Conceptual Model: Igneous and West Texas Bolsons Aquifers of Texas

Ian C. Jones, Ph.D., P.G.
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Texas Water Development Board
Groundwater Modeling

TEXAS WATER DEVELOPMENT BOARD

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Texas Water Development Board Report

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by
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EXECUTIVE SUMMARY

The Igneous and West Texas Bolsons aquifers are located in far west Texas in Jeff Davis, Presidio, western Brewster, and the southern parts of Culberson, Reeves, and Hudspeth counties. These aquifers are important sources of water for municipalities, irrigation, and livestock in west Texas. These aquifers underlie several relatively large cities in the region, including Alpine, Fort Davis, Marfa, Presidio, and Van Horn. This report documents the development of a conceptual model of the Igneous and West Texas Bolsons aquifers. 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 aquifers. It forms the basis for a numerical groundwater flow model.

The Igneous and West Texas Bolsons aquifers consist of several stratigraphic units that are grouped together to form the respective aquifers. The Igneous Aquifer is composed of several Tertiary age volcanic and intrusive formations. The West Texas Bolsons Aquifer is made up of Quaternary alluvial sediment that filled basins that formed due to late Tertiary tensional tectonics.

Available water-level data suggest that groundwater within the Igneous Aquifer generally flows from the highest elevations in the Davis Mountains radiating outwards to lower elevations. In the West Texas Bolsons Aquifer, groundwater flows to the Rio Grande in the topographically open bolsons—Red Light Draw, Green River, Presidio, and Redford bolsons. The fate of groundwater is less certain in the topographically closed bolsons—Eagle Flat, Lobo Flat, Michigan Flat, Ryan Flat, and Wild Horse Flat. In the Eagle Flat, groundwater may discharge to underlying Tertiary or older stratigraphic units and eventually flow southward to the Rio Grande. In the Lobo Flat, Michigan Flat, Ryan Flat, and Wild Horse Flat—together sometimes referred to as the Salt Basin (Angle, 2001)—groundwater flows northward from bolson to bolson, eventually flowing into the Salt Flats located north of the West Texas Bolsons Aquifer and discharging by evapotranspiration.

Groundwater in the West Texas Bolsons Aquifer is utilized primarily for irrigation uses (90 percent), but is also used locally for municipal, and livestock uses. Groundwater in the Igneous Aquifer is utilized for a combination of municipal (about 50 percent), irrigation (about 35 percent), and livestock (about 15 percent).

Most of the available hydraulic property data—data measuring how easily groundwater flows through a system—are from the northeastern portion of the Igneous Aquifer and the Lobo Flat, Michigan Flat, Ryan Flat, and Wild Horse Flat portions of the West Texas Bolsons Aquifer. The data available show significant variability in the aquifer properties resulting from structural complexity within the basin, and lithologic variability. Hydraulic conductivity values for the Igneous and West Texas Bolsons aquifers mostly lie within the range of 10 to 1,000 feet per day and 10 to 100 feet per day, respectively, with no apparent spatial trends.

Water quality in the Igneous Aquifer is generally fresh throughout the aquifer. In the West Texas Bolsons Aquifer, groundwater is also generally fresh, but the occurrence of slightly saline groundwater becomes more common in northernmost parts of the aquifer, especially in Wild Horse Flat and Michigan Flat, and in the south, in Presidio Bolson. Groundwater compositions in both aquifers range from calcium-bicarbonate compositions to sodium-sulfate-chloride compositions.

Groundwater isotope compositions in the two aquifers indicate: (1) the most recent recharge to the West Texas Bolsons Aquifer occurred in the Presidio Bolson, and (2) the most recent recharge to the Igneous Aquifer occurs along the margins of the aquifer. Please note that carbon-14 isotopes suggest that recent recharge in these aquifers occurred during the past 5,000 years. The oldest apparent groundwater ages occur in the northernmost bolsons of the West Texas Bolsons Aquifer and in central portions of the Igneous Aquifer. These apparent groundwater ages suggest that recharge took place several thousand years ago.

The conceptual model for the Igneous and West Texas Bolsons aquifers is composed of three model layers simulating groundwater flow through the West Texas Bolsons Aquifer, the Igneous Aquifer, and the underlying Cretaceous and Permian stratigraphic units. The three-layer model accommodates the processes of recharge to the aquifer outcrops, groundwater flow, inter-aquifer flow between the West Texas Bolsons and Igneous aquifers and the underlying Cretaceous and Permian rocks, discharge to streams and springs and through evapotranspiration, and pumping from the respective aquifers. This report is part of work being conducted to update previous groundwater availability models of the Igneous and West Texas Bolsons aquifers (Beach and others, 2004, 2008; Wade and Jigmond, 2013) into a single groundwater availability model.

1.0 INTRODUCTION

The Igneous and West Texas Bolsons aquifers are among the 22 minor aquifers in Texas. The Texas Water Development Board (TWDB) defines a major aquifer (Figure 1.0.1) as an aquifer that produces large amounts of water over a large area, and minor aquifers (Figure 1.0.2) as aquifers that produce minor amounts of water over large areas or large amounts of water over small areas (George and others, 2011). From 1980 through 2020, estimates of total pumping from the Igneous and West Texas Bolsons aquifers has ranged from about 8,000 to 4,000 acre-feet per year and 60,000 to 16,000 acre-feet per year, respectively. These aquifers are important sources of water for municipal and agricultural water users in the region.

This report describes the aquifer data used to develop an updated conceptual model for the Igneous and West Texas Bolsons aquifers. This conceptual model will be the basis for updating the groundwater availability model for the Igneous and West Texas Bolsons aquifers. The updated model will combine the previous three models simulating the Igneous Aquifer and different parts of the West Texas Bolsons Aquifer into a single model. The advantage of a single model is that it facilitates aquifer-wide calculations and better simulates groundwater flow between aquifers. 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 Igneous and West Texas Bolsons aquifers; (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.

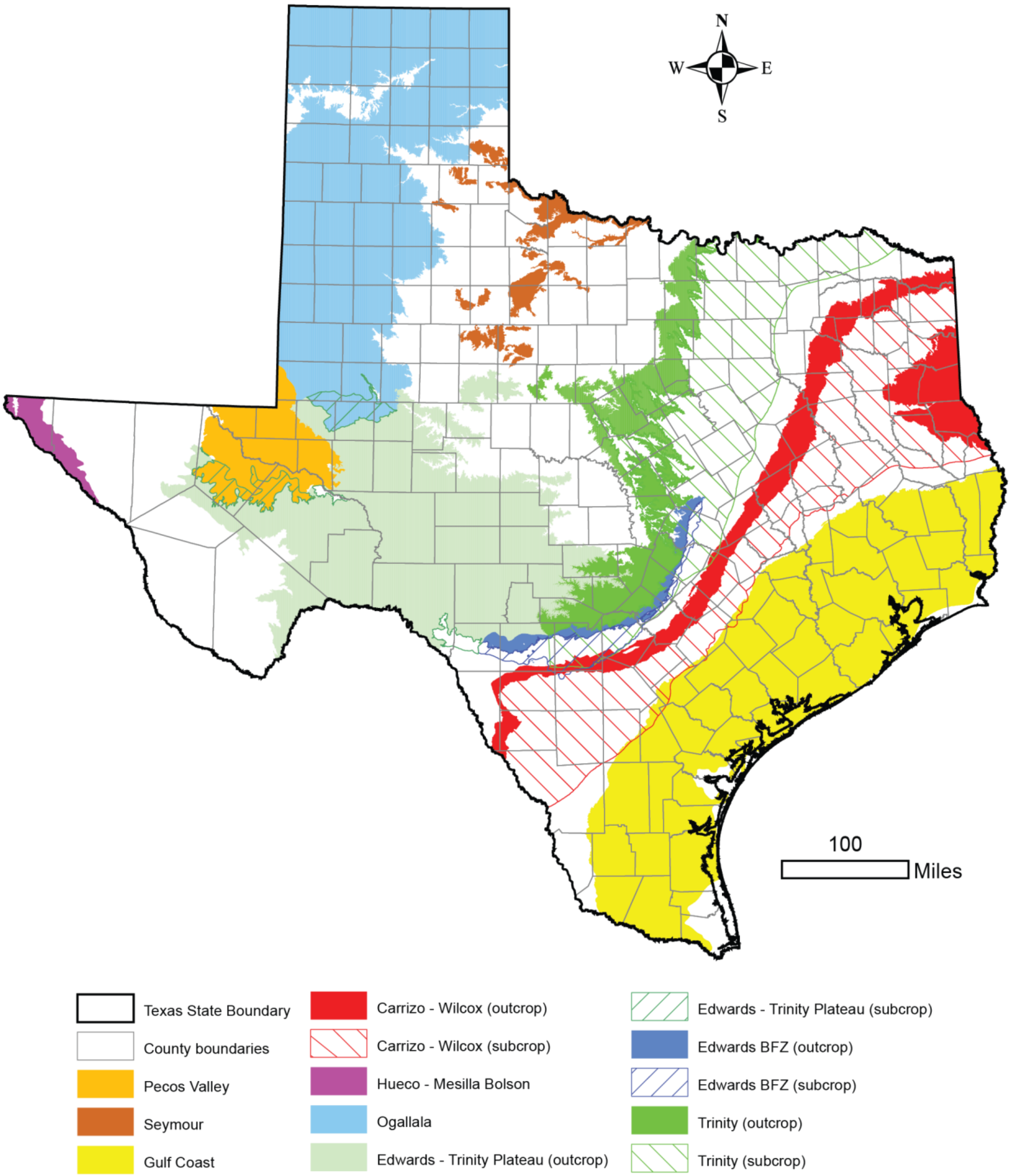


Figure 1.0.1. Locations of the major aquifers in Texas.

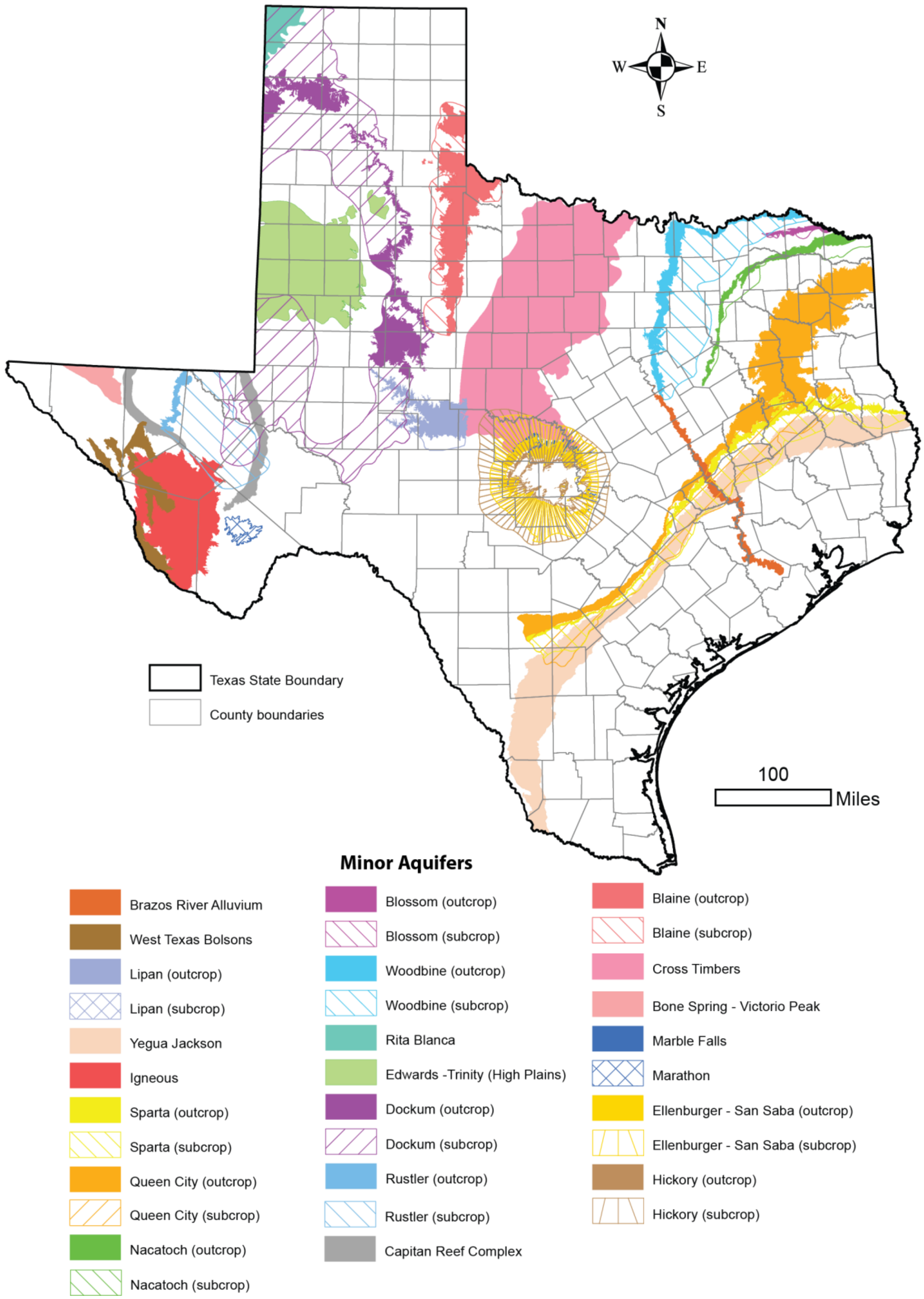


Figure 1.0.2. Locations of the minor aquifers in Texas.

2.0 STUDY AREA

The Igneous and West Texas Bolsons aquifers consist of igneous and sedimentary rocks and sediment that occur in far west Texas. The aquifers cover parts of Brewster, Culberson, Hudspeth, Jeff Davis, Pecos, Presidio, and Reeves counties (Figure 2.0.1). The West Texas Bolsons Aquifer is divided into nine bolsons, which are defined as extensive flat alluvium-floored depressions or basins—the Eagle Flat, Green River Valley, Lobo Flat, Michigan Flat, Presidio Bolson, Red Light Draw, Redford Bolson, Ryan Flat, and Wild Horse Flat (Figure 2.0.2). The northern extent of the West Texas Bolsons Aquifer represents the extent of fresh to slightly saline groundwater.

Figure 2.0.3 shows the counties, major roadways, and cities in the study area. Cities overlying the Igneous and West Texas Bolsons aquifers include Alpine, Marfa, Fort Davis, and Van Horn. Figure 2.0.4 shows the locations of rivers, streams, lakes, and reservoirs in the study area. There are few perennial streams and, therefore, surface runoff is typically associated with heavy rainfall events during the summer months.

Figures 2.0.5 and 2.0.6 show the major and minor aquifers that occur within the study area. The major aquifers occurring in the study area are the Edwards-Trinity (Plateau) and Pecos Valley aquifers that overlie small parts of the Igneous Aquifer. The minor aquifers in the study area—the Capitan Reef Complex and Rustler aquifers—underlie both the Igneous and West Texas Bolsons aquifers.

There are several entities and groups responsible for the planning and management of surface water and groundwater within the study area. The Igneous and West Texas Bolsons aquifers overlap part of the Far West Texas Regional Water Planning Area (Region E) and the Region F Regional Water Planning Area (Figure 2.0.7). There are parts of six different groundwater conservation districts (GCDs) within the study area: the Brewster County GCD, Culberson County GCD, Jeff Davis County Underground Water Conservation District (UWCD), Middle Pecos GCD, Presidio County UWCD, and Reeves County GCD (Figure 2.0.8). The Igneous and West Texas Bolsons aquifers lie mostly within Groundwater Management Area 4, but also occur within groundwater management areas 3 and 7 (Figure 2.0.9). The study area lies completely within the Rio Grande River Basin (Figure 2.0.10). There are no river authorities in the study area.

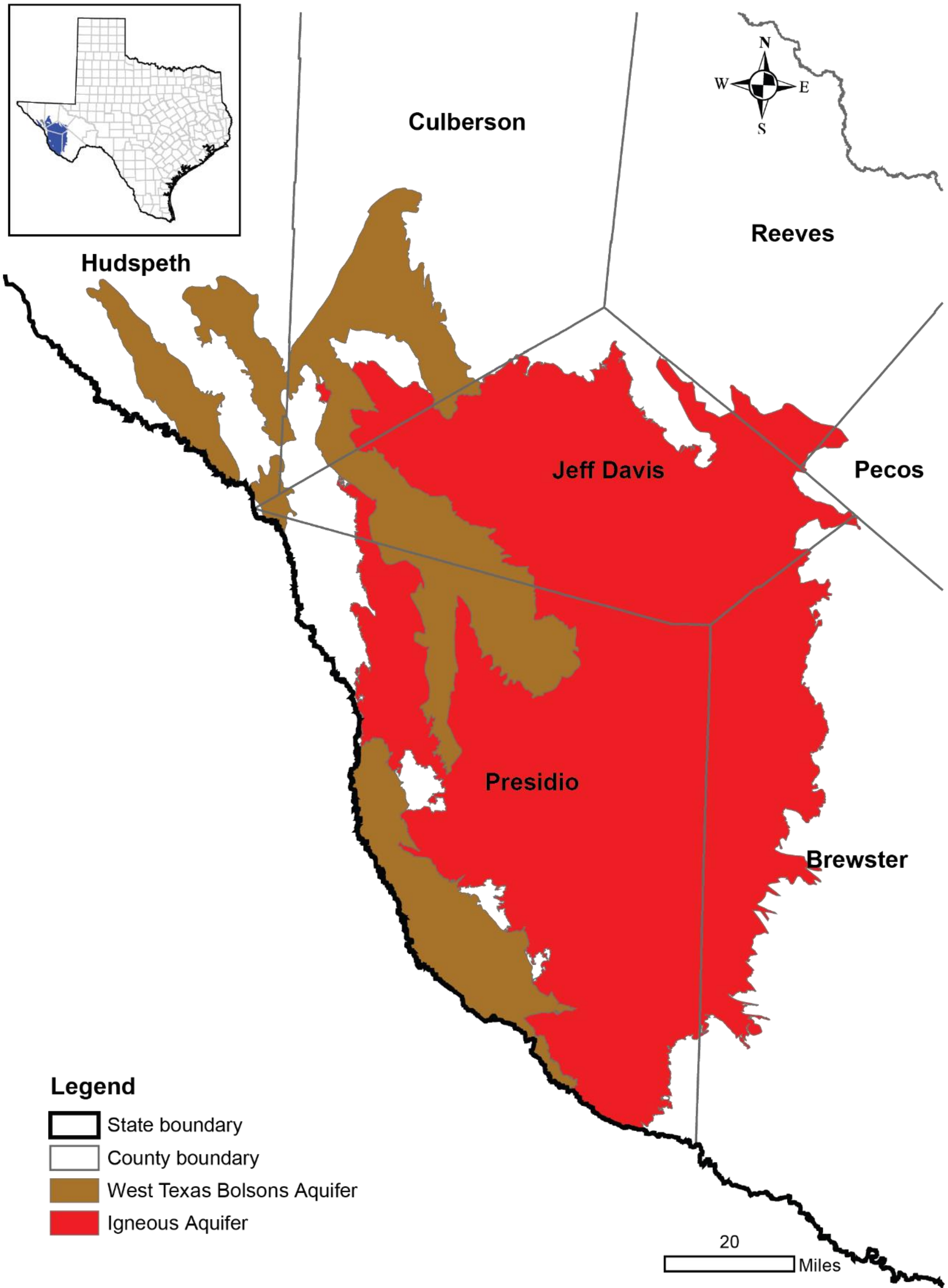


Figure 2.0.1. Location of the study area.

