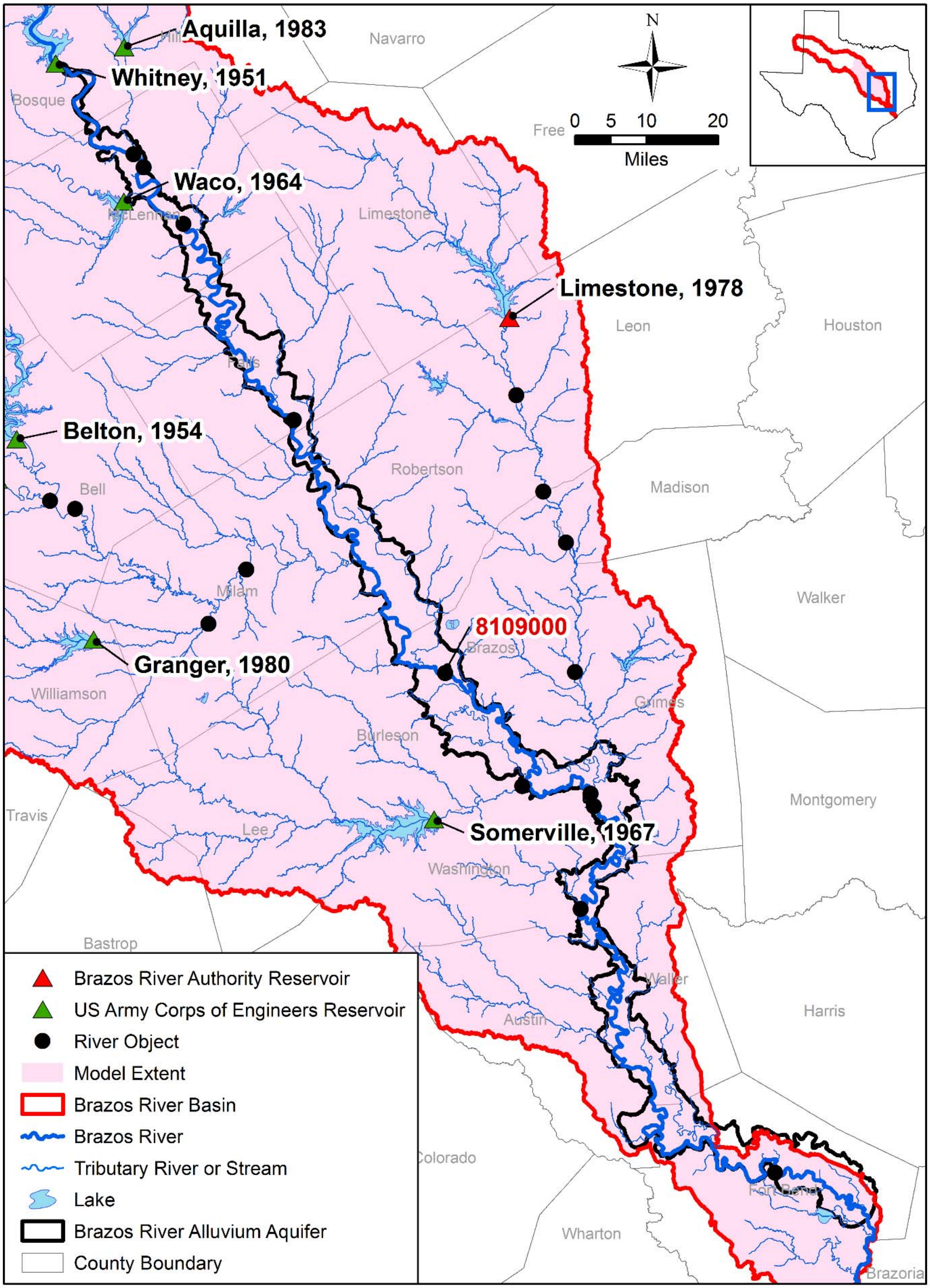


Figure 3.2.3 Location of gage 08109000 and nearby reservoirs.

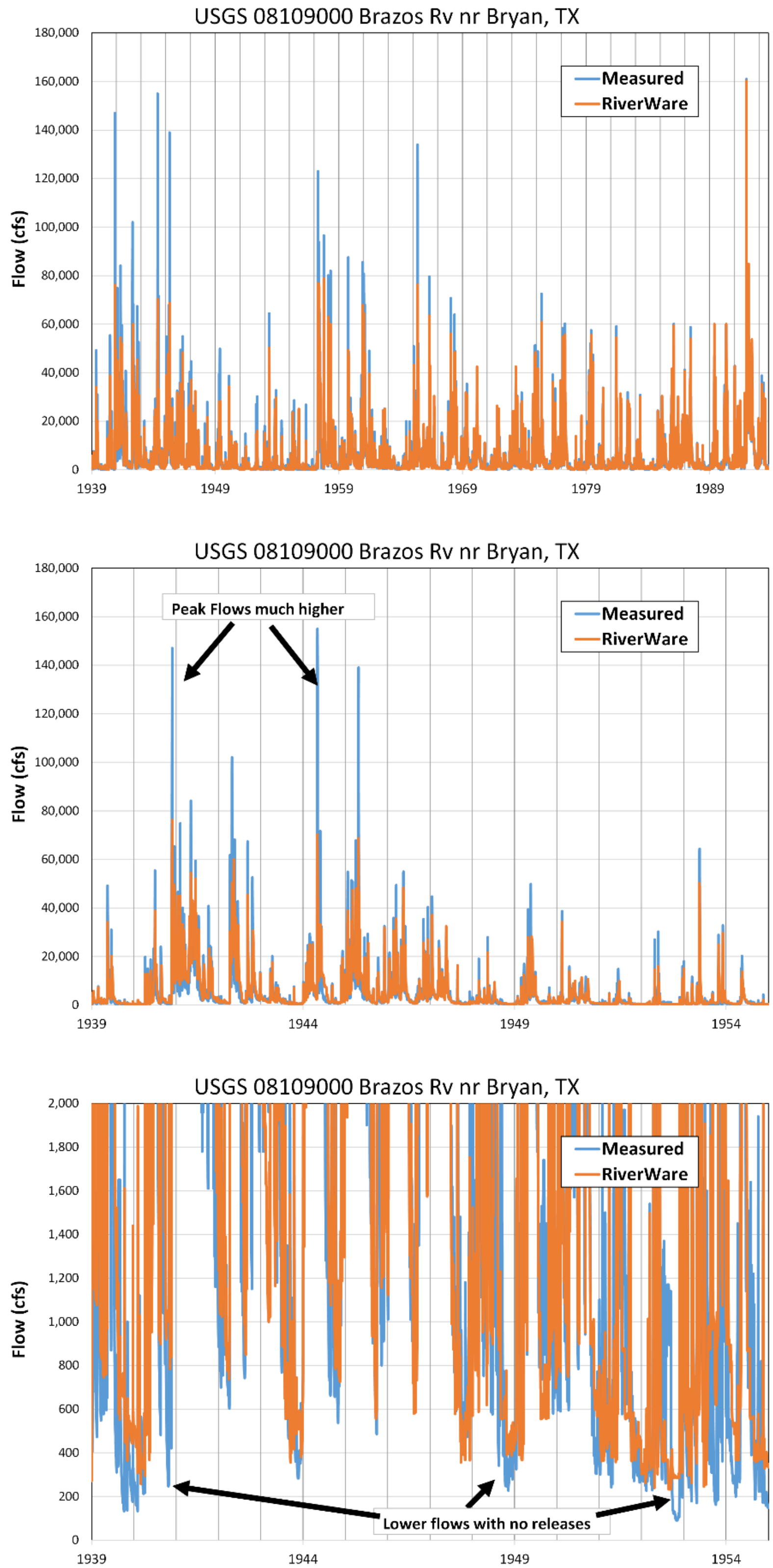


Figure 3.2.4 Actual streamflow at gage 08109000 compared to simulated streamflow.

4.0 Hydrogeologic Setting

The following sections discuss the data compilation and analyses performed to support development of the conceptual model for the Brazos River Alluvium Aquifer. This information, in total, is referred to as the hydrogeologic setting and includes a discussion of the hydrostratigraphy, hydrostratigraphic framework, water levels and regional groundwater flow, recharge, surface water interaction, hydraulic properties, discharge, and water quality of the aquifer.

4.1 Hydrostratigraphy and Hydrostratigraphic Framework

Discussion of the hydrostratigraphy and development of the hydrostratigraphic surfaces for the Brazos River Alluvium Aquifer are provided in this section. The hydrostratigraphy discusses the stratigraphy of the Brazos River Alluvium Aquifer as it relates to groundwater flow. The hydrostratigraphic framework discussion describes the development and presentation of the structural top and base of the aquifer and the aquifer thickness.

4.1.1 Hydrostratigraphy

Sediment deposition related to the Brazos River includes both floodplain and terrace alluvial deposits. The following discussion of the deposits making up the Brazos River Alluvium Aquifer was taken from Cronin and Wilson (1967). The deposits consist of typical alluvial sediments, including gravel, fine to coarse sand, silt, and clay, in lenses that pinch out or grade both laterally and vertically. In general, the deposits are coarser at the base and fine upward. The sequence of finer upper deposits transitioning to coarser lower deposits is consistent throughout the aquifer. However, due to pinching out and interfingering, the grain size and relative position of individual constituents in the sequence vary from place to place. The transition from one type of material to another, both laterally and vertically, can be either sharp and distinct or gradual.

A wide variety of gravel, in both size and composition, is found in the sediments of the Brazos River Alluvium Aquifer. In size, 3-foot diameter boulders as well as pea-sized gravel are observed. The materials comprising the gravel include limestone, sandstone, conglomerate, clay balls, siliceous, and concretions. The degree of mixing of gravel with sand and silt varies from place to place in the aquifer. In general, the aquifer consists of beds or lenses of variably mixed gravel, sand, silt, and clay. Clay lenses ranging in thickness from about 5 to 30 feet commonly occur in the upper portion of the floodplain alluvium. These clays vary in both texture and composition, generally due to the amount of mixing with sand or silt. The clay lenses typically overlie fine-grained sand or silty sand; however, clay lenses overlie coarser alluvial sediments in some areas.

Groundwater in the Brazos River Alluvium Aquifer is predominately under unconfined conditions. In areas where clay lenses overlie lenses of sand or gravel, locally confined conditions may exist. The Brazos River Alluvium Aquifer lies in the valley of the Brazos River. The depositional pattern and aquifer thickness within this valley are the result of a combination of influences, including past meandering of the river as well as the depositional surfaces provided by underlying formations. In general, the upper portion of the Brazos River Alluvium Aquifer has relatively higher clay content than the lower portion, which has relatively higher sand and gravel content. Two model layers will be used to represent the Brazos River Alluvium Aquifer.

The Brazos River Alluvium Aquifer overlies, in turn from northwest to southeast, outcrops of the Carrizo-Wilcox, Queen City, Sparta, Yegua-Jackson, and Gulf Coast aquifers (Figure 4.1.1). Since the Brazos River is a regional discharge boundary for the underlying aquifers, these aquifers are assumed to be hydraulically connected to the Brazos River Alluvium Aquifer in the portions of their outcrop areas that underlie the Brazos River Alluvium Aquifer. A single model layer will be used to represent the shallow portions of the geologic units underlying and surrounding the Brazos River Alluvium Aquifer.

4.1.2 Hydrostratigraphic Framework

Shah and others (2007a) studied the hydrogeologic character of the Brazos River Alluvium Aquifer to support the TWDB Groundwater Availability Model Program. Part of that characterization included the delineation of the elevations of the top and base of the aquifer and development of the aquifer thickness. The data supporting that work are contained in a geodatabase found in Shah and Houston (2007). This work was the basis for the hydrostratigraphic framework developed for the conceptual model of the Brazos River Alluvium Aquifer. The following subsections provide an overview of the structure delineation by Shah and others (2007a), development of the top surface of the Brazos River Alluvium Aquifer for the conceptual model, evaluation of the base of aquifer surface developed by Shah and others (2007a), and development of the aquifer thickness and basal elevation for the Brazos River Alluvium Aquifer based on the Shah and Houston (2007) data.

4.1.2.1 Overview of Structure Delineation in Shah and others (2007a)

The top elevation of the Brazos River Alluvium Aquifer was defined by Shah and others (2007a) using the 30-meter (98.4-foot) digital elevation model (DEM) resampled at 0.125 miles. They used picks from driller's logs, geophysical logs, and published geologic cross-sections as well as total well depths to generate a surface for the base of the aquifer. Well depth data were used only where other data were not available and were evaluated for consistency with data from logs. Control points for their final map of the base of the aquifer included data from 386 drillers' logs, 13 geophysical logs, 10 geologic cross-sections, and 955 total well depths. Shah and others (2007a) indicate that the base of the aquifer in Fort Bend County is uncertain due to the difficulty in distinguishing the alluvial sediments of the Brazos River Alluvium Aquifer from the alluvial sediments of the underlying Gulf Coast Aquifer System because the lithology of both is very similar. Raster surfaces of the top and base of the aquifer were created by Shah and others (2007a). The difference between those two surfaces provided their aquifer thickness. Note that the study presented in Shah and others (2007a) is also presented in Shah and others (2009).

4.1.2.2 Structural Top for the Brazos River Alluvium Aquifer

For the conceptual model of the Brazos River Alluvium Aquifer, the top of the aquifer was developed based on the 10-meter (32.8-foot) digital elevation model (DEM) (United States Geological Survey, 2014a) rather than the 30-meter (98.3-foot) digital elevation model used by Shah and others (2007a). The higher resolution digital elevation model was used to enable capture of small-scale changes in elevation across the top of the aquifer. The elevation of the top of the Brazos River Alluvium Aquifer for the conceptual model is shown in Figure 4.1.2. At any location perpendicular to the aquifer boundaries, the lowest elevation is found at the location of the Brazos River and the highest elevations are typically found along the aquifer boundary. Along the length of the Brazos River Alluvium Aquifer adjacent to the Brazos River, the elevation of the top of the aquifer varies from a high of about 588 feet at the very northwestern tip of the aquifer to a low of about 17 feet near the southeastern boundary of the aquifer.

4.1.2.3 Review of the Shah and others (2007a) Aquifer Base Elevation

The raster developed by Shah and others (2007a) for the base of the Brazos River Alluvium Aquifer was evaluated to determine whether it was adequate for the purposes of the conceptual model developed here or whether it needed to be updated. The review focused on reproducing the surface using the data provided in Shah and Houston (2007) and their use of well depths as control points to define the base of the aquifer. In addition, a search was conducted for additional data for use in refining the surface and generation of a higher-resolution surface was explored.

The information provided in Shah and Houston (2007) was found to be insufficient to reproduce the surface of the base of the aquifer. Shah and others (2007a) report that the process they used to create their final surface involved several steps. First, they created a preliminary raster and generated contour intervals from that raster using ArcGIS. They then used an iterative process to remove anomalous data. This process involved assessing the contours and underlying data, identifying discrepancies in the data, removing anomalous data, and then re-contouring. After this, they manually modified the resultant contours where necessary to match the data. Their final surface was created from both data points and hand-modified contours using the Topo to Raster interpolation tool in ArcGIS. Because only the point data but not the modified contours used to create the final surface are available in Shah and Houston (2007), reproduction of their surface was not possible.

Seventy percent of the control points used by Shah and others (2007a) to define the base of the Brazos River Alluvium Aquifer were total wells depths for wells known to be completed in the aquifer. Although a study by Wong (2012) that encompassed a small portion of the aquifer in central Texas supports this assumption, an analysis was conducted to evaluate the appropriateness of the assumption for the entire aquifer. A statistical analysis using a T-test was performed on the data used by Shah and others (2007a) to evaluate the appropriateness of using total well depth to define the base of the aquifer. That analysis indicated that the difference in the mean between control points based on total depth and control points based on geophysical logs, drillers' logs, and cross section picks is less than the standard deviation for the two control point populations. Therefore, the use of well depths to define the base of the aquifer does not significantly skew the developed surface as compared to the use of data only from geophysical logs, drillers' logs, and picks on published cross-sections.

In addition, an attempt was made to create a surface of the aquifer base using the data from drillers' logs, geophysical logs, and picks on published cross-sections from Shah and Houston (2007) and added control points enforcing a thickness of zero along the aquifer boundary. The resultant surface had a much lower resolution and more anomalies than the raster created by Shah and others (2007a). This indicated that updating the surface by eliminating the use of well depths as control points did not provide an improvement over the surface in Shah and others (2007a).

A search for additional structural information to use in refining the surface by Shah and others (2007a) was performed. Data on the base of the Brazos River Alluvium Aquifer were requested from the groundwater conservation and subsidence districts in which the aquifer is located. These requests resulted in no additional structural information for the aquifer. In addition, a driller who works in Fort Bend County was contacted (Weisinger Incorporated, 2014). Although he had anecdotal information related to the location of the base of the aquifer, no additional data were obtained from him.

The Brackish Resources Aquifer Characterization System database maintained by the TWDB was queried for well logs (TWDB, 2014e). The vast majority of logs found by the query were used by Shah and others (2007a), and many of the remaining logs did not include the shallow portion of the well where the Brazos River Alluvium Aquifer is located. Of the logs left, some were discarded due to poor quality and others were discarded if the log started at a depth greater than 20 feet below the base of the aquifer as defined by Shah and others (2007a). After this elimination process, eight logs where identified as potential sources of additional data. Of those, the base of the aquifer picked from the log matched the base from Shah and others (2007a) within 10 feet for all but one log. Therefore, it was concluded that little benefit would be gained by incorporating these eight logs as additional control points.

Well records maintained by the Texas Commission on Environmental Quality (2014a) were reviewed for additional data on the location of the base of the Brazos River Alluvium Aquifer. That review found few wells with potentially useful data. For these well records, the location of wells is given based on a 2.5-mile grid, which is significantly larger than the preliminary grid size of one eighth of a mile for the Brazos River Alluvium Aquifer groundwater availability model. Therefore, the addition of data from this source might introduce significant error in the surface due to uncertainty in well locations. As with the data from the Brackish Resources Aquifer Characterization System database, it was concluded that little benefit would be gained by incorporating these data as additional control points for the base of aquifer surface.

In summary, a search for additional data for the base of the Brazos River Alluvium Aquifer was conducted. That search included requesting data from groundwater conservation and subsidence districts and searching the Brackish Resources Aquifer Characterization System database and well records maintained by the Texas Commission on Environmental Quality. No additional data for use in refining the basal aquifer elevation were not found.

Several attempts were made to develop a basal surface for the Brazos River Alluvium Aquifer at a higher resolution than that provided by Shah and others (2007a). In the shapefile of point data for the base of aquifer in Shah and Houston (2007), each data point was labeled based on the type of data it represents. Their four data types are geophysical log, drillers' log, cross section, and control point, with the latter type representing the total well depth data. In the following discussion, all four of these types are referred to as control points. The attempts to create a new basal elevation included:

- Using the control points from Shah and others (2007a) and artificial control points along the aquifer boundary. The artificial points were assigned a basal elevation equal to the digital elevation model value to enforce zero thickness along the boundary. This resulted in a lower resolution surface, with many locations where the interpolated base was higher than the aquifer top elevation due to too little control.
- To increase control, additional artificial control points were added along a longitudinal centerline in the aquifer. The value for the base of the aquifer at those points was assumed to be the basal elevation, as extracted from the Shah and others (2007a) base of aquifer raster. Using these additional points with the control points from Shah and others (2007a) and the artificial control points along the aquifer boundary also resulted in a lower resolution surface due to sparse control. Again, there were many locations where the interpolated base was higher than the aquifer top elevation.
- The Shah and others (2007a) control points consisting of geophysical logs, drillers' logs, and cross section picks included both aquifer top and bottom elevations. To reduce inversions, the basal elevation for these control points was modified by subtracting the

reported thickness from the 10-meter (32.8-foot) digital elevation model value rather than the reported top elevation. Using this method also resulted in inversions between the interpolated base elevation and the top elevation and, in many areas, thickness values were significantly different from the thicknesses of nearby control points.

The above attempts indicated that interpolating the Shah and others (2007a) control points and artificial control points along the aquifer boundary and centerline would not produce a higher resolution raster than that provided by Shah and others (2007a). Therefore, another approach was investigated. The preliminary grid for the Brazos River Alluvium Aquifer groundwater availability model consists of one-eighth of a mile grid cells within the boundary of the aquifer. Basal elevations at the centroids of these grid cells were extracted from the Shah and Houston (2007) basal elevation raster (where that raster has a non-zero value) using the Extract Values to Points tool in ArcGIS 10.1. These points were then interpolated to generate a new basal elevation raster. This surface also resulted in inversions when compared to the aquifer top developed based on the 10-meter (32.8-foot) digital elevation model and had a lower resolution than the surface developed by Shah and others (2007a).

These attempts to develop a raster for the base of the Brazos River Alluvium Aquifer with a resolution higher than that of the Shah and others (2007a) raster were unsuccessful. Based on the description of how Shah and others (2007a) developed the base of aquifer surface, the evaluation of well depths as control points, the search for additional data, and the attempts to refine the existing Shah and others (2007a) surface, no compelling reason was found to re-interpolate the existing Shah and others (2007a) surface for the base of the Brazos River Alluvium Aquifer.

4.1.2.4 Base Elevation and Thickness for the Brazos Valley Alluvium Aquifer Conceptual Model

Although refinement to the base of the aquifer developed by Shah and others (2007a) was determined to be unnecessary, their existing surface and aquifer thickness could not be used directly for the Brazos River Alluvium conceptual model for two reasons. First, the grid size and orientation of the preliminary grid for the Brazos River Alluvium Aquifer groundwater availability model is not the same as that used by Shah and others (2007a), resulting in data gaps at the edges of the aquifer boundary. Second, Shah and others (2007a) report that aquifer thicknesses greater than 100 feet at some locations around the aquifer boundary are likely anomalous, caused by sparse data coverage in their basal surface of the aquifer.

Shah and others (2007a) defined the top elevation of the aquifer using the 30-meter (98.4-foot) digital elevation model (see Section 4.1.2.1) and this study defines the top elevation using the 10-meter (32.8-foot) digital elevation model (see Section 4.1.2.2). Therefore, in order to eliminate inconsistencies and inversions between the top and bottom surfaces for the conceptual model and maintain consistency with the work done by Shah and others (2007a), the thickness raster from Shah and others (2007a) was modified rather than their base of aquifer surface.

The method used to modify the aquifer thickness involved maintaining the inner portion of the Shah and Houston (2007) raster with no changes and re-interpolating the thickness near the boundary by enforcing pinch-out (zero thickness) of the aquifer along its edge. The modified thickness raster was developed using the following steps:

1. Converted the thickness raster from Shah and others (2007a) to points using the Convert Raster to Points tool in ArcGIS 10.1.
2. Removed the points created in step 1 located within half of a grid cell (one-sixteenth of a mile) from the aquifer boundary and points located near the boundary with a thickness greater than 100 feet.
3. Added points with zero thickness along the current aquifer boundary at one-eighth of a mile intervals.
4. Used the points created by steps 1 through 3 to create a new thickness raster using the Topo to Raster interpolation tool in ArcGIS 10.1.

This method preserved the vast majority of the high-resolution thickness raster developed by Shah and others (2007a) and limited changes to near the aquifer boundary. The modified aquifer thickness for the Brazos River Alluvium Aquifer is shown in Figure 4.1.3. Also shown on this figure are the control points used by Shah and others (2007a) to develop their original surface for the base of the aquifer. Several of the control points are located outside of the aquifer boundary because Shah and others (2007a) included a 1.5-mile buffer adjacent to the aquifer in their study. Table 4.1.2 gives the minimum, maximum, and mean thickness of the Brazos River Alluvium Aquifer in each county based on the modified raster, along with the standard deviation. Counties in this table are listed from north to south. Because the modified thickness raster was generated forcing zero thickness on the aquifer boundaries, the minimum thickness is near zero in all counties, the only exception being Waller County. The aquifer is overall thinnest in the northwest in Hill, Bosque, McLennan, and Falls counties and overall thickest in the southeast in Fort Bend County. The maximum thickness of 127 feet is located in Grimes County.

The base of the Brazos River Alluvium Aquifer for the current conceptual model was created by subtracting the modified aquifer thickness from the top surface represented by the 10-meter (32.8-foot) digital elevation model using the Raster Calculator tool in ArcGIS 10.1. This surface is shown in Figure 4.1.4 along with the control points used by Shah and others (2007a) in the development of their original base of aquifer surface. The elevation for the base of the aquifer ranges from a high of 571 feet in Hill and Bosque counties to a low of -39 feet in Fort Bend County.

Table 4.1.1 Model layers.

System	Series	Geologic Unit	Aquifer	Model Layer
Quaternary	Holocene	Alluvium, higher clay content	Brazos River Alluvium	1
		Alluvium, higher sand/gravel content		2
	Pleistocene	Fluvial terrace deposits	Gulf Coast	3
		Beaumont Formation		
		Lissie Formation		
Tertiary	Pliocene	Willis Sand		
	Miocene	Goliad Sand		
		Fleming Formation		
		Oakville Sandstone		
	Oligocene	Catahoula Sandstone		
	Eocene	Jackson Group	Yegua-Jackson	
		Yegua Formation		
		Cook Mountain Formation		
		Sparta Sand	Sparta	
		Weches Formation		
		Queen City Sand	Queen City	
		Reklaw Formation		
		Carrizo Sand	Carrizo-Wilcox	
		Wilcox Group		
	Paleocene	Midway Group		
Cretaceous	Gulfian	Navarro Group		
		Taylor Marl		
		Austin Chalk		
		Eagle Ford Group		
		Grayson Marl		
	Comanchean	Washita Group		
		Fredericksburg Group		

Table 4.1.2 Statistics of the Brazos River Alluvium Aquifer thickness for the conceptual model by county.

County	Minimum Thickness (feet)	Maximum Thickness (feet)	Mean Thickness (feet)	Thickness Standard Deviation (feet)
Hill	0.00	77.58	32.62	17.89
Bosque	0.00	75.16	38.60	18.78
McLennan	0.00	94.84	26.52	13.88
Falls	0.00	90.59	32.77	14.70
Robertson	0.03	95.54	53.75	13.14
Milam	0.00	101.39	45.42	20.60
Brazos	0.77	100.43	56.92	13.93
Burleson	0.00	101.24	53.98	13.49
Grimes	0.00	126.70	51.45	16.41
Washington	0.00	101.16	52.28	18.43
Waller	4.27	101.98	56.91	13.11
Austin	0.41	87.57	48.94	14.21
Fort Bend	0.16	100.28	67.00	11.40

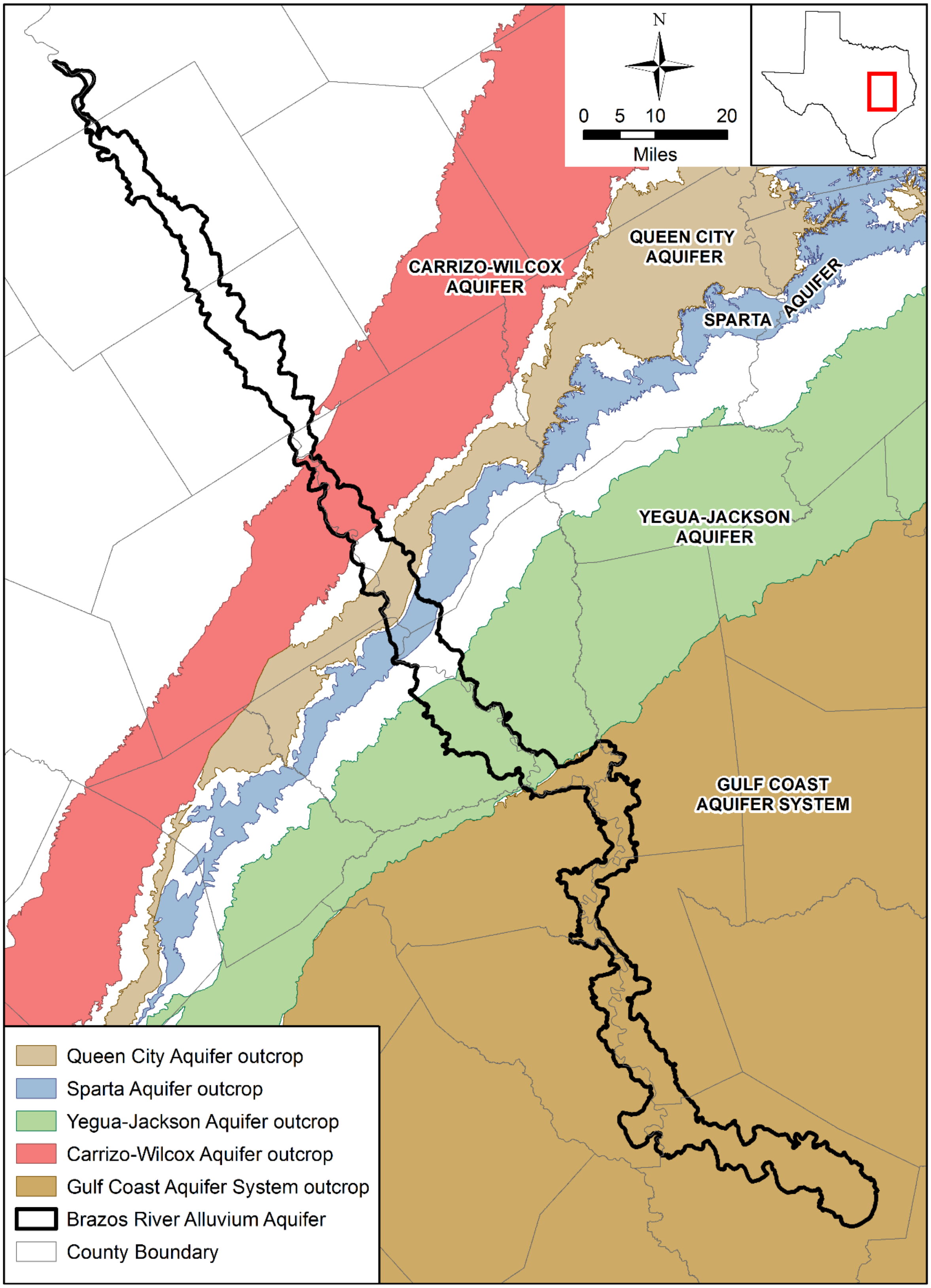


Figure 4.1.1 Outcrop area of aquifers underlying the Brazos River Alluvium Aquifer (TWDB, 2006a,b).

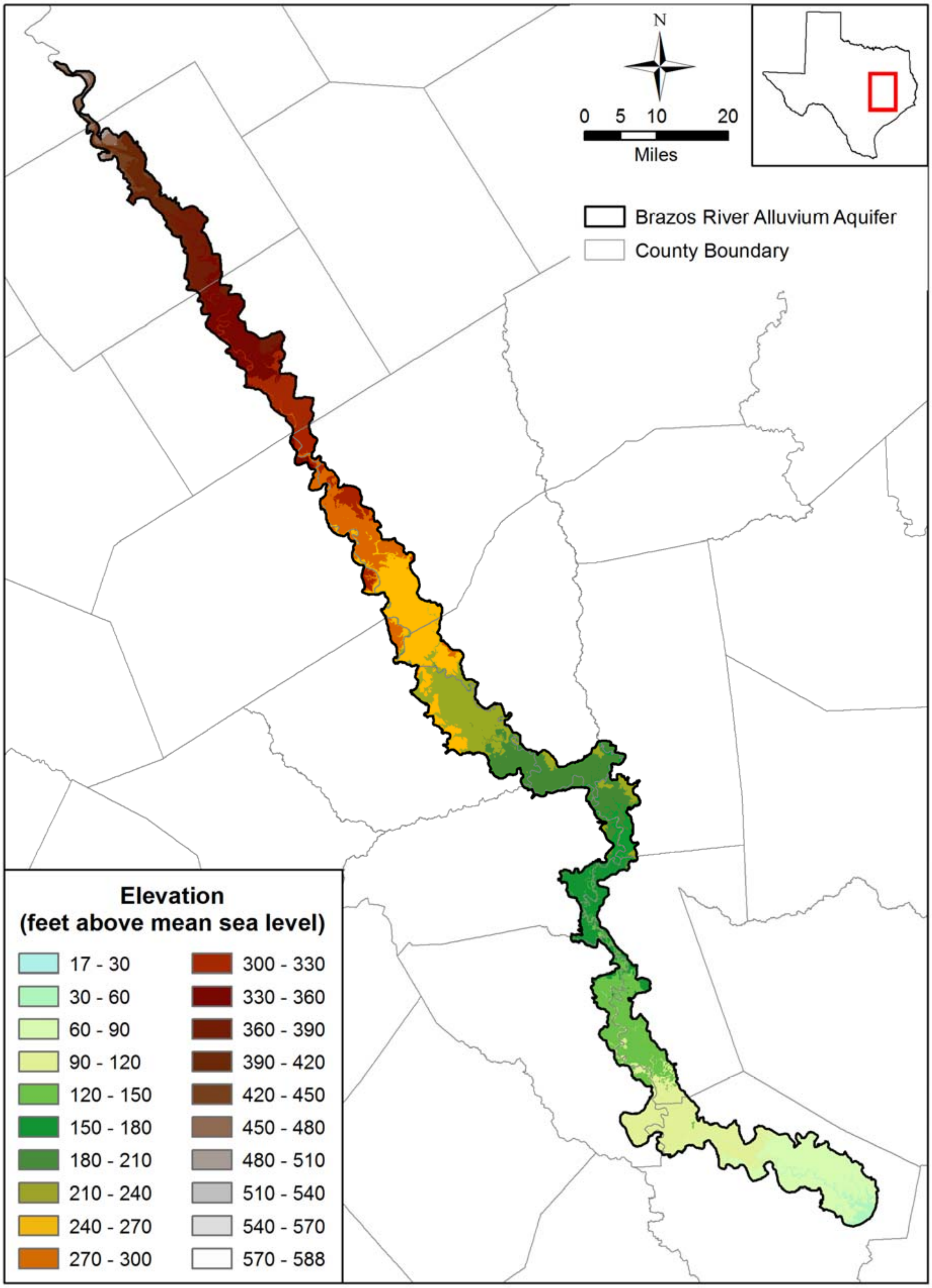


Figure 4.1.2 Elevation of the top of the Brazos River Alluvium Aquifer for the conceptual model.

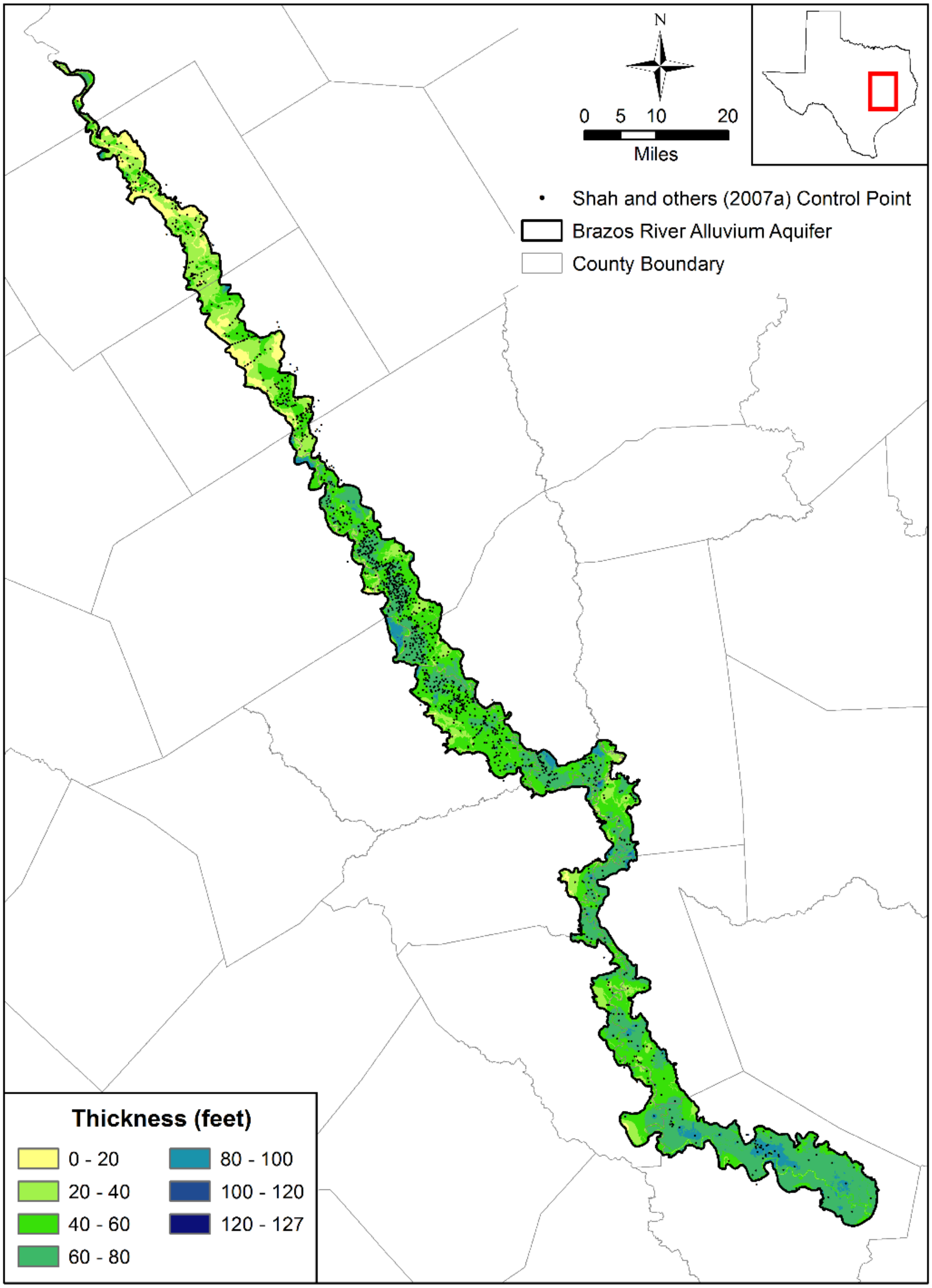


Figure 4.1.3 Thickness of the Brazos River Alluvium Aquifer for the conceptual model.

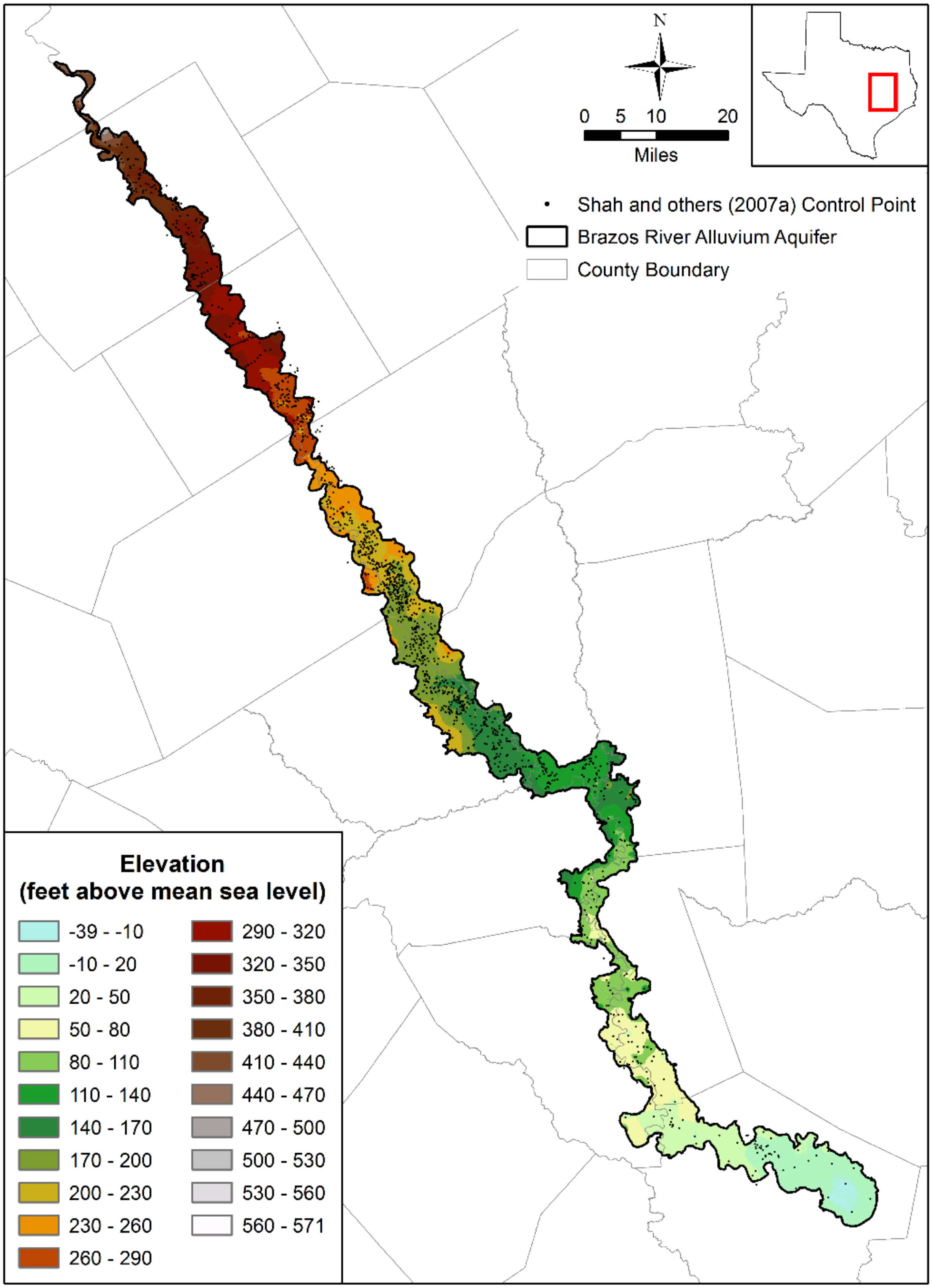


Figure 4.1.4 **Elevation of the base of the Brazos River Alluvium Aquifer for the conceptual model.**

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4.2 Water Levels and Groundwater Flow

This section discusses water levels and groundwater flow in the Brazos River Alluvium Aquifer. The following subsections provide the sources used to collect water-level data, discuss and present an estimate of the pre-development water level in the Brazos River Alluvium Aquifer, discuss available transient water-level data and present an analysis of select transient data, present estimated historical water-level surfaces for the Brazos River Alluvium Aquifer, discuss water-level calibration targets, and evaluate the difference in water-level elevation within the Brazos River Alluvium Aquifer and between the Brazos River Alluvium Aquifer and underlying aquifers

4.2.1 Data Sources

Water-level data were obtained from the TWDB groundwater database (TWDB, 2014f), the TWDB submitted drillers reports database (TWDB 2014g), the Brazos Valley Groundwater Conservation District (2014a), and the Post Oak Savannah Groundwater Conservation District (2014a). The TWDB groundwater database (TWDB, 2014f) was queried to obtain the available water-level data identified as representing the Brazos River Alluvium Aquifer based on the aquifer code 111ABZR. A review of the number of Brazos River Alluvium Aquifer wells with water-level data from the TWDB groundwater database against the number of Brazos River Alluvium Aquifer wells given in Cronin and Wilson (1967) showed a discrepancy. The number of wells in Cronin and Wilson (1967) is greater than the number of wells in the TWDB groundwater database. In an effort to identify additional Brazos River Alluvium Aquifer wells, the total well depth given in the TWDB groundwater database or the base of the lowermost screen given in Cronin and Wilson (1967) for wells located within the Brazos River Alluvium Aquifer boundary were compared to the base of the Brazos River Alluvium Aquifer as given by Shah and others (2007a). This comparison identified a total of 67 wells with either total depth or base of lowermost screen located above the base of the Brazos River Alluvium Aquifer, indicating that these wells are completed in the Brazos River Alluvium Aquifer. A list of those wells and the number of water-level measurements for each is given in Table 4.2.1. Only water-level data identified as publishable and not affected by pumping in the TWDB groundwater database were used. In addition, only water-level data with a measurement date after the drill date were used.

The TWDB submitted drillers report database (TWDB, 2014g) typically includes a single water-level measurement for the wells in the database. That database was queried for wells located in the counties in which the Brazos River Alluvium Aquifer is located. The subset of those located within the Brazos River Alluvium Aquifer boundary was determined. For that subset, either the total well depth or the base of the gravel pack, if available, was compared to the base of the Brazos River Alluvium Aquifer as given by Shah and others (2007a) to identify wells completed in the Brazos River Alluvium Aquifer. For those wells, the date of the water-level measurement was compared to the drill date. Only measurements taken after the drill date were used.

The Brazos River Alluvium Aquifer is located within six groundwater conservation districts and one subsidence district (see Figure 2.0.8). Water-level data for the Brazos River Alluvium Aquifer was requested from each of those districts. Only the Brazos Valley and Post Oak Savannah Groundwater Conservation Districts collect water-level data for Brazos River Alluvium Aquifer wells. Water-level data with a remark suggesting the measurement was effected by pumping were eliminated. Care was taken to eliminate duplicate measurements in the data from the groundwater conservation districts and the TWDB groundwater database. If both sources had a water-level measurement in the same well, on the same date but the measurements were different, the measurement from the TWDB groundwater database was used.

The number of Brazos River Alluvium Aquifer wells with water-level data and the number of water-level measurements for those wells by source and by county are summarized in Tables 4.2.2 and 4.2.3, respectively. The spatial distribution of Brazos River Alluvium Aquifer wells with water-level data is shown in Figure 4.2.1. The majority of wells and water-level measurements are found in Burleson, Robertson, and Brazos counties. The number of wells and water-level measurements in the southern five counties (Grimes, Washington, Waller, Austin, and Fort Bend counties) is significantly less than in Burleson, Robertson, and Brazos counties. The counties with the fewest wells and water-level measurements are Bosque, Hill, and Milam counties, which also have a small Brazos River Alluvium Aquifer footprint.

The temporal distribution of water-level measurements in the Brazos River Alluvium Aquifer is shown in Figure 4.2.2 and tabulated in Table 4.2.4. Note on Figure 4.2.2 that there is a break in the y-axis between 700 and 1,000. The majority of the water levels were measured in 1963 and 1964. This is the time period of the Cronin and Wilson (1967) study. Additional early years with large numbers of measurements are 1960 and 1969. The last four years (2011 through 2014) also show a significant number of measurements. A total of 12 water-level measurements are available prior to 1957 and the number of measurements per year from 1975 to 2012 is less than 100, with the number less than 50 for many of those years.

4.2.2 Pre-development Water-Level Surface

Pre-development conditions are defined as those existing in the aquifer before the natural flow of groundwater was disturbed by artificial discharge via pumping. Typically, pre-development conditions represent steady-state conditions in the aquifer, where aquifer recharge is balanced by natural aquifer discharge.

In general, groundwater in the Brazos River Alluvium Aquifer is unconfined. However, in some areas where permeable sands are overlain by less permeable silts and clays, confined conditions occur. Groundwater withdrawn from the Brazos River Alluvium Aquifer is primarily used for irrigation purposes (George and others, 2011). Citing Hughes and Magee (1962), Cronin and Wilson (1967) state some pumping of the Brazos River Alluvium Aquifer for irrigation purposes began in the late 1940s but really expanded from 1950 to 1957. Therefore, the pre-development period for the Brazos River Alluvium Aquifer was assumed to be prior to 1950.

Water levels measured prior to 1950 and representative of pre-development conditions in the Brazos River Alluvium Aquifer are available at only 11 wells, which is insufficient to construct a pre-development surface for the aquifer. Therefore, other data, in addition to the pre-1950 water-level measurements, were used to develop an estimated pre-development surface for the aquifer. Because data other than strictly pre-development water-level measurements were used, the pre-development surface is an estimated surface and is referred to as the estimated pre-development water-level surface. The rationale behind the data used to create the surface is sound and, therefore, the estimated surface is considered to be a good representation of pre-development conditions.

The data types used to create the estimated pre-development surface for the Brazos River Alluvium Aquifer are:

1. The 10-meter (32.8-foot) digital elevation model of the Brazos River.
2. Water levels measured prior to 1950.

3. The average water level at select wells with long-term transient data from around 1960 to the present (about 2013) that show little to no long-term change in water level.

4. An estimated pre-development water-level elevation at well locations with an elevation of land surface datum calculated using a fit to the type 2 and 3 data.

5. An estimated pre-development water-level elevation at defined intervals along the boundary of the Brazos River Alluvium Aquifer calculated from the digital elevation model value using a fit to the type 2 and 3 data.

Each of these types of data are briefly discussed below.

Type 1 - Because the Brazos River Alluvium Aquifer is connected to the Brazos River, the elevation of the Brazos River Alluvium Aquifer at the location of the river was assumed to be equivalent to the digital elevation model elevation of the river. The value from the 10-meter (32.8-foot) digital elevation model at 500 equally spaced locations along the Brazos River were used as control points in development of the estimated pre-development water-level surface for the Brazos River Alluvium Aquifer.

Type 2 – Individual water levels measured prior to 1950 were used as control points for developing the estimated pre-development water-level surface for the Brazos River Alluvium Aquifer. If multiple measurements prior to 1950 are available for a well, the average of those measurements was used. This resulted in 11 values.

Type 3 –Unlike in a confined aquifer with little recharge and pumped water supplied predominately from storage, the overall long-term change in water levels in the Brazos River Alluvium Aquifer, which is an unconfined aquifer in proximity to a major river, has been minimal from the early 1960s to about 2013 although pumping of the aquifer has increased over than time period (see Section 4.6). The only exception to this is for water levels in southern Brazos County, which do show an overall decline. This can be seen in the long-term water-level trends at select wells that show periods of water-level decline and periods of water-level rise, but do not show an overall decline in water levels in the aquifer since the early 1960s (see Section 4.2.3). Therefore, the average water level calculated from long-term water-level measurements available in select wells in the aquifer were assumed to reflect estimated pre-development water levels. Long-term data for wells in southern Brazos County were considered to be effected by pumping and were not used. The average water level was used rather than the maximum observed water level because, in pre-development, the aquifer would have experienced fluctuations in water levels about a mean as a result of changing climatic conditions rather than remaining at a constant high level. Obtaining average water level over the time period from about the early 1960s to 2013 consisted of first calculating the yearly average and then calculating the average of all the years. This resulted in 21 long-term average values that were assumed to be representative of pre-development conditions.

Type 4 – Type 4 data were necessary because using the 500 digital elevation model values along the Brazos River, the 11 pre-1950 values, and the 21 average values did not provide enough spatial coverage to interpolate a meaningful estimate of the estimated pre-development water-level surface. A plot of water-level elevation versus the elevation of the land surface datum as provided in the TWDB groundwater database for pre-development water levels (pre-1950 measurements) and assumed pre-development water levels (long-term average values), as well as a linear fit to these data, is shown in Figure 4.2.3. The linear fit to the data is good with a coefficient of determination (R^2) of 0.98 and is defined by the equation:

$$Y = 1.0X - 19.3 \tag{4.2.1}$$

where:

Y = the water-level elevation (feet)

X = the elevation of the land surface datum (feet).

A review of Figure 4.2.3 shows that the average water levels from the select long-term hydrographs are very similar to the pre-1950 water-level measurements. The similarity between the data is also indicated by the high coefficient of determination for the linear fit. This indicates that the average water levels from the selected long-term hydrographs are an appropriate estimate of pre-development conditions in the aquifer.

Equation 4.2.1 was used to calculate an estimated pre-development water-level elevation at the location of 527 wells with an elevation of land surface datum from the TWDB groundwater database. Only wells for which a land surface datum at the location of the wells was available were used because of the variability in elevation within the 10-meter (32.8-foot) digital elevation model and the use of the elevation of land surface datum to obtain the fit.

Type 5 – Even with the addition of the 527 Type 4 control points, the kriged pre-development surface was problematic, especially along the boundary of the Brazos River Alluvium Aquifer. To obtain control along the aquifer boundary, Equation 4.2.1 was used with the digital elevation model value at 2,090 locations along the Brazos River Alluvium Aquifer boundary.

The locations of the five types of data used to create the estimated pre-development water-level elevation surface for the Brazos River Alluvium Aquifer are shown in Figure 4.2.4. The Type 2 and 3 control points will be used as calibration targets for the steady-state model (Table 4.2.5). The Type 4 control points will be used to guide calibration of the steady-state model. Because these are not actual water-level measurements and there are a large number of them, the Type 4 control points are not tabulated in a table.

Kriging of the control points assumed to be representative of pre-development conditions was used to create the estimated pre-development water-level elevation surface for the Brazos River Alluvium Aquifer. The long, narrow geometry of the Brazos River Alluvium Aquifer made it challenging to krig a meaningful surface. To help accomplish this, the kriging was conducted using an angle of 40 degrees west of due north, a longitudinal to lateral distance ratio of 0.5, and an anisotropy of 0.5. An angle of 40 degrees was used because the axis of the aquifer is oriented at approximately this angle. A longitudinal to lateral distance ratio less than one was used because the aquifer is long a narrow. An anisotropy ratio less than one was used because the change in water level along the axis of the aquifer is greater than the change in water level perpendicular to the axis. A value of 0.5 was selected for the longitudinal to lateral distance ratio and anisotropy ratio after evaluating the kriged surface created using several different values. Using a value of 0.5 for these parameters resulted in a surface that was most consistent with the understanding of groundwater flow in the aquifer.

The estimated pre-development water-level elevation surface for the Brazos River Alluvium Aquifer is shown in Figure 4.2.5. The estimated pre-development water-level elevations range from a high of about 450 feet above mean sea level at the northern end of the aquifer in Hill County to a low of between 25 and 50 feet above mean sea level at the southern end of the aquifer in Fort Bend County. The maximum elevation of 550 feet above mean sea level is estimated at a high along the Brazos River Alluvium Aquifer boundary in Bosque County. In general, the contour lines show groundwater flow towards the Brazos River.

4.2.3 Transient Water-Level Data

An evaluation of the transient behavior of water levels in the Brazos River Alluvium Aquifer was conducted using transient water-level data in wells. Transient data were considered to consist of five or more water-level measurements in a given well over a period of five or more years. The locations of Brazos River Alluvium Aquifer wells with transient water-level data are shown in Figure 4.2.6. Hydrographs for these wells, showing the transient water-level elevations, land surface elevation, and the elevation of the base of the well, are provided in Appendix A. The following subsections discuss the evaluations of water-level trends in individual wells, water-level trends by county, and seasonal water-level trends.

4.2.3.1 Water-Level Trends in Individual Wells

All hydrographs could not be presented and discussed in the main body of the report. The hydrographs discussed here were selected based on several criteria. First, a review of all hydrographs was conducted in order to select those with a long-term record. Second, hydrographs were selected based on spatial location in an effort to show transient conditions across as much of the aquifer as possible. Third, an effort was made to select hydrographs with sufficient data to define a water-level trend and with data that appear to be free of measurements potentially impacted by drilling and/or pumping activities.

In addition to the water-level data (blue line and symbol), each hydrograph shown in Figures 4.2.7 through 4.2.11 includes the elevation of the land surface (green line) and the elevation of the base of the well (brown line). The land surface elevation is based on the land surface datum reported in the TWDB groundwater database. Note that, on some hydrographs, the line representing the ground surface lies on the upper y-axis. Including the ground surface and base of well elevations allows evaluation of the depth to groundwater and the height of groundwater in the well. For all hydrographs, the time scale of the x-axis is 1950 to 2020. The scale of the water-level elevation on the y-axis varies from hydrograph to hydrograph depending on the range of the observed data; however, the division of the y-axis is consistent at 10 feet.

Select hydrographs for wells located in McLennan County are shown in Figure 4.2.7. In general, these data show fluctuations in water levels of less than 10 feet over the period of record. At two of the wells (wells 4023801 and 4032802), an overall slightly declining trend of 4 and 5 feet, respectively, is observed. At the other two wells (wells 4023901 and 4040501), an overall slightly rising trend of 1 and 6 feet, respectively, is observed. These data show no long-term decline in water levels indicating that pumping has not had a long-term negative effect on water levels in the Brazos River Alluvium Aquifer in McLennan County.

Select hydrographs for wells located in Falls County are shown in Figure 4.2.8. For all three wells, the transient record shows an overall increase in water levels from the late 1950s/early 1960s to the early 2010s, with the largest increase observed in well 3950813. All three hydrographs also show the lowest water level in the wells during the 1960s. The hydrograph for well 3950408 shows fairly constant water levels in the well since about 1970. Although the hydrograph for well 3949301 shows an overall rising trend over the period of record, water levels since the late 1990s have been declining. These data indicate that pumping has not had a long-term negative effect on water levels in the Brazos River Alluvium Aquifer in Falls County.

Select hydrographs for wells located in Robertson County are shown in Figure 4.2.9. All hydrographs show cycles of rising and declining water levels over the period of record. An overall declining trend of about 9 feet is observed in well 5903101. Wells 5912807 and 5903801 show a sustained period of low water levels in the mid-1960s to mid-1970s. For the wells with recent data, historically low, or near historically low, water levels have been observed since about 2011. For the four wells with a period of record from the mid-1950s/mid-1960s to the early 2010s, the overall change in water level from the first to last measurement ranges from an increase of 5 feet to a decrease of 3 feet. These data indicate that pumping has not had a long-term negative effect on water levels in the Brazos River Alluvium Aquifer in Robertson County.

Select hydrographs for wells located in Brazos and Burleson counties are shown in Figure 4.2.10. For wells in both counties, the hydrographs show cycles of rising and declining water levels over the period of record. The time period for these cycles is about 2 to 5 years in most wells, but is much longer (about 5 to 25 years) in wells 5920603 and 5938904 in Brazos County. Historically low water levels are observed in the mid-1960s to mid-1970s in well 5920603 in Brazos County and well 5938701 in Burleson County. Historical lows in the 2010s are observed for wells 5920907 and 5938904 in Brazos County. For all of these wells, the period of record is over 50 years. Over this time period, the three wells in Burleson County show water-level changes of +0.2 to -4.2 feet and the three wells in Brazos County show changes of +1.8 to -18.2 feet. The decline of 18.2 feet is observed in well 5938904, which shows historically low water levels since 2011. Several other wells in Brazos County also show an overall decline in water levels of about 20 feet (see Appendix A). The wells with the largest declines are located in the southern portion of Brazos County. The transient data for wells in Burleson and Brazos counties indicate that pumping has not had a long-term negative effect on water levels in the Brazos River Alluvium Aquifer in Burleson and northern Brazos counties, but has resulted in overall water-level declines on the order of about 20 feet in southern Brazos County.

Select hydrographs for wells located in Grimes, Washington, and Austin counties are shown in Figure 4.2.11. The period of record for all transient data in these counties is short and recent data are available for only two wells, both of which are located in Grimes County (see Appendix A). Overall declines in water levels of 3.4 to 6.8 feet are observed in wells 5948707, 5955701, and 6607301 in Grimes, Washington, and Austin counties, respectively. Very little change in water levels is observed in well 5948204 in Grimes County over the period of record. Due to a lack of long-term records that include recent data, the long-term effect of pumping in water levels in these counties cannot be evaluated.

4.2.3.2 Correlation of Water-Levels in Individual Wells with Precipitation and River Stage

Individual comparisons were conducted to investigate whether a relationship could be developed between water-level elevations and river stage, precipitation, or pumping. The purpose of the comparisons was to see which, if any, of these is the driving force for the variations observed in historical water levels. The individual comparisons did not show any consistent relationship, suggesting that none of these components individually is the sole driving force for the observed water-level fluctuations. This suggests that the observed fluctuations in water level are a complex combination of all three components. Resent declines in water level have been observed in many wells completed in the aquifer. The declines are a function of the recent drought caused by decreased precipitation, which has resulted in decreased river stage and increased pumping. This indicates that when all three components are driving in the same direction (i.e., decreased precipitation and river stage and increased pumping), the aquifer shows a clear correlation with each. An additional component influencing water levels in the Brazos River Alluvium Aquifer is cross-formation flow from underlying aquifers. No direct measure of this component is available, therefore, a comparison could not be conducted. In conclusion, the historical variations in water level in the Brazos River Alluvium Aquifer are a complex combination of precipitation, river stage, pumping, and cross-formational flow.

4.2.3.3 Water-Level Trends by County

The water-level data in the Brazos River Alluvium Aquifer were evaluated on a county-wide basis and then compared to precipitation and river stage for the Brazos River. Each of these are discussed in the following subsections.

4.2.3.3.1 County-Wide Water-Level Trends

An investigation was conducted to estimate county-wide water-level trends using the transient water-level data. Because of the variability in water-level elevations across a county, normalized water levels were used. The normalized water level was calculated using the following steps for each well in a county.

1. Calculated the overall average water-level elevation in the well from the transient data.
2. Calculated the normalized water level as the measured water-level elevation divided by the overall average water-level elevation calculated in step 1.

The normalized water levels for all wells in a county were plotted and fit with a polynomial equation. In all cases, the data were fit with a tenth order polynomial. The normalized water-level data and polynomial fits are shown in Figure 4.2.12. Transient data for Washington and Austin counties were insufficient to obtain a meaningful fit.

In all counties, the transient data indicate low water levels at some point in the 1960s, extending into the 1970s in Robertson and Brazos counties. Two subsequent cycles of rising and declining water levels are observed in Robertson, Burleson, and Grimes counties. In these cycles, relatively high water levels are observed around the late 1970s/early 1980s and around the early/mid 2000s and relatively low water levels are observed around the early/mid-1990s and early 2010s. After the initial low water levels in the mid-1960s and subsequent recovery, the water levels in McLennan and Falls counties remained fairly stable for three decades in McLennan County and about one and a half decades in Falls County. Near the end of the record, the water-level trend slightly increased temporarily and then declined in both these counties. The trend in the water-level data for Brazos County is anomalous compared to the other counties with respect to the relatively high water levels in the 2000s.

4.2.3.3.2 Comparison of County-Wide Water-Level Trends to Precipitation

The county-wide, long-term water-level trends were compared to precipitation in terms of the Standard Precipitation Index, which is a measure of drought. The Standardized Precipitation Index is a probability index that considers only precipitation and is calculated based on a specified time period. A program for calculating the Standardized Precipitation Index was downloaded from the National Drought Mitigation Center at the University of Nebraska-Lincoln (2015). For the comparisons conducted here, time periods of 9, 12, and 18 months were used.

Precipitation data over a time period sufficient for calculating the Standardized Precipitation Index are available at only two precipitation gages in the vicinity of the Brazos River Alluvium Aquifer. These are gage 415611 in Falls County and gage 419491 in Washington County (see Figure 2.1.9). The Standardized Precipitation Indices calculated based on precipitation data for the gage in Falls County were compared to the county-wide, long-term water-level trend in Falls County (Figure 4.2.13a). The Standardized Precipitation Indices calculated based on precipitation data for the gage in Washington County were compared to the county-wide, long-term water-level trend in Grimes County (Figure 4.2.13b) because a county-wide, long-term water-level trend could not be determined for Washington County. These comparisons show times when precipitation and water levels appear to be correlated, such as low precipitation and low water levels in the early to mid-1960s and 2010s in both counties. The comparisons also show times when precipitation and water levels are not correlated, such as the high precipitation and low water levels in the late 1960s in both counties, high precipitation and no corresponding increase in water levels around 1980 and the late 2000s in Falls County, and relatively constant overall precipitation from about 1975 to 1988 but fluctuating water levels in Grimes County. Overall, little correlation between precipitation and county-wide, long-term water-level trends is observed.

4.2.3.3.3 Comparison of County-Wide Water-Level Trends to Brazos River Stage

Because the Brazos River Alluvium Aquifer is in communication with the Brazos River, a comparison between the county-wide, long-term water-level trends and the river stage was conducted. Stream stage data on the Brazos River are available for McLennan, Falls, Brazos, and Burleson counties at gages 8096500, 8098290, 8109000, and 8108700, respectively (see Figure 4.4.1). To eliminate the noise, the stream stage data were smoothed using a running average with a 9-year window. Figure 4.2.14 shows the comparison for McLennan and Falls counties and Figure 4.2.15 shows the comparison for Brazos and Burleson counties.

For McLennan County, the lower water levels in the mid-1960s appear to coincide with a long-term decline in river stage. However, lower relative water levels do not appear to be associated with other shorter-term declines in river stage. In addition, the water-level rise in the late 1960s is not associated with a significant increase, or any increase, in river stage. The only correlation in river stage and water levels is found in the early 2010s. For Falls County, there seems to be no correlation between the river stage and the long-term water-level trend (see Figure 4.2.14b). During water-level recovery in the early 1970s, the river stage was relatively low. Relatively high river stage is observed in the mid-1980s to early 1972, a time when relative water levels are low. In addition, in the 2000s when the relative water levels are high, there does not appear to be any correlated increase in river stage. A correlation between river stage and water level also appears to be absent for Brazos County and the river-stage data are insufficient to evaluate the correlation for Burleson County (see Figure 4.2.15).

4.2.3.4 Seasonal Water-Level Trends

Seasonal water-level data for the time period from early 1970 to mid-1974 are shown in Figure 4.2.16. The time period on the x-axis for all the plots in this figure is the same (January 1970 to July 1974), so they can be directly compared. The water-level elevation on the y-axis varies depending on the range of the data. For the three wells located in Robertson, Brazos, and Burleson counties, significant water-level declines are observed in the late spring to early fall time frame for some years. This is likely the result of seasonal irrigation pumping. For the well in Falls County, the lowest relative water levels occur in the winter, indicating no correlation with irrigation pumping.

Seasonal water-level data for the time period from early 2011 to early 2014 are shown in Figure 4.2.17. The time period on the x-axis for all the plots is the same (January 2011 to January 2014), so they can be directly compared. The water-level elevation range on the y-axis varies depending on the range of the data. Most of the data on this figure show low water levels in the summer indicating the impact of seasonal irrigation and high water levels in the winter indicating aquifer recovery between irrigation seasons.

4.2.4 Historical Water-Level Surfaces

Historical water-level surfaces for the Brazos River Alluvium Aquifer were estimated for the years 1965, 1980, 2000, and 2012. Water-level data are not available at regular time intervals in every well. Therefore, the coverage of water-level data for a particular month or even a year is sparse. Since the amount of available water-level data for a particular year of interest is typically not sufficient to interpolate a surface, the historical water-level surfaces were developed based on data from a few years before and after the year of interest. The range of years used was 1963 through 1967 for the 1965 water-level surface, 1975 through 1985 for the 1980 water-level surface, 1995 through 2005 for the 2000 water-level surface, and 2010 through 2014 for the 2012 water-level surface. The number of years in the range was variable depending upon the availability of data around the year of interest. If a well had multiple water-level measurements during the range of years, the average of those measurements was used.

The long, narrow geometry of the Brazos River Alluvium Aquifer made it challenging to krig meaningful surfaces. To help accomplish this, the kriging was conducted in the same way as was done for the pre-development surface using an anisotropy of 0.5, an angle of 40 degrees west of due north, and a longitudinal to lateral distance ratio of 0.5. In the kriging, the extent of the data were used to define the extent of the kriged surface. For some years, data are missing in the northern and southern portions of the Brazos River Alluvium Aquifer and, therefore, contours are also absent in those areas.

Water-level elevations estimated for the Brazos River Alluvium Aquifer in 1965 range from a high of 450 feet above mean sea level in Hill County to a low of 31 feet above means sea level in Fort Bend County (Figure 4.2.18). Data are available for this time period across the entire extent of the aquifer. Water-level elevations estimated for the Brazos River Alluvium Aquifer in 1980 range from a high of 412 feet above mean sea level in McLennan County to a low of 109 feet in Austin County (Figure 4.2.19). For this time period, data are not available for a portion of the aquifer in the north and a significant portion of the aquifer in the south. Water-level elevations estimated for the Brazos River Alluvium Aquifer in 2000 range from a high of 408 feet above mean sea level in McLennan County to a low of 105 feet above mean sea level in Austin and Waller counties (Figure 4.2.20). Again, data are not available for this time period in a portion of the aquifer in the north and a significant portion of the aquifer in the south. Water-level elevations estimated for the Brazos River Alluvium Aquifer in 2012 range from a high of

414 feet above mean sea level in McLennan County to a low of 184 feet above mean sea level in Brazos County (Figure 4.2.21). For this time period, there are no data in approximately the southern half of the aquifer from which a surface can be estimated and data are missing for a portion of the aquifer in the north.

In general, there is little variability between the different historical water-level elevation surfaces and little variation between these surfaces and the pre-development water-level elevation surface. This is due to the character of water levels in the Brazos River Alluvium Aquifer, which generally show temporary changes and no sustained long-term declines or rises.

4.2.5 Transient Water-Level Calibration Targets

Water-level calibration targets for the transient model will include all water-level measurements for the Brazos River Alluvium Aquifer. The model will be calibrated to both the ensemble of individual measurements using statistics and cross plots and to long-term hydrographs. The number of calibration targets for the transient model by county and decade is shown in Table 4.2.6. The greatest number of calibration targets across all counties are available for the decade of the 1960s. The decades of the 1970s and 2010s also have a large number of water-level measurements available for calibration targets. Few measurements are available in the other decades. The greatest number of calibration targets for all decades are available for Robertson, Burleson, and Brazos counties. Several of the counties have a very small number of water-level measurements for all decades combined (e.g., Bosque and Hill counties).

4.2.6 Cross Formational Flow

The potential for flow between the upper and lower portions of the Brazos River Alluvium Aquifer was investigated as well as cross-formational flow between the Brazos River Alluvium Aquifer and underlying aquifers. Each of these is discussed in the following subsections.

4.2.6.1 Vertical Flow within the Brazos River Alluvium Aquifer

An investigation was conducted to evaluate the potential for vertical flow within the Brazos River Alluvium Aquifer. Water-level elevations were compared for closely spaced wells with different total depths. Twenty-one well pairs were identified with differences in well depths ranging from 14 to 47 feet. The scanned images on the TWDB Water Information Integration and Dissemination website (TWDB, 2014h) were reviewed to obtain completion information for the wells. Unfortunately, data indicating that the two wells were completed in different portions of the aquifer were available for wells at only two locations. In the absence of completion information, comparisons of water levels for the wells at the other locations does not provide meaningful information since it is not possible to determine whether the water levels in the wells reflect hydraulic heads in the same or different vertical intervals in the aquifer.

Figure 4.2.22 shows water-level elevations in two wells each in Robertson and Grimes counties. In Robertson County, the water-level elevation in the shallower well (5911309 completed above its total depth of 58 feet) is lower than that in the deeper well (5911347 completed from 61 to 72 feet in depth). These water levels indicate that the gradient within the Brazos River Alluvium Aquifer at this location is vertically upward. In Grimes County, the shallower well (5948803) is completed above its total depth of 66 feet and the deeper well (5948807) is completed from the depths of 35 to 74 feet and 90 to 100 feet. Therefore, the deeper well is open to the aquifer at both the same depth as the shallower well and also at a deeper depth. The plot in Figure 4.2.22 shows that the water-level elevation in the deeper well is lower than that in the shallower well.

A comparison of water-level elevations at different vertical intervals within the Brazos River Alluvium Aquifer was possible at two locations. The results, however, are uncertain because only one measurement is available for at least one well in each well pair. Therefore, due to the limited spatial coverage in the aquifer and the limited number of available water-level measurements, significant conclusions regarding the vertical gradient within the Brazos River Alluvium Aquifer could not be reached.

4.2.6.2 Cross-Formational Flow between the Brazos River Alluvium Aquifer and Underlying Aquifers

Little information is available regarding cross-formational flow between the Brazos River Alluvium Aquifer and underlying aquifers. Cronin and Wilson (1967) observed a depression in the water-level elevations in the Brazos River Alluvium Aquifer in northern Brazos County. That depression is also observed in the historical 1965 water-level elevation surface discussed above. Figure 4.2.23 shows this surface with a 10-foot contour interval for a small area in Brazos and Burleson counties. Cronin and Wilson (1967) attribute the depression to the vertical movement of groundwater from the Brazos River Alluvium Aquifer to the underlying Sparta Aquifer in response to a cone of depression in the Sparta Aquifer caused by pumping.

Chowdhury and others (2010) concluded that upward discharge from underlying aquifers into the Brazos River Alluvium Aquifer is not significant based on isotopic composition data. However, their conclusion is based on data at only three locations, all of which are in the subcrop of the underlying aquifers. Therefore, the results from their analysis cannot be used to describe the interaction between the Brazos River Alluvium Aquifer and immediately underlying aquifers. See Section 4.7.1 for additional discussion on the Chowdhury and others (2010) study.

Additional information on the potential for cross-formational flow between the Brazos River Alluvium Aquifer and underlying aquifers was obtained by comparing observed water-level data in nearby wells completed into different aquifers. The comparisons are depicted through a series of plots. Note on the plots that both the year scale on the x-axis and the water-level elevation scale on the y-axis varies from plot to plot. The comparisons are for wells in the underlying aquifers located near the outcrop area. The plots are placed on a base map that shows the Brazos River Alluvium Aquifer and the outcrop and downdip portions of the underlying aquifers of interest.

Comparisons of water-level elevations in the Brazos River Alluvium Aquifer and the underlying Carrizo-Wilcox Aquifer are shown in Figure 4.2.24. The comparison is somewhat ambiguous. At Site 1, the water-level elevations in the Carrizo-Wilcox well are similar to those in one of the Brazos River Alluvium Aquifer wells but higher than those in the other Brazos River Alluvium Aquifer well. At Site 2, the water-level elevations in the two Brazos River Alluvium Aquifer wells are similar to those in Carrizo-Wilcox Aquifer well 5911311 and higher than those in Carrizo-Wilcox Aquifer well 3911314.

A comparison of a single water-level measurement in the Brazos River Alluvium and Queen City aquifers (Site 5) for vastly different years is shown in Figure 4.2.25. This comparison suggests that water-level elevations in the Brazos River Alluvium Aquifer are slightly higher than those in the Queen City Aquifer indicating a small downward vertical gradient. However, this conclusion is uncertain as it is based on a single measurement in each aquifer separated by over 30 years. The comparison between water-level elevations in the Brazos River Alluvium Aquifer and the underlying Sparta Aquifer at Site 6 shows higher water-level elevations in the Sparta Aquifer than in the Brazos River Alluvium Aquifer by about 40 feet (see Figure 4.2.25). This indicates an upward vertical gradient at this location. Note that Site 6 is located in the area of depression identified by Cronin and Wilson (1967) (see Figure 4.2.23). They hypothesized that the cause for the depression was downward flow in response to lower water levels in the Sparta Aquifer than in the Brazos River Alluvium Aquifer. The comparison plot for Site 6 shows that, in about 1970, the opposite is true, with the water level in the Sparta Aquifer about 40 feet higher than that in the Brazos River Alluvium Aquifer. Therefore, the depression in the Brazos River Alluvium Aquifer water-level elevations observed in the mid-1960s in northern Brazos County is likely unrelated to pumping in the underlying Sparta Aquifer.

In general, the comparison of water-level elevations in the Brazos River Alluvium and Yegua aquifers at three locations show similar values in the two aquifers (Figure 4.2.26). At Site 10, the water level in the Yegua Aquifer is about 7 feet lower than that in the Brazos River Alluvium Aquifer. At Sites 11 and 12, the water-level elevation in the Brazos River Alluvium Aquifer is about 5 to 15 feet higher than that in the Yegua Aquifer. These results are somewhat uncertain because at each location there is only one water-level measurement for the well completed in the Yegua Aquifer. At both sites with water-level data in the Brazos River Alluvium Aquifer and the Jasper Aquifer of the Gulf Coast Aquifer System, the water-level elevation in the Jasper Aquifer is higher than that in the Brazos River Alluvium Aquifer (see Figure 4.2.26). This indicates an upward vertical gradient from the Jasper Aquifer to the Brazos River Alluvium Aquifer.

Comparisons of water-level elevations in the Brazos River Alluvium Aquifer and the Evangeline Aquifer of the Gulf Coast Aquifer System at three locations consistently show lower water levels in the Brazos River Alluvium Aquifer than in the Evangeline Aquifer (Figure 4.2.27). At Sites 15 and 16, the difference is about 15 to 25 feet, but at Site 17, the difference is less than 5 feet. This indicates an upward vertical gradient from the Evangeline Aquifer to the Brazos River Alluvium Aquifer. The comparison of water-level elevations in the Brazos River Alluvium Aquifer and the Chicot Aquifer of the Gulf Coast Aquifer System is shown for one location in Figure 4.2.27. That comparison shows higher water levels in the Brazos River Alluvium Aquifer than in the Chicot Aquifer, indicating a downward vertical gradient between the two aquifers at this location.

Table 4.2.1 Wells identified as completed in the Brazos River Alluvium Aquifer based on total depth or base of lowermost screen.

State Well Number	County	Owner	Aquifer Code(1)	Number of Water-Level Measurements
3958906	Milam	Sneed Farm	100ALVM	4
3958907	Milam	Sneed Farm	100ALVM	4
3958908	Milam	Sneed Farm	100ALVM	3
3958909	Milam	Sneed Farm	100ALVM	2
3958911	Milam	Sneed Farm	100ALVM	2
3958912	Milam	Sneed Farm	100ALVM	1
4014103	Bosque	Ed Bynum	100ALVM	1
4014502	Bosque	B. G. Hill	100ALVM	1
4014505	Bosque	C. Smith	100ALVM	1
4014510	Bosque	L Smith	100ALVM	1
4014609	Bosque	Hiram Smith	100ALVM	1
5920401	Burleson	Oscar Weeber	124WCHS	1
5920404	Burleson	Barney Catron	110TRRC	3
5921103	Robertson	Bailey	124SPRT	1
5921801	Brazos	Frank Nemec	110TRRC	2
5929207	Brazos	Guy W. Foster	110AVFP	1
5929536	Brazos	Clifford Hill & Co.	110AVFP	1
5937107	Burleson	Raymond Sebesta, Sr.	100ALVM	1
5937110	Burleson	John Gunek	124YEGUU	1
5937304	Burleson	J. Varisco	110TRRC	3
5937305	Burleson	J. Varisco	110TRRC	2
5937306	Burleson	J. Varisco	110TRRC	2
5937308	Burleson	J. Varisco	110TRRC	2
5937309	Burleson	J. Varisco	110TRRC	1
5937310	Burleson	Longmire	110TRRC	2
5937311	Burleson		110TRRC	3
5937312	Burleson		110TRRC	2
5937313	Burleson		110TRRC	2
5937502	Burleson	Henry Kovar	124JCKSL	1
5938706	Burleson		124JCKSU	1
5948101	Grimes	C.V. Alexander	100ALVM	1
5948102	Grimes	C.V. Alexander	100ALVM	1
5948103	Grimes	C.V. Alexander	100ALVM	11
5948204	Grimes	Johnny Sache	122JSPR	22
5948401	Grimes	Worth Ware	110AVFP	6

Table 4.2.1, continued

State Well Number	County	Owner	Aquifer Code(1)	Number of Water-Level Measurements
5948704	Washington	J.F. Renn	121EVGL	1
5955507	Washington	R. Schaer	121EVGL	1
5955605	Waller	Duane Sheridan	100ALVM	1
5956105	Washington	T.J. Moore	110AVEV	2
5956106	Washington	T.J. Moore	110AVEV	1
6517403	Fort Bend	Unknown	112CHCT	1
6517601	Fort Bend	Hughes	112CHCT	1
6517704	Fort Bend	Joe Hede	112CHCT	1
6518801	Fort Bend	John Rosenbush	112CHCTU	1
6518901	Fort Bend	Unknown	112CHCT	2
6518903	Fort Bend	J.J. Adams Est.	112CHCTU	1
6526203	Fort Bend	Unknown	112CHCTU	1
6526304	Fort Bend	L.D. Tarrant	112CHCTU	2
6526504	Fort Bend	Unknown	112CHCTU	1
6527203	Fort Bend	Smith Ranches	112CHCTU	3
6527205	Fort Bend	State Prison	112CHCTU	3
6527206	Fort Bend	State Prison	112CHCTU	2
6527207	Fort Bend	State Prison	112CHCTU	2
6527305	Fort Bend	State Prison	112CHCTU	4
6527404	Fort Bend	Unknown	112CHCTL	2
6527604	Fort Bend	State Prison	112CHCTU	2
6528503	Fort Bend	Roy H. Schmidt	112CHCTU	1
6608501	Waller	E.F. Fillip	121EVGL	1
6624505	Austin	Ignac Pustka	121EVGL	1
6624604	Fort Bend	Tallman	112CHCT	2
6624901	Austin	Spring	100ALVM	1

(1) Aquifer code as given in the TWDB groundwater database (TWDB, 2014f)

Table 4.2.2 Number of Brazos River Alluvium Aquifer wells with water-level data and number of water-level measurements by source.

Source	Number of Wells with Water-Level Data	Number of Water-Level Measurements
TWDB Groundwater Database	1,175	6,520
TWDB Submitted Driller's Report Database	9	9
Brazos Valley Groundwater Conservation District	19	704
Post Oak Savannah Groundwater Conservation District	4	11
TOTAL	**1,207**	**7,244**

Table 4.2.3 Number of Brazos River Alluvium Aquifer wells with water-level data and number of water-level measurements by county.

County	Number of Wells with Water-Level Data	Number of Water-Level Measurements
Austin	14	47
Bosque	5	5
Brazos	236	1,319
Burleson	310	1,703
Falls	134	940
Fort Bend	21	35
Grimes	13	77
Hill	2	2
McLennan	100	544
Milam	8	18
Robertson	316	2,458
Waller	31	40
Washington	17	56
TOTAL	**1,207**	**7,244**

Table 4.2.4 Tabulation of water-level measurements by year.

Year	Number of Water-Level Measurements	Year	Number of Water-Level Measurements	Year	Number of Water-Level Measurements
1936	5	1963	1,141	1989	72
1937	0	1964	661	1990	37
1938	0	1965	127	1991	32
1939	0	1966	109	1992	36
1940	2	1967	103	1993	14
1941	2	1968	109	1994	64
1942	2	1969	449	1995	31
1943	0	1970	146	1996	25
1944	0	1971	203	1997	33
1945	0	1972	163	1998	23
1946	0	1973	196	1999	20
1947	0	1974	113	2000	12
1948	0	1975	80	2001	28
1949	0	1976	41	2002	21
1950	0	1977	49	2003	24
1951	0	1978	55	2004	11
1952	0	1979	48	2005	34
1953	0	1980	53	2006	24
1954	0	1981	4	2007	22
1955	0	1982	53	2008	13
1956	1	1983	28	2009	24
1957	130	1984	60	2010	46
1958	108	1985	34	2011	280
1959	58	1986	62	2012	359
1960	576	1987	37	2013	346
1961	271	1988	13	2014	195
1962	126				

Table 4.2.5 Pre-development calibration targets.

State Well Number	County	Aquifer Code	Pre-Development Water-Level Elevation (feet amsl)	Control Point Type (1)	Control Point Description	Source of Water-Level Data
5920603	Brazos	111ABZR	210.70	3	average of long-term water-level data	TWDB gw db
5920907	Brazos	111ABZR	210.21	3	average of long-term water-level data	TWDB gw db
5920401	Burleson	124WCHS	251.70	2	pre-1950 water-level measurement	TWDB gw db
5928601	Burleson	111ABZR	225.88	3	average of long-term water-level data	TWDB gw db
5929410	Burleson	111ABZR	213.02	3	average of long-term water-level data	TWDB gw db
5929433	Burleson	111ABZR	216.98	3	average of long-term water-level data	TWDB gw db
5937110	Burleson	124YEGUU	224.20	2	pre-1950 water-level measurement	TWDB gw db
5937329	Burleson	111ABZR	201.37	3	average of long-term water-level data	TWDB gw db
5938413	Burleson	111ABZR	193.90	2	pre-1950 water-level measurement	TWDB gw db
5938414	Burleson	111ABZR	203.80	2	pre-1950 water-level measurement	TWDB gw db
5938701	Burleson	111ABZR	193.24	3	average of long-term water-level data	TWDB gw db
3949301	Falls	111ABZR	320.81	3	average of long-term water-level data	TWDB gw db
3950408	Falls	111ABZR	298.21	3	average of long-term water-level data	TWDB gw db
3950813	Falls	111ABZR	299.11	3	average of long-term water-level data	TWDB gw db
6517704	Fort Bend	112CHCT	64.00	2	pre-1950 water-level measurement	TWDB gw db
4023801	McLennan	111ABZR	385.62	3	average of long-term water-level data	TWDB gw db
4023901	McLennan	111ABZR	407.97	3	average of long-term water-level data	TWDB gw db
3958207	Robertson	111ABZR	291.80	2	pre-1950 water-level measurement	TWDB gw db
5903106	Robertson	111ABZR	268.52	2	pre-1950 water-level measurement	TWDB gw db
5903402	Robertson	111ABZR	269.20	3	average of long-term water-level data	TWDB gw db
5903801	Robertson	111ABZR	253.22	3	average of long-term water-level data	TWDB gw db
5903908	Robertson	111ABZR	252.36	3	average of long-term water-level data	TWDB gw db

Table 4.2.5, continued

State Well Number	County	Aquifer Code	Pre-Development Water-Level Elevation (feet amsl)	Control Point Type (1)	Control Point Description	Source of Water-Level Data
5911202	Robertson	111ABZR	244.64	3	average of long-term water-level data	TWDB gw db
5911211	Robertson	111ABZR	257.80	2	pre-1950 water-level measurement	TWDB gw db
5911301	Robertson	111ABZR	249.22	3	average of long-term water-level data	TWDB gw db
5911308	Robertson	111ABZR	238.87	3	average of long-term water-level data	TWDB gw db
5912420	Robertson	111ABZR	242.70	3	average of long-term water-level data	TWDB gw db
5912726	Robertson	111ABZR	252.80	2	pre-1950 water-level measurement	TWDB gw db
5912807	Robertson	111ABZR	225.68	3	average of long-term water-level data	TWDB gw db
5920540	Robertson	111ABZR	214.41	3	average of long-term water-level data	TWDB gw db
5948701	Washington	111ABZR	163.30	2	pre-1950 water-level measurement	TWDB gw db
5955507	Washington	121EVGL	157.30	2	pre-1950 water-level measurement	TWDB gw db

(1) see text in Section 4.2.2
amsl = above mean sea level
gw db = groundwater database

Table 4.2.6 Number of water-level targets for the transient model by county and decade.

County	1950s	1960s	1970s	1980s	1990s	2000s	2010s	*Total by County*
Austin		25	6	6	9	1		*47*
Bosque		4	1					*5*
Brazos	54	613	132	49	46	23	402	*1,319*
Burleson	105	1,030	263	119	95	55	32	*1,699*
Falls		574	210	85	33	27	11	*940*
Fort Bend	1	28		2		3		*34*
Grimes	2	8	22	9	10	19	7	*77*
Hill		2						*2*
McLennan		362	100	32	21	19	10	*544*
Milam		16	1	1				*18*
Robertson	127	934	351	113	101	64	764	*2,454*
Waller	1	37				2		*40*
Washington	7	39	8					*54*
Total by Decade	***297***	***3,672***	***1,094***	***416***	***315***	***213***	***1,226***	***7,233***

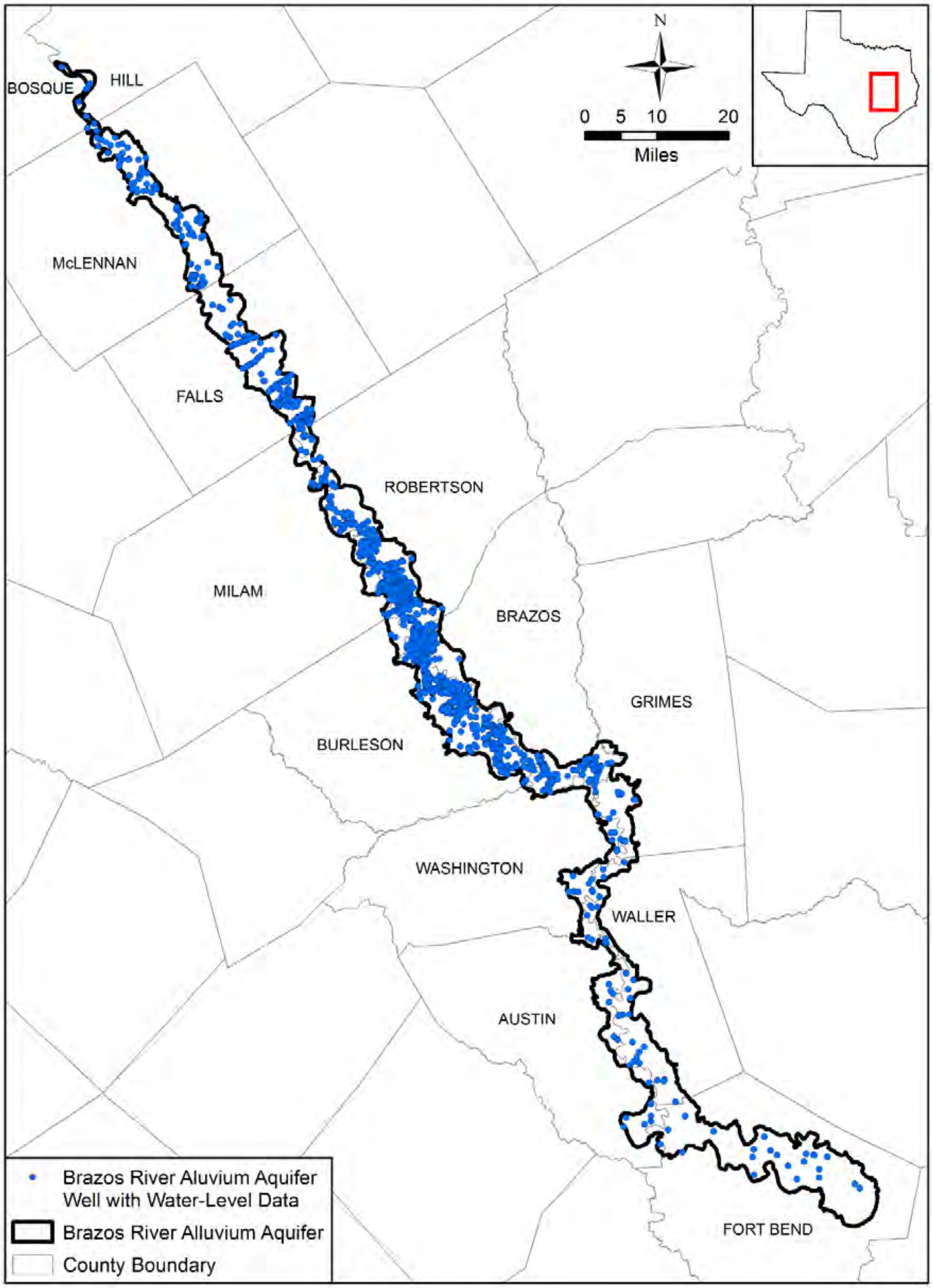


Figure 4.2.1 Spatial distribution of Brazos River Alluvium Aquifer wells with water-level data (Brazos Valley Groundwater Conservation District, 2014a; Post Oak Savannah Groundwater Conservation District, 2014a; TWDB, 2014f,g).

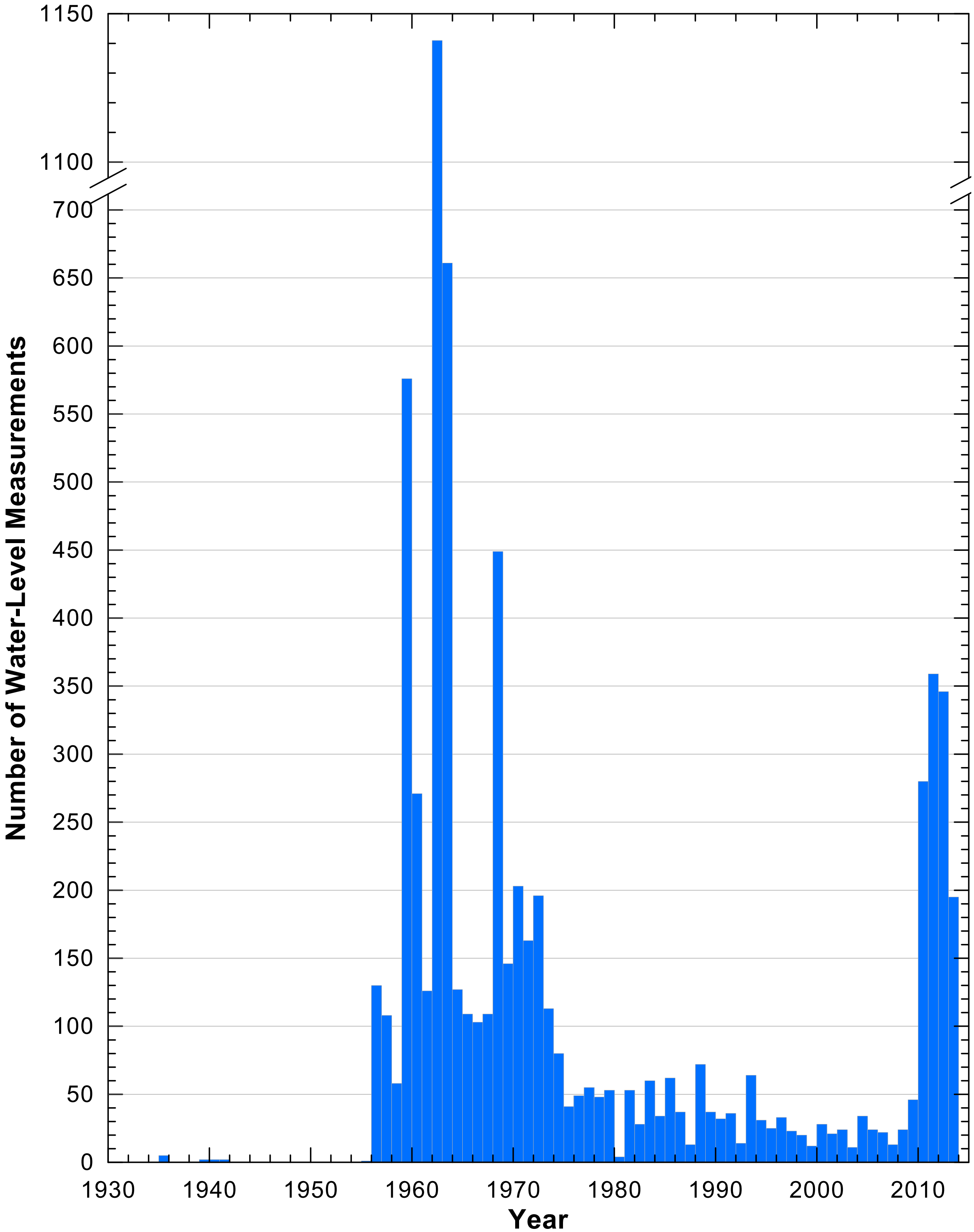


Figure 4.2.2 Temporal distribution of water-level measurements in the Brazos River Alluvium Aquifer (Brazos Valley Groundwater Conservation District, 2014a; Post Oak Savannah Groundwater Conservation District, 2014a; TWDB, 2014f,g).

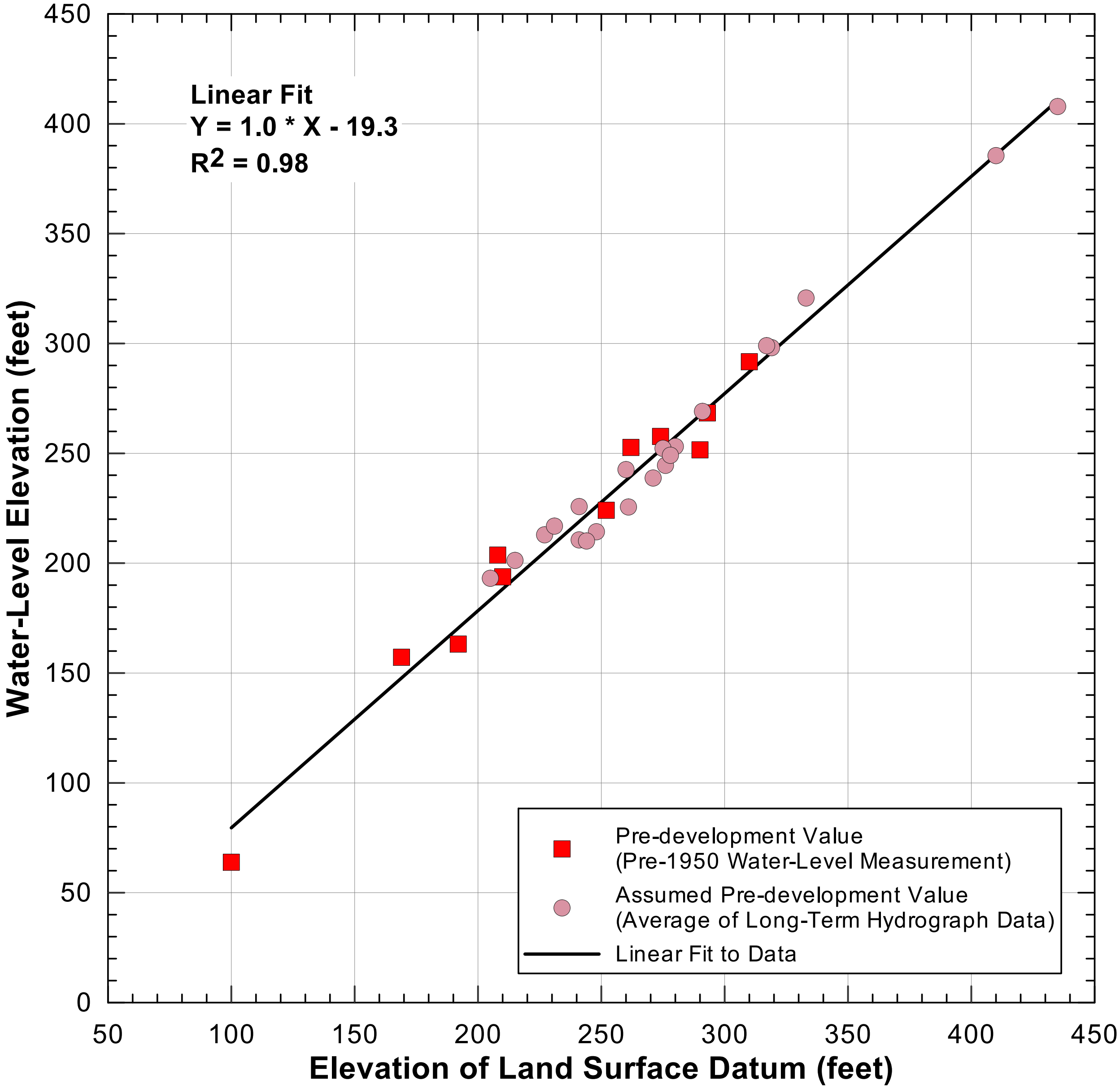
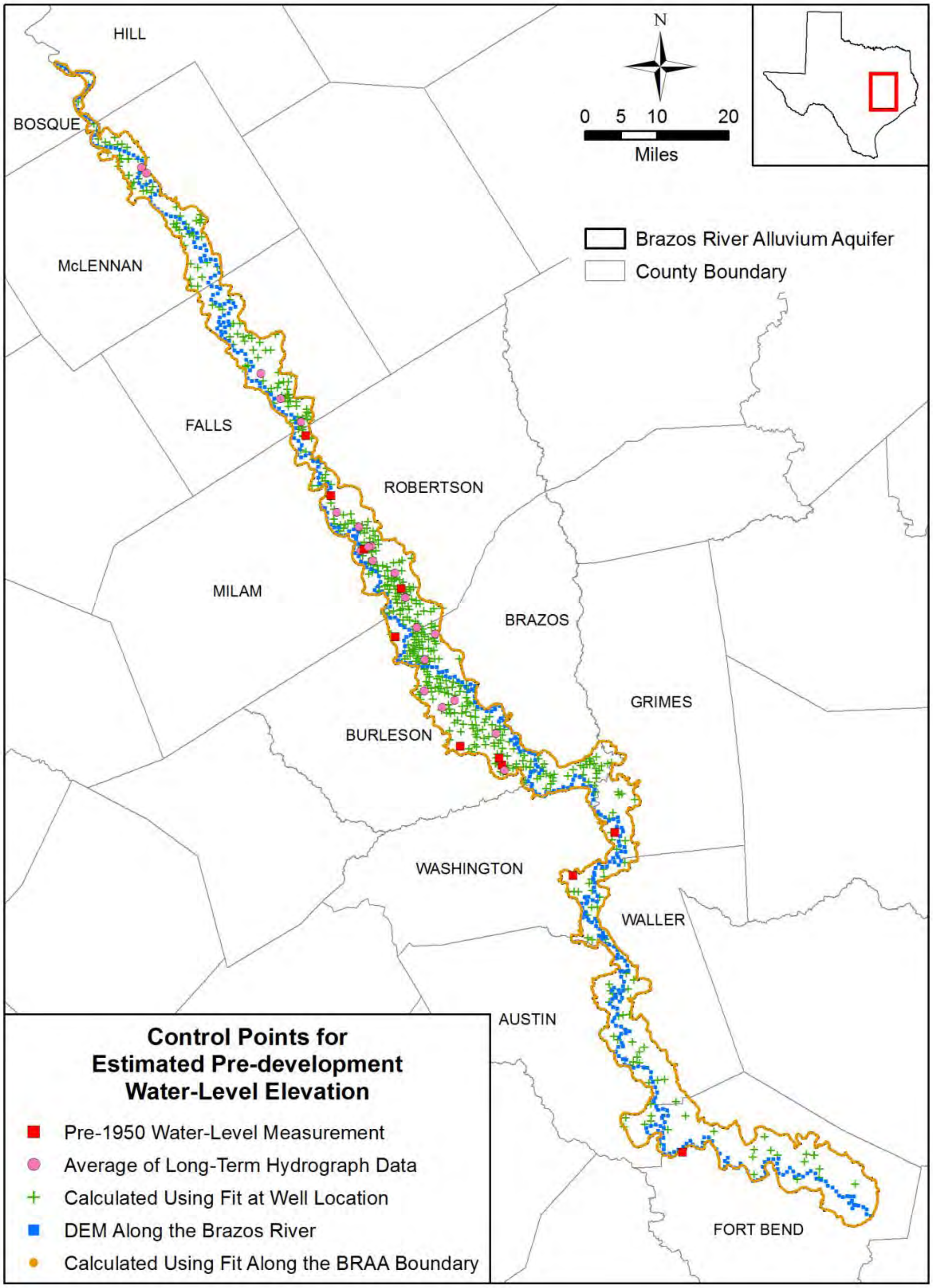


Figure 4.2.3 Linear fit to pre-development water–level elevation versus elevation of the land surface datum for pre-1950 water-level measurements and long-term average water levels.



DEM – digital elevation model

Figure 4.2.4 Location of control points by type used to estimate the pre-development water-level elevation surface for the Brazos River Alluvium Aquifer.

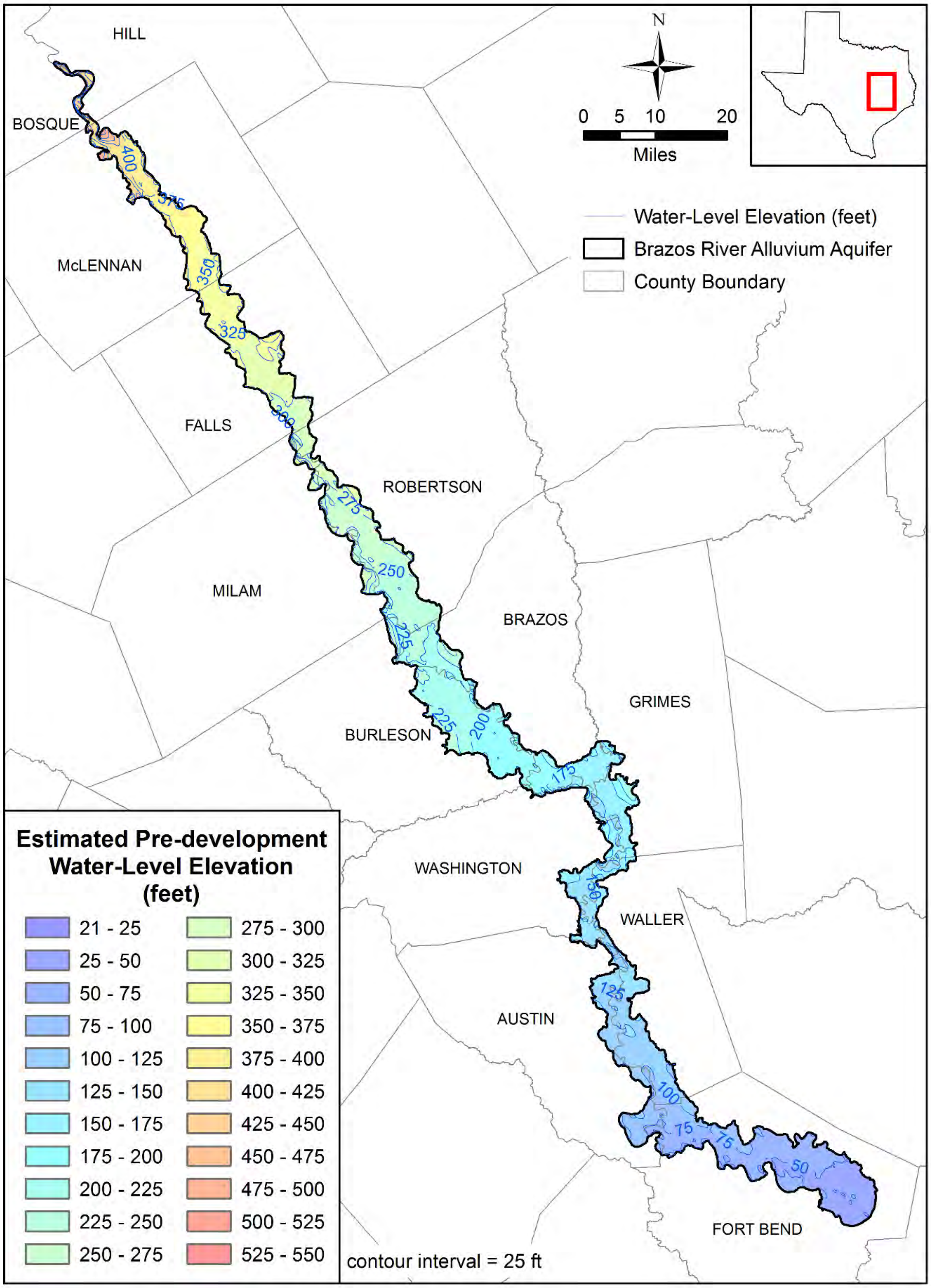


Figure 4.2.5 Estimated pre-development water-level elevation surface in feet above mean sea level for the Brazos River Alluvium Aquifer.

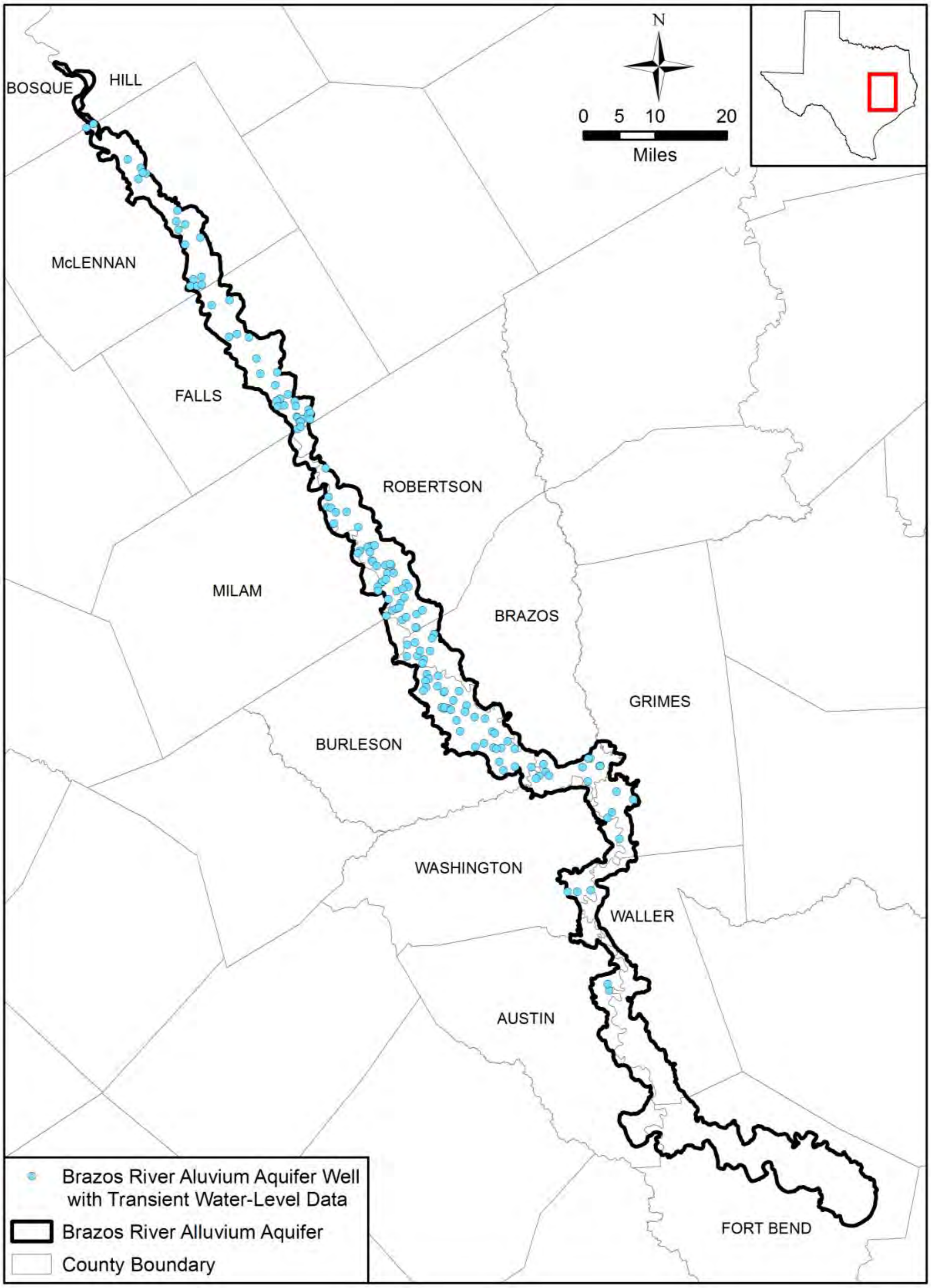


Figure 4.2.6 Location of Brazos River Alluvium Aquifer wells with transient water-level data (TWDB, 2014f).

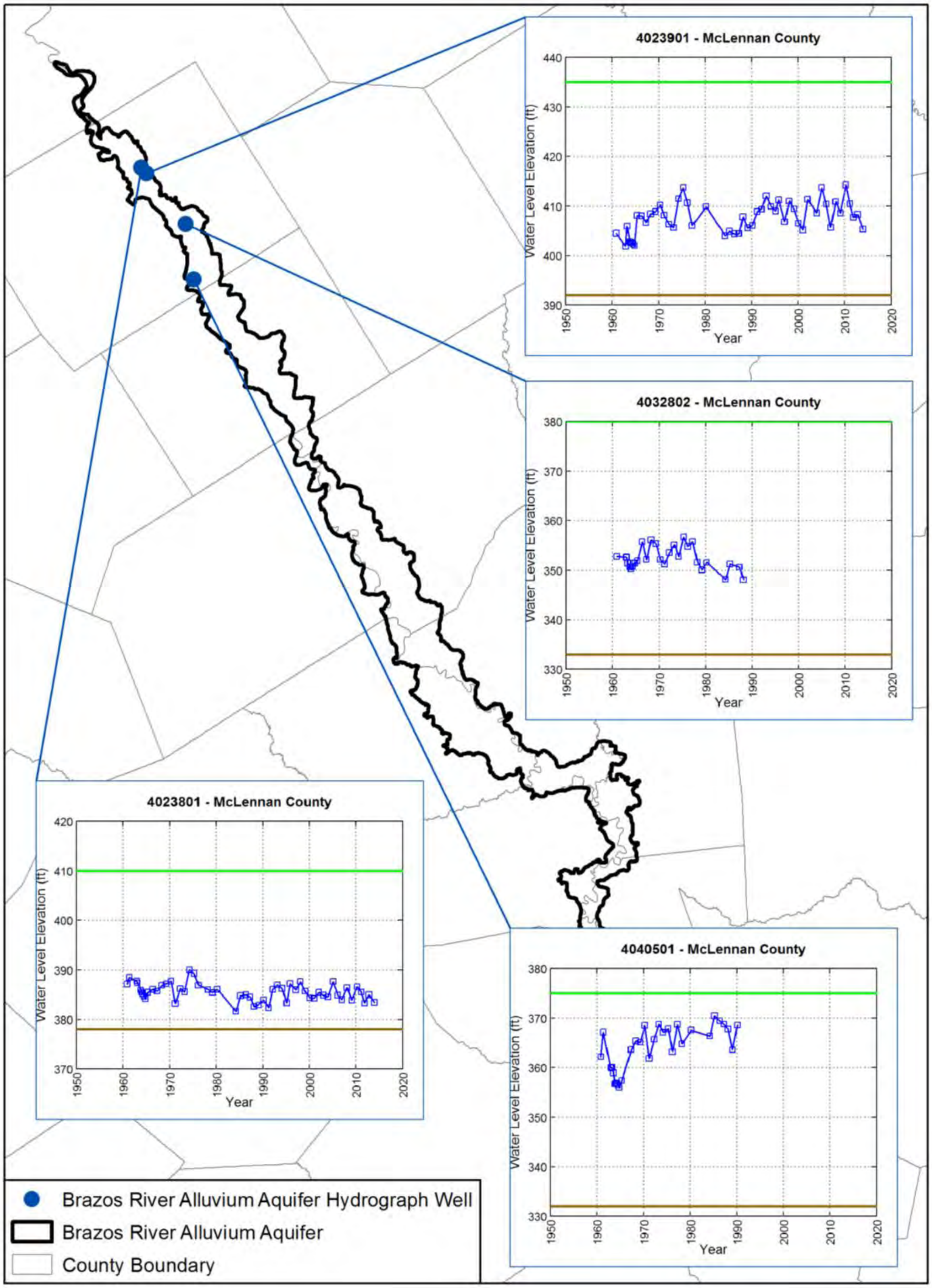


Figure 4.2.7 Select hydrographs for Brazos River Alluvium Aquifer wells located in McLennan County (TWDB, 2014f).

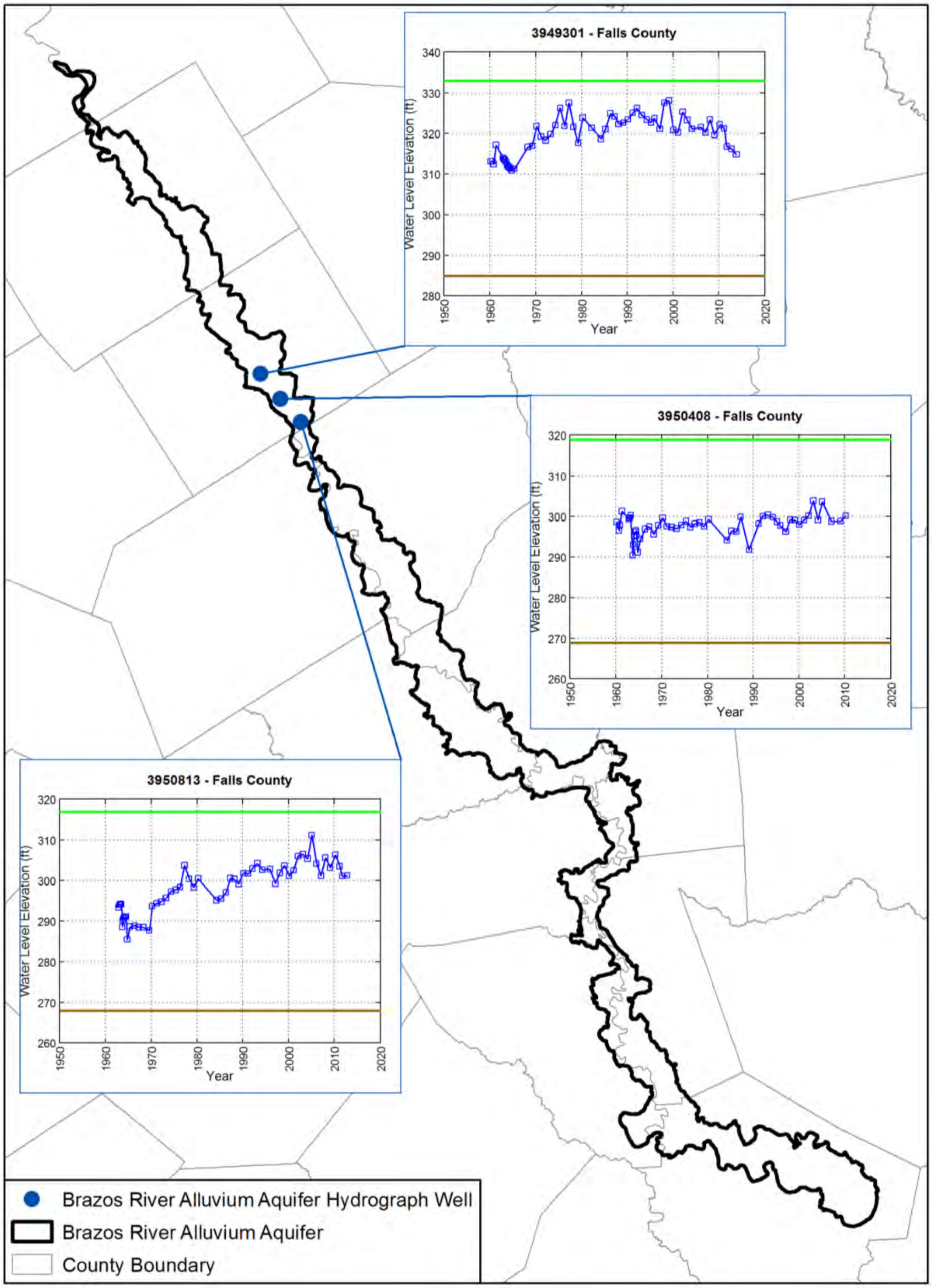


Figure 4.2.8 Select hydrographs for Brazos River Alluvium Aquifer wells located in Falls County (TWDB, 2014f).

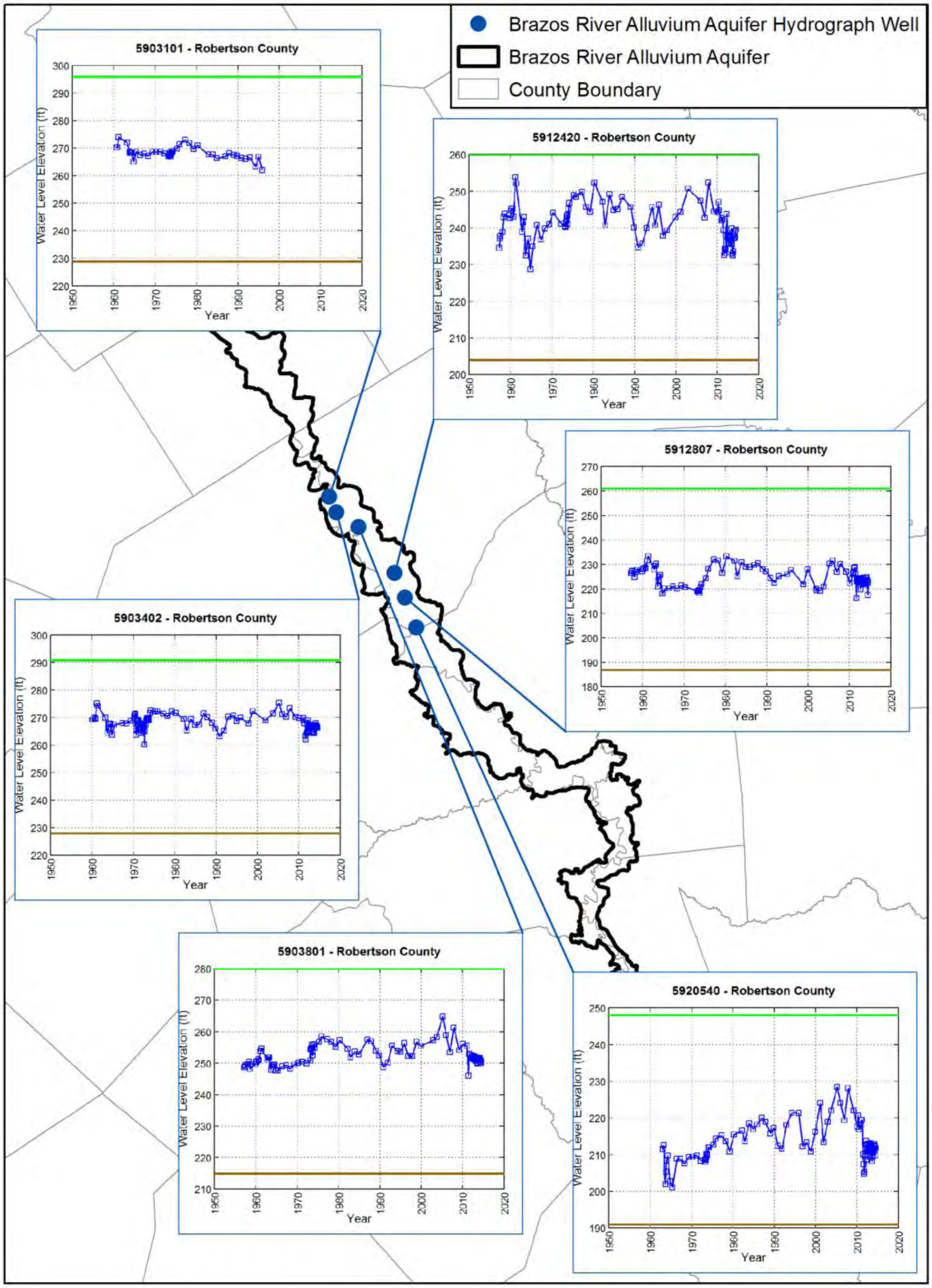


Figure 4.2.9 Select hydrographs for Brazos River Alluvium Aquifer wells located in Robertson County (TWDB, 2014f).

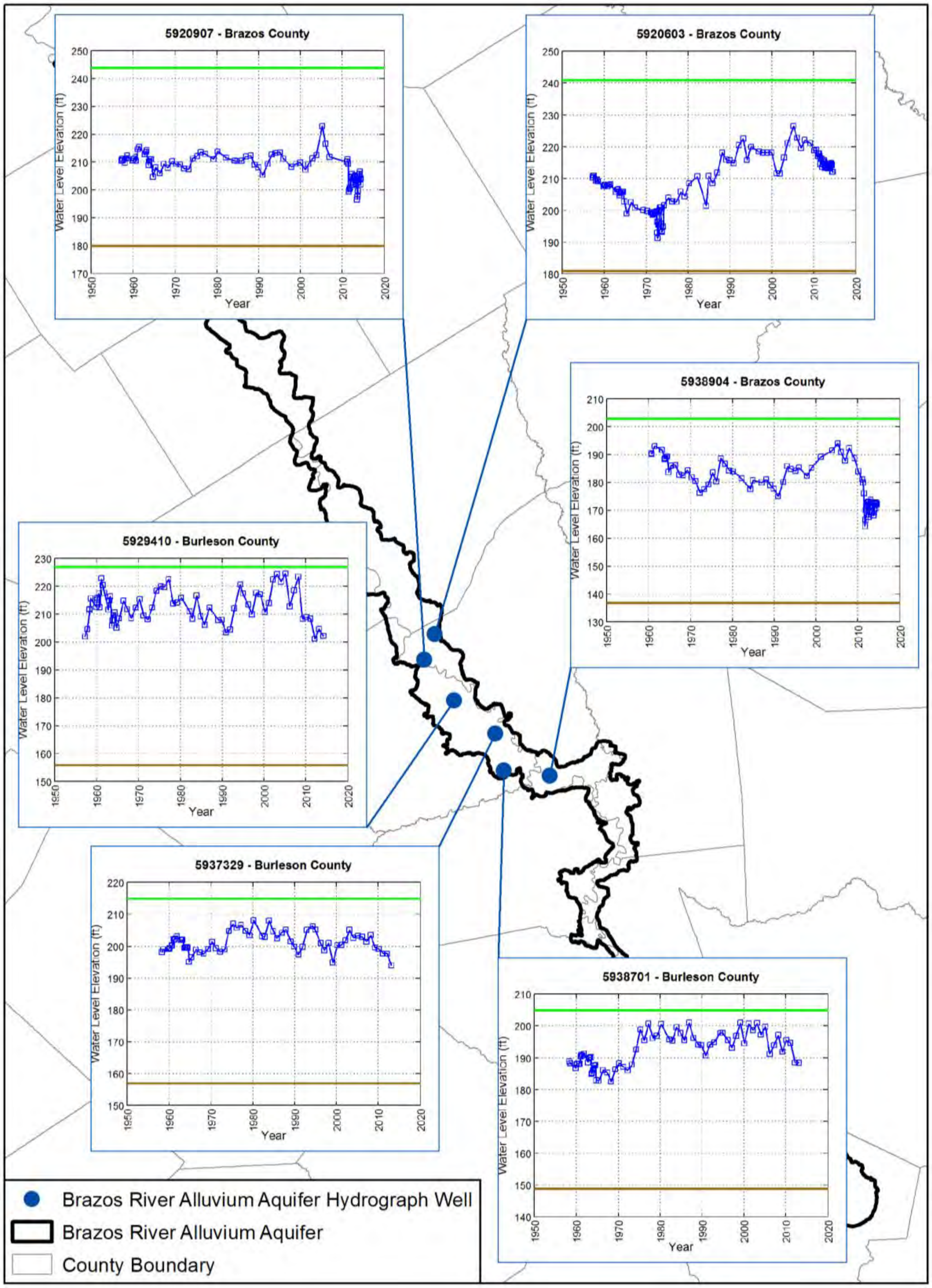


Figure 4.2.10 Select hydrographs for Brazos River Alluvium Aquifer wells located in Brazos and Burleson counties (TWDB, 2014f).

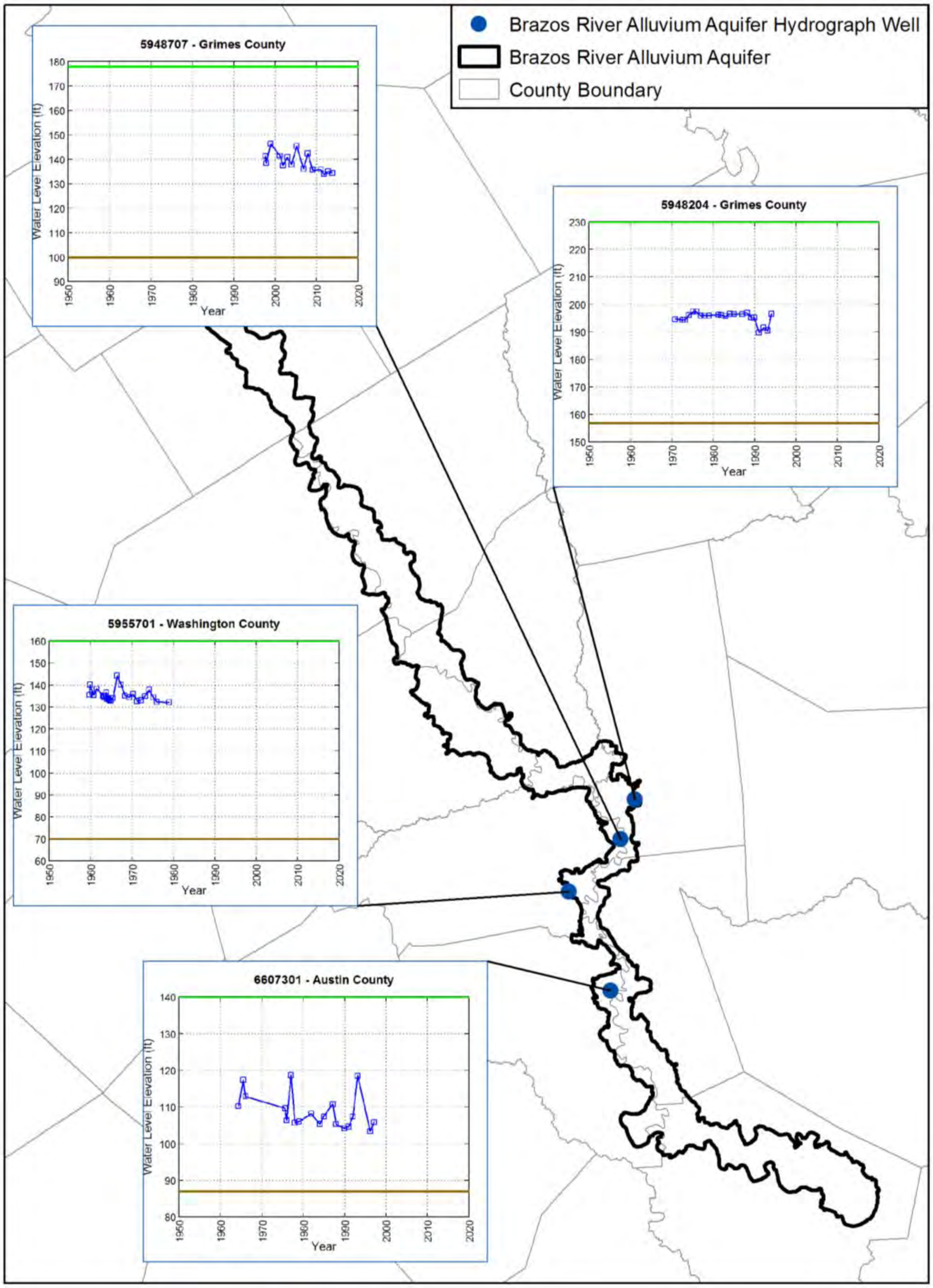


Figure 4.2.11 Select hydrographs for Brazos River Alluvium Aquifer wells located in Grimes, Washington, and Austin counties (TWDB, 2014f).

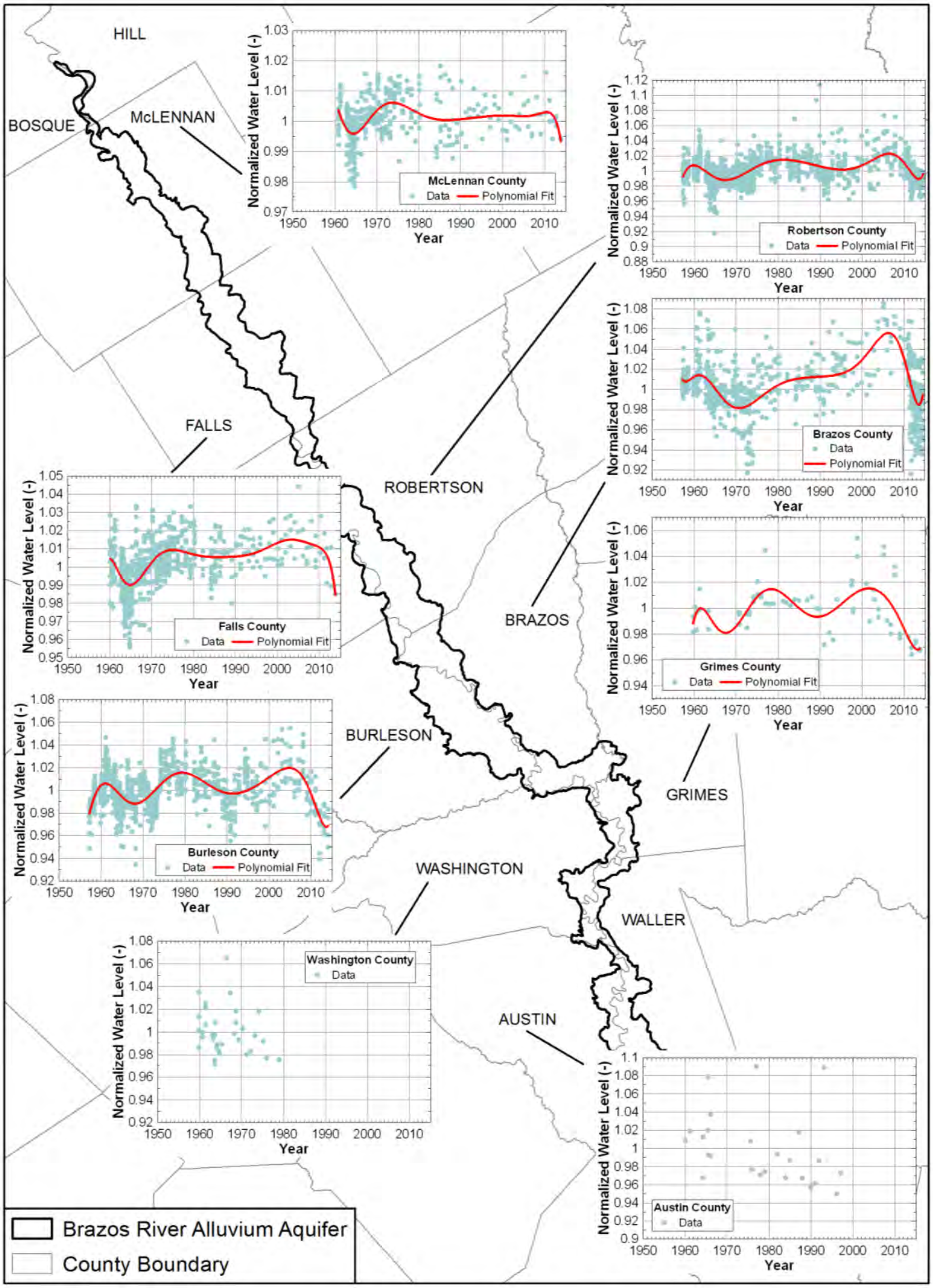


Figure 4.2.12 Polynomial fit to normalized water-level data by county.

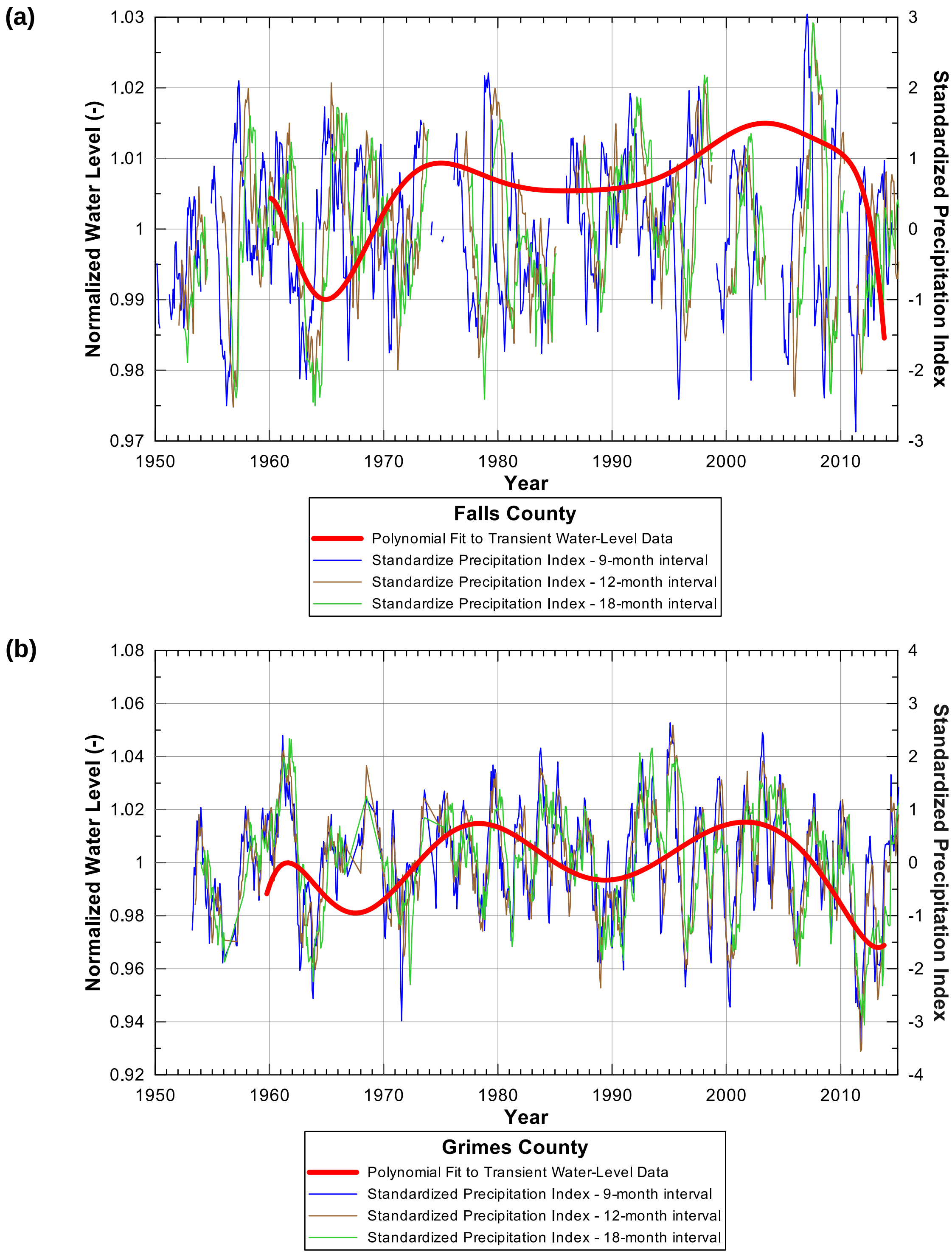


Figure 4.2.13 Comparison of county-wide, long-term trends in water level and Standardized Precipitation Index for (a) Falls and (b) Grimes counties (NOAA, 2014b).

