Conceptual Model: Northern Segment of the Edwards (Balcones Fault Zone) and Associated Trinity Aquifers of Texas

Ian C. Jones, Ph.D., P.G.
July 19, 2023

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by
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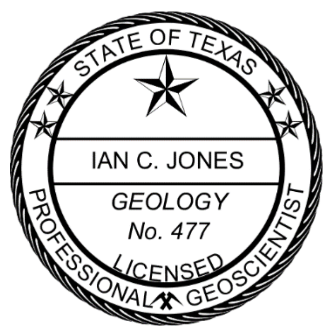

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February 6, 2023

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EXECUTIVE SUMMARY

The northern segment of the Edwards (Balcones Fault Zone) Aquifer is the part of the Edwards (Balcones Fault Zone) Aquifer located north of the Colorado River in northern Travis, central Williamson, and southern Bell counties. The aquifer is an important source of water for municipalities, industry, and landowners in central Texas. Rapid population growth in this part of Texas has increased interest in the northern segment of the Edwards (Balcones Fault Zone) Aquifer and heightened concerns about groundwater availability in the aquifer. This portion of the aquifer underlies several large cities in the region, including parts of Austin, Cedar Park, Pflugerville, Round Rock, Georgetown, Jarrell, Salado, and Belton. This report documents the development of a conceptual model of the northern segment of the Edwards (Balcones Fault Zone) Aquifer and adjacent parts of the underlying Trinity Aquifer. A conceptual model describes the hydrogeologic environment and the groundwater flow regime within a model study area. In other words, it describes a simplified representation of the hydrogeological features—hydrostratigraphy, hydraulic properties, hydrologic boundaries, recharge, and discharge—that influence groundwater flow through the aquifer. It forms the basis for a numerical groundwater flow model.

The northern segment of the Edwards (Balcones Fault Zone) Aquifer consists of the following stratigraphic units: the Comanche Peak Limestone, Edwards Limestone, and Georgetown Formation. Adjacent parts of the Trinity Aquifer are composed of the Glen Rose and Travis Peak formations. These aquifers dip—tilt downward—towards the east and are exposed at land surface along their western margins, forming outcrops.

Available water-level data show that groundwater within the northern segment of the Edwards (Balcones Fault Zone) and Trinity aquifers generally flows from aquifer outcrop recharge zones towards deeper parts of the respective aquifers with most of the flow occurring in the aquifer outcrop. Groundwater in these aquifers naturally discharges along the major rivers and streams that cross the respective outcrops—the Colorado, San Gabriel, and Lampasas rivers, and Salado Creek—and, to a lesser extent, by cross-formational flow through overlying stratigraphic units.

Groundwater in the northern segment of the Edwards (Balcones Fault Zone) Aquifer is utilized primarily for municipal uses (87 percent), but is also used locally for manufacturing, mining, and rural domestic uses. In the Bell County portion of the aquifer, rural domestic pumpage accounts for almost a quarter of pumping from the Edwards (Balcones Fault Zone) Aquifer, while in Williamson and Travis counties there is significant pumping for mining and manufacturing, respectively.

Most of the available hydraulic property data—data measuring how easily groundwater flows through a system—are from the confined portion of the aquifer, or the parts of the

aquifer that are overlain by non-aquifer stratigraphic units. The data available show significant variability in the aquifer properties resulting from structural complexity within the basin, lithologic variability, and the effects of post-depositional processes including karstification. Hydraulic conductivity values for the northern segment of the Edwards (Balcones Fault Zone) Aquifer range from less than 1 foot per day to more than 1,000 feet per day and display no apparent spatial trends.

Water quality in the northern segment of the Edwards (Balcones Fault Zone) Aquifer is generally fresh, becoming slightly saline with depth and is generally slightly fresher than groundwater in the underlying Trinity Aquifer. Groundwater compositions range from calcium-bicarbonate compositions to calcium-magnesium-bicarbonate compositions to sodium-bicarbonate and sodium-chloride compositions with increasing depth.

Groundwater isotope compositions in the northern segment of the Edwards (Balcones Fault Zone) Aquifer indicate: (1) the relative ages of groundwater within the aquifer with implications to the spatial distribution of groundwater flow, and (2) the seasonality of recharge to the aquifer. The data suggest that: (1) the groundwater flow system in the northern segment of the Edwards (Balcones Fault Zone) Aquifer is primarily restricted to the aquifer outcrop, (2) the confined portion of the aquifer is stagnant, and (3) most recharge occurs during fall and winter months despite the fact that highest monthly precipitation occurs during the spring.

The conceptual model for the northern segment of the Edwards (Balcones Fault Zone) Aquifer and adjacent parts of the Trinity Aquifer is composed of up to three model layers simulating groundwater flow through the Edwards (Balcones Fault Zone) Aquifer, the underlying Walnut Formation confining unit and the Trinity Aquifer. The three-layer model accommodates the processes of recharge to the aquifer outcrop(s), groundwater flow into confined parts of the northern segment of the Edwards (Balcones Fault Zone) and Trinity aquifers, groundwater flow between the Edwards (Balcones Fault Zone) and Trinity aquifers, and discharge to streams and by upward flow through overlying stratigraphic units.

1.0 INTRODUCTION

The Edwards (Balcones Fault Zone) Aquifer is one of nine major aquifers and 22 minor aquifers in Texas (Figures 1.0.1 and 1.0.2). The Texas Water Development Board defines a major aquifer as an aquifer that produces large amounts of water over a large area, and minor aquifers as aquifers that produce minor amounts of water over large areas or large amounts of water over small areas (George and others, 2011). The northern segment of the Edwards (Balcones Fault Zone) Aquifer is in the northern extent of the Edwards (Balcones Fault Zone) Aquifer, underlying northern Travis, central Williamson, and southern Bell counties. Total pumping from the northern segment of the Edwards (Balcones Fault Zone) Aquifer has ranged from a high of more than 25,000 acre-feet per year to about 10,000 acre-feet per year during the period of 1980 through 2015. This aquifer is important as a source of water—in addition to surface water—to provide for the needs of a rapidly growing population along the Interstate Highway 35 corridor.

This report describes the aquifer data used to develop an updated conceptual model for the northern segment of the Edwards (Balcones Fault Zone) Aquifer. This conceptual model will be the basis for updating the groundwater availability model for the northern portion of the Edwards (Balcones Fault Zone) Aquifer, including the addition of the underlying Trinity Aquifer. Once the groundwater availability model is calibrated, it can be used as a quantitative tool to evaluate the effects of pumping, drought, and different water management scenarios on the groundwater flow system. This report includes descriptions of (1) the study area, (2) previous investigations of the northern segment of the Edwards (Balcones Fault Zone) Aquifer, (3) the hydrologic setting including hydrostratigraphy, geologic framework, groundwater hydrology, recharge, discharge, surface water, hydraulic properties of the rocks, and water quality, and (4) the resultant conceptual model.

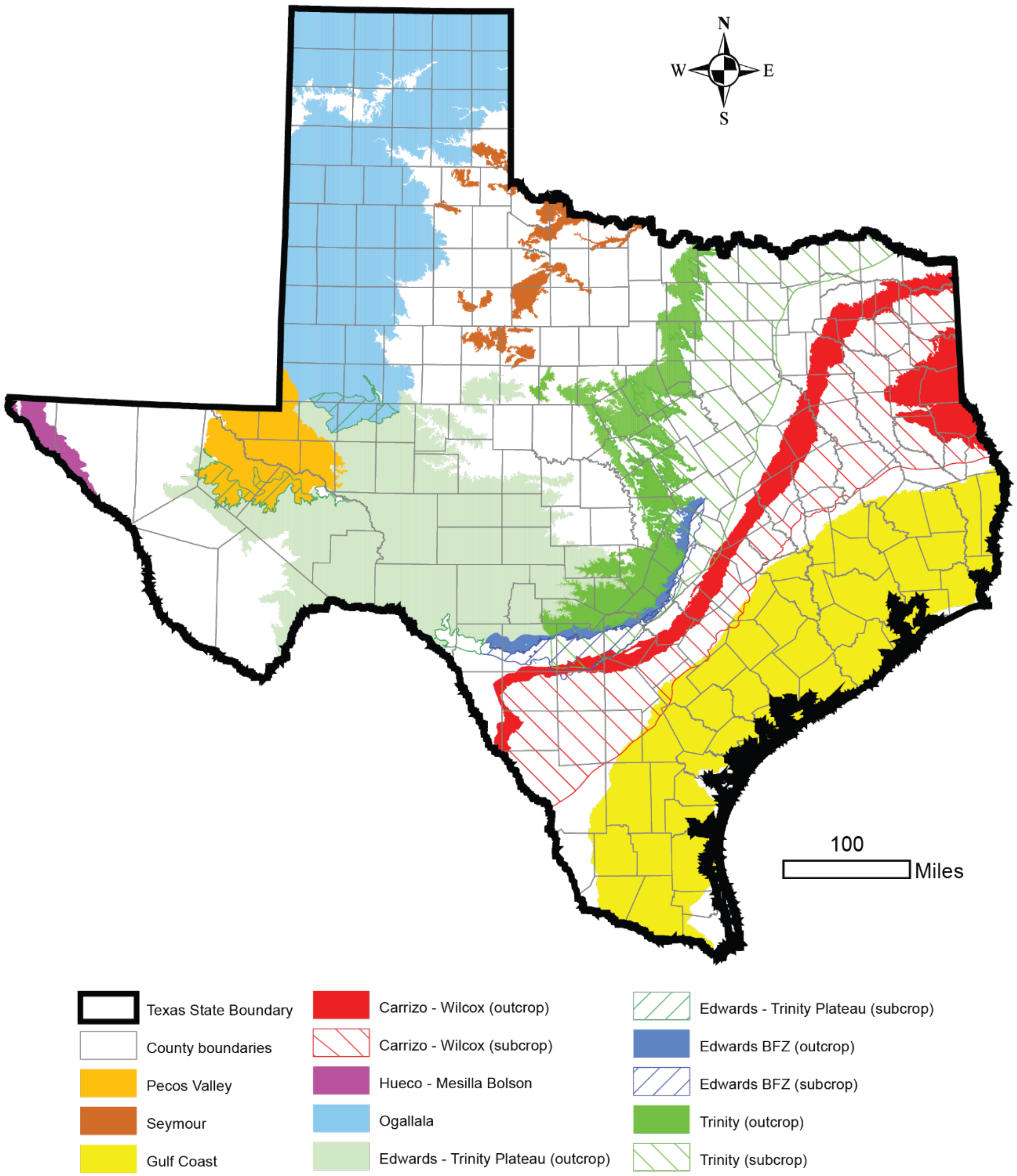


Figure 1.0.1. Locations of the major aquifers in Texas.

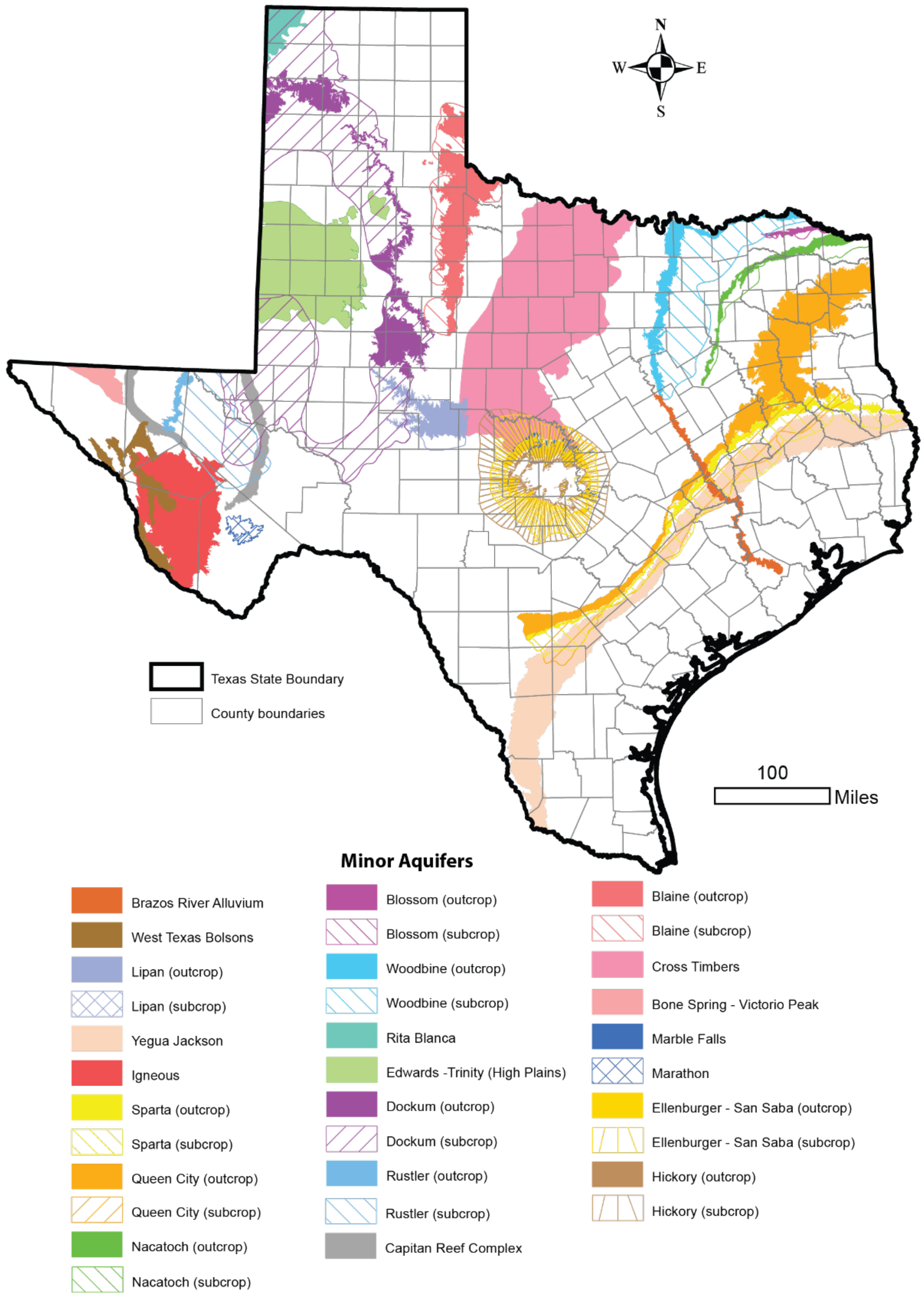


Figure 1.0.2. Locations of the minor aquifers in Texas.

2.0 STUDY AREA

The Edwards (Balcones Fault Zone) Aquifer consists of all the stratigraphic units below the Del Rio Formation and above either the Glen Rose Limestone or, when it is present, the Walnut Formation (Ashworth and Flores, 1991). The aquifer's outcrop runs uninterrupted from its northern extent in central Bell County, extending south and west to central Kinney County. Downdip, faulting resulted in abrupt changes in water quality and flow direction; and large displacement of the water-bearing units. The downdip limit of the aquifer represents the extent of water containing less than 1,000 milligrams per liter dissolved solids. The Edwards (Balcones Fault Zone) is divided into three segments: the San Antonio segment, Barton Springs, and the northern segment (Figure 2.0.1). The northern segment of the Edwards (Balcones Fault Zone) Aquifer is defined as the portion of the aquifer that lies north of the Colorado River. The northern segment of the Edwards (Balcones Fault Zone) Aquifer occurs at land surface (outcrop) and buried under other geologic units (subcrop) in a relatively narrow band in central Texas. The outcrops are located on the western side of the aquifer and it dips to the east (Figure 2.0.2). The eastern—downdip—boundary of the aquifer is defined by the occurrence of groundwater containing total dissolved solids less than 1,000 milligrams per liter. The northernmost part of the aquifer coincides with the Lampasas River where the river has cut through the stratigraphic units that make up the Edwards (Balcones Fault Zone) Aquifer. The stratigraphic units that make up the Edwards (Balcones Fault Zone) Aquifer continue north of the Lampasas River. North of the Lampasas River, these stratigraphic units provide groundwater for rural domestic, and livestock uses in areas west of the Balcones Fault Zone (Yelderman, 2019). These stratigraphic units are not classified as part of the aquifer by the Texas Water Development Board. The study area in this report includes the northern segment of the Edwards (Balcones Fault Zone) Aquifer and adjacent and underlying portions of the Trinity Aquifer (Figure 2.0.3). The Trinity Aquifer is defined as having groundwater with total dissolved solids less than 3,000 milligrams per liter.

Figure 2.0.4 shows the counties, major roadways, and cities in the study area. The northern segment of the Edwards (Balcones Fault Zone) Aquifer underlies parts of three counties—Travis, Williamson, and Bell counties. Cities overlying the northern segment of the Edwards (Balcones Fault Zone) Aquifer include Austin, Cedar Park, Pflugerville, Round Rock, Georgetown, Jarrell, Salado, and Belton. The locations of rivers, streams, lakes, and reservoirs in the study area are shown on Figure 2.0.5. The Lampasas and Colorado rivers form the northern and southern boundaries of the study area, respectively. The other major perennial streams in the study area include the San Gabriel River and the Salado and Brushy creeks.

Figures 2.0.6 and 2.0.7 show the major and minor aquifers that occur within the study area. The major aquifers occurring in the study area are the Edwards (Balcones Fault Zone)

Aquifer and the underlying Trinity Aquifer. The minor aquifers in the study area—the Marble Falls, Ellenburger-San Saba, and Hickory aquifers—mainly occur at depth, although small outcrops of the Marble Falls and Ellenburger-San Saba aquifers occur along the western boundary.

There are several entities and groups responsible for the management of both surface water and groundwater within the study zone. The northern segment of the Edwards (Balcones Fault Zone) Aquifer underlies part of the Lower Colorado Regional Water Planning Area (Region K) and the Brazos Regional Water Planning Area (Region G) (Figure 2.0.8). There are parts of five different Groundwater Conservation Districts (GCDs) within the study area, the largest portion underlying parts of the Clearwater Underground Water Conservation District (Figure 2.0.9). The other GCDs include the Central Texas, Lost Pines, and Post Oak Savanah groundwater conservation districts, and Saratoga Underground Water Conservation District. The northern segment of the Edwards (Balcones Fault Zone) Aquifer lies within Groundwater Management Area 8 (Figure 2.0.10). The northern segment of the Edwards (Balcones Fault Zone) Aquifer underlies parts of the Brazos and Lower Colorado river authorities (Figure 2.0.11). The boundaries of these river authorities coincide with the boundaries of the Brazos and Colorado river basins (Figure 2.0.12).

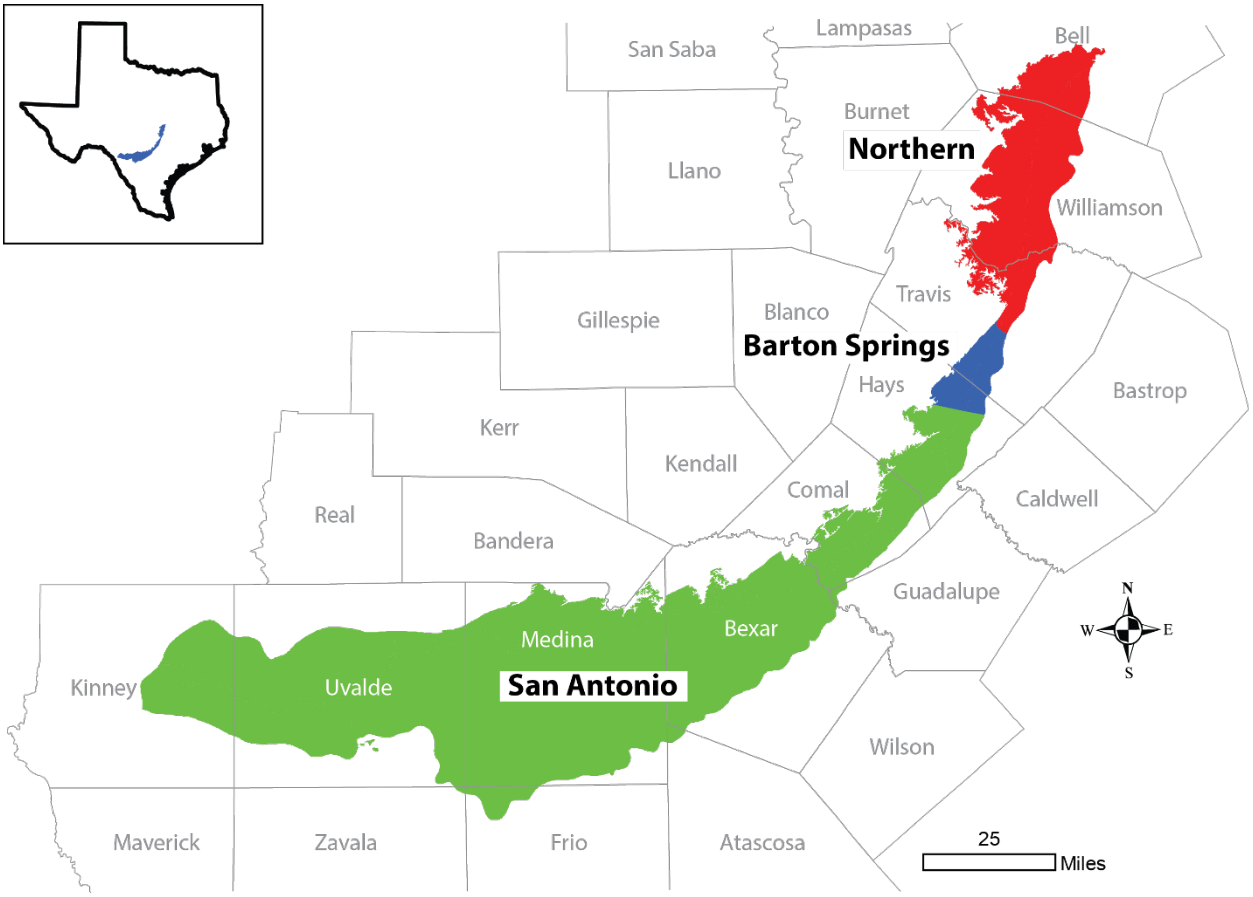


Figure 2.0.1. The Edwards (Balcones Fault Zone) Aquifer is divided into three segments—the San Antonio, Barton Springs, and northern segments.

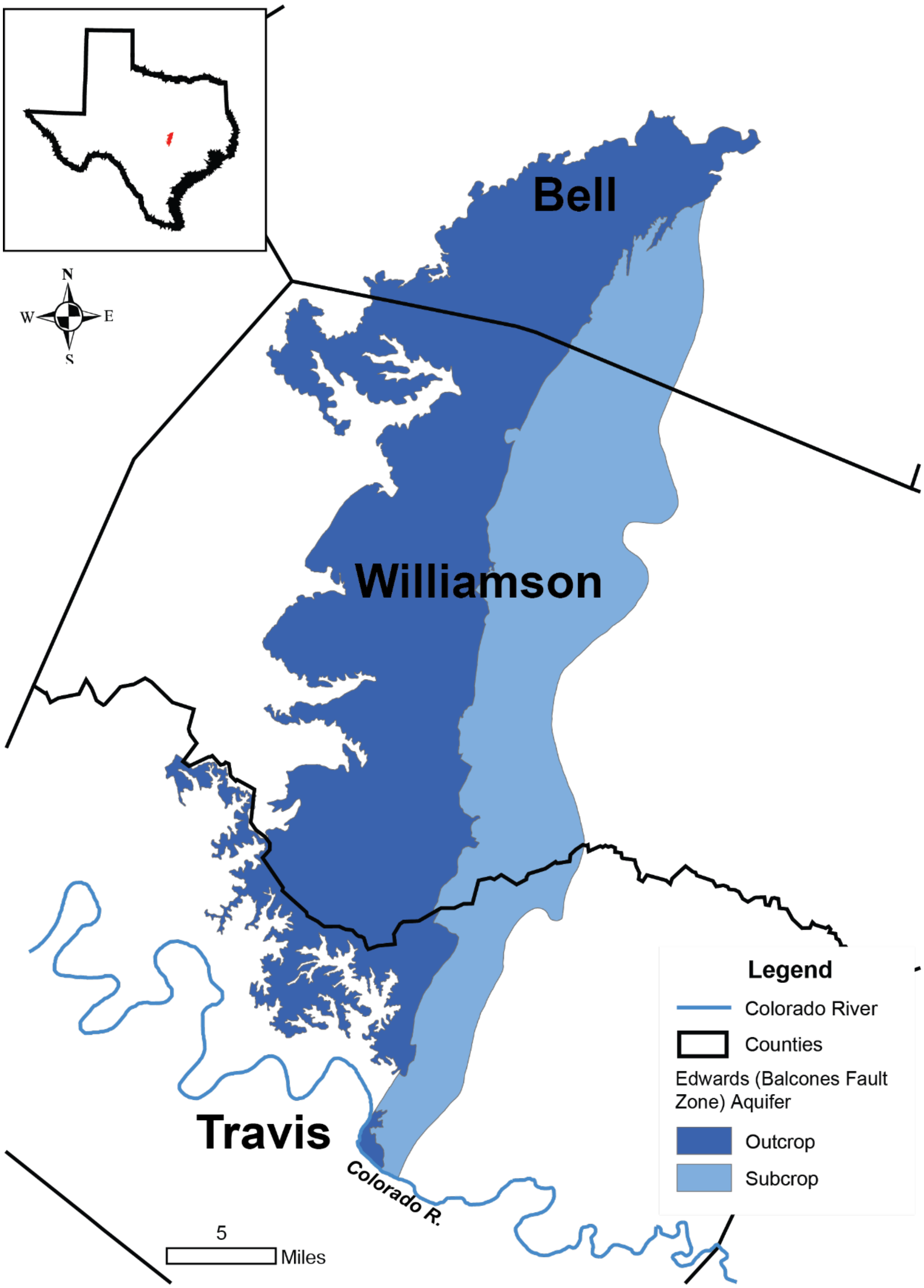


Figure 2.0.2. **The boundaries of the northern segment of the Edwards (Balcones Fault Zone) Aquifer include the portion of the Edwards (Balcones Fault Zone) Aquifer that lies north of the Colorado River.**

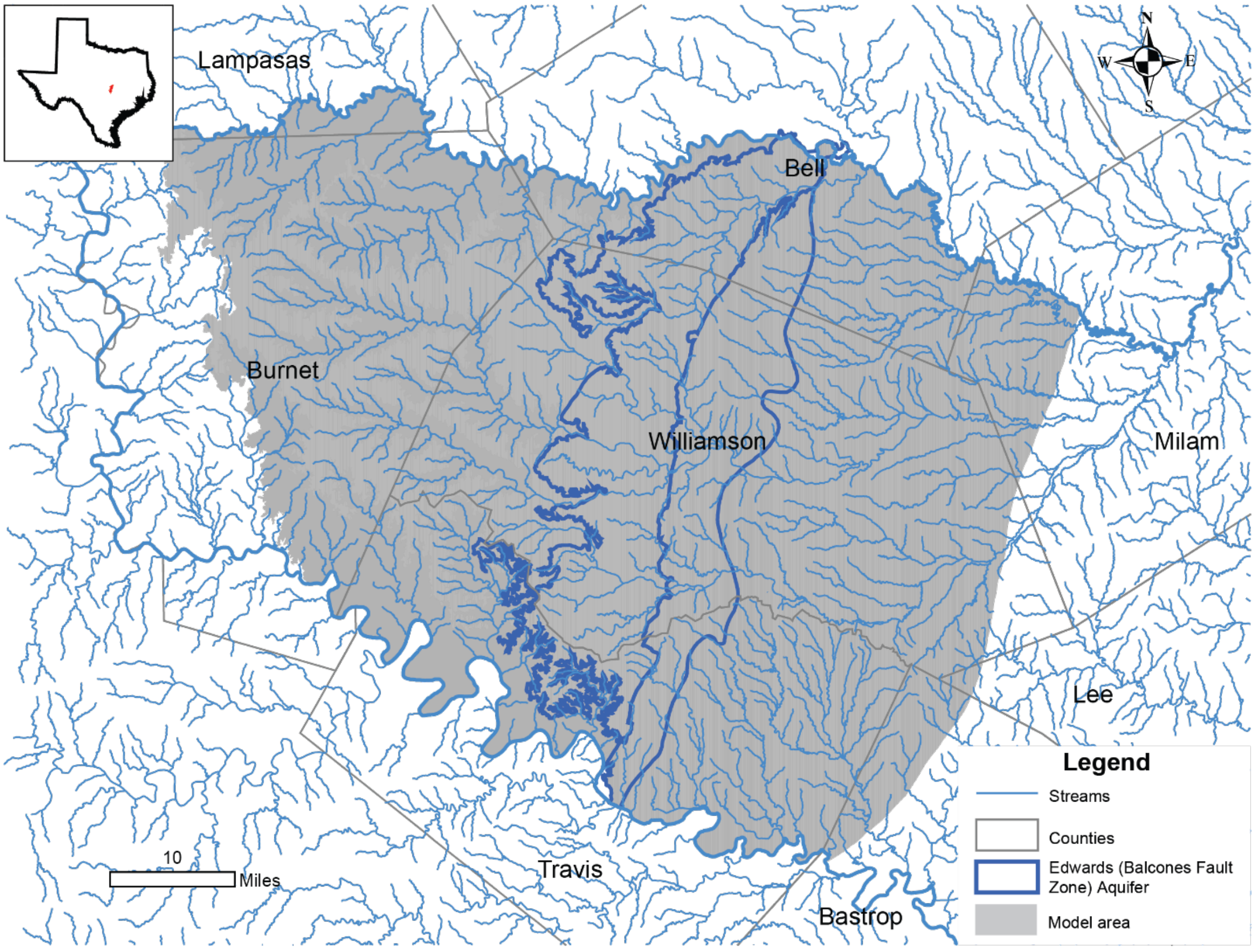


Figure 2.0.3. **The study area—indicated in gray—includes the northern segment of the Edwards (Balcones Fault Zone) Aquifer and adjacent and underlying portions of the Trinity Aquifer.**

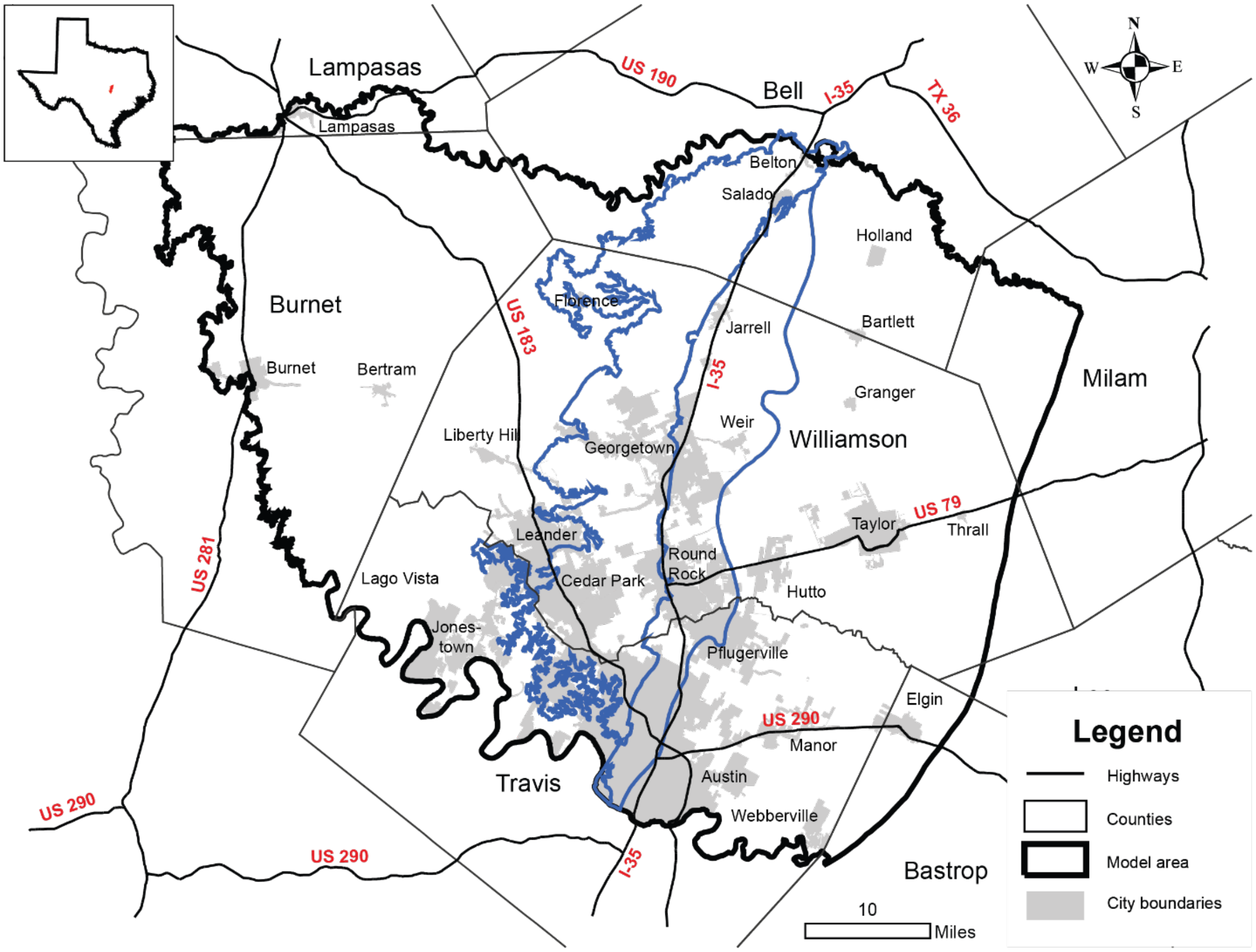


Figure 2.0.4. **Cities and major roadways over the northern segment of the Edwards (Balcones Fault Zone) Aquifer.**

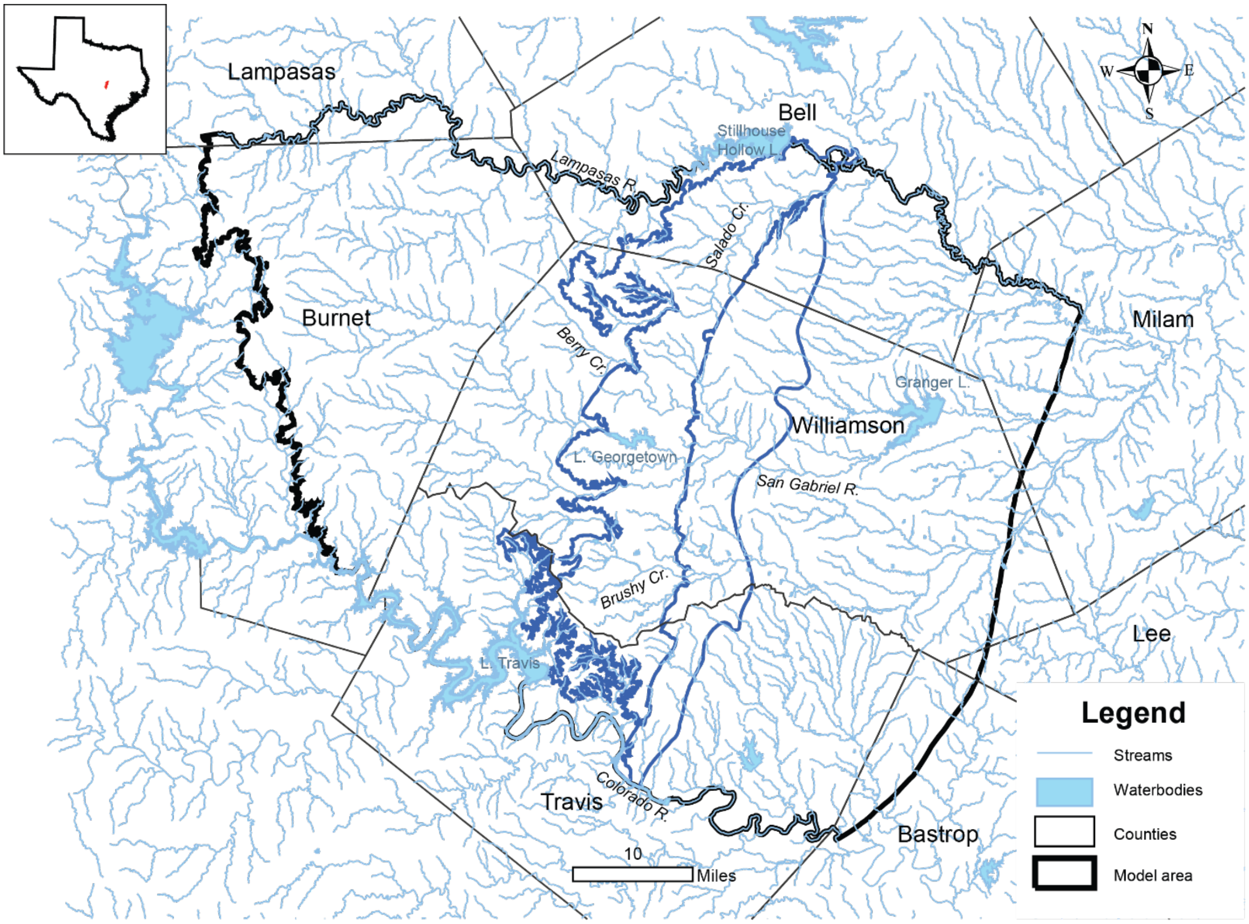


Figure 2.0.5. Rivers, streams, lakes, and reservoirs over the northern segment of the Edwards (Balcones Fault Zone) Aquifer.

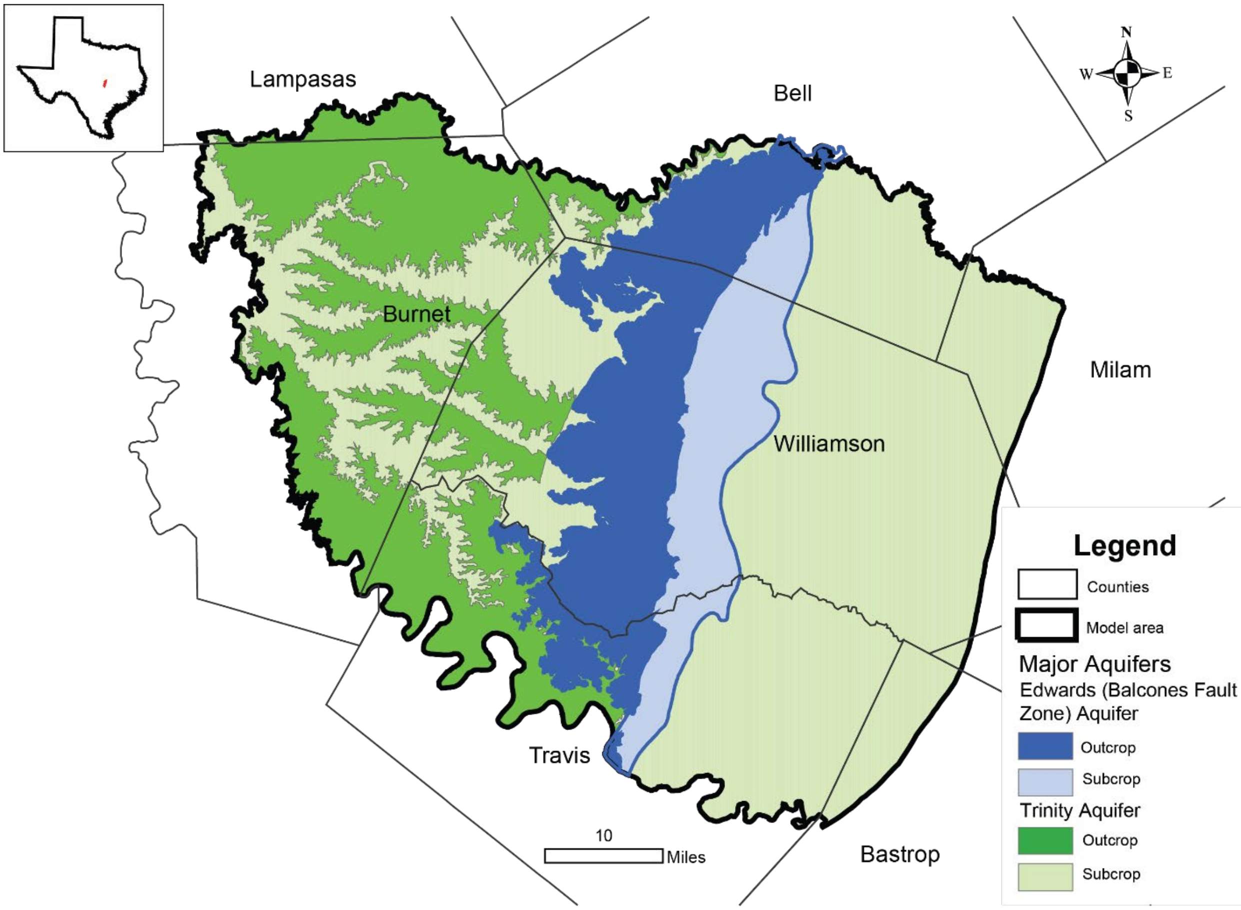


Figure 2.0.6. **Major aquifers in the study area.**

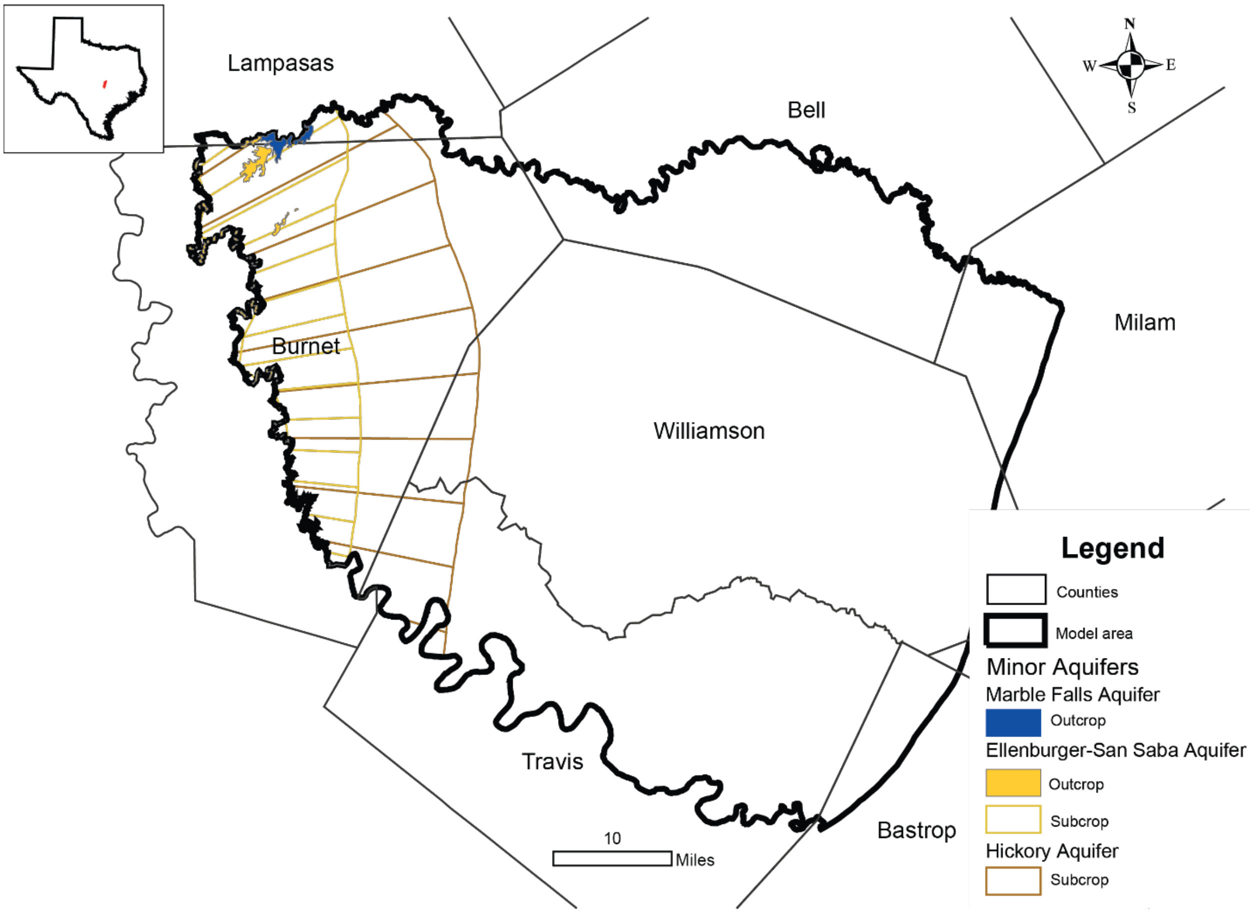


Figure 2.0.7. Minor aquifers in the study area.

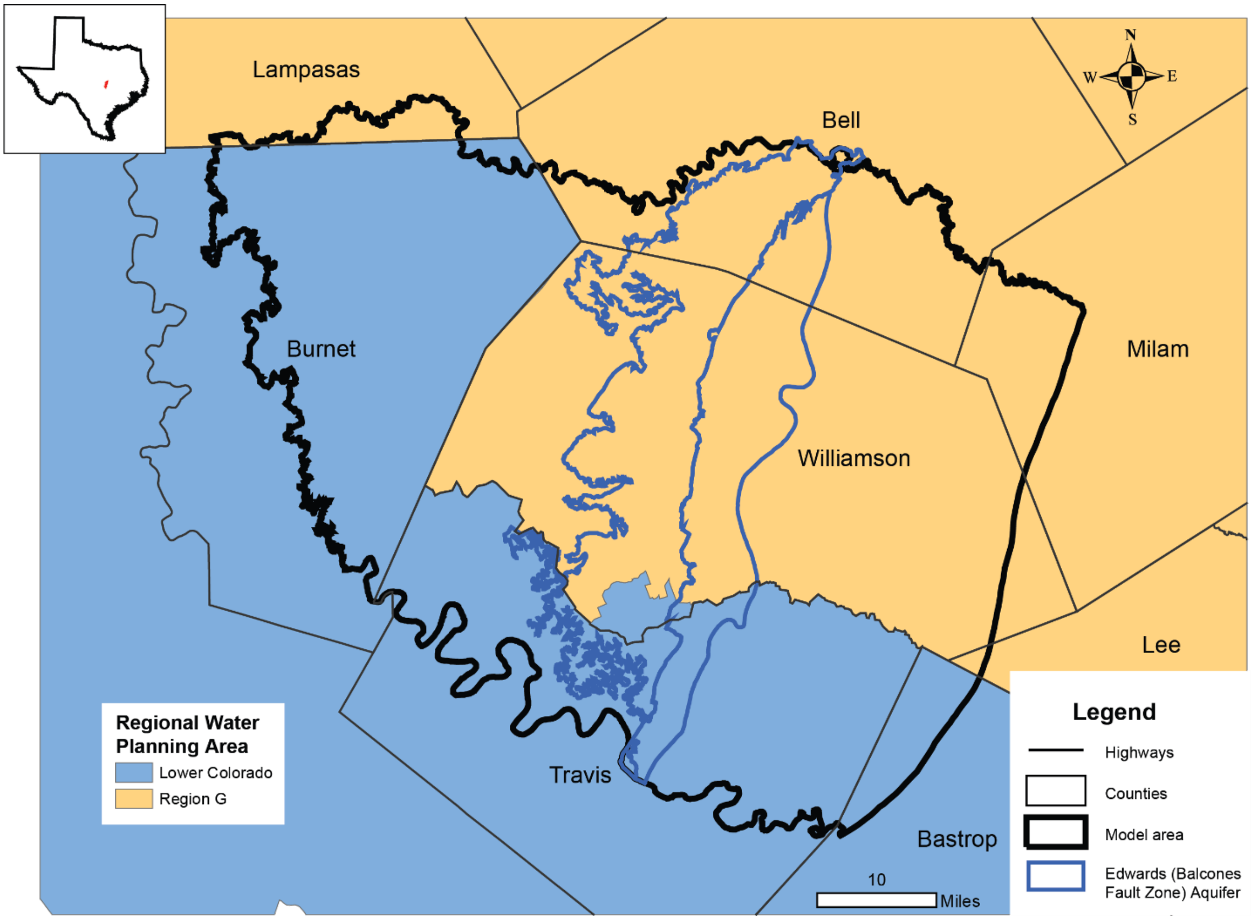


Figure 2.0.8. Texas regional water planning areas in the study area.

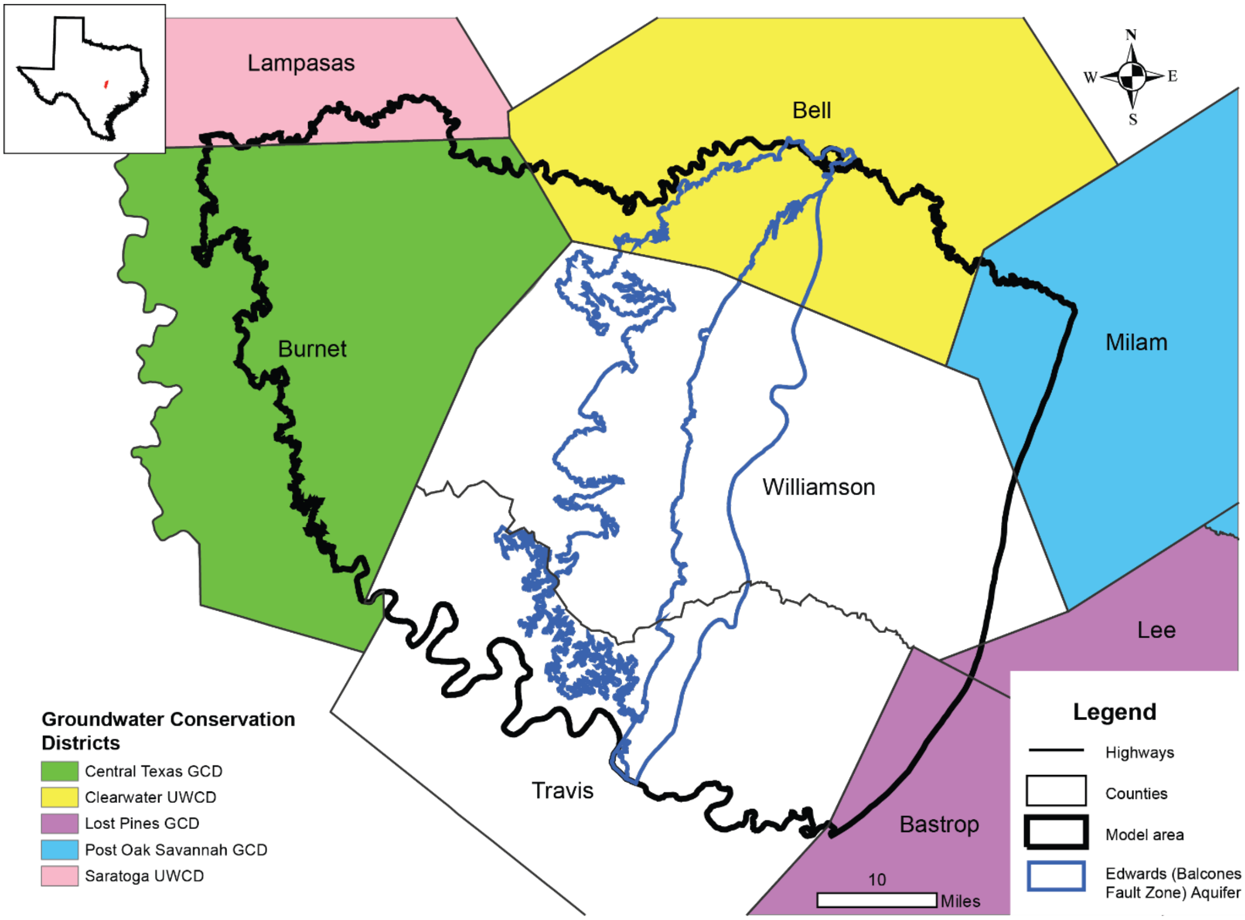


Figure 2.0.9. Texas groundwater conservation districts in the study area as of May 2020.

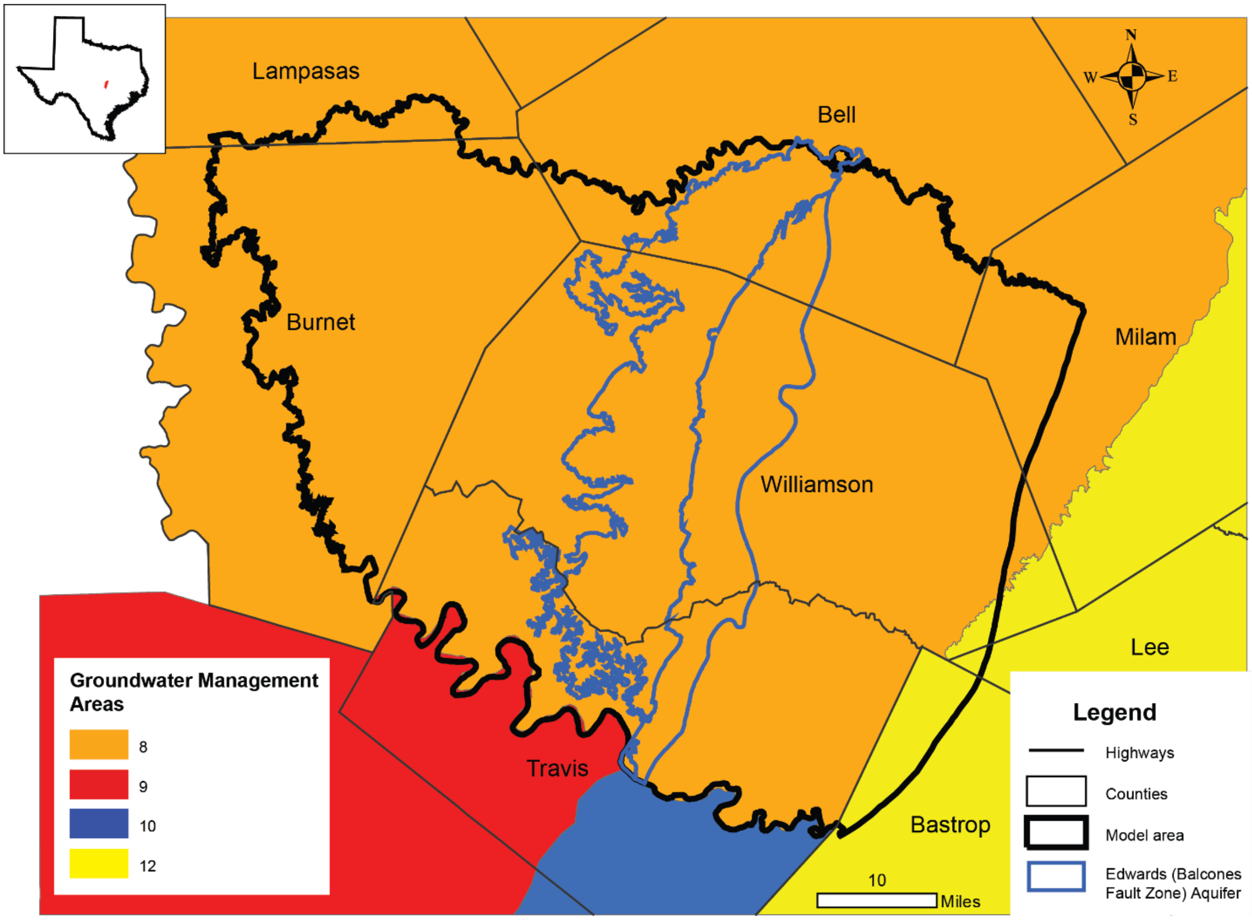


Figure 2.0.10. **Texas groundwater management areas in the study area.**

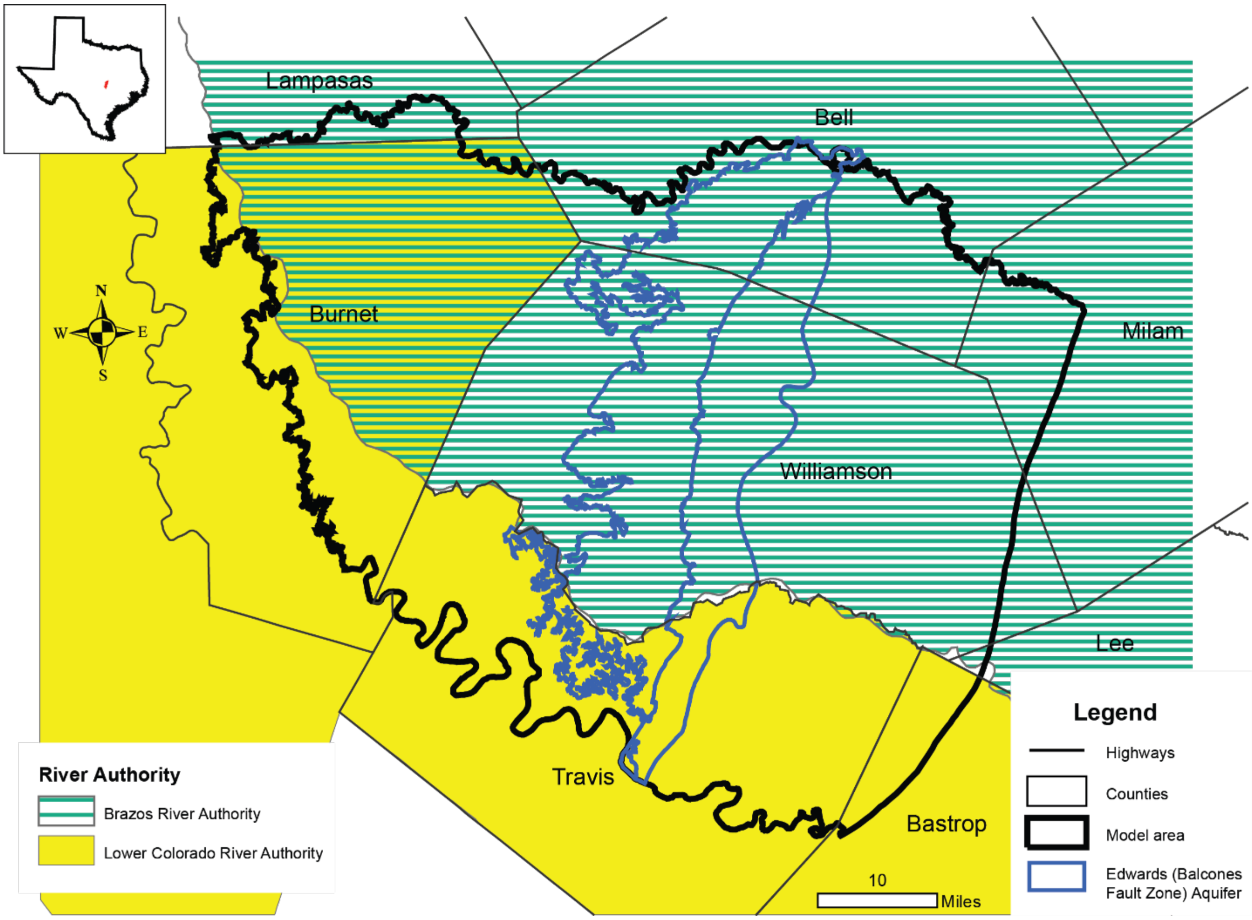


Figure 2.0.11. River authorities in the study area.

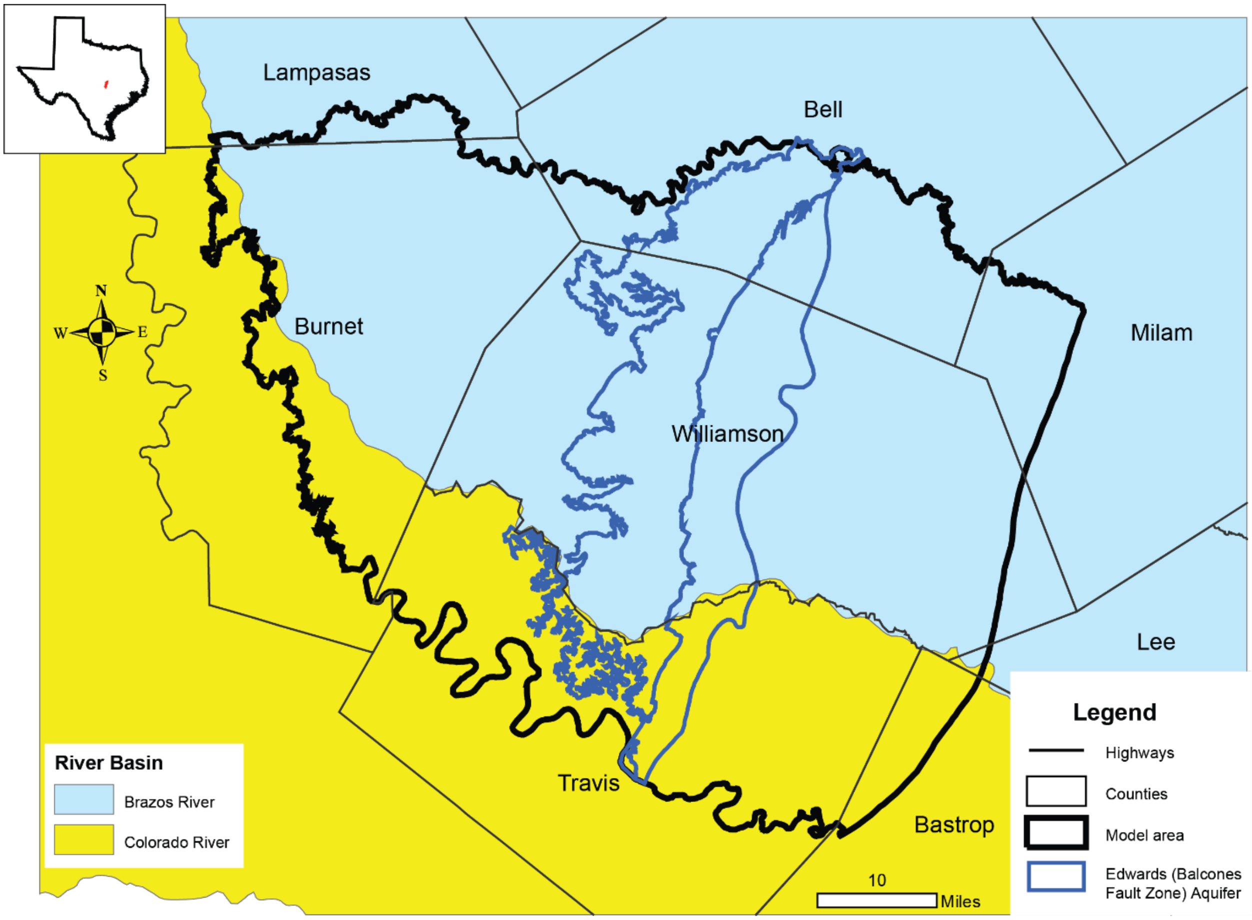


Figure 2.0.12. Major river basins in the study area.

2.1 Physiography and Climate

The study area for the northern segment of the Edwards (Balcones Fault Zone) Aquifer includes parts of the Central Texas Uplift, Edwards Plateau, Blackland Prairies, and Interior Coastal Plains physiographic provinces (Wermund, 1996; Figure 2.1.1). The Central Texas Uplift occurs along the western margin of the study area. It is made up of Precambrian intrusive and early Paleozoic sedimentary rocks that form a rolling landscape with hills up to 600 feet high (Wermund, 1996). The Edwards Plateau physiographic province includes the Jollyville Plateau and Lampasas Cutplains (Senger and others, 1990). The Jollyville Plateau has been separated from the Hill Country by erosion that resulted in the formation of the Colorado River valley. The Hill Country and Jollyville Plateau are characterized by highly dissected canyonland, while the Lampasas Cutplains is characterized by gently rolling terrain. The Blackland Prairie occurs where limestones are overlain by younger alluvial units that occur along the margin of the Interior Coastal Plains (Senger and others, 1990). The most prominent topographic feature is the Balcones Escarpment, a product of faulting in this region. This escarpment forms the boundary between the Jollyville Plateau and Hill Country parts of the Edwards Plateau and the Blackland Prairie (Trippet and Garner, 1976). The boundary becomes more subdued to the north in the Lampasas Cutplains. The Interior Coastal Plains, along with the Blackland Prairie, are subprovinces of the Gulf Coastal Plains. The Interior Coastal Plains is made up of alternating belts of resistant uncemented sands and weaker shales that erode, forming long, sandy ridges.

The northern segment of the Edwards (Balcones Fault Zone) Aquifer is located among the Cross Timbers, Edwards Plateau, and Blackland Prairies Level III ecological regions (United States Environmental Protection Agency, 2013; 2017; Figure 2.1.2). A small portion of the East Central Texas Plains Level III ecological region is also located along the eastern boundary of the study area. A wide variety of plant and animal life can be found in the study area.

The Cross Timbers ecoregion is a transition area between the former prairie regions to the west, and the forested hills to the east (United States Environmental Protection Agency, 2013; 2017). Average rainfall is highly variable, ranging from 25 inches in the west to 35 inches in the east (Texas Parks and Wildlife Department, 2017). The predominant land cover in this ecoregion is rangeland and pastureland, with some areas of woodland, primarily in the east. The native vegetation includes various types of grass, including little and big bluestem and Indiangrass with alternating bands of trees, such as Texas mulberry, American elm, live oak and post oak trees.

The Edwards Plateau ecoregion is largely a dissected limestone plateau with hillier terrain in the south and east; easily distinguished from bordering ecological regions by sharp fault lines (United States Environmental Protection Agency, 2013; 2017; Texas Parks and Wildlife Department, 2017). This semiarid region contains a sparse network of perennial streams. Originally covered by juniper-oak savanna and mesquite-oak savanna.

The Texas Blackland Prairies form an ecological region, distinguished from surrounding regions by its fine-textured, clayey soils and predominantly prairie natural vegetation (United States Environmental Protection Agency, 2013; 2017; Texas Parks and Wildlife Department, 2017). This ecoregion includes scattered woodlands made up of pecan, cedar elm, oak, and hackberry trees, with some mesquite. Grasses are the predominant natural vegetation, mainly little bluestem grass with lesser amounts of big bluestem, indiangrass, eastern gamagrass, switchgrass, and side oats grama. However, this ecoregion is now almost entirely cultivated.

Figure 2.1.3 is a topographic map of the study area (Gesch and others, 2002). Land-surface elevation is greatest along the western margin of the study area, reaching up to 1,600 feet above mean sea level, and generally decreases to the east to elevations of 200 to 400 feet above mean sea level.

The study area includes three climatic divisions, the Edwards Plateau, North Central, and South Central divisions (Figure 2.1.4). The Climate divisions represent regions with similar characteristics such as vegetation, temperature, humidity, rainfall, and seasonal weather changes. Climate data collected at locations throughout the state are averaged within each of the divisions. These divisions are commonly used to assess climate characteristics across the state (NCDC, 2011). In the study area, the climate is generally subtropical and subhumid to semi-arid. The Edwards Plateau division is characterized by subtropical steppe or semi-arid brushland and savanna. The North Central division is subtropical subhumid mixed savanna and woodlands, and the South Central division is subtropical subhumid mixed prairie, savanna, and woodlands.

The average annual maximum air temperature in the study area ranges from about 77 degrees Fahrenheit in Burnet County to about 79 degrees Fahrenheit in central Williamson County (Figure 2.1.5). Figure 2.1.6 shows average annual precipitation for the period 1981 through 2010 (NCDC, 2020). The annual average precipitation generally increases from west to east across the study area, from a high of 34 to 37 inches per year in eastern Bell, Travis and Williamson counties to a low of 31 to 32 inches per year in northern Burnet County.

Annual precipitation data recorded at four selected stations—Camp Mabry, Jarrell, Stillhouse Hollow Dam, and Taylor—over the period 1930 through 2016 are shown in Figures 2.1.7 and 2.1.8. Figure 2.1.8 indicates wide interannual variation of precipitation, ranging from lows of about 11 inches to highs of 60 inches per year. Figure 2.1.9 shows monthly precipitation for the four stations averaged over the period 1986 through 2016. In the study area, highest monthly precipitation occurs in May—exceeding 4 inches. Most precipitation occurs during spring and fall months—April through June and September through December—with least precipitation occurring in July and August. Median monthly precipitation at Camp Mabry is more evenly distributed than at the other stations with more precipitation during the dry summer months and less during the fall months.

The average annual lake evaporation rate in the study area ranges from a high of 59 inches per year to a low of 53 inches per year (Figure 2.1.10; Narasimhan and others, 2005). Average annual lake evaporation is generally lowest in the central and extreme southern parts of the study area, increasing to the west. Lake evaporation rates significantly exceed the annual average precipitation. Monthly variations in lake surface evaporation are shown for two locations in the study area (Figure 2.1.11; Narasimhan and others, 2005). These values represent the average of the monthly lake surface evaporation data from 1971 through 2000. Figure 2.1.11 shows that average lake evaporation peaks in July and August, the driest months in this region.