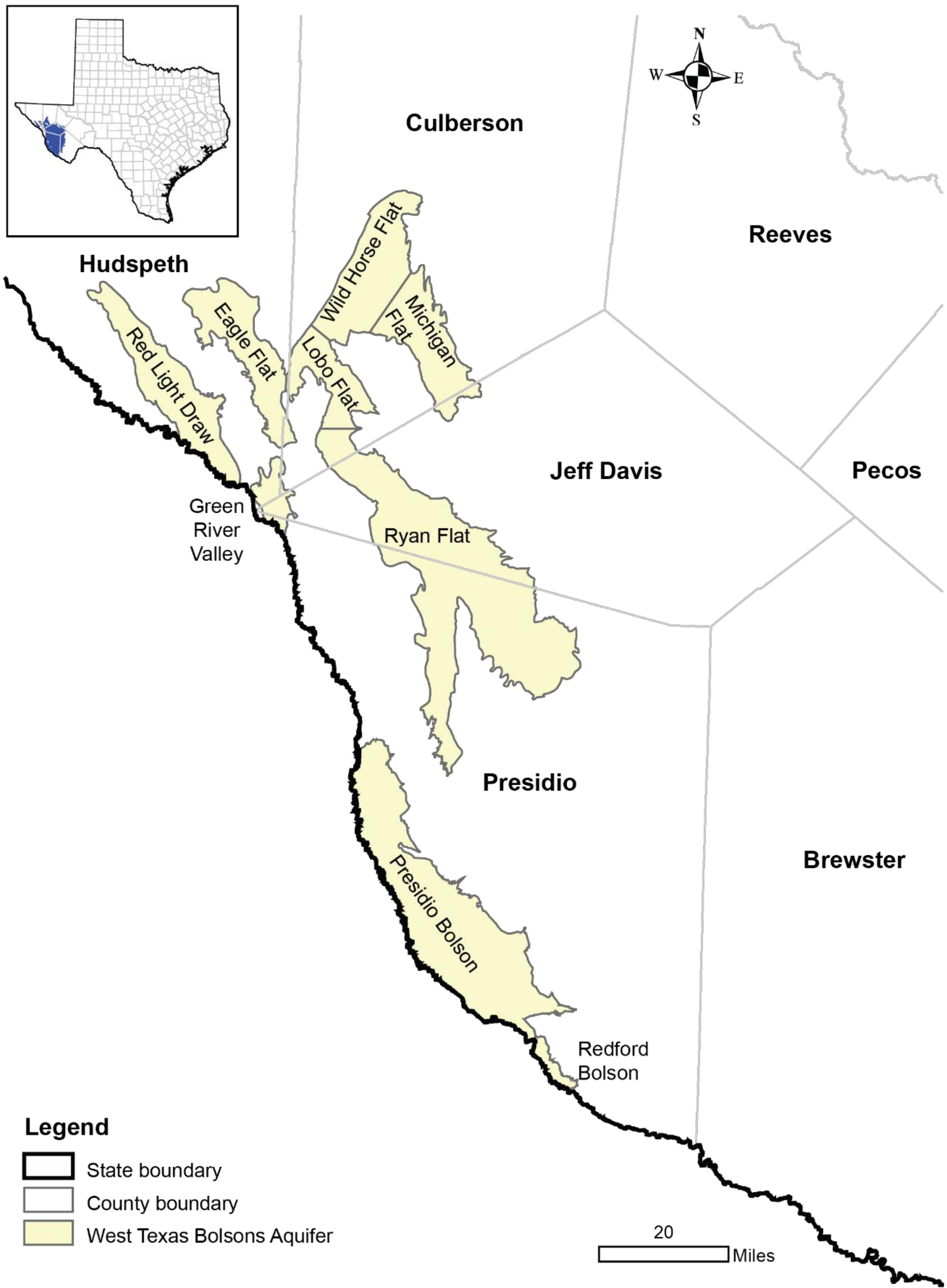


Figure 2.0.2. Map showing the nine bolsons (basins) that constitute the West Texas Bolsons Aquifer.

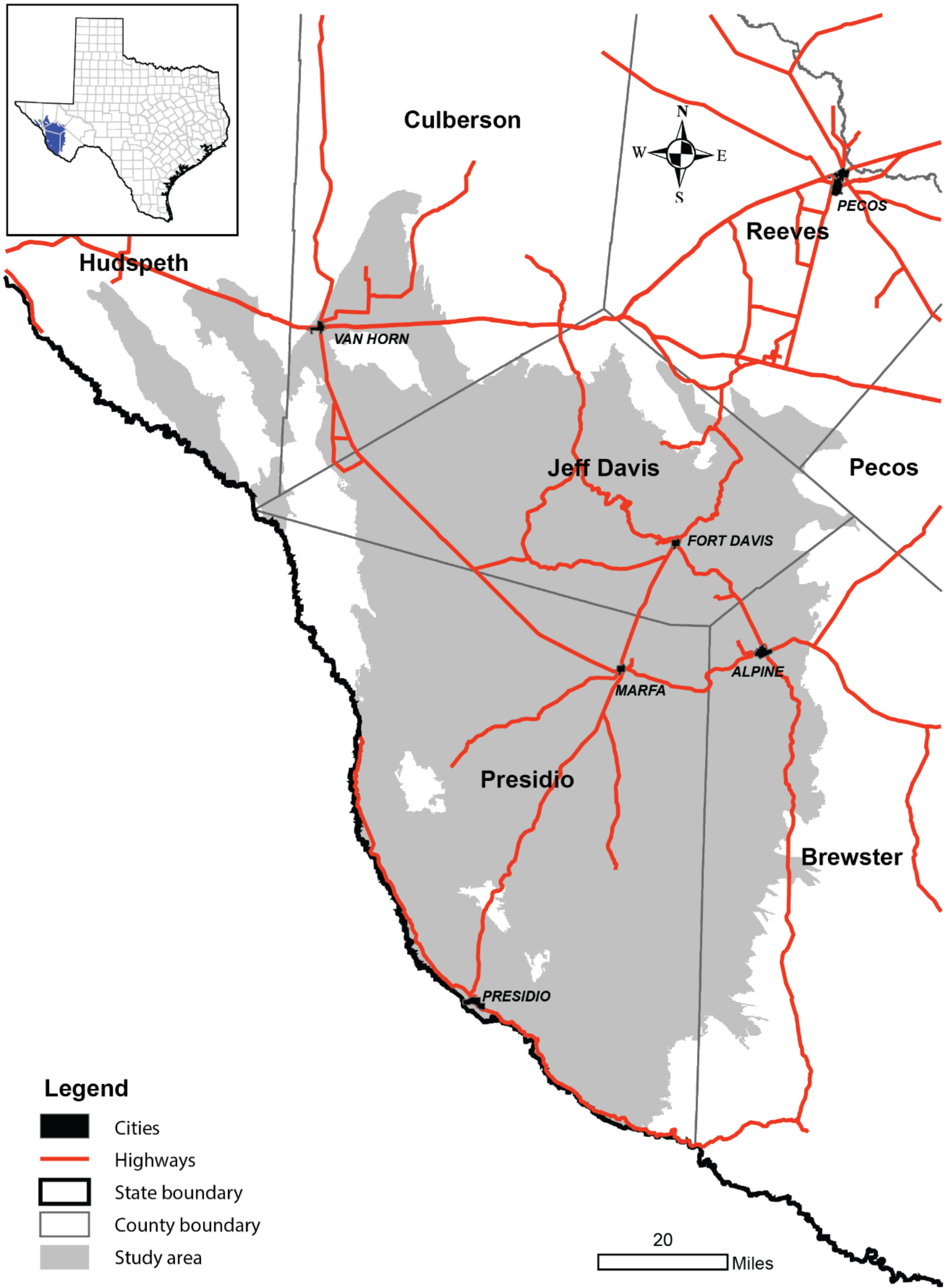


Figure 2.0.3. Cities and major roadways in the study area.

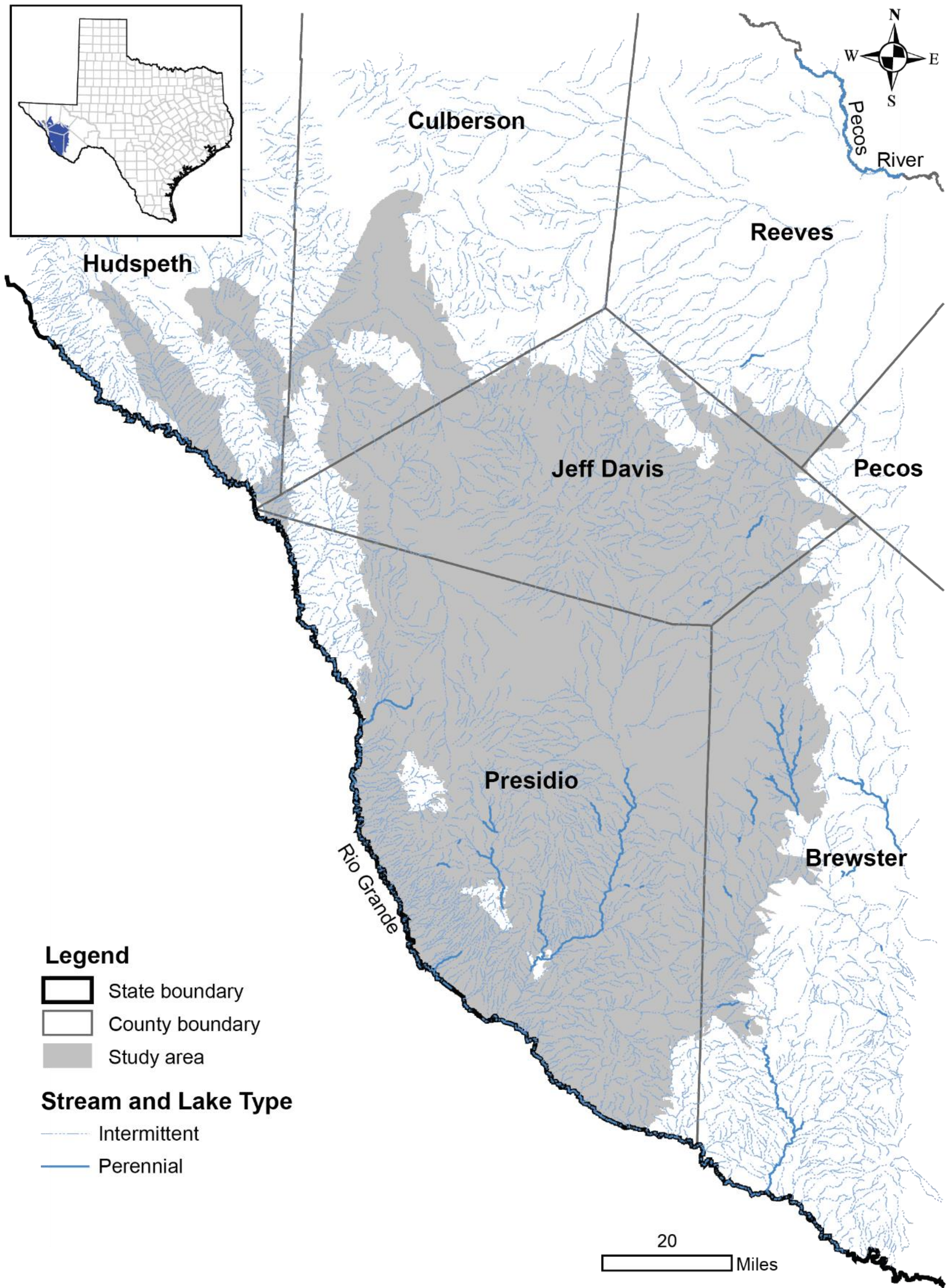


Figure 2.0.4. Rivers, streams, lakes, and reservoirs in the study area. From USGS (2021).

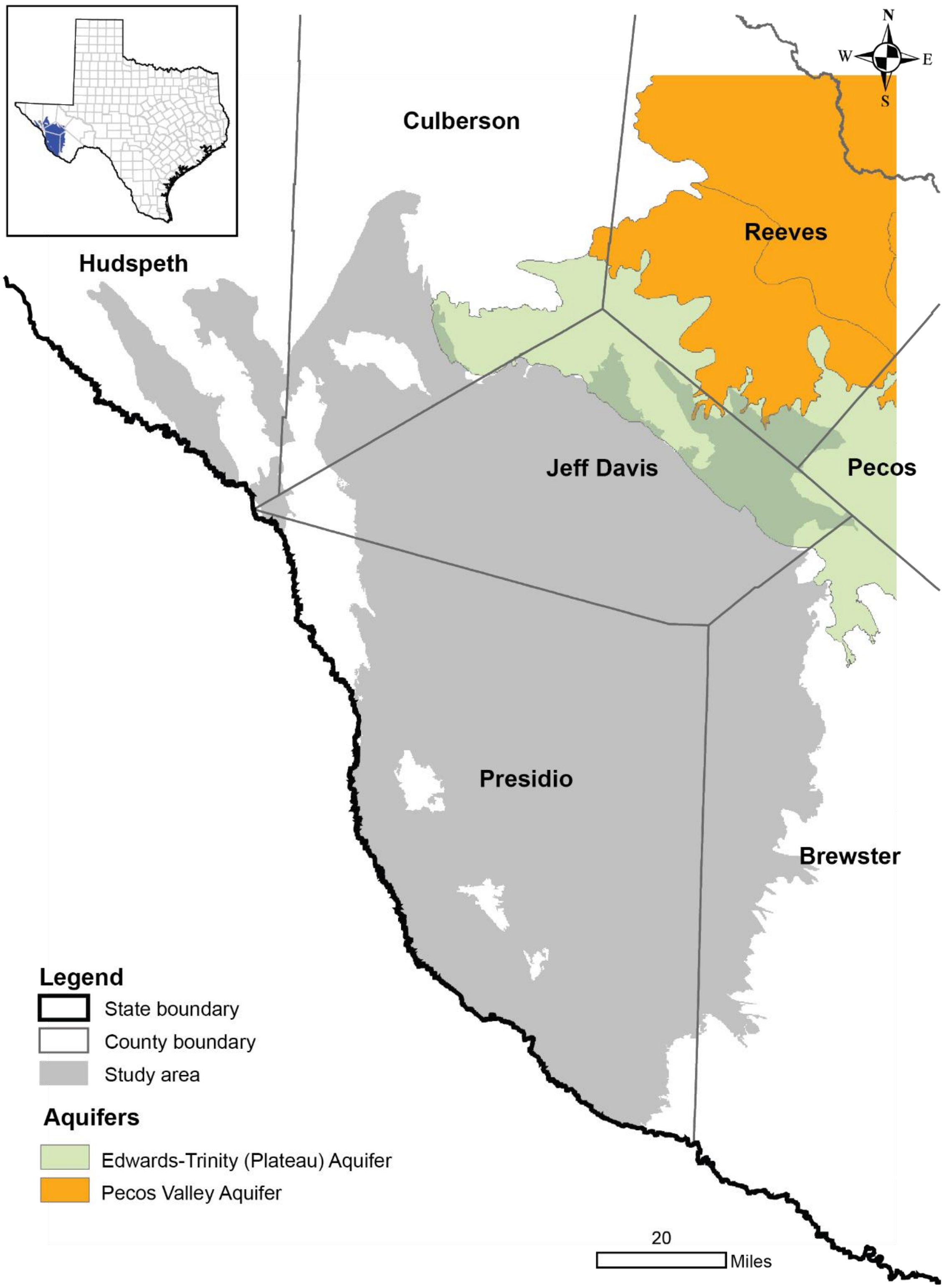


Figure 2.0.5. Major aquifers in the study area.