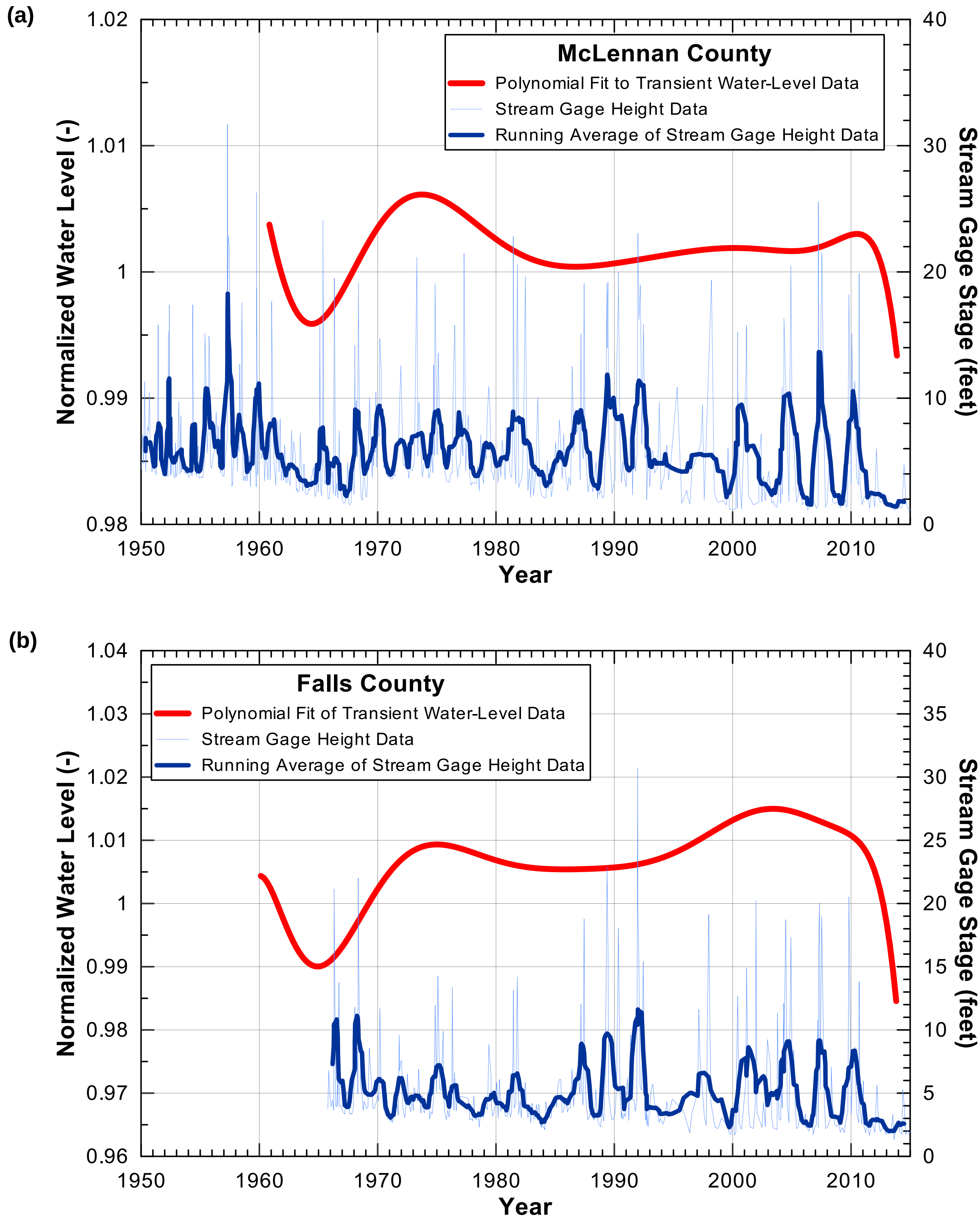


Figure 4.2.14 Comparison of county-wide, long-term trends in water level and the stage of the Brazos River for (a) McLennan and (b) Falls counties (USGS, 2014b).

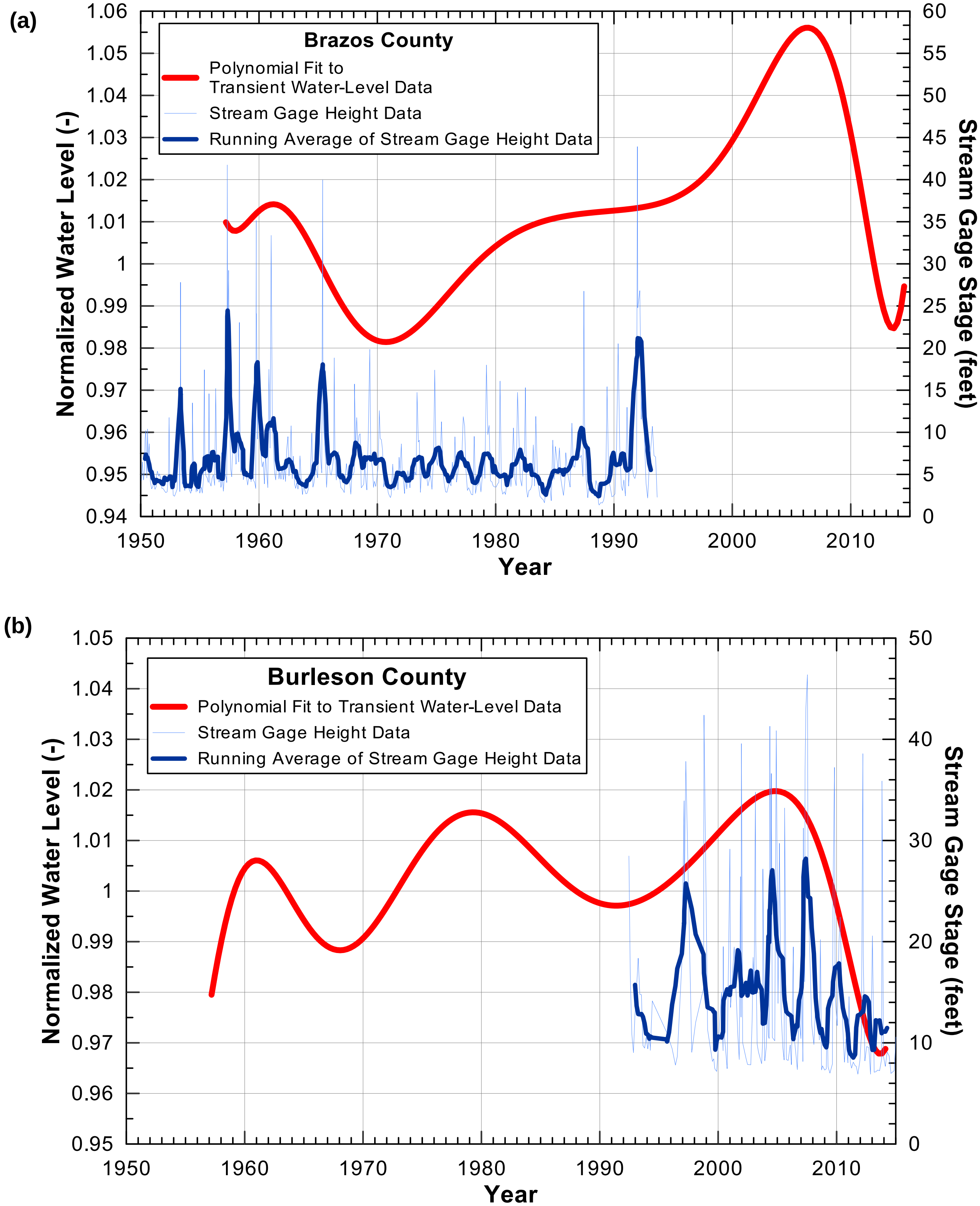


Figure 4.2.15 Comparison of county-wide, long-term trends in water level and the stage of the Brazos River for (a) Brazos and (b) Burleson counties (USGS, 2014b).

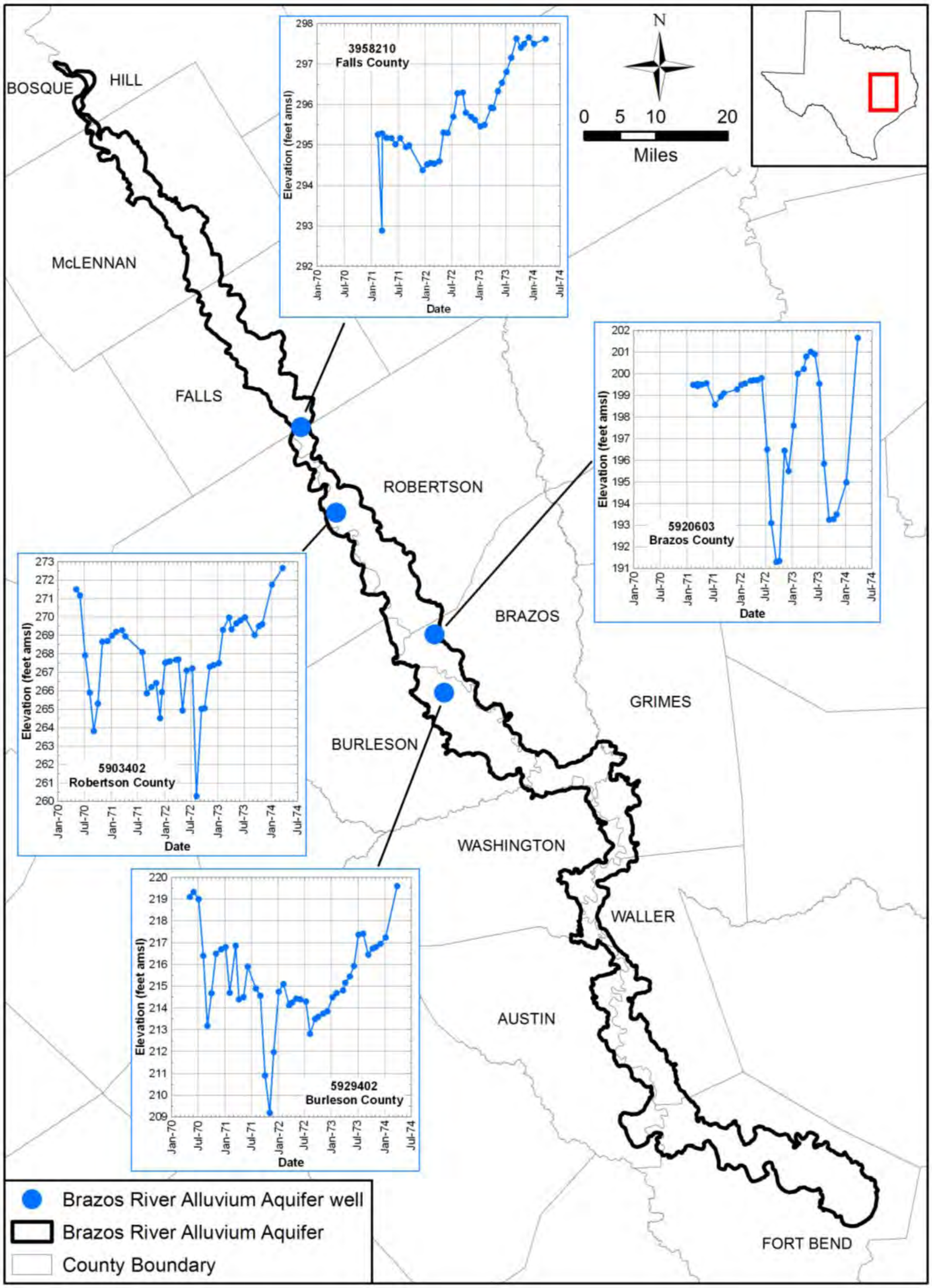


Figure 4.2.16 Seasonal water-level data from early 1970 to mid-1974 (TWDB, 2014f).

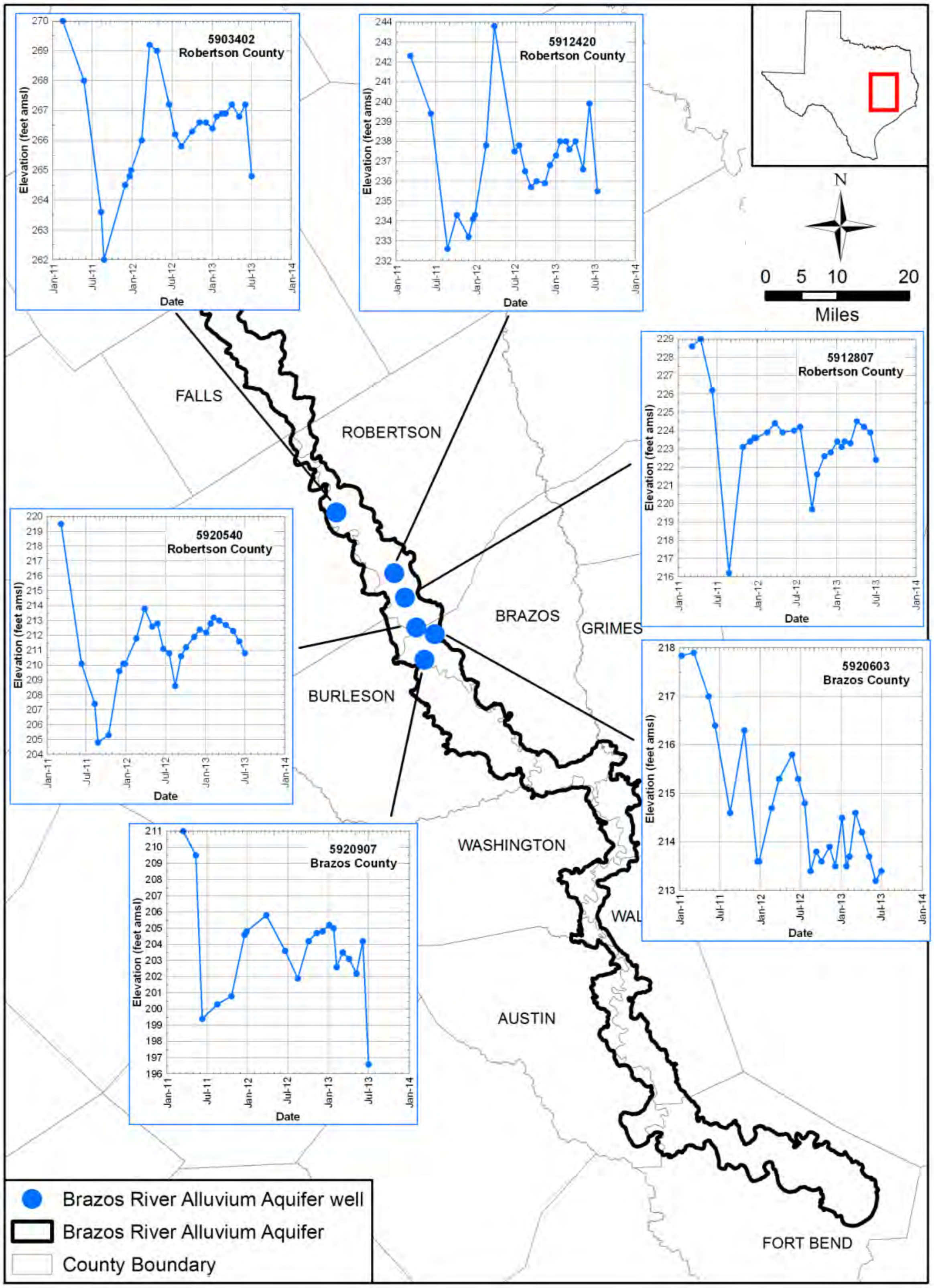


Figure 4.2.17 Seasonal water-level data from early 2011 to early 2014 (TWDB, 2014f).

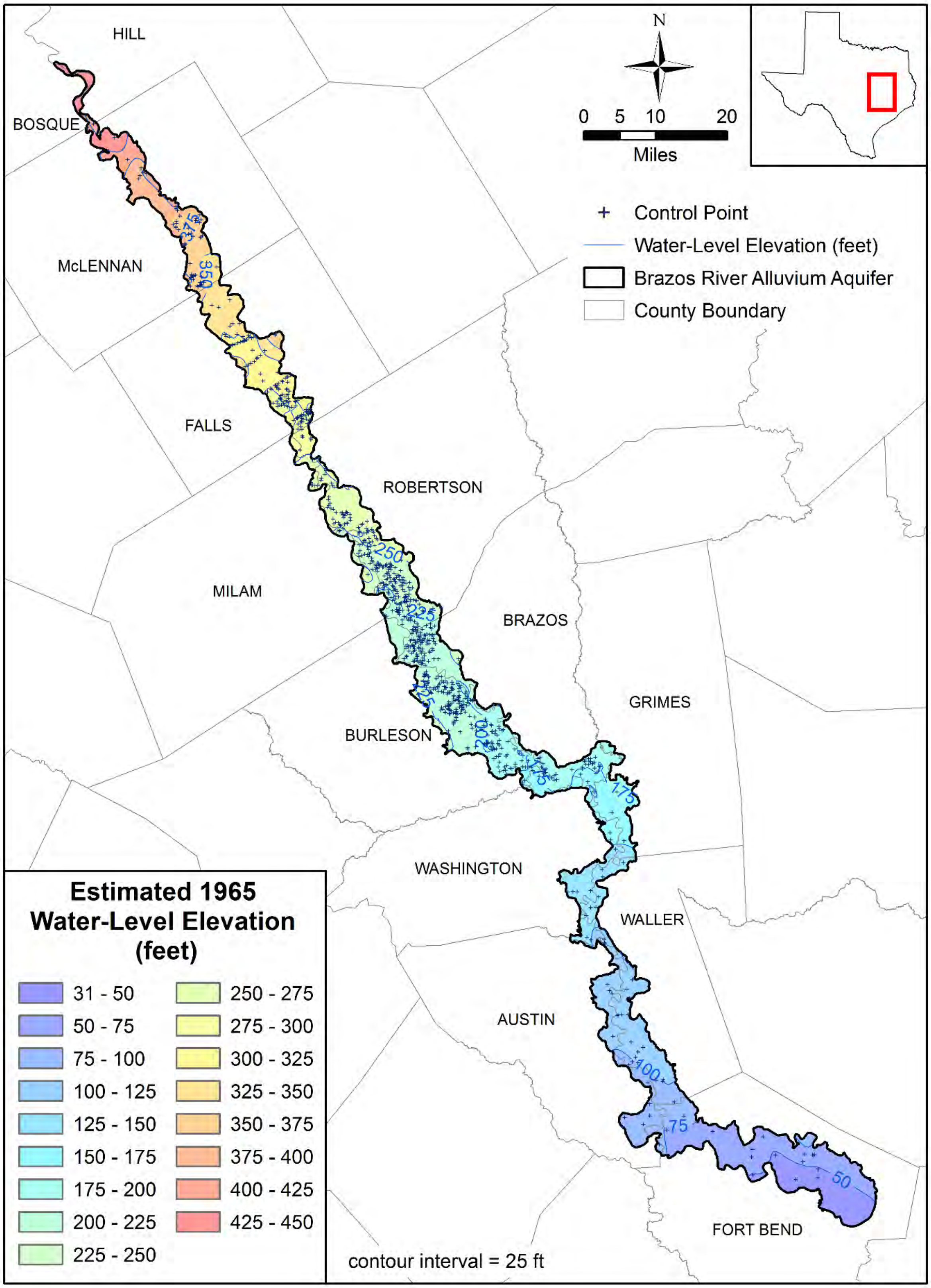


Figure 4.2.18 Estimated water-level elevation contours in feet above mean sea level in the Brazos River Alluvium Aquifer in 1965.

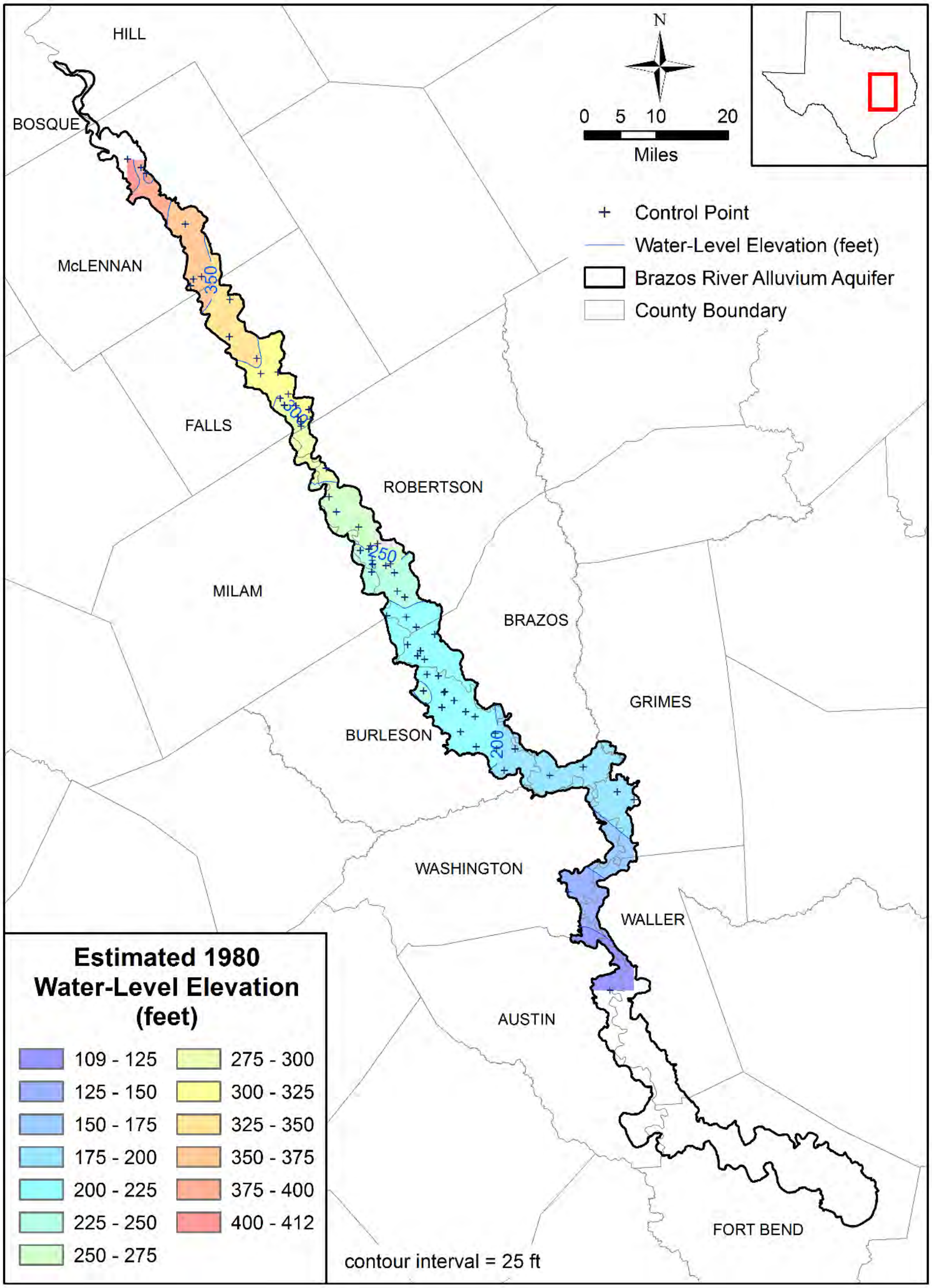


Figure 4.2.19 Estimated water-level elevation contours in feet above mean sea level in the Brazos River Alluvium Aquifer in 1980.

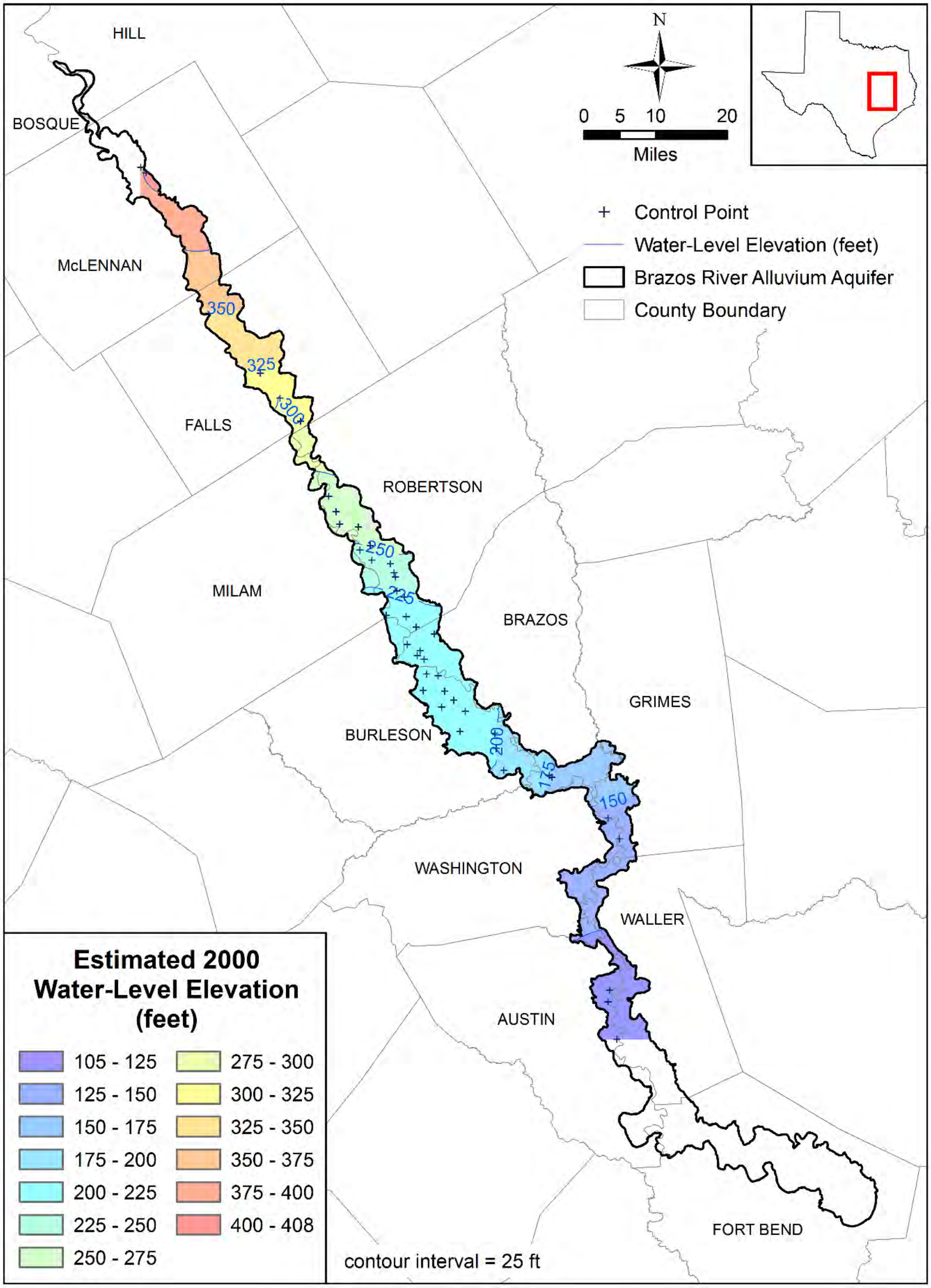


Figure 4.2.20 Estimated water-level elevation contours in feet above mean sea level in the Brazos River Alluvium Aquifer in 2000.

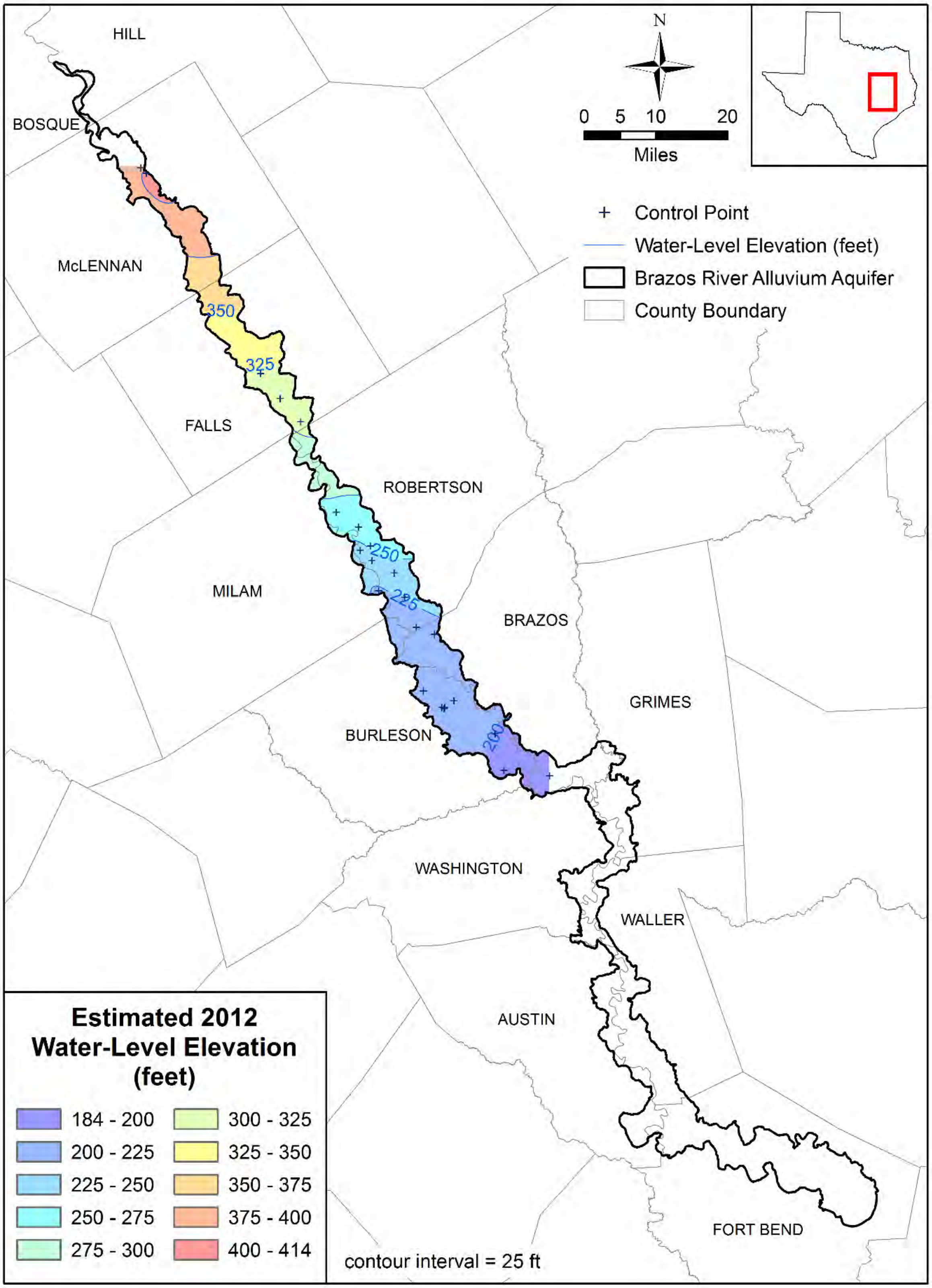


Figure 4.2.21 Estimated water-level elevation contours in feet above mean sea level in the Brazos River Alluvium Aquifer in 2012.

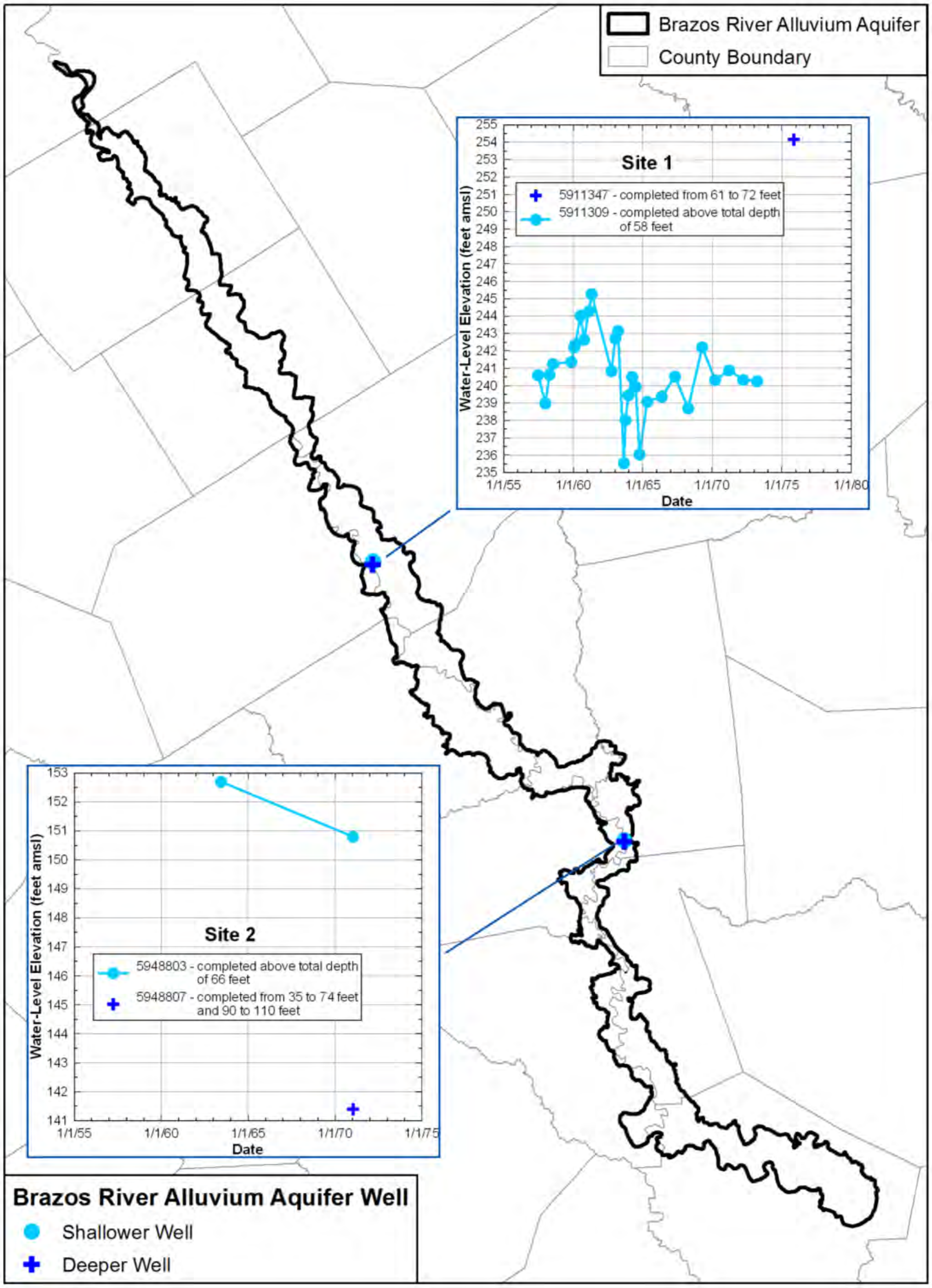


Figure 4.2.22 Comparison of water-level elevations in feet above mean sea level in the upper and lower portions of the Brazos River Alluvium Aquifer.

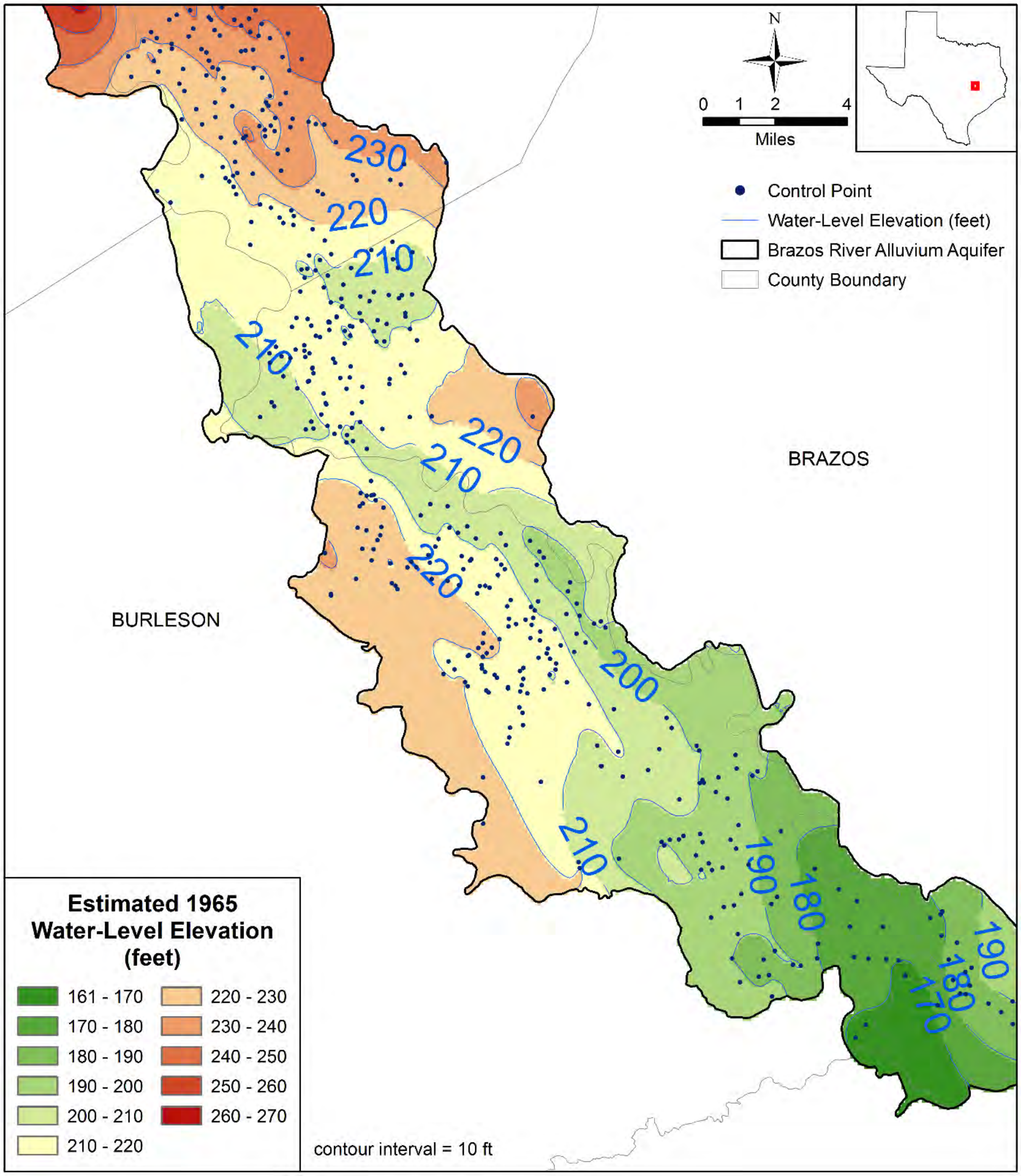


Figure 4.2.23 Estimated water-level elevation contours in feet above mean sea level in 1965 showing a depression in northern Brazos County.

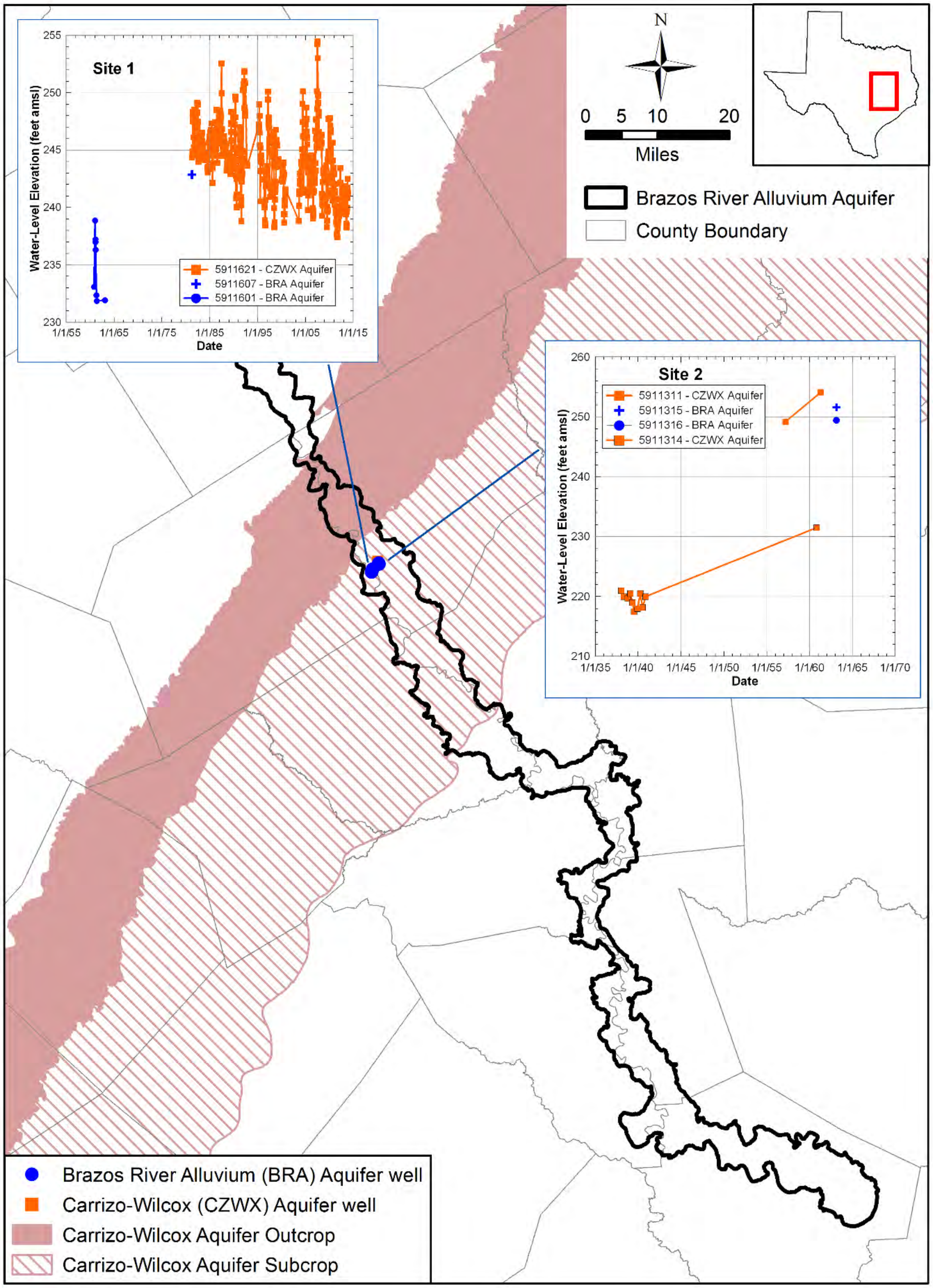


Figure 4.2.24 Comparison of water-level elevations in feet above mean sea level in the Brazos River Alluvium Aquifer and the underlying Carrizo-Wilcox Aquifer.

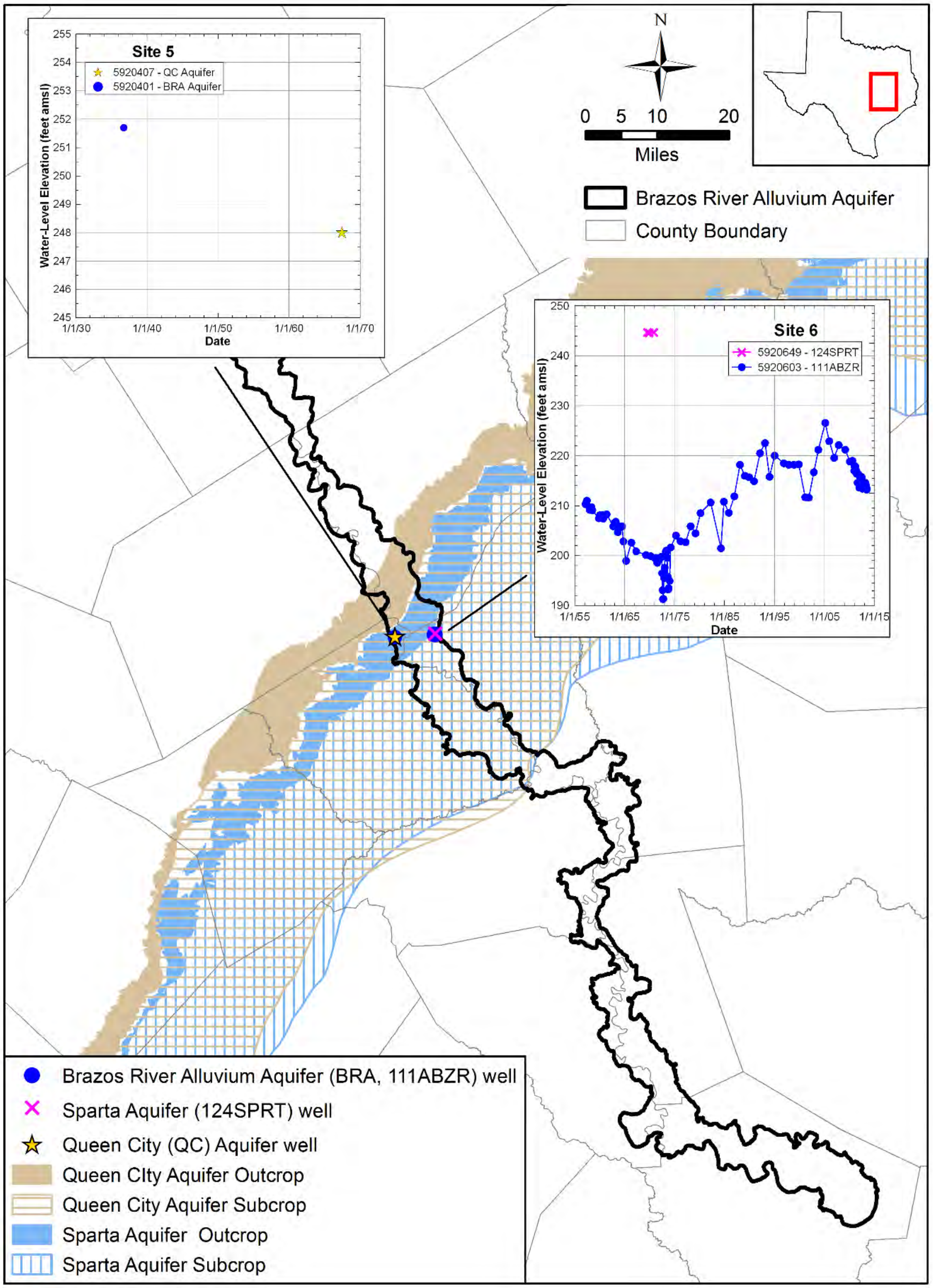


Figure 4.2.25 Comparison of water-level elevations in feet above mean sea level in the Brazos River Alluvium Aquifer and the underlying Queen City and Sparta aquifers.

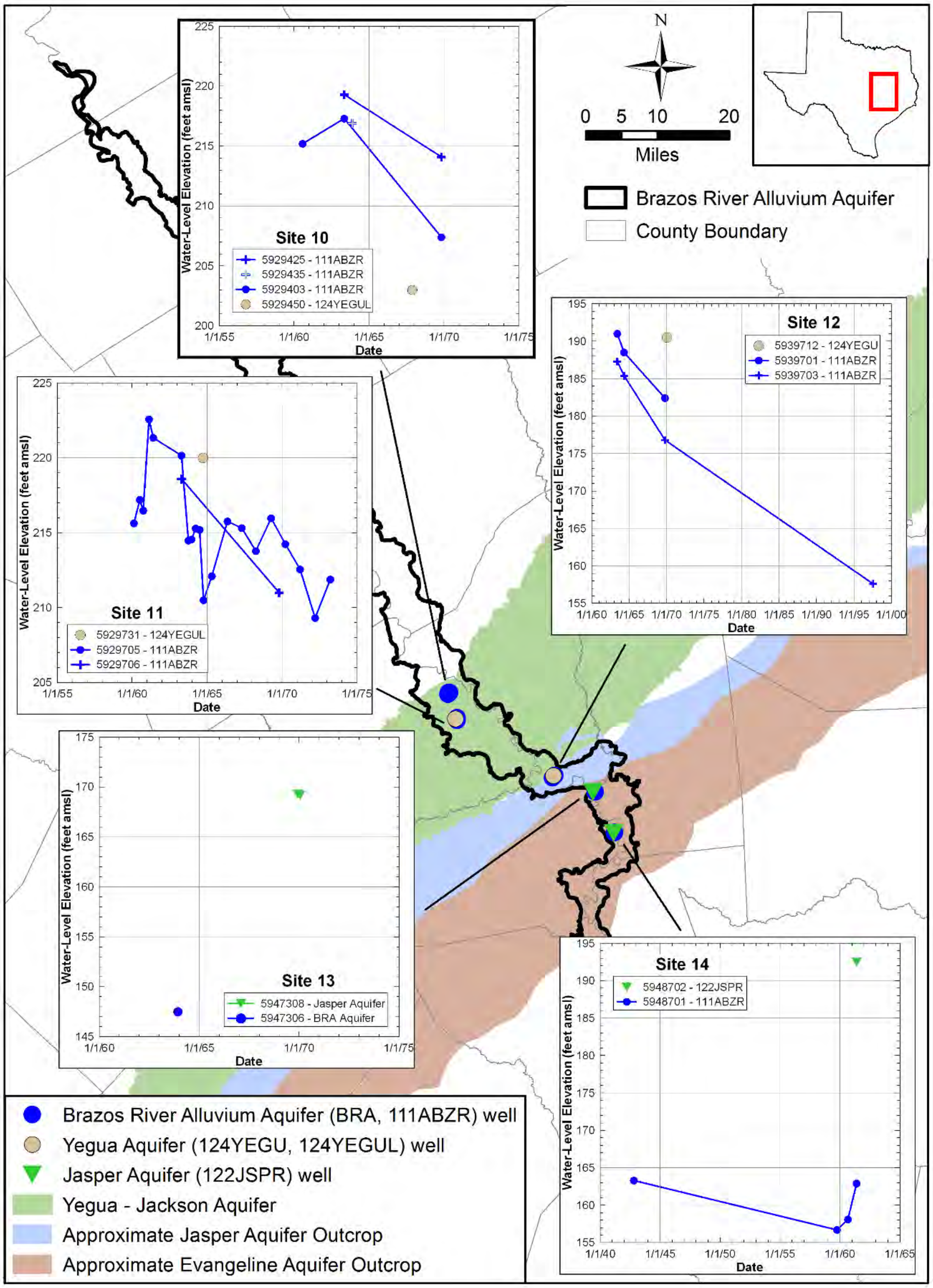


Figure 4.2.26 Comparison of water-level elevations in feet above mean sea level in the Brazos River Alluvium Aquifer and the underlying Yegua Aquifer and the Jasper Aquifer of the Gulf Coast Aquifer System.

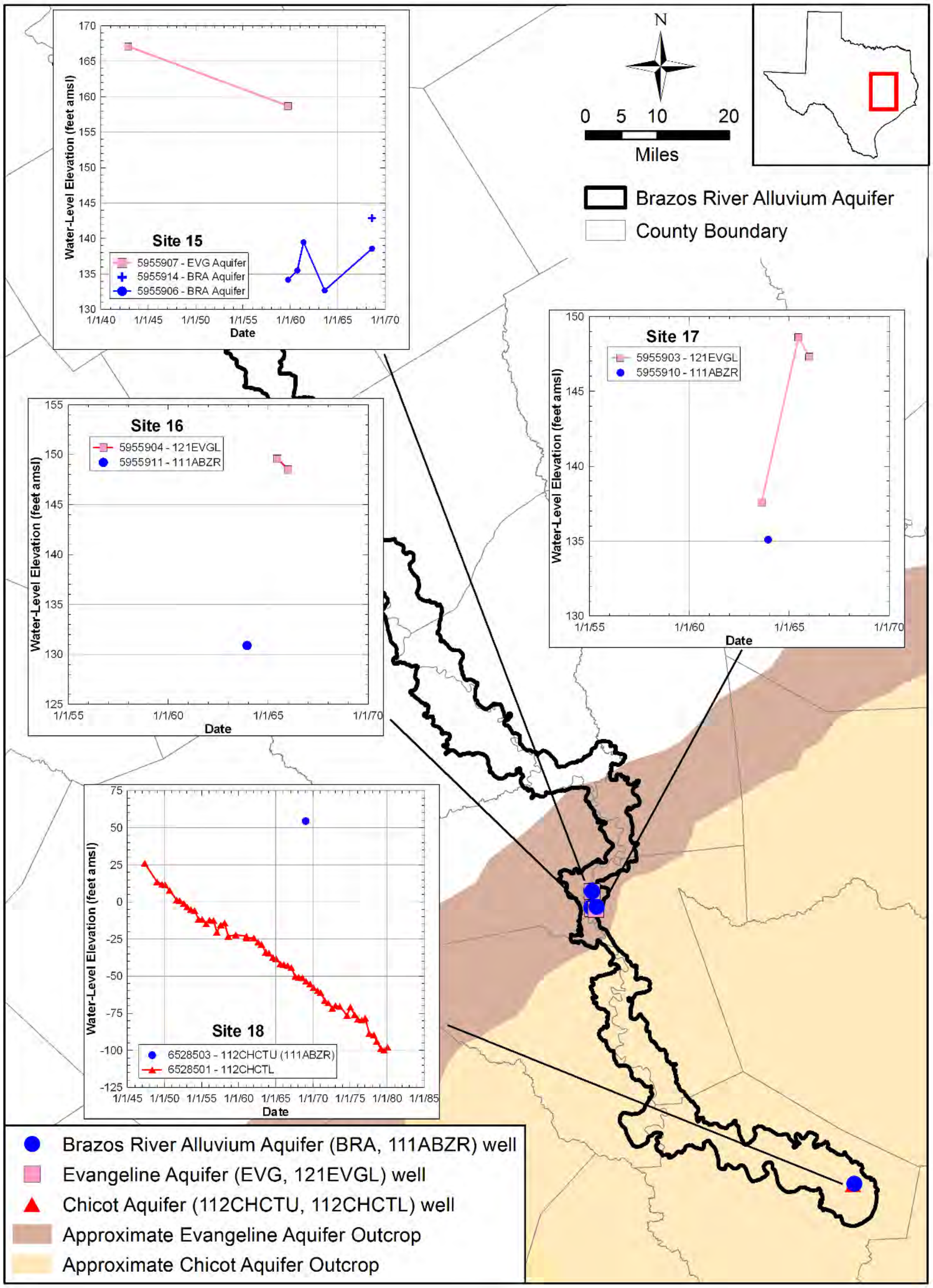


Figure 4.2.27 Comparison of water-level elevations in feet above mean sea level in the Brazos River Alluvium Aquifer and the underlying Evangeline and Chicot aquifers of the Gulf Coast Aquifer System.

4.3 Recharge

Recharge can be defined as water that enters the saturated zone at the water table (Freeze, 1969). Recharge is a complex function of the rate and volume of precipitation, soil type, water level, soil moisture, topography, and evapotranspiration (Freeze, 1969). In the Brazos River Alluvium Aquifer, potential sources of recharge include precipitation, subsurface return flow from irrigation, and leakage from streams, reservoirs, and lakes. Precipitation and irrigation return flow are generally considered to be diffuse sources of recharge, while stream or reservoir leakage are considered to be focused sources of recharge.

During a rainfall or irrigation event, water falling on the ground surface may run off to streams and surface water features or infiltrate into the soil. Much of the infiltrating water evaporates while still near the ground surface or is taken up by vegetation in the vadose zone (vadose zone evapotranspiration). If enough water infiltrates to satisfy the moisture deficit of the soil and the vegetation in the vadose zone, then the remaining water will continue to percolate downward to the water table. Water that reaches the water table is considered recharge.

A groundwater system can often act as a classic topographically-driven recharge/discharge system, where recharge primarily occurs in the areas of higher elevation, and discharge occurs in the areas of lower elevation through streams, seeps, and groundwater evapotranspiration. Recharge enters the outcrop portion of an aquifer, and the vast majority discharges relatively quickly through base flow and other surficial discharge components (such as groundwater evapotranspiration, springs, and seeps). A small fraction of the recharge entering the outcrop can enter the deep regional flow system and exit the aquifer regionally through cross-formational flow. Since the Brazos River Alluvium Aquifer is an unconfined aquifer, there is no deep flow system, and all recharge is expected to discharge from the shallow flow system. This shallow discharge component is sometimes termed “rejected recharge” and has the potential to be captured by pumping, if the water table is lowered enough to reverse the gradients driving flow towards the natural discharge points.

4.3.1 Previous Recharge Studies

Cronin and Wilson (1967) estimated recharge in the Brazos River Alluvium Aquifer using the method described by Keech and Dreeszen (1959) in which the difference in estimated flow at upstream and downstream sections of the alluvium was attributed to recharge. They found that rates of recharge were related to soil permeability with significantly lower recharge in areas with clay present near land surface and above the water table than in areas where the soil was sandy. Over the extent of the Brazos River Alluvium Aquifer, recharge rates estimated by Cronin and Wilson (1967) varied from about 2 to 5 inches per year, with an average value of 3.5 inches per year. Most subsequent studies that include the Brazos River Alluvium aquifer do not provide new recharge data, but rather re-use the original Cronin and Wilson (1967) values. An exception is Chowdhury and others (2010), who estimated recharge using digital hydrograph separation and chloride mass balance methods. They performed a hydrograph separation analysis using an automated recursive digital filter (Arnold and others, 1995) on data from streamflow gage 08108700 near Bryan, Texas and streamflow gage 08111500 near Hempstead, Texas. Their analysis yielded an average recharge of 0.74 inches per year for the data from the Bryan gage and 0.95 inches per year for the data from the Hempstead gage. They also calculated a recharge value for the entire aquifer using the chloride mass balance method, which incorporates precipitation amount, chloride in precipitation, and chloride in groundwater. The groundwater chloride value used was based on the average chloride concentrations for wells in the Brazos River Alluvium Aquifer, most of which were clustered in the central portion of the aquifer, particularly in Milam, Robertson and Falls counties. This method yielded a recharge estimate of 0.33 inches per year for the Brazos River Alluvium Aquifer. This is significantly lower than the two recharge values they estimated from the hydrograph separation analysis, but the chloride mass balance method can underestimate recharge if chloride is derived from sources other than precipitation. They note some lag time between precipitation and when recharge reaches the aquifer, potentially indicating the influence of clay in the upper parts of the aquifer. Table 4.3.1 summarizes the recharge estimates from these previous studies.

Scanlon and others (2002) compiled literature values of recharge for most Texas aquifers. While they do not provide values for the Brazos River Alluvium Aquifer, they do provide values for the Carrizo-Wilcox and Gulf Coast aquifers. The average recharge rate of the 19 estimates provided for the Carrizo-Wilcox aquifer is about 1.8 inches per year and the average recharge rate of the 11 estimates provided for the Gulf Coast Aquifer is about 1.2 inches per year.

The groundwater availability model for the central portion of the Carrizo-Wilcox Aquifer (Dutton and others, 2003) includes the Brazos River Alluvium Aquifer in an alluvium layer comprising the valley alluvium of the Brazos, Trinity and Colorado rivers. A steady-state recharge rate was calculated by multiplying a scaled recharge rate by a scaled soil hydraulic conductivity value. However, the scaled recharge rate is based on the calibrated recharge rate for the layer underlying the alluvium in any particular cell. There is no calibrated recharge rate calculated for the alluvium itself. Therefore, the recharge rates for the alluvium layer are not considered necessarily representative of the Brazos River Alluvium Aquifer. This groundwater model was eventually superseded by the combined groundwater availability model of the Queen City, Sparta, and Carrizo-Wilcox aquifers (Kelley and others, 2004). However, the recharge distribution from that model is also not applicable for the current study because the model uses recharge to simulate the deep downdip flow, rather than flow in the shallow surficial system.

A study of the Gulf Coast Aquifer calculated shallow recharge based on a combination of chloride mass balance and analyses of base flow (Scanlon and others, 2012). Their resulting recharge distribution covers much of the southern portion of the active model area for the Brazos River Alluvium Aquifer as shown in Figure 4.3.1. The Yegua-Jackson Aquifer groundwater availability model (Deeds and others, 2010) calculated shallow recharge as a function of precipitation, using a relationship developed from base flow analyses. They then refined their estimates of recharge through model calibration. Their resulting recharge distribution covers a small central portion of the active model area for the Brazos River Alluvium Aquifer, also shown in Figure 4.3.1. Note that neither the Scanlon and others (2012) study nor the Deeds and others (2010) model explicitly included the Brazos River Alluvium Aquifer. Figure 4.3.1 also shows the portion of the active model area where estimates of recharge are not available from previous studies.

4.3.2 Factors Affecting Recharge

Several factors can influence recharge, including precipitation, irrigation return flow, surface soils, topography, and surface water. The following subsections describe how the effects of these factors on recharge in the Brazos River Alluvium Aquifer were conceptualized.

4.3.2.1 Precipitation

All natural (that is, not irrigation return flow) recharge originates as precipitation. Even when other factors, such as soil texture, are used to estimate recharge distribution, the amount of recharge is, in general, expected to scale with precipitation. As shown in Figure 2.1.7, mean annual precipitation in the study area increases from northwest to southeast, with the highest precipitation rates nearest the coast. Within the boundary of the Brazos River Alluvium Aquifer, precipitation ranges from a low of about 35 inches in the northwest to a high of about 50 inches in the southeast. Section 4.3.3 describes how a relationship was developed to distribute recharge as a function of precipitation for the Brazos River Alluvium Aquifer.

4.3.2.2 Irrigation Return Flow

Except for the southernmost counties of Fort Bend, Waller, and Austin, all counties in which the Brazos River Alluvium Aquifer is located saw an almost 100 percent increase in irrigated land from 1949 to 1954 (United States Department of Agriculture, 1954a). This agrees with the conceptualization of a substantial increase in irrigation post-1950 due to the effects of the 1950s drought. Irrigation return flow can be a significant source of recharge, depending on the concentration of irrigation activities and the type of crops being grown. For example, a crop that is flood irrigated, such as rice, will provide more return flow to the water table than a crop that is irrigated more intermittently, such as corn. In general, current good agricultural management practices for most crops include balancing irrigation application with plant evapotranspiration requirements (Allen and others, 1998), so that the amount of water that moves beyond the root zone to the water table is minimized. However, while irrigation efficiency has increased in counties containing the Brazos River Alluvium Aquifer, much of the irrigated land, as of 2000, is not irrigated with efficient sprinkler or drip systems (Table 4.3.2). Washington County is the only county where all irrigation is conducted using sprinkler or drip systems (TWDB, 2001). Only a few counties (Bosque, Hill, and Milam) were completely or nearly completely sprinkler irrigated in 2000. Less than 50 percent of irrigated land in Burleson, Falls, and McLennan counties, less than 30 percent in Austin, Robertson and Waller counties, and less than 10 percent in Brazos, Grimes and Fort Bend counties were under sprinkler or drip irrigation (see Table 4.3.2).

Figure 4.3.2 shows a visible increase in pivot sprinkler irrigation between 1999 and 2011 in a portion of Brazos County, illustrating how recent the transition to more efficient irrigation has been in much of the study area. Assuming that land not irrigated by sprinkler or drip systems is under surface-applied or flood irrigation, irrigation return flow is expected to be significant under much of the irrigated land within the extent of the Brazos River Alluvium Aquifer. There is likely some irrigation return flow even under efficient sprinkler or drip systems, though it is expected to be less than that under surface-applied irrigation.

A study in the High Plains region of Texas estimated that irrigation return flow under surface irrigation is approximately 35 percent of applied irrigation (Blandford and others, 2003). This is slightly higher than a study in Colorado's Lower Arkansas River Valley that estimated 24 percent return flow under surface irrigation (Gates and others, 2012). The High Plains study estimated that irrigation return flow under sprinkler irrigation was approximately 15 percent of applied irrigation in the 1970s and 1980s, but closer to 10 percent in the 1990s and onwards due to more efficient technology (Blandford and others, 2003). Similarly, the Colorado study estimated irrigation return flow is 13 percent of applied irrigation under sprinkler irrigation (Gates and others, 2012).

The changing prevalence of different irrigation methods through time makes it possible to estimate irrigation return flows representative of different time periods. Values for time periods between 1940 and 2000 are presented in Table 4.3.3 for areas in the High Plains region of Texas and New Mexico (Blandford and others, 2003). While estimated return flow percentages in both states have declined drastically since 1960, the High Plains area of Texas has a lower estimated irrigation return flow percentage, as of 2000, than the High Plains area of New Mexico. This difference accounts for the slower implementation of more efficient irrigation techniques in New Mexico compared to west Texas (Blandford and others, 2003). In the Brazos River Alluvium Aquifer study area, the temporal trend in irrigation return flow percentage is expected to resemble that of New Mexico in counties with less widespread adoption of efficient sprinkler irrigation and to resemble that of west Texas in counties where efficient sprinkler and drip irrigation systems have been aggressively implemented (Table 4.3.3). While the climate differs considerably in the study area compared with west Texas and New Mexico, the irrigation techniques and efficiencies can be assumed to be comparable.

The absolute magnitude of irrigation return flow ultimately depends on the amount of applied irrigation. For the period from 1985 to 2012, the average irrigation requirement for non-rice crops for counties in the study area was approximately 14 inches per year and the average rice irrigation requirement was slightly over 40 inches per year (TWDB, 2015). The irrigation return flow would thus be much higher under rice crops than under other crops. For example, assuming the most efficient scenario (90 percent efficiency), irrigation return flow would be 4 inches per year under rice crops compared to 1.4 inches per year under other crops.

Estimating the spatial distribution of irrigation return flow is problematic because there is no existing spatial coverage that differentiates rain-fed from irrigated cropland. In order to establish a reasonable distribution pattern of irrigation return flow, a basic irrigation coverage was created using satellite imagery. Unlike areas where all irrigation is supplied by groundwater and tell-tale pivot irrigation circles located near irrigation wells can be used to identify irrigated land, there is not a straightforward way to identify irrigated land in the Brazos River Valley. Many farms in the Brazos River Valley have access to surface water for irrigation, which creates less visually-obvious cropping patterns. However, since irrigation return flow can occur whether the water is sourced from groundwater or surface water, it is important to account for all irrigated land when selecting areas where irrigation return flow is expected to occur.

To identify areas of potential irrigation return flow, the National Land Cover Database, which provides a basic coverage for total cropland for the years 1992, 2001, 2006, and 2011 (Multi-Resolution Land Characteristics Consortium, 2014), was used. From the 1992 National Land Cover Database map, areas classified as orchards/vineyards/other (61), pasture/hay (81), row crops (82), small grains (83), or fallow cropland (84) were considered to be cropland. From subsequent National Land Cover Database maps, which have a different classification system, areas classified as pasture/hay (81) and cultivated crops (82) were considered to be cropland. Unlike rain-fed cropland, irrigated cropland is expected to thrive even during times of water stress. The years 1988, 1999, and 2011 were chosen as representative "water-stressed" years, since annual precipitation in the study area was well below average at those times.

To establish the relative health of crops, the Normalized Difference Vegetation Index was used. This parameter is calculated using the visible and infrared wavelengths absorbed and reflected by vegetation and gives an idea of the health and extent of vegetation. The Normalized Difference Vegetation Index values were calculated from monthly LandSat 5 satellite imagery available from the United States Geological Survey Global Visualization Viewer (United States Geological Survey, 2015a). Each pixel in areas identified as cropland was assigned the highest Normalized Difference Vegetation Index value calculated that year, based on all available monthly images. This was done because different crops will cause the Normalized Difference Vegetation Index to peak at different times of the year, depending on the growth cycle of the crop. Using the peak Normalized Difference Vegetation Index value for the entire year rather than for a certain month should more accurately identify all irrigated crops rather than biasing the estimate towards crops that peak at a certain time of the year. This was necessary since a spatial distribution of crops by type is not available for all of the years considered.

Using the Zonal Statistics tool in ArcGIS 10.1, the dominant land use type as well as the average Normalized Difference Vegetation Index value for each grid cell in the preliminary Brazos River Alluvium Aquifer groundwater availability model grid was calculated. Although Normalized Difference Vegetation Index data are available for all years, land use data are only available for the years 1992, 2001, 2006, and 2011. Therefore, the 1988 Normalized Difference Vegetation Index distribution was paired with the 1992 land use map and the 1999 Normalized Difference Vegetation Index distribution was paired with the 2001 land use map. Both Normalized Difference Vegetation Index and land use maps are available for 2011. If the majority of a grid cell was comprised of cropland or pasture/hay and the highest Normalized Difference Vegetation Index value during a water-stressed year was over a threshold value, that grid cell was assumed to be irrigated. The threshold value was determined based on visual inspection of probable irrigated areas (tell-tale pivot irrigation circles, for instance) for each year. The assumed threshold values were 0.72 for 1988, 0.73 for 1999, and 0.65 for 2011. The 2011 distribution of irrigated and rain-fed cropland and pasture/hay developed using this method is shown in Figure 4.3.3.

Without ground-truthing, this method is not fool-proof because the Normalized Difference Vegetation Index calculation for a year can be affected by outside factors. For instance, cloud cover during the growing season could obscure what would otherwise be the highest Normalized Difference Vegetation Index value for the year, skewing the highest value for an irrigated pixel too low to reach the threshold, meaning it would not be classified as irrigated. Another potential concern is how different levels of water stress throughout the year overlap the growing season of particular plants. If, for instance, the summer season is severely water-stressed but the winter has relatively good precipitation, then there may not be enough of a difference between rain-fed and irrigated winter crops and some rain-fed pixels would erroneously be classified as irrigated. However, in general, this method appears to reliably account for areas that are likely irrigated and the amount of cropland classified as irrigated by this method is reasonable. This method classifies approximately 10 percent of total cropland as irrigated in 1988, about 9 percent in 1999, and about 10 percent in 2011. These estimates reasonably agree with the county-wide irrigation trends in the study area. Since 1978, the average percentage of irrigated land for the counties intersecting the Brazos River Alluvium Aquifer has been approximately 9 percent of total cropland (United States Department of Agriculture, 1978, 1997, 2007). Fort Bend County, where about 18 percent of the total cropland area is irrigated, contains the highest percentage of irrigated cropland in the aquifer, followed by Falls County (about 17 percent), and Robertson County (about 12 percent).

Additional recharge was applied to grid cells classified as irrigated to account for irrigation return flow. Applied irrigation within the extent of the Brazos River Alluvium Aquifer was assumed to be approximately 14 inches per year, which is the average irrigation requirement for non-rice crops in the counties in the study area (TWDB, 2015). The percentage of applied irrigation that becomes return flow will change through time according to Table 4.3.3.

4.3.2.3 Surface Soils

Soil properties can have a significant influence on recharge because of their impact on runoff, infiltration, and evapotranspiration. In general, sandy soils typically accept more infiltration for a given precipitation event than clayey soils. Clay soils tend to retain water, allowing more time for evapotranspiration by vegetation. Particularly in a shallow unconfined aquifer like the Brazos River Alluvium Aquifer, soil can have a major impact on the amount of water that reaches the water table. The primary property of surface soils effecting infiltration is saturated hydraulic conductivity, with infiltration to the water table correlated with the magnitude of the saturated hydraulic conductivity. Figure 2.1.4 shows the saturated hydraulic conductivity for surface soils in the active model boundary within the study area for the Brazos River Alluvium Aquifer.

4.3.2.4 Topography

Topography affects the distribution of recharge, concentrating recharge in highlands and discharge in lowlands (Meyboom, 1966; Toth, 1963). Areas with steeper slopes tend to have enhanced runoff and are, therefore, less likely to be areas where significant recharge occurs. In these regions, recharge is generally restricted to areas where runoff is focused, such as in stream beds, or areas with very coarse textured soils, such as sand dunes. Elevation changes within the extent of the Brazos River Alluvium Aquifer are minor. The Brazos River is conceptualized as the main discharge point with most of the rest of the aquifer serving as recharge areas. Beyond the extent of the Brazos River Alluvium Aquifer, areas with slopes higher than 5 percent (Figure 4.3.4) will likely have little to no recharge.

4.3.2.5 Focused Recharge from Surface Water Features

The Brazos River Alluvium Aquifer hosts a great deal of sand and gravel mining. If the excavation is deep enough to reach the water table, the mining sites can fill with water and have enhanced groundwater evaporation. In general, a gravel pit or other excavation that intersects the water table should be considered a discharge point for the aquifer (Ashworth and Hopkins, 1995). However, if the excavation does not reach the water table, the mining site can be a location of enhanced groundwater recharge. Since the process of mining removes the top layers of sediment, water has to percolate a shorter vertical distance to reach the water table. It is difficult to apply this concept to the study area though, as there is little to no information available on the degree to which excavations in the Brazos River Alluvium Aquifer intersect the water table, if at all. A study in the Pacific Northwest found that gravel mining excavations enhanced the recharge rate during the wet season and decreased the recharge rate during the dry season (Pacific Groundwater Group, 2000). However, because the current Brazos River Alluvium Aquifer groundwater model uses annual stress periods, it cannot account for these potential seasonal variations in recharge. Therefore, for the purposes of the current groundwater model, mining excavations are conceptualized as focused points of net recharge. This seems a reasonable assumption since the rainfall differences between the wet and dry season in the study area are not as pronounced as those in the Pacific Northwest, implying that the seasonal variation described in Pacific Groundwater Group (2000) is less likely to occur. Even if this assumption imperfectly captures the actual recharge behavior of these excavations, the impact to model recharge from these excavations, both in terms of areal footprint and total quantity of recharge, is miniscule compared to the overall areally-distributed recharge in the model. Figure 4.3.5 provides the locations of mining excavations mapped using point data for gravel pits, mines, and quarries from the SSURGO database (United States Department of Agriculture, 2014b). Locations of gravel pits georeferenced from Cronin and Wilson (1967) are also included on this figure.

4.3.3 Relationship between Base Flow and Precipitation

In the northern portion of the study area, where no previous studies to describe recharge exist, recharge had to be estimated as part of this study. Recharge as a function of precipitation was estimated based on base flow calculated from hydrograph separation analyses and a relationship between base flow and precipitation was developed.

4.3.3.1 Base Flow Calculations

Stream base flow can be used as a surrogate measure of shallow recharge, assuming that most of the shallow recharge discharges through base flow. In reality, some portion of shallow recharge will discharge through seeps and groundwater evapotranspiration. It is difficult to estimate how much shallow recharge exceeds the base flow estimates due to other sources of discharge, such as groundwater evapotranspiration. Groundwater availability models in Texas aquifers along the Gulf Coast have simulated groundwater evapotranspiration to be as low as 3 percent and as high as 48 percent of the total discharge water budget (Scanlon and others, 2005). However, there are no known estimates of groundwater evapotranspiration based on field measurements in the northern region of the study area. In general, since other discharge sources are so uncertain, base flow estimates should only be considered minimum estimates of shallow recharge. The minimum recharge flux rate is determined by dividing the base flow rate by the subwatershed area, which is the catchment area above the gage. For the current study, hydrograph separation analyses were completed on gages with subwatersheds that intersect the study area.

Hydrograph separation is a methodology in which streamflow hydrograph data are analyzed and surface runoff is partitioned from the stream base flow component. The basic premise is that, in the streamflow hydrograph, sharp peaks will represent surface runoff events, whereas the smooth, constant portion of the streamflow hydrograph represents base flow. There are several automated methods available to perform the separation. The hydrograph separation code Base Flow Index (Wahl and Wahl, 1995) was used for the analyses in the current study. Figure 4.3.6 shows an example of this technique for streamflow gage 08105000 on the San Gabriel River near Georgetown, Texas in 1970. This figure illustrates how the base flow component remains relatively steady while overall flow varies over several orders of magnitude.

Although hydrograph separation is relatively easy to perform, finding appropriate streamflow gage data can be difficult. Gages and their corresponding data must meet certain criteria before they can be considered for analysis. The primary criteria considered in the current study are:

1. The gage should be on a stream considered to be primarily gaining.

2. The catchment area for the gage must be primarily within the extent of the active model area.
3. If the catchment area for the gage extends well upstream of the extent of the active model area, there must be an upstream gage near the edge of the model area that can be used to subtract the effects of the upstream area (i.e., the contribution from the catchment area that is not within the area of interest).
4. The majority of the catchment area for the gage must be unregulated. If the gage is paired with an upstream gage, the unregulated periods must have a significant overlapping record.

To address criteria number one, gages on perennial streams are considered. Theoretically, an intermittent stream could be appropriate for those periods of time when the stream is flowing consistently. However, a comparison between recharge values estimated with the hydrograph separation method versus the chloride mass balance method revealed that, in the Gulf Coast Aquifer area, only recharge values estimated from gages on perennial streams agreed with estimates from the chloride mass balance method, while values estimated from gages on non-perennial streams did not (Scanlon and others, 2012). Therefore, for the purpose of this analysis, only gages on perennial streams, defined as having non-zero discharge 99 percent of the time, were used. Flow duration curves for the gages used in the analysis are provided in Appendix B.

To address criteria numbers two and three, gages that did not fall on the main stem of the Brazos River were included only if greater than 50 percent of the subwatershed fell within the active model area. The exception is gage 08095200 which is included, even though its subwatershed falls largely outside the study area, because it overlaps the subwatersheds of some main stem Brazos River gages. For gages located on the main stem of the Brazos River, all of the subwatersheds extended far beyond the active model area. Therefore, gages were paired with an upstream gage along the Brazos River and the upstream subwatershed area was removed from the downstream subwatershed so that the remaining subwatershed area fell mostly within the active model area. For these gages, only the incremental base flow (downstream base flow minus upstream base flow) was considered. The inclusion of one or two upstream gages increases the potential error in the base flow calculation, so this must be considered when analyzing the hydrograph separation results.

Criteria number four is difficult to overcome, since many of the major rivers in Texas are highly regulated. In some cases, analysts attempt to use local knowledge of river management to account for regulation of the river. This is a difficult and time-consuming approach that is not tractable for the current study. For the purposes of this analysis, regulation status was determined from Slade and others (2002). For gages not included in that study or listed as "unregulated," regulation status was determined using the National Water Information System (United States Geological Survey, 2015b). Gages listed as "urban" by Slade and others (2002) were also excluded. Like the regulated gages, streamflow at these gages does not represent the natural baseflow and higher runoff from impervious surfaces and urban effluent can skew recharge estimates. As expected, these gages did yield anomalously high recharge values compared to surrounding gages, justifying their exclusion. Gage 08074020 on Whiteoak Bayou at Alabonson Road in Houston, Texas, was also excluded from the analysis. It is not classified as "urban" or regulated in any of the sources but was assumed to be urban due to its proximity to other "urban" gages as well as its exceedingly high calculated recharge value.

Due to Whitney Dam, all gages on the Brazos River are categorized as regulated. For the period after the construction of Whitney Dam (1952 to 2013), the current study compared streamflow at gage 8093100 located a short distance downstream from the dam (Figure 4.3.7) to the daily release records for Lake Whitney. This comparison indicated that almost all the streamflow at gage 8093100 originates as a release from Lake Whitney rather than as base flow. Evaluating the influence of dam releases on gages further downstream was, however, difficult. For instance, some of the calculated base flow at gage 8096500 located in Waco (see Figure 4.3.7) may actually be releases from Lake Whitney rather than contribution from groundwater. To evaluate this, Lake Whitney releases were subtracted from the calculated base flow values for gage 8096500 at Waco. This adjustment resulted in little to no actual base flow at the gage after accounting for losses and travel time. Although this may be the case, it did not seem completely reasonable since the data prior to the construction of Lake Whitney show base flow originating in the reach between the gages 8093100 and 8096500, and it seems likely that this would continue after the construction of the reservoir. Therefore, the current study did not adjust the calculated base flow for the Waco gage based on releases from Whitney Dam and assumed no impacts from Lake Whitney on gages further downstream.

Figure 4.3.7 shows the gages used in the hydrograph separation analysis and the resulting recharge estimates. Table 4.3.4 provides information on the location of these gages and summarizes the recharge estimates obtained through the hydrograph separation analyses. As noted previously, the constraints imposed by the hydrograph separation technique result in a small set of potentially valid gages. These gages are on rivers and streams that vary widely in their basic characteristics of subwatershed area and overall flow. The temporal trends in base flow for the gages used in the current analyses are given in Appendix B.

4.3.3.2 Relationship between Base flow and Precipitation

The base flow estimates described above can provide a basis for deriving a relationship between shallow recharge and precipitation. Based on this relationship, the temporal variation in recharge under particular climatic conditions can be estimated.

Monthly precipitation for each subwatershed was estimated by intersecting the boundary of the subwatershed with monthly precipitation grids from the Parameter-elevation Regression on Independent Slopes Model (PRISM) precipitation dataset (PRISM Climate Group, 2014). Subwatershed boundaries were downloaded from the United States Geological Survey (2012). Subwatersheds not included in that dataset were delineated using the “batch subwatershed delineation” tool in ArcHydro Tools (Maidment, 2002) based on the 30-meter Digital Elevation Model (United States Geological Survey, 2015c). The daily base flow values for each month were summed so that monthly total base flow estimates were obtained and could be compared to the corresponding monthly precipitation estimates for each subwatershed.

Even in shallow systems, subregional groundwater flow is typically not a process that happens on short time scales. Because the measurement of base flow integrates recharge from flow paths of widely varying lengths, the base flow response will not occur at a single time, and so a correlation between precipitation and base flow is not expected, even on a monthly timescale. Therefore, the analysis of the relationship between precipitation and base flow was performed on an average timescale that captures the response time of the majority of the flow paths. The objective was to predict annual average base flow, based on a 12-month precipitation average that leads the base flow by some number of months. This annual average should allow all of the smaller temporal effects on base flow, such as bank storage, to be integrated within the time window. Note that this annual averaging aggregates any effects of in-year seasonal variations, which may be problematic for scenarios in which shorter (for instance, monthly) time periods are of interest. There is a significant seasonal component to base flow and the lowest base flow was found to occur during the growing season (April to September), likely due to the combination of low precipitation and high pumping withdrawals.

Regressions of annual average base flow versus a 12-month average precipitation were performed with a time lag (base flow lagging precipitation) varying from zero to 10 months. Note that in the regressions, the response variable was the logarithm of base flow and the predictor was untransformed precipitation, because annual average base flow is approximately lognormally distributed, while annual precipitation is approximately normally distributed. After performing the regressions for each of the lag times, the regression model with the best fit based on the coefficient of determination was selected. A summary of the results for the analyzed gages is shown in Table 4.3.5. Example plots of base flow versus precipitation and the corresponding linear trendlines are shown in Figure 4.3.8 and plots for all gages used in the analyses can be found in Appendix B. Of the regressions on the gage data, sixteen resulted in a coefficient of determination greater than 0.3. The median of the slopes for these lines was 0.021 and the median of the intercepts was -0.827.

The objective of the analysis was to produce a single equation describing the relationship between base flow and precipitation for the Brazos River Alluvium Aquifer and vicinity. Since creating multiple equations would be needlessly complex given the overall uncertainty in the base data, the following single relationship was developed using the median coefficients:

$$Recharge = 10^{(0.021 * precipitation - 0.827)} \tag{4.3.1}$$

Figure 4.3.9 shows the recharge distribution estimated using Equation 4.3.1. The precipitation values were taken from the average annual precipitation distribution for 1981 to 2010 from PRISM Climate Group (2014). The recharge increases from northwest to southeast, tracking the precipitation pattern.

4.3.4 Recharge Estimates

Recharge estimates from the previous studies of the Gulf Coast Aquifer System (Scanlon and others, 2012) and the Yegua-Jackson Aquifer (Deeds and others, 2010) were used as the basis to describe the pre-development recharge in the southern portion of the active model area. Previous studies of recharge are lacking in the northern portion of the active model area. Therefore, the relationship between precipitation and recharge given by Equation 4.3.1 was used as the basis to estimate recharge in the northern portion of the active model area. Estimates of recharge were developed for both the pre- and post-development periods for the Brazos River Alluvium Aquifer as discussed below.

4.3.4.1 Pre-development Recharge (pre-1950)

Prior to the introduction of widespread agricultural irrigation and groundwater pumping in the 1950s, the Brazos River Alluvium Aquifer was assumed to have been under steady-state conditions. Therefore, recharge to the aquifer during pre-development should be equivalent to natural aquifer discharge in the form of springs, base flow to streams, and groundwater evapotranspiration. Within the entire extent of the Brazos River Alluvium Aquifer, recharge patterns are affected by soil type, which is not accounted for in the recharge estimates from previous studies and developed using Equation 4.3.1. The conceptualization of the aquifer assumed that areas with low permeability soils, like the Ships Clay, represent areas with decreased recharge potential compared to the rest of the alluvium. The mean saturated hydraulic conductivity of the Ships Clay soil units in the study area is 0.054 feet per day. Therefore, areas within the boundary of the Brazos River Alluvium Aquifer with a saturated soil hydraulic conductivity value lower than 0.054 feet per day were assumed to only transmit 20 percent of the recharge expected based on the previous studies in the south and Equation 4.3.1 in the north. Figure 4.3.10 depicts the pre-development recharge distribution developed using the combination of approaches for describing recharge in the southern and northern portions of the study area along with the modification for soil type in the Brazos River Alluvium Aquifer.

4.3.4.2 Post-Development Recharge (1950 to present)

With the introduction of widespread groundwater pumping in the 1950s, as well as the increase in other anthropogenic influences, recharge patterns in the Brazos River Alluvium Aquifer changed from pre-development steady-state conditions. The conceptualization of the post-development recharge distribution takes into account increased recharge due to irrigation return flow and focused recharge from gravel pits. Irrigation return flow was distributed according to the spatial and temporal distribution developed in Section 4.3.2.2. The gravel pits and mine locations described in Section 4.3.2.5 were considered focused recharge points with recharge rates 1.5 times that during pre-development. Any changes to recharge in areas outside the extent of the Brazos River Alluvium Aquifer between pre- and post-development were not considered.

Figure 4.3.11 shows the estimated post-development distribution of recharge in the study area. This distribution is the same as the estimated pre-development recharge distribution, but with modifications accounting for irrigation return flow and enhanced recharge in gravel pits in the Brazos River Alluvium Aquifer. Because changes in precipitation over time may influence recharge, an evaluation of the importance of varying recharge as a function of precipitation will be made during the numerical modeling phase of this project.

Table 4.3.1 Summary of recharge estimates from the literature (adapted from Chowdhury and others, 2010).

Year	Recharge (inches per year)			Method	Source
	Minimum	Maximum	Average		
1957–1961	1.8	5.3	3.5	Flow between flow lines (Keech and Dreeszen, 1959)	Cronin and Wilson (1967)
1994–2004(1)	0.06	5.57	0.74	Digital base flow separation	Chowdhury and others (2010)
1934–1998(2)	0.02	9.7	0.95	Digital base flow separation	Chowdhury and others (2010)
1934–1998(2)	0.11	3.39	0.33	Chloride Mass Balance	Chowdhury and others (2010)

(1) Base flow estimates for streamgage 8108700 near Bryan, Texas
(2) Base flow estimates for streamgage 8111500 near Hempstead, Texas

Table 4.3.2 Irrigation methods by county (TWDB, 2001).

County	Year	Total Irrigated Land (acres)	Land Irrigated with Sprinkler Systems (acres)	Land Irrigated with Drip Systems (acres)	Percentage of Total Irrigated Land	
					Sprinkler	Drip
Austin	2000	2,980	831	37	28	1.2
Bosque	2000	1,982	1,902	50	96	2.5
Brazos	2000	8,325	0	25	0	0.3
Burleson	2000	18,959	6,903	0	36	0.0
Falls	2000	2,331	1,044	27	45	1.2
Grimes	2000	716	60	50	8	7.0
Fort Bend	2000	14,456	1,166	8	8	0.1
Hill	2000	26	26	0	100	0.0
McLennan	2000	3,972	1,820	112	46	2.8
Milam	2000	3,838	3,833	5	100	0.1
Robertson	2000	17,888	2,307	254	13	1.4
Waller	2000	7,453	1,330	308	18	4.1
Washington	2000	563	231	332	41	59.0

Table 4.3.3 Return flow as a percentage of applied irrigation from 1940 to present (Blandford and others, 2003.)

Time Period	Estimated Return Flow (percent)	
	Texas High Plains (similar to Bosque, Hill, Milam, Washington counties)	New Mexico High Plains (similar to Austin, Brazos, Burleson, Falls, Grimes, Fort Bend, McLennan, Robertson, Waller counties)
1940-1960	55	55
1961-1965	50	50
1966-1970	45	50
1971-1975	40	50
1976-1980	35	40
1981-1985	25	40
1986-1990	20	35
1991-1995	15	25
1996-2000	10	20

Table 4.3.4 Gage information and recharge estimates from the base flow analysis.

Gage Number	Gage Name	Estimated Recharge (inches/year)
08095200	North Bosque River at Valley Mills, TX	0.77
08069500	West Fork San Jacinto River near Humble, TX	1.49
08110500	Navasota River near Easterly, TX	0.40
08103800	Lampasas River near Kempner, TX	0.85
08105700	San Gabriel River at Laneport, TX	2.43
08117500	San Bernard River near Boling, TX	1.51
08105000	San Gabriel River at Georgetown, TX	1.82
08068500	Spring Creek near Spring, TX	1.41
08074000	Buffalo Bayou at Houston, TX	1.31
08068800	Cypress Creek at Grant Rd near Cypress, TX	0.90
08068740	Cypress Creek at House-Hahl Road near Cypress, TX	0.47
08072300	Buffalo Bayou near Katy, TX	1.04
08068325	Willow Creek near Tomball, TX	1.29
08076997	Clear Creek at Mykawa St near Pearland, TX	3.30
08109000	Brazos River near Bryan, TX	1.29
08108700	Brazos River at SH 21 near Bryan, TX	1.84
08096500	Brazos River at Waco, TX	0.78
08111500	Brazos River near Hempstead, TX	0.91
08114000	Brazos River at Richmond, TX	3.90

Table 4.3.5 Data used to develop a relationship between precipitation and base flow.

Gage Number	Lag (months)	Coefficient of Determination (R^2)	y - Intercept	Slope
8096500	3	0.18[1]	-0.872	0.020
8108700	6	0.42	-0.133	0.010
8109000	6	0.11[1]	-0.141	0.007
8111500	3	0.26[1]	-0.455	0.010
8114000	3	0.31	-0.047	0.014
8068325	0	0.37	-0.338	0.009
8068500	3	0.56	-0.707	0.018
8068740	1	0.51	-1.847	0.031
8068800	1	0.41	-1.139	0.020
8069500	4	0.59	-0.579	0.017
8072300	0	0.46	-0.631	0.013
8074000	0	0.66	-1.184	0.026
8076997	2	0.59	0.139	0.008
8095200	1	0.49	-2.335	0.065
8103800	3	0.30	-1.060	0.030
8105000	4	0.51	-1.758	0.057
8105700	5	0.54	-0.841	0.034
8110500	2	0.52	-1.754	0.034
8117500	1	0.54	-0.814	0.022

[1] R^2 coefficient is less than 0.3, so the y- intercept and slope were not included in the calculation of the average relationship between precipitation and base flow in the study area.

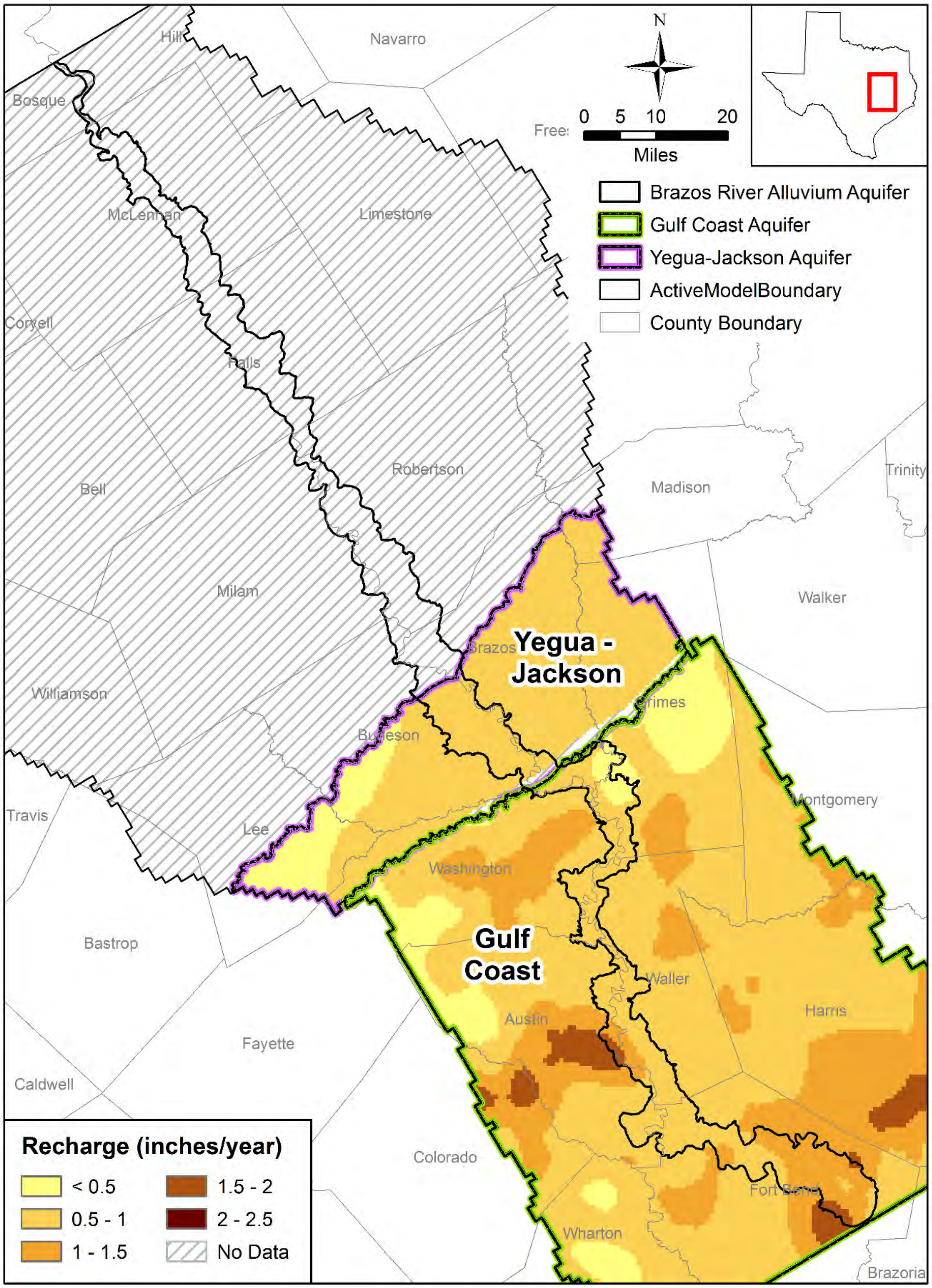


Figure 4.3.1 Recharge distributions in inches per year from previous work (after Deeds and others, 2010; Scanlon and others, 2012).

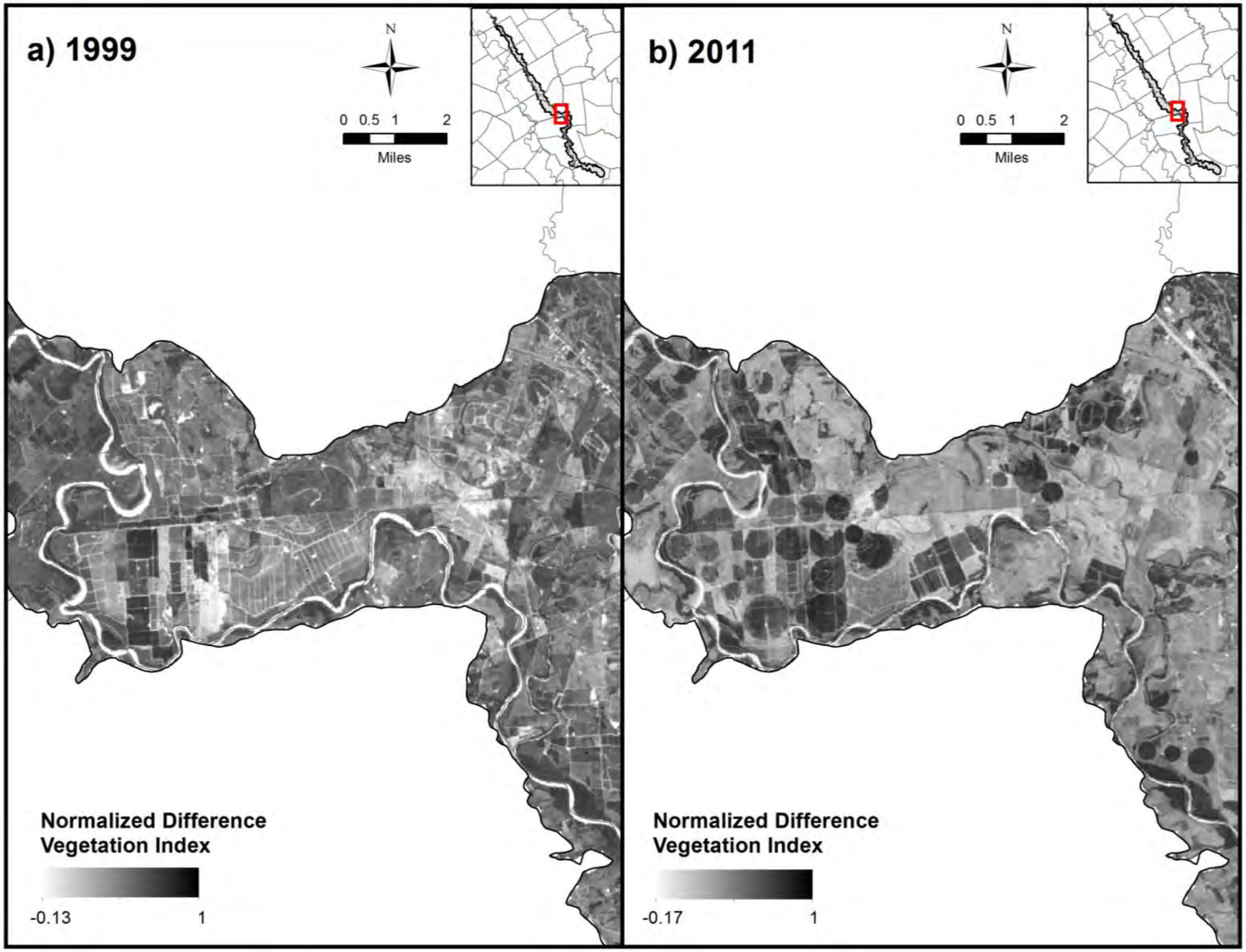


Figure 4.3.2 Example area illustrating the transition to sprinkler irrigation between 1999 and 2011.

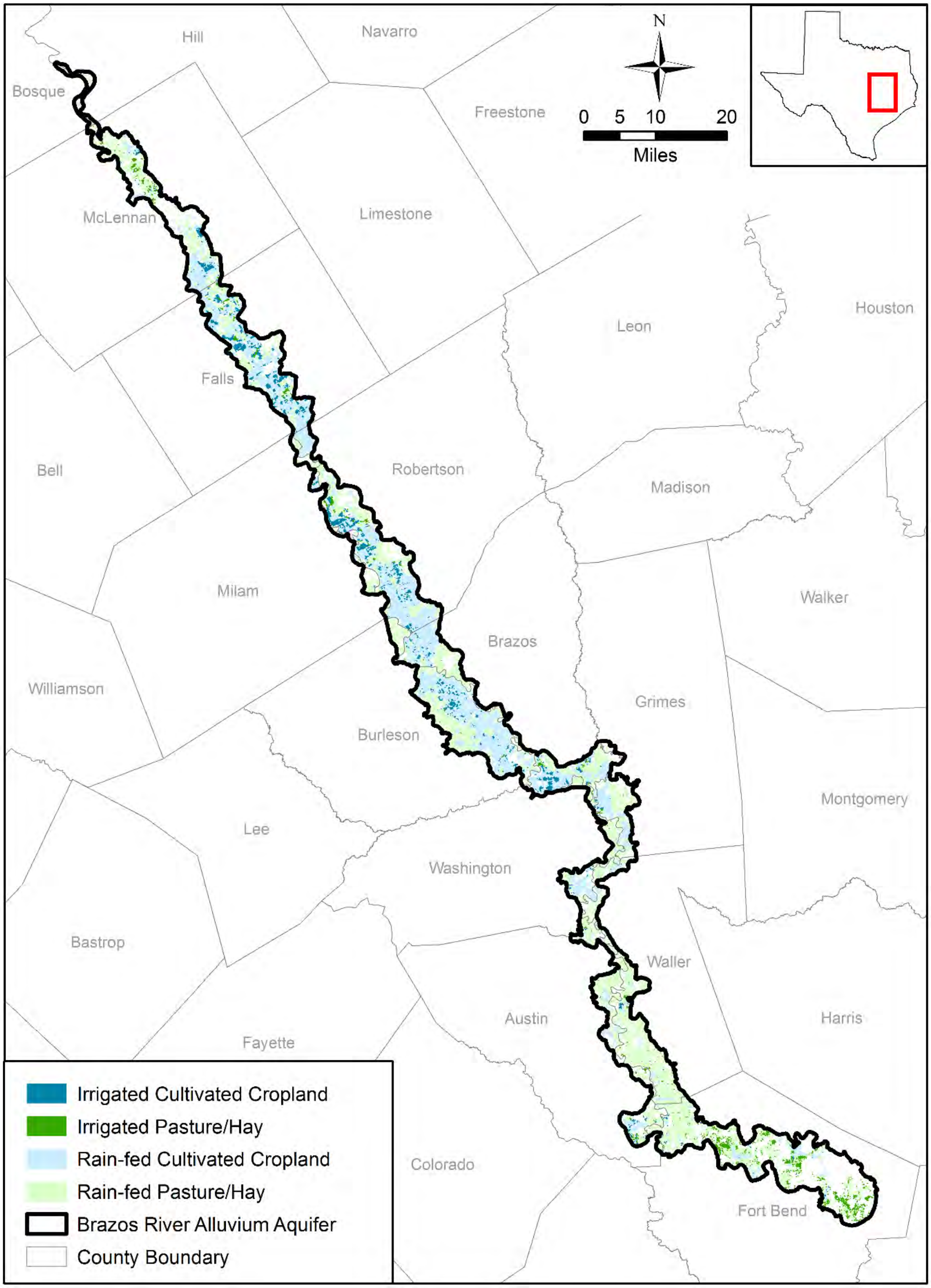


Figure 4.3.3 Estimated spatial distribution of irrigated and rain-fed cropland in 2011.

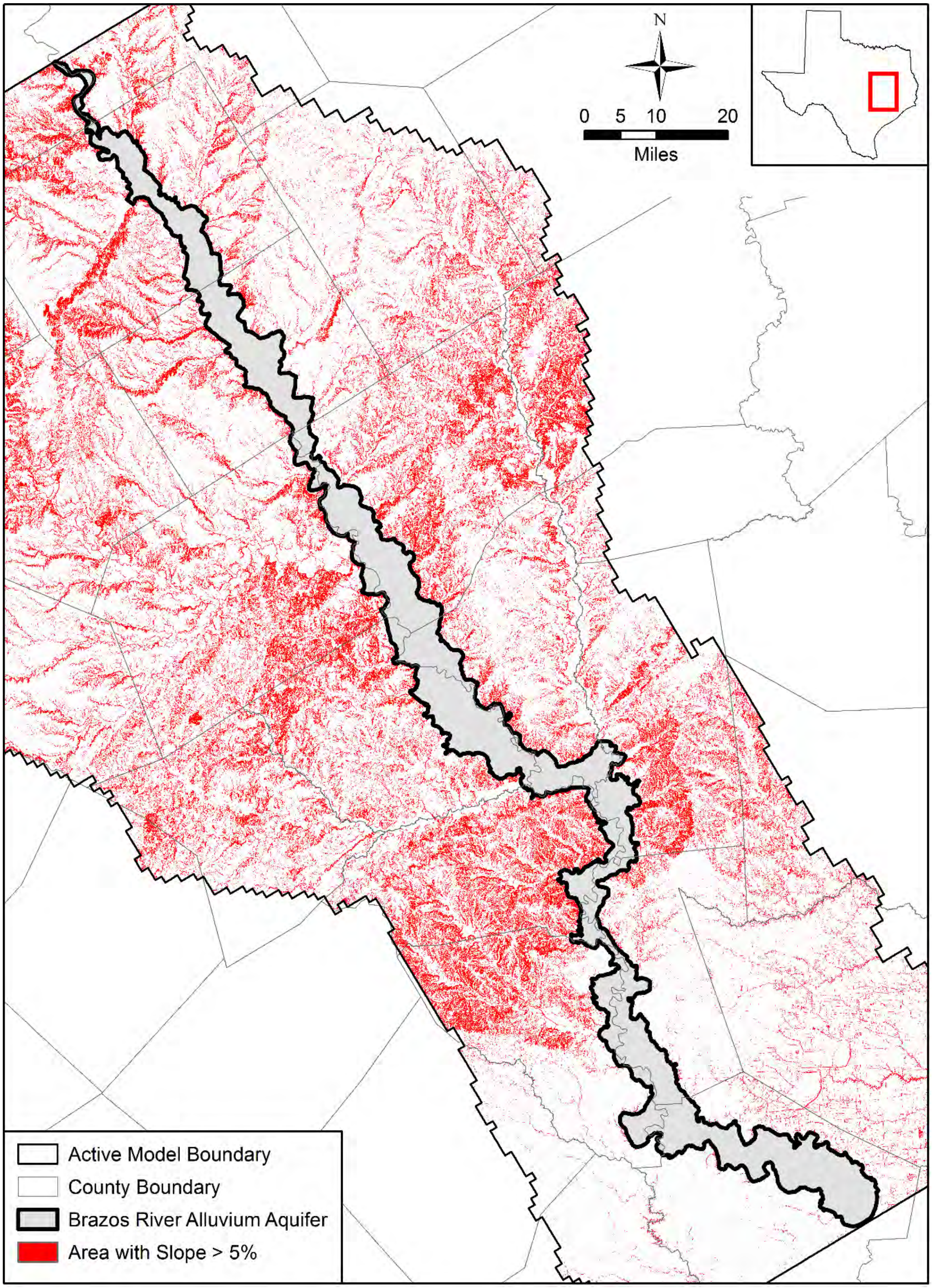


Figure 4.3.4 Areas with steep slopes (greater than 5 percent) in the study area.

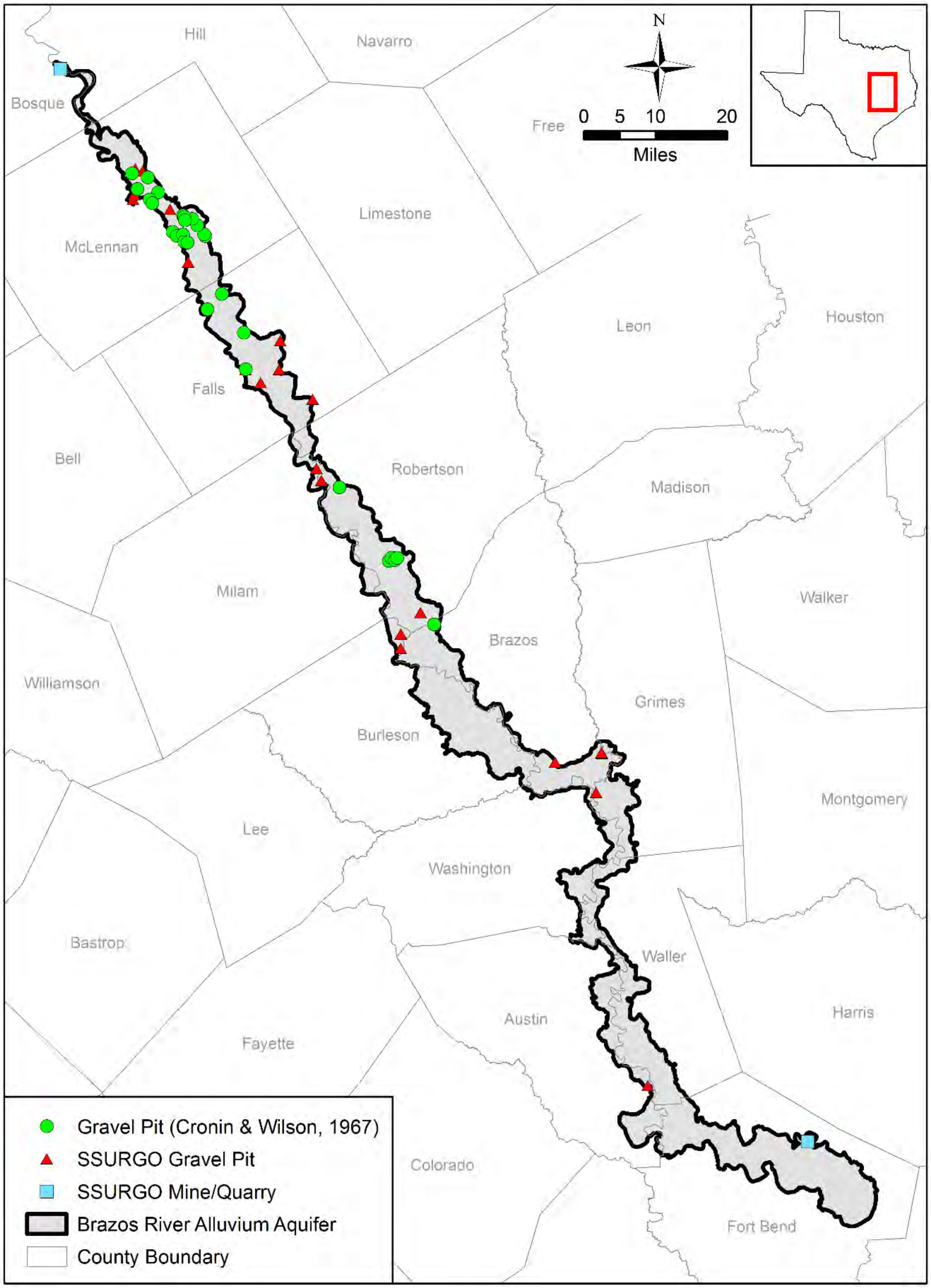


Figure 4.3.5 Location of gravel pits and mining excavations in the study area.

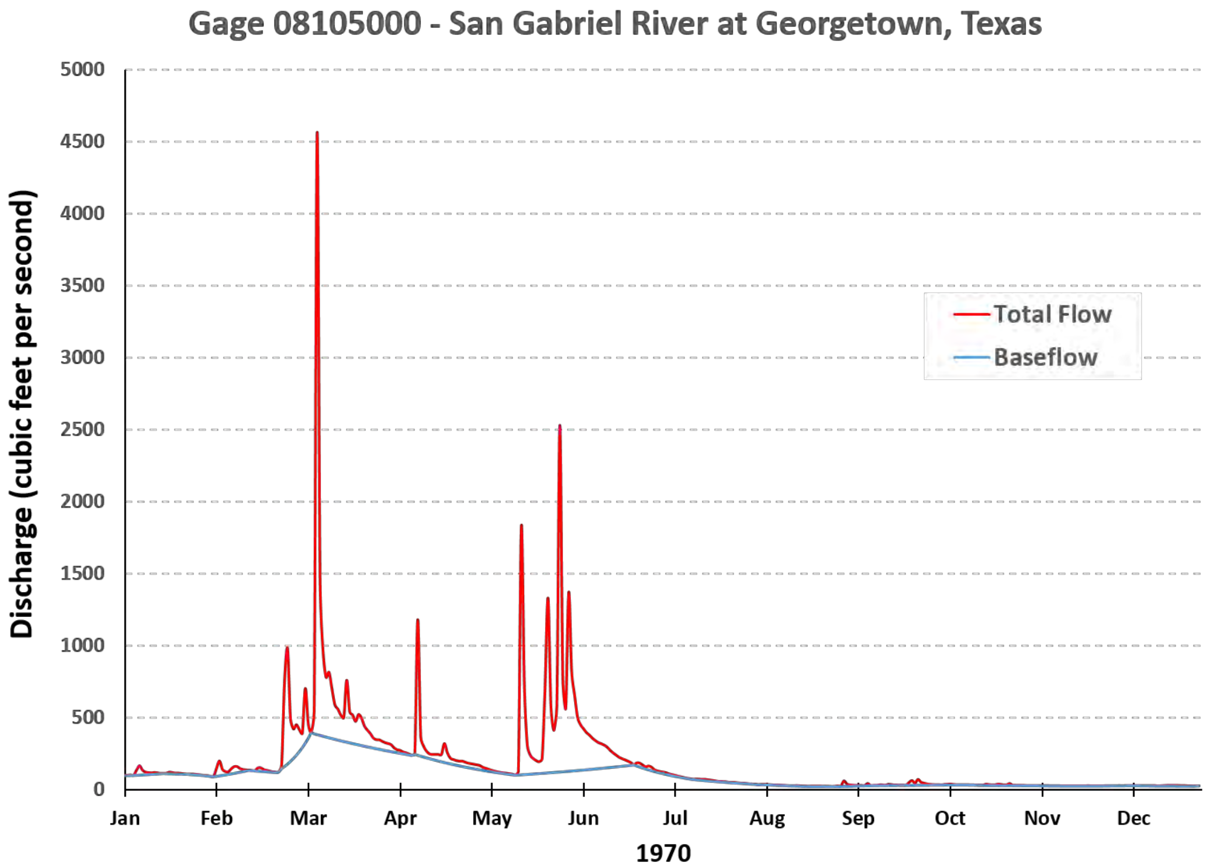


Figure 4.3.6 Example hydrograph separation for gage 08105000 on the San Gabriel River near Georgetown, Texas.

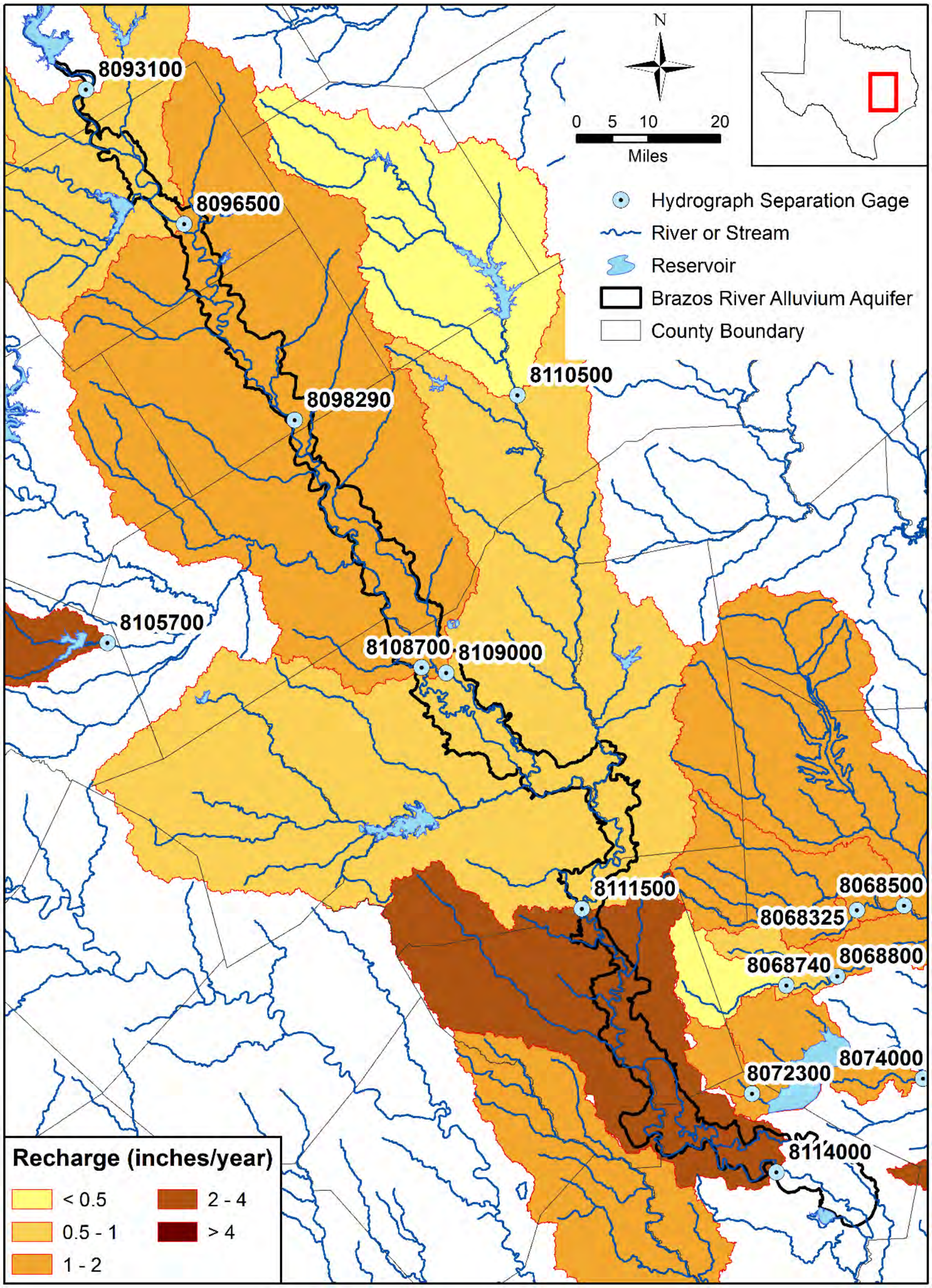


Figure 4.3.7 Recharge estimates in inches per year for the gages used in the hydrograph separation analysis.

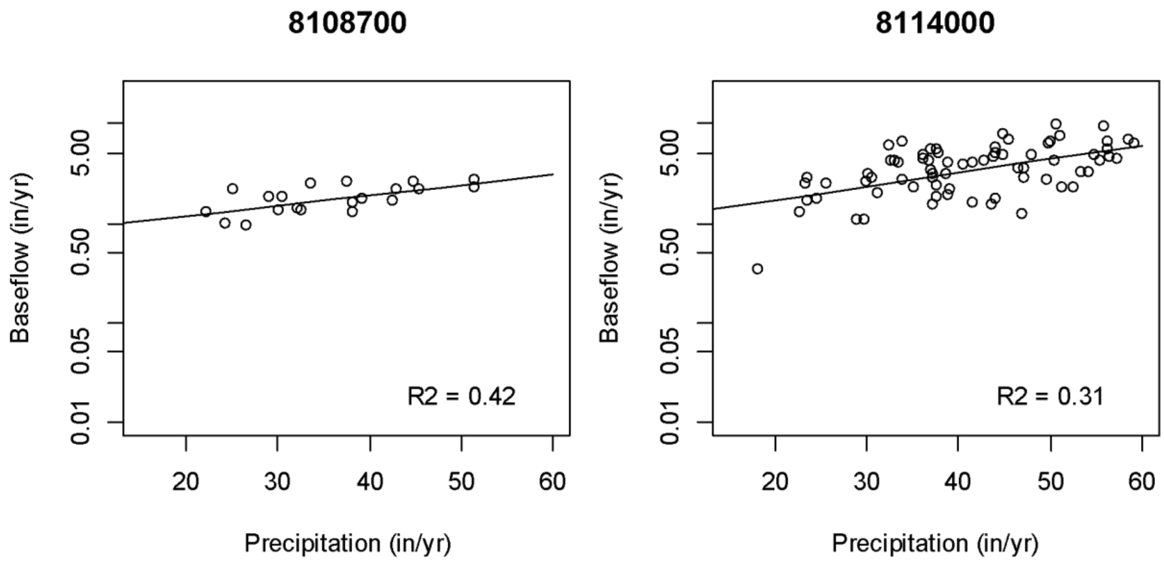


Figure 4.3.8 Example plots of baseflow versus precipitation and the corresponding linear trendlines.

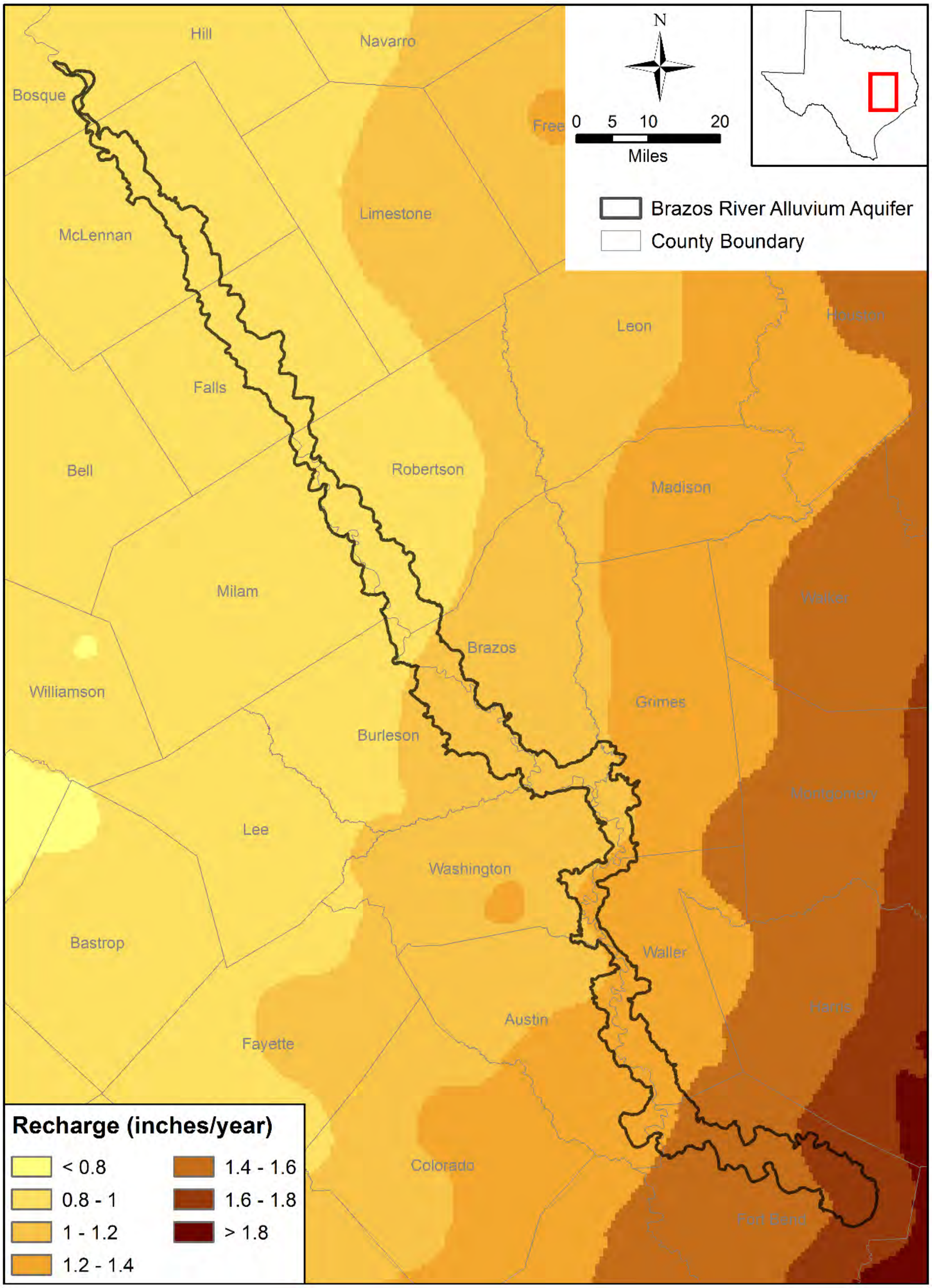


Figure 4.3.9 Recharge distribution in inches per year estimated using the developed relationship between precipitation and recharge.

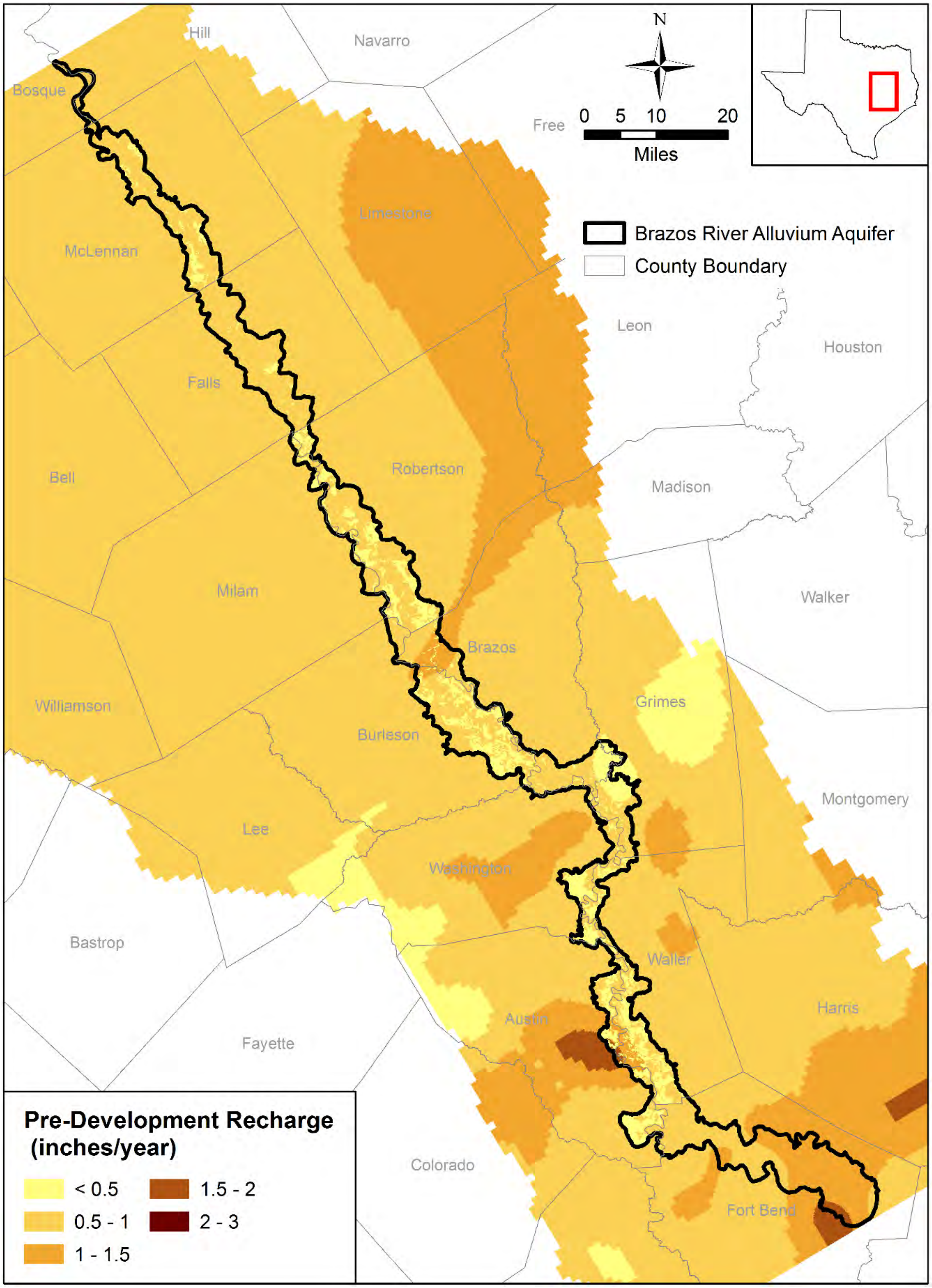


Figure 4.3.10 Estimated pre-development recharge distribution in inches per year.

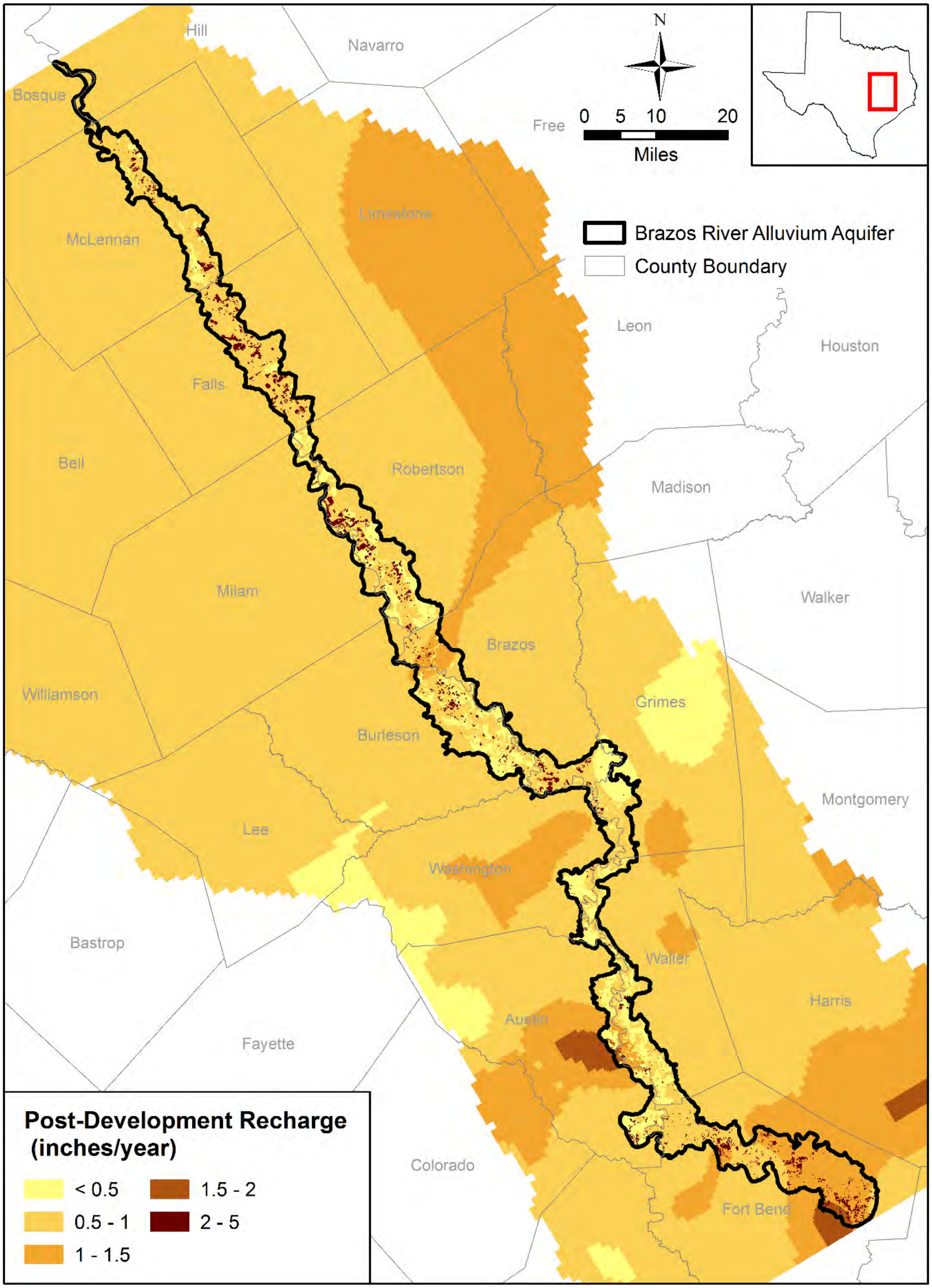


Figure 4.3.11 Estimated post-development recharge distribution in inches per year.

4.4 Rivers, Streams, Springs, and Reservoirs

In areas where an aquifer is unconfined, interaction between groundwater and surface water can occur at the locations of rivers, streams, springs, and lakes/reservoirs. Rivers and streams can either lose water to the underlying aquifer, resulting in aquifer recharge, or gain water from the underlying aquifer, resulting in aquifer discharge. Lakes/reservoirs, including oxbow lakes, are similar to rivers and streams in that they may provide a potential site of focused aquifer recharge when the water table is below the elevation of the lake, or may gain water from an aquifer when the water table is above the elevation of the lake. Springs and seeps, where the water table intersects the ground surface, are points of aquifer discharge.

4.4.1 Rivers and Streams

The Brazos River is the only major river that intersects the Brazos River Alluvium Aquifer. For the purposes of this conceptual model, groundwater divides were assumed to be equivalent to surface water divides. Therefore, surface water-groundwater interaction was predominantly considered only for the Brazos River and its tributaries within the surface water divides, as defined by the active model boundary (see Section 2.0), in the study area (Figure 4.4.1). Within this area, there are 86 current or former United States Geological Survey streamflow gages on the Brazos River and its tributaries. The locations of these gages are also shown on Figure 4.4.1. On this figure, the gage number for gages located on the Brazos River are shown. Figure 4.4.2 provides representative streamflow hydrographs for the Brazos River and its major tributaries in the study area.

Stream gage data can be used to characterize streamflow rates and determine aquifer-stream interaction through stream gain/loss studies and hydrograph separation studies. Gain/loss studies represent a snapshot of a river at a given time, while hydrograph separation studies provide a measure of long-term average river conditions. Stream gain/loss can change both temporally (for example, be both gaining and losing within the same year) and spatially (for example, have a gaining reach followed by a losing reach). Inconsistencies can arise between results from gain/loss studies and hydrograph separation studies for the same river reach because measurements during a gain/loss study are typically recorded over a relatively short time period and base flow, determined through hydrograph separation for long periods of record, reflects average, long-term interaction between the stream and aquifer. Generally, groundwater flow models attempt to reproduce average stream-aquifer interaction integrated over a season or even a year. Therefore, caution should be used in interpreting results from gain/loss studies as indications of long-term base flow.

The following subsections discuss gain/loss studies and hydrograph separation studies from the literature and those conducted as part of the development of the conceptual model for the Brazos River Alluvium Aquifer. The study by Baldys and Schalla (2011) includes both gain/loss and hydrograph separation analyses. However, the portion of the Brazos River included in their hydrograph separation analysis lies outside of the active model boundary for the Brazos River Alluvium Aquifer and so, those results are not discussed in this report. This section also includes a discussion of aquifer-stream interaction at local points along the Brazos River as determined by a hydraulic gradient estimation using stream stage and nearby groundwater levels.

4.4.1.1 Gain/Loss Studies

Gain/loss studies are used to estimate gaining or losing conditions in a stream by performing a flow balance between two stream control points. The net gain or loss of flow between the two control points is attributed to stream gain or loss. Gain/loss studies are typically performed during low-flow conditions because this method assumes surface runoff is negligible. To ensure an accurate analysis, streamflow measurements should be adjusted for the timing, quantity, and downstream propagation of diversions and return flows occurring over the period of the study. Three reports provide results of stream gain/loss studies relevant to the Brazos River Alluvium Aquifer. Slade and others (2002) contains a compilation of the results of all available gain/loss studies conducted by United State Geological Survey in Texas up to the time of their investigation. Aquifer-stream interaction along the Brazos River was studied by Baldys and Schalla (2011) for the portion of the river from the New Mexico-Texas state line to Waco, Texas and by Turco and others (2007) for the portion of the river from McLennan to Fort Bend counties, Texas. In addition to these three studies, the gain/loss study by Turco and others (2007) was re-analyzed, as discussed below, during development of the conceptual model for the Brazos River Alluvium Aquifer. Each of these four studies is discussed below.