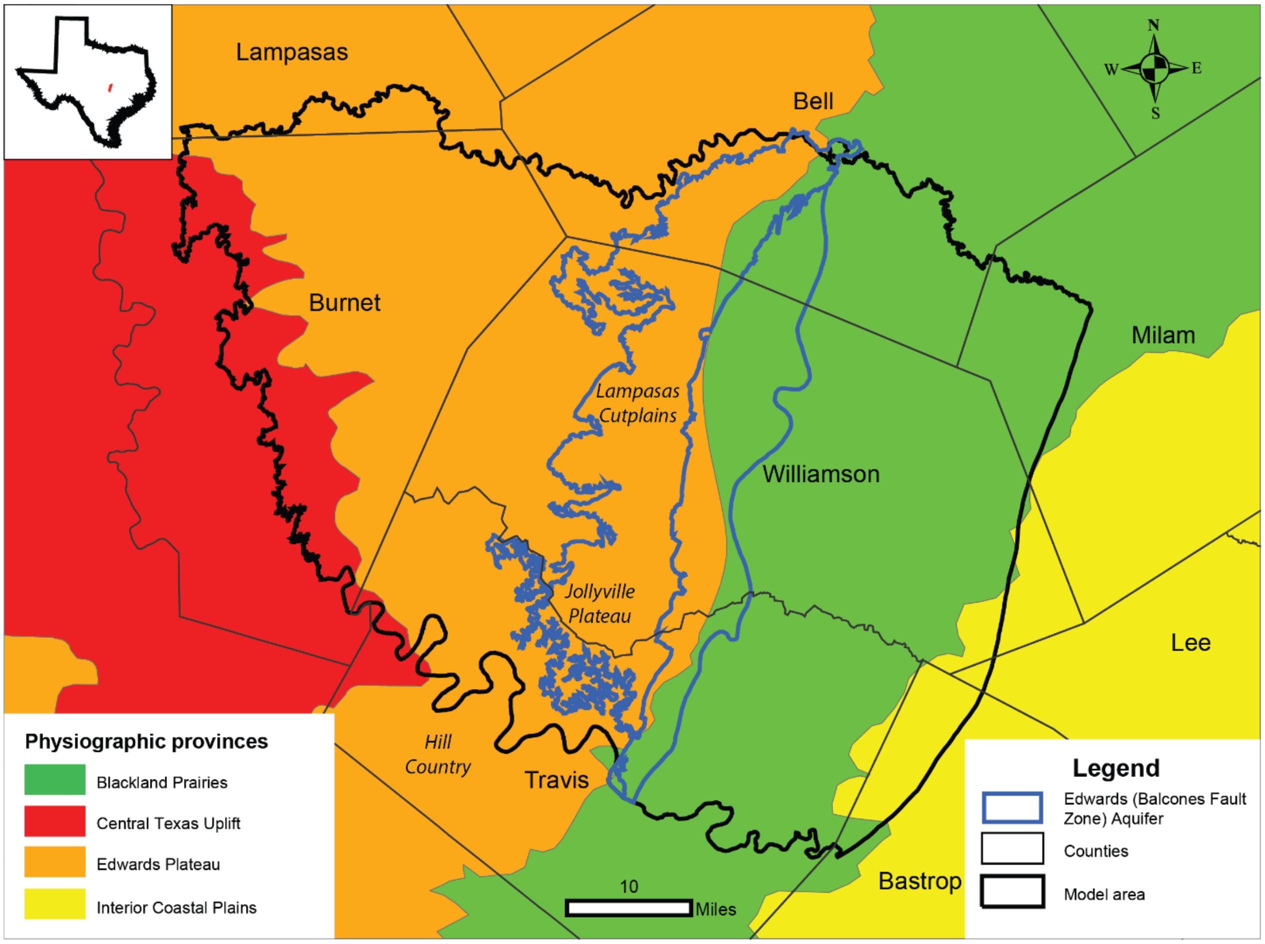


Figure 2.1.1. Physiographic provinces in the study area (Wermund, 1996).

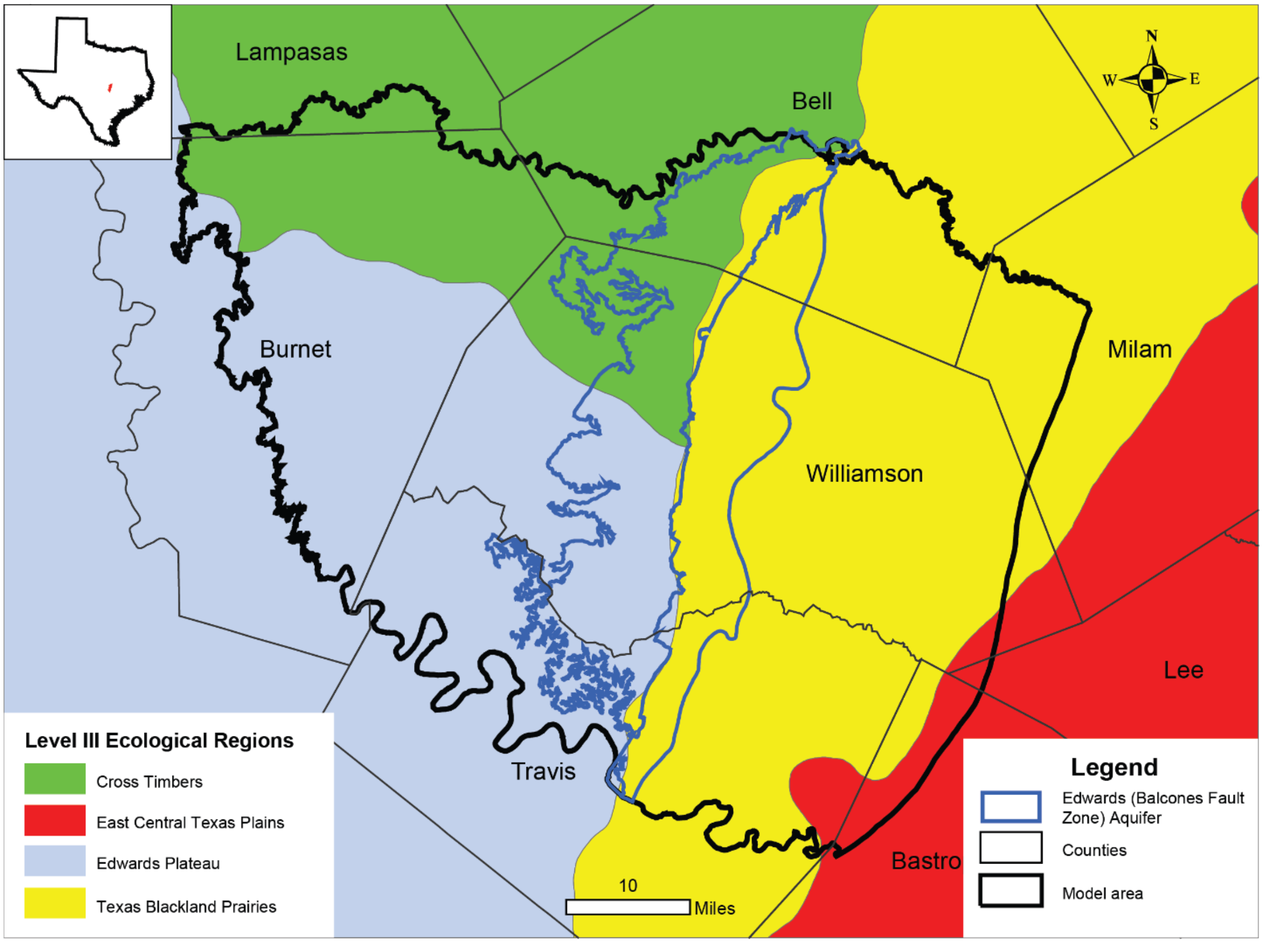


Figure 2.1.2. Level III ecological regions in the study area (United States Environmental Protection Agency, 2013).

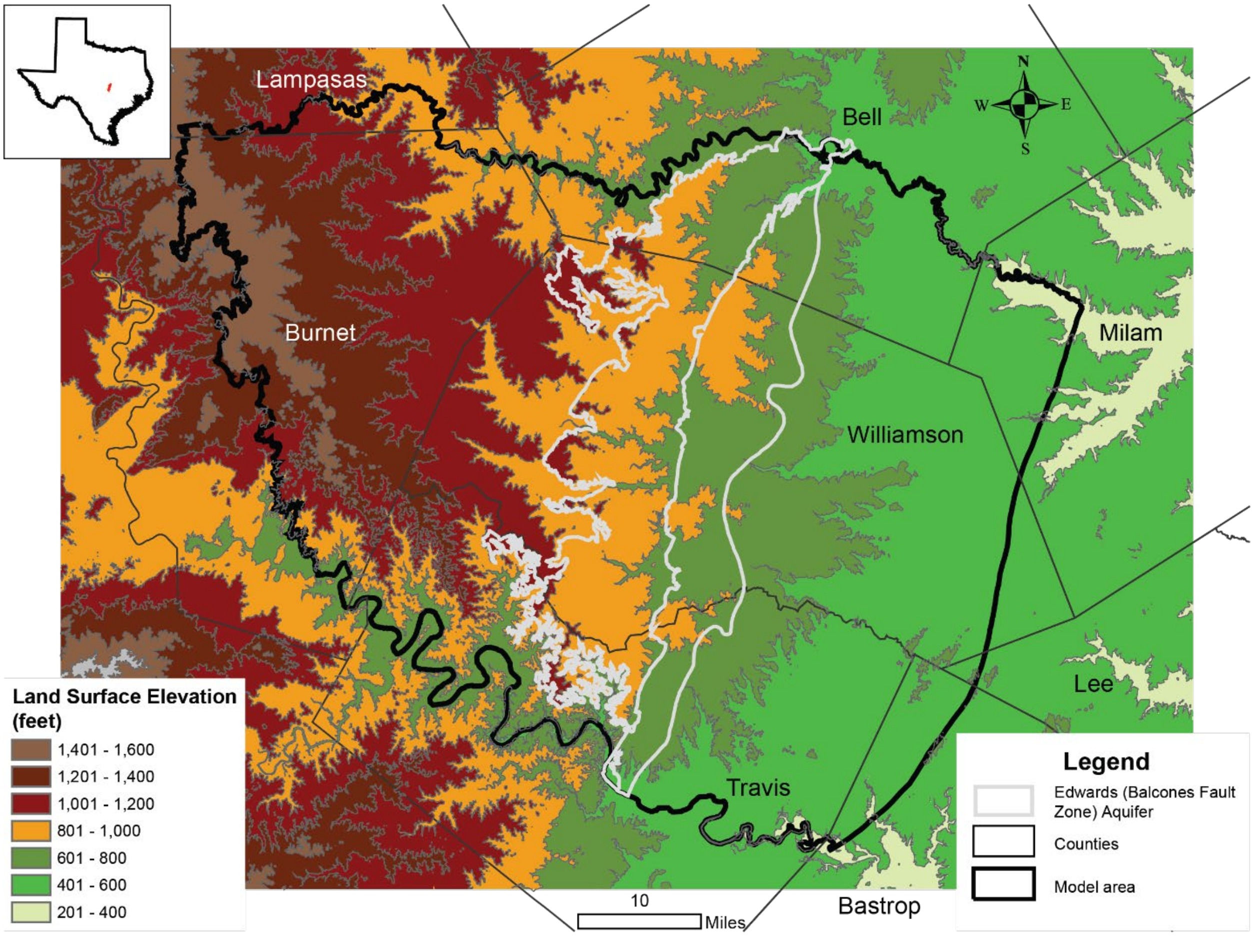


Figure 2.1.3. **Topographic map of the study area showing land surface elevation in feet above mean sea level. Based on data from Gesch and others (2002).**

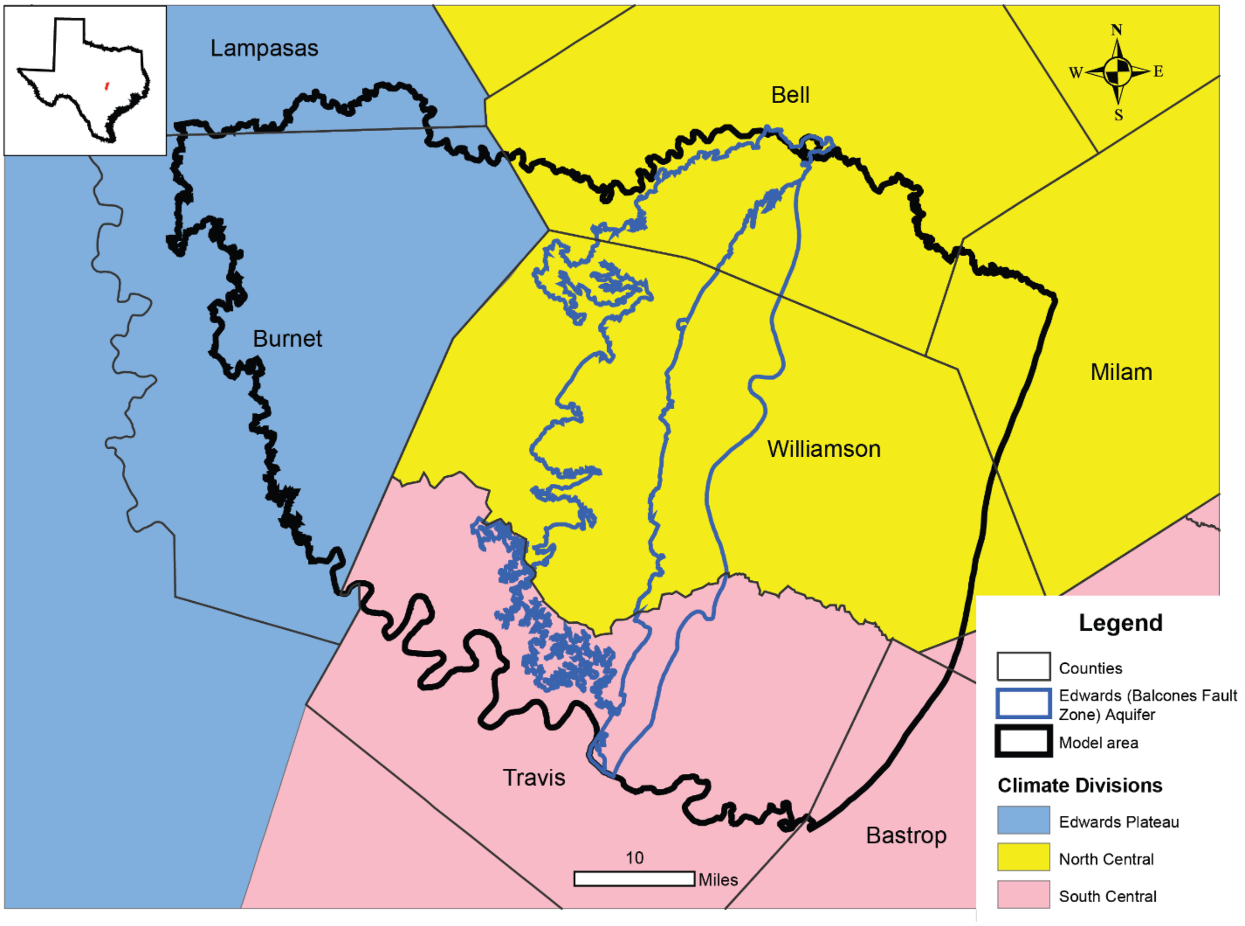


Figure 2.1.4. Climate divisions in the study area (modified from NCDC, 2011).

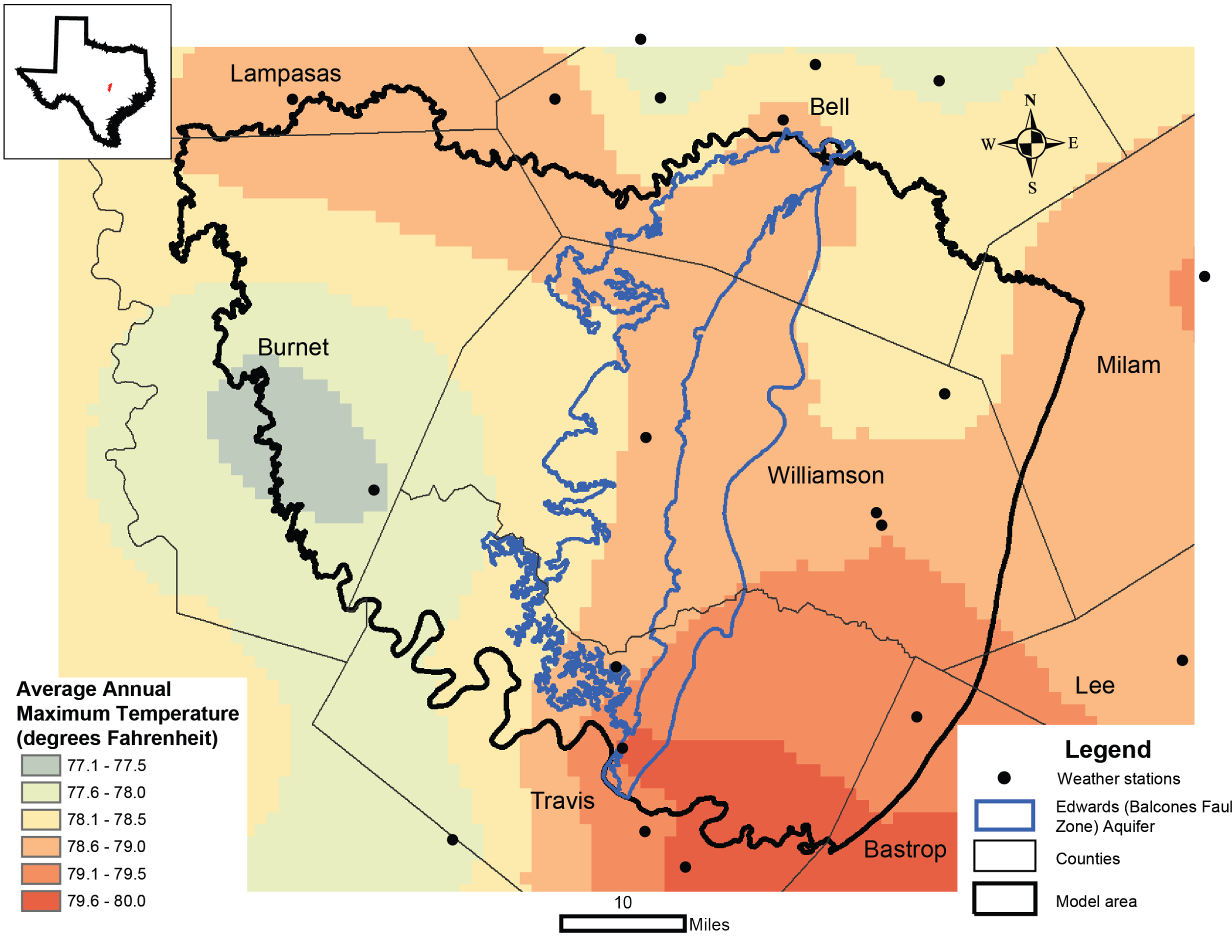


Figure 2.1.5. **Average annual air temperature in degrees Fahrenheit in the study area. Based on 1981 to 2010 data (NCDC, 2020).**

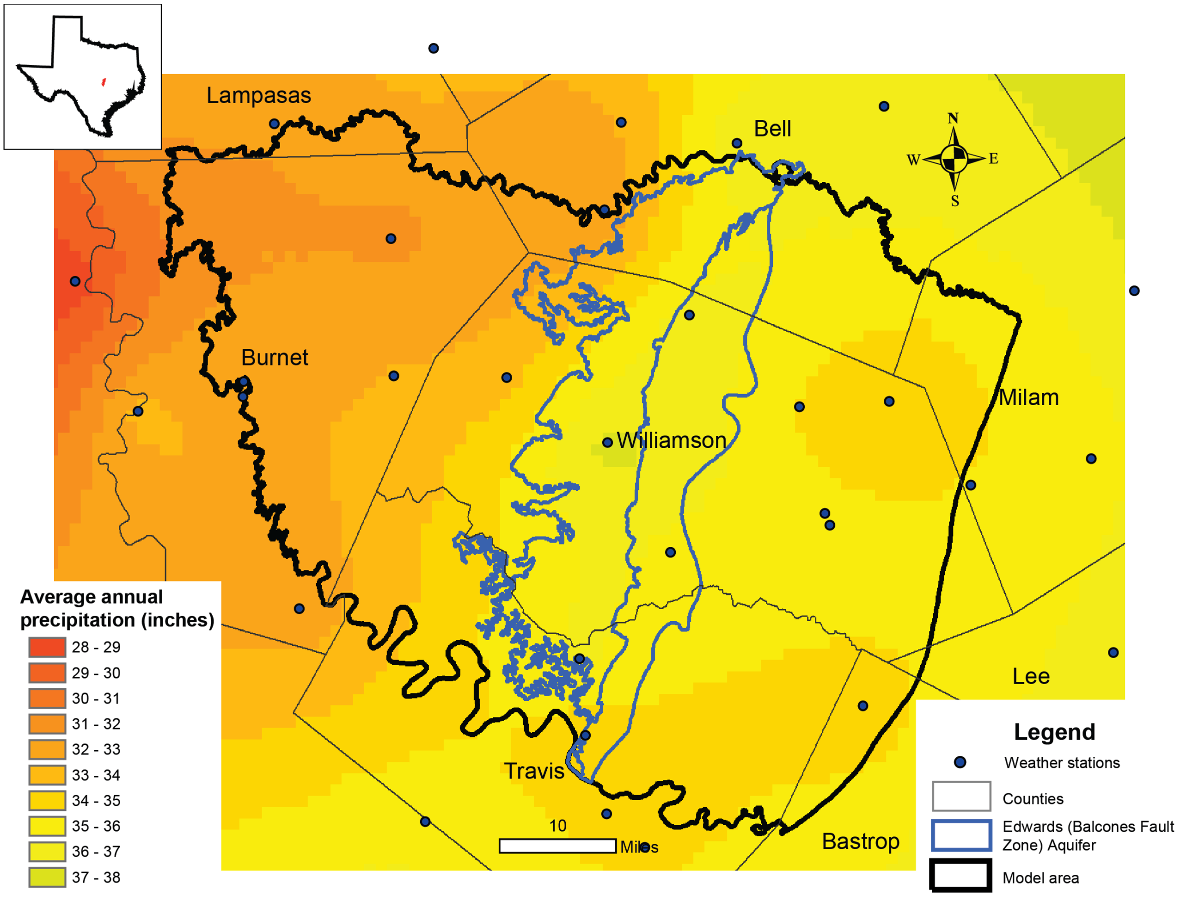


Figure 2.1.6. Average annual precipitation in inches per year in the study area for the time period 1981 through 2010 (NCDC, 2020).

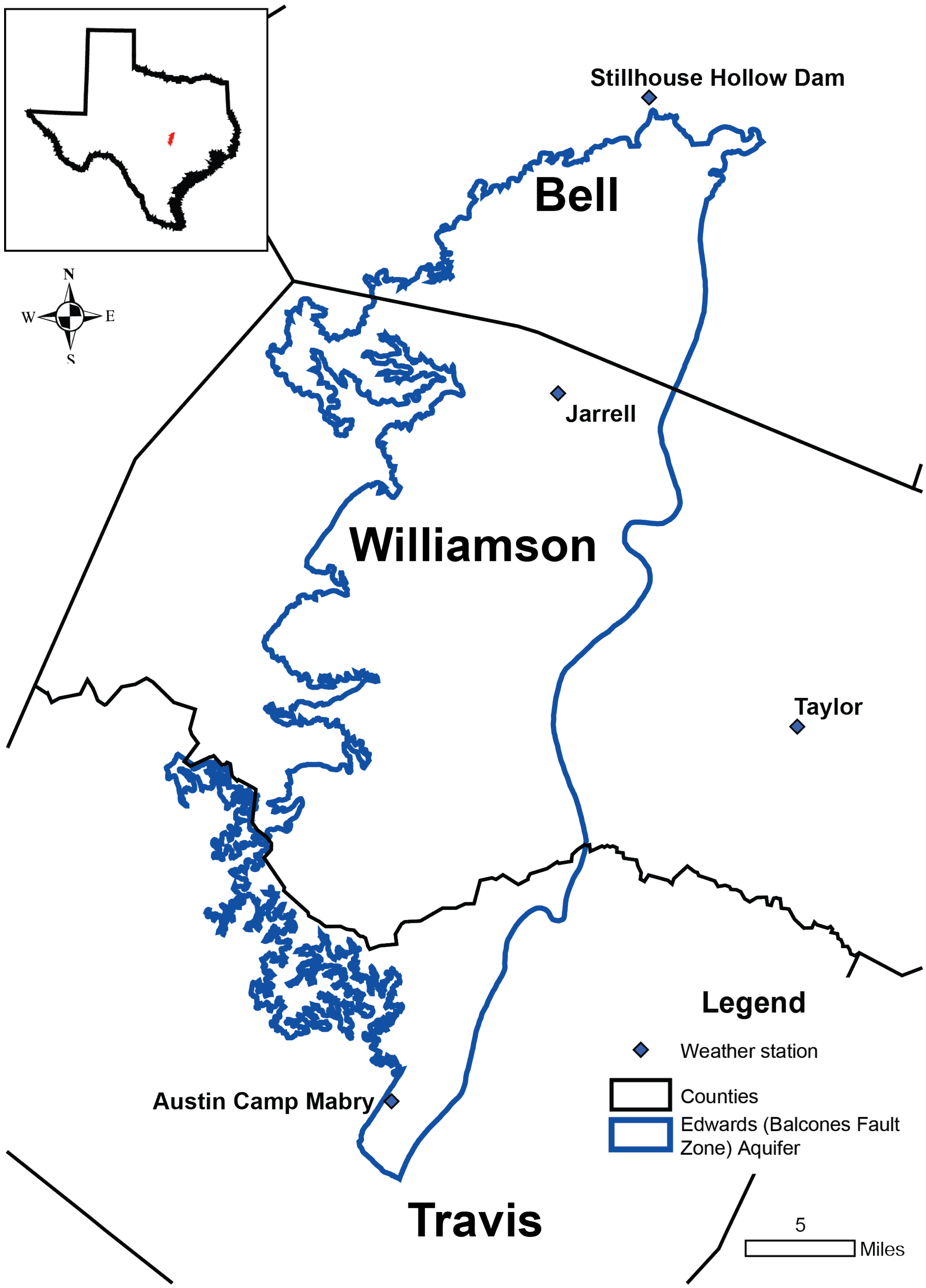


Figure 2.1.7. Location of precipitation gages in the northern segment of the Edwards (Balcones Fault Zone) Aquifer study area (National Climatic Data Center, 2017).

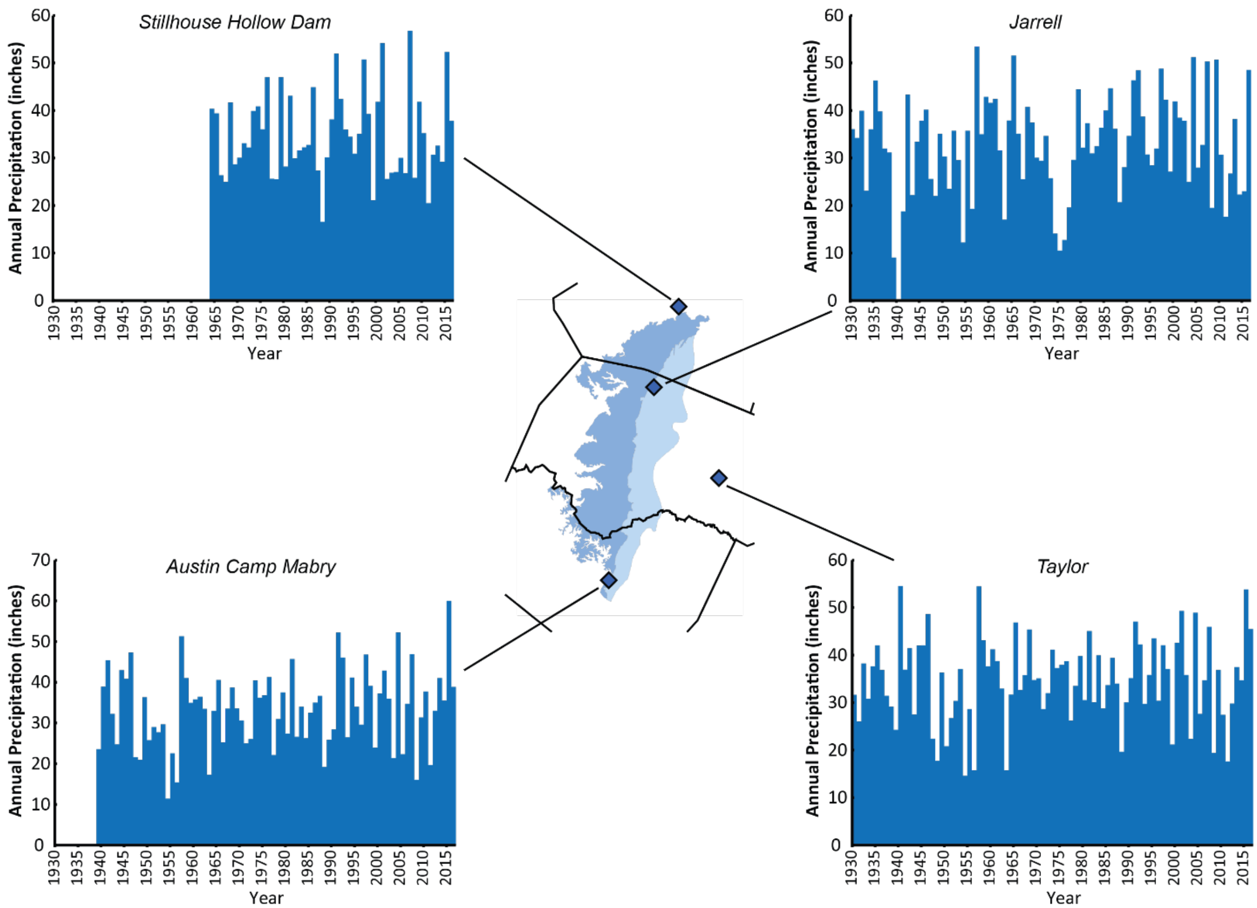


Figure 2.1.8. **Selected time series of annual precipitation in inches per year in the study area (National Climatic Data Center, 2017). Zero values indicate missing data.**

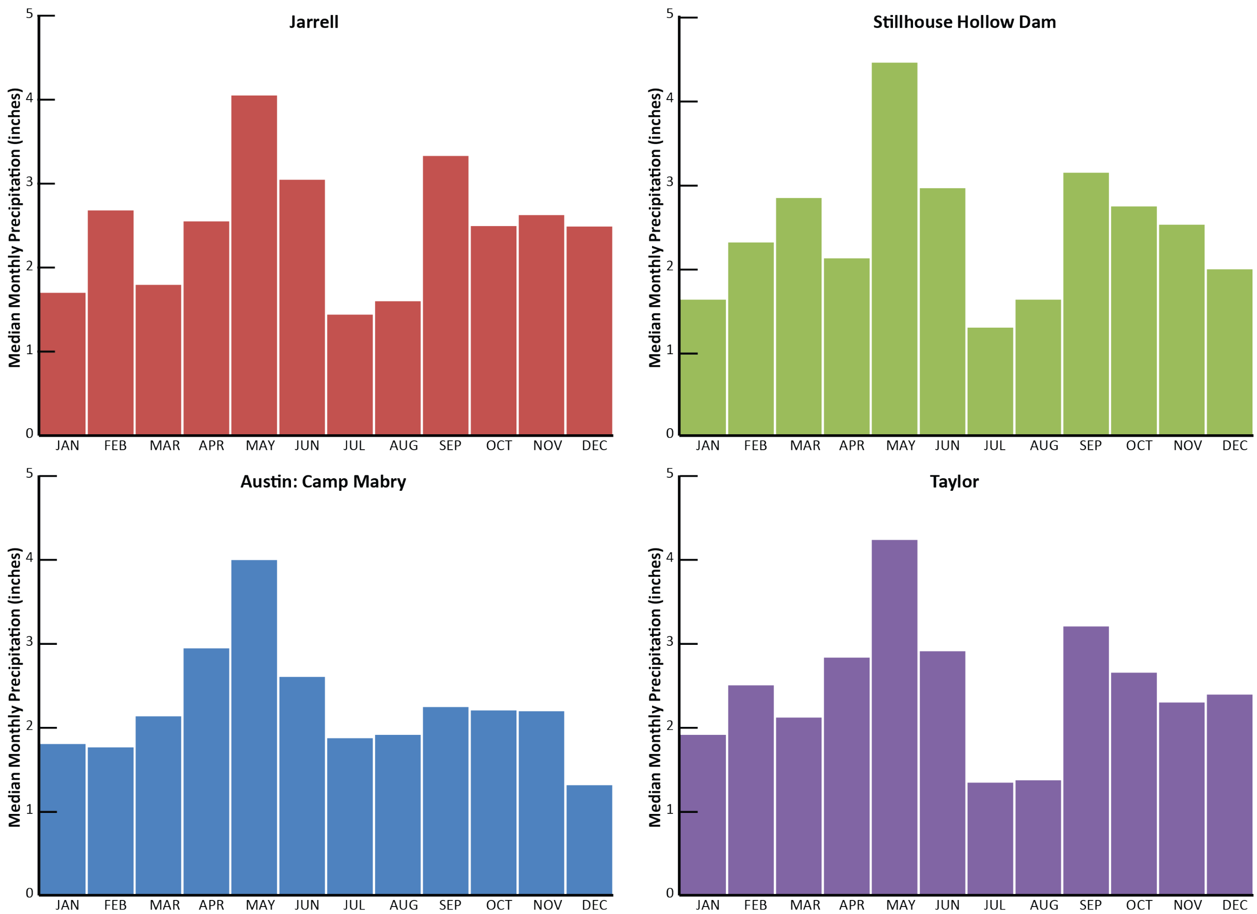


Figure 2.1.9. Selected time series of median monthly precipitation in inches per month in the study area for the time period 1986 through 2016 (National Climatic Data Center, 2017).

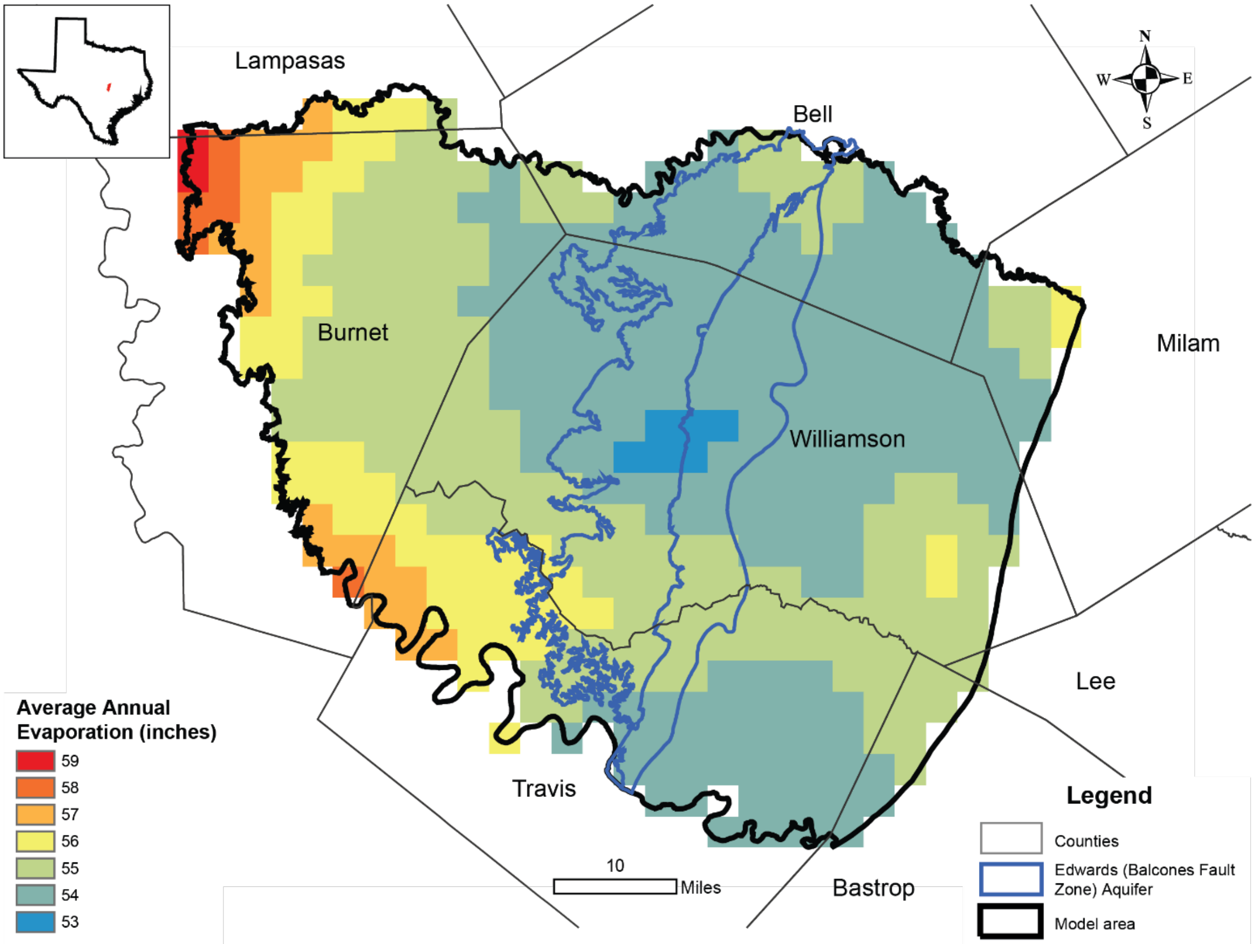


Figure 2.1.10. **Average annual lake evaporation rate in inches per year in the study area for the time period 1941 through 2000 (Narasimhan and others, 2005).**

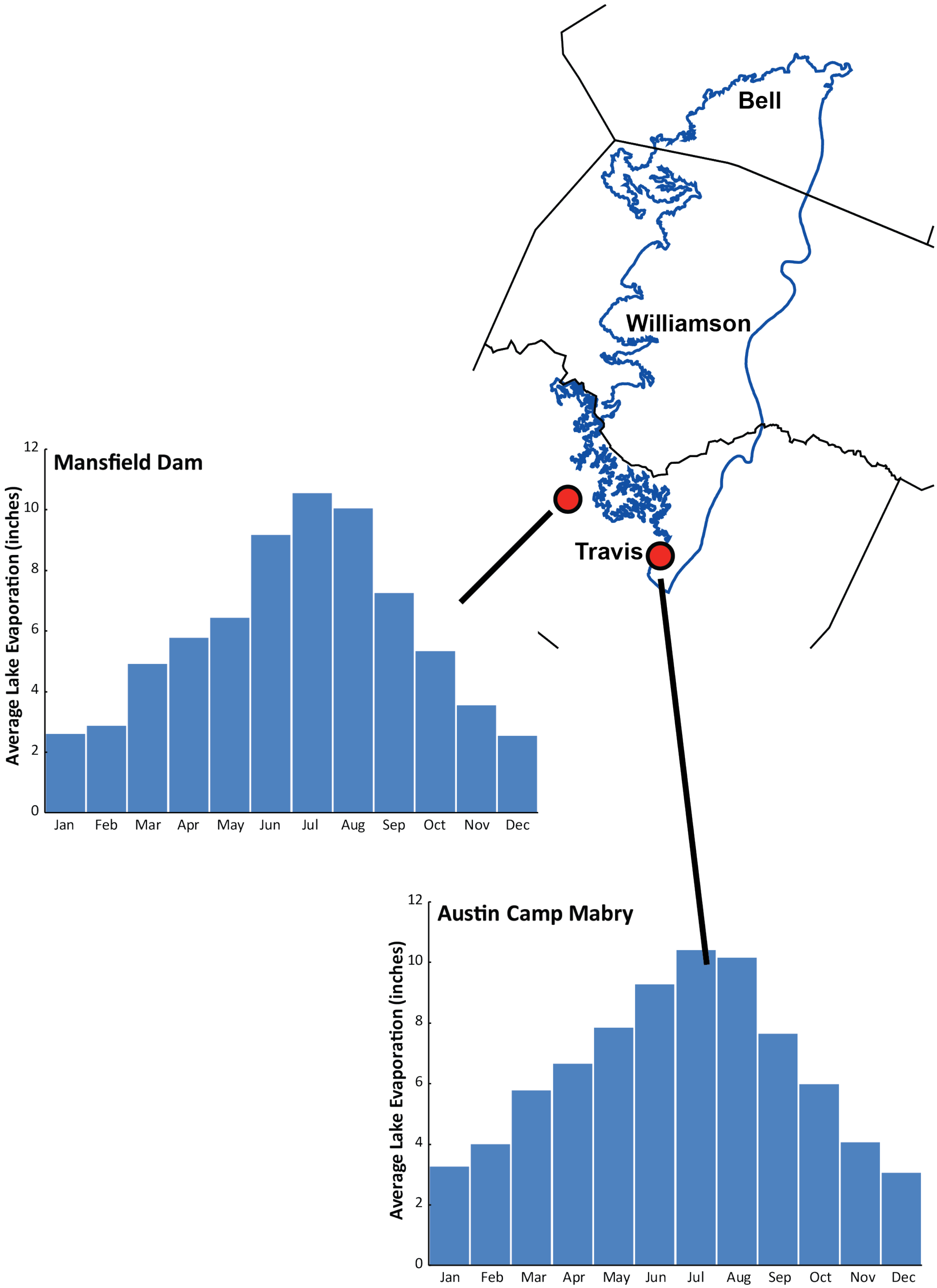


Figure 2.1.11. Average monthly lake surface evaporation in inches in selected weather stations in the study area (Narasimhan and others, 2005).

2.2 Geology

This section provides a brief discussion of the geology of the study area. The discussion is divided into the structural setting, surface geology, and stratigraphy of the northern segment of the Edwards (Balcones Fault Zone) and Trinity aquifers, including a description of geologic structural cross-sections through the study area.

2.2.1 Structural Setting

In the study area, Cretaceous rock units overlie Paleozoic rock units, forming an angular unconformity (Brune and Duffin, 1983), where eastward-dipping Cretaceous rock was deposited on an erosional surface over steeply westward-dipping Paleozoic rock. The Cretaceous rocks that make up the Trinity and Edwards (Balcones Fault Zone) aquifers dip toward the southeast with a slope of 10 to 300 feet per mile. Generally, the dip angle increases with depth (Duffin and Musick, 1991). This dip angle excludes the effects of faulting.

The aquifers in the study area are the Edwards (Balcones Fault Zone) Aquifer that extends from Bell County in the north, south and west to central Kinney County, and the southernmost extent of the northern Trinity Aquifer (Figure 2.2.1). The occurrence of the Edwards (Balcones Fault Zone) Aquifer coincides approximately with the normally faulted Balcones Fault Zone where it cuts through Cretaceous age rocks (Figure 2.2.2). Normal faults occur where tensional stress pulls rocks apart. This results in two blocks, where, in this case, the block east of the fault slides down relative to the western block. The faulting and associated fracturing influence groundwater movement in the limestone rocks, thus forming the aquifer (Kreitler and others, 1987; Senger and others, 1990). The normal faulting of the Balcones Fault Zone also cuts through the Trinity Aquifer where it underlies the Edwards (Balcones Fault Zone) Aquifer.

Faults and fractures play a very important role in local and regional groundwater flow patterns within the study area. Karstification of the fractures within the Cretaceous carbonates that make up the aquifers in the study area has produced highly permeable pathways for groundwater flow. In the northern segment of the Edwards (Balcones Fault Zone) Aquifer, the faulting appears to be more intense in the south, becoming more diffuse to the north (Figure 2.2.3; Senger and others, 1990). Major faults are generally oriented north-south to northeast-southwest and dip or tilt towards the east, although some dip to the west. In the southern part of the study area, the Balcones Fault Zone is generally composed of one large fault—the Mount Bonnell Fault. The vertical displacement of the Mount Bonnell Fault is 715 feet, much larger than any of the adjacent faults that mostly have displacements less than 50 feet (Trippet and Garner, 1976; Senger and others, 1990; Figure 2.2.3). To the north, maximum fault displacement decreases to about 150 feet (Senger and others, 1990). The Trinity Aquifer overlies and is likely unaffected by the

Paleozoic faults that are apparent immediately outside of the study area in western Burnet County (Figure 2.2.3).

The unconfined portion of the northern segment of the Edwards (Balcones Fault Zone) Aquifer is wider in Williamson County than in Travis County, near the Colorado River (Figure 2.0.2). The narrowing of the aquifer outcrop in the south occurs due to the combined effects of intense faulting and erosion by the Colorado River and its tributaries (Figures 2.1.3 and 2.2.3; Baker and others, 1986). Fracturing also enhances the porosity of the limestone and plays a role in the development of karst features, such as caves, springs, and conduits. Normal faulting, common in the southern portion of the study area, generally decreases toward the north (Baker and others, 1986). It is associated with the Balcones Fault Zone, a zone of faults about 6 to 8 miles wide that extends roughly from Del Rio in south-central Texas to Dallas (Figure 2.2.2). This zone of normal faulting is characterized by major faults that strike north-south to northeast-southwest and dip 40 to 80 degrees to the east, with a net displacement of 600 to 1,000 feet (Brune and Duffin, 1983; Collins, 1987). Cross-faults, sub-perpendicular to major faults, are also common (Collins, 1987). In the Balcones Fault Zone, minor faults and joints occur mainly adjacent to the major faults and flexures. These minor faults, characterized by displacement of less than 6 feet, tend to form fracture zones up to 1 mile wide. Fracture densities in these zones lie in the range of 6 to 120 joints per 100 feet. Joints are fracture with no associated displacement. Many of the minor faults are filled partly by calcite, while, the joints that occur in this area do not have mineral fillings. Abutting relationships between minor faults and joints suggest that the minor faults formed before the joints (Collins, 1987). Fracture apertures vary with stratigraphic units in the Edwards (Balcones Fault Zone) Aquifer. Fracture apertures are generally less than 0.04 inches in Comanche Peak and Georgetown Formations and are up to several inches wide in the Edwards Limestone (Collins, 1987). These faults influence groundwater flow in two ways: (1) faults provide preferential flow paths, and (2) fault displacement in some cases produces barriers to groundwater flow (Brune and Duffin, 1983). Preferential groundwater flow along faults and joints in this aquifer often results in formation of solution cavities such as caves (Brune and Duffin, 1983). Inner Space Caverns in Georgetown, Texas is an example of a cave formed in the Edwards Limestone.

Evaluation of fracture and lineament orientations in the northern part of the study area at different scales by Dahl (1990) shows different orientations of fractures varying in size from mapped major faults to field-observed fractures. The orientations of these fractures play a role in determining preferential flow directions in the aquifer. Preferential flow directions are generally parallel to fracture orientation. Dahl (1990) divided fractures into four groups: major mapped faults, high-altitude Landsat lineaments, field fractures, and topographic map lineaments. Major faults generally trend northeast-southwest. High-altitude Landsat lineaments are sparsely distributed and, together with the field fractures, are preferentially oriented northwest-southeast and northeast-southwest. The topographic map lineaments are generally randomly oriented, with only a slight northeast-southwest trend (Dahl, 1990). Adjacent to major faults, fractures are oriented generally northeast-southwest, approximately parallel to major faults of the Balcones Fault Zone. Away from major faults, fractures are oriented generally northwest-southeast. This trend of northwest-southeast- and northeast-southwest-oriented fractures is also observed in the more intensely faulted parts of the aquifer farther south (Kreitler and others, 1987).

2.2.2 Surface Geology

Stratigraphic units underlying the study area range in age from the Paleozoic Ellenburger Group to recent alluvium (Brune and Duffin, 1983). Stratigraphic units in the study area are composed mainly of limestone and shale or clay. The oldest rock units, the Ordovician Ellenburger Group and the Pennsylvanian Bend and Strawn groups, occur at great depth and are not known to yield usable water in the study area (Brune and Duffin, 1983).

Figure 2.2.4 is a simplified geologic map of the study area. Over most of the study area, the predominant surficial deposits are Cretaceous-age rocks of the Trinity, Fredericksburg, and Washita groups, the Eagle Ford Formation, Austin Chalk, and Navarro Group. The Cretaceous stratigraphic units all dip towards the east and are eventually overlain by younger units (Figure 2.2.5). These Cretaceous units are approximately 2,000 feet thick (Trippet and Garner, 1976). Tertiary and Quaternary alluvium primarily occurs along stream channels, especially east of the footprint of the northern segment of the Edwards (Balcones Fault Zone) Aquifer.

2.2.3 Stratigraphy

The northern segment of the Edwards (Balcones Fault Zone) Aquifer is composed of stratigraphic units within the Fredericksburg, and Washita Groups that overlie the Cretaceous Trinity Group that makes up the Trinity Aquifer (Figure 2.2.6). These units mainly consist of the Georgetown Formation, Edwards Limestone, and Comanche Peak Limestone. The Walnut Formation acts as a confining unit separating the Edwards (Balcones Fault Zone) and Trinity aquifers (see Section 4.1). The Walnut Formation is composed largely of four alternating limestone and marl members: Bull Creek Limestone, Bee Cave Marl, Cedar Park Limestone, and Keys Valley Marl members (Moore, 1964). The Cedar Park Limestone and Keys Valleys members are absent in the southernmost parts of the study area. The Trinity Group is divided into the Travis Peak, Glen Rose, and Paluxy Formations (Brune and Duffin, 1983). The Travis Peak Formation consists primarily of limestone, sand, and shale and is subdivided into Hosston, Sligo, Hammett Shale, Cow Creek Limestone, and Hensell Sand members. The Glen Rose Formation is predominantly composed of alternating layers of limestone and dolomite at the top and massive layers of limestone and dolomite at the base and is subdivided into upper and lower members. The Paluxy Formation is composed of fine quartz sand cemented with calcium carbonate.

Please note that the Paluxy Formation pinches out in northern Bell County and does not occur in the study area.

The Fredericksburg Group is divided into the Walnut Formation, Comanche Peak Limestone, and Edwards Limestone (Brune and Duffin, 1983). The Walnut and Comanche Peak Formations, which occur primarily in the subsurface in the northern part of the study area, are composed of fine-grained limestone and shale. The Edwards Limestone is composed of massive vuggy—filled with small cavities—limestone with fine-grained marl at the top of the formation. This marl is very thin in the study area and tends to become thicker toward the north.

The Washita Group is divided into the Georgetown Formation, Del Rio Clay, and Buda Limestone (Brune and Duffin, 1983). The Georgetown Formation thins southward and is composed of fine-grained nodular limestone that is interbedded with layers of marl. The Georgetown Formation is hydraulically connected to the Edwards Limestone throughout the study area. The Del Rio Clay is calcareous, pyritic clay that contains gypsum. It is about 65 feet thick in the study area and is usually poorly exposed below the Buda Limestone (Brune and Duffin, 1983; Senger and others, 1990). The Buda Limestone are composed of fine-grained limestone subdivided into lower, slightly glauconitic limestone and upper, hard, fossiliferous limestone members (Brune and Duffin, 1983; Senger and others, 1990).

The stratigraphic nomenclature of units that compose the Edwards (Balcones Fault Zone) Aquifer differs north and south of the Colorado River. South of the river, the "Edwards" is treated as a group composed of two formations, the Kainer and Person Formations (Rose, 1972). The Kainer Formation is equivalent to the Walnut Formation, Comanche Peak Limestone, and lower parts of the Edwards Limestone. Equivalents of the Person Formation are largely absent north of the Colorado River. North of the Colorado River, the uppermost parts of the Edwards Limestone are equivalent to the basal members of the Person Formation.

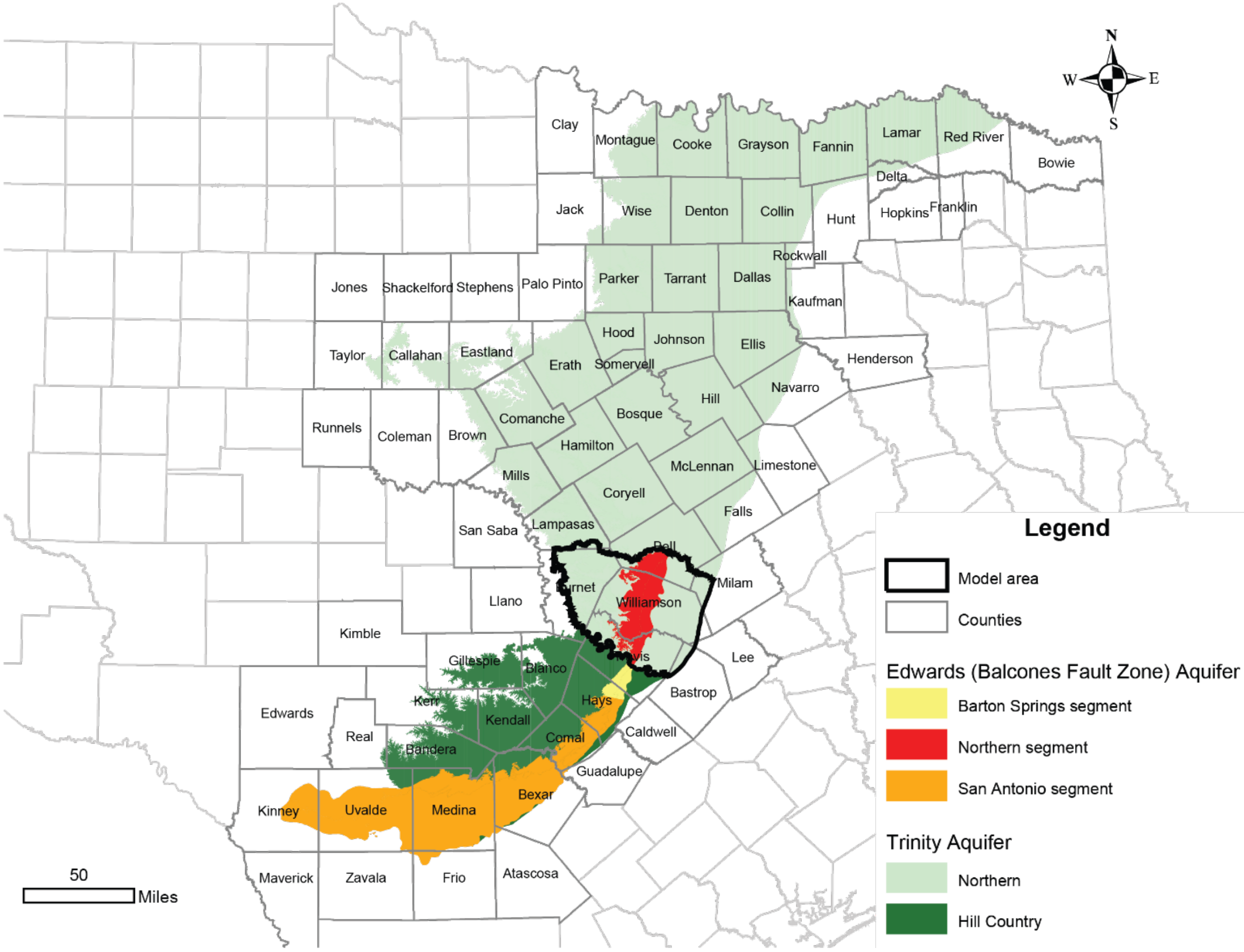


Figure 2.2.1. **The Edwards (Balcones Fault Zone) and Trinity aquifers. The study area includes the northern segment of the Edwards (Balcones Fault Zone) Aquifer and the southern extent of the northern part of the Trinity Aquifer.**

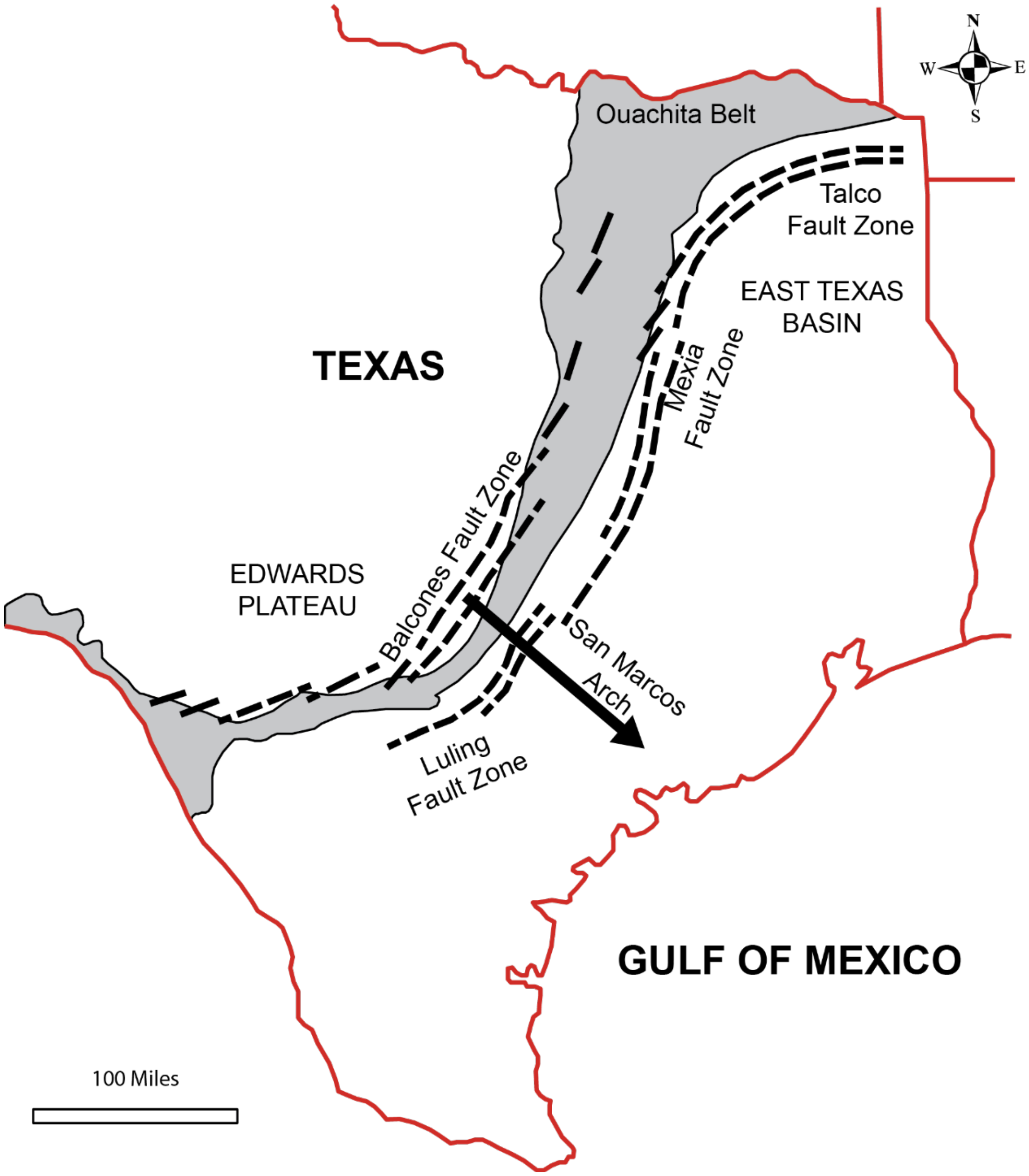


Figure 2.2.2. **Major structural features in the study area (from Senger and others, 1990).**

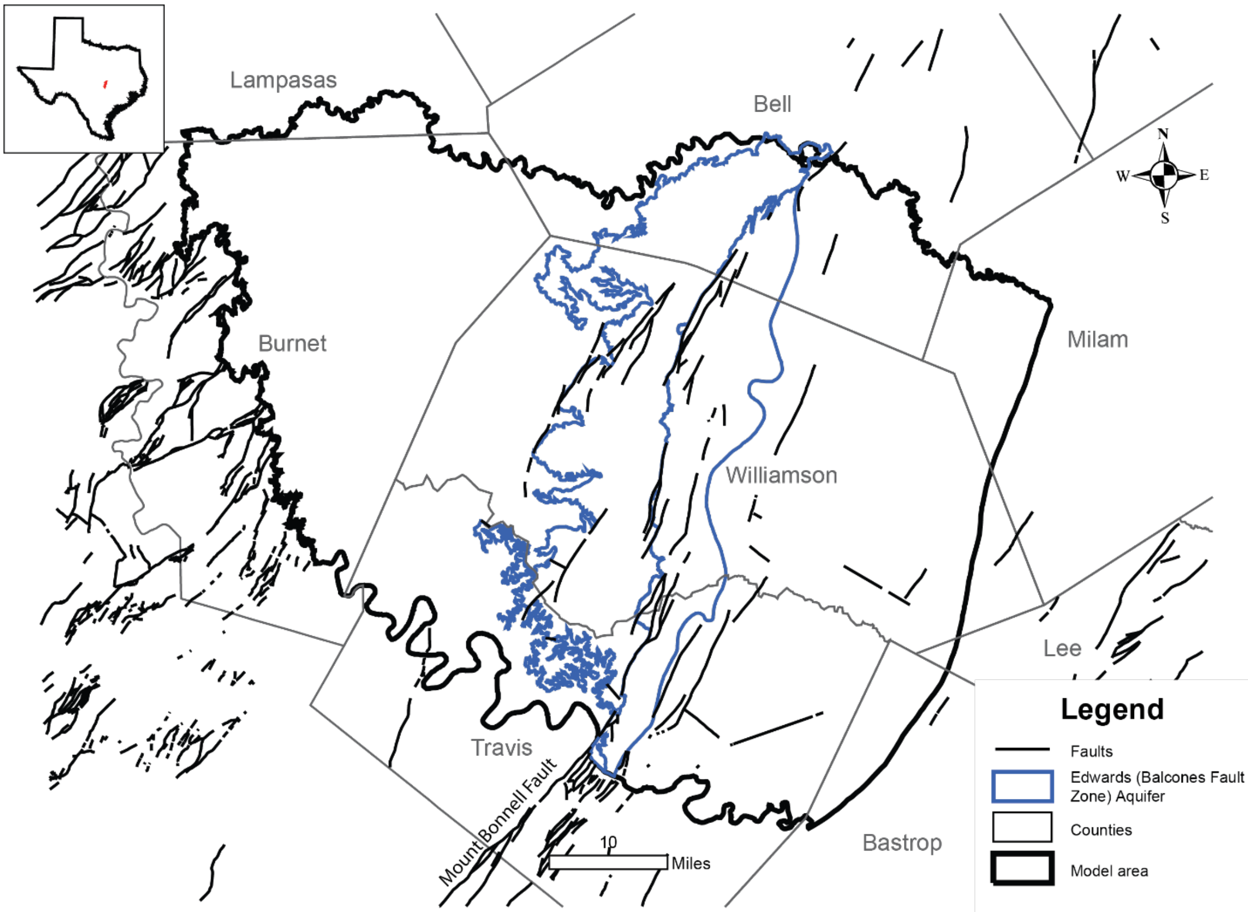


Figure 2.2.3. Faults that cut through or lie adjacent to the study area.

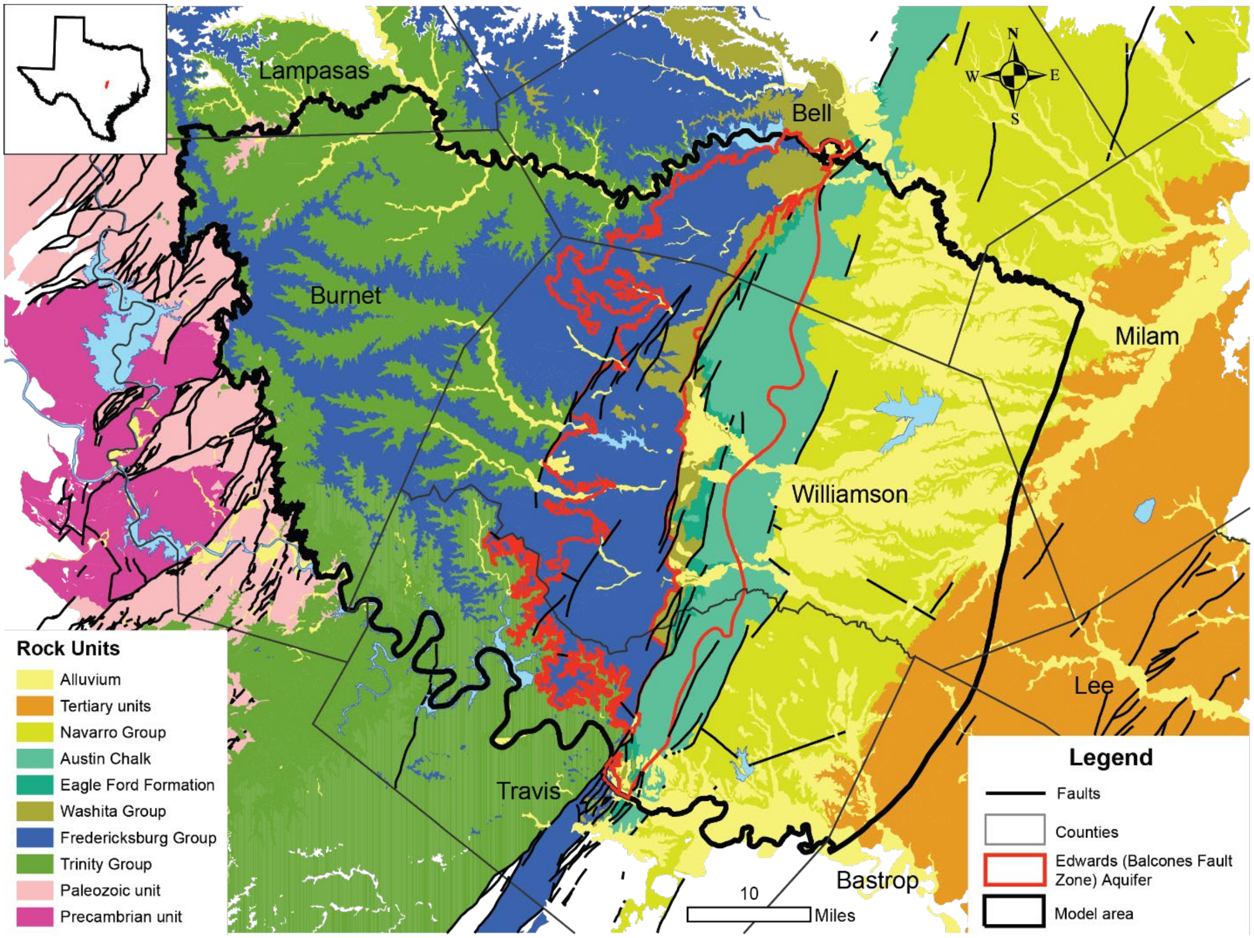


Figure 2.2.4. Generalized surface geology in the study area.