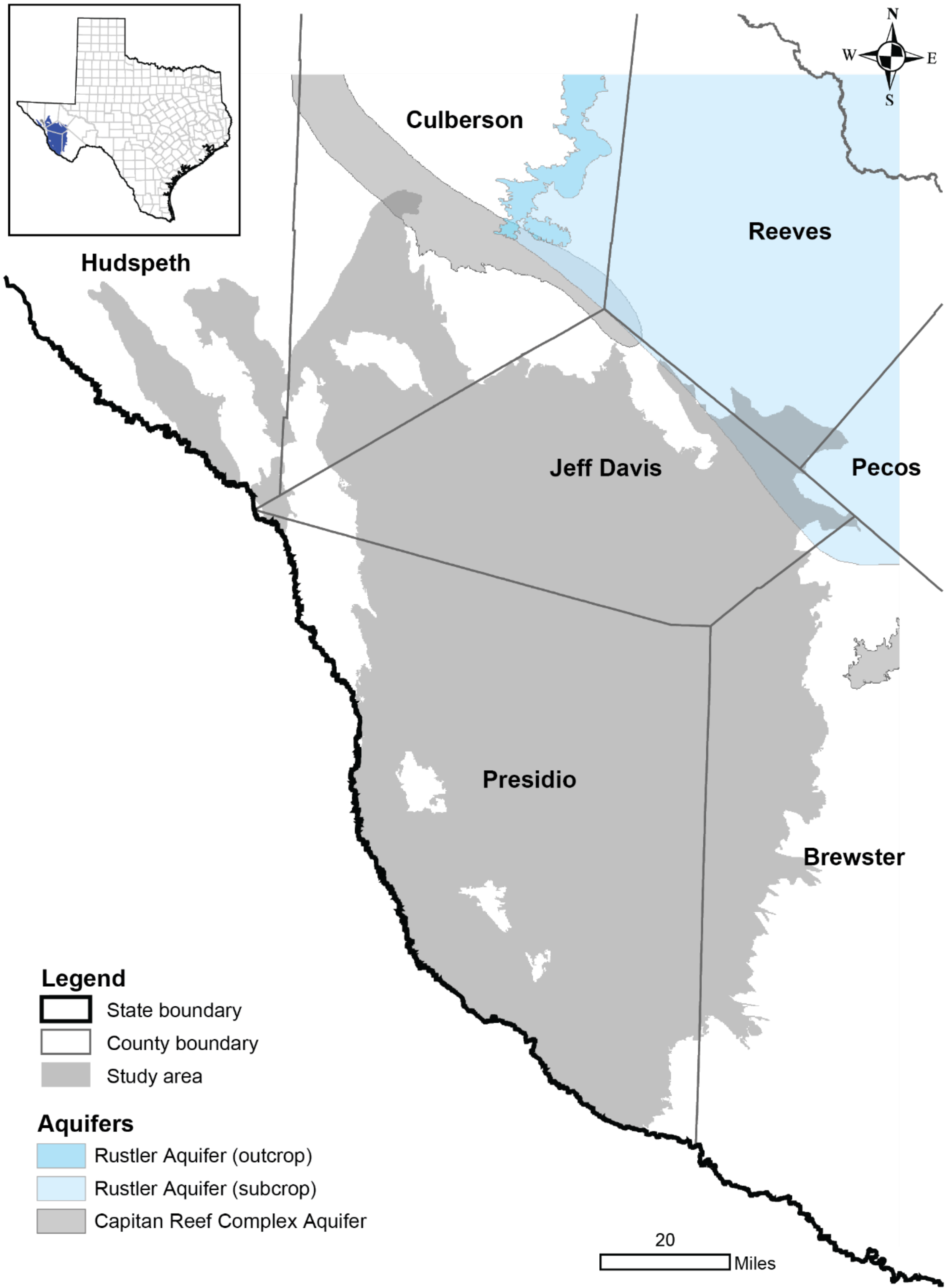


Figure 2.0.6. Minor aquifers in the study area.

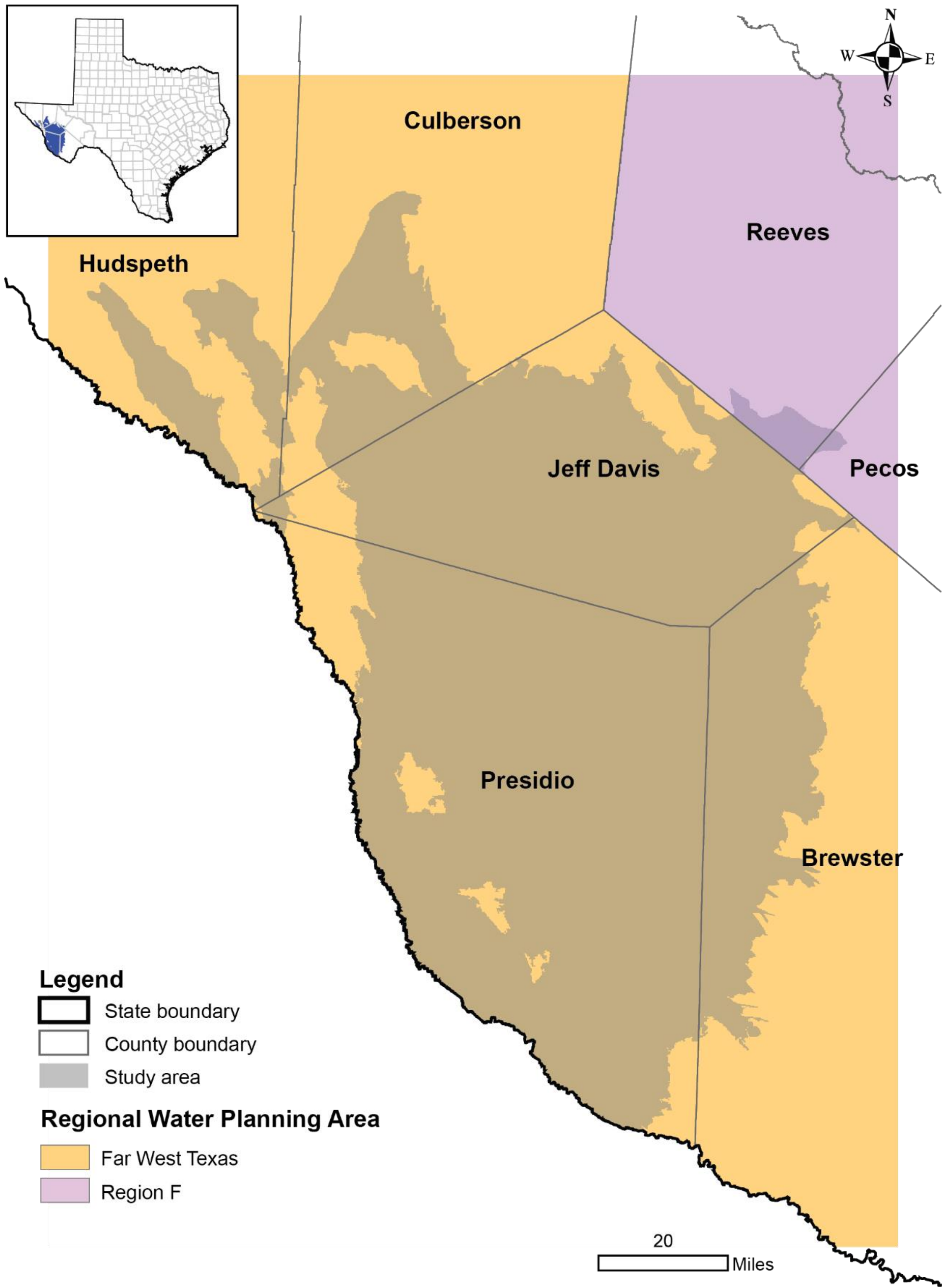


Figure 2.0.7. Regional water planning areas in the study area.

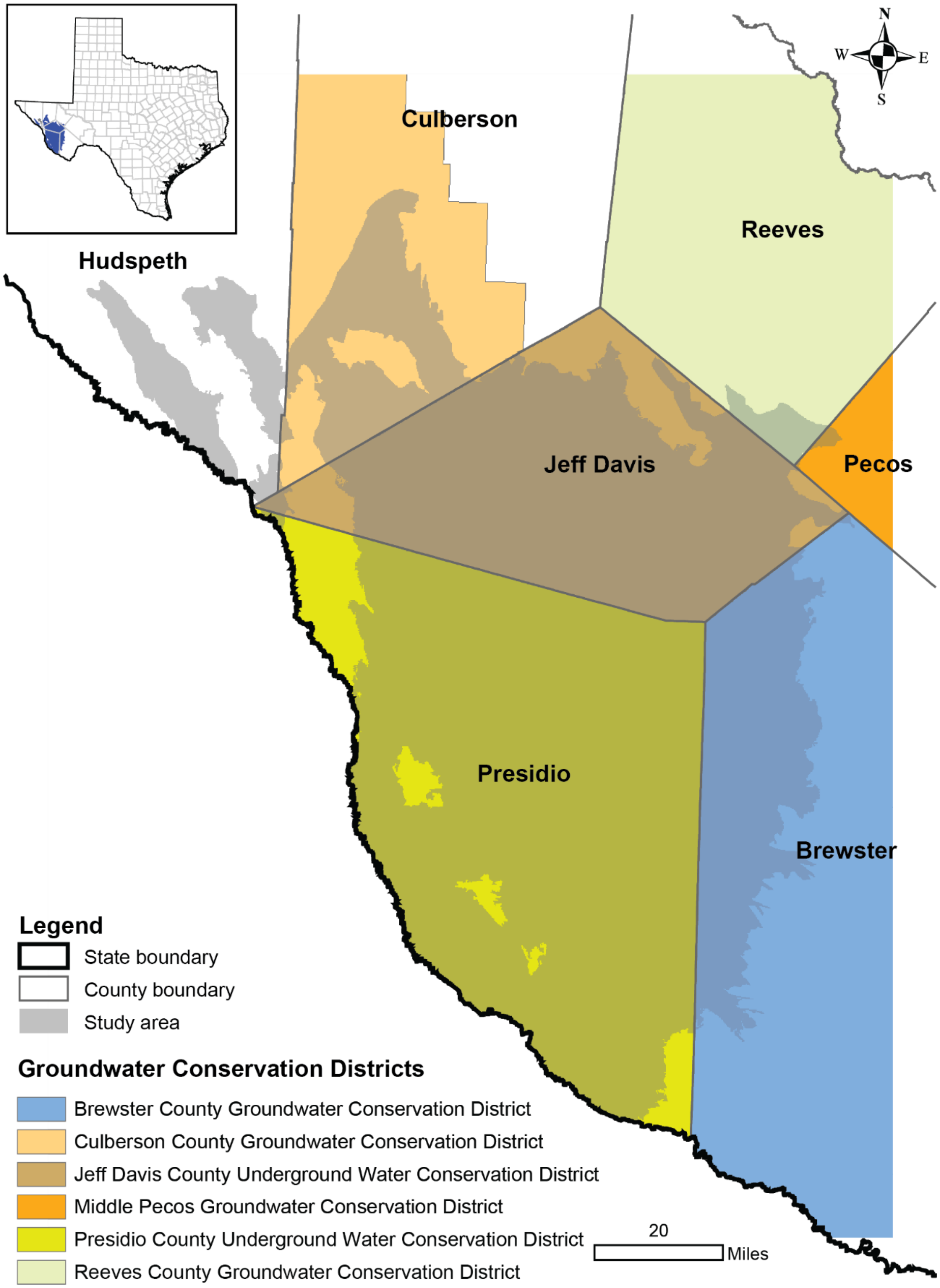


Figure 2.0.8. Groundwater conservation districts in the study area as of August 2023.

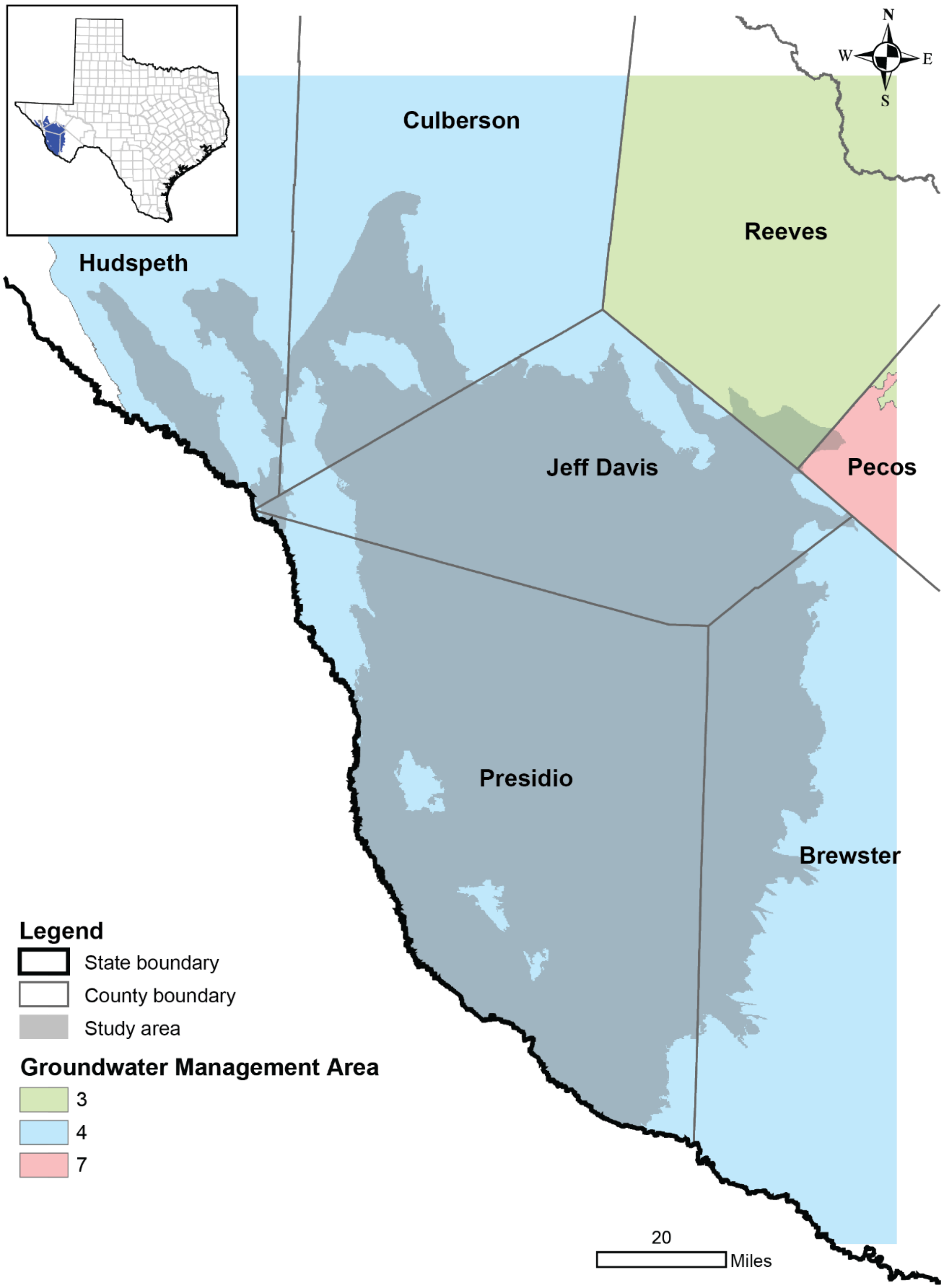


Figure 2.0.9. Groundwater management areas in the study area.

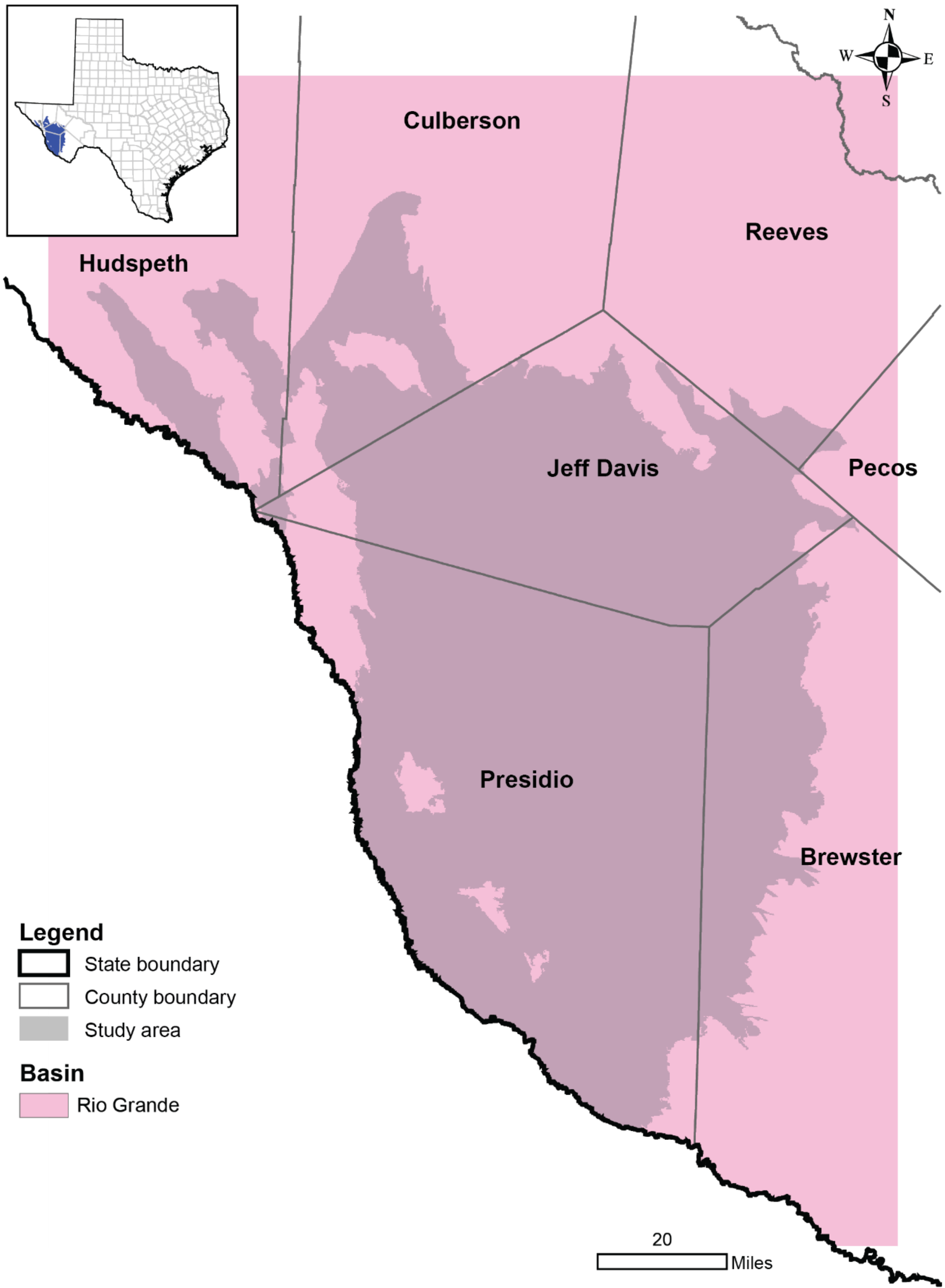


Figure 2.0.10. Major river basins in the study area.