United States Geological Survey Streamflow Gain-Loss Studies in Texas (Slade and others, 2002)

A comprehensive compilation of gain/loss studies in Texas was completed by Slade and others (2002). This compilation contains the results of 366 gain/loss studies conducted since 1918, which include 249 individual stream reaches throughout Texas. Although none of the studies intersect the Brazos River Alluvium Aquifer, they document 28 gain/loss studies within the active model boundary (Figure 4.4.3). The results of these studies, which were conducted on western tributaries of the Brazos River, are summarized in Table 4.4.1. Study results found:

- Consistently gaining conditions only for Salado Creek (Studies 19, 20, 21, 22) and Sulphur Creek (Studies 30, 31). The study on Salado Creek showed a few losing reaches but gained, on average, 1.3 cubic feet per second per river mile. The studies on Sulphur Creek had no losing reaches and gained 3.66 cubic feet per second per river mile on average.
- All portions of the San Gabriel River were found to have several losing reaches but overall, appeared to be weakly gaining. On the North Fork San Gabriel River, Studies 14 through 17 found gaining conditions of 0.69 cubic feet per second per river mile on average for one reach of the river and Study 18 found gaining conditions of 0.14 cubic feet per second per river mile on another stretch of the river. The study on the San Gabriel River (Study 24) found gaining conditions of 0.22 cubic feet per second per river mile and the studies on two reaches of the South Fork San Gabriel River (Study 25 and Studies 26 through 29) found gaining conditions of 0.11 and 0.39 cubic feet per second per river mile on average, respectively.
- Results of the studies on Brushy Creek (Studies 5 through 8) showed gaining conditions of 0.73 cubic feet per second per river mile on average.
- The only study on the Leon River (Study 12) found some strongly losing reaches but slightly gaining conditions, on average, of 0.28 cubic feet per second per river mile.
- The Berry Creek studies (Studies 1 through 4) found both gaining conditions and barely losing conditions, with an overall average gain of 0.46 cubic feet per second per river mile.

- The results from two studies on the Lampasas River disagree. One study found the river to be strongly gaining (1.01 cubic feet per second per river mile on average) below the Stillhouse Hollow Dam (Study 11) and another study found the river to be slightly losing (0.07 cubic feet per second per river mile on average) below the Stillhouse Hollow Dam and for much of the river reach above the dam as well (Study 10).

United States Geological Survey Gain/Loss Studies for the Brazos River Upstream of Waco, Texas (Baldys and Schalla, 2011)

The United States Geological Survey conducted streamflow measurements for gain/loss analysis in 2010 along the upstream portion of the Brazos River and its tributaries from the New Mexico-Texas state line to Waco, Texas (Baldys and Schalla, 2011). The gages they used that fall within the active model boundary are shown in Figure 4.4.4a and summarized in Table 4.4.2.

Baldys and Schalla (2011) collected seasonal measurements of streamflow and specific conductance in June and October 2010 along the Brazos River and its tributaries in order to characterize the gaining or losing nature of the stream. The streamflow measurements for the gages located in the active model boundary are provided in Table 4.4.2. They concluded that the portion of North Bosque River from NB-7 to NB-10 and Aquilla Creek from BMST-12 to BMST-14 (see Figure 4.4.4a) were gaining. Cobb Creek upstream of BMST-13 (see Figure 4.4.4a) was dry during both sample periods and they assumed that this is a losing reach when it does flow. Baldys and Schalla (2011) mention that the portion of the Brazos River directly below Whitney Dam is likely gaining, but could not confirm this since they collected measurements at only one location below the dam (BMS-8).

United States Geological Survey Gain/Loss Studies for the Brazos River from McLennan to Fort Bend Counties (Turco and others, 2007)

The United States Geological Survey conducted streamflow measurements for gain/loss analysis in 2006 along the portion of the Brazos River and its tributaries from McLennan to Fort Bend counties (Turco and others, 2007). The gages they used for their gain/loss studies are shown in Figures 4.4.4a and 4.4.4b and summarized in Table 4.4.3.

Turco and others (2007) made seasonal measurements of streamflow and specific conductance in March and August 2006 in order to characterize the gaining or losing nature of the stream. The streamflow measurements for the gages located in the active model boundary are provided in Table 4.4.3. Turco and others (2007) computed gain/loss for a given reach as:

$$G = Q_D - Q_U - I + D - R + E \quad (4.4.1)$$

where:

G = streamflow gain or loss,

Q_D = measured streamflow at the downstream boundary,

Q_U = measured streamflow at the upstream boundary,

I = measured inflow from tributaries,

D = measured outflows (diversions),

R = return flow, and

E = evaporation.

Gains or losses from diversions, return flow, and evaporation were considered minor and excluded from their calculation. They rated the potential error associated with a streamflow measurement as either excellent (within 2 percent of actual flow), good (within 5 percent of actual flow), fair (within 8 percent of actual flow), or poor (differed from actual flow by greater than 8 percent) using the method for determining error in individual discharge measurements given in Sauer and Meyer (1992). They calculated the potential error for a river reach as the sum of the errors from the measurements at the upstream and downstream gages. Turco and others (2007) considered only data where the calculated gain or loss exceeded the measurement error as valid.

The results from Turco and other (2007) in the study area are shown on Figures 4.4.5a and 4.4.6a for the March 2006 and August 2006 measurements, respectively. On these figures, reaches with a gain are shown in green, reaches with a loss are shown in red, and reaches where they did not determine gain or loss because the measurement error exceeded the calculated gain/loss are not shown. For all reaches where they determined gain/loss, the reach was gaining in March 2006 (i.e., B1 to B2, B8 to B9, B10 to B-11, B11 to B12, and B15 to B16) (see Figure 4.4.5a). In August 2006, they were able to determine gain/loss for six reaches with gaining conditions observed for four reaches (B3 to B6, B6 to B9, B13 to B14, B15 to B16) and losing conditions observed for two reaches (B1 to B3, B20 to B21) (see Figure 4.4.6a). For one of these reaches

(B15 to B16), the Turco and others (2007) study found gaining conditions in both March and August 2006.

Updated Analysis of Turco and others (2007) for the Current Study

As part of developing the conceptual model for the Brazos River Alluvium Aquifer, the findings of Turco and others (2007) discussed above were updated for two reasons. The first was to include the contribution of diversions and return flows, which Turco and others (2007) ignored. The second was to re-compute the potential composite errors, as the method used by Turco and others (2007) is overly conservative, resulting in the unnecessary exclusion of some data.

Turco and others (2007) did not consider diversions, return flows, and evaporation in their analysis on the assumption that the magnitude of the error associated with excluding these variables was minor. They did not, however, provide supporting data for this assumption. Therefore, their findings were updated for the current study using actual and/or estimated values for diversions and return flows to assess the impact of excluding these variables on their results. For the updated analysis, diversion data were obtained from the Texas Commission on Environmental Quality historical use data for the time period of the Turco and others (2007) measurements (Texas Commission on Environmental Quality, 2014b). These diversion values are provided in Table 4.4.4 by river reach. There are some limitations in the use of these diversion data as diversions are self-reporting with no enforcement for failure to report and, therefore, gaps in the data are likely. Return flow data used in the development of the Brazos River Basin Water Availability Model (Texas Commission on Environmental Quality, 2014c) were also compiled for the current analysis. These values are given in Table 4.4.5 by river reach. Both diversions and return flows are reported on a monthly basis with flow rates averaged over the entire month. Because diversions may or may not have been made during the same time period that the flow measurements were taken, and return flows fluctuate on a daily basis, the use of the monthly average values for these two variables is also a limitation in including them in the current analysis.

Turco and others (2007) considered a stream reach verifiably gaining or losing only if the magnitude of the calculated gain/loss was greater than the potential flow measurement error. Their study calculated the potential flow measurement error by adding the errors associated with the downstream and upstream measurements:

$$E_{combined} = E_1 + E_2 \tag{4.4.2}$$

where:

$E_{combined}$ = combined measurement error for the upstream and downstream gages,

E_1 = measurement error for the upstream gage

E_2 = measurement error for the downstream gage.

Their method of combining errors represents the upper bound of the composite error and, therefore, likely overestimates the actual error. In addition, it implicitly assumes that the errors in measurements at the different locations are dependent (i.e., there is no possibility that the errors could offset each other). In actuality, flow measurements at different locations are independent quantities, so the error in the measurements at two different locations are just as likely to cancel each other out as be additive. Therefore, the errors should be added in quadrature as:

$$E_{combined} = \sqrt{E_1^2 + E_2^2} \tag{4.4.3}$$

For the current analysis, the errors for the Turco and others (2007) measurements were recalculated using Equation 4.4.3 rather than Equation 4.4.2. These updated values for the combined error in measurements are given in Tables 4.4.6 and 4.4.7 for the March and August 2006 measurements, respectively.

Using the addition of diversion and return flow data, the gain/loss for each river reach in the Turco and others (2007) study was recalculated. Tables 4.4.6 and Table 4.4.7 provide the updated results from the current analysis for the measurements in March and August 2006, respectively. In these tables, information in red, italicized text was taken directly from Turco and others (2007) and information in black text is from the current analysis. The updated gain/loss values were compared to the updated errors to determine whether the reach was gaining or losing. If the updated gain/loss value was less than the updated error, the conditions of the reach (either gaining or losing) was indeterminate by the current analysis.

Tables 4.4.8 and 4.4.9 compare the updated values from the current analysis to the values in Turco and others (2007). A comparison of the gaining or losing status of each river reach from the current analysis and the Turco and others (2007) analysis is shown in Figure 4.4.5 for the

March 2006 measurements and in Figure 4.4.6 for the August 2006 measurements. Note that both the current analysis and the Turco and others (2007) analysis indicate gaining conditions for the reaches intersecting the outcrops of the Carrizo-Wilcox and Yegua-Jackson aquifers for both March and August 2006.

Given the limitations of the available diversion and return flow data discussed above, it is unclear whether the inclusion of these data in the current analysis provided a marked improvement over the Turco and others (2007) analysis. The most significant improvement with the current analysis relates to the recalculation of the error, which allowed for the inclusion of more data and provided greater spatial coverage of the Brazos River. The current analysis resulted in 12 “valid” March measurements and nine “valid” August measurements compared to five “valid” March measurements and six “valid” August measurements in Turco and others (2007). In short, a total of 21 “valid” measurements resulted from the current study compared to 11 in Turco and others (2007).

Even with the improvements in the updated analysis, there is still uncertainty in the results due to the timing of stream measurements. For the March 2006 measurements on 35 reaches, the downstream measurement was made after the upstream measurement for 19 reaches; the downstream measurement was made before the upstream measurement for nine reaches; and the upstream and downstream measurements were made on the same day, but the time of day is unknown for at least one of the measurements, for seven reaches (see Table 4.4.6). The time difference between measurements (downstream time minus upstream time) ranged from -75 to 94 hours. For the August 2006 measurements on 27 reaches, the downstream measurement was made after the upstream measurement for 24 reaches; the downstream measurement was made before the upstream measurement for two reaches; and the upstream and downstream measurements for one reach were made on the same day, but the time is unknown for the upstream measurement (see Table 4.4.7). The time difference between measurements (downstream time minus upstream time) ranged from -26 to 74 hours. These differences in timing between downstream and upstream measurements suggest that travel time was likely not considered by Turco and others (2007) in their measurements. How the variation in streamflow between the times of the upstream and downstream measurements might have affected the analysis results is unclear. Additional analyses incorporating corrections for travel time based on available data at United State Geological Survey streamflow gages could be considered.

However, the time differences between measurements are small, a couple of hours to a couple days, relative to the time resolution available for the information needed to calculate a correction factor (for example, diversions and return flow data are only available on a monthly basis). Consequently, it is doubtful that travel time corrections could actually be determined with any accuracy.

4.4.1.2 Hydrograph Separation Studies

Hydrograph separation is a methodology whereby streamflow hydrograph data are analyzed and surface runoff is partitioned from the stream base flow component. The basic premise of this method is that the sharp peaks in streamflow hydrographs represent surface runoff events, and the smooth, constant portion of streamflow hydrographs represents base flow. Base flow for a stream is assumed to be supplied primarily by groundwater. Since manual methods for hydrograph separation are subjective and can produce inconsistencies, several automated methods have been developed to perform hydrograph separation.

Base flow estimates from hydrograph separation analysis conducted in the study area for the Brazos River Alluvium Aquifer conceptual model are available from the literature for two studies. Wolock (2003a,b) conducted a historical base flow analysis for the United States, including over 90 gages in the study area, using the Base Flow Index code (Wahl and Wahl, 1995). Turco and others (2007) performed a hydrograph separation analysis on 10 gages in the study area using the Hydrograph Separation and Analysis code (Sloto and Crouse, 1996). In addition to these two studies, an independent hydrograph separation analysis on seven gages using the Wahl and Wahl (1995) Base Flow Index code was performed as part of the current study conducted to develop the conceptual model for the Brazos River Alluvium Aquifer. These three hydrograph separation analyses are discussed below.

United States Geological Survey Conterminous United States Base Flow Study (Wolock, 2003a,b)

In 2003, the United States Geological Survey published a study for the entire conterminous United States that estimated the base flow component of streamflow, referred to as the base flow index, at more than 19,000 United States Geological Survey stream gages (Wolock, 2003a). The base flow index is calculated as the base flow divided by the total streamflow, expressed as a percentage. The United States Geological Survey used the point estimate values of base flow index from Wolock (2003a) to interpolate a raster dataset of base flow index values on a 1-kilometer (0.62-mile) grid that could be used to estimate base flow index values for streams with no gaged data (Wolock, 2003b).

The estimates of stream base flow were calculated by Wolock (2003a) using the Base Flow Index code (Wahl and Wahl, 1995). The location of gages in the Brazos River Alluvium Aquifer boundary with a calculated base flow index value in Wolock (2003a) are shown in Figure 4.4.7. Included on this figure, adjacent to each gage, is the base flow index value from Wolock (2003a), which ranges from 13 to 59 percent and averages 38 percent.

In addition to the point data provided in Wolock (2003a), raster data across the entire study area are available from Wolock (2003b). The raster data are not shown here, however, because they are inconsistent with the point data. The point data indicate that the base flow index values vary from 13 to 59 percent for the gages in the Brazos River Alluvium Aquifer. The raster data, on the other hand, indicate that the base flow index in the aquifer ranges from 6 to 30 percent. Since the point data were determined from streamflow measurements using hydrograph separation and the raster data are an interpolated surface, the point data were considered to be more reliable than the raster data.

United States Geological Survey Hydrograph Separation for the Brazos River from McLennan to Fort Bend Counties (Turco and others, 2007)

The United States Geological Survey performed hydrograph separation analyses for three streamflow gages on the main stem and seven gages on tributaries of the Brazos River from McLennan to Fort Bend counties, Texas (Turco and others, 2007). The locations of these gages are shown in Figure 4.4.8. The data from the tributaries were used by Turco and others (2007) only as supplemental information, as their primary emphasis was on the behavior of the main stem of the Brazos River. The Turco and others (2007) hydrograph separation analyses calculated yearly base flow indexes for the time period from 1966 through 2005. The results of their analysis yielded yearly base flow index values ranging from a low of 30 percent at the northernmost gage (B6) to a high of 76 percent at the southernmost gage (B36). In general, their results indicate that the percentage of base flow increases from north to south, with a significant increase between the northernmost gage (B6) and the central gage (B26). This reach crosses the outcrops of the Carrizo-Wilcox, Queen City, Sparta, and Yegua-Jackson aquifers, indicating that the observed gain is supplied by groundwater from these aquifers. In contrast, Turco and others (2007) found that the average percentage of base flow remains the same between the central gage (B26) and the southernmost gage (B36), indicating little to no contribution of groundwater from the underlying Gulf Coast Aquifer System.

Hydrograph Separation for the Current Study

In order to better characterize long-term groundwater-surface water interaction along the Brazos River, an independent hydrograph separation study was conducted as part of the current study for developing the conceptual model for the Brazos River Alluvium Aquifer. The current study included more gages along the Brazos River in the northern portion of the Brazos River Alluvium Aquifer over a longer time period than was used by Turco and others (2007). For the current study, base flow analyses were performed over the time period from 1940 through 2013 for select gages on the Brazos River between Lake Whitney and Richmond, Texas and a single gage on the Little River. These gages are shown in Figure 4.4.8 and listed in Table 4.4.10. The gages for the current study were selected based on having a sufficiently long period of record and a geographic location relevant to the Brazos River Alluvium Aquifer. Flow duration curves and temporal trends in base flow for the gages used in the current hydrograph separation study are given in Appendix B.

All gages using in the current study, except the Cameron gage (8106500), are located on the main stem of the Brazos River. The Cameron gage measures flow in the Little River, one of the largest tributaries of the Brazos River. Gages on other major tributaries located near the confluence with the main stem of the Brazos River, such as the Navasota River and Yegua Creek, were not included in the current study because they do not have long periods of record. The Bosque River, another significant tributary of the Brazos River, has been controlled by Lake Waco (or its smaller predecessor) for the entire analysis period (1940 through 2013), so gages on it were not included in the current study.

The most upstream gage on the Brazos River, which is near Aquilla, Texas (8093100), is located just downstream of Lake Whitney. For the period prior to the construction of the reservoir (1940 to 1947), base flow was taken directly from the hydrograph separation results. Data during the construction period of the reservoir (1948 to 1951) were eliminated from the analysis. The calculated base flow values from the post-impoundment period (1952 to 2013) were compared to daily release records for Lake Whitney available from the United States Army Corps of Engineers. That comparison is discussed in Section 4.3.3.

In September 1993, the gage on the Brazos River near Bryan, Texas (8109000) was replaced by a gage on the Brazos River at State Highway 21 near Bryan, Texas (8108700). Since these two gages are located very close to each other, the data from both gages were combined for the purposes of the current study. The combined data for these two gages contains a gap in 1993 during the time period when gage 8109000 was replaced by gage 8108700. Since a full year of data is required for hydrograph separation, the 1993 data were eliminated for the current study.

The current study used the Base Flow Index code (Wahl and Wahl, 1995) to conduct the hydrograph separations. Like all automated flow separation procedures, erroneous results can be produced due to rare events like flooding or man-made alterations of natural flow patterns. The following discussions explain how the current study adjusted the base flow estimates obtained from the Base Flow Index code to account for the effects of flooding, dam releases, and diversions from the stream.

The basic premise of the Base Flow Index code is identification of places that are "turning points" between ascending and descending limbs of a streamflow hydrograph. These points are used to separate runoff from base flow by essentially smoothing sharp peaks in the hydrograph. Under normal streamflow conditions, this assumption is reasonably accurate for differentiating between normal flow and high flow. However, events like dam releases and floods can produce sustained high streamflow rather than a short peak in streamflow. The Base Flow Index code does not always identify these events as a peak and so does not necessarily differentiate these events from normal base flow. Since the code calculates base flow as a function of total streamflow, the resulting base flow calculated during these events is correspondingly high and, thus, inaccurate. To counteract this bias, a maximum base flow was estimated for each gage based on inspection of the gage records (Table 4.4.11). If the calculated base flow exceeded this maximum value, the current study used the maximum value rather than the value calculated by the code.

Diversions can also influence the base flow calculation and typically have the opposite effect of floods and dam releases. Diversions decrease total streamflow and, if unaccounted for, the calculated base flow, which scales accordingly, is biased low. The effect is especially pronounced during periods of low flow, when total streamflow consists primarily of base flow. Diversions have a particularly pronounced effect during low-flow periods on the reach between the Hempstead and Richmond gages (8111500 and 8114000, respectively), where almost all of the large diversions on the Brazos River occur. To account for diversions, the current study adjusted the calculated base flow at the Richmond gage by adding the amount of the upstream diversions determined based on historical monthly average diversions data. This adjustment assumed that the diversions come solely from base flow, a reasonable assumption during periods of low flow. Table 4.4.12 gives the historical monthly average diversions used for the adjustment. The diversions from 1940 through 1997 were obtained from the Texas Commission on Environmental Quality Brazos River Water Availability Model (Texas Commission on Environmental Quality, 2014c) and the diversions from 1998 through 2012 were obtained from the Texas Commission on Environmental Quality database of reported diversions by water rights holders (Texas Commission on Environmental Quality, 2014b). Data are not available for 2006, so the average value from 2004 through 2008 was used. Data from 2013 are also unavailable, so the average value from 2009 through 2012 was used.

Figure 4.4.9 shows the final calculated base flow, including the adjustments discussed above, for all gages used in the current study. Note that the 1950s drought period (1952 to 1956) shows a sustained decrease in base flow for all gages for the duration of the drought. There are also several isolated years with significantly lower-than-average base flow. Base flows during the most recent 2010s drought (2011 to 2013) are nearly as low as those in the 1950s drought. Figure 4.4.10 illustrates the average annual base flow values for periods of normal streamflow compared to the average base flow during the 1950s and 2010s droughts. Base flow dropped significantly during both droughts, but more severely during the 1950s drought than the 2010s drought. The exception is the Waco gage, where baseflow was very similar for both the 1950s and 2010s drought.

In addition to assessing base flow at each gage individually, the incremental base flow along the Brazos River, or the portion of the base flow that originates between gages, was also calculated for the current study. This analysis is similar in concept to gain/loss studies in that it provides a measure of how much the river is gaining or losing. However, unlike gain/loss studies, the analysis is not limited to periods of low flow, but rather can be performed for the entire period of record. For the purpose of this analysis, the Brazos River was divided into four segments from north to south (Figure 4.4.11). These four segments, and the aquifers underlying the Brazos River Alluvium Aquifer in those reaches, are:

Reach 1 – Aquilla to Waco (no aquifers)
Reach 2 – Waco to Bryan (Carrizo-Wilcox, Queen City, and Sparta aquifers)
Reach 3 – Bryan to Hempstead (Yegua-Jackson and Gulf Coast aquifers)
Reach 4 – Hempstead to Richmond (Gulf Coast Aquifer)

Base flow data for the Highbank gage are available from 1966 to 2013, so Segment 2 was further divided into two sections during that time period:

Reach 2a – Waco to Highbank (no aquifers)
Reach 2b – Highbank to Bryan (Carrizo-Wilcox, Queen City, and Sparta aquifers)

Incremental base flow for each reach was determined on a monthly basis for the 1940 to 2013 analysis period by subtracting base flow at the upstream gage from base flow at the downstream gage. The monthly time step was chosen to minimize errors associated with the timing of flows (for example, large flows recorded at the upstream gage one day may not reach the downstream gage until hours or days later). During high flow periods, when both the upstream and downstream gages are at the maxima, the incremental base flow was not calculated. Loss factors were applied to the base flow at the upstream gage to account for water lost during travel to the downstream gage. Loss factors, which were calculated based on loss data in the Brazos River Authority Water Management Plan (Brazos River Authority, 2014), are listed in Table 4.4.13. Base flows from the Cameron gage on the Little River were subtracted from the incremental base flows on Segments 2 and 2b to account for the contribution to that reach from the tributary. Long-term gage data are not available near the confluence of the other major tributaries, so no other adjustments were made for tributary flows.

Figures 4.4.11a through 4.4.11d show the average monthly and average annual incremental base flow for Reaches 1 through 4, respectively, calculated by the current study. Negative incremental base flow values (red bars in the figures) generally indicate losing conditions along the reach, although could also be attributed to timing issues or undocumented diversions and inflows. While occasional losing conditions on a monthly time scale were observed for Reaches 2 through 4, losing conditions over the annual time scale were observed only for Reach 4 during the 2010s drought.

The average annual incremental base flows shown in Figures 4.4.11a through 4.4.11d were averaged in order to compare incremental base flows between the reaches (Table 4.4.14). The average of the average annual incremental base flows is significantly higher in Reaches 2 through 4 than in Reach 1. The Brazos River Alluvium Aquifer is not underlain by any other aquifers in Reach 1 but is underlain by other aquifers in Reaches 2 through 4. This indicates that base flow to the Brazos River is higher for reaches where the Brazos River Alluvium Aquifer overlies another aquifer. Table 4.4.14 also shows that base flow in Reaches 2 and 3 is similar and lower than that in Reach 4.

Figure 4.4.13 and Table 4.4.14 show the average annual incremental base flow values for all years compared to those during the 1950s and 2010s droughts. The table also shows the percentage of incremental base flow during periods of drought relative to the average incremental base flow for all years. Groundwater contribution to Reaches 1 and 4 significantly declined, to below 50 percent of average base flow, during the 1950s and 2010s droughts. In contrast, base flow during the droughts in Reaches 2 and 3 retained over 50 percent of average base flow, with Reach 2 showing the most resiliency. This suggests some buffering effect associated with reaches where the Brazos River Alluvium Aquifer overlies another aquifer. The difference in behavior between Reaches 2a and 2b supports this conclusion (Figure 4.4.14). The groundwater contribution to Reach 2a, which crosses an area where the Brazos River Alluvium Aquifer does not overlie another aquifer, reduced to 56 percent of average base flow during the 2010s drought. On the other hand, Reach 2b, which crosses an area where the Brazos River Alluvium Aquifer overlies the Carrizo-Wilcox, Queen City, and Sparta aquifers, retained 80 percent of average base flow during the 2010s drought. If there is a buffering effect due to aquifers underlying the Brazos River Alluvium Aquifer, however, it seems to apply only to the Carrizo-Wilcox, Queen City, Sparta, and Yegua-Jackson aquifers. Reach 4, which crosses an area where the Brazos River Alluvium Aquifer overlies the Gulf Coast Aquifer, shows the most dramatic decrease in groundwater contribution during the droughts, dropping to a mere 28 percent of average base flow during the 2010s drought (see Figure 4.4.13). Another factor possibly contributing to the decrease in base flow during periods of drought in Reach 4 may be reduced water levels in the Gulf Coast Aquifer due to increased irrigation pumping.

4.4.1.3 Groundwater Level – Stream Stage Relationships

The losing or gaining nature of a river reach can be inferred by comparing stream stage to nearby groundwater levels. A gaining stream has a stage that is at a lower elevation than the local water table. Under gaining-stream conditions, the stream is a discharge boundary for groundwater. A losing stream has a stage that is at a higher elevation than the local water table and, as a result, surface water is a source of recharge to the groundwater. Historical stream stage (gage height) measurements along the Brazos River were compared to historical groundwater levels in relatively shallow (depth less than 100 feet) wells within two miles of the stream gage. Stream stage measurements at selected gages and the corresponding nearby groundwater levels are shown in Figures 4.4.15a through 4.4.15c. Gage height measurements for stream gages along the Brazos River were sourced from the “daily data” section of the National Water Information System (United States Geological Survey, 2014b). Stream stage elevation was calculated by adding the gage height to the datum of the gage given in the database (United States Geological Survey, 2014b). The blue solid line in Figures 4.4.15a through 4.4.15c represent stream stage elevations calculated from daily gage height data. Gages are labelled by the gage site number, as assigned in the database. Additional older discrete gage height measurements from the “field measurements” and/or “peak streamflow” section of the National Water Information System (United States Geological Survey, 2014b) were used, as available, to increase the historical time period available for comparison. Older measurements were only used if the gage datum was located at the same site as the more recent daily data. Stream stage elevations calculated from these discrete field measurements of gage height are represented by the dashed blue line in Figures 4.4.15a through 4.4.15c. Water level elevations for nearby wells were sourced from the Texas Water Development Board’s groundwater database (TWDB, 2014f). Well water levels are represented as points if there is only one water level measurement available and as points connected by lines if there are two or more measurements available. Wells are labelled by the state well number, as assigned in the groundwater database.

Ideally, the stream stage-groundwater level relationship would be developed using long-term comparisons of daily stage and water level measurements. Using long time periods of overlapping data would help account for the short-term variability in the hydraulic gradient, including the seasonal effects of precipitation and pumping. Unfortunately, the limited data availability makes this type of analysis nearly impossible. The availability of groundwater level measurements is by far the most limiting factor. The majority of available groundwater level records are only single point measurements rather than time series. For instance, gages 8093100, 8114000, and 8111850 have no nearby wells with more than one groundwater level measurement available. Even wells that do have time series of water level data available may not overlap with the stream stage data long enough to make any meaningful comparison. For instance, none of the groundwater level measurements for wells near gages 8093100, 8096500, 8111500, and 811850 were recorded during the same time period as the daily stage measurements. As mentioned before, older discrete stage measurements were added, when available, to increase the time period available for comparison. The comparison using the older discrete stage measurements is not ideal since they are only point measurements and also tend to be biased toward times of high flow. However, for gages 8093100, 8111500, and 811850, there are not even usable older stage measurements that overlap with the groundwater level records.

In order of most reliable comparison to least, these are the interpretations for each gage:

- Gage 8098290: The one well (3950813) with a water level time series that overlaps the available daily stream stage record shows a water level that is generally above stream stage. Wells (3950803, 3950804, and 3950812) with water level time series that overlap the older discrete stream stage records also show water levels generally above stream stage. None of the point measurements overlap with any of the stream stage measurements but the water levels for two wells (3950708 and 3950822) do plot much higher than the typical stream stage over time. The other two wells (3950815 and 3950821) appear to plot at or slightly higher than the typical stream stage over time. In general, it appears that the Brazos River is gaining in the vicinity of gage 8098290.

- Gage 8108700: The three wells (5920907, 5928304, and 5920804) with time series that overlap the available daily stream stage record show water levels generally above stream stage. Other wells (5920806, 5920808, 5920823, 5920908, 5920909, and 5920914) with water level time series do not overlap with any of the stream stage measurements but the water levels do plot higher than the typical stream stage over time. The exception is well 5928315. None of the point measurements overlap with any of the stream stage measurements but the water levels for two wells (5920828 and 5928334) do plot higher than the typical stream stage over time. The other well (5928301) plots at almost the same level as the typical stream stage over time. In general, it appears that the Brazos River has historically been gaining in the vicinity of gage 8098290. However, in recent years, the record for well 5920823 shows water levels at or below the stream stage, indicating that there might have been some change to the hydraulic gradient in which the Brazos River is now gaining less and potentially even losing in the vicinity of gage 8108700.

- Gage 8109000: The one well (5928310) with a water level time series that overlaps the available daily stream stage record shows a water level that is generally above stream stage. Other wells with water level time series (5928309, 5928311, 5928312, 5929101, 5929103, 5929104, 5929106, 5929107, 5929111, and 5929113) with water level time series that overlap the older discrete stream stage records also show water levels generally above stream stage. All of the wells (5928337, 5929102, 5929108, 5929115, and 5929114) with point measurements overlap with the older discrete stream stage measurements and all except well 5929114 plot above the typical stream stage. In general, it appears that the Brazos River is gaining in the vicinity of gage 8109000.

- Gage 8096500: None of the wells have water level time series that overlap with the daily stream stage record. One well (4032703) with a water level time series that overlaps the older discrete stream stage records shows water levels generally above stream stage. The other two wells (4032409 and 4032802) have water levels at or below stream stage. None of the point measurements overlap with any of the stream stage measurements but the water levels for all but two wells (4032503 and 4032807) do plot higher than the typical stream stage over time. It is unclear whether the Brazos River was historically gaining or losing in the vicinity of gage 8096500. Based on the record for well 4032802, the status might have transitioned from gaining to losing in the 1980s, but there is no recent water level data to confirm whether or not this trend continued.

- Gage 8093100: There are no water level time series available near this gage. None of the wells with point measurements (4014502, 4014505, 4014609, and 4014510) overlap with any of the stream stage measurements but the water levels do plot higher than the typical stream stage over time. This implies that the Brazos River may have been historically gaining in the vicinity of gage 8093100, but the data are too limited to draw any definite conclusion.

- Gage 8111500: The one well (5963202) with a water level time series does not overlap with any of the stream stage measurements but the water levels do plot higher than the typical stream stage over time. One well (5955911) plots at or above the typical stream stage over time while the other (5955803) plots lower. The data are too limited to determine the gaining or losing status of the Brazos River in the vicinity of gage 8111500.

- Gage 8111850: There are no water level time series available near this gage. None of the wells with point measurements (6616404, 6616502, 6616503, and 6616504) overlap with any of the stream stage measurements. The stream stage time series for Gage 8111850 is not even long enough to estimate what the typical stream stage would be over time, so it is unclear whether these water levels plot above or below a typical value. The data are too limited to determine the gaining or losing status of the Brazos River in the vicinity of gage 8111850.

- Gage 8114000: There are no water level time series available near this gage. The one nearby well (181243) overlaps the daily stream stage record and the point measurement plots at about the same level as stream stage. The data are too limited to determine the gaining or losing status of the Brazos River in the vicinity of gage 8114000.

In general, the stream stage-groundwater level relationships for the gages in the central portion of the aquifer (8098290, 8108700, and 8109000) do show some evidence that the Brazos River is gaining in these locations. This is consistent with the updated analysis of Turco and others (2007) discussed in Section 4.4.1.1, which also showed that this portion of the Brazos River is gaining (see Figure 4.4.5). The data for the other gages are too limited to determine whether the Brazos River is gaining or losing at those locations and the analysis is too uncertain to provide definite information on aquifer-stream interaction in the Brazos River Alluvium Aquifer.

4.4.2 Springs

A spring is a point where groundwater flows out of the ground because the elevation of the aquifer piezometric surface exceeds the land-surface elevation and a pathway exists for the water to flow to the surface. Springs typically occur in topographically low areas, such as river valleys, or in areas of the outcrop where hydrogeologic conditions preferentially reject recharge. Spring data for the Brazos River Alluvium Aquifer are available from: the TWDB groundwater database (TWDB, 2014f), a database of Texas springs compiled by the United States Geological Survey (Heitmuller and Reece, 2003), and a report on the springs of Texas (Brune, 2002). Figure 4.4.16 shows the locations of springs that flow or formerly flowed in the vicinity of the Brazos River Alluvium Aquifer. The locations of most springs from Brune (2002) were approximated using a georeferenced map. Table 4.4.15 lists all springs located in the Brazos River Alluvium Aquifer boundary and springs located within two miles of the aquifer that do not flow from older, non-Quaternary formations. A full list of springs located in the active model area is provided in Appendix C.

The literature review identified 298 springs or groups of spring in the active model area. Of the thirteen springs located in the extent of the Brazos River Alluvium Aquifer, 11 of them have flow data available, but none have more than one flow measurement. For the rest of the active model area, at least one measurement is available for 184 springs and 44 springs have more than one measurement.

Throughout much of the state, including the study area, spring flows have shown a general decline over time. Brune (2002) notes that declining water levels due to pumping has resulted in reduced flow in many of the springs, particularly in Fort Bend County, at the southern end of the Brazos River Alluvium Aquifer. In this area, the Brazos River historically was spring-fed and gaining, but is now a losing stream due to over pumping, and nearby springs and flowing wells have dried up (Brune, 2002).

4.4.3 Reservoirs

Areas where a surface water body intersects an aquifer outcrop often serve as discharge points for the aquifer when the water table is above the elevation of the lake or reservoir. A lake or reservoir can also act as a source of recharge to an aquifer when the elevation of the lake is above the water table. There are 18 reservoirs in the vicinity of the Brazos River Alluvium Aquifer, none of which actually intersect the aquifer (Figure 4.4.17). Names and information for these reservoirs are given in Table 4.4.16. Average annual lake levels for Lake Waco and Lake Whitney are shown in Figure 4.4.18. The red dashed lines on the graphs in this figure represent the average lake level over the period of record since the lake filled. Bathymetry information for Lake Waco and Lake Whitney is shown in Figure 4.4.19. Bathymetry information can be used in conjunction with the reservoir stage data to estimate the historical area of the lakes at different times.

4.4.4 Oxbow Lakes and other Surface Water Features

When meandering streams like the Brazos River change channel location, disconnected sections of the former channel can form long, narrow lakes called oxbow lakes. Although these oxbow lakes are small, many occur in the Brazos River valley and, therefore, can potentially act as significant recharge or discharge points for the Brazos River Alluvium Aquifer. Chemical and isotopic studies of Brazos River oxbow lakes indicate that the more isolated oxbow lakes (ones that rarely reconnect with the river during flood events) have much higher proportions of groundwater input than the more frequently re-connected oxbow lakes (Chowdhury, 2004; Chowdhury and others, 2010).

In addition to oxbow lakes, several other water bodies, including swamps and ponds, also occur in the extent of the Brazos River Alluvium Aquifer. Oxbow lakes and other significant surface water features are shown in Figures 4.4.20a and 4.4.20b. Features were taken from the National Hydrography Dataset high-resolution water body coverage (United States Geological Survey, 2014c). Only named features or features with an area greater than 0.0156 square miles (the size of a model grid cell) are included in the figures. Features designated for water storage, sewage treatment, or evaporation were excluded based on the assumption that they are lined and so do not readily interact with groundwater.

Table 4.4.1 Gain/loss estimates from Slade and others (2002).

Study	Date	Latitude	Longitude	Major Aquifer	Minor Aquifer	Gain/ Loss (cfs)	Length (miles)	Gain/Loss (cfs/mi)	Average Gain/Loss (cfs/mi)
Berry Creek - Briggs to mouth (northeast of Georgetown)									
1	4/21-24/1978	30.87972	-97.9197	--	--	0	4.9	0	0.46
		30.84278	-97.8589	--	--	0	3.2	0	
		30.81028	-97.8256	--	--	0.05	3	0.02	
		30.77889	-97.7958	--	--	-0.05	2.5	-0.02	
		30.76361	-97.7536	Edwards	--	-0.12	2.5	-0.05	
		30.7475	-97.7319	Edwards	--	-0.02	1.6	-0.01	
		30.72722	-97.7406	Edwards	--	0	1.3	0	
		30.71806	-97.7286	Edwards	--	-0.83	6.6	-0.13	
		30.70306	-97.6661	Edwards	--	0.18	1.3	0.14	
		30.69083	-97.655	--	--	3.04	3.2	0.95	
					TOTAL	2.25	30.1	0.07	
2	8/15/1978	30.87972	-97.9197	--	--	0	4.9	0	
		30.84278	-97.8589	--	--	0	3.2	0	
		30.81028	-97.8256	--	--	0	3	0	
		30.77889	-97.7958	--	--	0	2.5	0	
		30.76361	-97.7536	Edwards	--	0	2.5	0	
		30.7475	-97.7319	Edwards	--	0	1.6	0	
		30.72722	-97.7406	Edwards	--	0	1.3	0	
		30.71806	-97.7286	Edwards	--	-0.21	6.6	-0.03	
		30.70306	-97.6661	Edwards	--	0	1.3	0	
		30.69083	-97.655	--	--	0	3.2	0	
					TOTAL	-0.21	30.1	-0.01	
3	2/15/1979	30.87972	-97.9197	--	--	4.19	4.9	0.86	
		30.84278	-97.8589	--	--	5.34	3.2	1.67	
		30.81028	-97.8256	--	--	7.79	3	2.60	
		30.77889	-97.7958	--	--	0.8	2.5	0.32	
		30.76361	-97.7536	Edwards	--	0.83	2.5	0.33	
		30.7475	-97.7319	Edwards	--	-9.26	1.6	-5.79	
		30.72722	-97.7406	Edwards	--	-18.6	1.3	-14.31	
		30.71806	-97.7286	Edwards	--	20.5	6.6	3.11	
		30.70306	-97.6661	Edwards	--	6.2	1.3	4.77	
		30.69083	-97.655	--	--	13.5	3.2	4.22	
					TOTAL	31.29	30.1	1.04	
4	8/14-15/1979	30.87972	-97.9197	--	--	0.37	4.9	0.08	
		30.84278	-97.8589	--	--	0.77	3.2	0.24	
		30.81028	-97.8256	--	--	0.83	3	0.28	
		30.77889	-97.7958	--	--	0.56	2.5	0.22	
		30.76361	-97.7536	Edwards	--	-2.87	2.5	-1.15	
		30.7475	-97.7319	Edwards	--	-0.54	1.6	-0.34	
		30.72722	-97.7406	Edwards	--	0	1.3	0	
		30.71806	-97.7286	Edwards	--	4.69	6.6	0.71	
		30.70306	-97.6661	Edwards	--	6.95	1.3	5.35	
		30.69083	-97.655	--	--	10.99	3.2	3.43	
					TOTAL	21.75	30.1	0.72	

Table 4.4.1, continued

Study	Date	Latitude	Longitude	Major Aquifer	Minor Aquifer	Gain/ Loss (cfs)	Length (miles)	Gain/Loss (cfs/mi)	Average Gain/Loss (cfs/mi)
Brushy Creek - northwest of Leander to 4 miles east of Round Rock									
5	4/17-18/1978	30.58667	-97.8781	--	--	0.38	2.6	0.15	0.73
		30.58167	-97.8417	Edwards	--	0.34	3.1	0.11	
		30.57361	-97.7894	Edwards	--	0.2	3.2	0.06	
		30.53861	-97.7789	Edwards	--	1.45	4.8	0.30	
		30.52194	-97.7122	Edwards	--	0.72	2.1	0.34	
		30.5125	-97.6867	--	--	-1.03	1	-1.03	
		30.51639	-97.6619	--	--	3.99	4	1.00	
					TOTAL	6.05	20.8	0.29	
6	8/17-18/1978	30.58667	-97.8781	--	--	0	2.6	0	
		30.58194	-97.8417	Edwards	--	-0.08	3.1	-0.03	
		30.57361	-97.7894	Edwards	--	0	3.2	0	
		30.53861	-97.7789	Edwards	--	0.02	4.8	0	
		30.52194	-97.7122	Edwards	--	-0.02	2.1	-0.01	
		30.5125	-97.6867	--	--	0	1	0	
		30.51583	-97.6717	--	--	0.15	4	0.04	
					TOTAL	0.07	20.8	0	
7	2/13-14/1979	30.58667	-97.8781	--	--	3.77	2.6	1.45	
		30.58194	-97.8417	Edwards	--	6.85	3.1	2.21	
		30.57361	-97.7894	Edwards	--	3.34	3.2	1.04	
		30.53861	-97.7789	Edwards	--	1.27	4.8	0.26	
		30.52194	-97.7122	Edwards	--	18.6	2.1	8.86	
		30.5125	-97.6867	--	--	-3.07	1	-3.07	
		30.51583	-97.6717	--	--	17.29	4	4.32	
					TOTAL	48.05	20.8	2.31	
8	8/13-14/1979	30.58667	-97.8781	--	--	0.9	2.6	0.35	
		30.58194	-97.8417	Edwards	--	0.39	3.1	0.13	
		30.57361	-97.7894	Edwards	--	0.25	3.2	0.08	
		30.53861	-97.7789	Edwards	--	0.79	4.8	0.16	
		30.52194	-97.7122	Edwards	--	1.46	2.1	0.70	
		30.5125	-97.6867	--	--	1.01	1	1.01	
		30.51583	-97.6717	--	--	1.77	4	0.44	
					TOTAL	6.57	20.8	0.32	
Lampasas River- northeast of Lampasas to mouth									
10	6/3-6/1963	31.09694	-98.0394	Trinity	--	-0.75	2.3	-0.33	-0.07
		31.07694	-98.0125	Trinity	--	-1.38	12.9	-0.11	
		30.99444	-97.9253	Trinity	--	0.46	12.8	0.04	
		30.9775	-97.7975	Trinity	--	-0.77	2.5	-0.31	
		30.97194	-97.7769	Trinity	--	0.34	8	0.04	
		30.9525	-97.6964	Trinity	--	-1.85	7.8	-0.24	
		30.98556	-97.6517	--	--	0.76	11.8	0.06	
		31.02778	-97.5831	--	--	-0.46	2.8	-0.16	
		31.01028	-97.5644	Edwards	--	0.95	4.4	0.22	
		31.02056	-97.5119	Edwards	--	-1.99	2.2	-0.90	
		31.00167	-97.4919	Edwards	--	-0.81	12.3	-0.07	

Table 4.4.1, continued

Study	Date	Latitude	Longitude	Major Aquifer	Minor Aquifer	Gain/ Loss (cfs)	Length (miles)	Gain/Loss (cfs/mi)	Average Gain/Loss (cfs/mi)
					TOTAL	-5.5	79.8	-0.07	
Lampasas River -Stillhouse Hollow Dam site to confluence with Little River									
11	1/16/1968	31.04083	-97.5356	Edwards	--	8.2	2.6	3.15	1.01
		31.00194	-97.4919	Edwards	--	5.2	8.4	0.62	
		30.98972	-97.4444	Edwards	--	2.48	4.7	0.53	
					TOTAL	15.88	15.7	1.01	
Leon River - Belton Dam to Little River									
12	1/16-17/1968	31.10528	-97.4725	--	--	3.36	4.4	0.76	0.28
		31.06972	-97.4411	--	--	-52.94	4.4	-12.03	
		31.03389	-97.4364	--	--	52.06	0.2	260.30	
					TOTAL	2.48	9	0.28	
North Fork San Gabriel River - above Highway 183 to Country Club Road at Georgetown									
14	4/26-27/1978	30.73528	-97.9153	Trinity	--	0.73	4	0.18	0.69
		30.69972	-97.8742	Trinity	--	0.23	1	0.23	
		30.69889	-97.8589	Trinity	--	-0.22	0.9	-0.24	
		30.6975	-97.8453	Trinity	--	0.34	2.5	0.14	
		30.69056	-97.8125	Edwards	--	1.81	4.6	0.39	
		30.67194	-97.7503	Edwards	--	0.6	2.6	0.23	
		30.66222	-97.7172	Edwards	--	0.16	1.4	0.11	
					TOTAL	3.65	17	0.21	
15	8/16-26/1978	30.73528	-97.9153	Trinity	--	0	4	0	
		30.70278	-97.8767	Trinity	--	0	1	0	
		30.69889	-97.8589	Trinity	--	0	0.9	0	
		30.6975	-97.8453	Trinity	--	0.03	2.5	0.01	
		30.69056	-97.8125	Edwards	--	0.3	4.6	0.07	
		30.67194	-97.7503	Edwards	--	-0.12	2.6	-0.05	
		30.66222	-97.7172	Edwards	--	-0.14	1.4	-0.10	
					TOTAL	0.07	17	0	
16	2/13-15/1979	30.73528	-97.9153	Trinity	--	0.4	4	0.10	
		30.70278	-97.8767	Trinity	--	4.4	1	4.40	
		30.69889	-97.8589	Trinity	--	7	0.9	7.78	
		30.6975	-97.8453	Trinity	--	6.46	2.5	2.58	
		30.69056	-97.8125	Edwards	--	0.42	4.6	0.09	
		30.67194	-97.7503	Edwards	--	18	2.6	6.92	
		30.66222	-97.7172	Edwards	--	-2.94	1.4	-2.10	
					TOTAL	33.74	17	1.98	
17	8/13-15/1979	30.73528	-97.9153	Trinity	--	1.8	4	0.45	
		30.70278	-97.8767	Trinity	--	1.3	1	1.30	
		30.69889	-97.8589	Trinity	--	-3.6	0.9	-4.00	
		30.6975	-97.8453	Trinity	--	5.85	2.5	2.34	
		30.69056	-97.8125	Edwards	--	1.42	4.6	0.31	
		30.67194	-97.7503	Edwards	--	3	2.6	1.15	
		30.66222	-97.7172	Edwards	--	-0.37	1.4	-0.26	
					TOTAL	9.4	17	0.55	

Table 4.4.1, continued

Study	Date	Latitude	Longitude	Major Aquifer	Minor Aquifer	Gain/ Loss (cfs)	Length (miles)	Gain/Loss (cfs/mi)	Average Gain/Loss (cfs/mi)
North Fork San Gabriel River - north of Leander to mouth									
18	3/16-18/1964	30.70306	-97.8769	Trinity	--	-0.83	1	-0.83	0.14
		30.69889	-97.8589	Trinity	--	-0.23	0.8	-0.29	
		30.6975	-97.8453	Trinity	--	0.71	2.8	0.25	
		30.69028	-97.8122	Edwards	--	1.29	4.6	0.28	
		30.67861	-97.7747	Edwards	--	1.04	5.2	0.20	
					TOTAL	1.98	14.4	0.14	
Salado Creek - northwest of Florence to Salado									
19	4/24/1978	30.83306	-97.7894	Edwards	--	0	8.9	0	1.30
		30.82667	-97.6939	Edwards	--	-0.08	3.6	-0.02	
		30.82639	-97.6433	Edwards	--	0.47	3	0.16	
		30.865	-97.6342	Edwards	--	1.2	3.7	0.32	
		30.89694	-97.6144	Edwards	--	2.53	6.6	0.38	
		30.94667	-97.5542	Edwards	--	11.17	0.4	27.93	
					TOTAL	15.29	26.2	0.58	
20	8/14/1978	30.85139	-97.805	Edwards	--	0	8.9	0	
		30.82667	-97.6939	Edwards	--	0	3.6	0	
		30.82639	-97.6433	Edwards	--	0.11	3	0.04	
		30.865	-97.6342	Edwards	--	0.3	3.7	0.08	
		30.89694	-97.6144	Edwards	--	-0.69	6.6	-0.10	
		30.94667	-97.5542	Edwards	--	9.24	0.4	23.10	
					TOTAL	8.96	26.2	0.34	
21	2/16/1979	30.85139	-97.805	Edwards	--	5.93	8.9	0.67	
		30.82667	-97.6939	Edwards	--	-7.61	3.6	-2.11	
		30.82639	-97.6433	Edwards	--	2.24	3	0.75	
		30.865	-97.6342	Edwards	--	13.64	3.7	3.69	
		30.89694	-97.6144	Edwards	--	23.8	6.6	3.61	
		30.94667	-97.5542	Edwards	--	25	0.4	62.50	
					TOTAL	63	26.2	2.40	
22	8/15/1979	30.85139	-97.805	Edwards	--	0.41	8.9	0.05	
		30.82667	-97.6939	Edwards	--	-1.6	3.6	-0.44	
		30.82639	-97.6433	Edwards	--	1.53	3	0.51	
		30.865	-97.6342	Edwards	--	5.54	3.7	1.50	
		30.89694	-97.6144	Edwards	--	7.11	6.6	1.08	
		30.94667	-97.5542	Edwards	--	36.1	0.4	90.25	
					TOTAL	49.09	26.2	1.87	
San Gabriel River - Georgetown (08105000) to mouth									
24	3/17-18/1964	30.655	-97.635	--	--	-2.06	9	-0.23	0.22
		30.63583	-97.55	--	--	2.71	5	0.54	
		30.63111	-97.4703	--	--	1.7	2.2	0.77	
		30.64389	-97.4386	--	--	6.28	9.6	0.65	
		30.68611	-97.3683	--	--	1.75	4	0.44	
		30.69417	-97.2783	--	--	2.7	6	0.45	
		30.68722	-97.1928	--	--	-3.4	4	-0.85	
		30.69167	-97.1375	--	--	-0.84	2.4	-0.35	

Table 4.4.1, continued

Study	Date	Latitude	Longitude	Major Aquifer	Minor Aquifer	Gain/ Loss (cfs)	Length (miles)	Gain/Loss (cfs/mi)	Average Gain/Loss (cfs/mi)
		30.71	-97.1111	--	--	4.8	4.8	1.00	
		30.72722	-97.0383	--	--	-3.1	2	-1.55	
					TOTAL	10.54	49	0.22	
South Fork San Gabriel River - Highway 183 to Highway 29 at Georgetown									
25	3/16/1964	30.62056	-97.8606	Edwards	--	0.4	5.4	0.07	0.11
		30.61556	-97.7836	Edwards	--	1.21	4.4	0.28	
		30.62	-97.7086	Edwards	--	-0.23	3	-0.08	
					TOTAL	1.38	12.8	0.11	
South Fork San Gabriel River - near Bertram to Georgetown									
26	4/19-21/1978	30.71528	-98.0506	Trinity	--	0.24	2	0.12	0.39
		30.7025	-98.0311	Trinity	--	0.11	3.1	0.04	
		30.68806	-97.9833	Trinity	--	0.06	2.2	0.03	
		30.67528	-97.9625	Trinity	--	-0.09	2.2	-0.04	
		30.65889	-97.9369	Trinity	--	0.25	2.3	0.11	
		30.64806	-97.9097	Trinity	--	0.83	4.9	0.17	
		30.62056	-97.8606	--	--	-0.07	2.8	-0.03	
		30.61167	-97.8186	Edwards	--	0.25	3	0.08	
		30.61944	-97.7769	Edwards	--	-3.03	3.9	-0.78	
		30.62028	-97.7272	Edwards	--	1.78	1	1.78	
		30.62	-97.7119	Edwards	--	3.66	1.5	2.44	
		30.62611	-97.6931	Edwards	--	1.1	0.8	1.38	
					TOTAL	5.09	29.7	0.17	
27	8/17/1978	30.71528	-98.0506	Trinity	--	0	2	0	
		30.7025	-98.0311	Trinity	--	0	3.1	0	
		30.68806	-97.9833	Trinity	--	0.01	2.2	0	
		30.67528	-97.9625	Trinity	--	-0.01	2.2	0	
		30.65889	-97.9369	Trinity	--	0	2.3	0	
		30.64806	-97.9097	Trinity	--	20.01	4.9	4.08	
		30.62056	-97.8606	--	--	-20.01	2.8	-7.15	
		30.61167	-97.8186	Edwards	--	0	3	0	
		30.61944	-97.7769	Edwards	--	0	3.9	0	
		30.62028	-97.7272	Edwards	--	0.02	1	0.02	
		30.62	-97.7119	Edwards	--	0	1.5	0	
		30.62611	-97.6931	Edwards	--	-0.01	0.8	-0.01	
					TOTAL	0.01	29.7	0	
28	2/13-15/1979	30.71528	-98.0506	Trinity	--	1.38	2	0.69	
		30.7025	-98.0311	Trinity	--	1.19	3.1	0.38	
		30.68806	-97.9833	Trinity	--	1	2.2	0.45	
		30.67528	-97.9625	Trinity	--	-0.64	2.2	-0.29	
		30.65889	-97.9369	Trinity	--	9	2.3	3.91	
		30.64806	-97.9097	Trinity	--	4.82	4.9	0.98	
		30.62056	-97.8606	--	--	6	2.8	2.14	
		30.61167	-97.8186	Edwards	--	1.2	3	0.40	
		30.61944	-97.7769	Edwards	--	-46.93	3.9	-12.03	
		30.62028	-97.7272	Edwards	--	55	1	55.00	
		30.62	-97.7119	Edwards	--	0.1	1.5	0.07	

Table 4.4.1, continued

Study	Date	Latitude	Longitude	Major Aquifer	Minor Aquifer	Gain/ Loss (cfs)	Length (miles)	Gain/Loss (cfs/mi)	Average Gain/Loss (cfs/mi)
		30.62611	-97.6931	Edwards	--	1.1	0.8	1.38	
					TOTAL	33.22	29.7	1.12	
29	8/13-15/1979	30.71528	-98.0506	Trinity	--	0.23	2	0.12	
		30.7025	-98.0311	Trinity	--	0.43	3.1	0.14	
		30.68806	-97.9833	Trinity	--	0.33	2.2	0.15	
		30.67528	-97.9625	Trinity	--	-2.62	0.9	-2.91	
		30.67889	-97.95	Trinity	--	3.71	1.3	2.85	
		30.65889	-97.9369	Trinity	--	-0.54	2.3	-0.23	
		30.64806	-97.9097	Trinity	--	2.27	4.9	0.46	
		30.62056	-97.8606	--	--	1.41	2.8	0.50	
		30.61167	-97.8186	Edwards	--	0.33	3	0.11	
		30.61944	-97.7769	Edwards	--	-8.86	3.9	-2.27	
		30.62028	-97.7272	Edwards	--	11.7	1	11.70	
		30.62	-97.7119	Edwards	--	0.6	1.5	0.40	
		30.62611	-97.6931	Edwards	--	-0.4	0.8	-0.50	
					TOTAL	8.59	29.7	0.29	
Sulphur Creek - Lampasas to 1.5 miles downstream from Burleson Creek									
30	6/30/1942	31.05	-98.1847	Trinity	Marble	2.7	0.53	5.09	3.66
		31.05472	-98.1869	Trinity	--	0.7	0.24	2.92	
		31.05472	-98.1831	Trinity	--	3.1	0.1	31.00	
		31.055	-98.1822	Trinity	--	3.3	0.08	41.25	
		31.05528	-98.1814	Trinity	--	5.4	2.72	1.99	
					TOTAL	15.2	3.67	4.14	
31	8/10/1942	31.05	-98.1847	Trinity	Marble	1.8	0.53	3.40	
		31.05472	-98.1869	Trinity	--	3.5	0.24	14.58	
		31.05472	-98.1831	Trinity	--	3.2	0.1	32.00	
		31.055	-98.1822	Trinity	--	1.9	0.08	23.75	
		31.05528	-98.1814	Trinity	--	1.3	2.72	0.48	
					TOTAL	11.7	3.67	3.19	

cfs = cubic feet per second
cfs/mi = cubic feet per second per mile
Edwards = Edwards Balcones Fault Zone Aquifer
Trinity = Trinity Aquifer
Marble = Marble Falls Aquifer

Table 4.4.2 Streamflows at Baldys and Schalla (2011) gages in the study area.

USGS Station Name	USGS Station Number	Site Identifier	Latitude	Longitude	Streamflow (cfs)	
					June 2010	October 2010
Brazos River near Aquilla, Texas	8093100	BMS-8	31°48’46”	97°17’52”	252	252
Childress Creek at FM 2490 near Waco, Texas	314220097174100	BMST-11	31°42’21”	97°17’41”	3.54	4.33/5.02[1]
Aquilla Creek above Aquilla, Texas	8093360	BMST-12	31°53’43”	97°12’10”	2.26	14
Cobb Creek near Aquilla, Texas	315300097114200	BMST-13	31°53’01”	97°11’43”	no flow	no flow
Aquilla Creek at FM 1858 near Ross, Texas	8093560	BMST-14	31°43’33”	97°12’39”	15.5	22.1
North Bosque River near Clifton, Texas	8095000	NB-7	31°47’09”	97°34’04”	47.9	17.6
Neils Creek at Hwy 6 near Valley Mills, Texas	314136097320700	NB-8	31°41’37”	97°32’07”	18.2	6.84
North Bosque River at Valley Mills, Texas	8095200	NB-9	31°40’10”	97°28’09”	86.7	39.1
North Bosque River near China Springs, Texas	313830097220100	NB-10	31°38’30”	97°22’01”	103/107[1]	41.4

[1] two values indicate replicate measurements
USGS = United States Geological Survey
cfs = cubic feet per second
FM – Farm to Market
Hwy - Highway

Table 4.4.3 Discharges at Turco and others (2007) gages in the study area.

Site Identifier	USGS Station Number	USGS Station Name	Latitude	Longitude	Streamflow (cfs)	
					March 2006	August 2006
B1	8096500	Brazos River at Waco, Texas	31°32'9"	97°4'23"	133.	370.
T1	313210097015800	Tehuacana Creek at SH 6 near Waco, Texas	31°32'10"	97°1'58"	0.107	0.
T2	312934097045300	Flat Creek at CR 3400 near Robinson, Texas	31°29'34"	97°4'53"	0.802	0.500
B2	312723097020000	Brazos River near Robinson, Texas	31°27'23"	97°2'0"	162.	--
T3	312715096590800	Monas Creek at FM 1860 near Riesel, Texas	31°27'15"	96°59'8"	0.168	0.020
T4	312639097030500	Castleman Creek near Robinson, Texas	31°26'39"	97°3'5"	0.439	0.
T5	312335097022100	Bull Hide Creek at FM 434 near Golinda, Texas	31°23'35"	97°2'21"	1.00	--
B3	312201096572200	Brazos River near Golinda, Texas	31°22'1"	96°57'22"	159.	320.
T6	311927097011700	Cow Bayou below FM 434 near Chilton, Texas	31°19'27"	97°1'17"	2.87	--
B4	8097500	Brazos River near Marlin, Texas	31°17'18"	96°58'10"	182.	--
T7	311645096584400	Deer Creek at SH 320 near Marlin, Texas	31°16'45"	96°58'44"	1.06	0.
B5	311437096551300	Brazos River at FM 712 near Marlin, Texas	31°14'37"	96°55'13"	209.	--
T8	311204096523300	Mussel Run Creek near Highbank, Texas	31°12'4"	96°52'33"	1.59	1.00
B6	8098290	Brazos River near Highbank, Texas	31°8'2"	96°49'29"	218.	396.
B7	310354096472000	Brazos River below FM 1373 near Baileyville, Texas	31°3'54"	96°47'20"	223.	--
B8	310143096463800	Brazos River above Pond Creek near Baileyville, Texas	31°1'43"	96°46'38"	220.	--
T9	310120096481700	Pond Creek at FM 2027 near Baileyville, Texas	31°1'20"	96°48'17"	0.180	0
B9	305836096453800	Brazos River at FM 979 near Calvert, Texas	30°58'36"	96°45'38"	295.	590.
B10	305630096451400	Brazos River near Calvert, Texas	30°56'30"	96°45'14"	254.	--
B11	305349096414800	Brazos River at Big Bend near Calvert, Texas	30°53'49"	96°41'48"	301.	--
B12	305158096414500	Brazos River at FM 485 near Hearne, Texas	30°51'58"	96°41'45"	359.	629.
T10	304932096443900	Little River at CR 263 near Gause, Texas	30°49'32"	96°44'39"	239.	61.1
B13	8108500	Brazos River at Valley Junction, Texas	30°49'38"	96°39'5"	532.	623.
B14	8108700	Brazos River at SH 21 near Bryan, Texas	30°37'36"	96°32'38"	531.	757.
T11	8108990	Little Brazos River at SH 21 near Bryan, Texas	30°38'27"	96°31'16"	35.6	8.03
B15	8109500	Brazos River near College Station, Texas	30°32'33"	96°25'21"	594.	677.
B16	302932096201600	Brazos River at Batts Ferry near Wellborn, Texas	30°29'32"	96°20'16"	852.	
B17	302355096181000	Brazos River near FM 159 near Clay, Texas	30°23'55"	96°18'10"	817.	829.
T12	302208096203500	Yegua Creek at FM 50 near Clay, Texas	30°22'8"	96°20'35"	5.26	6.59

Table 4.4.3, continued

Site Identifier	USGS Station Number	USGS Station Name	Latitude	Longitude	Streamflow (cfs)	
					March 2006	August 2006
B18	302230096175000	Brazos River near FM 1955 near Clay, Texas	30°22'30"	96°17'50"	809.	811.
B19	302200096152900	Brazos River at Rogers Plantation near Millican, Texas	30°22'0"	96°15'29"	804.	825.
B20	302342096110400	Brazos River near FM 159 near Millican, Texas	30°23'42"	96°11'4"	898.	963.
B21	302134096091800	Brazos River at SH 105 near Washington, Texas	30°21'34"	96°9'18"	780.	726.
T13	302003096091400	Navasota River below SH 105 near Washington, Texas	30°20'3"	96°9'14"	93.0	--
B22	301927096085300	Brazos River below Navasota River near Washington, Texas	30°19'27"	96°8'53"	854.	702.
B23	301713096050000	Brazos River at Old River Road near Courtney, Texas	30°17'13"	96°5'0"	892.	799.
B24	301313096071200	Brazos River near FM 2726 near Courtney, Texas	30°13'13"	96°7'12"	920.	825.
B25	301014096092700	Brazos River near FM 1736 near Hempstead, Texas	30°10'14"	96°9'27"	995.	818.
B26	08111500 Brazos	River near Hempstead, Texas	30°7'44"	96°11'15"	843.	807.
T14	300343096123300	Caney Creek at FM 1371 near Hempstead, Texas	30°3'43"	96°12'33"	1.80	0
B27	300217096063400	Brazos River at SH 159 near Hempstead, Texas	30°2'17"	96°6'34"	922.	873.
B28	300024096050500	Brazos River near FM 1887 near Hempstead, Texas	30°0'24"	96°5'5"	941.	861.
T15	295936096051100	Clear Creek near FM 1887 near Hempstead, Texas	29°59'36"	96°5'11"	8.84	3.33
T16	295637096075400	Piney Creek at FM 331 near Burleigh, Texas	29°56'37"	96°7'54"	3.58	0.07
B29	295431096064800	Brazos River at FM 529 near Burleigh, Texas	29°54'31"	96°6'48"	978.	901.
T17	295211096091900	Mill Creek at FM 331 near Burleigh, Texas	29°52'11"	96°9'19"	20.8	3.84
B30	294830096054400	Brazos River at FM 1458 at San Felipe, Texas	29°48'30"	96°5'44"	963.	883.
B31	294617096021200	Brazos River at IH–10 near Brookshire, Texas	29°46'17"	96°2'12"	1,130.	884.
B32	294017096011400	Brazos River at FM 1093 at Simonton, Texas	29°40'17"	96°1'14"	1,090.	814.
B33	293820095583200	Brazos River at FM 1489 near Simonton, Texas	29°38'20"	95°58'32"	1,010.	870.
T18	294107095551800	Bessies Creek at FM 1093 near Fulshear, Texas	29°41'7"	95°55'18"	2.48	0.
T19	293835095525600	Jones Creek at Bois du Arc Road near Fulshear, Texas	29°38'35"	95°52'56"	1.00	-106.
B34	293621095521300	Brazos River at CR near FM 359 near Rosenberg, Texas	29°36'21"	95°52'13"	874.	--
B35	293403095483700	Brazos River at FM 723 near Rosenberg, Texas	29°34'3"	95°48'37"	930.	799.
B36	08114000 Brazos	River at Richmond, Texas	29°34'56"	95°45'27"	871.	696.

USGS = United States Geological Survey
cfs = cubic feet per second
SH = State Highway
CR = County Road
FM = Farm to Market
IH = Interstate Highway

Table 4.4.4 Diversions used by the current analysis for river reaches in Turco and others (2007) (Texas Commission on Environmental Quality, 2014b).

Reach	Water Right Number(1)	Entity with Water Right	Diversion (acre-feet per month)	
			March	August
B1-B2	5085	Robinson	166	158
	4342	Texas Utilities Electric Co.	0.0	197
	2315	City of Waco	2212	4852
B2-B3	3936	Holy Land & Cattle	0	145
	4345	Luminant Generation Co., LLC	0	29.0
	4345	Texas Utilities Electric Co.		
	4345	TXU Electric Co.		
	5840	City of Waco	0	0
	4042	Walden	0	0
	4042	Walden Family Properties, LTD.	0	0
	4042	Whaley	0	0
B3-B4	4346	Dube/Marlin	0	0
B4-B5	4355	City of Marlin	109	0
B5-B6	4063	Grimes and others	0	0
	4358	Isaacs	0	0.0
B6-B7	4359	Isaacs	0	0
B7-B8	4076	Jones	0	0.0
	4078	Woodall	0	2.4
B8-B9	4078	Woodall	0	2.4
B9-B10	4023	Weinacht	0	0
	4361	Eliot	0	0
B10-B11	4365	Anderson	0	0
	4365	Anderson Trustee	0	0
	4366	Brien	0	0
	4367	Carrabba	0	0
	4362	Fazzino	0	0
	4362	McCrary	0	0
	4367	Papp	0	0
	4367	Planters and Merchants State Bank	0	0
	4363	Reistino	0	0
	4364	Skiles	0	0
	4367	Skiles	0	0
B11-B12	5470	Skiles	0	0
B12-B13	4145	Nigliazzo	0	0

Table 4.4.4, continued

Reach	Water Right Number(1)	Entity with Water Right	Diversion (acre-feet per month)	
			March	August
B13-B14	4080	Durant	0	0
	4080	Reistino	0	0
B13-B14	4368	Holden	0	0
	4370	Penn	0	145
	4371	Destefano	0	65
	4372	Forbin Investments N V	0	0
B14-B15	5271	Devers Canal Rice Pro Assn, Inc.	955	4452
	5349	Brazos Farm	100	220
B15-B16	4128	Gunn	0	0
B16-B17	4017	Moore	0	0
	5603	Gavronovic	256	256
	5752	Gavronovic	44	110
B17-B18	none			
B18-B19	none			
B19-B20	12759	KR Sod-Brazos LP	0	0
B20-B21	none			
B21-B22	none			
B22-B23	5290	Texas Department of Criminal Justice	0	0
B23-B24	5290	Texas Department of Criminal Justice	0	0
B24-B25	none			
B25-B26	none			
B26-B27	none			
B27-B28	none			
B28-B29	4009	Williamson	0	0
B29-B30	4280	Acme Brick Company	0	0
	5665	Weinman	0	0
B30-B31	none			
B31-B32	2925	Texas Water Development Board	0	0
	5166	Brazos River Authority	0	0
B32-B33	2925	Texas Water Development Board	0	0
B33-B34	5167	Texas Util. Mining Co/TU Svcs	0	0
	5168	Gulf Coast Water Authority	0	0
	5171	Gulf Coast Water Authority	0	0
B34-B35	none			
B35-B36	5166	Brazos River Authority	0	0
	5320	Houston Lighting & Power	1459	2359

None indicates no water right in the reach

Table 4.4.5 Return flows used by the current analysis for river reaches in Turco and others (2007) (Texas Commission on Environmental Quality, 2014c).

Reach	TPDES Identification Number(1)	Entity	Return Flow(2) (million gallons per day)*	
			March	August
B1-B2	2893.001	Cornerstone C&M	0	0
	331.001	Transit Mix Concrete & Materials	1.08	1.08
	11071.001	BRA	35.2	21.63
B2-B3	11015.001	City of Riesel	0.06	0.04
	10780.003	Robinson, City of	1.66	0.13
	954.001	Texas Utilities Electric Company	0	0
	954.002	Texas Utilities Electric Company	0	0
B3-B4	none			
B4-B5	10110.002	City of Marlin	1.2	0.85
B5-B6	none			
B6-B7	none			
B7-B8	none			
B8-B9	none			
B9-B10	none			
B10-B11	none			
B11-B12	none			
B12-B13	none			
B13-B14	none			
B14-B15	11038.001	Berg, Ralph	0.02	0.22
	10426.002	City of Bryan	2.53	2.34
	10426.003	City of Bryan	0.42	0.48
B15-B16	2585.001	Texas A&M University	1.54	1.48
	10968.003	Texas A&M University	1.64	1.57
B16-B17	none			
B17-B18	none			
B18-B19	none			
B19-B20	none			
B20-B21	none			
B21-B22	none			
B22-B23	13743.001	Texas Department of Criminal Justice	0.24	0.26
B23-B24	12458.002	Texas Department of Criminal Justice	0.21	0.17
B24-B25	none			
B25-B26	none			
B26-B27	none			
B27-B28	none			

Table 4.4.5, continued

Reach	TPDES Identification Number(1)	Entity	Return Flow(2) (million gallons per day)*	
			March	August
B28-B29	none			
B29-B30	2314.001	Positive Feeds, Inc.	0.11	0
B30-B31	none			
B31-B32	2624.001	Pioneer Concrete of Texas	0.97	0.96
	2665.001	Pioneer Concrete of Texas		
	10276.001	City of Sealy	0.63	0.65
	10765.001	City of Wallis	0.16	0.14
B32-B33	11719.001	Wallis-Orchard ISD	0.006	0.006
B33-B34	10001.001	Brookshire MWD	0.56	0.44
B34-B35	2443.001	Frito lay, Inc.	0.67	0.43
B35-B36	10258.001	City of Richmond	0.78	0.86
	10607.003	City of Rosenberg	1.79	1.64
	11655.001	Pecan Grove MUD	1.18	1.26

(1) None indicates no return flows on reach

(2) Values are the maximum March and August return flows by reach in the 1990s.

TPDES = Texas Pollutant Discharge Elimination System

Table 4.4.6 Updated gains/losses recalculated by the current analysis from the Turco and others (2007) March 2006 discharge measurements.

Reach	Gage	Measurement Date/Time	Time Elapsed between Downstream and Upstream Measurements (hours)	Measured Flow (cfs)	Rating (percent)	Tributary Inflow (cfs)	Diversions (cfs)	Return Flow (cfs)	Computed Gain/Loss (cfs)	Total Error (cfs)	Gain/Loss Determination
B1-B2	B1	3/1/06 11:56		141	8	0.91	38.8	56.1	2.7	17.2	Indeterminate
	B2	3/3/06 16:08	52.2	162	8						
B2-B3	B2	3/3/06 16:08		162	8	1.61	0.0	2.7	-7.3	15.2	Indeterminate
	B3	3/7/06 13:45	93.6	159	5						
B3-B4	B3	3/7/06 13:45		159	5	2.87	0.0	0.0	20.1	16.6	Gain
	B4	3/9/06 15:36	49.9	182	8						
B4-B5	B4	3/9/06 15:36		182	8	1.06	1.8	1.9	25.9	22.2	Gain
	B5	3/9/06 13:57	-1.6	209	8						
B5-B6	B5	3/9/06 13:57		209	8	1.59	0.0	0.0	7.4	20.0	Indeterminate
	B6	3/9/06 12:00	-2.0	218	5						
B6-B7	B6	3/9/06 12:00		218	5	0	0.0	0.0	5.0	20.9	Indeterminate
	B7	3/9/06 9:24	-2.6	223	8						
B7-B8	B7	3/9/06 9:24		223	8	0	0.0	0.0	-3.0	25.1	Indeterminate
	B8	3/9/06 11:08	1.7	220	8						
B8-B9	B8	3/9/06 11:08		220	8	0.18	0.0	0.0	74.8	34.4	Gain
	B9	3/6/06 12:32	-70.6	295	10						
B9-B10	B9	3/6/06 12:32		295	10	0	0.0	0.0	-41.0	32.1	Loss
	B10	3/7/06 13:40	25.1	254	5						
B10-B11	B10	3/7/06 13:40		254	5	0	0.0	0.0	47.0	19.7	Gain
	B11	3/7/06 10:37	-3.0	301	5						

Table 4.4.6, continued

Reach	Gage	Measurement Date/Time	Time Elapsed between Downstream and Upstream Measurements (hours)	Measured Flow (cfs)	Rating (percent)	Tributary Inflow (cfs)	Diversions (cfs)	Return Flow (cfs)	Computed Gain/Loss (cfs)	Total Error (cfs)	Gain/Loss Determination
B11-B12	B11	3/7/06 10:37		301	5	0	0.0	0.0	58.0	32.4	Gain
	B12	3/6/06 15:05	-19.5	359	8						
B12-B13	B12	3/6/06 15:05		359	8	239	0.0	0.0	-66.0	51.3	Loss
	B13	3/7/06 8:40	17.6	532	8						
B13-B14	B13	3/7/06 8:40		532	8	0	0.0	0.0	-1.0	60.1	Indeterminate
	B14	3/10/06 8:26	71.8	531	8						
B14-B15	B14	3/10/06 8:26		531	8	35.6	17.2	4.6	40.0	63.7	Indeterminate
	B15	3/10/06 11:06	2.7	594	8						
B15-B16	B15	3/10/06 11:06		594	8	0	0.0	4.9	253.1	83.1	Gain
	B16	3/7/06 8:23	-74.7	852	8						
B16-B17	B16	3/7/06 8:23		852	8	0	4.9	0.0	-30.1	94.4	Indeterminate
	B17	3/7/06 12:30	4.1	817	8						
B17-B18	B17	3/7/06 12:30		817	8	5.26	0.0	0.0	-13.3	92.0	Indeterminate
	B18	3/7/06 13:51	1.3	809	8						
B18-B19	B18	3/7/06 13:51		809	8	0	0.0	0.0	-5.0	91.2	Indeterminate
	B19	3/7/06	N/A	804	8						
B19-B20	B19	3/7/06		804	8	0	0.0	0.0	94.0	96.4	Indeterminate
	B20	3/7/06 16:20	N/A	898	8						
B20-B21	B20	3/7/06 16:20		898	8	0	0.0	0.0	-118.0	95.2	Loss
	B21	3/8/06 8:42	16.4	780	8						

Table 4.4.6, continued

Reach	Gage	Measurement Date/Time	Time Elapsed between Downstream and Upstream Measurements (hours)	Measured Flow (cfs)	Rating (percent)	Tributary Inflow (cfs)	Diversions (cfs)	Return Flow (cfs)	Computed Gain/Loss (cfs)	Total Error (cfs)	Gain/Loss Determination
B21-B22	B21	3/8/06 8:42		780	8	93	0.0	0.0	-19.0	92.5	Indeterminate
	B22	3/8/06	NA	854	8						
B22-B23	B22	3/8/06		854	8	0	0.0	0.4	37.6	98.8	Indeterminate
	B23	3/8/06	N/A	892	8						
B23-B24	B23	3/8/06		892	8	0	0.0	0.3	27.7	102.5	Indeterminate
	B24	3/8/06	N/A	920	8						
B24-B25	B24	3/8/06		920	8	0	0.0	0.0	75.0	108.4	Indeterminate
	B25	3/8/06	N/A	995	8						
B25-B26	B25	3/8/06		995	8	0	0.0	0.0	-152.0	115.9	Loss
	B26	3/9/06 10:19	N/A	843	10						
B26-B27	B26	3/9/06 10:19		843	10	1.8	0.0	0.0	77.2	112.0	Indeterminate
	B27	3/9/06 8:57	-1.4	922	8						
B27-B28	B27	3/9/06 8:57		922	8	0	0.0	0.0	19.0	105.4	Indeterminate
	B28	3/9/06 11:51	2.9	941	8						
B28-B29	B28	3/9/06 11:51		941	8	12.4	0.0	0.0	24.6	108.6	Indeterminate
	B29	3/9/06 13:59	2.1	978	8						
B29-B30	B29	3/9/06 13:59		978	8	20.8	0.0	0.2	-36.0	109.8	Indeterminate
	B30	3/8/06 7:30	-30.5	963	8						
B30-B31	B30	3/8/06 7:30		963	8	0	0.0	0.0	167.0	118.8	Gain
	B31	3/8/06 10:48	3.3	1130	8						

Table 4.4.6, continued

Reach	*Gage*	*Measurement Date/Time*	*Time Elapsed between Downstream and Upstream Measurements (hours)*	*Measured Flow (cfs)*	*Rating (percent)*	*Tributary Inflow (cfs)*	Diversions (cfs)	Return Flow (cfs)	Computed Gain/Loss (cfs)	Total Error (cfs)	Gain/Loss Determination
B31-B32	*B31*	*3/8/06 10:48*		*1130*	*8*	*0*	0.0	2.7	-42.7	125.6	Indeterminate
	B32	*3/8/06 13:51*	*3.0*	*1090*	*8*						
B32-B33	*B32*	*3/8/06 13:51*		*1090*	*8*	*0*	0.0	0.0	-80.0	118.9	Indeterminate
	B33	*3/9/06 8:33*	*18.7*	*1010*	*8*						
B33-B34	*B33*	*3/9/06 8:33*		*1010*	*8*	*3.48*	0.0	0.9	-140.3	106.9	Loss
	B34	*3/9/06 11:03*	*2.5*	*874*	*8*						
B34-B35	*B34*	*3/9/06 11:03*		*874*	*8*	*0*	0.0	1.0	55.0	102.1	Indeterminate
	B35	*3/9/06 14:11*	*3.1*	*930*	*8*						
B35-B36	*B35*	*3/9/06 14:11*		*930*	*8*	*0*	23.8	5.8	-41.0	101.9	Indeterminate
	B36	*3/9/06 15:46*	*1.6*	*871*	*8*						

Red, italics text from Turco and others (2007)
black text for updated analysis
cfs = cubic feet per second

Table 4.4.7 Updated gains/losses recalculated by the current analysis from the Turco and others (2007) August 2006 discharge measurements.

Reach	Gage	Measurement Date/Time	Time Elapsed between Downstream and Upstream Measurements (hours)	Measured Flow (cfs)	Rating (percent)	Tributary Inflow (cfs)	Diversions (cfs)	Return Flow (cfs)	Computed Gain/Loss (cfs)	Total Error (cfs)	Gain/Loss Determination
B1-B3	B1	8/10/06		370	5	0.52	87.7	35.4	1.8	24.5	Indeterminate
	B3	8/10/06 13:34	N/A	320	5						
B3-B6	B3	8/10/06 13:34		320	5	1	0.0	1.3	140.7	28.1	Gain
	B6	8/11/06 9:27	19.9	463	5						
B6-B9	B6	8/11/06 9:27		463	5	0	0.1	0.0	127.1	37.5	Gain
	B9	8/14/06 11:16	73.8	590	5						
B9-B12	B9	8/14/06 11:16		590	5	0	0.0	0.0	39.0	43.1	Indeterminate
	B12	8/14/06 16:01	4.7	629	5						
B12-B13	B12	8/14/06 16:01		629	5	61.1	0.0	0.0	-67.1	58.9	Loss
	B13	8/15/06 8:26	16.4	623	8						
B13-B14	B13	8/15/06 8:26		623	8	0	3.4	0.0	137.4	62.6	Gain
	B14	8/15/06 10:32	2.1	757	5						
B14-B15	B14	8/15/06 10:32		757	5	8.03	76.2	4.7	-16.6	66.1	Indeterminate
	B15	8/16/06 10:44	24.2	677	8						
B15-B16	B15	8/16/06 10:44		677	8	0	0.0	4.7	68.3	65.9	Gain
	B16	8/16/06 9:16	-1.5	750	5						
B16-B17	B16	8/16/06 9:16		750	5	0	6.0	0.0	85.0	76.2	Gain
	B17	8/16/06 12:23	3.1	829	8						
B17-B18	B17	8/16/06 12:23		829	8	6.59	0.0	0.0	-24.6	92.8	Indeterminate
	B18	8/16/06 13:26	1.0	811	8						

Table 4.4.7, continued

Reach	Gage	Measurement Date/Time	Time Elapsed between Downstream and Upstream Measurements (hours)	Measured Flow (cfs)	Rating (percent)	Tributary Inflow (cfs)	Diversions (cfs)	Return Flow (cfs)	Computed Gain/Loss (cfs)	Total Error (cfs)	Gain/Loss Determination
B18-B19	B18	8/16/06 13:26		811	8	0	0.0	0.0	14.0	92.5	Indeterminate
	B19	8/16/06 14:39	1.2	825	8						
B19-B20	B19	8/16/06 14:39		825	8	0	0.0	0.0	138.0	101.4	Gain
	B20	8/16/06 16:00	1.3	963	8						
B20-B21	B20	8/16/06 16:00		963	8	0	0.0	0.0	-237.0	96.5	Loss
	B21	8/17/06 8:21	16.4	726	8						
B21-B22	B21	8/17/06 8:21		726	8	0	0.0	0.0	-24.0	80.8	Indeterminate
	B22	8/17/06 9:19	1.0	702	8						
B22-B23	B22	8/17/06 9:19		702	8	0	0.0	0.4	96.6	85.1	Gain
	B23	8/17/06 11:14	1.9	799	8						
B23-B24	B23	8/17/06 11:14		799	8	0	0.0	0.3	25.7	91.9	Indeterminate
	B24	8/17/06 13:31	2.3	825	8						
B24-B25	B24	8/17/06 13:31		825	8	0	0.0	0.0	-7.0	92.9	Indeterminate
	B25	8/17/06 15:04	1.5	818	8						
B25-B26	B25	8/17/06 15:04		818	8	0	0.0	0.0	-11.0	91.9	Indeterminate
	B26	8/17/06 16:49	1.7	807	8						
B26-B27	B26	8/17/06 16:49		807	8	0	0.0	0.0	66.0	95.1	Indeterminate
	B27	8/18/06 7:49	15.0	873	8						
B27-B28	B27	8/18/06 7:49		873	8	0	0.0	0.0	-12.0	98.1	Indeterminate
	B28	8/18/06 9:07	1.3	861	8						

Table 4.4.7, continued

Reach	Gage	Measurement Date/Time	Time Elapsed between Downstream and Upstream Measurements (hours)	Measured Flow (cfs)	Rating (percent)	Tributary Inflow (cfs)	Diversions (cfs)	Return Flow (cfs)	Computed Gain/Loss (cfs)	Total Error (cfs)	Gain/Loss Determination
B28-B29	*B28*	*8/18/06 9:07*		*861*	*8*	*3.4*	0.0	0.0	36.6	99.7	Indeterminate
	B29	*8/18/06 10:35*	*1.5*	*901*	*8*						
B29-B30	*B29*	*8/18/06 10:35*		*901*	*8*	*3.84*	0.0	0.0	-21.8	100.9	Indeterminate
	B30	*8/17/06 8:22*	*-26.2*	*883*	*8*						
B30-B31	*B30*	*8/17/06 8:22*		*883*	*8*	*0*	0.0	0.0	1.0	100.0	Indeterminate
	B31	*8/17/06 10:02*	*1.7*	*884*	*8*						
B31-B32	*B31*	*8/17/06 10:02*		*884*	*8*	*0*	0.0	2.7	-72.7	96.1	Indeterminate
	B32	*8/17/06 13:05*	*3.0*	*814*	*8*						
B32-B33	*B32*	*8/17/06 13:05*		*814*	*8*	*0*	0.0	0.0	56.0	95.3	Indeterminate
	B33	*8/17/06 15:36*	*2.5*	*870*	*8*						
B33-B35	*B33*	*8/17/06 15:36*		*870*	*8*	*-106*	0.0	1.3	33.7	94.5	Indeterminate
	B35	*8/18/06 12:43*	*21.1*	*799*	*8*						
B35-B36	*B35*	*8/18/06 12:43*		*799*	*8*	*0*	38.5	5.8	-70.4	84.8	Indeterminate
	B36	*8/18/06 14:43*	*2.0*	*696*	*8*						

Red, italics text from Turco and others (2007)
black text for updated analysis
cfs = cubic feet per second

Table 4.4.8 Comparison of Turco and others (2007) and current gain/loss analyses for the March 2006 streamflow measurements.

Reach	Turco and others (2007) Analysis			Current Analysis		
	Computed Gain/Loss (cfs)	Total Error (cfs)	Gain/Loss Determination	Computed Gain/Loss (cfs)	Total Error (cfs)	Gain/Loss Determination
B1-B2	28.1	23.6	Gain	2.7	17.2	Indeterminate
B2-B3	-4.6	20.9	Indeterminate	-7.3	15.2	Indeterminate
B3-B4	20.1	22.5	Indeterminate	20.1	16.6	Gain
B4-B5	25.9	31.3	Indeterminate	25.9	22.2	Gain
B5-B6	7.4	27.6	Indeterminate	7.4	20	Indeterminate
B6-B7	5	28.7	Indeterminate	5	20.9	Indeterminate
B7-B8	-3	35.4	Indeterminate	-3	25.1	Indeterminate
B8-B9	74.8	47.1	Gain	74.8	34.4	Gain
B9-B10	-41	42.2	Indeterminate	-41	32.1	Loss
B10-B11	47	27.8	Gain	47	19.7	Gain
B11-B12	58	43.8	Gain	58	32.4	Gain
B12-B13	-66	71.3	Indeterminate	-66	51.3	Loss
B13-B14	-1	85	Indeterminate	-1	60.1	Indeterminate
B14-B15	27.4	90	Indeterminate	40	63.7	Indeterminate
B15-B16	258	116	Gain	253.1	83.1	Gain
B16-B17	-35	134	Indeterminate	-30.1	94.4	Indeterminate
B17-B18	-13.3	130	Indeterminate	-13.3	92	Indeterminate
B18-B19	-5	129	Indeterminate	-5	91.2	Indeterminate
B19-B20	94	136	Indeterminate	94	96.4	Indeterminate
B20-B21	-118	134	Indeterminate	-118	95.2	Loss
B21-B22	-19	105	Indeterminate	-19	92.5	Indeterminate
B22-B23	38	140	Indeterminate	37.6	98.8	Indeterminate
B23-B24	28	145	Indeterminate	27.7	102.5	Indeterminate
B24-B25	75	153	Indeterminate	75	108.4	Indeterminate
B25-B26	-152	164	Indeterminate	-152	115.9	Loss
B26-B27	77.2	158	Indeterminate	77.2	112	Indeterminate
B27-B28	19	149	Indeterminate	19	105.4	Indeterminate
B28-B29	24.6	154	Indeterminate	24.6	108.6	Indeterminate
B29-B30	-35.8	155	Indeterminate	-36	109.8	Indeterminate
B30-B31	167	167	Indeterminate	167	118.8	Gain

Table 4.4.8, continued

Reach	Turco and others (2007) Analysis			Current Analysis		
	Computed Gain/Loss (cfs)	Total Error (cfs)	Gain/Loss Determination	Computed Gain/Loss (cfs)	Total Error (cfs)	Gain/Loss Determination
B31-B32	-40	178	Indeterminate	-42.7	125.6	Indeterminate
B32-B33	-80	168	Indeterminate	-80	118.9	Indeterminate
B33-B34	-139	151	Indeterminate	-140.3	106.9	Loss
B34-B35	56	144	Indeterminate	55	102.1	Indeterminate
B35-B36	-59	144	Indeterminate	-41	101.9	Indeterminate

cfs = cubic feet per second
green highlight indicates gaining reach
red highlight indicates losing reach

Table 4.4.9 Comparison of Turco and others (2007) and current gain/loss analyses for the August 2006 discharge measurements.

Reach	Turco and others (2007) Analysis			Current Analysis		
	Computed Gain/Loss (cfs)	Total Error (cfs)	Gain/Loss Determination	Computed Gain/Loss (cfs)	Total Error (cfs)	Gain/Loss Determination
B1-B3	-50.5	34.5	Loss	1.8	24.5	Indeterminate
B3-B6	75	35.8	Gain	140.7	28.1	Gain
B6-B9	194	49.3	Gain	127.1	37.5	Gain
B9-B12	39	61	Indeterminate	39	43.1	Indeterminate
B12-B13	-64.1	81.3	Indeterminate	-67.1	58.9	Loss
B13-B14	134	87.7	Gain	137.4	62.6	Gain
B14-B15	-88	92	Indeterminate	-16.6	66.1	Indeterminate
B15-B16	73	71.3	Gain	68.3	65.9	Gain
B16-B17	79	104	Indeterminate	85	76.2	Gain
B17-B18	-24.6	131	Indeterminate	-24.6	92.8	Indeterminate
B18-B19	14	131	Indeterminate	14	92.5	Indeterminate
B19-B20	138	143	Indeterminate	138	101.4	Gain
B20-B21	-237	135	Loss	-237	96.5	Loss
B21-B22	-24	114	Indeterminate	-24	80.8	Indeterminate
B22-B23	97	120	Indeterminate	96.6	85.1	Gain
B23-B24	26	130	Indeterminate	25.7	91.9	Indeterminate
B24-B25	-7	131	Indeterminate	-7	92.9	Indeterminate
B25-B26	-11	130	Indeterminate	-11	91.9	Indeterminate
B26-B27	66	134	Indeterminate	66	95.1	Indeterminate
B27-B28	-12	139	Indeterminate	-12	98.1	Indeterminate
B28-B29	36.6	141	Indeterminate	36.6	99.7	Indeterminate
B29-B30	-21.8	143	Indeterminate	-21.8	100.9	Indeterminate
B30-B31	1	141	Indeterminate	1	100	Indeterminate
B31-B32	-70	136	Indeterminate	-72.7	96.1	Indeterminate
B32-B33	56	135	Indeterminate	56	95.3	Indeterminate
B33-B35	-35	134	Indeterminate	33.7	94.5	Indeterminate
B35-B36	-103	120	Indeterminate	-70.4	84.8	Indeterminate

cfs = cubic feet per second
green highlight indicates gaining reach
red highlight indicates losing reach

Table 4.4.10 United States Geological Survey stream gages used in the current hydrograph separation study.

Gage Name	Gage Number	Gage Description	Period of Record
Aquilla	08093100	Brazos River near Aquilla, Texas	10/1938 to 12/2013
Waco	08096500	Brazos River at Waco, Texas	10/1898 to 12/2013
Highbank	08098290	Brazos River near Highbank, Texas	10/1965 to 12/2013
Cameron	08106500	Little River near Cameron, Texas	11/1916 to 12/2013
Bryan	08109000	Brazos River near Bryan, Texas	3/1918 to 12/1992
	08108700	Brazos River at SH 21 near Bryan, Texas	8/1993 to 12/2013
Hempstead	08111500	Brazos River near Hempstead, Texas	10/1938 to 12/2013
Richmond	08114000	Brazos River at Richmond, Texas	10/1922 to 12/2013

Table 4.4.11 Maximum assumed base flow by gage used in the current hydrograph separation study.

Gage Name	Assumed Maximum Base Flow (cubic feet per second)
Aquilla	500
Waco	600
Highbank	600
Cameron	300
Bryan	900
Hempstead	1,200
Richmond	2,000

Table 4.4.12 Historical diversions in acre-feet between the Hempstead and Richmond gages used in the current hydrograph separation analysis.

Year	January	February	March	April	May	June	July	August	September	October	November	December	ANNUAL
1940	0	0	2,384	7,016	12,628	15,953	16,066	9,031	3,340	651	174	0	67,243
1941	0	0	2,409	6,598	12,103	14,905	15,969	9,594	3,651	671	210	0	66,110
1942	`	0	2,938	7,829	14,471	17,642	19,358	11,907	4,574	825	271	0	79,815
1943	0	0	3,973	10,301	19,185	23,148	26,024	16,376	6,348	1,124	386	0	106,865
1944	0	0	3,407	8,711	16,289	19,549	22,251	14,160	5,512	967	340	0	91,186
1945	0	0	3,759	9,710	18,104	21,812	24,603	15,529	6,026	1,064	368	0	100,975
1946	0	0	2,895	7,657	14,182	17,241	19,044	11,789	4,540	815	271	0	78,434
1947	0	0	4,076	10,372	19,421	23,264	26,592	16,987	6,622	1,159	410	0	108,903
1948	0	0	4,406	11,124	20,875	24,930	28,697	18,445	7,207	1,255	449	0	117,388
1949	0	0	4,450	11,260	21,118	25,242	28,997	18,605	7,265	1,267	452	0	118,656
1950	0	0	4,556	11,320	21,343	25,328	29,577	19,249	7,556	1,303	477	0	120,709
1951	0	0	4,541	11,279	21,267	25,235	29,477	19,188	7,533	1,299	476	0	120,295
1952	60	0	4,306	10,918	20,356	24,259	28,028	18,076	7,073	1,328	442	0	114,846
1953	0	0	4,091	10,290	19,309	23,012	26,616	17,179	6,723	1,167	421	0	108,808
1954	0	0	4,740	11,746	22,141	26,234	30,744	20,069	7,886	1,357	499	0	125,416
1955	0	0	3,368	8,517	15,933	19,010	21,930	14,122	5,522	960	345	0	89,707
1956	32	0	4,521	12,599	18,326	15,582	23,832	11,786	3,963	40	1,421	0	92,102
1957	0	0	0	0	4,471	7,107	14,045	17,595	7,349	1,758	822	0	53,147
1958	0	0	2,000	5,752	13,784	21,318	20,885	14,312	1,179	1,165	0	0	80,395
1959	0	0	4,315	6,352	11,223	13,581	19,138	13,210	8,938	677	0	0	77,434
1960	0	0	1,894	10,547	19,346	21,443	21,937	12,427	4,312	302	0	0	92,208
1961	0	0	1,709	10,484	21,504	16,207	16,753	18,801	4,639	3,327	0	0	93,424
1962	0	0	6,157	15,213	24,678	22,780	19,975	21,775	6,539	2,964	0	0	120,081
1963	0	0	2,916	17,729	26,539	18,897	19,672	20,364	11,930	9,085	0	0	127,132
1964	0	0	0	11,122	21,673	21,503	20,795	13,728	9,941	3,389	58	0	102,209
1965	0	0	8,128	15,631	12,673	19,760	19,018	15,956	11,546	1,226	466	0	104,404

Table 4.4.12, continued

Year	January	February	March	April	May	June	July	August	September	October	November	December	ANNUAL
1966	0	0	0	3,622	6,055	21,952	26,971	15,410	9,682	755	670	0	85,117
1967	0	1,979	14,203	22,620	24,652	25,034	12,198	17,397	9,626	0	0	0	127,709
1968	0	0	3,053	13,061	16,252	15,431	23,393	17,588	4,264	4,908	840	40	98,830
1969	0	0	1,346	5,284	9,083	24,417	24,505	16,501	5,276	1,855	0	2,002	90,269
1970	0	0	753	8,627	9,424	19,462	20,263	11,831	4,156	3,923	0	0	78,439
1971	0	0	11,039	14,641	15,170	20,071	14,906	2,992	1,575	2,497	0	0	82,891
1972	0	0	5,741	12,117	11,968	16,685	13,399	9,672	9,793	939	0	0	80,314
1973	0	0	1,986	1,548	12,043	11,772	17,022	12,381	2,761	840	2,619	2,155	65,127
1974	0	0	7,169	14,209	17,895	30,362	26,776	13,539	3,781	2,259	0	0	115,990
1975	0	0	1,689	10,189	14,895	18,676	18,652	8,231	3,403	392	655	1,600	78,382
1976	2,579	1,772	1,460	11,615	14,199	15,687	8,719	4,955	1,152	709	1,758	4,371	68,976
1977	2,582	2,069	3,527	11,284	14,895	21,809	21,162	5,614	773	2,453	2,117	589	88,874
1978	4,640	2,468	2,266	10,401	25,562	27,056	27,905	5,384	3,871	2,586	5,333	553	118,025
1979	0	0	660	2,310	9,662	20,000	18,715	9,392	4,351	4,347	2,812	0	72,249
1980	1,616	0	2,750	9,643	16,932	30,779	32,289	7,904	3,191	10,600	6,568	0	122,272
1981	4,048	0	12,082	17,218	20,320	19,152	11,367	8,283	2,431	1,435	615	6,980	103,931
1982	6,585	1,664	1,803	4,288	10,605	28,705	21,954	7,530	5,103	5,100	261	655	94,253
1983	1,673	403	1,570	9,771	6,775	15,980	13,618	2,974	2,733	6,109	261	655	62,522
1984	750	56	5,026	14,787	17,636	20,334	23,360	9,189	9,511	8,249	6,014	7,543	122,455
1985	5,160	5,037	0	2,871	13,348	17,626	22,271	19,716	9,578	2,823	966	0	99,396
1986	695	1,439	4,709	10,413	8,942	10,466	23,008	10,153	7,042	6,935	4,001	3,441	91,244
1987	1,670	1,654	3,023	13,195	9,946	13,501	16,081	16,942	6,790	5,522	1,459	1,983	91,766
1988	531	262	4,013	8,293	17,725	24,016	26,693	14,386	11,844	7,628	3,492	2,232	121,115
1989	2,478	85	5,076	9,524	12,582	19,191	18,988	8,021	10,488	5,336	2,796	2,179	96,744
1990	980	2,172	5,063	4,062	5,895	19,960	20,996	23,647	11,567	4,339	4,132	3,850	106,663
1991	348	698	951	1,667	7,261	11,123	14,754	18,504	7,694	11,577	4,684	1,845	81,106
1992	6,668	5,684	9,827	11,226	12,195	15,224	17,991	18,829	16,334	16,976	7,548	5,996	144,498

Table 4.4.12, continued

Year	January	February	March	April	May	June	July	August	September	October	November	December	ANNUAL
1993	5,313	5,455	6,382	6,899	8,956	13,224	20,438	23,340	18,016	9,363	6,035	6,964	130,385
1994	2,944	2,963	3,770	5,840	8,279	16,782	38,035	16,387	11,343	4,019	3,898	1,169	115,429
1995	7,559	3,040	4,123	5,858	9,889	12,664	16,190	10,917	10,490	9,928	10,390	5,833	106,881
1996	2,998	3,570	7,998	8,666	11,317	11,954	13,137	10,043	3,411	5,258	6,667	1,588	86,607
1997	0	0	169	273	2,262	10,307	23,118	13,878	6,557	0	1,416	0	57,980
1998	0	0	0	4,989	5,827	7,454	5,755	4,485	1,097	0	1,947	0	31,554
1999	1,613	422	1,845	5,973	5,898	5,322	6,592	7,026	6,714	4,039	394	1,356	47,194
2000	467	0	1,899	1,462	3,639	6,004	7,562	6,552	8,484	5,046	687	0	41,802
2001	0	0	0	0	1,191	2,523	9,422	10,487	7,880	1,454	4,853	3,093	40,903
2002	3,959	2,771	6,122	6,006	7,667	6,893	6,041	4,926	5,243	3,816	4,427	2,039	59,910
2003	0	0	3,478	7,830	10,163	9,766	5,533	7,409	2,849	3,311	6,607	6,935	63,881
2004	3,028	887	4,403	3,607	3,186	3,060	4,898	7,151	6,505	5,063	930	2,083	44,801
2005	7,513	2,837	181	5,551	6,798	6,374	4,744	5,971	4,057	2,611	571	1,389	48,597
2006	3,135	1,414	1,721	2,997	4,157	5,120	4,802	4,135	3,367	2,405	896	1,177	35,325
2007	100	857	1,097	150	2,853	4,250	2,335	369	420	250	1,140	747	14,568
2008	1,900	1,073	1,203	2,681	3,792	6,797	7,231	3,047	2,484	1,696	941	489	33,334
2009	2,410	1,583	1,041	185	5,853	4,466	4,077	2,110	1,346	218	171	78	23,538
2010	154	189	160	1,016	1,891	2,786	2,089	6,338	1,778	3,039	1,152	8,109	28,701
2011	966	2,399	3,484	6,103	3,123	3,882	4,611	5,798	5,410	2,161	784	637	39,358
2012	339	262	317	338	3,839	6,762	4,679	5,595	5,703	3,679	6,605	9,475	47,593
2013	486	950	1,320	2,486	2,951	4,477	3,793	5,910	4,297	2,960	2,847	6,074	38,551
Average	1,189	785	3,425	8,074	12,681	16,355	17,879	12,015	6,134	3,143	1,780	1,458	84,918

Data from 1940 to 1997 are from Texas Commission on Environmental Quality (2014c)
Data from 1998 to 2005 and 2007 to 2012 are from Texas Commission on Environmental Quality (2014b)
Diversions from 2006 are based on the average data for 2004, 2005, 2007, and 2008
Diversions for 2013 are the average of diversions from 2009 to 2012.

Table 4.4.13 Loss factors between gages used in the current hydrograph separation study (Brazos River Authority, 2014).

Reach	Loss Factor (fraction)
Aquilla to Waco	0.00525
Waco to Highbank	0.0094
Highbank to Bryan	0.0147
Waco to Bryan	0.0241
Cameron to Bryan	0.0242
Bryan to Hempstead	0.0245
Hempstead to Richmond	0.0282

Table 4.4.14 Comparisons of incremental base flow between reaches and normal and drought years for the current study.

Reach	Average Annual Incremental Base Flow (cfs)	Average Annual Incremental Base Flow for 1950s Drought (cfs)	Percentage of Incremental Base Flow During 1950s Drought	Average Annual Incremental Base Flow for 2010s Drought (cfs)	Percentage of Incremental Base Flow During 2010s Drought
1. Aquilla to Waco	134	66	49%	55	41%
2. Waco to Bryan	289	191	66%	239	83%
2a. Waco to Highbank	142	-		80	56%
2b.Highbank to Bryan	201	-		160	80%
3. Bryan to Hempstead	300	177	59%	171	57%
4. Hempstead to Richmond	324	152	47%	92	28%

cfs = cubic feet per second
% = percent

Table 4.4.15 Springs in or within 2 miles of the Brazos River Alluvium Aquifer.

Spring Name and/or Number(1)	County	Geology	Minimum Flow (gpm)	Date of Minimum Flow	Maximum Flow (gpm)	Date of Maximum Flow	Number of Measure-ments	Source
Cumings Springs OR Austin_6 (Brune)	Austin	Lissie Sand	--	--	trickle	1978	1	Brune
Austin_1 (Brune)	Austin	Lissie Sand	--	--	former spring	1978	1	Brune
BB-40-14-503	Bosque	Fredericksburg and Washita Groups	--	--	50 - 60	1971	1	TWDB, USGS
BS-59-20-545	Burleson	Sparta Sand	--	--	--	--	--	TWDB, USGS
BS-59-20-130	Burleson	--	--	--	3	1936	1	TWDB, USGS
BS-59-20-129	Burleson	--	--	--	2	1936	1	TWDB, USGS
BS-59-38-707	Burleson	Terrace Deposits	--	--	1	1936	1	TWDB, USGS
Sulphur (Sulfur) Springs	Burleson	Terrace Deposits	--	--	3	1936	1	TWDB, USGS
Ft. Bend_3 (Brune)	Ft. Bend	--	--	--	former spring	1977	1	Brune
Ft. Bend_10 (Brune)	Ft. Bend	--	--	--	former spring	1977	1	Brune
Ft. Bend_11 (Brune)	Ft. Bend	--	--	--	former spring	1977	1	Brune
Ft. Bend_12 (Brune)	Ft. Bend	--	--	--	former spring	1977	1	Brune
Ft. Bend_2 (Brune)	Ft. Bend	--	--	--	former spring	1977	1	Brune
Spanish Springs OR Ft. Bend_4 (Brune)	Ft. Bend	terrace sands	--	--	former spring	1977	1	Brune
Waco Springs	McLennan	Alluvium	--	--	--	--	--	TWDB, USGS

Table 4.4.15, continued

Spring Name and/or Number[1]	County	Geology	Minimum Flow (gpm)	Date of Minimum Flow	Maximum Flow (gpm)	Date of Maximum Flow	Number of Measurements	Source
Caddo Springs OR Milam_1 (Brune)	Milam	terrace sands	4	1975	29	1936	2	Brune
Nashville Springs OR Milam_2 (Brune)	Milam	river terrace sands and gravels	--	--	2	1975	1	Brune
WK-59-03-407	Robertson	Brazos River Alluvium	--	--	10	1961	1	TWDB, USGS
Waller_4 (Brune)	Waller	--	--	--	former spring	1978	1	Brune
Irons Springs OR Waller_7 (Brune)	Waller	--	--	--	former spring	1978	1	Brune
Best Springs OR Waller_8 (Brune)	Waller	Lissie Sand	--	--	1.4	1978	1	Brune
Indian Oaks Springs OR Waller_9 (Brune)	Waller	Bentley sand and gravel	--	--	former spring	1978	1	Brune

[1] county name_# (Brune) indicates the number used by Brune (2002) to identify the spring in the county
gpm = gallons per minute
Brune = Brune (2002)
TWDB = TWDB (2014f)
USGS = Heitmuller and Reece (2003)

Table 4.4.16 Reservoirs in the vicinity of the Brazos River Alluvium Aquifer.

Reservoir Name[1]	Reservoir Owner	Impound Date	Surface Area (acres)
Aquilla Lake	U.S. Army Corps of Engineers	1983	3,066
Lake Whitney	U.S. Army Corps of Engineers	1951	23,220
Lake Mexia	Bistone Municipal Water Supply District	1961	1,009
Tradinghouse Creek Reservoir	Texas Power and Light Company	1968	2,010
Lake Waco	U.S. Army Corps of Engineers	1965	8,190
Lake Creek Lake	Texas Power and Light Company	1952	550
Lake Limestone	Brazos River Authority	1978	12,486
Twin Oak Reservoir	Texas Power and Light Company	1982	2,330
Belton Lake	U.S. Army Corps of Engineers	1954	12,135
Camp Creek Lake	Camp Creek Water Company	1949	750
Bryan Utilities Lake	City of Bryan	1974	829
Granger Lake	U.S. Army Corps of Engineers	1977	4,203
Gibbons Creek Reservoir	Texas Municipal Power Agency	1981	2,576
Alcoa Lake	Aluminum Company of America	1952	914
Somerville Lake	U.S. Army Corps of Engineers	1967	11,395
Addicks Reservoir[2]	U. S. Army Corps of Engineers	1948	16,780
Barker Reservoir[2]	U. S. Army Corps of Engineers	1945	17,225
Smithers Lake	Houston Lighting and Power Company	1957	2,480
Sheldon Reservoir	Texas Parks and Wildlife Department	1943	12,441
Stillhouse Hollow Lake	U. S. Army Corps of Engineers	1968	6,484
Lake Georgetown	U. S. Army Corps of Engineers	1980	1,287

(1) listed in order from north to south
(2) Flood control lake; not used for water supply and, under normal conditions, is empty
U.S. = United States

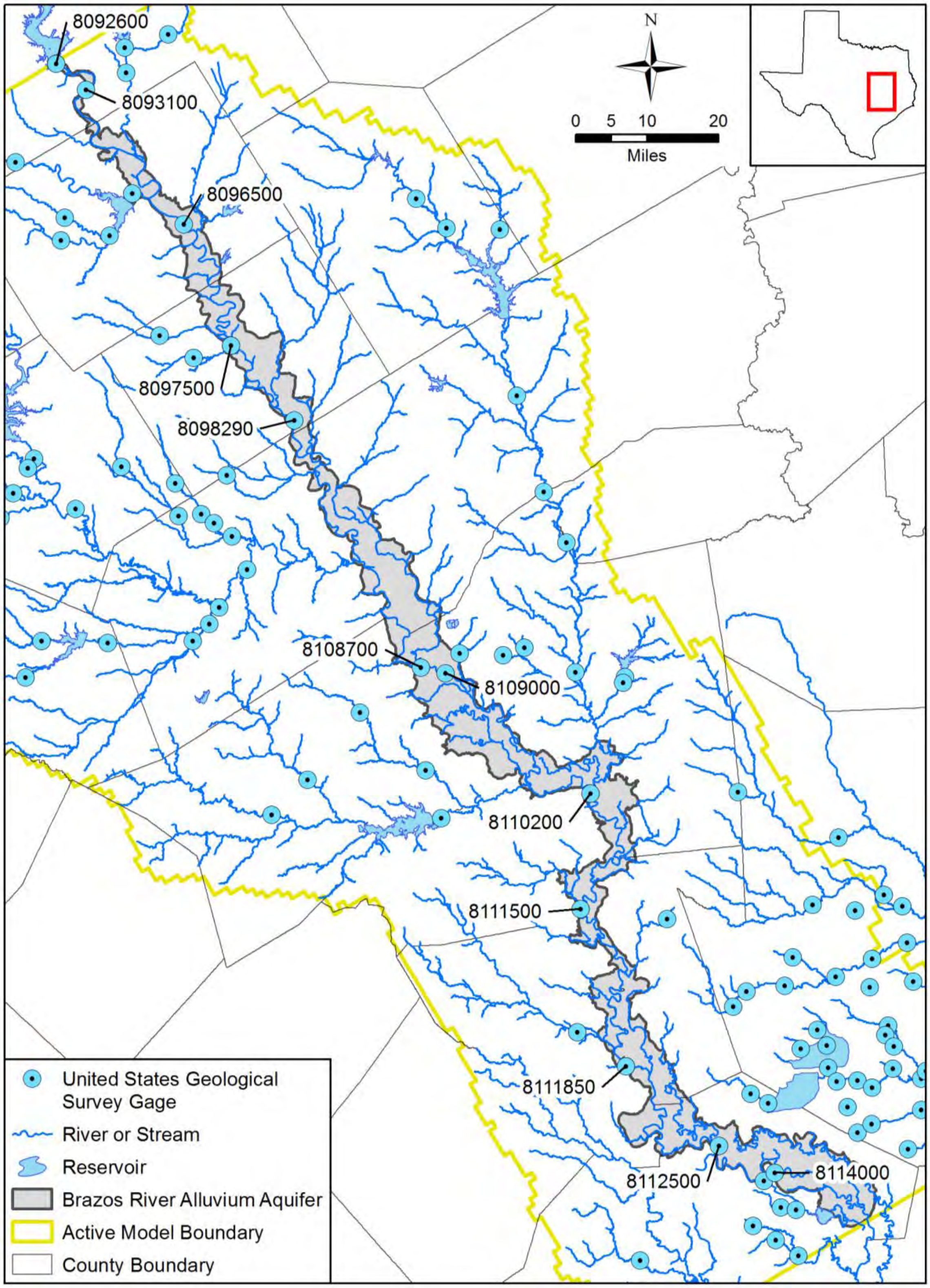


Figure 4.4.1 Rivers, streams, and United States Geological Survey stream gage locations in the vicinity of the Brazos River Alluvium Aquifer.

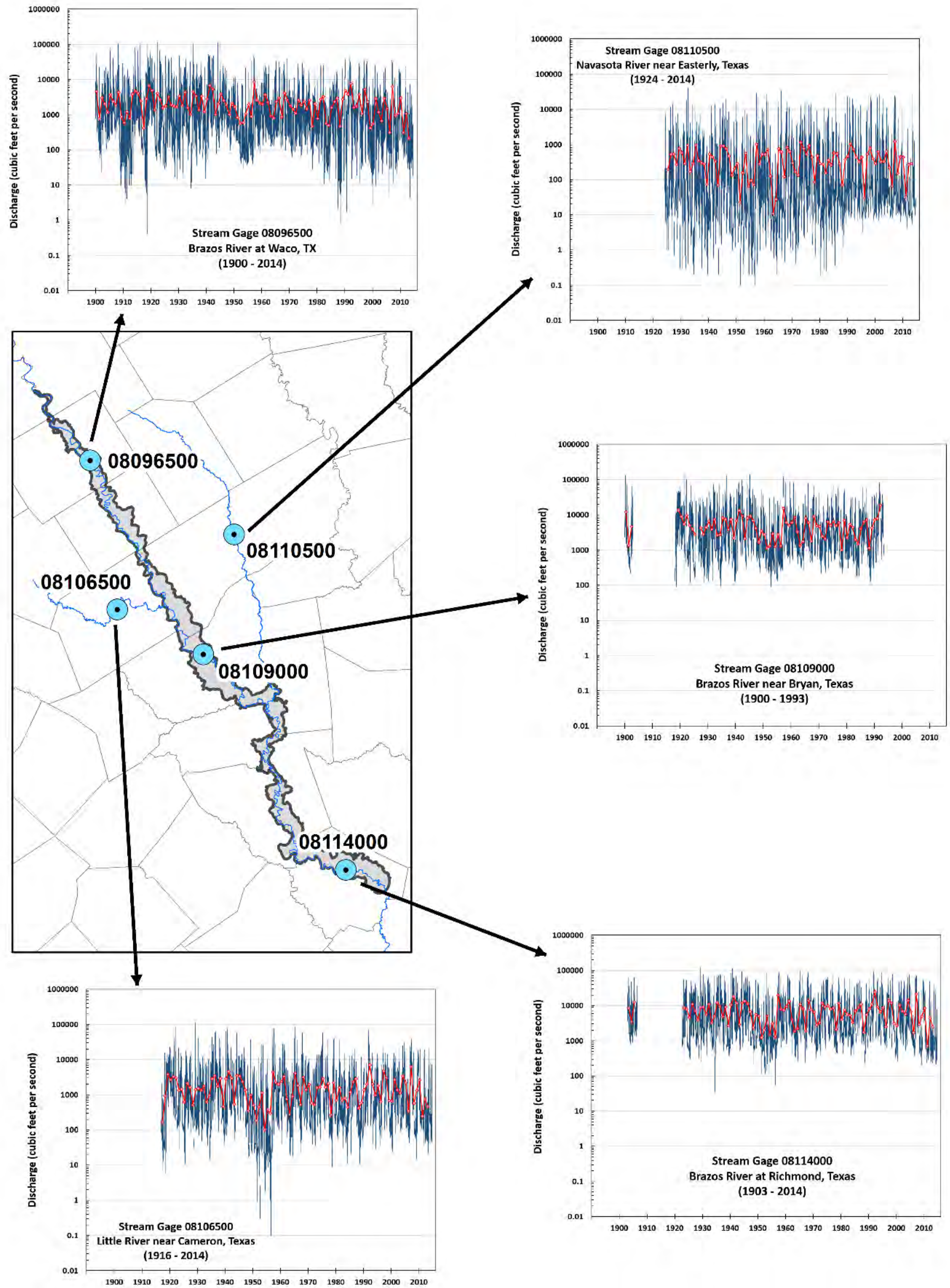


Figure 4.4.2 Representative streamflow hydrographs for the Brazos River and major tributaries in the study area.

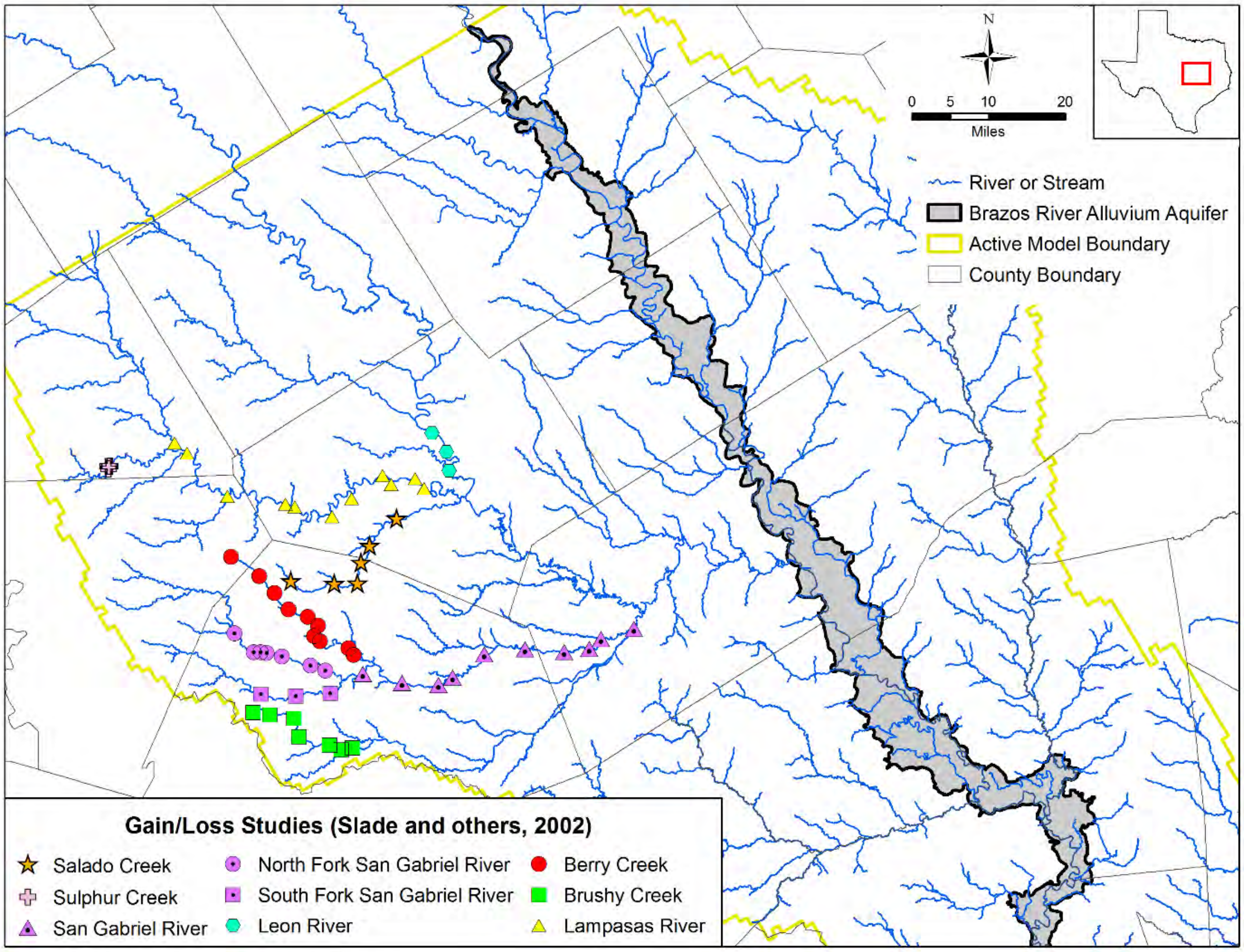


Figure 4.4.3 Locations of gain/loss studies in Slade and others (2002).

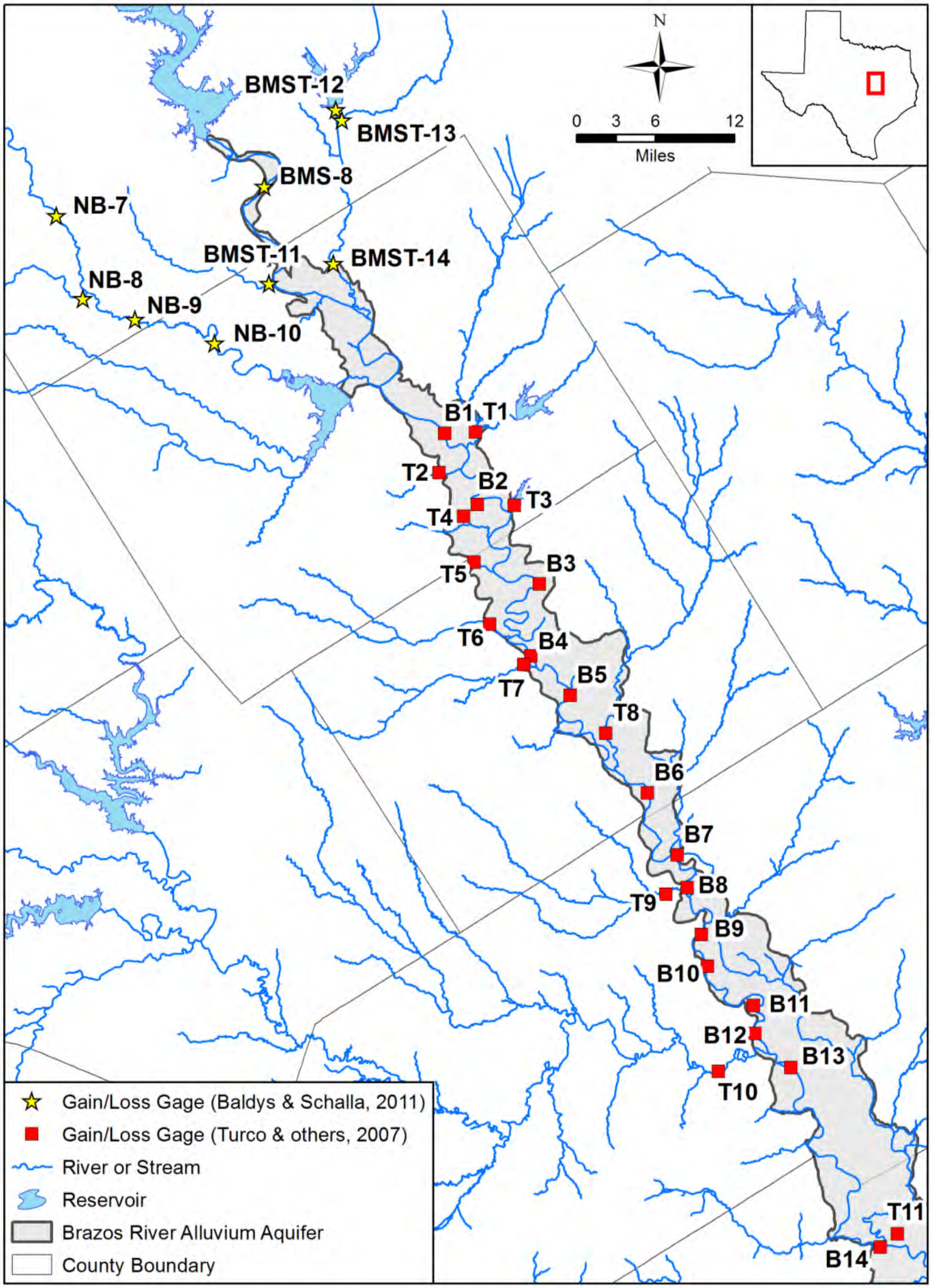


Figure 4.4.4a Locations of gages used for the gain/loss studies in Baldys and Schalla (2011) and Turco and others (2007) in the northern portion of study area.

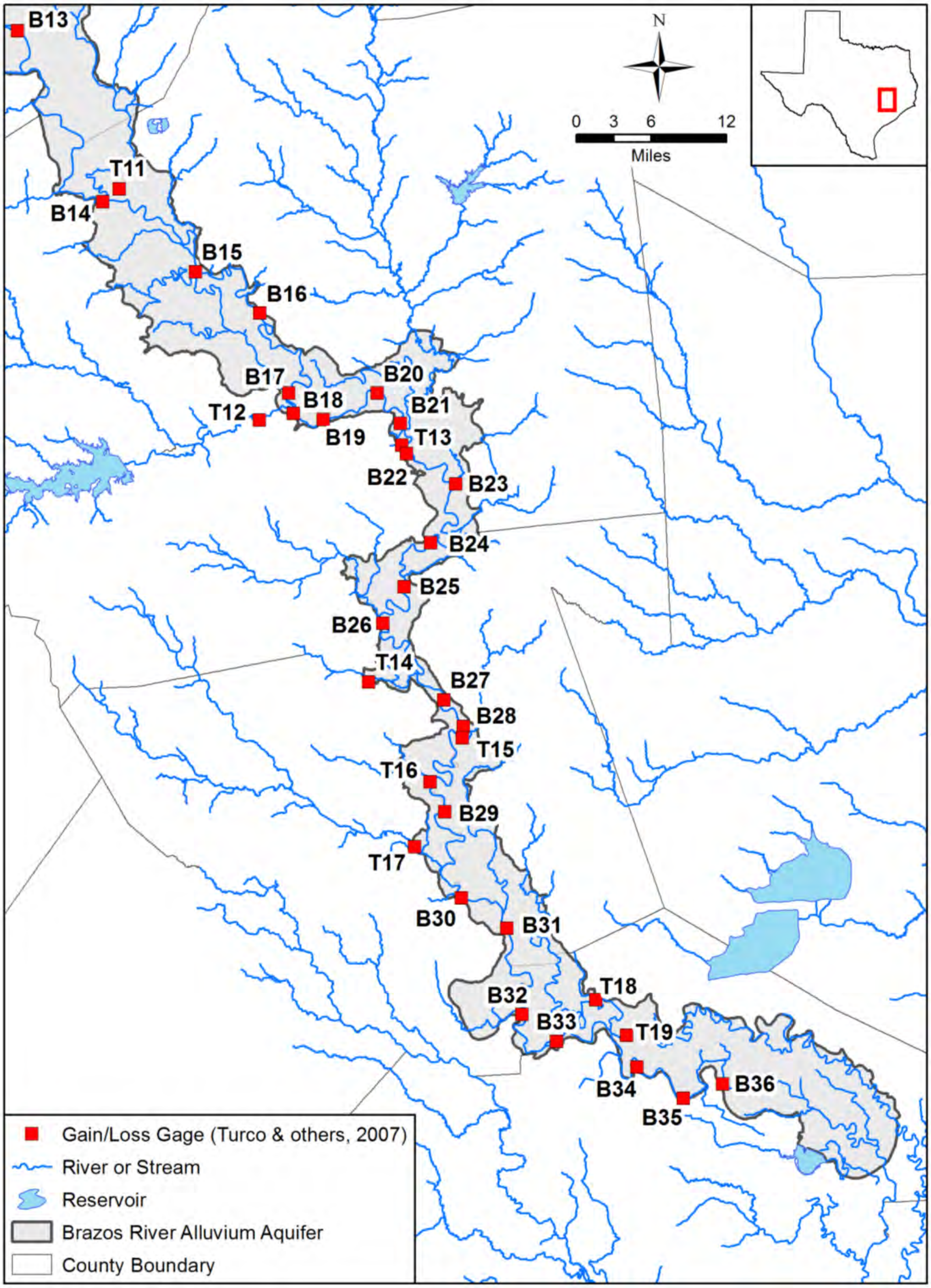


Figure 4.4.4b Locations of gages used for the gain/loss study in Turco and others (2007) in the southern portion of study area.

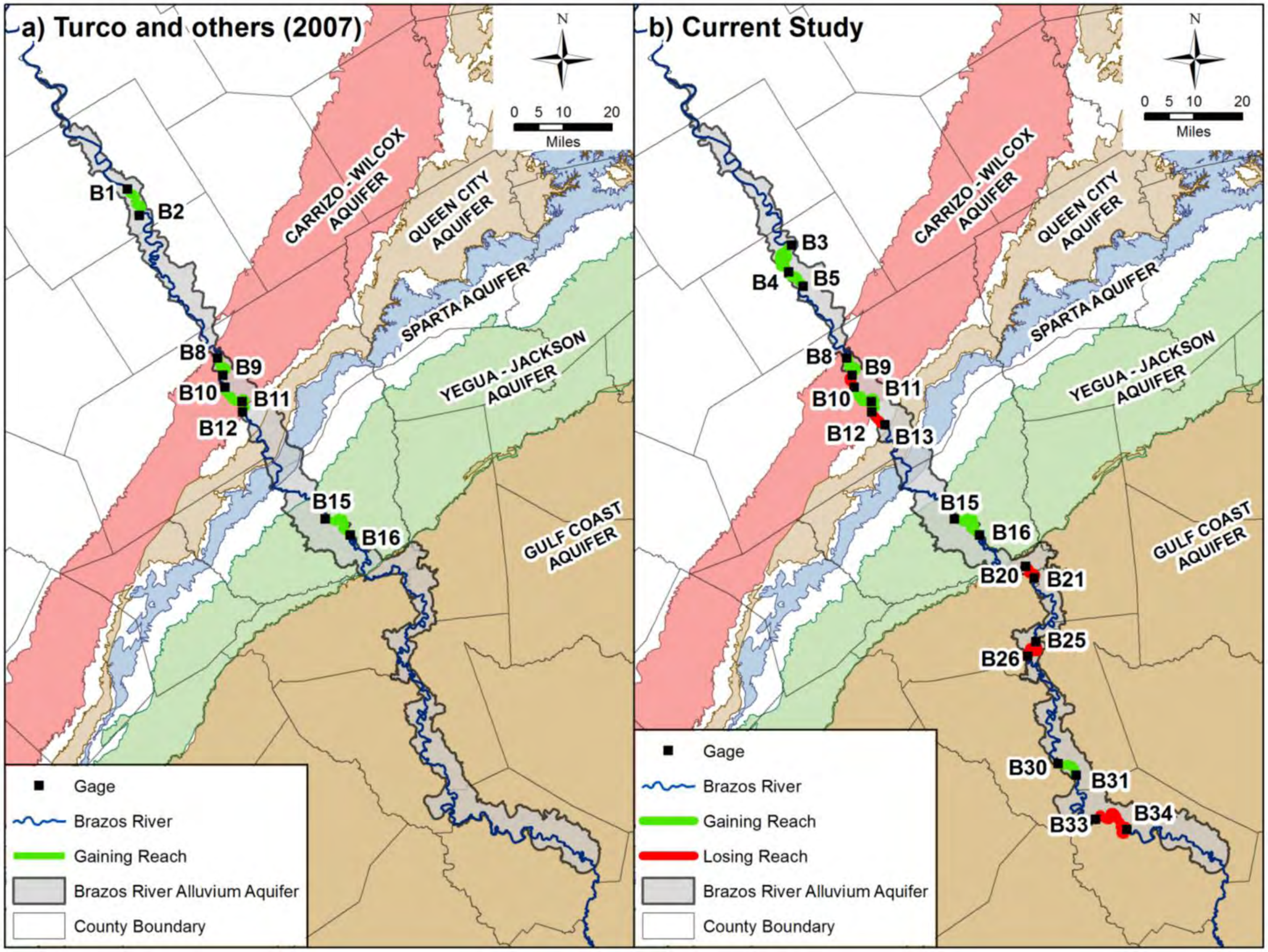


Figure 4.4.5 **Comparison of gain/loss study results from (a) Turco and others (2007) and (b) the current analysis for the March 2006 measurements.**

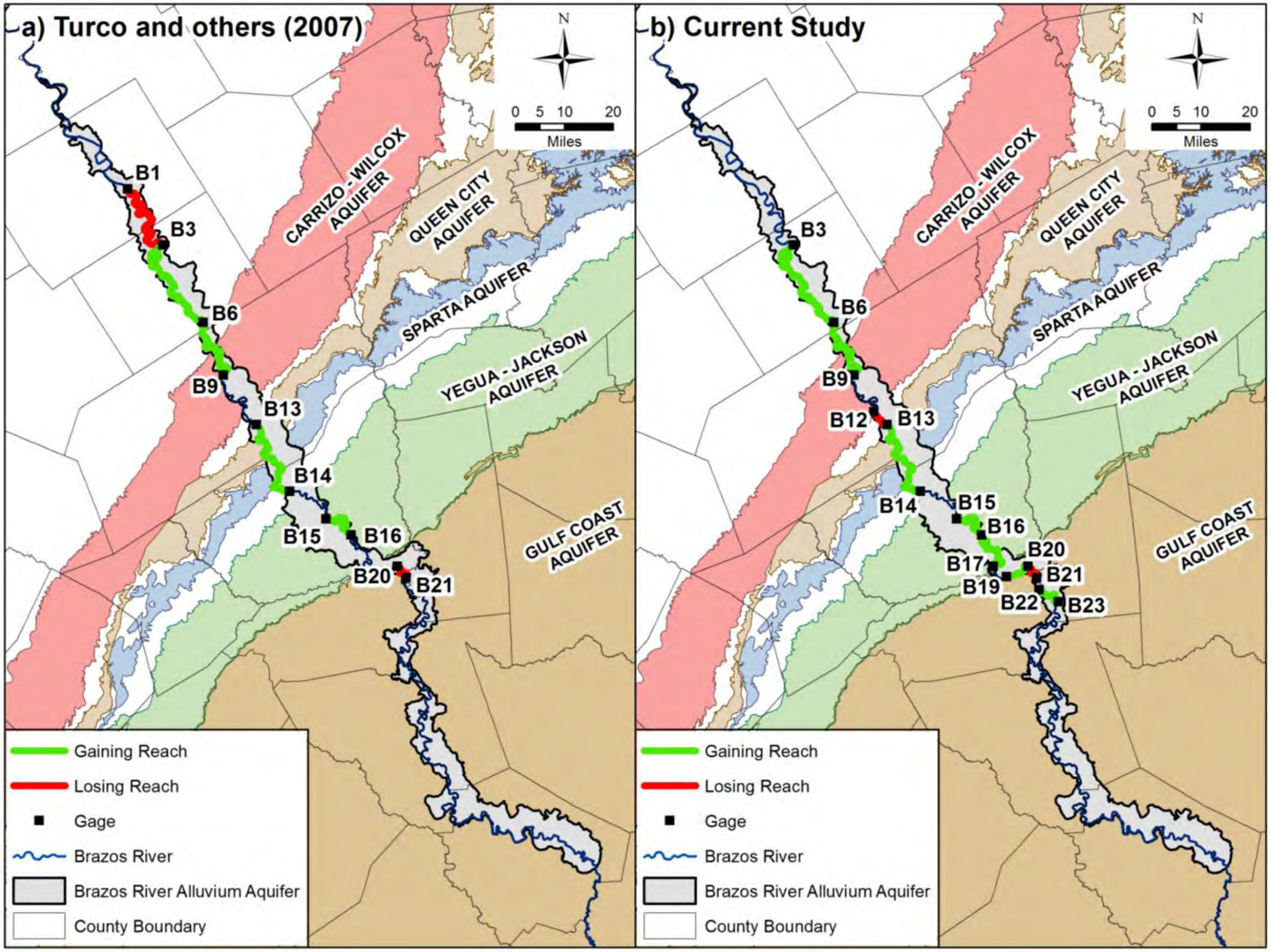


Figure 4.4.6 Comparison of gain/loss study results from (a) Turco and others (2007) and (b) the current analysis for the August 2006 measurements.