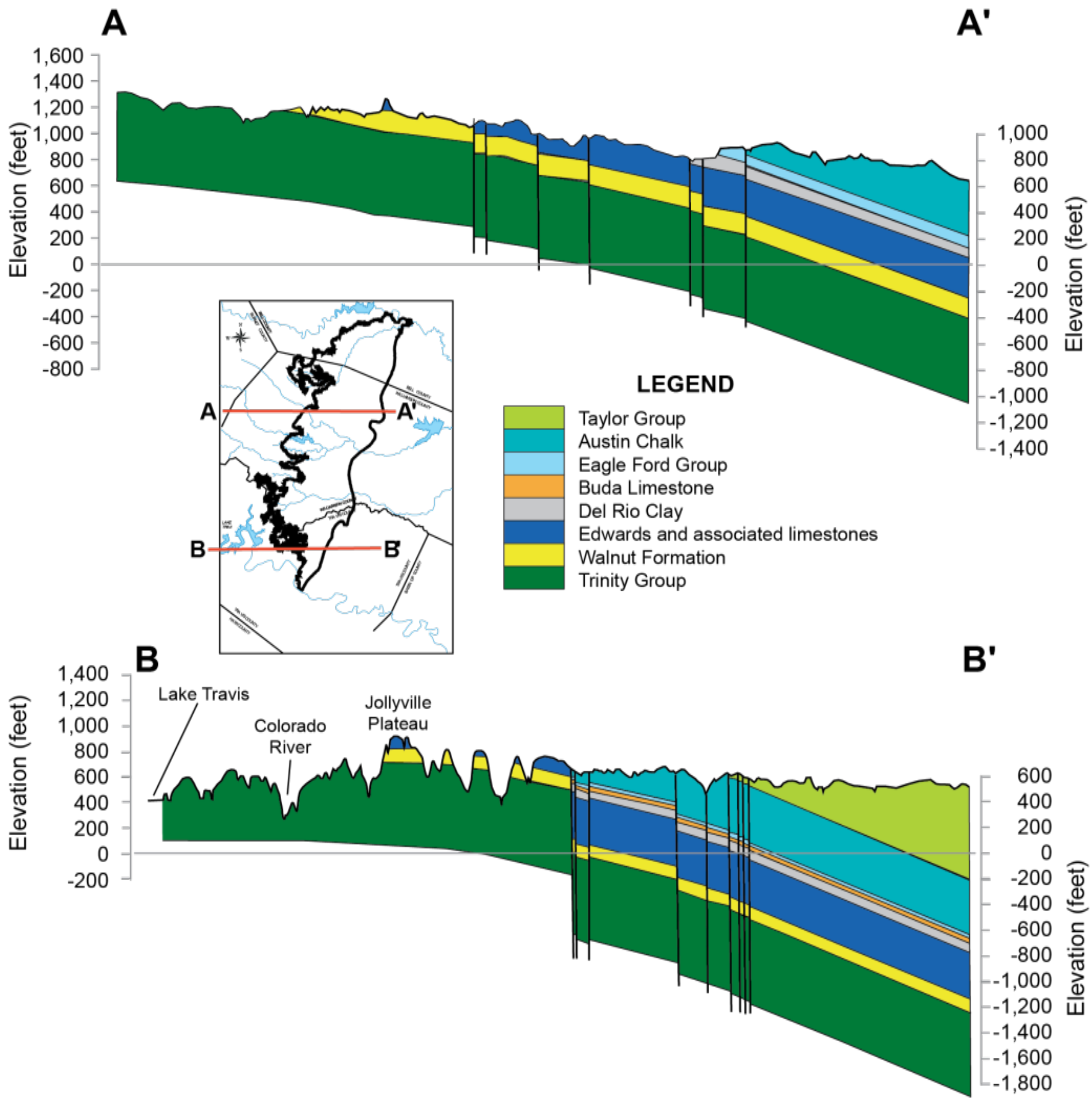


Figure 2.2.5. **Generalized cross-section through the northern segment of the Edwards (Balcones Fault Zone) and underlying Trinity aquifers (modified from Jones, 2003).**

Series	Group	Stratigraphic Unit	
Gulf	Navarro		
	Taylor		
	Austin		
Comanche	Eagle Ford		
	Washita	Buda Limestone	
		Del Rio Clay	
		Georgetown Formation	
	Fredericksburg	Edwards Limestone	
		Comanche Peak Limestone	
		Walnut Formation	
	Trinity	Paluxy Formation	
		Glen Rose	Upper Member
			Lower Member
		Travis Peak	Hensell Sand Member
			Cow Creek Limestone Member
			Hammett Shale Member
			Sligo Member
			Hosston Member

Figure 2.2.6. **Generalized stratigraphic column for the northern segment of the Edwards (Balcones Fault Zone) Aquifer and overlying and underlying formations.**

3.0 PREVIOUS WORK

Many geologic and hydrogeologic reports include the northern segment of the Edwards (Balcones Fault Zone) Aquifer. Studies of the stratigraphy and structure of the area include Tucker (1962), Rose (1972), Proctor and others (1974), Collins (1987), Land and Dorsey (1988), and Collins and others (2002). Woodruff and others (1985), and Yelderman and others (1987) are compendia that provide information on different aspects of the hydrogeology of the aquifers in the study area, such as water supply development, transmissivity distribution, and pump-test analysis. More detailed hydrogeologic studies include Klemt and others (1975), Brune and Duffin (1983), Kastning (1983), Senger and Kreitler (1984), Woodruff and others (1985), Baker and others (1986), Kreitler and others (1987), Dahl (1990), Flores (1990), Senger and others (1990), Duffin and Musick (1991), Ridgeway and Petrini (1999), Shah (2005), Yelderman (2013), Wong and Yelderman (2015; 2016), Eckhoff (2016); Keester and Konetchy (2017). Senger and others (1990) discussed both the groundwater geochemistry and hydrology of the northern segment.

Several regional and sub-regional models have simulated groundwater flow in the San Antonio and Barton Springs segments of the Edwards (Balcones Fault Zone) Aquifer (Campana, 1975; Knowles and Klemt, 1978; Mahin, 1978; Klemt and others, 1979; Mahin and Campana, 1983; Slade and others, 1985; Slade,1987; Maclay and Land, 1988; Thorkildsen and McElhaney, 1992; Kuniansky, 1993; Kuniansky and Holligan, 1994; Barrett, 1996; Uliana and Sharp, 1996; Scanlon and others, 2001; Lindgren and others, 2004; Brakefield and others, 2015; Fratesi and others, 2015). There have been four regional models simulating groundwater flow through all or parts of the northern Trinity Aquifer (Morton, 1992; Dutton and others, 1996; Harden and others, 2004; Kelley and others, 2014).

This report is part of work being conducted to update a groundwater availability model of the northern segment of the Edwards (Balcones Fault Zone) Aquifer (Jones, 2003; Figure 3.0.1). The 2003 groundwater flow model is a one-layer model run using MODFLOW-96 and assuming no interaction with the underlying Trinity Aquifer. The updated model will use up-to-date versions of MODFLOW, include interaction with the underlying Trinity Aquifer, and extend the calibration period to more recent times.

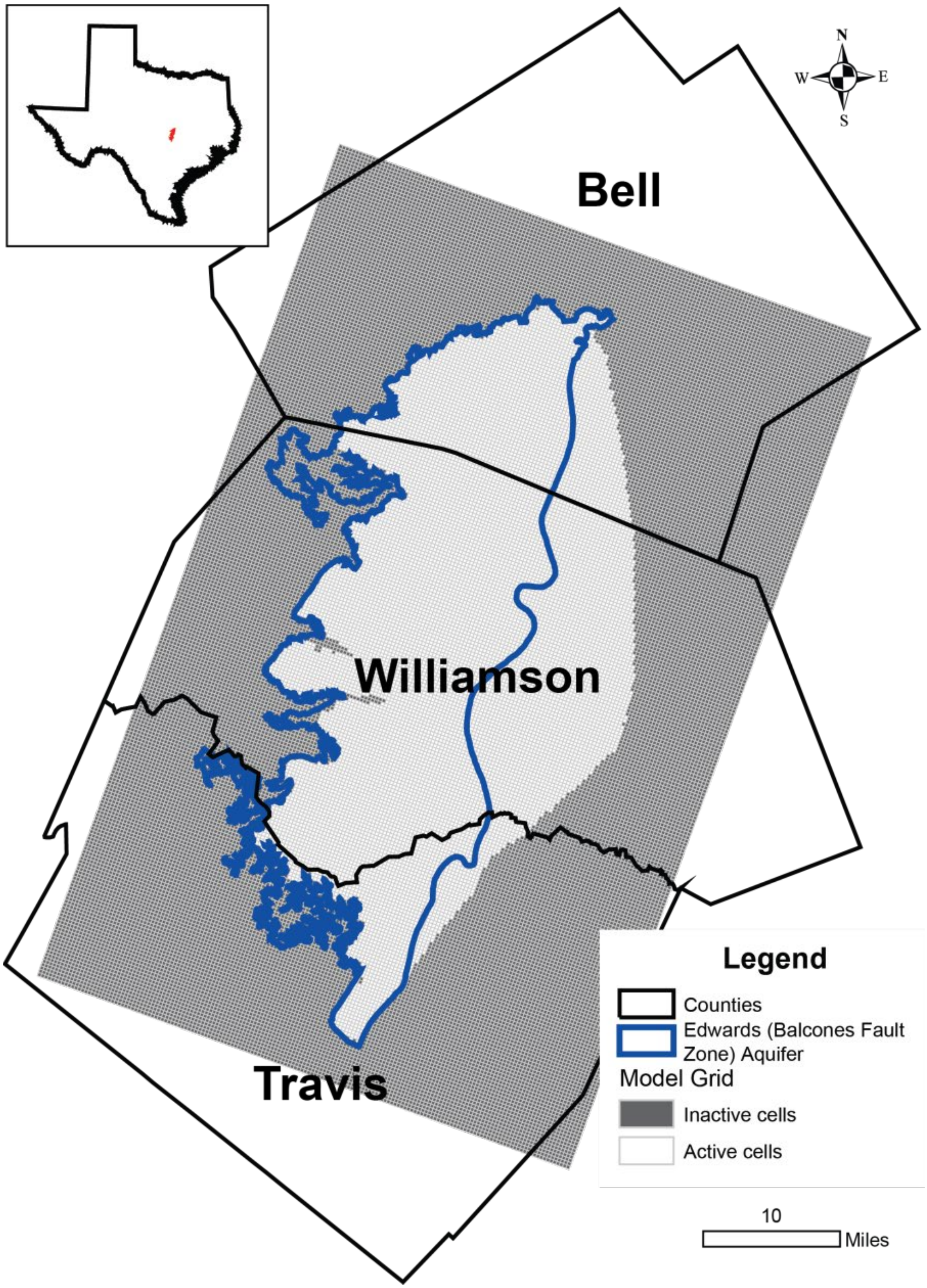


Figure 3.0.1. **Approximate extents of previous model grid for models used for simulating groundwater flow through the northern segment of the Edwards (Balcones Fault Zone) Aquifer.**

4.0 HYDROLOGIC SETTING

The hydrologic setting is a description of the factors that contribute to the groundwater hydrology of the northern segment of the Edwards (Balcones Fault Zone) Aquifer. These factors include the hydrostratigraphy, hydrogeologic framework, water levels and regional groundwater flow, recharge, surface-water bodies, hydraulic properties, discharge, and water quality.

4.1 Hydrostratigraphy and Hydrostratigraphic Framework

The northern segment of the Edwards (Balcones Fault Zone) Aquifer (Figure 2.0.2) generally consists of the Comanche Peak Limestone, Edwards Limestone, and Georgetown Formation (Figure 4.1.1). These stratigraphic units constitute the upper Fredericksburg and lower Washita Groups and are collectively referred to as the Edwards and associated limestones (Brune and Duffin, 1983). The aquifer overlies older Cretaceous rock of the Walnut and Glen Rose formations and is overlain by younger units that consist of the Del Rio Clay, Buda Limestone, Austin Chalk, Taylor Marl, and Navarro Group. The Walnut Formation and Del Rio Clay are recognized as confining units (Brune and Duffin, 1983; Baker and others, 1986). The base of the aquifer is defined as the base of rocks having greater water-yielding capabilities (Baker and others, 1986). In most areas, this excludes the Walnut Formation, although in other areas the Walnut Formation is composed of potentially permeable shell beds and may thus be included in the Edwards (Balcones Fault Zone) Aquifer.

4.1.1 Edwards (Balcones Fault Zone) Aquifer

The top of the northern segment of the Edwards (Balcones Fault Zone) Aquifer has elevations ranging from 400 feet below mean sea level to more than 1,000 feet above mean sea level (Figure 4.1.2). The subsurface top of the northern segment of the Edwards (Balcones Fault Zone) Aquifer is a combination of structural tops and erosional surfaces. Figure 4.1.3 shows the base elevations of the northern segment of the Edwards (Balcones Fault Zone) Aquifer that decrease towards the east, ranging from elevations of about 800 feet below mean sea level in the east to about 1,000 feet above mean sea level in the west. The northern segment of the Edwards (Balcones Fault Zone) Aquifer dips to the east at an average slope of 60 to 75 feet per mile (Figure 4.1.2 and 4.1.3). The slope varies generally because of faulting that produces a stair-step configuration downdip (Baker and others, 1986). The northern segment of the Edwards (Balcones Fault Zone) Aquifer thickness is highly variable, mostly ranging from 100 to 300 feet thick (Figure 4.1.4). In the study area, the northern segment of the Edwards (Balcones Fault Zone) Aquifer could be less than 100 feet thick due to erosion along some streams where the aquifer is exposed at land surface. Figures 4.1.2 and 4.1.3 indicate that the northern segment of the Edwards (Balcones Fault Zone) Aquifer dips to the east with highest elevations associated with outcrops along the western margin of the aquifer.

The Edwards (Balcones Fault Zone) Aquifer is composed of three distinct formations: the Comanche Peak Limestone; the Edwards Limestone; and the Georgetown Formation (Figure 4.1.1). The Comanche Peak Limestone is composed of nodular and fossiliferous marly limestone (Figure 4.1.1). This stratigraphic unit is characterized by considerable jointing (Brune and Duffin, 1983). The Edwards Limestone is composed of up to 200 feet of highly fractured and thickly bedded to massive limestone or dolomite, with minor shale, clay, and siliceous limestone (Senger and others, 1990). The Edwards Limestone is vuggy in places because of the occurrence of solution-collapse zones (Brune and Duffin, 1983). These zones, parallel to bedding planes, are the result of dissolution of gypsum beds that formerly occurred in this stratigraphic unit. They are cavernous and iron stained, and contain brecciated limestone, chert, crystalline calcite, and residual clay. These zones occur mainly 60 to 80 feet above the base of the Edwards Limestone (Brune and Duffin, 1983; Flores, 1990). These solution-collapse zones—as much as 20 feet thick—are the main water-bearing horizons in the aquifer, with well yields greater than 300 gallons per minute (Brune and Duffin, 1983; Flores, 1990). The Georgetown Formation is a massive nodular limestone that is often hydrologically connected to the underlying Edwards Limestone (Brune and Duffin, 1983).

In addition to solution-collapse zones, groundwater in the northern segment of the Edwards (Balcones Fault Zone) Aquifer flows through a network of steeply dipping faults and joints (Brune and Duffin, 1983). Field measurements indicate that effective porosity is greatest in the Comanche Peak Limestone and decreases in the overlying Edwards Limestone and Georgetown Formation (Dahl, 1990; Flores, 1990). This trend has been attributed to limestone in the Comanche Peak Limestone and Edwards Limestone being more brittle than that in the Georgetown Formation. Additionally, the lower units of the Edwards (Balcones Fault Zone) Aquifer display greater effects of karstification (Dahl, 1990; Flores, 1990). Fracture porosity of the northern segment of the Edwards (Balcones Fault Zone) Aquifer ranges from 0.4 to 2.5 percent away from major faults, to 1.5 to 4.25 percent adjacent to faults (Dahl, 1990). These porosity values are lower than porosities (4 to 42 percent) measured in the San Antonio segment of the Edwards (Balcones Fault Zone) Aquifer (Hovorka and others, 1996).

4.1.2 Walnut Formation Confining Unit

The Walnut Formation occurs at the base of the Fredericksburg Group separating the Edwards (Balcones Fault Zone) and Trinity aquifers (Figure 4.1.1). It is a confining unit that yields little to no water (Brune and Duffin, 1983). The Walnut Formation is composed of alternating beds of hard and soft marly limestone with occasional shale and shell beds (Brune and Duffin, 1983). In the study area, the top of the Walnut Formation is defined by land surface in the west where it crops out, or by the base of the stratigraphic units that make up the Edwards (Balcones Fault Zone) Aquifer in the east where it occurs in the subsurface (Figure 4.1.5). The base of the Walnut Formation coincides with the top of the underlying Trinity Aquifer—typically the Glen Rose Limestone (Figure 4.1.6). The Walnut Formation is generally less than 300 feet in subcrop and less than 100 feet in outcrop due to erosion (Figure 4.1.7).

4.1.3 Trinity Aquifer

Like the overlying Edwards (Balcones Fault Zone) Aquifer, the Trinity Aquifer stratigraphic units dip towards the east and southeast, cropping out west of the Edwards (Balcones Fault Zone) Aquifer outcrop (Figures 4.1.8 and 4.1.9). The Trinity Aquifer thickness increases down-dip from as little as 40 feet along stream channels in the outcrop to more than 2,000 feet down-dip (Figure 4.1.10). The Trinity Aquifer is subdivided into three hydrostratigraphic units, the Upper, Middle, and Lower Trinity hydrostratigraphic units (Figure 4.1.1).

In the study area, the members of the Travis Peak Formation make up the Lower Trinity hydrostratigraphic unit and most of the Middle Trinity hydrostratigraphic unit. The Lower Trinity hydrostratigraphic unit is composed of the Hosston and Sligo members, with a combined thickness range of up to 1,000 feet in southeastern Travis County (Brune and Duffin, 1983). The Hosston member is composed of poorly-sorted, basal, sandy conglomerate grading upward into a sand, siltstone, and shale mixture with some limestone beds. The Sligo member is composed of limestone and dolomite with some sand and shale. The Hosston and Sligo members thicken down-dip with the Sligo pinching out in western Travis County.

The Hammett Shale member of the Travis Peak Formation acts as a confining unit, separating the Lower and Middle Trinity hydrostratigraphic units. The Hammett shale is composed of about 60 feet of relatively uniformly thick shale with some dolomitic limestone (Brune and Duffin, 1983).

The Middle Trinity hydrostratigraphic unit is made up of the uppermost members of the Travis Peak Formation—the Cow Creek Limestone and Hensell Sand members—and the lower member of the Glen Rose Formation. In the study area, the thickness of the Middle Trinity hydrostratigraphic unit varies between 300 and 450 feet (Brune and Duffin, 1983). The Cow Creek Limestone member is made up of occasionally vuggy and fractured massive, dolomitic, fossiliferous limestone that includes some gypsum or anhydrite beds. The Hensell Sand member is made up of poorly-sorted, basal conglomerate grading upwards and downdip to sand and sandstone, then silt and sandy shale. In southeastern Travis County, the Hensell Sand member also grades into sandy limestone and dolomite. The lower member of the Glen Rose Formation consists of massive fossiliferous limestone and dolomite grading upward into thin beds of limestone, shale, marl, anhydrite and gypsum. Dissolution of the anhydrite and gypsum results in the development of dissolution cavities.

The top of the lower member is marked by the “Corbula bed”, a 1-foot thick accumulation of *Corbula martinae* clam fossils.

The Upper Trinity hydrostratigraphic unit is composed of the upper member of the Glen Rose Formation and the Paluxy Formation. The Upper Trinity hydrostratigraphic unit thickness in the subsurface increases down-dip ranging from about 200 feet to 600 feet. The upper member of the Glen Rose Formation is made up of layers of shale and marl alternating with layers of limestone and dolomite. Beds of gypsum and anhydrite also occur, but only in the subsurface. The occurrence of the Paluxy Formation, which is made up of fine-grained, compact, white quartz sand, is limited to small areas north of the study area. This formation is approximately 10 feet thick (Brune and Duffin, 1983).

Era	System	Age	Group	Stratigraphic Unit		Hydrologic Unit	Model Layer
Mesozoic	Cretaceous	Campanian	Navarro		Navarro and Taylor Group	Confining unit	
			Taylor				
		Coniacian	Austin		Austin Chalk		
		Turonian	Eagle Ford				
		Cenomanian	Washita		Buda Limestone		
					Del Rio Clay		
					Georgetown Formation	Edwards (Balcones Fault Zone) Aquifer	1
			Fredericksburg		Edwards Limestone		
		Albian			Comanche Peak Limestone		
					Walnut Formation	Confining unit	2
			Trinity		Paluxy Formation	Upper Trinity Aquifer	3
				Glen Rose	Upper Member		
		Aptian			Lower Member	Middle Trinity Aquifer	
				Travis Peak	Hensell Sand Member		
					Cow Cr. Limestone Member		
					Hammett Shale Member	Confining unit	
					Sligo Member	Lower Trinity Aquifer	
		Pre-Aptian			Hosston Member		

Figure 4.1.1. Hydrostratigraphic chart for down-dip portion of the northern segment of the Edwards (Balcones Fault Zone) Aquifer and overlying and underlying formations (modified from Brune and Duffin, 1983).

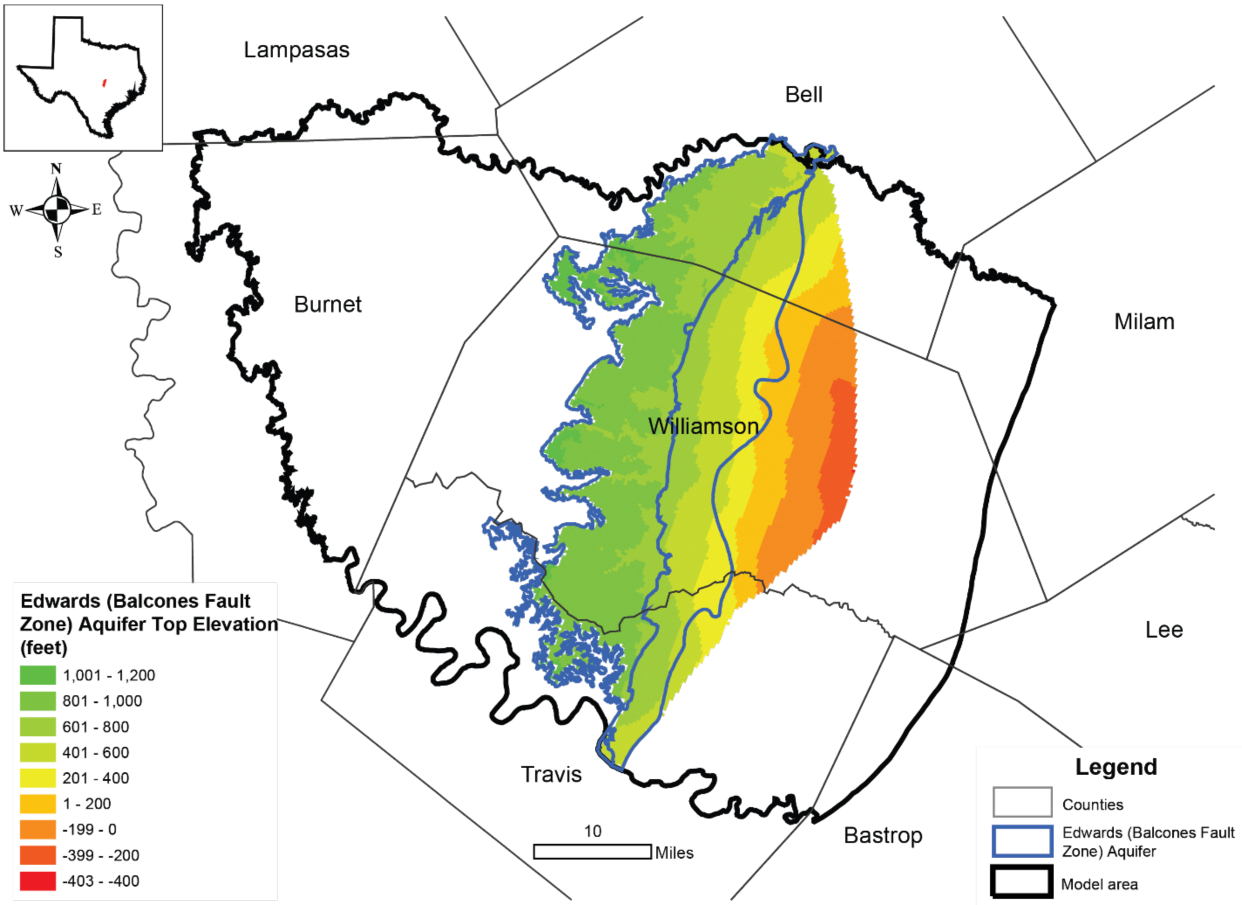


Figure 4.1.2. The elevation (in feet above mean sea level) of the top of the northern segment of the Edwards (Balcones Fault Zone) Aquifer.

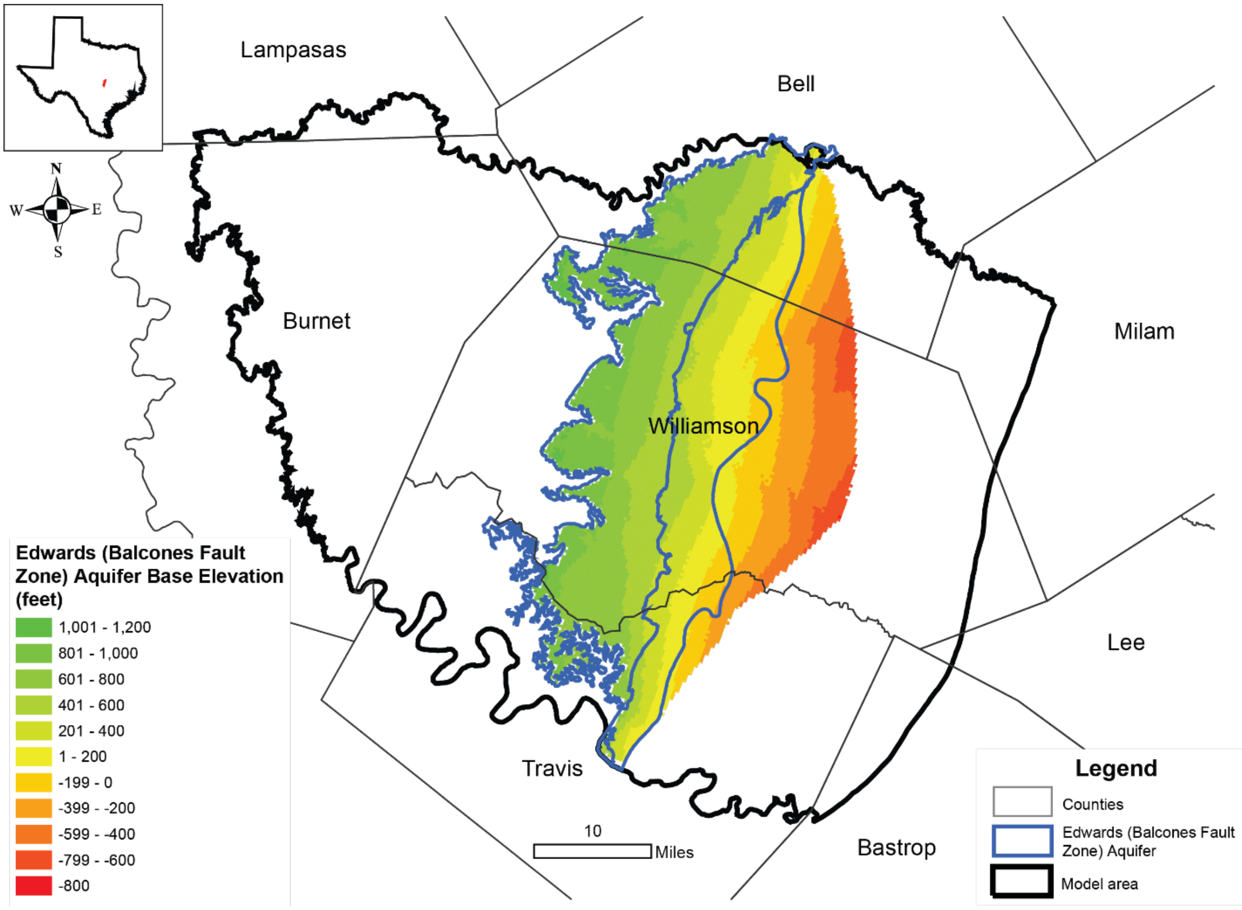


Figure 4.1.3. **The elevation (in feet above mean sea level) of the base of the northern segment of the Edwards (Balcones Fault Zone) Aquifer (based on data from Collins and others, 2002).**

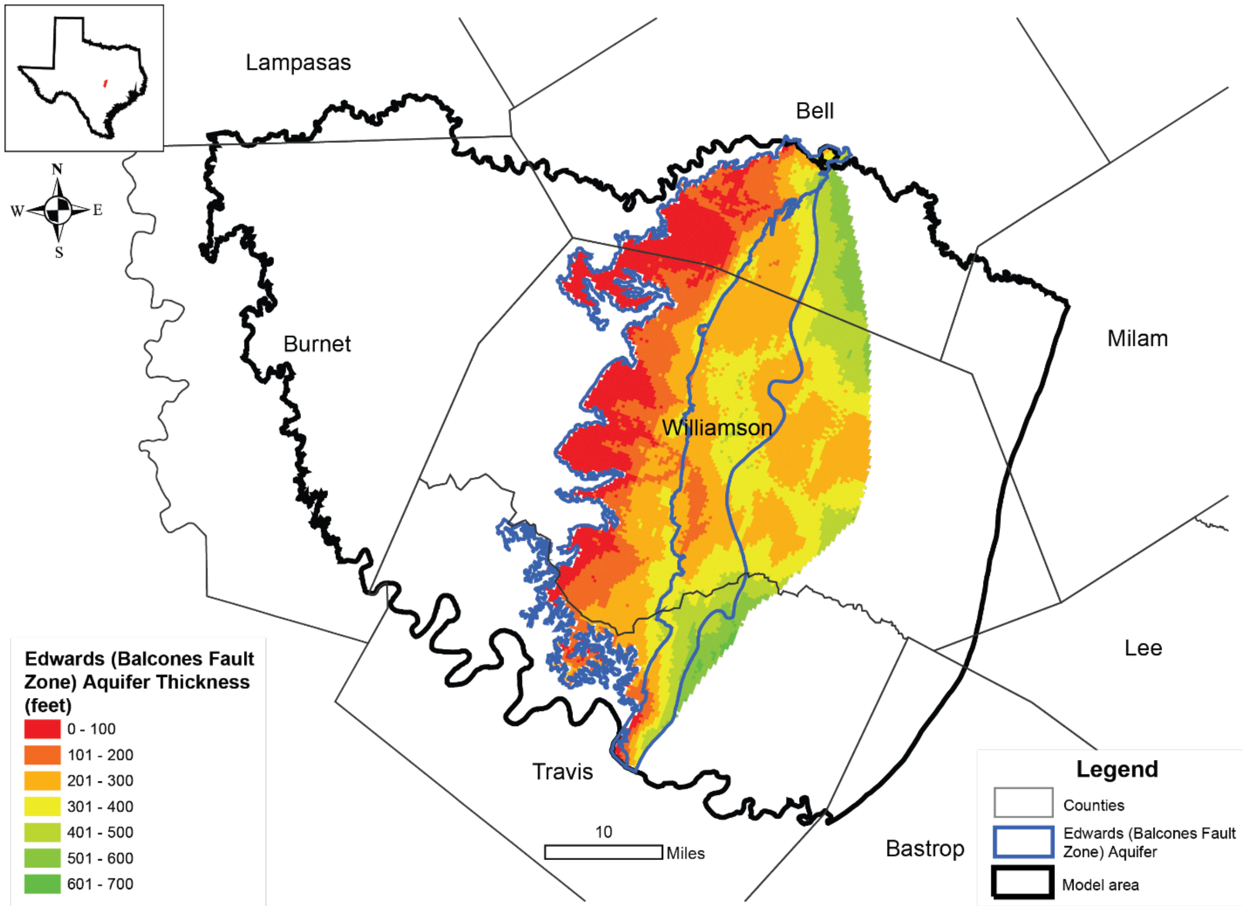


Figure 4.1.4. **Thickness (in feet) of the northern segment of the Edwards (Balcones Fault Zone) Aquifer.**

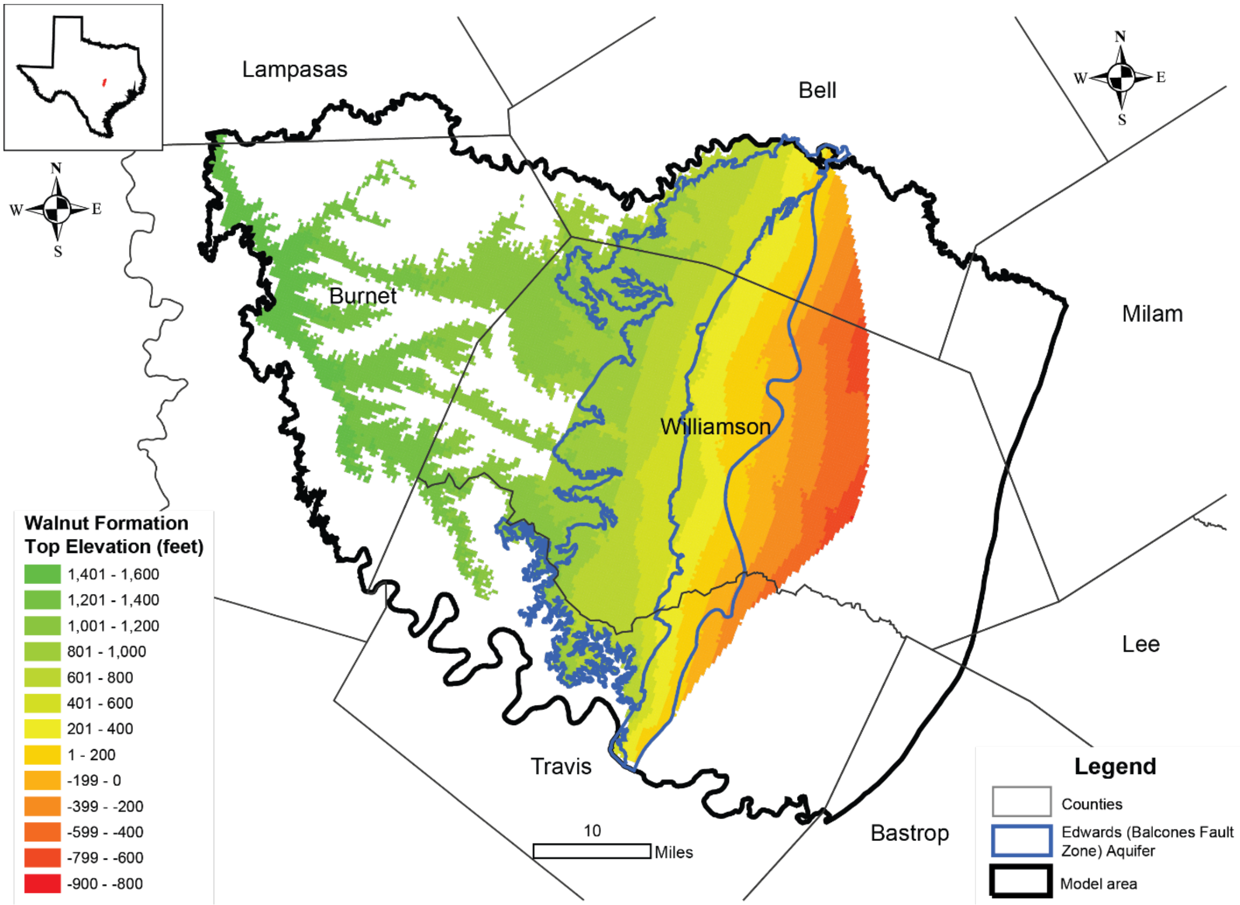


Figure 4.1.5. **The elevation (in feet above mean sea level) of the top of the Walnut Formation confining unit.**

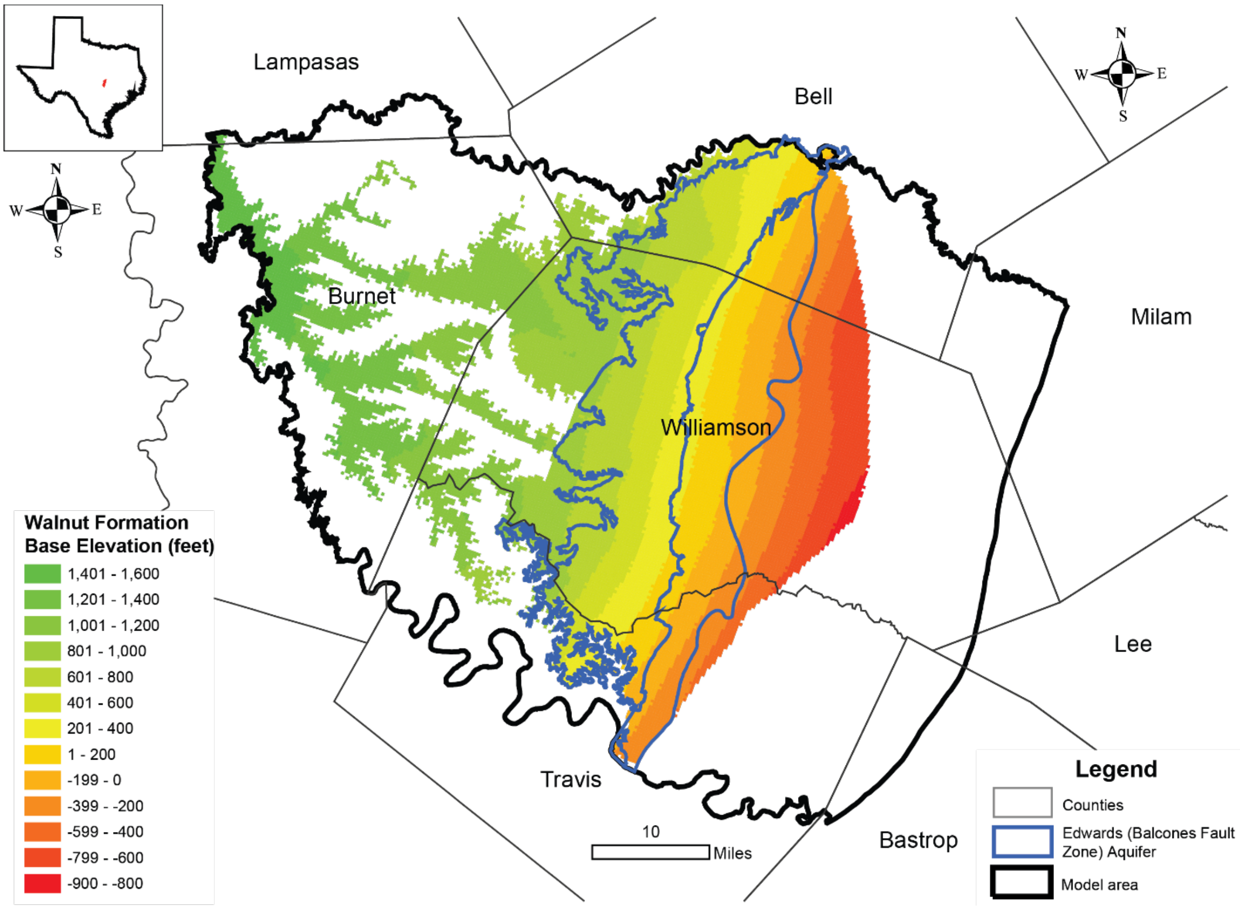


Figure 4.1.6. The elevation (in feet above mean sea level) of the base of the Walnut Formation confining unit.

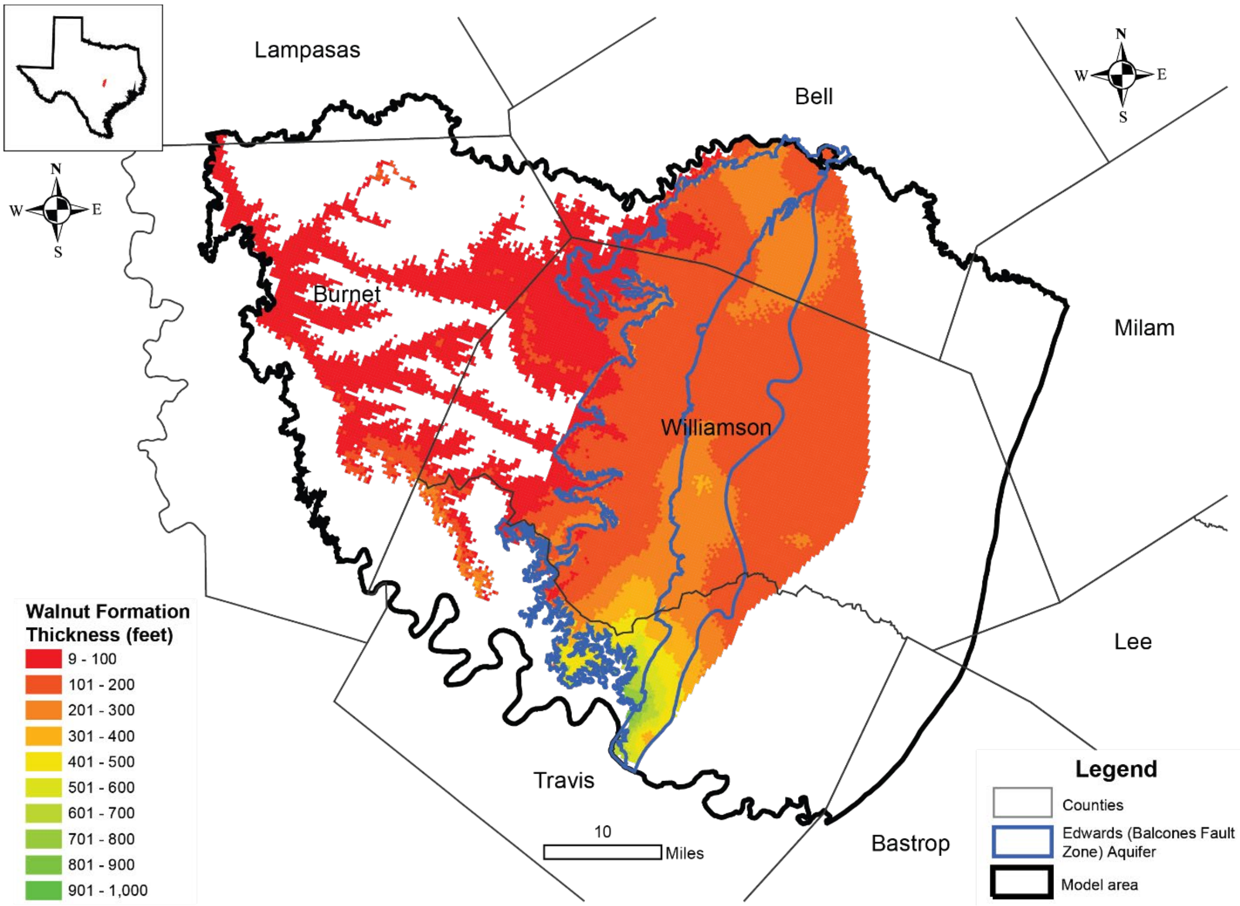


Figure 4.1.7. **Thickness (in feet) of the northern segment of the Walnut Formation confining unit.**

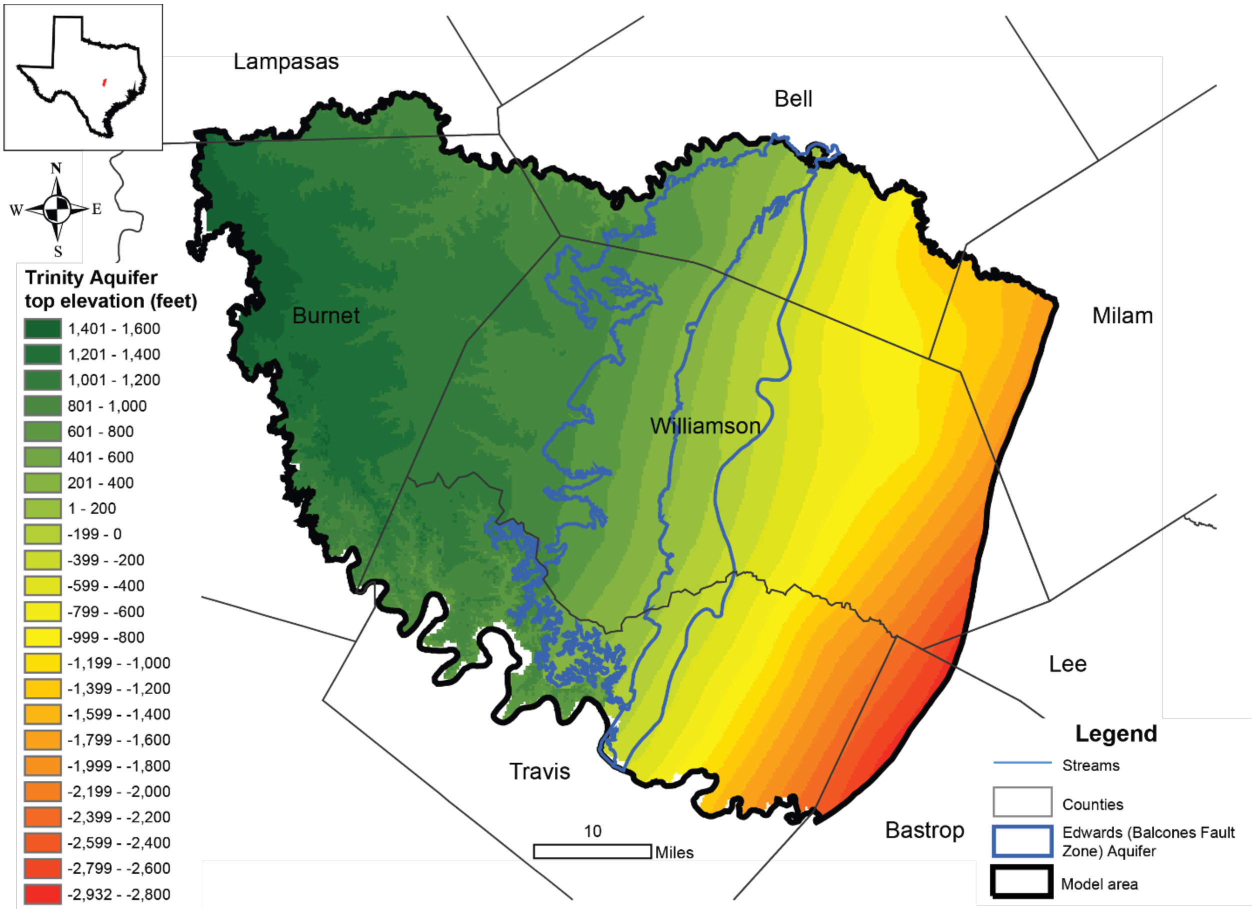


Figure 4.1.8. **The elevation (in feet above mean sea level) of the top of the Trinity Aquifer (based data from Kelley and others, 2014). The top of the Trinity Aquifer coincides with land surface or the base of the overlying Walnut Formation.**

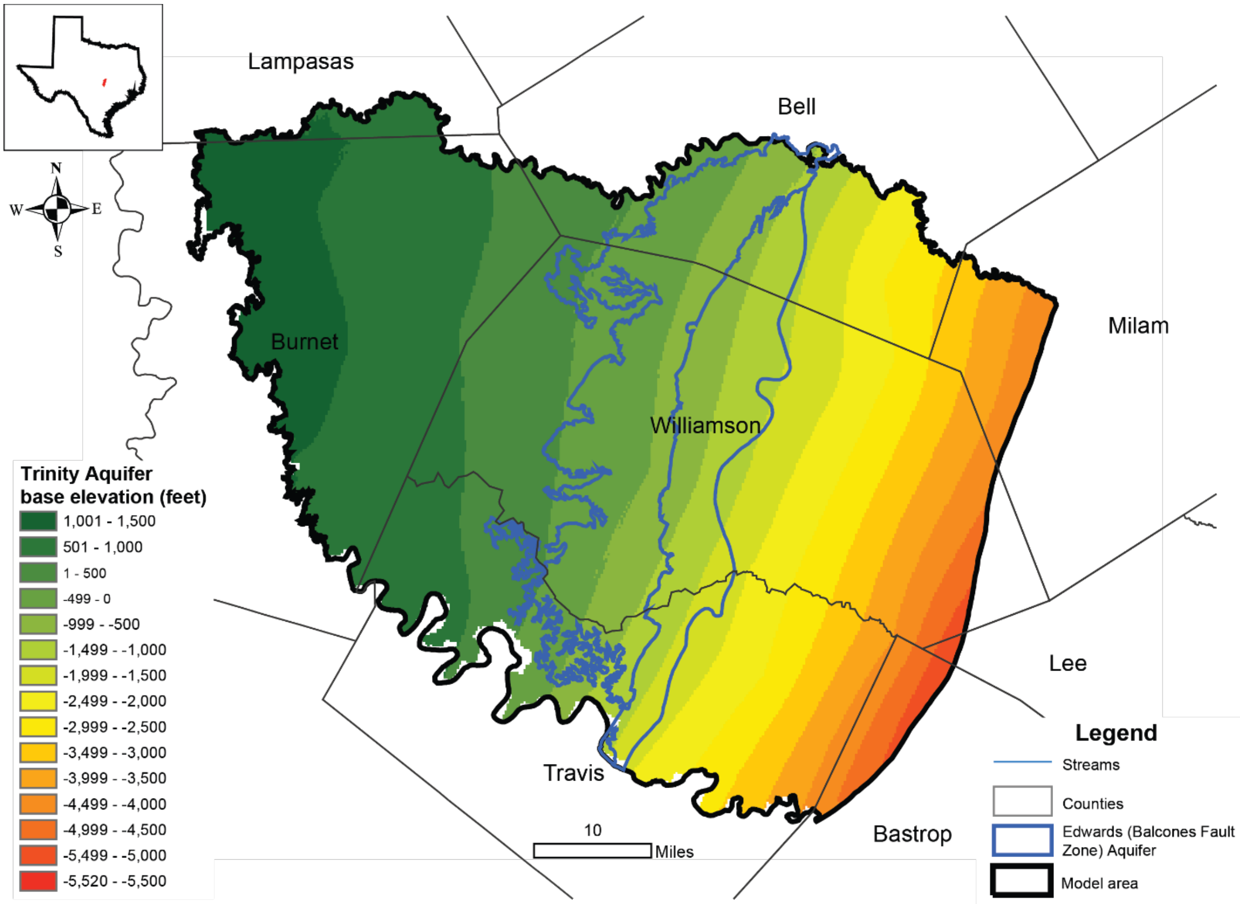


Figure 4.1.9. **The elevation (in feet above mean sea level) of the base of the Trinity Aquifer (based on data from Kelley and others, 2014).**

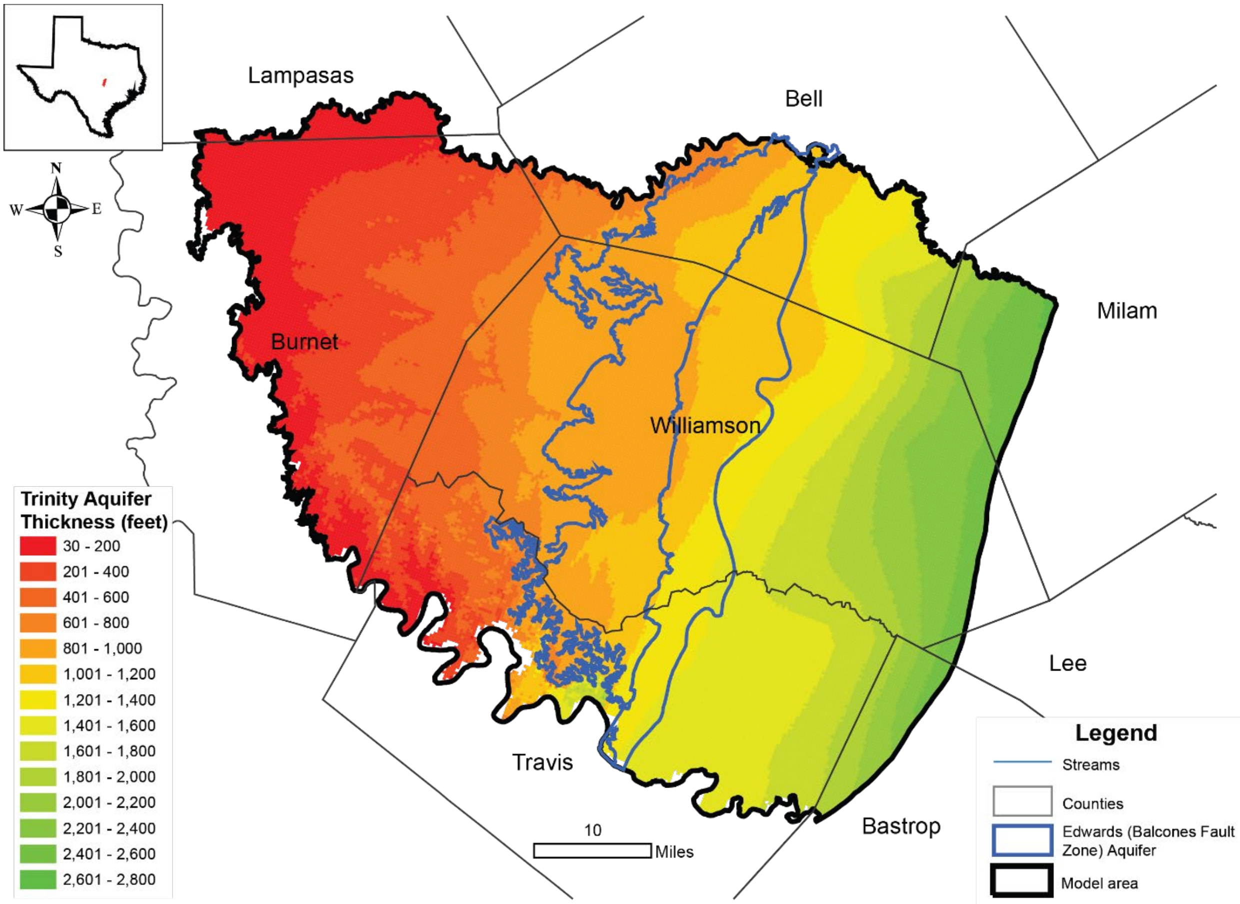


Figure 4.1.10. Thickness (in feet) of the Trinity Aquifer (based on data from Kelley and others, 2014).

4.2 Water Levels and Regional Groundwater Flow

The Texas Water Development Board groundwater database contains over 18,000 water-level measurements from about 580 wells in the northern segment of the Edwards (Balcones Fault Zone) Aquifer taken between 1935 and 2016 (Figure 4.2.1; Texas Water Development Board, 2017a). Figure 4.2.2 shows the temporal distribution of water-level data in the northern segment of the Edwards (Balcones Fault Zone) Aquifer from 1980 through 2016. In the study area, the Texas Water Development Board groundwater database also contains 4,340 water-level measurements from about 430 wells in the underlying Trinity Aquifer adjacent to the northern segment of the Edwards (Balcones Fault Zone) Aquifer (Figure 4.2.3; Texas Water Development Board, 2017a).

In the northern segment of the Edwards (Balcones Fault Zone) Aquifer, the potentiometric surface slopes generally toward the east (Figure 4.2.4). An eastward sloping potentiometric surface is also observed in the underlying Trinity Aquifer (Figure 4.2.5). Hydraulic gradients in the aquifer decrease east of the main faults of the Balcones Fault Zone (Senger and others, 1990). Intense fracturing in the Balcones Fault Zone suggests that the aquifer is anisotropic because of preferential flow through the generally northeast-southwest-oriented fractures (Baker and others, 1986; Duffin and Musick, 1991). Groundwater flow along fractures is partially responsible for the southward flow towards the Colorado River in the southern part of the study area, where fracturing is most intense (Figures 2.2.2 and 4.2.6). Senger and others (1990) suggested that some of the major faults, especially in the south, also act as hydraulic barriers, restricting west-to-east groundwater flow. In the central and northern parts of the aquifer, where faulting is less intense, the influence of fractures on regional groundwater flow is less apparent (Senger and others, 1990). In the central and northern parts of the study area, groundwater flows west to east with tendencies to converge on the major rivers and streams—Brushy Creek, San Gabriel River and Salado Creek (Figure 4.2.6). Groundwater flow convergence on major rivers is also apparent in the Trinity Aquifer, especially towards the Salado Creek and Colorado, San Gabriel, and Lampasas rivers (Figure 4.2.7).

In the unconfined part of the northern segment of the Edwards (Balcones Fault Zone) Aquifer, the water table occurs generally less than 100 feet below land surface and approaches land surface along stream channels (Senger and others, 1990). In the confined part of the aquifer, water levels approach or, in some cases exceed land surface, resulting in flowing wells. Water-level fluctuations observed in this aquifer (Figures 4.2.8 through 4.2.11) are responses to changes in recharge and discharge rates associated with rapid recharge during wet periods (Baker and others, 1986). These seasonal fluctuations are most apparent in wells with frequent water-level measurements, for example, wells 58-27-305 and 58-35-811 (Figures 4.2.10 and 4.2.11). Baker and others (1986) reports relatively small water-level fluctuations adjacent to the Colorado River because of the stabilizing effect of adjacent Lake Austin and Lady Bird Lake. Water-level declines have been observed during severe drought periods, such as the mid-1950s, 1983-84, and 1996 (Ridgeway and Petrini, 1999). A few available hydrographs indicate effects of pumping resulting in gradual long-term water-level decline, for example, Well 58-20-102 in Williamson County (Figure 4.2.11). Most hydrographs indicate a general balance between recharge and discharge in the aquifer, in other words, water levels fluctuate with no long-term water-level decline (Baker and others, 1986; Dahl, 1990; Duffin and Musick, 1991; Ridgeway and Petrini, 1999).

Locally, hydrographs in the unconfined part of the northern segment of the Edwards (Balcones Fault Zone) Aquifer show generally synchronous water-level variations at many locations and a close correlation between precipitation and water-level variation (Senger and others, 1990). Rapid water-level rises coincide with major rainfall events, especially during late spring and fall. The rate of water-level decline depends on the amount of recharge occurring during the recession period and the amount of nearby pumping (Senger and others, 1990). Continued rainfall tends to retard water-level declines, whereas pumping results in accelerated water-level declines. Hydrographs for wells in the confined part of the aquifer indicate a lag between major recharge events and water-level responses (Senger and others, 1990). According to Senger and others (1990), reversal of hydraulic gradients in some parts of the aquifer (Well 58-27-305; Figure 4.2.11), partly related to increased pumping, has been observed during drought periods. This reversal suggests a potential for the influx of saline groundwater from depth. However, large, persistent cones of depression that could potentially produce this influx of saline groundwater have not been identified (Senger and others, 1990).

On a longer-term scale, water-level variability over time varies across the study area. Edwards (Balcones Fault Zone) Aquifer wells with multiple years of water-level data were used to investigate water-level fluctuations over the period 1960 through 2016 (Figures 4.2.8 through 4.2.11). In Bell County, water-level fluctuations were generally minimal (Figure 4.2.9), while in the southernmost part of the study area—Travis County—water-level fluctuations of up to 200 feet can be observed in some wells (Figure 4.2.10). In most cases, groundwater hydrographs in Williamson County indicate water-level fluctuation around an average water level (Figure 4.2.11). The exception is well 58-20-102 which indicates gradual water-level decline since the mid-1970s, probably due to pumping.

Hydrographs in Trinity Aquifer wells in the study area indicate historic water-level decline that is often linear (Figure 4.2.12). Water levels in the northern segment of the Edwards (Balcones Fault Zone) Aquifer were compared to water levels in nearby wells in the underlying Trinity Aquifer. The paired Edwards (Balcones Fault Zone) and Trinity aquifer wells were located less than one mile from each other. This water-level comparison was conducted at six locations in the study area (Figure 4.2.13). Figure 4.2.14 indicates that in more down-dip portions of the Edwards (Balcones Fault Zone) Aquifer, water levels approach those in the Trinity Aquifer. While further up-dip, the differences between water levels in the Edwards (Balcones Fault Zone) and Trinity aquifers increase with higher water levels in the Edwards (Balcones Fault Zone) Aquifer.

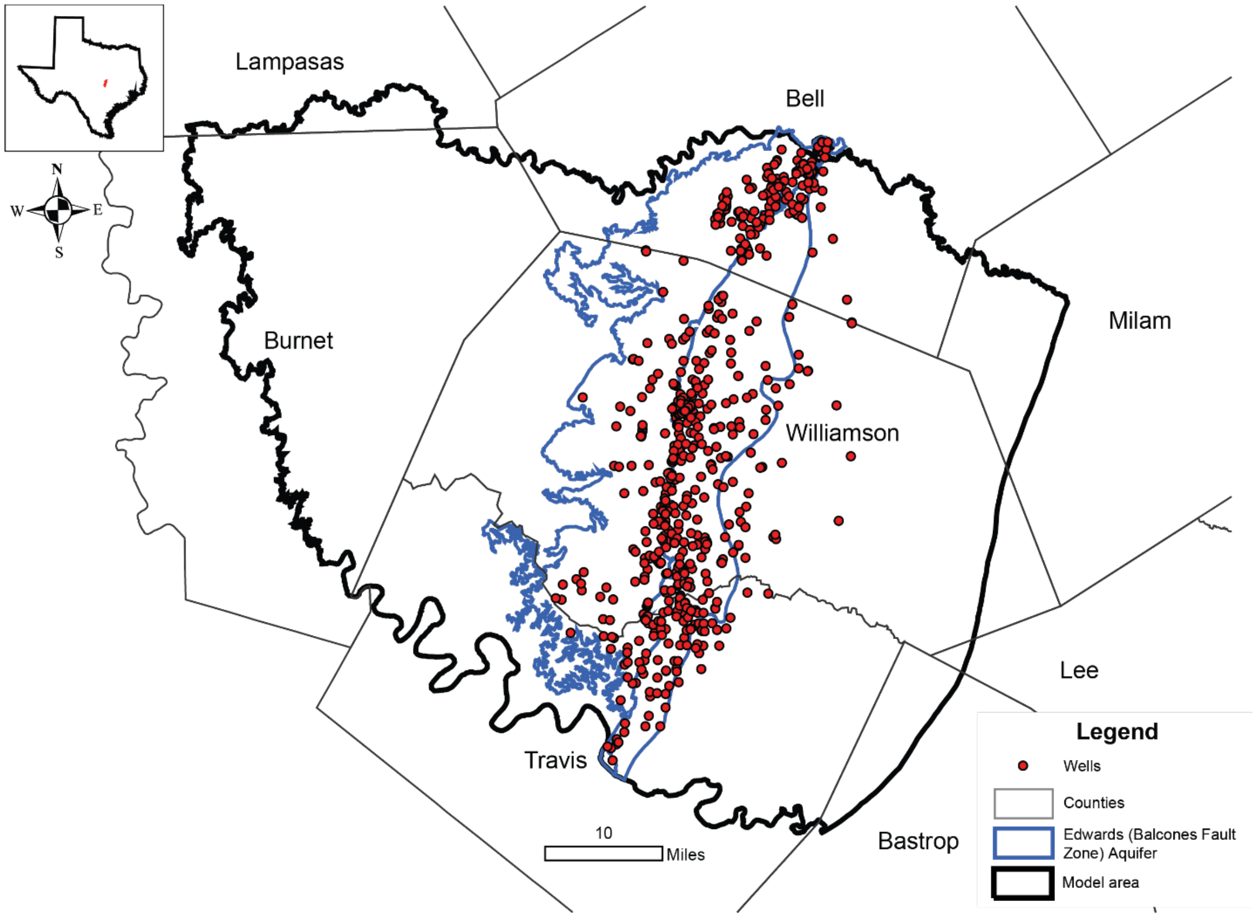


Figure 4.2.1. Water-level measurement locations for the northern segment of the Edwards (Balcones Fault Zone) Aquifer (Texas Water Development Board, 2017a).

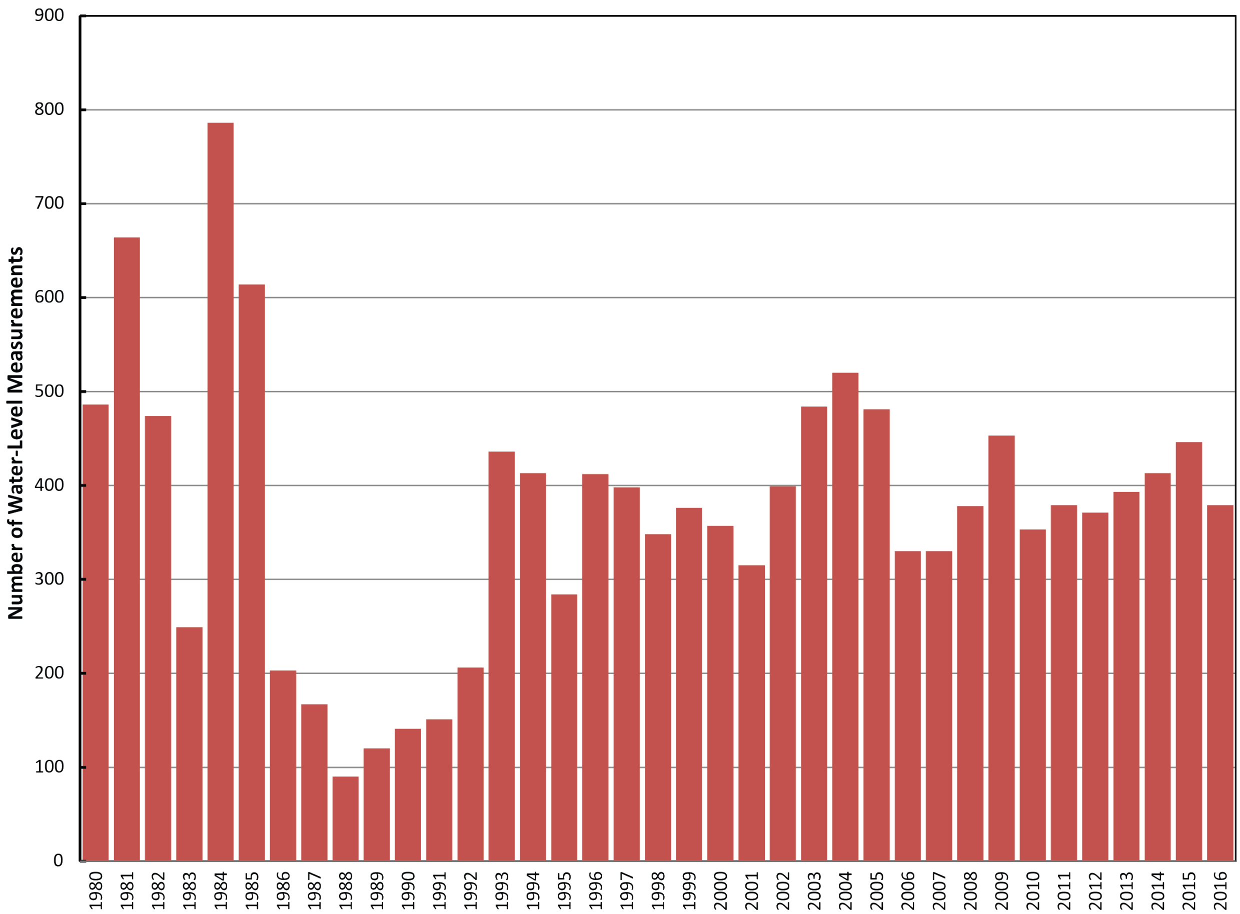


Figure 4.2.2. Temporal distribution of water-level measurements for 1980 to 2016 in the northern segment of the Edwards (Balcones Fault Zone) Aquifer (Texas Water Development Board, 2017a).