2.1 Physiography and climate

The study area for the Igneous and West Texas Bolsons aquifers lies within the Basin and Range physiographic province (Wermund, 1996; Figure 2.1.1). The Basin and Range is characterized by generally north-south oriented alternating mountain ranges and basins. Volcanic rocks form many of the mountain peaks which are flanked by large flows of volcanic ash and thick deposits of volcanic debris.

The Igneous and West Texas Bolsons aquifers are located in the Chihuahuan Desert Level III ecological region (USEPA, 2022a and 2022b; Figure 2.1.2). This is an ecological region that extends west to Arizona and south into Mexico and coincides with part of the Basin and Range physiographic province. The mountain ranges are a geologic mix of Tertiary volcanic and intrusive granitic rocks, Paleozoic sedimentary layers, and some Precambrian granitic plutonic rocks. Outside the major river drainages, such as the Rio Grande and Pecos rivers in New Mexico and Texas, the landscape primarily drains internally. Vegetative cover is predominantly desert grassland and arid shrubland, except for high elevation islands of oak, juniper, and pinyon pine woodland. The extent of desert shrubland is increasing across lowlands and mountain foothills due to gradual desertification caused in part by historical grazing pressure (USEPA, 2022a and 2022b).

Figure 2.1.3 is a topographic map of the study area (USGS, 2014). Land-surface elevation within the study area is greatest in the Davis Mountains of central Jeff Davis County and in other mountain ranges such as the Sierra Diablo, Eagle Mountains, Sierra Vieja, and Chinati Mountains.

The average annual maximum air temperature in the study area ranges from about 47 degrees Fahrenheit in the Davis Mountains to about 63 degrees Fahrenheit in the Rio Grande valley, with temperatures decreasing as elevation increases (Figure 2.1.4). Figure 2.1.5 shows average annual precipitation from 1991 through 2020 (National Centers for Environmental Information, 2022). The annual average precipitation generally increases with elevation in the study area, from a high of 26 inches per year in the Davis Mountains in Jeff Davis County to a low of 7 inches per year in the Rio Grande valley.

Figures 2.1.6 and 2.1.7 show annual precipitation data recorded at four selected stations—Alpine, Marfa, Mount Locke, and Van Horn—from 1940 through 2015. Figure 2.1.7 indicates wide interannual variation of precipitation, ranging from lows of about 5 inches to highs of over 35 inches per year. Figure 2.1.8 shows monthly precipitation for the four stations averaged over the period 2006 through 2020. In the study area, the highest monthly precipitation occurs in July at Mount Locke, exceeding 4 inches. Most precipitation occurs during late spring and summer months—June through September—with the least precipitation occurring in February.

The average annual lake evaporation rate in the study area ranges from a high of 90 inches per year to a low of 39 inches per year (Figure 2.1.9; Narasimhan and others, 2005). Average annual lake evaporation correlates to elevation and is generally lowest in the mountains in the study area, especially in the Davis Mountains in Jeff Davis County. Lake evaporation rates significantly exceed the annual average precipitation. Monthly variations in lake surface evaporation are shown for three locations in the study area (Figure 2.1.10; Narasimhan and others, 2005). These values represent the average of the monthly lake surface evaporation data from 1971 through 2000. Figure 2.1.10 shows that average lake evaporation peaks in May or June.

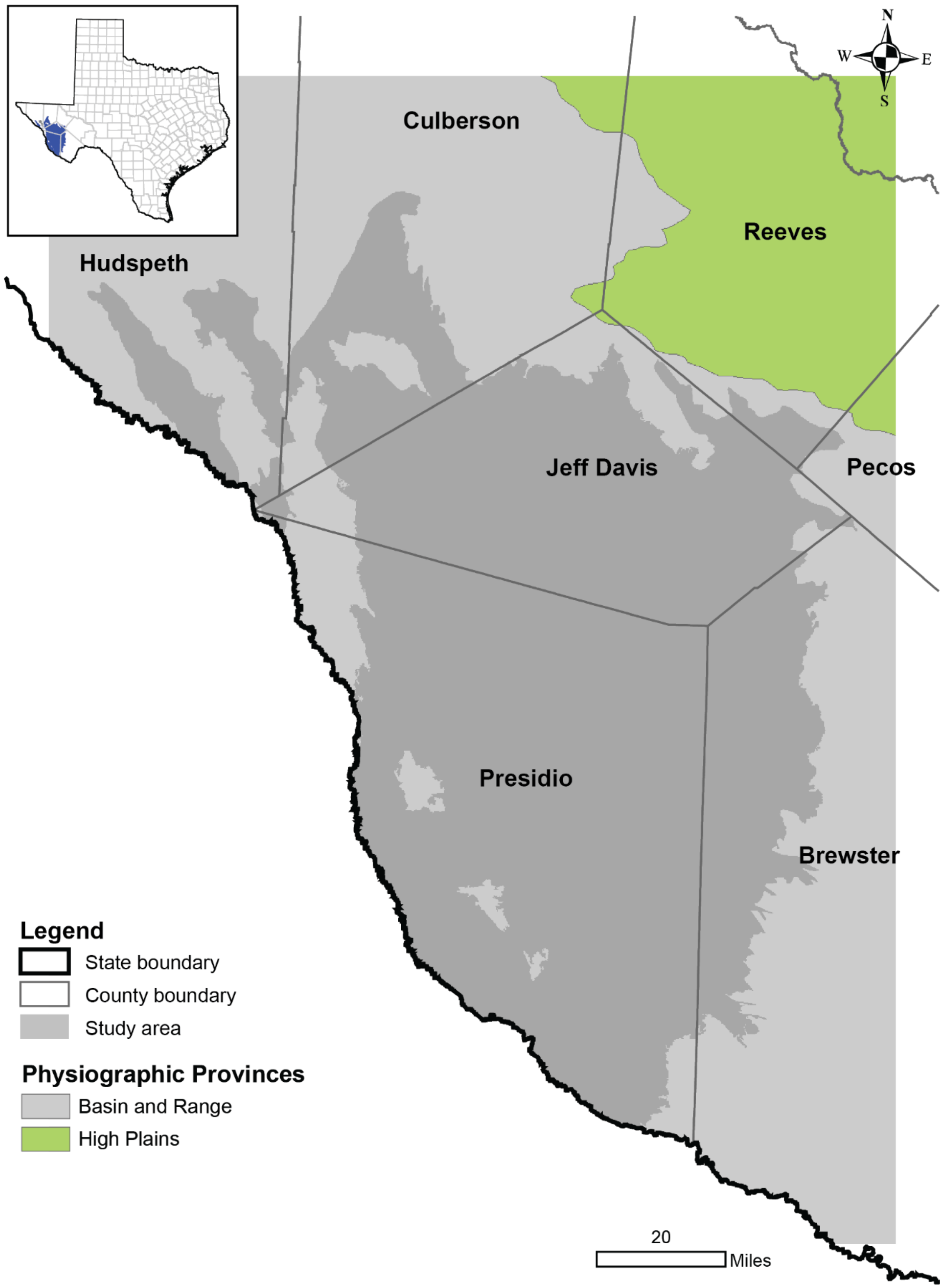


Figure 2.1.1. Physiographic provinces in the study area (Wermund, 1996).

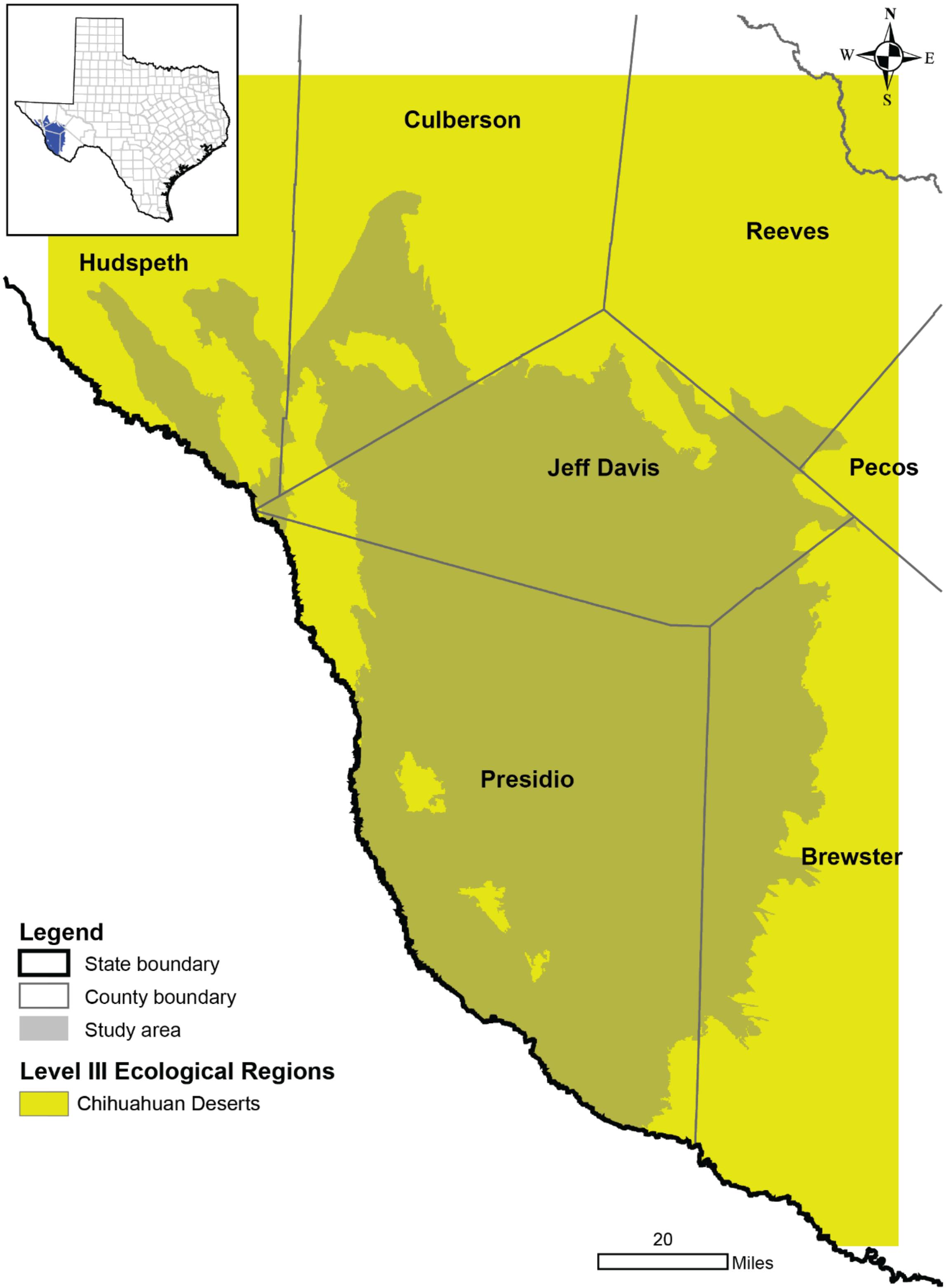


Figure 2.1.2. Level III ecological regions in the study area (USEPA, 2022a).

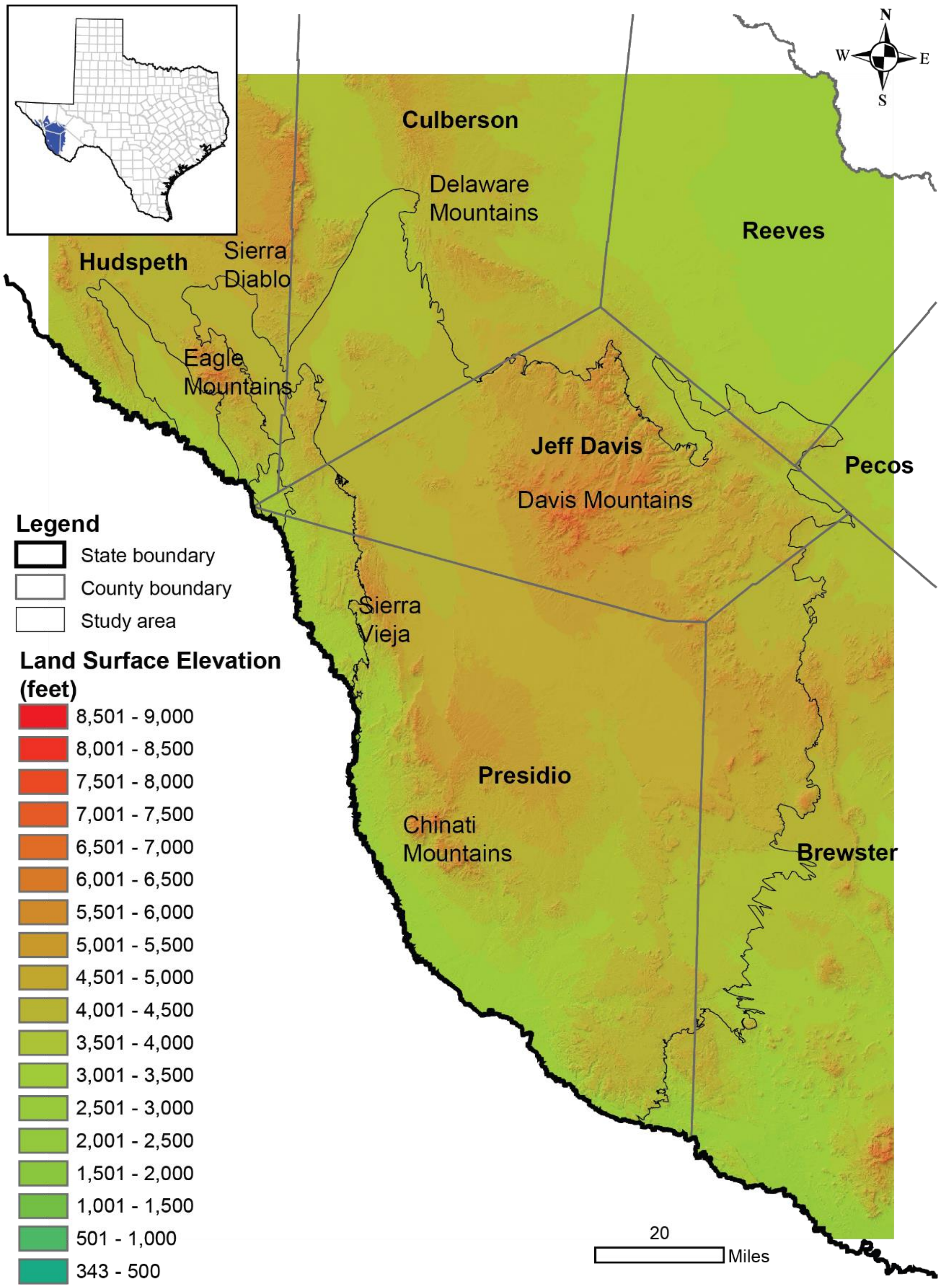


Figure 2.1.3. Topographic map of the study area showing land surface elevation in feet above mean sea level (data from USGS and NED, 2014).

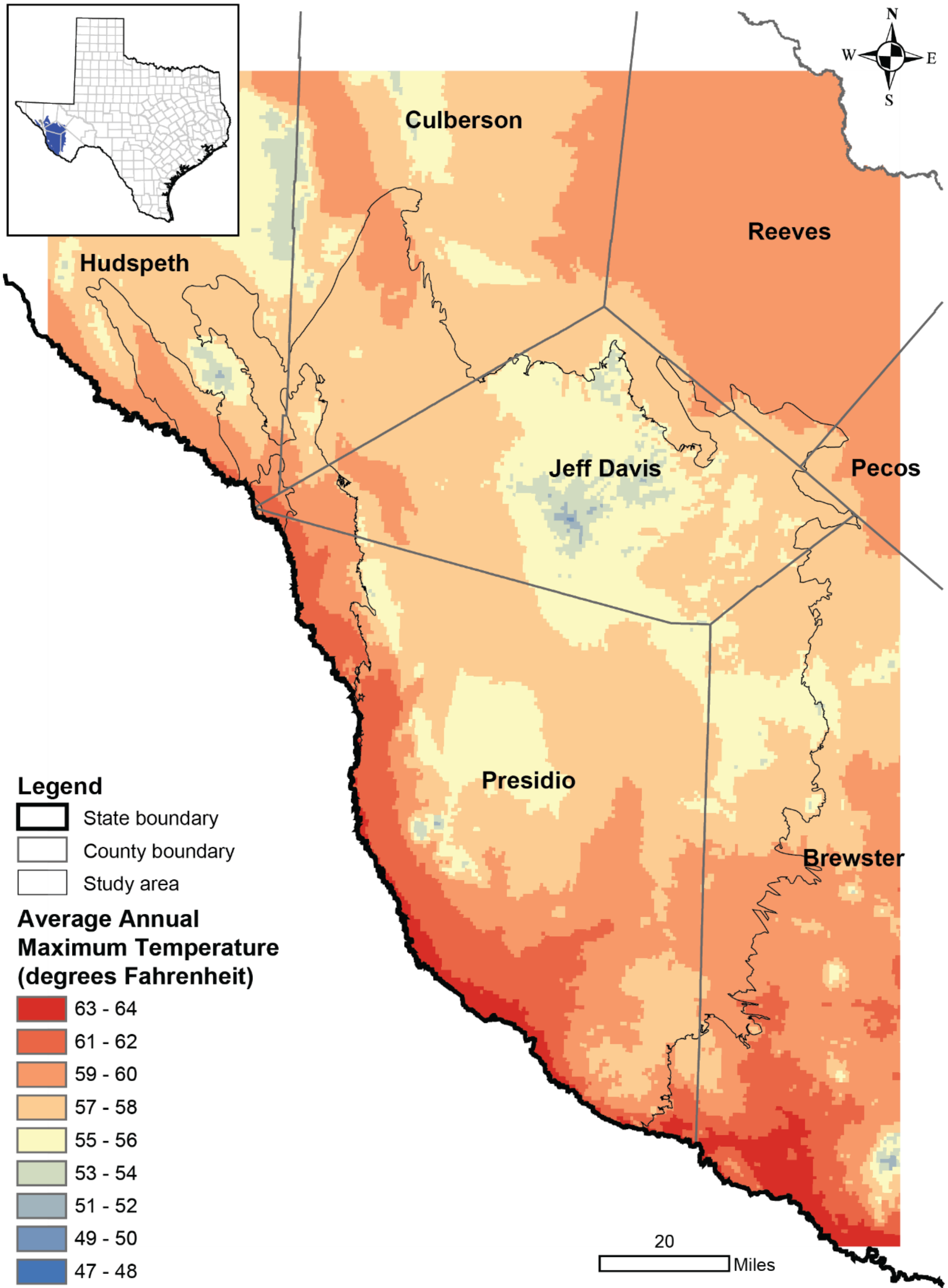


Figure 2.1.4. **Average annual maximum air temperature in degrees Fahrenheit in the study area from 1991 to 2020 (data from National Centers for Environmental Information, 2022).**