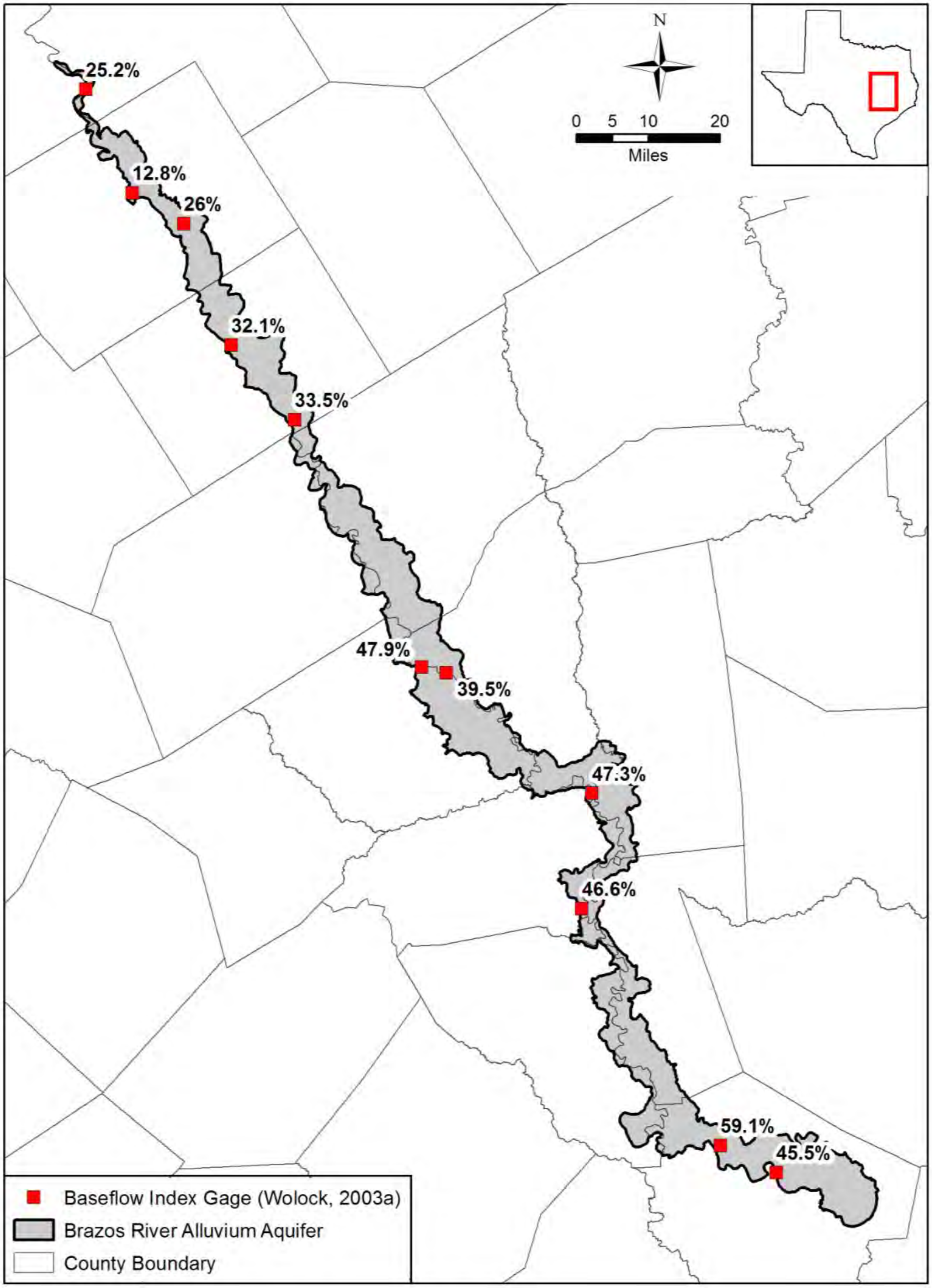


Figure 4.4.7 Base flow index values from Wolock (2003a).

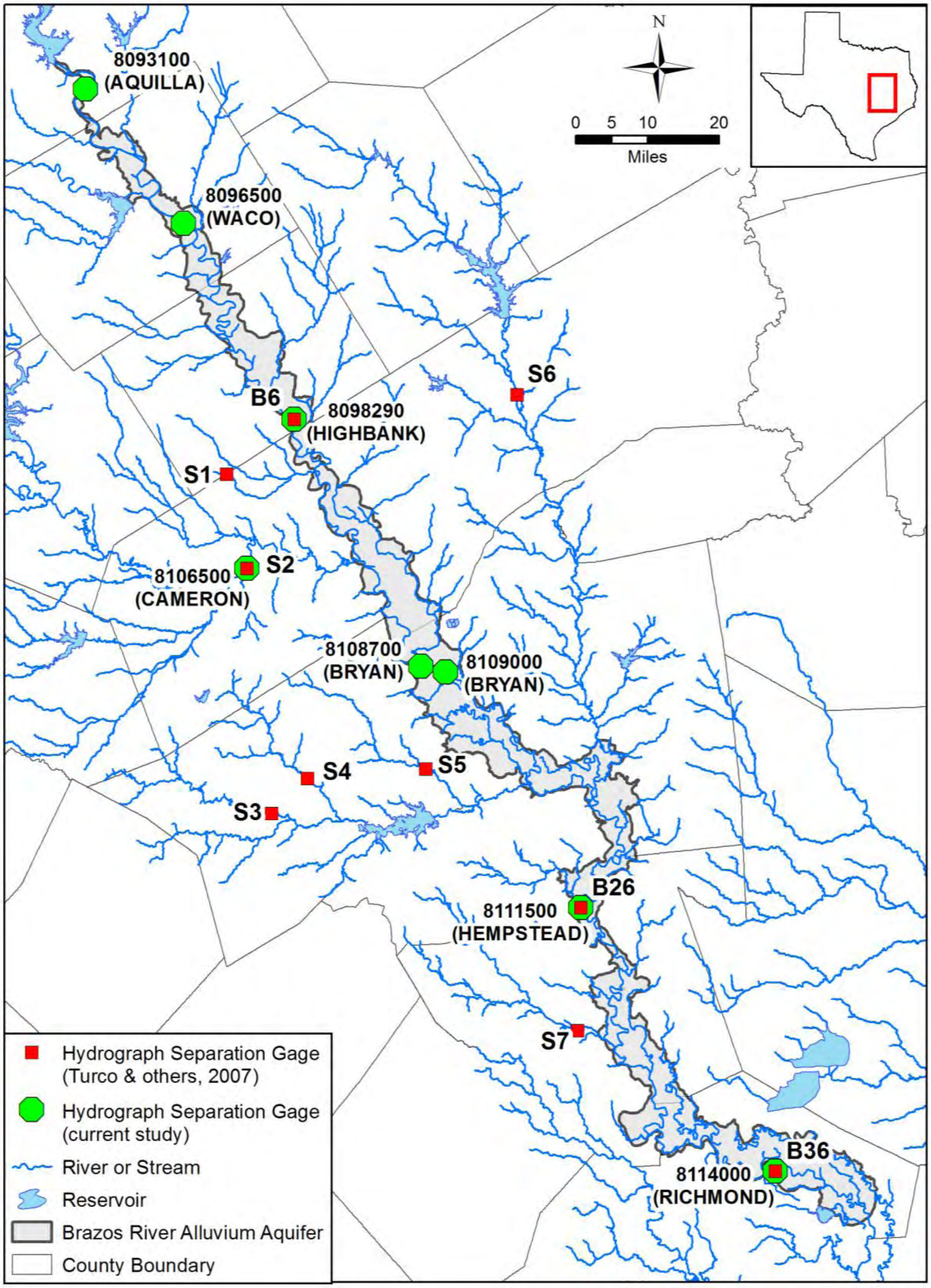


Figure 4.4.8 Gages used for hydrograph separation in the Turco and others (2007) and current studies.

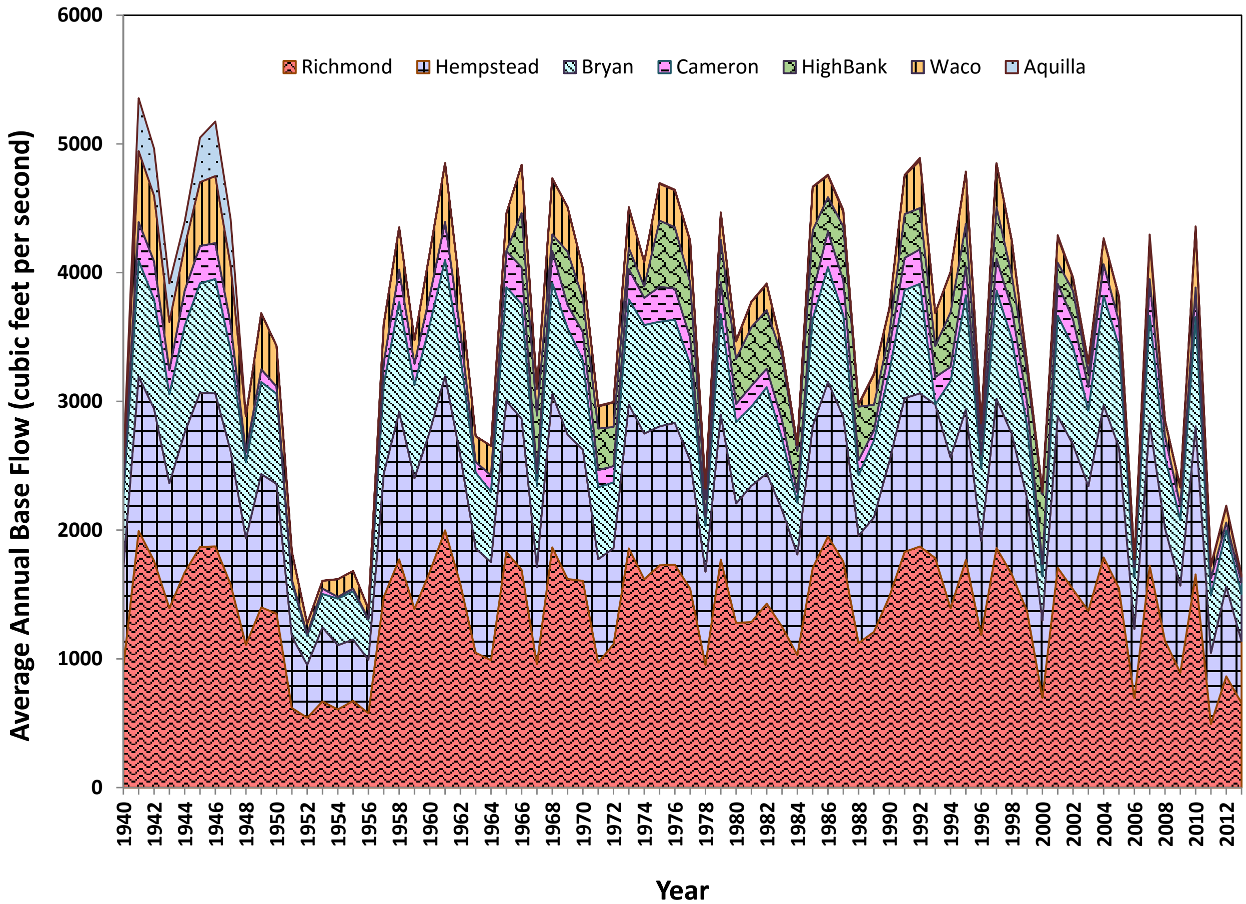


Figure 4.4.9 Graph of base flow at all gages over time determined by the current study.

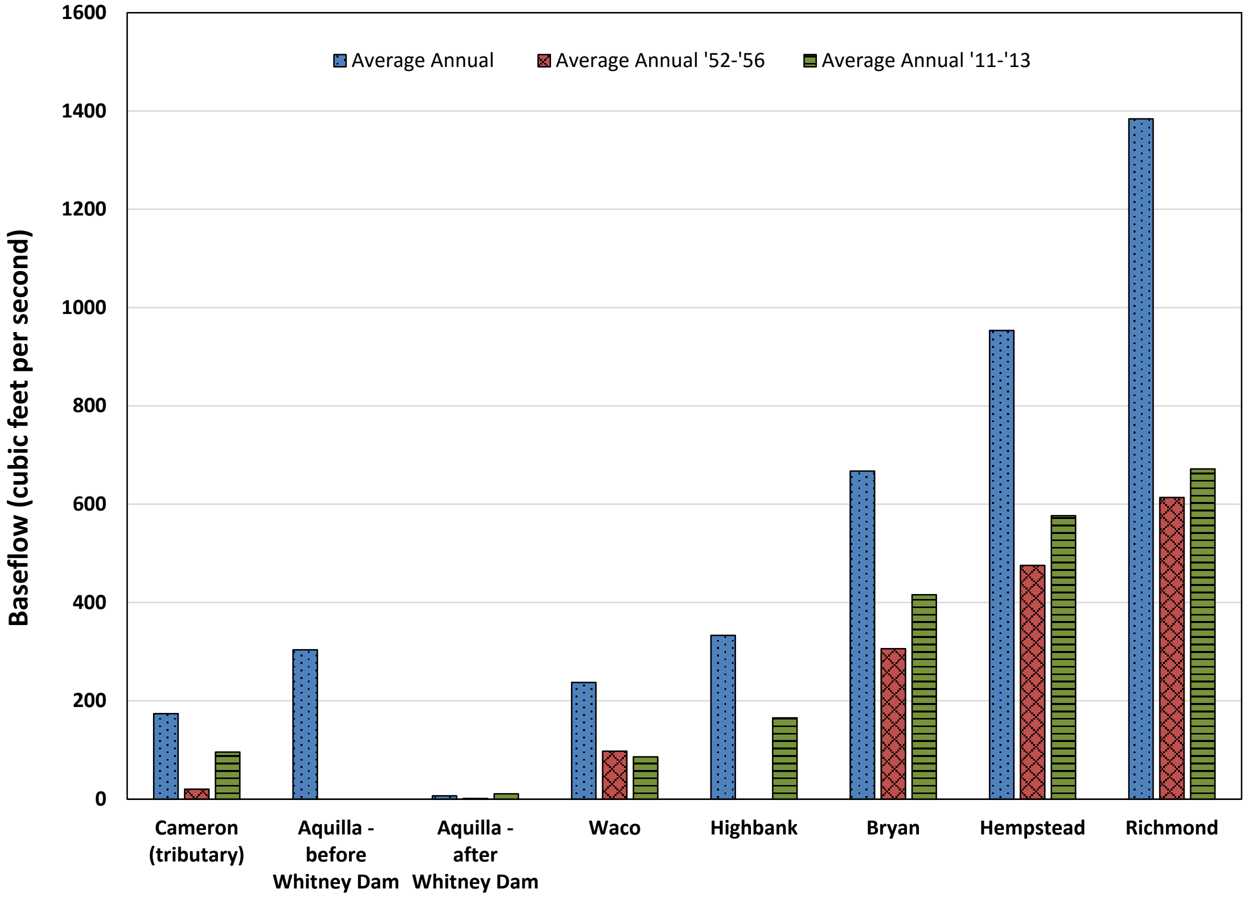


Figure 4.4.10 Comparison of average annual base flow to drought base flow based the current hydrograph separation study.

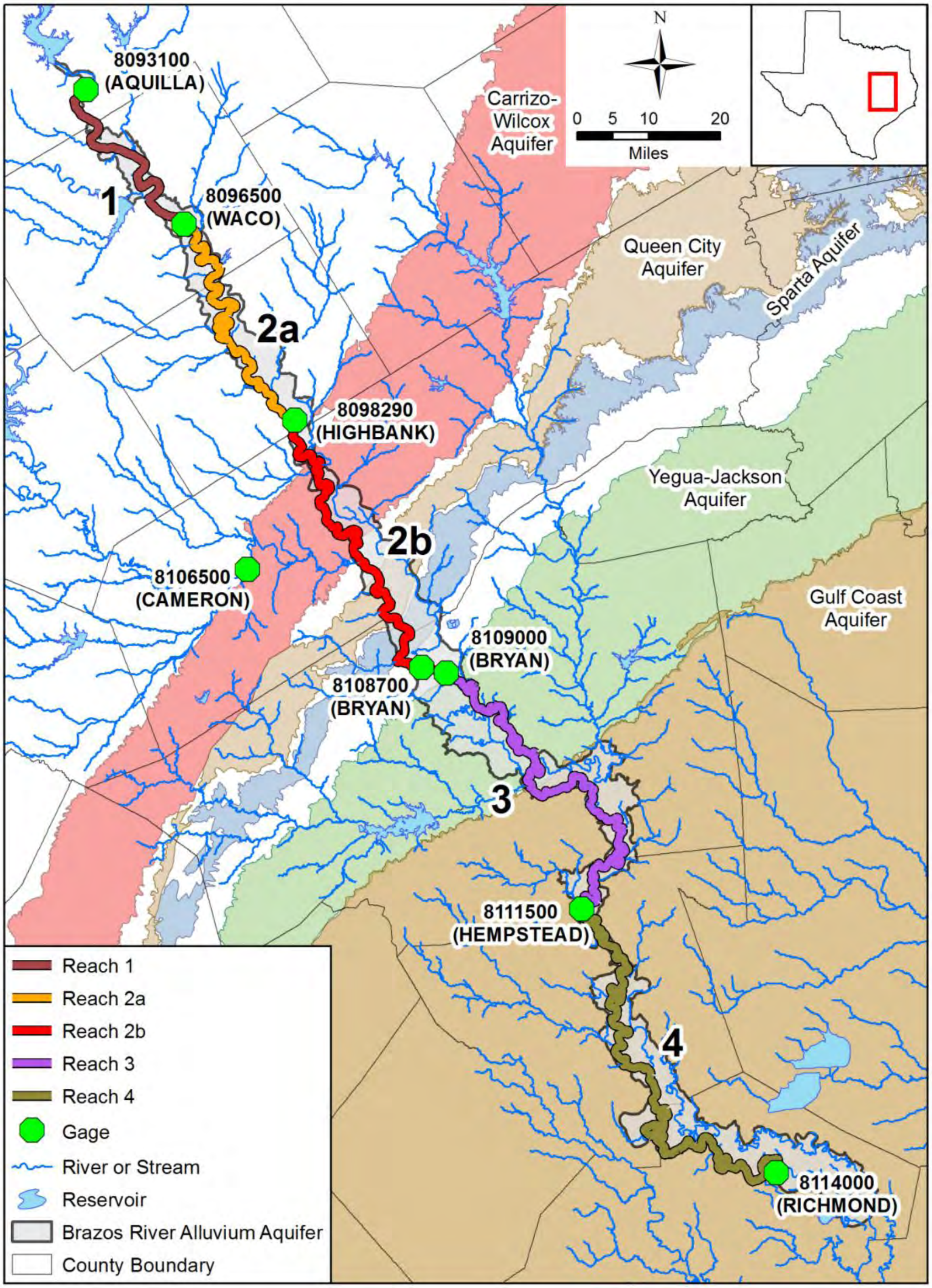


Figure 4.4.11 River reaches and gages used in the incremental base flow calculations for the current study.

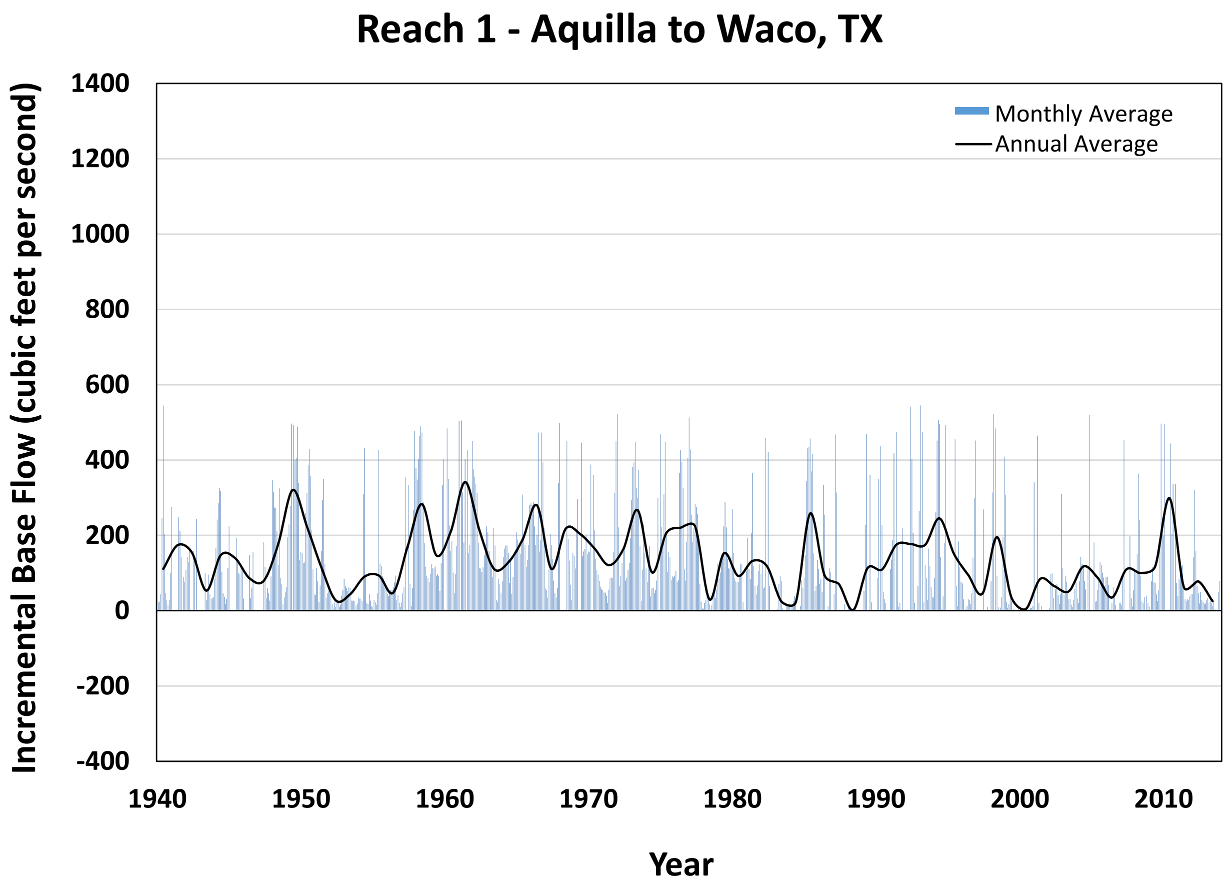


Figure 4.4.12a Incremental base flow for Reach 1 determined by the current study.

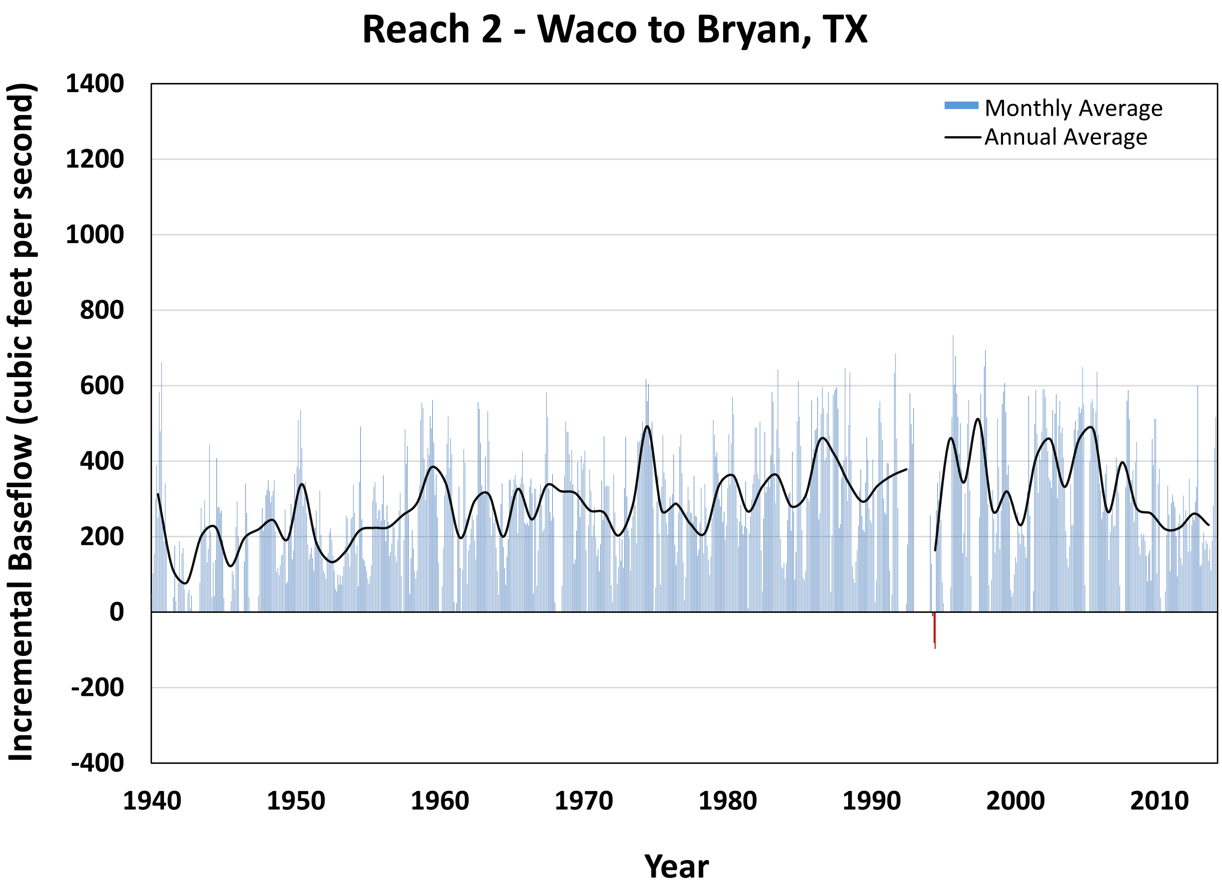


Figure 4.4.12b Incremental base flow for Reach 2 determined by the current study.

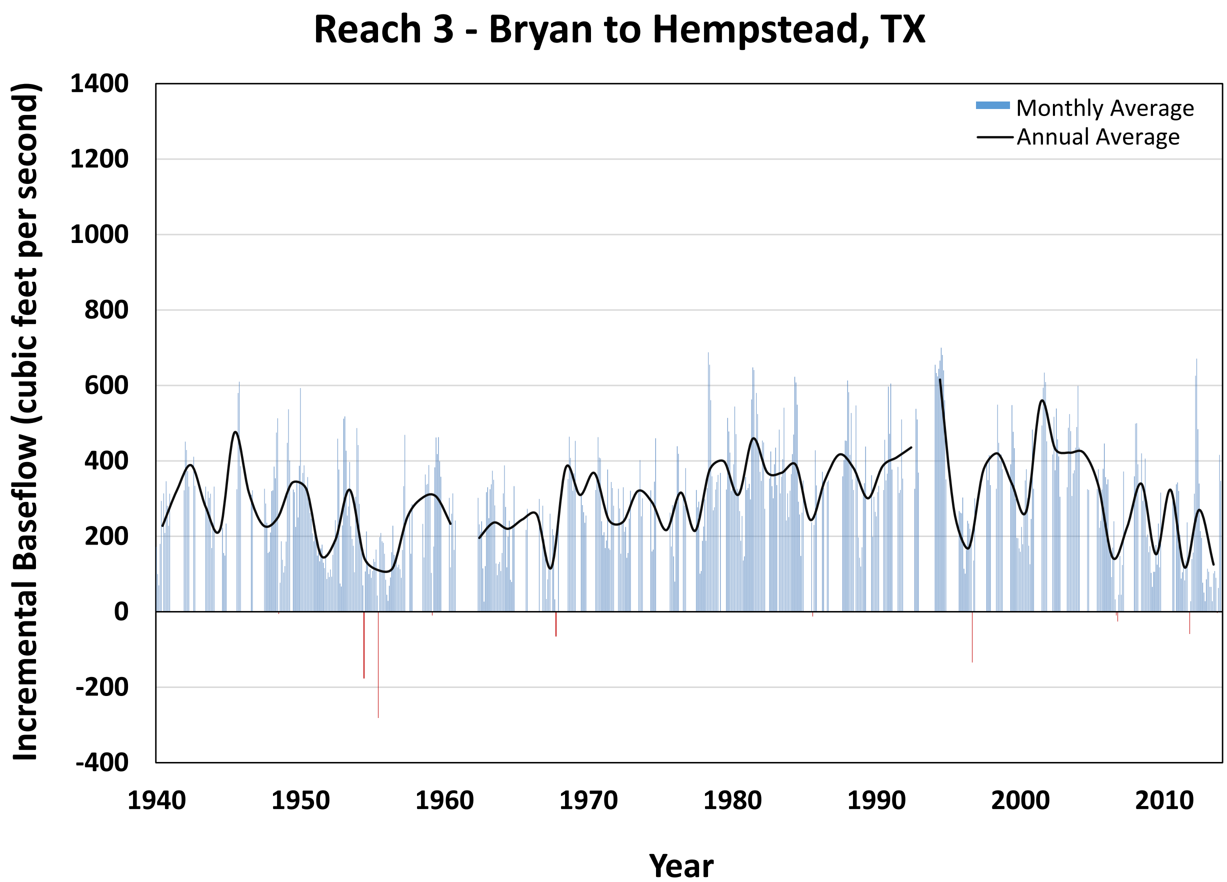


Figure 4.4.12c Incremental base flow for Reach 3 determined by the current study.

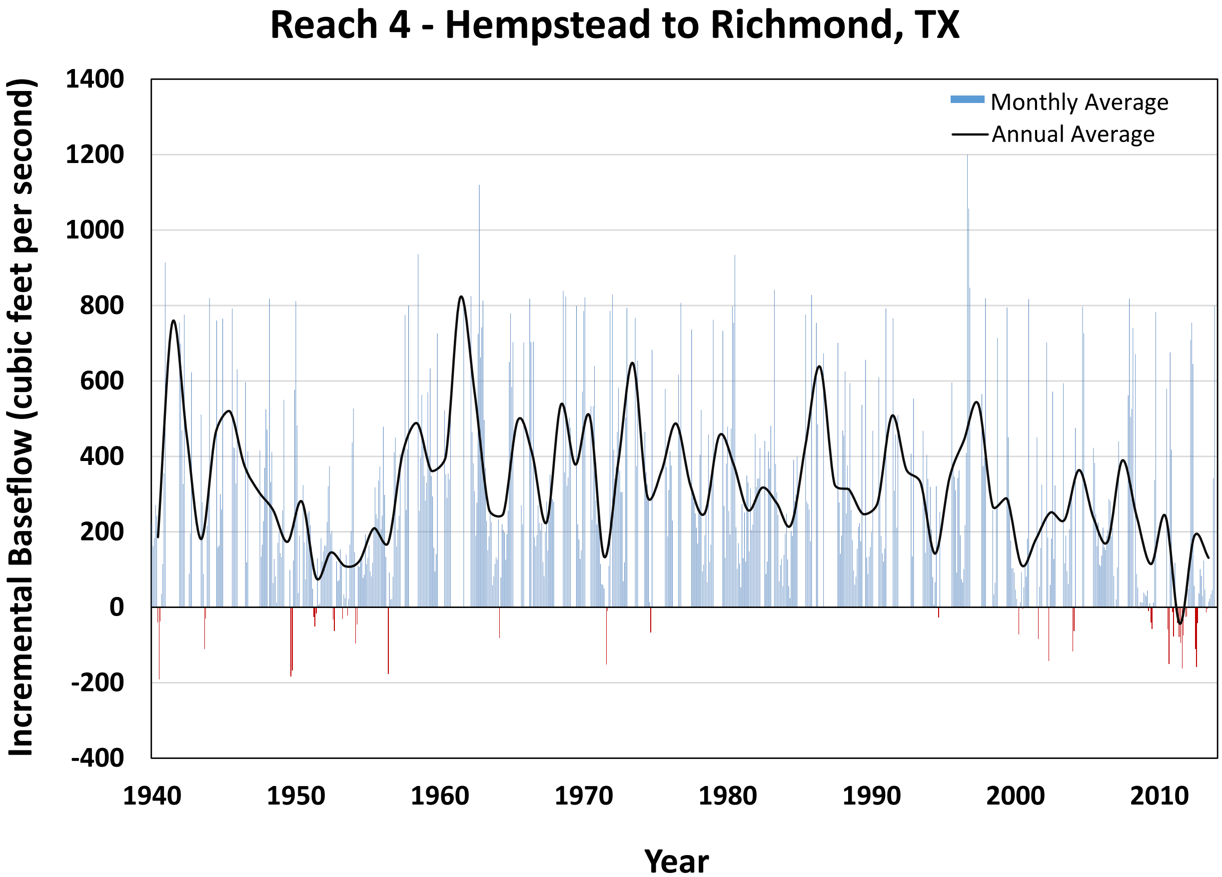


Figure 4.4.12d Incremental base flow for Reach 4 determined by the current study.

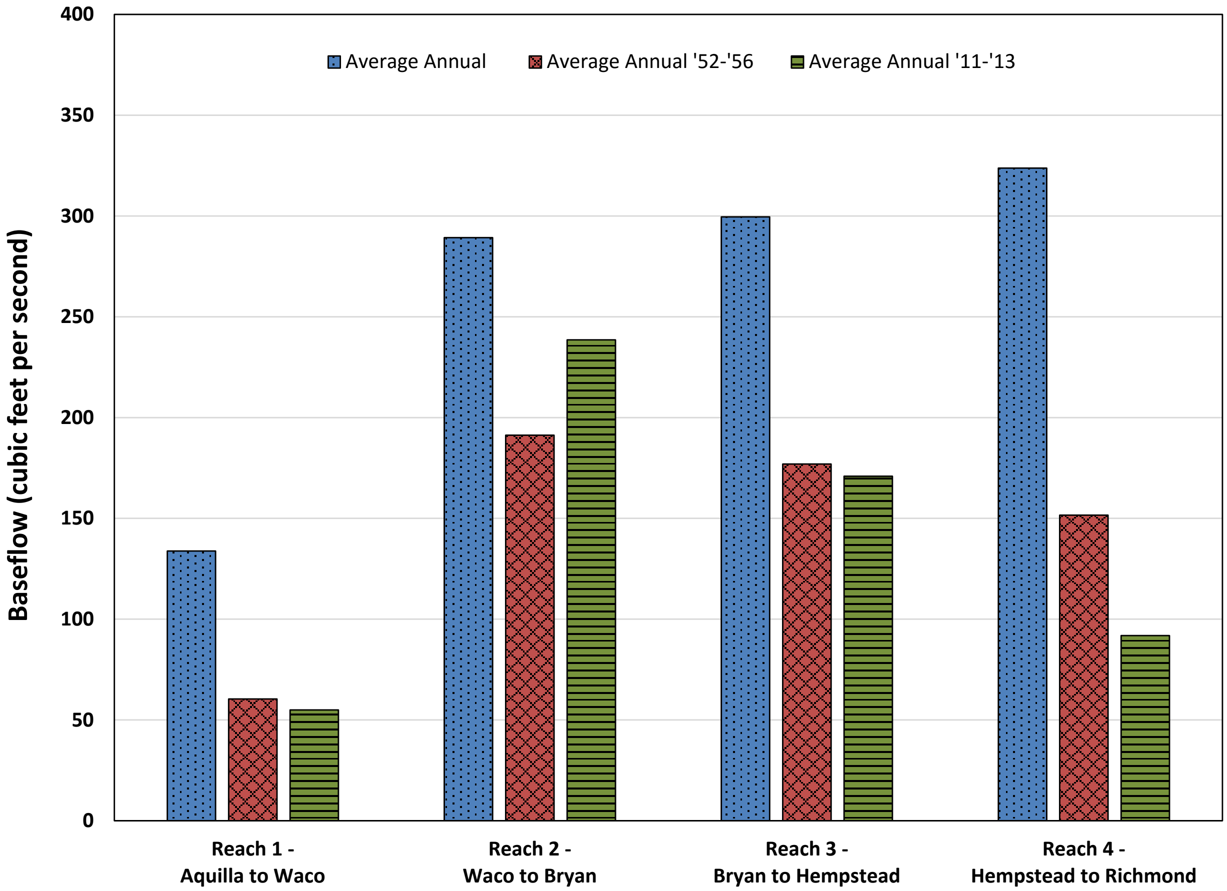


Figure 4.4.13 Comparison of average annual incremental base flow to drought base flow for Reaches 1 through 4 for the current study.

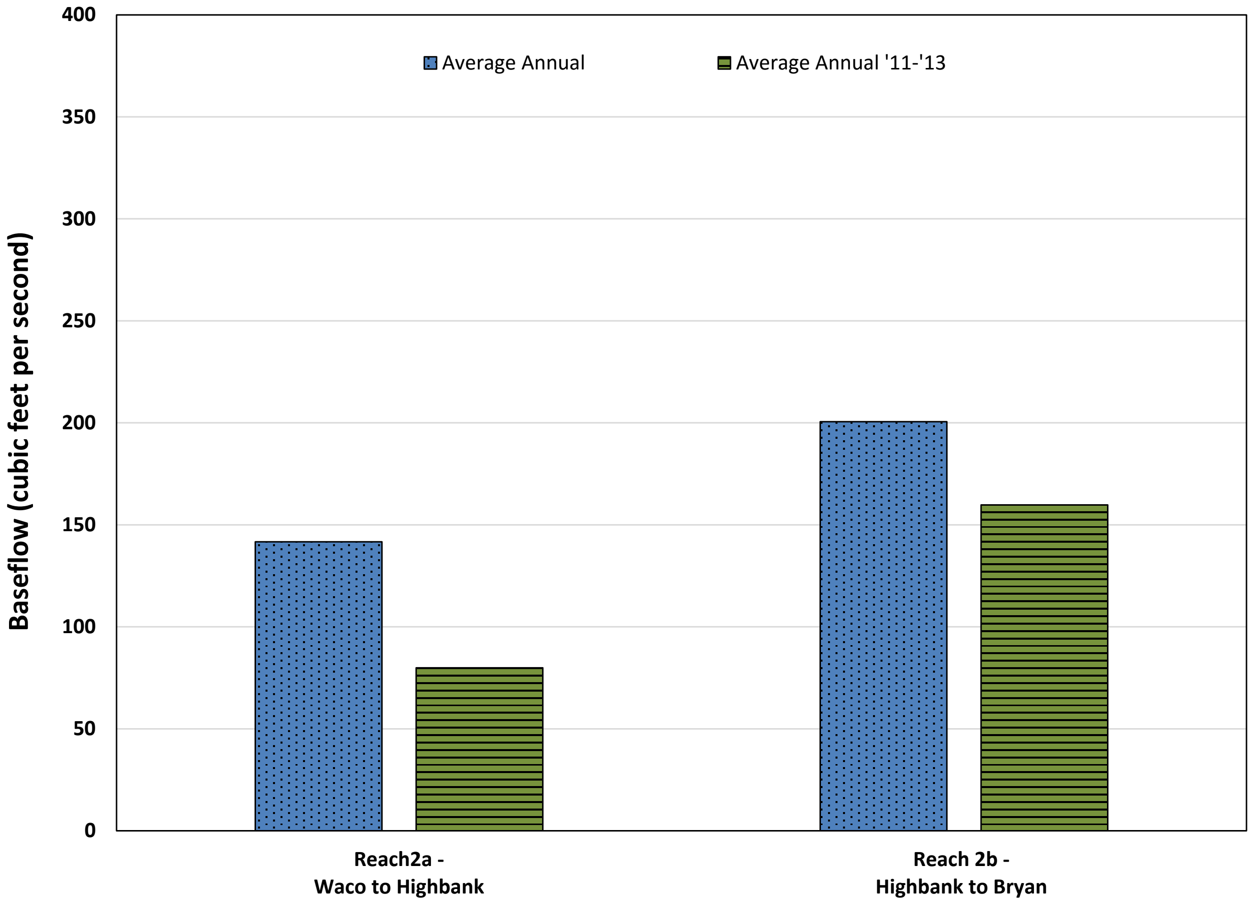


Figure 4.4.14 Comparison of average annual incremental base flow to 2010s drought base flow for Reaches 2a and 2b for the current study.

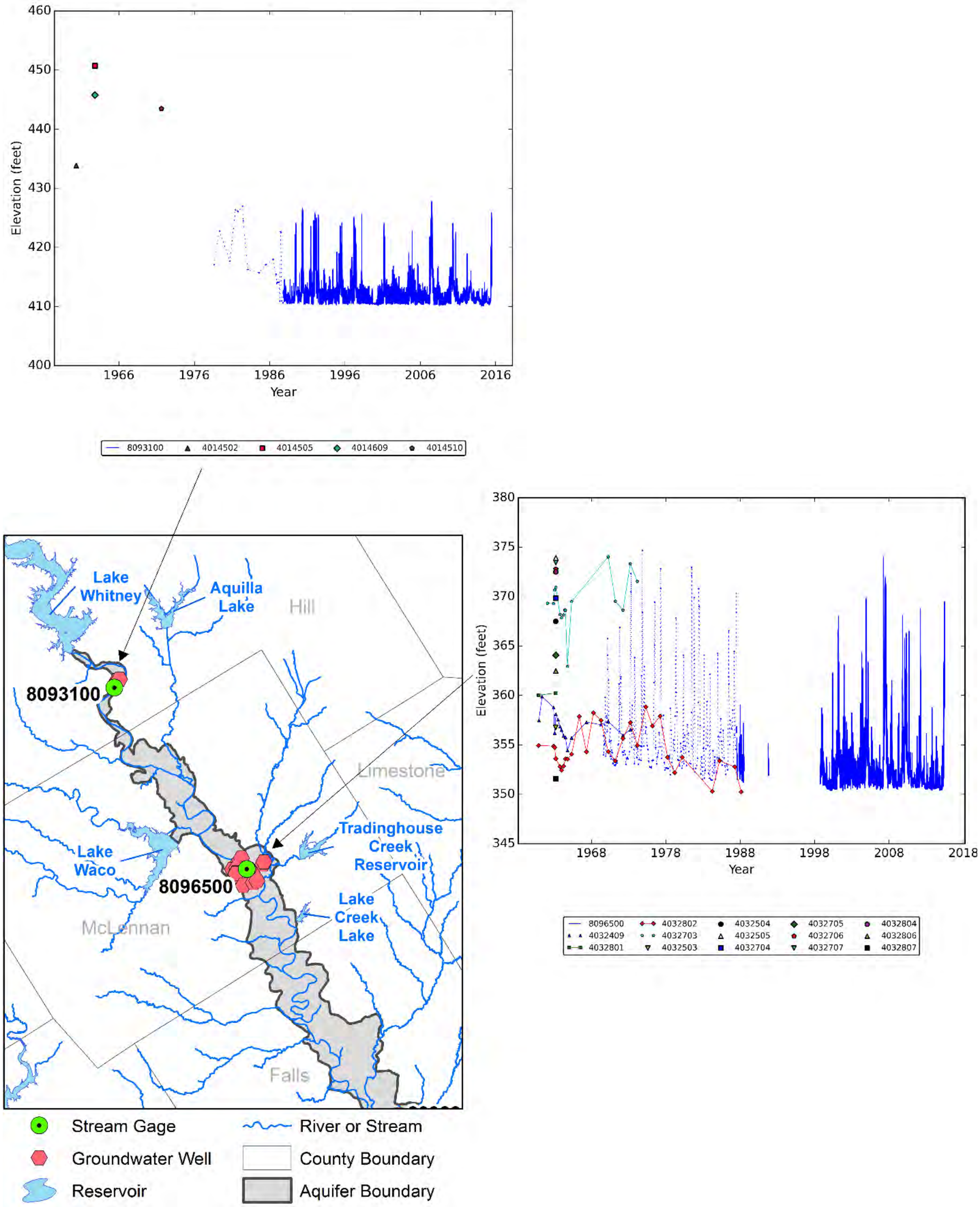


Figure 4.4.15a Selected stream stage – groundwater level comparisons in the northern portion of the Brazos River Alluvium Aquifer.

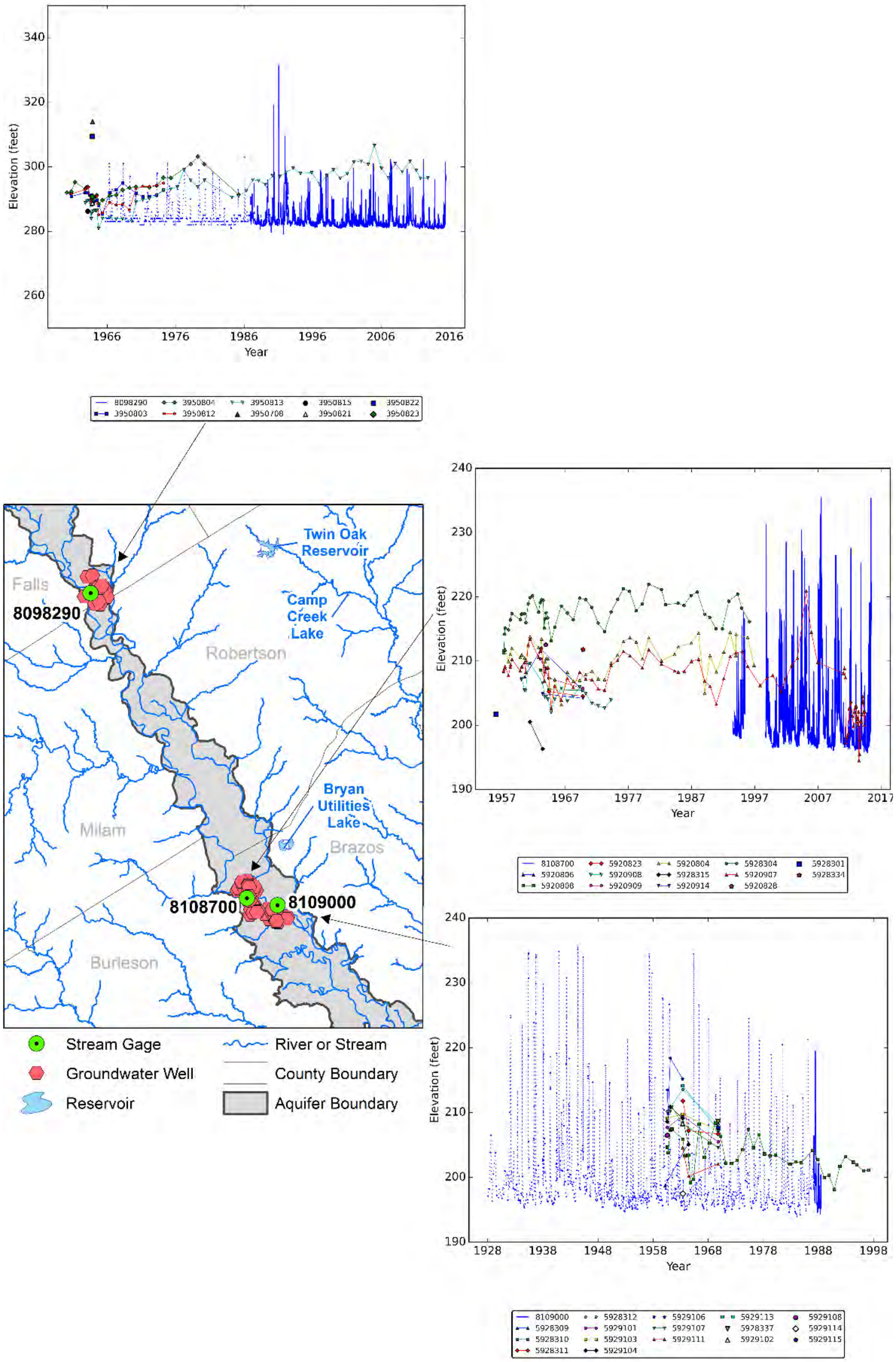


Figure 4.4.15b Selected stream stage – groundwater level comparisons in the central portion of the Brazos River Alluvium Aquifer.

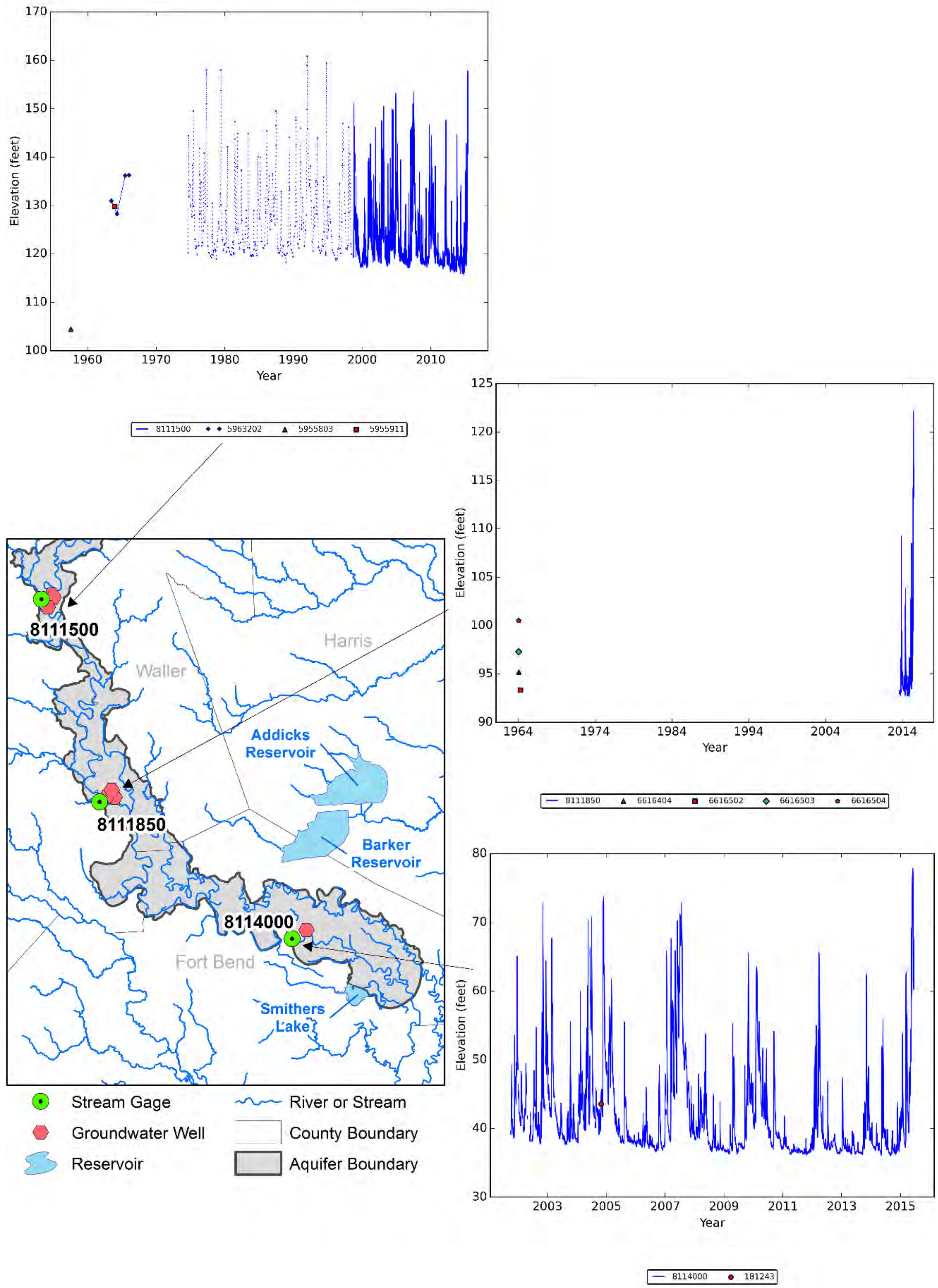


Figure 4.4.15c Selected stream stage – groundwater level comparisons in the southern portion of the Brazos River Alluvium Aquifer.

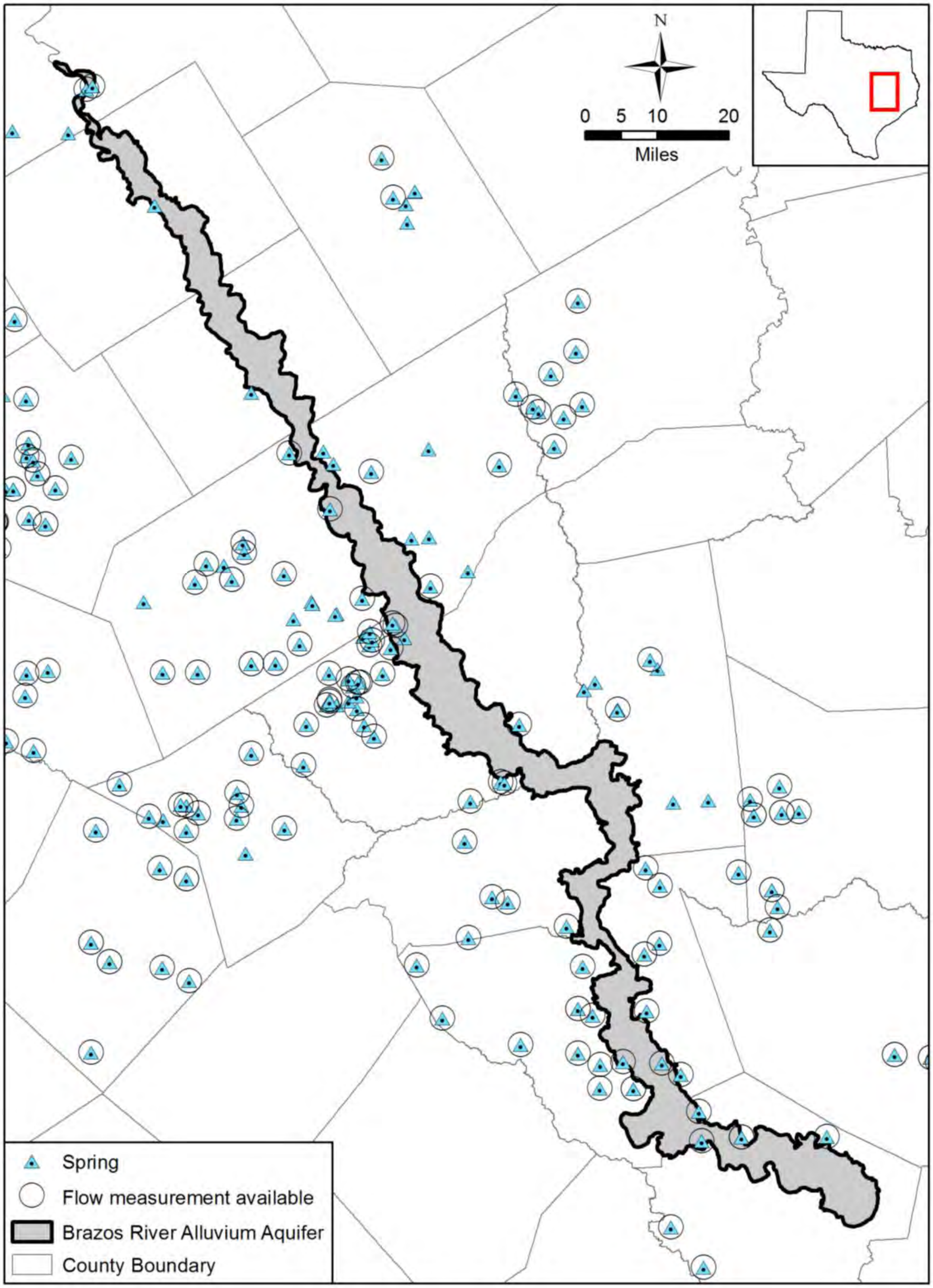


Figure 4.4.16 Locations of springs in the vicinity of the Brazos River Alluvium Aquifer.

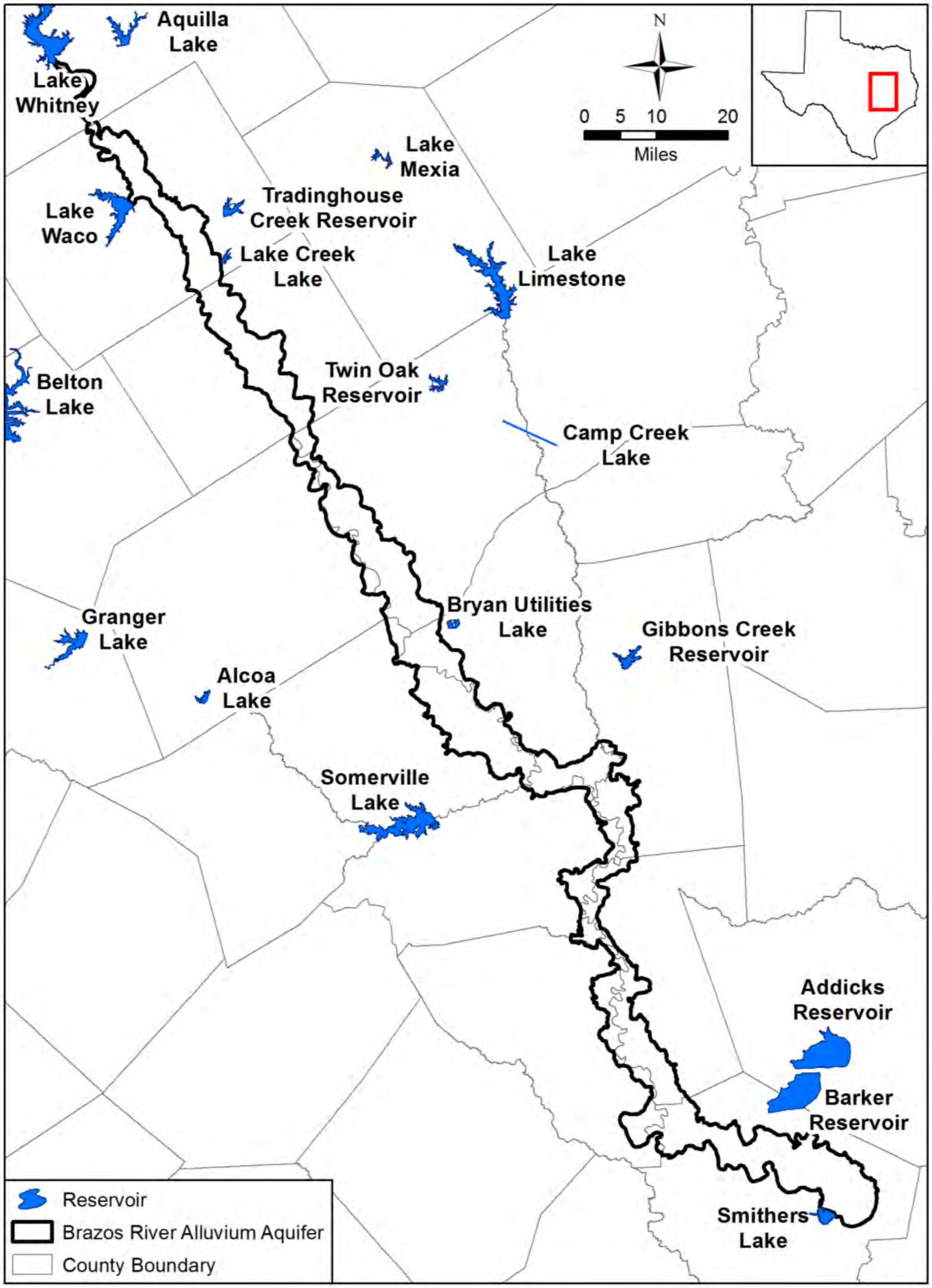


Figure 4.4.17 Reservoirs in the vicinity of the Brazos River Alluvium Aquifer.

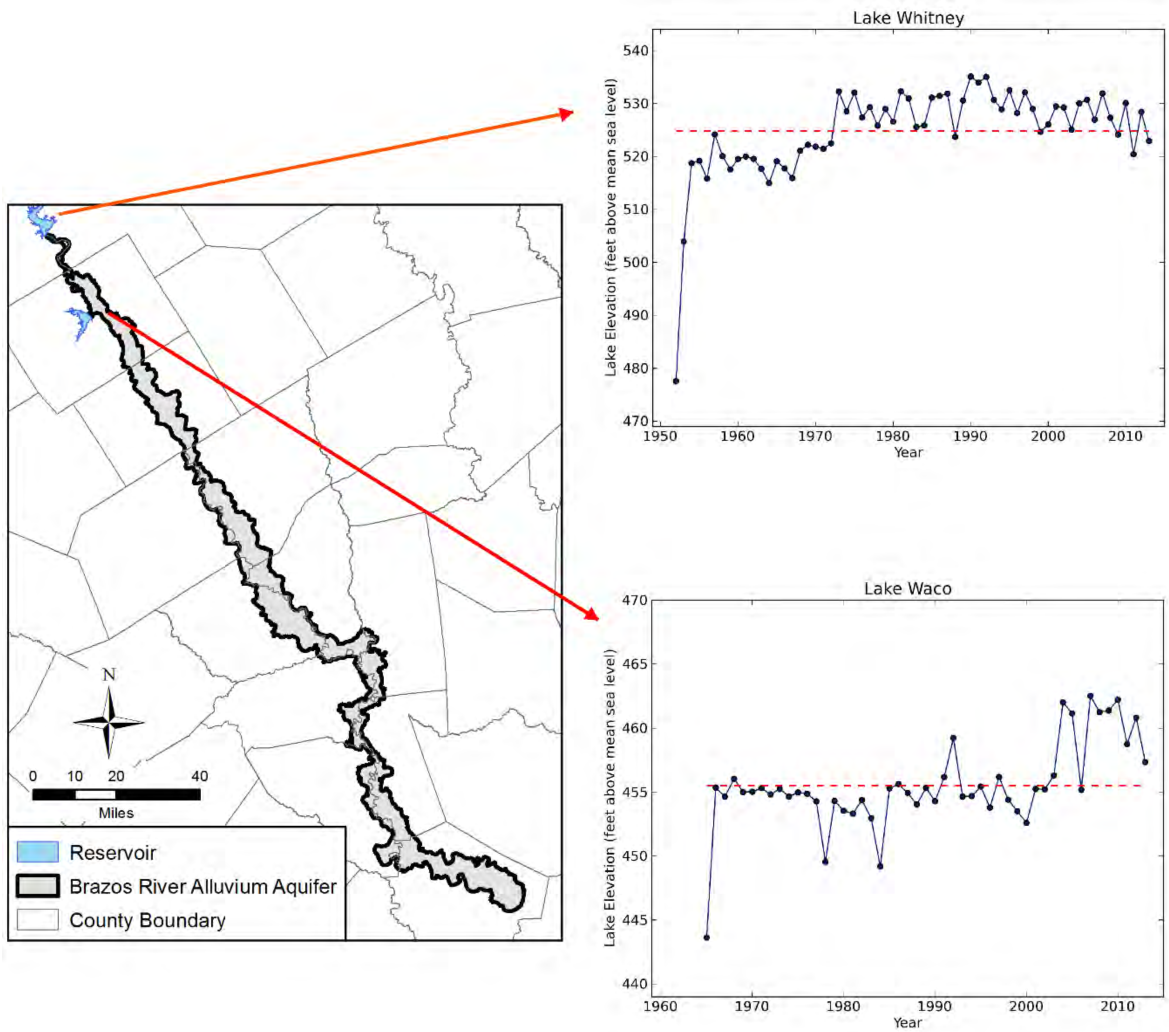


Figure 4.4.18 Average annual lake levels for Lake Waco and Lake Whitney (United States Army Corps of Engineers, 2014).

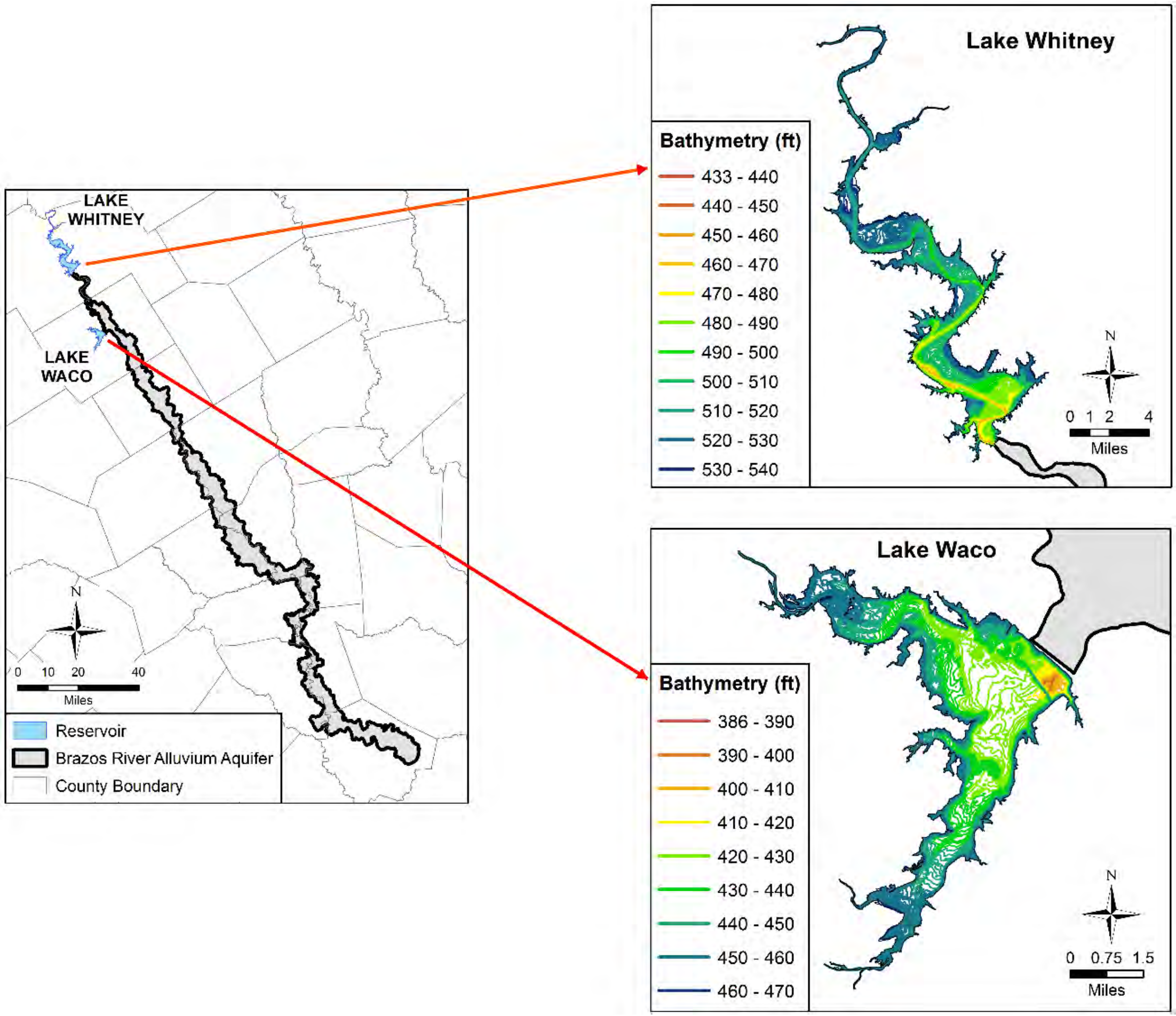


Figure 4.4.19 Bathymetry for Lake Waco and Lake Whitney (TWDB, 2006c and TWDB, 2012b).

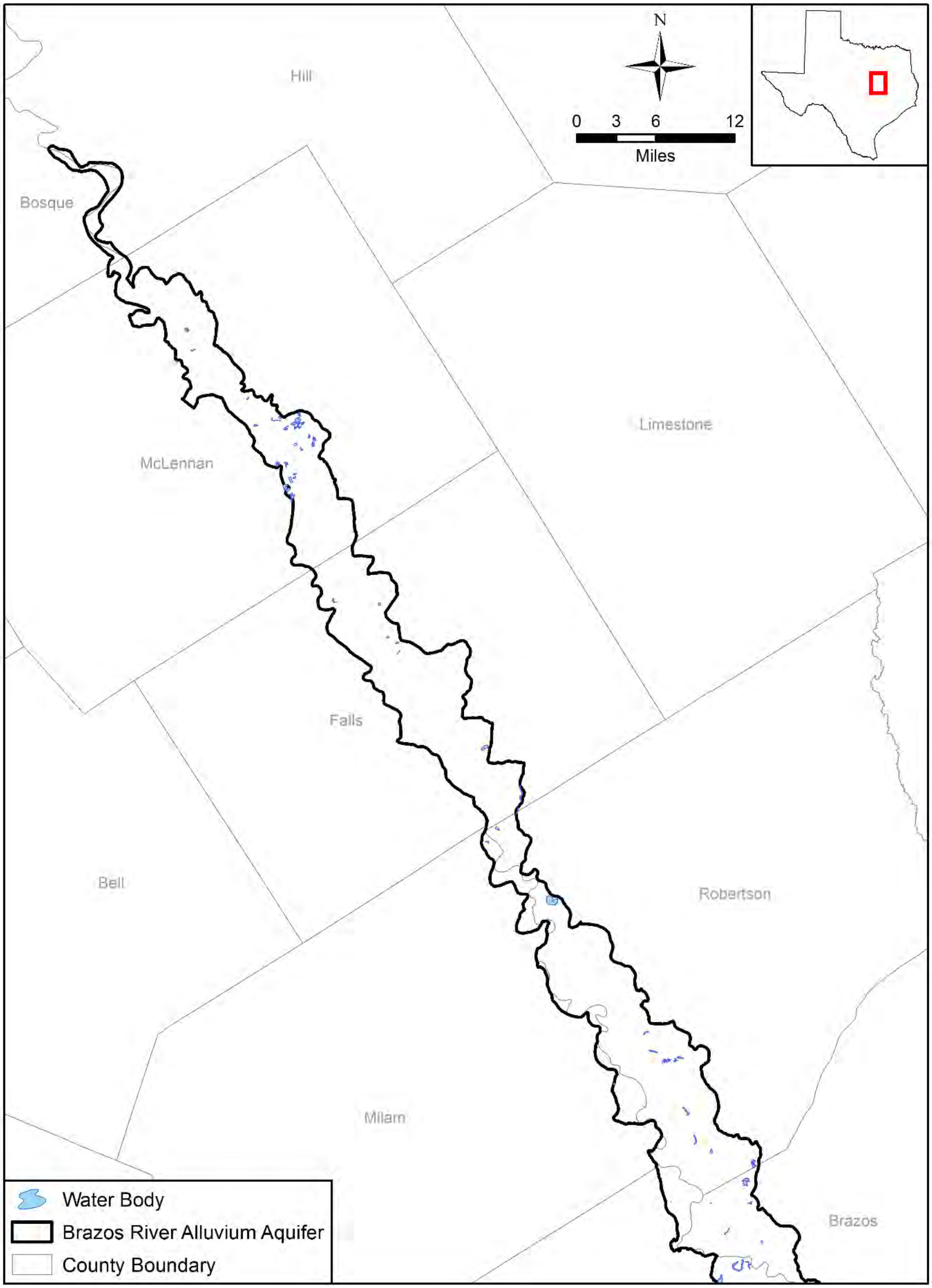


Figure 4.4.20a Oxbow lakes and other significant surface water features in the northern portion of the Brazos River Alluvium Aquifer.

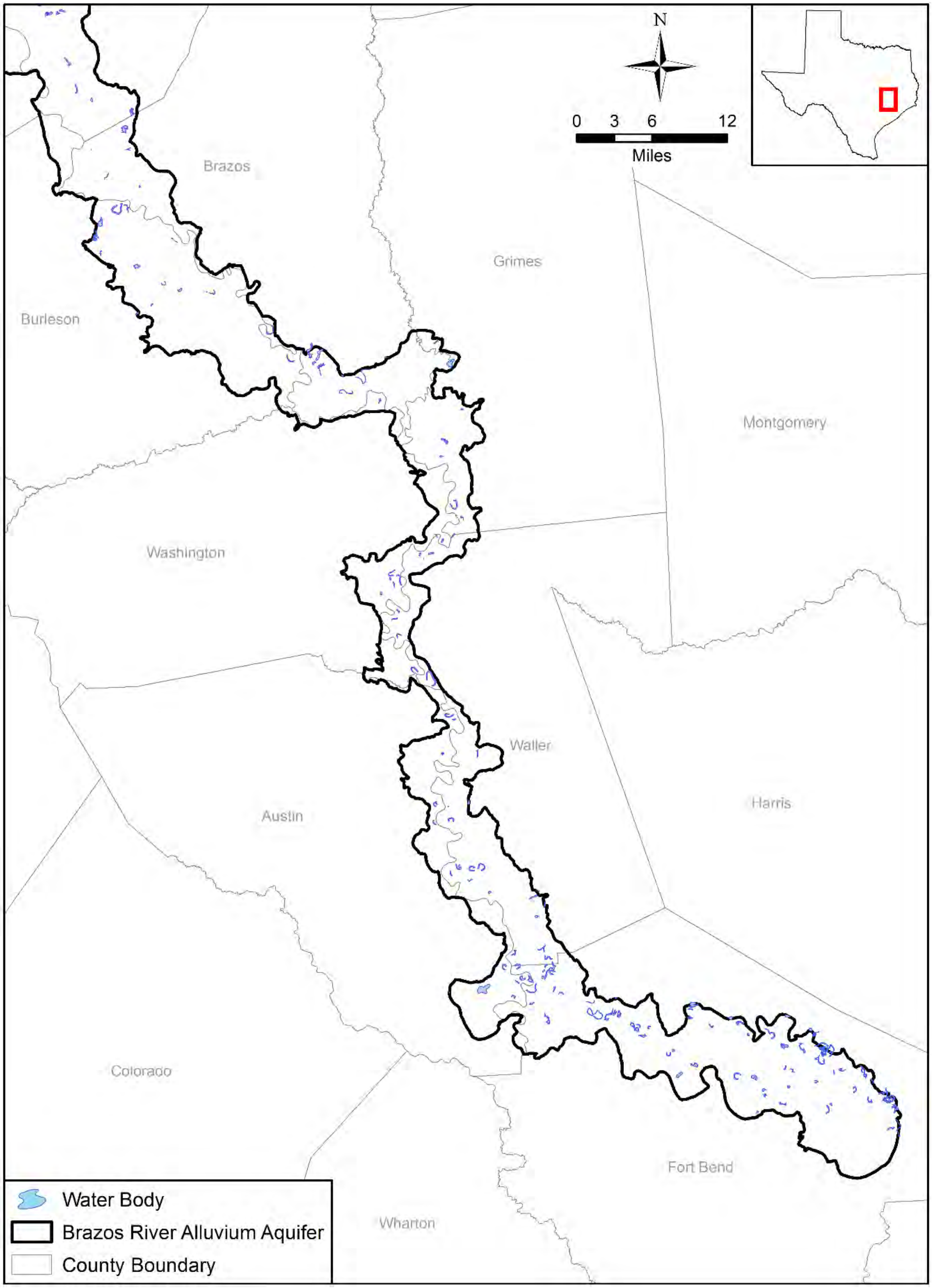


Figure 4.4.20b Oxbow lakes and other significant surface water features in the southern portion of the Brazos River Alluvium Aquifer.

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4.5 Hydraulic Properties

Hydraulic properties, which describe the ability of an aquifer to transmit and store groundwater, can vary greatly depending on the individual characteristics of an aquifer. Several hydraulic properties are used to describe groundwater flow in aquifers. The properties discussed here are hydraulic conductivity, transmissivity, specific yield, and specific capacity. Each of these terms is briefly described below.

Hydraulic Conductivity - The measure of the ease with which groundwater can flow through an aquifer. Higher hydraulic conductivity indicates that the aquifer will allow more water movement under the same hydraulic gradient. Units for hydraulic conductivity may be expressed in feet per day or gallons per day per square foot.

Specific Capacity - This parameter reflects the efficiency of a well and an aquifer to produce water to the well. Specific capacity is dependent on both the properties of the aquifer as well as the efficiency of the well. Specific capacity is expressed in terms of gallons per minute per foot of drawdown in the well.

Transmissivity - This term is closely related to hydraulic conductivity and refers to the product of the hydraulic conductivity times the effective aquifer thickness. Transmissivity describes the ability of groundwater to flow through the entire thickness of an aquifer. As the thickness of the aquifer increases, the transmissivity increases for a given hydraulic conductivity. Units for transmissivity may be expressed in square feet per day or gallons per day per foot.

Specific Yield – The measure of the amount of water that an unconfined aquifer releases from storage per unit surface area of aquifer per unit decline in water table due to the drainage of the pore spaces in the aquifer by gravity. Specific yield is a dimensionless parameter.

The assignment of values for aquifer hydraulic properties is an important aspect in numerical modeling because adjusting those values is typically an integral part of model calibration. Values for the hydraulic properties of the Brazos River Alluvium Aquifer were obtained from the literature and estimated. The following subsections describe the data sources and summarize the data from those sources, the estimation of hydraulic conductivity from specific capacity measurements, the estimated spatial distribution of transmissivity and horizontal hydraulic conductivity, vertical hydraulic conductivity, and specific yield.

4.5.1 Data Sources

Development of hydraulic properties for the Brazos River Alluvium Aquifer used multiple sources including:

- Specific capacity data from Shah and Houston (2007).
- Hydraulic conductivity from Munster and others (1996) based on work in Wrobelski (1996).
- Transmissivity and specific capacity data from Follett (1974).
- Drawdown, yield, and duration data for specific capacity tests from the TWDB groundwater database remarks table (TWDB, 2014f) and the TWDB submitted drillers' report database (TWDB, 2014g).
- Drawdown, yield, and duration data for specific capacity tests from scanned images of well records from the Texas Commission on Environmental Quality (2014a) and the TWDB Water Information Integration and Dissemination website (TWDB, 2014h).
- Specific yield data from Wrobelski (1996).
- Specific yield estimate from Cronin and Wilson (1967).

In their hydrogeologic characterization of the Brazos River Alluvium Aquifer, Shah and others (2007a) obtained hydraulic property data from previous investigations of the aquifer and the TWDB groundwater database. The data they compiled are available in Shah and Houston (2007). These data included data from 358 specific capacity tests from personal communications with the United State Geological Survey (255 values) and the remarks table in the TWDB groundwater database (103); seven hydraulic conductivity measurements from Wrobelski (1996), all from a single aquifer pumping test; and four transmissivity measurements, two each from Follett (1974) and Wilson (1967). A review of the specific capacity data Shah and Houston (2007) obtained via personal communication with the United States Geological Survey indicates that these data appear to be the same as that given in Cronin and Wilson (1967). The specific capacity data in Shah and Houston (2007) frequently consists of data for two specific capacity tests conducted at different times in a single well. For the current study, the average of the two specific capacities was calculated and used for the well. This resulted in a total of 249 specific capacity values from Shah and Houston (2007). In addition to the data in Shah and Houston

(2007), data from three additional specific capacity tests were obtained during this study from the remarks table in the TWDB groundwater database (TWDB, 2014f).

Shah and others (2007a) and Shah and Houston (2007) cite Follett (1974) and Wilson (1967) as sources of published transmissivity data for the Brazos River Alluvium Aquifer. A review of Follett (1974) indicates that the two transmissivity values in that report were estimated from aquifer pumping test data and a review of Wilson (1967) indicates that the two transmissivity values in that report were calculated from specific capacity data. Therefore, the current study considered the values from Follett (1974) as published transmissivity data but not the values in Wilson (1967).

Shah and others (2007a) and Shah and Houston (2007) cite Wrobelski (1996) as the source for seven hydraulic conductivity measurements for the Brazos River Alluvium Aquifer. Wrobelski (1996) conducted an aquifer characterization study of a small area in the Texas A&M University Brazos River Hydrologic Field Site, which is located in Burleson County near the western bank of the Brazos River across from College Station, Texas. That characterization consisted of an aquifer pumping test that included pumping at a central well and observations at 20 piezometers completed at various depths and distances from the pumping well. All of the piezometers were located within 520 feet of the pumping well. A review of Wrobelski (1996) indicated that she reports over 50 interpreted values for hydraulic conductivity for three different horizons in the Brazos River Alluvium Aquifer and multiple assumptions based on the results of an aquifer pumping test with 20 observation wells. Due to the small footprint and design of the characterization study, a single, representative hydraulic conductivity for the entire site is more applicable for use in developing the conceptual model for the Brazos River Alluvium Aquifer than multiple values. A single hydraulic conductivity for the aquifer is not given by Wrobelski (1996), but is provided in Munster and others (1996). Therefore, the value from Munster and others (1996) was used rather than the seven values given in Shah and others (2007a) and Shah and Houston (2007) to represent the hydraulic conductivity of the aquifer at the location of the Texas A&M University Brazos River Hydrologic Field Site.

Scanned images of well records for wells identified as completed in the Brazos River Alluvium Aquifer were obtained from the TWDB Water Information Integration and Dissemination database (TWDB, 2014h). Those records were reviewed for drawdown, yield, and time from well specific capacity tests. After removing duplicates of data in Shah and Houston (2007) and data found in the remarks table of the TWDB groundwater database, data for an additional 73 wells were obtained. The specific capacity for these wells was calculated as the well yield (in gallons per minute) divided by the observed drawdown in the well (in feet). Locations for these wells are known as the coordinates for each well are available in the TWDB groundwater database.

The TWDB submitted drillers' report database (TWDB, 2014g) was also searched for data from specific capacity tests in wells completed in the Brazos River Alluvium Aquifer. This database does not include the aquifer in which the wells are completed. Therefore, well depths, or gravel lengths when available, were compared to the aquifer thickness raster from Shah and Houston (2007) to identify wells completed in the aquifer. This resulted in specific capacity data for 197 wells. The specific capacity for these wells was calculated as the well yield divided by the drawdown. Locations for these wells are known as the database includes coordinates for each well.

A search of the Texas Commission on Environmental Quality well records was conducted in an effort to obtain specific capacity data for wells completed into the Brazos River Alluvium Aquifer (Texas Commission on Environmental Quality, 2014a). The Texas Commission on Environmental Quality well records do not include the aquifer in which the wells are completed. Therefore, the maximum thickness of the aquifer was determined for each Texas Commission on Environmental Quality grid located totally or predominantly in the boundary of the Brazos River Alluvium Aquifer. Specific capacity test data found in the well records were collected only for wells with a total depth less than or equal to the total aquifer depth in the grid plus 10 feet. This resulted in specific capacity data for 394 wells. These data were used to calculate the specific capacity for the well as the well yield divided by the drawdown. For all of the wells contained in the Texas Commission on Environmental Quality well records, locations are identified only at the Texas Commission on Environmental Quality grid-block level, which is a 2.5-minute by 2.5-minute area. Therefore, the locations of wells with specific capacity data from the Texas Commission on Environmental Quality well records are uncertain.

Wrobelski (1996) also includes estimates of specific yield for the Brazos River Alluvium Aquifer interpreted based on results of the aquifer pumping test at the Texas A&M University

Brazos River Hydrologic Field Site. In addition, Cronin and Wilson (1967) provide estimates of specific yield based on laboratory measurements of soil samples collected from test holes in the aquifer. The locations of the test holes are unknown as they are not provided in Cronin and Wilson (1967).

Table 4.5.1 summaries the hydraulic property data obtained for the Brazos River Alluvium Aquifer. As illustrated by the table, hydraulic conductivity and transmissivity data for the aquifer are scarce, specific capacity data are abundant, and specific yield data are scarce. The spatial distribution of the hydraulic property data is shown in Figure 4.5.1. Hydraulic conductivity and transmissivity values are available for Brazos and Burleson counties. The majority of the available specific capacity data are in the central portion of the aquifer in Milam, Robertson, Burleson, and Brazos counties. Few specific capacity measurements are available in the northern and southern portions of the aquifer. The locations of the laboratory specific yield data from Cronin and Wilson (1967) are not shown because they are unknown.

4.5.2 Calculation of Horizontal Hydraulic Conductivity from Specific Capacity

Field-scale hydraulic conductivity can be estimated from various types of aquifer performance tests, including slug tests (local near-well estimate), specific capacity tests (relatively near-well estimate), and multi-hour to multi-day aquifer pumping tests (integrated estimate over radius of influence, the size of which depends on the duration of the test). The results from aquifer pumping tests are most appropriate for estimating hydraulic conductivity for use in regional groundwater models as they stress a larger area of the aquifer than do slug and specific capacity tests. In addition, results from specific capacity tests are dependent on the efficiency of the well as well as properties of the aquifer, making it the least useful for regional-scale groundwater models. However, specific capacity is relatively easily to measure, requiring only the pumping rate and drawdown, and is commonly reported for wells. Aquifer pumping tests, on the other hand, are much more time consuming and expensive to conduct and interpret than are specific capacity tests.

The only hydraulic conductivity value for the Brazos River Alluvium Aquifer from an aquifer pumping test is the value from Munster and others (1996) for a location in Burleson County (see Section 4.5.1 and Figure 4.5.1). In addition to this hydraulic conductivity value, two transmissivity values estimated from aquifer pumping tests are available for the Brazos River

Alluvium Aquifer, one in Burleson County and one in Brazos County (see Section 4.5.1 and Figure 4.5.1).

Because high quality data from multi-day aquifer pumping tests are scarce for the Brazos River Alluvium Aquifer but a large volume of specific capacity data are available, a methodology was developed to estimate transmissivity from the specific capacity data. An aquifer-specific relationship between transmissivity and specific capacity can be developed using both types of data from a single well (Mace, 2001). Developing this empirical relationship requires at least 25 wells with coincident specific capacity and transmissivity values (Razack and Huntley, 1991), many more than the values at two wells available for the Brazos River Alluvium Aquifer (Table 4.5.2). When less than 25 wells are available, Mace (2001) suggests using either an existing empirical equation or an analytical approach. Figure 4.5.2 shows the two data points for the Brazos River Alluvium Aquifer wells plotted against existing empirical equations for several different aquifers obtained from Mace (2001). Though obviously a limited sample size, the points for the Brazos River Alluvium Aquifer are not consistent with any of these empirical relationships.

Since the comparison of the data for the Brazos River Alluvium Aquifer to existing empirical relationships for other aquifers did not provide a match, the analytical approach presented in Mace (2001) was used to estimate transmissivity from the available specific capacity for the aquifer. 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):

$$S_c = \frac{4\pi T}{\left[ln\left(\frac{2.25Tt}{r^2S}\right)\right]} \qquad (4.5.1)$$

where:

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

Equation 4.5.1 cannot be solved directly, so it was solved iteratively using Microsoft Excel. The duration of the specific capacity test and the well radius are available for 339 of the wells with specific capacity data. An additional 235 wells have pumping duration data, but no reported well radius. For these latter wells, a well radius equal to the average value for the 339 wells with a radius was assumed (approximately 6 inches). As suggested by Mace (2001), data for wells with no recorded pumping duration and wells where the type of specific capacity test was recorded as "bailed" were not used. Aquifer storativity was assumed to be 0.15 (see Section 4.5.5).

If only a small portion of the aquifer thickness is screened, specific capacity will be overestimated and the resulting transmissivity value calculated from Equation 4.5.1 will not be representative of the entire aquifer thickness (Mace, 2001). This "partial penetration" can be addressed through mathematical methods that correct for the short screen or by only considering wells that are screened over a large percentage of the aquifer thickness. However, implementing these methods require that both the screen length and the aquifer thickness at wells be known. Unfortunately, many wells in this specific capacity dataset lack screen information. In addition, over half of the wells with specific capacity information lack precise location information. Therefore, even if these wells have screen information, estimating a saturated thickness value (from the water level surfaces given in Chapter 4.2, for example) at a given well point yields a highly uncertain result. Rather than introduce more uncertainty by trying to correct for an uncertain value, no additional mathematical corrections were added to account for partially penetrating wells. There was also no attempt to filter the well dataset using a ratio of screen length to aquifer thickness. Fortunately, in the case of the Brazos River Alluvium Aquifer, assuming little to no bias from partially penetrating wells appears to be a reasonable assumption. The average screen length for wells that do have screen information available is about 25 feet, while the average saturated thickness of the entire aquifer during the predevelopment period is only about 35 feet. This implies that most wells are screened over a majority of the total aquifer thickness, thus limiting the bias expected to be introduced to the transmissivity calculations by partially penetrating wells. Transmissivity values for the wells were therefore calculated using Equation 4.5.1, as-is, with no partial penetration correction. The calculated transmissivity values for the entire specific capacity dataset are shown in Figure 4.5.3. In the figure, the transmissivity values calculated for wells with a reported well radius are shown separately from the values calculated for wells with an assumed well radius.

Shah and others (2007a) also established a relationship between specific capacity and transmissivity based on a modified version of the Theis non-equilibrium equation from Cooper and Jacob (1946):

$$S_c = \frac{T}{264\left(log\frac{0.3Tt}{r^2S}\right)} \tag{4.5.2}$$

This modification applies when time is sufficiently large and the well radius is sufficiently small. Because values for all of the variables in Equation 4.5.2 were not available for the wells with specific capacity data, Shah and others (2007a) used the empirical version of the equation assuming typical values for variables to calculate transmissivity:

$$S_c = \frac{T}{1500} \tag{4.5.3}$$

For comparison purposes, the transmissivity was calculated from the specific capacity data for the Brazos River Alluvium Aquifer using Equation 4.5.3. These results are also shown in Figure 4.5.3. This figure shows that the simplified equation used by Shah and others (2007a) overestimates the transmissivity values for a given specific capacity relative to the values calculated using Equation 4.5.1. Because simplifying assumptions were limited, the transmissivity values calculated in the current analysis using Equation 4.5.1 were considered more representative of the Brazos River Alluvium Aquifer than the transmissivity values calculated by Shah and others (2007a) using Equation 4.5.3. In addition, the current set of specific capacity data is larger than that of Shah and others (2007a) due to the addition of data from the TWDB submitted drillers' reports and Water Information Integration and Dissemination databases and well records from the Texas Commission on Environmental Quality. Therefore, the transmissivity values calculated for this study were used in the development of the conceptual model for the Brazos River Alluvium Aquifer rather than the calculated transmissivities in Shah and Houston (2007).

Because of the many assumptions involved in calculating transmissivity from specific capacity, the transmissivity values calculated using Equation 4.5.1 are considered more uncertain than values determined from aquifer pumping tests. However, the available data from aquifer pumping tests are insufficient to develop a distribution of transmissivity across the entire Brazos River Valley Alluvium Aquifer. Therefore, using the specific capacity data greatly improves coverage and is useful for providing a general idea of reasonable transmissivity values in the aquifer.

It was proposed that, as part of this study, two to three aquifer tests would be performed using pairs of proximal wells with one well completed in the Brazos River Alluvium Aquifer and another well completed in the underlying formations. First, all potential well pairs were located that were within 200 feet of each other. Second, the screen intervals of the wells completed in the underlying formations were compared with the screen intervals of the wells completed in the Brazos River Alluvium Aquifer. In all cases, the wells completed in the underlying formations were several hundred feet deeper than the wells in the alluvium often with intermediate confining units between the two screen intervals. This disparity in depths and lack of hydraulic communication between the wells in every potential well pair precluded getting meaningful results from the proposed aquifer tests. Therefore, a change in scope, involving analyzing and incorporating data from an existing United States Army Corps of Engineers RiverWare model of the Brazos River was proposed as a substitution for the aquifer tests. This scope is discussed in Section 3 and Section 4.4.

4.5.3 Spatial Distribution of Transmissivity and Horizontal Hydraulic Conductivity

The transmissivity values calculated from specific capacity data using Equation 4.5.1 and the two transmissivity values each reported in Follett (1974) and Wilson (1967) were interpolated using the Topo-to-Raster tool in ArcGIS 10.1 to generate an estimated transmissivity distribution for the Brazos River Alluvium Aquifer. Transmissivity values calculated from specific capacity data for wells both with known and estimated well radius were used for the interpolation. The resultant transmissivity distribution for the Brazos River Alluvium Aquifer is shown in Figure 4.5.4. In general, the highest transmissivities occur in the central portion of the aquifer in southern Milam, southern Robertson, Burleson, and Brazos counties.

In an unconfined aquifer, hydraulic conductivity can be calculated as the transmissivity divided by the saturated thickness. Using the aquifer saturated thickness based on the pre-development water-level elevation surface (see Figure 4.2.5) and the transmissivity values shown in Figure 4.5.4, estimated hydraulic conductivities for the aquifer were generated. The resultant distribution of estimated horizontal hydraulic conductivity for the Brazos River Alluvium Aquifer is shown in Figure 4.5.5. Like transmissivity, the highest hydraulic conductivities are in the central portion of the aquifer. A histogram of the horizontal hydraulic conductivity estimates is shown in Figure 4.5.6. The majority (72 percent) of the estimates fall between 30 and 300 feet per day.

To estimate the horizontal hydraulic conductivity of the formations underlying the Brazos River Alluvium Aquifer in the active model area, the final calibrated values were taken from groundwater availability models developed for the TWDB or accepted by the TWDB as the representative model for the aquifer. The properties for the Carrizo-Wilcox, Queen City, and Sparta aquifers were extracted from the Queen City and Sparta aquifers groundwater availability model (Kelley and others, 2004). Properties were extracted from the Yegua-Jackson Aquifer groundwater availability model (Deeds and others, 2010) for that aquifer. The properties for the Gulf Coast Aquifer System were extracted from the Houston Area Groundwater Model (Kasmarek, 2013). To fill in gaps for the undifferentiated Cretaceous-age and Tertiary-age formations beneath the bottom of the Carrizo-Wilcox Aquifer as well as the Cook Mountain Formation, average values from the Weches and Reklaw formations in the Queen City and Sparta aquifers groundwater availability model (Kelley and others, 2004) were applied. The resulting horizontal hydraulic conductivity distribution is shown in Figure 4.5.7.

4.5.4 Vertical Hydraulic Conductivity

At very small scales, the vertical and horizontal hydraulic conductivity of an aquifer may differ by very little. However, on a regional scale, the differences between the vertical and horizontal hydraulic conductivities can be very large. In areas where the aquifer is thought to be largely structurally intact, the vertical hydraulic conductivity is limited by the hydraulic conductivity of the lower permeability units. For instance, a continuous low permeability clay layer in the middle of a sandy aquifer could greatly impede vertical flow in what would otherwise be a high permeability system. This could create a difference of several orders of magnitude between vertical and horizontal hydraulic conductivity. The presence of clays will generally have the largest effect on vertical conductivity. However, with the exception of regions with laterally-extensive clay lenses, the difference between horizontal and vertical hydraulic conductivity is expected to be small in the Brazos River Alluvium Aquifer because sediments in the aquifer grade from fine to coarse grained in both the horizontal and vertical directions.

Because vertical hydraulic conductivity is not measurable at the large scale typical of a regional model grid, it is usually estimated through model calibration. It is generally accepted that groundwater models provide the best means for estimating vertical hydraulic conductivity at a regional scale (Anderson and Woessner, 1992). Currently, literature estimates of vertical hydraulic conductivity are not available for the Brazos River Alluvium Aquifer.

4.5.5 Storage Properties

The most representative storage properties are determined through analysis of observation well data from aquifer pumping tests. Wrobelski (1996) estimated specific yield values of 0.001 to 0.015 with an average of 0.004 based on results of an aquifer pumping test conducted in the Brazos River Alluvium Aquifer at the Texas A&M University Brazos River Hydrologic Field Site. She indicates that these values are significantly lower than expected for an unconfined aquifer and the calculated average is more consistent with values for a confined aquifer, indicating semi-confined conditions may exist in the aquifer at the location of this test. Freeze and Cherry (1979) and Domenico and Schwartz (1990) indicate that typical specific yield values for an unconfined aquifer are 0.01 to 0.3 and 0.03 to 0.44, respectively. Although Follett (1974) provides estimates of hydraulic conductivity from aquifer pumping tests conducted in Burleson and Brazos counties, he does not provide estimates of specific yield for those tests.

Cronin and Wilson (1967) provide laboratory measurements of specific yield on samples collected from test holes completed in the Brazos River Alluvium Aquifer. The specific yield values were measured using a centrifuge method, which exerts a greater force on the sample than gravity, resulting in more water drainage from the samples than would be expected under gravitational forces alone. Therefore, the measured values reported in Cronin and Wilson (1967) are likely higher than applicable for in-situ sediments draining under gravitation forces. In addition, the measurements were conducted on discrete samples so are not representative of the aquifer on a regional scale. Cronin and Wilson (1967) suggest that a specific yield of 15 percent is a “reasonable, possibly conservative” value for the Brazos River Alluvium Aquifer rather than the average value for the lab samples (23.6 percent). O’Rourke (2006) used this value of 15 percent in a groundwater model for the central portion of the Brazos River Alluvium Aquifer. The groundwater availability model for the central Carrizo-Wilcox Aquifer included a model layer representing the alluvium of the Colorado, Brazos, and Trinity rivers (Dutton and others, 2003). They assigned a specific yield of 25 percent to that layer, but it should be noted that modeling the alluvium was not a primary goal of their model. For the purposes of the conceptual model of the Brazos River Alluvium Aquifer, the specific yield value of 15 percent recommended by Cronin and Wilson (1967) is adopted.

Table 4.5.1 Summary of hydraulic property data for the Brazos River Alluvium Aquifer.

Type Data	Value/Range	Units	Number of Values	Source
Hydraulic Conductivity	272	feet per day	1	Munster and others (1996)
Transmissivity	6,950 and 9,620	square feet per day	2	Follett (1974)
Specific Capacity	17.2 to 28.6	gallons per minute per foot	2	Wilson (1967)
	3.7 to 116.3		249	Shah and Houston (2007)
	7.7 to 17.3		3	remarks table in the TWDB groundwater database (TWDB, 2014f)
	2.3 to 140.5		73	TWDB Water Information Integration and Dissemination database (TWDB, 2014h)
	0.3 to 266.7		197	TWDB submitted driller's report database (TWDB, 2014g)
	0.1 to 258.1		394	Texas Commission on Environmental Quality (2014a)
Specific Yield	0.07 to 1.5	percent	44(1)	Wrobelski (1996)
	25		1	"reasonable, possible conservative, estimate" from Cronin and Wilson (1967)

(1) values from multiple interpretations of a single aquifer pumping test with 20 observation wells

Table 4.5.2 Wells with coincident transmissivity data from an aquifer pumping test and specific capacity data.

State Well Number	County	Latitude	Longitude	Transmissivity (ft^2/day)	Specific Capacity (gpm/ft)	Specific Capacity (ft^2/day)	Source
5929431	Burleson	30.546666	-96.489444	9,620	37.6	7,238.5	Follett (1974)
5939606	Brazos	30.420277	-96.158333	6,950	46	8,855.6	Follett (1974)

gpm/ft = gallons per minute per foot ft^2/day = square feet per day

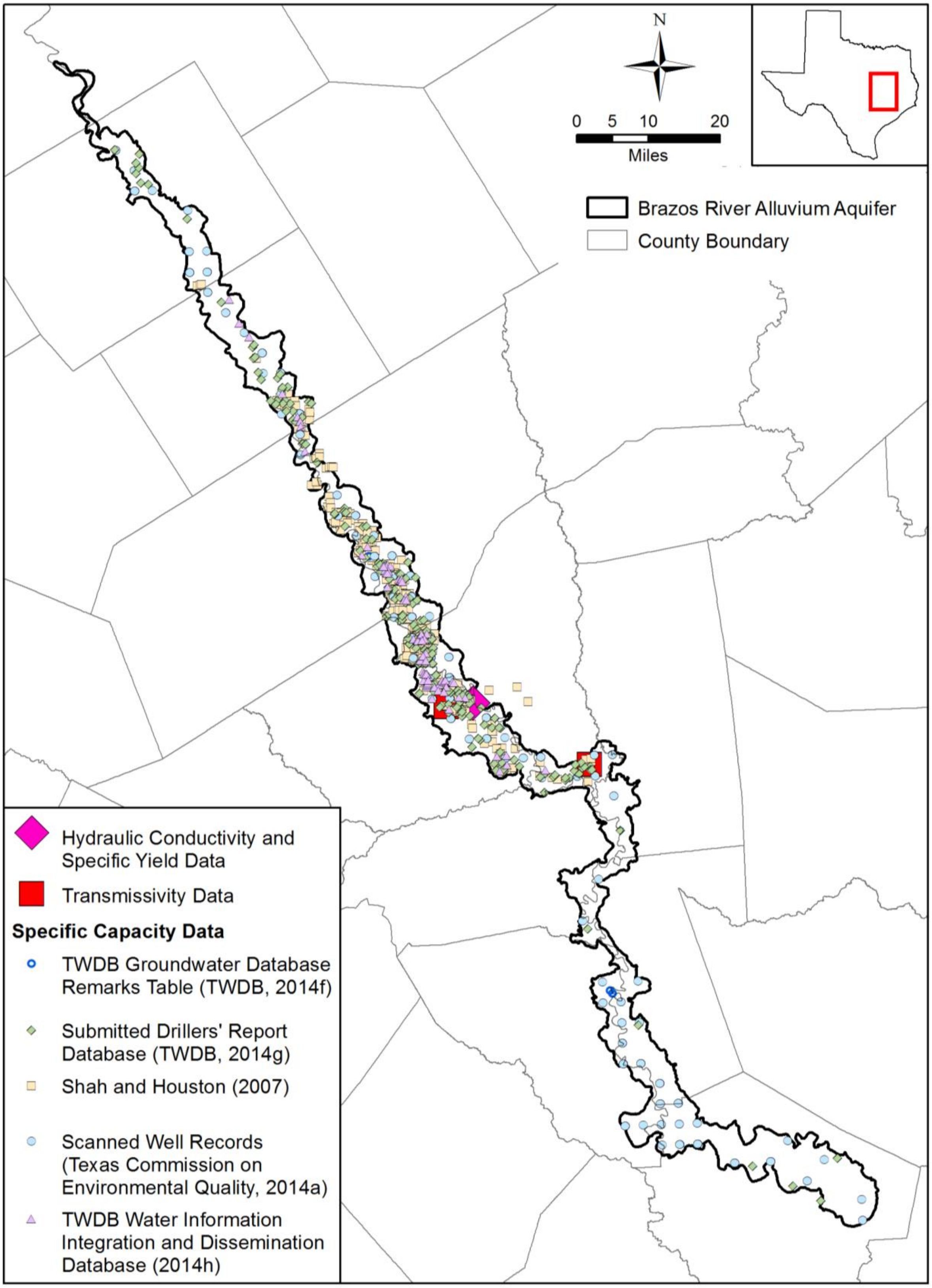


Figure 4.5.1 Available hydraulic property data for the Brazos River Alluvium Aquifer.

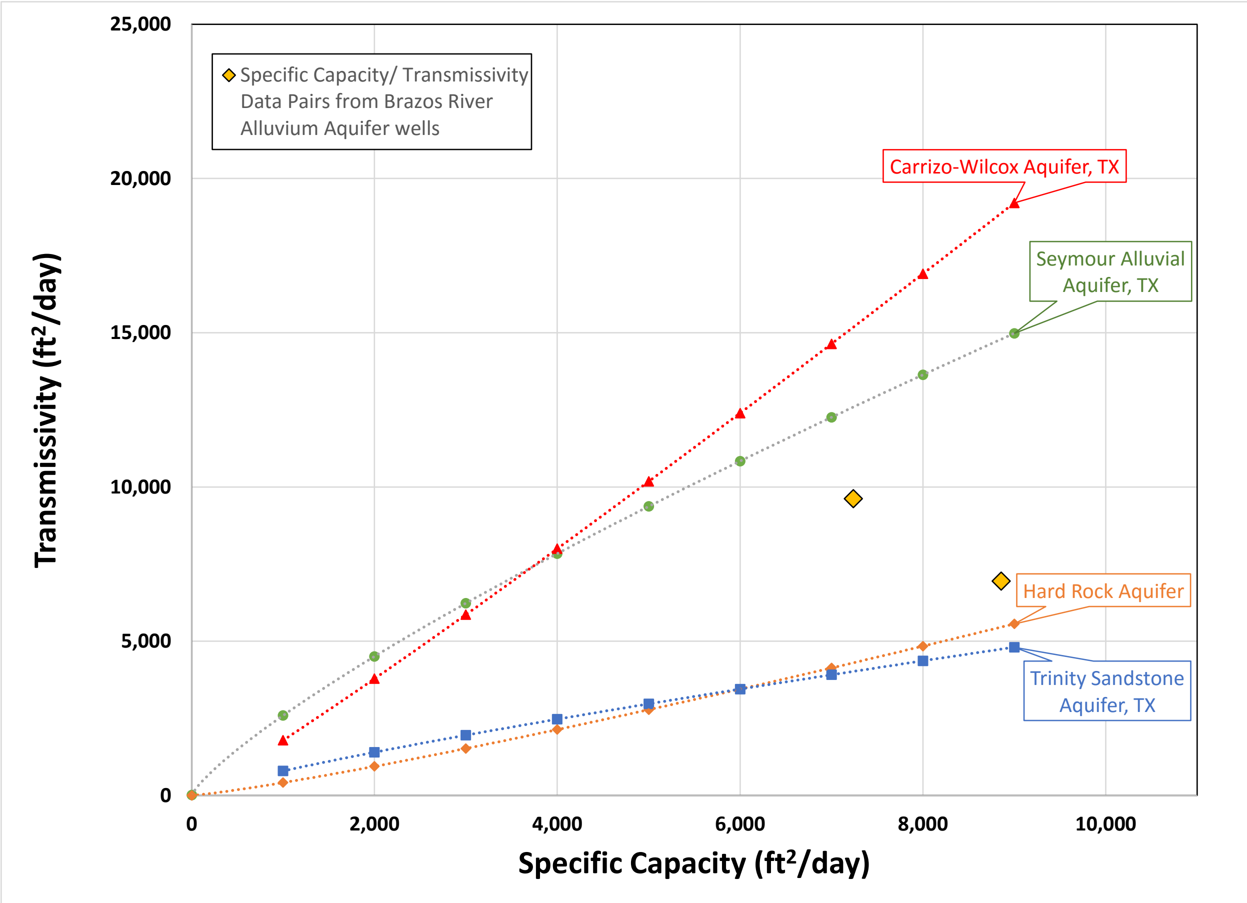


Figure 4.5.2 **Data pairs of specific capacity and transmissivity in square feet per day for Brazos River Alluvium Aquifer wells plotted against existing empirically-derived specific capacity/transmissivity relationships from Mace (2001).**

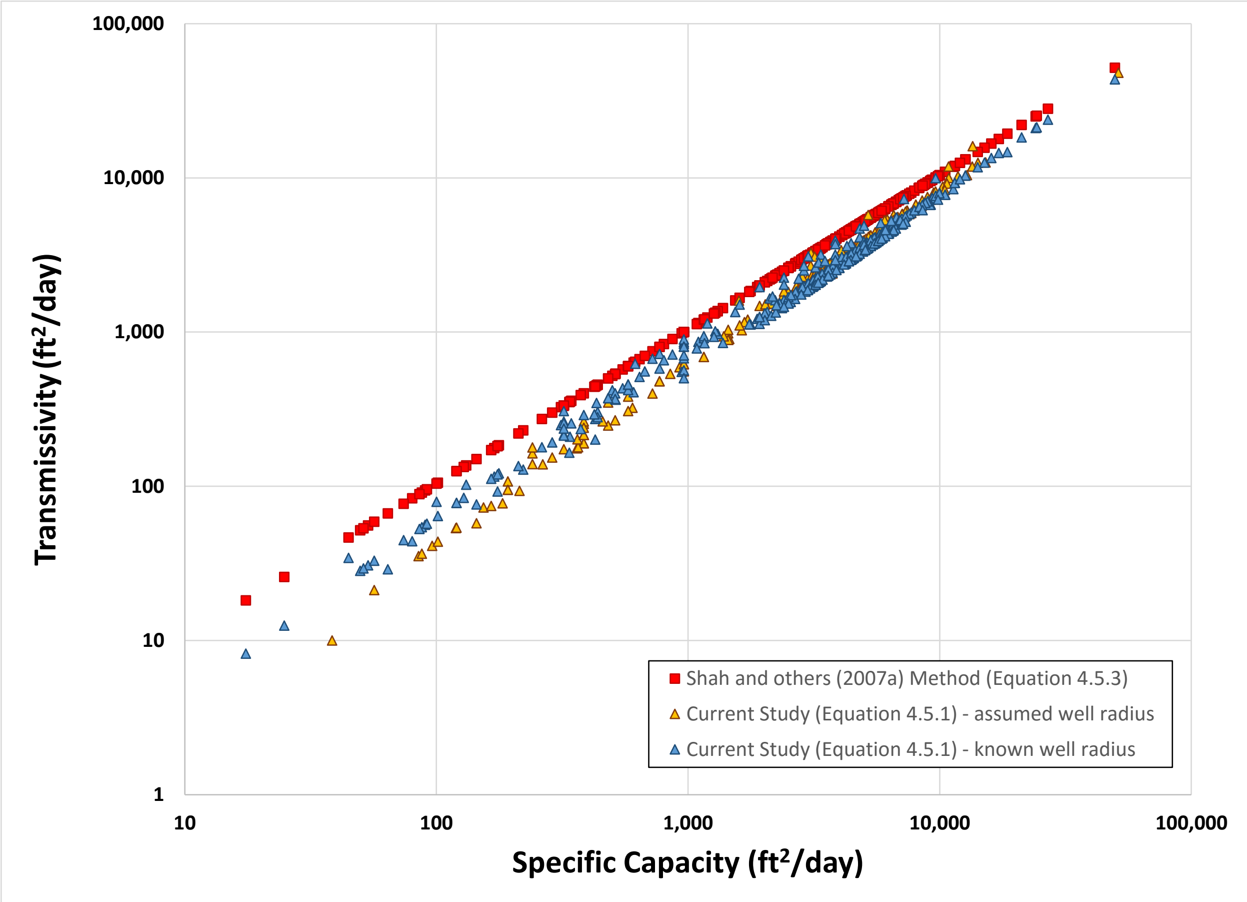


Figure 4.5.3 Transmissivity values calculated from specific capacity data in square feet per day for the current study and using the Shah and others (2007a) method.

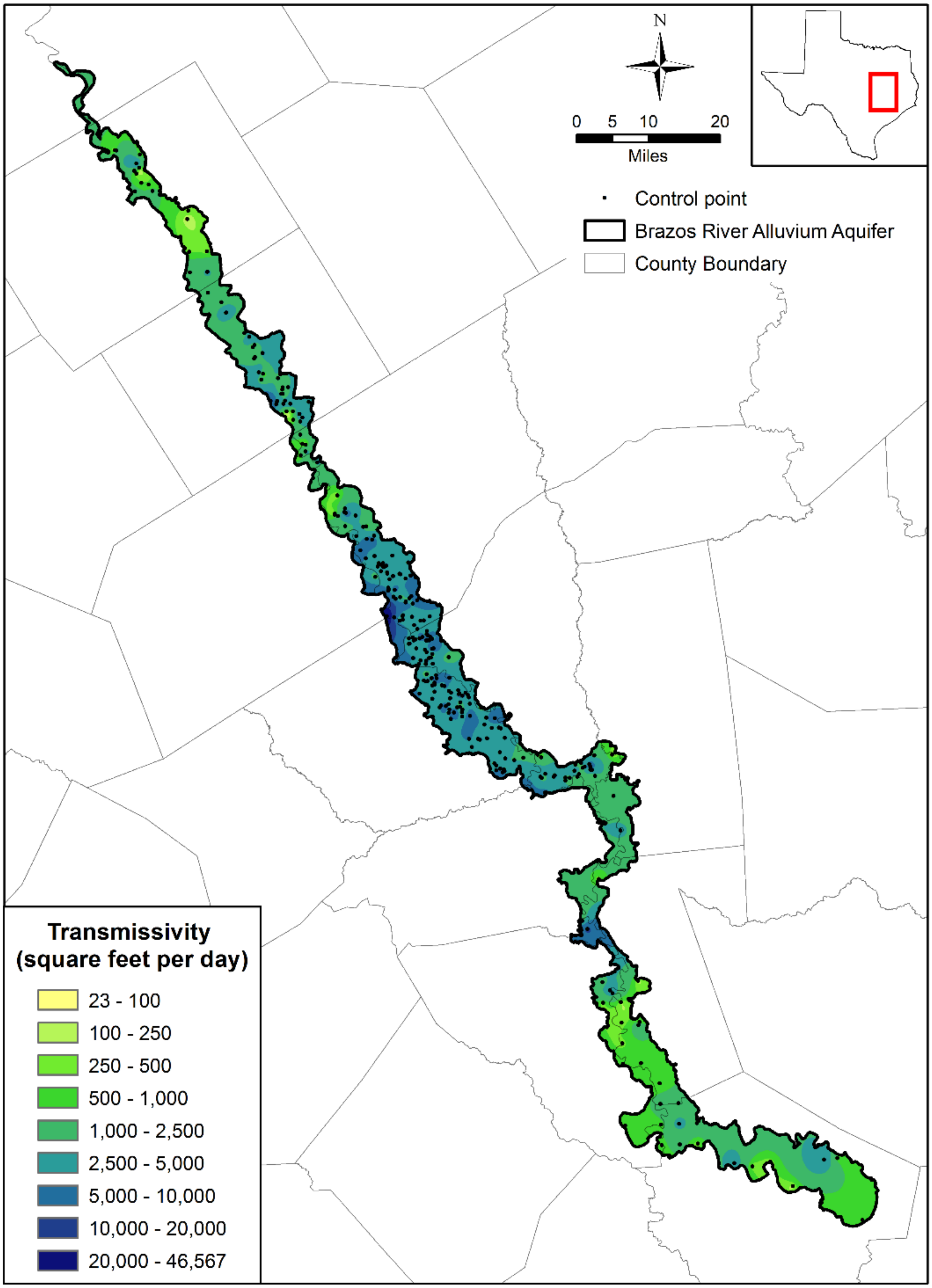


Figure 4.5.4 Estimated transmissivity distribution for the Brazos River Alluvium Aquifer.

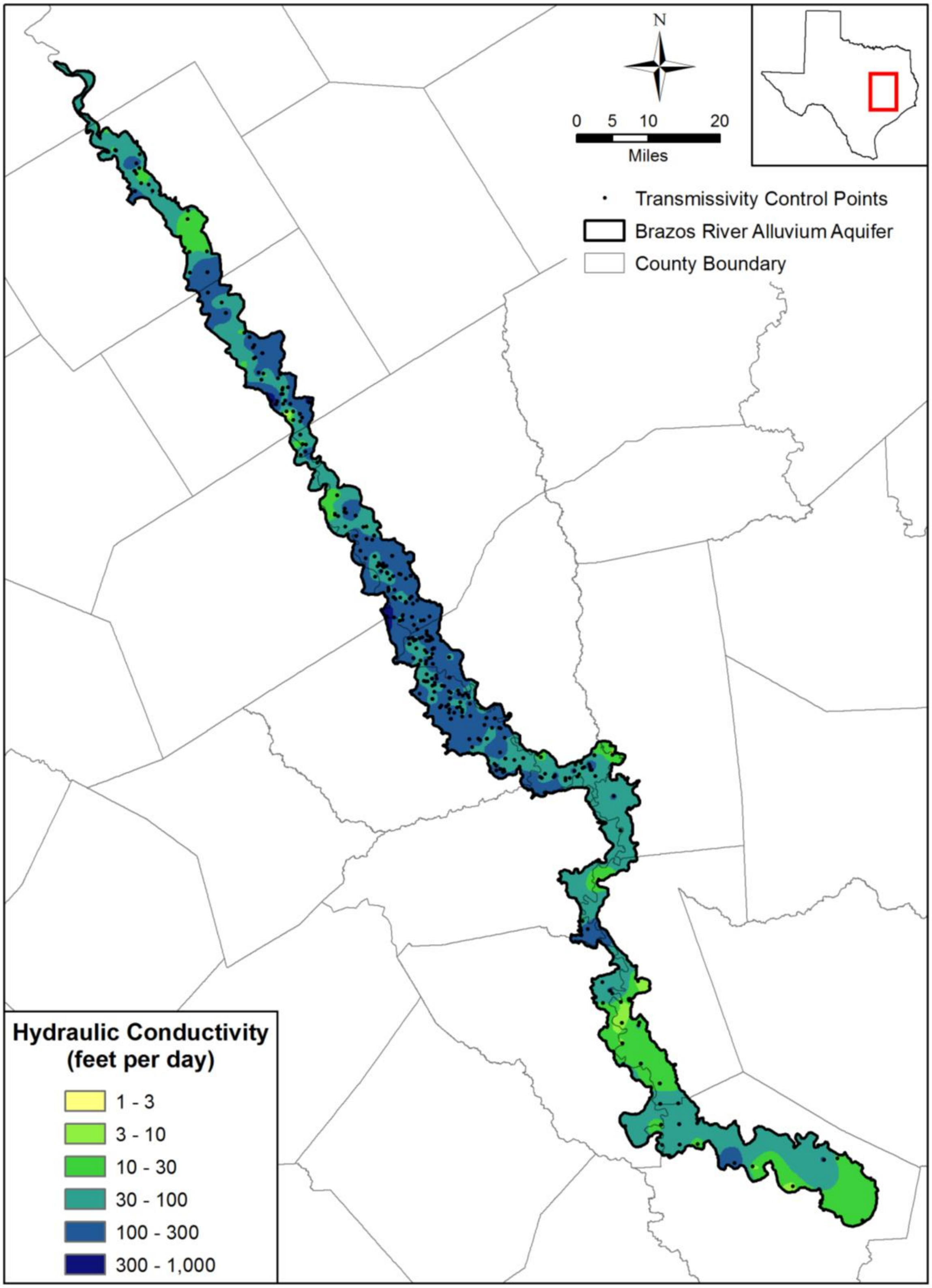


Figure 4.5.5 Estimated horizontal hydraulic conductivity distribution for the Brazos River Alluvium Aquifer.

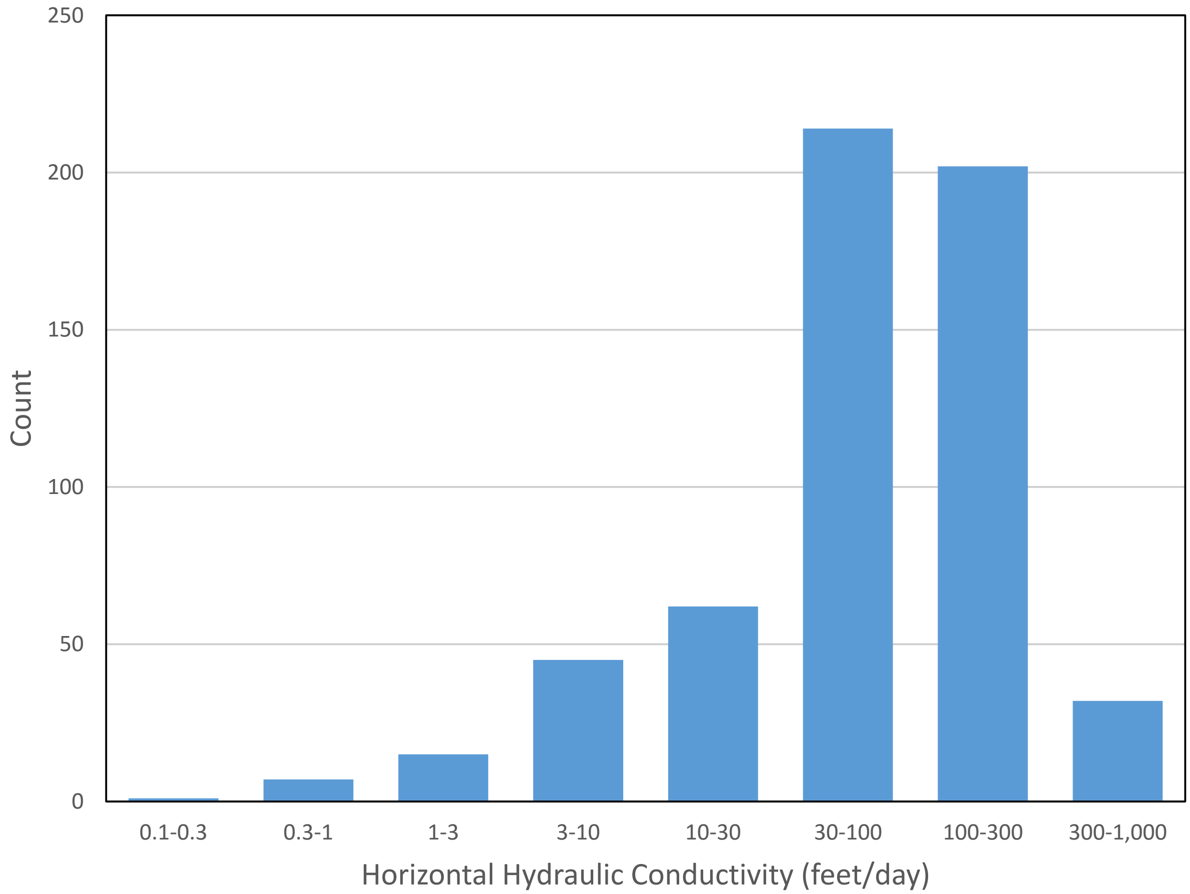


Figure 4.5.6 Histogram of horizontal hydraulic conductivity in feet per day for the Brazos River Alluvium Aquifer.

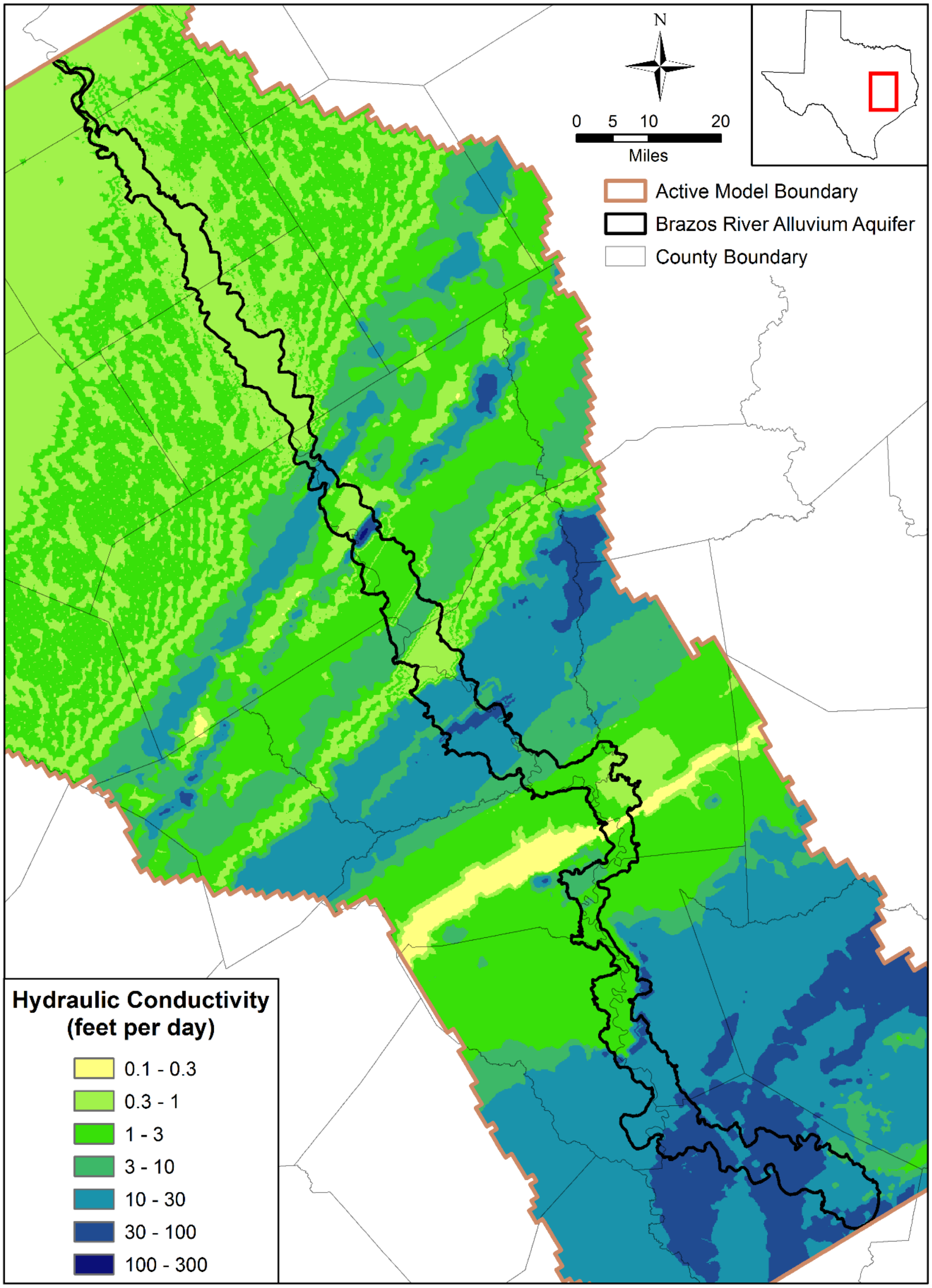


Figure 4.5.7 Horizontal hydraulic conductivity distribution for geologic units underlying the Brazos River Alluvium Aquifer.

4.6 Discharge

Discharge refers to water moving out of the aquifer by one of several possible processes. The first group of processes discussed in this section are the natural ones, including discharge through streams, springs, evapotranspiration, and cross-formational flow. These natural processes have been discussed in previous sections. The second important discharge mechanism is pumping.

4.6.1 Natural Aquifer Discharge

Under pre-development conditions, without any pumping, aquifer recharge and discharge are balanced. In the typical topographically-driven system, percolation of precipitation results in recharge at the water table, which flows from topographic highs and discharges at topographic lows through streams, springs, and groundwater evapotranspiration. Discharge through base flow to the Brazos River is discussed in Section 4.4.1 and discharge through springs is discussed in Section 4.4.2. Discharge via groundwater evapotranspiration is discussed in Section 2.1.

Natural aquifer discharge can also occur through cross-formational flow to underlying aquifers in the presence of a downward hydraulic gradient. This mechanism of natural aquifer discharge is discussed in Section 4.2.6.

4.6.2 Aquifer Discharge through Pumping

Estimates of pumping discharge from the Brazos River Alluvium Aquifer were developed for each county for the time period of the transient model (i.e., 1950 through 2012). The majority of the groundwater pumped from the Brazos River Alluvium Aquifer is used for irrigation purposes (George and others, 2011). The following subsections describe (1) sources of historical pumping data, (2) estimates of specific historical pumping data for the Brazos River Alluvium Aquifer, (3) a summary of historical pumping data for 1980 through 2012, (4) integrated historical pumping estimates for 1950 through 2012, (5) a comparison of estimated historical pumping and long-term water-level trends by county, and (6) the estimated spatial distribution of pumping.

4.6.2.1 Historical Pumping Data Sources

A search was conducted to identify sources of historical pumping estimates for the Brazos River Alluvium Aquifer. This search included a literature survey, a request of water use survey data from the TWDB, and requests of production data from groundwater conservation districts. An additional source of historical pumping data was the calculation of rural domestic pumping from census block data and estimated per capita water use.

Table 4.6.1 summarizes the sources of historical pumping identified during the search. Included in this table are the citations for the source report or data, the counties for which pumping data are available, the year(s) of the pumping data, the aquifer(s) associated with the pumping data, and the groundwater use type associated with the pumping.

4.6.2.1.1 Literature Review Results

Several sources of historical pumping were identified through the literature review. Baker and others (1974) provide estimated pumping data for all aquifers in Grimes County combined for the years 1958, 1964, 1969, and 1970. Cronin and Wilson (1967) report estimates of pumping from the Brazos River Alluvium Aquifer for irrigation purposes in 1963 and 1964 for all counties. Follett (1974) provides estimates of pumping from the Brazos River Alluvium Aquifer in Brazos and Burleson counties for irrigation purposes in 1958, 1964, and 1969. TWDB (2001) provides estimates of total pumping for irrigation purposes from all aquifers in a county combined for the years 1958, 1964, 1969, 1974, 1979, 1984, 1989, 1994, and 2000. Estimates of pumping from the Brazos River Alluvium Aquifer in Austin and Waller counties in 1965 are provided in Wilson (1967).

4.6.2.1.2 TWDB Water Use Survey Data

Estimates of historical pumping for 1980 and 1984 through 2012 are available from the TWDB for municipal, manufacturing, mining, power, irrigation, and livestock water use categories. These estimates have been developed by the TWDB as a water use survey database to support state water planning and the TWDB Groundwater Availability Model program and are considered the most reliable source of historical pumping information available. A formal request for these data was made to the TWDB. In response to that request, water use survey data consisting of two data sets were received from the TWDB (2014i). One of the data sets contains groundwater use estimates for 1980 and 1984 through 1999 and the other contains groundwater use estimates for 2000 through 2012. The data received from the TWDB includes water use estimates for all aquifers individually in the counties of interest.

Table 4.6.2 summarizes the water use survey data received from the TWDB for the Brazos River Alluvium Aquifer. Because two sets of data were provided by the TWDB, the numbers 1 and 2 are listed under each water use type in the tables. The number 1 represents the 1980 and 1984 through 1999 data and the number 2 represents the 2000 through 2012 data. An 'x' in the table indicates that at least one non-zero value is included in the data. If the data set does not include values for all years, the years with data or, in one case without data, are indicated in a superscript. Table 4.6.2 shows that groundwater was not pumped from the Brazos River Alluvium Aquifer for power use, was used for mining purposes in Brazos and Falls counties, and was used for a few years for manufacturing purposes in Brazos and McLennan counties. The water use survey data indicate that groundwater from the Brazos River Alluvium Aquifer was used to some degree for municipal and livestock purposes in most counties and irrigation purposes in all counties.

For all counties and water use categories, groundwater use data for the years 1981 through 1983 are not included in the TWDB water use survey data. For some counties and use categories, groundwater use estimates for the Brazos River Alluvium Aquifer are missing or anomalous in the water use survey data. In addition, use estimates are provided for the Brazos River Alluvium Aquifer in one of the data sets received from the TWDB but not in the other data set for some counties and water use categories (see Table 4.6.2). Where groundwater use data are missing or anomalous in the water use survey data, estimates were developed. Table 4.6.3 summarizes, by county, year, and water use category, the reasons estimates were developed. The methodologies used to develop the groundwater use estimates are given in Appendix D. In all cases, the estimated values were developed using other portions of the water use survey data received from the TWDB as explained in Appendix D. The purpose for estimating data was to provide a continuous record of pumping estimates for the period from 1980 through 2012 based on the most reliable pumping information available. Table 4.6.3 also indicates whether pumping from the Brazos River Alluvium Aquifer for the indicated purposes was included in the 1980 and 1984 through 1999 data set and in the 2000 through 2012 data set.

4.6.2.1.3 Groundwater Conservation District Data

Estimates of historical pumping from the Brazos River Alluvium Aquifer for irrigation purposes in Brazos and Robertson counties for 2011 through 2013 were obtained from the Brazos Valley Groundwater Conservation District (2014b). These estimates account for essentially all of the pumping from the Brazos River Alluvium Aquifer in these two counties (Brazos Valley Groundwater Conservation District, 2014b). Estimates of pumping of the Brazos River

Alluvium Aquifer for all purposes in Burleson and Milam counties for the period from 2005 through 2013 were obtained from the Post Oak Savannah Groundwater Conservation District (2014a) in the form of production data. The Post Oak Savannah Groundwater Conservation District (2014b) indicates that these production data represent voluntary reporting by water users, so the accuracy of these data is unknown, and they likely under represent actual production.

4.6.2.1.4 Calculated Rural Domestic Pumping

Estimates of rural domestic pumping for the period from 1950 through 2012 were developed using census block data from 1990 and 2010, total population data at select years, and an assumed per capita water use. These calculations assumed that all groundwater used for rural domestic purposes is supplied by the Brazos River Alluvium Aquifer within the aquifer boundary. The use of groundwater from the Brazos River Alluvium Aquifer for rural domestic purposes by year and county was calculated as:

$$RD_{BRAA} = Pop_{cnty} \bullet RurPopRatio_{\frac{BRAA}{cnty}} \bullet PerCapitaUse \bullet \%GW \tag{4.6.1}$$

where:

RD_{BRAA} = groundwater use from the Brazos River Alluvium Aquifer for rural domestic purposes (acre-feet per year),

Pop_{cnty} = total county population,

$RurPopRatio_{BRAA/cnty}$ = ratio of total county population to rural population in the Brazos River Alluvium Aquifer boundary,

PerCapitaUse = per capita water use (acre-feet per year), and

%GW = percentage of total water use in the county supplied by groundwater.

The source of the values used for each term in Equation 4.6.1 are discussed below.

Census block data for 1990 were obtained from the TWDB as a geographic information system (GIS) coverage. Historically, the TWDB has provided these data in support of estimating rural domestic pumping for groundwater availability models. This coverage includes an identifier in each census block that indicates whether the population in the block represents an urban or rural population. Three types of census blocks are identified: (1) rural; (2) cities having municipal water supplies in the 2002 State Water Plan (urban areas); and (3) other urban areas, incorporated places, and census designated places (assumed to be urban areas for this application). Using this identifier, the rural population within the Brazos River Alluvium Aquifer boundary based on the 1990 census data was calculated for each county (Figure 4.6.1). Census block data for 2010 were obtained from the United States Census Bureau as geographic information system (GIS) coverages (United States Census Bureau, 2014). In addition, coverages of urban areas for 2010 were also obtained from the United States Census Bureau. Using these two coverages, the rural population in the Brazos River Alluvium Aquifer boundary, based on the 2010 census data, was calculated for each county (Figure 4.6.2).

In order to estimate the rural population in the Brazos River Alluvium Aquifer boundary for years other than 1990 and 2010, an estimate of the ratio of rural population in the Brazos River Alluvium Aquifer boundary to total county population was needed for each county. These ratios were calculated using the 1990 and 2010 census block data. For the years 1991 through 2009, the ratios were estimated assuming linear interpolation between the calculated ratios for 1990 and 2010. The calculated ratios for 1990 were assumed for the years 1950 through 1989, and the calculated ratios for 2010 were assumed for the years 2011 and 2012.

Total county populations were obtained from the Texas Association of Counties (2014) for the years 1950, 1960, and 1970, from the TWDB (2014j) for every year from 1980 through 1989, from the TWDB (2014k) for every year from 1990 through 1999, and from the TWDB (2014l) for every year from 2000 through 2012. Using these total county populations and the ratios of total county population to rural population in the Brazos River Alluvium Aquifer boundary, the rural population by county in the Brazos River Alluvium Aquifer boundary was estimated for every year from 1950 through 2012.

The rural water use in the Brazos River Alluvium Aquifer boundary was calculated as the rural population times an estimated per capita water use. The per capita use was assumed to be 110 gallons per day (0.1232 acre-feet per year) for the years 1970 and 1980 through 2012 based on the approximate median per capita water use in Texas between 1980 and 1997 (Hamlin and Anaya, 2006). The per capita water use was assumed to be 75 percent of 110 gallons per day (0.09 acre-feet per year) in 1950 and 85 percent of 110 gallons per day (0.1 acre-feet per year) in 1960.

Water used for rural domestic purposes was assumed to be supplied by both groundwater and surface water. Total water used in the counties supplied by groundwater and surface water was obtained from TWDB (2014m) for the years 1974, 1980, and 1984 through 1999 and from TWDB (2014l) for the years 2000 through 2012. Using these data, the percent of total water use supplied by groundwater by county was calculated for the years 1974, 1980, and 1984 through 2012. These percentages were assumed to apply to the Brazos River Alluvium Aquifer. The percent groundwater calculated for 1974 was assumed for 1950, 1960, and 1970. The percent groundwater for 1981 through 1983 was calculated using linear interpolation between the 1980 and 1984 values.

Using the total county populations, the estimated ratio of the rural population in the Brazos River Alluvium Aquifer boundary to the total county population, the estimated per capita water use, and the estimated percent groundwater use, estimated pumping from the Brazos River Alluvium Aquifer for rural domestic purposes for the years 1950, 1960, 1970, and 1980 through 2012 was calculated using Equation 4.6.1 for each county. Rural domestic pumping for the non-decadal years between 1950 and 1980 was calculated using linear interpolation between the decadal years.

4.6.2.2 Estimation of Brazos River Alluvium Aquifer Specific Historical Pumping Data

As indicated in Section 4.6.1.1.1 and Table 4.6.1, the estimated historical pumping data obtained from Baker and others (1974) for Grimes County and TWDB (2001) for all counties are values for all aquifers combined. Therefore, a methodology was developed to estimate how much of this pumping was from the Brazos River Alluvium Aquifer. Baker and others (1974) state that, in 1970, 21 percent of the total pumping in Grimes County was from the Brazos River Alluvium Aquifer and all of that pumping was for irrigation purposes. It was assumed that this percentage was applicable for all years with pumping data in Baker and others (1974) (i.e., 1958, 1964, 1969, and 1970). Therefore, pumping from the Brazos River Alluvium Aquifer in Grimes County based on data in Baker and others (1974) was estimated as 21 percent of the total pumping estimate they provide.