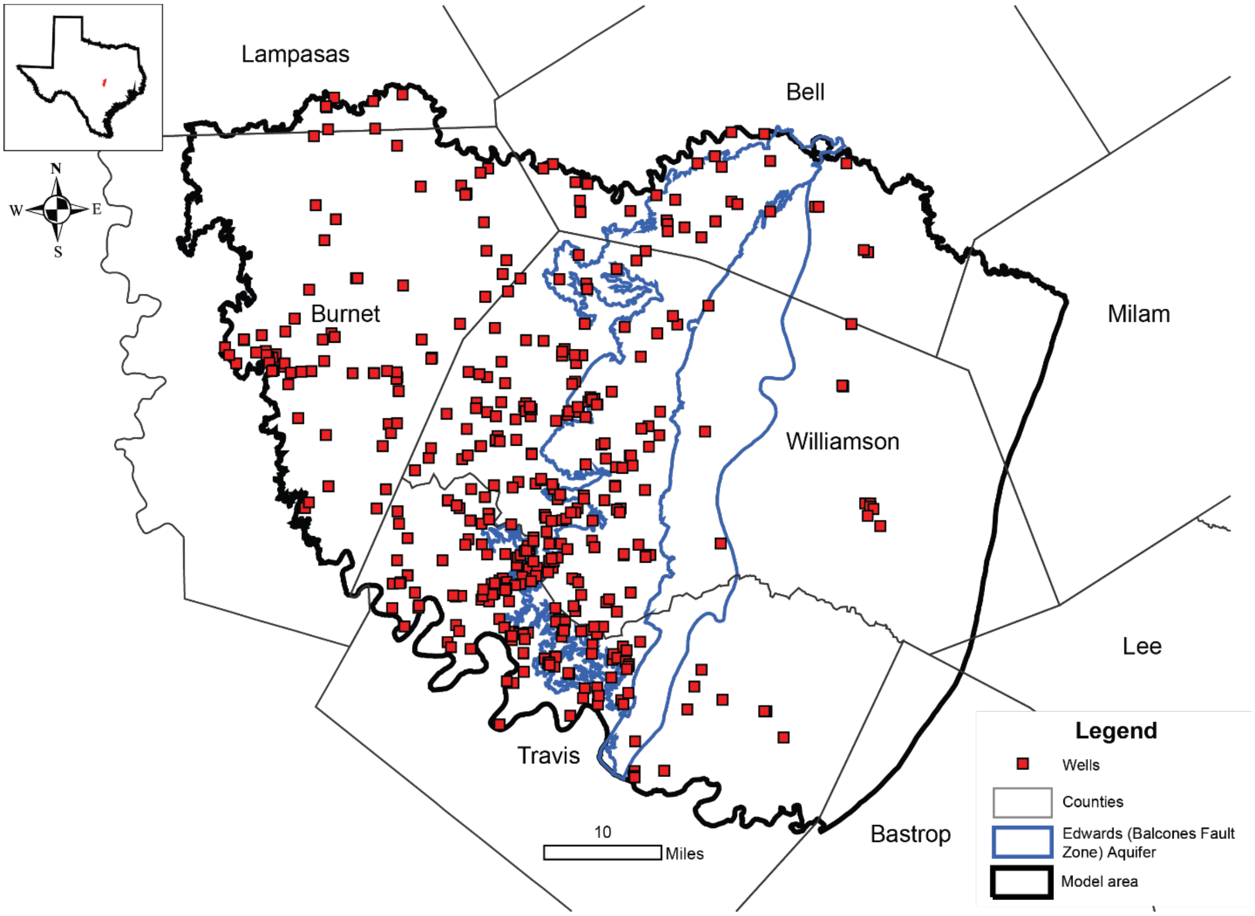


Figure 4.2.3. **Water-level measurement locations for the Trinity Aquifer (Texas Water Development Board, 2017a).**

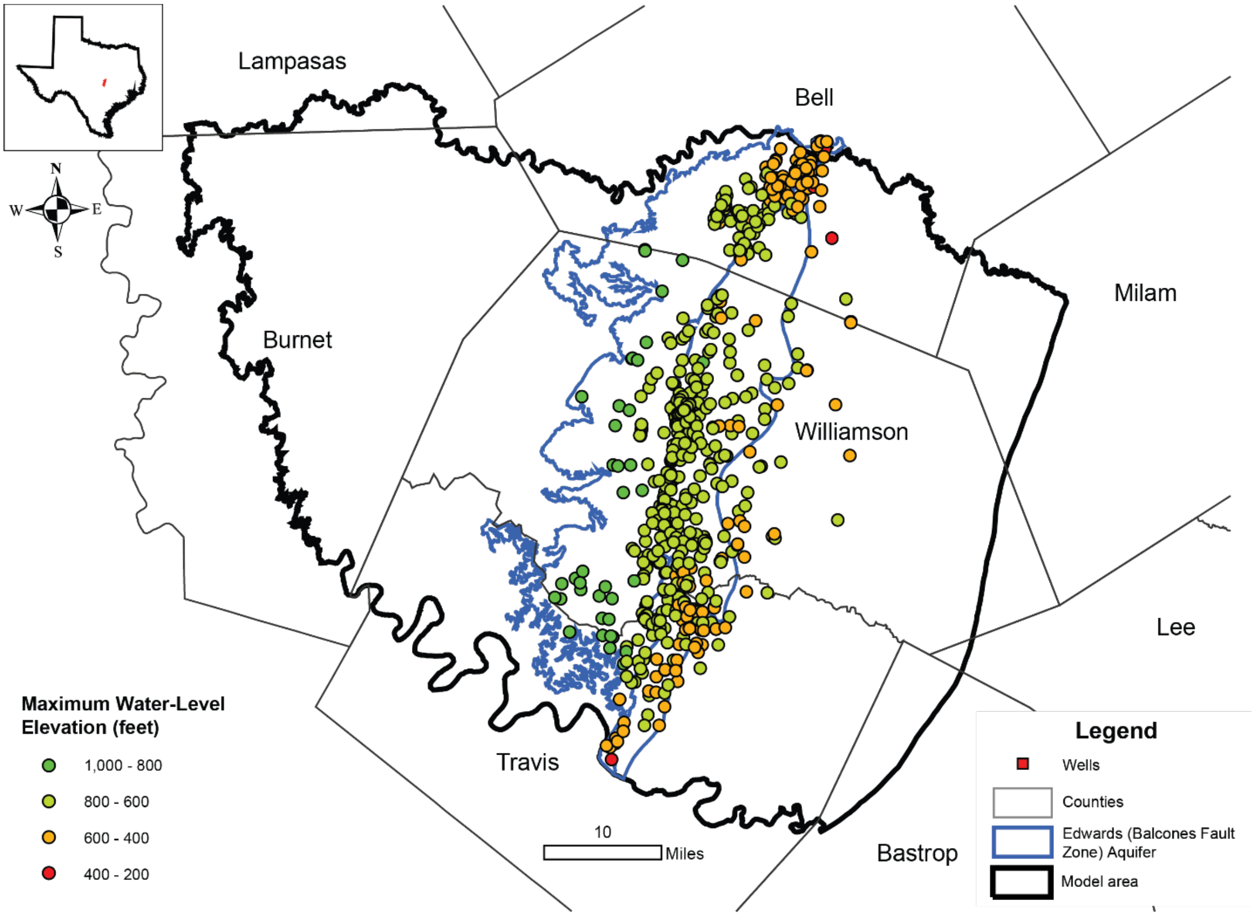


Figure 4.2.4. **Maximum water-level elevations (in feet above mean sea level) for wells completed in the northern segment of the Edwards (Balcones Fault Zone) Aquifer. This is based on water-level measurements mostly collected over the period 1980 to 2018 (Texas Water Development Board, 2017a).**

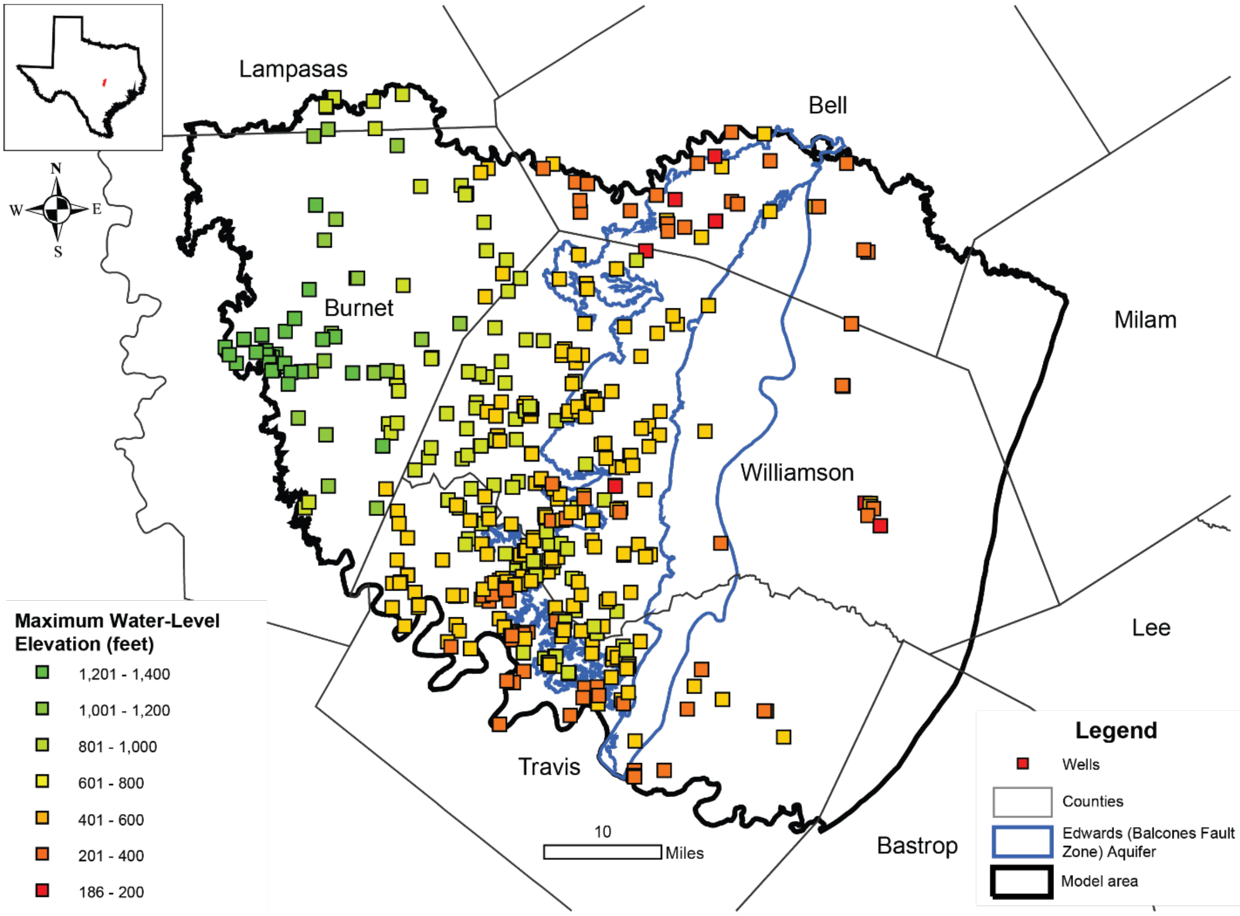


Figure 4.2.5. Maximum water-level elevations (in feet above mean sea level) for wells completed in the Trinity Aquifer. This is based on water-level measurements mostly collected over the period 1980 to 2018 (Texas Water Development Board, 2017a).

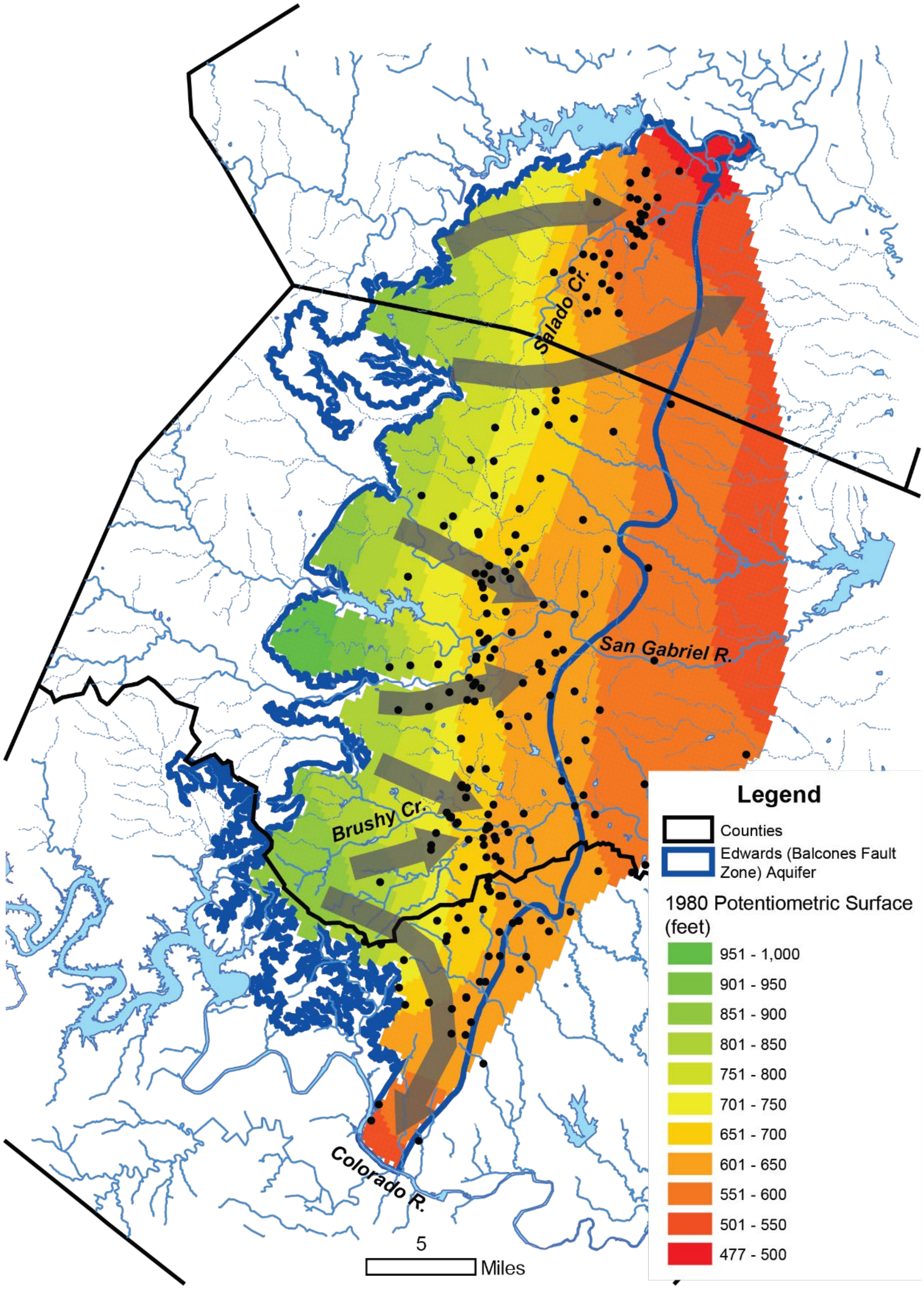


Figure 4.2.6. Simulated water levels for 1980 in the northern segment of the Edwards (Balcones Fault Zone) Aquifer (from Jones, 2003). Groundwater generally flows from west to east, converging on the Salado Creek in the north, San Gabriel River in the center and Colorado River in the south.

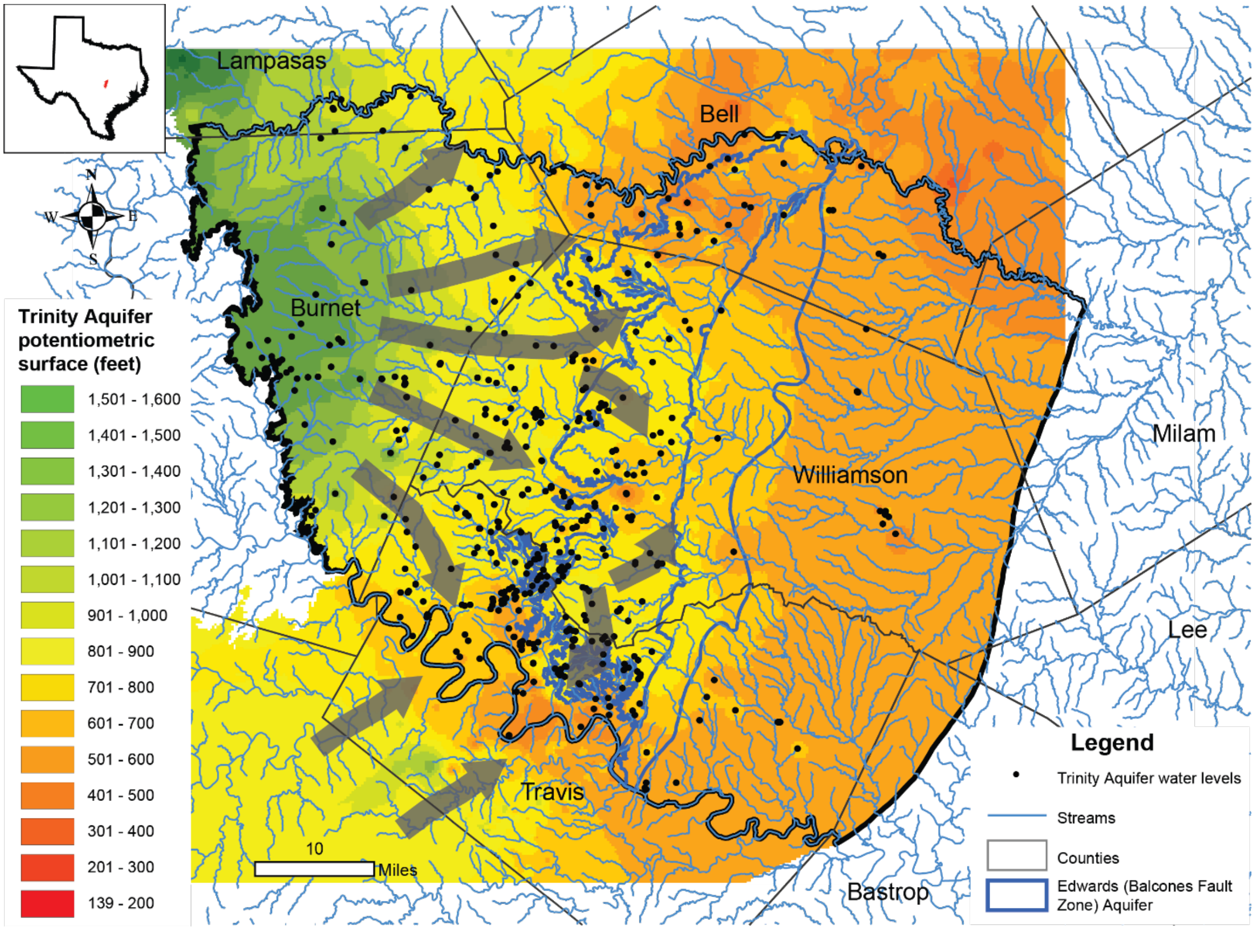


Figure 4.2.7. **Maximum water levels for the Trinity Aquifer. This is based on water-level measurements mostly collected over the period 1980 to 2018 (Texas Water Development Board, 2017a). Groundwater generally flows from west to east, converging on the Salado Creek in the north and Colorado River in the south.**

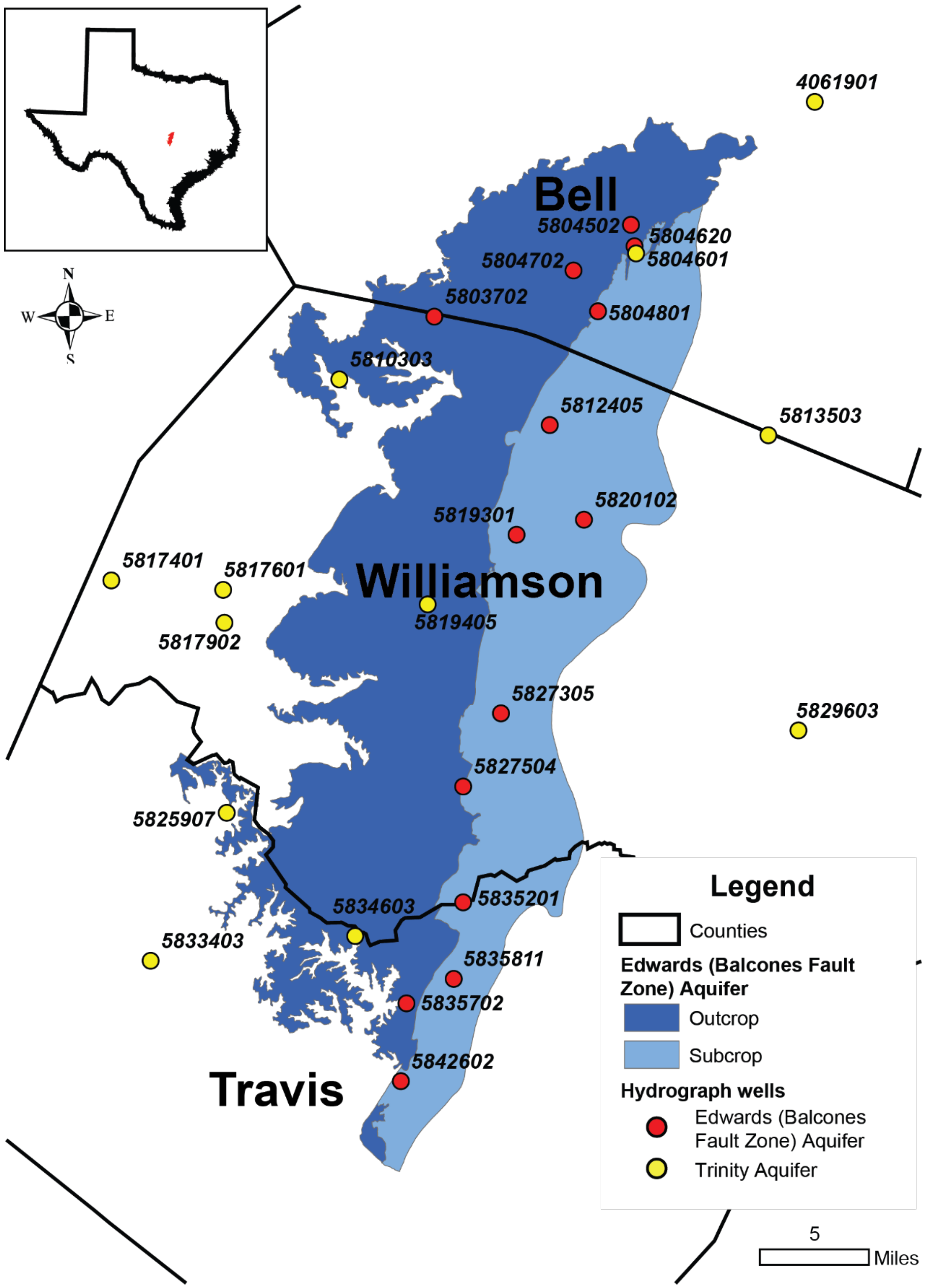
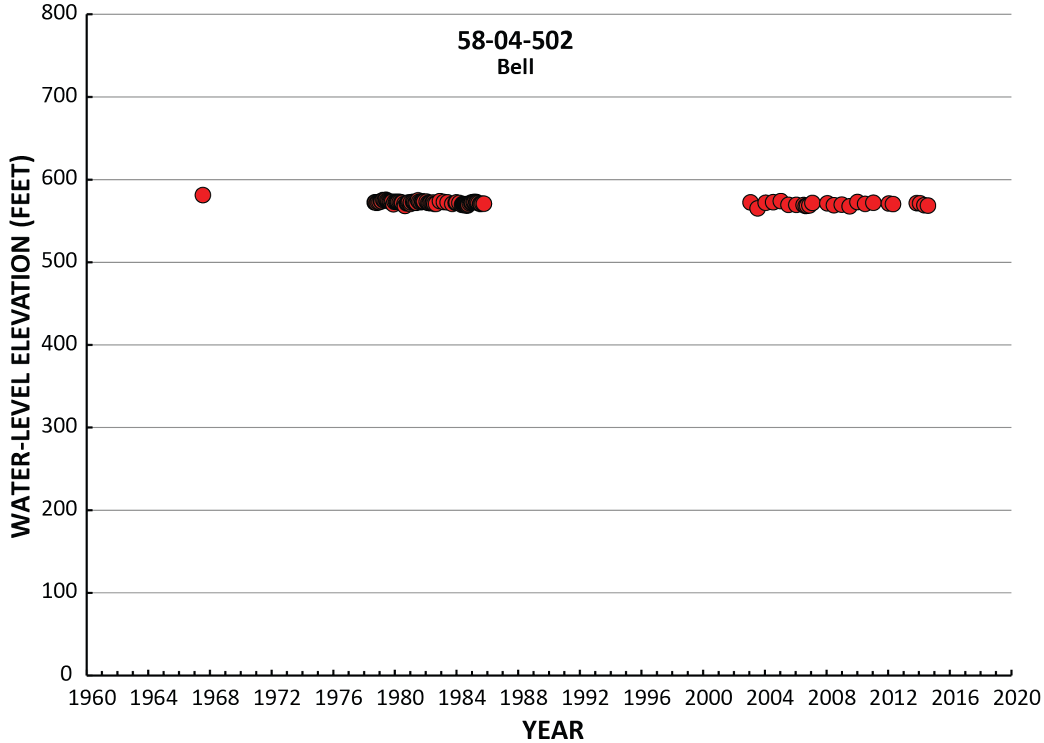


Figure 4.2.8. **Locations of selected northern segment of the Edwards (Balcones Fault Zone) and Trinity aquifers wells with transient water-level data (Texas Water Development Board, 2017a; United States Geological Survey, 2017a).**



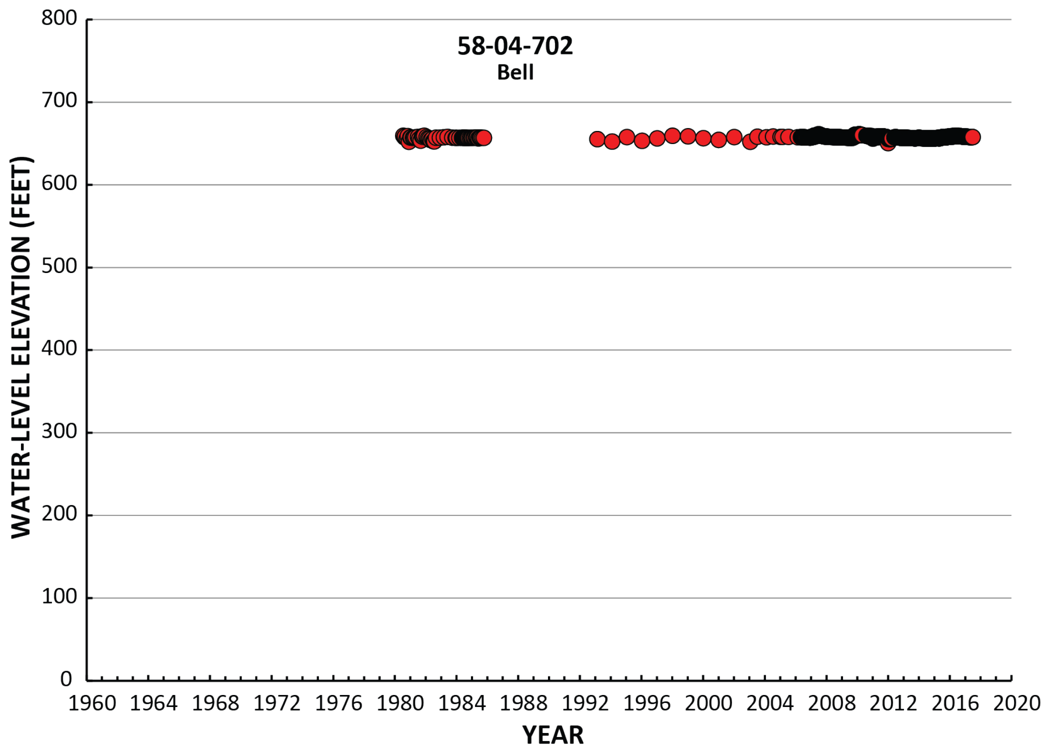
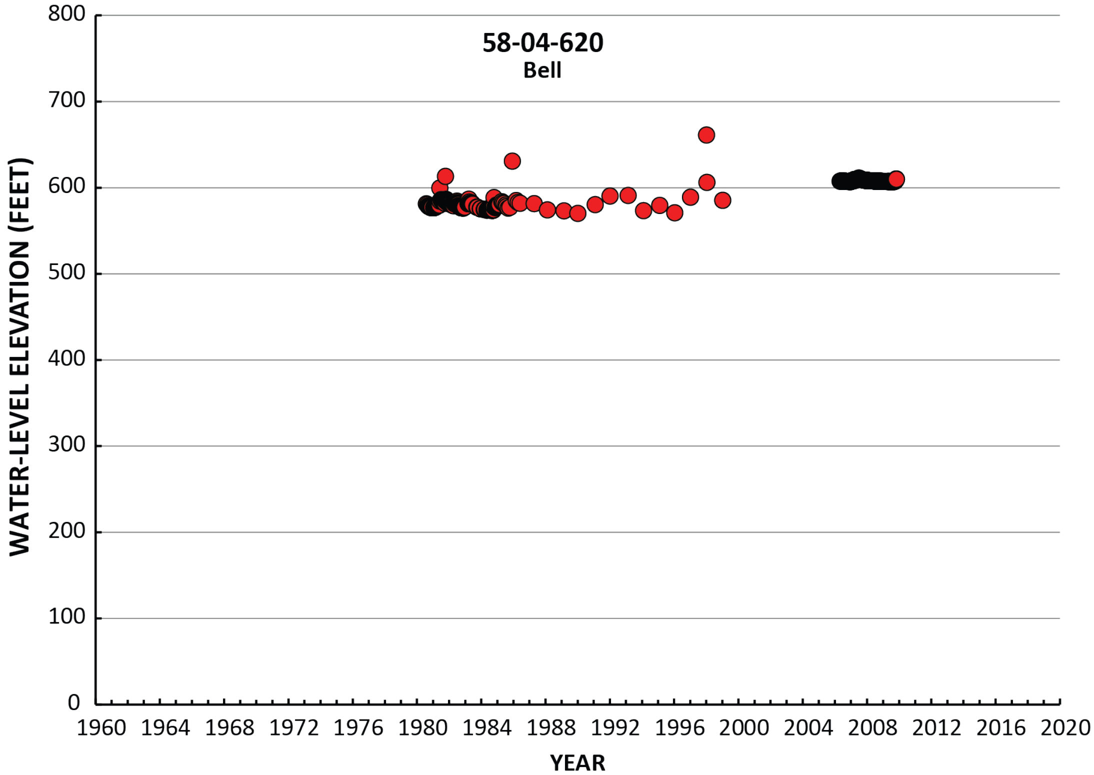


Figure 4.2.9. Hydrographs of transient water-level data (in feet above mean sea level) for the selected northern segment of the Edwards (Balcones Fault Zone) Aquifer wells in Bell County (Texas Water Development Board, 2017a). See Figure 4.2.10 for locations.



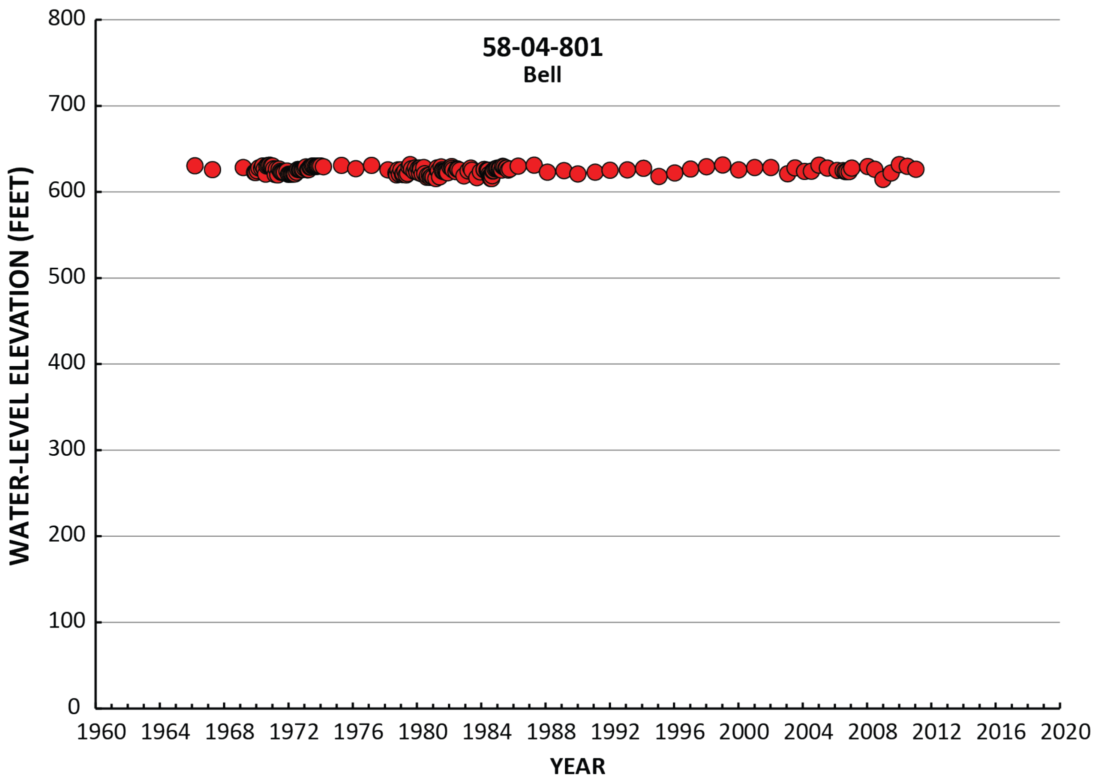
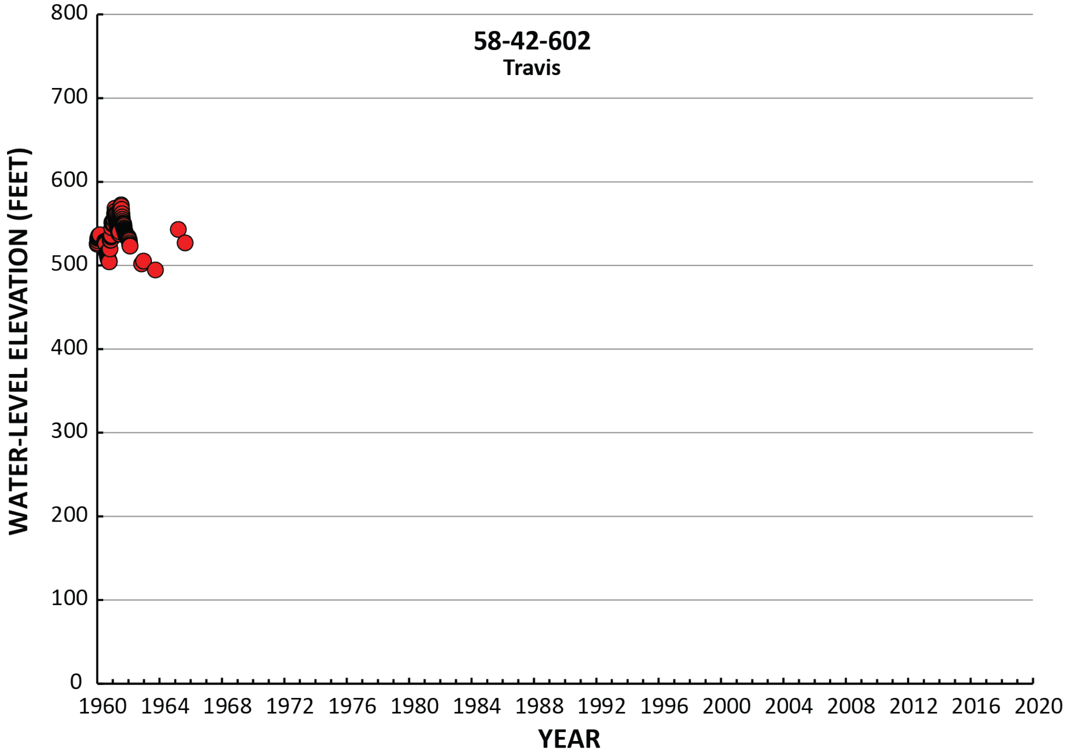


Figure 4.2.9. (continued)



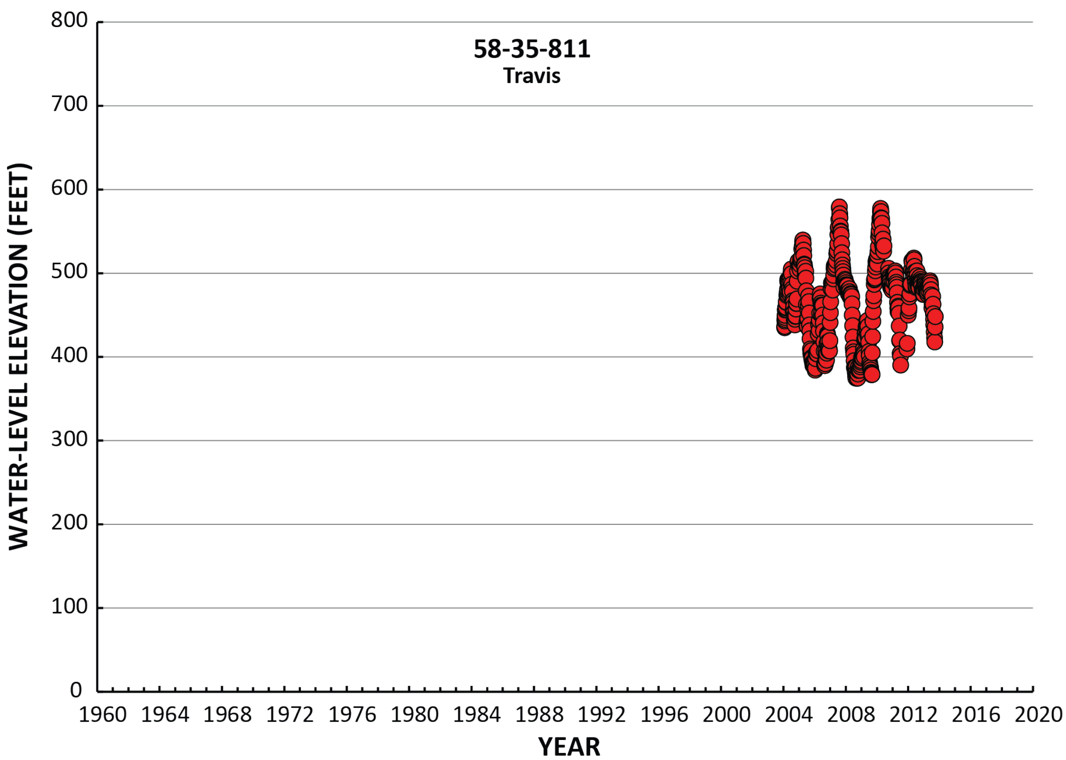
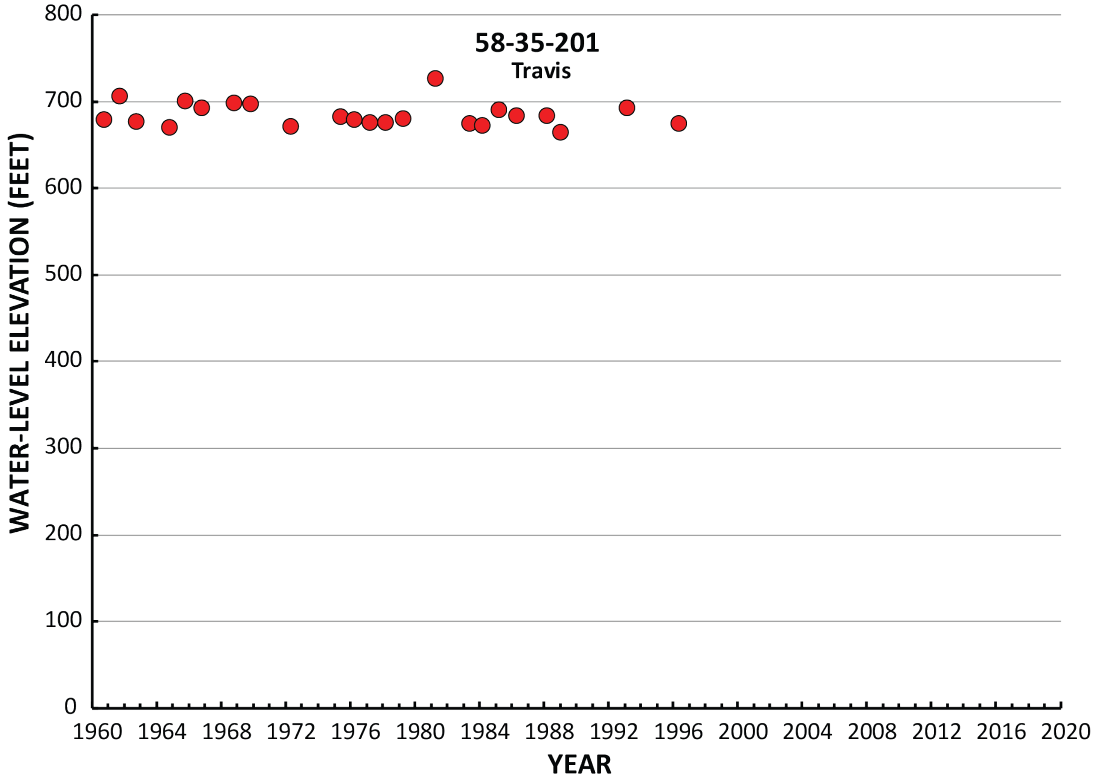


Figure 4.2.10. Hydrographs of transient water-level data (in feet above mean sea level) for the selected northern segment of the Edwards (Balcones Fault Zone) Aquifer wells in Travis County (Texas Water Development Board, 2017a). See Figure 4.2.10 for locations.



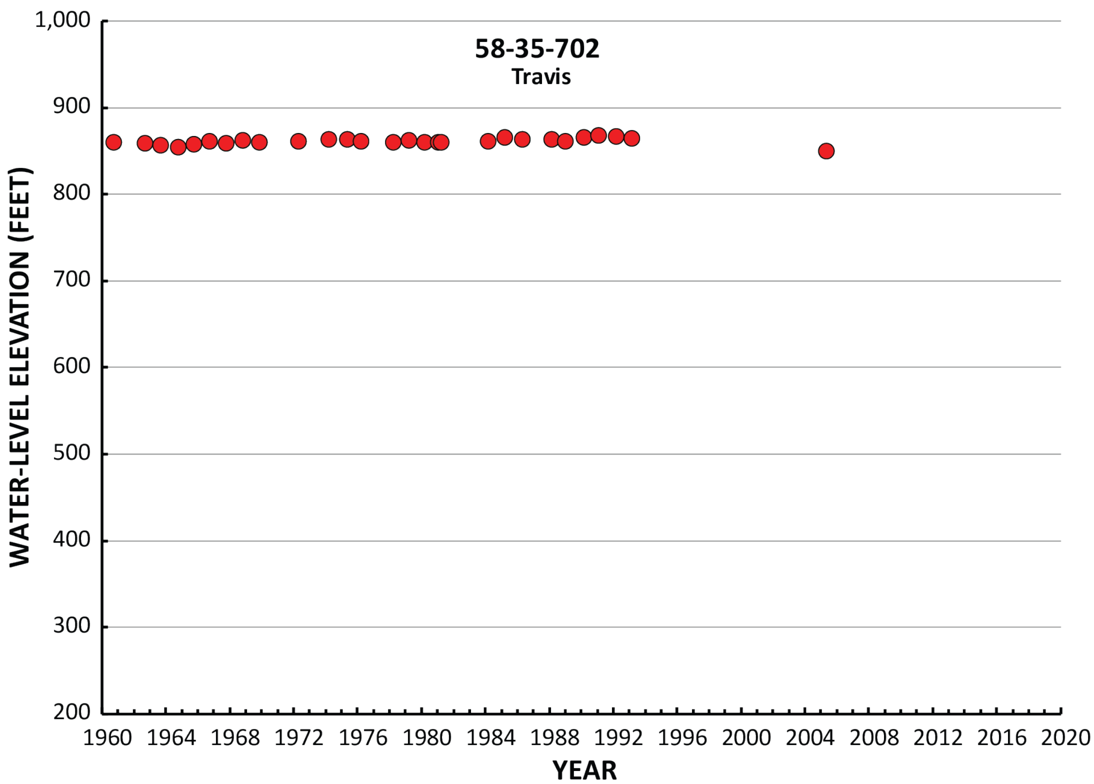
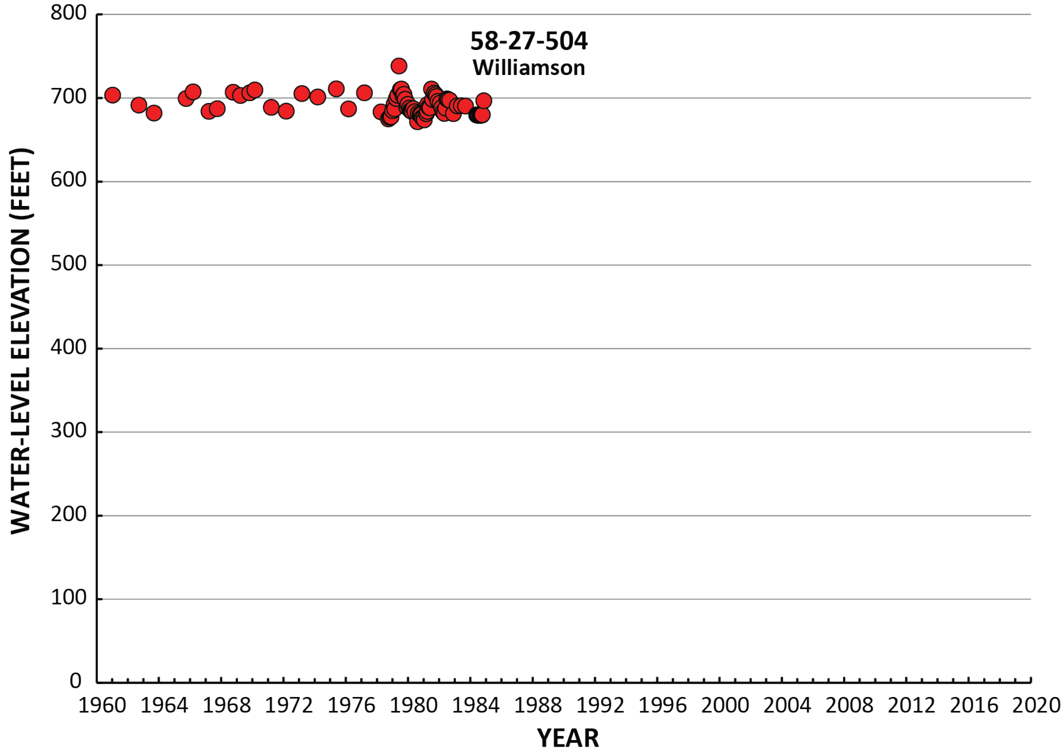


Figure 4.2.10. (continued)



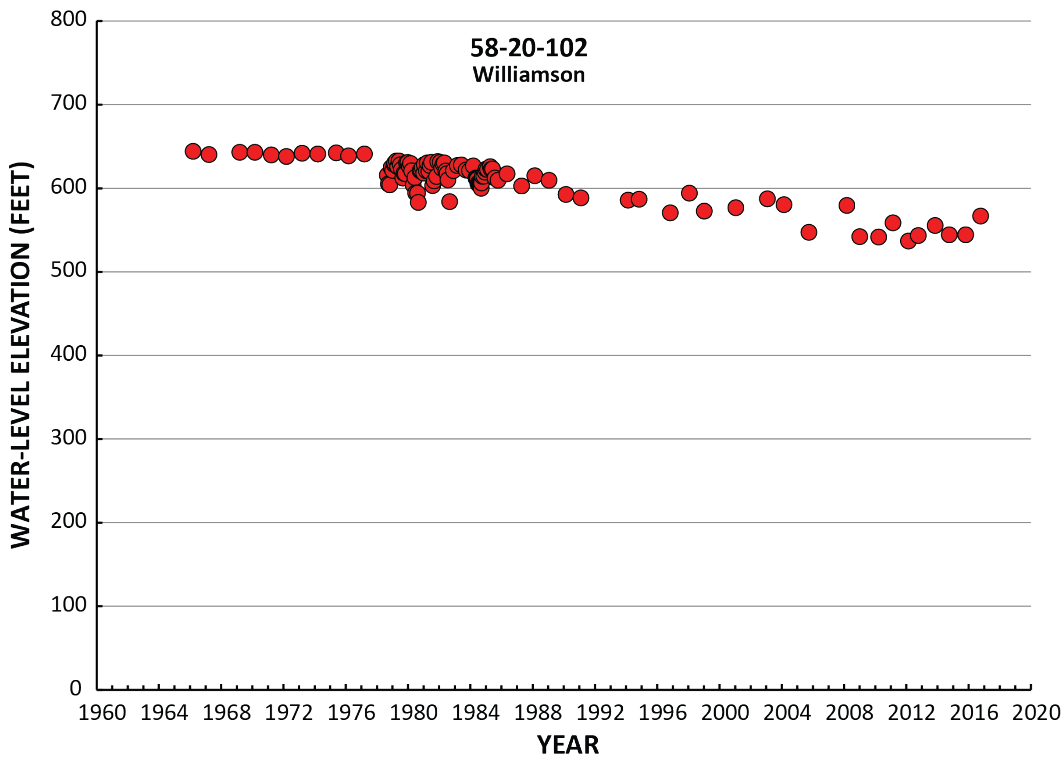
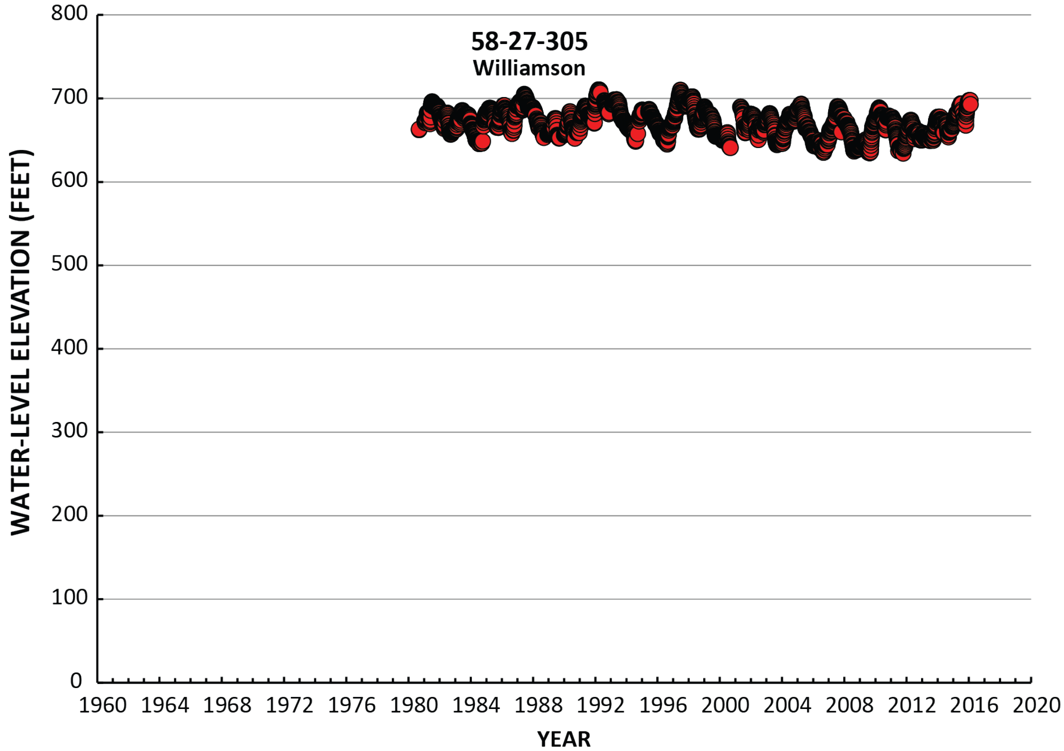


Figure 4.2.11. Hydrographs of transient water-level data (in feet above mean sea level) for the selected northern segment of the Edwards (Balcones Fault Zone) Aquifer wells in Williamson County (Texas Water Development Board, 2017a). See Figure 4.2.10 for locations.



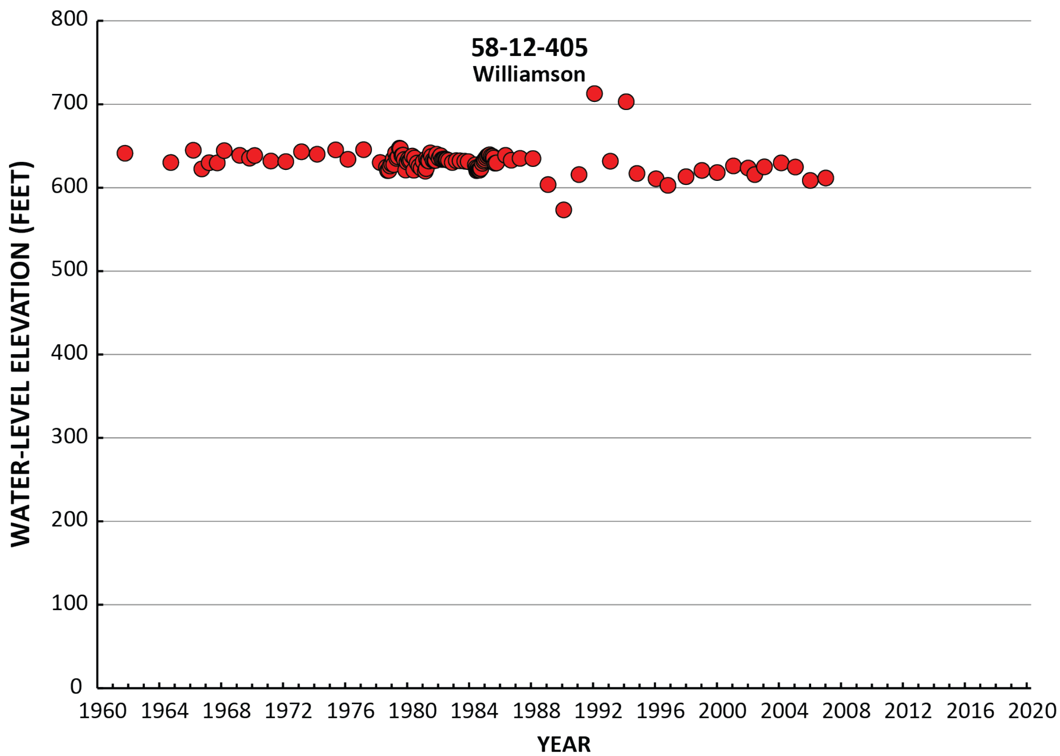
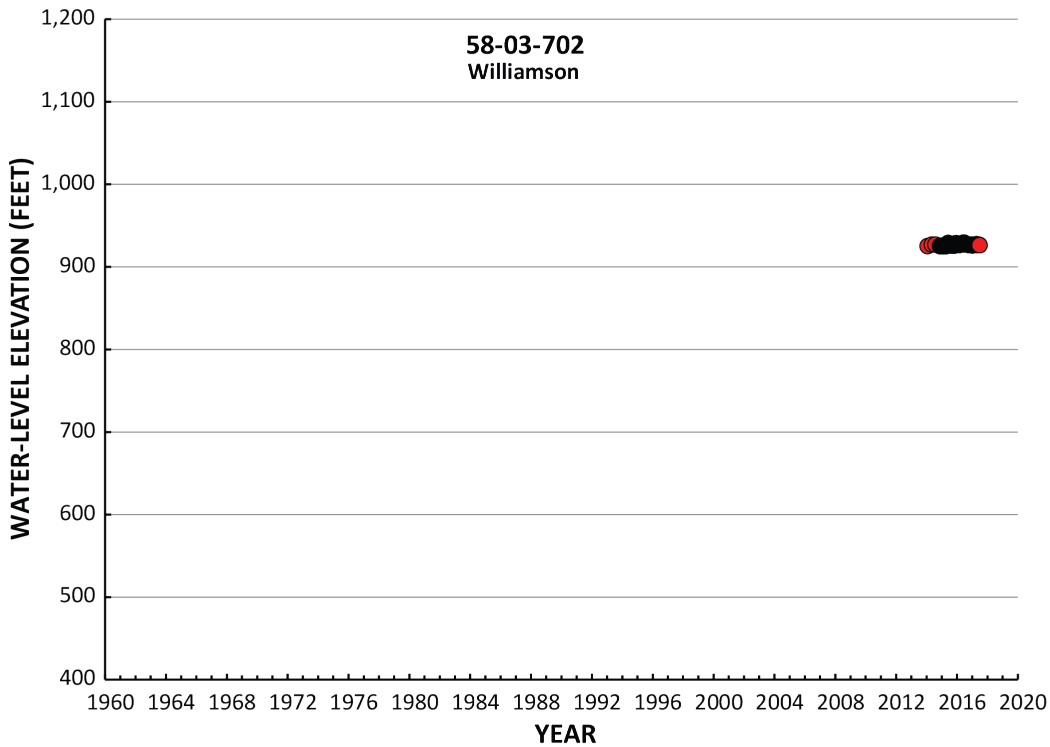


Figure 4.2.11. (continued)



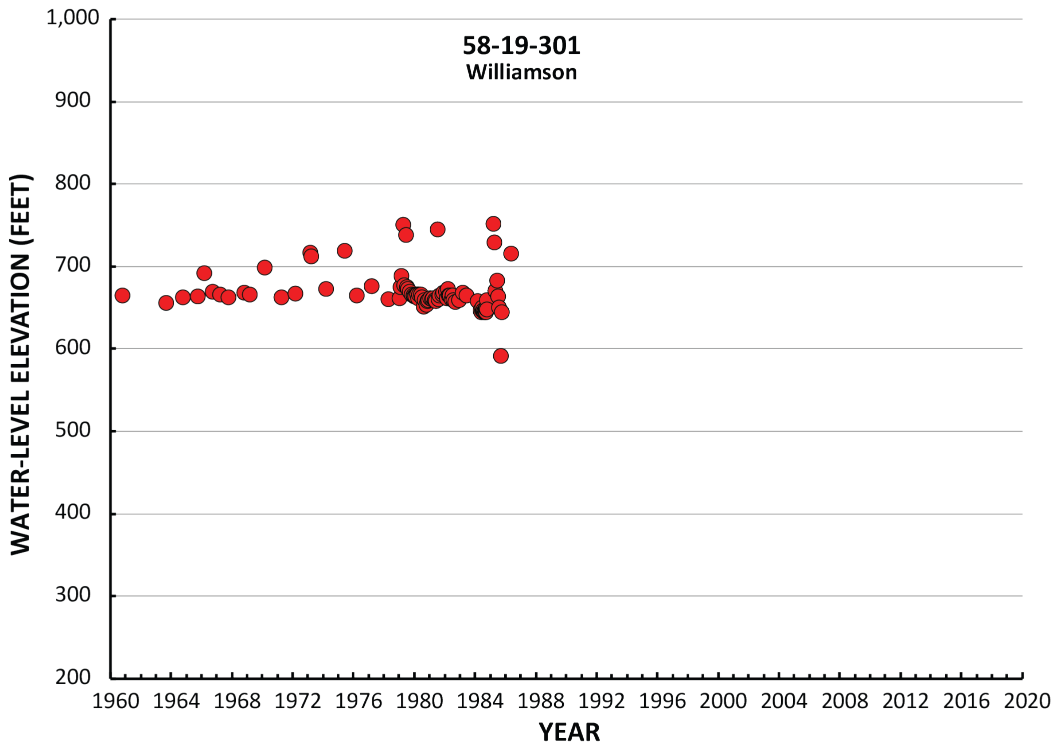
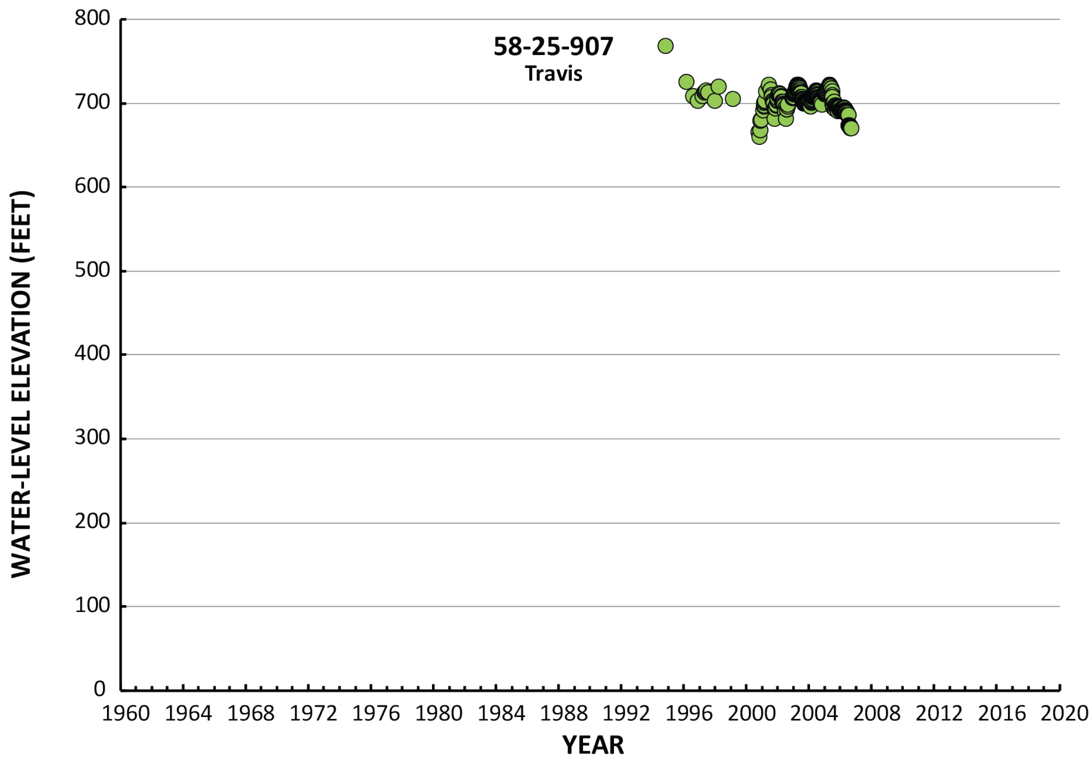


Figure 4.2.11. (continued)



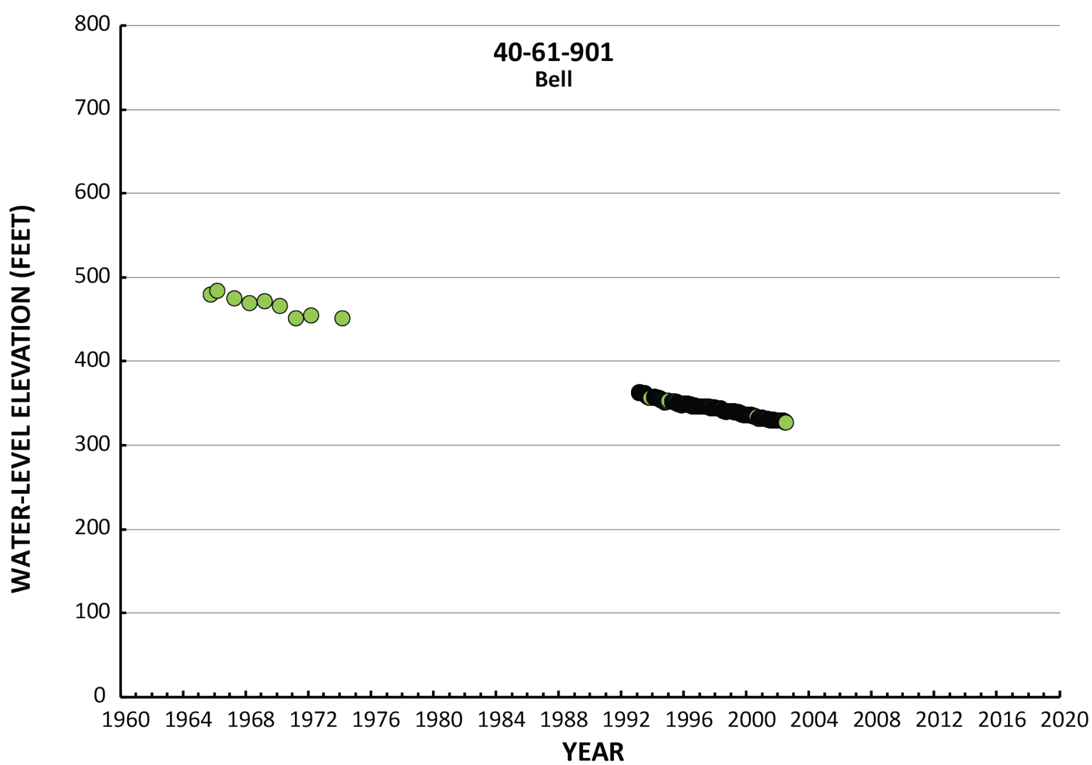
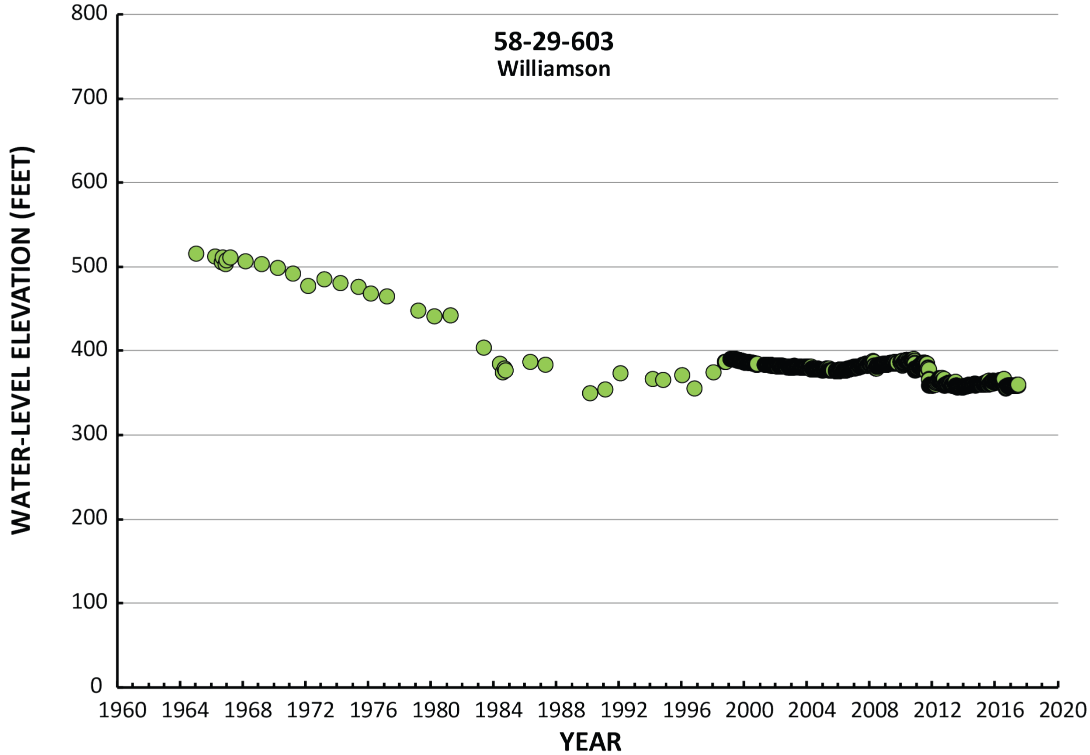
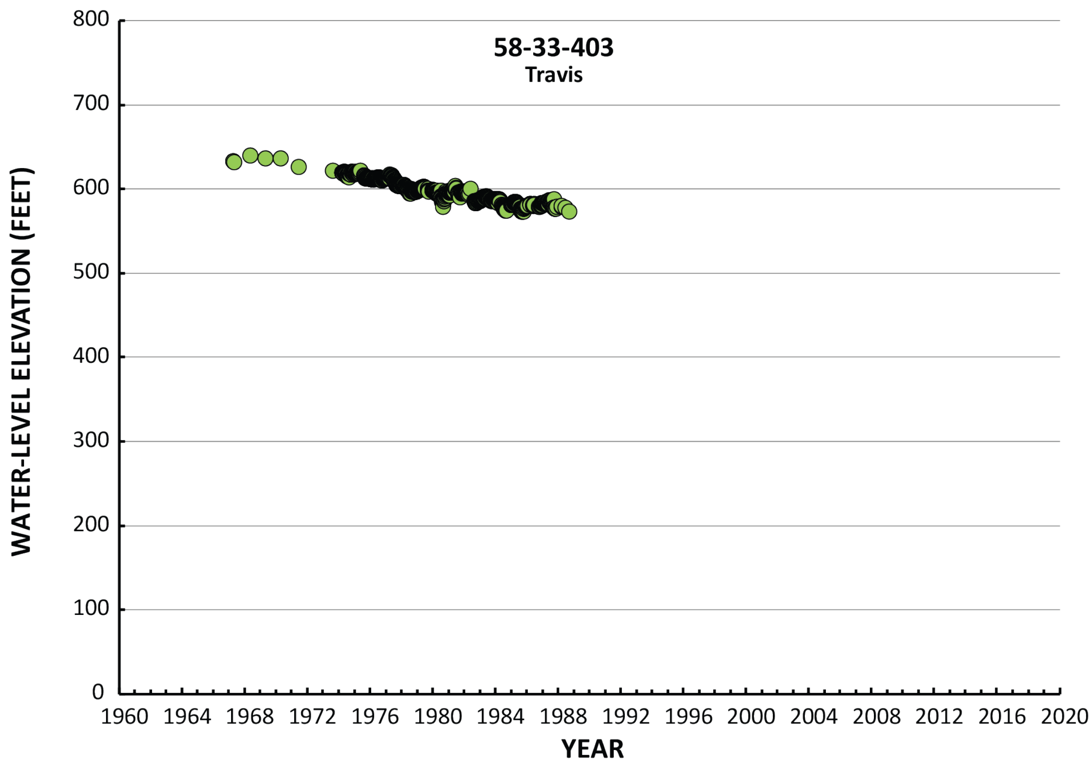


Figure 4.2.12. Hydrographs of transient water-level data (in feet above mean sea level) for selected Trinity Aquifer wells in Bell, Travis, and Williamson counties (Texas Water Development Board, 2017a). See Figure 4.2.10 for locations.