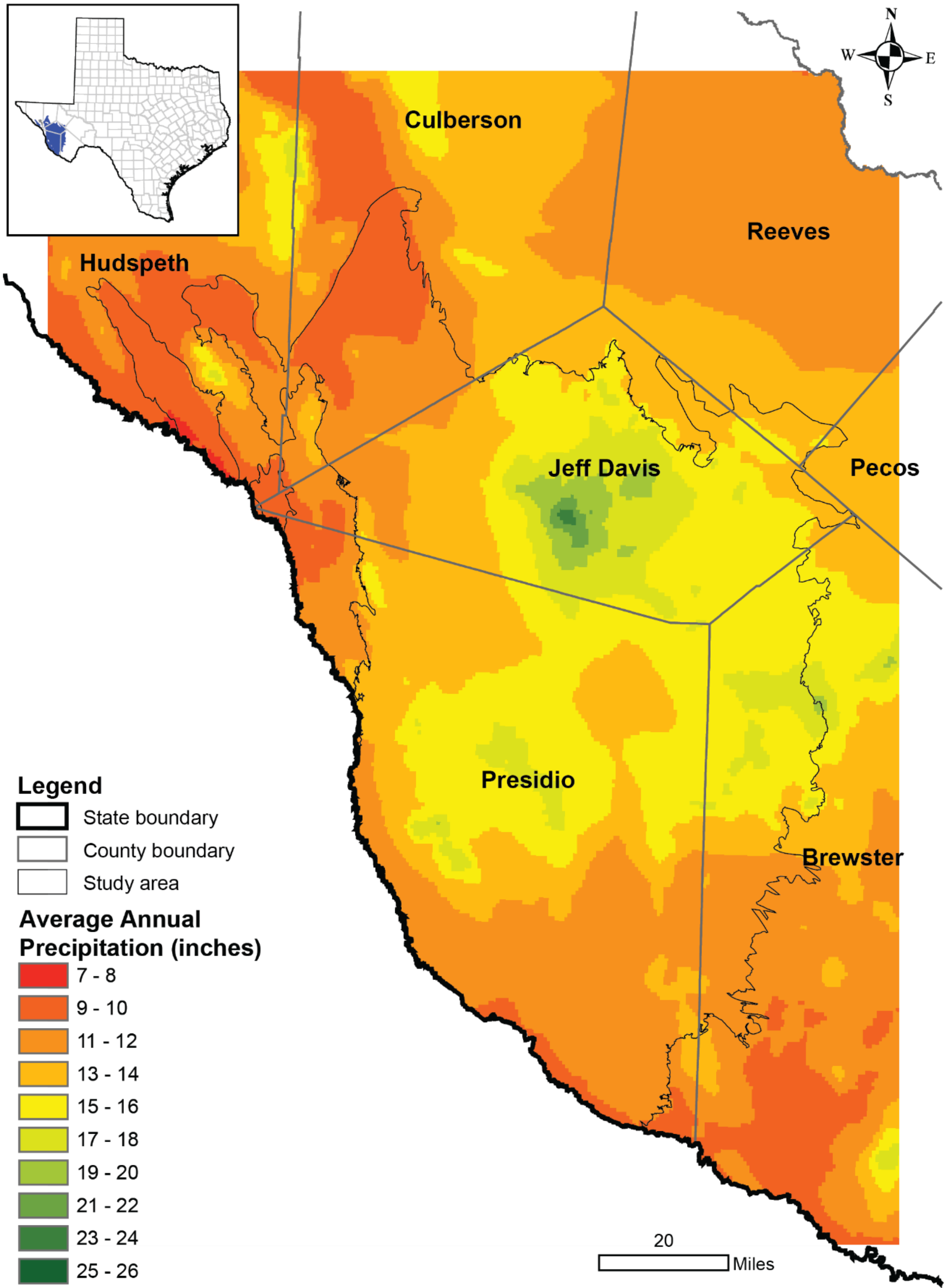


Figure 2.1.5. Average annual precipitation in inches in the study area from 1991 through 2020 (data from National Centers for Environmental Information, 2022).

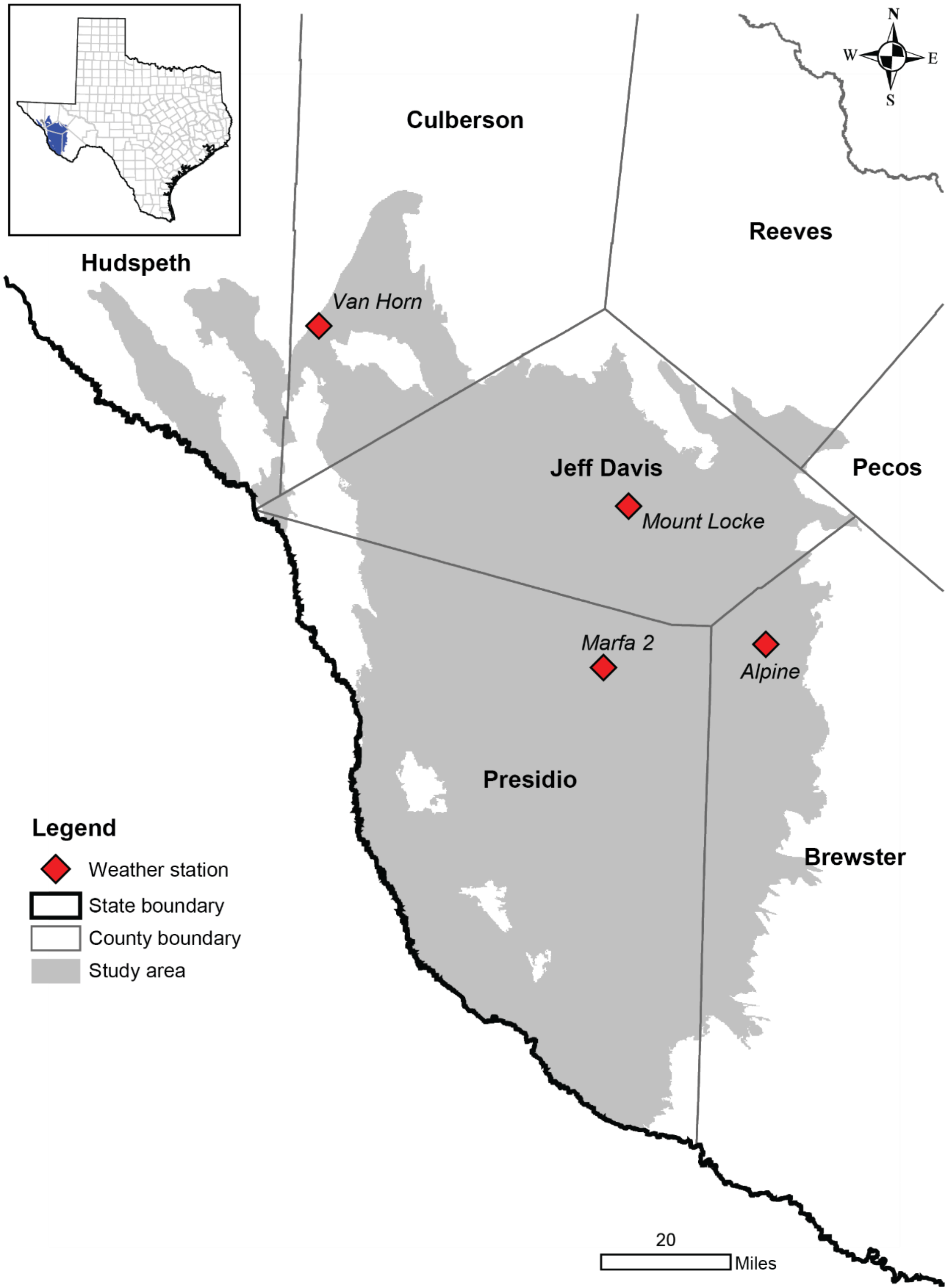


Figure 2.1.6. Location of selected precipitation gages in the study area (National Centers for Environmental Information, 2022).

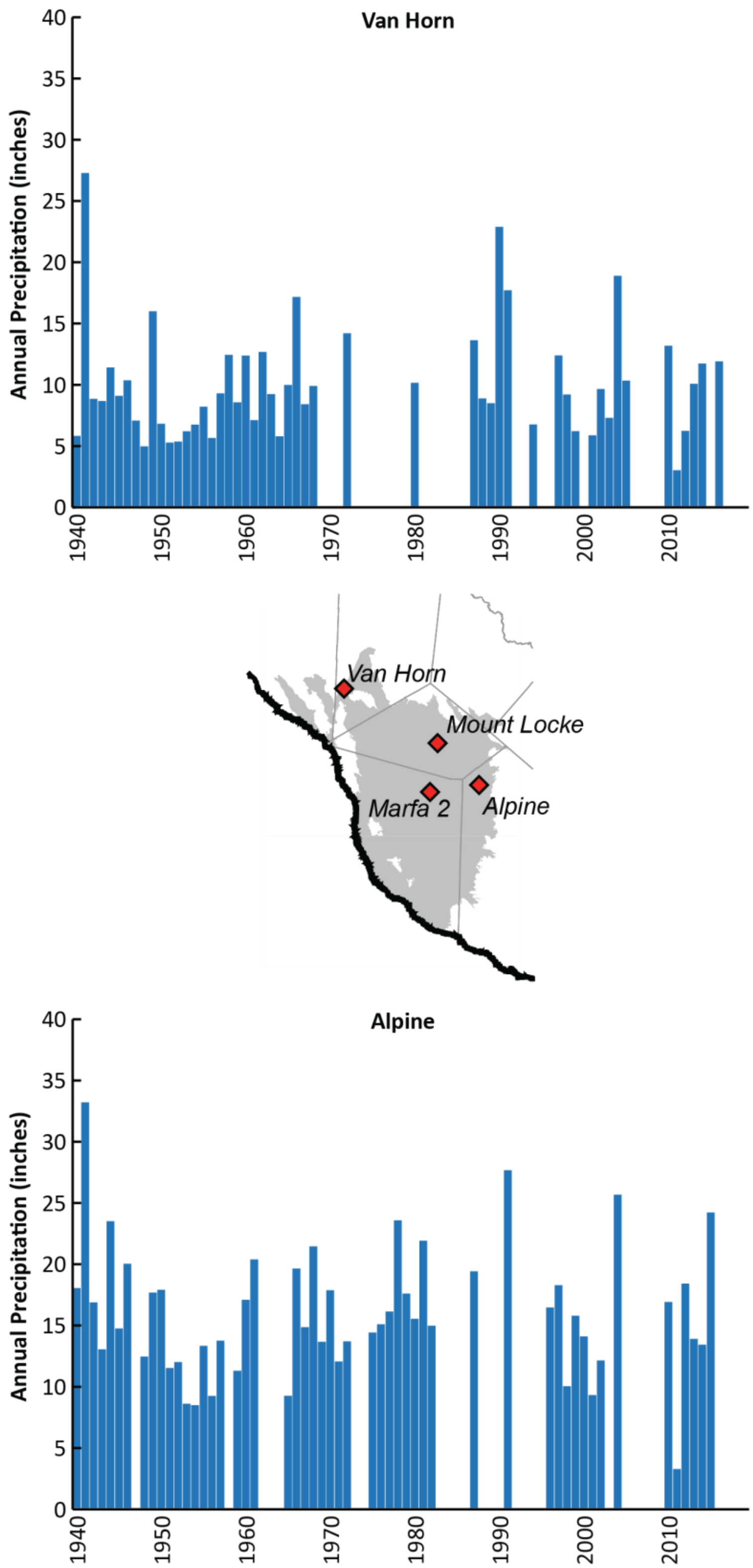


Figure 2.1.7. Selected time series of annual precipitation in inches in the study area (data from National Centers for Environmental Information, 2022). Zero values indicate missing data.

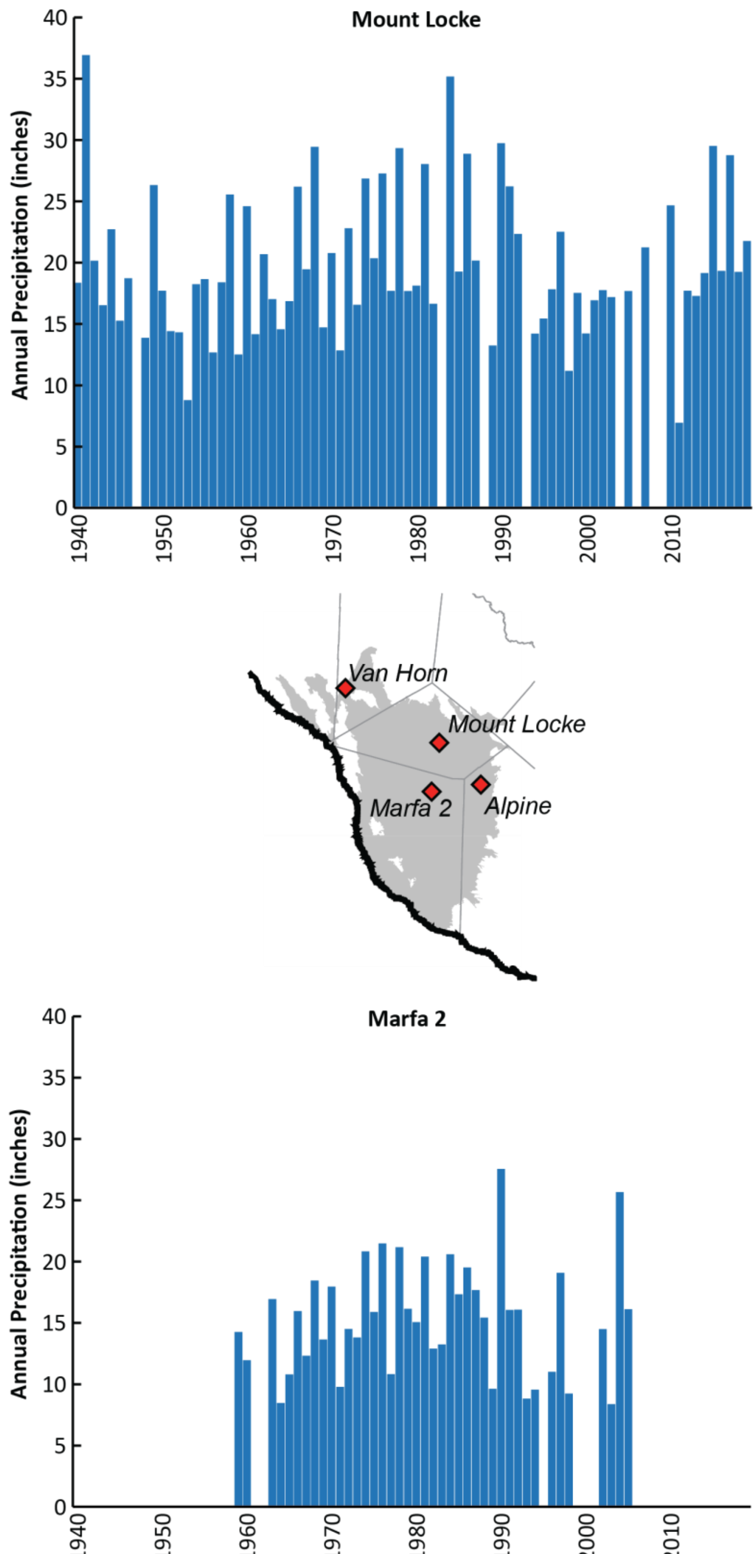


Figure 2.1.7. (continued). **Selected time series of annual precipitation in inches in the study area (data from National Centers for Environmental Information, 2022). Zero values indicate missing data.**

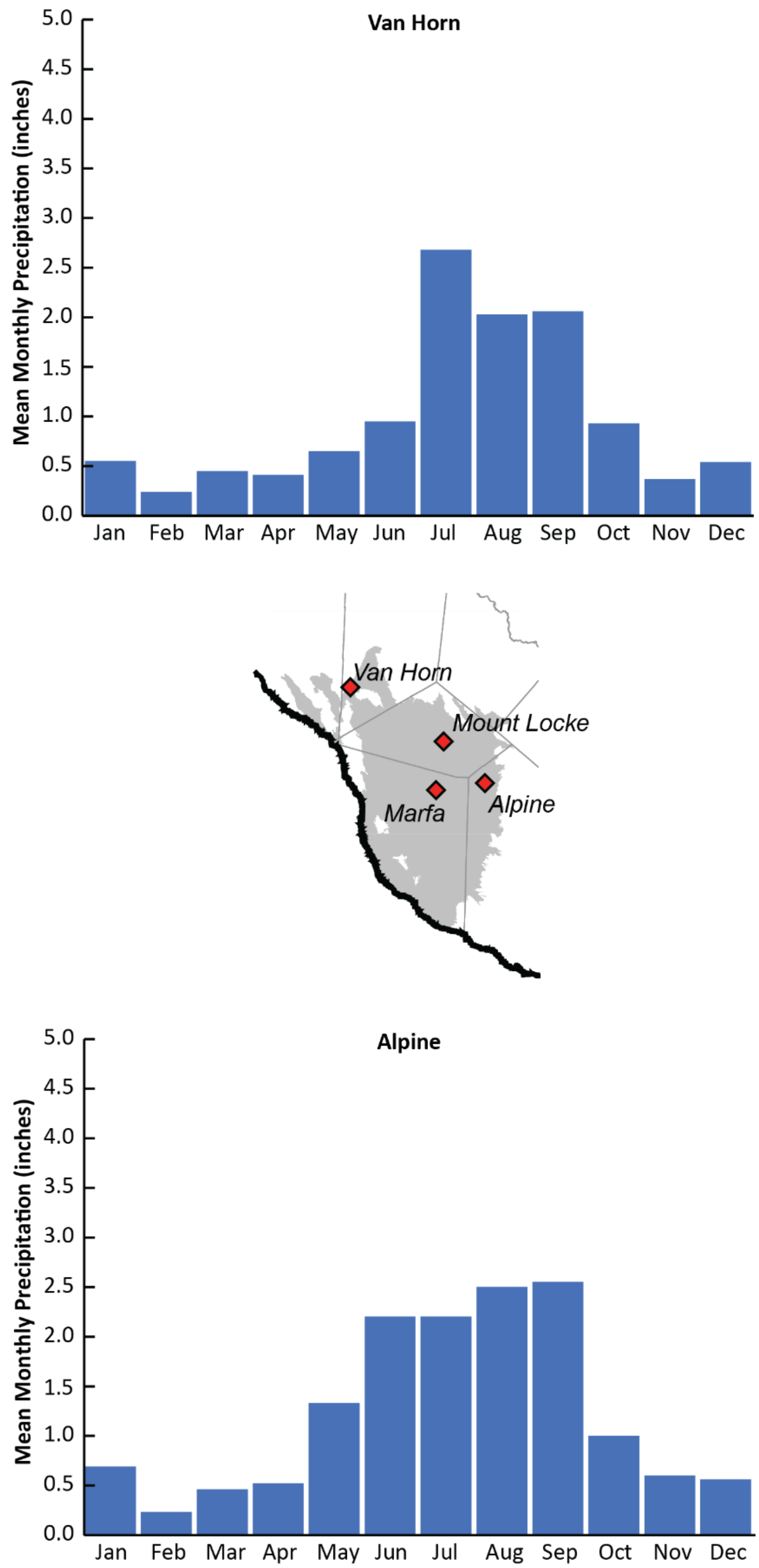


Figure 2.1.8. Selected time series of median monthly precipitation in inches in the study area between 2006 and 2020 (data from National Centers for Environmental Information, 2022).