The irrigation pumping from the Brazos River Alluvium Aquifer was estimated from total county irrigation pumping for all aquifers given in TWDB (2001) using the ratio of Brazos River Alluvium Aquifer irrigation pumping to total county irrigation pumping calculated from the TWDB water use survey data. The ratios for 1980 were used for the years 1958, 1964, 1969, 1974, and 1979, and the ratios for 1984, 1989, 1994, and 2000 were used for those years. If there was no value or a value of zero for Brazos River Alluvium Aquifer irrigation pumping for one of these years in the water use survey data, the ratio for the next closest year with data was used. For example, the water use survey data do not include pumping information for the Brazos River Alluvium Aquifer in Austin, Waller, and Washington counties for 1980 or 1984 through 1999. Therefore, the ratio calculated from the 2000 data was used for the years 1958, 1964, 1969, 1974, 1979, 1984, 1989, and 1994 as well as for 2000.

4.6.2.3 Summary of Historical Pumping Estimates for 1980 through 2012

The historical pumping estimates from the water use survey data provided by the TWDB and calculated from water use survey data (see Section 4.6.2.1.2) were combined with the calculated rural domestic pumping estimates (see Section 4.6.2.1.4) to obtain an estimate of total historical pumping for the time period from 1980 through 2012.

Tables 4.6.4 through 4.6.8 give the estimated totals for municipal, mining, irrigation, livestock, and rural domestic pumping from the Brazos River Alluvium Aquifer, respectively, for the years 1980, 1985, 1990, 1995, 2000, 2005, and 2010. Because the Brazos River Alluvium Aquifer is not pumped for power purposes, a table for that use is not included. Although the Brazos River Alluvium Aquifer was pumped for manufacturing purposes for a few years in two counties (see Table 4.6.2), pumping for this purpose was zero for the years 1980, 1985, 1990, 1995, 2000, 2005, and 2010. Therefore, no table of manufacturing pumping from the Brazos River Alluvium Aquifer is shown.

In general, little groundwater is pumped from the Brazos River Alluvium Aquifer for municipal, mining, and livestock purposes (see Tables 4.6.4, 4.6.5, and 4.6.7, respectively). The majority of groundwater pumped from the Brazos River Alluvium Aquifer is used for irrigation purposes (see Table 4.6.6). Pumping of the aquifer for irrigation purposes increased by over 100,000 acre-feet per year from 1980 to 2010 and is greatest in Robertson, Burleson, and Brazos counties. Use of the Brazos River Alluvium Aquifer for rural domestic purposes (see Table 4.6.8) was greater than that for municipal, mining, and livestock purposes but significantly less than that for irrigation purposes.

Total estimated pumping from the Brazos River Alluvium Aquifer for the years 1980, 1985, 1990, 1995, 2000, 2005, and 2010 is shown in Table 4.6.9. Also included in this table is the percentage of the total pumping that is used for irrigation purposes. This percentage ranges from 89 percent in 1980 to 97 percent in 2005 and 2010.

Stacked bar charts of pumping by use category were developed for all counties for the time period 1980 through 2012. These charts, which are useful for visualizing total pumping trends and trends of pumping for individual use categories, are shown by county (from north to south) in Figures 4.6.3 through 4.6.8. On the charts, a distinction is made between pumping data received from the TWDB and estimated pumping data. The legend for each chart shows the water use categories for groundwater pumped from the Brazos River Alluvium Aquifer in that county. The years on the x-axis for all charts are 1980 to 2012. The scale on the y-axis varies from chart to chart depending on the magnitude of pumping in each county.

For several counties, pumping for irrigation purposes increased significantly in the early 2000s. For most counties, the most significant use of groundwater from the Brazos River Alluvium Aquifer is for irrigation purposes. The exceptions are:

- Grimes County, which has about equal pumping for irrigation and rural domestic purposes.
- Milam County, which has greater livestock pumping than irrigation pumping for the years 1980 through 1992.
- Washington County, which has greater rural domestic pumping than irrigation pumping from 1980 through 1999.

Pumping from the entire Brazos River Alluvium Aquifer by water use category for the years 1980 through 2010 is shown in Figure 4.6.9. This chart shows that the largest use category for groundwater pumped from the Brazos River Alluvium Aquifer is irrigation. Irrigation pumping fluctuated between 20,000 and 60,000 acre-feet per year from 1980 through 2003 and averaged about 38,000 acre-feet per year during this time period. After 2003, irrigation pumping increased significantly and was highest in 2011 with a total of about 160,000 acre-feet that year.

4.6.2.4 Integrated Historical Pumping for 1950 through 2012

Historical pumping estimates were plotted in graphical form as time-series plots in order to present, evaluate, and compare the available data (Figures 4.6.10a through 4.6.21a). For sources with estimates for multiple use types, the sum of pumping for all types was plotted. The plots include the source of the historical estimate and the water use type for the estimate in the legend. For the period from 1980 through 2012, the water use survey data received from the TWDB are combined with the calculated estimates of rural domestic pumping. In addition, data that include estimated values where TWDB water use survey data are missing or anomalous are distinguished from values received from the TWDB. Several abbreviations are used in the plot legend. These abbreviations are:

- RD – rural domestic
- IRR – irrigation
- RD/STK – combined rural domestic and livestock
- TOT – total (i.e., all water uses combined)
- est – estimated
- BVGCD – Brazos Valley Groundwater Conservation District
- POSGCD – Post Oak Savannah Groundwater Conservation District

The historical estimates from these time-series plots were reviewed, and an integrated estimate of total pumping was developed for each county and plotted on a second time-series plot (Figures 4.6.10b through 4.6.21b). The objective for developing the integrated curves was to produce a continuous estimate of pumping for the time period 1950 through 2012. Prior to 1980, the integrated pumping curves were developed by summing historical estimates for different use types, typically irrigation and rural domestic. If a historical estimate for the same use type was available from different sources, the data that appeared most consistent with the 1980 through 2012 data were selected for developing the integrated curve. The integrated curves provide an estimate of historical pumping from the Brazos River Alluvium Aquifer by county for the time period from 1950 through 2012.

For both sets of time-series plots, the year scale on the x-axis is from 1950 through 2013. The pumping scale on the y-axis varies from county to county based on the magnitude of the pumping estimates for that county. In McLennan, Milam, Robertson, and Brazos counties, pumping of the Brazos River Alluvium Aquifer since about 2000 or 2010 has been significantly greater than pumping prior to that time. In Falls, Burleson, Grimes, Waller, and Austin counties, historical pumping since about the mid-1960s or mid-1970s has varied throughout the years but does not show any long-term increasing or decreasing trend. Maximum historical pumping occurred in 2010, 2011, or 2012 in Hill, McLennan, Falls, Milam, Robertson, Burleson, and Brazos counties; in the 1980s in Grimes and Waller counties; in the 1990s in Austin and Fort Bend counties; and in 2000 in Washington County. A peak in historical pumping during the time period from 1950 to 2000 occurred in the 1960s in Falls, Robertson, Burleson, Brazos, Washington counties.

A bar chart of total pumping from the Brazos River Alluvium Aquifer from 1950 through 2012 is shown in Figure 4.6.22. Pumping of the aquifer increased from 1950 to the late 1960s and then declined until approximately 1979. From 1980 through about 2004, pumping of the aquifer was fairly stable with a few years of increased pumping. A significant increase in pumping occurred between 2004 and 2005 and pumping, in general, has increased since that time. Maximum pumping of the aquifer occurred in 2011.

Total estimates of pumping from the Brazos River Alluvium Aquifer by county in 1960, 1980, 2000, and 2012 are shown in Figures 4.6.23 through 4.6.26, respectively. The scale in the legend is the same for all four figures so that they can be easily compared. In each figure, the actual pumping in acre-feet per year is posted for each county. Pumping was greatest in Robertson, Burleson, and Brazos counties for all four years. These three counties also had the greatest increase in pumping from 1960 to 2012.

4.6.2.5 Comparison of Integrated Pumping Curves and Long-Term Water-Level Trends

In Section 4.2.3.2, transient water-level data were used to develop a county-wide, long-term water-level trend for counties with sufficient data. Those trends were compared to the integrated pumping curves by county to evaluate the consistency between water-level trends and historical pumping estimates. These comparisons are shown for Falls and McLennan counties in Figure 4.6.27, for Robertson and Burleson counties in Figure 4.6.28, and for Brazos and Grimes counties in Figure 4.6.29.

Except for recent years, there seems to be little correlation between the integrated pumping curve and the long-term water-level trend for McLennan County (see Figure 4.6.27a). The low in the water levels in the 1960s is not associated with a period of relatively higher pumping rates. In addition, the higher pumping rates in the 1980s and the significant increase in pumping from about 2008 to 2011 do not have correspondingly low water levels. The data for Falls County show a correlation between the integrated pumping curve and the long-term water-level trend (see Figure 4.6.27b). The higher pumping in the 1960s, 1980s, and late 2000s/early 2010s corresponds to relatively lower water levels, and the lower pumping in the 1970s and 1990s/early 2000s corresponds to relatively higher water levels.

The integrated pumping curve and long-term water-level trend for Robertson County are consistent during some time periods and inconsistent during others (see Figure 4.6.28a). On one hand, the higher pumping rates in the mid-1960s appear to correspond to relatively lower water levels in the late 1960s and the higher pumping rates in the 2010s correspond to relatively lower water levels. On the other hand, the increase in water levels in the late 1970s/early 1980s does not correspond to a decrease in pumping, and the decrease in water levels in the 1990s does not correspond to an increase in pumping. The relatively higher water levels in the mid-2000s are inconsistent with the significant increase in pumping during the early 2000s. A correlation between estimated pumping and long-term water-level trends is observed in the time period from about the mid-1960s to early 1980s and late 2000s/early 2010s for Burleson County (see Figure 4.6.28b). However, the water-level decline centered on the early 1990s and the water level rise centered on the mid-2000s are inconsistent with the estimated pumping.

In Brazos County, the relative water-level decline centered on 1970 and the recent decline starting in the late 2000s correspond to increases in historical pumping (see Figure 4.6.29a). In addition, the early portion of the water-level rise starting in about 1970 appears to be related to a corresponding decrease in pumping. However, the later part of this rise is inconsistent with the estimated increase in pumping, and the large rise in water levels centered in the mid/late 2000s is inconsistent with the increase in pumping starting in about 2002. In Grimes County, the water level fluctuations in the 1960s, 1970s, 2000s, and 2010s appear to be consistent with the historical pumping estimates (see Figure 4.6.29b). However, the relatively low water levels centered on 1990 are inconsistent with the estimated decrease in pumping during this time.

Table 4.6.1 Summary of historical pumping sources.

Source	Data Location	Data Period of Record	Aquifer(s)	Use
Baker and others (1974)	Grimes County	1958, 1964, 1969-1970	all aquifers combined	Municipal, Irrigation, Rural Domestic/Livestock
Brazos Valley GCD (2014b)	Robertson and Brazos counties	2011-2013	Brazos River Alluvium Aquifer	Irrigation
Cronin and Wilson (1967)	all counties of interest	1963, 1964	Brazos River Alluvium Aquifer	Irrigation
Follett (1974)	Brazos and Burleson counties	1958, 1964, 1969	Brazos River Alluvium Aquifer	Irrigation
Post Oak Savannah GCD (2014a)(1)	Burleson and Milam counties	2005-2013	Brazos River Alluvium Aquifer	all
TWDB (2001)	all counties of interest	1958, 1964, 1969, 1974, 1979, 1984, 1989, 1994, 2000	all aquifers combined	Irrigation
TWDB (2014i)	all counties of interest	1980, 1984-2012	Brazos River Alluvium Aquifer	Municipal, Manufacturing, Power, Mining, Irrigation, Livestock
Wilson (1967)	Austin and Waller counties	1965	Brazos River Alluvium Aquifer	Irrigation, Rural Domestic/Livestock combined
Current Report	all counties of interest	1950-1012	Brazos River Alluvium Aquifer	Rural Domestic

(1) consists of partial pumping data only
GCD = groundwater conservation district

Table 4.6.2 Summary of water use survey data for the Brazos River Alluvium Aquifer.

County	Municipal		Manufacturing		Mining		Power		Irrigation		Livestock	
	1	2	1	2	1	2	1	2	1	2	1	2
Austin		x$^{2006-2012}$								x		x
Brazos			x$^{1996-1997}$		x^{1980}	x$^{2000-2001}$			x	x		
Burleson									x$^{1996\ missing}$	x		
Falls	x$^{1980,1984-1993}$	x$^{2006-2012}$			x				x	x	x	x
Fort Bend									x			
Grimes		x$^{2006-2012}$							x$^{1980,1984-1993}$	x		x
Hill		x$^{2006-2012}$							x			
McLennan		x$^{2006-2012}$		x$^{2011-2012}$					x	x		x
Milam	x								x	x$^{2000-2003}$	x	x$^{2000-2003}$
Robertson	x$^{1980,1984-1993}$	x$^{2006-2012}$							x$^{1980,1984-1993}$	x	x	x
Waller		x$^{2006-2012}$								x		x
Washington										x		x

1 = 1980 and 1984 through 1999 data set
2 = 2000 through 2012 data set
x = data set includes values for all years
x*** = data set includes, or is missing, values for year(s) indicated by the *** superscript

Table 4.6.3 Reasons for estimating some pumping from the TWDB water use survey data.

County	Brazos River Alluvium Aquifer Pumping in the TWDB Water Use Survey Data		Years Estimated	Use Estimated	Reason Estimated
	1980, 1984-1999 Data Set	2000-2012 Data Set			
All Counties	no	no	1981-1983	various	The water use survey data received from the TWDB do not include pumping estimates for 1981-1983, therefore, pumping for those years was estimated for water use categories with non-zero pumping in 1980 and 1984.
Austin	no	yes	1980-1999	Irrigation, Livestock	The water use survey data received from the TWDB have no pumping from the Brazos River Alluvium Aquifer in 1980 and 1984-1999 but do have irrigation and livestock pumping from the Brazos River Alluvium Aquifer in 2000-2012. A review of wells in Austin County indicated irrigation and livestock wells in the Brazos River Alluvium Aquifer drilled prior to 1980. Therefore, assumed that the Brazos River Alluvium Aquifer was used as a source of irrigation and livestock water for 1980-1999 and estimated values for those years.
Burleson	yes	yes	1981-1983 and 1996-1997	Irrigation	The water use survey data received from the TWDB do not include irrigation pumping from the Brazos River Alluvium Aquifer in 1996, and the value given for 1997 is anomalous. Therefore, values for both of those years were estimated.
Fort Bend	yes	no	1981-1983 and 2000-2012	Irrigation	The water use survey data received from the TWDB have no pumping from the Brazos River Alluvium Aquifer in 2000-2012 but do have irrigation pumping from the Brazos River Alluvium Aquifer in 1980 and 1984-1999. Assumed that irrigation pumping from the Brazos River Alluvium Aquifer continued after 1999 and estimated values for 2000-2012.
Grimes	yes	yes	1981-1983 and 1994-1999	Irrigation	The water use survey data received from the TWDB do not include irrigation pumping from the Brazos River Alluvium Aquifer in 1994-1999 but do include it for 1980, 1984-1993, and 2000-2012. Therefore, assumed that the Brazos River Alluvium Aquifer was pumped for irrigation purposes in 1994-1999 and estimated values for those years.
			1980-1999	Livestock	The water use survey data received from the TWDB have no livestock pumping from the Brazos River Alluvium Aquifer in 1980 and 1984-1999 but do include livestock pumping from the Brazos River Alluvium Aquifer in 2000-2012. A review of wells in Grimes County indicated livestock wells in the Brazos River Alluvium Aquifer drilled prior to 2000. Therefore, assumed that the Brazos River Alluvium Aquifer was used as a source of livestock water for 1980-1999 and estimated values for those years.

Table 4.6.3, continued

County	Brazos River Alluvium Aquifer Pumping in the TWDB Water Use Survey Data		Years Estimated	Use Estimated	Reason Estimated
	1980, 1984-1999 Data Set	2000-2012 Data Set			
Hill	yes	yes	1981-1983 and 2000-2012	Irrigation	The water use survey data received from the TWDB have no pumping from the Brazos River Alluvium Aquifer in 2000-2012 but irrigation pumping from the Brazos River Alluvium Aquifer in 1980 and 1984-1999. Assumed that irrigation pumping from the Brazos River Alluvium Aquifer continued after 1999 and estimated values for 2000-2012.
McLennan	no	yes	1980-1999	Livestock	The water use survey data received from the TWDB have no livestock pumping from the Brazos River Alluvium Aquifer in 1980 and 1984-1999 but do have livestock pumping from the Brazos River Alluvium Aquifer in 2000-2012. A review of wells in McLennan County indicated livestock wells in the Brazos River Alluvium Aquifer drilled prior to 1980. Therefore, assumed that the Brazos River Alluvium Aquifer was used as a source of livestock water for 1980-1999 and estimated values for those years.
Milam	yes	yes	2004-2012	Irrigation, Livestock	The water use survey data received from the TWDB have no irrigation or livestock pumping from the Brazos River Alluvium Aquifer in 2004-2012 but irrigation and livestock pumping from the Brazos River Alluvium Aquifer in 1980 and 1984-2003. Assumed that irrigation and livestock pumping from the Brazos River Alluvium Aquifer continued after 2003 and estimated values for 2004-2012.
Robertson	yes	yes	1981-1983 and 1994-1999	Irrigation	The water use survey data received from the TWDB have non-zero irrigation pumping for 1980, 1984-1993, and 2000-2012 but say that irrigation pumping for 1994-1999 was zero. These zero values were considered to be anomalous, so irrigation pumping for 1994-1999 was estimated.
Waller	no	yes	1980-1999	Irrigation, Livestock	The water use survey data received from the TWDB have no pumping from the Brazos River Alluvium Aquifer in 1980 and 1984-1999 but irrigation and livestock pumping from the Brazos River Alluvium Aquifer in 2000-2012. A review of wells in Waller County indicated irrigation and livestock wells in the Brazos River Alluvium Aquifer drilled prior to 1980. Therefore, assumed that the Brazos River Alluvium Aquifer was used as a source of irrigation and livestock water for 1980-1999 and estimated values for those years.

Table 4.6.3, continued

County	Brazos River Alluvium Aquifer Pumping in the TWDB Water Use Survey Data		Years Estimated	Use Estimated	Reason Estimated
	1980, 1984-1999 Data Set	2000-2012 Data Set			
Washington	no	yes	1980-1999	Irrigation, Livestock	The water use survey data received from the TWDB have no pumping from the Brazos River Alluvium Aquifer in 1980 and 1984-1999 but do have irrigation and livestock pumping from the Brazos River Alluvium Aquifer in 2000-2012. A review of wells in Washington County indicated irrigation and livestock wells in the Brazos River Alluvium Aquifer drilled prior to 1980. Therefore, assumed that the Brazos River Alluvium Aquifer was used as a source of irrigation and livestock water for 1980-1999 and estimated values for those years.

Table 4.6.4 Summary of municipal pumping in acre-feet from the Brazos River Alluvium Aquifer by county for the years 1980, 1985, 1990, 1995, 2000, 2005, and 2010.

County	1980	1985	1990	1995	2000	2005	2010
Austin	0	0	0	0	0	0	29
Brazos	0	0	0	0	0	0	0
Burleson	0	0	0	0	0	0	0
Falls	164	113	108	0	0	0	434
Fort Bend	0	0	0	0	0	0	0
Grimes	0	0	0	0	0	0	2
Hill	0	0	0	0	0	0	109
McLennan	0	0	0	0	0	0	668
Milam	11	4	5	3	0	0	0
Robertson	3	2	3	0	0	0	7
Waller	0	0	0	0	0	0	19
Washington	0	0	0	0	0	0	0
Municipal Total	***178***	***119***	***116***	***3***	***0***	***0***	***1,268***

Table 4.6.5 Summary of mining pumping in acre-feet from the Brazos River Alluvium Aquifer by county for the years 1980, 1985, 1990, 1995, 2000, 2005, and 2010.

County	1980	1985	1990	1995	2000	2005	2010
Austin	0	0	0	0	0	0	0
Brazos	1,100	0	0	0	10	0	0
Burleson	0	0	0	0	0	0	0
Falls	0	61	55	133	0	0	0
Fort Bend	0	0	0	0	0	0	0
Grimes	0	0	0	0	0	0	0
Hill	0	0	0	0	0	0	0
McLennan	0	0	0	0	0	0	0
Milam	0	0	0	0	0	0	0
Robertson	0	0	0	0	0	0	0
Waller	0	0	0	0	0	0	0
Washington	0	0	0	0	0	0	0
Mining Total	***1,100***	***61***	***55***	***133***	***10***	***0***	***0***

Table 4.6.6 Summary of irrigation pumping in acre-feet from the Brazos River Alluvium Aquifer by county for the years 1980, 1985, 1990, 1995, 2000, 2005, and 2010.

County	1980	1985	1990	1995	2000	2005	2010
Austin	1,059	772	1,021	834	965	686	422
Brazos	2,970	6,440	7,821	10,388	5,293	26,651	29,771
Burleson	5,544	6,096	6,490	13,981	14,134	16,243	17,851
Falls	3,000	2,295	4,819	4,131	1,704	2,561	6,261
Fort Bend	3,229	2,054	3,023	10,775	8,778	4,498	5,404
Grimes	140	112	19	113	46	22	15
Hill	300	217	54	126	43	108	181
McLennan	750	1,748	737	983	350	1,158	737
Milam	0	9	17	53	56	339	137
Robertson	15,300	14,746	16,258	12,680	13,720	56,866	72,523
Waller	879	1,087	892	634	750	710	742
Washington	27	18	37	17	238	82	55
Irrigation Total	***33,198***	***35,594***	***41,188***	***54,715***	***46,077***	***109,925***	***134,099***

Table 4.6.7 Summary of livestock pumping in acre-feet from the Brazos River Alluvium Aquifer by county for the years 1980, 1985, 1990, 1995, 2000, 2005, and 2010.

County	1980	1985	1990	1995	2000	2005	2010
Austin	11	9	7	9	6	23	14
Brazos	0	0	0	0	0	0	0
Burleson	0	0	0	0	0	0	0
Falls	85	105	82	82	58	268	292
Fort Bend	0	0	0	0	0	0	0
Grimes	77	71	72	84	50	49	55
Hill	0	0	0	0	0	0	0
McLennan	229	91	105	145	41	195	175
Milam	20	24	22	23	20	17	17
Robertson	39	47	38	53	36	69	97
Waller	61	77	74	77	58	70	65
Washington	16	13	12	11	12	14	12
Livestock Total	***538***	***436***	***413***	***484***	***281***	***705***	***727***

Table 4.6.8 Summary of rural domestic pumping in acre-feet from the Brazos River Alluvium Aquifer by county for the years 1980, 1985, 1990, 1995, 2000, 2005, and 2010.

County	1980	1985	1990	1995	2000	2005	2010
Austin	99	107	108	132	148	205	247
Brazos	208	266	243	262	297	301	324
Burleson	231	292	271	296	264	240	210
Falls	107	105	136	126	104	136	204
Fort Bend	753	1,080	1,361	1,503	1,462	856	779
Grimes	187	111	81	149	89	177	94
Hill	20	17	15	16	20	22	23
McLennan	90	127	115	144	208	209	258
Milam	5	3	12	17	18	24	15
Robertson	217	245	232	223	222	207	175
Waller	139	157	164	194	277	335	419
Washington	27	35	37	38	47	39	47
Rural Domestic Total	***2,083***	***2,546***	***2,776***	***3,099***	***3,156***	***2,751***	***2,795***

Table 4.6.9 Summary of total pumping in acre-feet from the Brazos River Alluvium Aquifer by county for the years 1980, 1985, 1990, 1995, 2000, 2005, and 2010.

County	1980	1985	1990	1995	2000	2005	2010
Austin	1,169	888	1,137	976	1,119	914	712
Brazos	4,278	6,706	8,064	10,650	5,600	26,952	30,095
Burleson	5,775	6,388	6,761	14,277	14,398	16,483	18,061
Falls	3,356	2,679	5,200	4,472	1,866	2,965	7,191
Fort Bend	3,982	3,134	4,384	12,278	10,240	5,354	6,183
Grimes	404	294	172	346	185	248	166
Hill	320	234	69	142	63	130	313
McLennan	1,068	1,966	957	1,273	599	1,562	1,838
Milam	36	40	56	96	94	380	170
Robertson	15,559	15,040	16,531	12,956	13,978	57,142	72,802
Waller	1,080	1,320	1,130	904	1,085	1,115	1,245
Washington	71	66	86	66	297	135	114
Aquifer Total	***37,097***	***38,756***	***44,548***	***58,434***	***49,524***	***113,380***	***138,890***
Percentage of Total Pumping Used for Irrigation Purposes	0.89	0.92	0.92	0.94	0.93	0.97	0.97

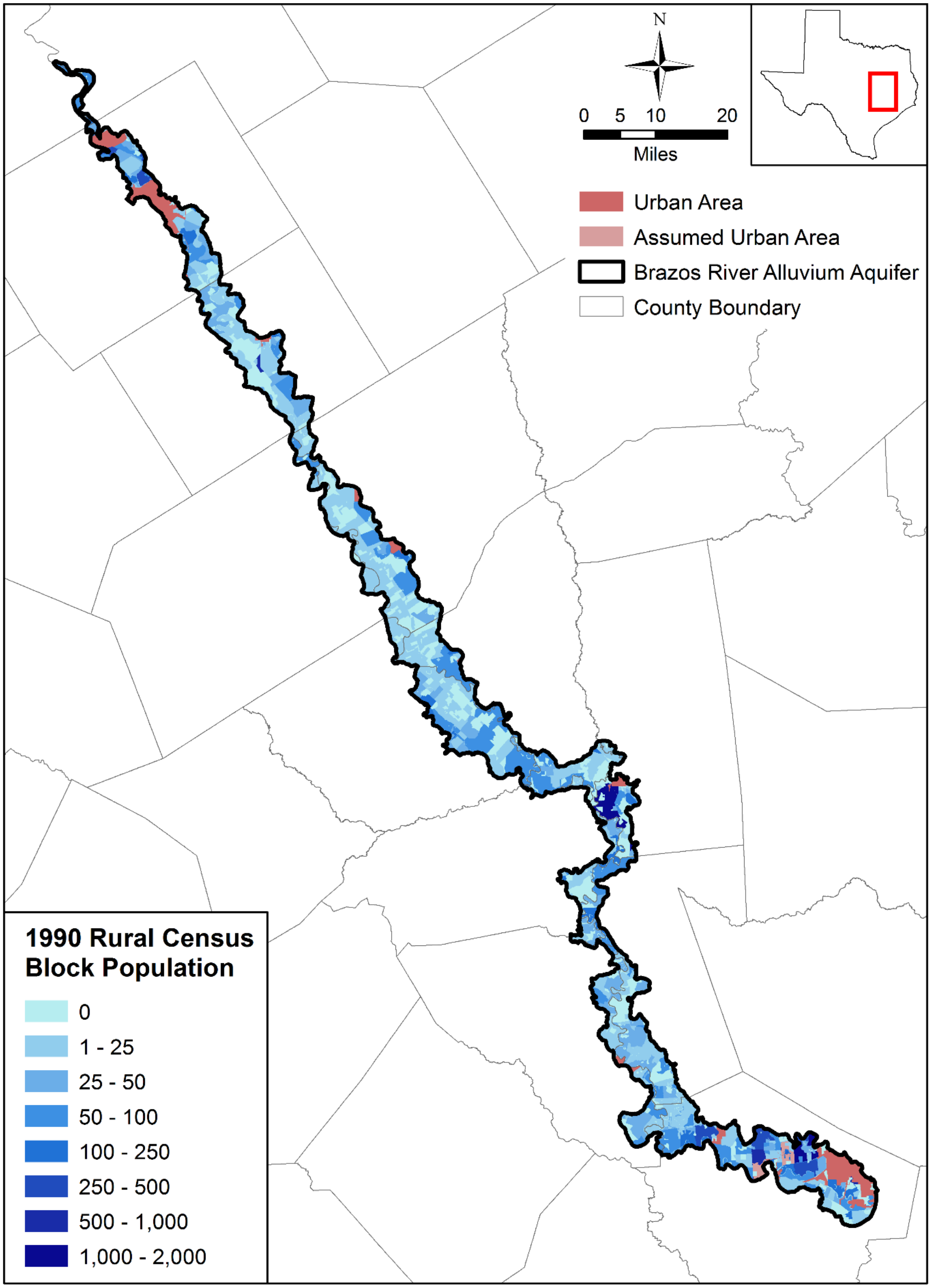


Figure 4.6.1 Rural population in the Brazos River Alluvium Aquifer boundary based on 1990 census block data.

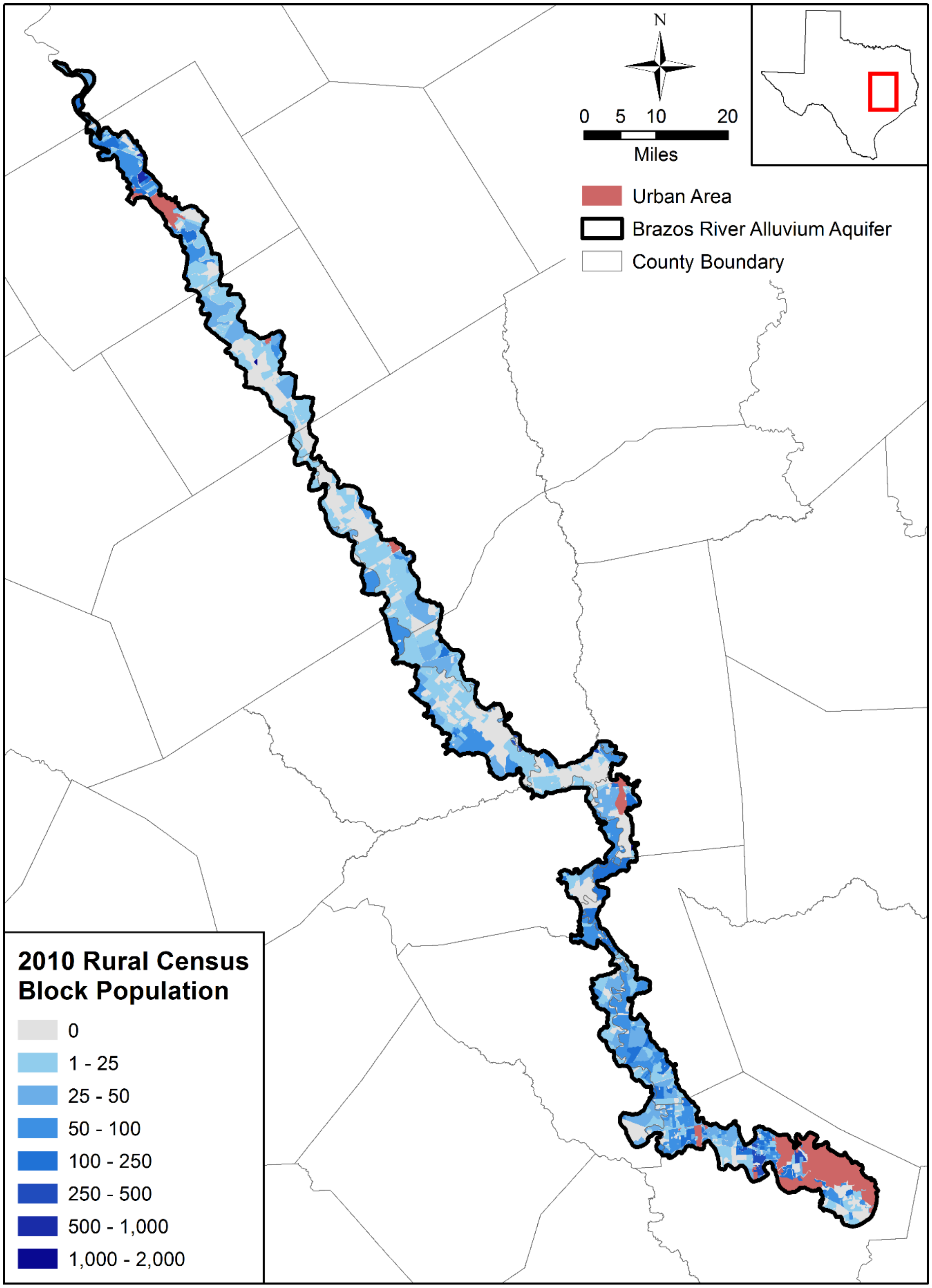
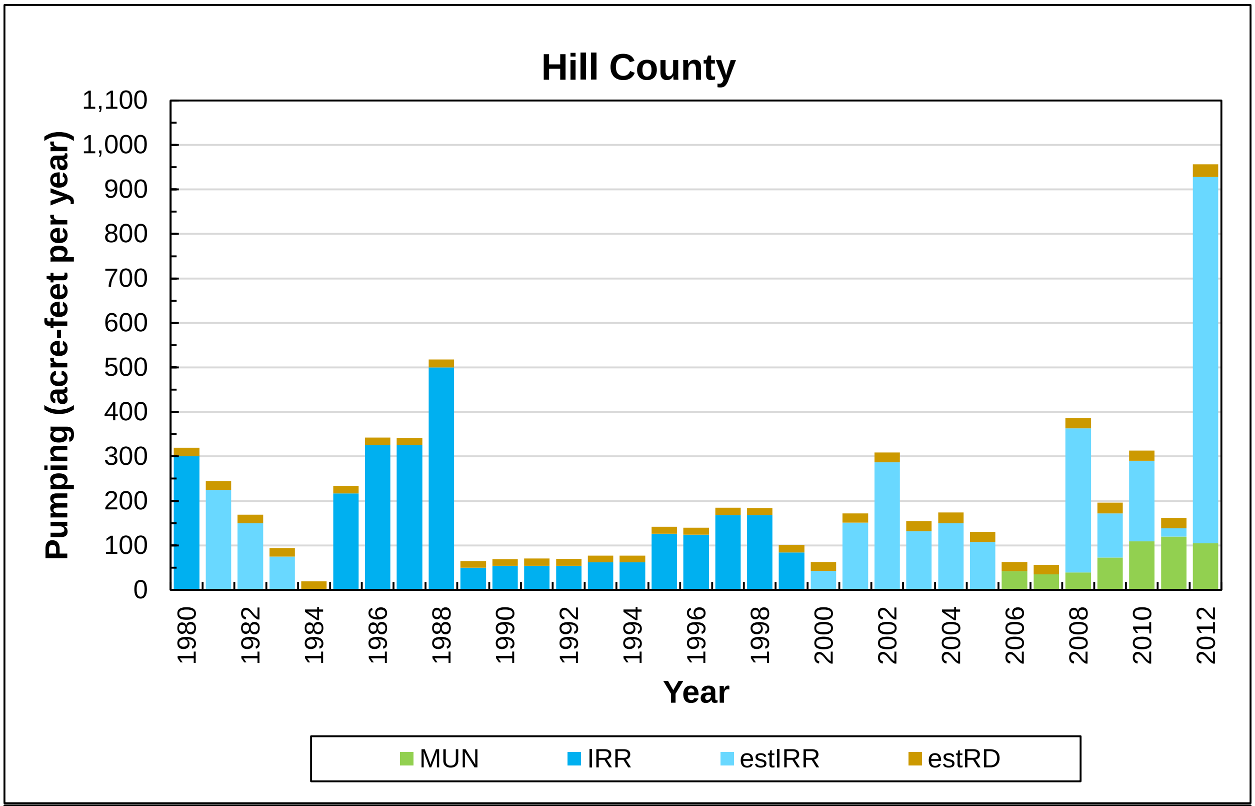


Figure 4.6.2 Rural population in the Brazos River Alluvium Aquifer boundary based on 2010 census block data.

(a)



(b)

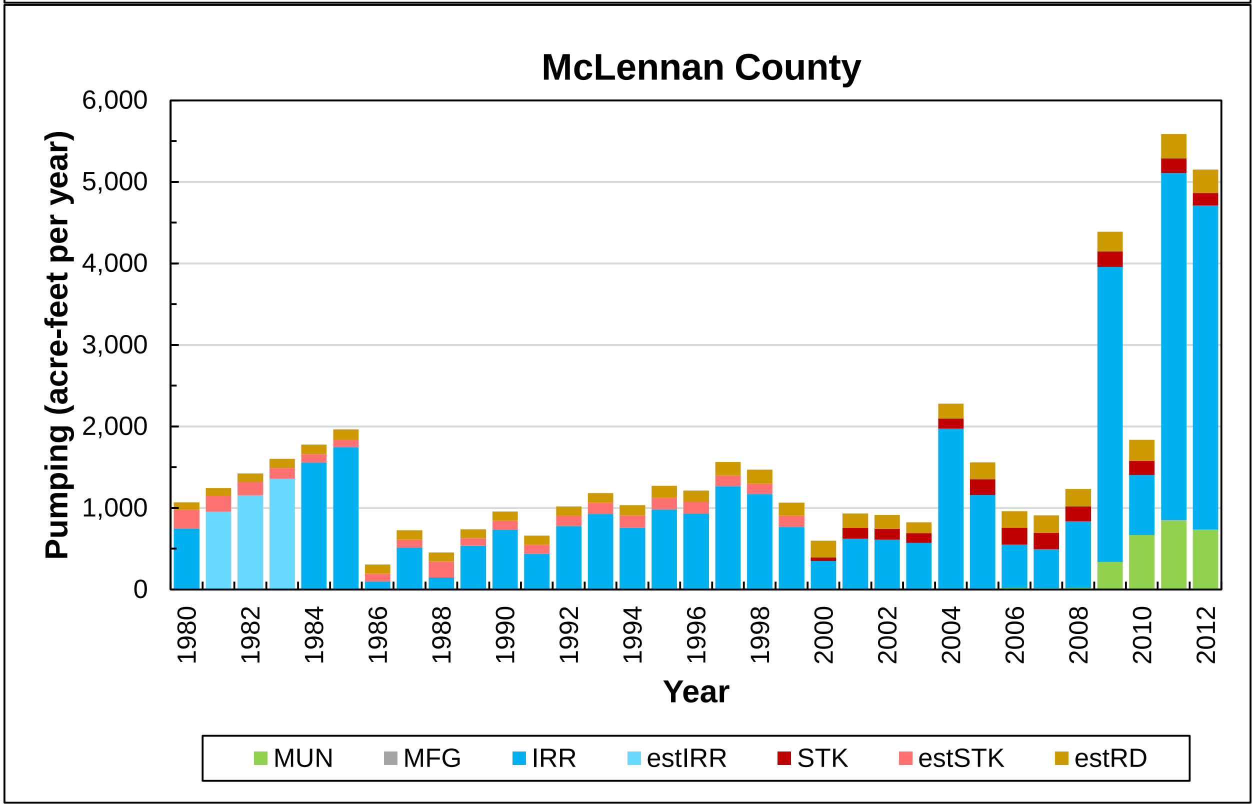


Figure 4.6.3 Bar chart of pumping from the Brazos River Alluvium Aquifer by use category from 1980 through 2012 for (a) Hill and (b) McLennan counties.

(a)

(b)

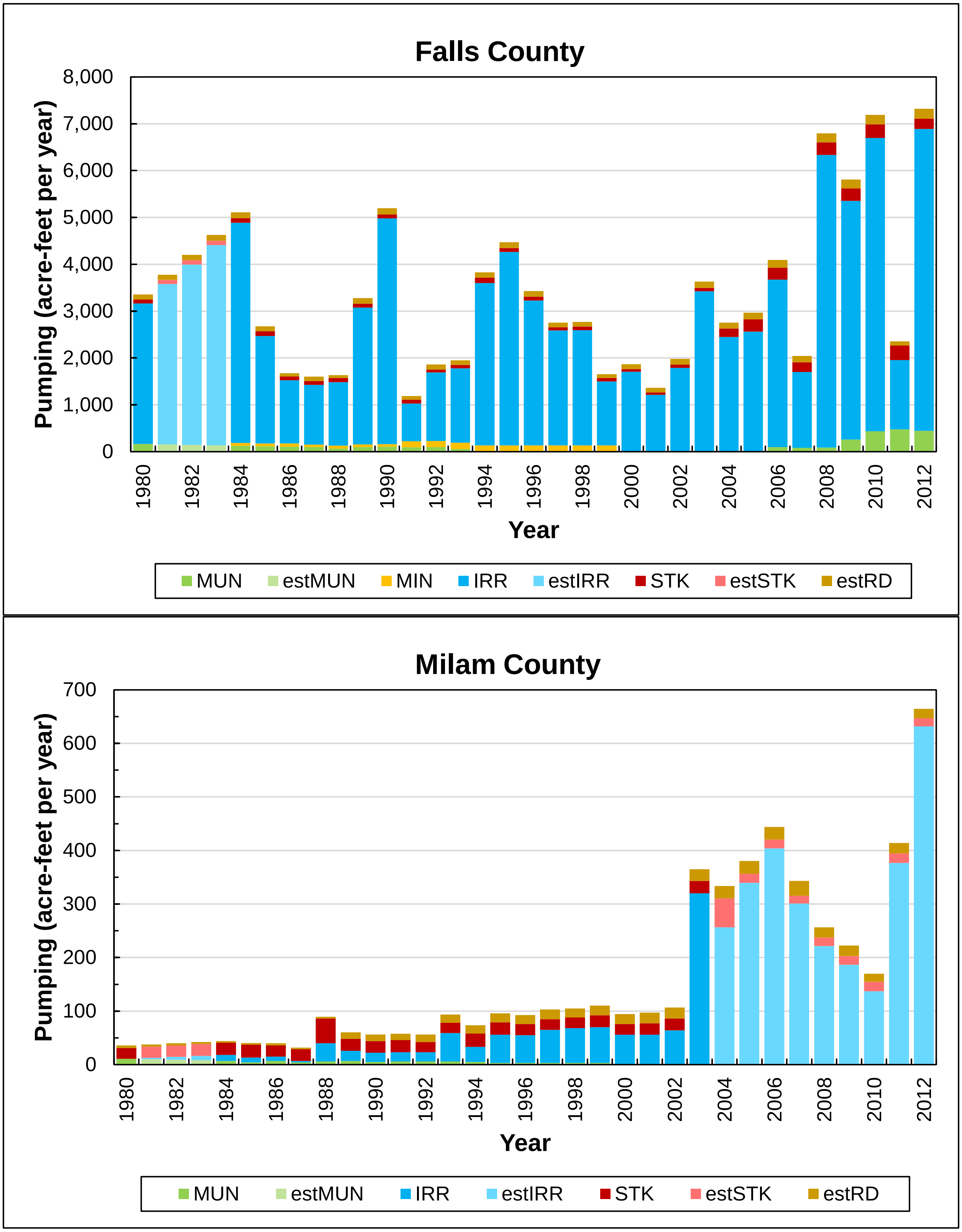
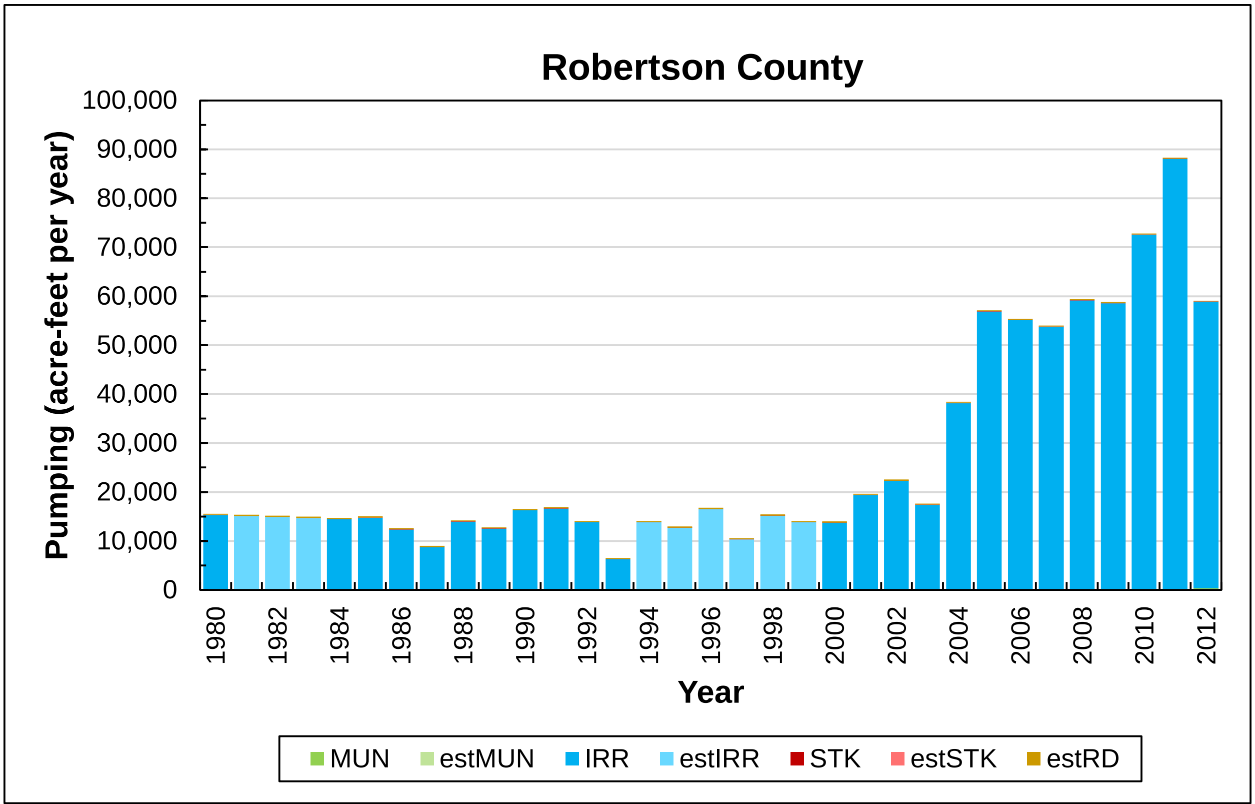


Figure 4.6.4 Bar chart of pumping from the Brazos River Alluvium Aquifer by use category from 1980 through 2012 for (a) Falls and (b) Milam counties.

(a)



(b)

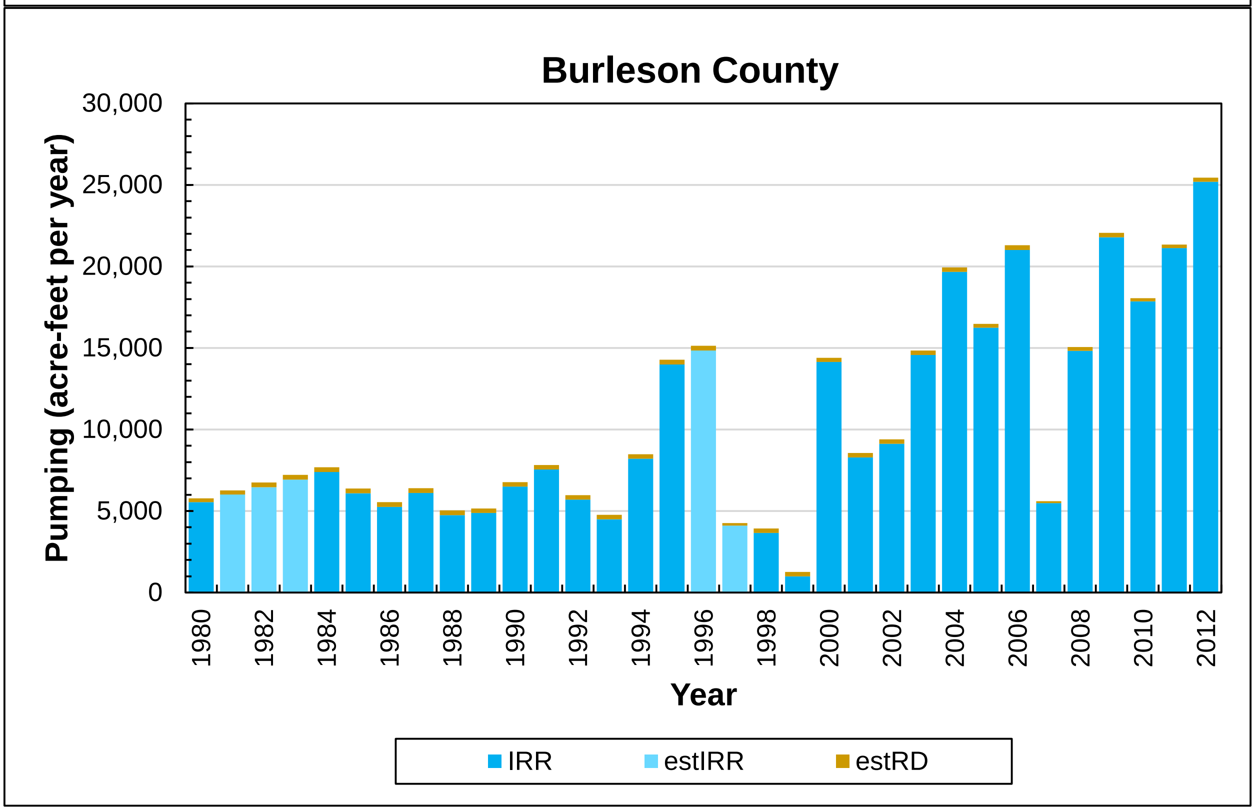


Figure 4.6.5 Bar chart of pumping from the Brazos River Alluvium Aquifer by use category from 1980 through 2012 for (a) Robertson and (b) Burleson counties.

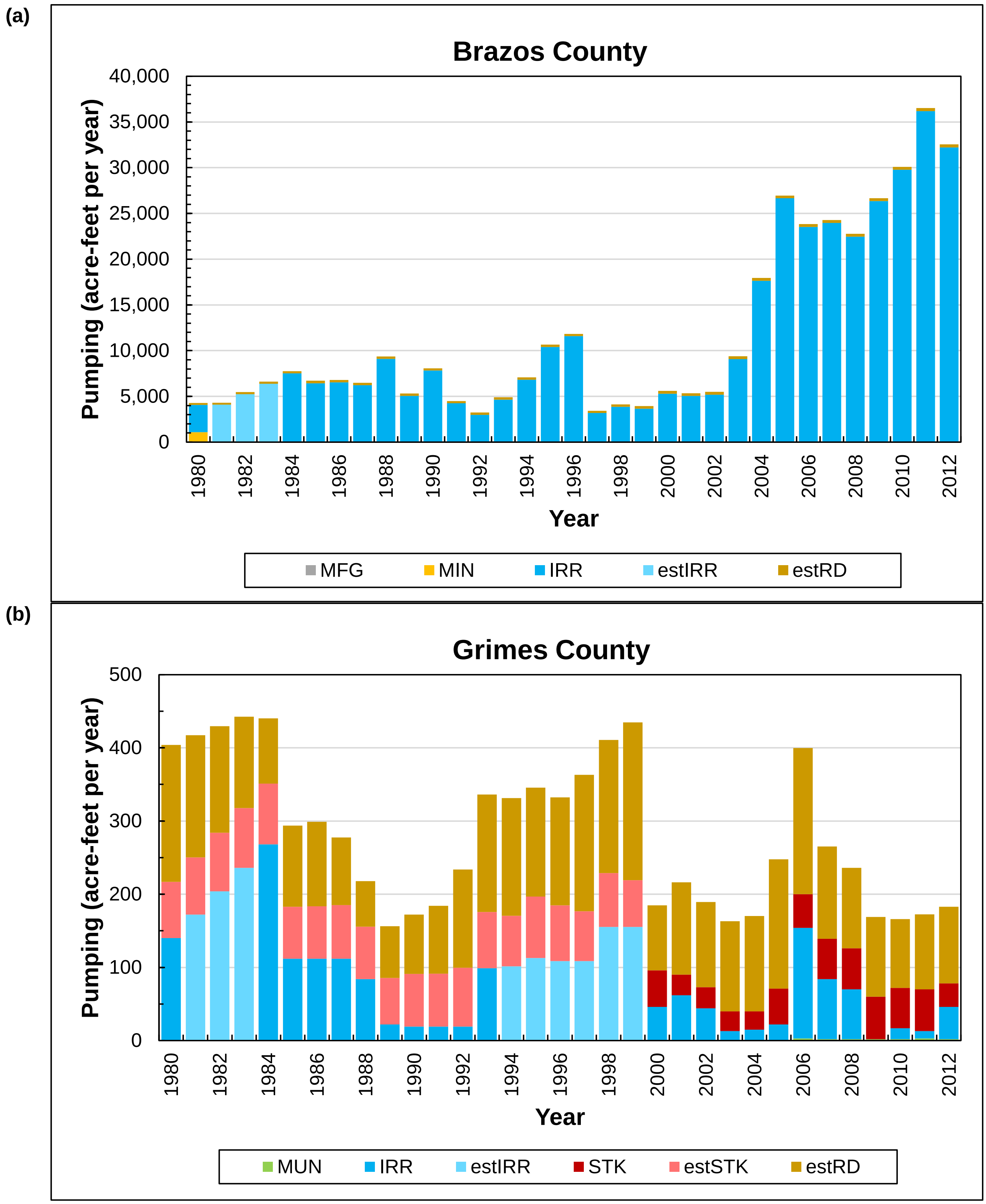
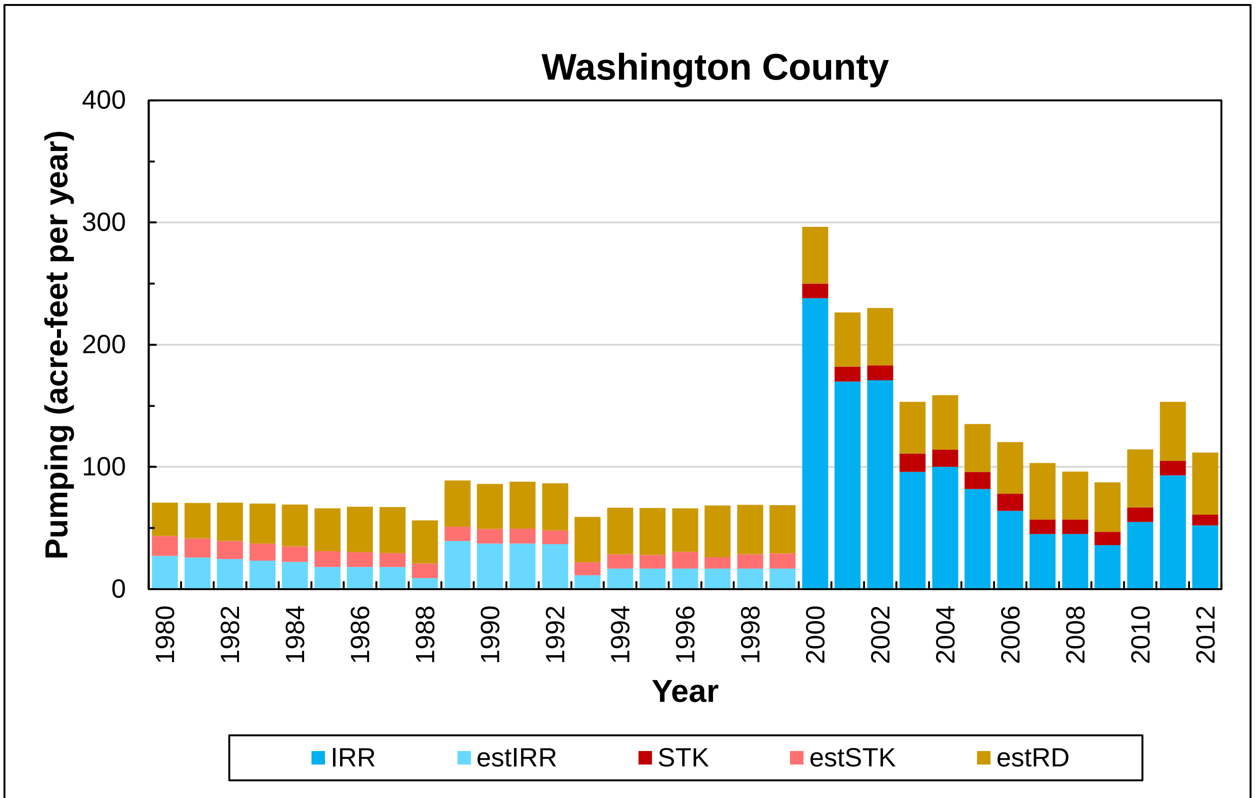


Figure 4.6.6 Bar chart of pumping from the Brazos River Alluvium Aquifer by use category from 1980 through 2012 for (a) Brazos and (b) Grimes counties.

(a)



(b)

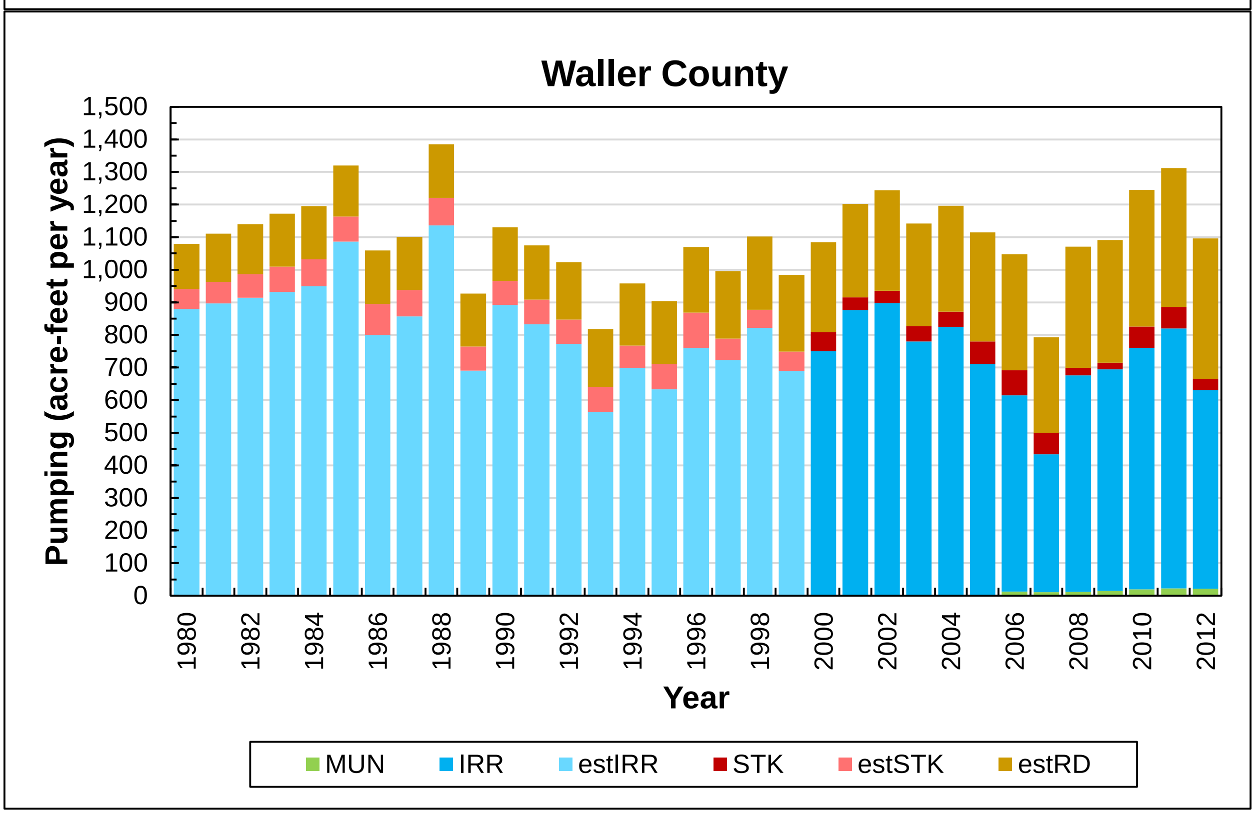
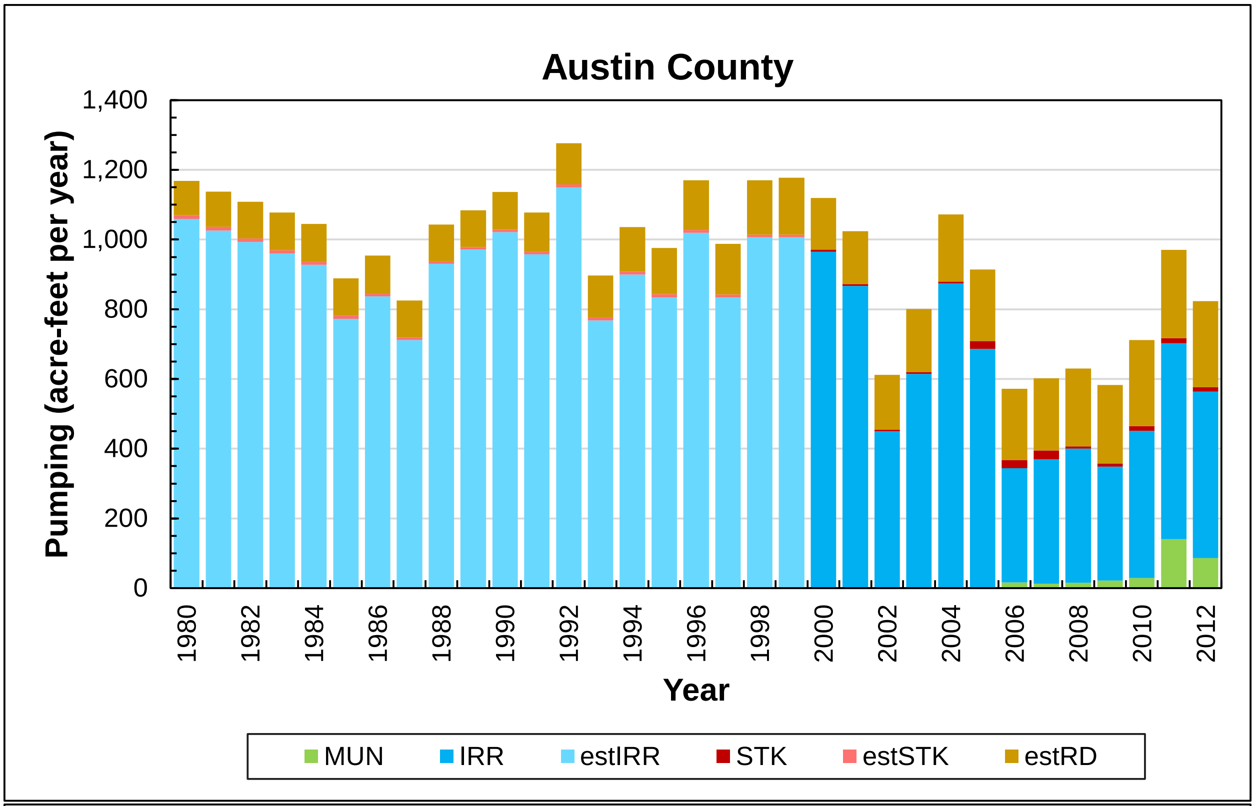


Figure 4.6.7 Bar chart of pumping from the Brazos River Alluvium Aquifer by use category from 1980 through 2012 for (a) Washington and (b) Waller counties.

(a)



(b)

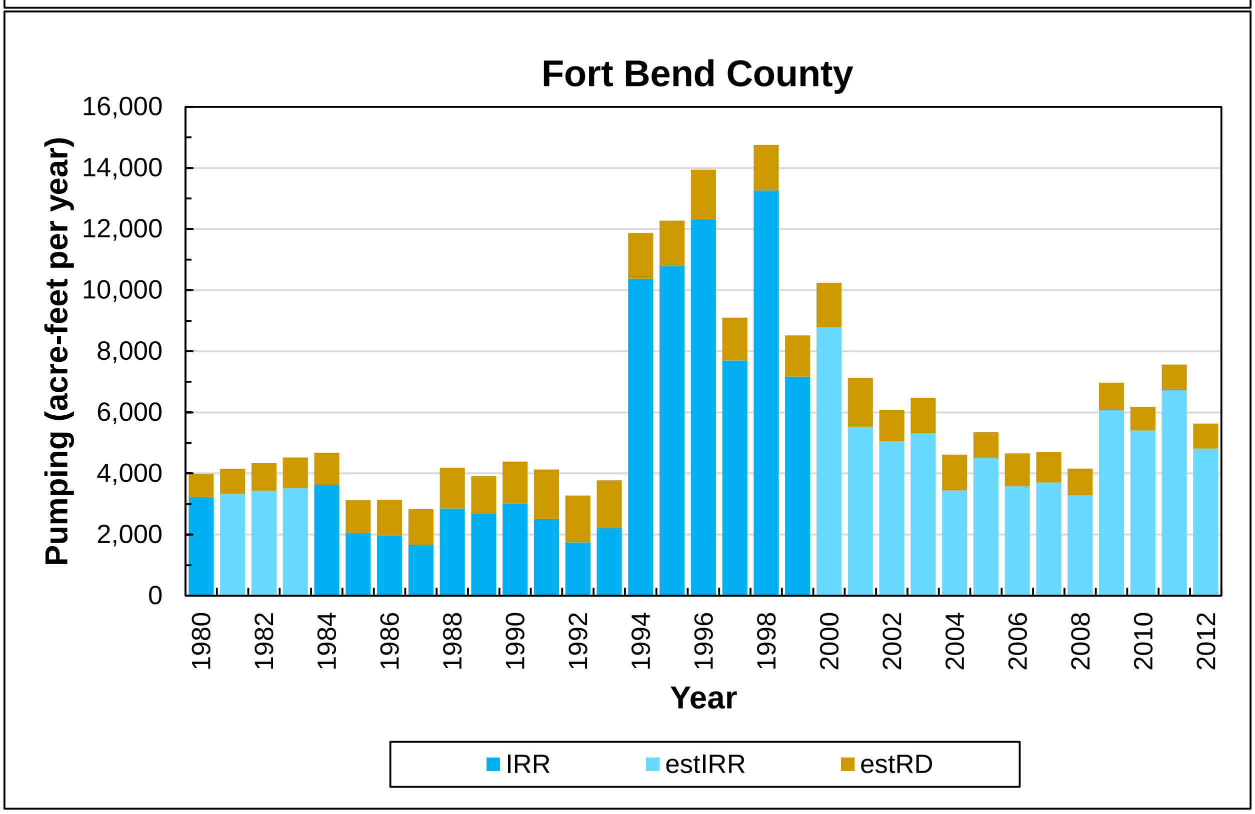


Figure 4.6.8 Bar chart of pumping from the Brazos River Alluvium Aquifer by use category from 1980 through 2012 for (a) Austin and (b) Fort Bend counties.

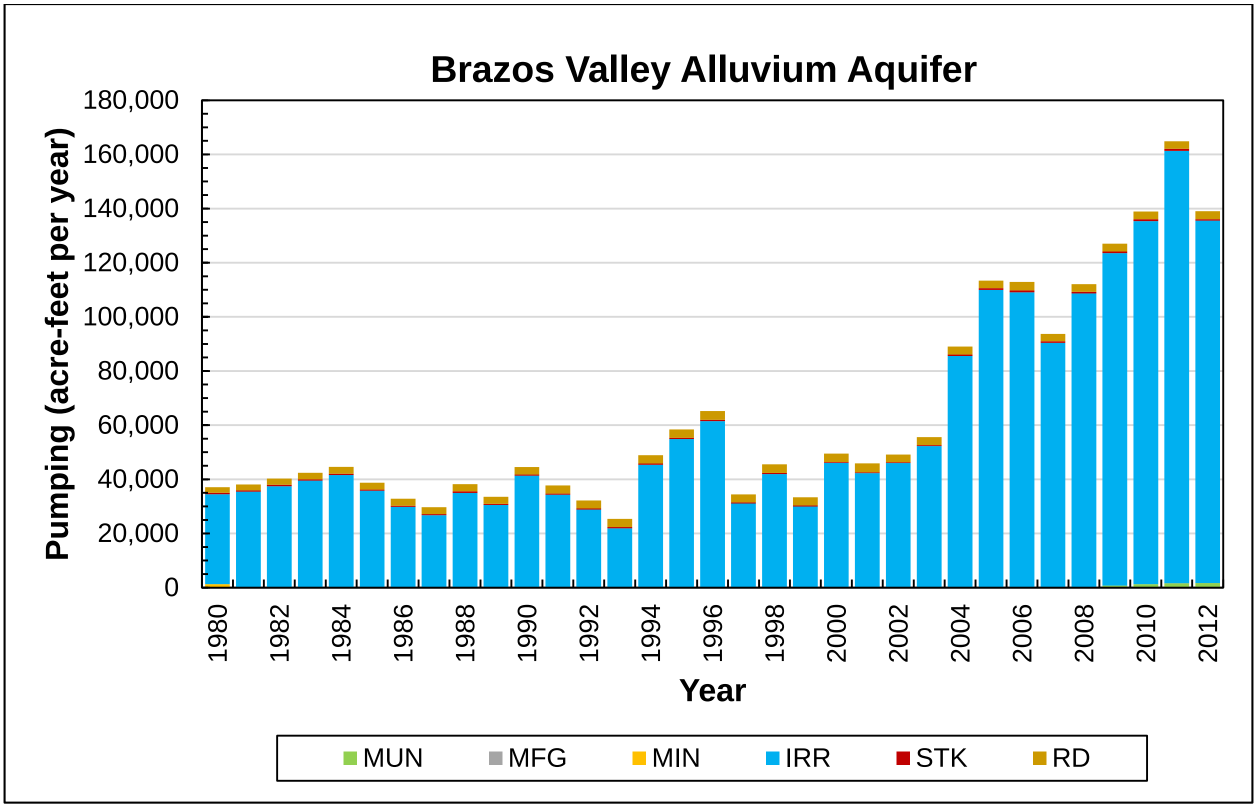


Figure 4.6.9 Bar chart of pumping from the entire Brazos River Alluvium Aquifer by use category from 1980 through 2012.

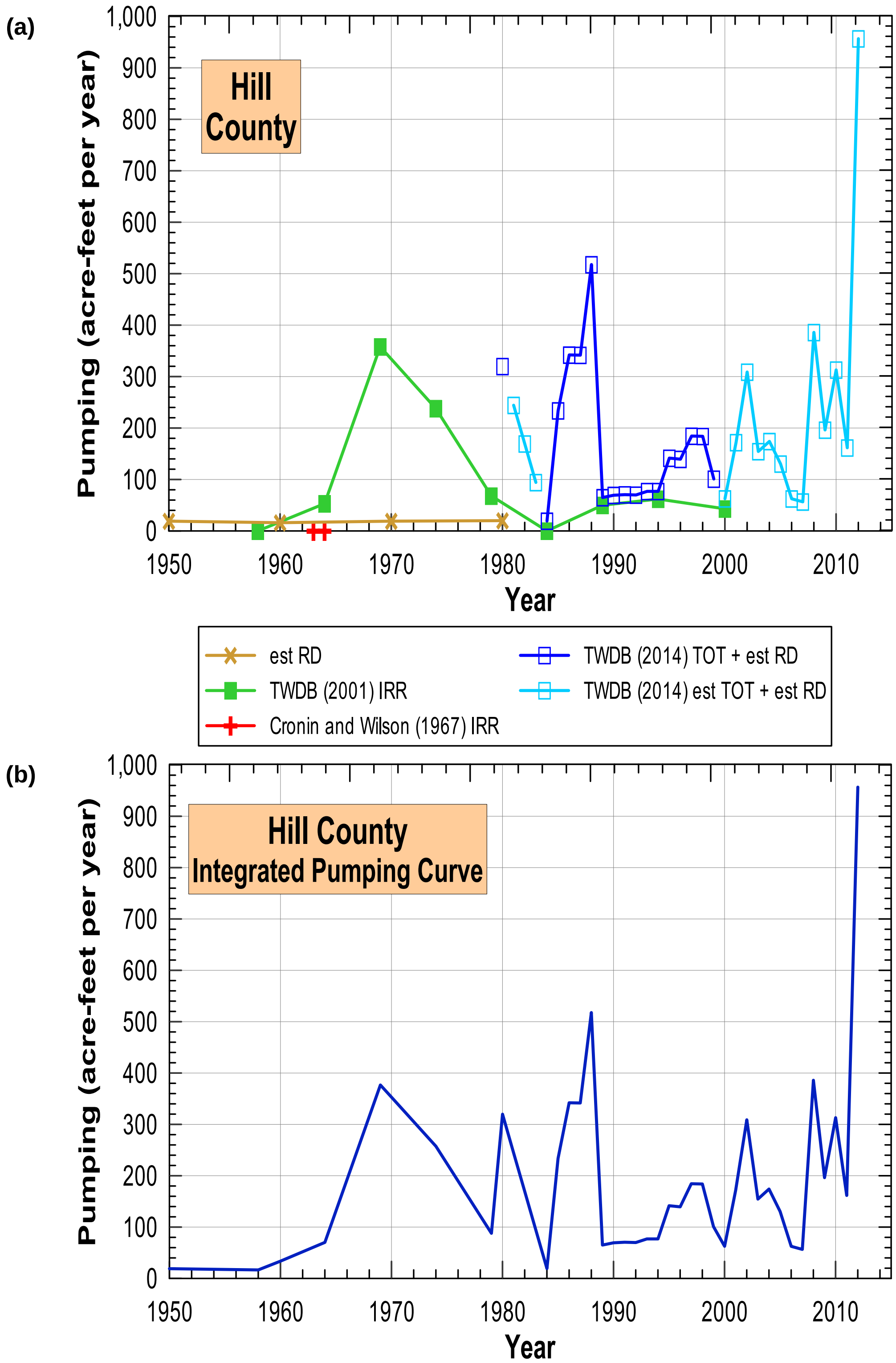


Figure 4.6.10 Plots of (a) historical pumping data and (b) integrated pumping curve for the Brazos River Alluvium Aquifer in Hill County.

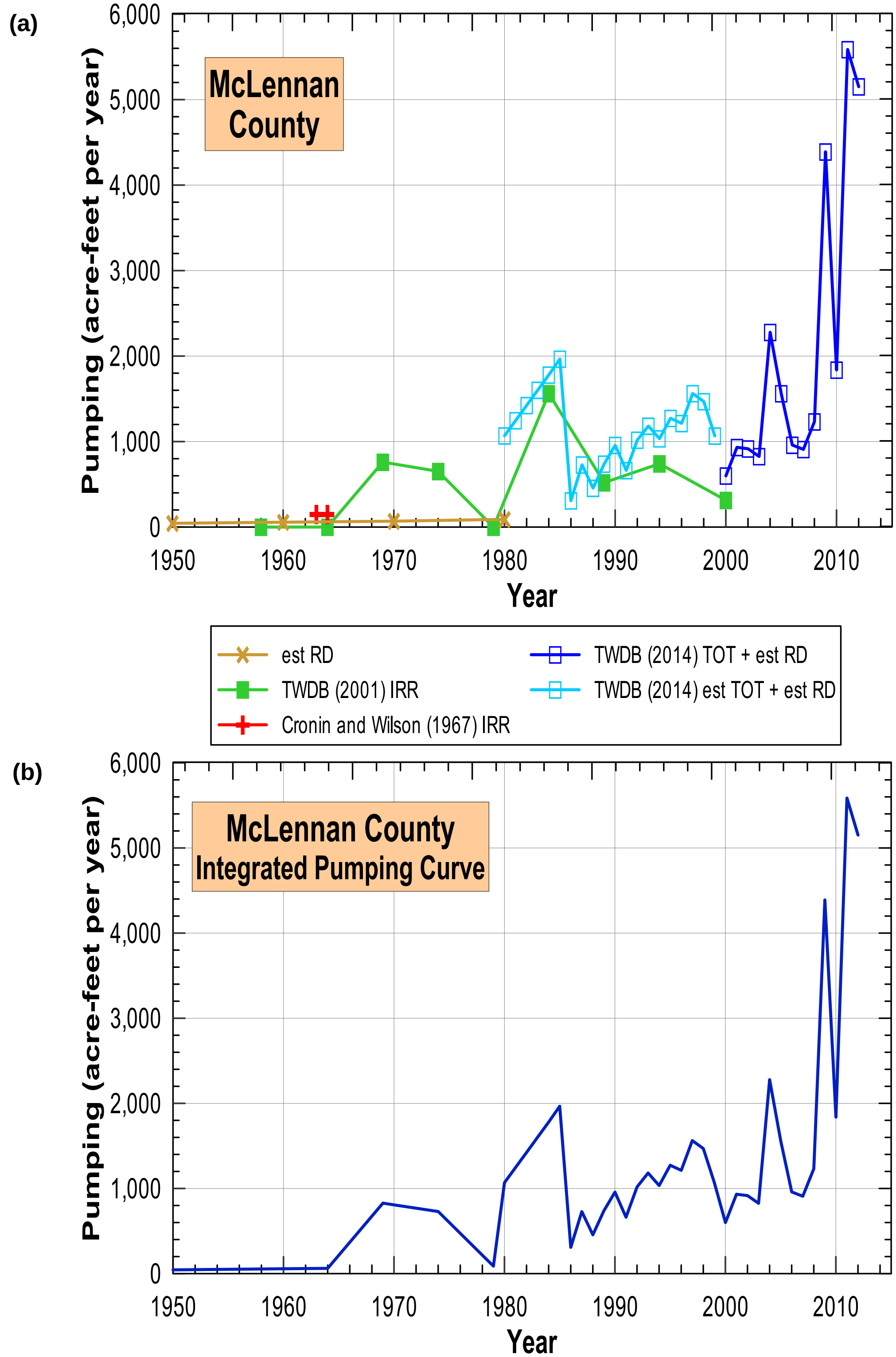


Figure 4.6.11 Plots of (a) historical pumping data and (b) integrated pumping curve for the Brazos River Alluvium Aquifer in McLennan County.

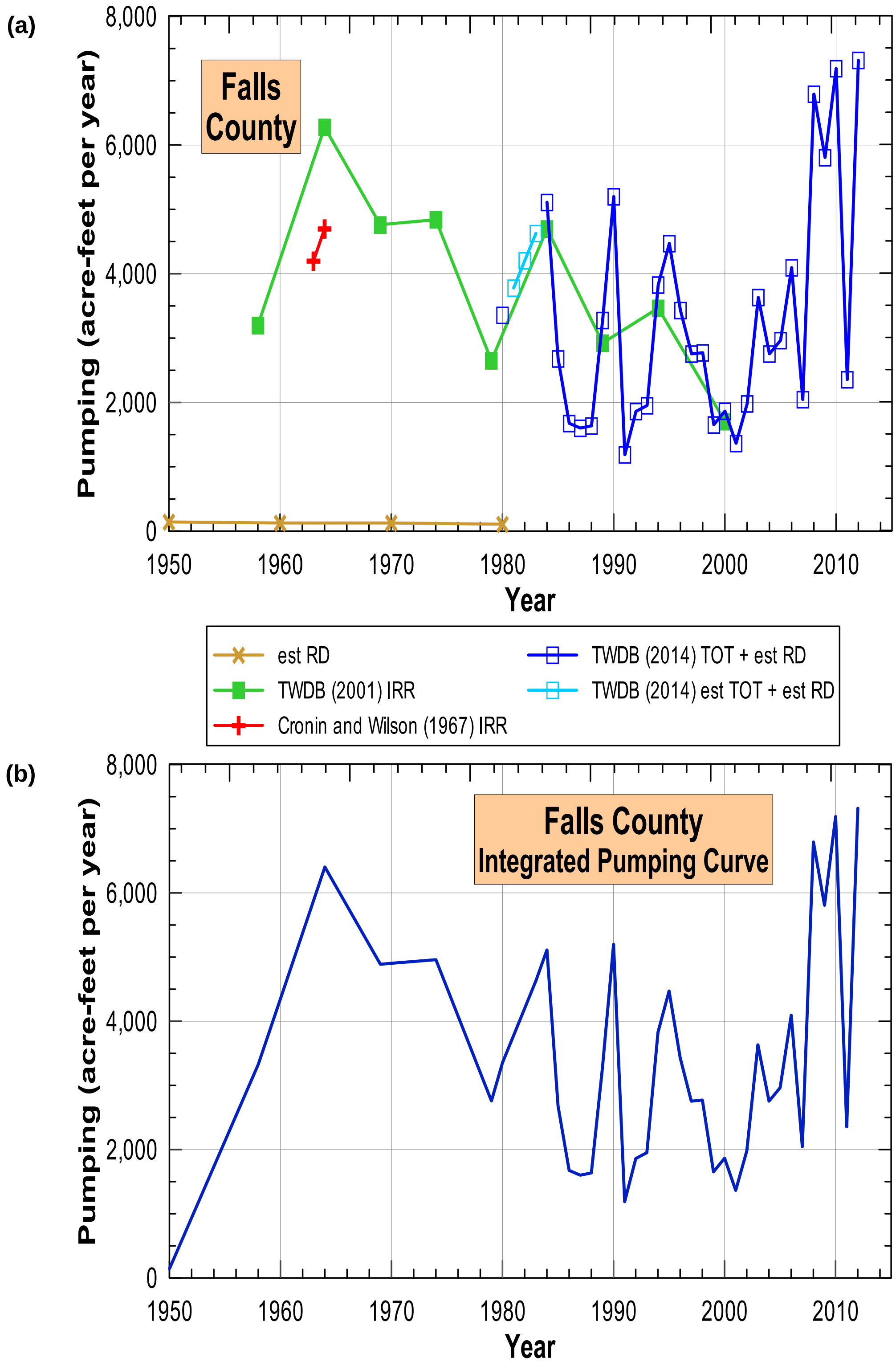


Figure 4.6.12 Plots of (a) historical pumping data and (b) integrated pumping curve for the Brazos River Alluvium Aquifer in Falls County.

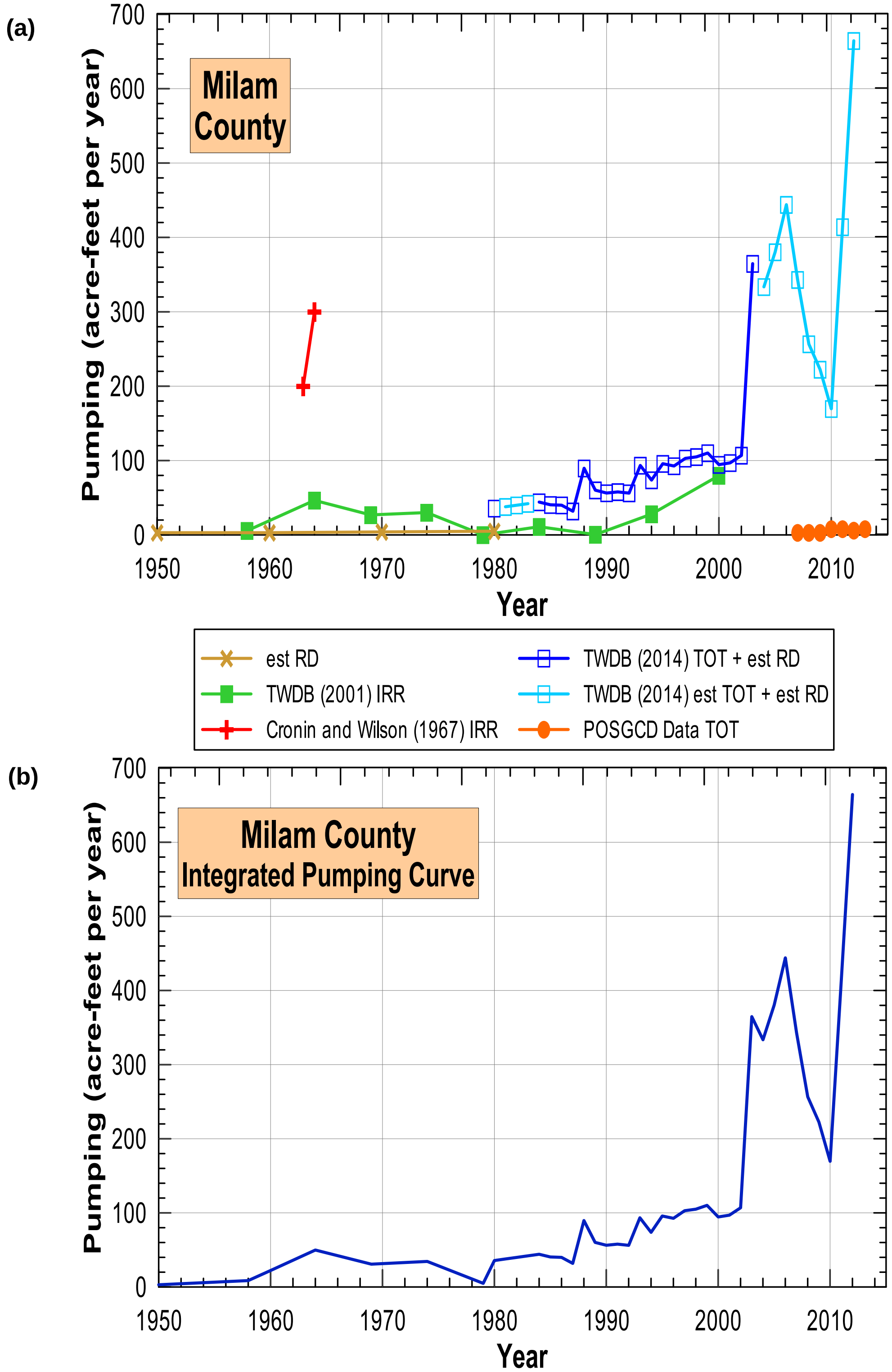


Figure 4.6.13 Plots of (a) historical pumping data and (b) integrated pumping curve for the Brazos River Alluvium Aquifer in Milam County.

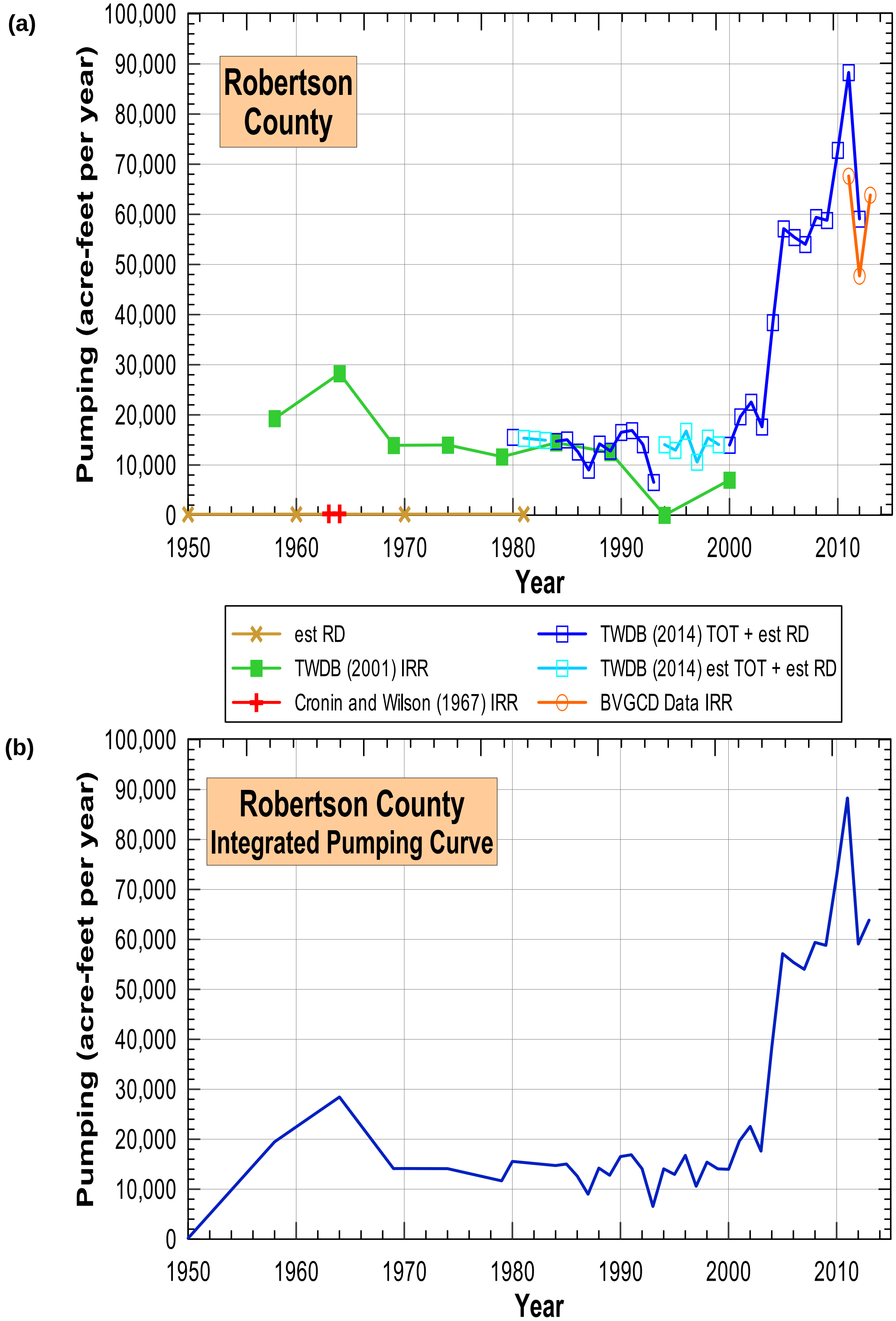


Figure 4.6.14 Plots of (a) historical pumping data and (b) integrated pumping curve for the Brazos River Alluvium Aquifer in Robertson County.

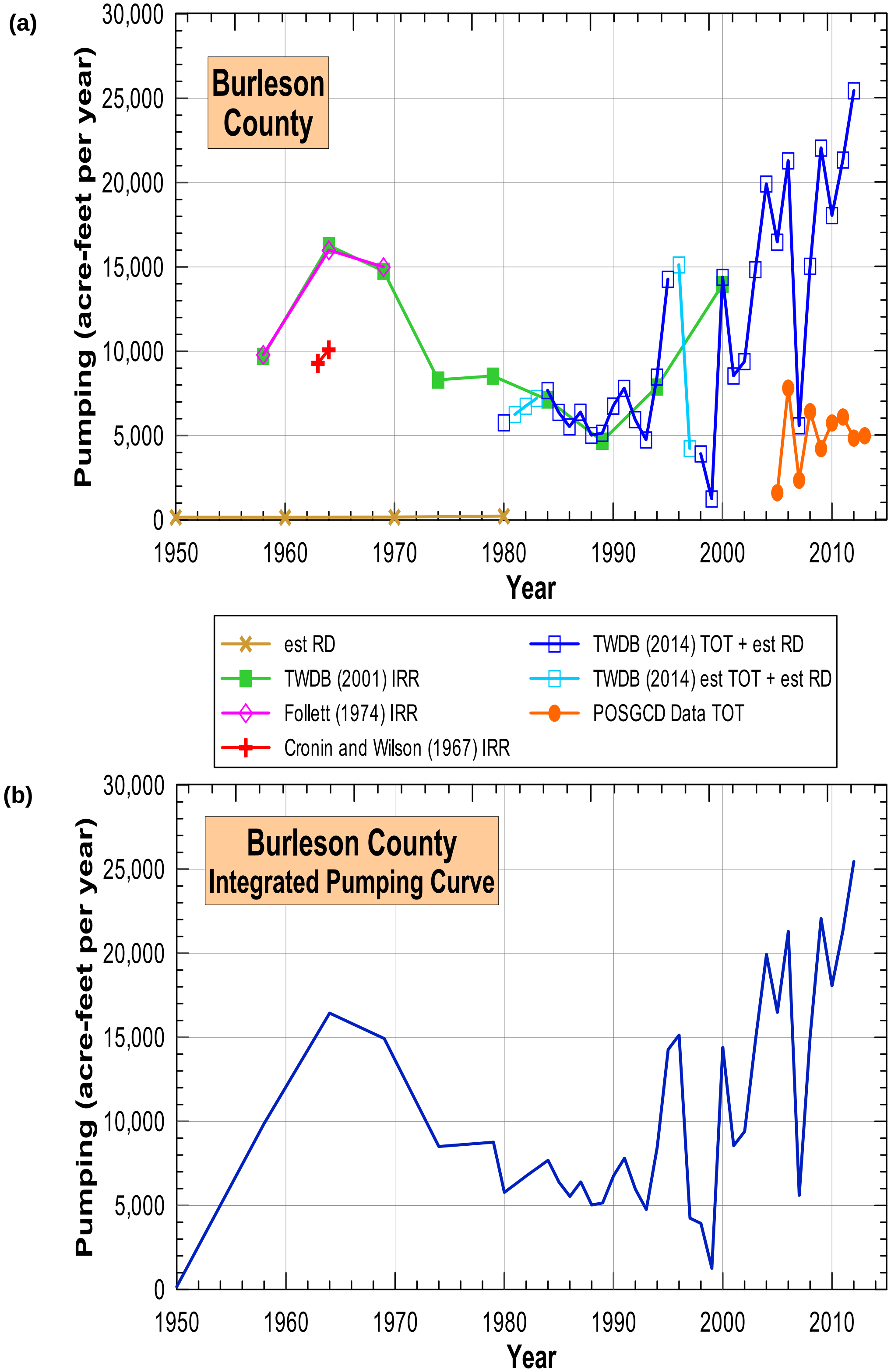
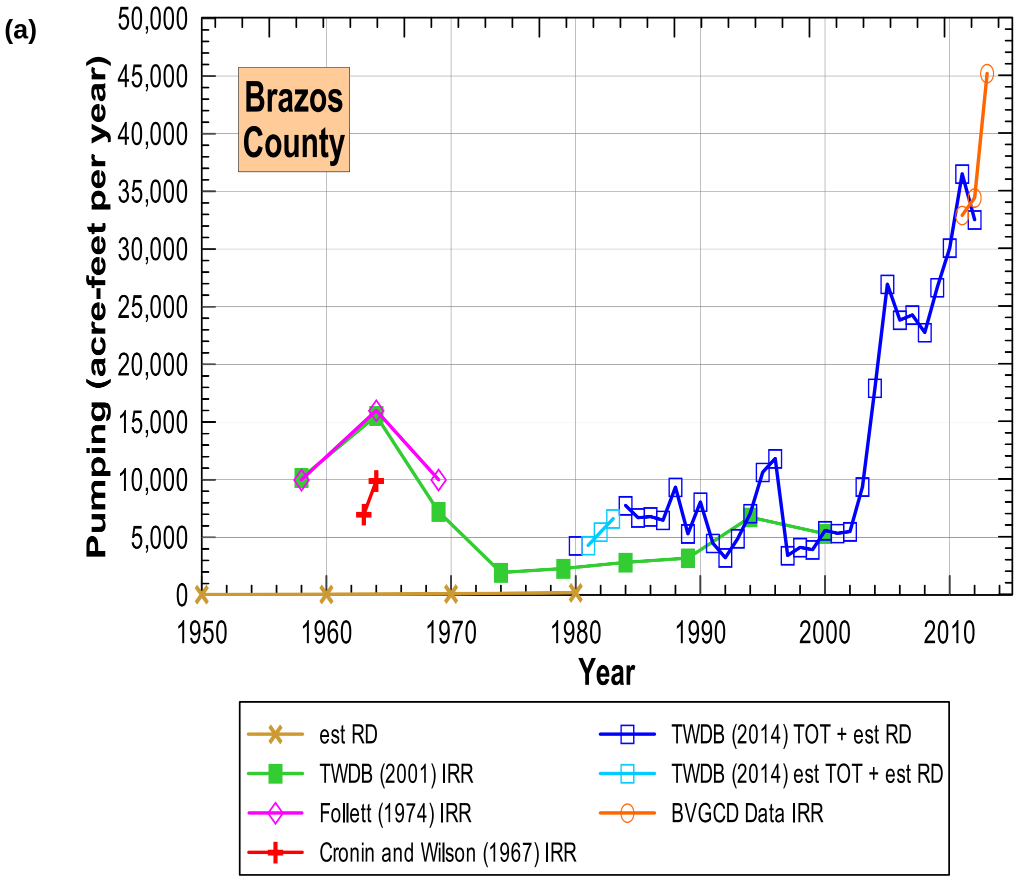


Figure 4.6.15 Plots of (a) historical pumping data and (b) integrated pumping curve for the Brazos River Alluvium Aquifer in Burleson County.



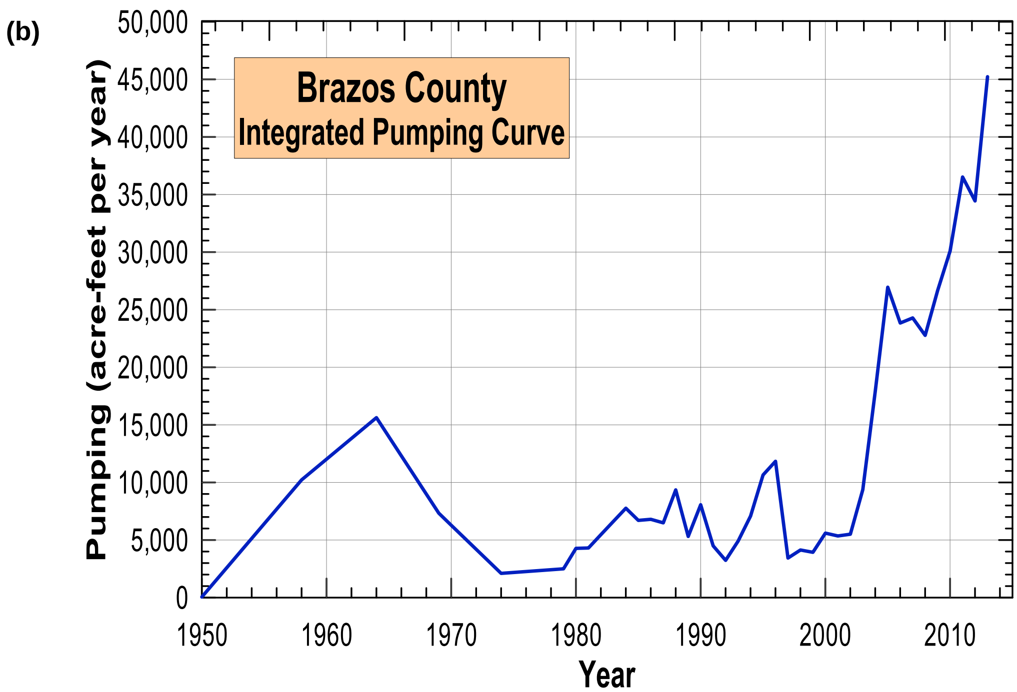
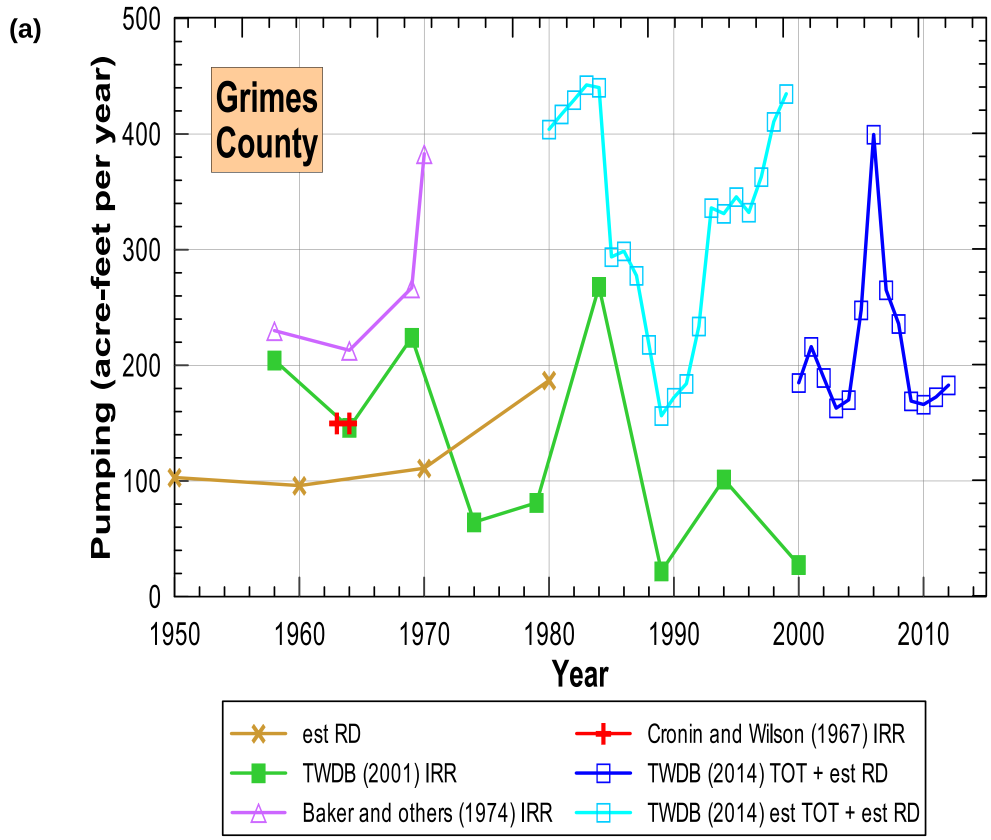


Figure 4.6.16 Plots of (a) historical pumping data and (b) integrated pumping curve for the Brazos River Alluvium Aquifer in Brazos County.



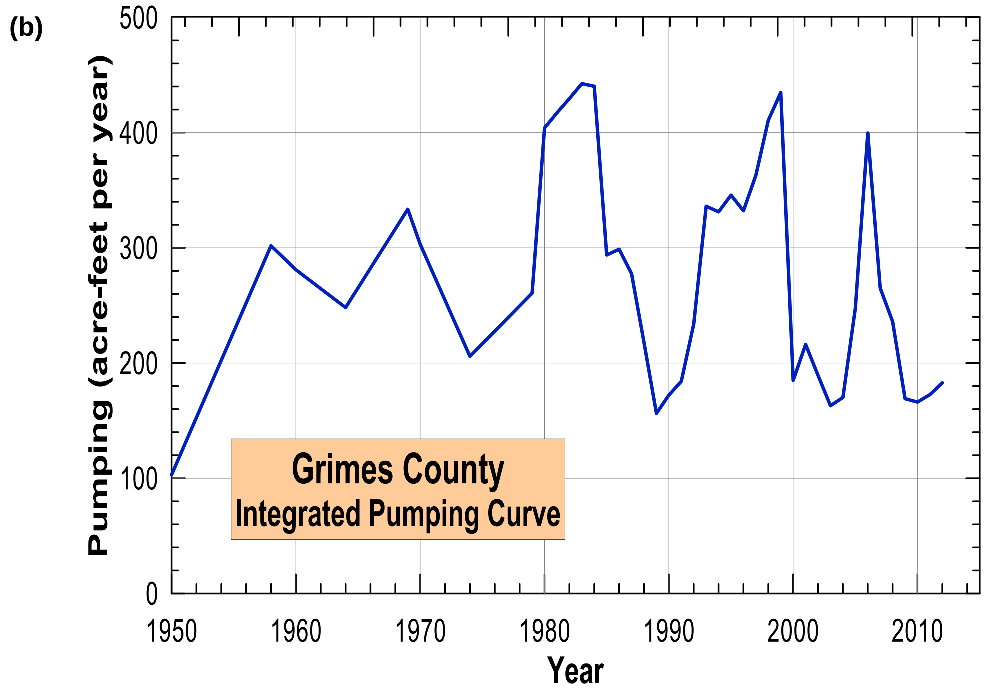


Figure 4.6.17 Plots of (a) historical pumping data and (b) integrated pumping curve for the Brazos River Alluvium Aquifer in Grimes County.

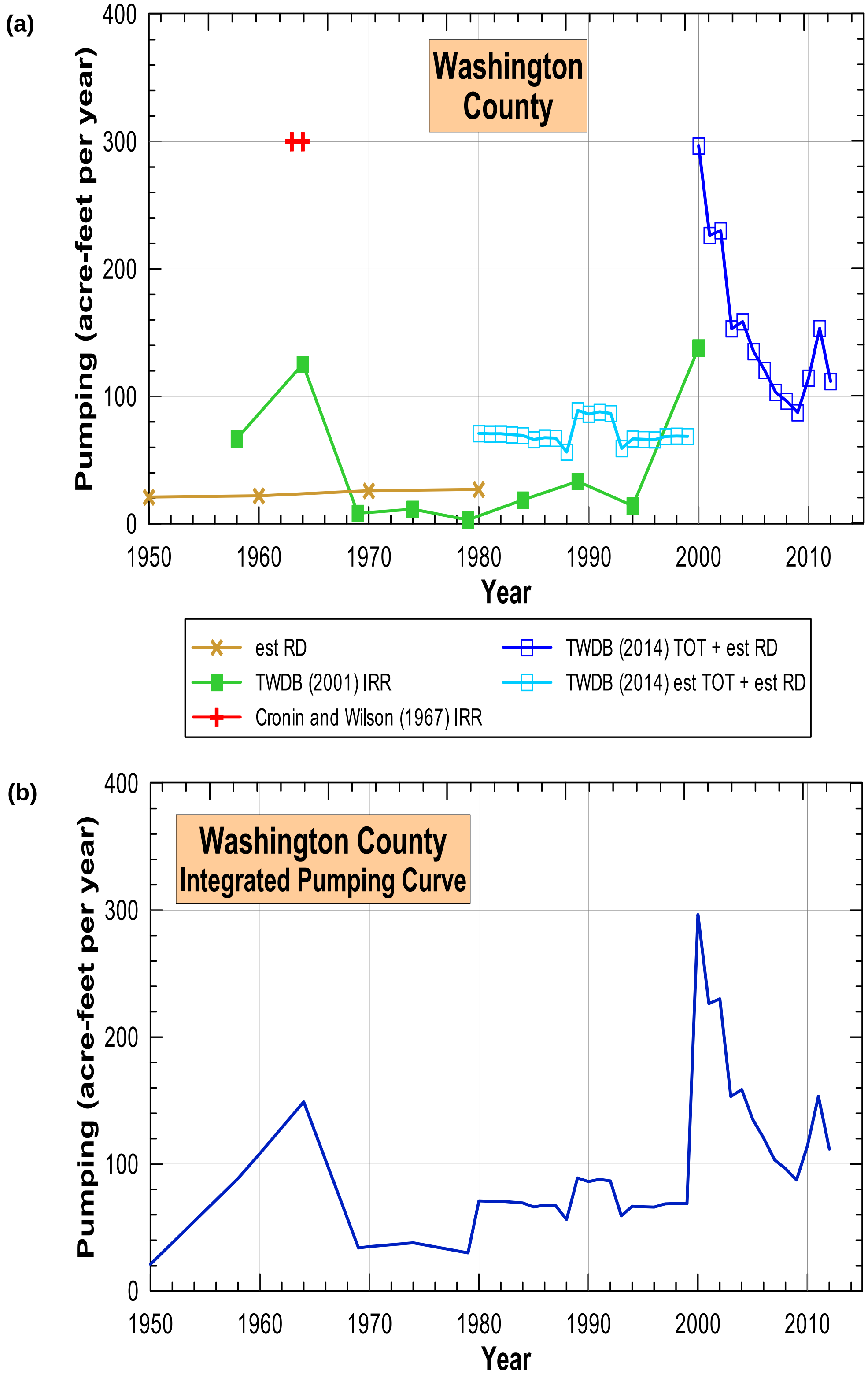


Figure 4.6.18 Plots of (a) historical pumping data and (b) integrated pumping curve for the Brazos River Alluvium Aquifer in Washington County.

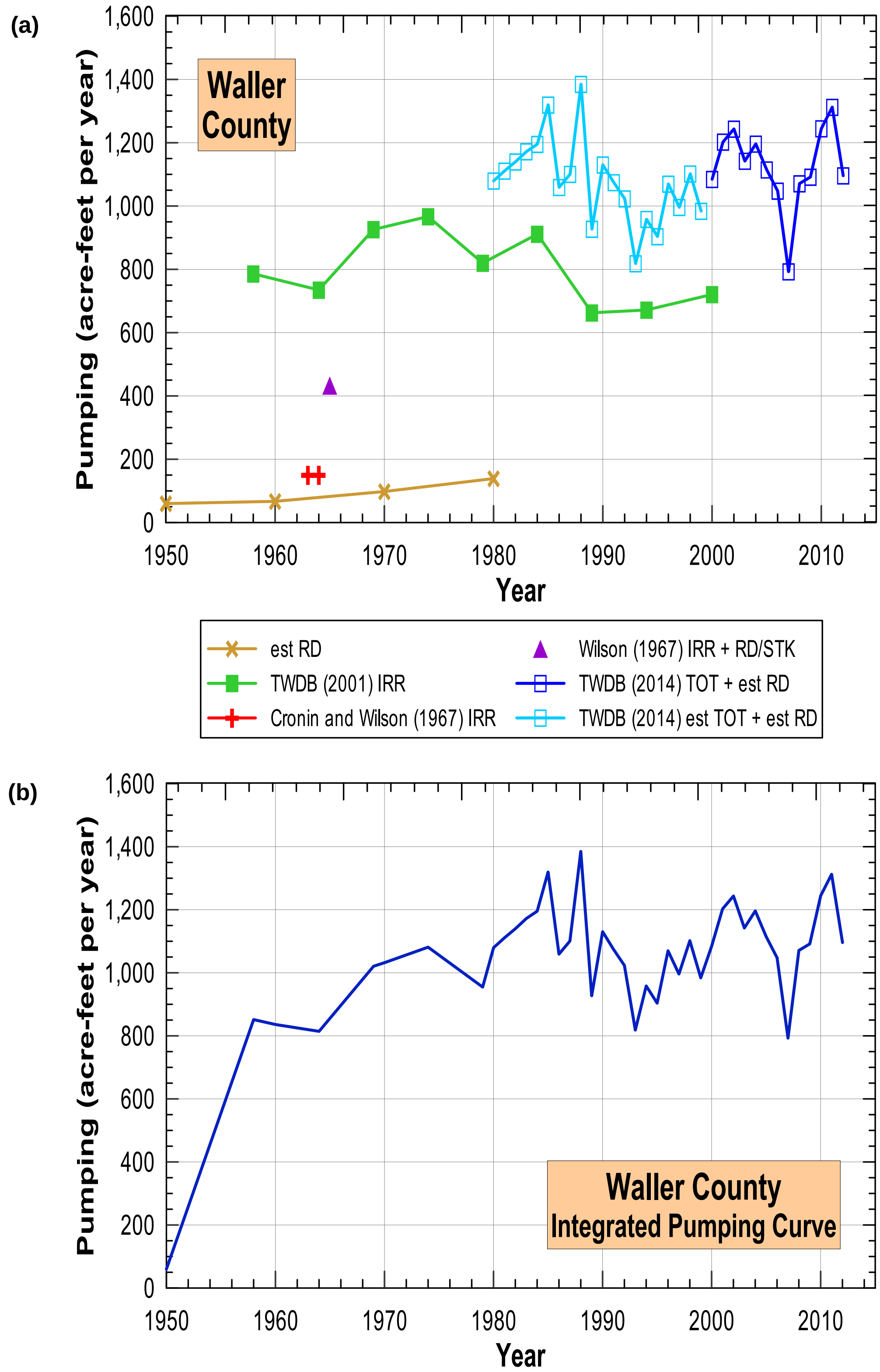
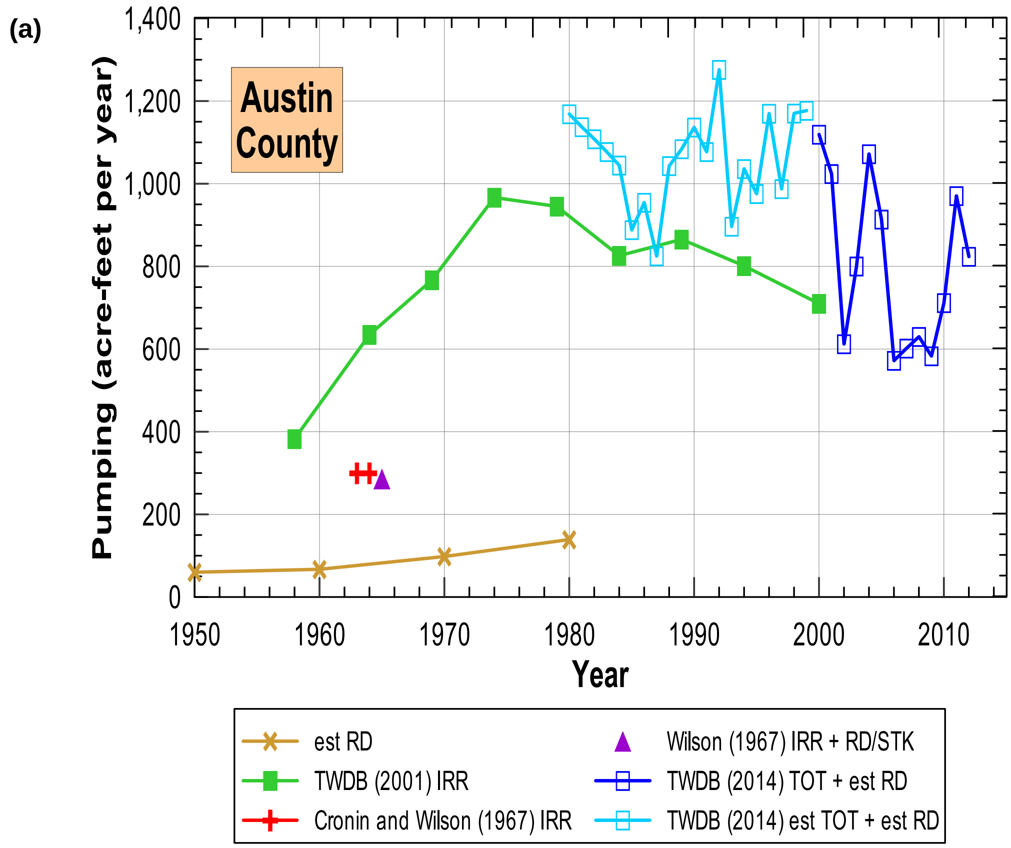


Figure 4.6.19 Plots of (a) historical pumping data and (b) integrated pumping curve for the Brazos River Alluvium Aquifer in Waller County.



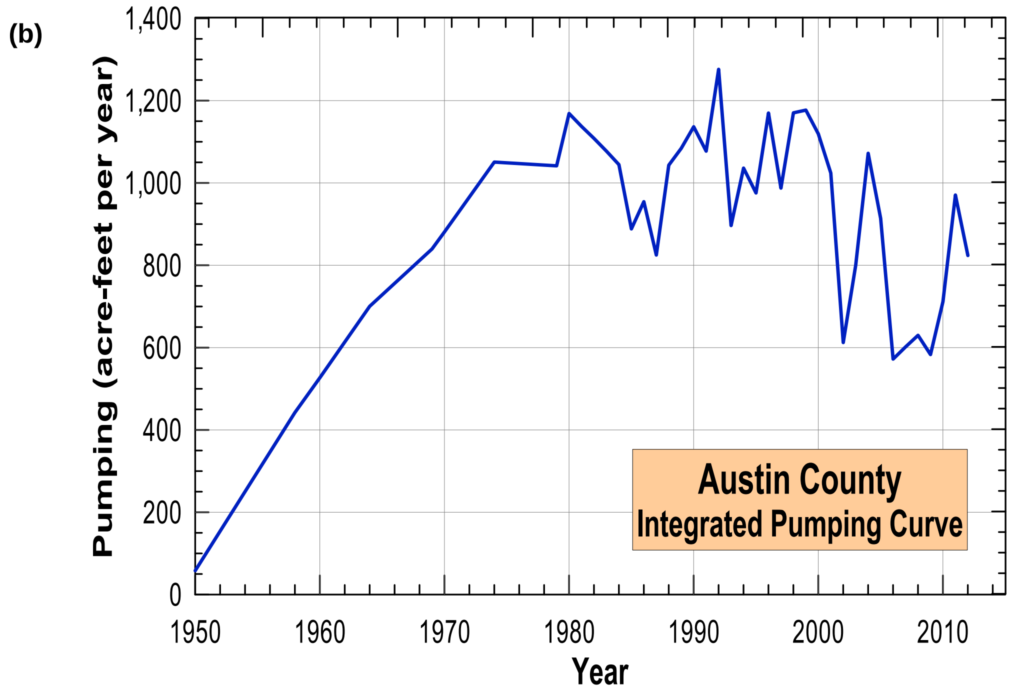


Figure 4.6.20 Plots of (a) historical pumping data and (b) integrated pumping curve for the Brazos River Alluvium Aquifer in Austin County.

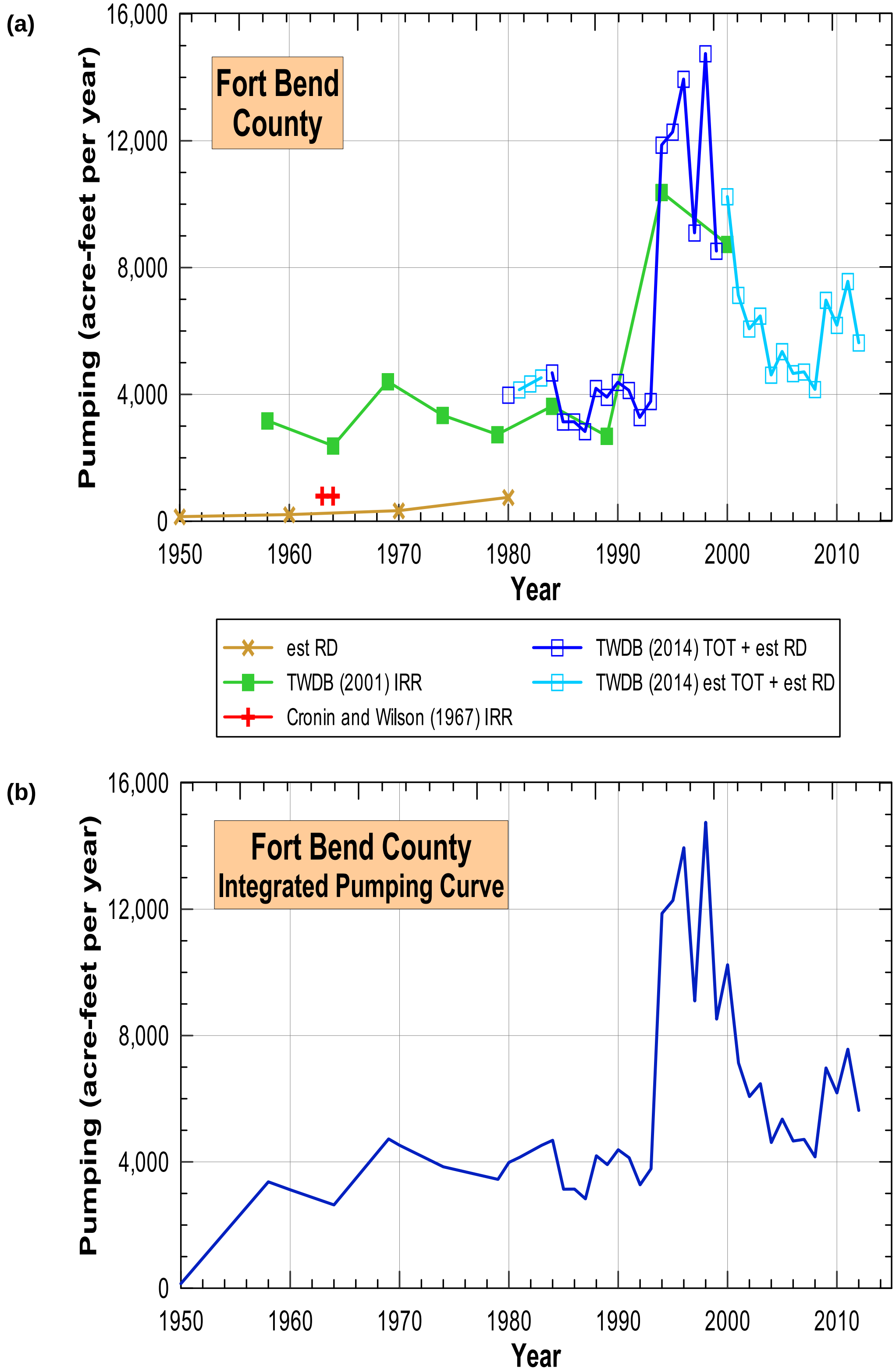


Figure 4.6.21 Plots of (a) historical pumping data and (b) integrated pumping curve for the Brazos River Alluvium Aquifer in Fort Bend County.

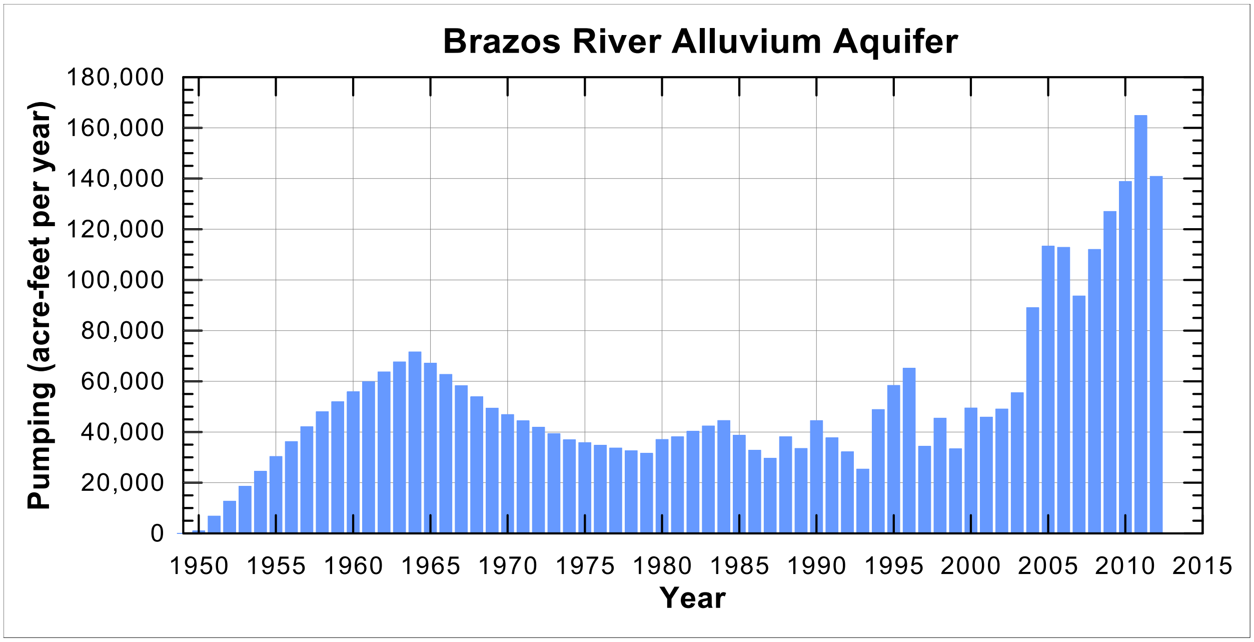


Figure 4.6.22 Bar chart of total pumping from the Brazos River Alluvium Aquifer for 1950 through 2012.

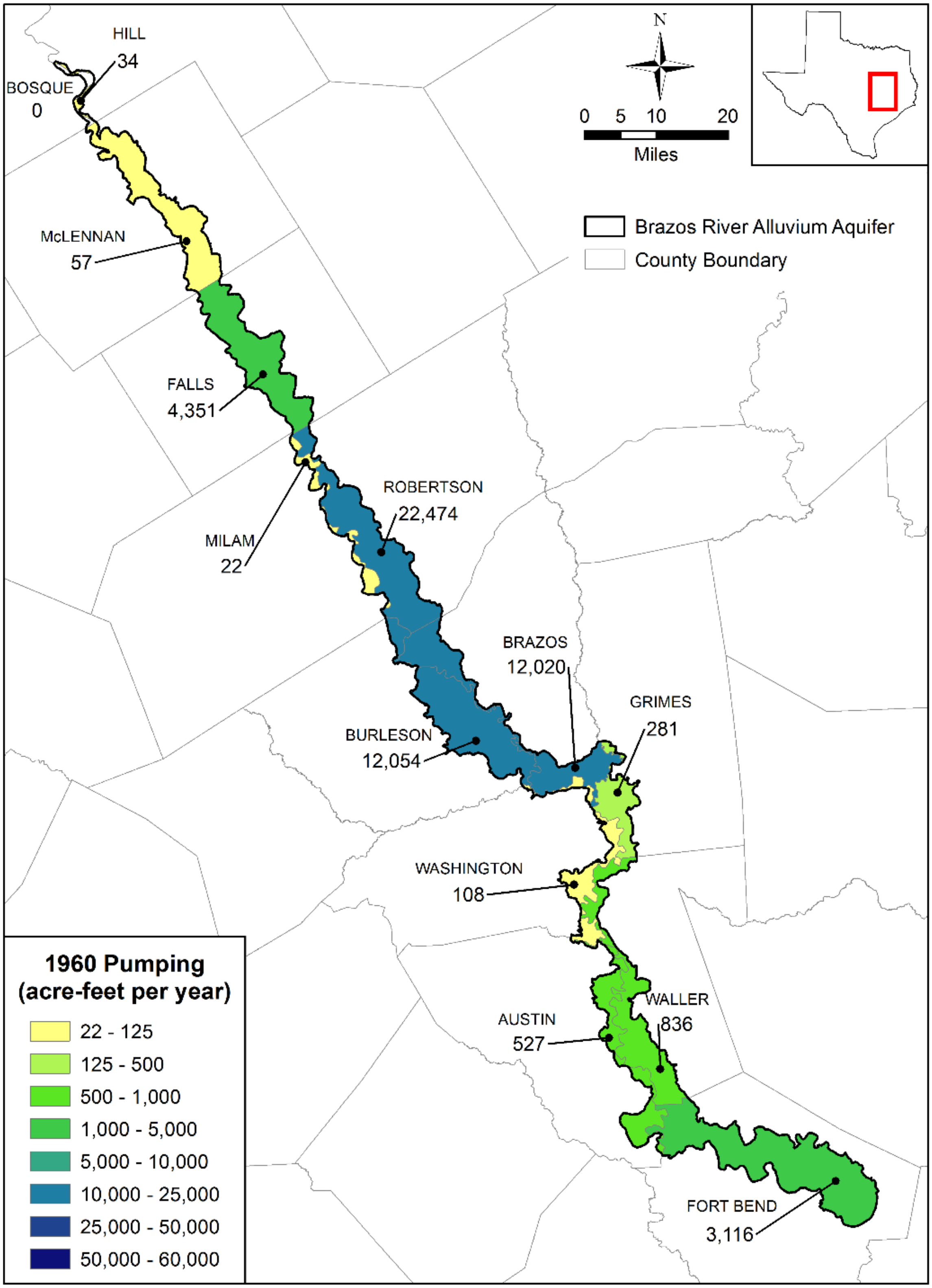


Figure 4.6.23 Estimated historical pumping from the Brazos River Alluvium Aquifer in 1960 by county.

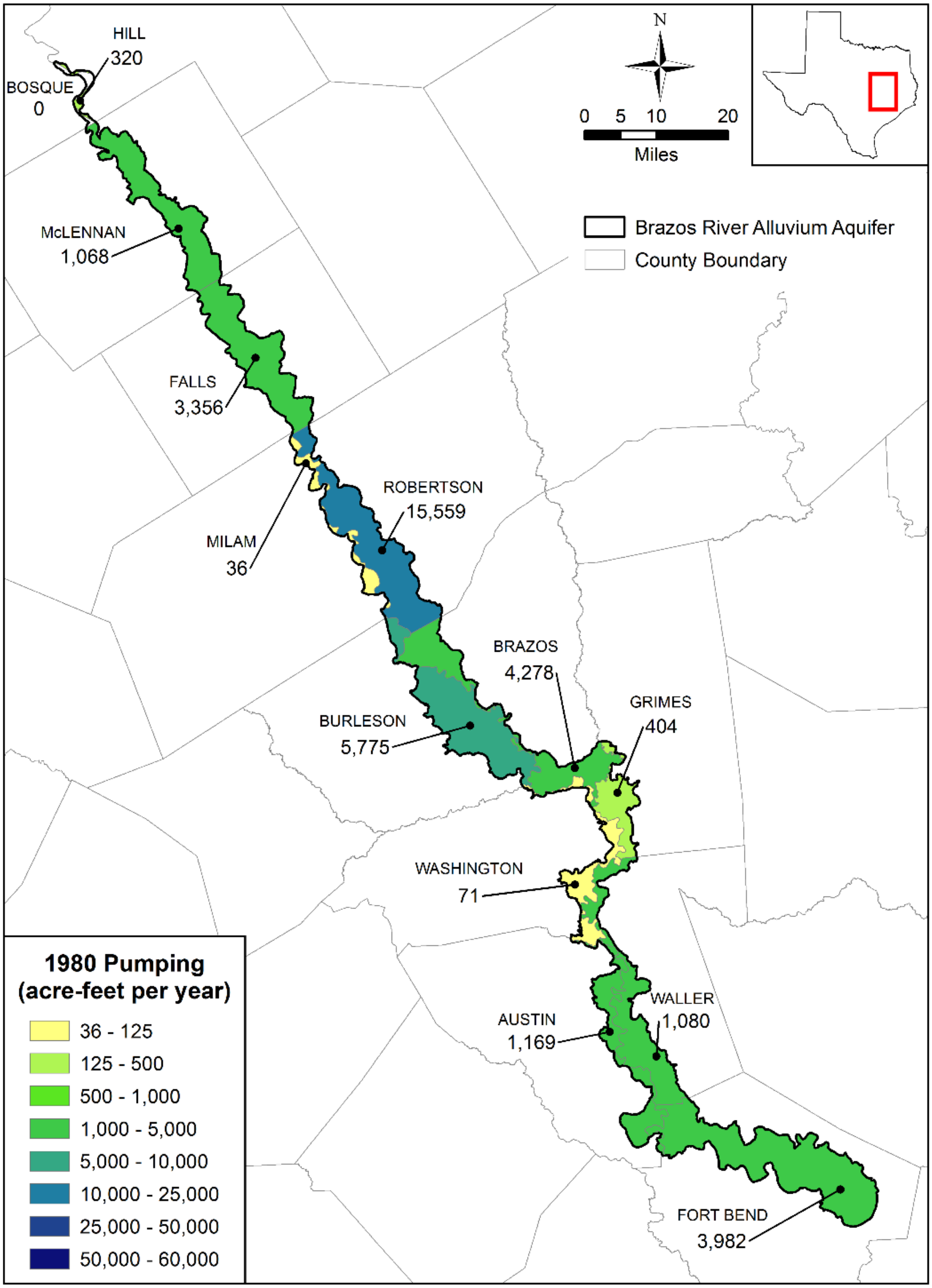


Figure 4.6.24 Estimated historical pumping from the Brazos River Alluvium Aquifer in 1980 by county.

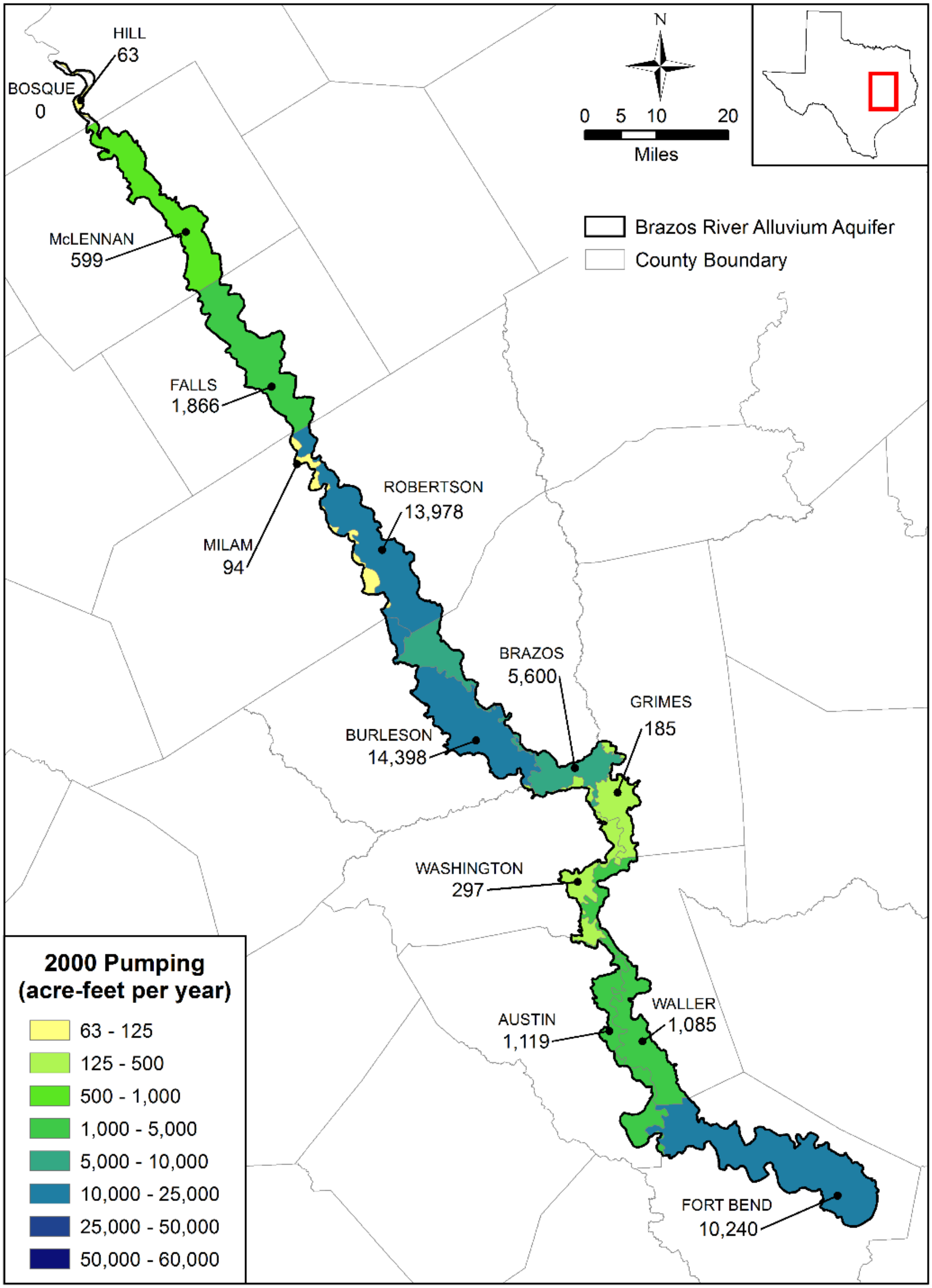


Figure 4.6.25 Estimated historical pumping from the Brazos River Alluvium Aquifer in 2000 by county.

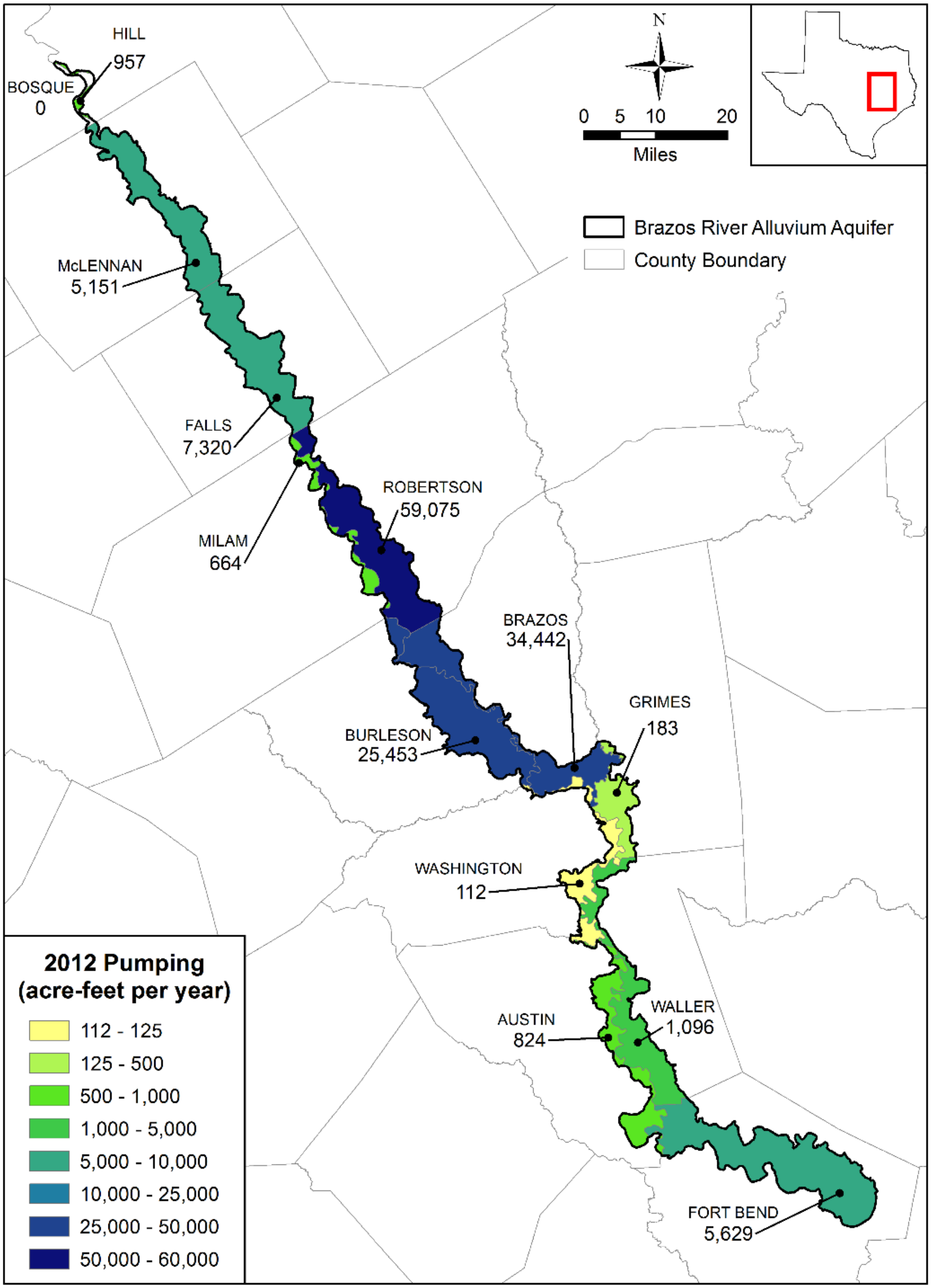


Figure 4.6.26 Estimated historical pumping from the Brazos River Alluvium Aquifer in 2012 by county.