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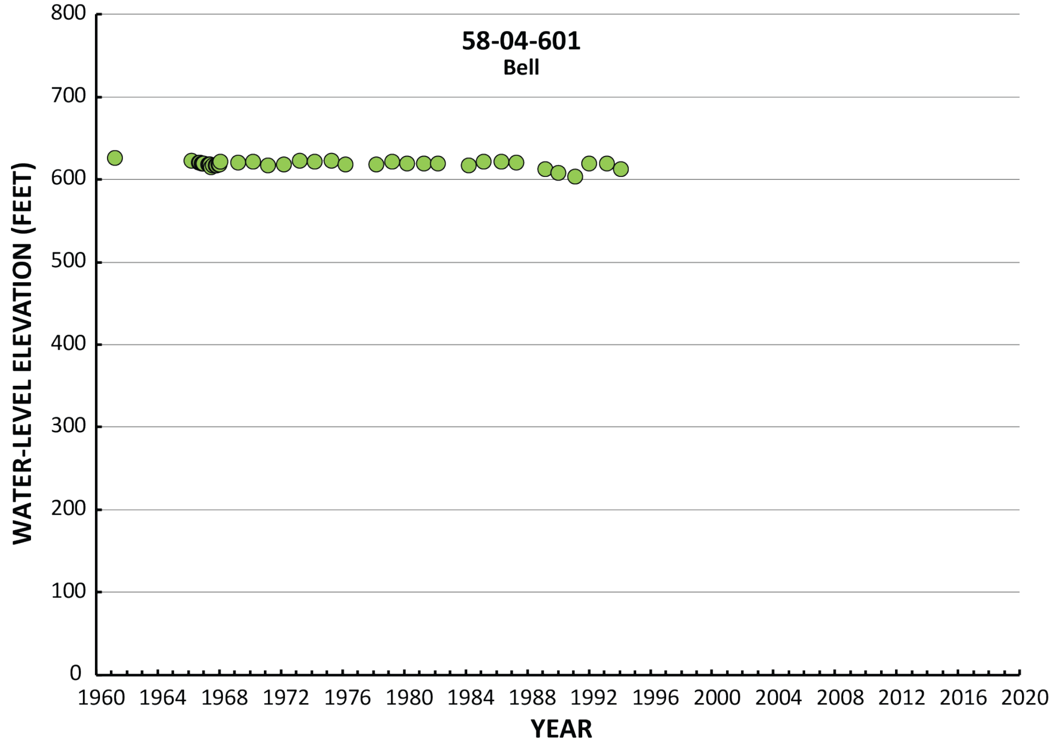

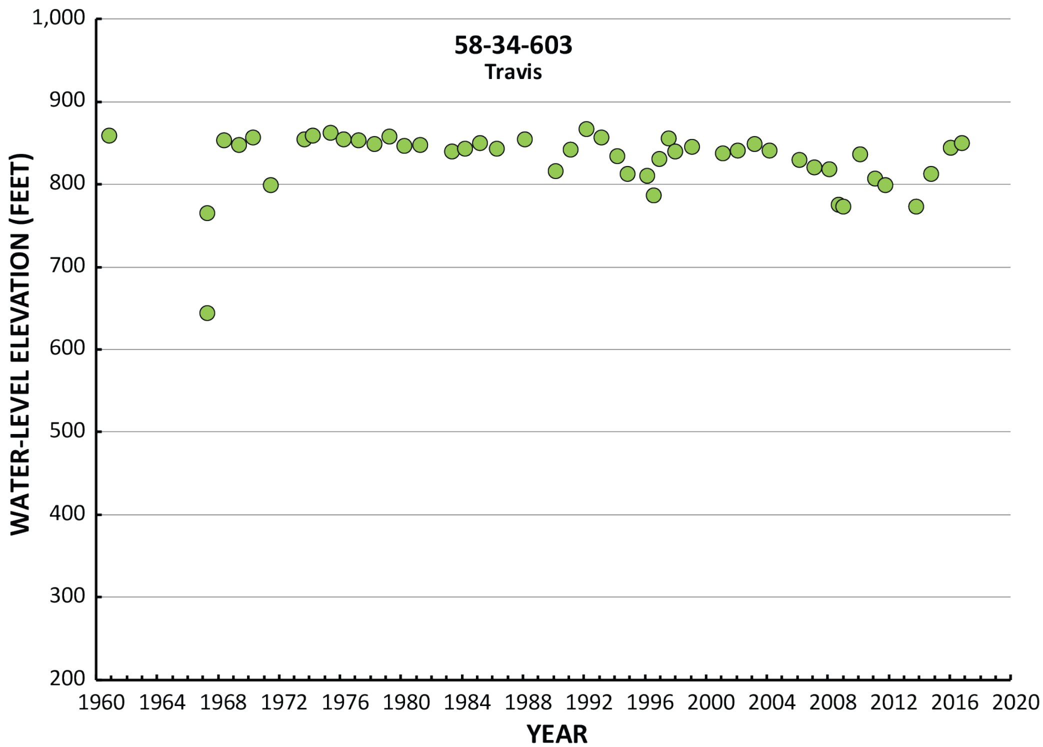

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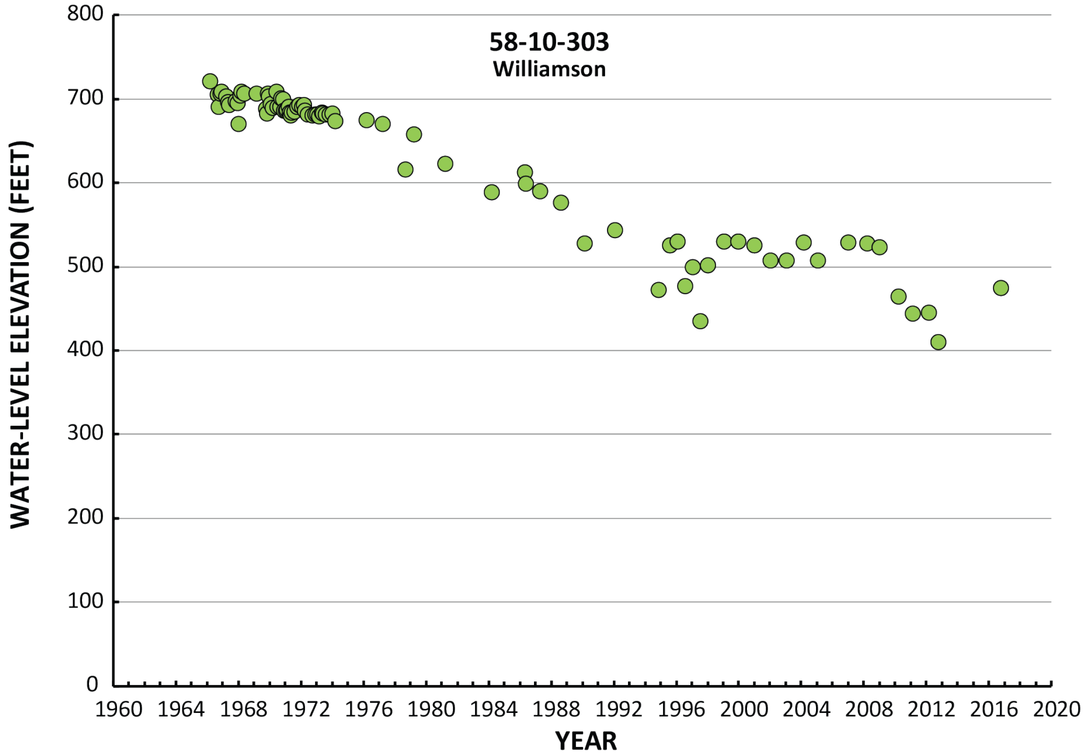


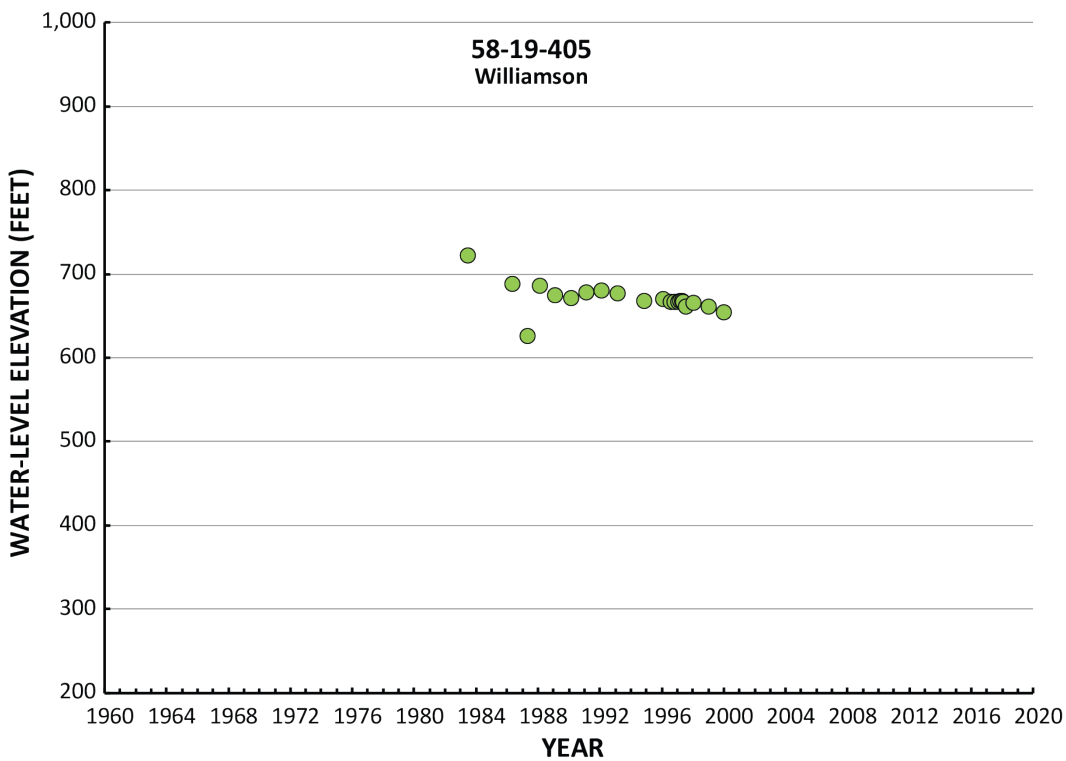
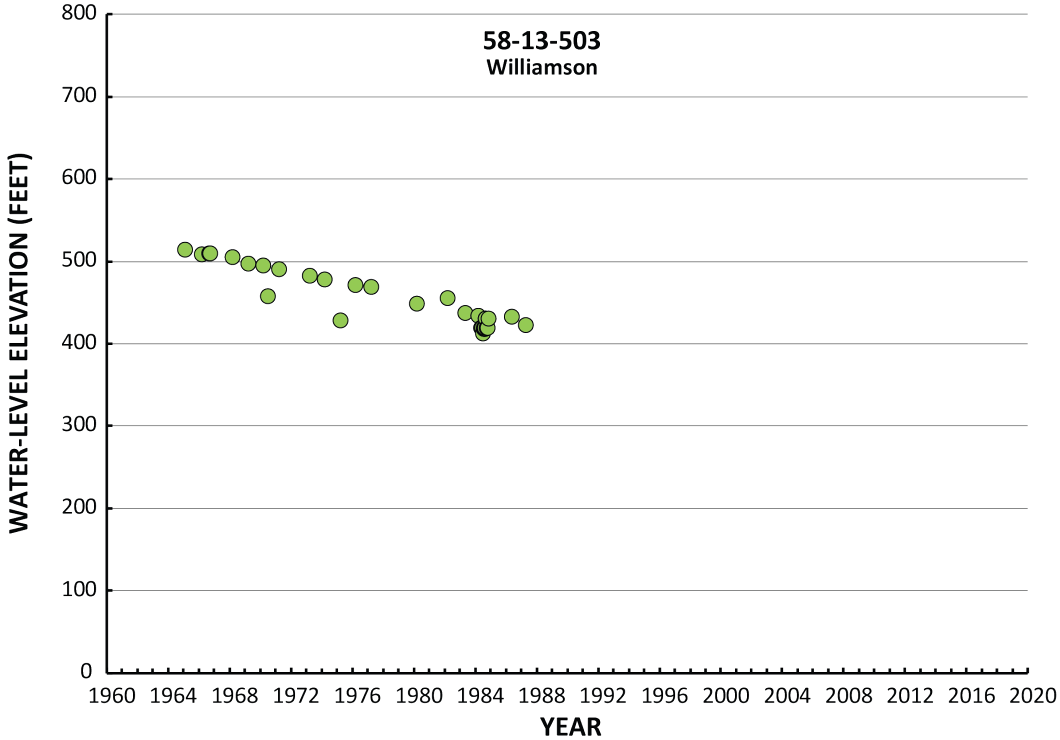


Figure 4.2.12. (continued)



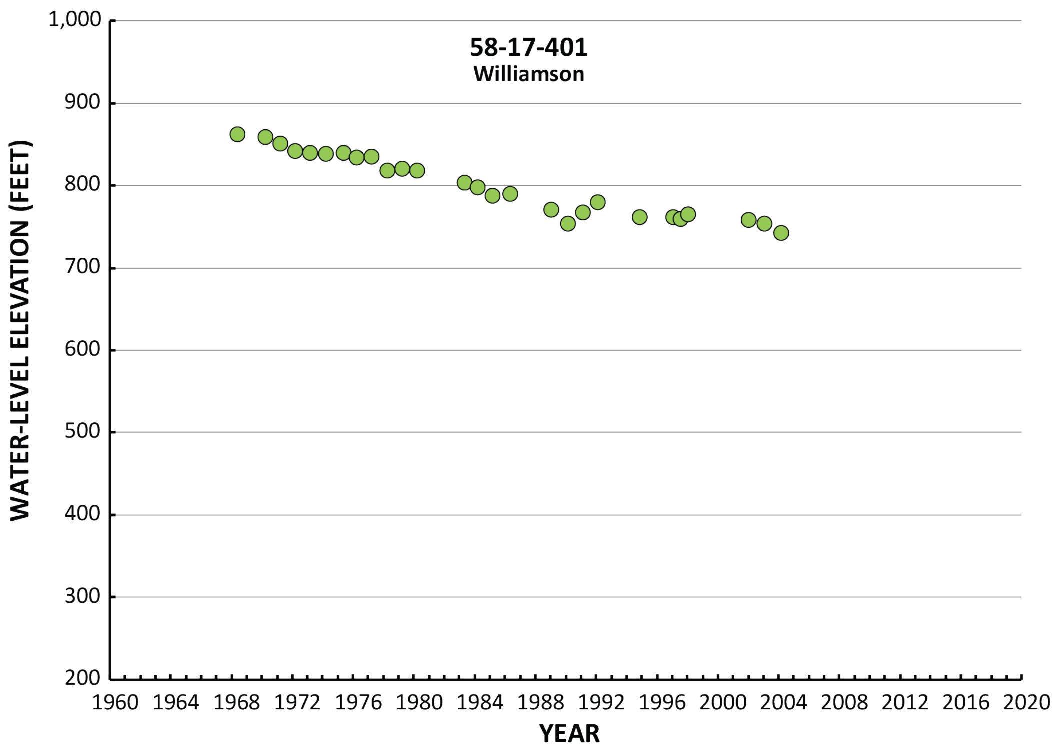
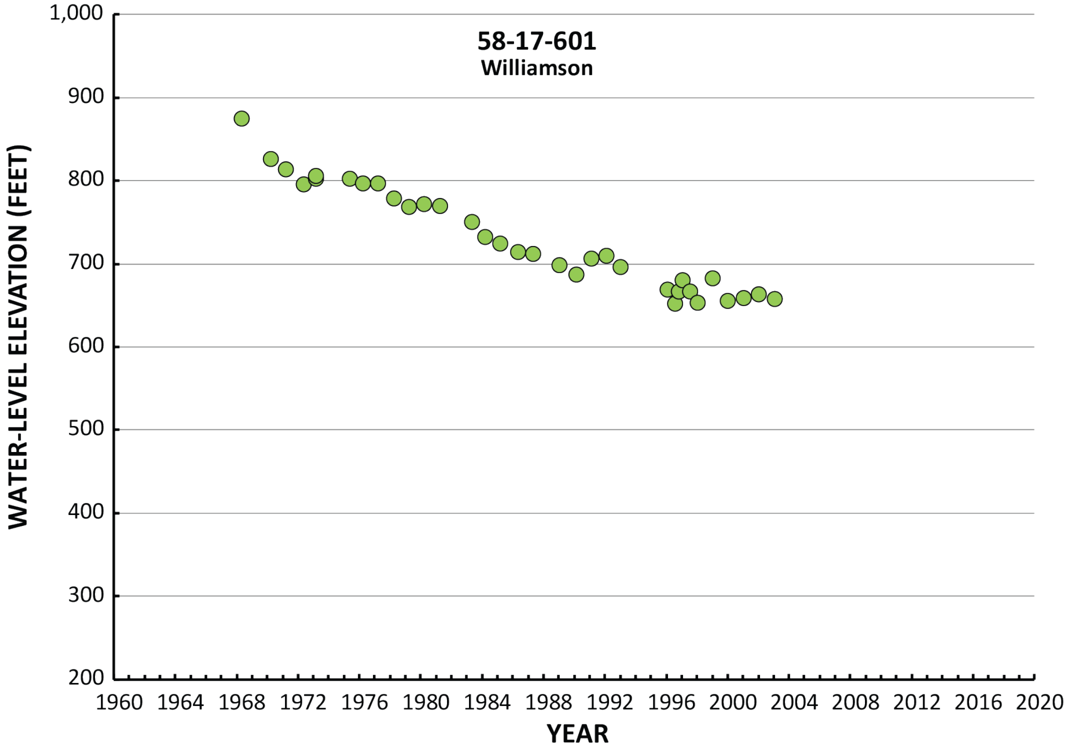
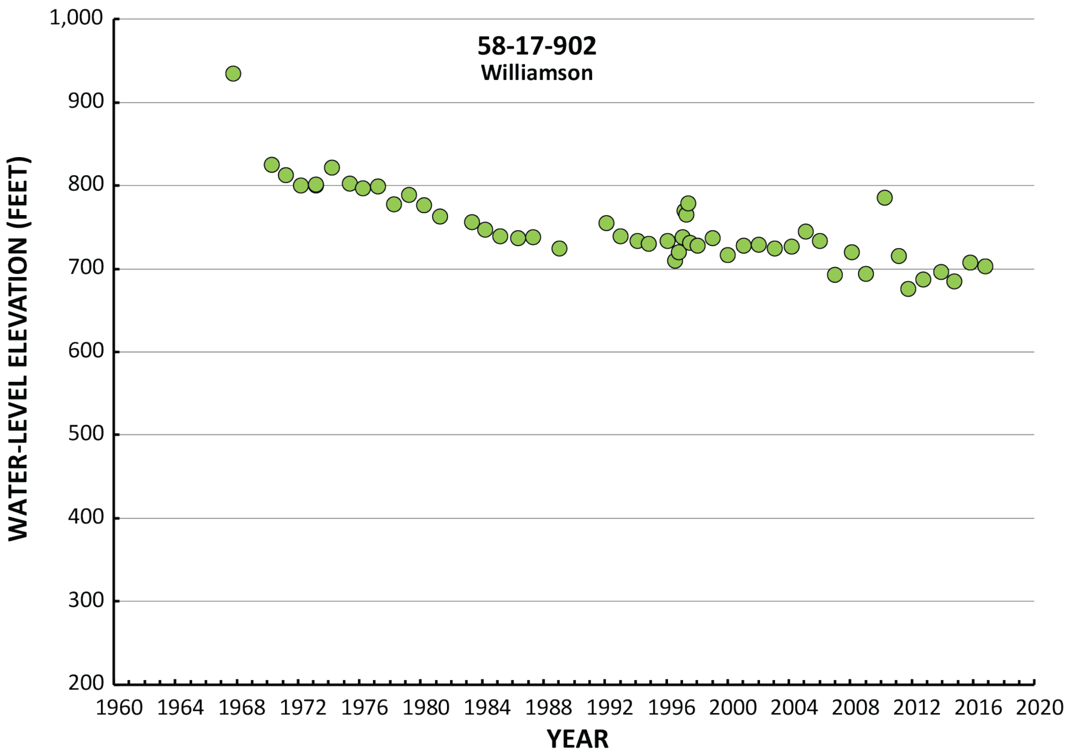


Figure 4.2.12. (continued)





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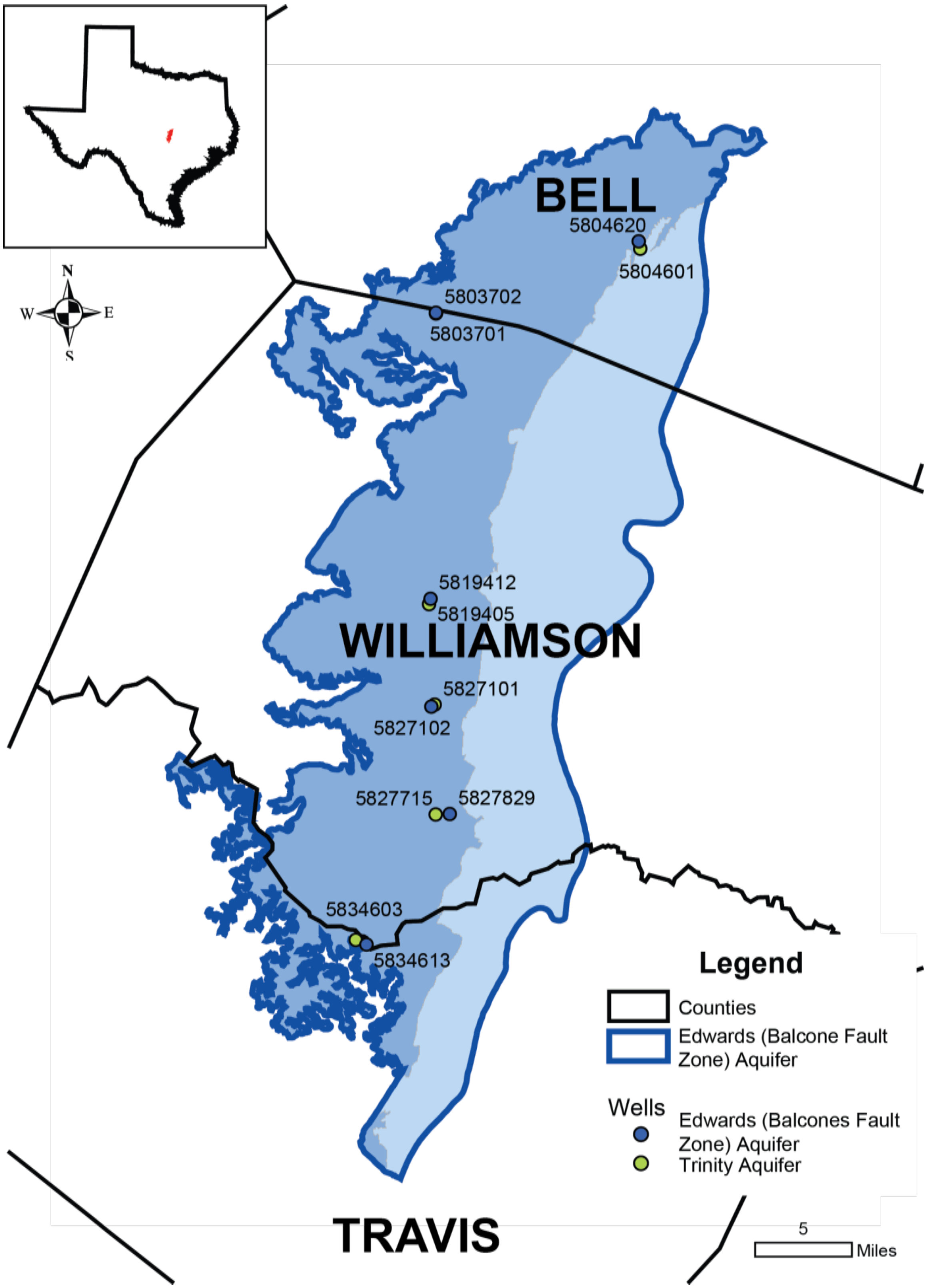


Figure 4.2.13. **Locations of wells used for comparing water-level elevations between the northern segment of the Edwards (Balcones Fault Zone) and Trinity aquifers (Texas Water Development Board, 2017a).**

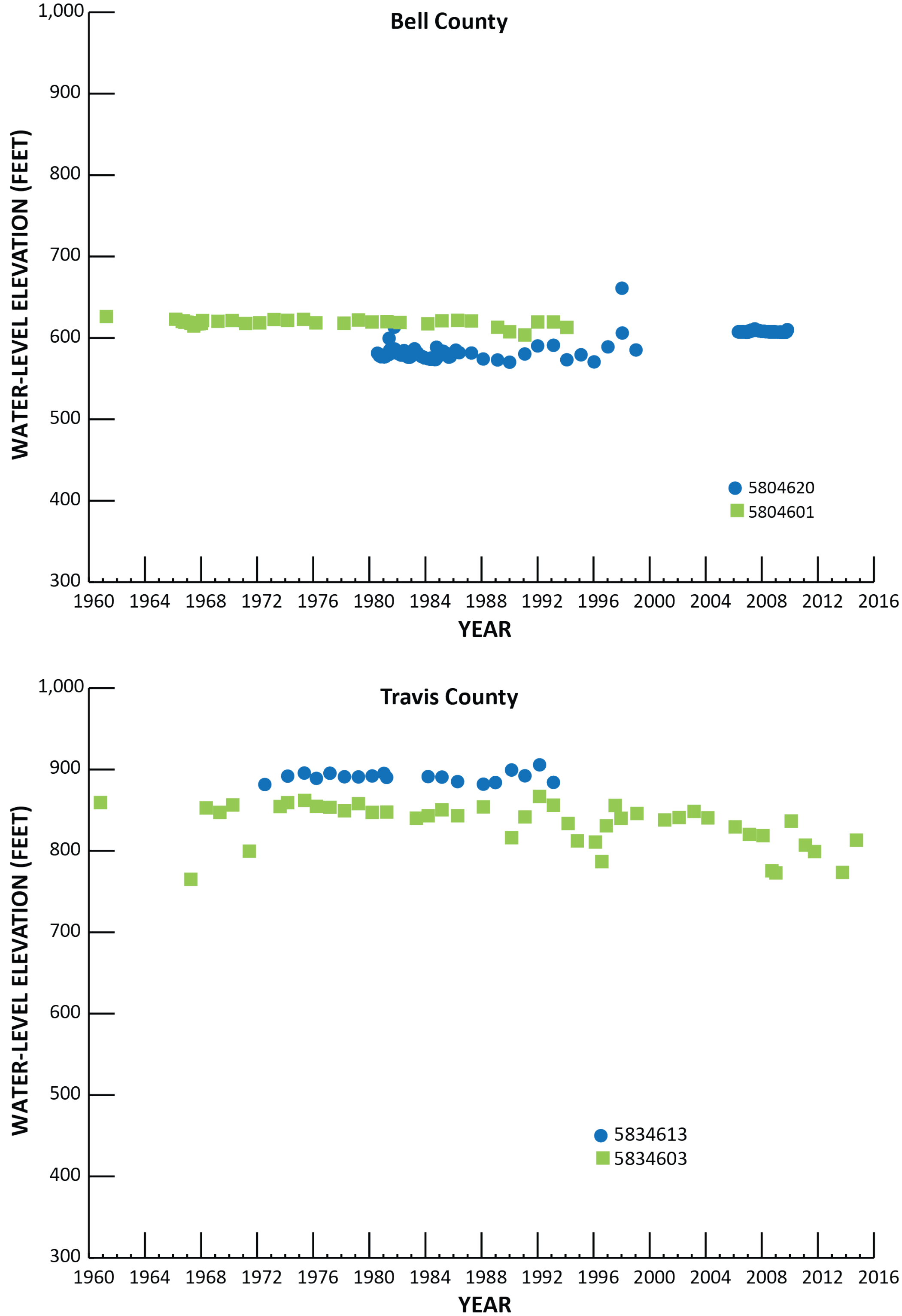
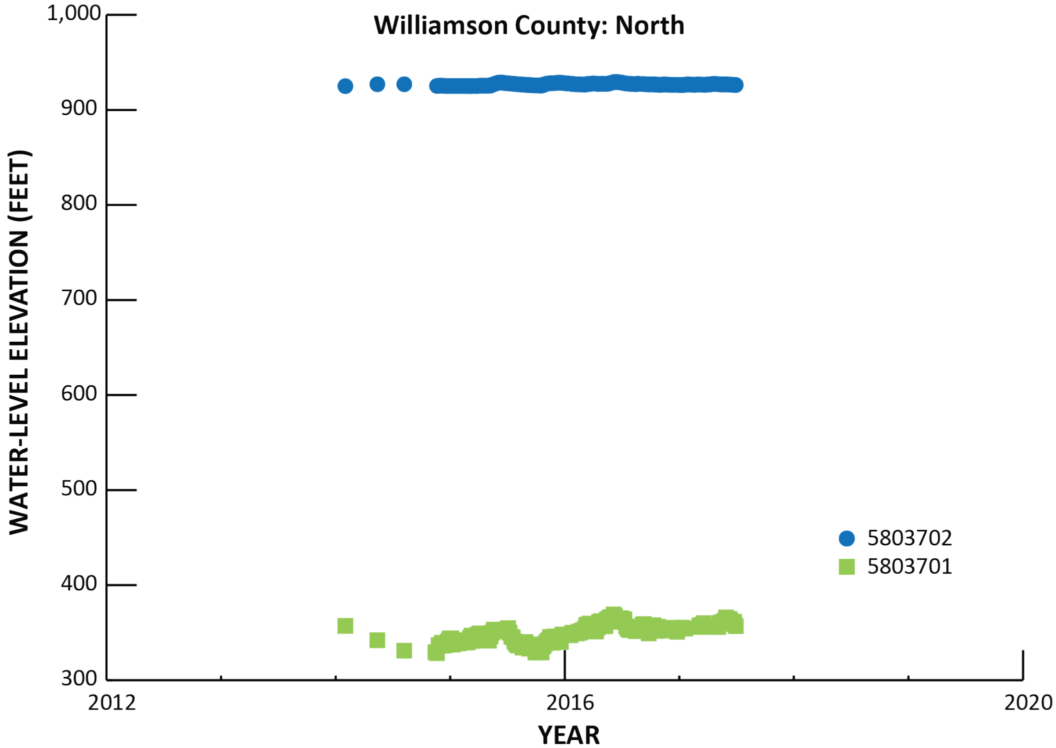
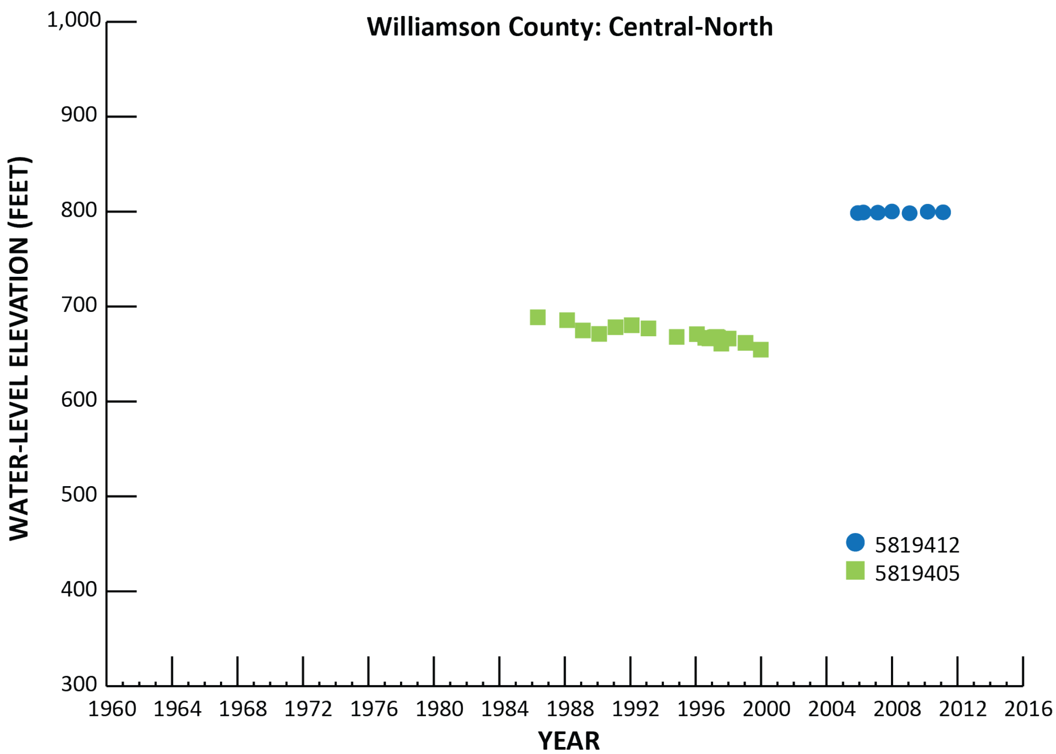


Figure 4.2.14. Comparison of water-level elevations (in feet above mean sea level) in the northern segment of the Edwards (Balcones Fault Zone) Aquifer (blue) and Trinity Aquifer (green) (Texas Water Development Board, 2017a).





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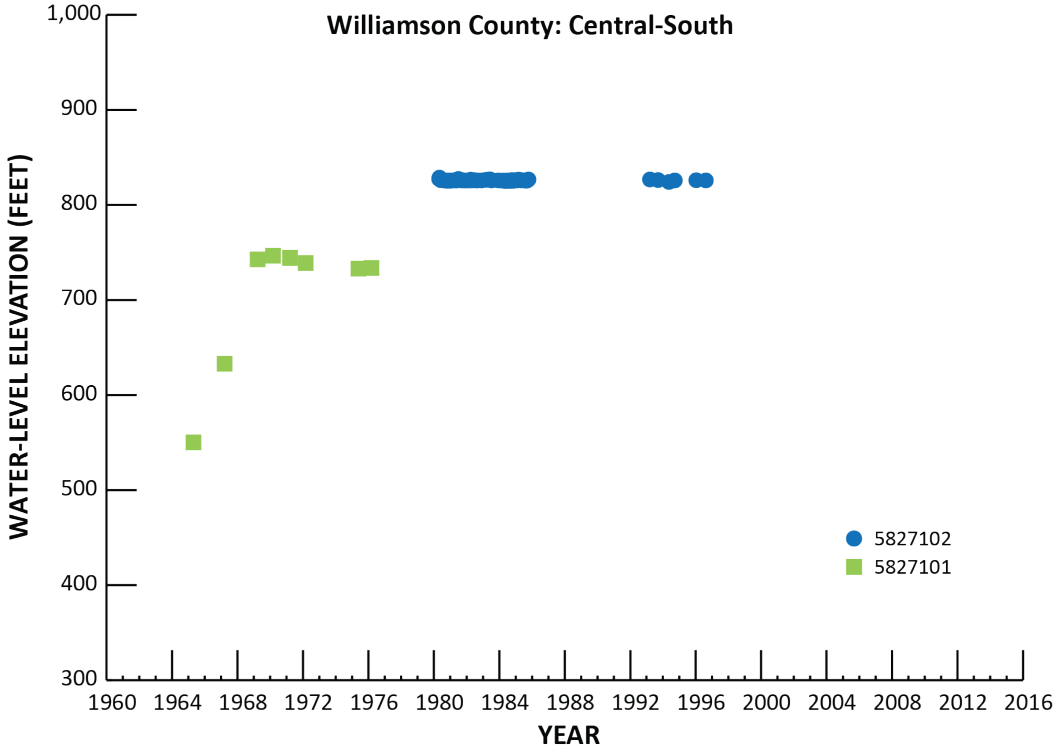


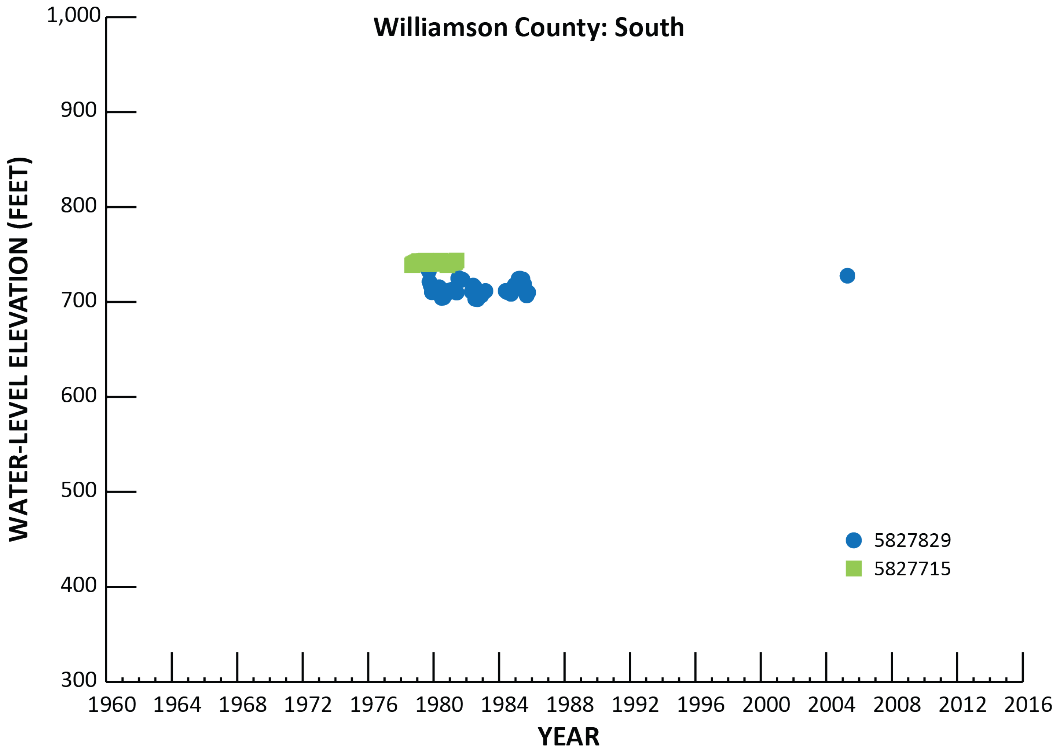


Figure 4.2.14. (continued)

4.3 Recharge

Recharge is defined as the processes involved in the addition of water to the water table (Jackson, 1997). Potential sources for recharge include infiltration of precipitation and stream water, and irrigation return-flow.

During a rainfall event: (1) some of the precipitation is transmitted by surface runoff into streams, (2) some of the precipitation is taken up by plants, and released back into the atmosphere through evapotranspiration, and (3) the remainder—if any—infiltrates into the soil and rock and recharges the underlying aquifer. The potential for the occurrence of recharge in the northern segment of the Edwards (Balcones Fault Zone) Aquifer is greater where it is exposed at land surface (see Figure 2.0.2) compared to areas where infiltrating water must pass through overlying units. Faults and karst dissolution features potentially facilitate recharge by acting as pathways for rapid infiltration of water both where the northern segment of the Edwards (Balcones Fault Zone) Aquifer crops out and where it is confined by overlying aquifers or aquitards—rocks that do not transmit useable amounts of water and thus do not meet the criteria to be aquifers. Recharge to the northern segment of the Edwards (Balcones Fault Zone) Aquifer is potentially topographically controlled, with higher recharge in the areas of higher elevation.

Recharge to the northern segment of the Edwards (Balcones Fault Zone) Aquifer takes the form of infiltration of precipitation that falls on the aquifer outcrop or infiltration of runoff derived from watershed areas upstream from the aquifer outcrop. The recharge zone in the study area consists mainly of gently rolling terrain of the Lampasas Cutplains in the north, and is characterized by steeper, more highly dissected terrain of the Jollyville Plateau in the south (Figure 2.1.1; Duffin and Musick, 1991). The aquifer outcrop is characterized by the occurrence of numerous scattered karst features, such as dissolution-enhanced fractures, sinkholes, and caves, which are potential recharge sites.

Sinkholes that occur in the Jollyville Plateau can transmit large amounts of water to the aquifer following heavy rainfall events (Figure 2.1.1; Kreitler and others, 1987). Recharge also takes the form of infiltration along faults and joints that intersect losing segments of perennial and intermittent streams that cross the study area. These fractures are often enlarged by karstification (Brune and Duffin, 1983). Infiltrating water tends to perch within the Georgetown Formation because of the occurrence of low-permeability shale members. Resultant lateral flow often discharges from small seeps and springs. Rapid recharge occurs when underlying Edwards and Comanche Peak limestones are encountered (Dahl, 1990).

Recharge processes are more complex in the north, where stream segments are either gaining or losing depending on relative elevations of the water table and streambeds and thus may vary seasonally (Duffin and Musick, 1991). Streamflow studies by the United

States Geological Survey (USGS) in 1978 and 1979 indicate that, in the north, streams generally act as points of groundwater discharge rather than recharge (Figure 4.3.1; Senger and others, 1990; Duffin and Musick, 1991; Slade and others, 2002). Recharge in the north occurs primarily by infiltration along intermittent streams and by infiltration of precipitation on the aquifer outcrop. Recharge also occurs in losing segments of the major rivers that occur along the western margin of the aquifer (Dahl, 1990; Slade and others, 2002). This recharge results in the formation of groundwater mounds along the western margin of the aquifer (Figure 4.2.6). Potential for groundwater inflow by cross-formational flow also exists from the underlying Trinity Aquifer (Duffin and Musick, 1991). However, the water-level differences of more than 100 feet in the up-dip portions of the Edwards (Balcones Fault Zone) Aquifer suggest groundwater perching in the Edwards (Balcones Fault Zone) Aquifer due to isolation from the Trinity Aquifer by aquitards in parts of the Walnut and Glen Rose formations, separating the two aquifers (Figures 4.2.13 and 4.2.14).

Recharge estimates in the Salado Creek basin by Dahl (1990) indicate recharge of 15 percent of precipitation over the Edwards (Balcones Fault Zone) Aquifer outcrop and 60 percent of storm runoff originating from upstream of the aquifer outcrop. These estimates of precipitation recharge were based on groundwater-level responses and an assumption of 2 percent porosity. The storm-runoff recharge was estimated based on stream discharge measurements above and below losing stream segments. Dahl (1990) indicated that recharge of precipitation in the Salado Creek basin contributes much larger volumes of water to the aquifer (about 29,000 acre-feet in 1985) than storm runoff (about 2,700 acre-feet).

Isotopes in groundwater, such as carbon-13, carbon-14, tritium, and stable hydrogen and oxygen can be used to determine the spatial and seasonal distribution of recharge to an aquifer (See Section 4.7). The tritium, carbon-13, and carbon-14 isotopic compositions of northern segment of the Edwards (Balcones Fault Zone) Aquifer groundwater indicate recharge zones where the aquifer crops out and suggests little groundwater circulation in the confined parts of the aquifer. The stable oxygen and hydrogen isotopes indicate that most recharge to the northern segment of the Edwards (Balcones Fault Zone) Aquifer occurs during fall and winter months (Jones, 2006).

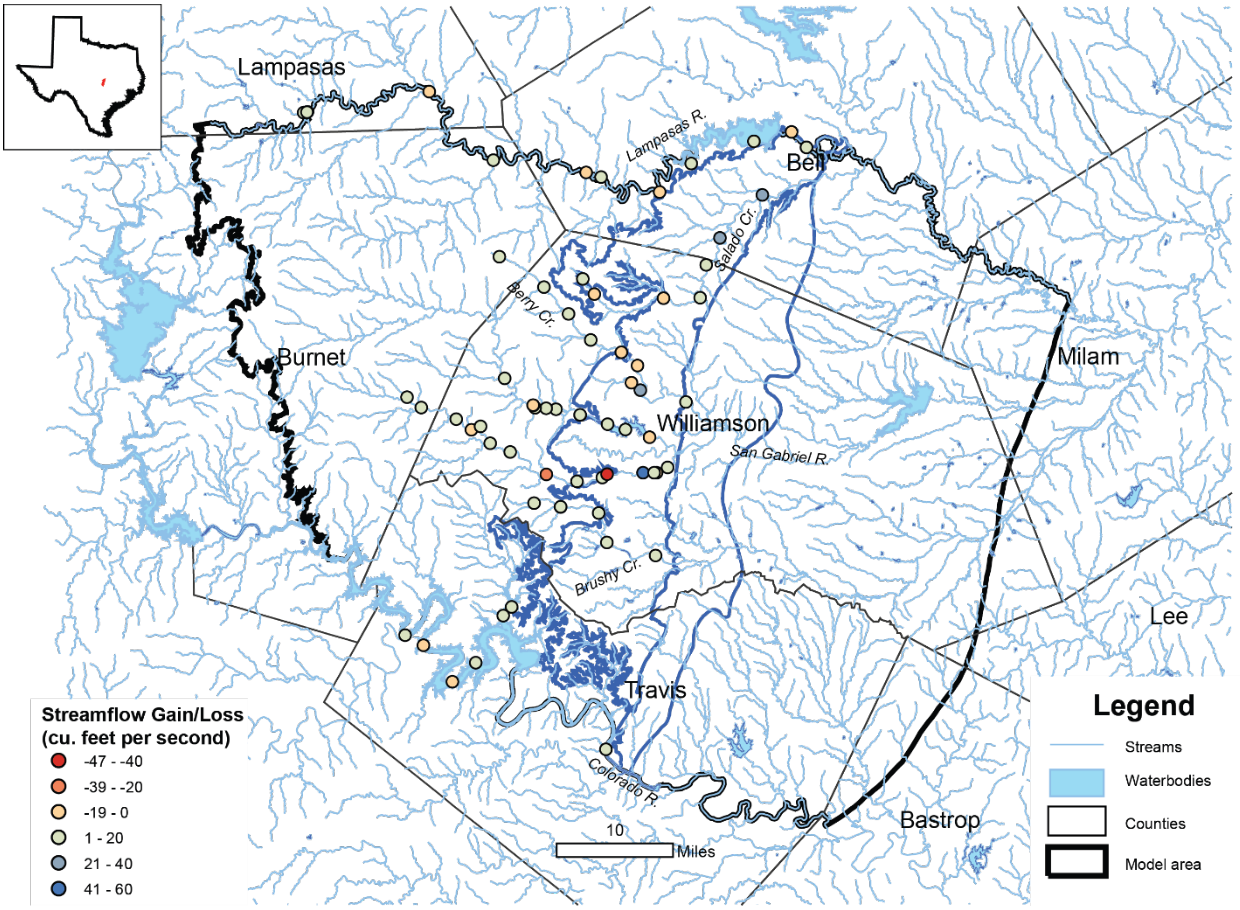


Figure 4.3.1. Streamflow gain-loss data from Slade and others (2002), where negative values indicate losing streams while positive values indicate gaining streams.

4.4 Rivers, Streams, Springs, and Lakes

Interaction between groundwater and surface water occurs primarily where surface water bodies—rivers and streams, springs, and lakes—intersect with aquifer outcrops. These interactions result in flow between the aquifer and surface-water bodies. The direction of flow depends on the relative groundwater and surface-water levels with water flowing from relatively high to relatively low water levels.

4.4.1 Rivers and Streams

The northern segment of the Edwards (Balcones Fault Zone) Aquifer is bisected by the hydrologic divide between the Colorado and Brazos River basins (Figure 2.0.11). This hydrologic divide coincides approximately with the boundary between Travis and Williamson counties. Consequently, surface water flows to the north and east toward the Brazos River in Bell and Williamson counties and toward the south to the Colorado River in Travis County. The Lampasas and Colorado rivers that form the northern and southern boundaries of the study area are the largest rivers in the area (Figure 2.0.4). Smaller rivers and creeks, such as Brushy Creek, Berry Creek, Salado Creek, and San Gabriel River, cross the outcrop of the aquifer and are likely recipients of groundwater discharge, indicated by their perennial flow (Figure 4.3.1). Smaller tributaries of these rivers and creeks often flow intermittently because of storm-related runoff. Groundwater and surface-water systems are closely related in recharge and discharge zones, where interchange occurs as a result of recharge and discharge processes, respectively (Baker and others, 1986). Groundwater-surface-water interaction along gaining and losing stream segments of major rivers and creeks varies by location and hydrologic conditions because of significant hydrologic connections between streams and the underlying aquifer (Land and Dorsey, 1988).

Interaction between groundwater and rivers and streams depends on the relative elevations of the aquifer water table and the stream stage. In losing streams, the water table is below the elevation of the stream stage, and the gradient causes water to flow from the stream into the aquifer. In gaining streams, the water table is above the elevation of the stream stage and consequently water flows from the aquifer into the stream. The results of several streamflow gain/loss studies in the northern segment of the Edwards (Balcones Fault Zone) Aquifer study area are documented by Slade and others (2002) (Figure 4.3.1).

In the study area, there is variation of the relative impacts on streamflow of (1) storm-related runoff and (2) groundwater discharge in the form of baseflow. Streams in which streamflow is dominated by baseflow are characterized by relatively small flow-rate fluctuations (Figures 4.4.1 and 4.4.2). Salado Creek, which is dominated by discharge from numerous springs, notably from Salado Springs, is an example of this type of stream. Streams dominated by storm runoff, such as Shoal Creek, are characterized by rapid recession after storms and low baseflow. Streamflow in Berry Creek is more representative of the streams in the study area, and streamflow fluctuations indicate inputs from both baseflow and storm-related runoff. Comparison of streamflow at pairs of stream gages can be used to indicate whether the stream is losing flow owing to recharge or receiving groundwater discharge (Figure 4.4.2). Decreased downstream flow commonly indicates a losing stream because of recharge to the underlying aquifer, whereas consistent increases in flow are quite often the result of groundwater discharge entering the stream. In the study area, decreased streamflow in downstream parts of Shoal Creek is consistent with recharge to the aquifer, whereas increased downstream flow in Berry Creek and the San Gabriel River can be attributed to groundwater discharge through numerous springs and seeps that occur in the area (Figure 4.4.2).

4.4.2 Springs

Springs are locations where the water table intersects the ground surface (Figure 4.4.3). Spring data for the northern segment of the Edwards (Balcones Fault Zone) Aquifer were found in the Texas Water Development Board groundwater database (Texas Water Development Board, 2017a), a database of Texas springs compiled by the United States

Geological Survey (Heitmuller and Reece, 2003), and a report on the springs of Texas by Brune (2002).

Springs and seeps in the western part of the aquifer discharge mostly from fractures or cavities in the Edwards Limestone, or along the contact between the Edwards and Comanche Peak Limestones (Kreitler and others, 1987). The identified springs mostly occur in the Salado Creek, Brushy Creek, and San Gabriel River watersheds and along the southern boundary of the Edwards (Balcones Fault Zone) Aquifer outcrop where contact between the Edwards (Balcones Fault Zone) Aquifer and underlying confining unit is exposed by downward erosion by streams such as Bull Creek. The springs with the highest discharge rates, known as major springs, are associated with major faults, generally occurring some distance east of these faults (Figure 4.4.4). Major springs occur primarily in the Salado Creek and San Gabriel River watersheds (Figure 4.4.5).

4.4.3 Lakes and Reservoirs

Typically, interaction between an aquifer and a lake or reservoir is restricted to the outcrop area of an aquifer where the lake or reservoir lies directly on the aquifer. There are no natural lakes on the outcrop of the northern segment of the Edwards (Balcones Fault Zone) Aquifer. However, there is thought to be interaction between the Edwards (Balcones Fault Zone) Aquifer and Lake Georgetown, which is located on the San Gabriel River overlying the Edwards (Balcones Fault Zone) Aquifer. Slade and others (2002) indicate that Lake Georgetown receives baseflow from the Edwards (Balcones Fault Zone) Aquifer (Figure 4.3.1).

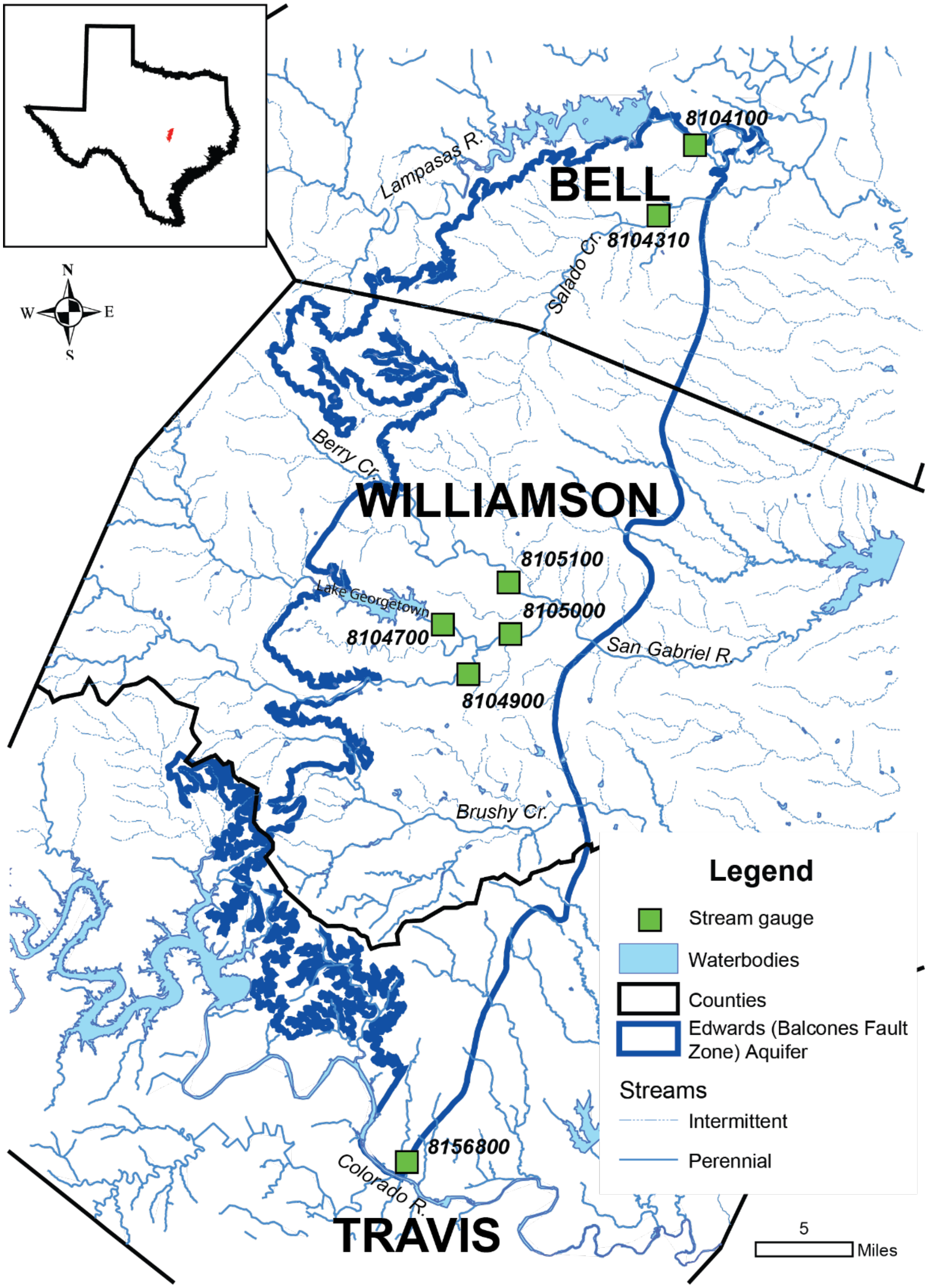


Figure 4.4.1. Locations of hydrographs from stream gauges in the northern segment of the Edwards (Balcones Fault Zone) Aquifer.

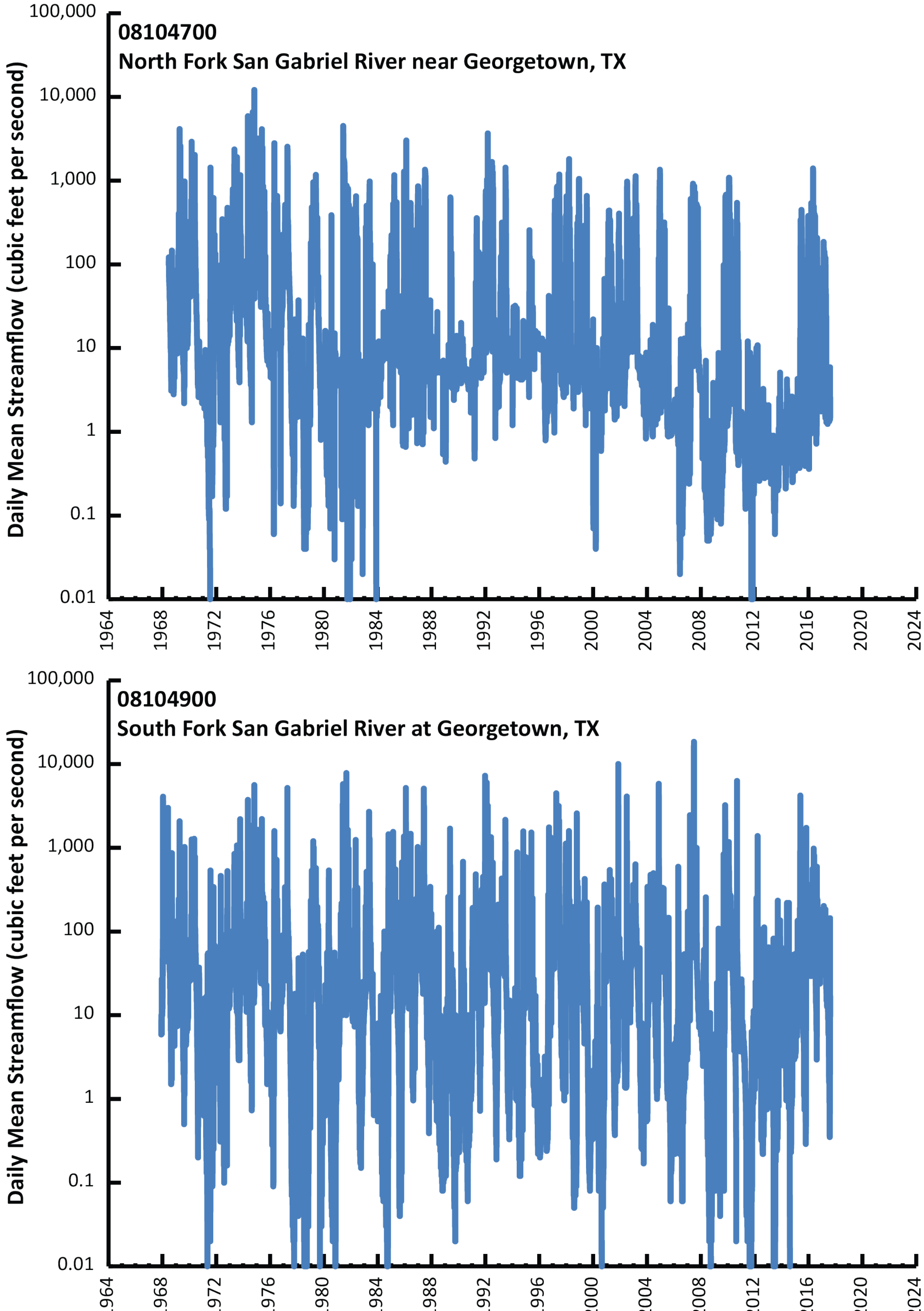
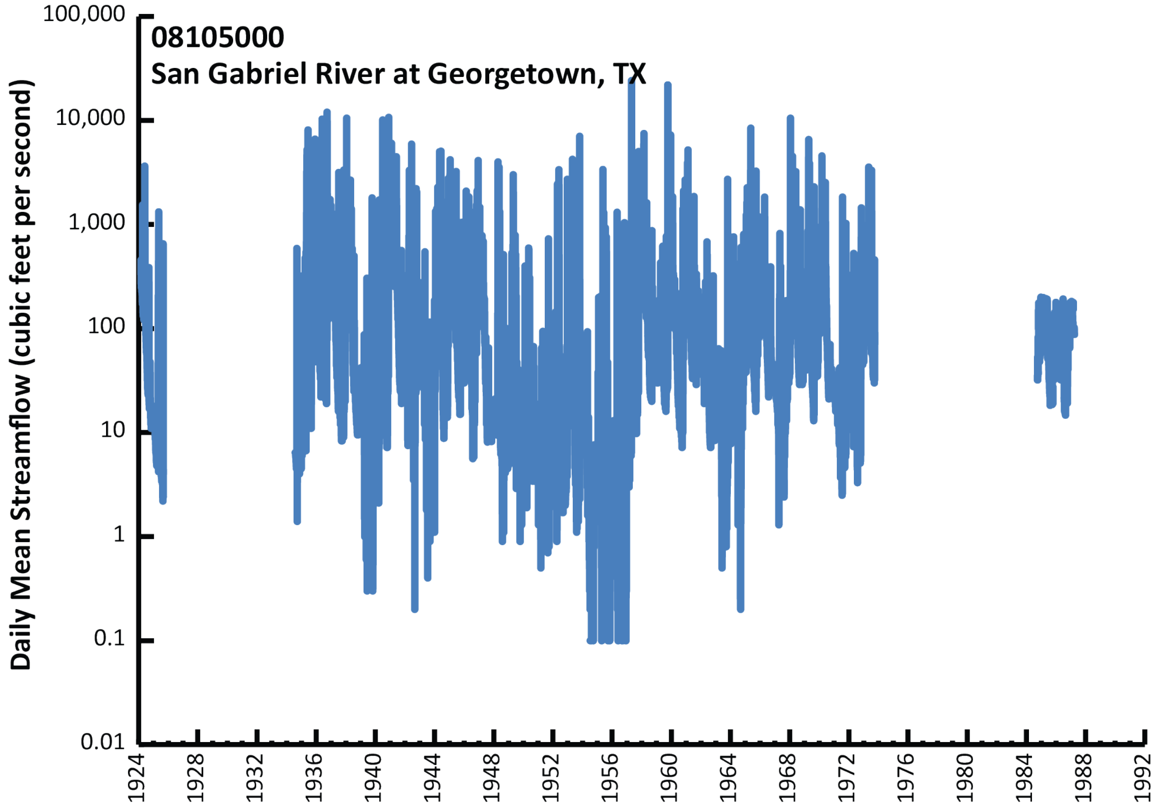


Figure 4.4.2. Streamflow hydrographs for selected stream gages in the study area (United States Geological Survey, 2017b). See Figure 4.4.1 for locations.



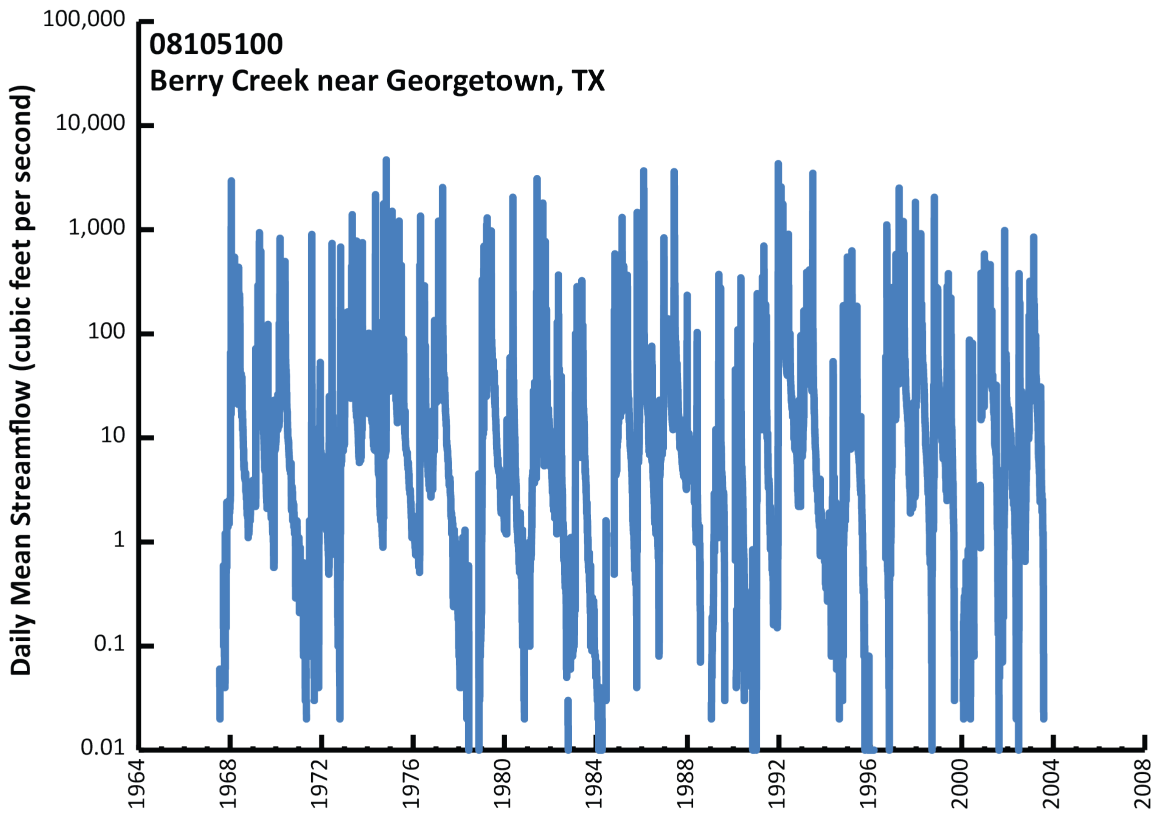
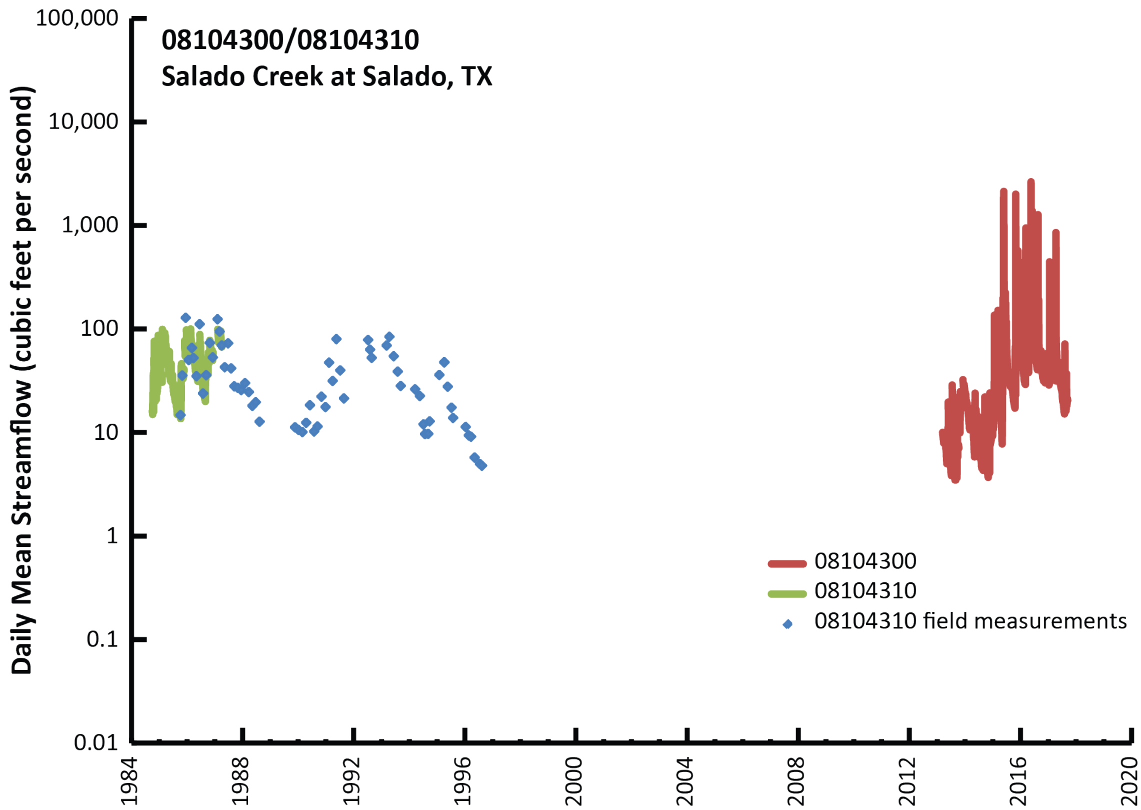


Figure 4.4.2. (continued).