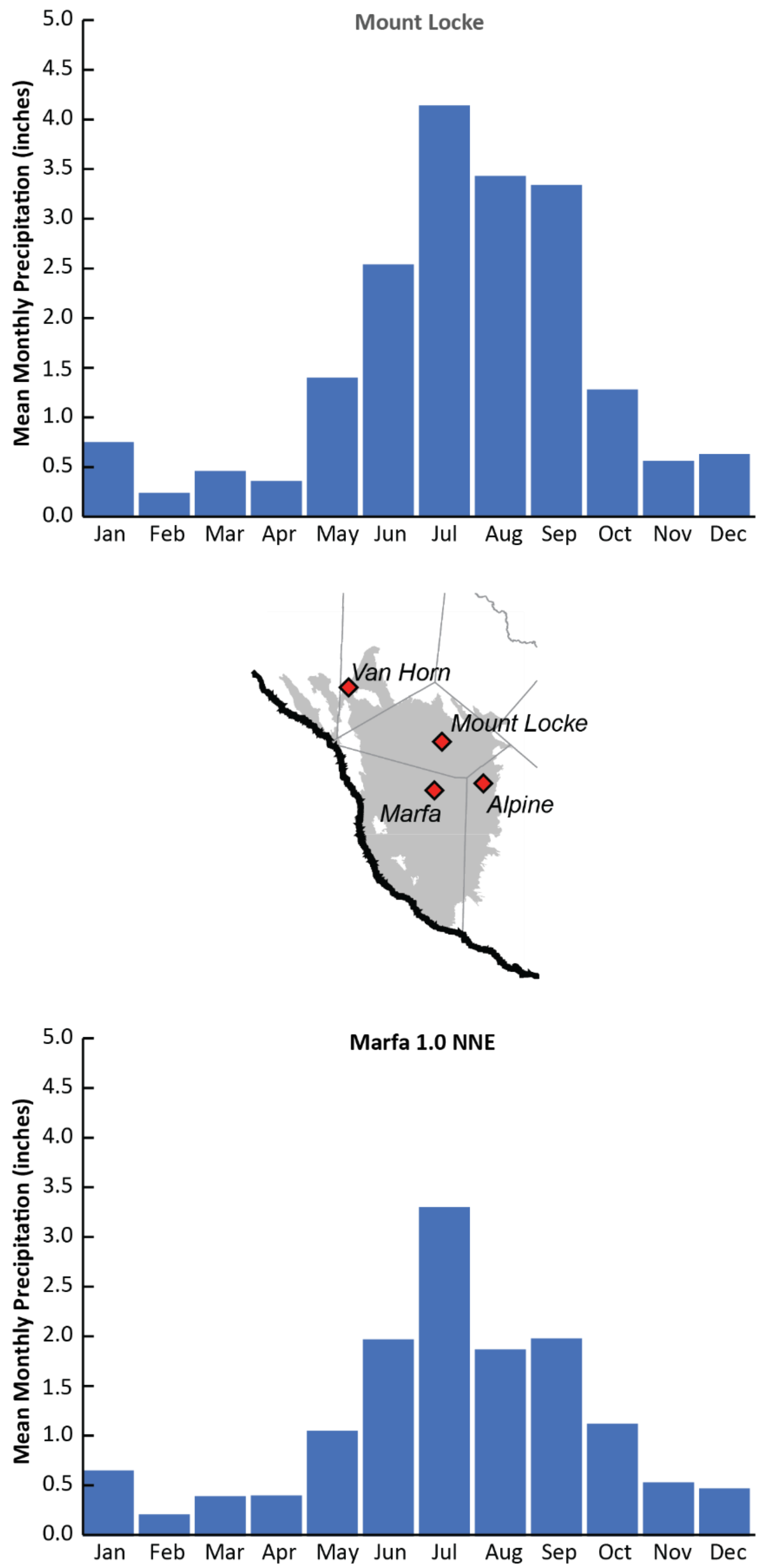


Figure 2.1.8. (continued). **Selected time series of median monthly precipitation in inches in the study area between 2006 and 2020 (data from National Centers for Environmental Information, 2022).**

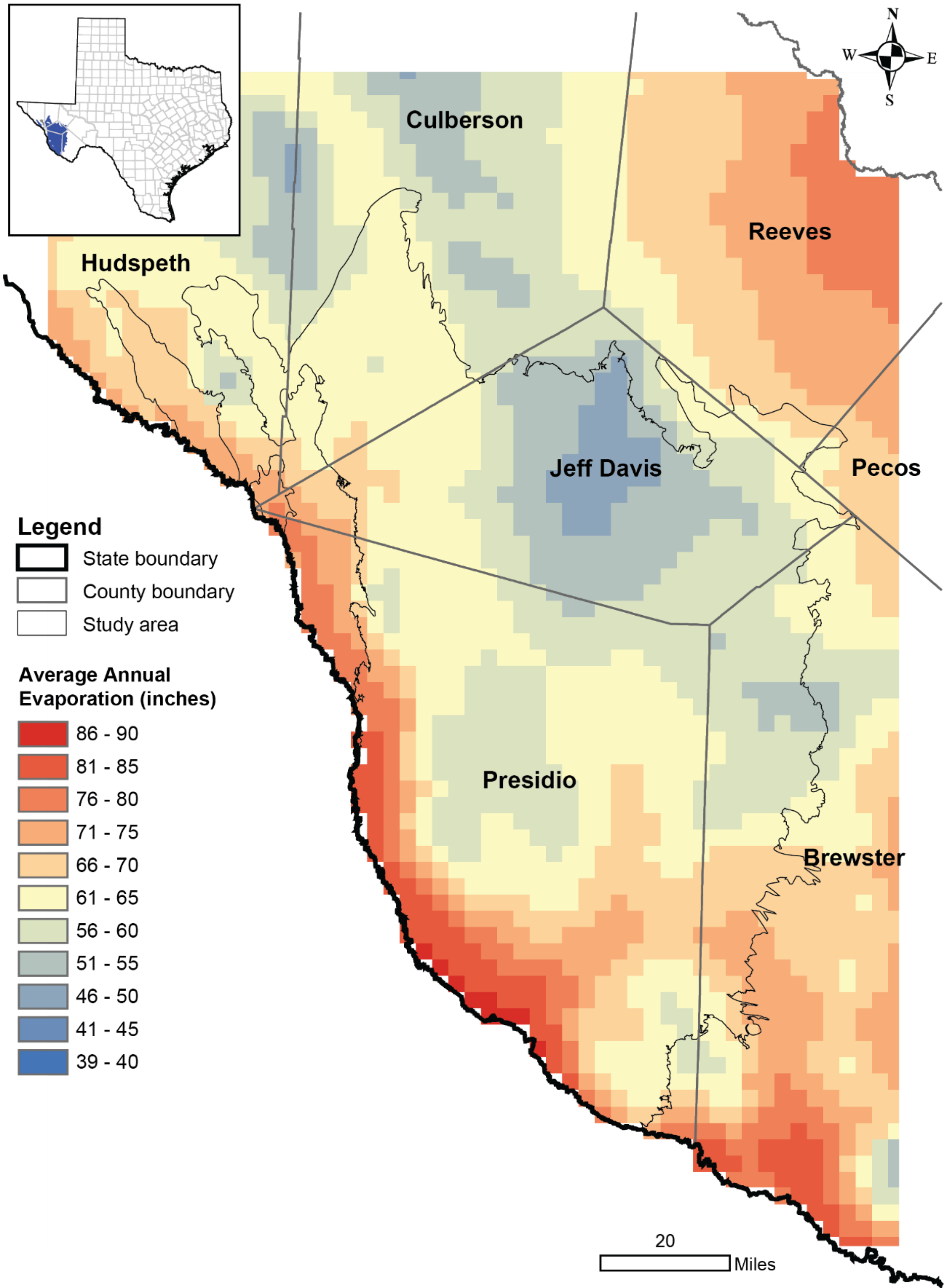


Figure 2.1.9. Average annual lake evaporation rate in inches in the study area between 1941 and 2000 (data from Narasimhan and others, 2005).

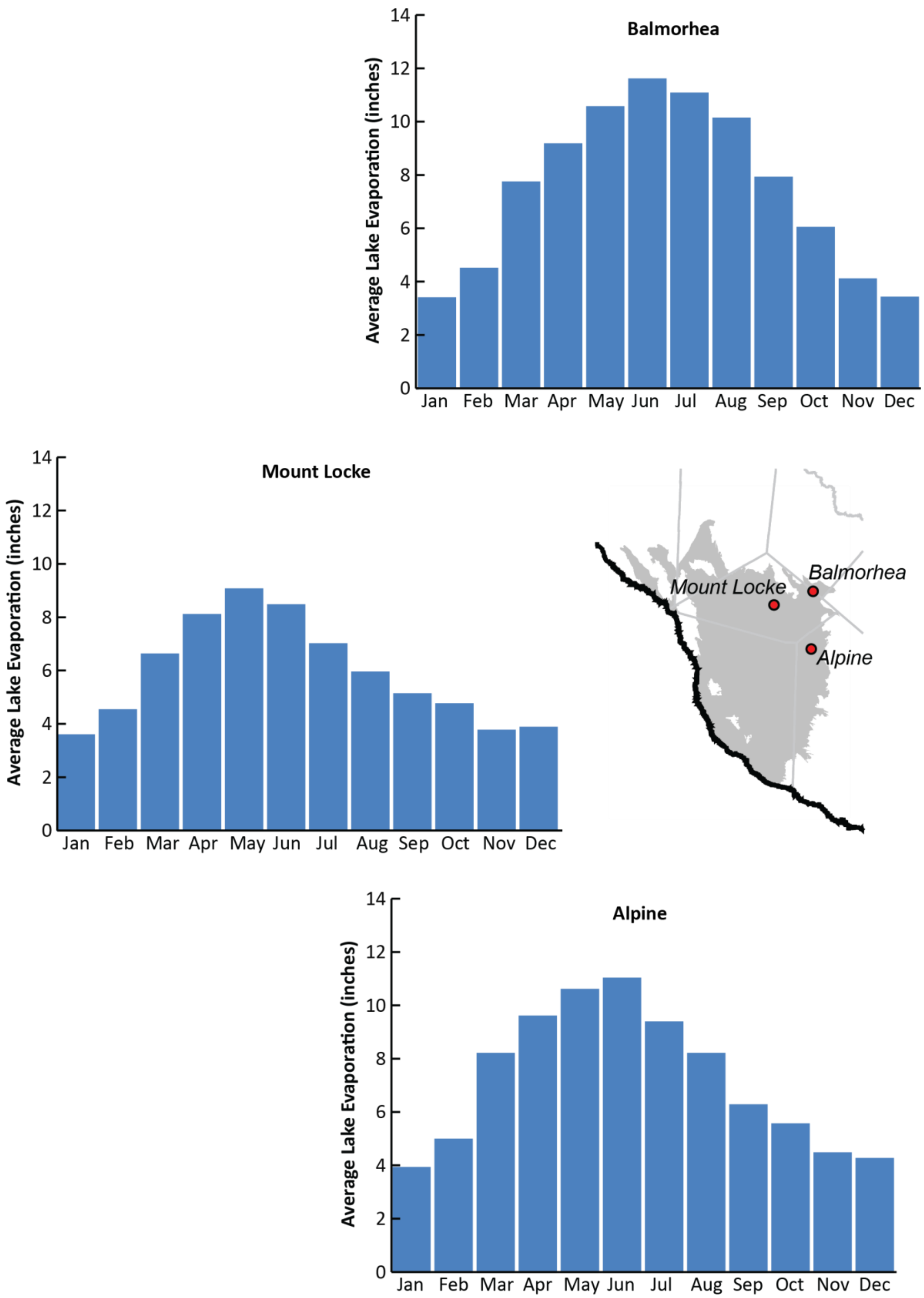


Figure 2.1.10. Average monthly lake surface evaporation in inches at selected weather stations in the study area (data from Narasimhan and others, 2005).

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 Igneous and West Texas Bolsons aquifers, including a description of geologic structural cross-sections through the study area.

The study area is underlain by Precambrian rocks and Paleozoic sedimentary rocks of the Permian Basin that crop out in the Van Horn, Chinati, and Sierra Diablo mountains (King, 1959). The Precambrian rocks in the study area have undergone several processes over geologic time and include sedimentary, metamorphic, and igneous rocks. The Paleozoic limestones were mostly deposited in a passive-margin marine environment. There was a depositional hiatus from the Triassic to Mid-Cretaceous due to the study area being exposed at land surface (Twiss, 1959; Albritton and Smith, 1965; King, 1965; Underwood, 1980). This period of erosion was followed by the deposition of the Cretaceous limestones that cover much of central and far west Texas and comprises important aquifers such as the Edwards-Trinity (Plateau) Aquifer (Henry and Price, 1985; Muehlberger and Dickerson, 1989; Raney and Collins, 1993; Collins and Raney, 1994 and 1997; Figure 2.2.1).

Tertiary Laramide orogeny compression was followed by a long period of large-scale volcanism in the study area (Henry and McDowell, 1986). This volcanic event produced a complex series of welded pyroclastic rocks, lavas, and volcaniclastic sediments. These igneous rocks include more than 40 different named units (see Figure 2.2.1; Beach and others, 2004). There is a wide compositional and textural range among these igneous formations, from tuffs and breccias to basalts and trachytes. Each has a different geographic extent, and there are only a few mappable units in the study area, such as the Petan Basalt and the Mitchell Mesa Rhyolite. These igneous rocks were formed between 48 and 27 million years ago. The volcanic rocks consist of a complex layering of vents, flows, and interbedded volcanic-sedimentary units, which were deposited in numerous intervals between eruptions. This layering has led to the very complex interrelationships between the igneous units. Although Tertiary-age volcanic rocks occur elsewhere in far west Texas, the Davis Mountains igneous rocks that make up the Igneous Aquifer occur mostly in Brewster, Jeff Davis and Presidio counties.

As Laramide orogeny and associated volcanism ended, the compressional tectonic forces in the study area changed to extensional tectonics that resulted in the formation of the Basin and Range structures in the study area (Muehlberger and others, 1978; Henry and others, 1991). Between these mountain ranges, which include the Sierra Diablo, Sierra Vieja, and Van Horn mountains, large intermontane basins formed, beginning in the Tertiary and continuing throughout the Quaternary. The basins filled with thick sequences of gravel and sand eroded from the adjacent mountains and represent deposition in different settings, including alluvial fan, lacustrine, fluvial, and eolian deposits. These basins (bolsons)—

including the Eagle Flat, Green River Valley, Lobo Flat, Michigan Flat, Presidio Bolson, Red Light Draw, Redford Bolson, Ryan Flat, and Wild Horse Flat—formed as the result of the extensional tectonics that produced a discontinuous series of north-northwest-trending grabens that terminate at west-northwest-trending strike-slip faults (Figure 2.2.2).

The surface geology in the study area is shown in Figure 2.2.3. This map shows the Quaternary sediments overlying Tertiary igneous rocks in the study area. Older Precambrian through Cretaceous rocks crop out along the mountains along the margins of the study area. The generalized stratigraphy of the study area is illustrated in a series of hydrostratigraphic cross-sections, the locations of which are shown in Figure 2.2.4. Individual cross-sections are shown in Figures 2.2.5 through Figure 2.2.10.