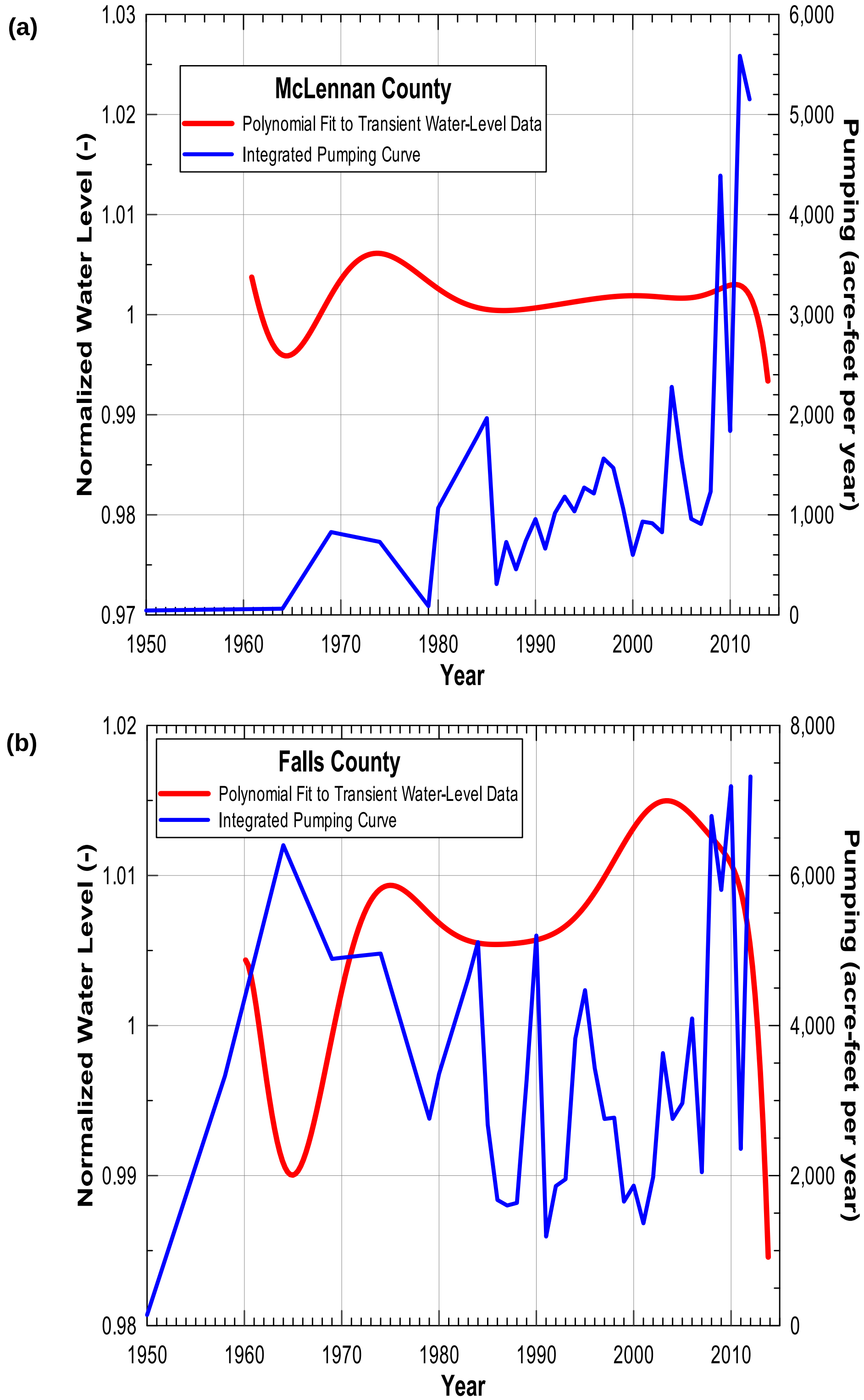


Figure 4.6.27 Comparison of integrated pumping curve and long-term water-level trend in (a) McLennan and (b) Falls counties.

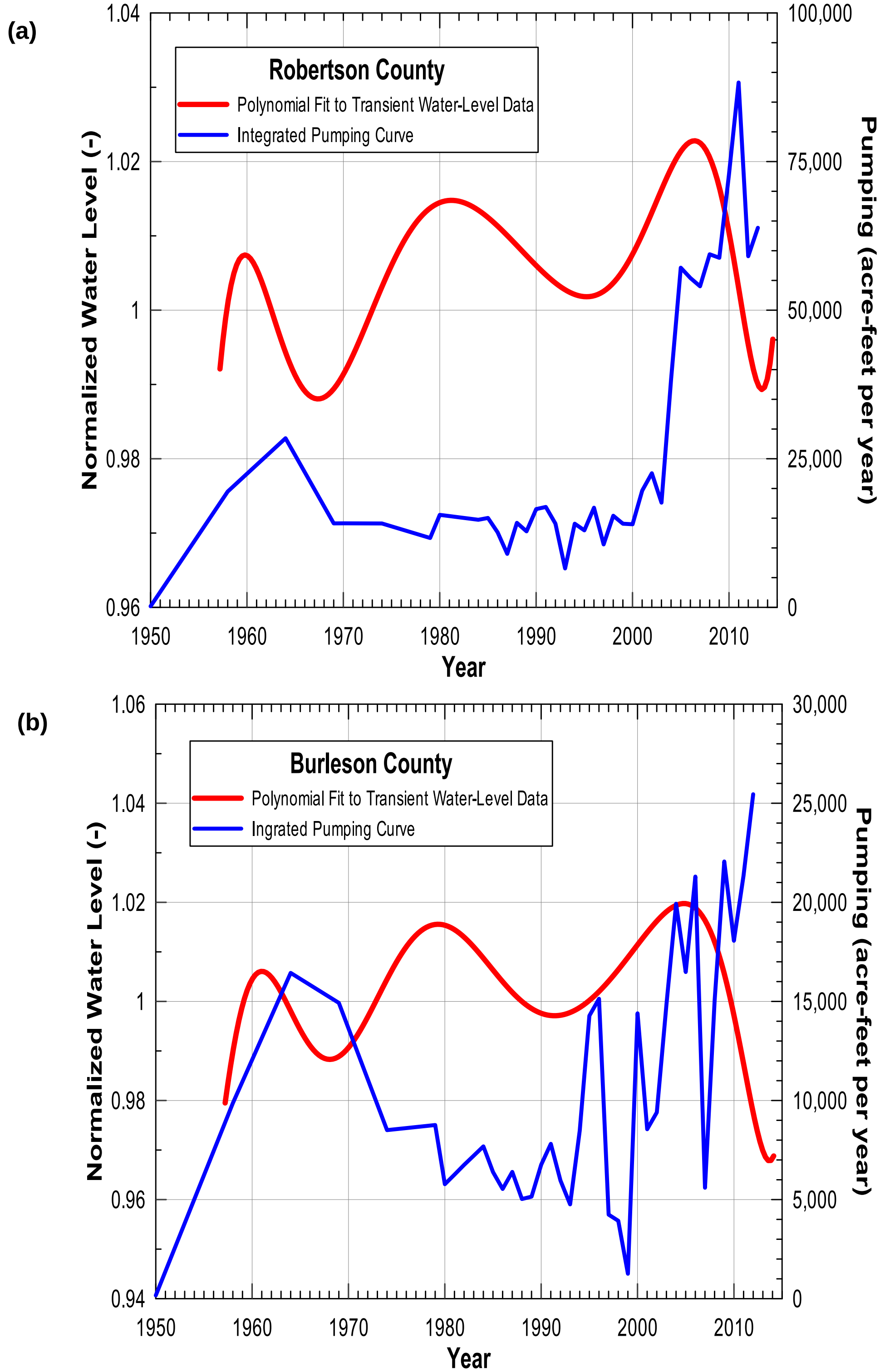


Figure 4.6.28 Comparison of integrated pumping curve and long-term water-level trend in (a) Robertson and (b) Burleson counties.

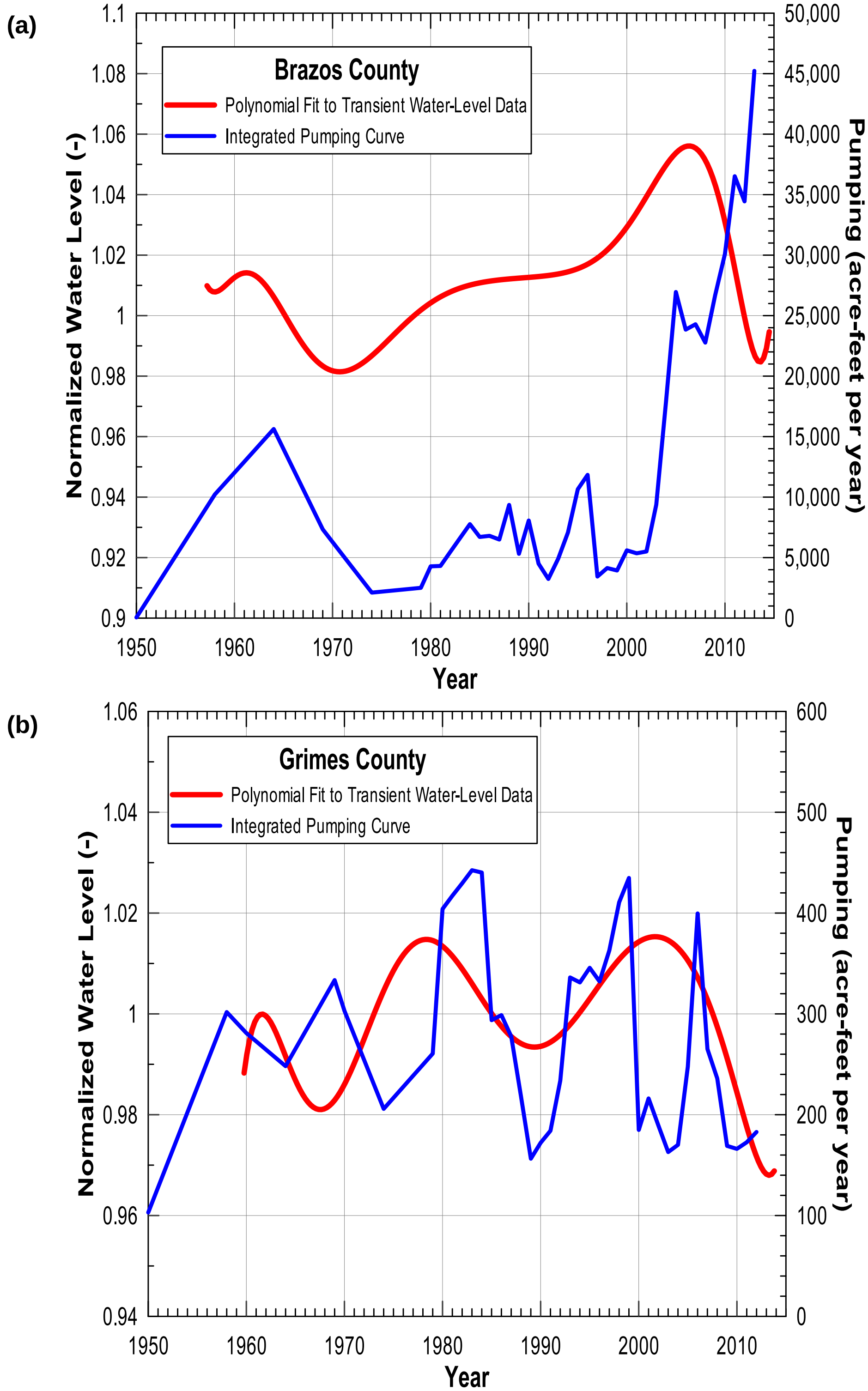


Figure 4.6.29 Comparison of integrated pumping curve and long-term water-level trend in (a) Brazos and (b) Grimes counties.

4.7 Water Quality

Groundwater in the Brazos River Alluvium Aquifer is very hard and mostly fresh with some slightly saline areas (George and others, 2011). In the current study, groundwater in the Brazos River Alluvium Aquifer was evaluated for its quality as a drinking water supply and for irrigation of crops by comparing the measured chemical and physical properties of the water to screening levels. Water quality measurements were retrieved from the TWDB groundwater database (TWDB, 2014f), which contains water quality data from 1896 to the present (October 2014). Measurement dates for water quality data retrieved for wells completed in the Brazos River Alluvium Aquifer and considered for this analysis range from 1940 to 2011.

4.7.1 Previous Studies

Few previous studies have focused specifically on water quality in the Brazos River Alluvium Aquifer. Rather, most studies discuss water quality as part of a broader hydrogeologic conceptual model. Several studies, including Sandeen (1972), Cronin and others (1973), and Munster and others (1996), include water quality analyses for groundwater samples from the Brazos River Alluvium Aquifer but do not otherwise discuss the quality of the groundwater in the aquifer in detail. Other studies provide more in-depth analysis of regional water quality patterns.

Cronin and Wilson (1967) compared water quality measurements from the Brazos River, the Brazos River Alluvium Aquifer, and underlying units. They found that the principle cation and anion in Brazos River Alluvium Aquifer groundwater are calcium and bicarbonate, respectively. They state, however, that the composition of the groundwater can vary over short distances, likely reflecting mineralogical variations of the alluvial material and underlying sediments and possible differences in the rates of groundwater flow and evapotranspiration across the aquifer. They also conclude that groundwater in the underlying sediments has a different chemical composition, principally sodium and bicarbonate, and a lower total dissolved solids concentration than the Brazos River Alluvium Aquifer. Cronin and Wilson (1967) deemed almost all groundwater in the Brazos River Alluvium Aquifer suitable for irrigation and livestock use. However, one area near the Falls/Robertson county line was observed to have a high sodium hazard, which they attributed to highly mineralized waters intruding from the underlying Midway Group.

Chowdhury (2004) and Chowdhury and others (2010) investigated potential water sources for oxbow lakes in the southern portion of the Brazos River Alluvium Aquifer by comparing the water chemistry in the oxbow lakes to that in the Brazos River and groundwater in the Brazos River Alluvium Aquifer. Both Chowdhury (2004) and Chowdhury and others (2010) conclude that the Brazos River Alluvium Aquifer contributes most of the base flow feeding the Brazos River. Chowdhury and others (2010) note that groundwater in the Brazos River Alluvium Aquifer is fresher in the southern portion of the aquifer, which likely accounts for the observed fresher water in the Brazos River in this area. In addition, the isotopic composition of groundwater in the Brazos River implies increased contribution to base flow by the Brazos River Alluvium Aquifer in this area.

According to Chowdhury and others (2010), differences in isotopic composition and water chemistry at three locations indicate little to no significant upward discharge from underlying aquifers into either the Brazos River Alluvium Aquifer or the Brazos River itself. It should be noted that the three wells completed in underlying formations used by Chowdhury and others (2010) are not located in the outcrops of those formations. Based on the surface geology, the Queen City well (5928208) they used is located where the Brazos River Alluvium Aquifer overlies the Cook Mountain Formation. Similarly, the two Evangeline wells (5964701 and 6608103) they used are located where the Brazos River Alluvium Aquifer overlies the Lissie Formation of the Chicot Aquifer. Therefore, the results from their analysis cannot be used to describe the interaction between the Brazos River Alluvium Aquifer and aquifers that directly underlie it.

Chakka and Munster (1997a,b) used the behavior of agricultural chemicals (atrazine and ammonium-nitrate) to determine transport mechanisms in the Brazos River Alluvium Aquifer. They determined that while clays in the aquifer can retard infiltration into the coarse alluvial materials, preferential flow through macropores still provides paths for potential agricultural contamination.

Young and others (2014) conducted a hydrogeochemical evaluation of the Gulf Coast Aquifer System that included the portion of the Brazos River Alluvium Aquifer that overlies that aquifer. They concluded that their geochemical analysis suggests that groundwater flows from the Gulf

Coast Aquifer System into the Brazos River Alluvium Aquifer but that the relative magnitude of the inflows are unknown.

4.7.2 Data Sources and Methods of Analysis

Water quality in the Brazos River Alluvium Aquifer can be affected by recharge from the surface making non-point source contamination from agriculture a particular concern. In addition, water quality in the Brazos River is significantly impacted by the water quality in the Brazos River Alluvium Aquifer due to large base flow contributions. The current study presents an analysis of water quality data for the Brazos River Alluvium Aquifer only. The water quality of the Brazos River and the five aquifers underlying the Brazos River Alluvium Aquifer was not considered. In addition, the current study does not investigate the presence or absence of agricultural chemicals and pesticides in the Brazos River Alluvium Aquifer.

Water quality data for the Brazos River Alluvium Aquifer were obtained from the TWDB groundwater database (TWDB, 2014f). If a well had screen information or total depth indicating it was above the base of the aquifer (as described in Section 4.1), the well was assigned to the Brazos River Alluvium Aquifer regardless of the aquifer designation given in the database. To increase coverage, data from wells without well depth information were included if they were designated as Brazos River Alluvium Aquifer wells in the TWDB groundwater database.

This analysis included water quality measurements from 262 wells completed in the Brazos River Alluvium Aquifer. For the purpose of statistical evaluation and mapping, only the most recent sampling event for each well was used in order to assess the most current status of the quality of groundwater in the aquifer. Water quality measurements for major ions were omitted if the analysis was labelled “unbalanced” in the TWDB groundwater database. Measurements were also omitted if the analysis was assigned reliability code 01 (“Sample collected from tank, distribution, or bailed from well. Not indicative of aquifer quality. Data should be used carefully”) in the TWDB groundwater database. These measurements were considered unreliable and were not used in the water quality analysis.

4.7.3 Drinking Water Quality

Screening levels for drinking water supply are based on the maximum contaminant levels established by the United States Environmental Protection Agency (2014). Primary maximum contaminant levels are legally enforceable standards that apply to public water systems to protect human health from contaminants in drinking water. Secondary maximum contaminant levels are non-enforceable guidelines for drinking water contaminants that may cause aesthetic effects (taste, color, odor, and foaming), cosmetic effects (skin or tooth discoloration), and technical effects (corrosivity, expensive water treatment, plumbing fixture staining, scaling, and sediment). Table 4.7.1 summarizes the occurrence and levels of some constituents commonly measured in groundwater for the Brazos River Alluvium Aquifer.

Total dissolved solids, a measure of salinity, is the sum of concentrations of all dissolved ions (such as sodium, calcium, magnesium, potassium, chloride, sulfate, carbonates) plus silica. Some dissolved solids, such as calcium, give water a pleasant taste, but most make water taste salty, bitter, or metallic. Dissolved solids can also increase the corrosiveness of water. The total dissolved solids concentration exceeds the secondary maximum contaminant level of 500 milligrams per liter in approximately 92 percent of the groundwater sampled from Brazos River Alluvium Aquifer wells.

Table 4.7.2 divides groundwater into five classes based on total dissolved solids concentration (Collier, 1993). Based on this classification, the majority of the groundwater in the Brazos River Alluvium Aquifer is fresh to slightly saline. Figure 4.7.1 shows the spatial distribution of the total dissolved solids concentration in Brazos River Alluvium Aquifer groundwater relative to the secondary maximum contaminant level and the salinity classes.

Sulfate and chloride are major components of total dissolved solids. The secondary maximum contaminant level for both sulfate and chloride is 250 milligrams per liter. Sixteen percent of groundwater samples from Brazos River Alluvium Aquifer wells exceed this level for sulfate and 18 percent exceed this level for chloride. The spatial distributions of sulfate and chloride concentrations in the Brazos River Alluvium Aquifer relative to the secondary maximum contamination level are shown in Figures 4.7.2 and 4.7.3, respectively.

Fluoride is a naturally-occurring element found in most rocks. At very low concentrations, fluoride is a beneficial nutrient. For instance, at a concentration of 1 milligram per liter, fluoride helps to prevent dental cavities. However, at concentrations above the secondary maximum contaminant level of 2 milligrams per liter, fluoride can stain children's teeth. At concentrations above the primary maximum contaminant level of 4 milligrams per liter, fluoride can cause a type of bone disease. Neither of these maximum contaminant levels are exceeded in any of the groundwater samples from Brazos River Alluvium Aquifer wells.

Nitrate, which is often indicative of agricultural contamination, is another potentially hazardous constituent of drinking water. Since high concentrations of nitrate can cause serious illness in infants younger than 6 months old, the United State Environmental Protection Agency established a primary maximum contaminant level of 10 milligrams per liter of nitrate as nitrogen. This level is exceeded in 13 percent of the groundwater samples from Brazos River Alluvium Aquifer wells. Figure 4.7.4 shows the distribution of nitrate concentrations in the Brazos River Alluvium Aquifer relative to the primary maximum contaminant level.

Arsenic can be another hazardous, but often naturally-occurring, constituent in groundwater. Long-term exposure to arsenic can cause various forms of cancer, resulting in a low primary maximum concentration for arsenic of 10 micrograms per liter. This level is exceeded in 7 percent of the groundwater samples from Brazos River Alluvium Aquifer wells. Figure 4.7.5 shows the distribution of arsenic concentrations in the Brazos River Alluvium Aquifer relative to the primary contaminant level.

4.7.4 Irrigation Water Quality

The utility of groundwater from the Brazos River Alluvium Aquifer for crop irrigation was evaluated based on its salinity hazard, sodium hazard, and concentration of chloride. Although crops can differ in their tolerance to high salinity, saline irrigation water is generally undesirable as it limits the ability of plants to take up water from soils. The salinity hazard classification system of the United States Department of Agriculture (1954b) classifies waters with electrical conductivity over 750 micromhos per centimeter as a high salinity hazard, and those with electrical conductivity over 2,250 micromhos centimeter as a very high salinity hazard. Of the wells in the Brazos River Alluvium Aquifer with chemical analyses, groundwater samples from 96 percent exhibit a high salinity hazard and 81 percent exhibit a very high salinity hazard. Figure 4.7.6 shows the distribution of salinity hazard in the Brazos River Alluvium Aquifer.

Groundwater with a high sodium concentration compared to the concentration of other major ions can negatively affect soil cultivation and permeability in irrigated land. A sodium hazard condition generally results when the sodium concentration is in excess of 60 percent of the concentration of total cations. The sodium hazard of groundwater is typically calculated in terms of sodium adsorption ratio (United States Department of Agriculture, 1954b):

$$Sodium\ Adsorption\ Ratio = \frac{Na}{\sqrt{\frac{Ca+Mg}{2}}} \tag{4.7.1}$$

where the sodium (Na), calcium (Ca), and magnesium (Mg) concentrations are expressed in milliequivalents per liter. The United States Department of Agriculture (1954b) classifies groundwater into low (less than 10), medium (10 to 18), high (18 to 26), and very high (greater than 26) sodium adsorption ratio ranges. In the Brazos River Alluvium Aquifer, none of the sampled wells has groundwater that falls into the high category but 1 percent of the sampled wells has groundwater with a very high sodium hazard. The sodium hazard (sodium adsorption ratio) of groundwater for the Brazos River Alluvium Aquifer is shown in Figure 4.7.7.

Chloride is another constituent potentially toxic to crops at higher concentrations. Most crops cannot tolerate chloride concentrations above 1,000 milligrams per liter for an extended period of time (Tanji, 1990). Less than 1 percent of the groundwater samples from Brazos River Alluvium Aquifer wells have a chloride concentration greater than 1,000 milligrams per liter (see Figure 4.7.3).

Table 4.7.1 Occurrence and levels of commonly measured groundwater quality constituents in the Brazos River Alluvium Aquifer.

Constituent	Type of Standard	Screening Level	Units	Number of Results	Mean Value (*Std Dev*)	Results Exceeding Screening Level (percent)
Fluoride	Primary maximum contaminant level[(1)]	4	mg/L	248	0.34 *(0.19)*	0
Nitrate	Primary maximum contaminant level[(1)]	10	mg/L as Nitrogen	252	6.08 *(16.8)*	13
Arsenic	Primary maximum contaminant level[(1)]	10	μg/L	31	3.62 *(4.02)*	6.5
pH	Secondary maximum contaminant level[(1)]	6.5 to 8.5	-	250	7.14 *(0.36)*	0.4
Chloride	Secondary maximum contaminant level[(1)]	250	mg/L	261	167 *(186)*	18
Fluoride	Secondary maximum contaminant level[(1)]	2	mg/L	248	0.34 *(0.19)*	0.0
Sulfate	Secondary maximum contaminant level[(1)]	250	mg/L	261	141 *(142)*	16
Total Dissolved Solids	Secondary maximum contaminant level[(1)]	500	mg/L	261	959 *(470)*	92
Specific Conductance	Irrigation Salinity Hazard-High[(2)]	750	μmhos/cm	243	1,583 *(746)*	96
Specific Conductance	Irrigation Salinity Hazard - Very High[(2)]	2,250	μmhos/cm	243	1,583 *(746)*	81
Sodium Adsorption Ratio	Sodium hazard – Medium[(2)]	10	-	261	2.98 *(5.20)*	0.0
Sodium Adsorption Ratio	Sodium hazard – High[(2)]	18	-	261	2.98 *(5.20)*	0.0
Sodium Adsorption Ratio	Sodium hazard –Very High[(2)]	26	-	261	2.98 *(5.20)*	1.1
Chloride	Irrigation Hazard[(3)]	1,000	mg/L	261	167 *(186)*	0.4

[(1)] Drinking Water Standards (United States Environmental Protection Agency, 2014)
[(2)] United States Department of Agriculture (1954b)
[(3)] Tanji (1990)

Std Dev = standard deviation
mg/L = milligrams per liter μg/L = micrograms per liter μmhos/cm = micromhos per centimeter
pCi/L = picocuries per liter

Table 4.7.2. Groundwater classifications based on total dissolved solids concentration (Collier, 1993).

Class	Total Dissolved Solids Concentration (milligrams per liter)
Freshwater	0 to 1,000
Slightly saline water	more than 1,000 to 3,000
Moderately saline water	more than 3,000 to 10,000
Very saline water	more than 10,000 to 100,000
Brine water	more than 100,000

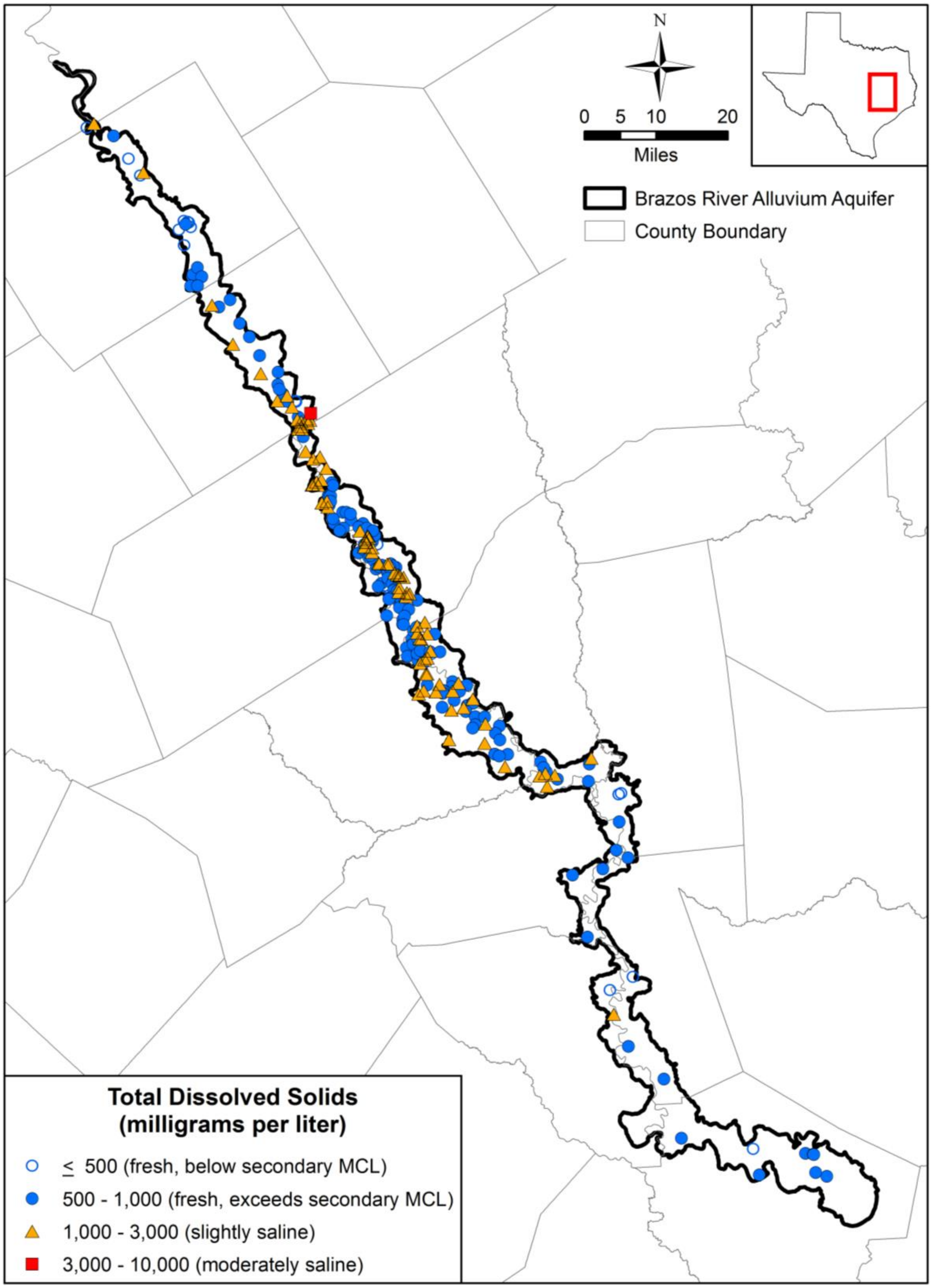


Figure 4.7.1 Total dissolved solids concentrations in the Brazos River Alluvium Aquifer relative to the secondary maximum contaminant level (MCL) and salinity classes (TWDB, 2014f).

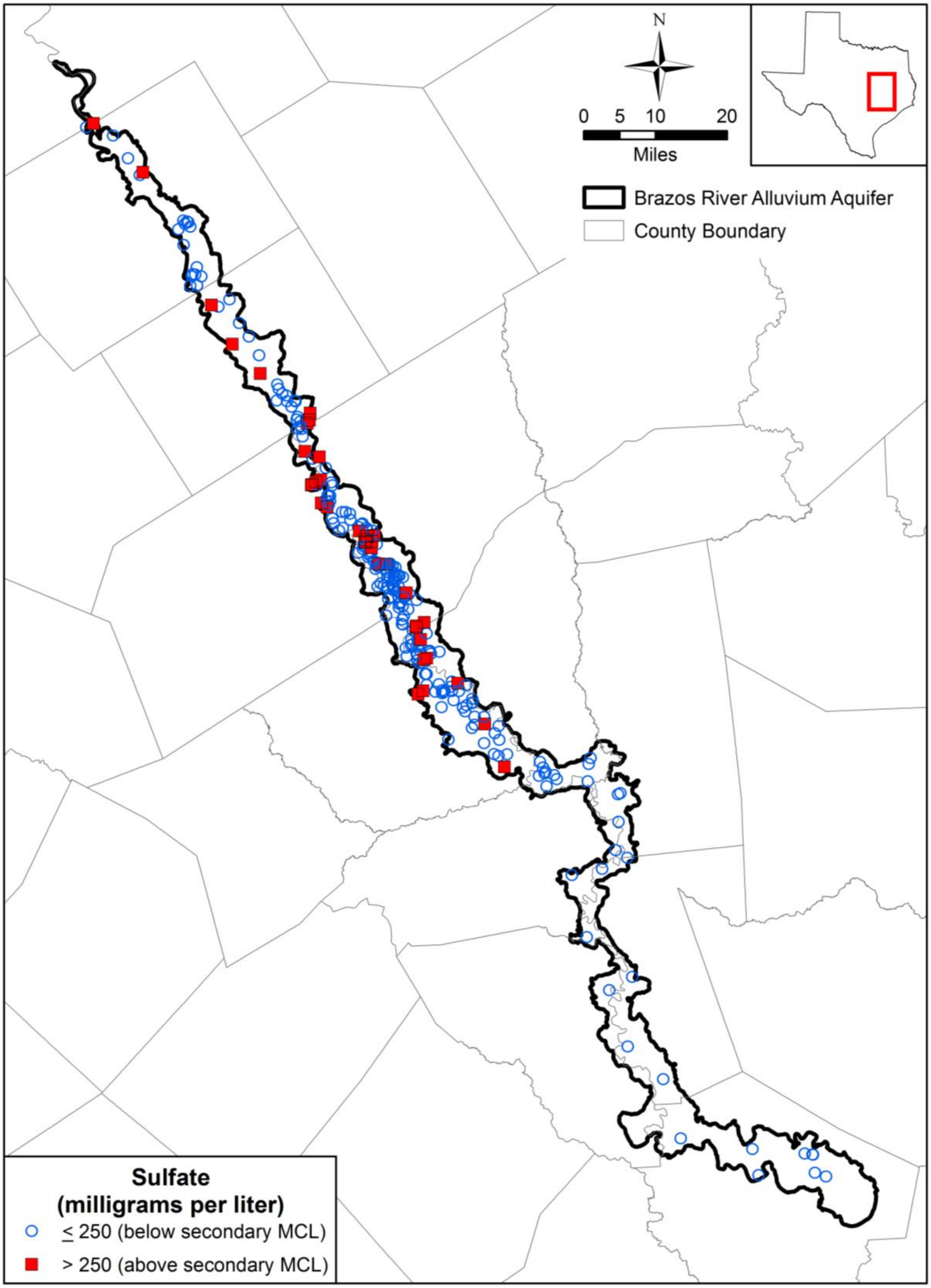


Figure 4.7.2 Sulfate concentrations in the Brazos River Alluvium Aquifer relative to the secondary maximum contaminant level (MCL) (TWDB, 2014f).

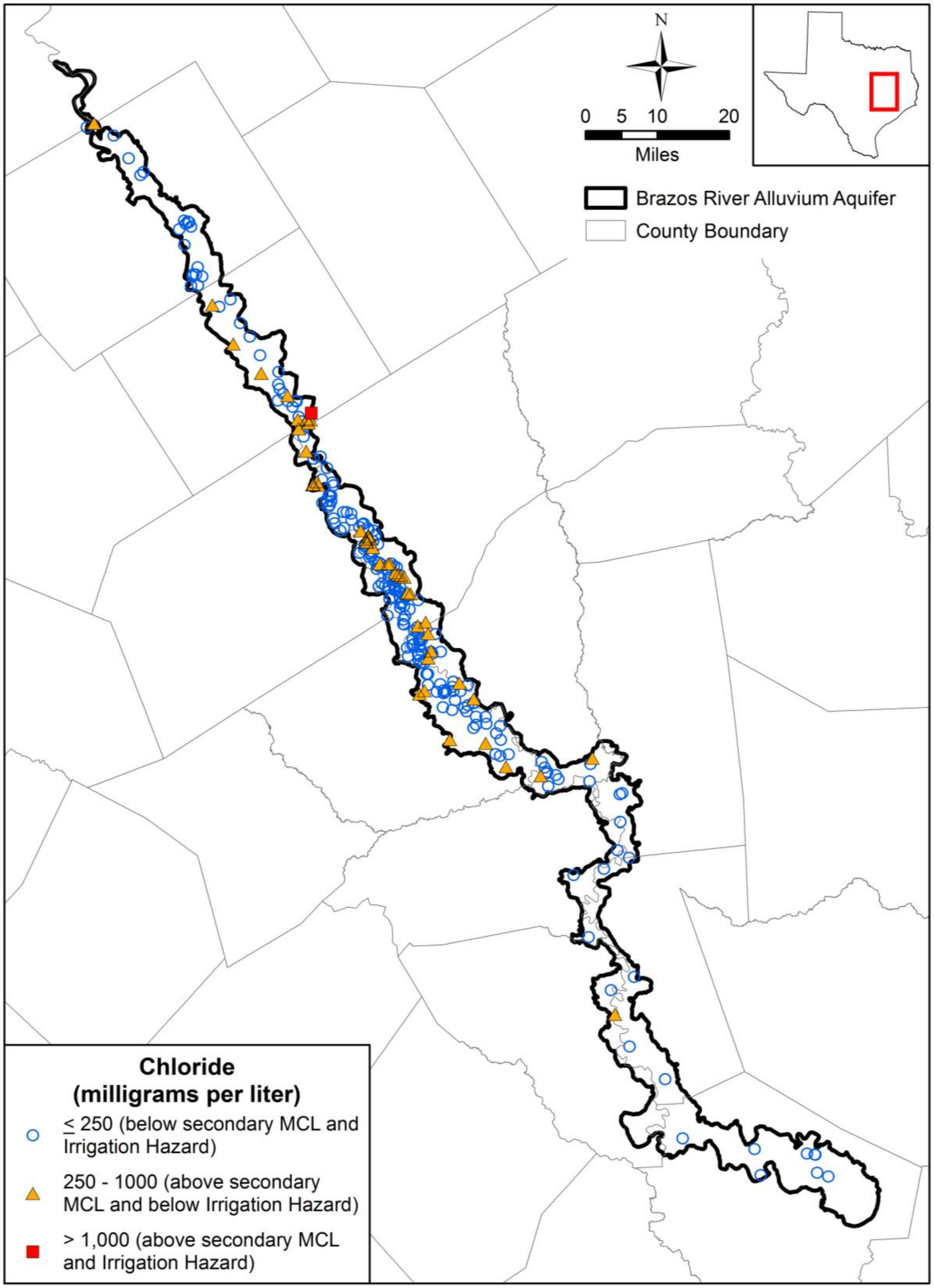


Figure 4.7.3 Chloride concentrations in the Brazos River Alluvium Aquifer relative to the secondary maximum contaminant level (MCL) and the irrigation hazard (TWDB, 2014f).

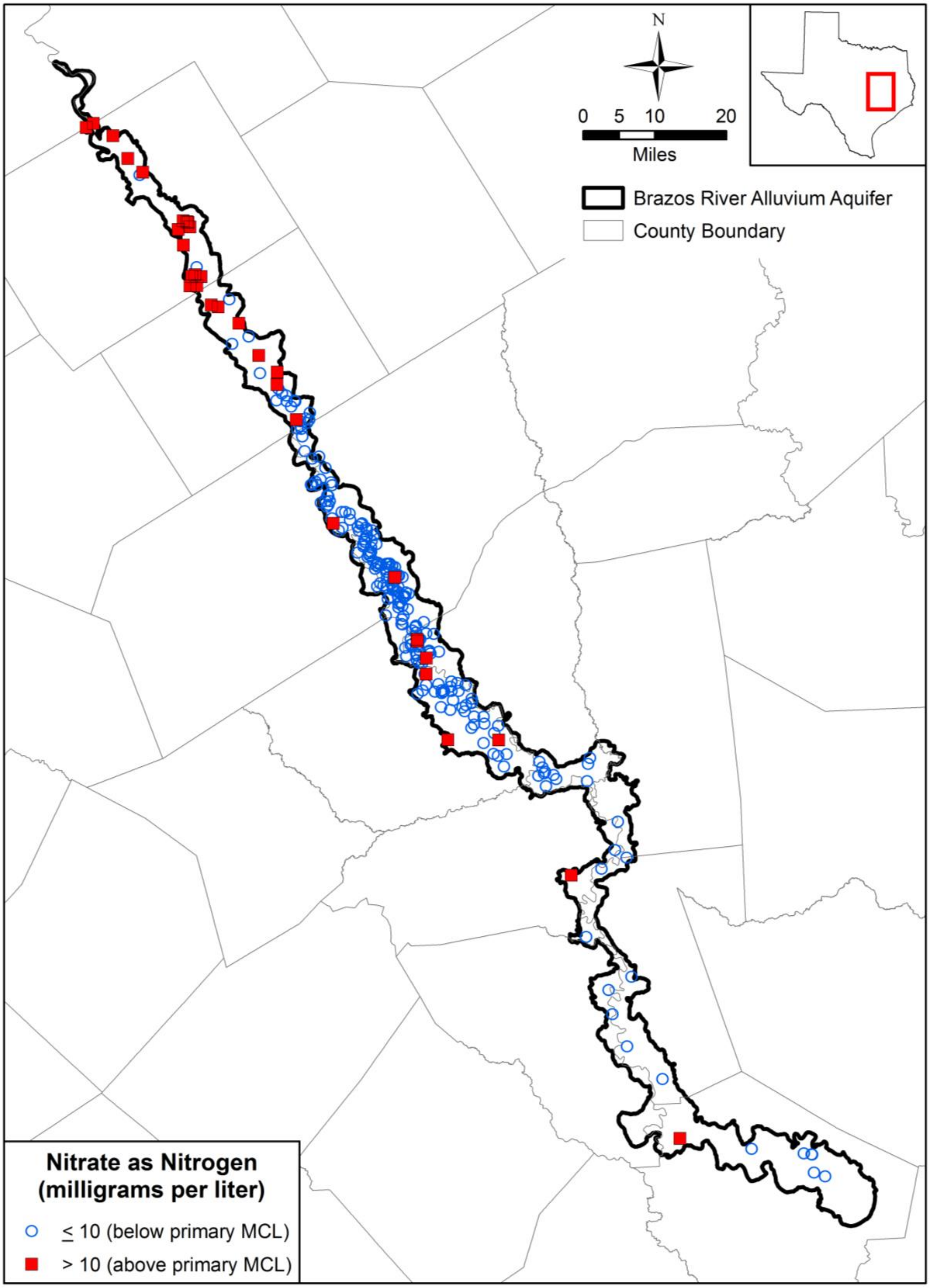


Figure 4.7.4 Nitrate as nitrogen concentrations in the Brazos River Alluvium Aquifer relative to the primary maximum contaminant level (MCL) (TWDB, 2014f).

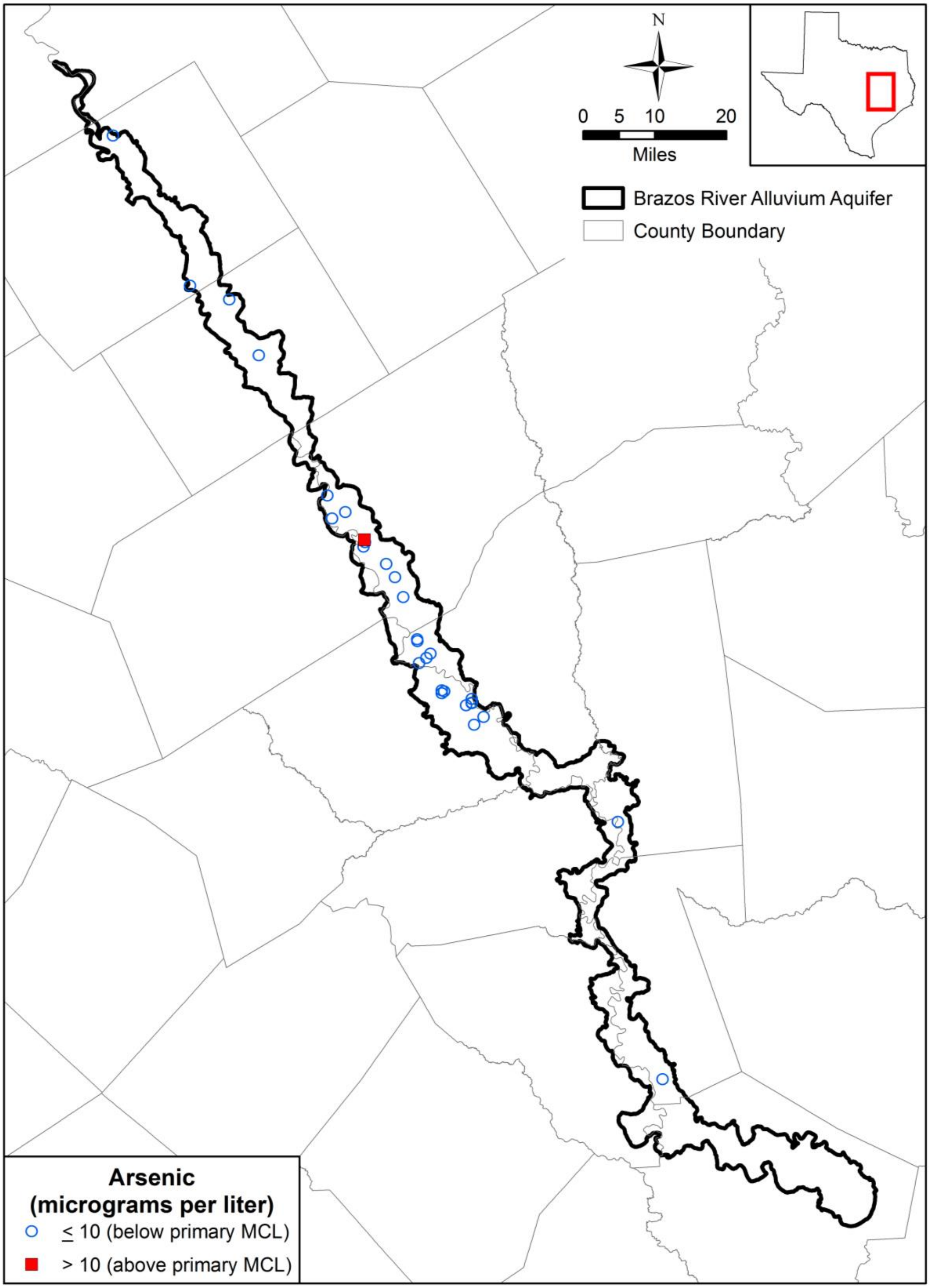


Figure 4.7.5 Arsenic concentrations in the Brazos River Alluvium Aquifer relative to the primary maximum contaminant level (MCL) (TWDB, 2014f).

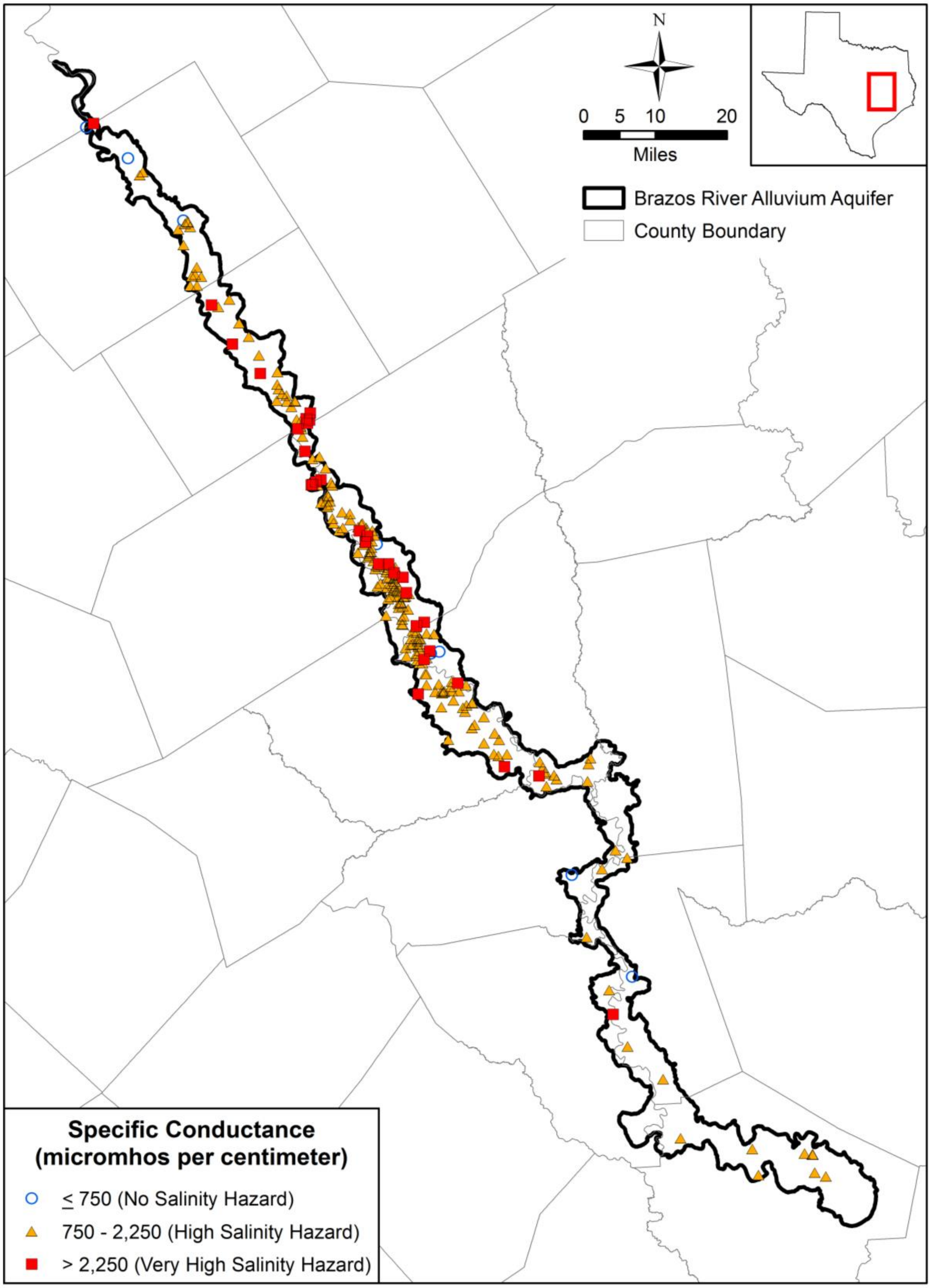


Figure 4.7.6 Irrigation salinity hazard in the Brazos River Alluvium Aquifer (TWDB, 2014f).

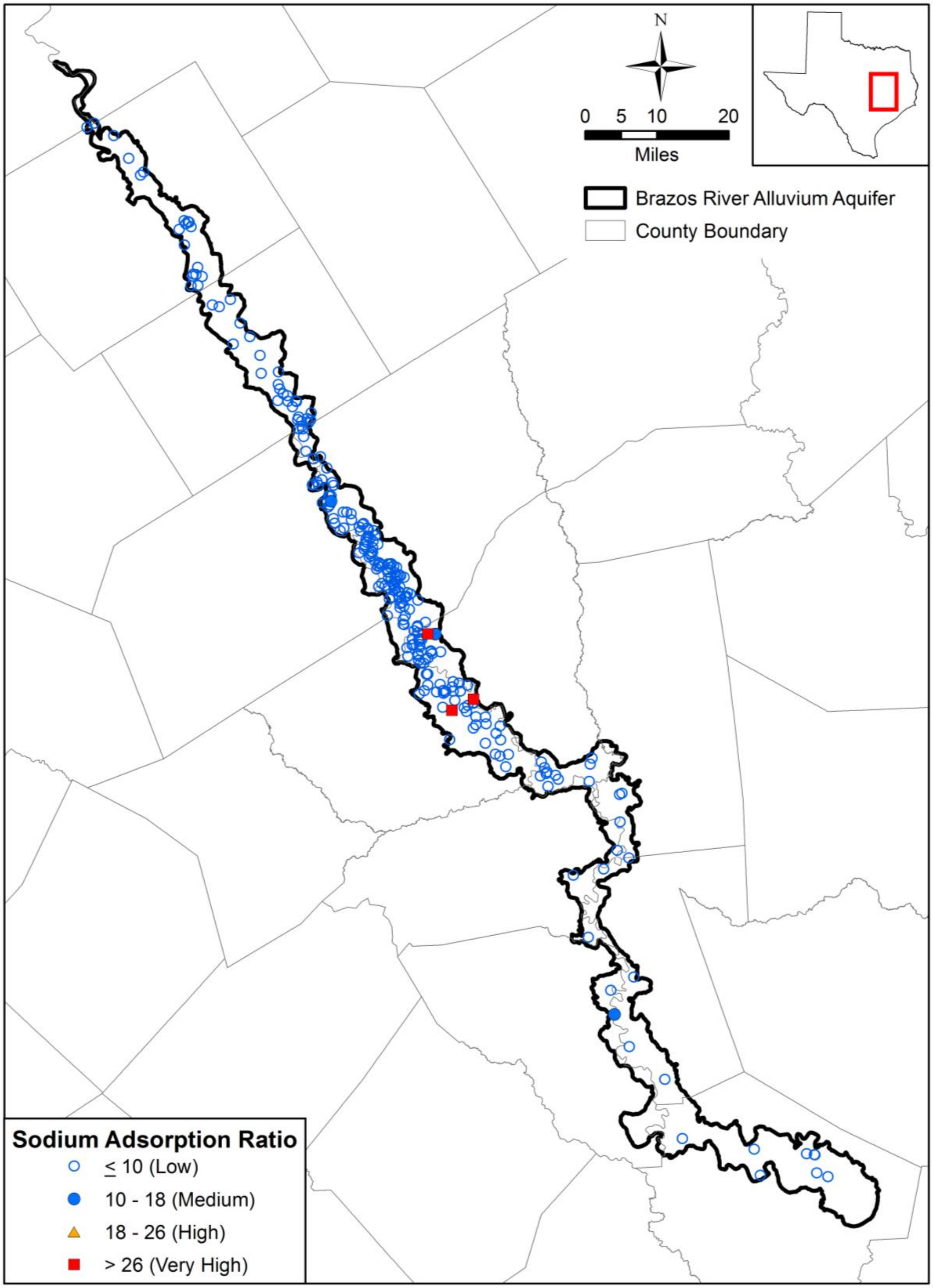


Figure 4.7.7 Sodium hazard in the Brazos River Alluvium Aquifer (TWDB, 2014f).

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5.0 Conceptual Model of Groundwater Flow in the Aquifer

The conceptual model of groundwater flow in the Brazos River Alluvium Aquifer is based on the hydrogeologic setting, described in Section 4.0. The conceptual model is a simplified representation of the hydrogeological features that govern groundwater flow in the aquifer. These include the hydrostratigraphy, structure, hydraulic properties, hydraulic boundaries, recharge and natural discharge, and anthropogenic stresses, such as pumping. Each of the elements of the conceptual model are summarized below. The Brazos River Alluvium Aquifer is unique compared to other Texas aquifers in that it extends regionally (hundreds of miles) in length but only locally (less than ten miles and as little as one quarter mile) in width, requiring both regional- and local-scale considerations. The aquifer is in direct contact with the Brazos River along the entirety of its length and never more than a few miles distant from the river throughout its width. Therefore, characterizing the surface water/groundwater interaction between the river and the alluvium is paramount to a conceptual understanding of flow within the aquifer. Because the Brazos River acts as a regional discharge boundary for the shallow flow systems in the aquifers and less-productive formations beneath the Brazos River Alluvium, it is also important to account for cross-formational flow between these underlying formations and the Brazos River Alluvium Aquifer.

The Brazos River Alluvium Aquifer stretches from Whitney Dam in Bosque and Hill counties south-southeastward along the path of the Brazos River into Fort Bend County. The boundaries of the Brazos River Alluvium Aquifer defined by the TWDB comprise floodplain alluvium and hydraulically connected terrace deposits consisting of fine to coarse sand, gravel, silt, and clay deposited by the Brazos River (Cronin and Wilson, 1967). Cronin and Wilson (1967) describe the composition of the alluvium as varying from place to place, with beds or lenses of sand and gravel that pinch out or grade laterally and vertically into finer or coarser material. In general, the finer material is in the upper part of the aquifer, and the coarser material is in the lower part. The aquifer is under water-table conditions in most places and is used mainly for irrigation. The water table generally slopes toward the Brazos River, indicating that the river is a gaining stream in most places.

The Quaternary-age Brazos River Alluvium Aquifer was deposited atop Cretaceous-, Tertiary- and older Quaternary-age formations throughout the Brazos River Basin, including two major and three minor aquifers. No Cretaceous-age aquifers directly underlie the Brazos River Alluvium in the study area. The Tertiary-age sediments contain, from northwest to southeast, the Carrizo-Wilcox, Queen City, Sparta, and Yegua-Jackson aquifers along with older portions of the Gulf Coast Aquifer System. The Quaternary-age sediments underlying the Brazos River Alluvium are composed of younger portions of the Gulf Coast Aquifer System. Including the shallow portion of these underlying formations as a model layer accounts for the shallow, local and intermediate scale groundwater flow system in the Brazos River Basin. The Brazos River acts as a regional discharge boundary for this shallow flow system via cross-formational flow into and through the Brazos River Alluvium Aquifer.

Hydraulic properties for the Brazos River Alluvium Aquifer are poorly defined. Hydraulic properties from long-duration aquifer pumping tests are available at only three locations within the aquifer. Given the paucity of long-duration aquifer pumping tests, aquifer transmissivities were estimated from 575 specific capacity measurements based on a theoretical relationship between specific capacity and transmissivity. Horizontal hydraulic conductivities were calculated by dividing the transmissivities by the estimated saturated thickness defined as the difference between the pre-development water-level surface and the aquifer base. Horizontal hydraulic conductivities range from 0.26 to 890 feet per day, with a geometric mean and median value of 59 and 83 feet per day, respectively. No estimates for the vertical hydraulic conductivity of the aquifer are available. Storage estimates range from values of 0.15, representative of an unconfined alluvial aquifer, to estimates as low as 0.004 from aquifer pumping tests reported in Wrobelski (1996), representative of a semi-confined aquifer.

The entirety of the Brazos River Alluvium Aquifer is outcropping and is directly affected by recharge and surface water bodies. Estimates of recharge in the southern portion of the Brazos River Basin were developed based on previous studies of the Yegua-Jackson Aquifer (Deeds and others, 2010) and the Gulf Coast Aquifer System (Scanlon and others, 2012). These studies estimate recharge rates ranging from less than 0.5 inches per year to over 2 inches per year. For the northern portion of the Brazos River Basin, a relationship between recharge and precipitation was developed based on hydrograph separation analyses and used to estimate recharge rates.

These recharge rates are generally between 0.5 and 1.5 inches per year. Recharge rates in both the northern and southern portions of the study area were adjusted in the Brazos River Alluvium Aquifer to account for surficial clays, where recharge was estimated to be less than 0.5 inches per year. Recharge for pre-development conditions was estimated to result in approximately 750,000 acre-feet per year entering the formations in the Brazos River Basin in the study area with 40,000 and 710,000 acre-feet per year recharging the Brazos River Alluvium Aquifer and the underlying formations, respectively. During the post-development period, irrigation return flow was estimated to result in localized increases in recharge. A maximum recharge rate directly beneath crop land of 7.7 inches per year was estimated through the 1950s. Irrigation induced recharge was estimated to decrease through time as irrigation efficiencies improved, culminating in a rate of 1.4 inches per year from the year 2000 onward. This irrigation return flow was estimated to contribute an additional 10,000 acre-feet per year of recharge to the Brazos River Alluvium Aquifer at the end of the post-development period.

The Brazos River is the only major river that intersects the Brazos River Alluvium Aquifer. Numerous tributaries to the Brazos River are also within the study area. Gain/loss studies are short duration tests that indicate whether a stream reach is gaining or losing at a particular point in time. Previous gain/loss studies on reaches of Brazos River tributaries indicate, on average, gaining conditions, with a range of -0.07 to 3.66 cubic feet per second per river mile (Slade and others, 2002). A re-analysis of the Turco and others (2007) gain/loss study on the main stem of the Brazos River shows both gaining and losing reaches along the river, with gains outweighing losses overall. Hydrograph separation analyses can be used to estimate long-term average base flow rates. Incremental base flow estimates indicate a total gain in base flow for the Brazos River of approximately 760,000 acre-feet per year across the entire study area. Note that this estimate includes the base flow contributions from all Brazos River tributaries except the Little River, and not solely base flow contributions directly to the main stem of the Brazos River. Therefore, it can be interpreted as an estimated total modern recharge value for the entire Brazos River Basin within the study area, as a whole.

Groundwater development in the Brazos River Alluvium Aquifer is thought to have begun in earnest during the 1950s drought when a significant number of wells were drilled in the aquifer for irrigation purposes (Cronin and Wilson, 1967). Groundwater from the aquifer has historically been used primarily for irrigation purposes, with an estimated 90 percent or more of the total pumping generally being used for irrigation. Groundwater production from the aquifer was estimated to have increased through the 1950s and early 1960s up to roughly 70,000 acre-feet per year in 1964. This was followed by a gradual decrease in pumping during the late 1960s and 1970s to roughly 30,000 acre-feet per year in 1979. Between 1980 and 2003, groundwater production in the aquifer fluctuated annually between 20,000 and 60,000 acre-feet per year, but saw no significant trends. Beginning in 2004, groundwater production has increased significantly and steadily in the aquifer culminating in a peak production of over 160,000 acre-feet per year in 2011. The recent dramatic increase in pumping has occurred primarily in Robertson County and, to a lesser-degree, Brazos and Burleson counties.

The schematic diagram in Figure 5.0.1 shows a west to east cross-section through the study area, based on cross-section 7 in Figure 2.2.6c through Burleson and Robertson counties, along with a conceptual block diagram illustrating aquifer layering and sources and sinks for groundwater. The strategy for constructing the Brazos River Alluvium Aquifer groundwater availability model required three model layers. In general, the upper portion of the Brazos River Alluvium Aquifer has relatively higher clay content than the lower portion, which has relatively higher sand and gravel content. Two model layers will be used to represent the Brazos River Alluvium Aquifer. A third layer will be used to represent the shallow portion of the underlying formations. The groundwater flow between the layers along with the pertinent boundary conditions for each layer are depicted in the block diagram. While it is not obvious in Figure 5.0.1, the underlying formations are extended laterally a significant distance to the lateral extents of the Brazos River Basin, which is a natural hydrologic boundary.

Under pre-development conditions, downdip flow into the underlying formations is conceptualized to be a very small portion of the recharge into the shallow groundwater flow system. By extending the lateral boundaries to the extents of the Brazos River Basin, the model domain can be considered a closed system, where the vast majority of the recharge within the basin discharges through surface water boundaries and evapotranspiration. This allows the lateral and basal boundaries of the active model domain to be considered no-flow boundaries. Defining boundaries in this way significantly reduces the error associated with prescribing either heads or fluxes at boundaries where data are incomplete.

A conceptual water balance of the pre-development flow system in the aquifer can be estimated from information reviewed in Section 4.0. Based on the recharge distribution developed in Section 4.3, approximately 40,000 acre-feet per year recharges the Brazos River Alluvium Aquifer as a result of precipitation falling directly on its outcrop. Of the approximately 710,000 acre-feet per year recharging the underlying units in the Brazos River Basin, the majority is expected to discharge to streams, springs, and evapotranspiration in the underlying units, with the remainder entering the Brazos River Alluvium Aquifer through cross-formational flow. The volume of cross-formational flow will be estimated during the numerical modeling phase of this project. The water entering the Brazos Alluvium Aquifer through areal recharge and cross-formational flow must discharge from the aquifer through streams, springs, and evapotranspiration. Stream gains to the Brazos River are expected to constitute the majority of this discharge, with a smaller portion discharging through evapotranspiration, smaller streams, and springs.

The post-development period for the aquifer describes the onset of groundwater production from both the Brazos River Alluvium Aquifer and the underlying aquifers. This period also includes land-use changes from agricultural activities, which may impact recharge to the aquifer from plowing and irrigation return flow, as well as changes in evapotranspiration resulting from anthropogenic changes to vegetation cover. Groundwater production from the Brazos River Alluvium Aquifer can be accounted for directly by applying flux boundary conditions at well locations within the aquifer based on the pumping estimates in Section 4.6. The impact of pumping in the aquifers underlying the alluvium is less straight-forward. Pumping from the shallow flow system of the underlying aquifers can be accounted for directly at well locations. However, pumping from the downdip portions of the underlying aquifers will be outside the model domain but may impact the cross-formational flow between the underlying aquifers and the Brazos River Alluvium Aquifer. The impact will depend on pumping rates, proximity to the Brazos River Alluvium Aquifer, and the local hydraulic properties of the underlying aquifers. This impact is currently unknown, but can be estimated by running the groundwater models for each of the underlying aquifers and, if necessary, replacing the basal no-flow boundary condition with a flux boundary condition during the numerical modeling phase of this project. The impacts of land-use changes during the post-development period can be accounted for by altering recharge rates, as well as evapotranspiration rates and rooting depths based on crop type and coverage, as discussed in Sections 4.3 and 2.2, respectively. Implementation of all model boundaries will be discussed in the Numerical Model Report that is a companion to this Conceptual Model Report. Modern increases to recharge from irrigation return flow are estimated to be approximately 10,000 acre-feet per year at the end of the post-development period. This indicates that the recent production rates of around 160,000 acre-feet per year may not only be capturing rejected recharge from the surface water system through decreases in evapotranspiration and/or spring flow, but may also be capturing streamflow from the Brazos River and its tributaries in areas of high groundwater production located near streams. Estimates of capture will be made during the numerical model phase of this project.

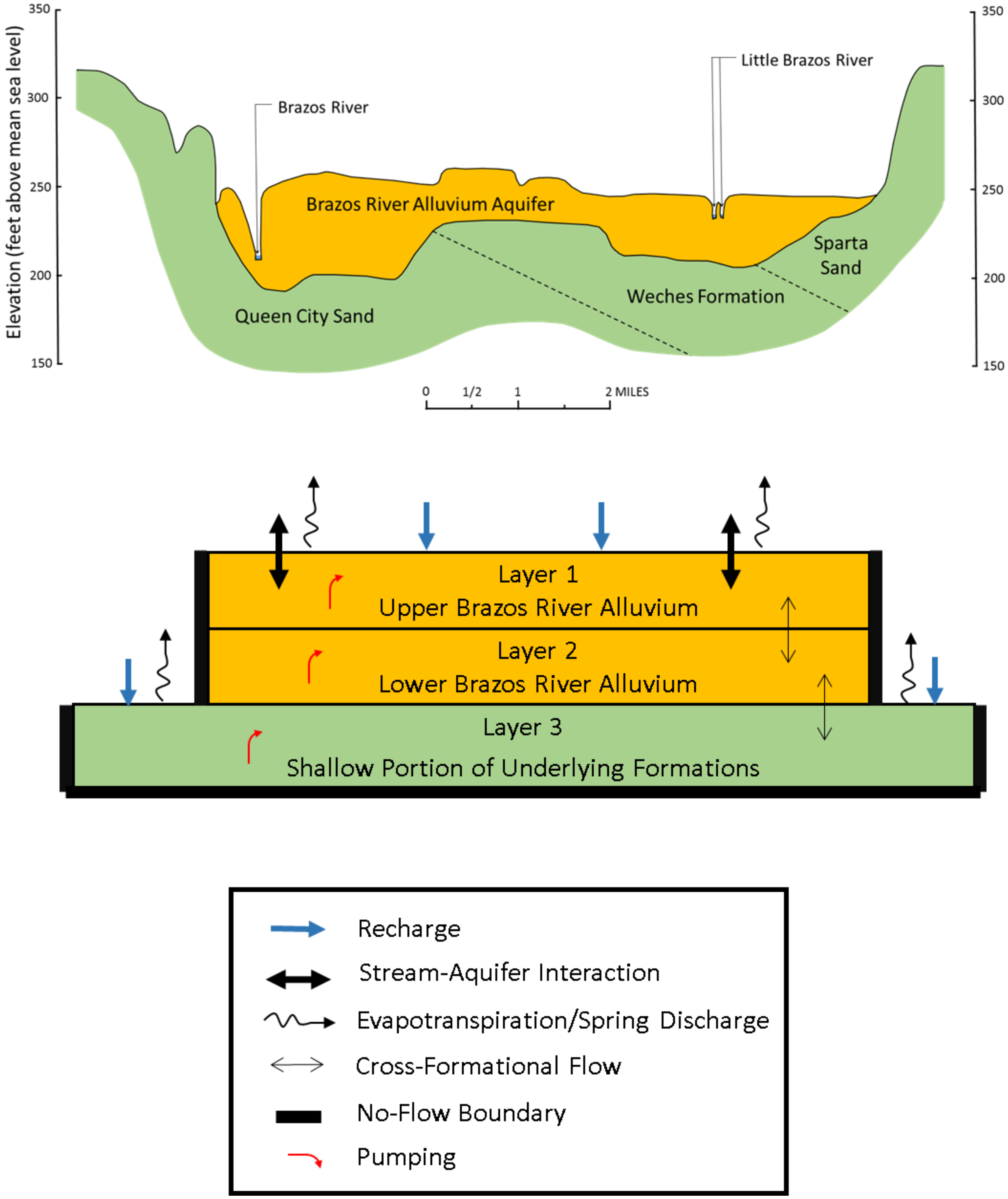

Figure 5.0.1 Conceptual groundwater flow model (cross-sectional view) for the Brazos River Alluvium Aquifer.

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6.0 Future Improvements

In this section, recommendations for potential future improvements in the conceptual model are provided. Additional ideas may occur through the continued stakeholder process and the development of the numerical model. The recommendations are approximately grouped, when applicable, according to the subsections in Section 4.0.

Hydrostratigraphic Framework

The base of the Brazos River Alluvium Aquifer is uncertain for the following reasons:

- Development of the basal surface of the aquifer relied strongly on the assumption that total depth for wells completed in the aquifer represent the base of the aquifer. This assumption was made due to an overall lack of geophysical log data from which the base of the aquifer could be estimated.
- The sediments of the Brazos River Alluvium Aquifer and underlying Gulf Coast Aquifer are very similar making it difficult to distinguish between the two aquifers.
- The density of data for determining the base of the aquifer is low at the northern and southern portions of the aquifer.

The basal surface of the aquifer could be improved in the future by incorporating additional analyses, either geophysical logs or drillers' logs, as they become available. Although this would provide some improvement in the understanding of the aquifer base, it does not address the difficulty in distinguishing between the Brazos River Alluvium and Gulf Coast aquifers. If it is important to tighten up estimates of water in storage in the Brazos River Alluvium Aquifer, additional detailed core studies to identify the base of the aquifer where it overlies the Gulf Coast Aquifer would be helpful.

Water Levels

Although available for the northern and central portions of the aquifer, the distribution of water-level data in the southern third of the aquifer is sparse. The understanding of water levels in this portion of the aquifer could be improved by developing monitoring plans for existing wells and collecting data in new wells.

A comparison of vertical gradients within the Brazos River Alluvium Aquifer was limited due to an overall lack of information on completion intervals in wells. As new wells are drilled, records on completion intervals could be used to identify well pairs appropriate for assessing vertical flow in the aquifer.

An understanding of the relationship between the Brazos River Alluvium Aquifer and the underlying aquifers would be enhanced by conducting aquifer pumping tests at nearby wells completed in each aquifer. Such an analysis was attempted in developing this conceptual model, but appropriate well pairs could not be identified. As new wells are drilled, appropriate well pairs may become available for analyzing vertical flow between the aquifers.

Recharge

The characterization of recharge in the Brazos River Alluvium Aquifer is limited due to the uncertainty of the factors used to estimate recharge values. For instance, while the literature mentions that clay units such as Ships Clay restrict flow locally within the aquifer, there are few measurements that actually quantify this effect and describe its spatial variation. Further investigations specifically studying the impact of clay layers in the alluvium could help identify areas where the flow system might be under confined or semi-confined conditions.

Irrigation return flow estimates were also limited due to the lack of studies specific to the area. While irrigation efficiencies by type are available for counties in the study area, efficiency values do not differentiate between losses to evaporation, runoff to streams, and irrigation return flow. Detailed studies to quantify the irrigation return flow component under local conditions would help constrain the impact that irrigation has on the water table. In addition, the spatial distribution of irrigation return flow is uncertain due to the lack spatial coverage differentiating irrigated versus rain-fed cropland. The method used in the current study, while capable of providing a rough estimate of irrigated areas, would be greatly improved by the addition of control points that could be used to ground-truth the satellite imagery-based classifications. Another point of concern is the conceptualization of gravel pits and mining excavations. Further study investigating the recharge, or discharge, potential of these features could help describe their impact on the local flow system.

The base flow study presented in the current study could be improved as well. Currently the base flow analyses along the main stem of the Brazos River include recharge input from areas outside the footprint of the Brazos River Alluvium Aquifer. Obtaining additional flow estimates for some of the major tributaries flowing into the Brazos River would allow the recharge analyses to hone in on just the area falling within the footprint of the aquifer. Conducting chloride mass balance analyses in the study area could provide an additional check on the validity of the recharge estimates derived from the base flow analyses

Surface Water Interaction

Beyond the gain/loss studies and hydrograph separation analyses discussed in the current study, little has been done to quantify surface water/groundwater interaction along the Brazos River. Further work to identify gaining and losing stretches of the river and explore the connection these sections have with underlying formations could improve the understanding of the river and aquifer as a connected system. The TWDB is currently conducting a bathymetry survey of the Brazos River that could be helpful for characterizing the interface between the river and the Brazos River Alluvium Aquifer.

Knowledge of surface water/groundwater interaction is limited at surface water bodies as well as at rivers and streams. In the Brazos River Alluvium Aquifer, only one study has tried to explore the connection between oxbow lakes and the underlying aquifer and this is limited to three point locations. Given the ubiquity of oxbow lakes within the footprint of the Brazos River Alluvium Aquifer, further study on aquifer/oxbow lake interactions could be warranted.

Hydraulic Properties

Understanding of the hydraulic character of the aquifer is significantly restricted due to an overall lack of hydraulic property data, which is available from aquifer pumping tests at only three locations. Because specific capacity is a function of both the aquifer and the well, using these data to estimate aquifer transmissivity is not ideal. Additional aquifer pumping tests in the Brazos River Alluvium Aquifer in different portions of the aquifer would significantly increase the resolution of the hydraulic conductivity data. In addition, aquifer pumping tests specifically in the Brazos River Alluvium Aquifer, with monitoring in an underlying aquifer, would be useful for estimating the vertical conductivity between the two aquifers.

Pumping

The vast majority of irrigation pumping in the Brazos River Alluvium Aquifer does not have rate measurements at the wellhead or at the pivot. In the absence of these measurements, other strategies, such as GIS-based analyses of crop water use, might improve estimates of production.

Water Quality

The use of water quality to assess the interaction between the Brazos River Alluvium Aquifer and underlying aquifers is limited due to a lack of nearby wells completed in the outcrop area of the underlying aquifers. As new wells are drilled, collection of groundwater chemistry data from well pairs in the Brazos River Alluvium Aquifer and outcrop area of the underlying aquifer could enhance the understanding of flow between the aquifers.

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Appendix A
County Hydrographs

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Hydrographs of transient water-level data for wells completed in the Brazos River Alluvium Aquifer were too numerous to include in the main body of this report. Therefore, this appendix was created to show all hydrographs. Not all of the available transient water-level data were plotted as hydrographs and included here. Data for wells with fewer than five water-level measurements or water-level measurements over a period of less than 5 years were not plotted.

Each hydrograph contains a title that consists of the state well number for the well and the county in which the well is located on the first line and the aquifer (Brazos River Alluvium Aquifer) on the second line. Each hydrograph contains three pieces of data: water levels in the well (blue line with open blue squares), the land surface datum for the well as given in the TWDB groundwater database (green line), and the bottom of the well (brown line). In a few instances, the total depth of the well was not included in the TWDB groundwater database, so the base of the well is not indicated. The purpose for including the land surface datum and base of well were to show the depth to groundwater and the saturated thickness. Note that in some cases, the land surface datum plots on the upper x-axis of the hydrograph and/or the bottom of the well plots on the bottom x-axis of the hydrograph.

For all hydrographs, the scale for years on the x-axis is from 1950 to 2020. The scale for the water-level elevation on the y-axis varies from hydrograph to hydrograph depending on the range of the observed data; however, the division of the y-axis is consistent at 10 feet. For wells with a range in water level, surface elevation, and bottom of well data of less than 50 feet, the scale for the y-axis was set at 50 feet.

Hydrographs are shown as individual figures. The locations with hydrograph data are provided on Figure 4.2.6 in the main body of the report. Up to six hydrographs are shown on a page. The hydrographs are organized by county from north to south and, for each county, are in order by well number. For several counties, the criteria of greater than or equal to five measurements over a period of 5 years or more was not met for any wells. Therefore, no hydrographs for those counties are shown here. The counties falling into this category are Hill, Milam, Waller, and Fort Bend counties.

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McLennan County

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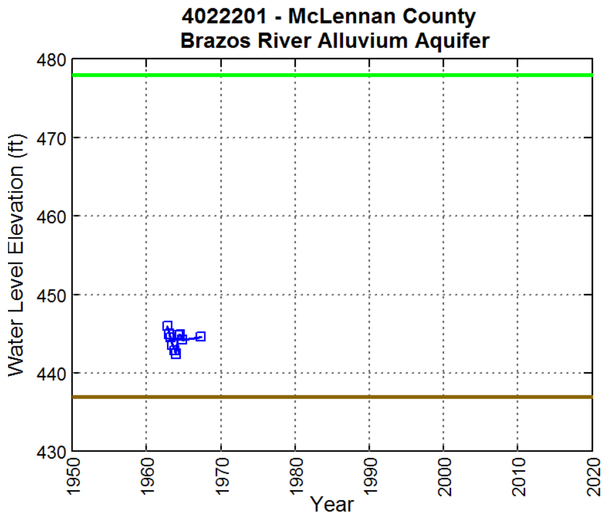
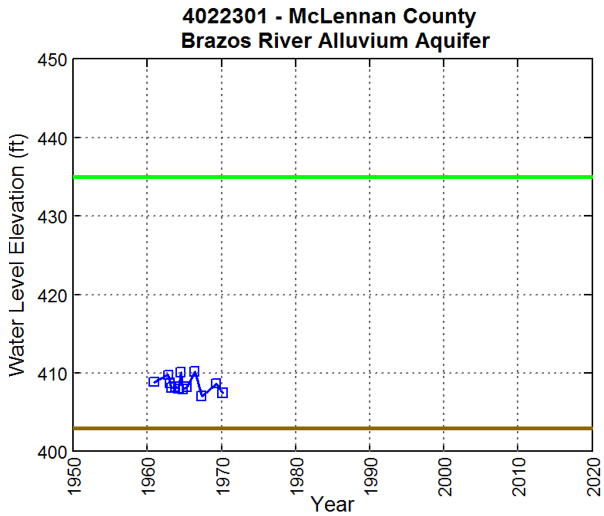
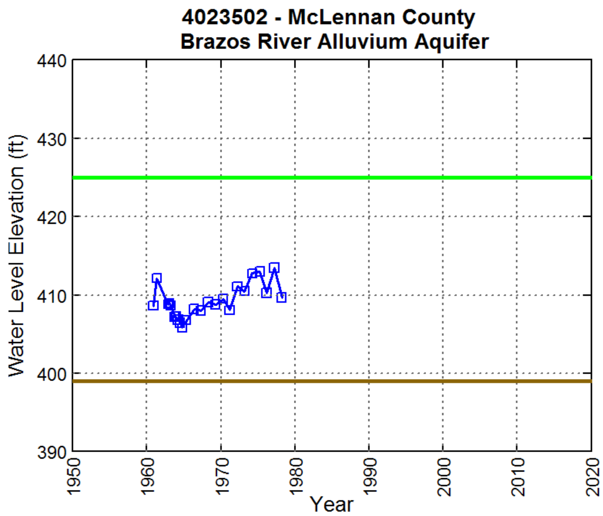
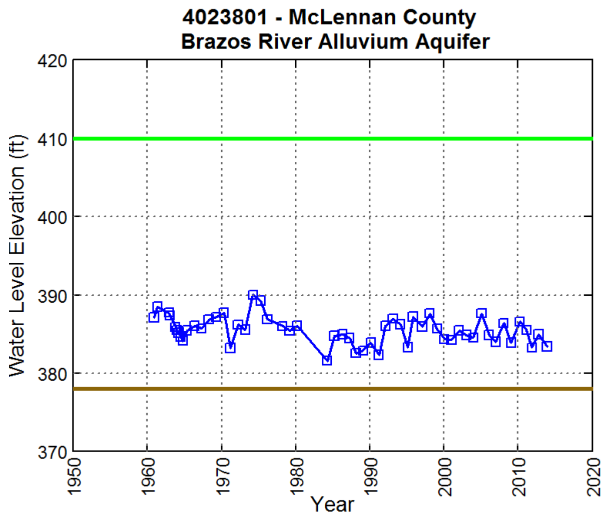
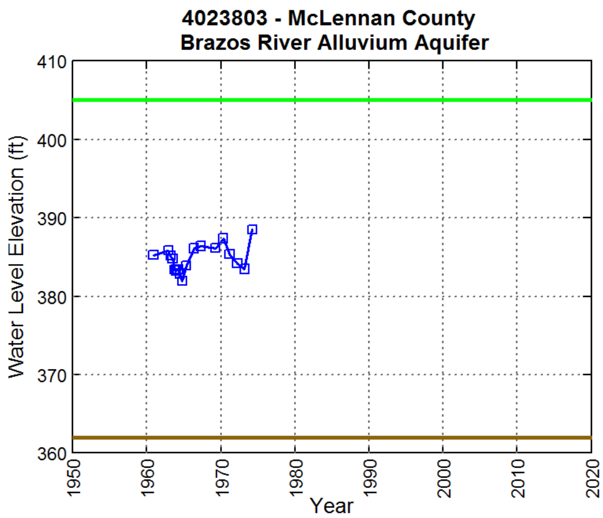
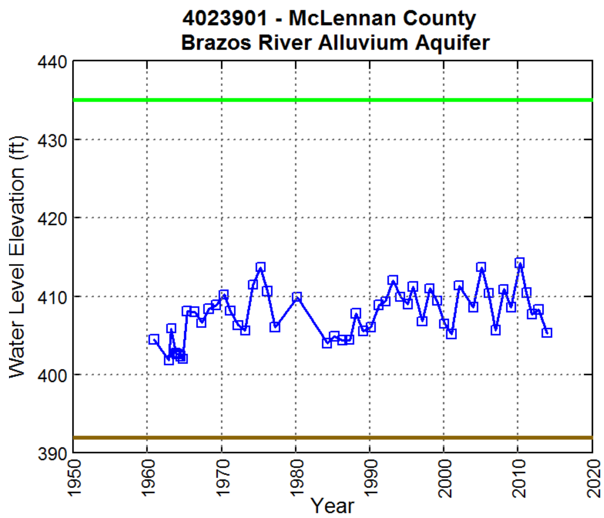

4022201 - McLennan County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year
480
470
460
450
440
430
1950
1960
1970
1980
1990
2000
2010
2020

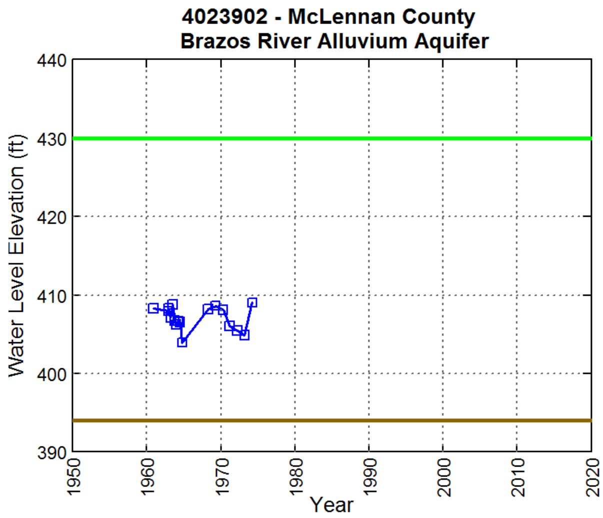

4022301 - McLennan County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year
450
440
430
420
410
400
1950
1960
1970
1980
1990
2000
2010
2020

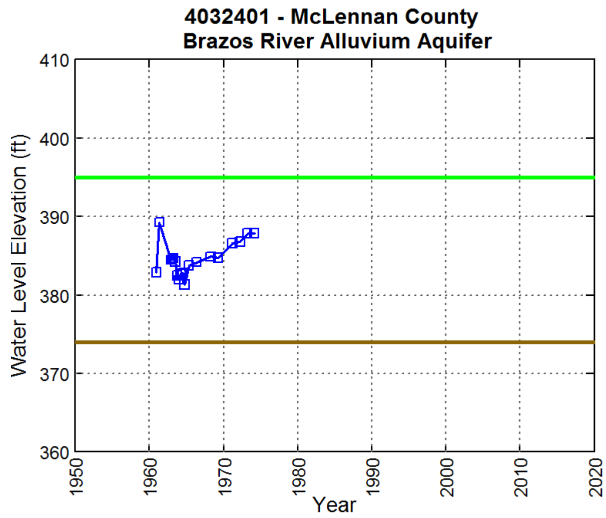

4023502 - McLennan County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year
440
430
420
410
400
390
1950
1960
1970
1980
1990
2000
2010
2020


4023801 - McLennan County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year
420
410
400
390
380
370
1950
1960
1970
1980
1990
2000
2010
2020


4023803 - McLennan County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year
410
400
390
380
370
360
1950
1960
1970
1980
1990
2000
2010
2020


4023901 - McLennan County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year
440
430
420
410
400
390
1950
1960
1970
1980
1990
2000
2010
2020


4023902 - McLennan County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year
440
430
420
410
400
390
1950
1960
1970
1980
1990
2000
2010
2020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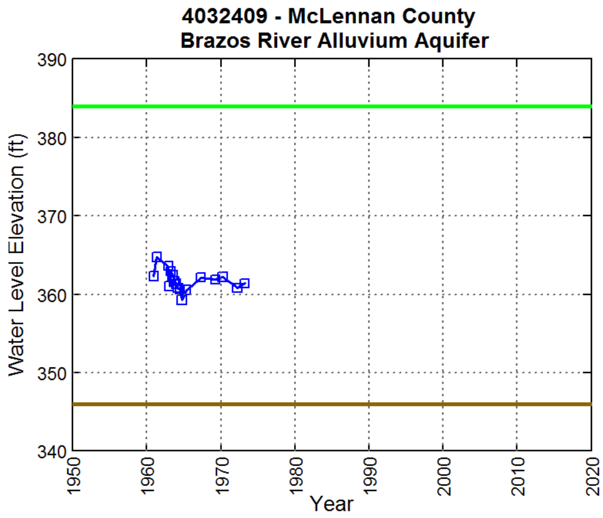
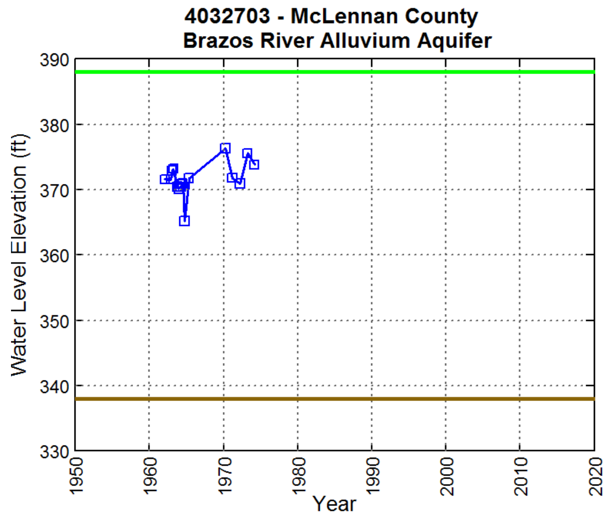
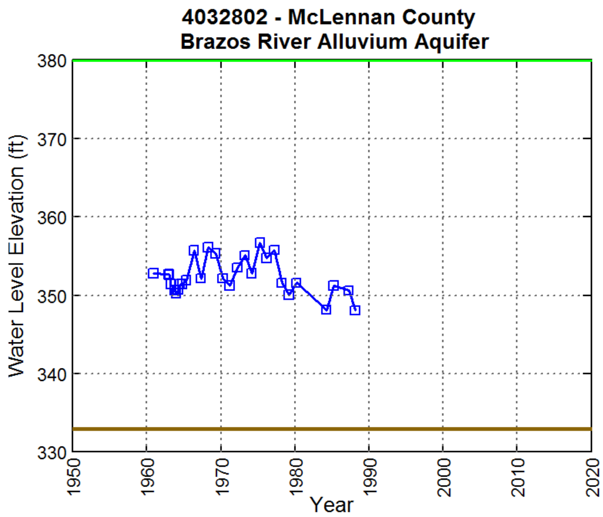
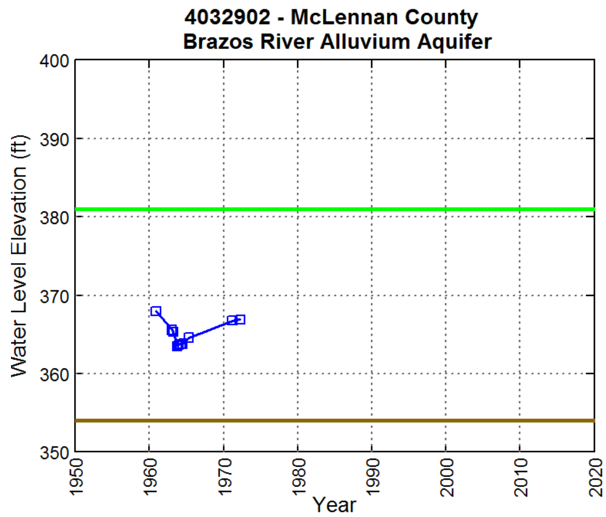
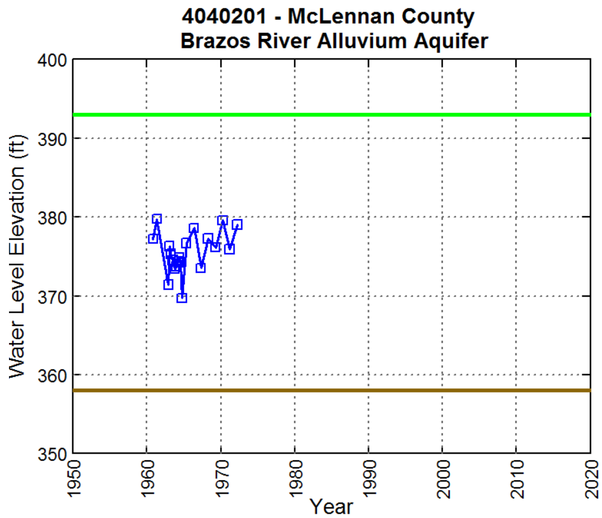
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year
410
400
390
380
370
360
1950
1960
1970
1980
1990
2000
2010
2020

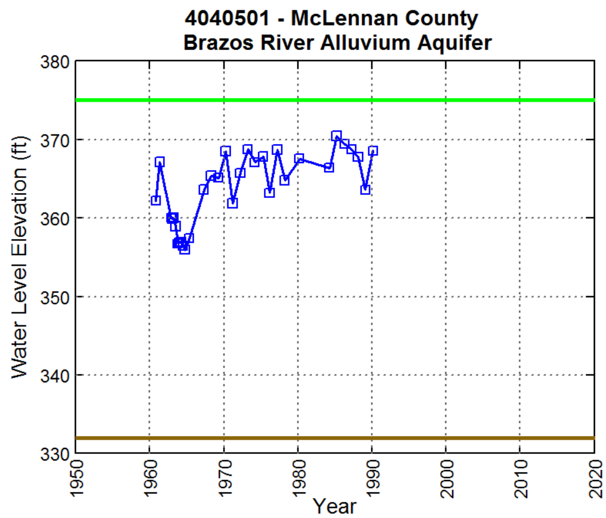

4032409 - McLennan County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year
390
380
370
360
350
340
1950
1960
1970
1980
1990
2000
2010
2020

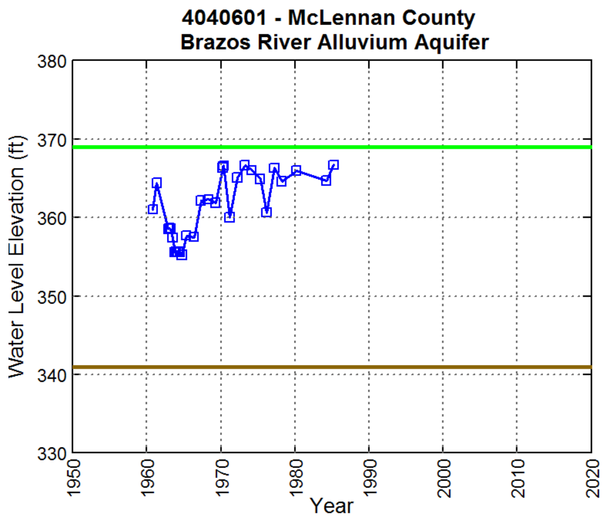

4032703 - McLennan County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year
390
380
370
360
350
340
330
1950
1960
1970
1980
1990
2000
2010
2020

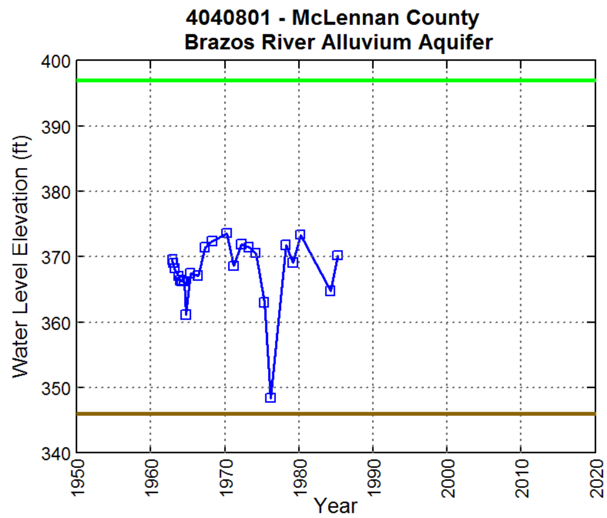

4032802 - McLennan County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year
380
370
360
350
340
330
1950
1960
1970
1980
1990
2000
2010
2020


4032902 - McLennan County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year
400
390
380
370
360
350
1950
1960
1970
1980
1990
2000
2010
2020


4040201 - McLennan County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
400
390
380
370
360
350
1950
1960
1970
1980
1990
2000
2010
2020
Year


4040501 - McLennan County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
380
370
360
350
340
330
1950
1960
1970
1980
1990
2000
2010
2020
Year


4040601 - McLennan County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
380
370
360
350
340
330
1950
1960
1970
1980
1990
2000
2010
2020
Year


4040801 - McLennan County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
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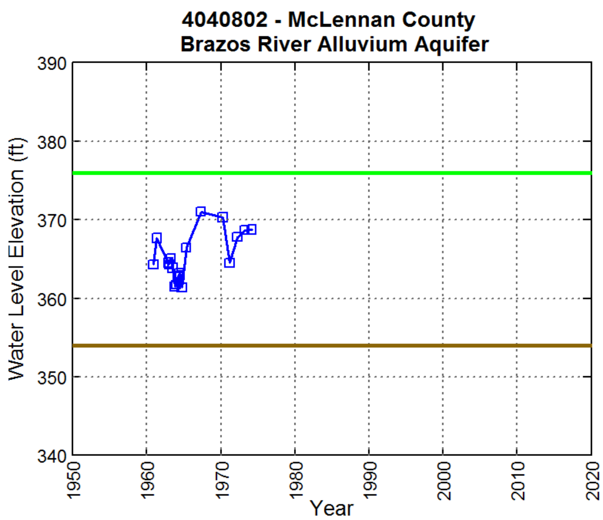
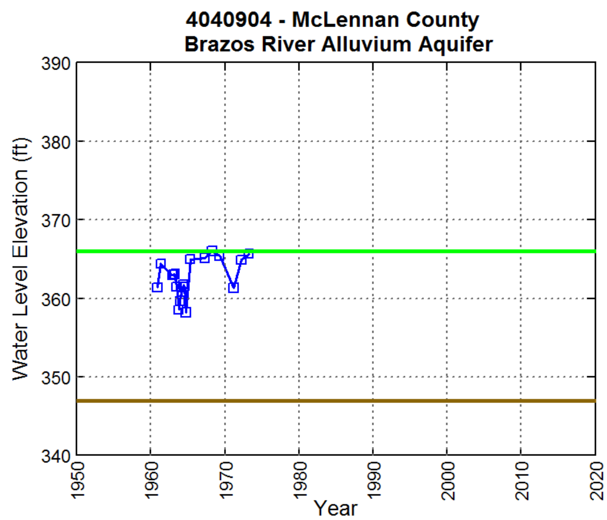
390
380
370
360
350
340
1950
1960
1970
1980
1990
2000
2010
2020
Year


4040802 - McLennan County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
390
380
370
360
350
340
1950
1960
1970
1980
1990
2000
2010
2020
Year


4040904 - McLennan County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
390
380
370
360
350
340
1950
1960
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1990
2000
2010
2020
Year

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Falls County

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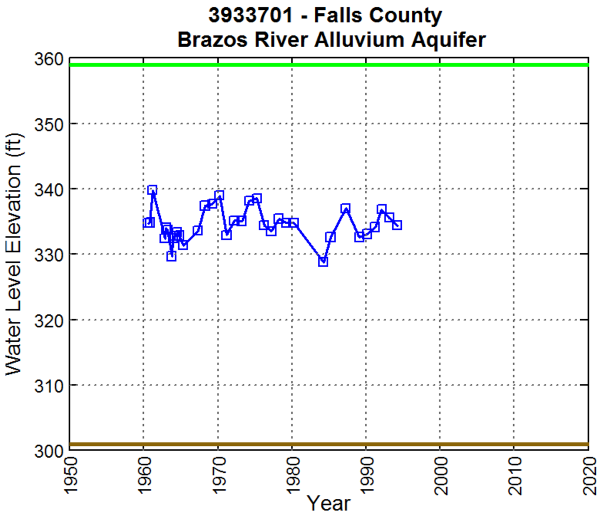
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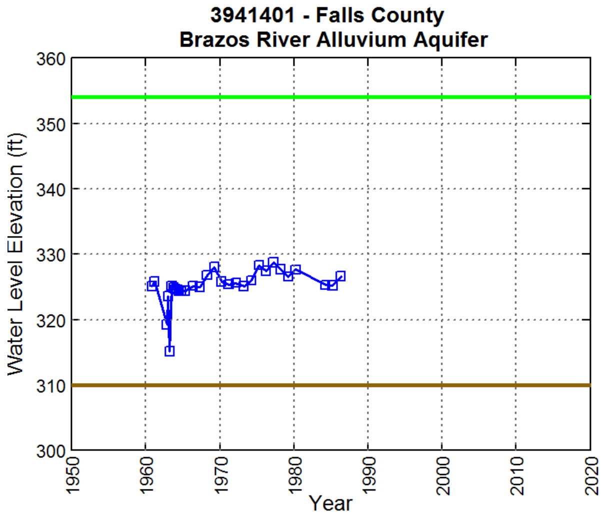
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year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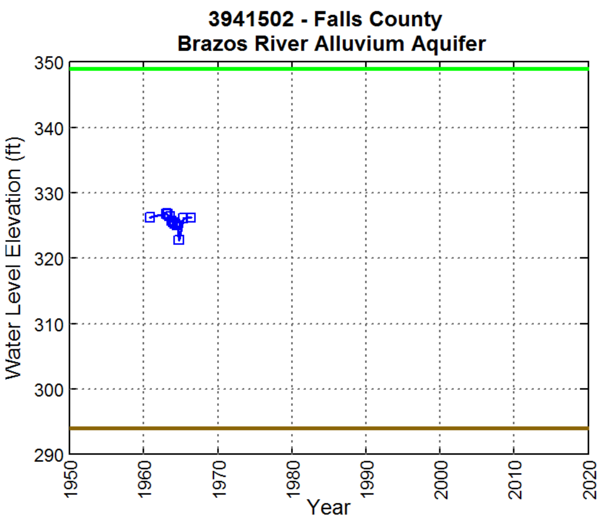
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year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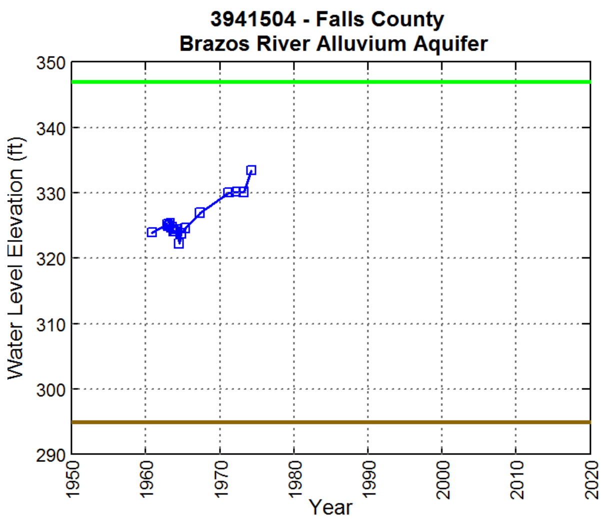
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year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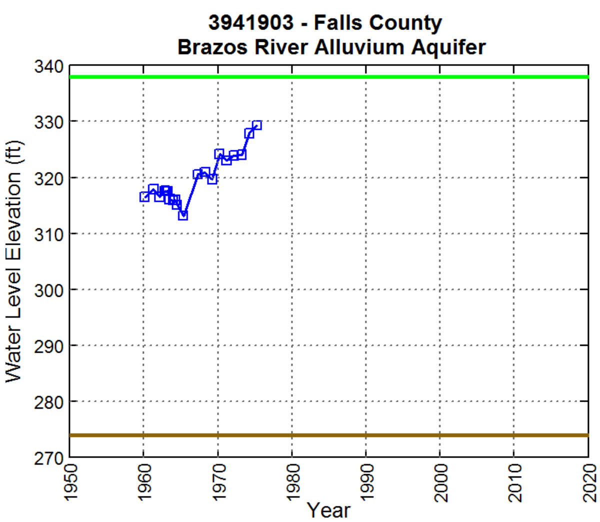
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year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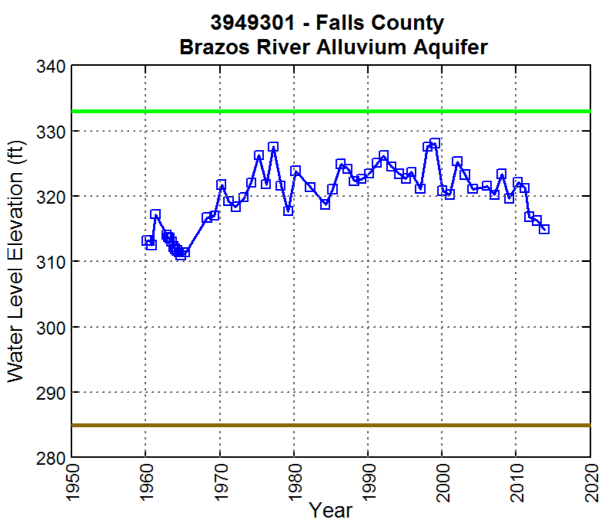
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year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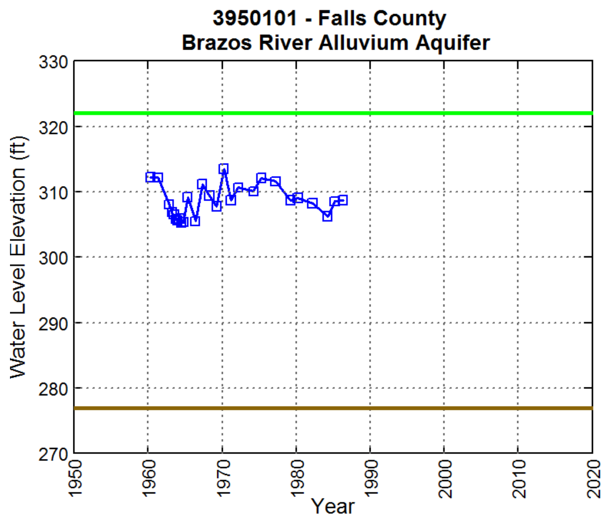
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year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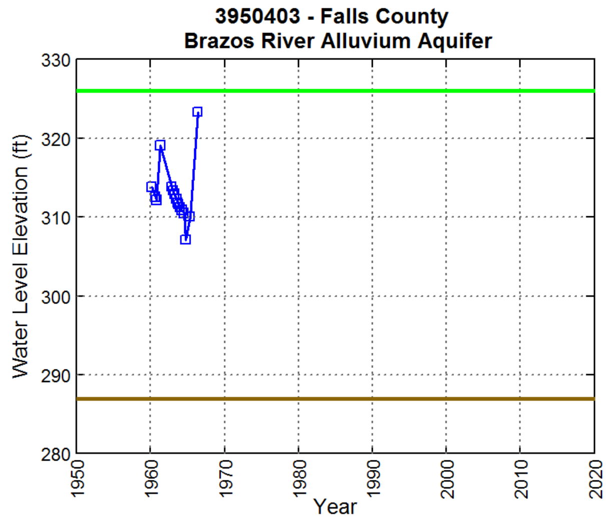
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year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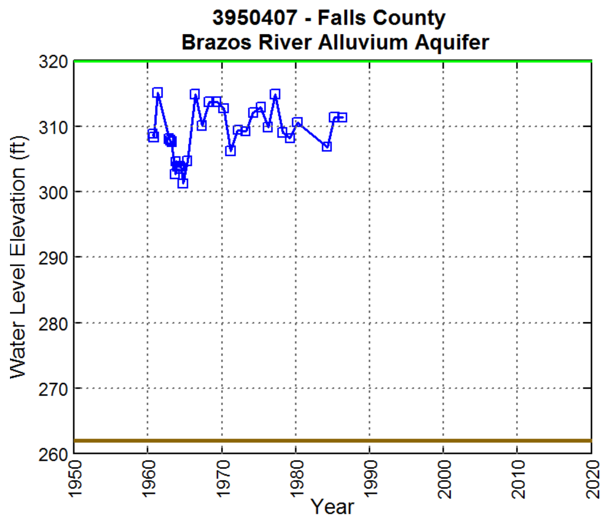
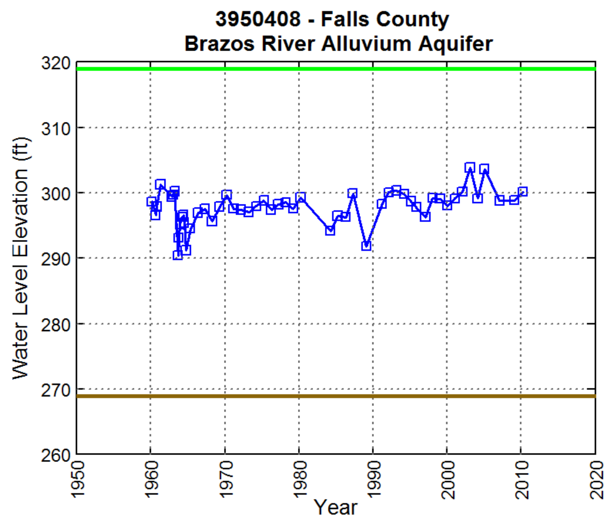
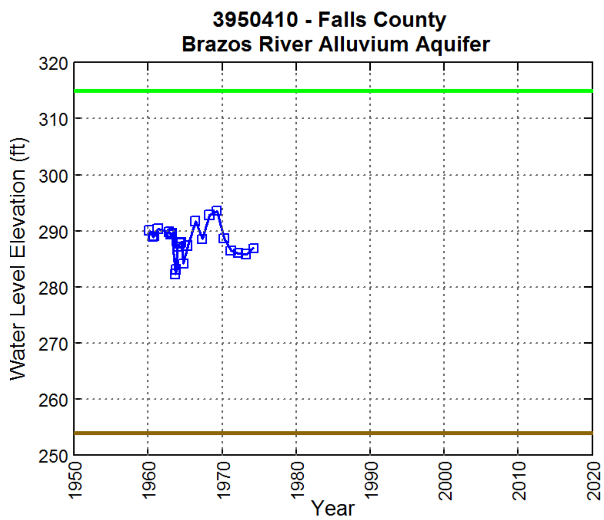
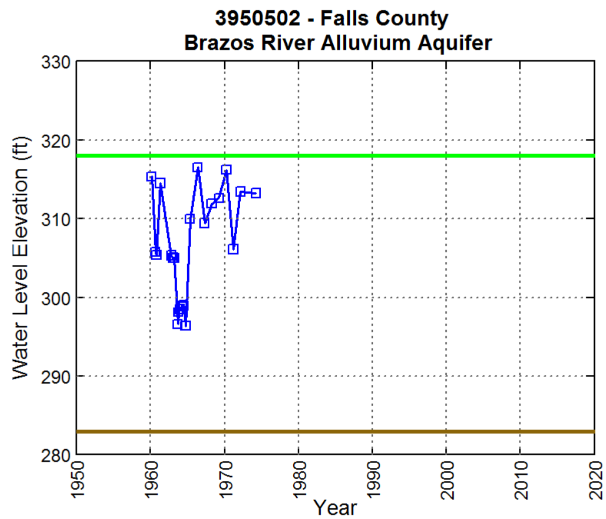
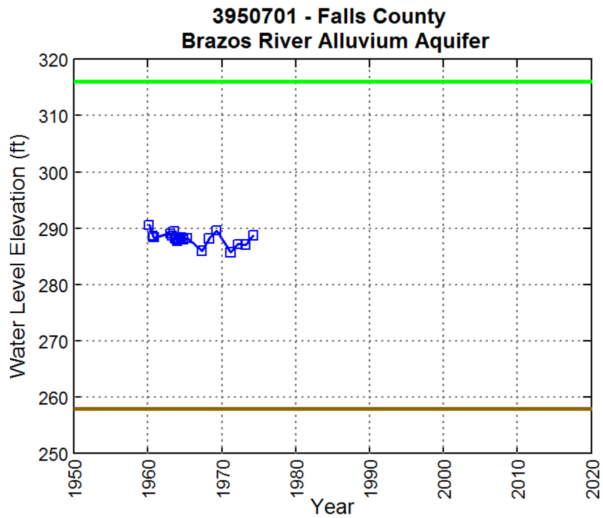
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year

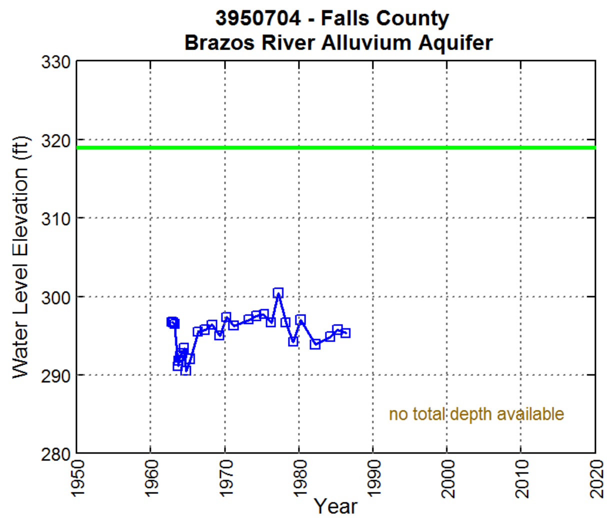

3950407 - Falls County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year

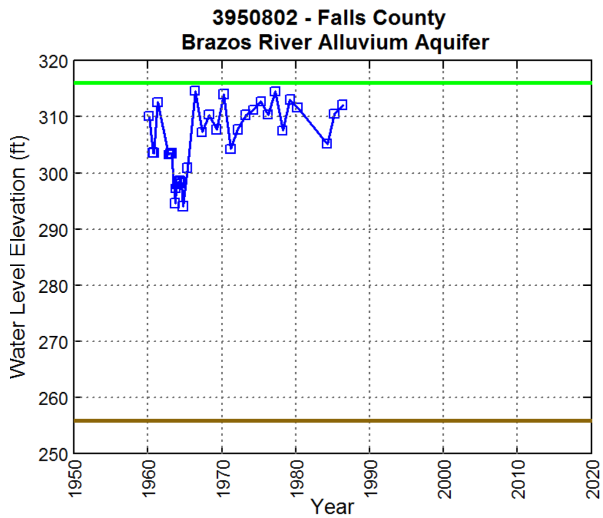

3950408 - Falls County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year

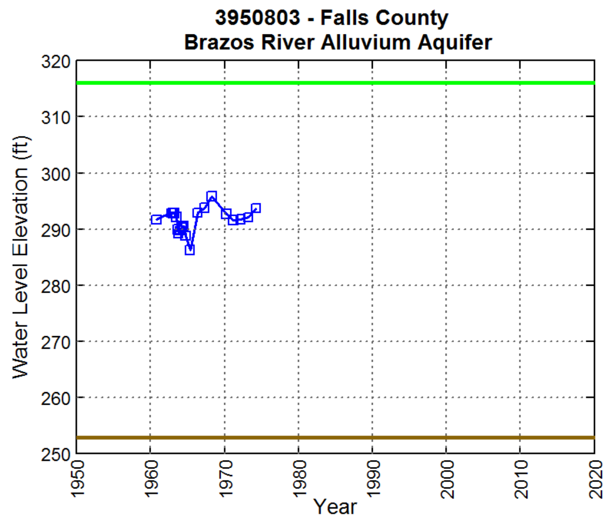

3950410 - Falls County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year

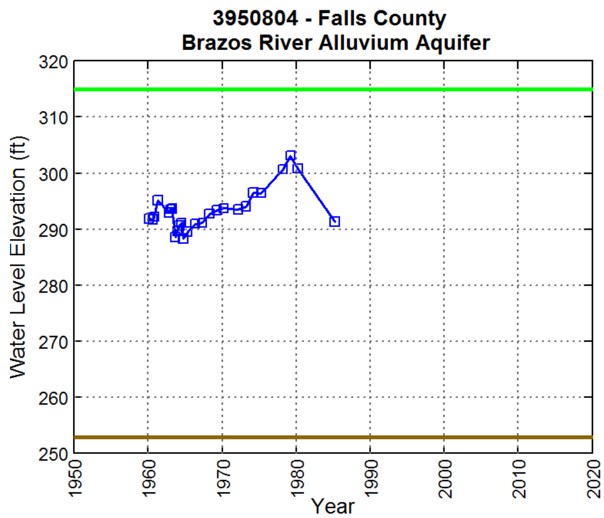

3950502 - Falls County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year

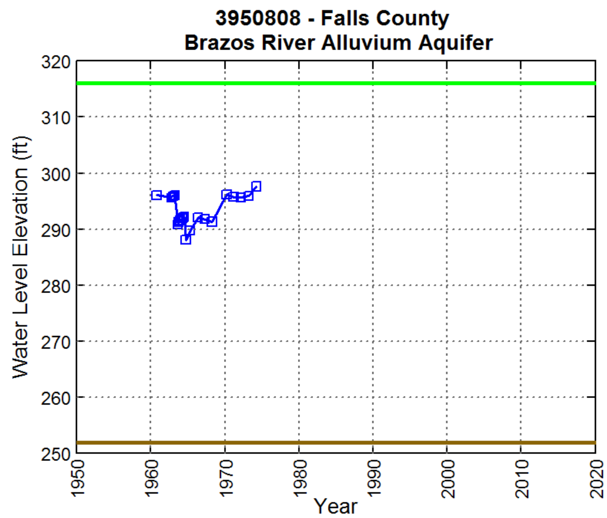

3950701 - Falls County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year

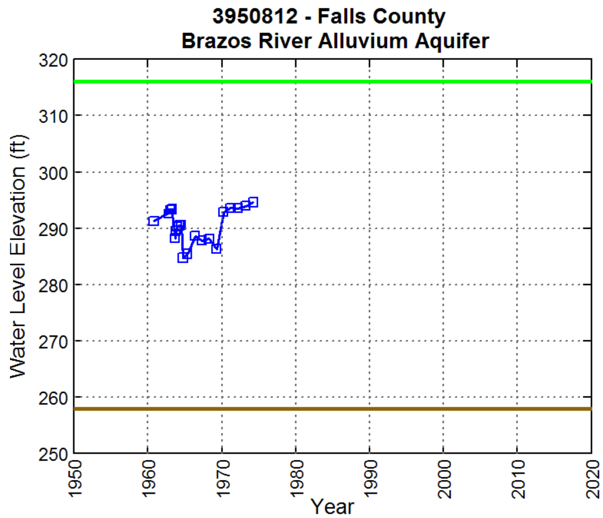

3950704 - Falls County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
no total depth available
Year

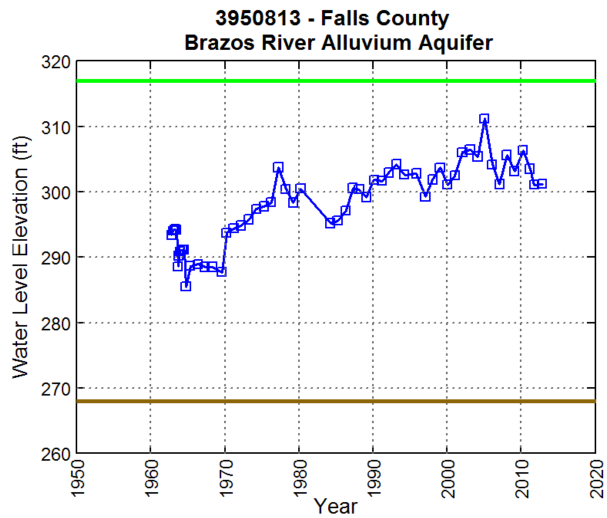

3950802 - Falls County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year

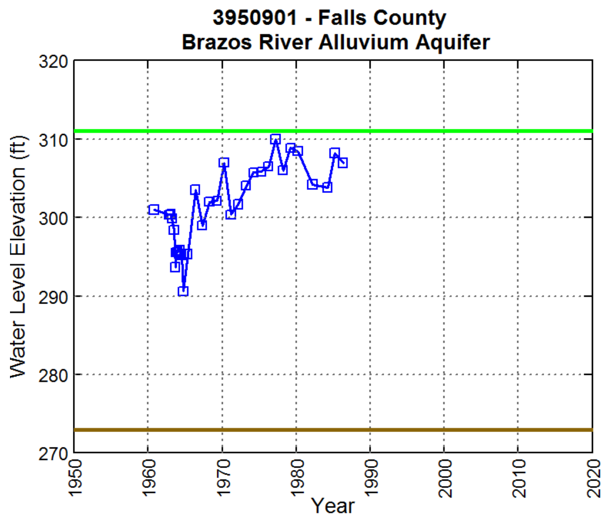

3950803 - Falls County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year

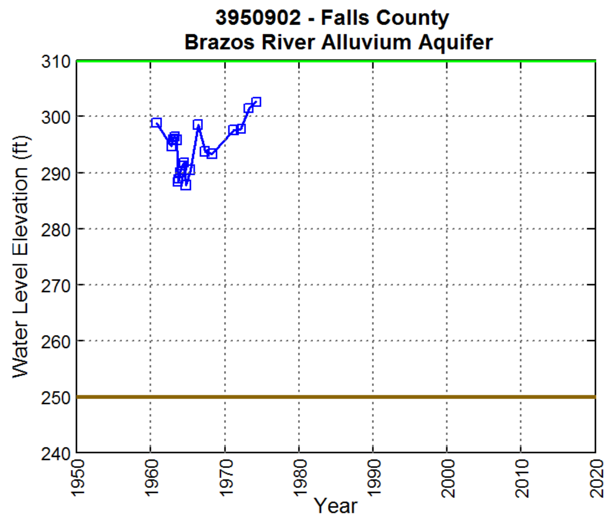

3950804 - Falls County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year

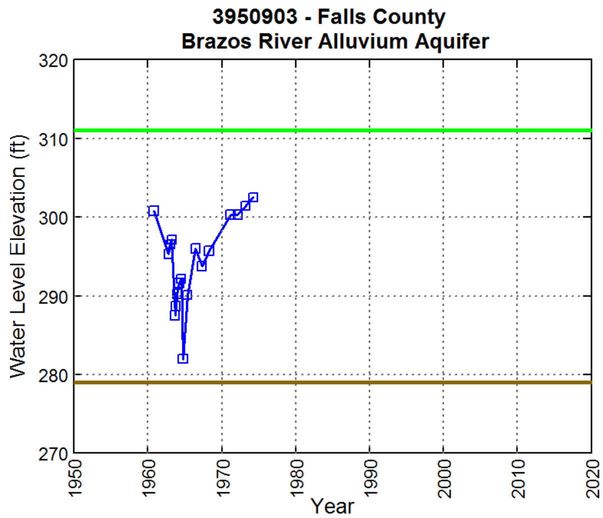

3950808 - Falls County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year

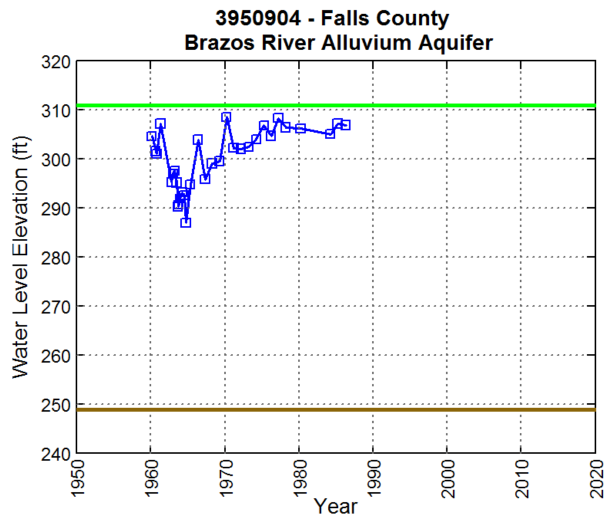

3950812 - Falls County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year

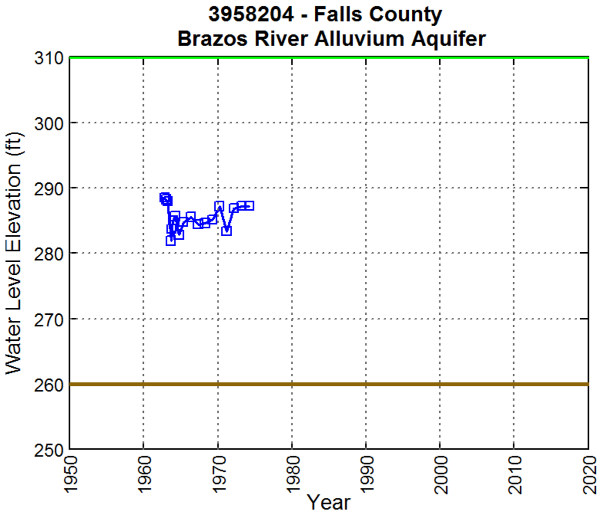

3950813 - Falls County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year

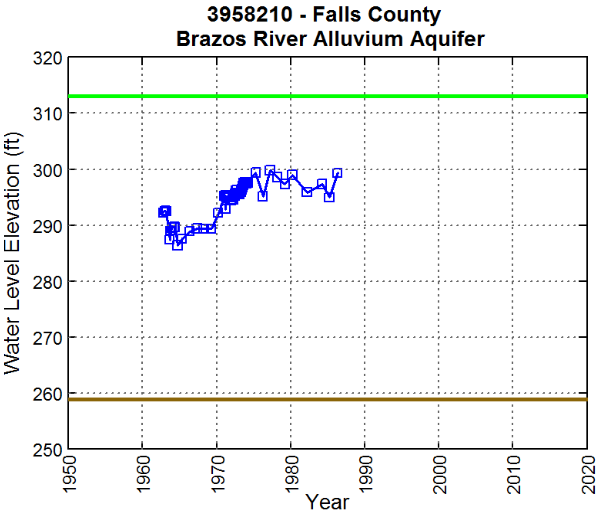

3950901 - Falls County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year

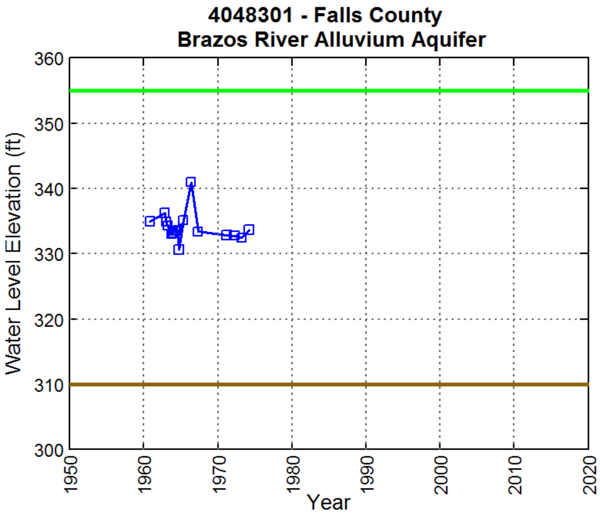

3950902 - Falls County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year


3950903 - Falls County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year


3950904 - Falls County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year


3958204 - Falls County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year
310
300
290
280
270
260
250
1950
1960
1970
1980
1990
2000
2010
2020


3958210 - Falls County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year
320
310
300
290
280
270
260
250
1950
1960
1970
1980
1990
2000
2010
2020


4048301 - Falls County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year
360
350
340
330
320
310
300
1950
1960
1970
1980
1990
2000
2010
2020

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Robertson County

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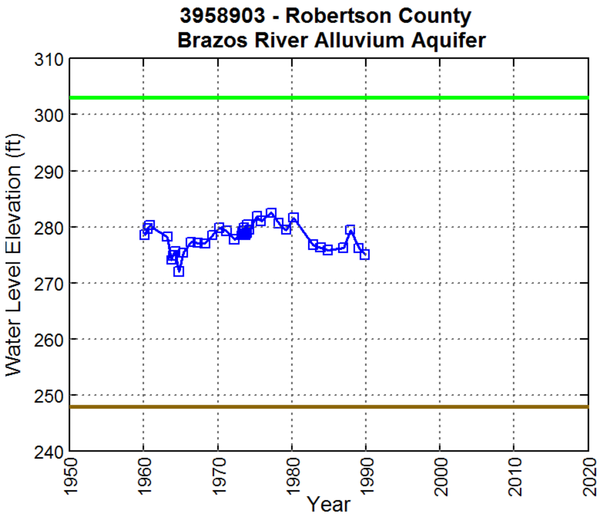
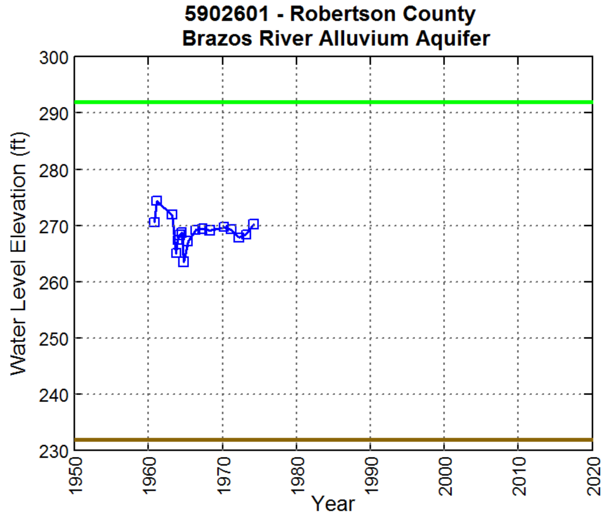
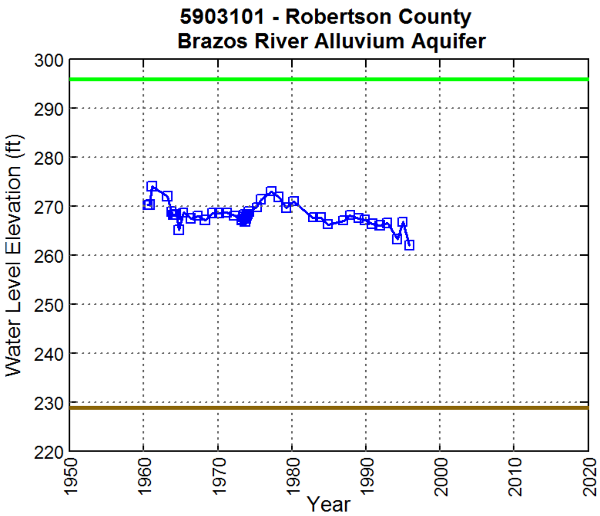
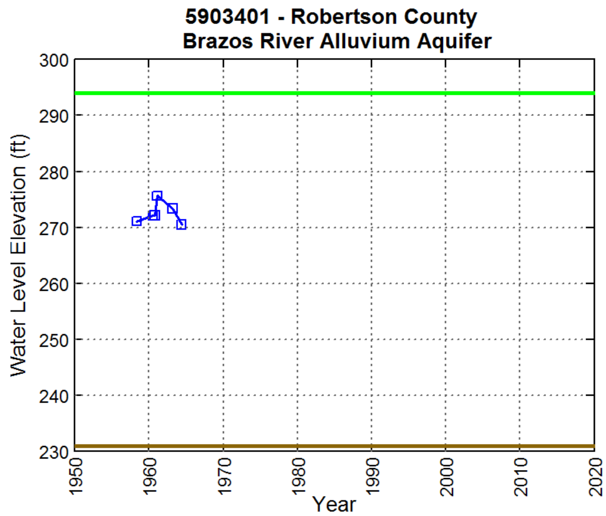
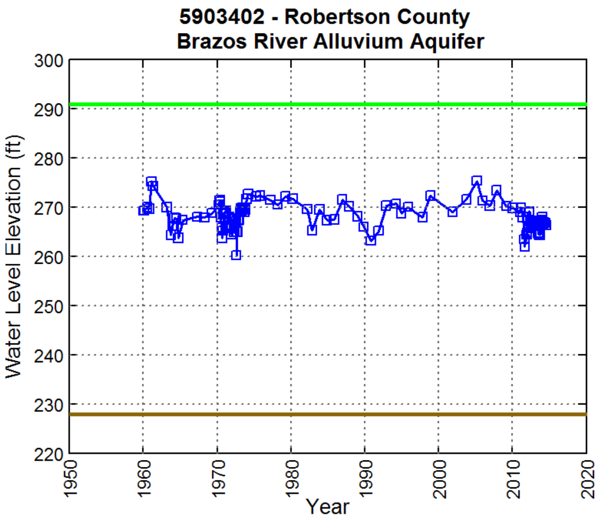

3958903 - Robertson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year
310
300
290
280
270
260
250
240
1950
1960
1970
1980
1990
2000
2010
2020


5902601 - Robertson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year
300
290
280
270
260
250
240
230
1950
1960
1970
1980
1990
2000
2010
2020


5903101 - Robertson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year
300
290
280
270
260
250
240
230
220
1950
1960
1970
1980
1990
2000
2010
2020


5903401 - Robertson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year
300
290
280
270
260
250
240
230
1950
1960
1970
1980
1990
2000
2010
2020


5903402 - Robertson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year
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290
280
270
260
250
240
230
220
1950
1960
1970
1980
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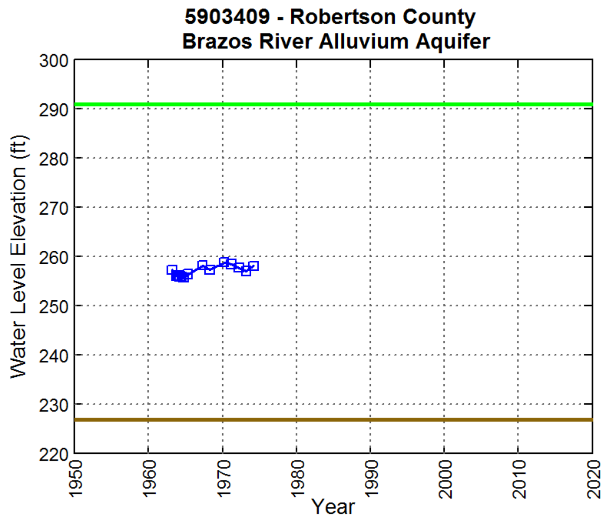
2000
2010
2020


5903409 - Robertson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year
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290
280
270
260
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1950
1960
1970
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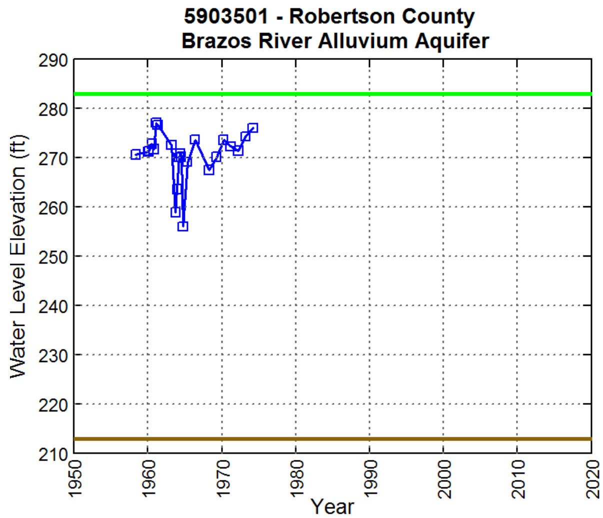
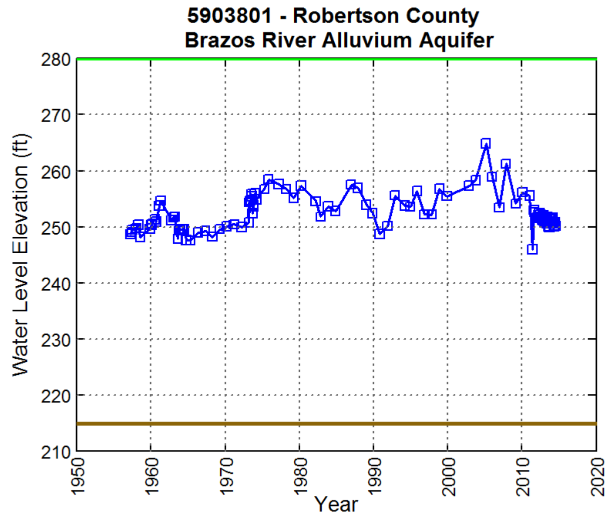
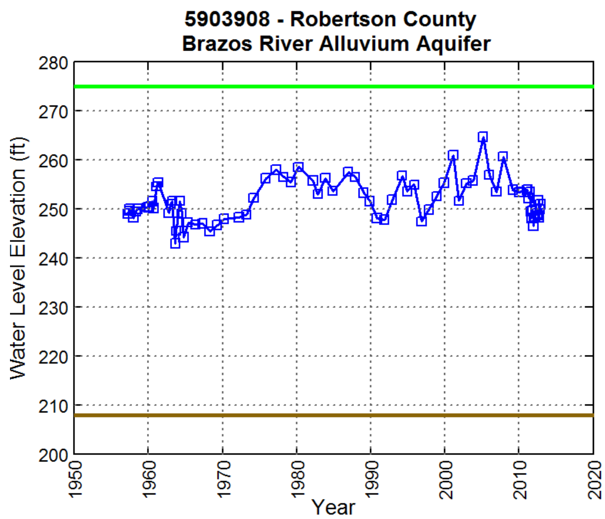
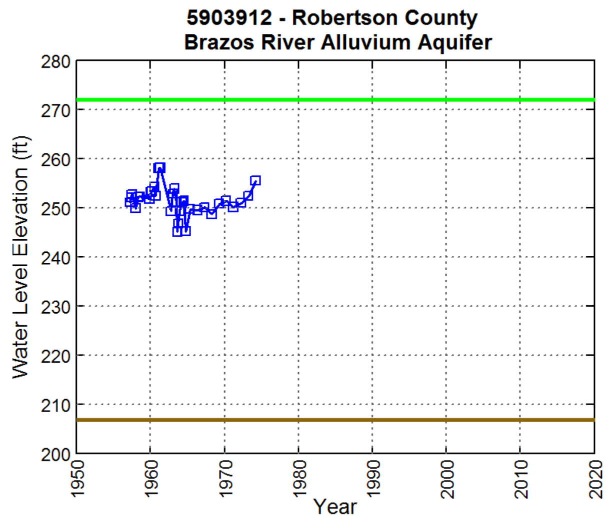
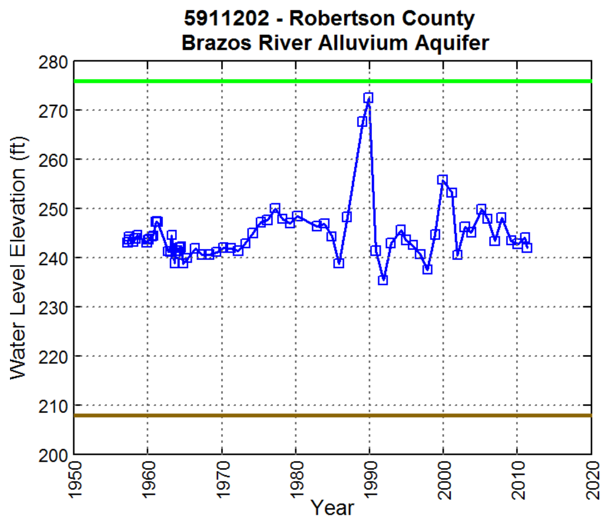
2000
2010
2020