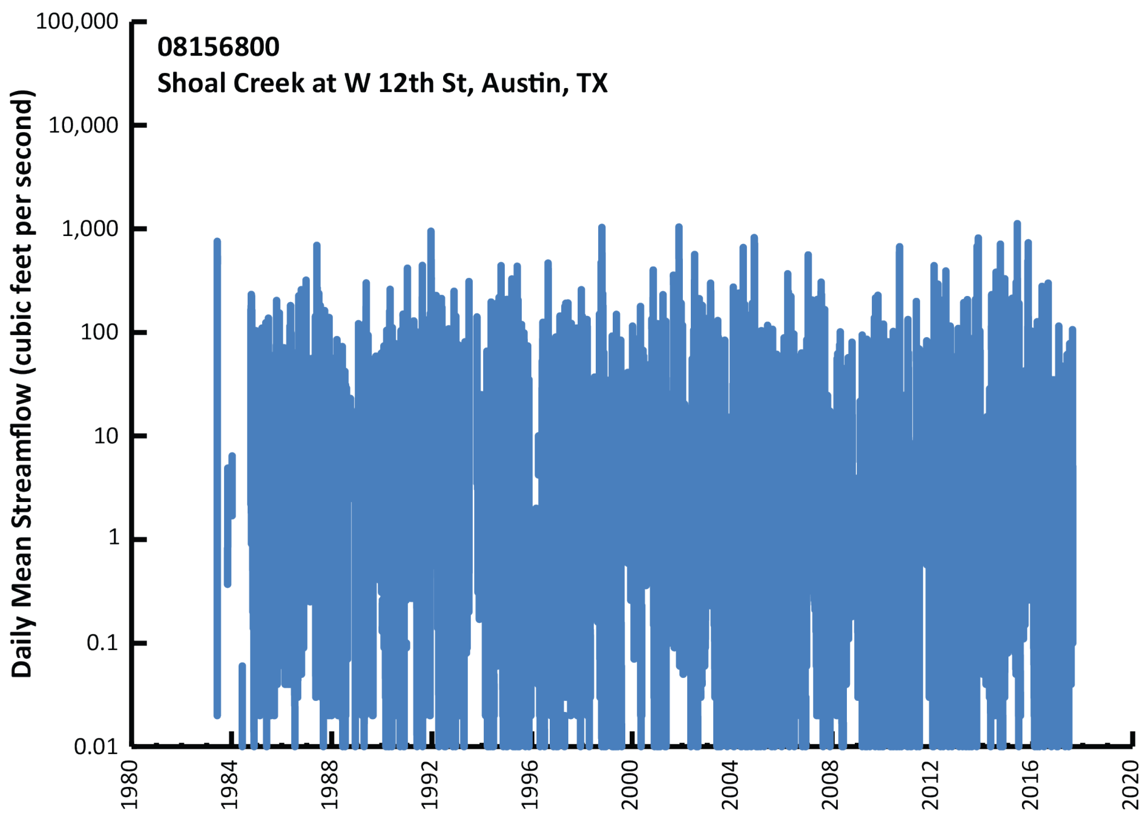


Figure 4.4.2. (continued).

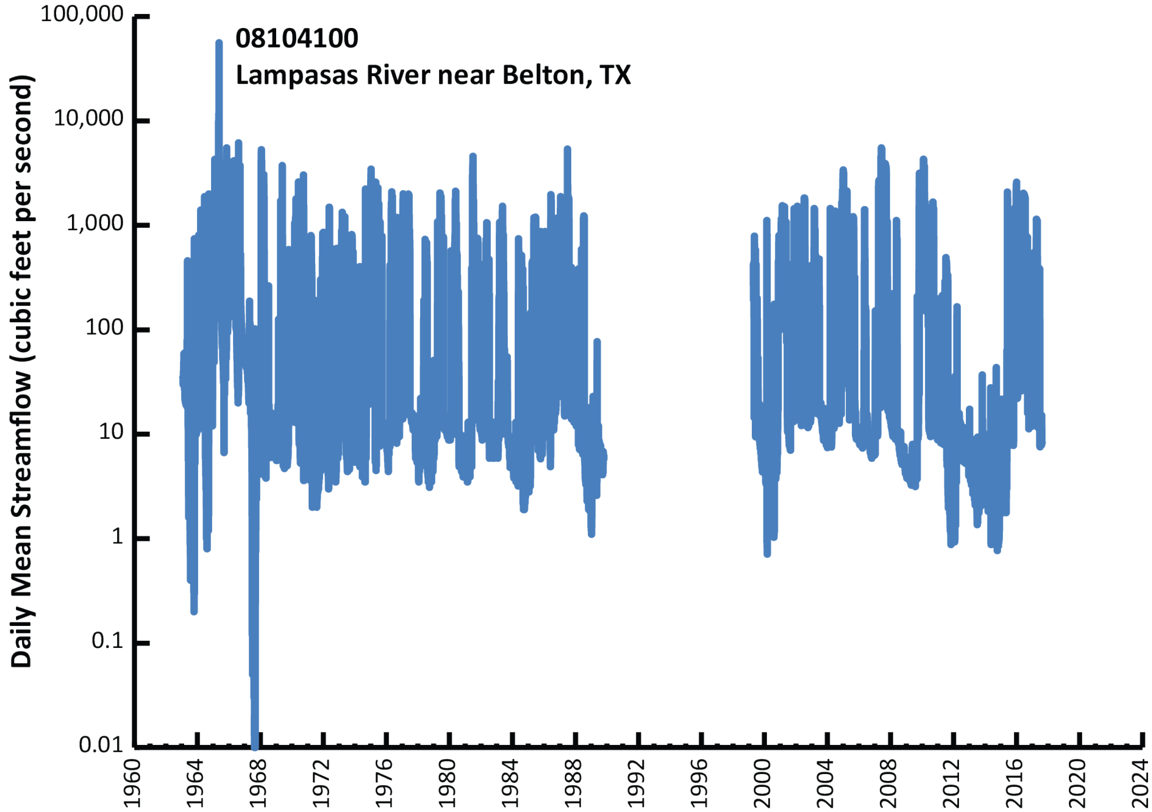


Figure 4.4.2. (continued).

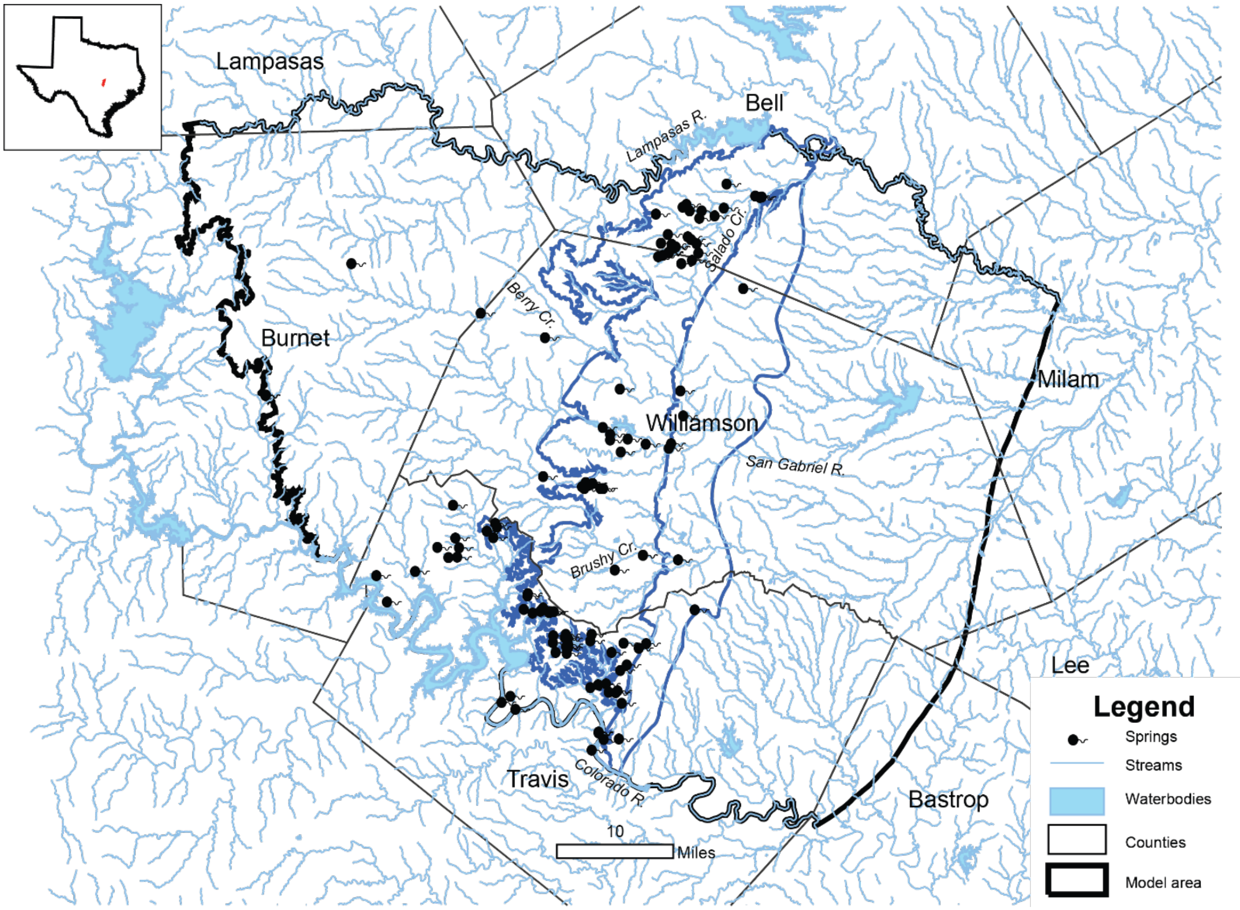


Figure 4.4.3. **Locations of springs in the northern segment of the Edwards (Balcones Fault Zone) Aquifer study area.**

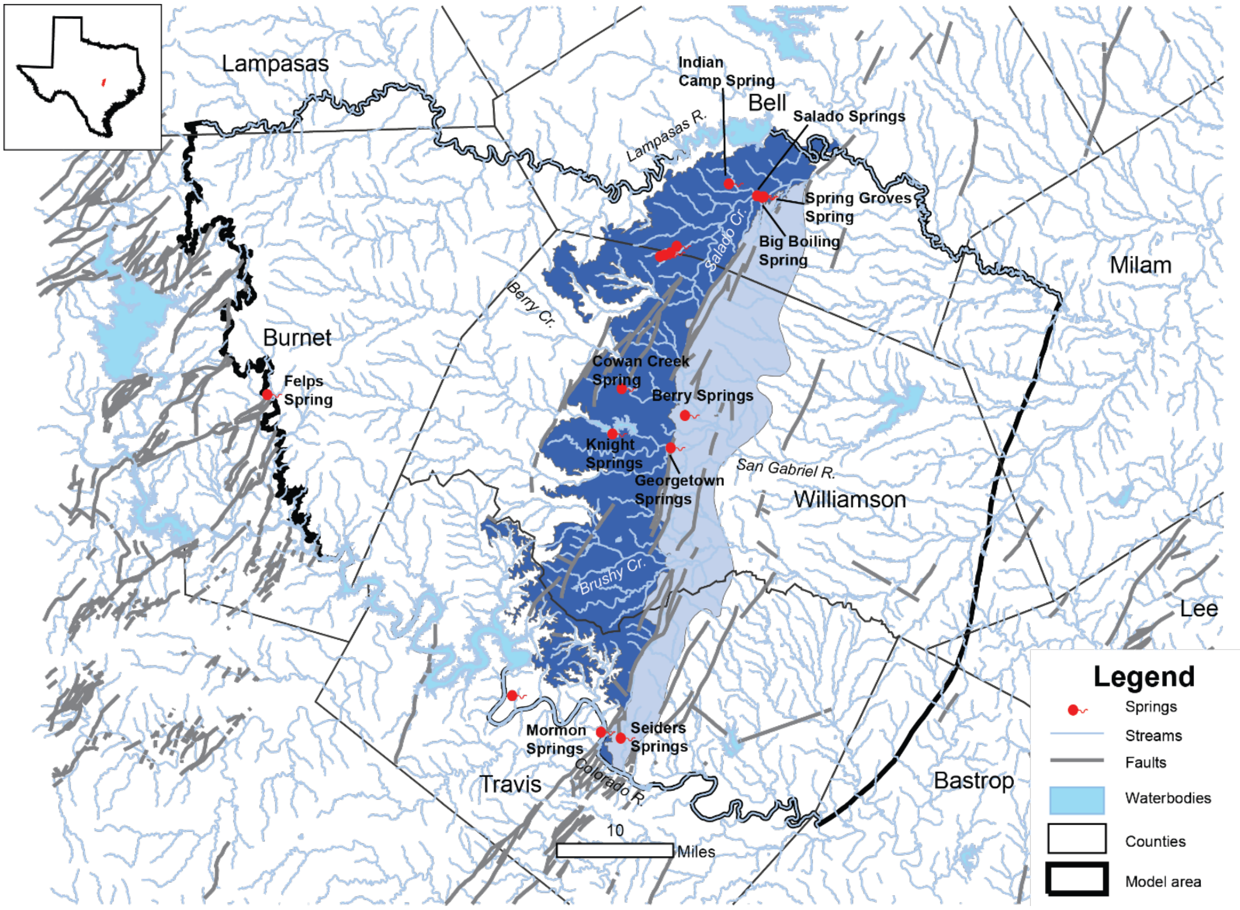


Figure 4.4.4. Locations of the major springs in the northern segment of the Edwards (Balcones Fault Zone) Aquifer study area.

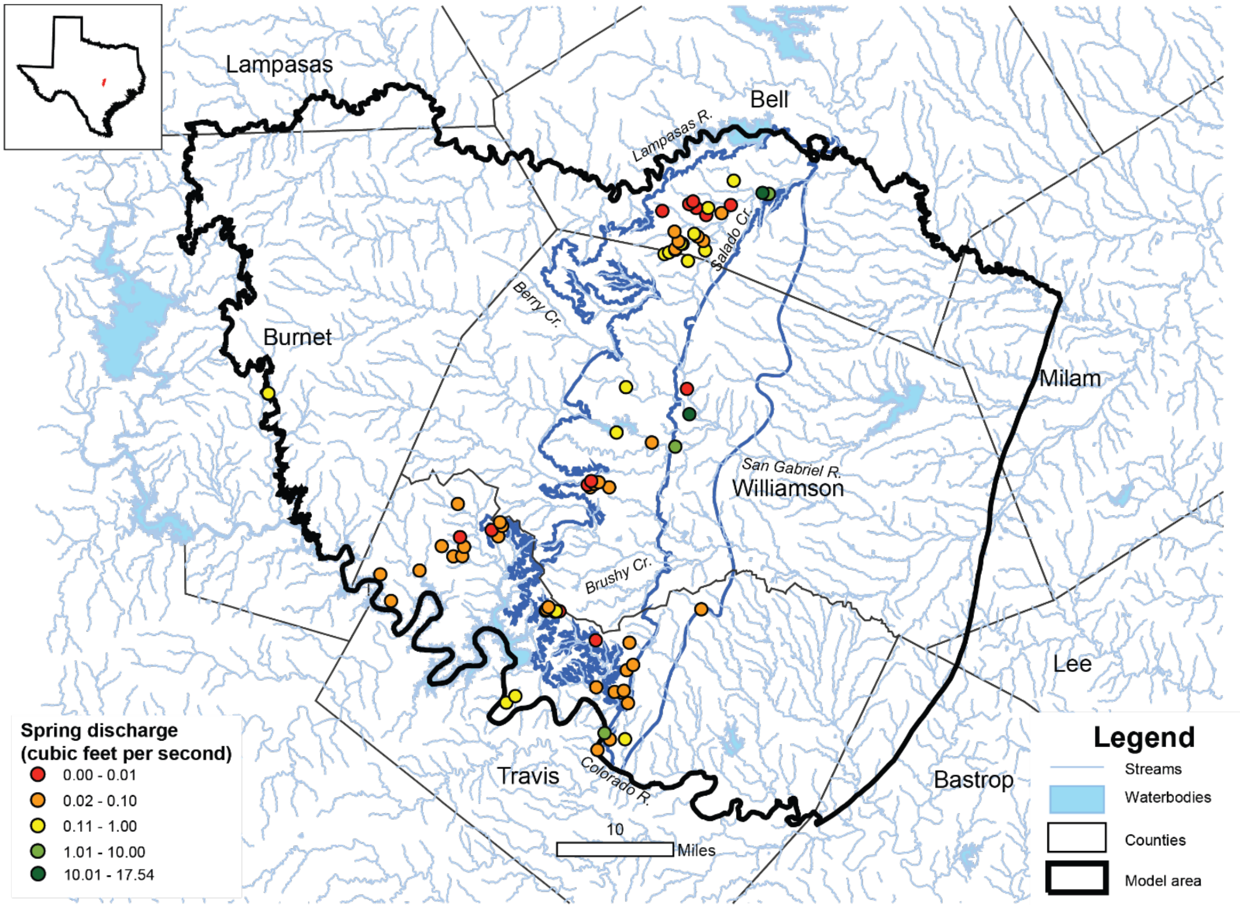


Figure 4.4.5. **Spring discharge measurements from springs in the northern segment of the Edwards (Balcones Fault Zone) Aquifer study area.**

4.5 Hydraulic Properties

There is a paucity of hydraulic property data for the northern segment of the Edwards (Balcones Fault Zone) Aquifer. The ability of the aquifer to transmit groundwater to a well varies greatly. Factors impacting the ability of the aquifer to transmit groundwater include: aquifer lithology, karstification, structural deformation, and fracturing. This section reviews the sources of available data describing the northern segment of the Edwards (Balcones Fault Zone) Aquifer hydraulic properties. Several hydraulic properties are used to describe groundwater flow in aquifers. The properties discussed here are hydraulic conductivity, transmissivity, coefficient of storage or storativity, and specific capacity. Each of these terms is briefly described below.

Hydraulic conductivity is a measure of the ease with which groundwater can flow through an aquifer. Higher hydraulic conductivity indicates that an aquifer will allow more groundwater flow under the same hydraulic gradient. In this study, units for hydraulic conductivity are feet per day.

Transmissivity is a term closely related to hydraulic conductivity but is a function of the saturated thickness of an aquifer. Transmissivity describes the ability of groundwater to flow through the entire saturated thickness of an aquifer. As the saturated thickness increases, the transmissivity increases for a given hydraulic conductivity. In this study, units for transmissivity are square feet per day.

Storativity—also referred to as the coefficient of storage—is the volume of water that a confined aquifer releases per square foot of surface area per foot decline of water level. Storativity is a dimensionless parameter.

Specific capacity is a measure of well productivity represented by the ratio between the well pumping rate and the corresponding drawdown decline in water level. In this study, specific capacity is expressed in gallons per minute per foot of drawdown in a well.

4.5.1 Data Sources

Development of hydraulic properties for the northern segment of the Edwards (Balcones Fault Zone) Aquifer in the study area used multiple sources including submitted drillers' reports and the groundwater database the Texas Water Development Board website (Texas Department of Licensing and Regulation, 2017; Texas Water Development Board, 2017a).

The hydraulic property data for the northern segment of the Edwards (Balcones Fault Zone) Aquifer are shown in Figures 4.5.1 through 4.5.3 and Table 4.5.1. Using all sources available, 83 estimates of specific capacity were found for the northern segment of the Edwards (Balcones Fault Zone) Aquifer.

4.5.2 Calculation of Hydraulic Conductivity from Specific Capacity

Specific capacity values are calculated from the pumping rate and corresponding drawdown, which are commonly reported in well records. However, hydraulic conductivity or transmissivity are more useful parameters than specific capacity for regional groundwater flow modeling. The following methodology was used to estimate transmissivity from specific capacity data.

Point estimates of aquifer transmissivity can be made based on measurements of specific capacity. In the absence of pump test data, transmissivity can still be estimated using the Cooper-Jacob solution for drawdown in a pumping well (Cooper and Jacob, 1946):

$$s = \frac{Q}{4\pi T} ln\left(\frac{2.25Tt}{r^2 S}\right) \tag{4.5.1}$$

where:

s = drawdown in the well [L],

Q = pumping rate [L3/T],

T = transmissivity [L2/T],

t = time [T],

r = radius of the well [L], and

S = storativity [--].

Equation (4.5.1) can be rearranged to solve for specific capacity as:

$$\frac{Q}{s} = \frac{4\pi T}{ln\left(\frac{2.25Tt}{r^2 S}\right)} \tag{4.5.2}$$

For a given specific capacity, transmissivity can be solved iteratively. Table 4.5.1 provides specific capacity and calculated transmissivity and hydraulic conductivity data for Edwards (Balcones Fault Zone) Aquifer wells. Transmissivity was calculated using the iterative method outlined by Equation 4.5.2 and assuming a storativity value of 0.0001. Hydraulic conductivity was calculated by dividing the transmissivity by the well screen length or, in the absence of screen information, by the thickness of the Edwards (Balcones Fault Zone) Aquifer indicated in Figure 4.1.4.

As one would expect in a karst system, the hydraulic properties of the northern segment Edwards (Balcones Fault Zone) Aquifer are highly variable. This variability can be attributed to many factors, such as (1) limestone primary porosity due to facies changes within or between individual stratigraphic units, (2) fracture densities, and (3) development of karst features. Hovorka and others (1996) showed that limestones deposited in subtidal environments exhibit lower porosities than carbonate sandstones or dolomite. Based on outcrop descriptions, Hovorka and others (1998) showed that fractures and karst features make up 1 to 3 percent of the outcrop area, and karst features develop preferentially adjacent to faults and in dolomitized limestone. Matrix permeability accounts for only about 1 percent of the flow through the aquifer, and the remainder is contributed by fractures and karst features.

Transmissivity estimates for the Edwards and associated limestones in the northern segment of the Edwards (Balcones Fault Zone) Aquifer vary widely, lying in the range of 0.5

to 4×10^6 square feet per day, seven orders of magnitude (Figure 4.5.1). These transmissivity estimates are calculated from specific-capacity data from the Texas Water Development Board (TWDB) well database using methods outlined in Mace (2001). The highest transmissivities can be attributed to cave systems, whereas solution-enhanced fracture porosity and intergranular porosity produce intermediate and low transmissivities, respectively (Hovorka and others, 1998). In the aquifer, transmissivity in the central part of the study area—along the eastern boundary of the outcrop—is generally higher than along the eastern or western boundaries (Slade, 1987). This phenomenon is attributed to fracture densities that are associated with the major faults of the Balcones Fault Zone.

There is little hydraulic conductivity data that are based on pumping tests for the northern segment of the Edwards (Balcones Fault Zone) Aquifer. Transmissivity data from the available specific capacity test data were converted to hydraulic conductivity based on aquifer thickness (Figure 4.5.2). Resultant hydraulic conductivity values range between 0.005 and more than 30,000 feet per day, and median and geometric mean values are 9 feet per day (Figure 4.5.3). These values overlap with hydraulic conductivity data—2.7×10^{-5} to 13 feet per day—for the San Antonio segment of the Edwards (Balcones Fault Zone) Aquifer (Hovorka and others, 1996). There is very little hydraulic conductivity data on the unconfined part of the aquifer. Spatial distribution of the data suggests no apparent trends, with the highest hydraulic conductivity occurring within a few hundred feet of very low hydraulic conductivity values. The Jollyville Plateau zone (Figure 2.1.1) coincides with the outcrop of relatively low permeability stratigraphic units, such as the Keys Valley Marl member and Cedar Park limestone member of the Walnut Formation, and the Comanche Peak Limestone. The remainder of the aquifer outcrop is composed of the Edwards Limestone and Georgetown Formation, which have generally higher permeability than the Jollyville Plateau.

The estimated hydraulic conductivity values for the Edwards (Balcones Fault Zone) Aquifer range from 0.005 to 31,178 feet per day, with a median of 10 feet per day (Figures 4.5.2 and 4.5.3). Highest hydraulic conductivity in the northern segment of the Edwards (Balcones Fault Zone) Aquifer is associated with karstification of the limestone (Senger and others, 1990). Underlying estimates of Trinity hydraulic conductivity of 0.01 to 4 feet per day are much lower than hydraulic conductivities in the overlying Edwards (Balcones Fault Zone) Aquifer (Table 4.5.1; Figure 4.5.4).

4.5.3 Storativity

The specific storage of a confined aquifer is defined as the volume of water that a unit volume of aquifer releases from storage under a unit decline in hydraulic head (Freeze and Cherry, 1979). The storativity is equal to the product of specific storage and aquifer thickness and is dimensionless. For unconfined conditions, the storage is referred to as the specific yield and is defined as the volume of water an unconfined aquifer releases from storage per unit surface area of aquifer per unit decline in water table (Freeze and Cherry, 1979). Aquifer storage properties are directly related to aquifer porosity in the unconfined portions of an aquifer and aquifer porosity and matrix compressibility in the confined portions of the aquifer.

No published storativity data exist for the northern segment of the Edwards (Balcones Fault Zone) Aquifer. Consequently, specific yield and specific storage values from the groundwater availability model for the adjacent Barton Spring segment of the Edwards (Balcones Fault Zone) Aquifer were used to represent storage in the northern segment of the Edwards (Balcones Fault Zone) Aquifer (Scanlon and others, 2001). This is appropriate considering the close proximity, relatively small size, and stratigraphic similarities of the two aquifer segments.

Table 4.5.1. Hydraulic property data from wells shown in Figure 4.5.1, located within the northern segment of the Edwards (Balcones Fault Zone) Aquifer. Q = well discharge (gallons per minute), s = drawdown (feet), SC = specific capacity (gallons per minute per foot), t = time (hours), r = casing diameter (inches), T= transmissivity (square feet per day), K = hydraulic conductivity (feet per day).

Well Number	Longitude	Latitude	County	Q	s	SC	t	r	T	K
5804509	-97.5428	30.9194	Bell	380	5	76	40	8	26,557	178
5804510	-97.5433	30.9227	Bell	350	15	23	70	8	7,655	51.4
5804602	-97.5364	30.9421	Bell	130	30	4	24	11	1,273	11.8
5804604	-97.5297	30.9555	Bell	125	3	42	24	6	14,543	137
5804611	-97.5400	30.9457	Bell	25	15	2	0	0	167	1.58
5804615	-97.5350	30.9435	Bell	30	15	2	0	0	203	1.88
5804616	-97.5345	30.9427	Bell	20	30	1	0	0	62.0	0.574
5804619	-97.5167	30.9419	Bell	25	118	0	0	0	18.0	0.099
5804701	-97.6075	30.9155	Bell	3	380	0	0	0	1.00	0.008
5804806	-97.5806	30.8971	Bell	15	30	1	0	0	45.0	0.265
5804808	-97.5703	30.8830	Bell	170	2	85	23	9	29,649	171
5804809	-97.5536	30.8849	Bell	5	150	0	1	5	8.00	0.045
5804811	-97.5703	30.8827	Bell	225	30	8	36	7	2,387	13.8
5805102	-97.4997	30.9871	Bell	2	142	0	0	0	1.00	0.005
5805401	-97.4689	30.9319	Bell	15	5	3	1	5	937	4.78
5811908	-97.6283	30.7874	Williamson	100	64	2	31	8	224	1.59
5811909	-97.6283	30.7906	Williamson	130	70	2	36	8	158	1.37
5812410	-97.6120	30.8260	Williamson	130	53	3	36	8	722	5.55
5819201	-97.6728	30.7257	Williamson	15	29	1	0	7	47.0	0.260
5819507	-97.6733	30.6880	Williamson	602	10	60	5	12	20,028	112
5819622	-97.6545	30.6996	Williamson	850	92	9	24	12	2,795	20.3
5819632	-97.6470	30.6824	Williamson	700	112	6	4	10	1,888	9.68
5819803	-97.6803	30.6360	Williamson	754	12	63	24	12	20,947	134
5819804	-97.6797	30.6360	Williamson	759	8	95	24	12	32,256	188
5819805	-97.6692	30.6502	Williamson	2,005	6	365	7	16	56,781	299
5819906	-97.7192	30.3383	Travis	285	79	4	24	16	763	6.20
5820103	-97.6000	30.7444	Williamson	200	77	3	28	16	260	1.35
5820401	-97.5867	30.6752	Williamson	10	47	0	0	6	18.0	0.063
5820408	-97.5945	30.7082	Williamson	434	28	16	36	10	7,410	28.3
5820704	-97.6067	30.6419	Williamson	10	130	0	1	6	6.00	0.023
5827301	-97.6403	30.6119	Williamson	300	70	4	41	12	284	1.30

Table 4.5.1. (continued).

Well Number	Longitude	Latitude	County	Q	s	SC	t	r	T	K
5827306	-97.6375	30.5938	Williamson	280	50	6	24	12	621	3.27
5827505	-97.6917	30.5491	Williamson	83	104	1	4	6	228	2.28
5827508	-97.6872	30.5785	Williamson	280	60	5	24	13	1,351	7.90
5827509	-97.6872	30.5785	Williamson	115	30	4	1	13	1,098	6.42
5827514	-97.6939	30.5794	Williamson	200	0	20,000	48	7	4,240,174	31,178
5827516	-97.6872	30.5563	Williamson	200	40	5	24		546	4.27
5827518	-97.6942	30.5788	Williamson	200	10	20	1	7	3,212	23.6
5827535	-97.6831	30.5519	Williamson	500	27	19	2	8	6,051	60.5
5827801	-97.6761	30.5055	Williamson	1,332	4	386	3	12	17,525	175
5827801	-97.6761	30.5055	Williamson	1,062	3	312	3	12	17,442	174
5827805	-97.6756	30.5071	Williamson	1,700	20	85	0	13	15,595	156
5827805	-97.6756	30.5071	Williamson	1,700	20	85	3	13	18,135	181
5827806	-97.6775	30.5066	Williamson	3,000	116	26	0		17,261	173
5827806	-97.6775	30.5066	Williamson	3,000	116	26	3		17,087	171
5827808	-97.6720	30.5141	Williamson	0	0	0	0	8	25,212	219
5827809	-97.6728	30.5152	Williamson	0	0	0	0	8	4,533	45.3
5827810	-97.6736	30.5152	Williamson	415	7	98	0	18	1,671	16.7
5827818	-97.6750	30.5124	Williamson	2,000	55	36	18	15	11,542	115
5827819	-97.7020	30.5188	Williamson	70	92	1	2	8	207	1.62
5827824	-97.7075	30.5255	Williamson	720	21	34	36	15	10,851	84.1
5827913	-97.6561	30.5102	Williamson	75	90	1	1	8	231	1.13
5828103	-97.6111	30.6052	Williamson	257	206	1	35	10	1,125	4.46
5828504	-97.5439	30.5452	Williamson	20	70	0	0	7	25.0	0.097
5835204	-97.6750	30.4924	Williamson	310	120	3	25		762	6.46
5835215	-97.6672	30.4930	Williamson	45	60	1	1	6	213	1.33
5835218	-97.6942	30.4858	Williamson	30	20	2	2	6	149	1.06
5835219	-97.6683	30.4591	Travis	270	8	36	24	20	10,853	68.3
5835308	-97.6664	30.4702	Travis	250	40	6	36		1,892	14.8
5835311	-97.6339	30.4813	Travis	300	20	15	36	10	4,743	25.2
5835316	-97.6256	30.4627	Travis	760	266	3	36		298	1.24
5835607	-97.6303	30.4458	Travis	130	40	3	0	9	343	1.71
5835612	-97.6350	30.4471	Travis	40	11	4	1	13	601	3.83
5835619	-97.6433	30.4405	Travis	2,979	39	76	24	16	11,357	70.5
5835624	-97.6444	30.4374	Travis	3,052	12	254	28	15	6,147	39.2
5835627	-97.6600	30.4391	Travis	455	7	65	9	12	21,705	197
5835701	-97.7261	30.3881	Travis	185	0	3	0	8	346	2.62

Table 4.5.1. (continued).

Well Number	Longitude	Latitude	County	Q	s	SC	t	r	T	K
5836107	-97.6242	30.4702	Travis	300	37	8	36	16	2,360	10.5
5836208	-97.5808	30.4746	Travis	300	150	2	24	8	580	2.50
Observation Well	-97.6433	30.4405	Travis						14,910	92.6
3106	-97.6728	30.5739	Williamson	3500	1	3500	9	16	1,233,994	9,566
3115	-97.6889	30.5669	Williamson	1535	47	33	2	16	8,214	48.9
23652	-97.7350	30.4833	Williamson	14.5	2	7	36	4	2,315	15.9
67571	-97.6503	30.6978	Williamson	230	87	3	12	8.5	686	4.51
127294	-97.6139	30.8036	Williamson	180	35	5	24	8	1,461	10.4
127316	-97.5886	30.8061	Williamson	39	167	0.2	36	8	55.9	0.469
140217	-97.6469	30.7133	Williamson	400	102	4	24	10	1,067	7.73
141584	-97.6394	30.6128	Williamson	600	72	8	36	12.75	2,361	11.3
159552	-97.6092	30.8058	Williamson	110	124	1	36	8	232	1.59
181993	-97.5786	30.8733	Bell	30	1	30	24	6	9,681	60.9
224612	-97.6086	30.8089	Williamson	550	11	50	36	10.75	15,929	131
395693	-97.5425	30.9933	Bell	450	131	3	36	6.5	999	7.87
433748	-97.8783	30.5091	Travis	3	1	3	36	5	892	3.95
433837	-97.8784	30.5092	Travis	3	295	0.01	36	5	2.06	0.010
433842	-97.8784	30.5104	Travis	5	237	0.02	36	5	4.53	0.023
436006	-97.8784	30.5108	Travis	10	289	0.03	36	5	7.71	0.039
433837*	-97.8784	30.5092	Travis	3	295	0.01	36	5	2.06	0.010
433842*	-97.8784	30.5104	Travis	5	237	0.02	36	5	4.53	0.023
436006*	-97.8784	30.5108	Travis	10	289	0.03	36	5	7.71	0.039

* - Trinity Aquifer wells

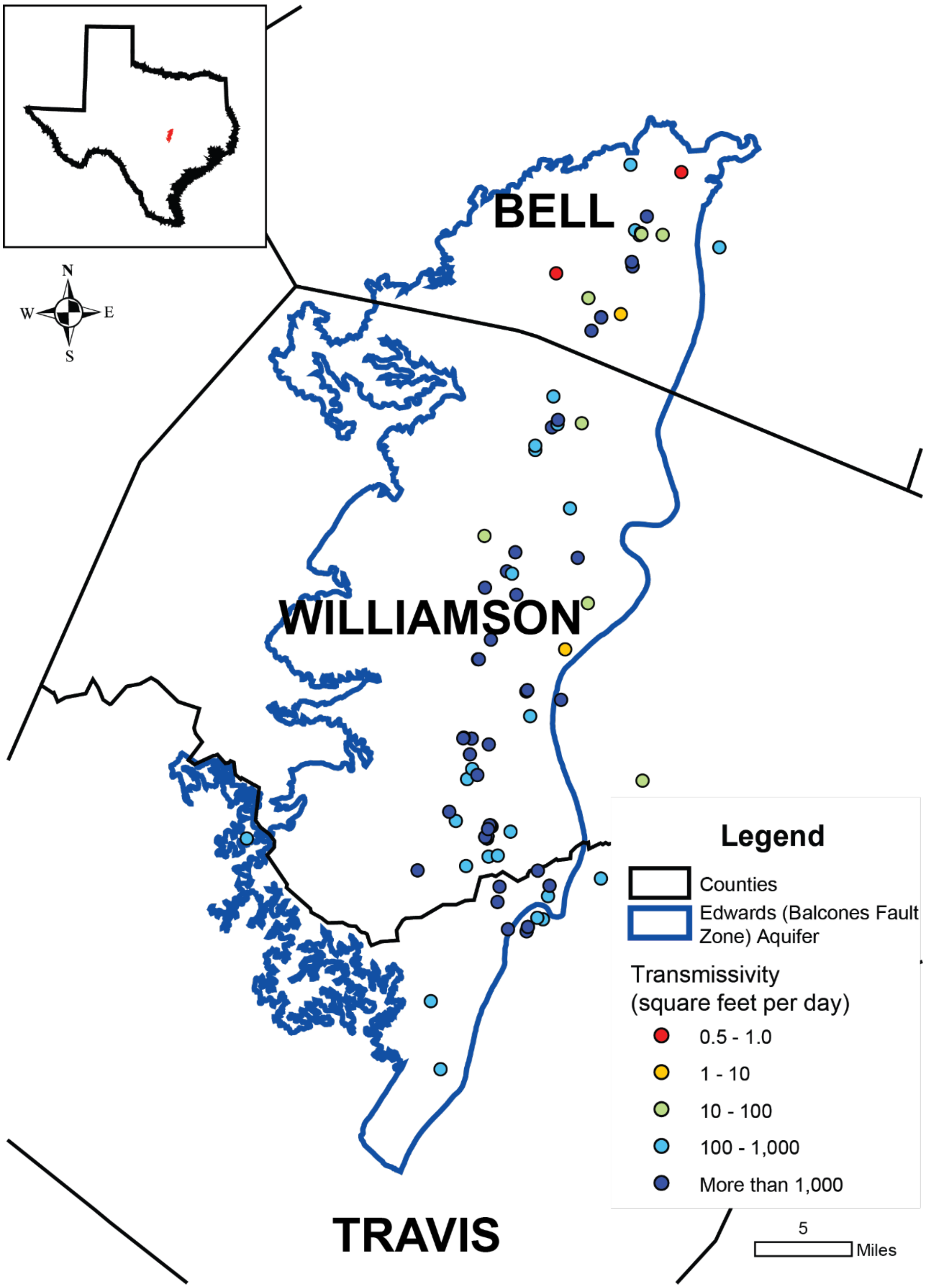


Figure 4.5.1. Transmissivity estimates based on specific capacity data for the northern segment of the Edwards (Balcones Fault Zone) Aquifer (see Table 4.5.1 for the specific capacity data used to calculated transmissivity).

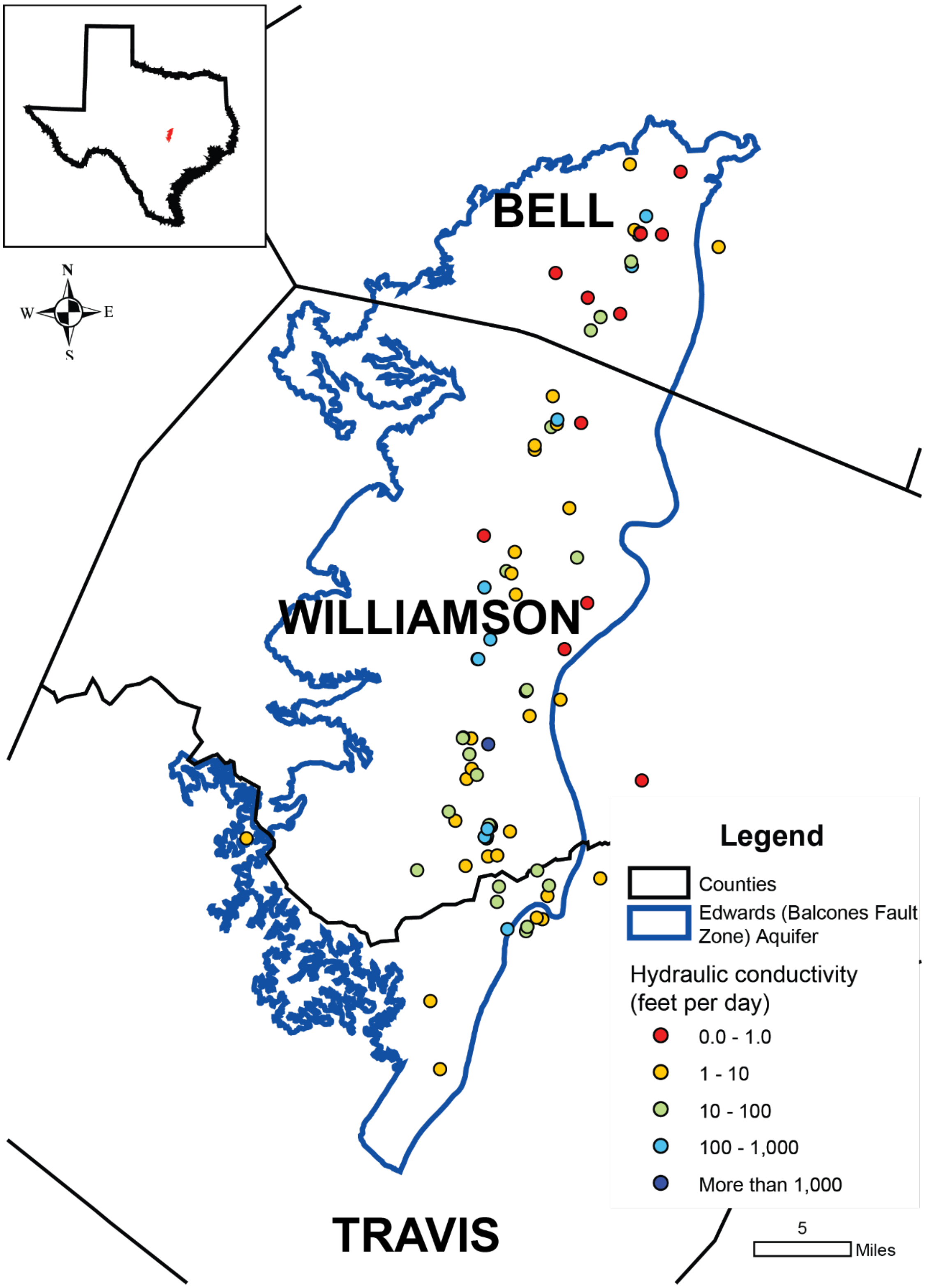


Figure 4.5.2. **Hydraulic conductivity data for the northern segment of the Edwards (Balcones Fault Zone) Aquifer (see Table 4.5.1 for the specific capacity data used to calculated hydraulic conductivity).**

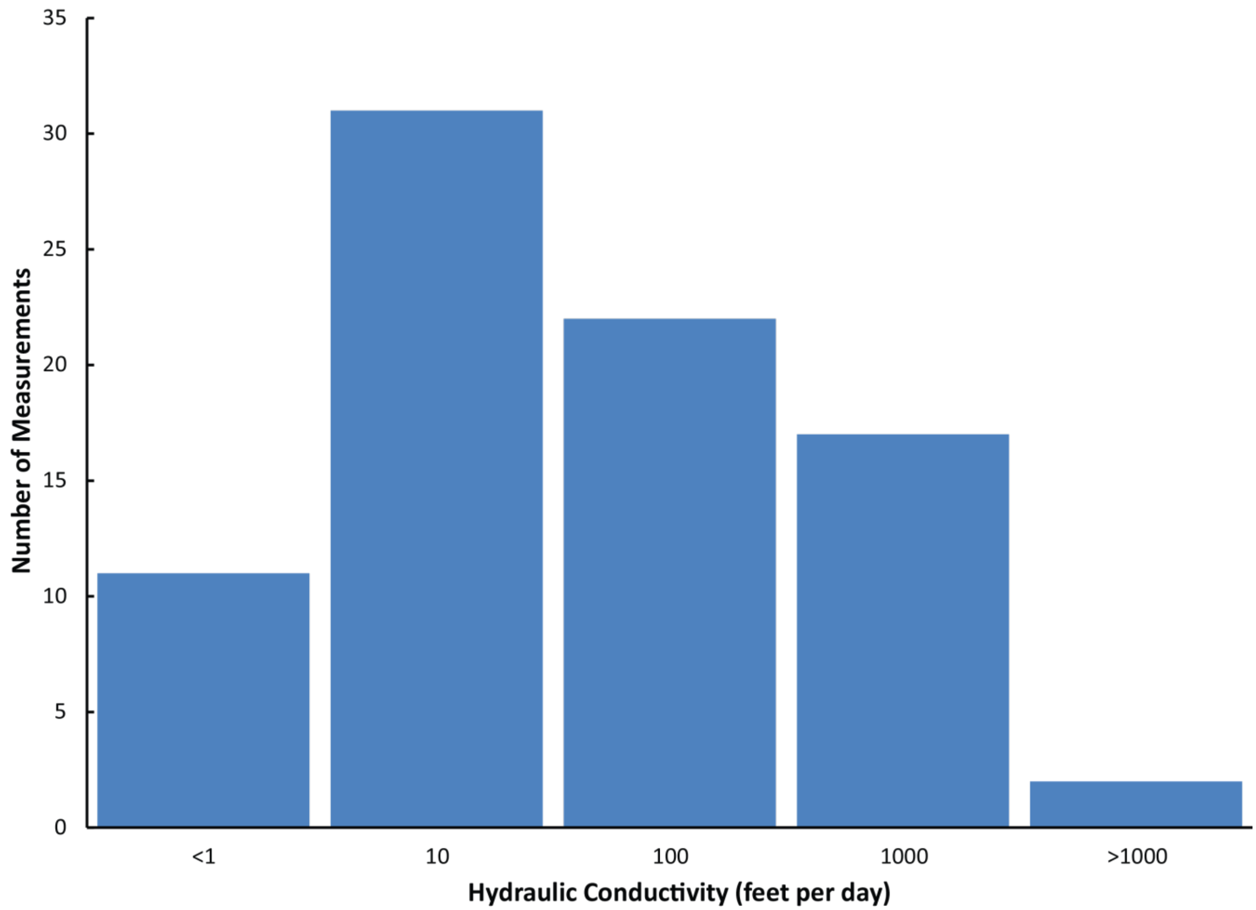


Figure 4.5.3. Histogram of hydraulic conductivity data in feet per day for the northern segment of the Edwards (Balcones Fault Zone) Aquifer based on data from the hydraulic data indicated in Table 4.5.1.

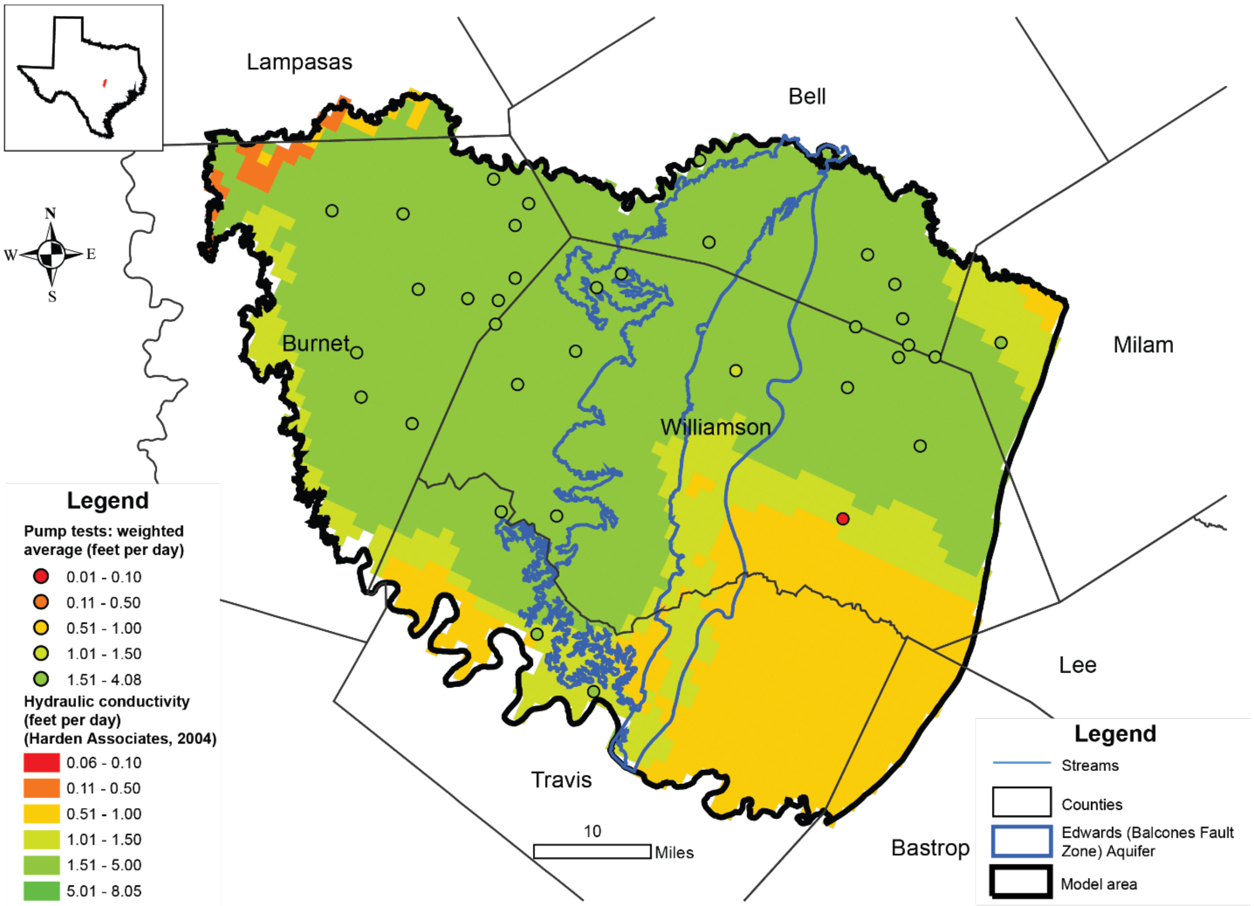


Figure 4.5.4. Hydraulic conductivity data for the Trinity Aquifer in the study area (based on data from Harden & Associates and others, 2004).

4.6 Discharge

The term, discharge, refers to processes by which water leaves an aquifer. These processes include both natural and anthropogenic processes. Groundwater discharges from aquifers naturally to streams or springs, evapotranspiration, and cross-formational flow. Pumping wells are an anthropogenic form of discharge from aquifers.

4.6.1 Natural Aquifer Discharge

In a typical topographically-driven flow system, percolation of precipitation results in recharge at the water table, which flows from topographic highs and discharges at topographic lows through streams and springs and groundwater evapotranspiration. Water that moves down-dip eventually discharges upward through cross-formational flow. In the northern segment of the Edwards (Balcones Fault Zone) Aquifer, the most likely forms of discharge are stream and spring discharge and cross-formational flow in the subsurface. Groundwater isotopes in the northern segment of the Edwards (Balcones Fault Zone) Aquifer indicate that most groundwater flow is limited to the unconfined portion of the aquifer (see Section 4.7). Consequently, most of the natural discharge is likely to take the form of discharge to the perennial rivers and streams in the study area.

Groundwater discharge to surface water bodies is discussed in Sections 4.4.1 through 4.4.3. This discharge primarily occurs in the outcrop of the northern segment of the Edwards (Balcones Fault Zone) Aquifer or adjacent to the boundary between the unconfined and confined parts of the aquifer (Figure 4.4.4).

Discharge via cross-formational flow is likely to occur in the confined part of the northern segment of the Edwards (Balcones Fault Zone) Aquifer by upward discharge through overlying stratigraphic units such as the Del Rio Clay and Austin Chalk. It is unlikely that cross-formation discharge is a major factor in groundwater discharge from the northern segment of the Edwards (Balcones Fault Zone) Aquifer because (1) groundwater isotopes suggest little groundwater circulation in the confined portion of the aquifer (Jones, 2006), and (2) the non-aquifer rocks, such as the Del Rio Clay, Buda Limestone and Austin Chalk that overlie the Edwards (Balcones Fault Zone) Aquifer have low hydraulic conductivities.

4.6.2 Aquifer Discharge through Pumping

Estimates of groundwater pumping from the northern segment of the Edwards (Balcones Fault Zone) Aquifer for the years 1980 through 2015 were obtained from the Texas Water Development Board historical water use estimates. The six water-use categories defined in the Texas Water Development Board database are municipal, manufacturing, steam electric generation, irrigation, mining, and livestock. Rural domestic pumping is likely to be more important in less urbanized parts of the study area.

Potential areas for irrigation pumping from the northern segment of the Edwards (Balcones Fault Zone) Aquifer are in the eastern and northern parts of the study area (Figure 4.6.1). This spatial distribution assumes that irrigation pumping from the northern segment of the Edwards (Balcones Fault Zone) Aquifer is directly associated with crops, such as orchards, hay, row crops, and small grains, as determined by National Land Cover Database land classification (Vogelmann and others, 1998a; 1998b). This spatial distribution is supported by the spatial distribution of irrigation wells drilled during the period 2001 through 2017 (Texas Department of Licensing and Regulation, 2017). Texas Water Development Board pumping data for the northern segment of the Edwards (Balcones Fault Zone) Aquifer indicate irrigation pumping up to 130 acre-feet per year—mostly in Bell County (Figure 4.6.2; Table 4.6.1).

Livestock pumping was distributed using land cover data obtained from the National Land Cover Dataset (Vogelman and others, 1998a; 1998b). We assume that livestock pumping is associated with grassland and scrubland land cover (Figure 4.6.3). These types of land cover are distributed over most of the land cover over the northern segment of the Edwards (Balcones Fault Zone) Aquifer; however, recent livestock well drilling suggests that livestock pumping is most likely to be restricted to the more rural eastern and northern parts of the study area. Estimates of livestock pumping from the northern segment of the Edwards (Balcones Fault Zone) Aquifer peak at about 600 acre-feet per year (Figure 4.6.2; Table 4.6.2).

Manufacturing, mining and municipal pumping are spatially distributed based on known well locations (Figure 4.6.4). These wells are primarily located in or adjacent to the confined part of the northern segment of the Edwards (Balcones Fault Zone) Aquifer. Pumping estimates are taken from Texas Water Development Board water use surveys (TWDB, 2017b). Texas Water Development Board pumping data indicates manufacturing pumping from the northern segment of the Edwards (Balcones Fault Zone) Aquifer is mostly in Travis and Williamson counties, totaling up to 1,400 acre-feet per year (Figure 4.6.5; Table 4.6.3). These data show a decline of manufacturing in the mid-2000s to about 800 acre-feet per year. Mining pumping estimates are as high as 1,800 acre-feet per year (Figure 4.6.5; Table 4.6.4). Pumping estimates from the water use survey suggest that mining pumping from the northern segment of the Edwards (Balcones Fault Zone) Aquifer occurs mostly in Williamson County, in association with the limestone quarries located there. Municipal pumping from the northern segment of the Edwards (Balcones Fault Zone) Aquifer are as high as 26,000 acre-feet per year (Figure 4.6.6; Table 4.6.5).

Rural domestic pumping—which consists primarily of unreported domestic water use—is assumed to be related to the lower population densities in non-urban areas (Figure 4.6.7). The Submitted Drillers' Reports database suggests that rural domestic pumping from the northern segment of the Edwards (Balcones Fault Zone) Aquifer is expected to occur in the rural eastern and northern parts of the study area (Figure 4.6.7). Rural domestic pumping estimates are based partially on per capita water usage rate estimates of 137 gallons per day, 131 gallons per day, and 132 gallons per day in Bell, Travis, and Williamson counties, respectively. These estimates suggest relatively constant pumping rates of about 3,000 to 5,000 acre-feet per year prior to 2000, increasing rapidly with population to over 30,000 acre-feet per year (Figure 4.6.6; Table 4.6.6). The domestic pumping estimates include lawn irrigation. Monthly domestic pumping is distributed temporally similar to irrigation pumping such that pumpage is highest during summer months and lowest in the winter.

Total pumping from the northern segment of the Edwards (Balcones Fault Zone) Aquifer over the period 1980 through 2015 has risen from about 16,000 acre-feet per year to about 50,000 acre-feet per year (Table 4.6.7; Figure 4.6.8). This variation of pumping largely reflects variation of municipal and domestic pumpage over that time period. Overall, municipal and domestic pumpage accounts for 90 percent of all pumpage from the northern segment of the Edwards (Balcones Fault Zone) Aquifer (Figure 4.6.9). Locally, irrigation, mining and manufacturing pumpage are significant.

Pumping from the Trinity Aquifer in the study area is lower than in the northern segment of the Edwards (Balcones Fault Zone) Aquifer. Unlike pumping from the northern segment of the Edwards (Balcones Fault Zone) Aquifer, annual pumping from the adjacent Trinity Aquifer has been relatively constant, ranging from a low of about 7,000 acre-feet to a high in excess of 15,000 acre-feet and averaging about 10,000 acre-feet (Figure 4.6.10; Table 4.6.8).

Table 4.6.1. Estimates of northern segment of the Edwards (Balcones Fault Zone) Aquifer irrigation pumping. The data—expressed in acre-feet per year (AFY)—was taken from Texas Water Development Board (2017b).

	Irrigation			
Year	**Bell**	**Travis**	**Williamson**	**Total**
1980	0	0	0	0
1981	0	0	0	0
1982	0	0	0	0
1983	0	0	0	0
1984	0	0	0	0
1985	1	0	0	1
1986	1	0	0	1
1987	0	0	0	1
1988	0	0	0	1
1989	0	0	3	3
1990	0	0	3	3
1991	0	0	3	3
1992	0	0	3	3
1993	0	0	0	0
1994	0	0	0	0
1995	0	0	0	0
1996	0	0	0	0
1997	0	0	0	0
1998	0	0	0	0
1999	0	0	0	0
2000	27	12	0	39
2001	27	13	0	41
2002	30	13	0	43
2003	22	8	0	30
2004	8	8	0	16
2005	11	15	0	25
2006	3	20	3	26

2007	15	7	2	24

Table 4.6.1. (continued).

		Irrigation		
Year	**Bell**	**Travis**	**Williamson**	**Total**
2008	3	12	0	15
2009	28	3	16	47
2010	75	7	40	123
2011	71	28	31	131
2012	43	12	26	81
2013	61	17	20	98
2014	33	10	14	58
2015	41	7	16	63

Table 4.6.2. Estimates of northern segment of the Edwards (Balcones Fault Zone) Aquifer livestock pumping. The data—expressed in acre-feet per year (AFY)—was taken from Texas Water Development Board (2017b).

		Livestock		
Year	**Bell**	**Travis**	**Williamson**	**Total**
1980	3	1	8	11
1981	2	2	10	15
1982	2	4	13	19
1983	2	6	15	23
1984	2	8	18	27
1985	2	8	8	17
1986	1	9	8	18
1987	2	8	7	17
1988	2	8	8	18
1989	2	8	7	17
1990	2	8	7	17
1991	2	9	7	17
1992	2	8	6	16
1993	2	9	6	17
1994	2	8	8	17
1995	2	8	5	15
1996	1	16	8	25
1997	1	7	6	15

1998	1	5	5	12
1999	1	7	6	14
2000	1	7	33	41

Table 4.6.2. (continued).

		Livestock		
Year	**Bell**	**Travis**	**Williamson**	**Total**
2001	1	9	34	44
2002	1	9	32	42
2003	2	5	32	39
2004	4	5	32	41
2005	14	2	96	113
2006	14	2	110	127
2007	13	2	117	133
2008	14	2	109	124
2009	14	2	101	118
2010	24	2	160	186
2011	24	2	164	190
2012	11	2	88	101
2013	11	2	96	108
2014	12	1	101	114
2015	12	1	99	113

Table 4.6.3. Estimates of northern segment of the Edwards (Balcones Fault Zone) Aquifer manufacturing pumping. The data—expressed in acre-feet per year (AFY)—was taken from Texas Water Development Board (2017b).

		Manufacturing		
Year	**Bell**	**Travis**	**Williamson**	**Total**
1980	0	2	242	244
1981	0	2	204	206
1982	0	2	150	152
1983	0	2	158	160
1984	0	21	220	241
1985	0	82	152	233
1986	0	97	196	293
1987	0	163	187	349
1988	0	186	245	431
1989	0	208	233	441

1990	0	219	304	523

Table 4.6.3. (continued).

		Manufacturing		
Year	Bell	Travis	Williamson	Total
1991	0	215	306	521
1992	0	221	260	480
1993	0	219	401	621
1994	0	197	477	675
1995	0	244	734	978
1996	0	153	395	547
1997	0	176	365	541
1998	0	582	650	1232
1999	0	676	676	1352
2000	0	410	633	1043
2001	0	566	636	1202
2002	0	539	640	1178
2003	0	625	739	1364
2004	0	813	598	1411
2005	0	464	670	1134
2006	0	546	631	1177
2007	0	350	691	1041
2008	0	772	304	1076
2009	0	722	0	722
2010	0	772	0	772
2011	0	380	0	380
2012	0	569	0	569
2013	0	740	0	740
2014	0	750	0	750
2015	0	709	0	709

Table 4.6.4. Estimates of northern segment of the Edwards (Balcones Fault Zone) Aquifer mining pumping. The data—expressed in acre-feet per year (AFY)—was taken from Texas Water Development Board (2017b).

	Mining			
Year	**Bell**	**Travis**	**Williamson**	**Total (AFY)**
1980	0	0	1,347	1,347
1981	0	0	1,374	1,374
1982	0	0	1,442	1,442
1983	0	0	1,653	1,653
1984	0	0	1,653	1,653
1985	0	0	1,653	1,653
1986	0	0	1,654	1,654
1987	0	0	1,654	1,654
1988	0	0	1,654	1,654
1989	0	0	1,654	1,654
1990	0	0	1,654	1,654
1991	0	0	1,654	1,654
1992	0	0	1,654	1,654
1993	0	0	1,654	1,654
1994	0	0	1,654	1,654
1995	0	0	1,654	1,654
1996	0	0	1,654	1,654
1997	0	0	1,654	1,654
1998	0	0	1,654	1,654
1999	0	0	1,654	1,654
2000	0	0	1,848	1,848
2001	0	0	1,848	1,848
2002	0	0	1,844	1,844
2003	0	0	1,844	1,844
2004	0	0	1,844	1,844
2005	0	0	1,844	1,844
2006	0	0	1,844	1,844
2007	0	0	793	793
2008	0	0	1,031	1,031
2009	0	0	610	610

Table 4.6.4. (continued).

	Mining			
Year	Bell	Travis	Williamson	Total (AFY)
2010	0	0	783	783
2011	0	0	971	971
2012	0	0	907	907
2013	0	0	456	456
2014	0	0	971	971
2015	0	0	828	828

Table 4.6.5. Estimates of northern segment of the Edwards (Balcones Fault Zone) Aquifer municipal pumping. The data—expressed in acre-feet per year (AFY)—was taken from Texas Water Development Board (2017b).

	Municipal			
Year	Bell	Travis	Williamson	Total
1980	206	781	7,034	8,021
1981	223	750	6,801	7,774
1982	243	1,001	7,925	9,169
1983	273	1,051	9,229	10,554
1984	311	1,401	9,833	11,544
1985	298	1,688	10,981	12,967
1986	299	2,066	12,381	14,745
1987	316	2,648	12,455	15,419
1988	365	2,880	10,062	13,307
1989	516	2,836	9,610	12,962
1990	510	2,685	9,359	12,554
1991	530	2,677	8,010	11,217
1992	599	2,681	10,125	13,405
1993	625	3,698	9,569	13,892
1994	670	3,944	10,777	15,391
1995	742	4,403	11,561	16,706
1996	848	5,007	13,004	18,860
1997	814	5,073	14,865	20,752
1998	928	5,901	13,084	19,913
1999	1,023	6,258	12,646	19,927
2000	1,012	6,124	13,456	20,592
2001	980	7,351	12,018	20,349

Table 4.6.5. (continued).

	Municipal			
Year	Bell	Travis	Williamson	Total
2002	1,061	6,776	12,471	20,308
2003	1,120	7,938	9,386	18,443
2004	970	7,854	12,487	21,311
2005	1,070	9,558	15,395	26,022
2006	1,258	9,561	14,020	24,839
2007	1,012	4,021	11,647	16,680
2008	1,297	7,070	14,095	22,462
2009	1,333	5,991	13,570	20,894
2010	1,269	2,721	11,809	15,799
2011	1,848	3,851	13,767	19,465
2012	1,577	3,244	13,600	18,421
2013	1,265	3,405	12,283	16,953
2014	1,220	4,737	11,164	17,122
2015	1,233	4,806	12,034	18,073

Table 4.6.6. Estimates of northern segment of the Edwards (Balcones Fault Zone) Aquifer domestic pumping expressed in acre-feet per year (AFY).

	Domestic			
Year	Bell	Travis	Williamson	Total (AFY)
1980	177	134	1,426	1,736
1981	176	137	1,433	1,746
1982	176	141	1,442	1,759
1983	177	145	1,453	1,774
1984	178	149	1,468	1,795
1985	180	153	1,489	1,823
1986	181	159	1,512	1,852
1987	183	165	1,541	1,889
1988	186	172	1,581	1,939
1989	190	181	1,636	2,007
1990	195	195	1,719	2,109
1991	201	216	1,841	2,259
1992	208	237	1,963	2,408
1993	214	258	2,085	2,557
1994	220	279	2,208	2,707

Table 4.6.6. (continued).

Year	Bell	Travis	Williamson	Total (AFY)
		Domestic		
1995	226	300	2,330	2,856
1996	233	321	2,452	3,006
1997	239	342	2,574	3,155
1998	245	363	2,696	3,305
1999	251	384	2,819	3,454
2000	257	405	2,941	3,604
2001	260	500	3,281	4,041
2002	263	595	3,621	4,479
2003	266	689	3,961	4,916
2004	269	784	4,301	5,354
2005	272	879	4,641	5,791
2006	274	973	4,981	6,229
2007	277	1,068	5,321	6,667
2008	280	1,163	5,661	7,104
2009	283	1,257	6,001	7,542
2010	286	1,352	6,342	7,979
2011	289	1,447	6,692	8,428
2012	292	1,542	7,057	8,891
2013	295	1,636	7,432	9,363
2014	298	1,731	7,809	9,839
2015	302	1,826	8,190	10,318

Table 4.6.7. Estimates of northern segment of the Edwards (Balcones Fault Zone) Aquifer total pumping expressed in acre-feet per year (AFY).

Year	Bell	Travis	Williamson	Total (AFY)
		Total		
1980	386	917	10,057	11,359
1981	402	892	9,823	11,116
1982	421	1,148	10,972	12,541
1983	452	1,203	12,509	14,164
1984	491	1,578	13,192	15,261
1985	479	1,932	14,283	16,694
1986	482	2,330	15,751	18,563
1987	502	2,983	15,844	19,329

Table 4.6.7. (continued).

		Total		
Year	**Bell**	**Travis**	**Williamson**	**Total (AFY)**
1988	553	3,247	13,550	17,349
1989	708	3,233	13,142	17,082
1990	707	3,107	13,046	16,860
1991	733	3,116	11,820	15,670
1992	809	3,147	14,010	17,966
1993	841	4,185	13,716	18,742
1994	891	4,429	15,123	20,443
1995	970	4,955	16,284	22,209
1996	1,082	5,497	17,512	24,092
1997	1,054	5,599	19,464	26,117
1998	1,174	6,851	18,089	26,115
1999	1,276	7,325	17,801	26,401
2000	1,298	6,958	18,911	27,166
2001	1,269	8,439	17,817	27,525
2002	1,355	7,931	18,607	27,894
2003	1,409	9,266	15,962	26,637
2004	1,251	9,464	19,262	29,977
2005	1,366	10,917	22,646	34,930
2006	1,549	11,103	21,590	34,242
2007	1,318	5,449	18,572	25,338
2008	1,594	9,020	21,199	31,813
2009	1,658	7,976	20,300	29,933
2010	1,654	4,855	19,134	25,642
2011	2,232	5,708	21,626	29,566
2012	1,923	5,369	21,678	28,970
2013	1,632	5,800	20,287	27,720
2014	1,564	7,231	20,060	28,855
2015	1,587	7,350	21,167	30,104

Table 4.6.8. Estimates of Trinity Aquifer pumping in the study area expressed in acre-feet per year (AFY).