Era	System	Stratigraphic Units	
Cenozoic	Quaternary	Quaternary deposits	
		Windblown sand	
		Bolson deposits	
	Tertiary	Volcanic rocks undivided	Merrill Formation
		Intrusive Igneous rocks	Duff Formation/Decie Member
		Chambers Tuff	Sheep Pasture Formation
		Garren Group	Sleeping Lion Formation
		Tarantula Gravel	Frazier Canyon Formation
		Hogeye Tuff	Cottonwood Spring Basalt
		Trachyte Porphery	Bracks Rhyolite
		Upper Rhyolite	Adobe Canyon Formation
		Pantera Trachyte	Chambers Tuff
		Perdiz Conglomerate	Limpia Formation
		Petan Basalt	Potato Hill Andesite
		Tascotal Formation	Gomez Tuff
		Mitchell Mesa Welded Tuff	Star Mountain Rhyolite
		Brooks Mountain Formation	Crossen Trachyte
		Goat Canyon Formation	Sheep Canyon Basalt
		Medley Formation	Pruett Formation
		Wild Cherry Formation	Huelster Formation
		Eppenauer Ranch Formation	Buckshot Ignimbrite
		Mount Locke Formation	Colmena Tuff
		Barrel Springs Formation	Gill Breccia
		Capote Mountain Tuff	
Mesozoic	Cretaceous	Cretaceous undivided	Benevides Formation
		Buda Limestone	Finlay Limestone
		Boracho Formation	Cox Sandstone
		San Martine Limestone Member	Bluff Mesa Formation
		Levinson Limestone Member	Yucca Formation
		Eagle Mountain Sandstone	Etholean Conglomerate
		Espy Limestone	Torcer Formation
	Jurassic	Malone Formation	
Paleozoic	Permian	Hueco Limestone	
Precambrian	Precambrian	Carrizo Mountain Group	
		Precambrian bedrock undivided	

Figure 2.2.1. Generalized stratigraphic column for the Igneous and West Texas Bolsons aquifers and underlying formations.

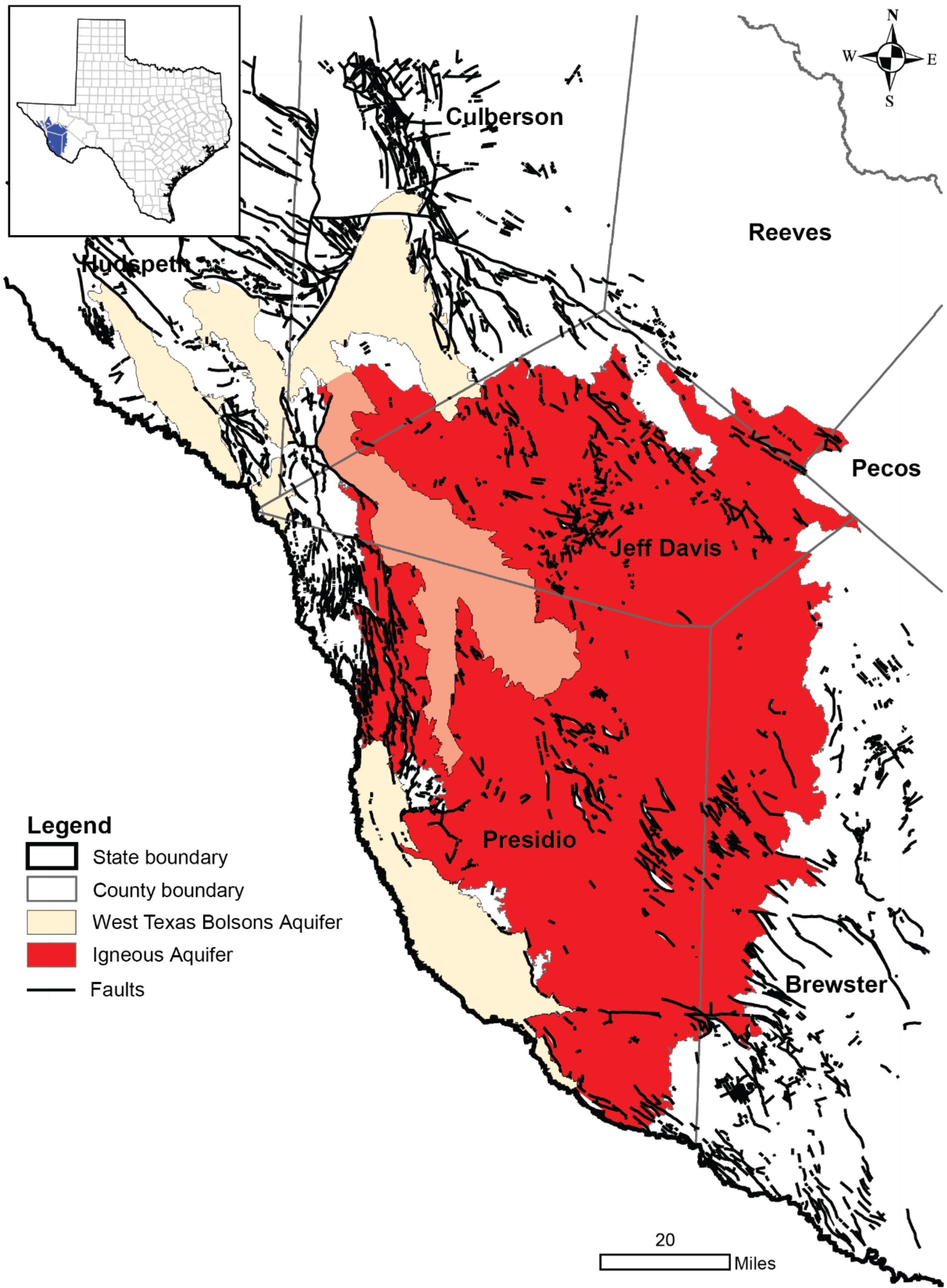


Figure 2.2.2. Faults that cut through or lie adjacent to the study area.

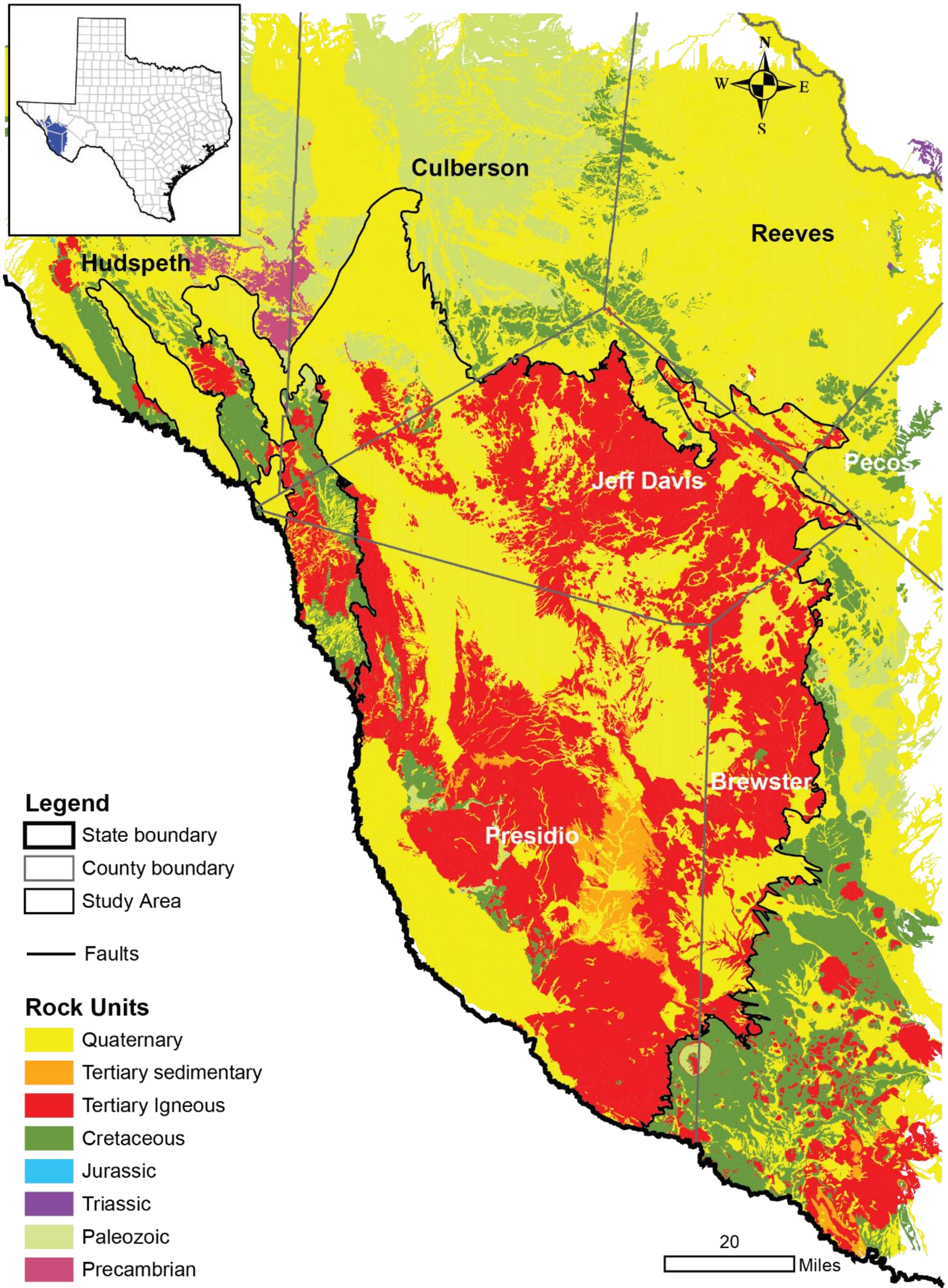


Figure 2.2.3. Generalized surface geology in the study area.

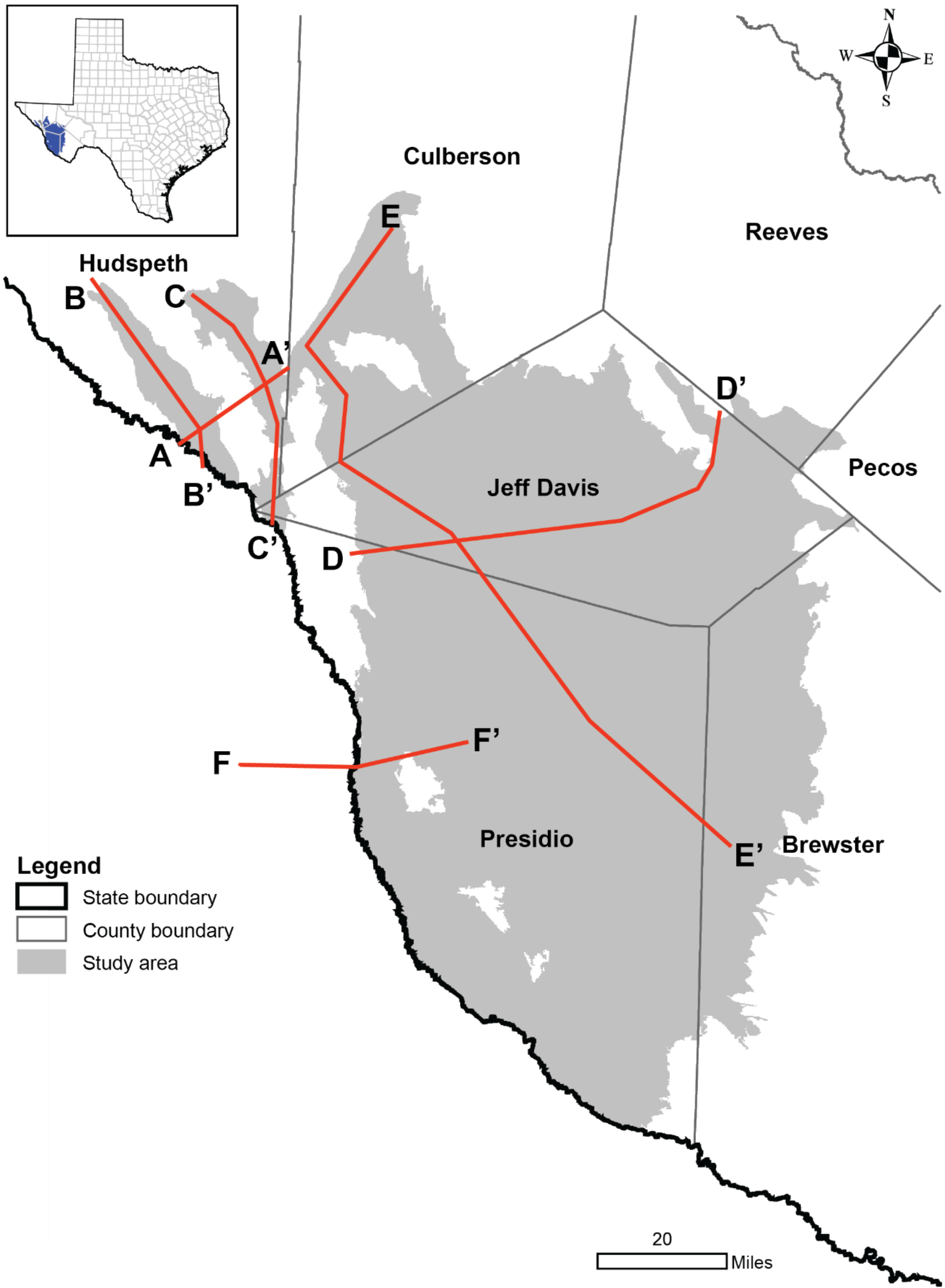


Figure 2.2.4. Locations of cross-sections through the study area.

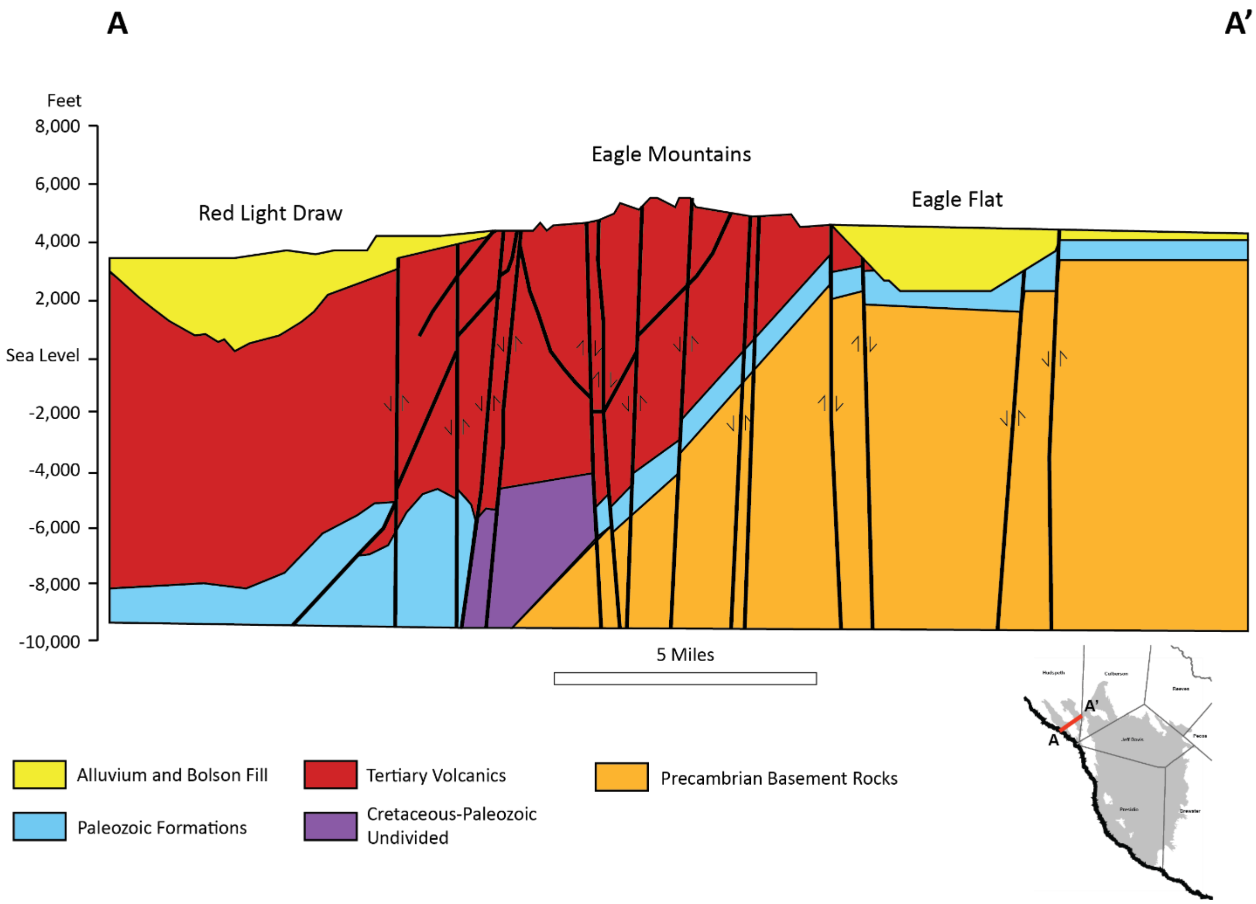


Figure 2.2.5. **Generalized cross-section across Eagle Flat and Red Light Draw (modified from Beach and others, 2008).**

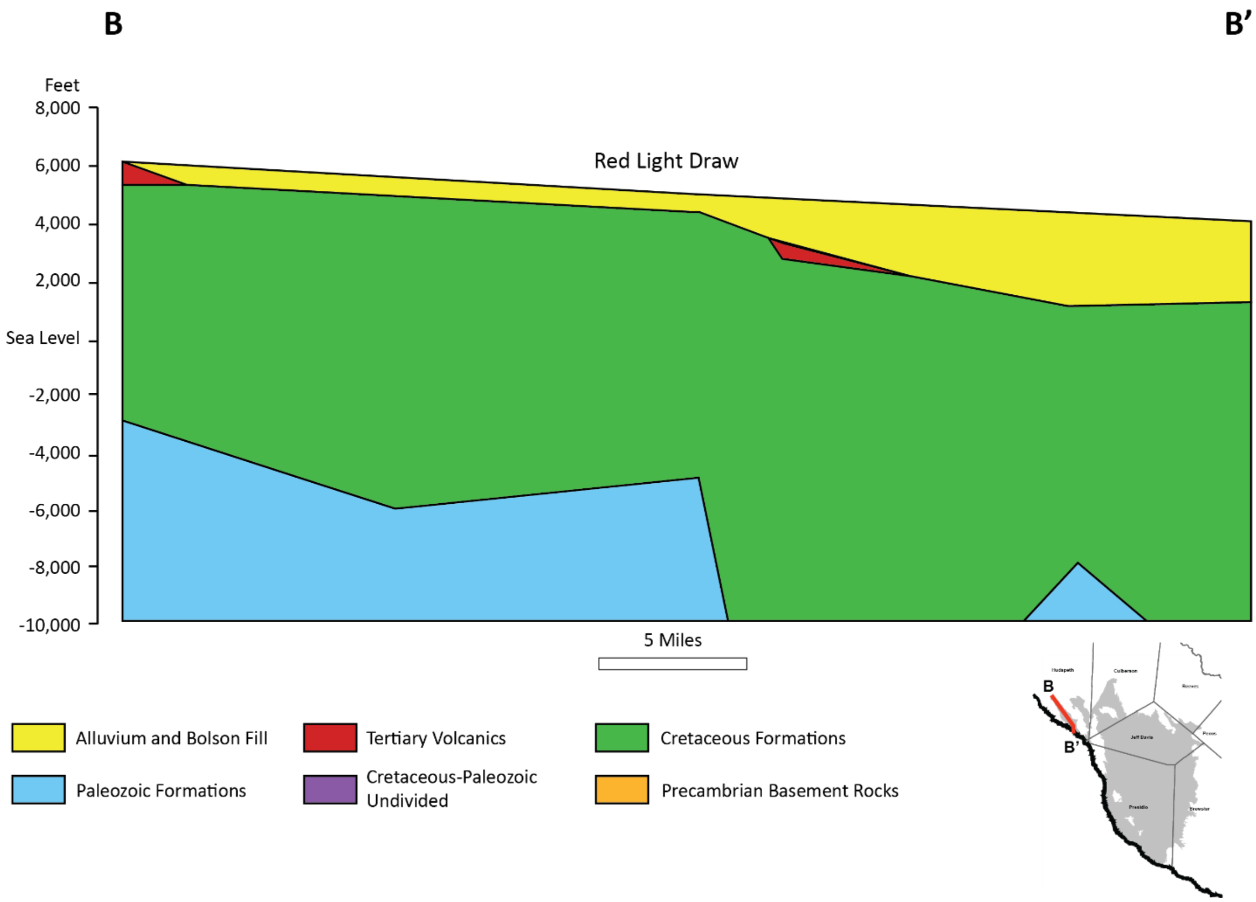


Figure 2.2.6. Generalized cross-section along the axis of Red Light Draw (modified from Beach and others, 2008).