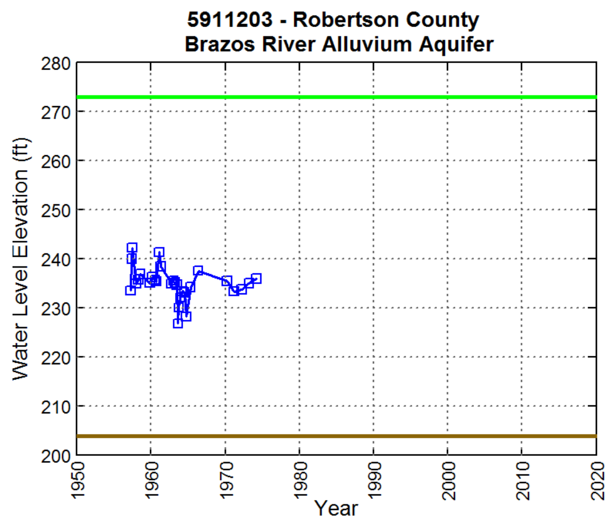

5903501 - Robertson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year

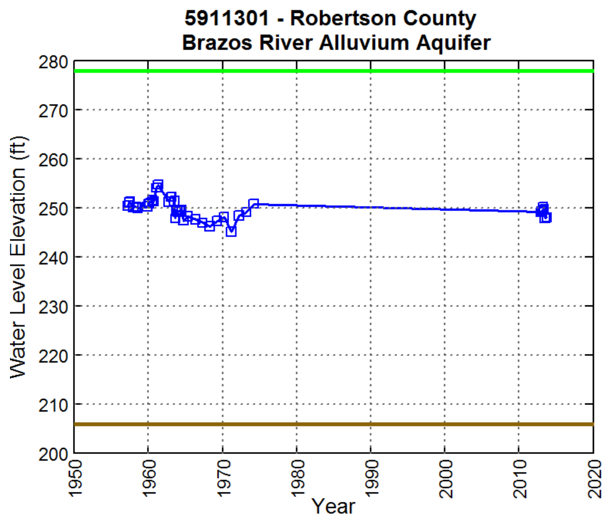

5903801 - Robertson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year


5903908 - Robertson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year


5903912 - Robertson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year


5911202 - Robertson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year


5911203 - Robertson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year


5911301 - Robertson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
280
270
260
250
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230
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210
200
1950
1960
1970
1980
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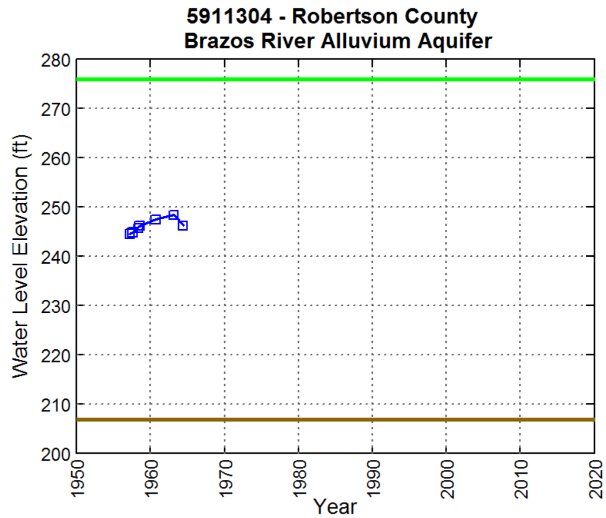
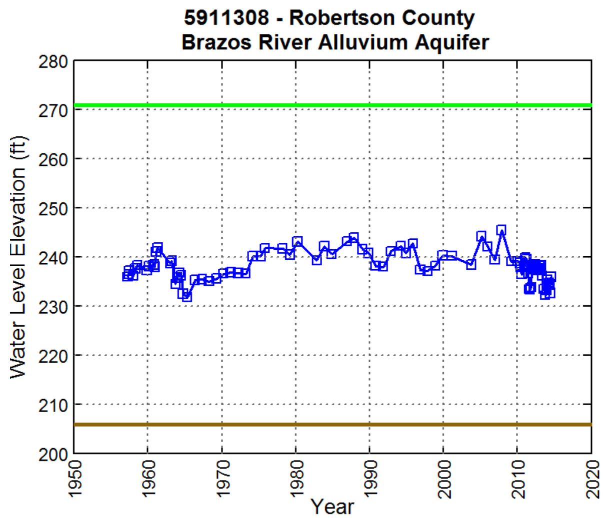
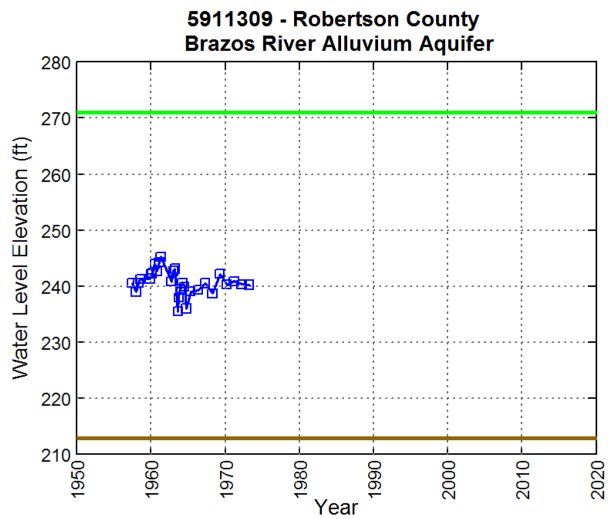
2000
2010
2020
Year


5911304 - Robertson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
280
270
260
250
240
230
220
210
200
1950
1960
1970
1980
1990
2000
2010
2020
Year


5911308 - Robertson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
280
270
260
250
240
230
220
210
200
1950
1960
1970
1980
1990
2000
2010
2020
Year


5911309 - Robertson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
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270
260
250
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210
1950
1960
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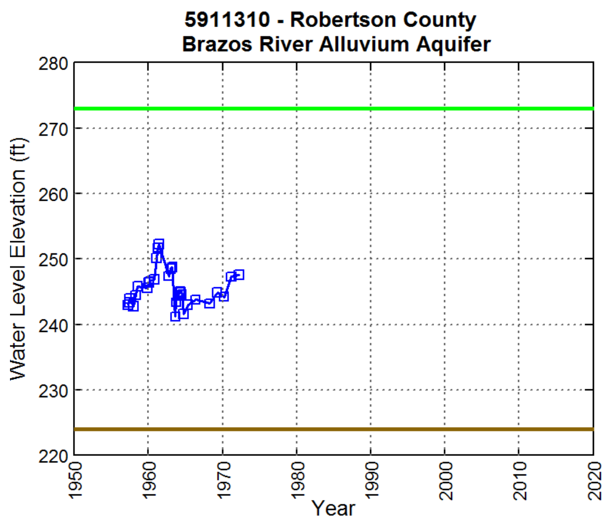
2000
2010
2020
Year


5911310 - Robertson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
280
270
260
250
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220
1950
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2000
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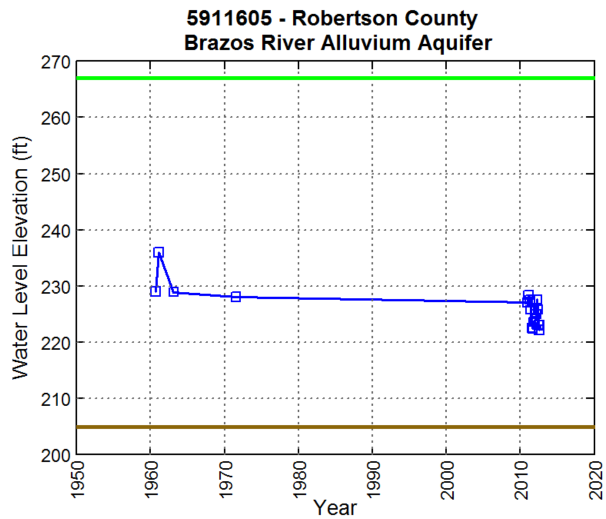
2020
Year


5911605 - Robertson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
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260
250
240
230
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210
200
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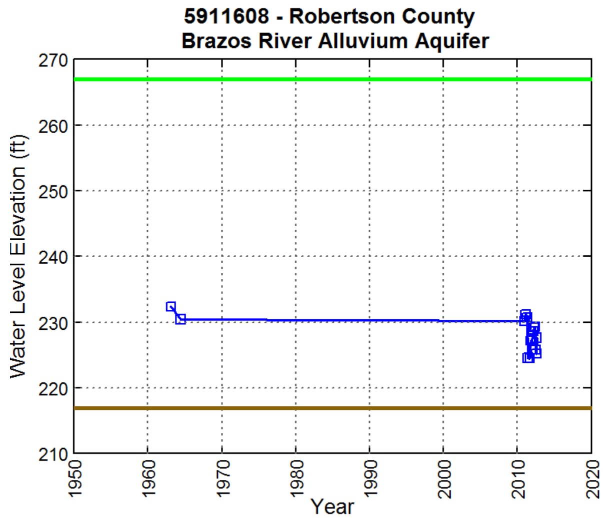
1970
1980
1990
2000
2010
2020
Year


5911608 - Robertson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year
270
260
250
240
230
220
210
1950
1960
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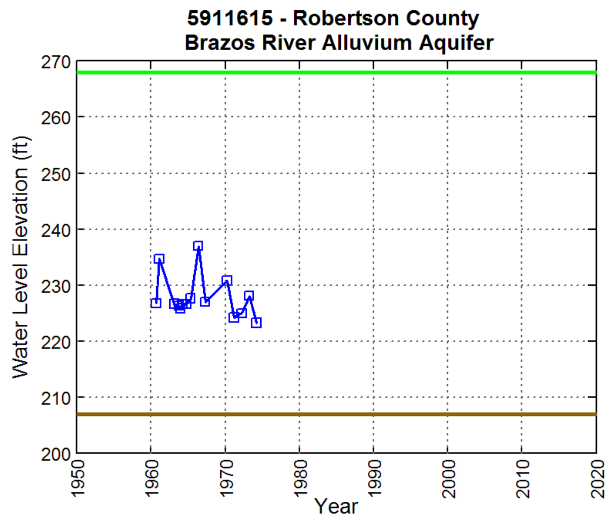
2000
2010
2020


5911615 - Robertson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year
270
260
250
240
230
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210
200
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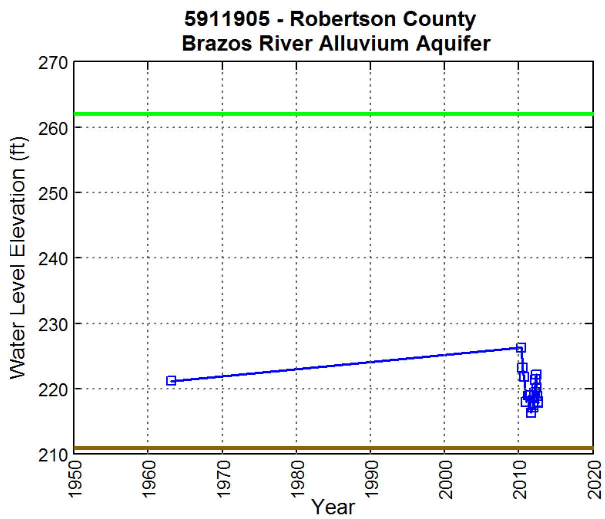
2010
2020


5911905 - Robertson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year
270
260
250
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210
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2000
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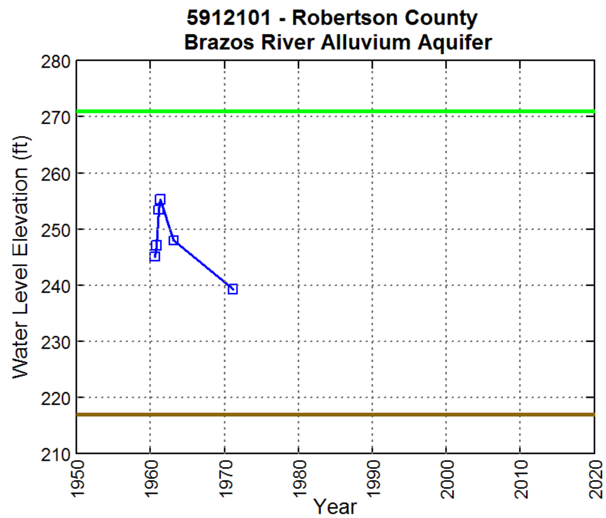
5912101 - Robertson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year
280
270
260
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2010
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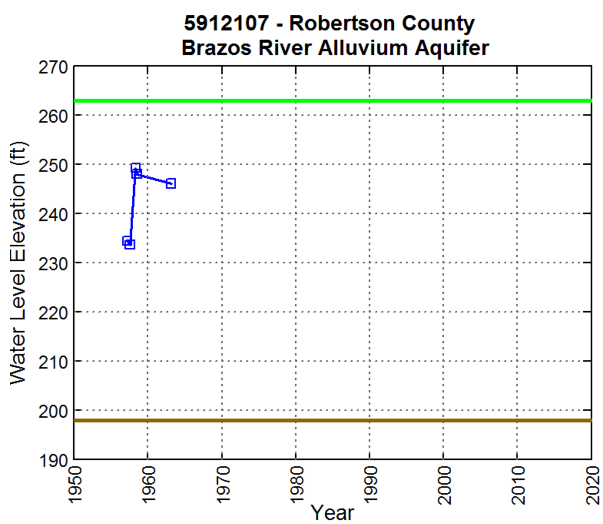
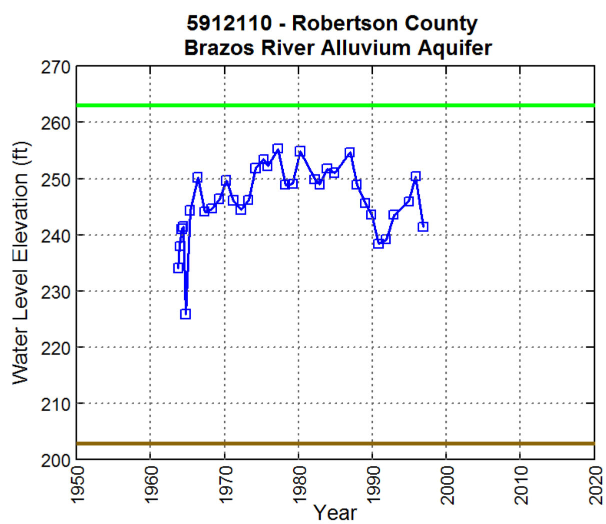

5912107 - Robertson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year
270
260
250
240
230
220
210
200
190
1950
1960
1970
1980
1990
2000
2010
2020


5912110 - Robertson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year
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230
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210
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1950
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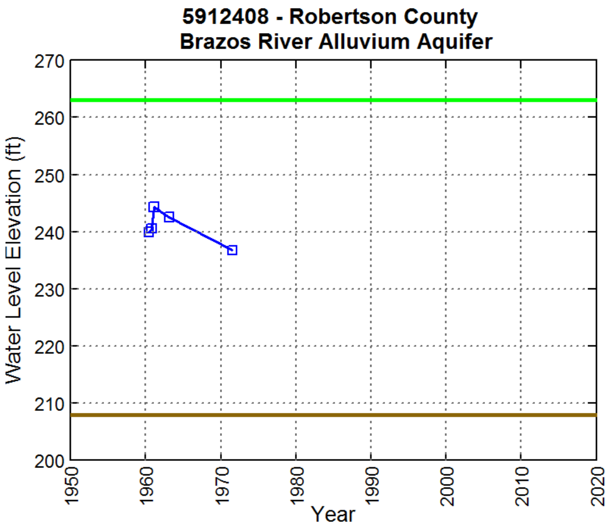
1990
2000
2010
2020


5912408 - Robertson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
270
260
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220
210
200
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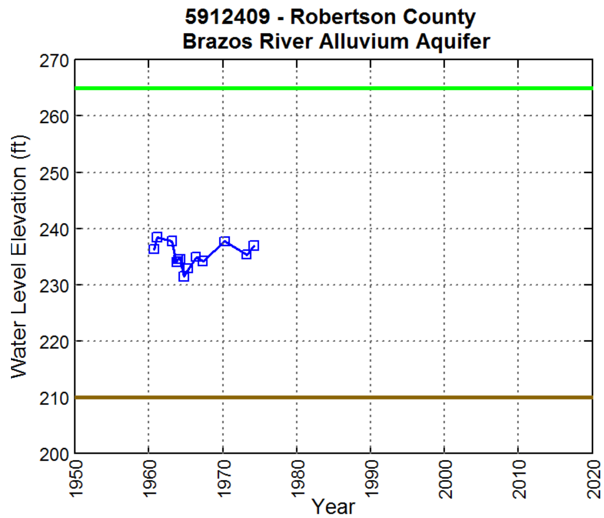
2000
2010
2020
Year


5912409 - Robertson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
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240
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220
210
200
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1960
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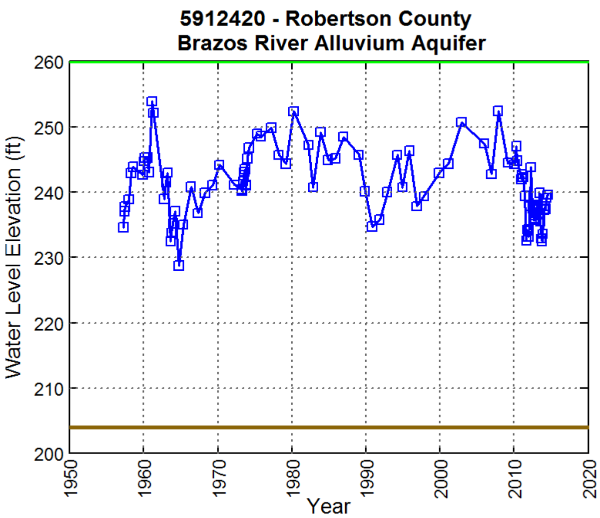
2020
Year


5912420 - Robertson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
260
250
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230
220
210
200
1950
1960
1970
1980
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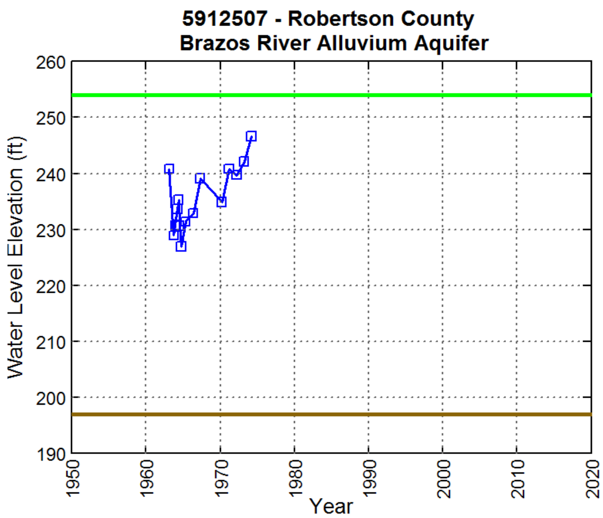
2000
2010
2020
Year


5912507 - Robertson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
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250
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230
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210
200
190
1950
1960
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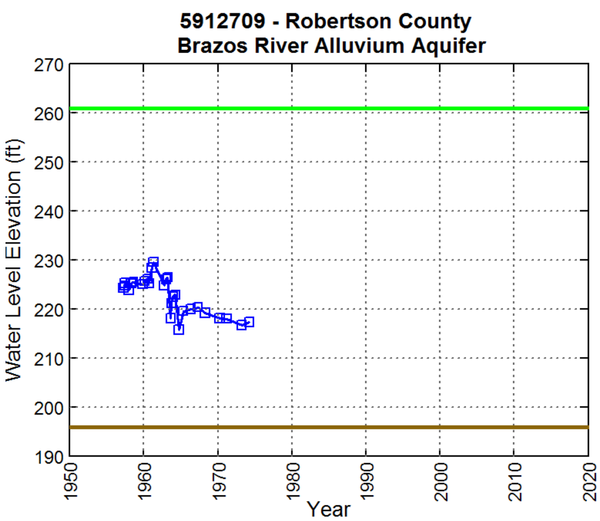
1990
2000
2010
2020
Year


5912709 - Robertson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
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210
200
190
1950
1960
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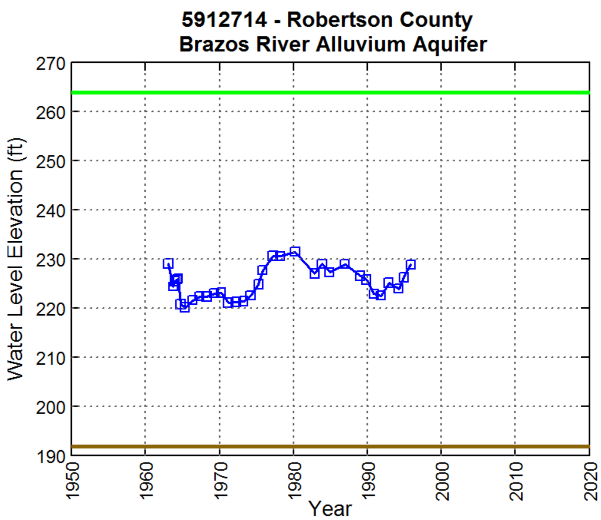
1980
1990
2000
2010
2020
Year


5912714 - Robertson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
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210
200
190
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1980
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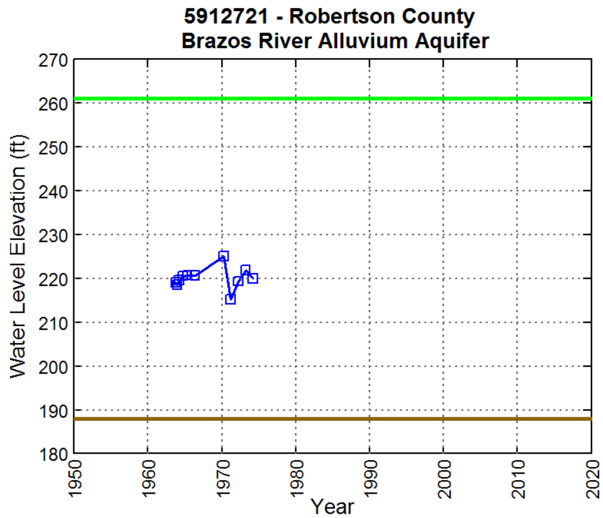
2000
2010
2020
Year


5912721 - Robertson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year
180
190
200
210
220
230
240
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260
270
1950
1960
1970
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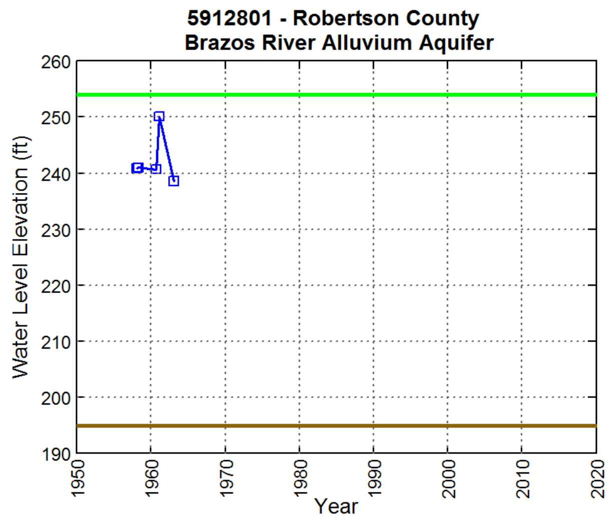
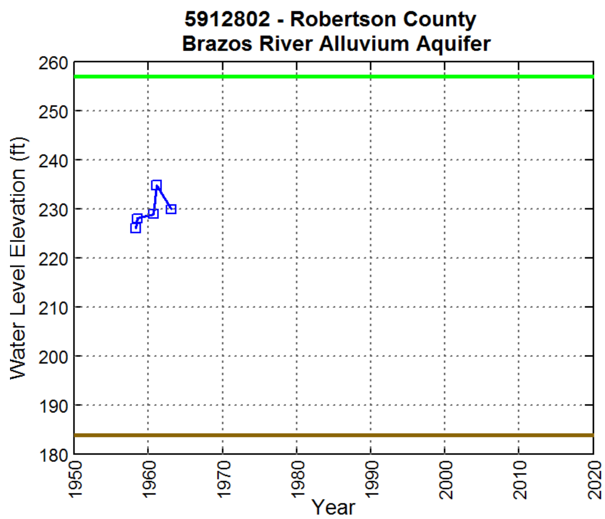
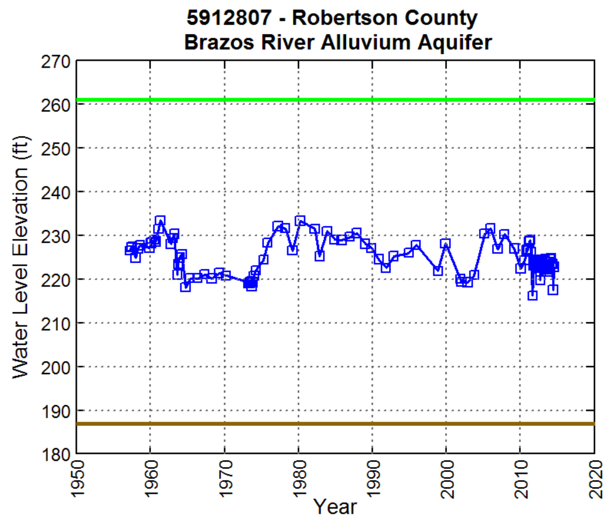
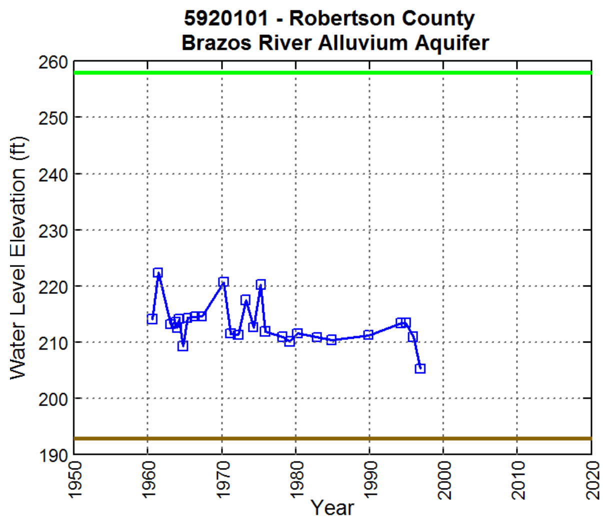
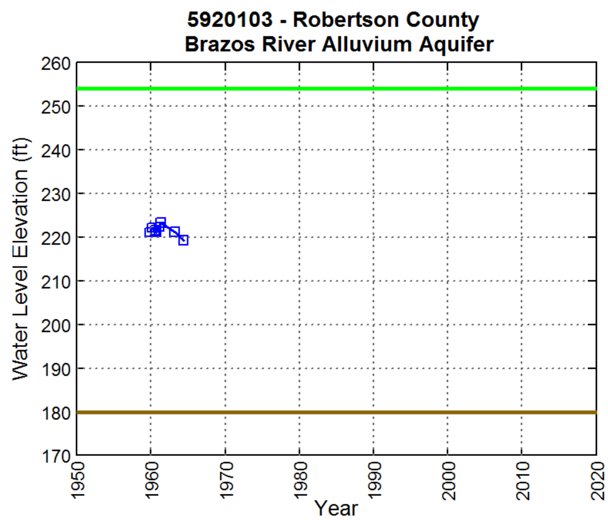
1990
2000
2010
2020

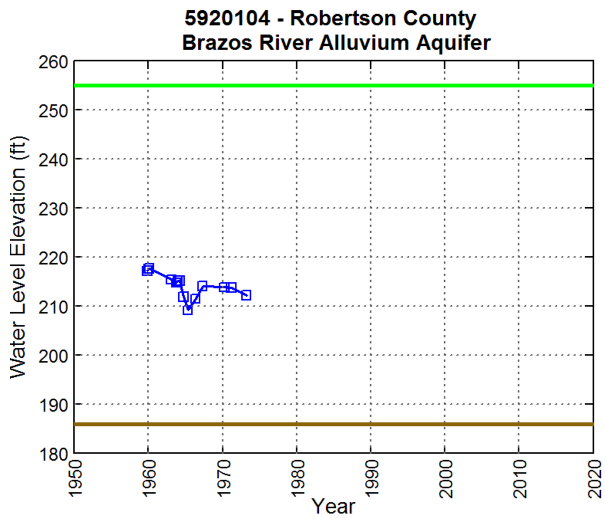

5912801 - Robertson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year
190
200
210
220
230
240
250
260
1950
1960
1970
1980
1990
2000
2010
2020

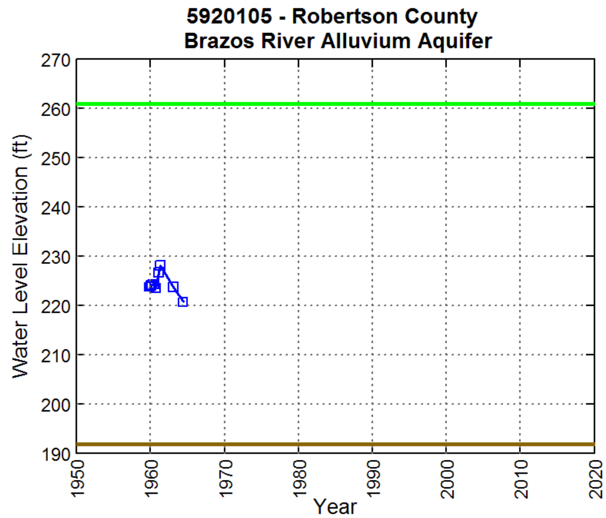

5912802 - Robertson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year
180
190
200
210
220
230
240
250
260
1950
1960
1970
1980
1990
2000
2010
2020

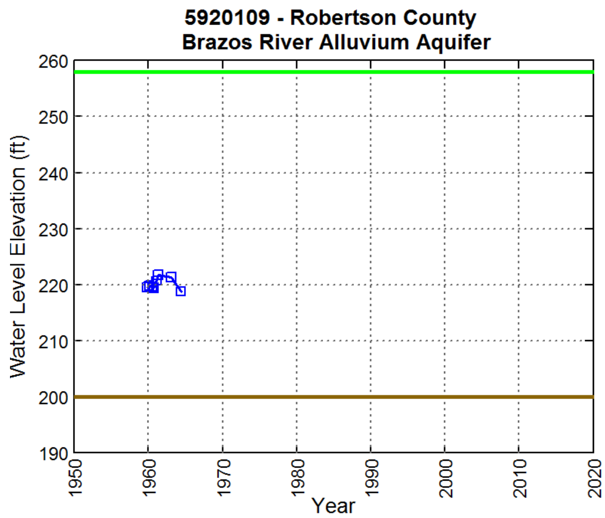

5912807 - Robertson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year
180
190
200
210
220
230
240
250
260
270
1950
1960
1970
1980
1990
2000
2010
2020

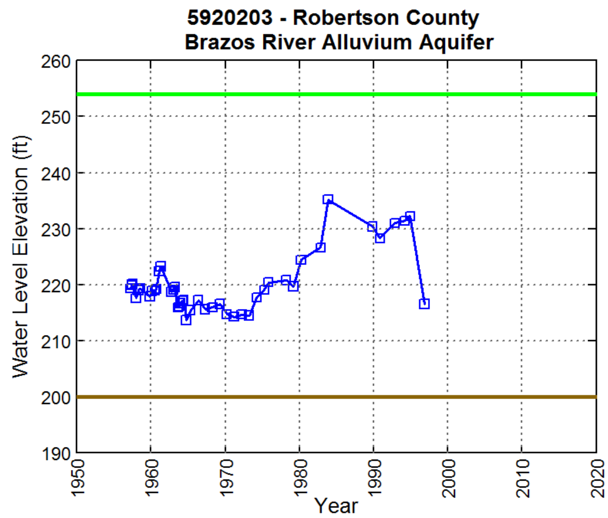

5920101 - Robertson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year
190
200
210
220
230
240
250
260
1950
1960
1970
1980
1990
2000
2010
2020

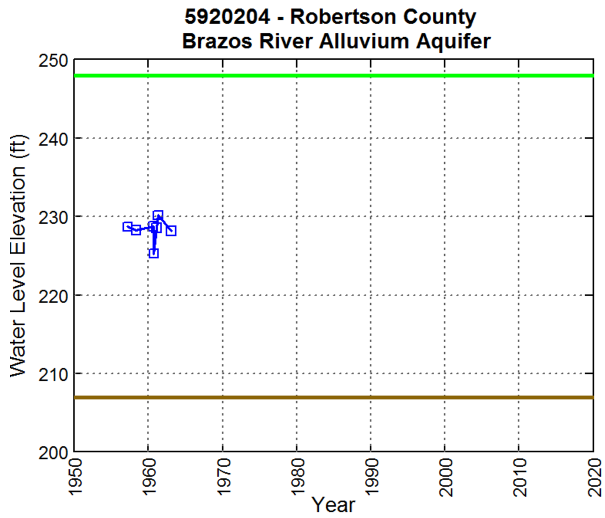

5920103 - Robertson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year
170
180
190
200
210
220
230
240
250
260
1950
1960
1970
1980
1990
2000
2010
2020

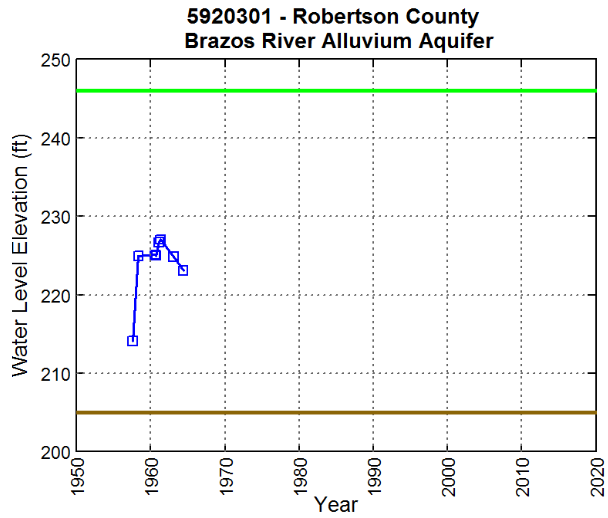

5920104 - Robertson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year
260
250
240
230
220
210
200
190
180
1950
1960
1970
1980
1990
2000
2010
2020

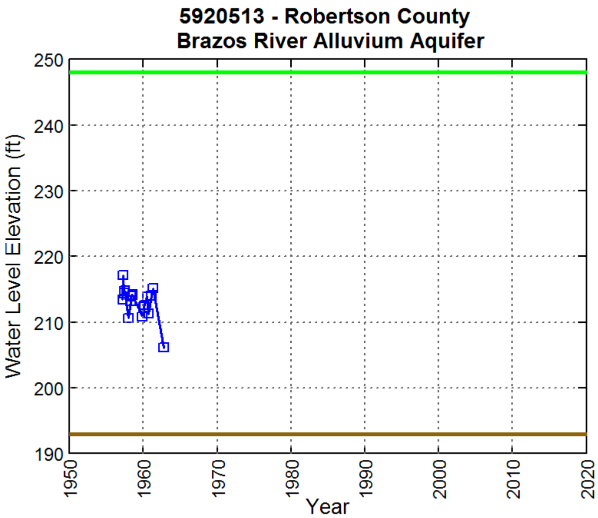

5920105 - Robertson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year
270
260
250
240
230
220
210
200
190
1950
1960
1970
1980
1990
2000
2010
2020

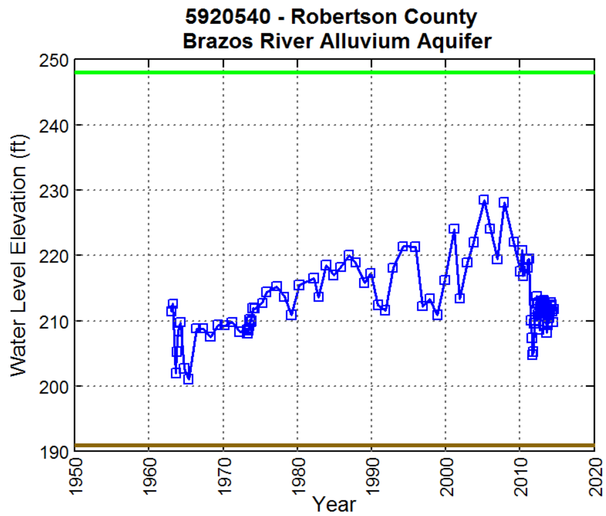

5920109 - Robertson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year
260
250
240
230
220
210
200
190
1950
1960
1970
1980
1990
2000
2010
2020


5920203 - Robertson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year
260
250
240
230
220
210
200
190
1950
1960
1970
1980
1990
2000
2010
2020


5920204 - Robertson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year
250
240
230
220
210
200
1950
1960
1970
1980
1990
2000
2010
2020


5920301 - Robertson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year
250
240
230
220
210
200
1950
1960
1970
1980
1990
2000
2010
2020


5920513 - Robertson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
250
240
230
220
210
200
190
1950
1960
1970
1980
1990
2000
2010
2020
Year


5920540 - Robertson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
250
240
230
220
210
200
190
1950
1960
1970
1980
1990
2000
2010
2020
Year

Brazos County

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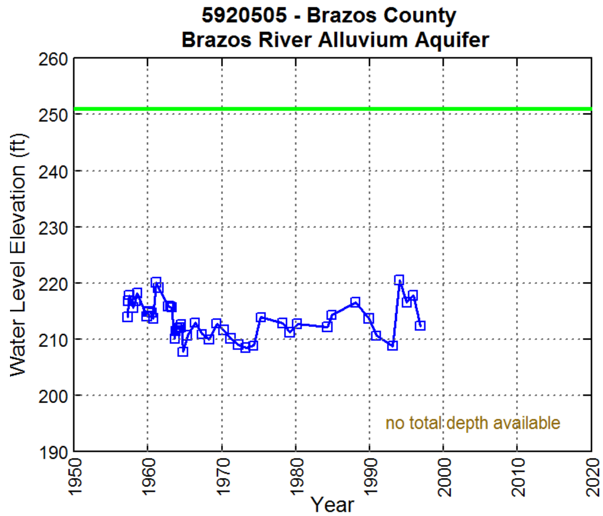
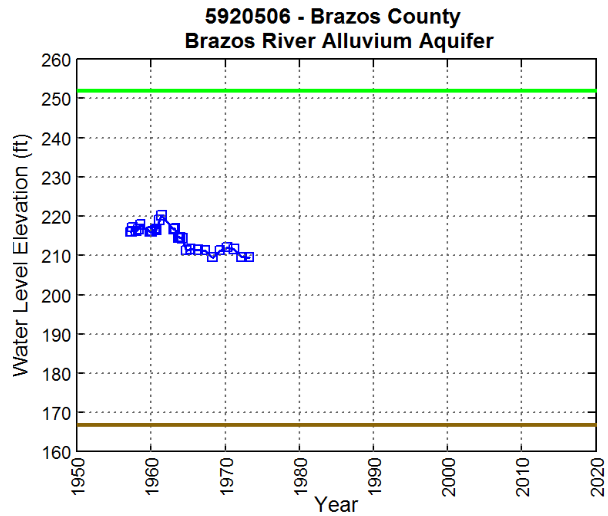
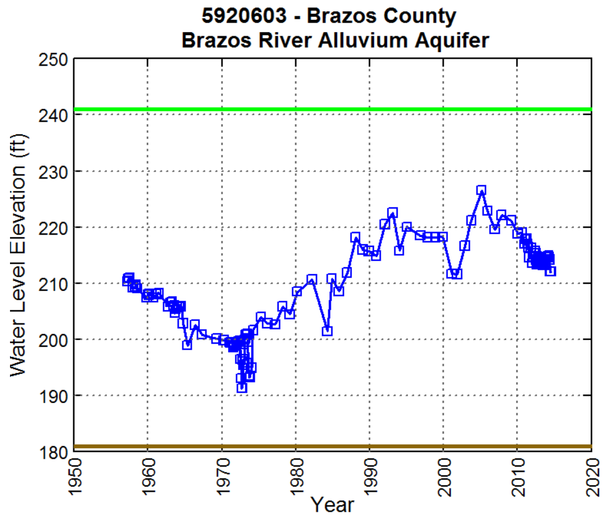
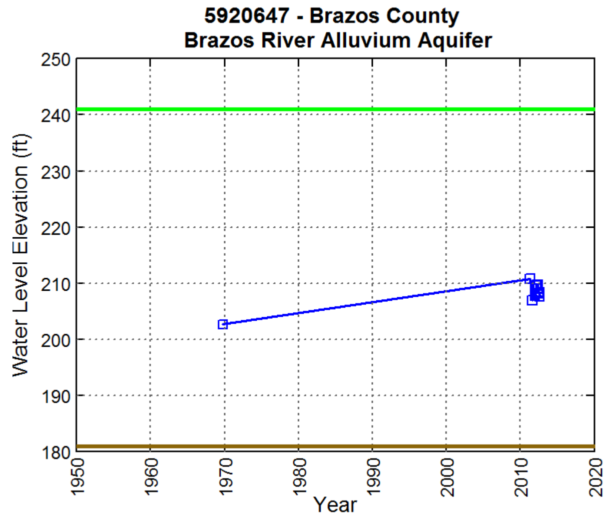
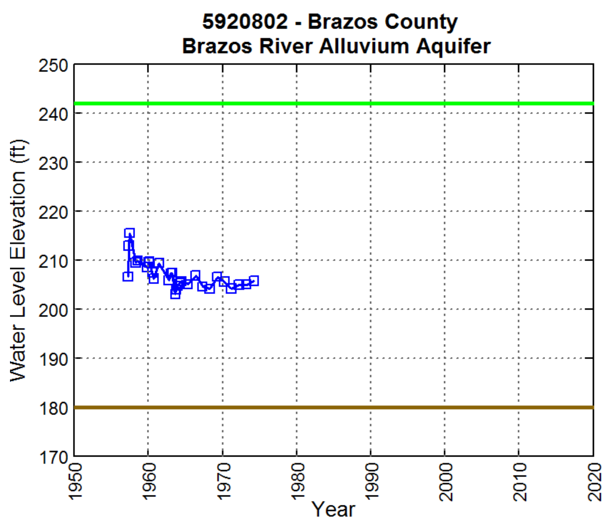
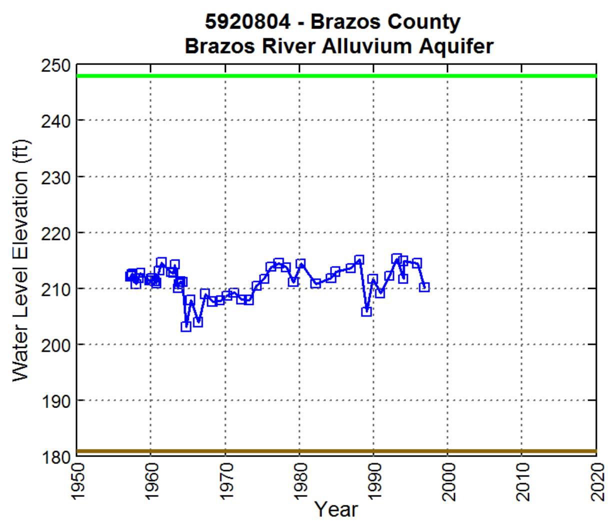

5920505 - Brazos County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year
no total depth available

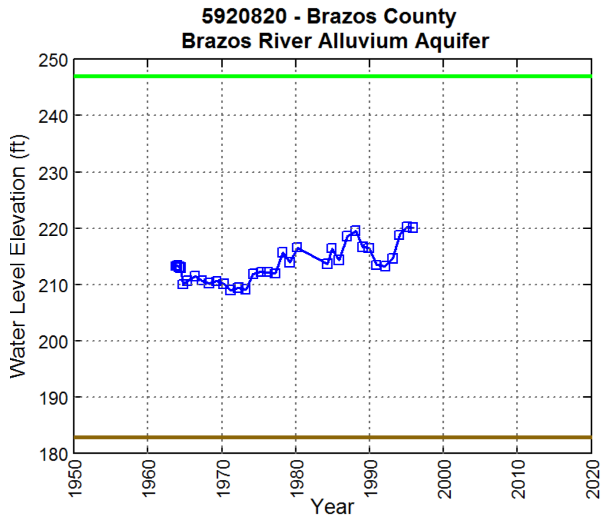

5920506 - Brazos County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year

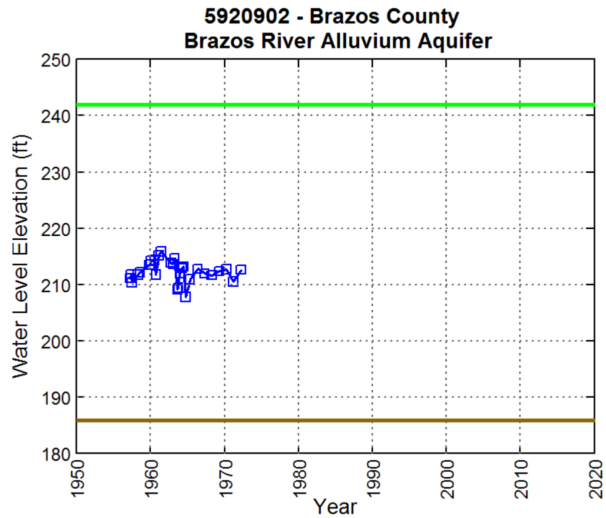

5920603 - Brazos County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year

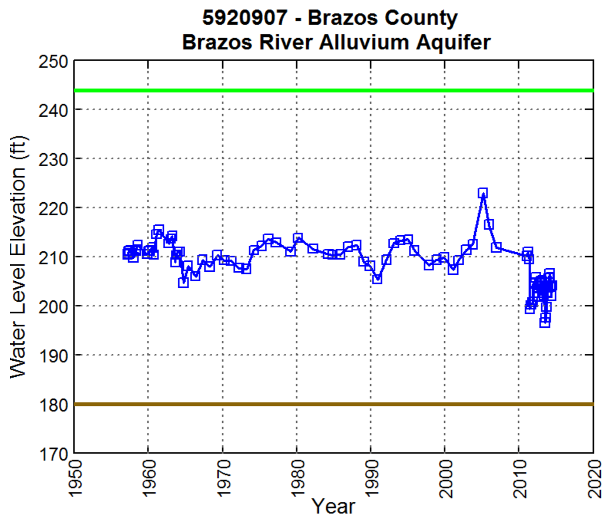

5920647 - Brazos County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year

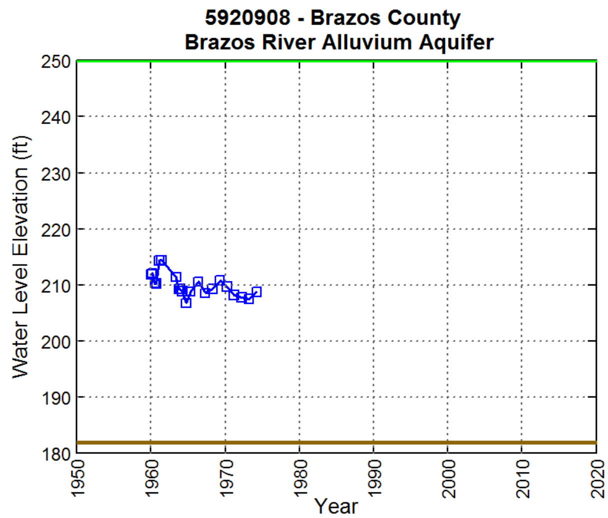

5920802 - Brazos County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year

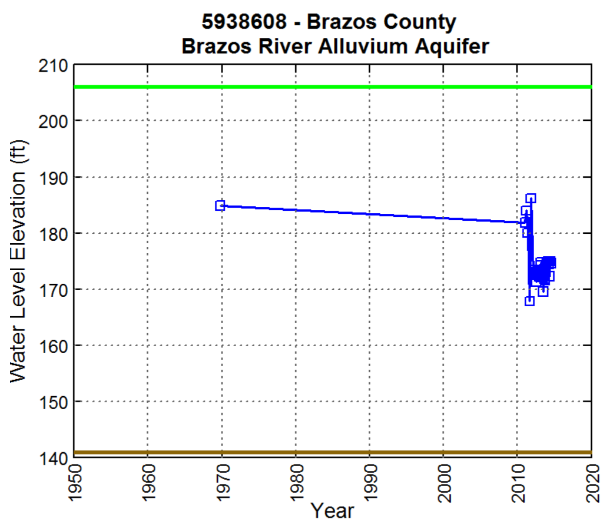

5920804 - Brazos County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year

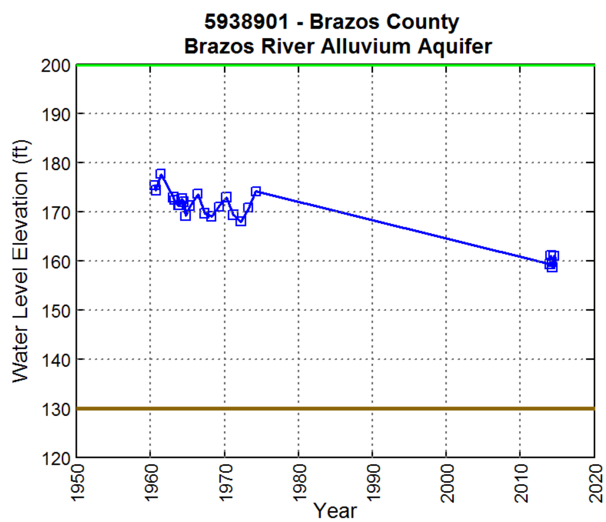

5920820 - Brazos County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year

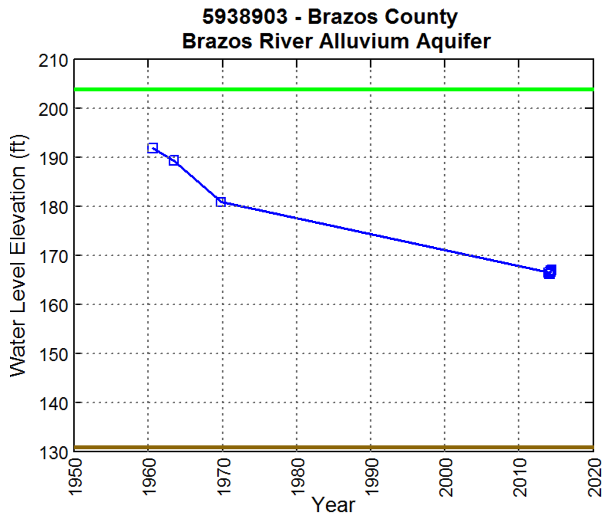

5920902 - Brazos County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year

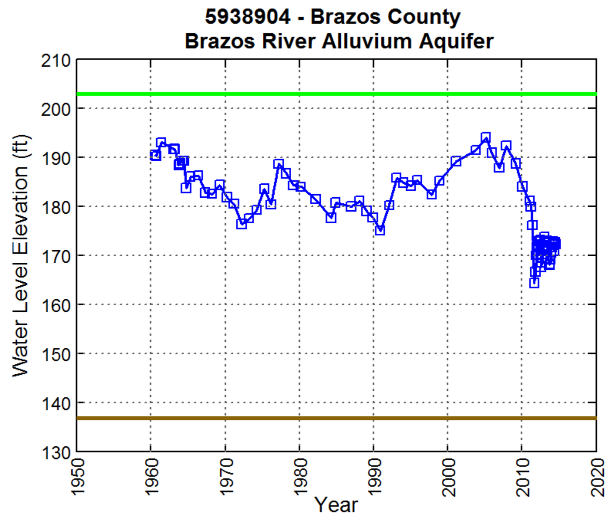

5920907 - Brazos County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year

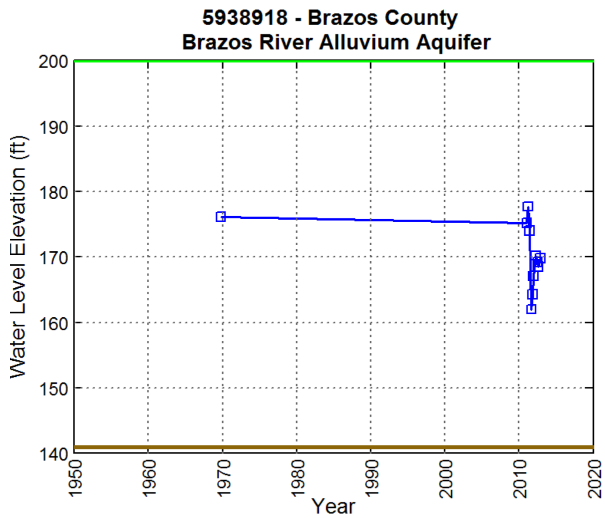

5920908 - Brazos County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year

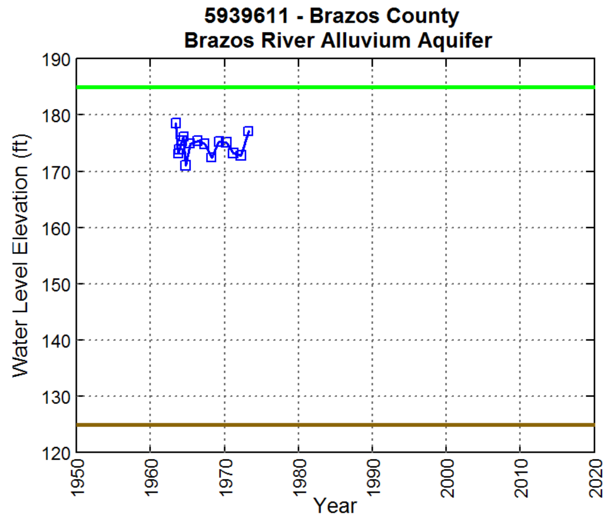

5938608 - Brazos County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year

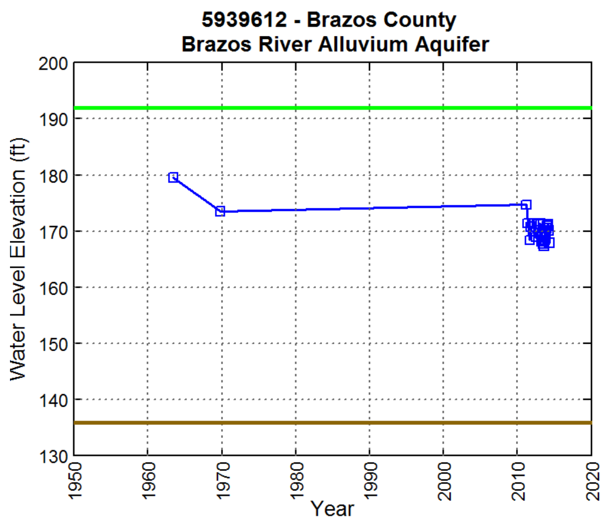

5938901 - Brazos County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year

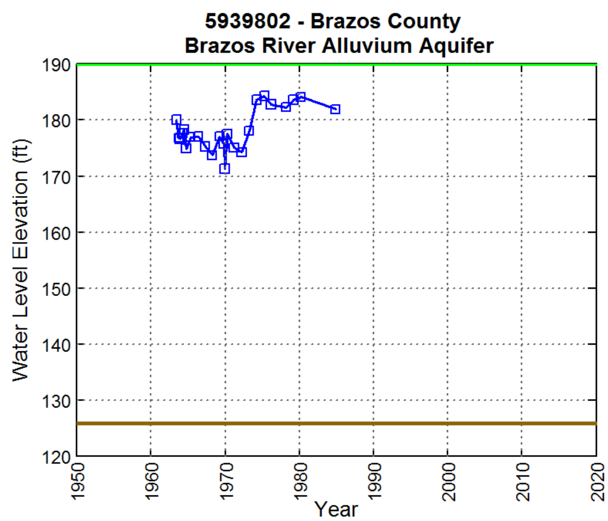

5938903 - Brazos County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year

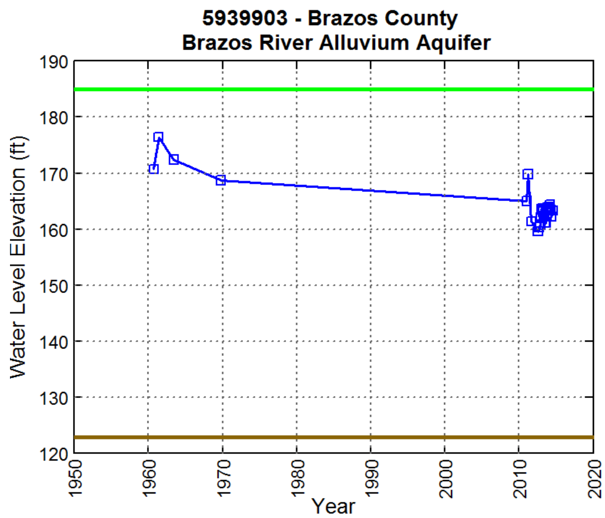

5938904 - Brazos County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year

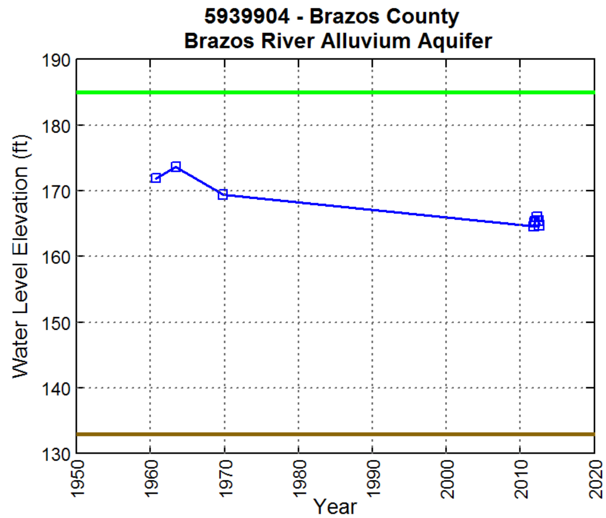

5938918 - Brazos County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year

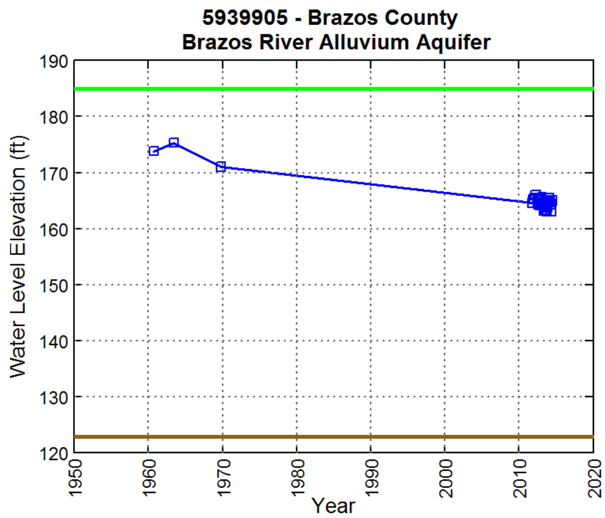

5939611 - Brazos County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year

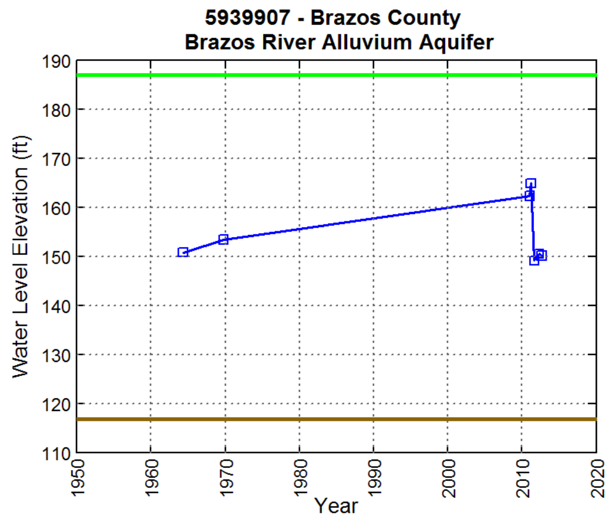

5939612 - Brazos County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year


5939802 - Brazos County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year


5939903 - Brazos County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year


5939904 - Brazos County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year


5939905 - Brazos County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year


5939907 - Brazos County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year

Burleson County

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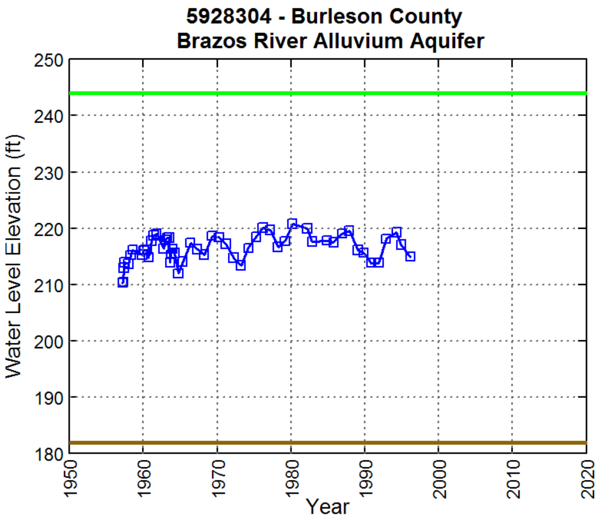
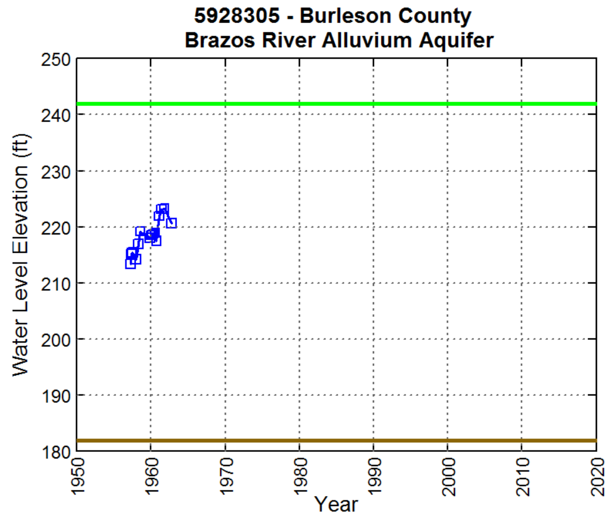
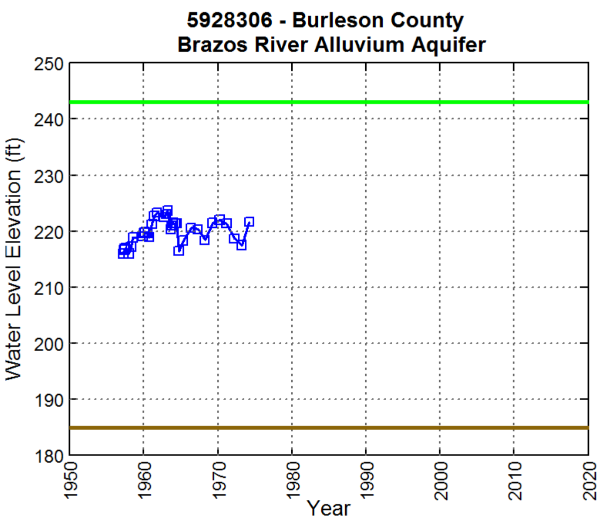
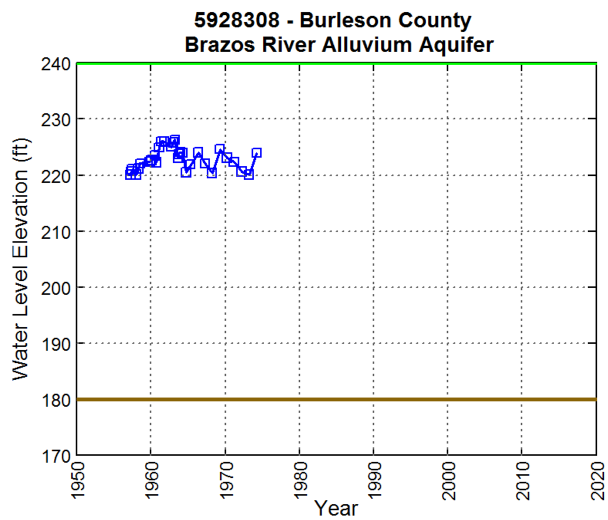
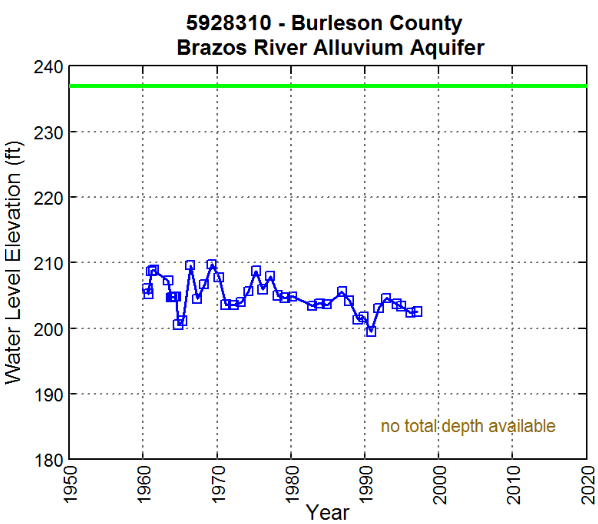
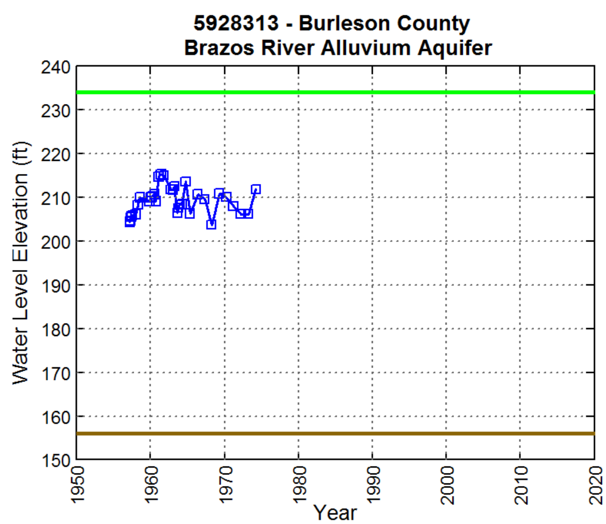

5928304 - Burleson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year

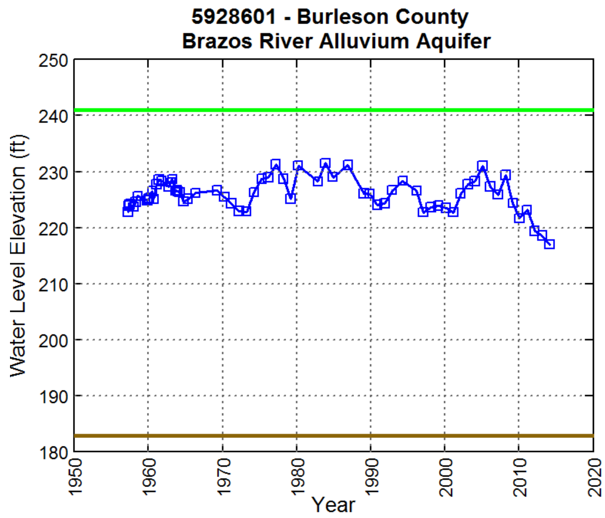

5928305 - Burleson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year

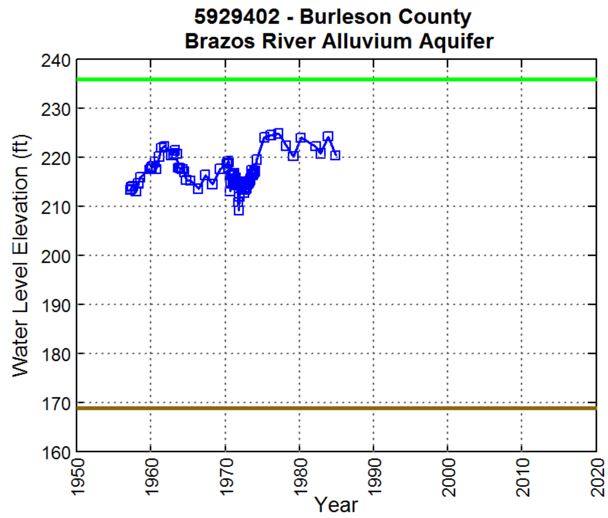

5928306 - Burleson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year

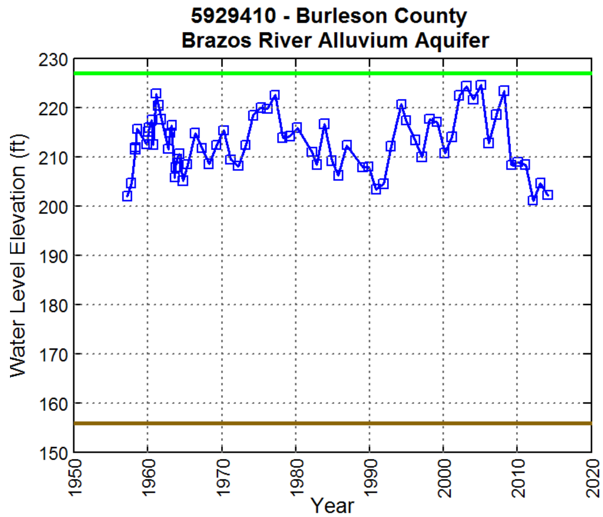

5928308 - Burleson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year

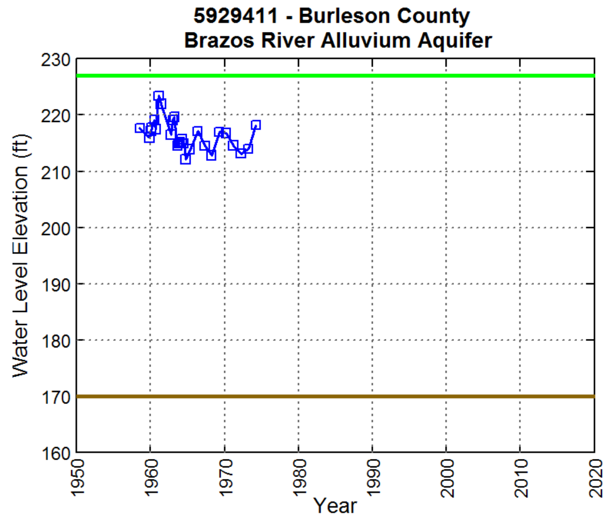

5928310 - Burleson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
no total depth available
Year

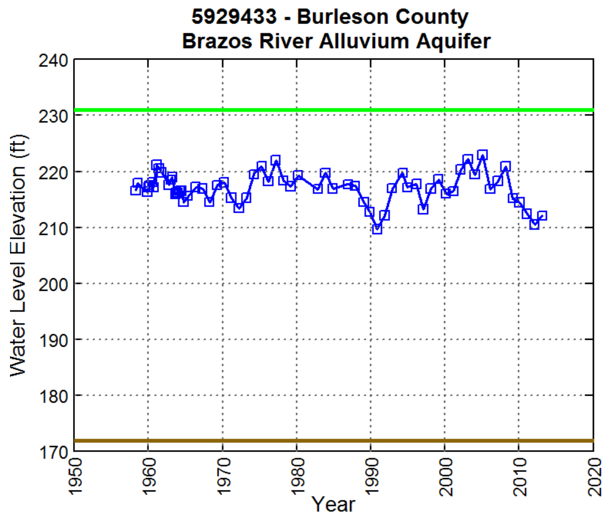

5928313 - Burleson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year

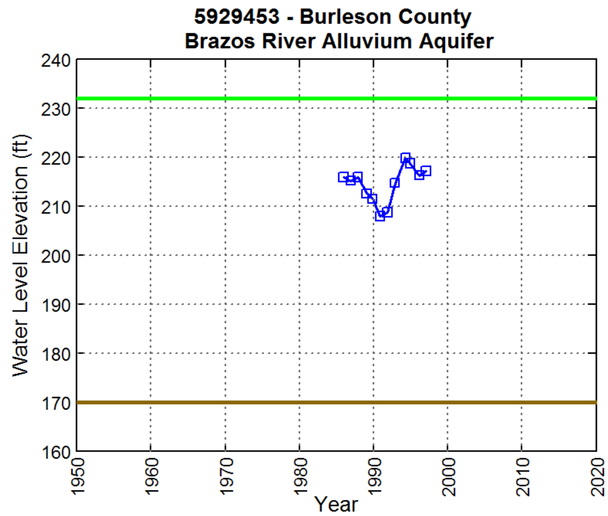

5928601 - Burleson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year
250
240
230
220
210
200
190
180
1950
1960
1970
1980
1990
2000
2010
2020

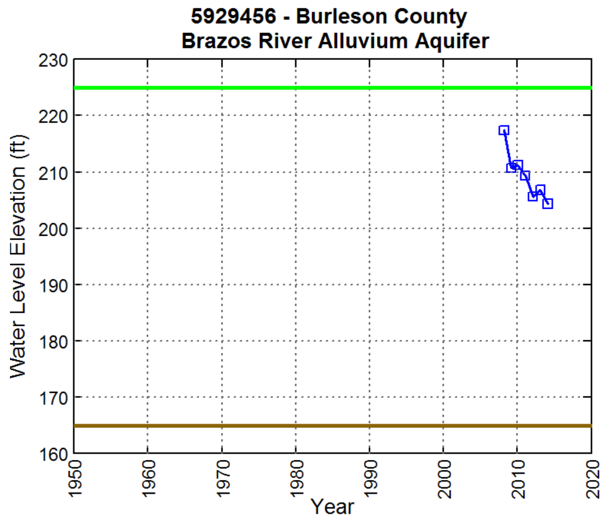

5929402 - Burleson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year
240
230
220
210
200
190
180
170
160
1950
1960
1970
1980
1990
2000
2010
2020

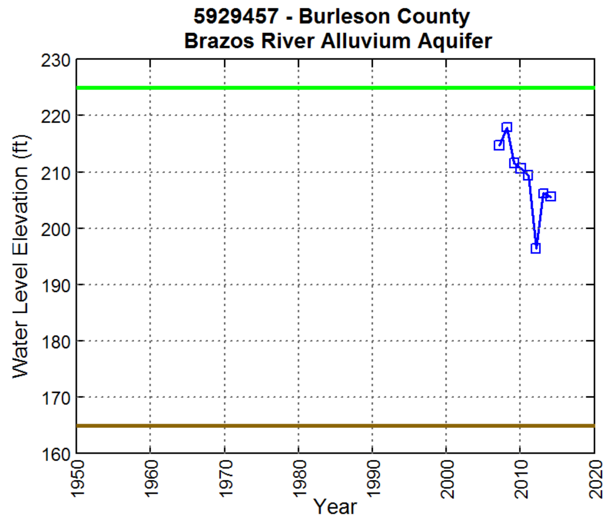

5929410 - Burleson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year
230
220
210
200
190
180
170
160
150
1950
1960
1970
1980
1990
2000
2010
2020

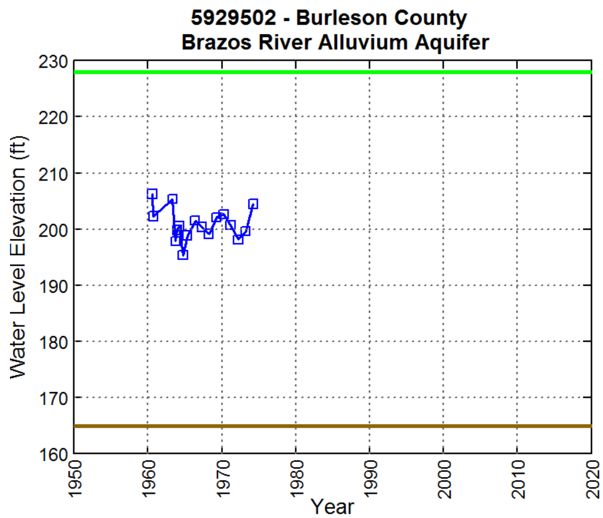

5929411 - Burleson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year
230
220
210
200
190
180
170
160
1950
1960
1970
1980
1990
2000
2010
2020

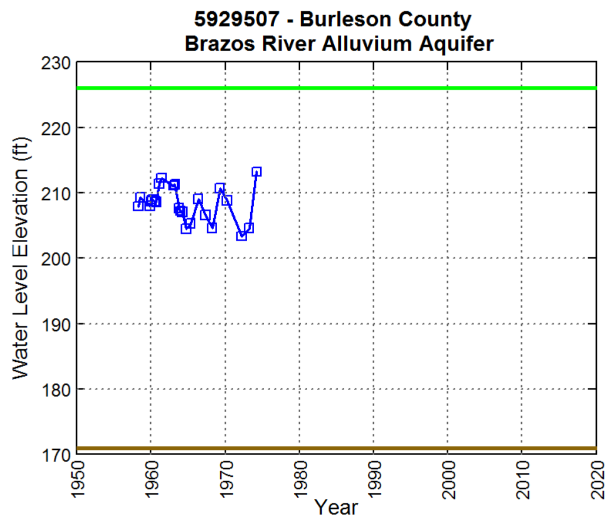

5929433 - Burleson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year
240
230
220
210
200
190
180
170
1950
1960
1970
1980
1990
2000
2010
2020

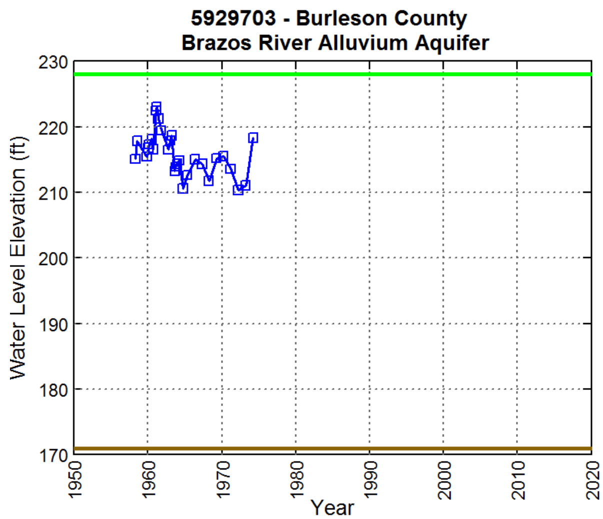

5929453 - Burleson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year
240
230
220
210
200
190
180
170
160
1950
1960
1970
1980
1990
2000
2010
2020

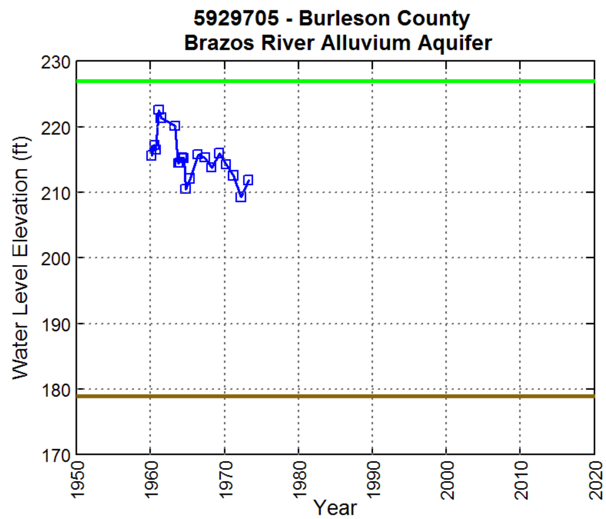

5929456 - Burleson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year

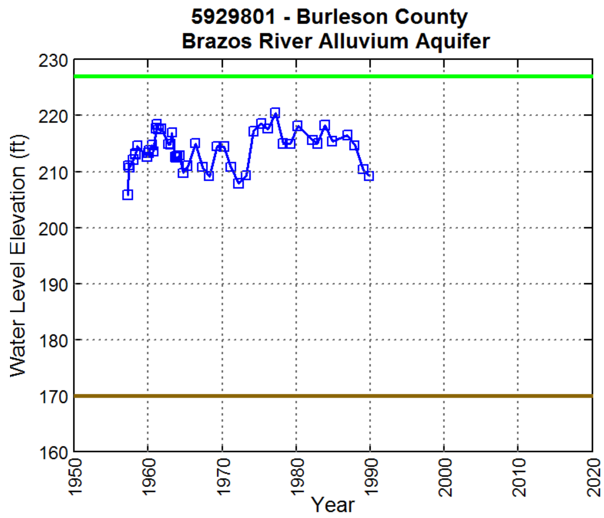

5929457 - Burleson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year

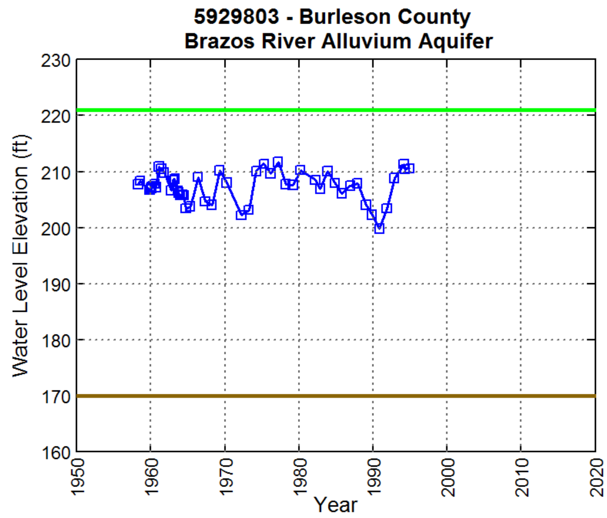

5929502 - Burleson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year

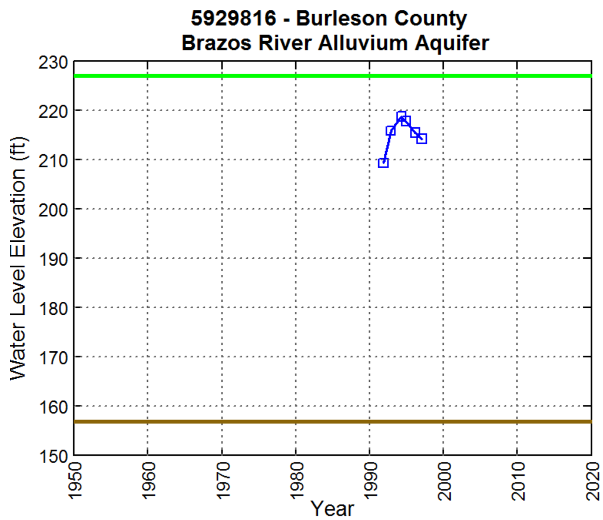

5929507 - Burleson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year

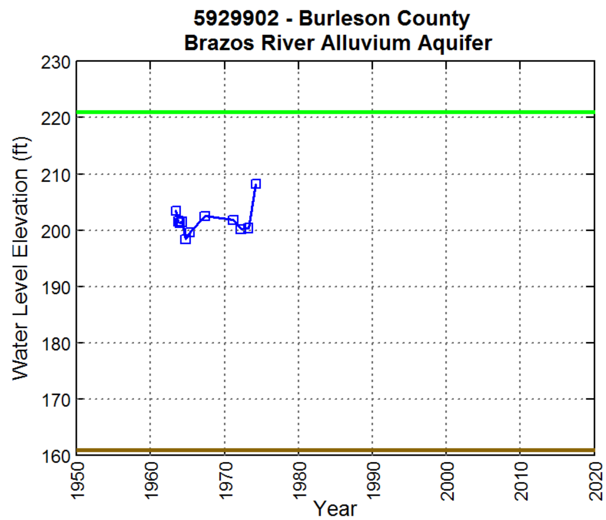

5929703 - Burleson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year

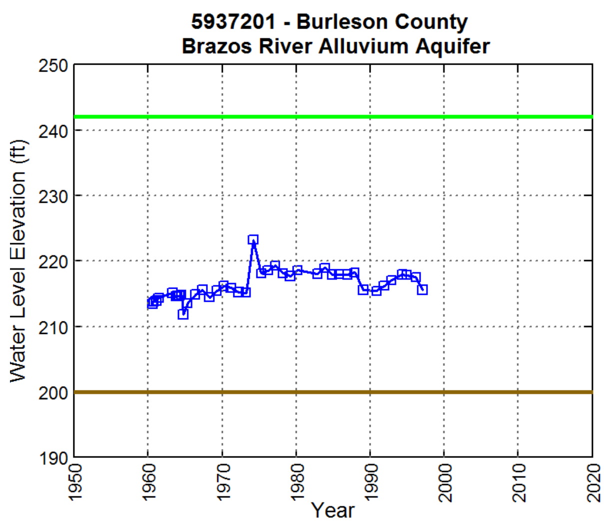

5929705 - Burleson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year

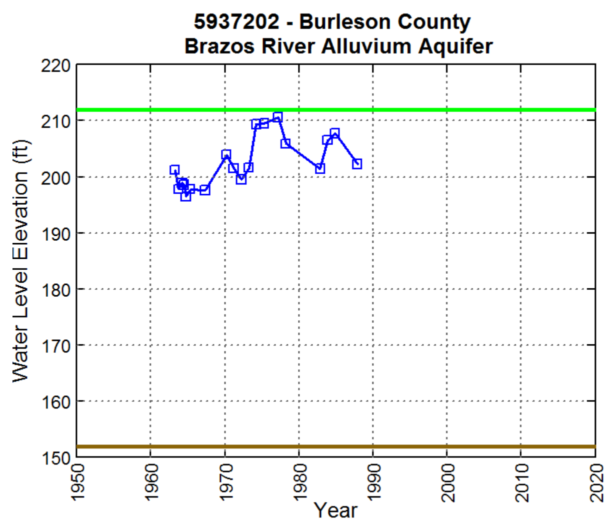

5929801 - Burleson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year

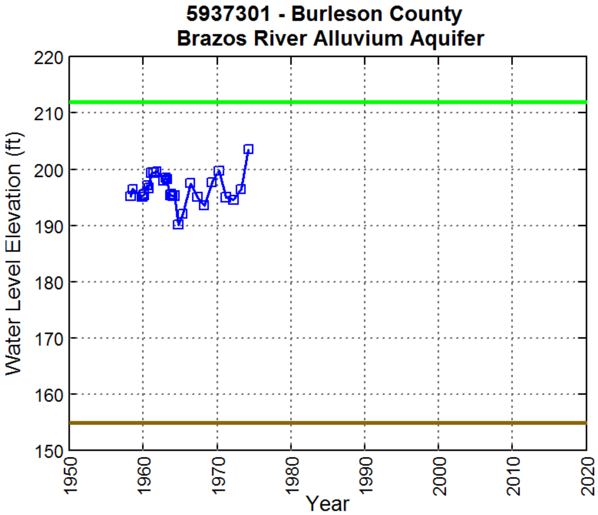

5929803 - Burleson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year

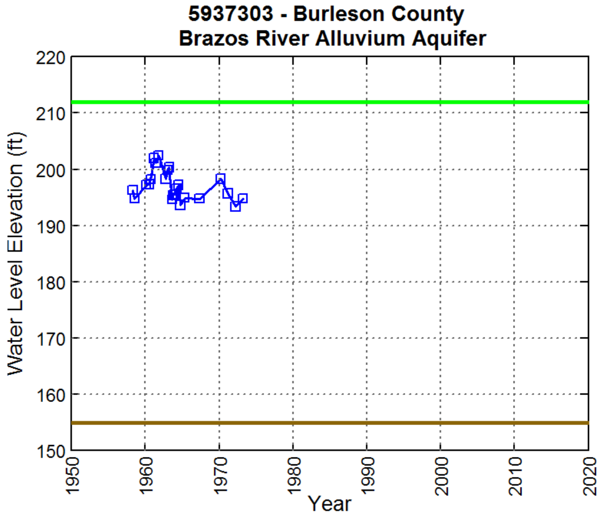

5929816 - Burleson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year

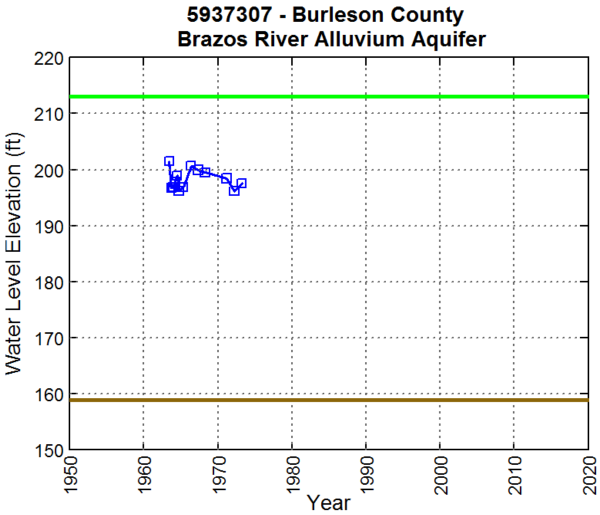

5929902 - Burleson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year

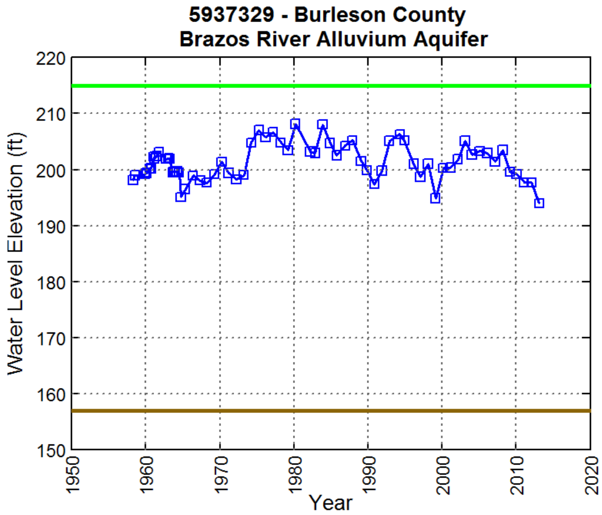

5937201 - Burleson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year

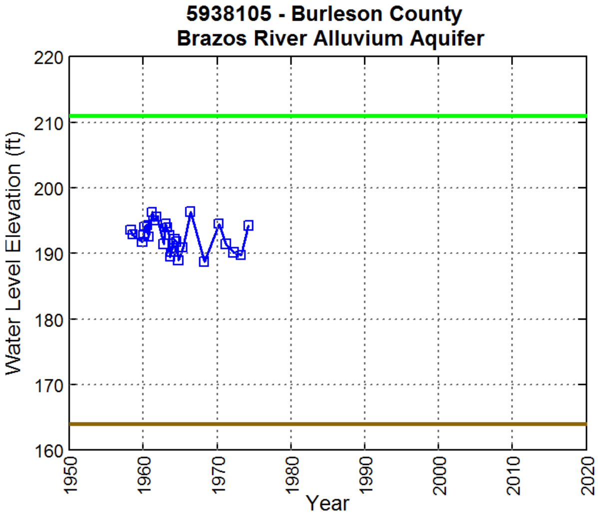

5937202 - Burleson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year

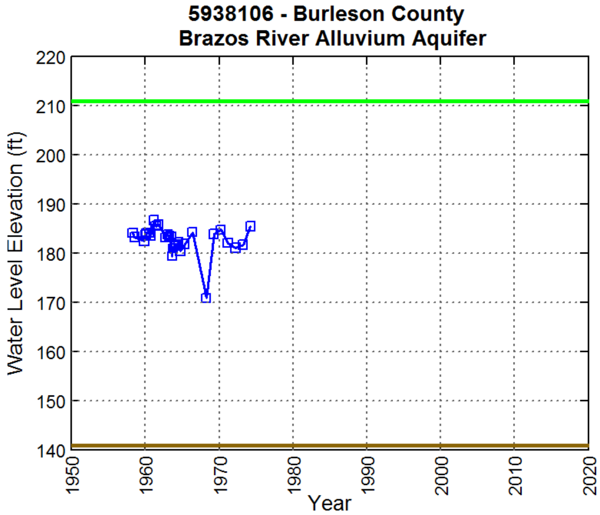

5937301 - Burleson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year

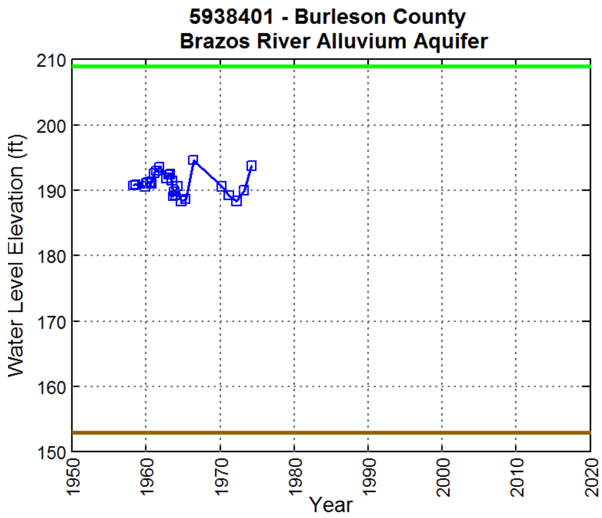

5937303 - Burleson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year

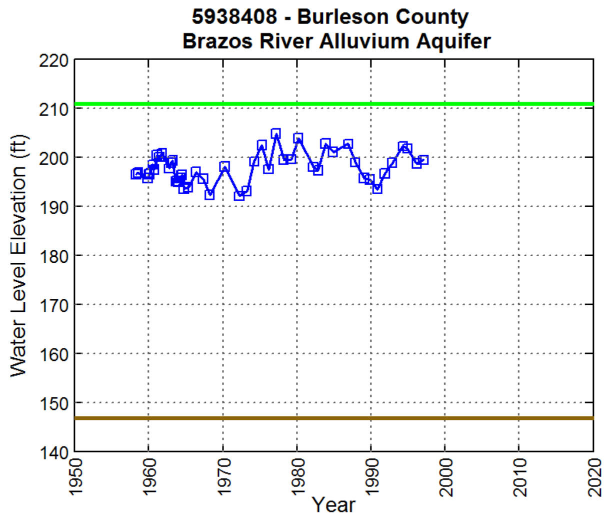

5937307 - Burleson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year

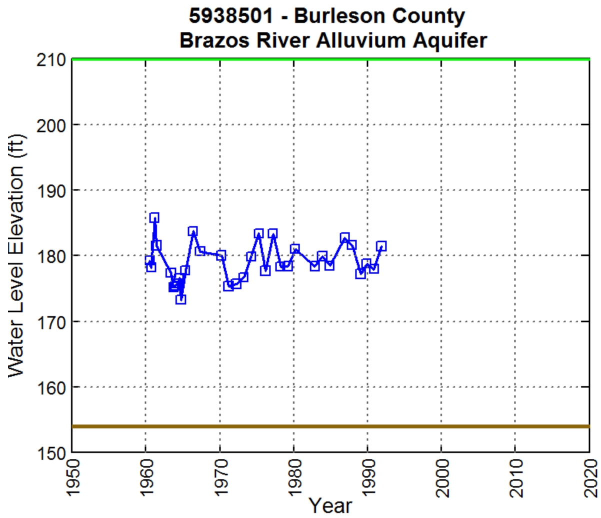

5937329 - Burleson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year

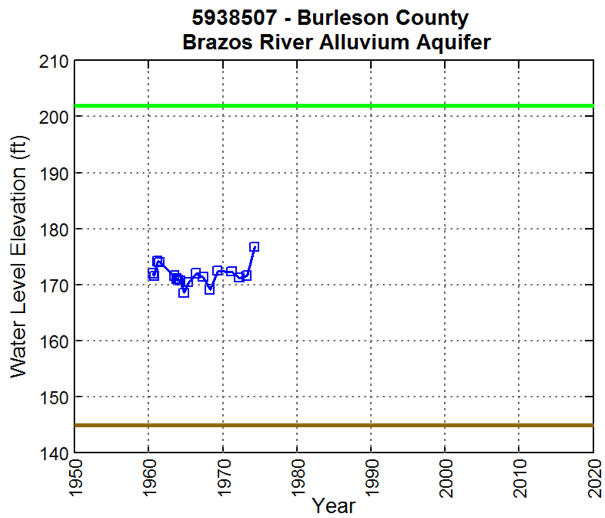

5938105 - Burleson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year

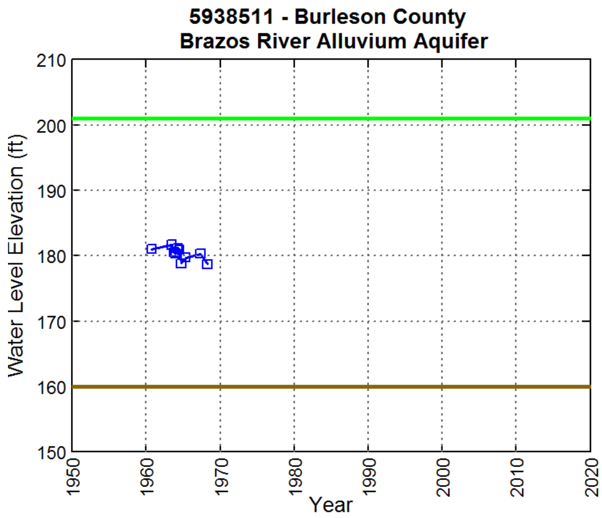

5938106 - Burleson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year

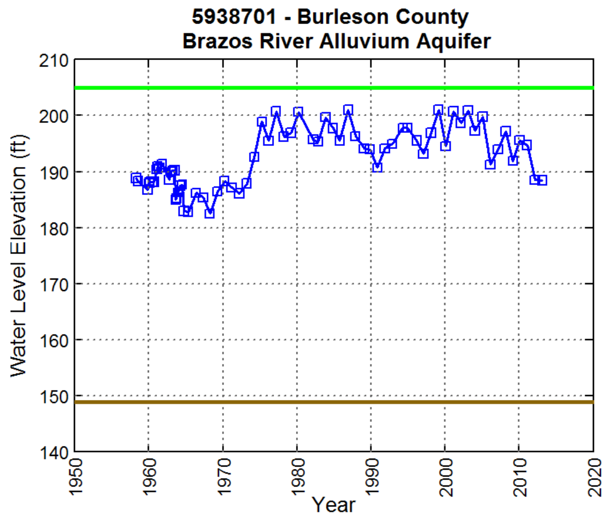

5938401 - Burleson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year
150
160
170
180
190
200
210
1950
1960
1970
1980
1990
2000
2010
2020


5938408 - Burleson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year
140
150
160
170
180
190
200
210
220
1950
1960
1970
1980
1990
2000
2010
2020


5938501 - Burleson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year
150
160
170
180
190
200
210
1950
1960
1970
1980
1990
2000
2010
2020


5938507 - Burleson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year
140
150
160
170
180
190
200
210
1950
1960
1970
1980
1990
2000
2010
2020


5938511 - Burleson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year
150
160
170
180
190
200
210
1950
1960
1970
1980
1990
2000
2010
2020


5938701 - Burleson County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year
140
150
160
170
180
190
200
210
1950
1960
1970
1980
1990
2000
2010
2020

Grimes County

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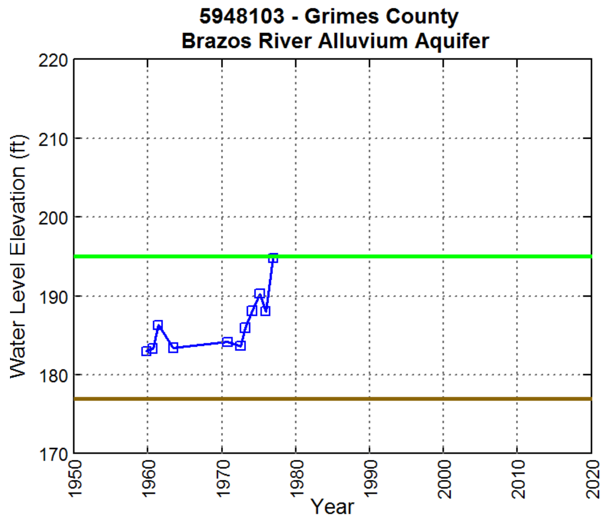
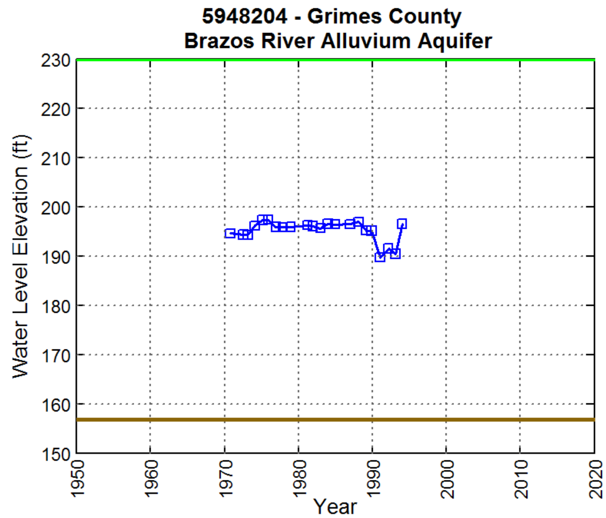
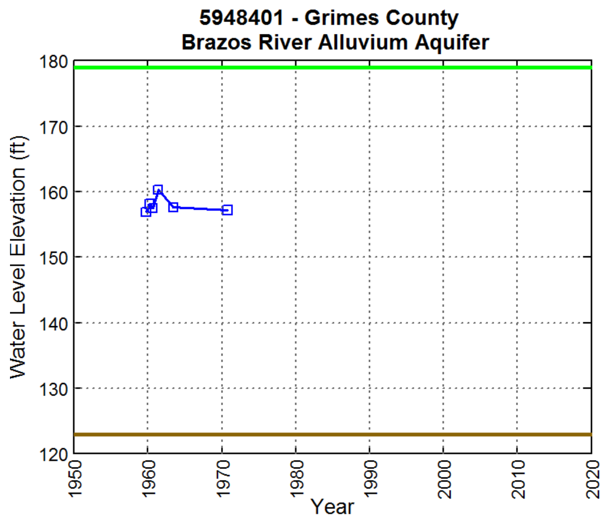
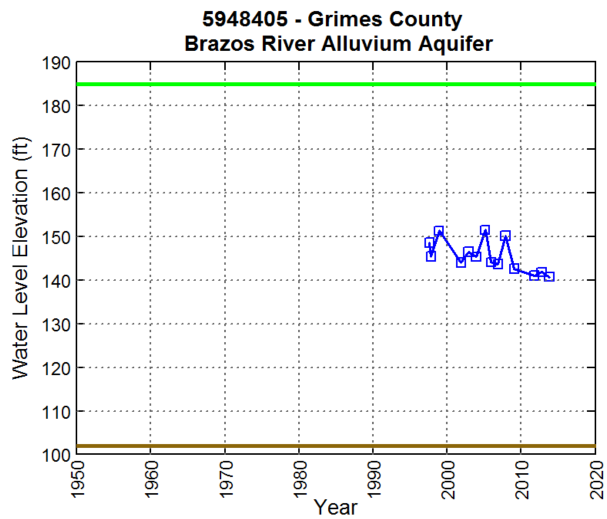
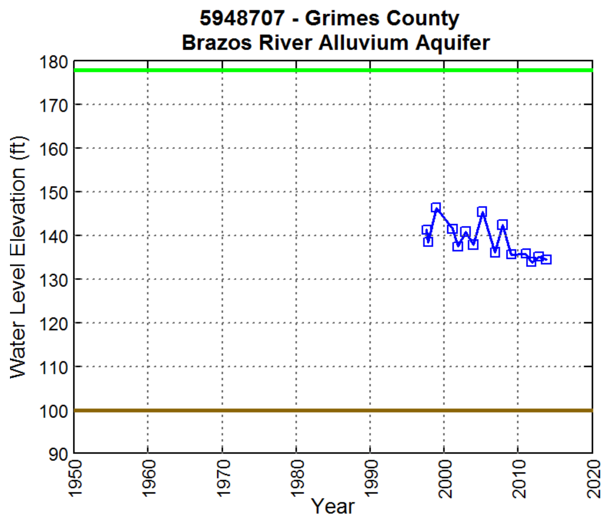

5948103 - Grimes County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
220
210
200
190
180
170
1950
1960
1970
1980
1990
2000
2010
2020
Year


5948204 - Grimes County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
230
220
210
200
190
180
170
160
150
1950
1960
1970
1980
1990
2000
2010
2020
Year


5948401 - Grimes County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
180
170
160
150
140
130
120
1950
1960
1970
1980
1990
2000
2010
2020
Year


5948405 - Grimes County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
190
180
170
160
150
140
130
120
110
100
1950
1960
1970
1980
1990
2000
2010
2020
Year


5948707 - Grimes County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
180
170
160
150
140
130
120
110
100
90
1950
1960
1970
1980
1990
2000
2010
2020
Year

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Washington County

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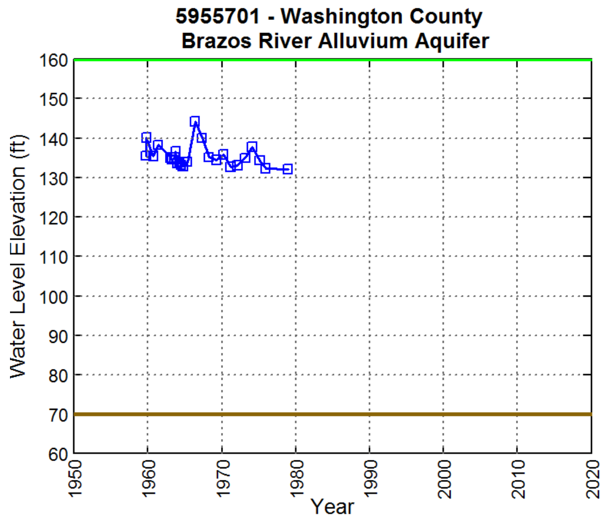
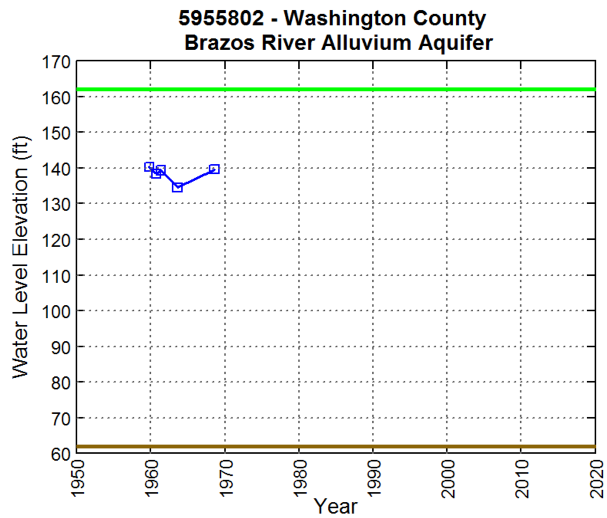
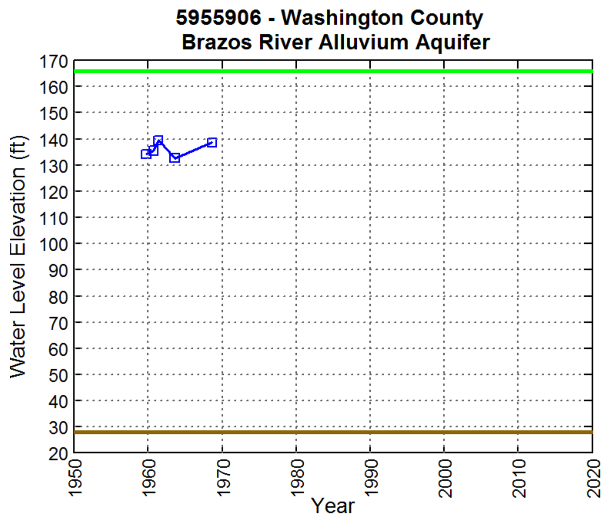

5955701 - Washington County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year
160
150
140
130
120
110
100
90
80
70
60
1950
1960
1970
1980
1990
2000
2010
2020


5955802 - Washington County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year
170
160
150
140
130
120
110
100
90
80
70
60
1950
1960
1970
1980
1990
2000
2010
2020


5955906 - Washington County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
1950
1960
1970
1980
1990
2000
2010
2020

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Austin County

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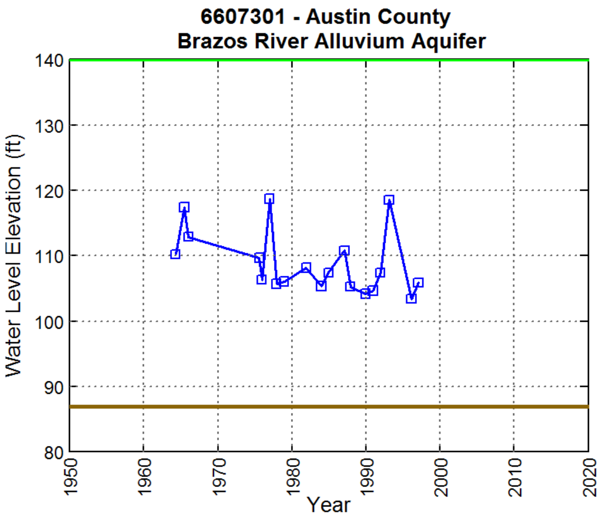
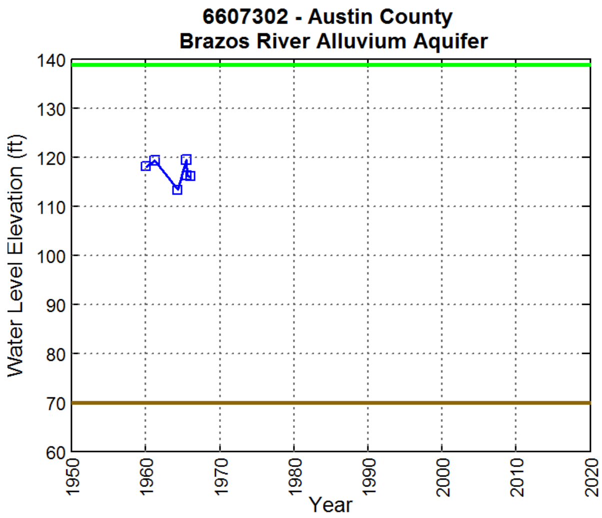

6607301 - Austin County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year
140
130
120
110
100
90
80
1950
1960
1970
1980
1990
2000
2010
2020


6607302 - Austin County
Brazos River Alluvium Aquifer
Water Level Elevation (ft)
Year
140
130
120
110
100
90
80
70
60
1950
1960
1970
1980
1990
2000
2010
2020

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APPENDIX B

Flow Duration Curves, Long-Term Base Blow Curves, and Base Flow/Precipitation Regression Curves

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This appendix provides additional data related to the hydrograph separation analysis conducted in the current study and discussed in Sections 4.3.3.1 and 4.3.3.2. Due to the large volume, not all of the available data were included in the main body of this report. All calculated flow duration curves, long-term base flow trends, and correlation plots between precipitation and base flow for the gages used in the hydrograph separation analysis are provided below.

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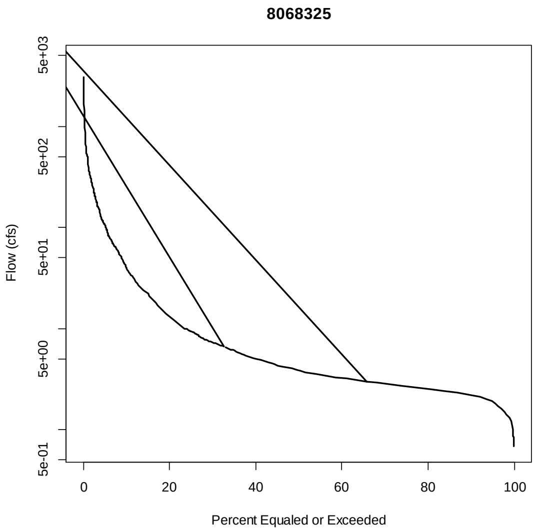
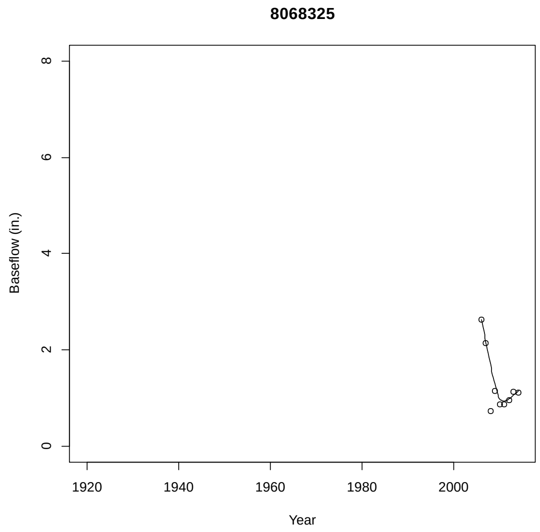
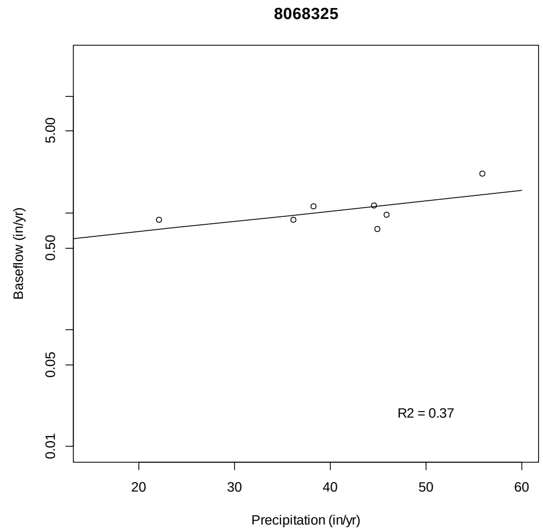
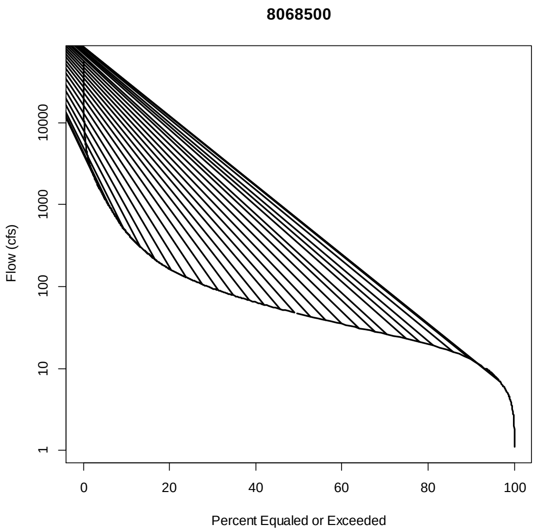
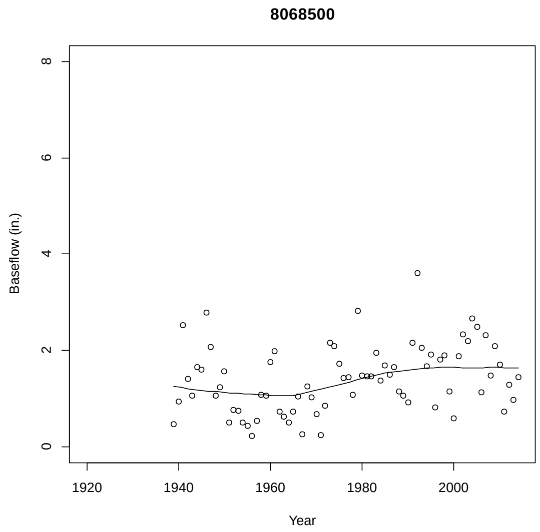
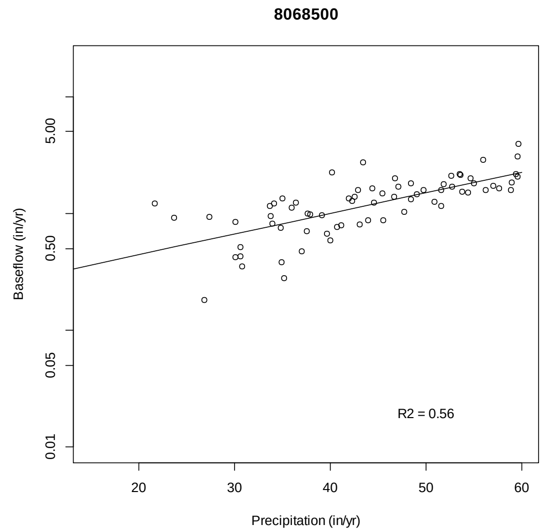

8068325
Flow (cfs)
Percent Equaled or Exceeded

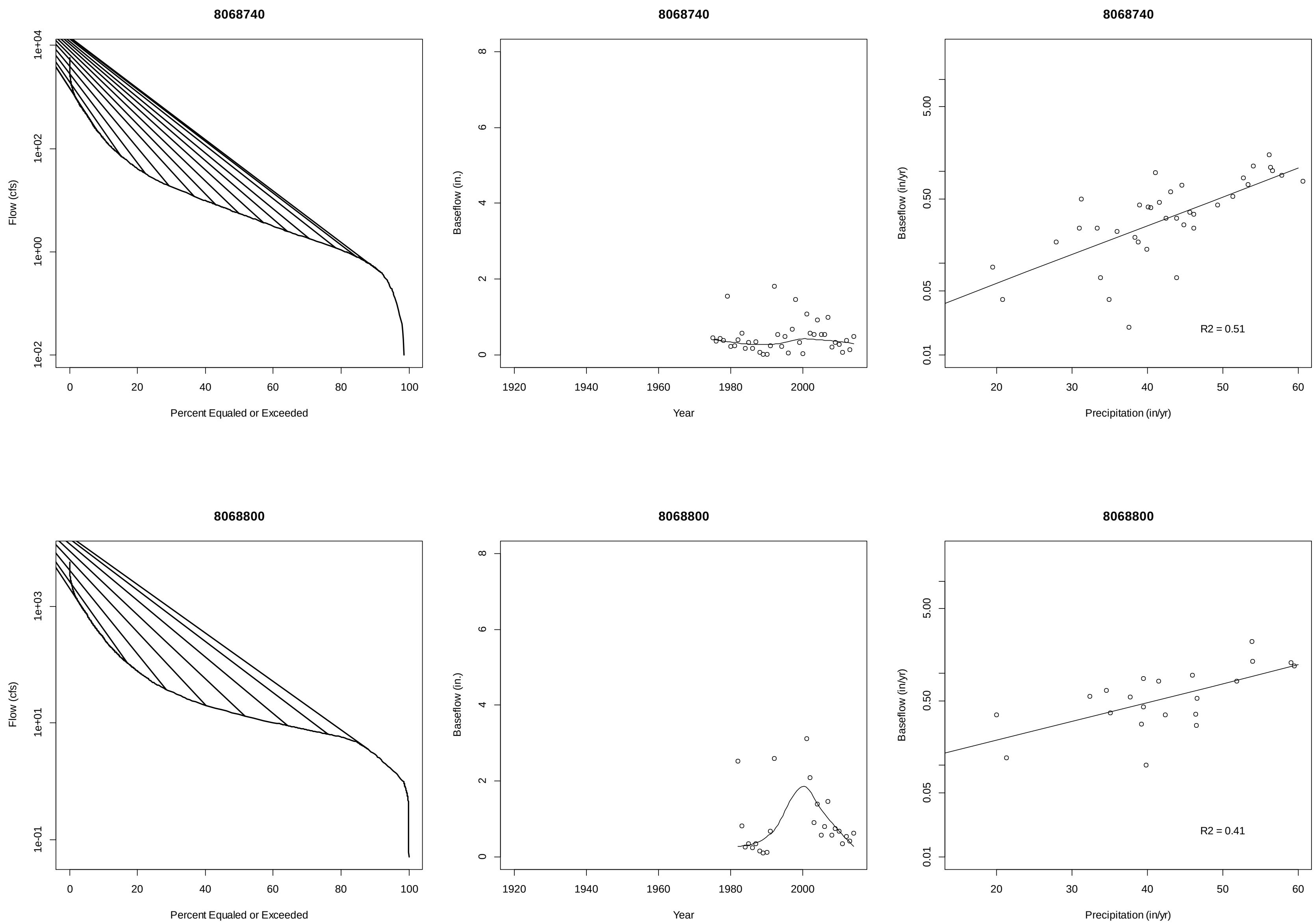

8068325
Baseflow (in.)
Year

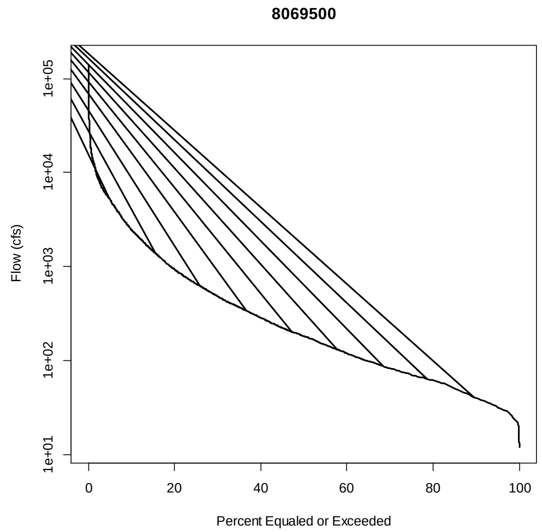

8068325
Baseflow (in/yr)
Precipitation (in/yr)
R2 = 0.37

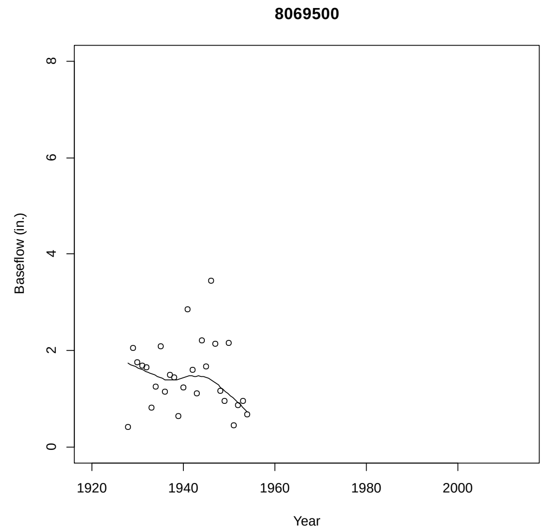

8068500
Flow (cfs)
Percent Equaled or Exceeded

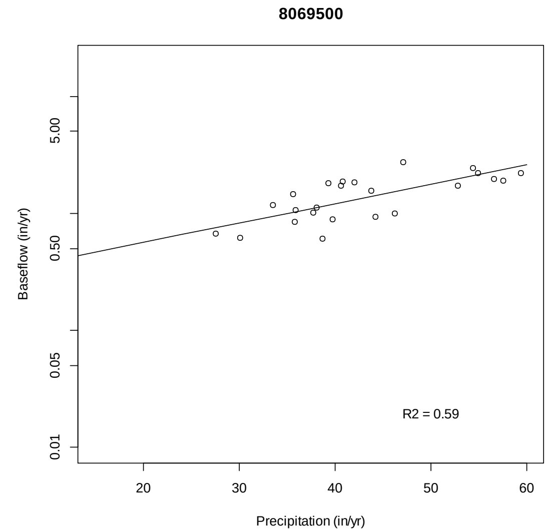

8068500
Baseflow (in.)
Year

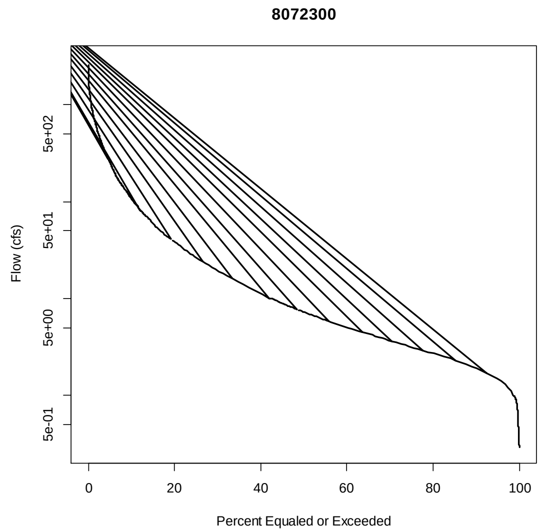

8068500
Baseflow (in/yr)
Precipitation (in/yr)
R2 = 0.56

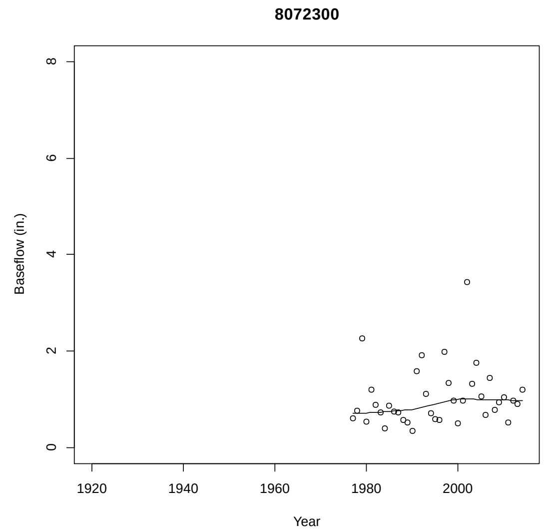

8068740
Flow (cfs)
Percent Equaled or Exceeded
8068740
Baseflow (in.)
Year
8068740
Baseflow (in/yr)
Precipitation (in/yr)
R2 = 0.51
8068800
Flow (cfs)
Percent Equaled or Exceeded
8068800
Baseflow (in.)
Year
8068800
Baseflow (in/yr)
Precipitation (in/yr)
R2 = 0.41