Year	Bell	Burnet	Lampasas	Milam	Travis	Williamson	Total
1980	1,668	6	396	184	3,153	4,812	10,218
1981	1,469	6	399	183	3,484	5,127	10,668
1982	1,256	6	419	249	3,796	5,730	11,457
1983	1,177	6	444	218	4,125	6,516	12,486
1984	957	7	441	208	4,454	7,288	13,355
1985	992	6	455	319	3,111	5,212	10,094
1986	1,028	6	475	331	1,647	4,858	8,345
1987	940	6	303	185	1,797	4,324	7,556
1988	922	6	292	204	1,751	4,485	7,661
1989	978	6	322	106	1,492	4,634	7,538
1990	1,108	6	413	167	3,579	5,882	11,154
1991	921	6	439	63	3,713	5,959	11,102
1992	1,080	6	480	344	4,080	6,158	12,147
1993	1,181	6	486	474	3,828	6,112	12,087
1994	1,129	6	497	51	3,256	5,158	10,098
1995	1,177	6	497	260	3,404	4,184	9,528
1996	1,169	6	505	52	2,439	4,170	8,341
1997	1,355	6	533	57	2,169	3,880	8,000
1998	1,264	6	511	83	2,374	3,514	7,752
1999	1,566	6	594	77	2,324	3,670	8,238
2000	1,269	6	752	127	2,260	3,612	8,025
2001	1,174	8	438	39	2,061	3,689	7,410
2002	1,285	9	506	42	2,104	3,068	7,015
2003	1,002	12	405	217	2,156	3,338	7,130
2004	733	10	365	150	3,597	2,145	7,001
2005	722	13	393	109	4,095	2,386	7,717
2006	749	13	412	126	4,200	2,430	7,929
2007	822	11	381	180	3,419	2,010	6,823
2008	1,152	12	392	186	4,296	3,109	9,147
2009	1,572	12	377	398	4,219	3,693	10,271
2010	1,850	15	391	363	4,906	3,383	10,908
2011	1,198	16	179	471	9,905	3,847	15,616
2012	1,360	16	168	320	9,832	3,417	15,113
2013	1,360	16	168	320	9,832	3,417	15,113
2014	1,360	16	168	320	9,832	3,417	15,113
2015	1,360	16	168	320	9,832	3,417	15,113

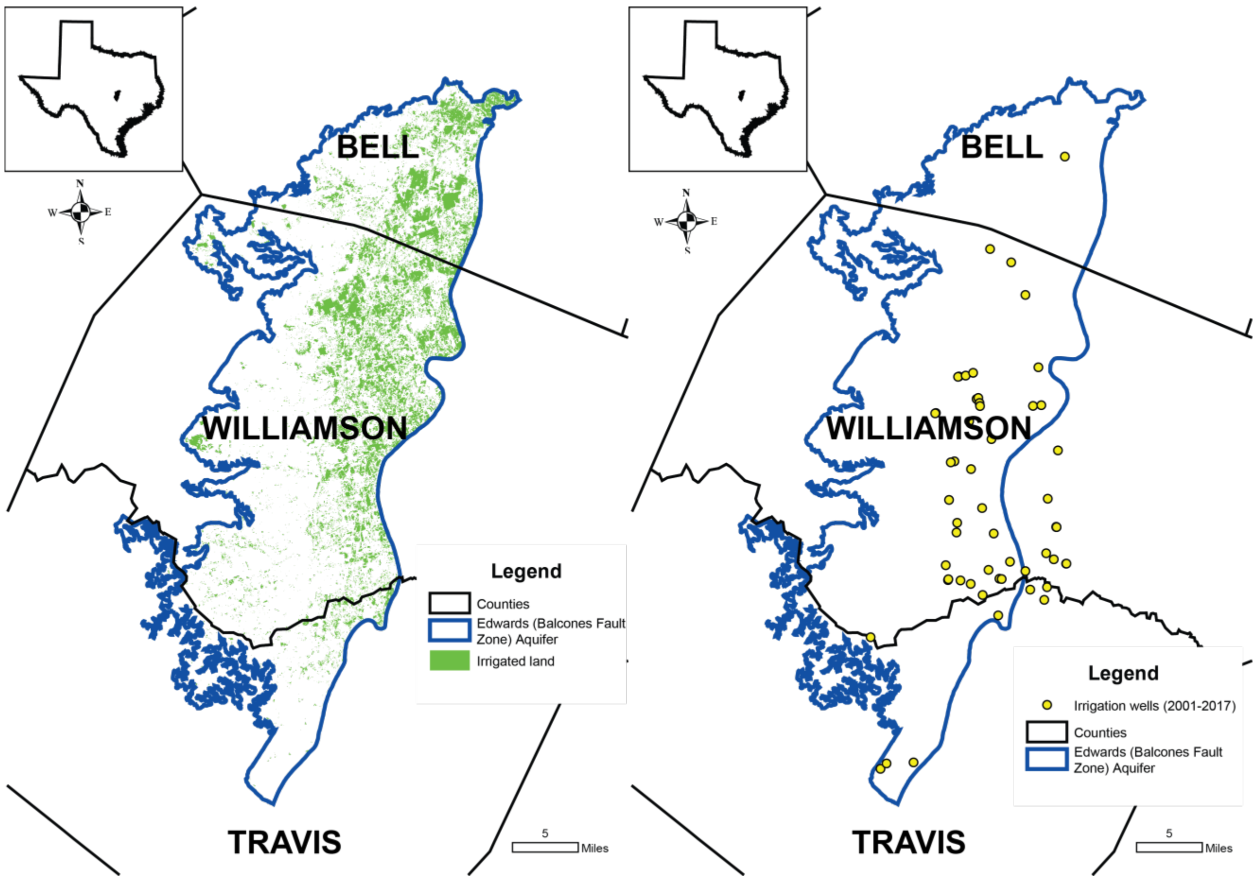


Figure 4.6.1. **Spatial distribution of potentially groundwater-irrigated farmland overlying the northern segment of the Edwards (Balcones Fault Zone) Aquifer (left) and irrigation wells drilled over the period 2001 through 2017 (right). Data from Vogelmann and others (1998a and 1998b) and the Submitted Drillers' Reports database (TDLR, 2017).**

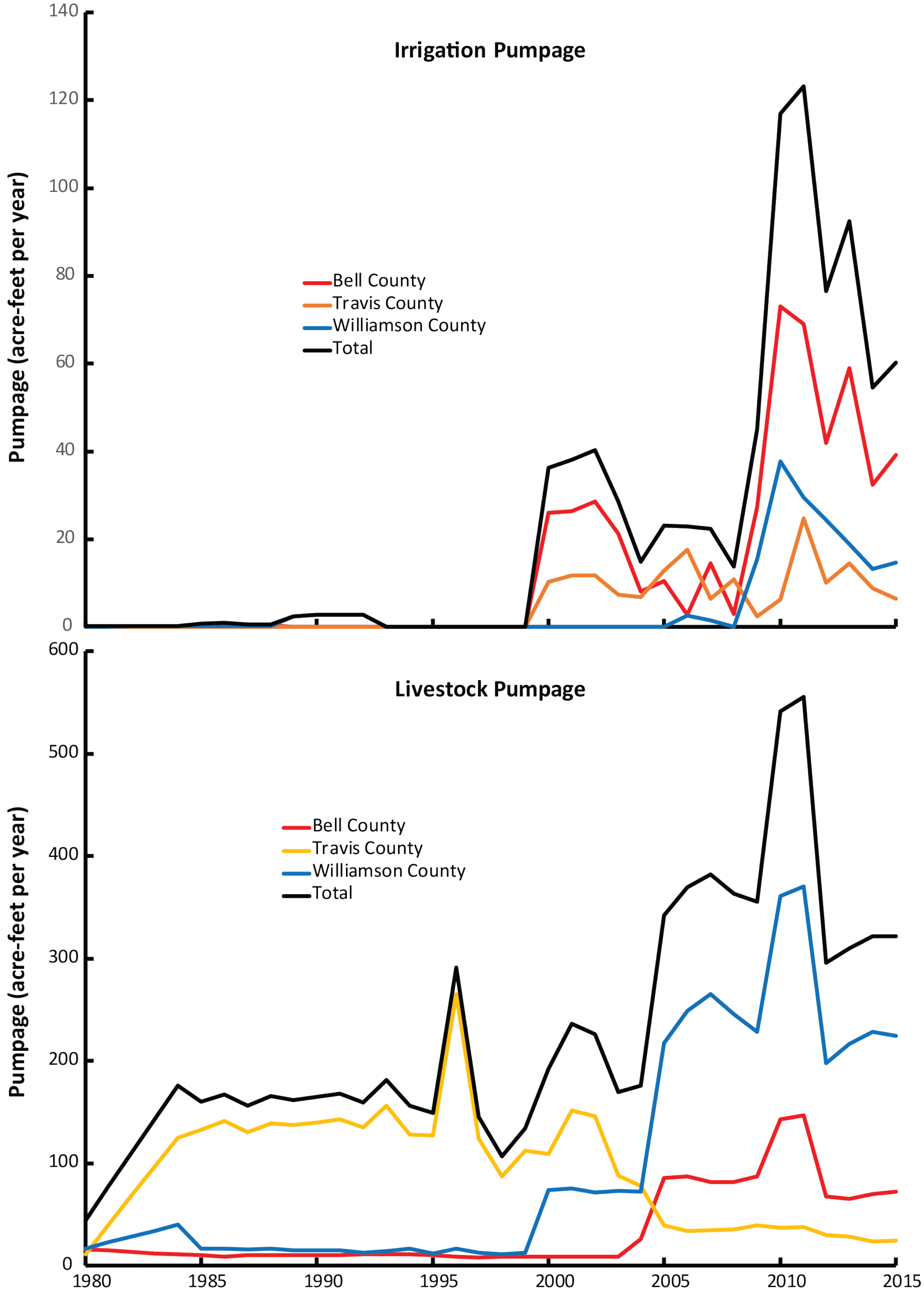


Figure 4.6.2. **Estimated irrigation and livestock pumpage from the northern segment of the Edwards (Balcones Fault Zone) Aquifer. Data from Texas Water Development Board (2017b).**

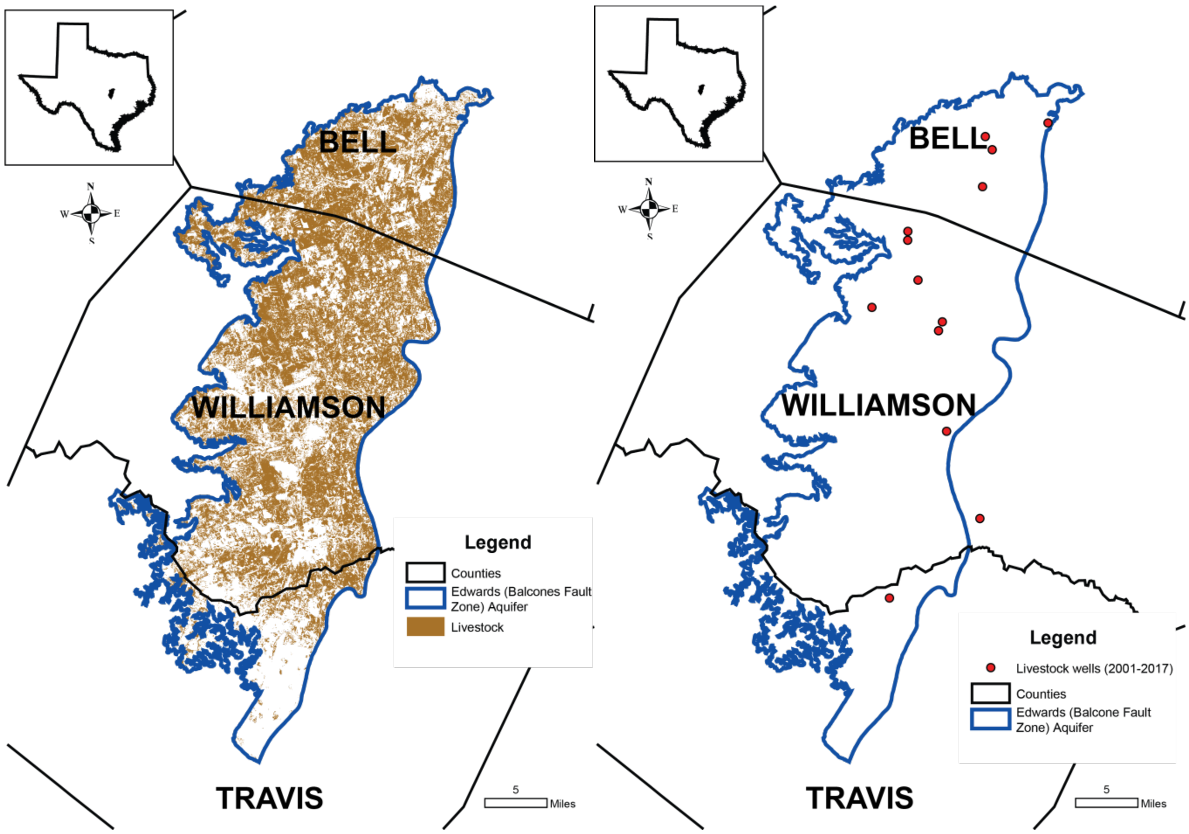


Figure 4.6.3. **The spatial distribution of livestock pumping (left) from the northern segment of the Edwards (Balcones Fault Zone) Aquifer based grassland and scrubland land cover from the National Land Cover Dataset throughout the study area (Vogelman and others, 1998a; 1998b) and (right) livestock wells drilled over the period 2001 through 2017 from the Submitted Drillers' Reports database (TDLR, 2017).**

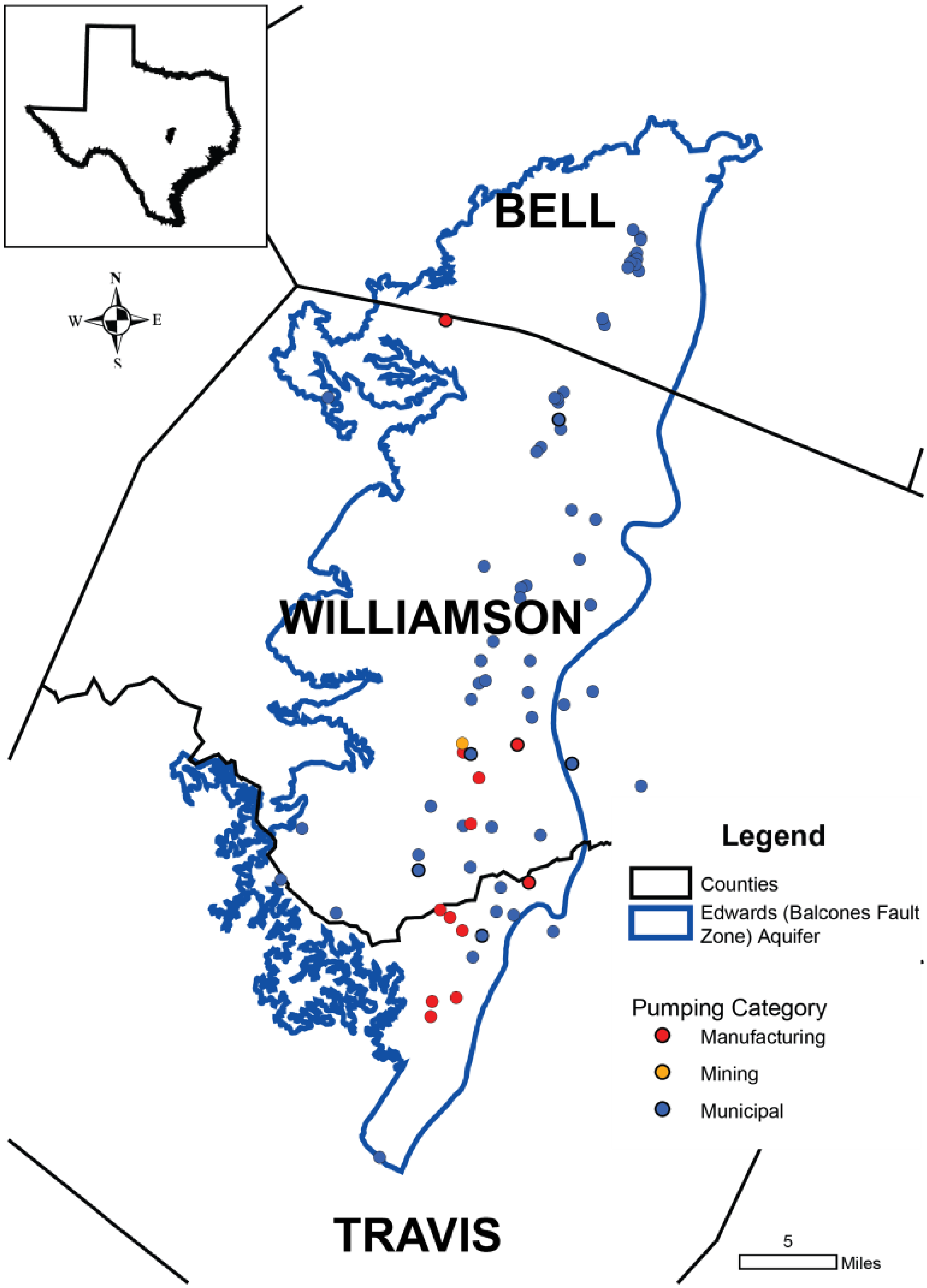


Figure 4.6.4. **The spatial distribution of manufacturing (industrial), mining and municipal (public supply) pumping. Manufacturing, mining and public supply pumping will be distributed in model cells that coincide with the well locations. Data from Water Use Survey and the Submitted Drillers' Reports database (TDLR, 2017).**

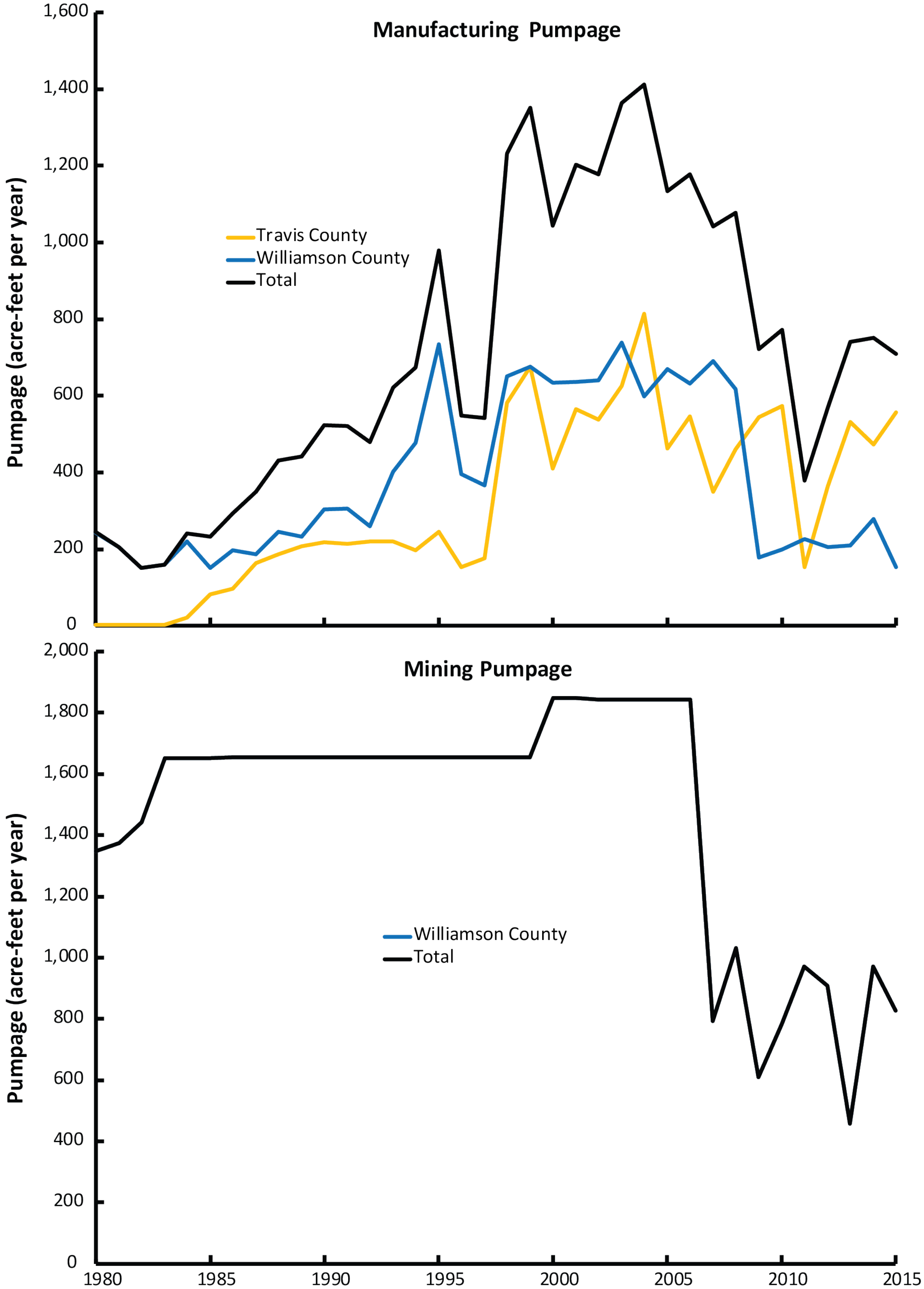


Figure 4.6.5. **Estimated manufacturing and mining pumpage from the northern segment of the Edwards (Balcones Fault Zone) Aquifer. Data from Texas Water Development Board (2017b).**

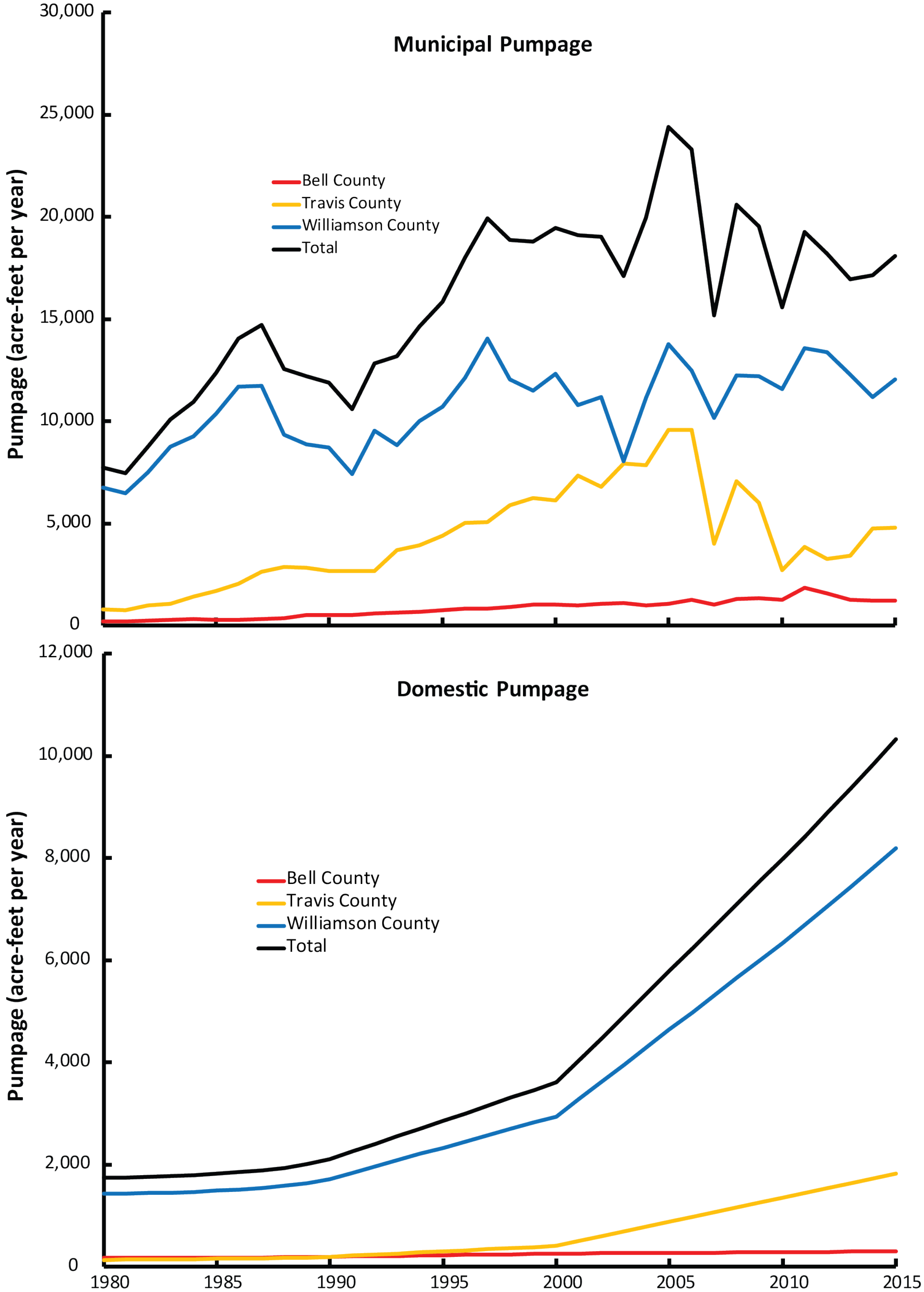


Figure 4.6.6. **Estimated municipal and rural domestic pumpage from the northern segment of the Edwards (Balcones Fault Zone) Aquifer. Data from Texas Water Development Board (2017b).**

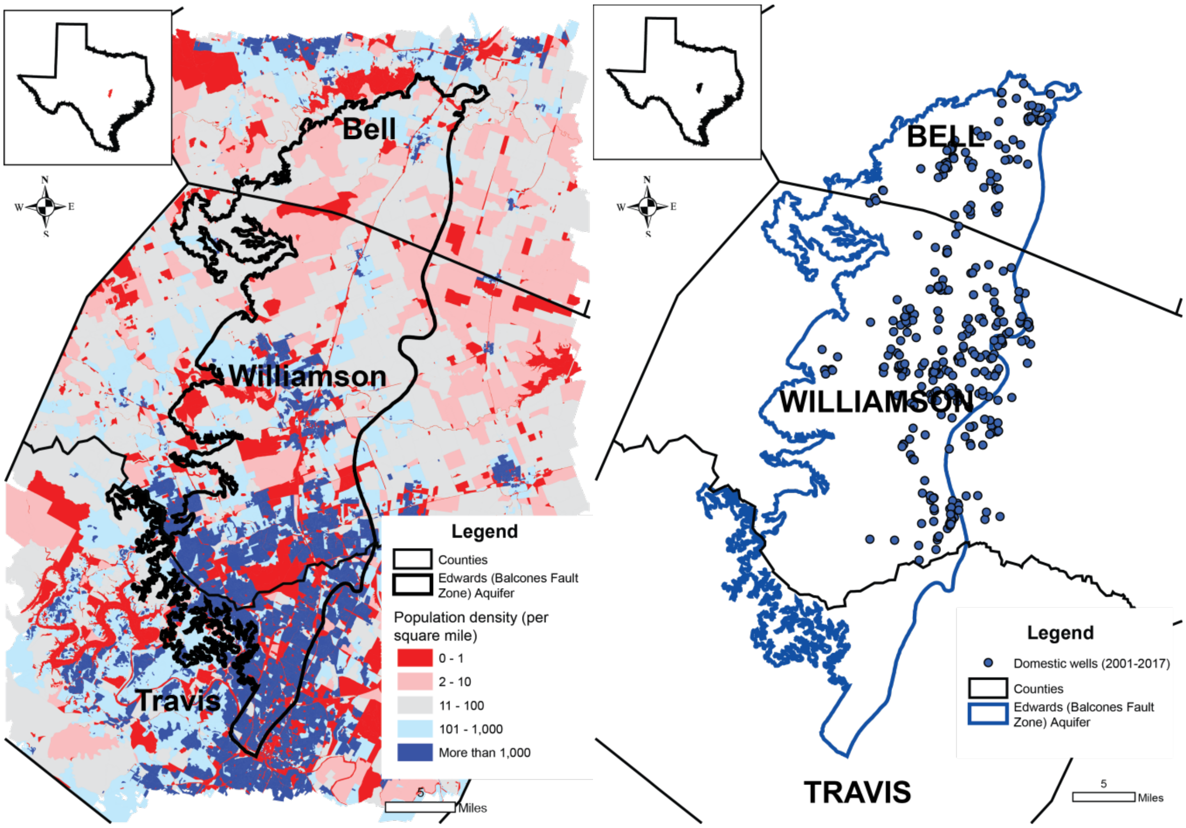


Figure 4.6.7. Population density in the northern segment of the Edwards (Balcones Fault Zone) Aquifer study area (left). Spatial distribution of domestic wells drilled over the period 2001 through 2017 (right). Data from U.S. Department of Commerce (2013) and Submitted Drillers' Reports database (TDLR, 2017).

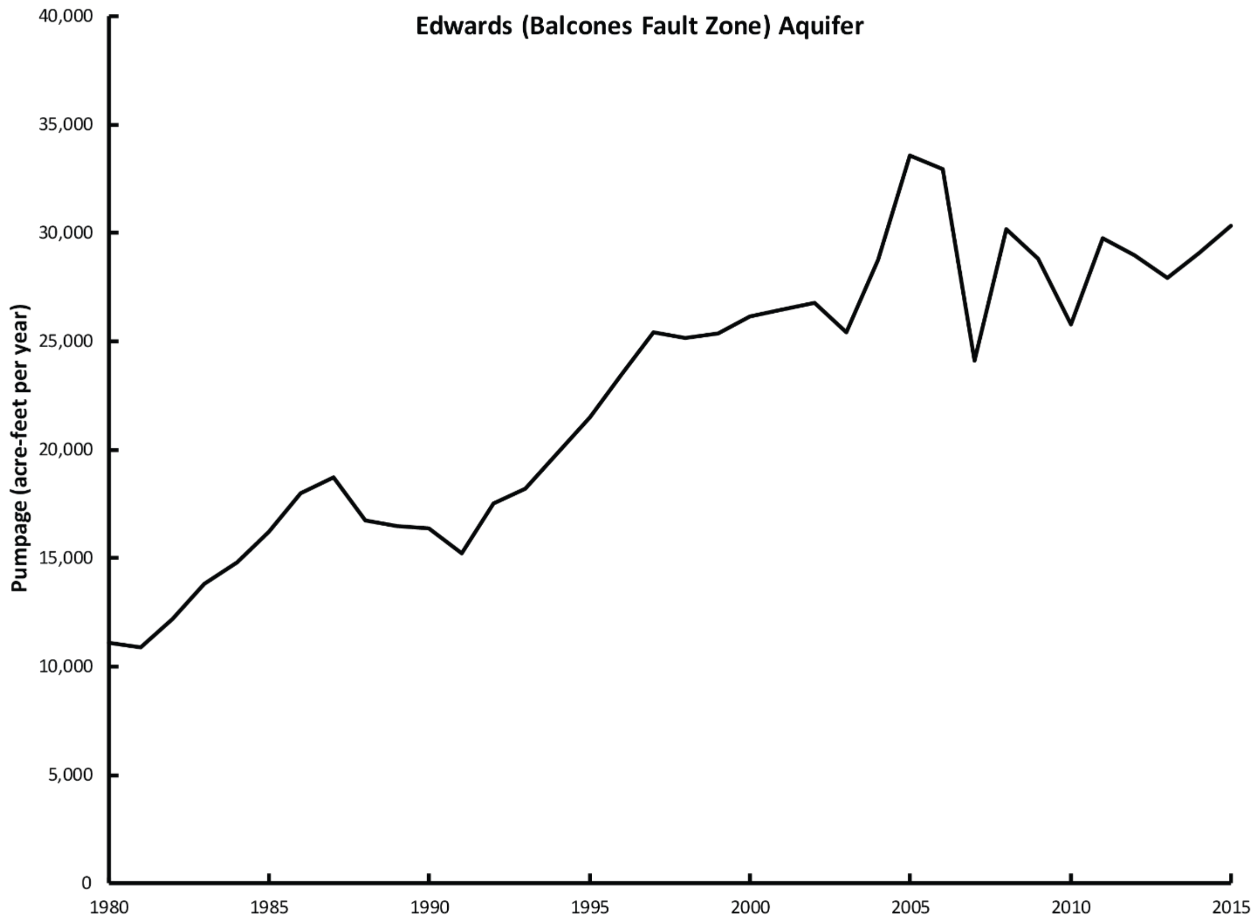


Figure 4.6.8. Total estimated pumpage from the northern segment of the Edwards (Balcones Fault Zone) Aquifer. Data from Texas Water Development Board (2017b).

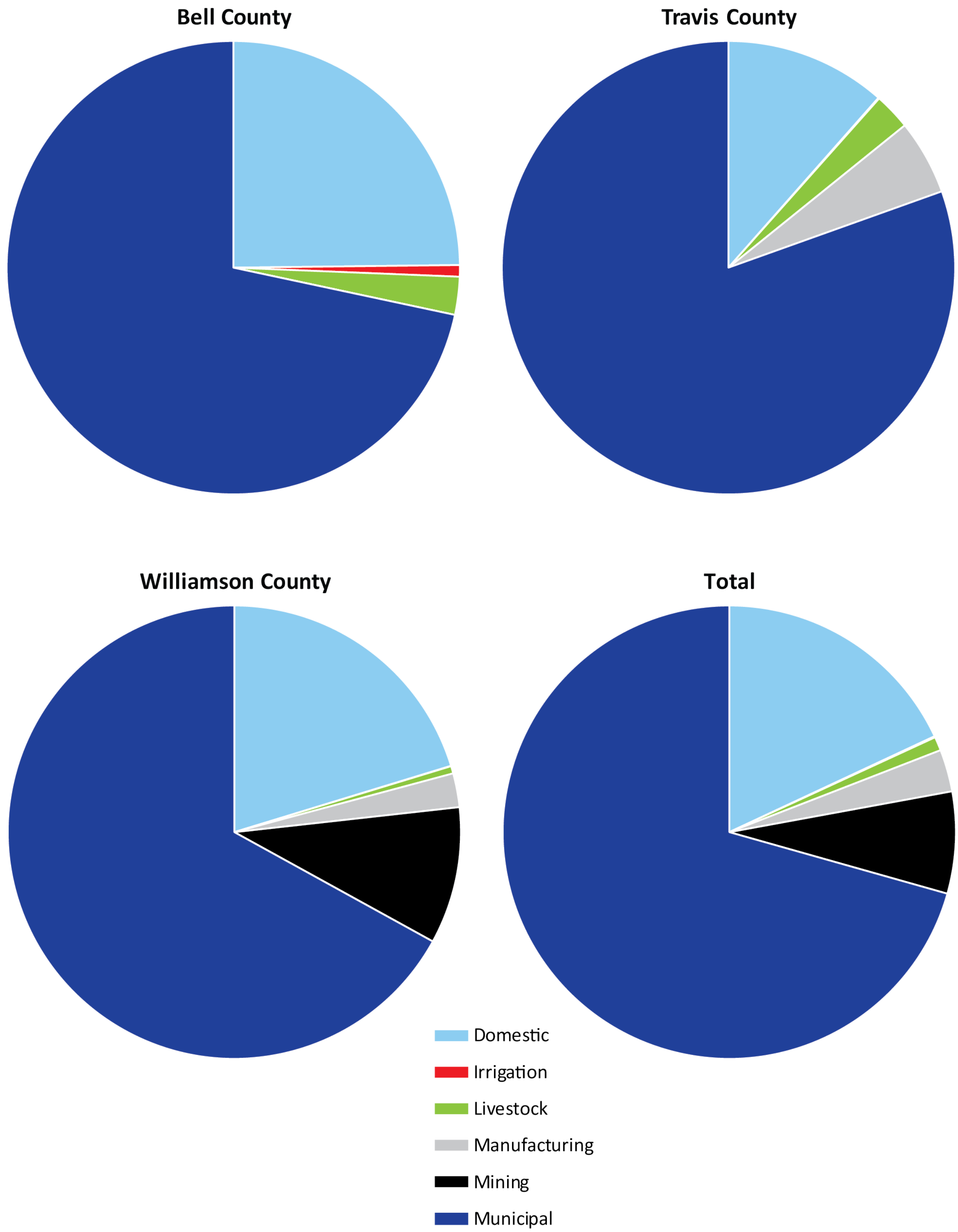


Figure 4.6.9. **Pie charts showing relative amounts of each category of pumping—rural domestic, irrigation, livestock, manufacturing, and municipal—in each of the three counties that overlie the northern segment of the Edwards (Balcones Fault Zone) Aquifer and for the entire aquifer segment.**

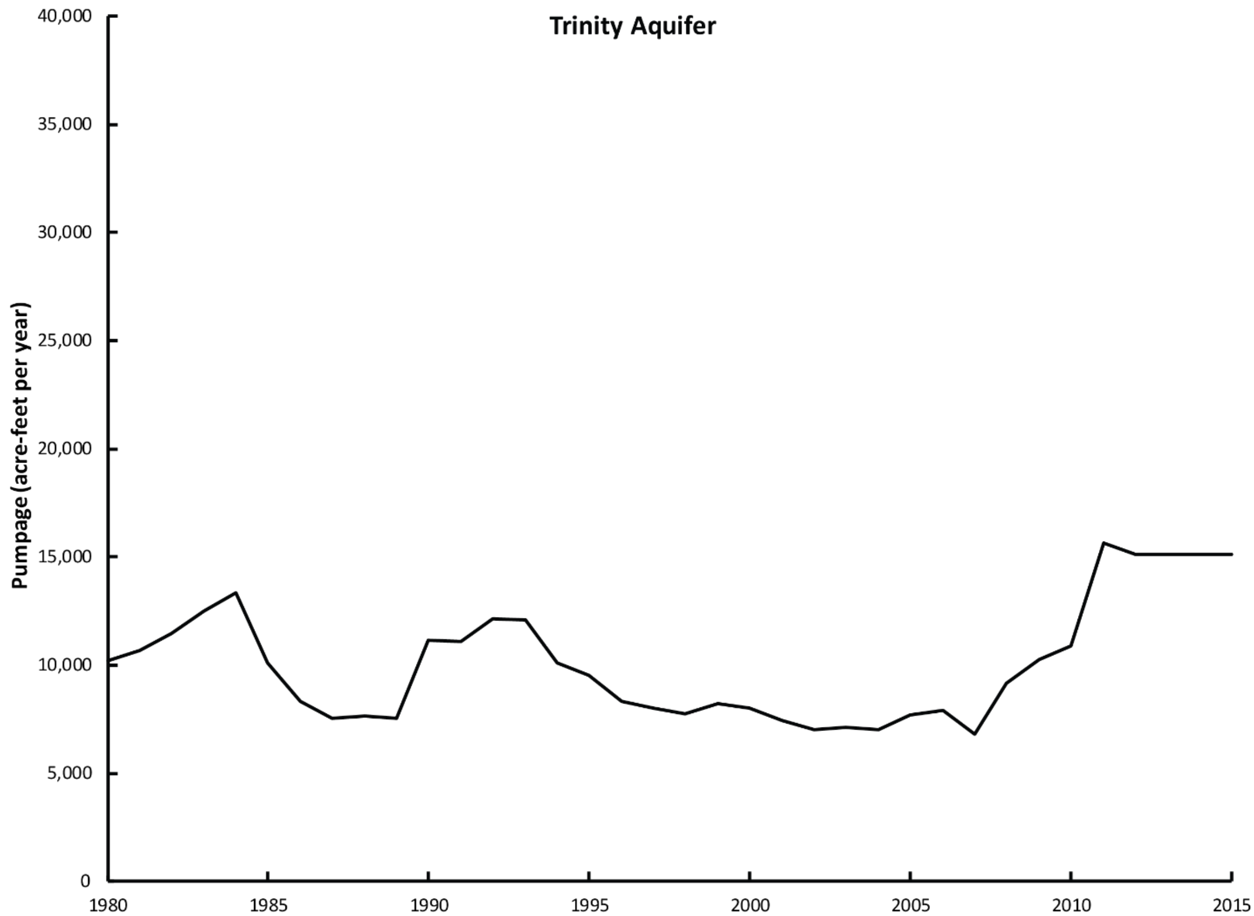


Figure 4.6.10. Total estimated pumpage from the Trinity Aquifer in the study area. Data from Texas Water Development Board (2017b).

4.7 Water Quality

The northern segment of the Edwards (Balcones Fault Zone) Aquifer generally has fresh groundwater and is generally less saline than the underlying Trinity Aquifer. This section is a discussion of the major element and isotopic compositions of groundwater in the northern segment of the Edwards (Balcones Fault Zone) Aquifer and adjacent Trinity Aquifer with implications for determination of groundwater flow through and recharge to the respective aquifers.

4.7.1 Major Elements

In some parts of the northern segment of the Edwards (Balcones Fault Zone) Aquifer, concentrations of total dissolved solids, chloride, nitrate and sulfate exceed applicable water quality standards. Except for nitrate, high concentrations of these constituents occur in down-dip portions of the aquifer (Baker and others, 1986). Excessively high concentrations of nitrate have been identified in a few wells, mostly located in urbanized parts of the northern segment of the Edwards (Balcones Fault Zone) Aquifer in Travis and Williamson counties, and seem to be associated with major faults. This suggests that faults are acting as preferential pathways for recharge and therefore the potential transmission of contaminants to the aquifer.

Figure 4.7.1 shows total dissolved solids concentrations in northern segment of the Edwards (Balcones Fault Zone) Aquifer groundwater. Fresh groundwater—total dissolved solids less than 1,000 milligrams per liter—occurs throughout the aquifer. Slightly to very saline groundwater—total dissolved solids of 1,000 milligrams per liter to greater than 10,000 milligrams per liter—occur mostly in the deeper parts of the aquifer. These more saline groundwaters occur beyond the official down-dip boundary of the Edwards (Balcones Fault Zone) Aquifer, which is defined by the occurrence of groundwater with total dissolved solids less than 1,000 milligrams per liter. The most saline groundwater occurs in the southernmost, narrowest parts of the Edwards (Balcones Fault Zone) Aquifer. This moderate to very saline groundwater is also the shallowest consistent occurrence of saline groundwater in the study area. This has been attributed to the effects of intense faulting that acts as a barrier to down-dip flow of fresh groundwater and facilitates upward influxes of very saline groundwater (Baker and others, 1986; Senger and others, 1990; Ridgeway and Petrini, 1999).

In the Trinity Aquifer, groundwater is fresh to moderately saline (Figure 4.7.2). There is a tendency for Trinity Aquifer groundwater to be more saline in lower formations that make up the aquifer. In the study area, this is most evident by the more frequent occurrence of moderately saline groundwater in the southern part of the study area where Trinity Aquifer groundwater is discharging in the Colorado River Valley (Figures 4.2.7 and 4.7.2).

Groundwater in the northern segment of the Edwards (Balcones Fault Zone) Aquifer displays a wide range of geochemical compositions (Figure 4.7.3). Groundwater compositions range from calcium-magnesium to sodium compositions and bicarbonate to sulfate and chloride compositions. These compositional ranges are determined by geochemical processes that take place as the groundwater flows through the aquifer interacting with aquifer rock and mixing with groundwater inflows from surrounding stratigraphic units (Figure 4.7.4). These compositions indicate groundwater interaction with calcite, dolomite, and gypsum, minerals that occur within the Edwards (Balcones Fault Zone) Aquifer and adjacent stratigraphic units. Groundwater interaction with dolomite and calcite would produce calcium-magnesium-bicarbonate compositions, gypsum would produce calcium-sulfate compositions, and sodium-chloride groundwater compositions are most likely the result of upward migration of groundwater from deep evaporite units. In the northern segment of the Edwards (Balcones Fault Zone) Aquifer, groundwater compositions change from calcium and bicarbonate compositions in up-dip parts of the aquifer to become increasingly sodium-rich with depth. These changes in groundwater compositions are also accompanied by increasing total dissolved solids concentrations.

4.7.2 Isotopes

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

Groundwater carbon-13 isotopic compositions ($\delta^{13}C$) represent the ratios of stable carbon isotopes—^{12}C and ^{13}C—in groundwater relative to the composition of a standard—Peedee Belemnite calcite (Clark and Fritz, 1997). These isotope ratios are expressed as the relative difference in parts per thousand—per mil. Groundwater carbon-13 isotopic compositions often reflect relative carbon inputs from interaction with soil and aquifer rock. Groundwater near recharge zones tend to have more negative carbon-13 compositions reflecting recent contact with the soil. As the groundwater flows through the aquifer—away from the recharge zone—water-rock interaction results in the groundwater taking on more positive carbon-13 isotopic compositions, reflecting those of the aquifer rock. This trend is most apparent in the northern segment of the Edwards (Balcones Fault Zone) Aquifer when comparing carbon-13 compositions of groundwater in the unconfined and confined parts of the aquifer (Figure 4.7.5). In the unconfined parts of the Edwards (Balcones Fault Zone) Aquifer, groundwater is characterized by more negative groundwater carbon-13 compositions—about -15 to -9 per mil—indicating recent recharge. On the other hand, in the confined parts of the northern segment of the Edwards (Balcones Fault Zone) Aquifer, groundwater carbon-13 compositions range from about -12 to -4 per mil with the more negative compositions—about -12 per mil—occurring immediately adjacent to the boundary between the unconfined and confined parts of the aquifer. In the down-dip parts of the aquifer, groundwater carbon-13 compositions are less negative with compositions of about -4 to -5 per mil, indicative of more rock and less soil influences on groundwater compositions.

Carbon-14 decays over time and, consequently, without a continuous influx of carbon-14 with recharging groundwater, the carbon-14 activity in groundwater will decrease over time. The result typically is that groundwater carbon-14 activity is higher in shallower parts of an aquifer where recharge is occurring. In the northern segment of the Edwards (Balcones Fault Zone) Aquifer, carbon-14 activity is generally highest—up to 100 percent modern carbon—within and immediately adjacent to the unconfined parts of the aquifer where the aquifer crops out and recharge occurs, and lowest—less than 10 percent modern carbon—in the subcrop where there is no recharge and almost all of the groundwater carbon-14 has decayed (Figure 4.7.6).

Groundwater tritium behaves like carbon-14. The difference is that tritium has a faster decay rate with a half-life of 12.3 years compared to 5,730 years for carbon-14 (Clark and Fritz, 1997). High tritium activity indicates the most recent recharge. In the northern segment of the Edwards (Balcones Fault Zone) Aquifer, the groundwater tritium activity ranges between 0 and 3 Tritium Units (Figure 4.7.7). In or immediately adjacent to the unconfined parts of the aquifer tritium activity lies in the range of about 1.5 to 3 Tritium Units. In the confined part of the aquifer, tritium activity is below detection indicating groundwater that is much older than the groundwater in the unconfined part of the aquifer.

Groundwater stable hydrogen (δ^2H) and oxygen ($\delta^{18}O$) isotopic compositions represent the ratios of stable hydrogen isotopes—H and ^2H—and stable oxygen isotopes—^{16}O and ^{18}O—in groundwater relative to the composition of standard mean ocean water (Clark and Fritz, 1997). These isotope ratios are expressed as the relative difference in parts per thousand—per mil. Groundwater stable hydrogen (δ^2H) and oxygen ($\delta^{18}O$) isotopic compositions reflect the composition of the precipitation that recharged the aquifer which may vary spatially or temporally in response to factors such as elevation, temperature, and amount of precipitation (Dansgaard, 1964; Fontes and Olivry, 1977; Fontes, 1980; Gonfiantini, 1985; Scholl and others, 1996). Consequently, the hydrogen and oxygen isotopic compositions of groundwater can be used as an indicator of the conditions under which recharge to the aquifer occurred. Figures 4.7.8 and 4.7.9 show groundwater hydrogen and oxygen isotopic compositions in the northern segment of the Edwards (Balcones Fault Zone) Aquifer. Groundwater stable hydrogen and oxygen isotopic compositions in the northern segment of the Edwards (Balcones Fault Zone) Aquifer lie in the ranges -31 to -13 per mil and -6 to -2 per mil, respectively. Stable hydrogen and oxygen isotope compositions generally lie along the Global Meteoric Water Line—the average relationship between stable hydrogen and oxygen isotopic compositions in precipitation around the world (Craig, 1961). Figure 4.7.9 shows northern segment of the Edwards (Balcones Fault Zone) Aquifer groundwater stable hydrogen and oxygen isotopic compositions relative to the Global Meteoric Water Line. Hydrogen and oxygen isotopic compositions in the underlying Trinity Aquifer are similar to those in the overlying Edwards (Balcones Fault Zone) Aquifer (Figure 4.7.9).

4.7.3 Implications for Recharge Based on Groundwater Major Element and Isotopic Compositions

Figure 4.7.10 shows a comparison of hydrogen and oxygen isotopic compositions in the northern segment of the Edwards (Balcones Fault Zone) Aquifer groundwater in the San Gabriel River and Salado Creek watersheds with precipitation compositions. The figure shows that groundwater has a much narrower range of compositions than precipitation. This occurs because groundwater compositions reflect the fraction of precipitation that recharges the aquifer; most precipitation is taken up by runoff, evaporation or transpiration (Jones, 2002).

The range of stable hydrogen and oxygen isotopic compositions in precipitation can be influenced by the effects of temperature, altitude, and amount of precipitation (Dansgaard, 1964; Fontes and Olivry, 1977; Fontes, 1980; Gonfiantini, 1985; Scholl and others, 1996). The most likely effects influencing the range of precipitation stable hydrogen and oxygen isotopic compositions in the northern segment of the Edwards (Balcones Fault Zone) Aquifer are the temperature and amount effects. Together, the temperature and amount effects would result in seasonal fluctuations of stable hydrogen and oxygen isotopic compositions. Higher precipitation amounts, and/or lower temperatures produce more negative isotopic compositions in the precipitation and resultant groundwater. Figure 4.7.11 shows the variation of average monthly precipitation oxygen isotopic compositions together with the range of northern segment of the Edwards (Balcones Fault Zone) Aquifer groundwater compositions. If groundwater compositions are the average composition of precipitation water that recharges the aquifer, then most recharge to the northern segment of the Edwards (Balcones Fault Zone) Aquifer is likely to occur in the winter and fall months where median precipitation compositions approach that of groundwater (Figure 4.7.11).

The groundwater flow characteristics in the northern segment of the Edwards (Balcones Fault Zone) Aquifer were investigated by Jones (2006). This study investigated changes in groundwater major element and isotopic compositions along two flow paths in the San Gabriel River and Salado Creek watersheds. Please note: groundwater flow is approximately parallel to these rivers. Figures 4.7.12 shows variation of total dissolved solids, and carbon-13 and tritium isotopic compositions. The variation of total dissolved solids along the respective flow paths shows relatively uniform concentrations along the Salado Creek flow path, which is entirely located in the unconfined portion of the aquifer, and a rise in total dissolved solids in the confined part of the aquifer along the San Gabriel River flow path; these being the two most down-gradient wells. We see similar trends in carbon-13 and tritium isotopes where isotope activity is much lower in the confined part of the aquifer than in the unconfined part of the aquifer. These trends indicate: (1) groundwater in the confined parts of the northern segment of the Edwards (Balcones Fault Zone) Aquifer is much older than in the unconfined part of the aquifer, (2) the higher groundwater salinity in the confined part of the aquifer can be attributed to the lack of freshwater influxes from the unconfined part of the aquifer. These trends indicate that there is very little groundwater flow in the confined part of the aquifer and that most hydrologic activity—recharge, groundwater flow and discharge—is occurring in the unconfined part of the aquifer. The decrease in hydraulic gradient noted in Section 4.2 is additional evidence of relatively less groundwater flow in the confined parts of the aquifer (Figure 4.2.6).

Figures 4.7.13 and 4.7.14 show a comparison of groundwater isotopic composition in the northern segment of the Edwards (Balcones Fault Zone) Aquifer and underlying Trinity Aquifer. This comparison indicates that in most cases, Trinity Aquifer groundwater is isotopically similar to the confined portion of the Edwards (Balcones Fault Zone) Aquifer groundwater. In other words, old groundwater with little tritium and carbon-14 indicating little to no recent recharge.

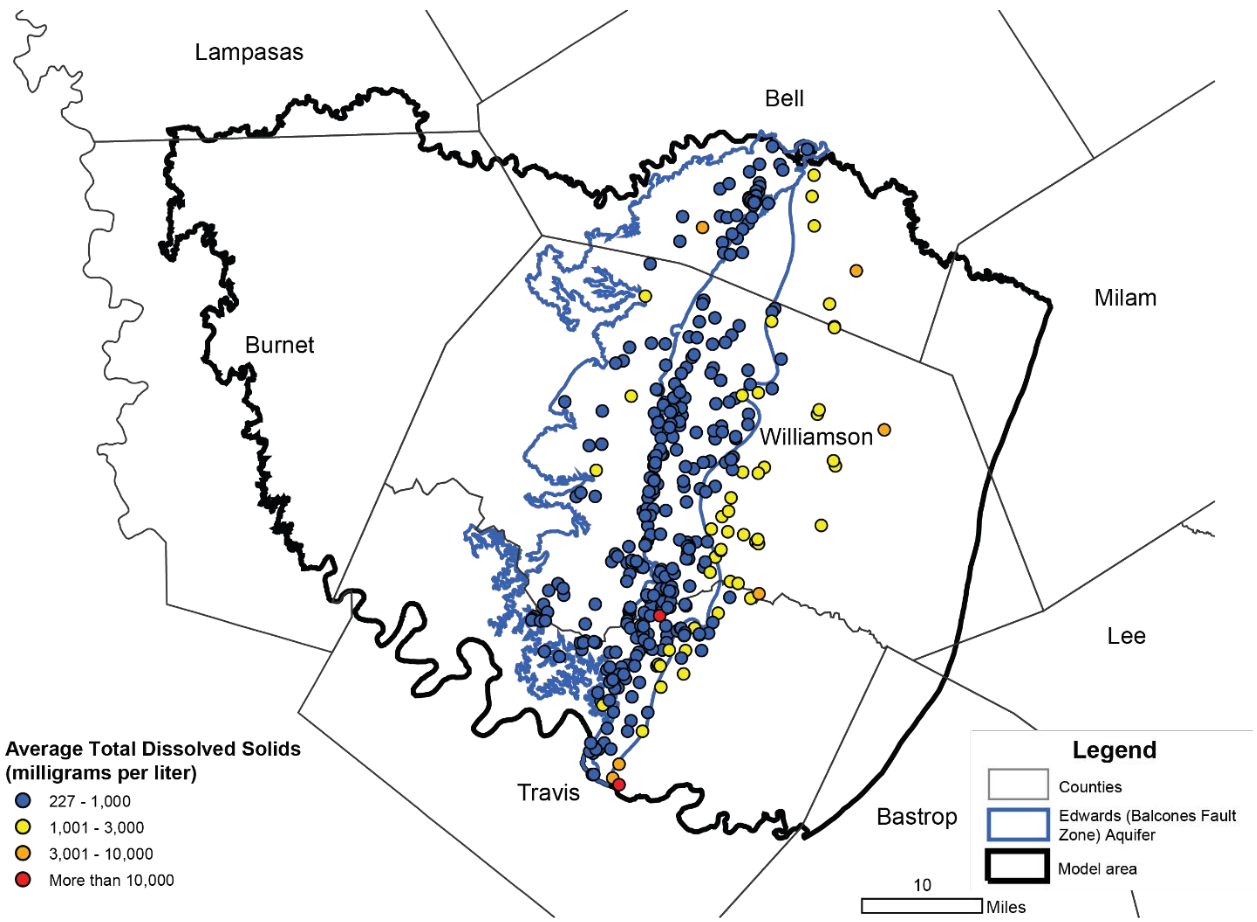


Figure 4.7.1. **Total dissolved solids concentration (in milligrams per liter) in the northern segment of the Edwards (Balcones Fault Zone) Aquifer (Data from Texas Water Development Board, 2017a).**

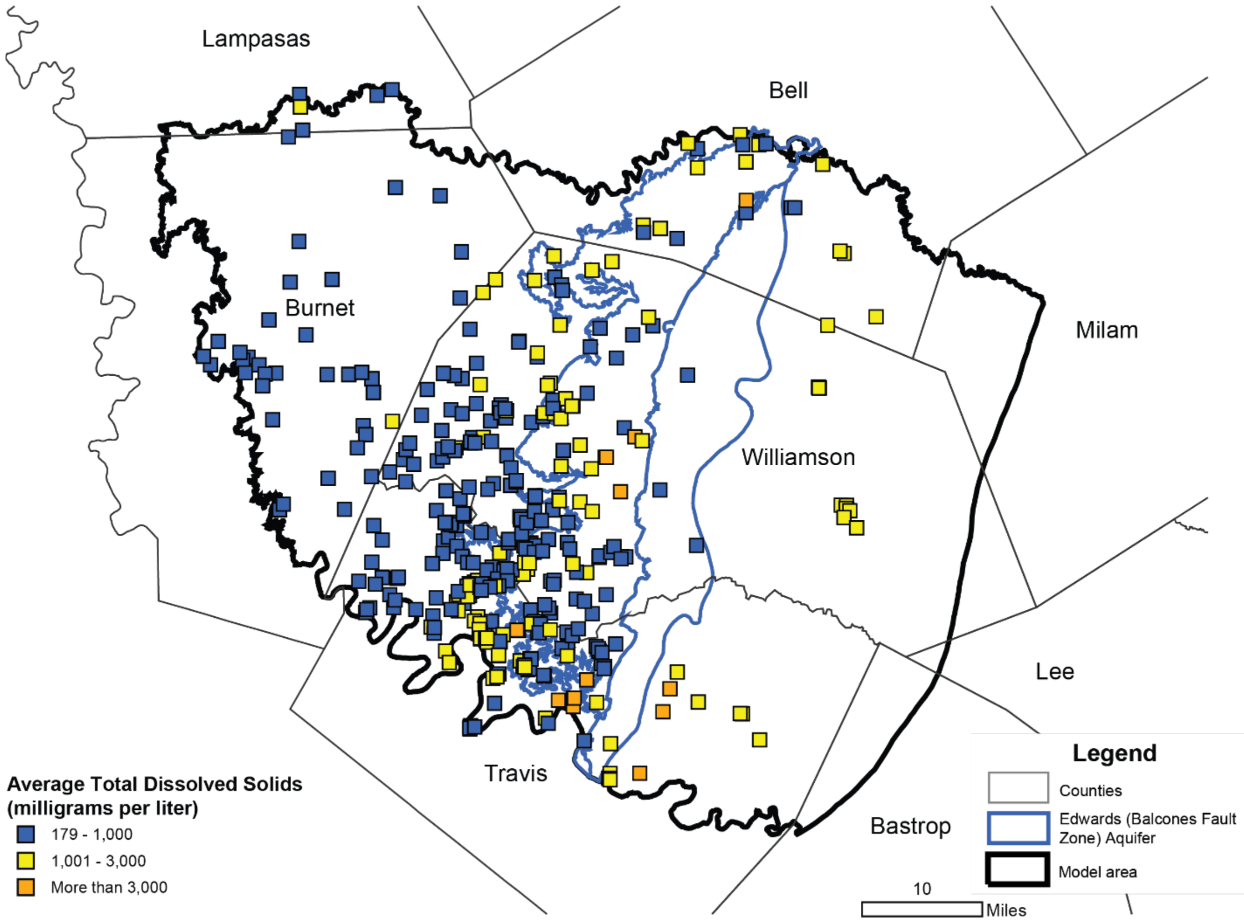


Figure 4.7.2. Total dissolved solids concentration (in milligrams per liter) in the Trinity Aquifer (Data from Texas Water Development Board, 2017a).

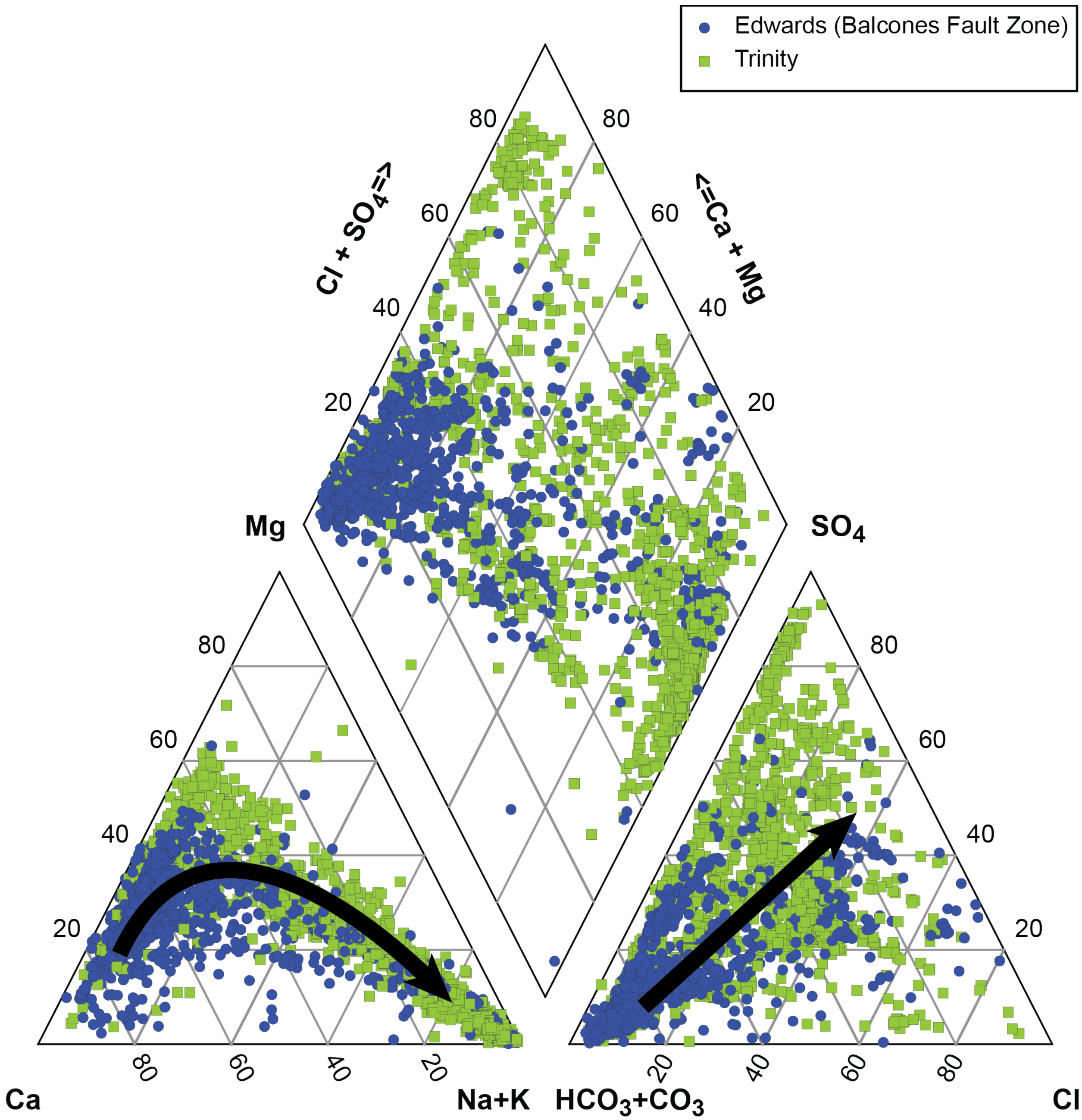


Figure 4.7.3. A Piper diagram showing the range of groundwater compositions in the northern segment of the Edwards (Balcones Fault Zone) Aquifer (blue dots) and the underlying Trinity Aquifer (green dots). The arrows indicate compositional changes along flow paths (Data from Texas Water Development Board, 2017a).

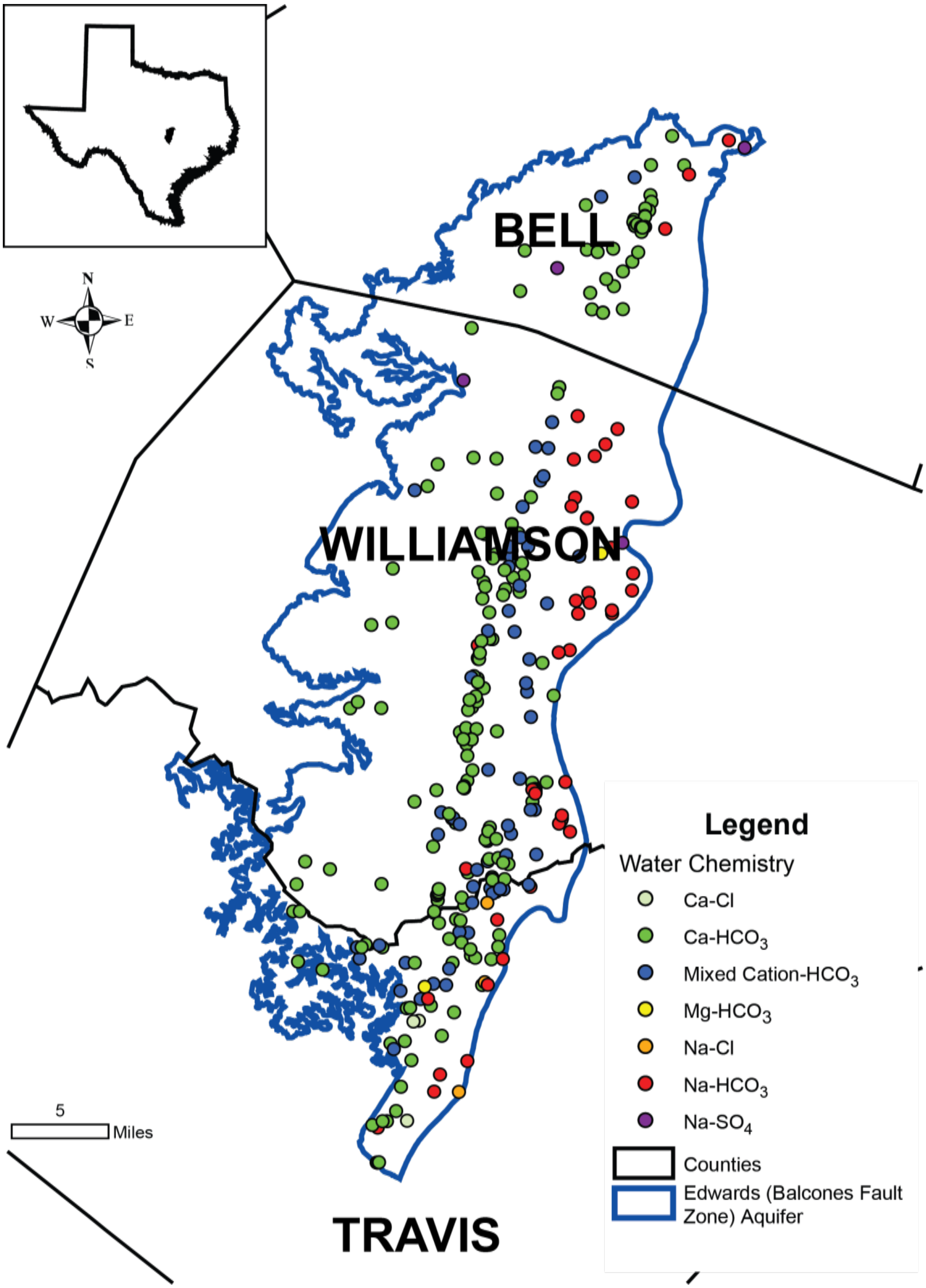


Figure 4.7.4. Groundwater types in the northern segment of the Edwards (Balcones Fault Zone) Aquifer (Data from Texas Water Development Board, 2017a).

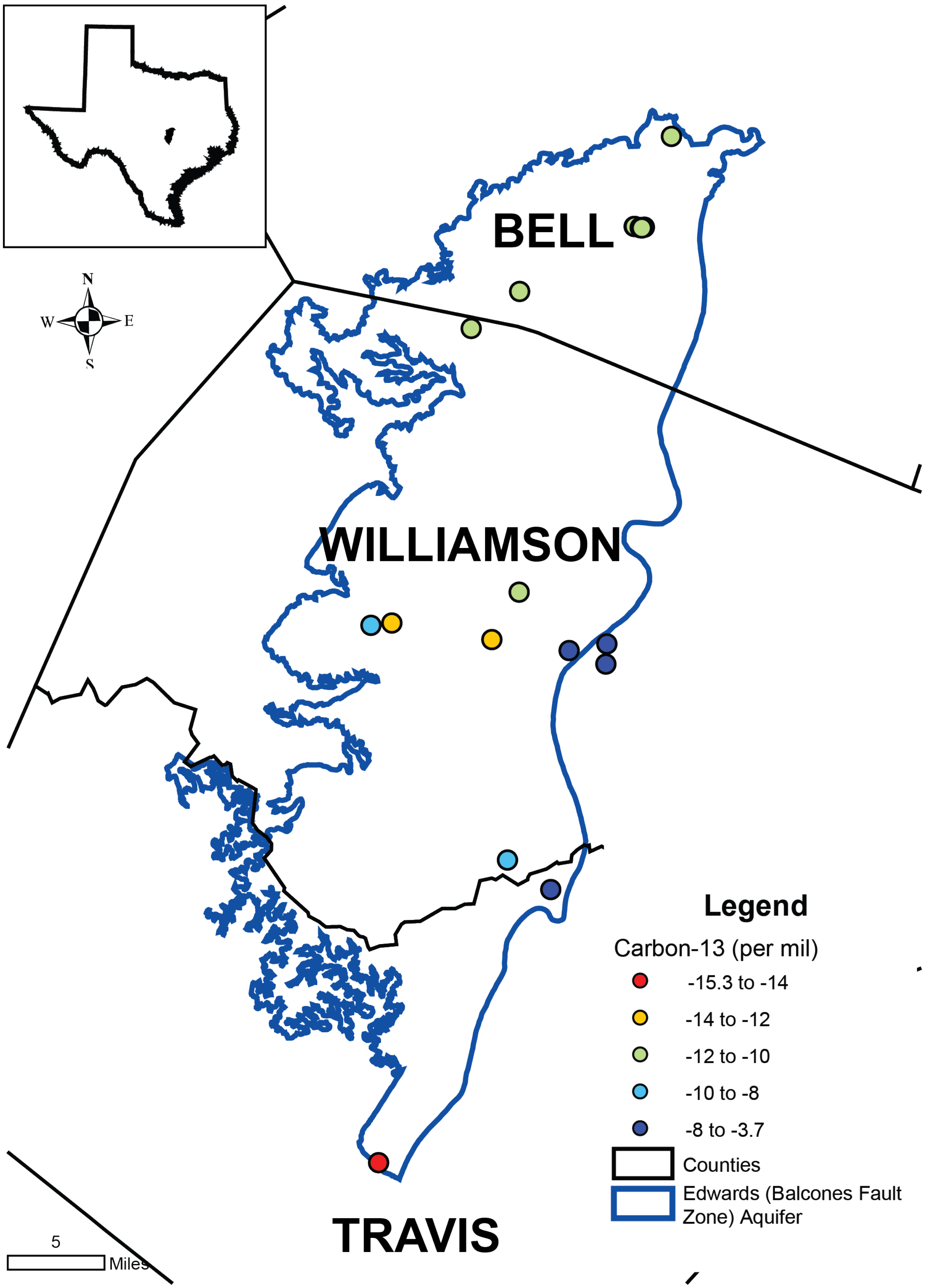


Figure 4.7.5. Groundwater Carbon-13 isotopes (in per mil) in the northern segment of the Edwards (Balcones Fault Zone) Aquifer (Data from Texas Water Development Board, 2017a).