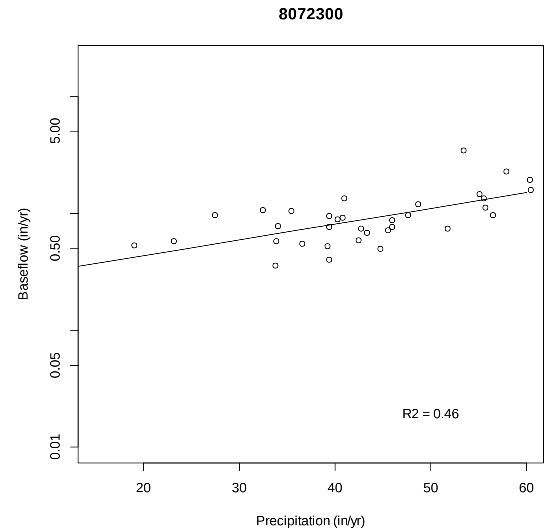

8069500
Flow (cfs)
1e+01
1e+02
1e+03
1e+04
1e+05
0
20
40
60
80
100
Percent Equaled or Exceeded

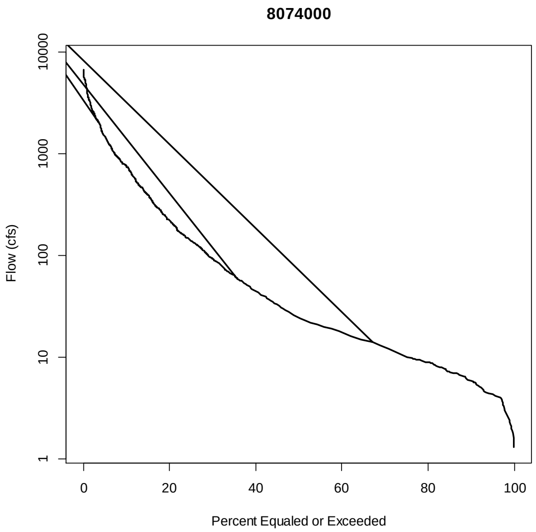

8069500
Baseflow (in.)
0
2
4
6
8
1920
1940
1960
1980
2000
Year

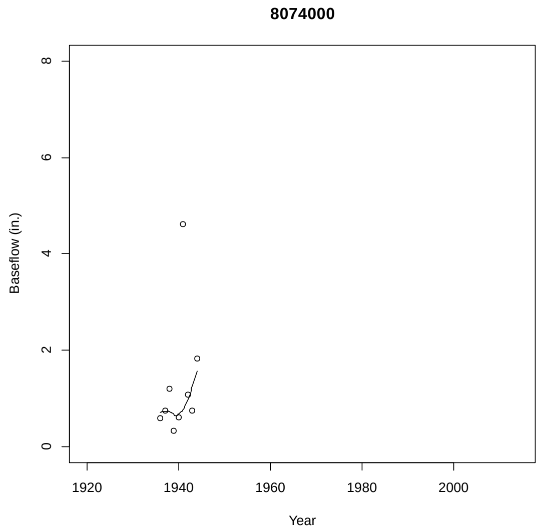

8069500
Baseflow (in/yr)
0.01
0.05
0.50
5.00
R2 = 0.59
20
30
40
50
60
Precipitation (in/yr)

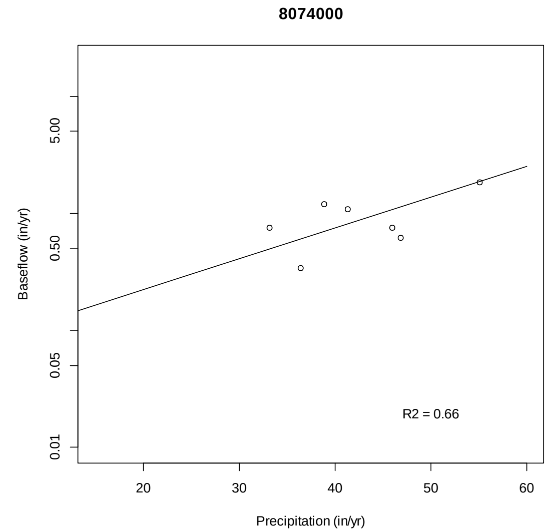

8072300
Flow (cfs)
5e-01
5e+00
5e+01
5e+02
0
20
40
60
80
100
Percent Equaled or Exceeded

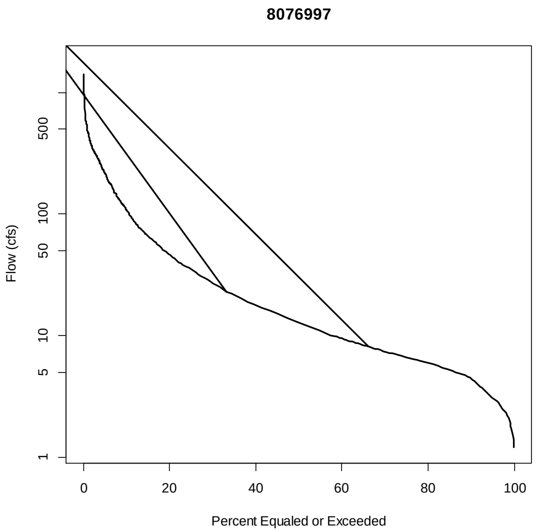

8072300
Baseflow (in.)
0
2
4
6
8
1920
1940
1960
1980
2000
Year

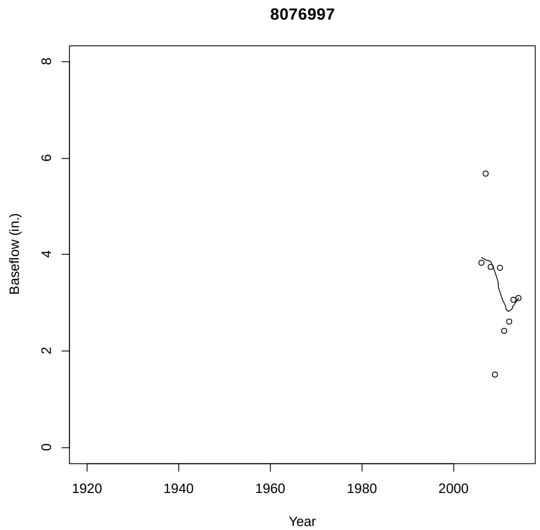

8072300
Baseflow (in/yr)
0.01
0.05
0.50
5.00
R2 = 0.46
20
30
40
50
60
Precipitation (in/yr)

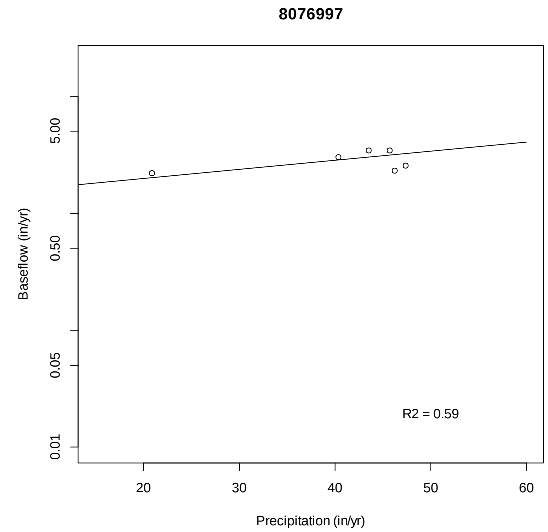

8074000
Flow (cfs)
Percent Equaled or Exceeded

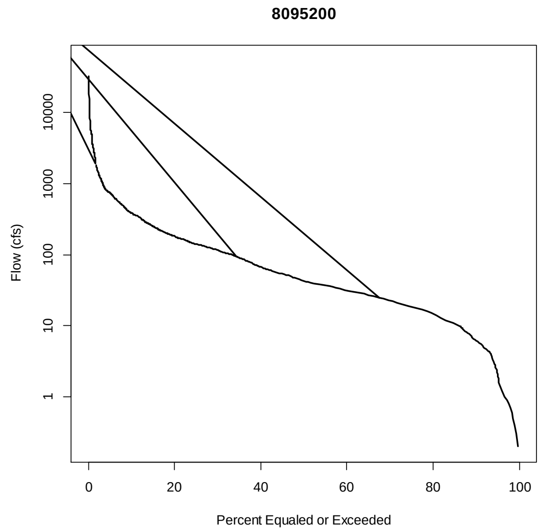

8074000
Baseflow (in.)
Year

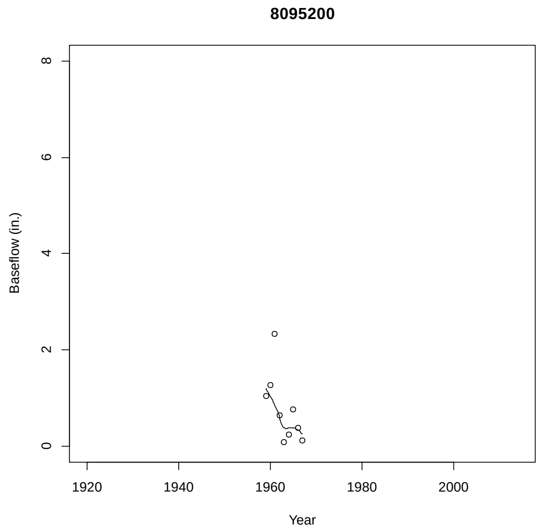

8074000
Baseflow (in/yr)
Precipitation (in/yr)
R2 = 0.66

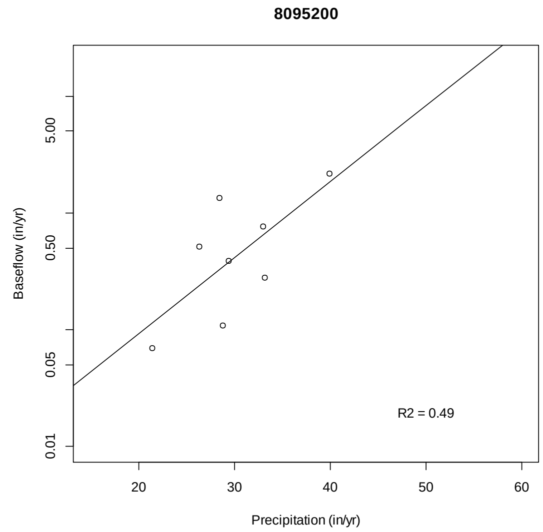

8076997
Flow (cfs)
Percent Equaled or Exceeded

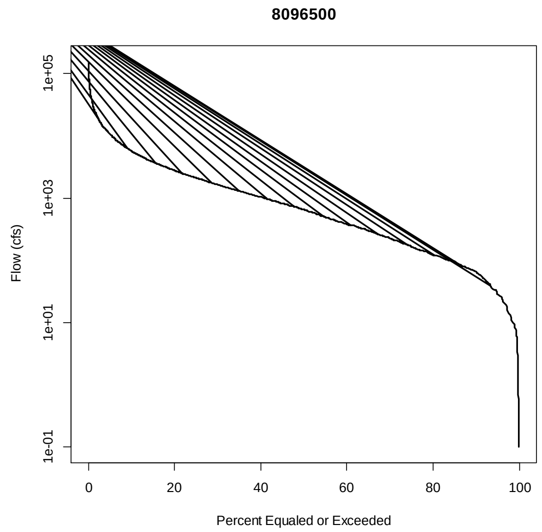

8076997
Baseflow (in.)
Year

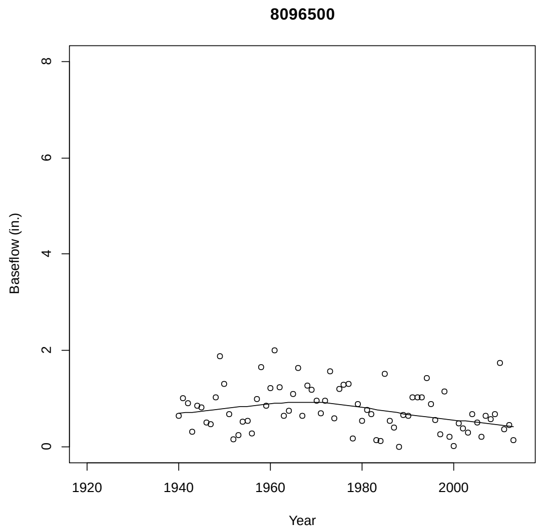

8076997
Baseflow (in/yr)
Precipitation (in/yr)
R2 = 0.59

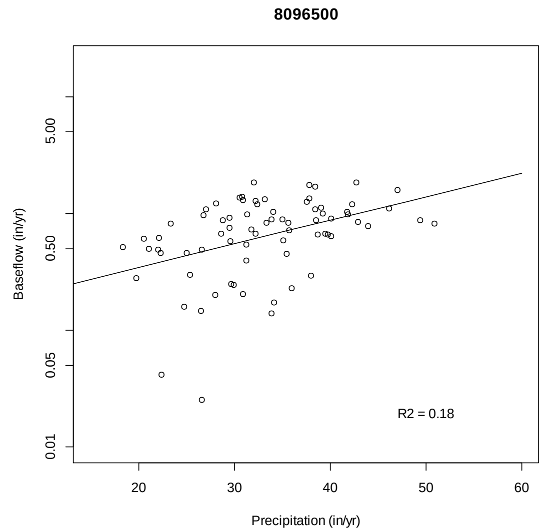

8095200
Flow (cfs)
Percent Equaled or Exceeded

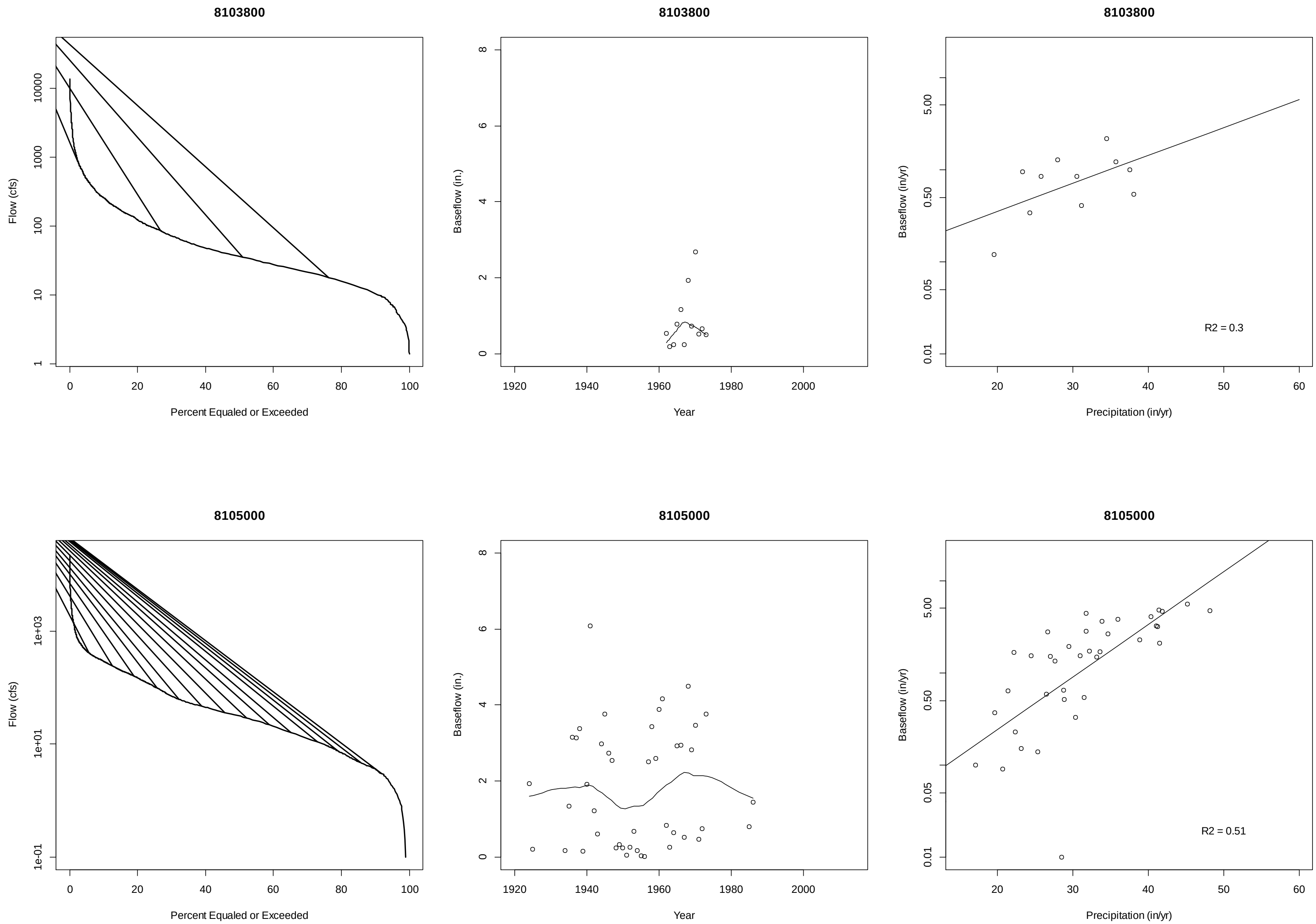

8095200
Baseflow (in.)
Year

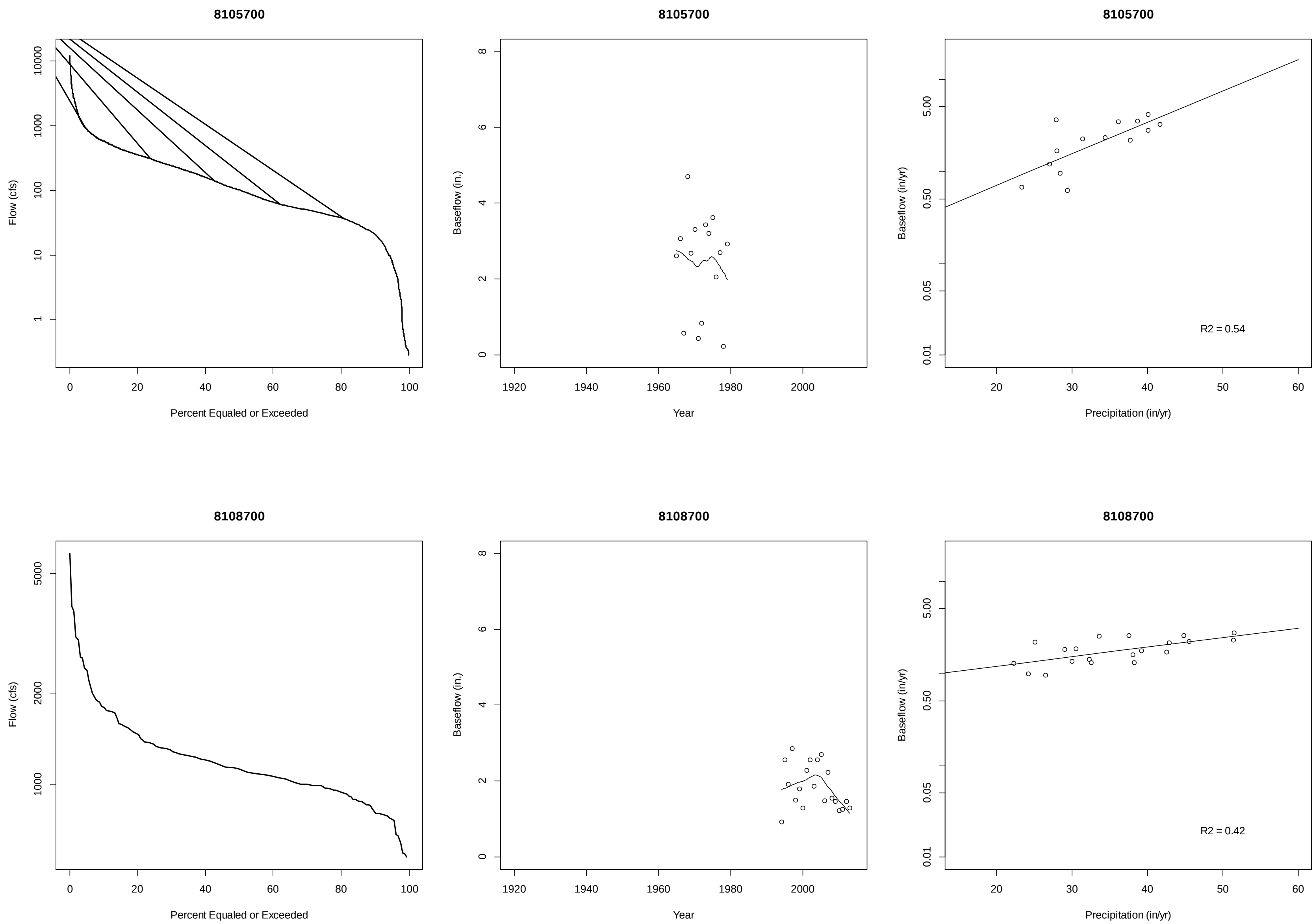

8095200
Baseflow (in/yr)
Precipitation (in/yr)
R2 = 0.49

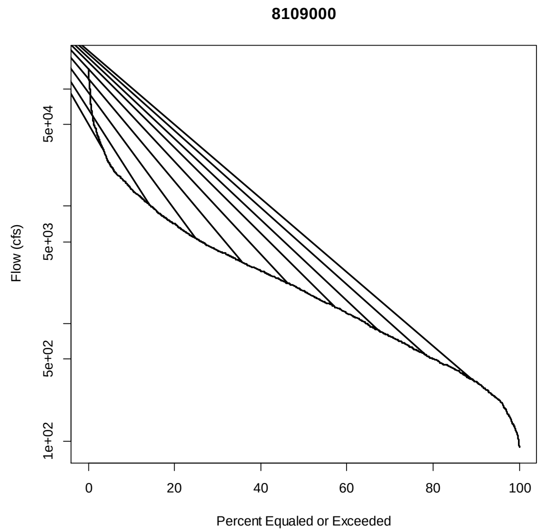

8096500
Flow (cfs)
Percent Equaled or Exceeded

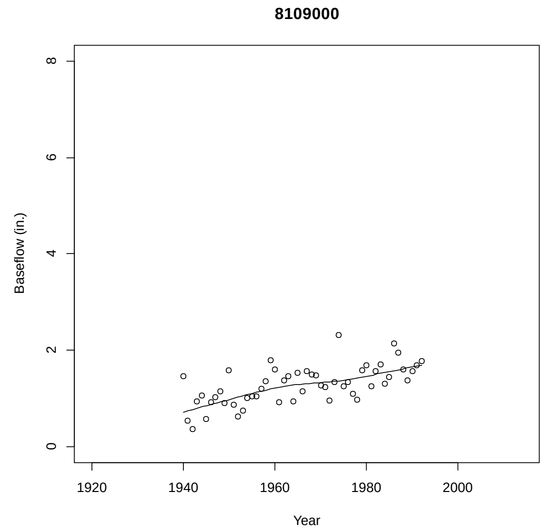

8096500
Baseflow (in.)
Year

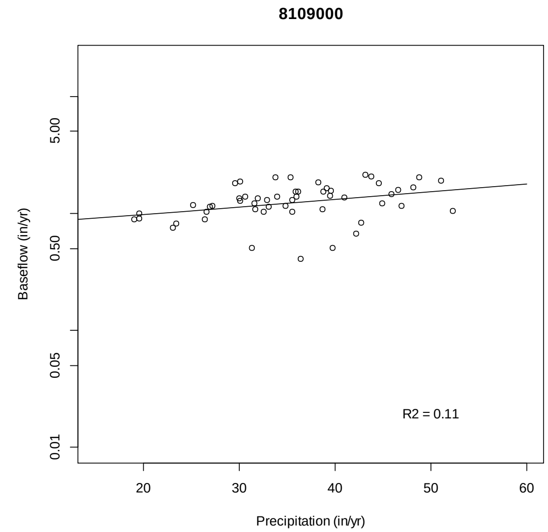

8096500
Baseflow (in/yr)
Precipitation (in/yr)
R2 = 0.18

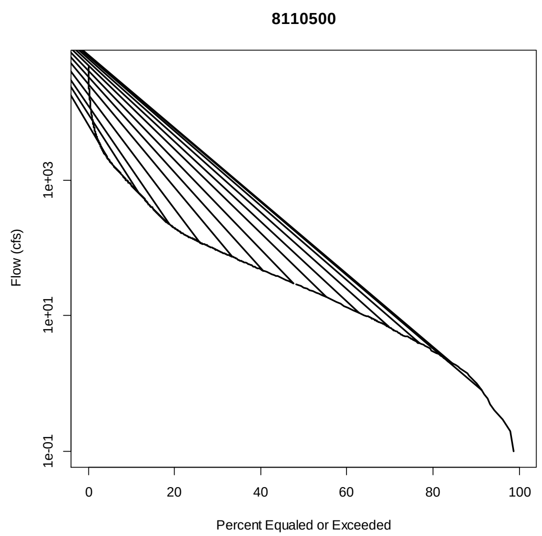

8103800
Flow (cfs)
Percent Equaled or Exceeded
8103800
Baseflow (in.)
Year
8103800
Baseflow (in/yr)
Precipitation (in/yr)
R2 = 0.3
8105000
Flow (cfs)
Percent Equaled or Exceeded
8105000
Baseflow (in.)
Year
8105000
Baseflow (in/yr)
Precipitation (in/yr)
R2 = 0.51

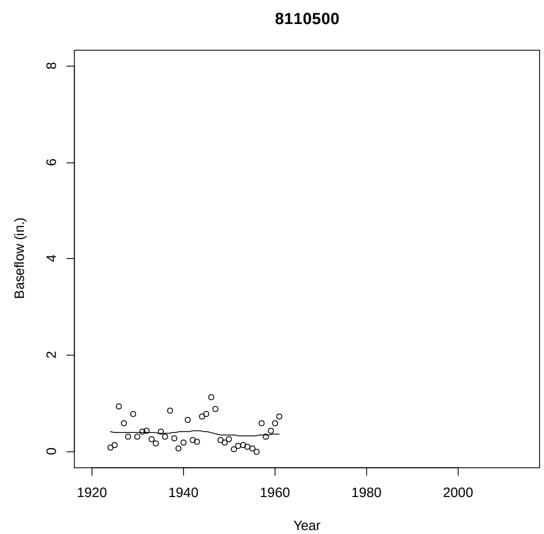

8105700
Flow (cfs)
Percent Equaled or Exceeded
8105700
Baseflow (in.)
Year
8105700
Baseflow (in/yr)
Precipitation (in/yr)
R2 = 0.54
8108700
Flow (cfs)
Percent Equaled or Exceeded
8108700
Baseflow (in.)
Year
8108700
Baseflow (in/yr)
Precipitation (in/yr)
R2 = 0.42

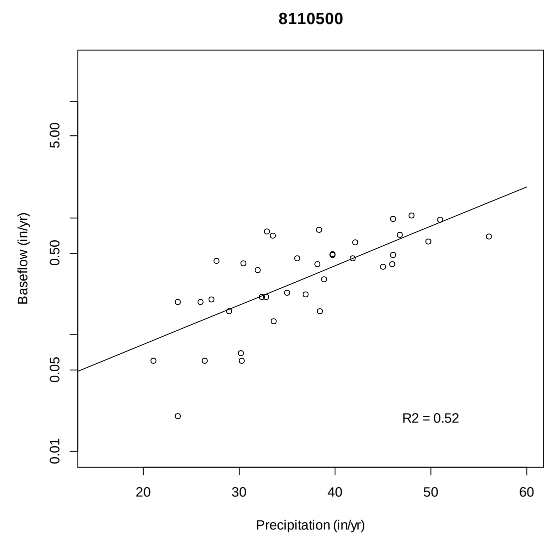

8109000
Flow (cfs)
5e+04
5e+03
5e+02
1e+02
0
20
40
60
80
100
Percent Equaled or Exceeded

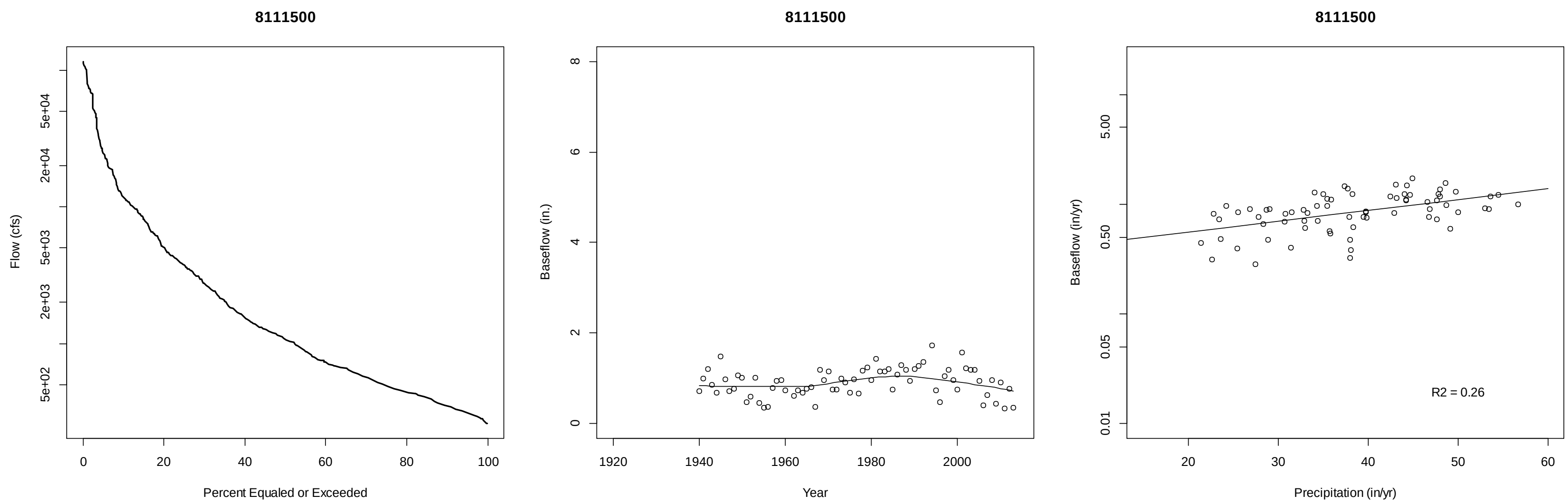

8109000
Baseflow (in.)
8
6
4
2
0
1920
1940
1960
1980
2000
Year

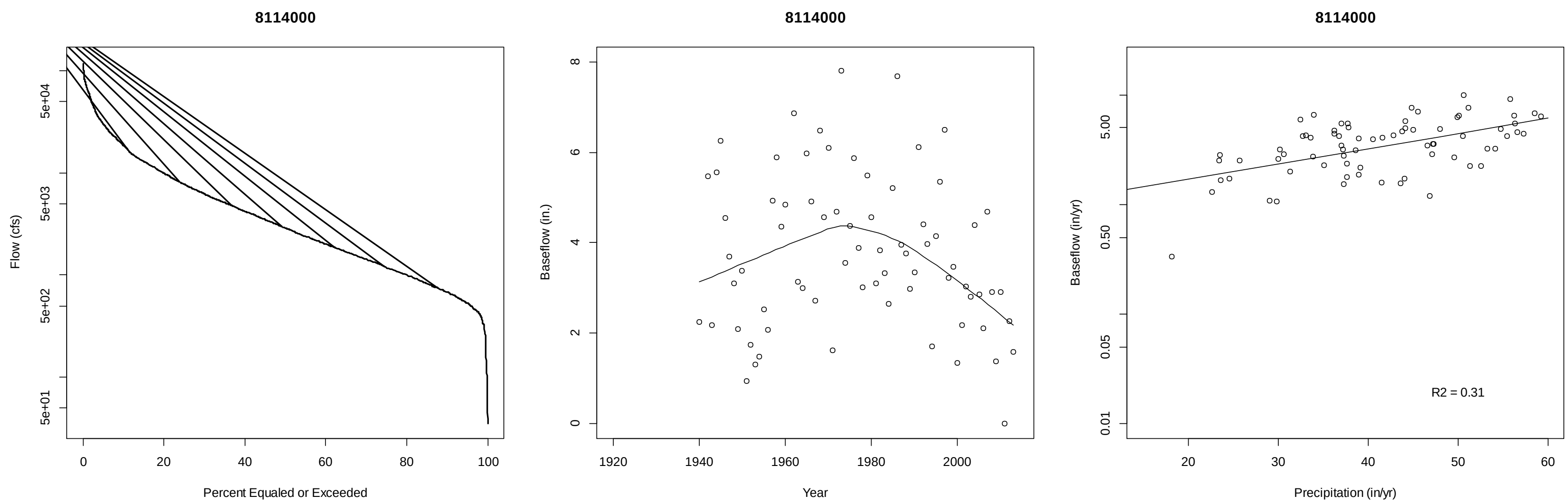

8109000
Baseflow (in/yr)
5.00
0.50
0.05
0.01
R2 = 0.11
20
30
40
50
60
Precipitation (in/yr)

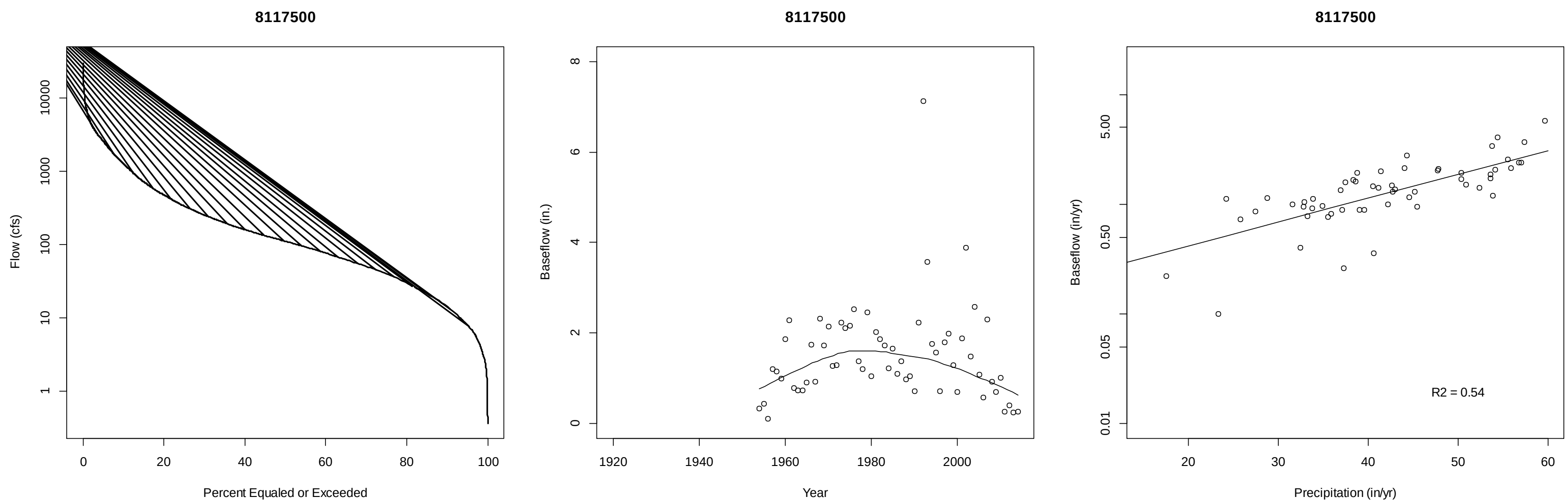

8110500
Flow (cfs)
1e+03
1e+01
1e-01
0
20
40
60
80
100
Percent Equaled or Exceeded


8110500
Baseflow (in.)
8
6
4
2
0
1920
1940
1960
1980
2000
Year


8110500
Baseflow (in/yr)
5.00
0.50
0.05
0.01
R2 = 0.52
20
30
40
50
60
Precipitation (in/yr)


8111500
Flow (cfs)
Percent Equaled or Exceeded
8111500
Baseflow (in.)
Year
8111500
Baseflow (in/yr)
Precipitation (in/yr)
R2 = 0.26


8114000
Flow (cfs)
Percent Equaled or Exceeded
8114000
Baseflow (in.)
Year
8114000
Baseflow (in/yr)
Precipitation (in/yr)
R2 = 0.31


8117500
Flow (cfs)
10000
1000
100
10
1
0
20
40
60
80
100
Percent Equaled or Exceeded
8117500
Baseflow (in.)
8
6
4
2
0
1920
1940
1960
1980
2000
Year
8117500
Baseflow (in/yr)
5.00
0.50
0.05
0.01
R2 = 0.54
20
30
40
50
60
Precipitation (in/yr)

APPENDIX C

Spring Information

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This appendix provides additional data related to the springs found in the active model area. The section on springs in the main body of this report (Section 4.4.2) focuses on springs issuing from the Brazos River Alluvium Aquifer. However, there are many additional springs in the active model area issuing from other formations. However, due to space constraints, only data from Brazos River Alluvium Aquifer springs were included in Table 4.4.15. Table C.1 provides data for all springs in the active model area.

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Table C-1 Springs in the active model boundary.

Spring Name	Spring Number[(1)]	County	Spring Source Formation	GAMx[(2)] (feet)	GAMy[(2)] (feet)	Minimum Flow (gpm)	Date of Minimum Flow	Maximum Flow (gpm)	Date of Maximum Flow	Number of Measure-ments	Source[(3)]
Comanche Springs	TWDB_3920703 AND USGS_313925096360401	Limestone	TEHUACANA MEMBER OF KINCAID FORMATION	19849600	5976460	--	--	8	1981	1	TWDB, USGS
Fort Parker Springs	TWDB_3928501 AND USGS_313346096325301	Limestone	MIDWAY GROUP	19815800	5994000	--	--	--	--	--	TWDB, USGS
Sulphur Springs	TWDB_3928503 AND USGS_313440096344001	Limestone	TEHUACANA MEMBER OF KINCAID FORMATION	19820900	5984600	--	--	2	1981	1	TWDB, USGS
Groesbeck Springs	TWDB_3928803	Limestone	TEHUACANA MEMBER OF KINCAID FORMATION	19802200	5995030	--	--	--	--	--	TWDB
Cedar Springs	TWDB_3949502 AND USGS_311131096553101	Falls	TAYLOR MARL	19677200	5880560	--	--	--	--	--	TWDB, USGS
Mill Branch Spring	TWDB_3954908 AND USGS_310842096155001	Leon	QUEEN CITY SAND OF CLAIBORNE GROUP	19666400	6087420	--	--	1	1936	1	TWDB, USGS
WK-39-58-609	TWDB_3958609 AND USGS_310406096454201	Robertson	CARRIZO SAND	19634000	5933330	--	--	--	--	--	TWDB, USGS
WK-39-59-401	TWDB_3959401 AND USGS_310236096441501	Robertson	SIMSBORO SAND MEMBER OF ROCKDALE FORMATION	19624700	5940730	--	--	--	--	--	TWDB, USGS
Elmwood Ranch Springs OR WK-39-59-904	TWDB_3959904 AND USGS_310126096385901	Robertson	CALVERT BLUFF FORMATION	19619100	5968600	--	--	10	1972	1	TWDB, USGS
Blackgum Spring	TWDB_3963403 AND USGS_310351096125901	Leon	SPARTA SAND	19637500	6103250	--	--	2	1936	1	TWDB, USGS
BB-40-14-503	TWDB_4014503 AND USGS_314847097175001	Bosque	LIMESTONES OF FREDERICKSBURG AND WASHITA GROUPS	19900400	5759010	--	--	50 - 60	1971	1	TWDB, USGS
Latham Springs OR LW-40-14-603	TWDB_4014603 AND USGS_314907097165401	Hill	FREDERICKSBURG GROUP	19902600	5763780	--	--	50 - 60	1960	1	TWDB, USGS
Hurst Springs OR HB-40-19-801	TWDB_4019801 AND USGS_313957097413101	Coryell	FREDERICKSBURG GROUP	19844000	5637890	--	--	--	--	--	TWDB, USGS
BB-40-21-103	TWDB_4021103 AND USGS_314354097282701	Bosque	WASHITA GROUP	19869500	5704850	--	--	--	--	--	TWDB, USGS
El Flechazo Spring OR Love at First Sight Spring	TWDB_4022102 AND USGS_314331097203101	Bosque	FORT WORTH LIMESTONE AND DUCK CREEK FORMATION, UNDIVIDED	19868200	5745920	--	--	--	--	--	TWDB, USGS

Table C-1, continued

Spring Name	Spring Number[1]	County	Spring Source Formation	GAMx[2] (feet)	GAMy[2] (feet)	Minimum Flow (gpm)	Date of Minimum Flow	Maximum Flow (gpm)	Date of Maximum Flow	Number of Measure-ments	Source[3]
Waco Springs	TWDB_4031616 AND USGS_313431097083101	Mclennan	ALLUVIUM,FLOOD PLAIN	19815000	5809370	--	--	--	--	--	TWDB, USGS
Eagle Springs	TWDB_4045102 AND USGS_312106097284301	Coryell	LIMESTONES OF FREDERICKSBURG AND WASHITA GROUPS	19731000	5706630	--	--	100	1942	1	TWDB, USGS
McDaniel Farm Spring	TWDB_4052904 AND USGS_310759097322401 AND Bell_34 (Brune)	Bell	EDWARDS AND ASSOCIATED LIMESTONES	19650900	5689280	25	1978	90	1937	2	TWDB, USGS
Tahuaya Spring	TWDB_4060912	Bell	EDWARDS AND ASSOCIATED LIMESTONES	19605800	5699930	--	--	--	--	--	TWDB
Leon Springs	TWDB_4061406 AND USGS_310431097273101 AND Bell_6 (Brune)	Bell	EDWARDS AND ASSOCIATED LIMESTONES	19630400	5715170	--	--	54	1968	1	TWDB, USGS
Childers Springs	TWDB_4061706 AND USGS_310031097293101 AND Spicewood Spring, Bell_8 (Brune)	Bell	EDWARDS AND ASSOCIATED LIMESTONES	19605900	5705310	--	--	1522	1975	1	TWDB, USGS
Fort Little River Springs	TWDB_4061902 AND USGS_310031097233101 AND Bell_9 (Brune)	Bell	ALLUVIUM AND AUSTIN CHALK	19606600	5736560	dry in dry weather	1965	10	1975	2	TWDB, USGS
Sulphur Creek Springs	TWDB_4163501 AND USGS_310410098103001	Lampasas	TRAVIS PEAK FORMATION	19623800	5491520	600	1970	3097	1924	2	TWDB, USGS
Hancock Springs	TWDB_4163505 AND USGS_310320098110001 AND Lampasas_2 (Brune)	Lampasas	MARBLE FALLS LIMESTONE	19618700	5489000	1744	1957, 1975	5865	1970, 1973	26	TWDB, USGS
Hannah Springs	TWDB_4163510 AND USGS_08103500 AND Lampasas_6 (Brune)	Lampasas	TRAVIS PEAK FORMATION	19623700	5490910	222	1975	1744	1900	24	TWDB, USGS
Swimming Pool Springs OR Hancock Park Spring OR Lampasas Spring	TWDB_4163521 AND USGS_310331098113101 AND Lampasas_3 (Brune)	Lampasas	TRAVIS PEAK FORMATION	19619800	5486200	90	1931	761	1901, 1924, 1962	12	TWDB, USGS
BT-57-16-102	TWDB_5716102 AND USGS_305230098061401	Burnet	PALUXY SAND	19553300	5514950	--	--	--	--	--	TWDB, USGS
AX-58-03-502	TWDB_5803502 AND USGS_305537097405401	Bell	EDWARDS AND ASSOCIATED LIMESTONES	19574700	5646720	--	--	0.5	1981	1	TWDB, USGS

Table C-1, continued

Spring Name	Spring Number[1]	County	Spring Source Formation	GAMx[2] (feet)	GAMy[2] (feet)	Minimum Flow (gpm)	Date of Minimum Flow	Maximum Flow (gpm)	Date of Maximum Flow	Number of Measure-ments	Source[3]
Willingham Place Spring 1	TWDB_5803601 AND USGS_305546097380601	Bell	EDWARDS AND ASSOCIATED LIMESTONES	19575800	5661390	--	--	< 0.5	1978	1	TWDB, USGS
Willingham Place Spring 2	TWDB_5803602 AND USGS_305603097384001	Bell	EDWARDS AND ASSOCIATED LIMESTONES	19577600	5658310	< 0.5	1978	3	1981	2	TWDB, USGS
Willingham Place Spring 3	TWDB_5803603 AND USGS_305614097382101	Bell	EDWARDS AND ASSOCIATED LIMESTONES	19578800	5659940	0.5	1978	2	1981	2	TWDB, USGS
ZK-58-03-802	TWDB_5803802 AND USGS_305240097402401	Williamson	EDWARDS AND ASSOCIATED LIMESTONES	19556900	5649700	--	--	175	1981	1	TWDB, USGS
Headquarters Springs	TWDB_5803806 AND USGS_305331097403102 AND Bell_22 (Brune)	Bell	EDWARDS AND ASSOCIATED LIMESTONES - (BALCONES FAULT ZONE AQUIFER)	19562100	5648900	--	--	100	1975	1	TWDB, USGS
Warwick Springs	TWDB_5803807 AND USGS_305331097403101 AND Bell_23 (Brune)	Bell	EDWARDS AND ASSOCIATED LIMESTONES - (BALCONES FAULT ZONE AQUIFER)	19562100	5648900	--	--	206	1975	1	TWDB, USGS
AX-58-03-903	TWDB_5803903 AND USGS_305357097381801	Bell	EDWARDS AND ASSOCIATED LIMESTONES	19565200	5660230	--	--	80	1981	1	TWDB, USGS
AX-58-03-904	TWDB_5803904 AND USGS_305408097395601	Bell	EDWARDS AND ASSOCIATED LIMESTONES	19565800	5651950	--	--	35	1981	1	TWDB, USGS
AX-58-03-905	TWDB_5803905 AND USGS_305326097373501	Bell	EDWARDS AND ASSOCIATED LIMESTONES	19561800	5664300	--	--	24	1981	1	TWDB, USGS
AX-58-03-906	TWDB_5803906 AND USGS_305254097395401	Bell	EDWARDS AND ASSOCIATED LIMESTONES	19558300	5652280	--	--	22	1981	1	TWDB, USGS
AX-58-03-907	TWDB_5803907 AND USGS_305345097380201	Bell	EDWARDS AND ASSOCIATED LIMESTONES	19563700	5661910	--	--	10	1981	1	TWDB, USGS
AX-58-03-908	TWDB_5803908 AND USGS_305326097393701	Bell	EDWARDS AND ASSOCIATED LIMESTONES	19561400	5653960	--	--	36	1981	1	TWDB, USGS

Table C-1, continued

Spring Name	Spring Number(1)	County	Spring Source Formation	GAMx(2) (feet)	GAMy(2) (feet)	Minimum Flow (gpm)	Date of Minimum Flow	Maximum Flow (gpm)	Date of Maximum Flow	Number of Measure-ments	Source(3)
AX-58-03-909	TWDB_5803909 AND USGS_305317097392401	Bell	EDWARDS AND ASSOCIATED LIMESTONES	19560700	5654840	--	--	197	1981	1	TWDB, USGS
AX-58-03-910	TWDB_5803910 AND USGS_305315097391701	Bell	EDWARDS AND ASSOCIATED LIMESTONES	19560500	5655450	--	--	5	1981	1	TWDB, USGS
AX-58-03-911	TWDB_5803911 AND USGS_305250097395401	Bell	EDWARDS AND ASSOCIATED LIMESTONES	19558000	5652290	130	1981	193	1981	2	TWDB, USGS
Indian Camp Spring	TWDB_5804201 AND USGS_305738097345801	Bell	EDWARDS AND ASSOCIATED LIMESTONES	19587600	5677390	--	--	170	1981	1	TWDB, USGS
Willingham Church Spring	TWDB_5804401 AND USGS_305515097371801 AND Bell_35 (Brune)	Bell	EDWARDS AND ASSOCIATED LIMESTONES	19572700	5665630	0.5	1978	0.5	1981	2	TWDB, USGS
Hodge Place Spring	TWDB_5804402 AND USGS_305522097360101	Bell	EDWARDS AND ASSOCIATED LIMESTONES	19573800	5672210	0.5	1978	18	1981	2	TWDB, USGS
Holmes Spring	TWDB_5804403 AND USGS_305555097351501	Bell	EDWARDS AND ASSOCIATED LIMESTONES	19577200	5676140	0.5	1978	4	1981	2	TWDB, USGS
AX-58-04-404	TWDB_5804404 AND USGS_305545097370701	Bell	EDWARDS AND ASSOCIATED LIMESTONES	19575900	5666430	54	1991	54	1981	2	TWDB, USGS
Salado Springs	TWDB_5804501 AND USGS_305644097323701 AND Bell_2 (Brune)	Bell	EDWARDS AND ASSOCIATED LIMESTONES	19582200	5690200	2061	1956	15850	1961	27	TWDB, USGS
Robertson Spring	TWDB_5804515 AND Bell_2a/2b (Brune)	Bell	EDWARDS AND ASSOCIATED LIMESTONES	19582200	5690290	174	1951	444	1948	3	TWDB
Little Bubbly OR Big Boiling Spring	TWDB_5804613 AND USGS_305638097321401 AND TWDB_5804629 AND Bell_2d/2e (Brune)	Bell	EDWARDS AND ASSOCIATED LIMESTONES	19581900	5691770	127	1950, 1951	1497	1981	4	TWDB, USGS
Benedict Spring OR Spring Groves Spring	TWDB_5804614 AND USGS_305639097320601 AND Bell_2g (Brune)	Bell	EDWARDS AND ASSOCIATED LIMESTONES	19582000	5692810	48	1950, 1951	1219	1981	4	TWDB, USGS
Critchfield Spring	TWDB_5804630 AND Bell_2f (Brune)	Bell	EDWARDS AND ASSOCIATED LIMESTONES	19581800	5692210	365	1950	761	1948, 1951	3	TWDB

Table C-1, continued

Spring Name	Spring Number[(1)]	County	Spring Source Formation	GAMx[(2)] (feet)	GAMy[(2)] (feet)	Minimum Flow (gpm)	Date of Minimum Flow	Maximum Flow (gpm)	Date of Maximum Flow	Number of Measure-ments	Source[(3)]
AX-58-04-703	TWDB_5804703 AND USGS_305246097372601	Bell	EDWARDS AND ASSOCIATED LIMESTONES	19557800	5665170	--	--	45	1981	1	TWDB, USGS
Sycamore Springs	TWDB_5809503 AND USGS_304849097553401 AND Williamson_18 (Brune)	Williamson	--	19532000	5570930	--	--	301	1975	1	TWDB, USGS
Andice Spring	TWDB_5810703 AND USGS_304659097501701	Williamson	--	19521400	5598730	--	--	--	--	--	TWDB, USGS
S Rumsey/Moore Pasture	TWDB_5811202 AND Williamson_26 (Brune)	Williamson	EDWARDS AND ASSOCIATED LIMESTONES	19555500	5647560	112	1981	1744	1975	2	TWDB
ZK-58-11-301	TWDB_5811301 AND USGS_305216097380001	Williamson	EDWARDS AND ASSOCIATED LIMESTONES	19554700	5662190	--	--	59	1981	1	TWDB, USGS
ZK-58-11-302	TWDB_5811302 AND USGS_305203097385201	Williamson	EDWARDS AND ASSOCIATED LIMESTONES	19553300	5657870	--	--	97	1981	1	TWDB, USGS
ZK-58-12-202	TWDB_5812202 AND USGS_305011097334601	Williamson	EDWARDS AND ASSOCIATED LIMESTONES	19542400	5684470	--	--	0.5	1978	1	TWDB, USGS
Sharp Springs	TWDB_5815803 AND USGS_304631097113101	Milam	ALLUVIUM AND TAYLOR GROUP	19523100	5801230	--	--	--	--	--	TWDB, USGS
Elm Ridge Spring	TWDB_5816301 AND USGS_305054097020501	Milam	MIDWAY GROUP	19551000	5847430	--	--	41769	1971	1	TWDB, USGS
TK-58-16-302	TWDB_5816302 AND USGS_305036097000501	Milam	MIDWAY GROUP	19549800	5860340	--	--	--	--	--	TWDB, USGS
Jim Hagg Road Spring OR Knight Springs	TWDB_5818603 AND USGS_304002097450201 AND TWDB_5818604 AND USGS_304032097453901 AND Williamson_4 (Brune)	Williamson	EDWARDS AND ASSOCIATED LIMESTONES	19482700	5623720	285	1964	396	1940	4	TWDB, USGS
Crockett Gardens Spring	TWDB_5818907	Williamson	EDWARDS AND ASSOCIATED LIMESTONES	19478400	5626770	27	1964	399	1940	3	TWDB
Cedar Hollow Spring	TWDB_5818908	Williamson	EDWARDS AND ASSOCIATED LIMESTONES	19477800	5621290	--	--	9	2002	1	TWDB
Cowan Creek Spring	TWDB_5819102 AND USGS_304313097441101	Williamson	--	19499200	5631050	--	--	278	1938	1	TWDB, USGS

Table C-1, continued

Spring Name	Spring Number[1]	County	Spring Source Formation	GAMx[2] (feet)	GAMy[2] (feet)	Minimum Flow (gpm)	Date of Minimum Flow	Maximum Flow (gpm)	Date of Maximum Flow	Number of Measure-ments	Source[3]
ZK-58-19-305	TWDB_5819305 AND USGS_304300097391101	Williamson	EDWARDS AND ASSOCIATED LIMESTONES	19498300	5657300	1	1978	2	1981	2	TWDB, USGS
Berry Springs	TWDB_5819609 AND USGS_304113097390101 AND Williamson_1 (Brune)	Williamson	EDWARDS AND ASSOCIATED LIMESTONES	19486500	5660070	151	1975	5548	1964	3	TWDB, USGS
Avant's Spring	TWDB_5819708 AND USGS_303845097441201	Williamson	--	19472000	5631520	--	--	--	--	--	TWDB, USGS
Buford Hollow Springs	TWDB_5819709 AND USGS_303940097433701	Williamson	--	19477700	5634460	--	--	--	--	--	TWDB, USGS
Cottonwood Spring OR Georgetown Springs	TWDB_5819806 AND USGS_303857097401401 AND Williamson_5 (Brune)	Williamson	EDWARDS AND ASSOCIATED LIMESTONES	19474100	5652930	103	2002	2267	1975	4	TWDB, USGS
ZK-58-19-822	TWDB_5819822 AND USGS_303916097420901	Williamson	EDWARDS AND ASSOCIATED LIMESTONES	19475400	5642090	--	--	13	1981	1	TWDB, USGS
San Gabriel River Spring	TWDB_5819827 AND USGS_303916097400201	Williamson	--	19475600	5653240	--	--	--	--	--	TWDB, USGS
--	TWDB_5820405	Williamson	EDWARDS AND ASSOCIATED LIMESTONES	19481000	5675010	--	--	2	--	1	TWDB
Manske Branch Springs	TWDB_5820801 AND USGS_303821097345901 AND Williamson_2 (Brune)	Williamson	EDWARDS AND ASSOCIATED LIMESTONES	19470600	5679860	206	1975	1030	1964	2	TWDB, USGS
McFaden Spring OR ZK-58-21-803	TWDB_5821803 AND USGS_303828097251201	Williamson	TERRACE DEPOSITS	19472500	5730920	--	--	7	1996	1	TWDB, USGS
ZK-58-26-302	TWDB_5826302 AND USGS_303612097471701	Williamson	EDWARDS AND ASSOCIATED LIMESTONES	19456000	5615800	--	--	15	1981	1	TWDB, USGS
ZK-58-26-303	TWDB_5826303 AND USGS_303622097472901	Williamson	EDWARDS AND ASSOCIATED LIMESTONES	19457100	5614730	--	--	dry	1981	1	TWDB, USGS
ZK-58-26-304	TWDB_5826304 AND USGS_303638097471101	Williamson	EDWARDS AND ASSOCIATED LIMESTONES	19458800	5616260	--	--	4	1981	1	TWDB, USGS
ZK-58-26-305	TWDB_5826305 AND USGS_303626097465501	Williamson	EDWARDS AND ASSOCIATED LIMESTONES	19457700	5617770	--	--	40	1981	1	TWDB, USGS

Table C-1, continued

Spring Name	Spring Number[1]	County	Spring Source Formation	GAMx[2] (feet)	GAMy[2] (feet)	Minimum Flow (gpm)	Date of Minimum Flow	Maximum Flow (gpm)	Date of Maximum Flow	Number of Measure-ments	Source[3]
ZK-58-26-306	TWDB_5826306 AND USGS_303633097463501	Williamson	EDWARDS AND ASSOCIATED LIMESTONES	19458300	5619410	--	--	13	1981	1	TWDB, USGS
ZK-58-26-307	TWDB_5826307 AND USGS_303612097455701	Williamson	EDWARDS AND ASSOCIATED LIMESTONES	19456400	5622680	--	--	--	--	--	TWDB, USGS
ZK-58-26-308	TWDB_5826308 AND USGS_303610097454401	Williamson	EDWARDS AND ASSOCIATED LIMESTONES	19456100	5623910	--	--	27	1981	1	TWDB, USGS
ZK-58-27-716	TWDB_5827716 AND USGS_303123097423201	Williamson	EDWARDS AND ASSOCIATED LIMESTONES	19427500	5641160	--	--	--	--	--	TWDB, USGS
ZK-58-27-717	TWDB_5827717 AND USGS_303123097423202	Williamson	EDWARDS AND ASSOCIATED LIMESTONES	19427500	5641160	--	--	--	--	--	TWDB, USGS
Krienke Spring	TWDB_5827719 AND USGS_303023097445501	Williamson	--	19421200	5628810	--	--	--	--	--	TWDB, USGS
Brushy Creek Spring	TWDB_5827918 AND USGS_303101097393901	Williamson	--	19425600	5656310	--	--	--	--	--	TWDB, USGS
Wilson Spring	TWDB_5829101 AND USGS_303531097283101 AND Williamson_3 (Brune)	Williamson	--	19454200	5713980	206	1978	349	1975	2	TWDB, USGS
Lawhon Springs	TWDB_5838907 AND USGS_302431097153101 AND Lee_1 (Brune)	Lee	HOOPER FORMATION	19389000	5783650	--	--	22	1975	1	TWDB, USGS
Knobbs Springs	TWDB_5847202 AND USGS_302031097113101 AND Lee_2 (Brune)	Lee	CALVERT BLUFF FORMATION	19365200	5805240	3	1975	21	1937	2	TWDB, USGS
Black Spring OR RZ-58-48-103	TWDB_5848103 AND USGS_302128097061701	Lee	QUEEN CITY SAND OF CLAIBORNE GROUP	19373000	5832850	--	--	30	1937	1	TWDB, USGS
Indian Springs (upper)	TWDB_5901801 AND USGS_305321096571901	Milam	TERRACE DEPOSITS	19566700	5874500	--	--	15 - 20	1971	1	TWDB, USGS
Indian Springs (lower)	TWDB_5901802 AND USGS_305318096572101	Milam	TERRACE DEPOSITS	19566200	5874160	--	--	--	--	--	TWDB, USGS
WK-59-04-802	TWDB_5904802 AND USGS_305314096333601	Robertson	QUEEN CITY SAND OF CLAIBORNE GROUP	19569700	5998110	--	--	--	--	--	TWDB, USGS
WK-59-04-901	TWDB_5904901 AND USGS_305311096310301	Robertson	QUEEN CITY SAND OF CLAIBORNE GROUP	19570700	6011220	--	--	--	--	--	TWDB, USGS
Pin Oak Creek (Atkinson) Bog OR TK-59-10-801	TWDB_5910801 AND USGS_304545096474401	Milam	CARRIZO SAND	19523300	5924810	--	--	--	--	--	TWDB, USGS

Table C-1, continued

Spring Name	Spring Number[1]	County	Spring Source Formation	GAMx[2] (feet)	GAMy[2] (feet)	Minimum Flow (gpm)	Date of Minimum Flow	Maximum Flow (gpm)	Date of Maximum Flow	Number of Measure-ments	Source[3]
Beaver Springs	TWDB_5910802 AND USGS_304545096474501	Milam	CARRIZO SAND	19521800	5925470	--	--	--	--	--	TWDB, USGS
WK-59-12-903	TWDB_5912903 AND USGS_304727096310901	Robertson	SPARTA SAND	19534700	6012260	--	--	15	1972	1	TWDB, USGS
WK-59-13-501	TWDB_5913501 AND USGS_304914096253601	Robertson	COOK MOUNTAIN FORMATION	19545600	6039780	--	--	--	--	--	TWDB, USGS
Old Rockhouse Spring	TWDB_5918503 AND USGS_304055096493201	Milam	QUEEN CITY SAND OF CLAIBORNE GROUP	19491900	5916130	--	--	1	--	1	TWDB, USGS
TK-59-19-101	TWDB_5919101 AND USGS_304426096442401	Milam	QUEEN CITY SAND OF CLAIBORNE GROUP	19514400	5943200	--	--	--	--	--	TWDB, USGS
TK-59-19-102	TWDB_5919102 AND USGS_304420096443601	Milam	QUEEN CITY SAND OF CLAIBORNE GROUP	19513700	5942170	--	--	--	--	--	TWDB, USGS
Manse Springs	TWDB_5919611 AND USGS_304031096395601	Burleson	SPARTA SAND	19491300	5967240	--	--	5	1936	1	TWDB, USGS
BS-59-20-545	TWDB_5920545 AND USGS_304114096350001	Burleson	SPARTA SAND	19496700	5993140	--	--	--	--	--	TWDB, USGS
Tipton Spring	TWDB_5920705 AND USGS_304006096365801	Burleson	SPARTA SAND	19489200	5982820	--	--	2	1936	1	TWDB, USGS
Kellum Springs	TWDB_5924901 AND USGS_303737096003200	Grimes	JACKSON GROUP	19480500	6173700	--	--	25	1970	1	TWDB, USGS
BS-59-26-304	TWDB_5926304 AND USGS_303721096460001	Burleson	QUEEN CITY SAND OF CLAIBORNE GROUP	19470600	5937590	--	--	3	1936	1	TWDB, USGS
Spring Lake Springs OR Sour Spring	TWDB_5926606 AND USGS_303407096454701	Burleson	SPARTA SAND	19451400	5937890	--	--	20	1936	1	TWDB, USGS
Liberty Spring	TWDB_5926804 AND USGS_303106096490601	Burleson	SPARTA SAND	19432700	5920970	--	--	3	1936	1	TWDB, USGS
Denton Valley Springs	TWDB_5927208 AND USGS_303537096422101	Burleson	SPARTA SAND	19461100	5955500	--	--	2	1937	1	TWDB, USGS
Pettis Spring	TWDB_5927308 AND USGS_303700096381301	Burleson	SPARTA SAND	19470200	5976860	--	--	30	1936	1	TWDB, USGS
BS-59-27-402	TWDB_5927402 AND USGS_303323096444701	Burleson	COOK MOUNTAIN FORMATION	19447100	5943260	--	--	--	--	--	TWDB, USGS
Evans Spring OR Scotts Spring	TWDB_5927508 AND USGS_303249096415601	Burleson	QUATERNARY ALLUVIUM	19444200	5958180	--	--	3	1936	1	TWDB, USGS
Minter Spring OR BJ-59-30-801, TWDB_5930810	TWDB_5930801 AND USGS_303020096191501 AND TWDB_5930810	Brazos	JACKSON GROUP	19432800	6077490	--	--	4	1970	1	TWDB, USGS
Sulphur Spring OR BJ-59-31-601	TWDB_5931601 AND USGS_303400096094901	Brazos	JACKSON GROUP	19458400	6124910	--	--	--	--	--	TWDB, USGS
Piedmont Springs OR White Sulphur	TWDB_5932702 AND USGS_303139096052800	Grimes	JACKSON GROUP	19444000	6150040	--	--	2	--	1	TWDB, USGS

Table C-1, continued

Spring Name	Spring Number[(1)]	County	Spring Source Formation	GAMx[(2)] (feet)	GAMy[(2)] (feet)	Minimum Flow (gpm)	Date of Minimum Flow	Maximum Flow (gpm)	Date of Maximum Flow	Number of Measure-ments	Source[(3)]
Spring OR Black Spring											
KW-59-32-703	TWDB_5932703 AND USGS_303139096052400	Grimes	JACKSON GROUP	19443200	6149450	--	--	--	--	--	TWDB, USGS
Black Sulphur Spring	TWDB_5932704 AND USGS_303139096052000	Grimes	JACKSON GROUP	19443400	6149360	--	--	--	--	--	TWDB, USGS
Copperas Springs	TWDB_5934506 AND USGS_302612096494201	Burleson	WECHES FORMATION OF CLAIBORNE GROUP	19402700	5918780	--	--	2	1936	1	TWDB, USGS
Pabulek Spring	TWDB_5935303 AND USGS_302927096393901	Burleson	YEGUA FORMATION	19424100	5970750	--	--	1	1936	1	TWDB, USGS
BS-59-38-707	TWDB_5938707 AND USGS_302327096220601	Burleson	TERRACE DEPOSITS	19390600	6063850	--	--	1	1936	1	TWDB, USGS
Sulphur (Sulfur) Springs	TWDB_5938711 AND USGS_302316096213501	Burleson	TERRACE DEPOSITS	19389600	6066590	--	--	3	1936	1	TWDB, USGS
Doak Springs	TWDB_5941105 AND USGS_302131096583101 AND Lee_9 (Brune)	Lee	ALLUVIUM AND FLUVIATILE TERRACE DEPOSITS	19373100	5873260	--	--	seeps	1975	1	TWDB, USGS
BS-59-45-204	TWDB_5945204 AND USGS_302112096262801	Burleson	JACKSON GROUP	19376200	6041400	--	--	2	1936	1	TWDB, USGS
Big Springs	TWDB_5945804 AND USGS_301621096272900	Washington	JACKSON GROUP	19346700	6037440	--	--	10	1942	1	TWDB, USGS
YY-59-53-912	TWDB_5953912 AND USGS_300932096234800	Washington	BURKEVILLE AQUICLUDE	19305800	6057510	--	--	12	1969	1	TWDB, USGS
YY-59-54-703	TWDB_5954703 AND USGS_300850096214300	Washington	EVANGELINE AQUIFER	19302100	6069210	--	--	30	1968	1	TWDB, USGS
YY-59-61-503	TWDB_5961503 AND USGS_300443096272100	Washington	BURKEVILLE AQUICLUDE	19275800	6040240	--	--	5	1942	1	TWDB, USGS
YY-59-63-104	TWDB_5963104 AND USGS_300543096133500	Washington	EVANGELINE AQUIFER	19284300	6112430	--	--	10	1942	1	TWDB, USGS
Gibbons Spring	TWDB_6025102 AND USGS_303631095593101	Grimes	UPPER JACKSON UNIT	19474000	6179340	--	--	--	--	--	TWDB, USGS
Beauchamps Springs	TWDB_6513947 AND USGS_294731095223101 AND Harris_1 (Brune)	Harris	BEAUMONT CLAY	19184200	6385240	--	--	1.3	1978	1	TWDB, USGS
Cat Springs OR Katzenquelle Spring OR Wildcat Spring	TWDB_6614103 AND USGS_295131096203101 AND Austin_4 (Brune)	Austin	WILLIS SAND	19197000	6078560	--	--	11	1978	1	TWDB, USGS, Brune
KW-60-41-109	TWDB_6041109 AND USGS_302015095580201	Grimes	--	19375500	6190700	--	--	--	--	--	TWDB, USGS
KW-60-41-304	TWDB_6041304 AND USGS_302020095530501	Grimes	--	19377000	6216640	--	--	--	--	--	TWDB, USGS

Table C-1, continued

Spring Name	Spring Number(1)	County	Spring Source Formation	GAMx(2) (feet)	GAMy(2) (feet)	Minimum Flow (gpm)	Date of Minimum Flow	Maximum Flow (gpm)	Date of Maximum Flow	Number of Measure-ments	Source(3)
BS-59-27-811	TWDB_5927811 AND USGS_303053096405901	Burleson	--	19432600	5963510	--	--	1	1936	1	TWDB, USGS
BS-59-26-608	TWDB_5926608 AND USGS_303324096461001	Burleson	--	19447100	5935920	--	--	50	1936	1	TWDB, USGS
BS-59-27-404	TWDB_5927404 AND USGS_303346096430501	Burleson	--	19449800	5951990	--	--	--	--	--	TWDB, USGS
BS-59-26-607	TWDB_5926607 AND USGS_303352096454601	Burleson	--	19450000	5937930	--	--	15	1936	1	TWDB, USGS
BS-59-27-507	TWDB_5927507 AND USGS_303423096415601	Burleson	--	19453700	5957900	--	--	--	--	--	TWDB, USGS
BS-59-27-209	TWDB_5927209 AND USGS_303601096412601	Burleson	--	19463700	5960220	--	--	30	1936	1	TWDB, USGS
BS-59-27-207	TWDB_5927207 AND USGS_303603096414201	Burleson	--	19463900	5958820	--	--	15	1936	1	TWDB, USGS
BS-59-27-101	TWDB_5927101 AND USGS_303628096430101	Burleson	--	19466200	5951860	--	--	1	1937	1	TWDB, USGS
South Fork San Gabriel River Spring	TWDB_5826111 AND USGS_303707097504101	Williamson	--	19461400	5597810	--	--	--	--	--	TWDB, USGS
Cedar Breaks (Creek) Hiking Trail Spring	TWDB_5818909 AND USGS_303937097450301	Williamson	--	19477200	5626970	--	--	--	--	--	TWDB, USGS
BS-59-19-612	TWDB_5919612 AND USGS_304106096393201	Burleson	--	19494900	5969230	--	--	2	1936	1	TWDB, USGS
BS-59-19-503	TWDB_5919503 AND USGS_304135096404401	Burleson	--	19497600	5962870	--	--	--	--	--	TWDB, USGS
BS-59-19-610	TWDB_5919610 AND USGS_304207096394901	Burleson	--	19501000	5967560	--	--	10	1936	1	TWDB, USGS
BS-59-20-130	TWDB_5920130 AND USGS_304249096360901	Burleson	--	19505800	5986590	--	--	3	1936	1	TWDB, USGS
BS-59-20-129	TWDB_5920129 AND USGS_304305096363501	Burleson	--	19507400	5984270	--	--	2	1936	1	TWDB, USGS
WK-39-62-702	TWDB_3962702 AND USGS_310149096205101	Robertson	WECHES FORMATION OF CLAIBORNE GROUP	19623700	6062710	--	--	2	1940	1	TWDB, USGS
WK-39-60-602	TWDB_3960602 AND USGS_310404096304201	Robertson	CARRIZO SAND	19635800	6010990	--	--	--	--	--	TWDB, USGS
SA-39-63-201	TWDB_3963201 AND USGS_310721096113001	Leon	SPARTA SAND	19659000	6110230	--	--	0.5	1936	1	TWDB, USGS
SA-39-54-907	TWDB_3954907 AND USGS_310807096150201	Leon	QUEEN CITY SAND OF CLAIBORNE GROUP	19663000	6091700	--	--	2	1936	1	TWDB, USGS
SA-39-55-903	TWDB_3955903 AND USGS_310846096084901	Leon	SPARTA SAND	19668100	6123890	--	--	0.5	1936	1	TWDB, USGS

Table C-1, continued

Spring Name	Spring Number[(1)]	County	Spring Source Formation	GAMx[(2)] (feet)	GAMy[(2)] (feet)	Minimum Flow (gpm)	Date of Minimum Flow	Maximum Flow (gpm)	Date of Maximum Flow	Number of Measure-ments	Source[(3)]
WK-39-54-501	TWDB_3954501 AND USGS_311017096181001	Robertson	ALLUVIUM,FLOOD PLAIN	19675600	6074960	--	--	2	1940	1	TWDB, USGS
SA-39-55-102	TWDB_3955102 AND USGS_311237096130501	Leon	QUEEN CITY SAND OF CLAIBORNE GROUP	19690700	6100910	--	--	0.5	1936	1	TWDB, USGS
SA-39-47-909	TWDB_3947909 AND USGS_311516096092501	Leon	QUEEN CITY SAND OF CLAIBORNE GROUP	19707400	6119400	--	--	5	1936	1	TWDB, USGS
SA-39-47-305	TWDB_3947305 AND USGS_312120096085501	Leon	QUEEN CITY SAND OF CLAIBORNE GROUP	19744400	6120720	--	--	0.5	1936	1	TWDB, USGS
WK-59-03-407	TWDB_5903407 AND USGS_305708096445501	Robertson	ALLUVIUM,BRAZOS RIVER	19591400	5938230	--	--	10	1961	1	TWDB, USGS
SD-39-28-302	TWDB_3928302 AND USGS_313516096313301	Limestone	MIDWAY GROUP	19825100	6000540	--	--	--	--	--	TWDB, USGS
AX-58-05-501	TWDB_5805501 AND USGS_305656097272401	Bell	EDWARDS AND ASSOCIATED LIMESTONES - (BALCONES FAULT ZONE AQUIFER)	19584400	5716830	--	--	8	--	1	TWDB, USGS
ZK-58-03-803	TWDB_5803803 AND USGS_305234097404701	Williamson	EDWARDS AND ASSOCIATED LIMESTONES	19556300	5647630	--	--	112	1981	1	TWDB, USGS
AX-40-61-505	TWDB_4061505 AND USGS_310400097263601	Bell	HENSELL SAND AND HOSSTON FORMATION	19627400	5720010	11	1960	100	1941	2	TWDB, USGS
--	Austin_1 (Brune)	Austin	Lissie Sand	19164700	6161310	--	--	former spring	1978	1	Brune
Mayeye Springs	Austin_10 (Brune)	Austin	--	19223700	6120510	--	--	36	1978	1	Brune
Glenn Springs	Austin_11 (Brune)	Austin	Willis Sand	19223700	6120510	--	--	seep	1978	1	Brune
Spring/Ives creek	Austin_12 (Brune)	Austin	Willis sand	19254500	6123990	--	--	285	1978	1	Brune
Arroyo Dulce (Sweetwater) Springs	Austin_13 (Brune)	Austin	Willis sand	19165100	6136570	--	--	51	1978	1	Brune
Shelby Springs	Austin_2 (Brune)	Austin	Fleming sand	19255800	6002020	--	--	7.9 - 15.9	1978	1	Brune
Post Oak Springs	Austin_3 (Brune)	Austin	Fleming sand	19216700	6020770	--	--	19	1978	1	Brune
--	Austin_5 (Brune)	Austin	willis sand	19164700	6161310	--	--	dry	1950's	1	Brune
Cumings Springs	Austin_6 (Brune)	Austin	Lissie Sand	19184700	6153900	--	--	trickle	1978	1	Brune
Deadman Springs	Austin_7 (Brune)	Austin	Willis Sand	19182500	6137010	--	--	11	1978	1	Brune
Swearingen Springs	Austin_8 (Brune)	Austin	Willis sand	19190700	6120510	--	--	15	1978	1	Brune

Table C-1, continued

Spring Name	Spring Number(1)	County	Spring Source Formation	GAMx(2) (feet)	GAMy(2) (feet)	Minimum Flow (gpm)	Date of Minimum Flow	Maximum Flow (gpm)	Date of Maximum Flow	Number of Measure-ments	Source(3)
Coushatta Springs	Austin_9 (Brune)	Austin	Willis sand	19218900	6131360	--	--	seeps	1978	1	Brune
Burleson Springs	Bastrop_1 (Brune)	Bastrop	river terrace sands and gravels	19272300	5762660	--	--	--	--	--	Brune
Bastrop Springs	Bastrop_2 (Brune)	Bastrop	terrace gravels	19272300	5762660	--	--	5	1975	1	Brune
Murchison Springs	Bastrop_20 (Brune)	Bastrop	Carrizo Sand	19191600	5762660	--	--	0.8	1978	1	Brune
Elgin Springs	Bastrop_21 (Brune)	Bastrop	Wilcox sand	19355200	5766130	--	--	44	1922	1	Brune
Goodwater Springs	Bastrop_22 (Brune)	Bastrop	Cook Mountain sand	19319300	5832530	--	--	4	1978	1	Brune
Fitzwilliam Springs	Bastrop_3 (Brune)	Bastrop	terrace gravel on dotop of Wilcox sandstone	19272300	5762660	5	1953	97	1975	3	Brune
Trigg Springs	Bastrop_4 (Brune)	Bastrop	terrace gravel on top of the wilcox sandstone	19258000	5776110	--	--	76	1964	1	Brune
Blue Springs	Bastrop_5 (Brune)	Bastrop	high gravel on top of carrizo sand	19258000	5776110	--	--	seeps	1975	1	Brune
Alum Springs	Bastrop_6 (Brune)	Bastrop	river terrace sands and gravels	19254100	5814740	--	--	19	1975	1	Brune
Thorn Springs	Bastrop_7 (Brune)	Bastrop	terrace gravel	19244100	5834710	1	1953	19	1975	4	Brune
Sand Springs (Middleton or "Mid" Springs)	Bastrop_8 (Brune)	Bastrop	Carrizo Sand	19327000	5813000	--	--	1	1975	1	Brune
Paige Springs	Bastrop_9 (Brune)	Bastrop	Cook Mountain sand	19319300	5832530	dry	--	16	1977	2	Brune
Miller Spring	Bell_10 (Brune) AND GNIS_1385337	Bell	--	19639900	5716510	--	--	21	1975	1	Brune, GNIS
Ransomer Springs	Bell_12 (Brune)	Bell	Edwards Limestone	19644600	5654370	--	--	21	1979	1	Brune
Buchanan (Willow) Springs	Bell_13 (Brune)	Bell	Quaternary gravel	19580400	5729020	29	1978	55	1975	2	Brune
--	Bell_14 (Brune)	Bell	--	19672400	5714700	--	--	51	1975	1	Brune
Taylor Spring	Bell_16 (Brune)	Bell	--	19617300	5723380	--	--	dry	1975	1	Brune
Nolan Spring	Bell_17 (Brune)	Bell	Edwards Limestone	19617300	5723380	dry	1978	40	1975	2	Brune
Sulphur Springs	Bell_18 (Brune)	Bell	Edwards Limestone	19605900	5705310	--	--	51	1975	1	Brune
Elm Springs	Bell_21 (Brune)	Bell	Edwards Limestone	19581700	5665650	--	--	444	1975	1	Brune
Fryars Springs	Bell_3 (Brune)	Bell	Austin Chalk	19629400	5748120	--	--	20.6 - 47.6	1975	1	Brune
Elm Springs	Bell_30 (Brune)	Bell	Austin chalk	19562600	5694730	--	--	former spring	1975	1	Brune

Table C-1, continued

Spring Name	Spring Number(1)	County	Spring Source Formation	GAMx(2) (feet)	GAMy(2) (feet)	Minimum Flow (gpm)	Date of Minimum Flow	Maximum Flow (gpm)	Date of Maximum Flow	Number of Measure-ments	Source(3)
Abbott Springs	Bell_32 (Brune)	Bell	Edwards Limestone	19570900	5639610	--	--	40	1978	1	Brune
Willow Springs	Bell_33 (Brune)	Bell	Walnut Limestone	19632500	5614870	--	--	seeps	1975	1	Brune
Bluff Springs	Bell_37 (Brune)	Bell	Edwards Limestone	19605900	5705310	--	--	seep	1978	1	Brune
Elliot Springs	Bell_38 (Brune)	Bell	gravel	19580400	5729020	--	--	21	1978	1	Brune
Mountain Springs	Bell_39 (Brune)	Bell	Edwards Limestone	19675500	5697770	--	--	--	--	--	Brune
Gum Springs	Burnet_14 (Brune)	Burnet	Edwards Limestone	19555000	5576680	--	--	dry	1915	1	Brune
Strickling Spring	Burnet_6 (Brune)	Burnet	glen rose limestone	19535000	5533710	--	--	3	1975	1	Brune
Black Spring	Burnet_7 (Brune)	Burnet	glen rose limestone	19535000	5533710	--	--	4	1975	1	Brune
Oatmeal Spring	Burnet_8 (Brune)	Burnet	glen rose limestone	19491600	5538050	--	--	15	1975	1	Brune
--	Ft. Bend_10 (Brune)	Ft. Bend	--	19129200	6240880	--	--	former spring	1977	1	Brune
--	Ft. Bend_11 (Brune)	Ft. Bend	--	19129200	6240880	--	--	former spring	1977	1	Brune
--	Ft. Bend_12 (Brune)	Ft. Bend	--	19126400	6211660	--	--	former spring	1977	1	Brune
Powell Springs	Ft. Bend_13 (Brune)	Ft. Bend	--	19063000	6188820	--	--	0.5	1977	1	Brune
--	Ft. Bend_2 (Brune)	Ft. Bend	--	19147800	6209590	--	--	former spring	1977	1	Brune
--	Ft. Bend_3 (Brune)	Ft. Bend	--	19129600	6303830	--	--	former spring	1977	1	Brune
Spanish Springs	Ft. Bend_4 (Brune)	Ft. Bend	terrace sands	19129200	6240880	--	--	former spring	1977	1	Brune
--	Ft. Bend_8 (Brune)	Ft. Bend	--	19033400	6213020	--	--	former spring	1977	1	Brune
--	Harris_10 (Brune)	Harris	--	19187700	6379840	--	--	seep	1978	1	Brune
New Kentucky Springs	Harris_11 (Brune)	Harris	Willis sand	19281400	6261790	--	--	159	1978	1	Brune
Nichols' Springs	Harris_12 (Brune)	Harris	Willis sand	19281400	6261790	--	--	21	1978	1	Brune
--	Harris_14 (Brune)	Harris	Beaumont silt and sand	19203300	6439740	--	--	seep	1978	1	Brune
--	Harris_3 (Brune)	Harris	Beaumont Sand	19189900	6353370	--	--	4	1978	1	Brune
--	Harris_4 (Brune)	Harris	Beaumont silt and shell deposits	19189900	6353370	--	--	159	1978	1	Brune

Table C-1, continued

Spring Name	Spring Number(1)	County	Spring Source Formation	GAMx(2) (feet)	GAMy(2) (feet)	Minimum Flow (gpm)	Date of Minimum Flow	Maximum Flow (gpm)	Date of Maximum Flow	Number of Measure-ments	Source(3)
--	Harris_6 (Brune)	Harris	--	19187700	6379840	--	--	--	--	--	Brune
Smith Springs	Harris_7 (Brune)	Harris	Beaumont Sand	19187700	6379840	--	--	174	1978	1	Brune
Gold/Rock Springs	Lampasas_1 (Brune) AND GNIS_1358118	Lampasas	--	19615800	5489570	444	1964	2695	1886, 1970	19	Brune, GNIS
Townsen Springs	Lampasas_10 (Brune)	Lampasas	glen rose limestone	19707900	5501990	--	--	former spring	1975	1	Brune
Cooper Springs	Lampasas_11 (Brune)	Lampasas	Marble Falls Limestone	19639200	5490530	--	--	10	1975	1	Brune
Beef Pen Springs	Lampasas_12 (Brune)	Lampasas	--	19743900	5486880	--	--	15	1977	1	Brune
Hughes/Gooch Springs	Lampasas_4 (Brune) AND GNIS_1358144	Lampasas	--	19624000	5497070	--	--	former spring	1975	1	Brune, GNIS
Copperas Springs	Lee_10 (Brune)	Lee	Sparta sand	19356400	5904800	1	1937	1	1975	2	Brune
Lincoln Springs	Lee_11 (Brune)	Lee	Cook Mountain sand	19337800	5876160	--	--	--	--	--	Brune
King Springs	Lee_3 (Brune)	Lee	wilcox sands	19373800	5828410	--	--	21	1937	1	Brune
Darden Springs	Lee_4 (Brune)	Lee	Queen City Sand	19354700	5832750	5	1937	6	1975	2	Brune
Endor (Black) Springs	Lee_5 (Brune)	Lee	Queen City Sand	19367700	5841430	30	1937	52	1975	2	Brune
Roberts Springs	Lee_6 (Brune)	Lee	Sparta sand	19411600	5880500	3	1975	30	1937	2	Brune
Indian Camp Springs	Lee_7 (Brune)	Lee	--	19382500	5870080	--	--	5	1975	1	Brune
Gum Springs	Lee_8 (Brune) AND GNIS_1337127	Lee	Sparta sand	19363600	5869760	3	1937	5	1964	2	Brune, GNIS
Caddo Springs	Milam_1 (Brune)	Milam	terrace sands	19632700	5908270	4	1975	29	1936	2	Brune
Buer Springs	Milam_10 (Brune)	Milam	--	19477700	5898290	--	--	--	--	--	Brune
Lee Garden Springs	Milam_12 (Brune)	Milam	Queen City Sand	19477700	5898290	12	1978	15	1936	2	Brune
Sipe Springs	Milam_11 (Brune)	Milam	wilcox sand	19477300	5880500	--	--	27	1978	1	Brune
Ross Springs	Milam_13 (Brune)	Milam	terrace sands	19539300	5866170	--	--	4	1978	1	Brune
Nashville Springs	Milam_2 (Brune)	Milam	river terrace sands and gravels	19525500	5962090	--	--	2	1975	1	Brune
Vineville Springs	Milam_3 (Brune)	Milam	--	19543700	5904370	--	--	former spring	1975	1	Brune
Allen Springs	Milam_4 (Brune)	Milam	wilcox sands	19559300	5875290	--	--	11	1975	1	Brune

Table C-1, continued

Spring Name	Spring Number(1)	County	Spring Source Formation	GAMx(2) (feet)	GAMy(2) (feet)	Minimum Flow (gpm)	Date of Minimum Flow	Maximum Flow (gpm)	Date of Maximum Flow	Number of Measure-ments	Source(3)
Tappan (Post Oak) Springs	Milam_5 (Brune)	Milam	Midway group sand	19537200	5838830	--	--	2	1975	1	Brune
Hefley Springs	Milam_6 (Brune)	Milam	terrace sands	19539300	5866170	6	1978	51	1936	2	Brune
Taylor Springs	Milam_7 (Brune)	Milam	Carrizo Sand	19477300	5880500	8	1975	30	1936	3	Brune
San Ildefonso Springs	Milam_8 (Brune)	Milam	river terrace sands and gravels	19471200	5841000	--	--	16	1975	1	Brune
Clement Springs	Milam_9 (Brune)	Milam	--	19471200	5815390	--	--	former spring	1975	1	Brune
--	Montgomery_10 (Brune)	Montgomery	--	19368700	6283060	--	--	3	1978	1	Brune
Sulphur Springs	Montgomery_15 (Brune)	Montgomery	willis sand	19311000	6263090	--	--	dry	1950s	1	Brune
Stagecoach Springs	Montgomery_16 (Brune)	Montgomery	--	19311000	6263090	--	--	21	1978	1	Brune
Walnut Springs	Montgomery_17 (Brune)	Montgomery	willis sand	19298400	6267430	--	--	0.6	1978	1	Brune
Mineral (Double) Springs	Montgomery_20 (Brune)	Montgomery	willis sand	19367900	6270470	--	--	12	1978	1	Brune
Rocky Springs	Montgomery_4 (Brune)	Montgomery	Fleming sand	19377800	6247030	--	--	12	1978	1	Brune
Beckworth Springs	Montgomery_5 (Brune)	Montgomery	Fleming sand	19366100	6250070	--	--	9	1978	1	Brune
Griffith Springs	Montgomery_6 (Brune)	Montgomery	Fleming sand	19366100	6250070	--	--	16	1978	1	Brune
--	Montgomery_8 (Brune)	Montgomery	--	19387400	6268730	--	--	40	1978	1	Brune
One Seventy-Seven Springs	Montgomery_9 (Brune)	Montgomery	Willis gravel	19367900	6270470	--	--	27	1978	1	Brune
--	Waller_1 (Brune)	Waller	willis sand	19324100	6238790	--	--	seeps	1978	1	Brune
Heise Springs	Waller_2 (Brune)	Waller	willis sand	19327100	6170640	--	--	trickle	1978	1	Brune
Liendo Springs	Waller_3 (Brune)	Waller	Willis gravel	19314100	6181060	--	--	4	1978	1	Brune
--	Waller_4 (Brune)	Waller	--	19263800	6169340	--	--	former spring	1978	1	Brune
Hubbard Springs	Waller_5 (Brune)	Waller	Willis gravel	19271600	6180630	--	--	15	1978	1	Brune
Donoho Springs	Waller_6 (Brune)	Waller	willis sand	19263800	6169340	--	--	seeps	1978	1	Brune
Irons Springs	Waller_7 (Brune)	Waller	--	19221700	6171080	--	--	former spring	1978	1	Brune
Best Springs	Waller_8 (Brune)	Waller	Lissie Sand	19183500	6182360	--	--	1.4	1978	1	Brune
Indian Oaks Springs	Waller_9 (Brune)	Waller	Bentley sand and gravel	19175300	6196240	--	--	former spring	1978	1	Brune

Table C-1, continued

Spring Name	Spring Number[1]	County	Spring Source Formation	GAMx[2] (feet)	GAMy[2] (feet)	Minimum Flow (gpm)	Date of Minimum Flow	Maximum Flow (gpm)	Date of Maximum Flow	Number of Measure-ments	Source[3]
Kenney Springs	Williamson_11 (Brune)	Williamson	Austin chalk	19417900	5644380	--	--	--	--	--	Brune
Block House Springs	Williamson_12 (Brune)	Williamson	Edwards Limestone	19429100	5600110	--	--	51	1975	1	Brune
Pond Springs	Williamson_13 (Brune)	Williamson	--	19405300	5618340	--	--	40	1975	1	Brune
Camp (Campground) Springs	Williamson_14 (Brune)	Williamson	--	19470400	5715130	--	--	seep	1975	1	Brune
Buffalo (Prairie) Springs	Williamson_16 (Brune)	Williamson	Austin chalk	19475600	5659580	--	--	44	1975	1	Brune
Rock House Springs	Williamson_17 (Brune)	Williamson	--	19483000	5592740	--	--	151	1975	1	Brune
Tanyard Spring	Williamson_24 (Brune)	Williamson	--	19549400	5630930	--	--	1331	1975	1	Brune
Fisher Spring	Williamson_25 (Brune)	Williamson	--	19549400	5630930	--	--	1744	1975	1	Brune
Rice (Thompson) Springs	Williamson_30 (Brune)	Williamson	gravel on top of Navarro shale	19413500	5720340	--	--	21	1975	1	Brune
Walnut Springs	Williamson_31 (Brune)	Williamson	gravel on top of shale	19420500	5700370	--	--	16	1975	1	Brune
Tonkawa Springs	Williamson_32 (Brune)	Williamson	Edwards Limestone	19425200	5625720	30	1940	30	1978	2	Brune
Cobbs Springs	Williamson_33 (Brune)	Williamson	--	19515100	5626590	--	--	--	--	--	Brune
Whitewalker Spring	GNIS_1371462	Coryell	--	19760400	5512610	--	--	--	--	--	GNIS
Walnut Spring	GNIS_1370823	Williamson	--	19491200	5614830	--	--	--	--	--	GNIS
Underwood Spring	GNIS_1370431	Bell	--	19568300	5631640	--	--	--	--	--	GNIS
Tan Yard Spring	GNIS_1369576	Coryell	--	19755200	5503970	--	--	--	--	--	GNIS
Sulphur Springs	GNIS_1369369	Grimes	--	19443300	6149450	--	--	--	--	--	GNIS
Sulphur Spring	GNIS_1369366	Grimes	--	19458400	6125080	--	--	--	--	--	GNIS
Springfield Springs	GNIS_1377244	Limestone	--	19825400	6000610	--	--	--	--	--	GNIS
Soldiers Spring	GNIS_1368596	Coryell	--	19712200	5533530	--	--	--	--	--	GNIS
Picnic Spring	GNIS_1365166	Lampasas	--	19655400	5544510	--	--	--	--	--	GNIS
Pecan Springs	GNIS_1364989	Williamson	--	19547700	5647290	--	--	--	--	--	GNIS
Old Cottonwood Spring	GNIS_1364412	Coryell	--	19755000	5509240	--	--	--	--	--	GNIS

Table C-1, continued

Spring Name	Spring Number[1]	County	Spring Source Formation	GAMx[2] (feet)	GAMy[2] (feet)	Minimum Flow (gpm)	Date of Minimum Flow	Maximum Flow (gpm)	Date of Maximum Flow	Number of Measure-ments	Source[3]
Manos Spring	GNIS_1362146	Coryell	--	19762700	5516980	--	--	--	--	--	GNIS
Lamb Spring	GNIS_1360907	Grimes	--	19463900	6133270	--	--	--	--	--	GNIS
Kendrick Spring	GNIS_1360571	Coryell	--	19743400	5510130	--	--	--	--	--	GNIS
Jones Spring	GNIS_1360412	Coryell	--	19743700	5505370	--	--	--	--	--	GNIS
Jakes Spring	GNIS_1360137	Milam	--	19510500	5911330	--	--	--	--	--	GNIS
Hensley Spring	GNIS_1359053	Mills	--	19734100	5431040	--	--	--	--	--	GNIS
Gum Spring	GNIS_1337128	Lee	--	19362800	5815710	--	--	--	--	--	GNIS

(1) "county name_# (Brune)" = the number used by Brune (2002) to identify the spring in the named county
"TWDB_#" = the state well number for the spring in TWDB (2014f)
"USGS_#" = the spring number in Heitmuller and Reece (2003)
"GNIS_#" = the spring number in United States Board on Geographic Names (2014)

(2) GAM = groundwater availability modeling coordinate statewide mapping system

(3) Brune = Brune (2002)
TWDB = TWDB (2014f)
USGS = Heitmuller and Reece (2003)
GNIS = United States Board on Geographic Names (2014)
"Brune, GNIS" indicates that the location information is sourced from United States Board on Geographic Names (2014) rather than georeferenced from Brune (2002)

gpm = gallons per minute

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Appendix D

Methodologies Used to Estimate Pumping from the TWDB Water Use Survey Data

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D.1 Introduction

The water use survey data received from the TWDB (2014i) consists of two data sets: one with groundwater use for 1980 and 1984 through 1999 and the other with groundwater use for 2000 through 2012. For all counties and water use categories, groundwater use data for the years 1981 through 1983 are not included in the TWDB water use survey data. In addition, for some counties and use categories, groundwater use data are missing or anomalous, or are included in one of the data sets received from the TWDB but not in the other. Where groundwater use data are missing or anomalous in the water use survey data, estimates were developed. For the groundwater use estimates developed, Table 4.6.3 in the main body of this report provides the county, year, water use category, and reason groundwater use was estimated. The purpose of this appendix is to explain the methodology used to develop the groundwater use estimates.

D.2 Austin, Waller, and Washington Counties

For Austin, Waller, and Washington counties, the water use survey data include groundwater use from the Brazos River Alluvium Aquifer in 2000 through 2012 for the water use categories irrigation and livestock but do not include any groundwater use from the Brazos River Alluvium Aquifer in 1980 and 1984 through 1999. For these two use categories, all groundwater use in 1980 and 1984 through 1999 is assigned to aquifer(s) other than the Brazos River Alluvium Aquifer in the water use survey data. A review of the well data for these three counties indicated that Brazos River Alluvium Aquifer irrigation and livestock wells had been drilled prior to 1980. Therefore, use of the Brazos River Alluvium Aquifer for irrigation and livestock purposes was assumed to have occurred in 1980 and 1984 through 1999.

The groundwater use for these years was estimated using the following steps:

1. Calculated the ratio of Brazos River Alluvium Aquifer to total groundwater use for irrigation and livestock purposes in 2000 through 2012 using the water use survey data. These ratios are consistent for all 13 years.
2. Calculated the average of the ratios for the years 2000 through 2012.
3. Multiplied the total irrigation and livestock use for other aquifer(s) in the water use survey data by the average ratios calculated in step 2 to get estimated Brazos River

Alluvium Aquifer groundwater use for irrigation and livestock purposes in 1980 and 1984 through 1999.

For Austin and Waller counties, the estimated groundwater use for 1980 and 1981 through 1999 is consistent with the water use survey data for 2000 through 2012 for both the irrigation and livestock water use categories. For Washington County, the estimated livestock use for 1980 and 1984 through 1999 is consistent with the water use survey data for 2000 through 2012, but the estimated groundwater use for irrigation purposes is substantially less than the 2000 though 2012 data. The total groundwater use for irrigation purposes from the water use survey data is 92 acre-feet in 1999 and 1,311 acre-feet in 2000.

D.3 Burleson County

For Burleson County, the only water use category with groundwater use from the Brazos River Alluvium Aquifer in the water use survey data is irrigation. These data do not include groundwater use for irrigation purposes in 1996 for the Brazos River Alluvium Aquifer, and the value for 1997 is anomalous (19 acre-feet in 1997 versus 13,981 and 3,650 acre-feet in 1995 and 1998, respectively). Therefore, groundwater use for irrigation purposes was estimated for 1996 and 1997.

The water use survey data include groundwater use data for irrigation purposes in 1994 through 1999 only for the Brazos River Alluvium Aquifer, so the ratio of Brazos River Alluvium Aquifer to total irrigation use could not be calculated and used to estimate values for 1996 and 1997. Estimating values for these two years consisted of the following steps:

1. Assumed that the weather conditions in Burleson County were the same as those in adjacent Brazos County for 1996 and 1997.
2. Calculated the ratio of groundwater use for irrigation purposes in Burleson County to that in Brazos County for the years 1990 through 1995 and 1998 through 1999 using the water use survey data. These ratios ranged from 0.83 to 1.91 for the years 1990 through 1995 and 1998. For 1999, the ratio was significantly lower at 0.28.
3. Calculated the average of the ratios for years 1990 through 1995 and 1998.

4. Multiplied the irrigation groundwater use in Brazos County from the water use survey data in 1996 and 1997 by the average ratio calculated in step 3 to estimate irrigation groundwater use in Burleson County for 1996 and 1997.

The estimated groundwater use for irrigation purposes is consistent with the irrigation groundwater use given in the water use survey data.

D.4 Fort Bend County

For Fort Bend County, the water use survey data include groundwater use from the Brazos River Alluvium Aquifer in 1980 and 1984 through 1999 for the water use category irrigation but do not include any groundwater use estimates for the Brazos River Alluvium Aquifer in 2000 through 2012. All irrigation groundwater use in 2000 through 2012 is assigned to the Gulf Coast Aquifer in the water use survey data. It was assumed that if the Brazos River Alluvium Aquifer was pumped for irrigation purposes in 1980 and 1984 through 1999, it was also pumped for irrigation purposes in 2000 through 2012.

The groundwater use for irrigation purposes in 2000 through 2012 was estimated using the following steps:

1. Calculated the ratio of Brazos River Alluvium Aquifer to total groundwater use for irrigation purposes in 1980 and 1984 through 1999 using the water use survey data.
2. Evaluated the ratios. The ratios are consistently lower for the years 1980 and 1984 through 1993 (average of 0.07) and consistently higher for the years 1994 through 1999 (average of 0.36). Assumed that the average for the latter years is more applicable for estimating pumping in 2000 through 2012.
3. Multiplied the total irrigation use for the Gulf Coast Aquifer in the water use survey data by the higher average ratio calculated in step 2 to get estimated Brazos River Alluvium Aquifer groundwater use for irrigation purposes in 2000 through 2012.

The estimated irrigation groundwater use for 2000 through 2012 is consistent with the water use survey data for 1994 through 1999.

D.5 Grimes County

For the Brazos River Alluvium Aquifer in Grimes County, the water use survey data are missing data for the years 1995 through 1999 for irrigation use but includes irrigation groundwater use for all other years. In addition, the water use survey data give a value of zero for the year 1994. Therefore, groundwater use from the Brazos River Alluvium Aquifer for irrigation purposes was estimated for the years 1994 through 1999.

Also, the water use survey data include livestock groundwater use from the Brazos River Alluvium Aquifer in 2000 through 2012, but zero values for 1980 and 1984 through 1999. A review of wells in Grimes County indicates the presence of livestock wells drilled prior to 2000. Therefore, groundwater use from the Brazos River Alluvium Aquifer for livestock purposes was estimated for the years 1980 and 1984 through 1999.

Groundwater use for irrigation purposes for 1994 through 1999 was estimated using the following steps:

1. Calculated the ratio of Brazos River Alluvium Aquifer to total groundwater use for irrigation purposes in 1980 and 1984 through 1993 using the water use survey data.
2. Evaluated the calculated ratios. The ratios were relatively consistent for 1980 and 1984 through 1992 (average of 0.55) but lower for 1993 (0.42). Assumed that the lower ratio from 1993 is more applicable for estimating pumping in 1994 through 1999.
3. Multiplied the total irrigation use for other aquifer(s) in the water use survey data by the ratio in 1993 calculated in step 2 to get estimated Brazos River Alluvium Aquifer groundwater use for irrigation purposes in 1994 through 1999.

The estimated values are consistent with the values in the water use survey data.

Groundwater use for livestock purposes for 1980 and 1984 through 1999 was estimated using the following steps:

1. Calculated the ratio of Brazos River Alluvium Aquifer to total groundwater use for livestock purposes in 2000 through 2012 using the water use survey data. These ratios were fairly consistent for all 13 years.
2. Calculated the average of the ratios for the years 2000 through 2012.

3. Multiplied the total livestock use for other aquifer(s) in the water use survey data by the average ratio calculated in step 2 to get estimated Brazos River Alluvium Aquifer groundwater use for livestock purposes in 1980 and 1984 through 1999.

The estimated values for 1980 and 1984 through 1999 are consistent with the values in the water use survey data for 2000 through 2012.

D.6 Hill County

For Hill County, the water use survey data include groundwater use for irrigation purposes from the Brazos River Alluvium Aquifer only in 1980 and 1984 through 1999 but give the source of all irrigation groundwater use in 2000 through 2012 as Other Aquifer. It was assumed that if the Brazos River Alluvium Aquifer was the source for irrigation use in 1980 and 1984 through 1999, it was also the source in 2000 through 2012. The irrigation groundwater use for Other Aquifer in the water use survey data for 2000 through 2012 is similar in magnitude to that for the Brazos River Alluvium Aquifer in 1980 and 1984 through 1999. Therefore, the irrigation groundwater use for Other Aquifer for 2000 through 2012 in the water use survey data was assumed to be supplied by the Brazos River Alluvium Aquifer. Except for the value in 2012, these values are consistent with those from the water use survey data for irrigation groundwater use from the Brazos River Alluvium Aquifer in 1980 and 1984 through 1999.

D.7 McLennan County

For the Brazos River Alluvium Aquifer in McLennan County, the water use survey data include livestock groundwater use in 2000 through 2012 but zero values for 1980 and 1984 through 1999. The water use survey data give the Trinity Aquifer as the source of all groundwater use for livestock purposes for 1980 and 1984 through 1999 and give both the Brazos River Alluvium and Trinity aquifers as the source of groundwater use for livestock purposes for 2000 through 2012. A review of wells in McLennan County indicates the presence of livestock wells drilled prior to 2000. Therefore, groundwater use from the Brazos River Alluvium Aquifer for livestock purposes was estimated for the years 1980 and 1984 through 1999.

Groundwater use for livestock purposes for 1980 and 1984 through 1999 was estimated using the following steps:

1. Calculated the ratio of Brazos River Alluvium Aquifer to total groundwater use for livestock purposes in 2000 through 2012 using the water use survey data. These ratios were consistent for all 13 years.
2. Calculated the average of the ratios for the years 2000 through 2012.
3. Multiplied the total livestock use from the Trinity Aquifer in the water use survey data by the average ratio calculated in step 2 to get estimated Brazos River Alluvium Aquifer groundwater use for livestock purposes in 1980 and 1984 through 1999.

The estimated values for 1980 and 1984 through 1999 are consistent with the values in the water use survey data for 2000 through 2012.

D.8 Milam County

For the Brazos River Alluvium Aquifer in Milam County, the water use survey data are missing data for the years 2006 through 2012 for irrigation and livestock use but include irrigation and livestock groundwater use from the Brazos River Alluvium Aquifer for all other years. In addition, the water use survey data give a value of zero for the years 2004 and 2005 for irrigation and livestock use from the Brazos River Alluvium Aquifer. It was assumed that if the Brazos River Alluvium Aquifer was pumped for irrigation and livestock purposes in 1980 and 1984 through 2003, it was also pumped for irrigation and livestock purposes in 2004 through 2012. Therefore, groundwater use from the Brazos River Alluvium Aquifer for irrigation and livestock purposes was estimated for the years 2004 through 2012 using the following steps:

1. Calculated the ratio of Brazos River Alluvium Aquifer to total groundwater use for irrigation and livestock purposes in 2000 through 2003 using the water use survey data. These ratios were consistent for all 4 years.
2. Calculated the average of the ratios for the years 2000 through 2003.
3. Multiplied the total irrigation and livestock use for other aquifer(s) in the water use survey data by the average ratios calculated in step 2 to get estimated Brazos River Alluvium Aquifer groundwater use for irrigation and livestock purposes in 2004 through 2012.

The estimated values for 2004 through 2012 are consistent with the values in the water use survey data for 1980 and 1984 through 2003 for livestock use and consistent with the value in the water use survey data in 2003 for irrigation use. Use of the Brazos River Alluvium Aquifer for irrigation purposes is about three times greater in 2003 than in 1980 and 1984 through 2002 in the water use survey data.

The water use survey data include estimates for municipal use of the Brazos River Alluvium Aquifer in Milam County for 1980 and 1984 through 1999 but not for 2000 through 2012. However, the estimated use in 1995 through 1999 was only 3 acre-feet per year, and the values of zero in the water use survey data for 2000 through 2003 were not considered to be anomalous. Therefore, no estimates of use from the Brazos River Alluvium Aquifer for municipal purposes were developed for 2000 through 2012.

D.9 Robertson County

For the Brazos River Alluvium Aquifer in Robertson County, the water use survey data report zero values for the years 1994 through 1999 for irrigation use but include irrigation groundwater use in the thousands for all other years. It was assumed that if Brazos River Alluvium Aquifer use for irrigation purposes was is the thousands for other years, it was not zero in 1994 through 1999. Therefore, groundwater use from the Brazos River Alluvium Aquifer for irrigation purposes was estimated for the years 1994 through 1999 using the following steps:

1. Calculated the ratio of Brazos River Alluvium Aquifer to total groundwater use for irrigation purposes in 1980 and 1984 through 1993 using the water use survey data. These ratios were consistent for all 11 years.
2. Calculated the average of the ratios for the years 1980 and 1984 through 1993.
3. Multiplied the total irrigation use for other aquifer(s) in the water use survey data by the average ratio calculated in step 2 to get estimated Brazos River Alluvium Aquifer groundwater use for irrigation purposes in 1994 through 1999.

The estimated values for 1994 through 1999 are consistent with the values in the water use survey data for 1982, 1984 through 1993, and 2000 through 2003.

The water use survey data also have zero values for municipal use from the Brazos River Alluvium Aquifer for the years 1994 through 2005 and non-zero values for all other years.

However, the non-zero values are low (2 to 8 acre-feet per year) for all years except 2012, and the values of zero were not considered to be anomalous. Therefore, no estimates of use from the Brazos River Alluvium Aquifer for municipal purposes were developed for 1994 through 2005.

D.10 Groundwater Use Estimates for 1981 through 1983 for All Counties

As stated in Section D.1, groundwater use data for the years 1981 through 1983 are not included in the TWDB water use survey data for all counties and all water use categories. Therefore, groundwater use was estimated for these years for counties and water use categories with water use survey data or estimated data for 1980 and 1984. The groundwater use in 1981 through 1983 was estimated assuming a linear change in groundwater use between 1980 and 1984.

Appendix E

Comments and Responses
for
Review of "Draft Conceptual Model for the Brazos River Alluvium Aquifer Groundwater Availability Model" Report and deliverables for TWDB Contract No. 1348301620 dated February 2015

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Appendix E

Comments and Responses
for
Review of "Draft Conceptual Model for the Brazos River Alluvium Aquifer Groundwater Availability Model" Report and deliverables for TWDB Contract No. 1348301620 dated February 2015

Attachment 1

The following report and data review comments shall be addressed and included in the final draft deliverables due March 31, 2016. Please note the items listed under suggestions are editorial in context and are not contractually required; however, adjustments noted may improve the readability of the report.

Draft conceptual report comments:

General comments to be addressed

1. Please update Chapter 3, possibly Chapter 4.3, and Chapter 4.4 with information from the United States Army Corps of Engineers (USACE) RiverWare model for the Brazos River to be consistent with the amendment to the contract.

   The United States Army Corps of Engineers RiverWare in the Brazos River Basin is introduced in Section 3.2.

2. In the final report for the conceptual model please insert a page before the Table of Contents for sealing the report per the Occupation Code, Title 6, Subtitle A, Chapters 1001 and 1002.

   Done.

3. Please submit final conceptual report/geodatabase when delivering the draft final of the model report and associated files.

   Done.

Specific comments to be addressed

4. Executive Summary, Page ES-2, Paragraph 1: Please clarify in the text if the recharge value cited for the underlying aquifers is based on the extent of the study area, the vertical connection to the aquifers that lie directly beneath the Brazos River Alluvium Aquifer, or for the entire extent of the associated aquifers.

The text was reworded to clarify that this recharge is based on the extent of the study area and only for the outcrops of the underlying formations. See Executive Summary.

5. Section 1.0, Page 1.0-1, Paragraph 4: Please reword references to the 2012 State Water Plan. Suggest removing "supplies" or clarifying that "supplies" means groundwater available through existing infrastructure. The groundwater availability for the Brazos River Alluvium Aquifer was estimated to be 108,183 acre-feet per year for the entire planning horizon (2010 to 2060) in the 2012 State Water Plan; noting current estimates of pumping from the aquifer appear to exceed values considered in the planning process.

   Done. See Section 1.0.

6. Section 1.0, Page 1.0-2, Paragraph 4: Please cite legislative session or year when referring to bills since each legislative session could use the same bill number. For example, House Bill 1763 concerned groundwater in 2005 (79th session) and now references public education in the 84th session in 2015.

   Done. See Section 1.0.

7. Section 2.0, Page 2.0-13, Figure 2.0.9: Please check the boundary between Groundwater Management Area 12 and Groundwater Management Area 14 in the Brazos Valley Groundwater Conservation District; it was changed in 2014.

   GMA boundaries updated. See Figure 2.0.9.

8. Section 2.1, Page 2.1-4, Paragraph 2: Last sentence states highest evaporation peaks occur in the east. Please clarify in the text, and correct if appropriate, if this should have said west.

   Text corrected. See Section 2.1.

9. Figure 2.1.4, Page 2.1-11: Please add citation to figure caption for soil data derived to develop this figure.

   Citation added. See Figure 2.1.4.

10. Figures 2.2.6 "a" to "e", Pages 2.2-12 through 2.2-16: Please clarify in the text in Section 4.1 or 5.0 if these figures will serve as the basis for defining the boundary between Layer 1 and Layer 2.

    Due to the large gaps between cross-sections, these figures do not provide enough detail to define a boundary between Layer 1 and 2 throughout the model. The actual process used to define the model layers is included in the model implementation discussion in the numerical model report.

11. Section 3.2, Page 3.2-1, Paragraph 2: Text states none of the previous models in the area modeled the Brazos River Alluvium Aquifer explicitly; however, in version 1.01 of the GAM for the central part of the Carrizo-Wilcox Aquifer, layer 1 represents the alluvium in the valleys of the Colorado, Brazos, and Trinity rivers. Please verify and update the text as appropriate.

    Done. See Section 3.2.

12. Figure 4.1.1, Page 4.1-12: Please adjust label for the Carrizo Aquifer to match the legend or adjust the legend to match the figure label, as appropriate.

    Corrected. See Figure 4.1.1.

13. Figure 4.1.3, Page 4.1-14: Based on the description of the process to create the aquifer thickness map, please clarify why the boundary thickness of zero (yellow) is not observed throughout the aquifer boundaries in the figure. Possibly provide inset showing more detail in county or counties south of Falls County. Please clarify and update the text if necessary (Section 4.1.2.4). In addition, please revise legends to eliminate "gaps" in the contour intervals; for example, please use 0 to 20, 20 to 40, and so on rather than 0-20, 21-40, 41-60, and so on and please replace "-" with "to". Please check all figures in Section 4 for similar "gaps" in contour interval explanations.

    As described in bullet #3 in the third paragraph of Section 4.1.2.4, the "zero" boundary thickness was not enforced continuously along the aquifer boundary but at discrete points 1/8 mile apart. This could account for the non-zero thickness at places along the boundary. In addition, although the thickness raster was interpolated using very small grid cells, the zero thickness boundary is enforced by points, which are inherently smaller than any size grid cell. Thus, the interpolation process will naturally smooth over some zero values in order to transition to non-zero thickness values in neighboring grid cells.
    "Gaps" in Section 4 figure legends corrected. For consistency within the report, dashes left unchanged. See Figures 4.1.3, 4.1.4, 4.2.5, 4.2.18, 4.2.19, 4.2.20, 4.2.21, 4.2.23, 4.4.18, 4.5.4, 4.6.1, 4.6.2, 4.6.23, 4.6.24, 4.6.25, and 4.6.26.

14. Section 4.2, Pages 4.2-1 to 4.2-50: Analyses in this section suggest that precipitation and Brazos River stage are not correlated with water levels. Further, the use of average (1960 to 2013) water levels for pre-development suggests that water levels are not a function of pumping, since pumping has increased over that period. Please clarify what might be causing the annual variation in water levels and please provide more justification for using post-development water levels potentially influenced by pumping to estimate pre-development water levels.

    Individual comparisons were conducted to investigate whether a relationship could be developed between water-level elevations and river stage, precipitation, or pumping. The purpose of the comparisons was to see which, if any, of these is the driving force for the variations observed in historical water levels. The individual

comparisons did not show any consistent relationship, suggesting that none of these components individually is the sole driving force for the observed water-level fluctuations. This suggests that the observed fluctuations in water level are a complex combination of all three components. Recent declines in water level have been observed in many wells completed in the aquifer. The declines are a function of the recent drought caused by decreased precipitation, which has resulted in decreased river stage and increased pumping. This indicates that when all three components are driving in the same direction (that is., decreased precipitation and river stage and increased pumping), the aquifer shows a clear correlation with each. An additional component influencing water levels in the Brazos River Alluvium Aquifer is cross-formational flow from underlying aquifers. No direct measure of this component is available, therefore a comparison could not be conducted. In conclusion, the historical variations in water level in the Brazos River Alluvium Aquifer are a complex combination of precipitation, river stage, pumping, and cross-formational flow. This discussion has been added to the text in Section 4.2.3.2.

A review of the county-wide water-level trends over the approximately 50-year period of record for McLennan, Roberson, Brazos, Falls, and Burleson counties shows no systematic decline in water levels in the aquifer (see Figure 4.2.12). All of these trends show periods of water-level decline and periods of water-level rise. However, none show an overall decline in water levels in the aquifer since the early 1960s. In McLennan, Robertson, and Falls counties, the most recent water levels are not the lowest water levels observed in the counties although recent pumping is greater than at any other time. The lowest water levels were observed in these counties in the 1960. Based on the available data, pumping in McLennan County in the 1960s was about a factor of five or more lower than recent pumping and pumping in Robertson County in the 1960s was about a factor of two to three lower than recent pumping. In Falls County, pumping in the 1960s was comparable to recent pumping. In Brazos and Burleson counties, the recently observed low water levels are comparable to those in the 1960s. Pumping in the 1960s was about a factor of two to three and a factor of 1.5 less than recent pumping for Brazos and Burleson counties, respectively. The fact that recent water levels in the aquifer are not lower than those historically observed although pumping has increased anywhere from a factor of 1.5 to five indicates that observed water levels are not solely a function of pumping. In addition, a review of hydrographs for individual wells do not show an overall decline in water levels in the aquifer even though pumping has increased, except in southern Brazos County. Of the 22 long-term hydrographs used to estimate pre-development conditions in the aquifer for the draft report, the recent water levels represent the lowest historical water levels in the well for only two of the wells. One of these wells is located in southern Brazos County. For all other wells, the recent water levels, which correspond to the time period with the highest pumping, are not the lowest water level observed in the historical record. This indicates that long-term water-level trend in the wells are not influenced by pumping and, therefore, an average of the data are appropriate for use as an estimate of pre-development conditions. The only exception is for the well located in southern Brazos County, which shows a long-term decline of 20 feet.

That well was removed from the long-term averages assumed to represent pre-development conditions and the estimated pre-development surface was re-done. Justification for using post-development water levels at select wells, except in southern Brazos County, to estimate pre-development water levels has been added to the text in Section 4.2.2, paragraphs 7 (discussion of Type 3 data) and 9 (discussion of Type 4 data).

15. Section 4.2.2 Pre-development Water-Level Surface, Pages 4.2-4 and 4.2-5: Type 3 Pre-development data type –average water levels over time. Since there has been increasingly significant groundwater pumping in the aquifer since 1960, using average water levels from wells from 1960 to 2013 for a pre-development surface suggests the aquifer water levels are insensitive to pumping. Please provide additional justification and clarification in the text of the report for using this approach for pre-development water levels versus an analysis that considers depth to water using highest measured water level (possibly compared against precipitation) to lower any possible bias caused by pumping when calculating averages.

    As indicated by the second portion of the response to Comment 15, the long-term water-level trends by county and in individual wells indicate that the overall long-term water level trends in the aquifer are insensitive to pumping. Based on the observed long-term stable water levels in the aquifer, using Type 3 data (average of long-term transient data in 21 wells) to estimate pre-development conditions does not result in any bias caused by pumping. Using maximum observed water levels to estimate pre-development conditions would result in bias high pre-development water levels because, in pre-development, the aquifer would have experienced fluctuations in water levels about a mean as a result of changing climatic conditions rather than remaining at a constant high level. This discussion has been added to the text in Section 4.2.2, paragraphs 7 (discussion of Type 3 data) and 9 (discussion of Type 4 data).

16. Section 4.2.2 Pre-development Water-Level Surface, Page 4.2-5 (and later on Page 4.2-11), Paragraph 4: Please provide basis, reasoning, and clarification in the text of the report for using an anisotropy of 0.5, an angle of 40 degrees west of due north, and a longitudinal to lateral distance ratio of 0.5 to krig pre-development water level elevations.

    Done. See Section 4.2.2, second to last paragraph.

17. Section 4.2.6.2, Pages 4.2-14 to 4.2.16: Please clarify in the text if there is any correlation between upward or downward gradients in relationship to the cutbank or point bar portions of the fluvial system or in distance to a river channel.

    Data are insufficient to evaluate vertical gradients within the Brazos River Alluvium Aquifer as indicated in Section 4.2.6.1. Therefore, correlations in relationship to the cutbank or point bar portions of the system could not be determined. No change.

18. Table 4.2.1, Pages 4.2-17 to 4.2-18: TWDB Groundwater Resources staff have reviewed the aquifer identification codes noted in Table 4.2.1 and updated the TWDB groundwater database to aquifer_code 111ABZR and aquifer_id1 to 5 with the following exceptions:
    - 5911622 – no depth or screen information, might be 5911612 in which case it is Carrizo-Wilcox, pending verification from Brazos Valley Groundwater Conservation District.

      This well was incorrectly included in this table. This well was considered a Brazos River Alluvium Aquifer Well based on its "aquifer_id1" equal to 5 in the TWDB groundwater database (TWDB, 2014f) NOT based on a comparison of total depth or base of lowermost screen to the aquifer base. This well has been removed from this table and maintained as a Brazos River Alluvium Aquifer well.

    - 5911623 – no depth or screen information, might be tracking #200146, pending verification from Brazos Valley Groundwater Conservation District.

      This well was incorrectly included in this table. This well was considered a Brazos River Alluvium Aquifer Well based on its "aquifer_id1" equal to 5 in the TWDB groundwater database (TWDB, 2014f) NOT based on a comparison of total depth or base of lowermost screen to the aquifer base. In addition, this well is listed as a Brazos River Alluvium Aquifer well in a spreadsheet received from Alan Day with the Brazos Valley Groundwater Conservation District. This well has been removed from this table and maintained as a Brazos River Alluvium Aquifer well.

    - 5920573 – no depth or screen information, pending verification from Brazos Valley Groundwater Conservation District.

      This well was incorrectly included in this table. This well was considered a Brazos River Alluvium Aquifer Well based on its "aquifer_id1" equal to 5 in the TWDB groundwater database (TWDB, 2014f) NOT based on a comparison of total depth or base of lowermost screen to the aquifer base. In addition, this well is listed as a Brazos River Alluvium Aquifer well in a spreadsheet received from Alan Day with the Brazos Valley Groundwater Conservation District. This well has been removed from this table and maintained as a Brazos River Alluvium Aquifer well.

    - 6517704 – this is right on the edge of the aquifer boundary, staff believe this well should be kept as Chicot Aquifer.

      This well has a total depth of 76 feet based on the TWDB groundwater database (TWDB, 2014f). The base of the Brazos River Alluvium Aquifer at the location of this well is 83 feet based on the data in Shah and others (2007a). Therefore, this well is maintained as a Brazos River Alluvium Aquifer well.

- 6527309 – incorrect slotted casing information in remarks, updated to show depth as 700’, staff believe this well should be kept as Chicot Aquifer.

  Agree.

Please review and adjust as needed.

The well and water-level data sets were adjusted to remove well 6527309.

19. Table 4.2.5, Page 4.2-21: Numbers for control point type do not match text. Table should list type 2 and 3, not 1 and 2. Table lists average water levels as Type 2, whereas text lists average water levels as Type 3. Please verify and update table and/or text as appropriate.

    Done. Table 4.2.5 was updated so that types in the table match those in the text.

20. Figure 4.2.3, Page 4.2-26: Please spell out “LSD” on graph axis.

    Done. See Figure 4.2.3

21. Figure 4.2.5, Page 4.2-28: Please clarify in the text of the report why this is not referenced as a map of estimated long-term average water levels rather than pre-development water levels and/or update caption to note “estimated long term average water levels assumed to reflect estimated pre-development water-level elevations…”

    Disagree. The figure is referenced as “estimated” pre-development water levels. Many types of data were used to estimate the pre-development water levels, not just long-term average water levels. Text was added in Section 4.2.2 stating that the long-term average water levels were assumed to provide an estimate of pre-development water levels.

22. Figures 4.2.6 through Figure 4.2.11, Pages 4.2-29 through 4.2-34: Please provide citations in the figure captions for the source of the water level data (TWDB gwdb or other).

    Done. See Figures 4.2.6 through 4.2.11.

23. Figures 4.2.13 through 4.2.15, Pages 4.2-36 through 4.2-38: Please provide citations in the captions for the source of the precipitation and river stage data.

    Done. See Figure 4.2.13 through 4.2.15.

24. Figures 4.2.16 and 4.2.17, Pages 4.2-39 and 4.2-40: Please provide citations in the figure captions for the source of the water level data (TWDB gwdb or other).

    Done. See Figures 4.2.16 and 4.2.17.

25. Figures 4.2.24 to 4.2.27, Pages 4.2-47 to 4.2-50: Please update figure legends to include the abbreviations (CRWX, QC, 124SPRT, 111ABZR, 124YEGUL, 124YEGU, 122JSPR, EVG, 121EVGL, 112CHCTU, and BRA) found in the inset hydrographs legends.

    Done. See Figures 4.2.24 through 4.2.27.

26. Section 4.3.1, Page 4.3-3 and Section 4.3.4, Page 4.3-14: Please update text to reflect version 1.01 of the GAM for the central part of the Carrizo-Wilcox Aquifer modeled recharge for the shallow groundwater flow system (layer 1 represents the alluvium in the valleys of the Colorado, Brazos, and Trinity rivers).

    Text updated. See Section 4.3.1. No change to Section 4.3.4, as the text in Section 4.3.1 explains why recharge values from this model are not used.

27. Section 4.3, Page 4.3-7, Paragraph 2, Last sentence and Figure 4.3.3: Text notes that irrigated cropland is concentrated in Fort Bend County; however, Figure 4.3.3 shows mainly light blue and light green (rain fed) in Fort Bend County. Please verify and update figure and/or text as appropriate.

    This refers to the percentage of cropland that is irrigated, a calculated value that is not necessarily clear in the figure. The sentence was reworded to better clarify the intended meaning. See Section 4.3.

28. Section 4.3.4.2, Page 4.3-15: Please clarify and site references in the text why recharge in areas outside the extent of the Brazos River Alluvium were assumed to be effectively unchanged between pre- and post-development.

    The sentence was reworded to better clarify the intended meaning. See Section 4.3.4.2.

29. Figure 4.3.3: Please add county names to all figures in this section, especially if the text refers to a county on the figure.

    County names added. See Figures 4.3.1, 4.3.3, 4.3.5, 4.3.9, 4.3.10, and 4.3.11.

30. Section 4.4.1.2, Page 4.4-15: Please clarify in the text if the significant decrease in baseflow during droughts in Reach 4 may reflect the fact that very large diversions for senior surface water rights may exceed any buffering or contributions from the Gulf Coast Aquifer seen in this analysis and approach.

    The calculations of incremental baseflow in the report already account for Reach 4 diversions, as listed in Table 4.4.12. It was assumed that all diversions came solely from baseflow, a reasonable assumption during periods of low flow. The significant decrease seen in the calculated incremental Reach 4 baseflow during droughts therefore seems to be real and not just due to diversions.

31. Section 4.4.3, Figures 4.4.16 and 4.4.17, Pages 4.4-68 and 4.4-69: Please provide references and citations for the lake level data and bathymetry data.

    Citations added to caption (see Figures 4.4.16 and 4.4.17) and references added to Section 8.

32. Section 4.4., Per Exhibit A (SOQ) Page 16 of 180 of the contract (Surface Water-Groundwater Interaction), contractor will estimate local interaction at several points along the river. If this evaluation was performed please document it in the report. Otherwise please explain why the analysis was not done.

    Text and figures for analysis added. See Section 4.4.1.3.

33. Section 4.0, Pages 4.4-11, Paragraph 3: Please correct "Lake Whiney" to "Lake Whitney."

    Corrected. See Section 4.0.

34. Section 4.0, Figure 4.4-18: The scale of the map makes the water body features that are displayed much too small. Please consider converting this figure into 2 or 3 figures to improve clarity.

    Figure converted to 2 figures. See Figures 4.4.19a and 4.4.19b.

35. Section 4.4: Per Exhibit B, Attachment 1 of the Contract, please provide charts of representative streamflow hydrographs (in addition to the estimated base flow charts).

    Figure added. See Figure 4.4.2.

36. Section 4.5.2, Per Exhibit A (SOQ), Page 15 of 180 of the contract, contractor will compare screen length to total saturated thickness and evaluate whether the typical analytical solutions to the modified Theis non-equilibrium solution are valid for estimating transmissivity from specific capacity. If this evaluation was performed please document it in the report. Otherwise please explain why the analysis was not done.

    Explanation added. See Section 4.5.2.

37. Section 4.5.2, Per Exhibit A (SOQ), Page 15 of 180 of the contract, contractor will classify specific capacity data according to amount of screen penetration. If this evaluation was performed please document it in the report. Otherwise please explain why the analysis was not done.

    Explanation added. See Section 4.5.2.

38. Section 4.5.2: Per Exhibit A (SOQ), Page 16 of 180 of the contract, contractor proposed to perform two to three aquifer tests in the Brazos River Alluvium Aquifer. Those tests

were not performed. Please document why the tests were not performed and please describe the change in scope of work noted in the 2015 contract amendment.

A paragraph was added to Section 4.5.2 documenting the reasons the aquifer tests could not be performed and describing the change in scope.

39. Section 4.6.2.1, Pages 4.6-1 to 4.6-12: Additional TWDB resources for irrigation can be found http://www.twdb.texas.gov/conservation/agriculture/irrigation/index.asp or contact staff in Agricultural Water Conservation: http://www.twdb.texas.gov/conservation/stafflist.asp#contact-conservation

    The irrigation estimates related to these links are those developed by the conservation staff and given to the water planning staff and included in the water use survey data, which were used to develop pumping for the Brazos River Alluvium Aquifer. Therefore, this is not an additional source of irrigation pumping data. No change.

40. Section 4.6.2.1.3, Page 4.6-5, Paragraph 4: Please note that the 110 median per capita is gallons per day not gallons per minute. Please update text and adjust calculations as needed.

    Done. Units in text were incorrect but calculations were correct, therefore, no adjustment to calculations was needed.

41. Section 4.6, Figure 4.6.30, Page 4.6-50: Comparing domestic well locations with rural population distribution (Figures 4.6.1 and 4.6.2), it appears that many domestic wells are not represented. In other words there are many people where there are few or no wells. Please justify using point locations for rural domestic pumping or consider distributing based on population density. Please also evaluate and discuss whether livestock and irrigation wells are represented well enough with point locations.

    Section 4.6.2.6 indicates that well locations will "initially" be used to distribute pumping, it does not indicate that pumping will be distributed only to the indicated wells. No change.

42. Section 4.6: Per Exhibit A (SOQ), Page 19 of 180 of the contract, National Agricultural Statistics Service (NASS) imagery will be used to distribute irrigation pumping. However, the report (Section 4.6.2.5, Page 4.6-11, last Paragraph) states pumping will be assigned to the location of wells that match the primary use category. Please explain in the text of the report why the imagery will not be used. Also, please reconsider distributing irrigation and livestock pumping according to some kind of land use coverage rather than point locations unless the distribution and number of wells identified as irrigation appears to be well spread and reasonable.

    Because the spatial distribution of pumping is discussed in the numerical model report, Section 4.6.2 was removed from the conceptual model report. Imagery data

is used in conjunction with well locations in the model implementation which is not part of this report.

43. Figure 4.6.30, Page 4.6-50: Please provide citation and reference for the well locations.

    Done. See Figure 4.6.30

44. Figures 4.7.1 through 4.7.7, Pages 4.7-1 through 4.7-15: Please provide citations in the figure captions for the source of the water quality data (possibly TWDB, 2014f).

    Citations added. See Figures 4.7.1 through 4.7.7.

45. Section 5.0, Pg. 5.0-2, Paragraph 1: Consider adding the words "in the study area." to the end of the sentence that reads "No Cretaceous-age aquifers directly underlie the Brazos River Alluvium."

    Text added. See Section 5.0.

46. Section 5.0, Page 5.0-3, Paragraph 2: Sentence 7 states that " … base flow estimates indicate … a gain of approximately 760,000 acre-feet per year across the entire study area." But then sentence 8 states it is not representative of the main stem of the Brazos, and sentence 9 states the tributary base flow estimates are consistent with the modern recharge estimate of 760,000 acre-feet per year across the study area. The text seems to suggest that the main stem of the Brazos has no net base flow. Please review these three sentences and clarify by rewording if appropriate.

    Text re-worded to avoid confusion. See Section 5.0.

47. Section 5.0, Page 5.0-4, Paragraph 2: In sentence 1 please change Figure 2.2.5 to Figure 2.2.6c.

    Reference corrected. See Section 5.0.

48. Section 5.0, Pg. 5.0-7, Figure 5.0-1: Would there be no stream-aquifer interaction involving Layer 2? The upper portion of the figure is drawn to suggest that there could be such interaction.

    For numerical convergence reasons, we set a minimum thickness of 10 feet for layers 1 and 2 so there is no stream interaction with layer 2 as layer 1 is always present where layer 2 is present.

49. Section 5.0, Pg. 5.0-7, Figure 5.0-1: How will the boundary between Layers 1 and 2 be determined? What are the criteria (or range of criteria) that will used?

    This determination is considered part of the numerical model implementation and will be discussed in the model calibration report.

50. Section 6.0, Page 6.0-3, Surface Water Interaction: Please possibly expand this section with the assumptions from the Brazos Riverware surface water model.

    Discussion of the RiverWare model is included in Section 3 as a previous model rather than in this section.

Draft geodatabase comments to be addressed

51. No comments.

General suggestions for Draft geodatabase

52. Please consider providing mxd files associated with the geodatabase for comparison of figures in the reports to the data provided.

    Figures included in accompanying digital files.

Suggestions for Conceptual Model Report:

General suggestions

53. Please check for grammar (noun and verb agreement), spelling, and punctuation throughout the report.

    Done.

54. Please only capitalize groundwater conservation district, regional water planning groups, and groundwater management areas when used as part of a single district, region, or management area name.

    Done.

55. Please use parenthesis around Balcones Fault Zone when referring to the Edwards (Balcones Fault Zone) Aquifer and please refrain from using BFZ in figures or legends without footnoting the meaning of the acronym somewhere in the figure, legend, or caption.

    Done.

Specific suggestions

56. First two pages of the report: Please add “River” to, “…Brazos [River] Alluvium Aquifer…” in the title.

Done.

57. Executive Summary, Page ES-2, Paragraph 4, last sentence: Please use lower case for groundwater conservation districts, as it should only be capitalized when used as part of a single district name.

    Done.

58. Section 1.0, Page 1.0-2, Paragraph 4: Please make “a tool” plural (tools).

    Done.

59. Section 1.0, Figures 1.0.1 and 1.0.2: Suggest using the same colors to identify the aquifers as used the maps produced by TWDB.

    No change.

60. Figure 2.0.8, Page 2.0-12: Please footnote acronyms in legend or add to caption.

    Abbreviation key added to legend. See Figure 2.0.8

61. Figure 2.0.10, Page 2.0-14 Please footnote in legend or caption the meaning MWSD.

    Abbreviation removed. See Figure 2.0.10.

62. Section 2.1, Page 2.1-1, last Paragraph, Sentence 1: Please spell out meter and feet instead of using abbreviations.

    Corrected. See Section 2.1.

63. Section 2.1, Page 2.1-2, Paragraph 3: In sentence 1 the text “(weighted by the thickness of the layers)” is a misleading description of harmonic mean. Please remove description in parenthesis and provide a more detailed, accurate description or provide a formula for harmonic mean.

    Description and formula added. See Section 2.1.

64. Section 2.1, Page 2.1-3, Paragraph 2: In sentence 1, “…by the PRIMS Climate Group…”, please change to “by the <u>PRISM</u> Climate Group”

    Corrected. See Section 2.1.

65. Section 2.1, Page 2.1-6, Para 3: Sentence 3 states that “the vegetative coefficients for land use on the Brazos River Alluvium Aquifer were assumed to be the same as the values they report for Austin, Texas.” Should this be the “vegetative coefficients for <u>developed</u>

land use on the Brazos River Alluvium …" Please verify and update the text if necessary. Also, please consider adding "developed land use" category to table 2.1.2.

Although the vegetative coefficients reported in Scanlon and others (2005) are labelled with a city name (Austin, Texas), they do not actually refer to the developed land within that city. Instead, the city label refers to the fact that the vegetative coefficients were calculated using the historical average monthly temperature at Austin, Texas. Therefore, the coefficients should be applicable to our study area which has similar climatic conditions. The text has been re-worded to clarify how these values were calculated. Table 2.1.2 was not changed. See Section 2.1.

66. Figure 2.1.8, Page 2.1-15: Please spell out NCDC Coop or footnote in legend or add to caption.

    Abbreviation key added to caption. See Figure 2.1.8.

67. Figure 2.2.1, Page 2.2-5: Please correct spelling of Fault in Balcones Fault Zone and Mount Enterprise Fault Zone.

    Corrected. See Figure 2.2.1.

68. Section 3.2, Page 3.2-1, Paragraph 1 Please spell out feet instead of using abbreviations.

    Done.

69. Section 4.1.1, Page 4.1-2, last Sentence in this section: Text states a single model layer will be used to represent the geologic units underlying the Brazos River Alluvium Aquifer. Please consider re-wording to shallow portions of the geologic units surrounding the Brazos River Alluvium Aquifer.

    Corrected. See Section 4.1.1.

70. Section 4.5, Page 4.5-1, Paragraph 6: According to the text, "Little is known regarding the hydraulic properties of the Brazos River Alluvium Aquifer." However, on the following page there is a discussion of hundreds of hydraulic property measurements and table 4.5.1 and Figure 4.5.1 show quite a bit of data. Please clarify what is meant by "Little is known".

    Corrected. See Section 4.5.

Public Comments:

General

The report is excellent in that it is thorough with excellent documentation. It is one of the best ones I have seen so far. The discussion regarding the thickening of the alluvium deposits on page 2.2-3 are correct in determining the base of the aquifer but the northern portion of the aquifer definitely shows a thickening to the south from Lake Whitney to Robertson County and in this portion of the aquifer it is much easier to determine the base of the aquifer.

71. Recharge is perhaps the most difficult of all the aquifer characteristics to quantify and this conceptual model works very hard on this parameter. Although the stream flow gain between points can be used to estimate recharge, it only accounts for net recharge and would not properly quantify the actual recharge the aquifer received if the aquifer was losing water in that stretch of the stream. In addition, when the flow gain is quantified (divided by the area of the alluvium outcrop to determine the depth of recharge in inches), this assumes that no recharge came from bedrock or underlying aquifers and no recharge came from hydraulically connected tributary alluvium. Both these assumptions may not be true. The recharge should only scale with precipitation (section 4.3.2.1, p. 4.3-3) if precipitation is the only contributing recharge. I think the discussion of gravel pits as possibly sources of recharge is okay but then the assumption that all pits are focused points of recharge (p. 4.3-9 line 1 and 2) ignores the discussion. In my observations most pits have a very small catchment area and act as discharge points due to evaporation.

    In this report, "recharge" is defined as water that enters the saturated zone at the water table. Water that enters the aquifer through losing streams is discussed in Section 4.4.1. Water that enters the aquifer from the underlying formations and tributary alluvium is discussed in Section 4.2.6. Text added to the gravel pit discussion to more fully explain the assumptions made. See Section 4.3.2.5.

72. The water quality discussion in section 4.7 correctly mentions the high level of variability that occurs spatially within the aquifer. However, I think it is a severe omission to not consider the impacts of the underlying aquifers on water quality (p. 4.7-3). I also think omitting the data that were deemed "not indicative of aquifer quality" in section 4.7.2 on page 4.7-3 is not appropriate in all cases. I think local contamination is a part of the variability that is characteristic of the aquifer.

    There is insufficient data to determine the actual impacts of cross-formational flow to the Brazos River Alluvium Aquifer, both in terms of quantity and quality, and so this was not included in the water quality discussion, as it would have been largely speculation. Note that the "not indicative of aquifer quality" label refers to the reliability of the sampling technique, not to the level of contamination in a sample. Text has been revised for clarification. See Section 4.7.2.

73. The use of specific capacity tests and other aquifer tests in this aquifer are misleading in that the aquifer variability is preselected to the best parts or the most productive portions of the aquifer. There are many areas with fine-grained materials that are not ever tested because the drilling does result in a well completion. I think it is critical [that] some sort of statistical analysis that takes into consideration this factor is included in the GAM and its assessment.

This is a bias common to other aquifers. There are several factors that mitigate this bias, however. First, when we use kriging to interpolate between point data to fill in the gaps, we interpolate in logarithmic space. This means that, in the absence of data, interpolated values will tend toward the lower end of the range in measured data. Second, during the numerical model calibration we adjust the hydraulic properties to match the observed water levels and temporal trends in water levels. In this way, we attempt to fit the ensemble hydraulic properties, which include both high and low conductivity zones, when matching observed water levels.

74. The conceptual model in Figure 5.0.1 does not allow for lateral flow from bedrock or the tributary alluvium that comes in hydraulic connection with the aquifer where floodplains meet. I think this is an important flaw or omission.

The extreme vertical exaggeration in this figure overemphasizes the importance of this aspect of flow. The aquifer is, on average, about 5 miles wide and the saturated thickness is typically no more than 20 feet at the edges of the aquifer. This means that the area available for flow is over 1,000 times greater vertically than it is in the horizontal and layer 3 is connected to layer 2 vertically. Even a single grid cell has over 30 times greater area available for flow in the vertical dimension. So we do not believe this a serious flaw in the model.

Specific

75. Line 3, page ES-1: I would suggest that the word “connected” be replaced with the word “adjacent”. The floodplain deposits are not even connect everywhere but still constitute the aquifer and some terraces within the boundary are not connected. The adjective “hydraulically” is used with connected in the introduction p. 1.0-1.

The “Aquifer” is meant to be distinguished from other Brazos River Alluvium deposits that are not hydraulically connected.

76. Last sentence on paragraph 2 page ES-2: The effects of the river stage on the aquifer levels and long-term decreases in flow affecting aquifer storage should also have been investigated.

This was investigated in Section 4 but we do not believe it warrants discussion in the Executive Summary.

77. I think the omission of potential recharge from bedrock is a serious [oversight]. I think it may contribute more than expected; even in the northern segment. See 1st paragraph on page 4.3-1.

We agree that the contribution of groundwater inflow from bedrock is an important portion of the water balance for the Brazos River Alluvium Aquifer, however, this is discussed in Section 4.2.6 Cross-Formational Flow between the Brazos River Alluvium Aquifer and Underlying Aquifers rather than in Section 4.3. In this

report "recharge" is defined as water that enters the saturated zone at the water table.

78. Page 4.3-11: the exclusion of urban gages because they yielded high recharge values is not explained.

    Text revised for clarity. See Section 4.3.3.1.

79. The decision to use the recharge formula 4.3.1 on page 4.3-13 for the northern segment seems arbitrary and I could not see if it was calibrated to any other method such as the base flow separation method. If this method is okay for the northern portion is [it] also used in the other portions?

    The recharge formula 4.3.1 was derived directly from the results of the base flow separation analysis discussed in Section 4.3.3.1 and presented in Table 4.3.5 and Figure 4.3.7. As shown in Figure 4.3.7, the considered gage watersheds do cover most of the study area. Therefore, the recharge formula 4.3.1 should apply to the entire study area. However, as discussed in Section 4.3.4, there are existing (and much more detailed) recharge estimates available for the southern portion of the model, based on previous studies. Therefore, there was no reason to apply the new formula to these areas, since it only provides a rough estimate of recharge based on precipitation. We only applied the new formula in the northern section because there were no other existing recharge estimates available there.

80. Table 4.3.1 lists the results of several different recharge estimates but in every case they ignored lateral flow from bedrock or gain and loss from underlying aquifers. It appears they just divided the recharge amount by the BRAA outcrop area to get inches of recharge.

    This section only discusses recharge from precipitation through the outcrop. A discussion of cross-formational flow (i.e. lateral flow from bedrock or gain and loss from underlying aquifers) can be found in Section 4.2.6.2.

81. Figure 4.4.9 is discussed on p. 4.4-13 and there is no mention of the Waco baseflow being anomalous with slightly lower baseflow from 2011-2013 than from 1952-1956. I think this warrants some discussion. There is some discussion of this topic on p. 4.4-15 which references fig. 4.4.12 that contains the same graph data. There is reference to the absence of underlying aquifers for the Waco segment but no mention of the urban area or the large number of mining pits.

    Anomaly noted in text. See Section 4.4.1.2. Please note that Figures 4.4.9 and 4.4.12 do not "contain the same graph data." Figure 4.4.9 represents the portion of the total measured streamflow that can be attributed to baseflow rather than run-off. This baseflow could have entered the river anywhere upstream of the gage. Figure 4.4.12 represents the portion of the total measured streamflow that can be attributed to baseflow but ONLY includes baseflow that has entered the river in the

reach directly upstream of the gage (with "reach" referring to the reaches shown in Figure 4.4.10).

Edits

82. p. 3.1-4 Wong is referenced as "he" but Wong's first name is Stephanie so it should be "she".

    Done.

83. There is a line that does not connect anything but points to the edge of the aquifer in McLennan County near the top of fig. 4.2.22.

    Line removed.

84. There are numerous places where the word "data" is considered singular instead of plural.

    Done.

Suggestions

85. The northern portion of the Brazos River Alluvium Aquifer should be separated from the lower part of the aquifer in similar fashion to the Edwards Balcones Fault Zone Aquifer, another long, skinny aquifer. The suggested separation would be most appropriate along the boundary between Falls and Robertson/Milam counties. The reasons discussed below assume the boundary would be in the above location.

    Reasons include:
    1. The suggested boundary coincides with the boundary between Groundwater Management area 8 and area 12.
    2. It contains the only large urban area that is located directly on the aquifer.
    3. The underlying bedrock units do not contain any aquifers in direct contact with the BRAA (figs. 2.0.6 and 4.1.1) and the northern segment of the BRAA is the only portion of the BRAA underlain by the confined Trinity aquifer (fig 2.0.5).

4. It is the only part of the BRAA that contains the Great Plains Province (fig. 2.1.1).
5. It is the only part of the BRAA that contains the Cross Timbers and the Texas Blackland Prairies border occurs right on the falls county line (fig. 2.1.2).
6. It is the only part of the BRAA that lies within the Balcones Fault Zone (fig. 2.2.1).
7. The longitudinal cross section A-A' show underlying bedrock dip unique to this portion of the aquifer (fig, 2.2.3).
8. The Falls County boundary coincides well with the boundary for the Queen City and Sparta GAM boundary (fig. 3.2.1).
9. On page 5.0-1 the report concludes the aquifer is unique in that it requires "both regional- and local-scale considerations." I agree and think splitting it into three segments would aid management.

We agree with the sentiment of this comment, however, the Texas Water Development Board defines the extent of the Brazos River Alluvium Aquifer and has contracted the development of a single groundwater availability model for the aquifer. By using a quadtree mesh in MODFLOW-USG, we were able to keep the grid discretization of the entire Brazos River Alluvium Aquifer to one eighth mile squares while rapidly expanding the grid to one mile squares outside the alluvium. In this way, both the regional- and local-scale aspects could be considered in a single model with relatively fast runtimes.

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