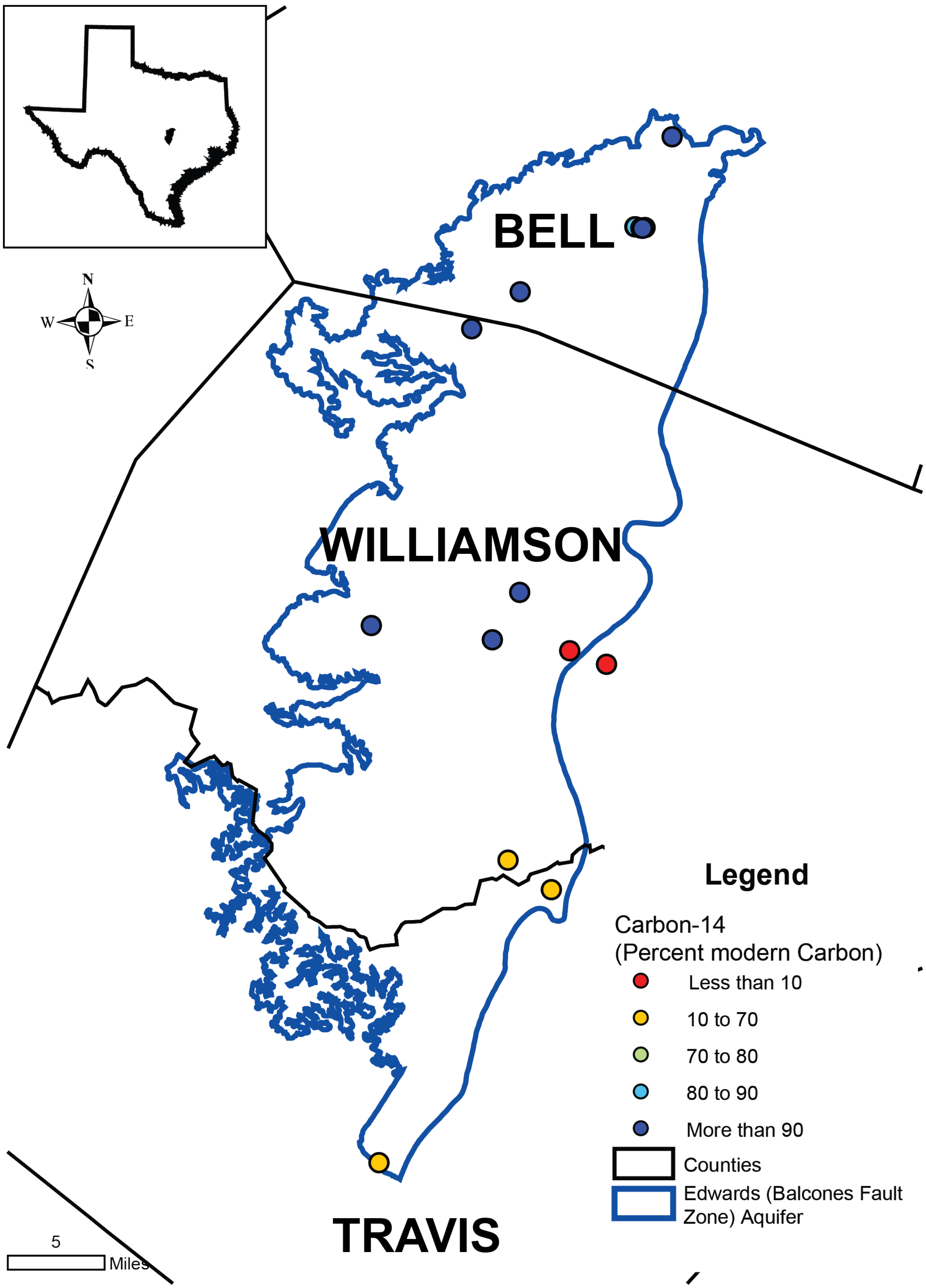


Figure 4.7.6. Groundwater Carbon-14 (in percent modern carbon) in the northern segment of the Edwards (Balcones Fault Zone) Aquifer (Data from Texas Water Development Board, 2017a).

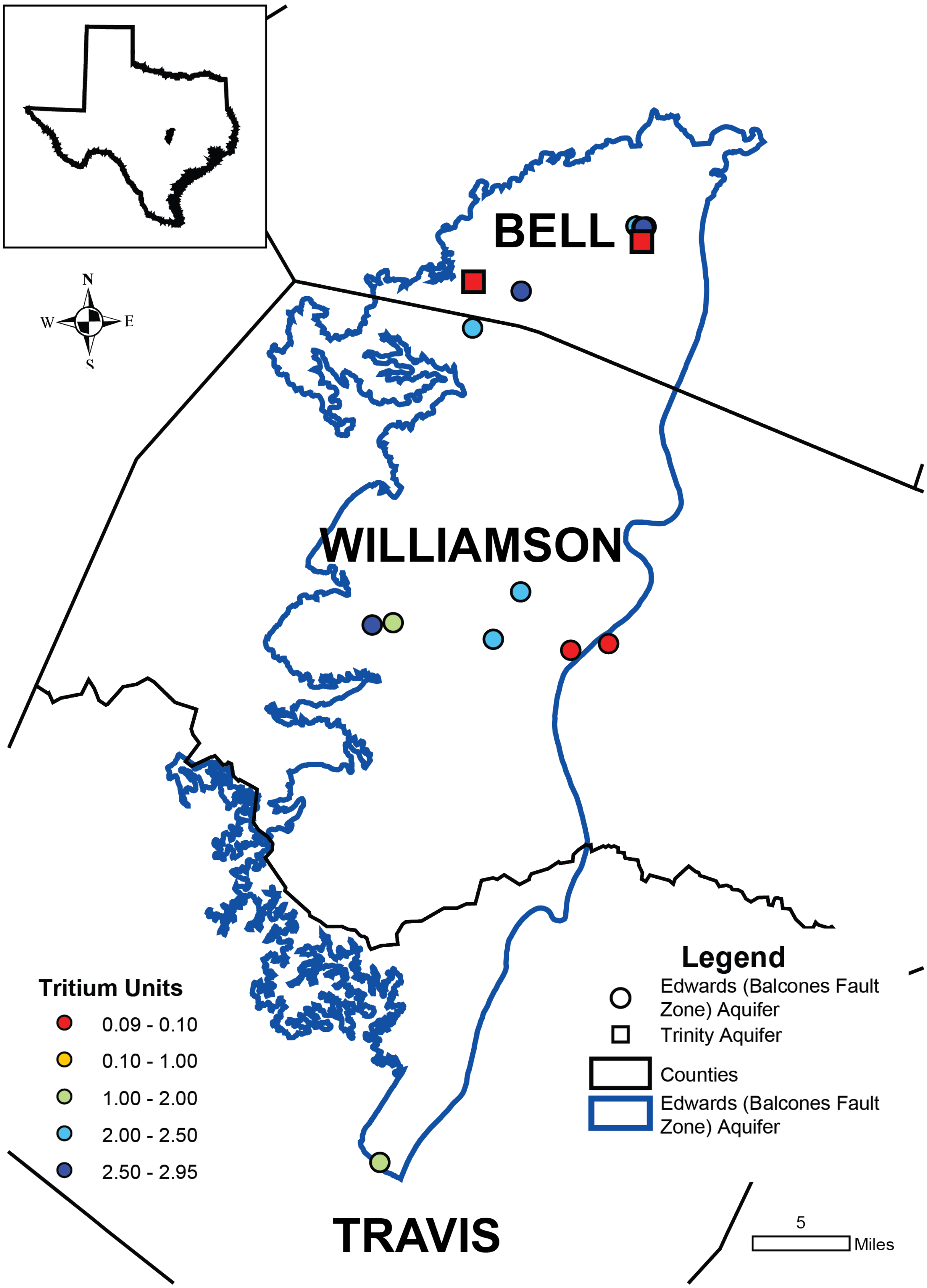


Figure 4.7.7. **Groundwater tritium (in Tritium Units) in the northern segment of the Edwards (Balcones Fault Zone) Aquifer (Data from Texas Water Development Board, 2017a).**

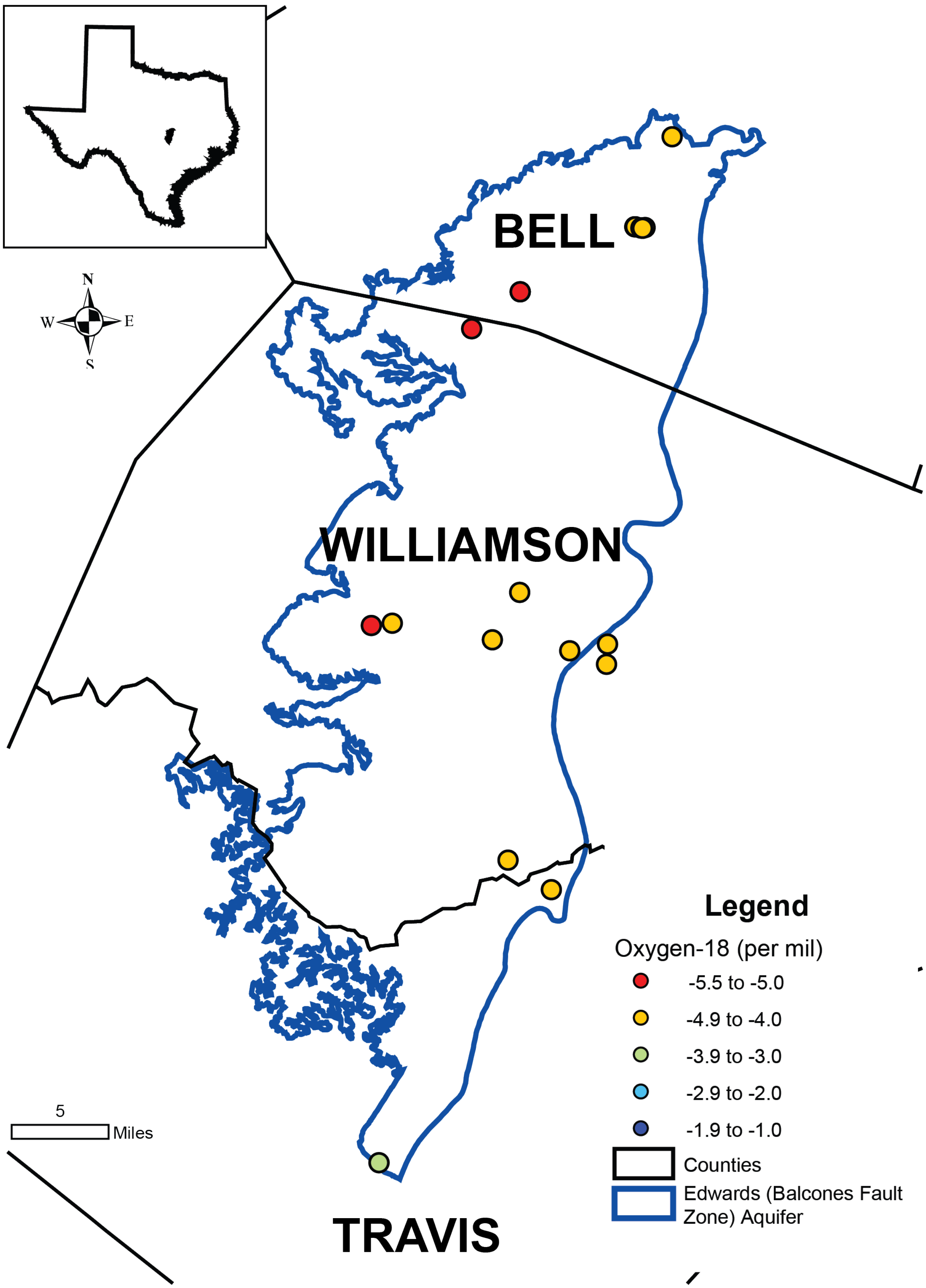


Figure 4.7.8. **Groundwater stable oxygen isotopes ($\delta^{18}O$, in per mil) in the northern segment of the Edwards (Balcones Fault Zone) Aquifer (Data from Texas Water Development Board, 2017a).**

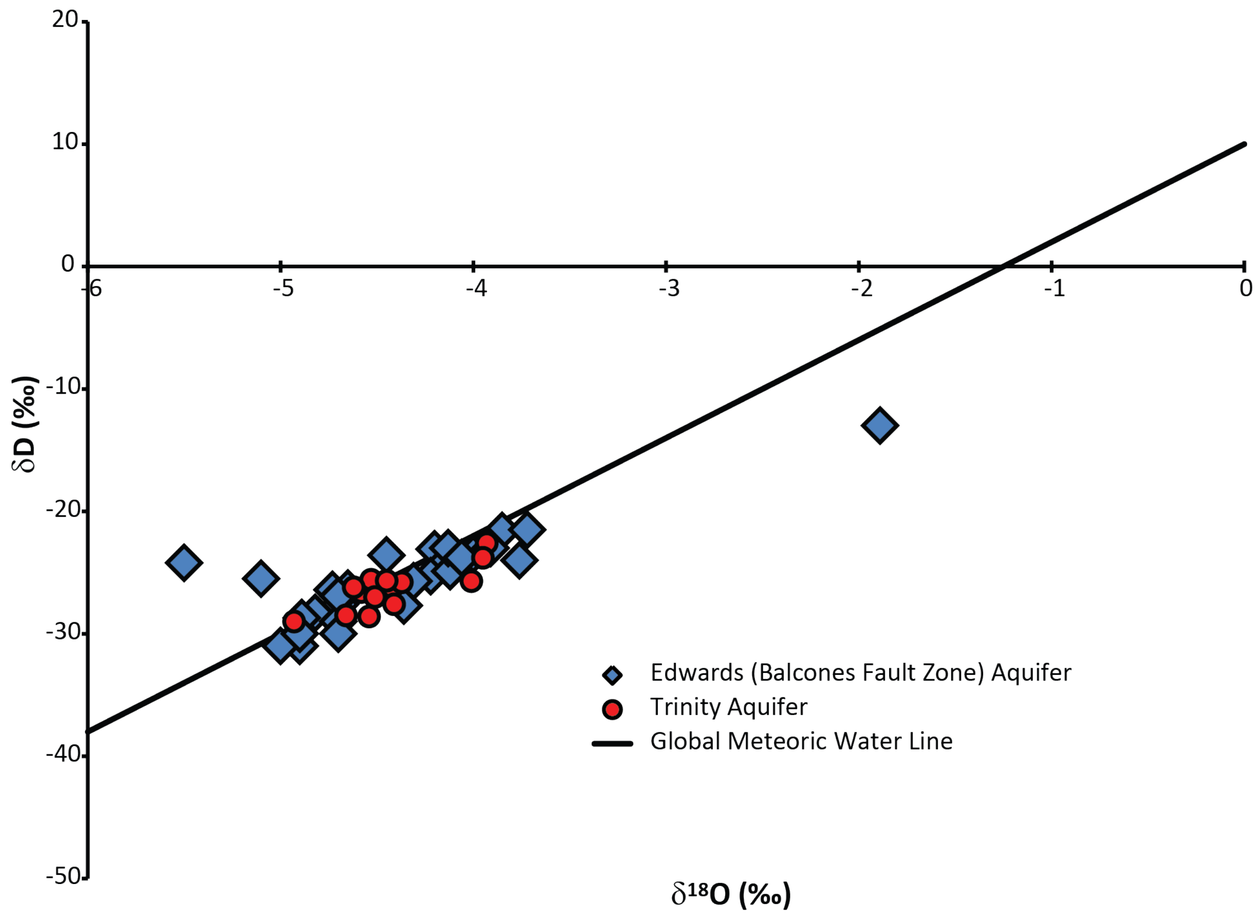


Figure 4.7.9. Groundwater stable oxygen isotopes ($\delta^{18}O$, in per mil) and stable hydrogen isotopes ($\delta^{2}H$, in per mil) in the northern segment of the Edwards (Balcones Fault Zone) and underlying Trinity aquifers (Data from Texas Water Development Board, 2017a).

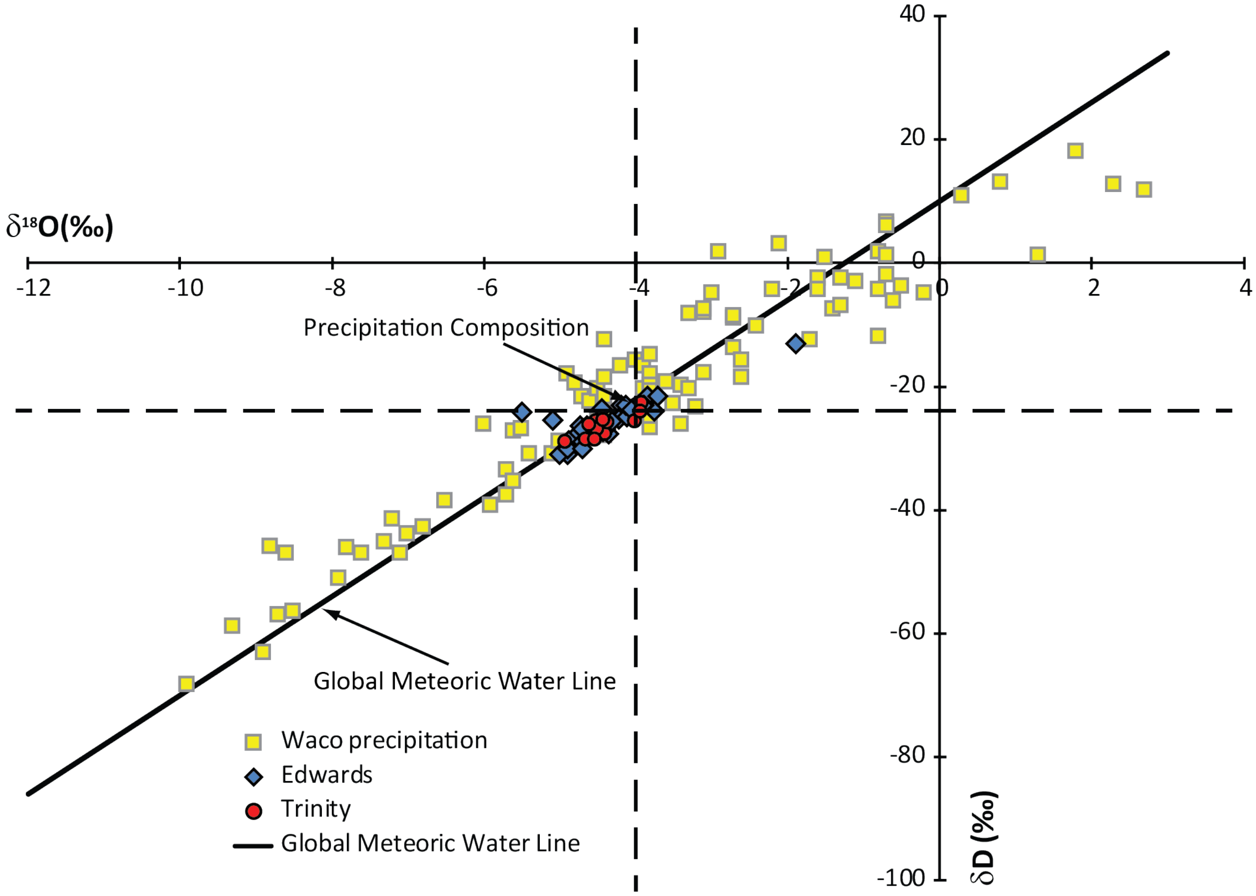


Figure 4.7.10. **Northern segment of the Edwards (Balcones Fault Zone) Aquifer and Trinity Aquifer groundwater and Waco precipitation stable hydrogen and oxygen isotopes (in per mil) relative to the Global Meteoric Water Line (Data from IAEA/WMO, 2004; Texas Water Development Board, 2017a).**

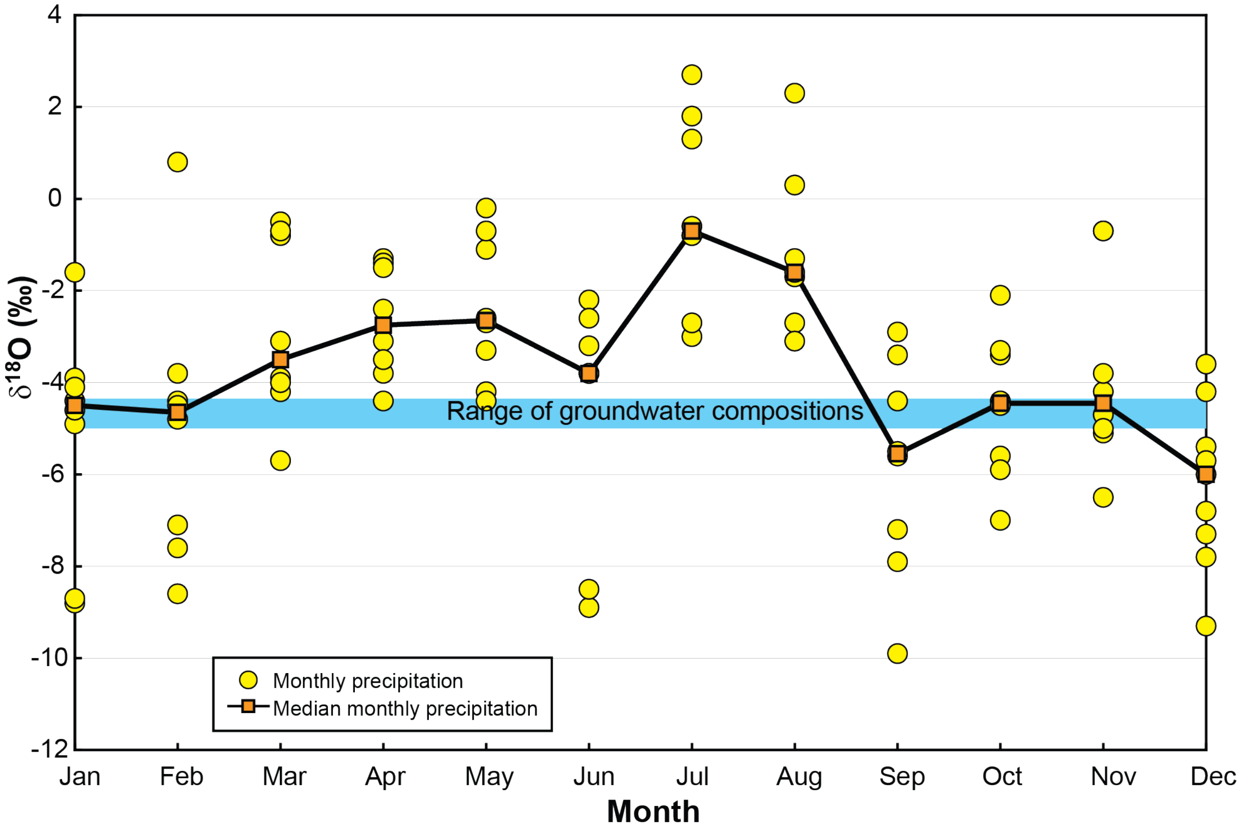


Figure 4.7.11. Plot of precipitation oxygen isotopes versus time showing variation in isotopic composition during different months of the year (Data from IAEA/WMO, 2004; Texas Water Development Board, 2017a).

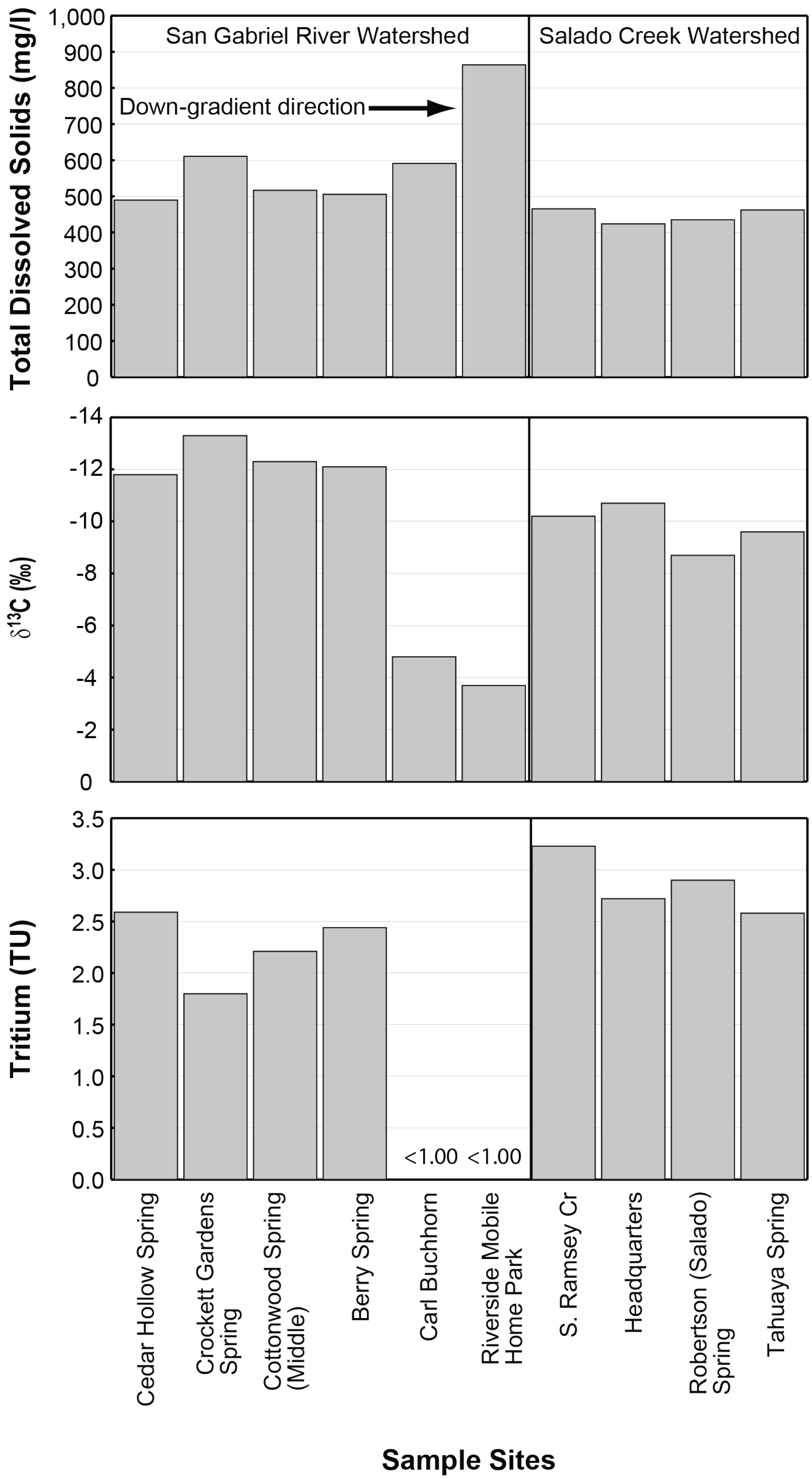


Figure 4.7.12. Bar diagrams showing changes in groundwater total dissolved solids, stable carbon and tritium isotope compositions along flow paths (Data from Texas Water Development Board, 2017a).

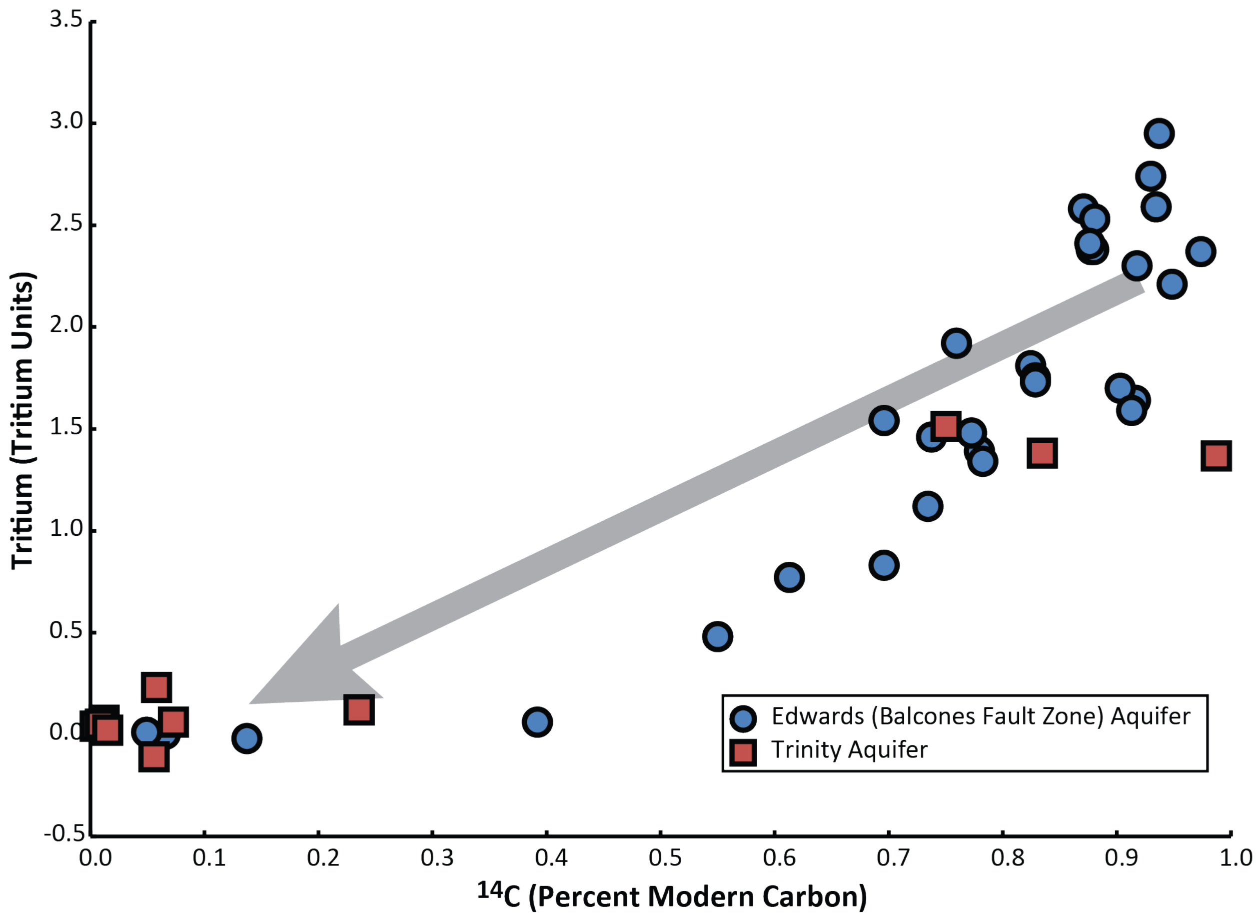


Figure 4.7.13. Groundwater tritium and carbon-14 isotopes in the northern segment of the Edwards (Balcones Fault Zone) and underlying Trinity aquifers. The arrow indicates down-dip groundwater compositions (Data from Texas Water Development Board, 2017a).

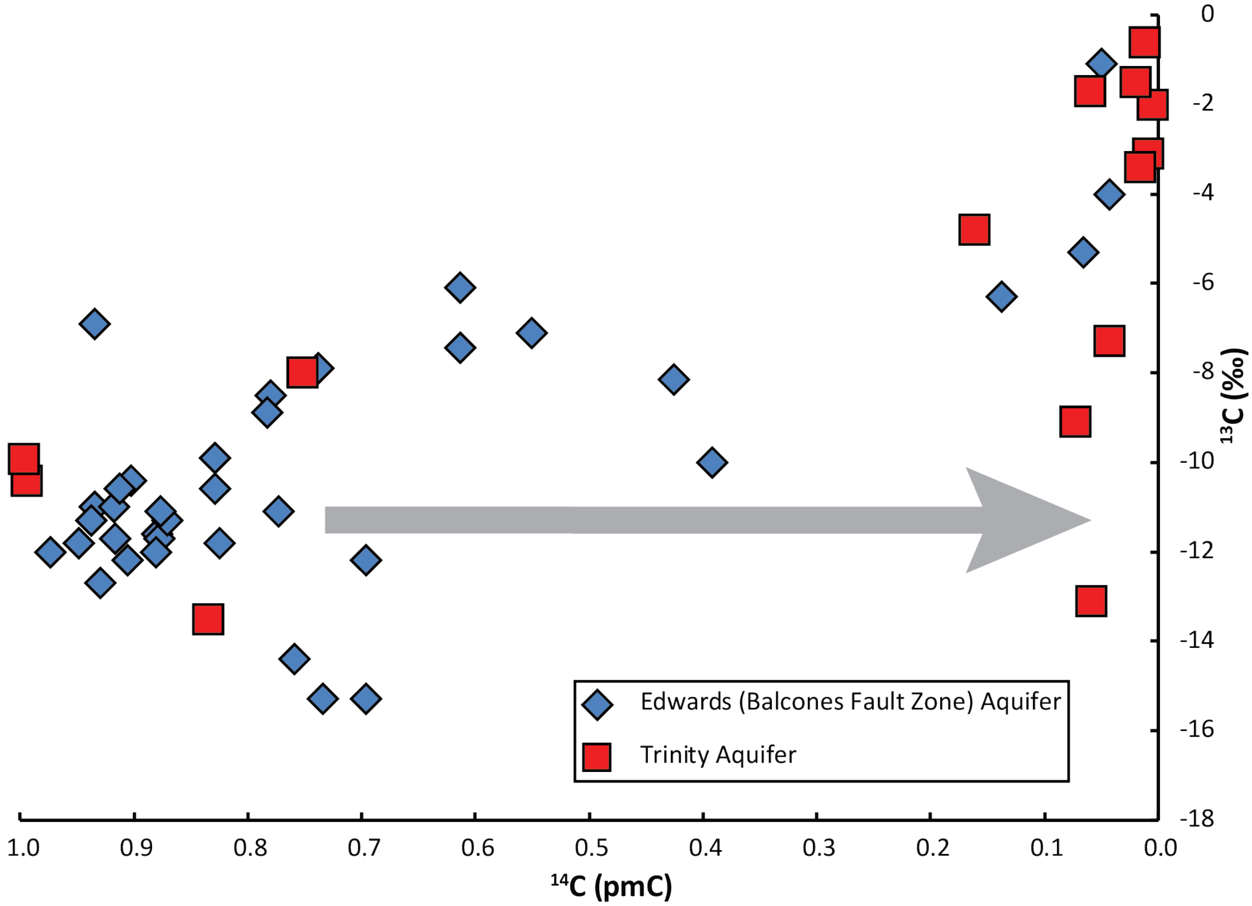


Figure 4.7.14. Groundwater carbon-13 and carbon-14 isotopes in the northern segment of the Edwards (Balcones Fault Zone) and underlying Trinity aquifers. The arrow indicates down-dip groundwater compositions (Data from Texas Water Development Board, 2017a).

5.0 CONCEPTUAL MODEL OF GROUNDWATER FLOW IN THE NORTHERN SEGMENT OF THE EDWARDS (BALCONES FAULT ZONE) AND ASSOCIATED TRINITY AQUIFERS

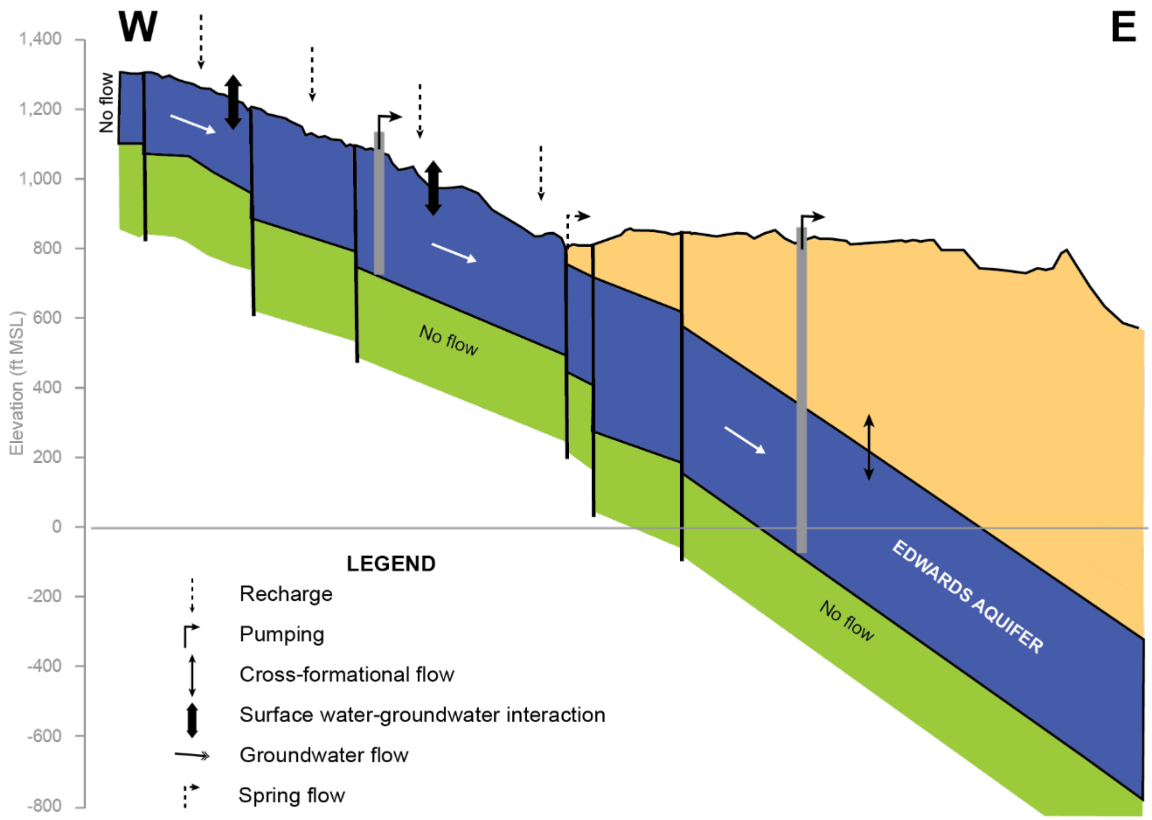
The conceptual model of groundwater flow in the northern segment of the Edwards (Balcones Fault Zone) Aquifer is based on the hydrogeologic setting, described in Section 4.0. The conceptual model is a simplified representation of the hydrogeological features that govern groundwater flow in the aquifer. It includes the hydrostratigraphy, hydrogeologic framework, hydraulic properties, hydrologic boundaries, recharge, and discharge.

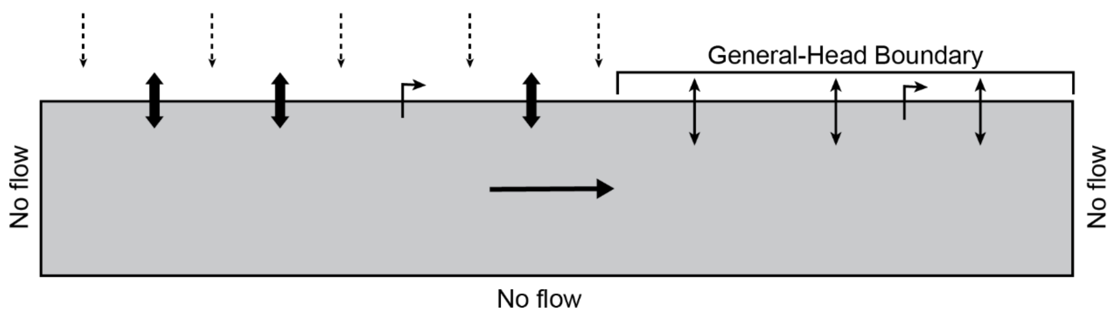
The northern segment of the Edwards (Balcones Fault Zone) Aquifer is the northern extent of the larger Edwards (Balcones Fault Zone) Aquifer that extends north of the Colorado River. The Edwards (Balcones Fault Zone) Aquifer is composed of the Georgetown

Formation, Edwards Limestone, and Comanche Peak Limestone (Figure 2.2.6). The northern segment of the Edwards (Balcones Fault Zone) Aquifer is also bounded by the Del Rio Clay and Walnut Formation that act as confining units. In the study area, the Trinity Aquifer is composed of the Glen Rose and Travis formations.

Work by Jones (2003; 2006) indicates groundwater flow through the northern segment of the Edwards (Balcones Fault Zone) Aquifer is generally west to east (Figure 4.2.6). Groundwater flow apparently converges on the major rivers and streams in or near the unconfined part of the aquifer and are the most likely discharge zones; including Brushy Creek, Colorado River, Salado Creek, San Gabriel River, and Lampasas River. The northern segment of the Edwards (Balcones Fault Zone) Aquifer likely recharges by infiltration of precipitation where the aquifer crops out as noted in Section 4.3. Groundwater inflow to and outflow from the northern segment of the Edwards (Balcones Fault Zone) Aquifer in the form of cross-formational flow is believed to be relatively minor, indicated by: (1) the lower hydraulic gradients in the confined part of the aquifer, probably indicative of an inactive aquifer characterized by little groundwater flow (Figure 4.2.6), (2) low hydraulic conductivity of bounding stratigraphic units, such as the Del Rio Clay and the Walnut Formation and Glen Rose Formation, and (3) the low vertical hydraulic gradients between the Edwards (Balcones Fault Zone) Aquifer and underlying Trinity Aquifer (Figure 4.2.14). Cross-formation flow is also likely to be minor in up-gradient parts of the northern segment of the Edwards (Balcones Fault Zone) Aquifer as suggested by large differences in water levels between the Edwards (Balcones Fault Zone) Aquifer and underlying Trinity Aquifer suggesting perched groundwater at some locations in the Edwards (Balcones Fault Zone) Aquifer (Figure 4.2.14).

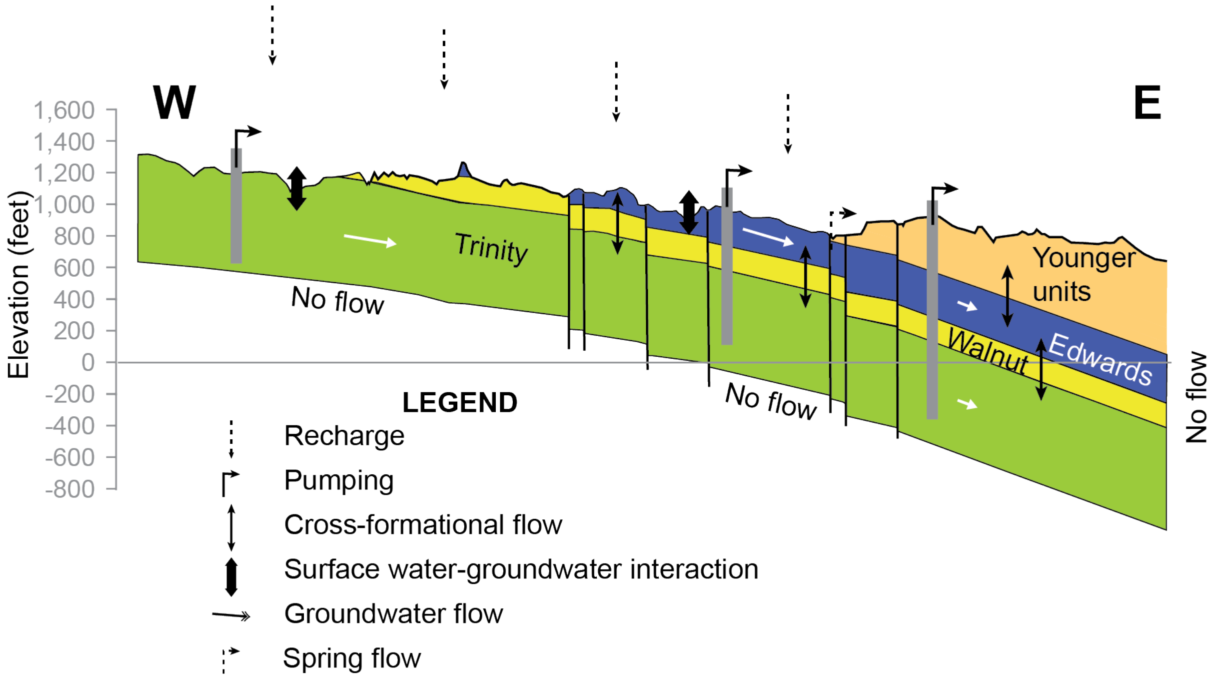
The schematic diagram in Figure 5.0.1(A) is a conceptual block diagram illustrating aquifer contact relationships and sources and sinks of groundwater in the northern segment of the Edwards (Balcones Fault Zone) Aquifer used by Jones (2003). The original groundwater availability model for the northern segment of the Edwards (Balcones Fault Zone) Aquifer was a one-layer model that assumed no interaction with the underlying Trinity Aquifer and simulates cross-formation discharge to overlying units using a general-head boundary. Figure 5.0.1(B) shows the proposed conceptual model for the updated groundwater availability model for the northern segment of the Edwards (Balcones Fault Zone) Aquifer. The updated model would be made up of at least three layers simulating the northern segment of the Edwards (Balcones Fault Zone) Aquifer and underlying parts of the Walnut Formation and Trinity Aquifer. Cross-formational flow between the Edwards (Balcones Fault Zone) Aquifer and overlying stratigraphic units would be simulated either using a general-head boundary or and additional model layer.

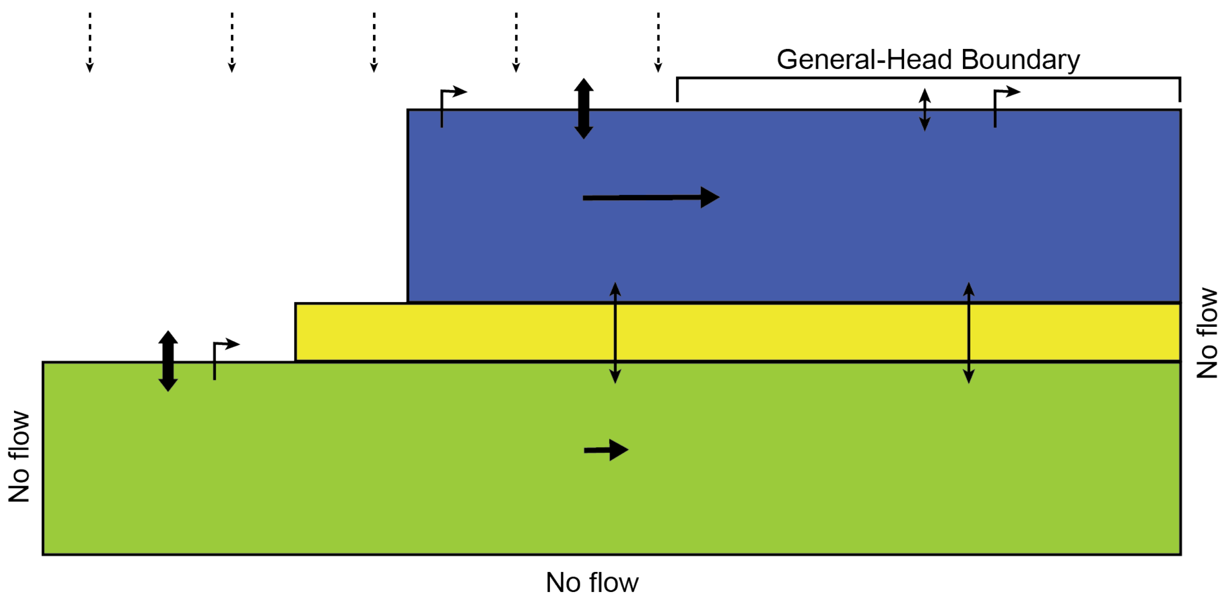




(A)

Figure 5.0.1. Schematic cross section and conceptual groundwater flow model for the northern segment of the Edwards (Balcones Fault Zone) Aquifer Groundwater Availability Model. (A) conceptual model used in Jones (2003) and (B) proposed conceptual model.





(B)

Figure 5.0.1. (continued).

6.0 ACKNOWLEDGEMENTS

I would like to acknowledge the interest in this project shown by the stakeholders who attended the initial and conceptual model stakeholder advisory forums. I would also like to thank the Clearwater Underground Water Conservation District and Mike Keester for their help that made completion of this project possible. I would also like to acknowledge staff who reviewed and otherwise contributed to this conceptual model report, Cindy Ridgeway, Larry French, and Alisa Richey.

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APPENDIX A. CONCEPTUAL MODEL REPORT COMMENTS AND RESPONSES

General Comments

The conceptual model report references the studies by Dahl (1990), and Slade (2002) for recharge and groundwater-surface water interactions, especially in Salado Creek watershed. Can TWDB clarify the approach that will be used to develop temporal recharge and stream-aquifer interaction for the updated model for northern Travis, Williamson, and Bell counties?

In the updated model, temporal variation of recharge will be determined based on monthly precipitation measurement variation over the model period. Groundwater-surface water interaction in the model will be simulated using the River package in MODFLOW.

Clearwater Underground Water Conservation District recently completed a study to more accurately estimate and assess groundwater production in the Northern Edwards (Balcones Fault Zone) Aquifer Groundwater Availability Model study area of Northern Travis, Williamson and Bell Counties (Keester May 2020). Based on the TWDB forum presentation, the pumping data presented referenced in the newest update of the conceptual model report partially extends only through 2015 and is based in incomplete water use surveys. Would the additional estimates of pumping referenced in the third-party study (Keester May 2020) funded by Clearwater Underground Water Conservation District be incorporated at an appropriate when pumping files are being prepared as input to the numerical model?

Keester (2020) uses a methodology different from that used by the TWDB and consequently the two methods have different results. Upon completion of this project, the model can be used to evaluate the two pumping datasets.

Major faults and fractures within the structural system may heavily influence the movement of groundwater. However, simulating these conduits (or barriers) to groundwater flow may sometime prove controversial in terms of location of these features within the model domain. It is our opinion that the major impact of faults and fractures within a regional aquifer system may be represented by a more complex distribution of anisotropy in the aquifer. A complexly distributed anisotropy may also achieve similar goals in terms of more accurate simulation of groundwater migration in a structurally complex aquifer such as the Northern Edwards (Balcones Fault Zone) Aquifer.

At the regional scale of the model, the numerous and randomly oriented fractures in the form of major and minor faults and joints form a network of flow paths that contribute to the hydraulic properties of the aquifer rock without necessarily resulting in regional-scale anisotropy in the aquifer. The primary driving force for groundwater flow in the study area is gravity flow toward the Colorado, Lampasas and San Gabriel river valleys.

We respectfully recommend the use of MODFLOW 6 as the selected code for construction of the numerical model. The XT3D option in MODFLOW 6 will allow better representation and simulation of the anisotropy in the numerical model. The unstructured grid option in MODFLOW 6 would also allow improved discretization to better represent the surface-water features on a refined grid structure. However, we understand that TWDB staff may make a separate determination based on internal discussions and would continue our commitment to be involved in this project.

We plan to initially construct the groundwater flow model of the northern segment of the Edwards (Balcones Fault Zone) Aquifer using MODFLOW 2005 followed by converting it to a MODFLOW 6 or MODFLOW USG model.

What is the anticipated calibration period for the model?

The anticipated calibration period is 1980 through 2015.

In addition to needing more recent data, my main concerns are that major components of the water budget such as discharge and recharge may need adjustments. These concerns are discussed in the paragraphs that follow.

Discharge: Pumping amounts for domestic wells are extrapolated from estimates for average daily household use that do not appear to include lawn irrigation. Much of the population growth impacting domestic groundwater use in the Northern Segment of the Edwards BFZ aquifer is exurban development with large houses containing large lawns. The irrigation of these large lawn areas results in average daily domestic pumping rates that are much higher than the numbers cited in the report. Lawn irrigation also occurs mostly in the summer months when there is little recharge. In the unconfined portion of the aquifer this may impact springs and stream baseflow. This is an important part of the water budget in that page 109 of the report states that municipal and domestic pumping account for approximately 90% of the total pumping in the Northern Segment of the Edwards BFZ aquifer.

Recharge: The general locations of recharge (outcrop and losing stream segments) are conceptually correct. However, the timing of when most recharge occurs may be misunderstood and perhaps misrepresent the critical timing of most of the annual recharge. The suggestion in this draft report that most recharge occurs in the fall and winter months appears to be based upon isotopic values of oxygen (18O) in groundwater compared to median values of 18O from monthly composite samples of precipitation (Jones, 2006). While this is an insightful and creative use of isotopic data, it does not agree with other observations related to recharge. Jones (2006) correctly points out that this interpretation is surprising since spring is the wettest season of the year. My concern is that this interpretation is contradictory to aquifer responses to rainfall observed in wells and springs. The isotopic interpretation using median values does not appear to consider the weighted amounts of monthly rain which can affect the amount of recharge and the mixing model results. Isotopic values from small rains that do not contribute to the groundwater recharge are included in the composite sample data and rainfall amounts can affect the isotopic signature as stated in the draft report. There are a number of different mixing models that could result in the same groundwater isotope values observed and in my opinion the hydrograph responses seen in the wettest months of spring and fall should be given priority for when most of the recharge occurs.

The domestic pumping estimates include lawn irrigation. Monthly domestic pumping is distributed temporally similar to irrigation pumping such that pumpage is highest during summer months and lowest in the winter.

Using median precipitation oxygen isotopic values reflects the range of data for the respective months and indicates overall monthly trends. The fact that the groundwater compositions do not overlap with either the wettest or driest months—May and July-August, respectively—suggest that they contribute the least to the isotopic composition of groundwater. However, that does not suggest that no recharge occurs during these months. Relatively low contributions to the isotopic composition of groundwater could be attributed to precipitation runoff exceeding infiltration capacity during wet months or insufficient precipitation to infiltrate to the water table during dry months. Weighting based on amounts of precipitation—a method that was used in Jones (2002)—is not applicable to temperate climates where multiple factors, not just the amount, influence the seasonal variation of precipitation isotopic compositions.

Land Use: Land use can have a significant bearing on the hydrologic system regarding recharge and pumping demands. Although population growth was addressed in the report, the land use dynamics did not appear to be included. In the Northern Segment of the

Edwards BFZ Aquifer, land use is in a dynamic flux. Perhaps a section on land use trends could provide additional guidance for the GAM.

Discussion of future land use trends is not applicable to this project which is based on historical data used to calibrate the model and thus falls outside the scope of this project.

Specific Comments

Executive Summary, Page 1-2, Paragraph 5: The confined portion of the aquifer is defined as "the parts of the aquifer that are below the land surface". I guess, technically, all parts of the aquifer are below, not above, the land surface. But even recognizing what is meant by this sentence it is not exactly correct because covered aquifers may still be unconfined. Even if the intent is to try to keep definitions simple and understandable by most readers, this could prove problematic if all covered aquifers in the model are treated as confined because of how the two types of aquifers function hydrogeologically.

Revised the text from "the parts of the aquifer that are below the land surface" to "the parts of the aquifer that are overlain by non-aquifer stratigraphic units".

Executive Summary, Page 2, Paragraph 1: Although "trends" might not be the best word to describe the spatial variations caused by karst processes, several previous studies referenced in this draft conceptual model speak of dissolution zones in certain parts of the aquifer. Dahl (1990) and other studies mention the effects of faults increasing fracture density that, in turn, enhances transmissivity. Addressing these patterns may help the model.

The term "trends" refers to the random distribution of widely ranging hydraulic conductivity data in the northern segment of the Edwards (Balcones Fault Zone) Aquifer. The northwest-southeast and northeast-southwest orientations of fractures in the study area discussed are discussed in Section 2.2.1 of this report.

Section 2.0, Page 6, Paragraph 1: "The eastern—downdip—boundary of the aquifer is defined by the occurrence of groundwater containing total dissolved solids more than 1,000 milligrams per liter": Please clarify if the boundary will be at or less than 1,000 mg/L or if more than 1,000 mg/L then what is proposed to be the higher limit of the TDS for the boundary?

Revised the text to state that “The eastern—downdip—boundary of the aquifer is defined by the occurrence of groundwater containing total dissolved solids **<u>less</u>** than 1,000 milligrams per liter”.

Figure 4.1.1.: The updated GAM is proposed to contain 3 layers that will simulate: 1. Edwards BFZ Aquifer, 2. Walnut formation, and 3. Trinity Aquifer. The top layer is proposed to simulate groundwater-surface water interactions through GHB or an additional model layer. In our discussions with other users around the State, the experience with GHB in the top layer to simulate processes such as groundwater-surface water interactions or recharge has not been positive for other GAMs. To avoid potential similar issues with the latest updated model for the Northern segment of the Edwards (Balcones Fault Zone) Aquifer, we would appreciate some discussion on other potential ways to simulate cross-formational flow between Edwards and the overlying formations – including additional model layer or inclusion of other processes.

The top model layer represents the Edwards (Balcones Fault Zone) Aquifer and includes a general-head boundary (GHB) used to simulate interaction between the Edwards (Balcones Fault Zone) Aquifer and overlying non-aquifer stratigraphic units. Groundwater-surface water interaction in the model will be simulated using the more appropriate river and drain packages in MODFLOW. Discussion of potential ways of simulating cross-formational flow and groundwater-surface water interaction is appropriate for the model report not the conceptual model report which discusses the hydrologic processes taking place in the aquifer.

It appears that there’s been an error in the units for spring discharge that overestimates discharge. Values for spring discharge that are represented in Figure 4.4.5 of the May 11, 2020, conceptual model report should be in gallons per minute and not cubic feet per second as shown in the figure. Section 4.4.2 of the report, as well as my communication with the author, indicates that the data for the magnitude of spring discharge originates from the USGS (Heitmuller and Reece 2003). This reference contains a README file that states “Spring flow - Equivalent to discharge, or the volume of water flowing past a given cross section over a given duration. Universally provided in gallons per minute (gpm) in this report. Some spring flow measurements originally were in cubic feet per second (cfs), but these values were converted.” This is the basis for the comment that the values should be represented in gallons per minute. Additionally, the author provided me a spreadsheet of the USGS spring data that includes discharge values in cfs units. The units shown on the spreadsheet appear to be in error. Using the Berry Springs location as an example, the value “5834.8” is given in the TWDB spreadsheet while my copy of the same spring data at the same location (screen shot provided) has an identical value that is in gpm units. How are spring discharge values used in the GAM and what ramifications would there be considering this overestimation?

Figure 4.4.5 has been revised to use the correct (cubic feet per second) units.

Section 4.6.2: Agricultural (Irrigation) pumping is only described for Bell County (130 AFY) but not for other parts of Edwards BFZ aquifer. However, towards the end of page 109, the text states: “Locally, irrigation, mining and manufacturing pumpage are significant”. Please clarify.

Per Figure 4.6.9, “locally” refers to the fact that irrigation pumping in Bell County is larger relative to total pumping—about 2 percent—than in Williamson and Travis counties where irrigation accounts for less than one percent of total pumping.

Section 2.1, Paragraph 1: The Lampasas Cut Plain is singular and its steep sided mesas are probably not best described as gently rolling topography. The regional studies (EPA level III) referenced in this section probably do not adequately describe the smaller area that represents the conceptual model of the Northern Segment of the Edwards BFZ aquifer. Listing some of the original native grasses may not be as important as pointing out that although the Blackland Prairie region was almost completed cultivated at one time, the cultivated land is rapidly being developed and converted to pasture and lawns in the Northern Segment of the Edwards (Balcones Fault Zone) aquifer.

Please note that Section 2.1 is a discussion of the natural ecoregions that make up most of the land in the study area.

Section 2.1, Paragraphs 8 and 9, and Figures 2.1.6 and 2.1.7: There appears to be a number of rain gages available but the text implies that only 4 gages were used. Is this correct? And if it is, why not use the broader coverage.

Deleted the first sentence in paragraph 9 and revised the second sentence to indicate that four selected stations were used to interannual variation of annual precipitation in Figure 2.1.7.

Section 4.2: There are a number of hydrographs shown but many of them are incomplete and don’t contain data in the most recent years. References cited to support the statement on page 57 that ”most hydrographs indicate a general balance between recharge and discharge" were written in 1986, 1990, 1991, and 1999. I think this is a concern since we are looking at an area that is changing rapidly and this will be the model we will be using for the near future.

The hydrographs in Figures 4.2.9 through 4.2.14 display water-level data for the wells with the most data in the study area. These data are rarely continuous. The citations dates is a reflection of the time period during which most areawide research was conducted. Much of the more recent research is more site-specific.

In Figure 4.2.6 there is a flow arrow (second from the top) that cuts across groundwater contours at acute angles which violates the rules of flow nets and groundwater flow. This arrow is misleading.

The figure has been revised in response to the comment.

Section 5.0, Paragraph 3 speaks to the Edwards Aquifer being "perched". I don't think this is correct. A perched aquifer requires an unsaturated zone below the aquifer. This sentence is referenced to Figure 4.2.6 but I don't think that particular figure addresses this statement and the intent probably was to reference a different figure.

Revised the text to cite the correct figure, Figure 4.2.14 instead of Figure 4.2.6. In Figure 4.2.14, there are locations where the water level in the northern segment of the Edwards (Balcones Fault Zone) Aquifer is hundreds of feet higher than the water level in the underlying Trinity Aquifer. These large water-level differences suggest perching of Edwards Aquifer groundwater with an underlying unsaturated zone separating groundwater in the respective aquifers.

Section 3.0: I think you should add the citation of your recent GSA paper, I didn't see it in the references. Add the reference: Ian C. Jones, 2019. "Northern segment of the Edwards (Balcones Fault Zone) Aquifer", The Edwards Aquifer: The Past, Present, and Future of a Vital Water Resource, John M. Sharp, Jr., Ronald T. Green, Geary M. Schindel https://pubs.geoscienceworld.org/books/book/2156/chapter/122197378/Northern-segment-of-the-Edwards-Balcones-Fault.

This report is cited in the GSA paper.

Section 2.0: Additional description of the delineation of the boundaries of the aquifer would be useful.

Added the Edwards (Balcones Fault Zone) Aquifer definition from Ashworth and Flores (1991).

Section 2.0: Describe the basis for the northern boundary of the Edwards Aquifer. The Edwards units extend far to the north and locally have small wells producing west of Waco as part of the Washita Prairie segment of the Edwards Aquifer (Yelderman, 2019). Is it the saturated thickness that limits the northern boundary or is the river a regional hydrologic divide? Add the reference: Joe C. Yelderman, Jr., 2019. "The Washita Prairie segment of the Edwards (Balcones Fault Zone) Aquifer", The Edwards Aquifer: The Past, Present, and Future of a Vital Water Resource, John M. Sharp, Jr., Ronald T. Green, Geary M. Schindel https://pubs.geoscienceworld.org/books/book/2156/chapter/121271835/The-Washita-Prairie-segment-of-the-Edwards

Added the following statement to the text: "The northernmost part of the aquifer coincides with the Lampasas River where the river has cut through the stratigraphic units that make up the Edwards (Balcones Fault Zone) Aquifer." Added statement regarding the continuation of Edwards (Balcones Fault Zone) Aquifer stratigraphic units north of the Lampasas River along with the statement that the Texas Water Development Board does not classify these rocks as part of the Edwards (Balcones Fault Zone) Aquifer. Added the Yelderman reference to the list of references.

Section 2.0: The eastern boundary is the freshwater portion of the Edwards as shown in Figure 4.7.1. It appears that the boundary could be re-evaluated based on the data shown. An example of a recent re-evaluation that includes a portion of study area has shown that the boundary could shift from its original delineation based on more recent data compilations (Hunt et al., 2014). Add the reference: Hunt, B.B., R. Gary, B.A. Smith, A. Andrews, 2014, Refining the Freshwater/Saline-Water Interface, Edwards Aquifer, Hays and Travis Counties, Texas, BSEACD Report of Investigations, BSEACD RI 2014-1001, October 2014, 16 p. + Appendices
https://bseacd.org/uploads/Refining_the_Saline_FINAL.pdf

The aquifer boundaries shown in Figure 4.7.1 are the official Texas Water Development Board aquifer boundaries that are subject to change based available geochemical data that appears in the figure.

Section 4.1: The lithostratigraphy of the region could be further described as it relates to the Georgetown Formation to include the Duck Creek, Fort Worth, and Denton members. In addition, the Walnut Formation has members that include the Bull Creek, Bee Caves Marl, Cedar Park, Whitestone, and Key's Valley Marl members (Moore, 1996). Both of these units increase in thickness to the north and may have important hydrologic properties to consider. I think a more detailed lithostratigraphic and hydrostratigraphic column is needed.

The Duck Creek, Fort Worth, and Denton members nomenclature occurs north of the study area and is therefore not relevant to this report. Added mention of the members that make up the Walnut Formation.

Section 4.1: The hydrostratigraphy of the Washita group is discussed in Yelderman (2019) and could be further expanded for this publication and referenced in a revised and more detailed hydrostratigraphic column.

The hydrostratigraphy of the Washita Prairie is discussed in Yelderman (2019). This discussion lies outside of the model study area.

Section 4.1: Please be specific to which Trinity Aquifer unit (Middle or Lower) when referencing the Trinity. We find that use of undifferentiated term "Trinity" is problematic as the Lower and Middle are hydrostratigraphically distinct units and may have different geochemistry and groundwater flow potentials.

Changed terminology with reference to the Trinity Aquifer hydrostratigraphic units from the Upper, Middle, and Lower Trinity Aquifer to the Upper, Middle, and Lower Trinity hydrostratigraphic units. In Section 4.1, all discussion refers to the specific Trinity Aquifer hydrostratigraphic units.

Section 4.1: Groundwater convergence of the "Trinity" to the rivers may not be an accurate description. Convergence of flow to Colorado river in western Travis County is complicated. Potential exists for Middle Trinity to discharge to Lake Travis in the far western reaches, yet may also be recharged from the Colorado River further east. The same is true for the Lower Trinity, however water levels are substantially lower for Lower Trinity below Lake Austin and flows to the northeast. A relevant citation for the Trinity in Travis County is the recent publication of Hunt et al., 2020. Add the reference: Hunt, B.B., Cockrell, L.P., Gary, R.H., Vay, J.M., Kennedy, V., Smith, B.A., and Camp, J.P., 2020, Hydrogeologic Atlas of Southwest Travis County, Central Texas. BSEACD Report of Investigations 2020-0331 March 2020, 80 p. + digital datasets. https://repositories.lib.utexas.edu/handle/2152/81562

All discussions in this report reflect regional-scale water-level datasets that show lowest Trinity Aquifer groundwater levels along the Colorado River Valley indicating groundwater flow from areas of high head to areas with lower heads. The conclusion of Trinity Aquifer groundwater flow toward the northeast flowing under the Colorado River is often the product of: (1) groundwater level datasets skewed to areas south of the Colorado River with only a few measurements north of the river, (2) extrapolation in areas with few, widely space data points. The publication above not relevant because its study lies south of the Colorado River, outside of the study area for this report.

Section 4.7: There are a couple of Edwards wells that I was involved in sampling for the TWDB that appear to be omitted from the isotope compilation. These are from the Manville WSC and are Edwards wells.

TWDB ID	NAME	COUNTY	AQUIFER	TDS (MG/L)	PMC	C13	D	O10
5836107	Wilke ln #5	Travis	Edwards	670	42%	-8	-23.9	-4.12
5835306	Dell #2	Williamson	Edwards	356	61%	-7.4	-23.1	-4.19

Added the data to Figures 4.7.5, 4.7.6, 4.7.8, 4.7.9 and 4.7.14.