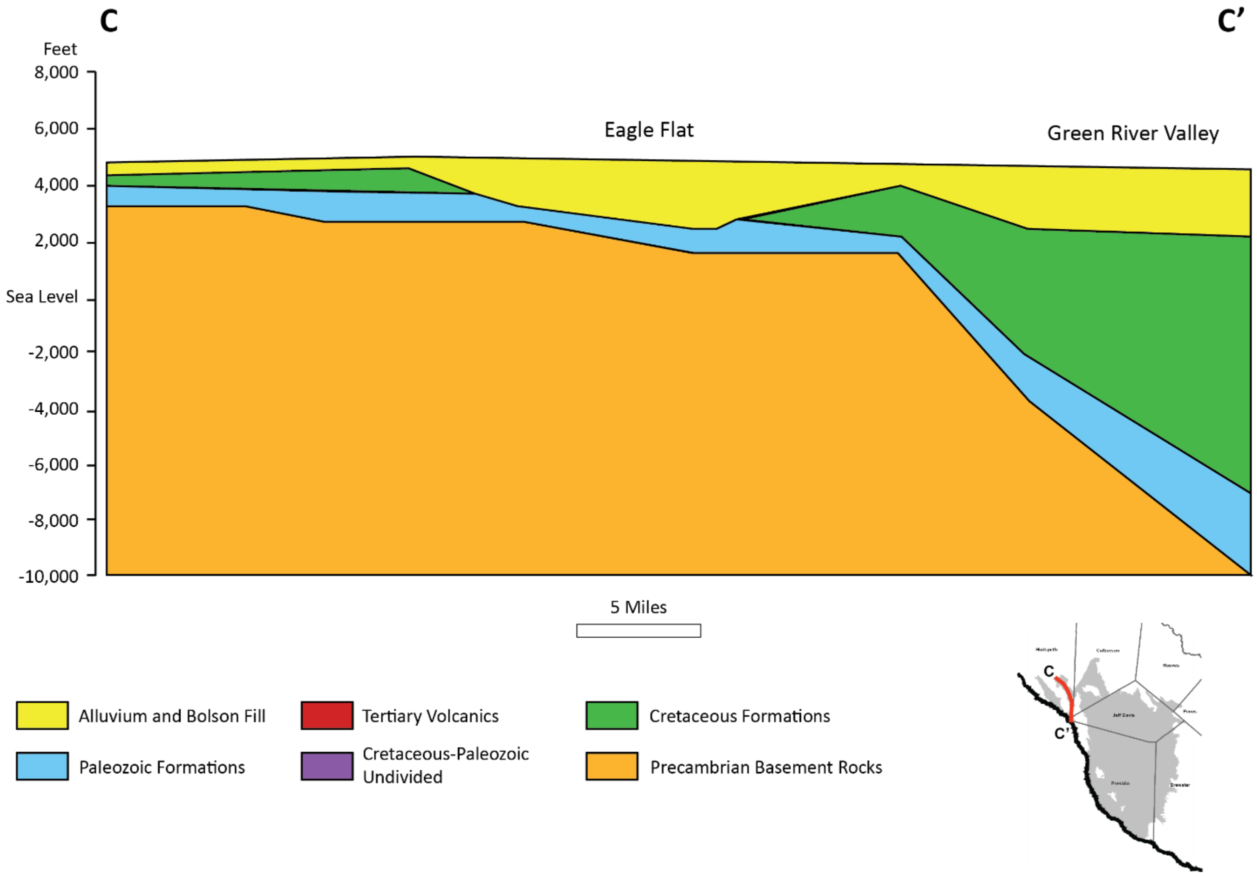


Figure 2.2.7. Generalized cross-section along the axes of Eagle Flat and Green River Valley (modified from Beach and others, 2008).

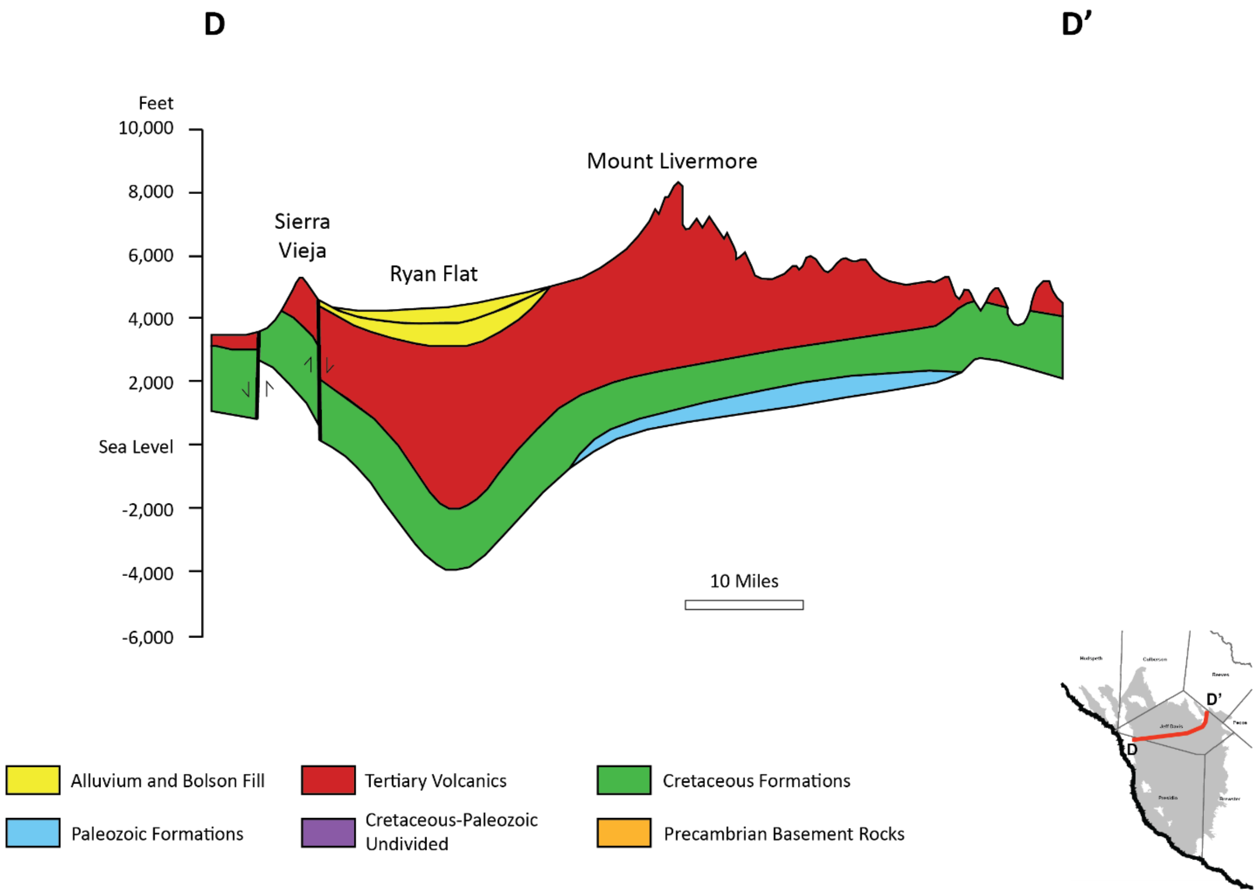


Figure 2.2.8. **Generalized cross-section across the Davis Mountains and Ryan Flat (modified from Beach and others, 2004).**

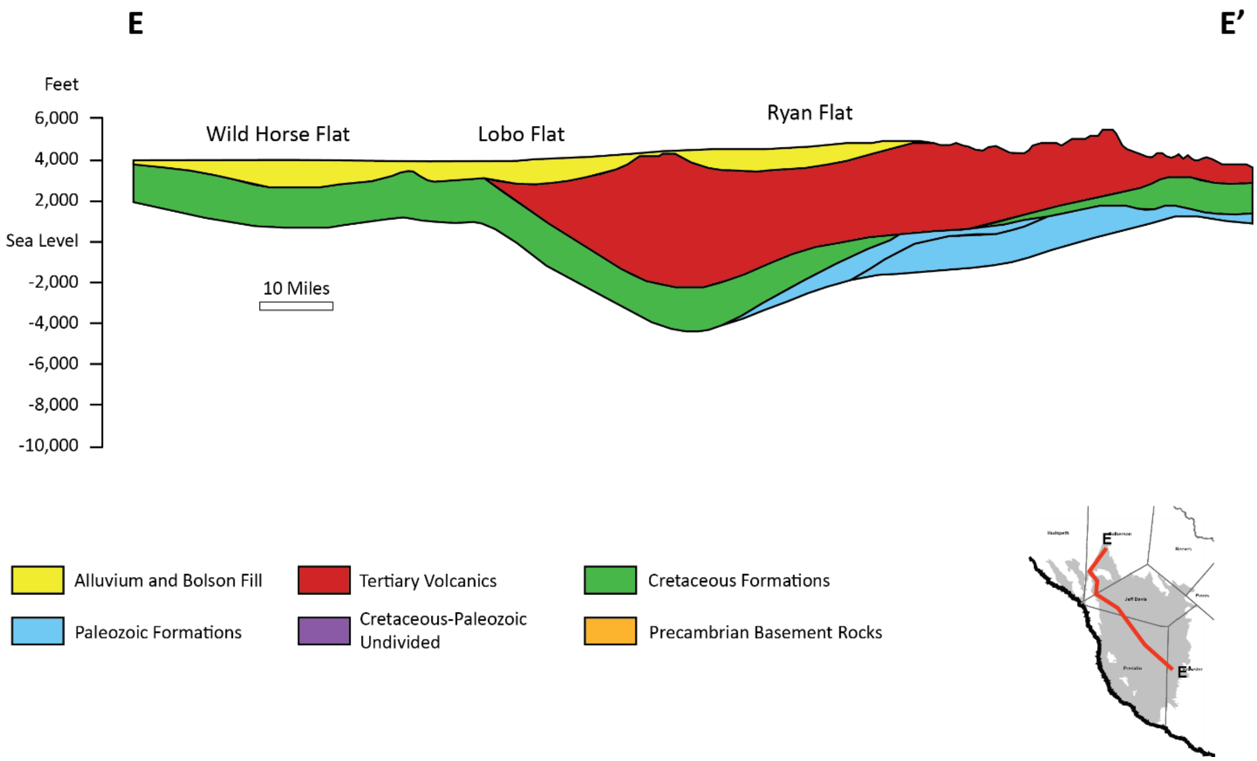


Figure 2.2.9. **Generalized cross-section along the axes of Wild Horse Flat, Lobo Flat, and Ryan Flat (modified from Beach and others, 2004).**

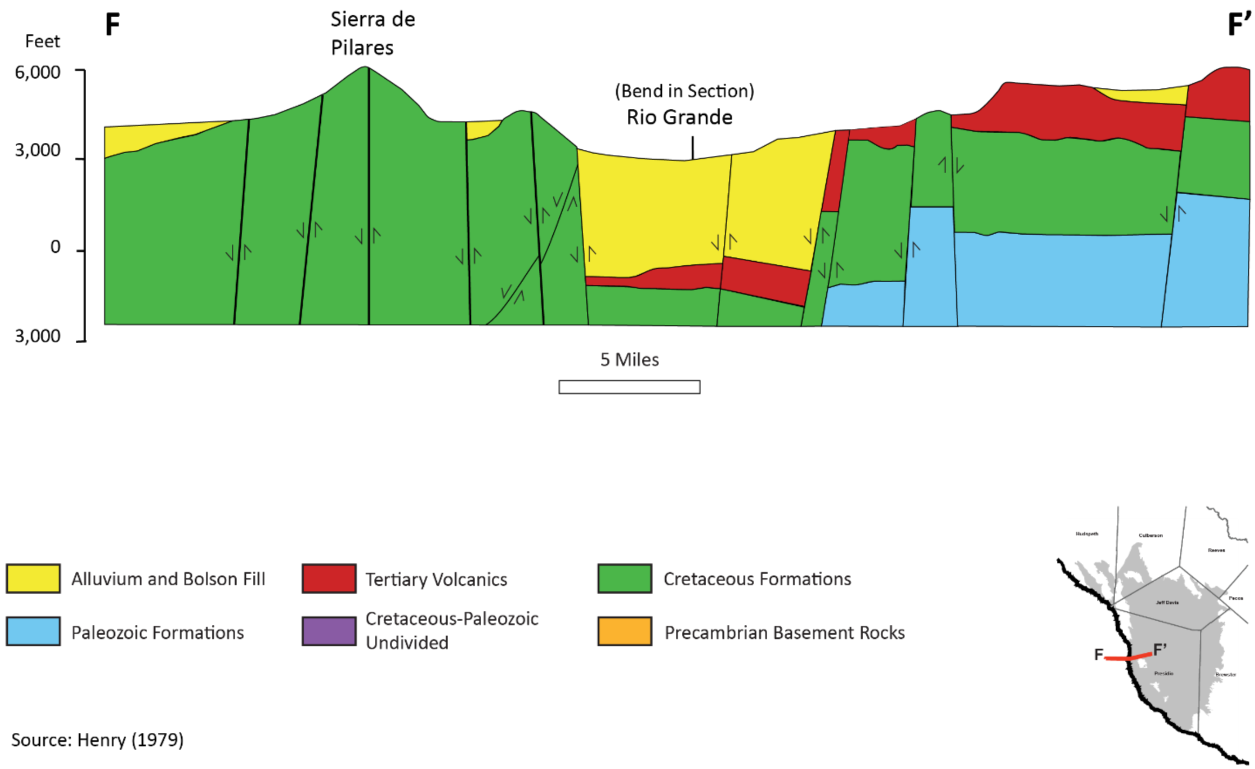


Figure 2.2.10. Generalized cross-section across the Rio Grande valley (modified from Henry, 1979).

3.0 PREVIOUS WORK

Many geologic and hydrogeologic reports include the Igneous and West Texas Bolsons aquifers. Several studies of the stratigraphy and structure of the study area include: Albritton and Smith, 1965; Chastain-Howley, 2001; Collins and Raney, 1994; 1997; DeFord and Bridges, 1959; DeFord and Haenggi, 1971; Groat, 1972; Gries and Haenggi, 1971; Gries, 1980; Henry and others, 1986; 1991; Henry and Price, 1985; 1986; 1989; Horak, 1985; Jackson and others, 1993; King and Flawn, 1953; King, 1965; Langford, 1993; Mack and Seager, 1990; Mack and others, 1998; Muehlberger, 1980; Muehlberger and Dickerson, 1989; Muehlberger and others, 1978; Mraz and Keller, 1980; Mraz, 1977; Price and Henry, 1984; 1985; Price and others, 1986; Raney and Collins, 1993; Seager and others, 1984; Stevens and Stevens, 1985; Strain, 1971; Urbanczyk and others, 2001. More detailed hydrogeologic studies discuss both the groundwater geochemistry and hydrology of the study area (Muse, 1966; Henry, 1979; Gates and others, 1980; Hibbs and others, 1995; Hibbs and Darling, 1995; Darling, 1997; George and others, 2005).

Three regional groundwater availability models have been constructed to simulate groundwater flow in the Igneous and West Texas Bolsons aquifers (Beach and others, 2004, 2008; Wade and others, 2011; Wade and Jigmond, 2013; Figure 3.0.1). Prior to the groundwater availability models, five other two- or three-dimensional groundwater flow models were constructed covering parts of the study area (Nielson and Sharp, 1990; Black, 1993; Darling and others, 1994; Brown and Caldwell, 2001; Finch and Armour, 2001)

This report is part of work being conducted to update the groundwater availability models of the Igneous and West Texas Bolsons aquifers (Beach and others, 2004, 2008; Wade and Jigmond, 2013) into a single groundwater availability model. The previous groundwater flow models are three-layer models using MODFLOW-96 (Beach and others, 2004), and MODFLOW-2000 (Beach and others, 2008; Wade and Jigmond, 2013). The updated model will use up-to-date versions of MODFLOW and extend the calibration period to more recent times.

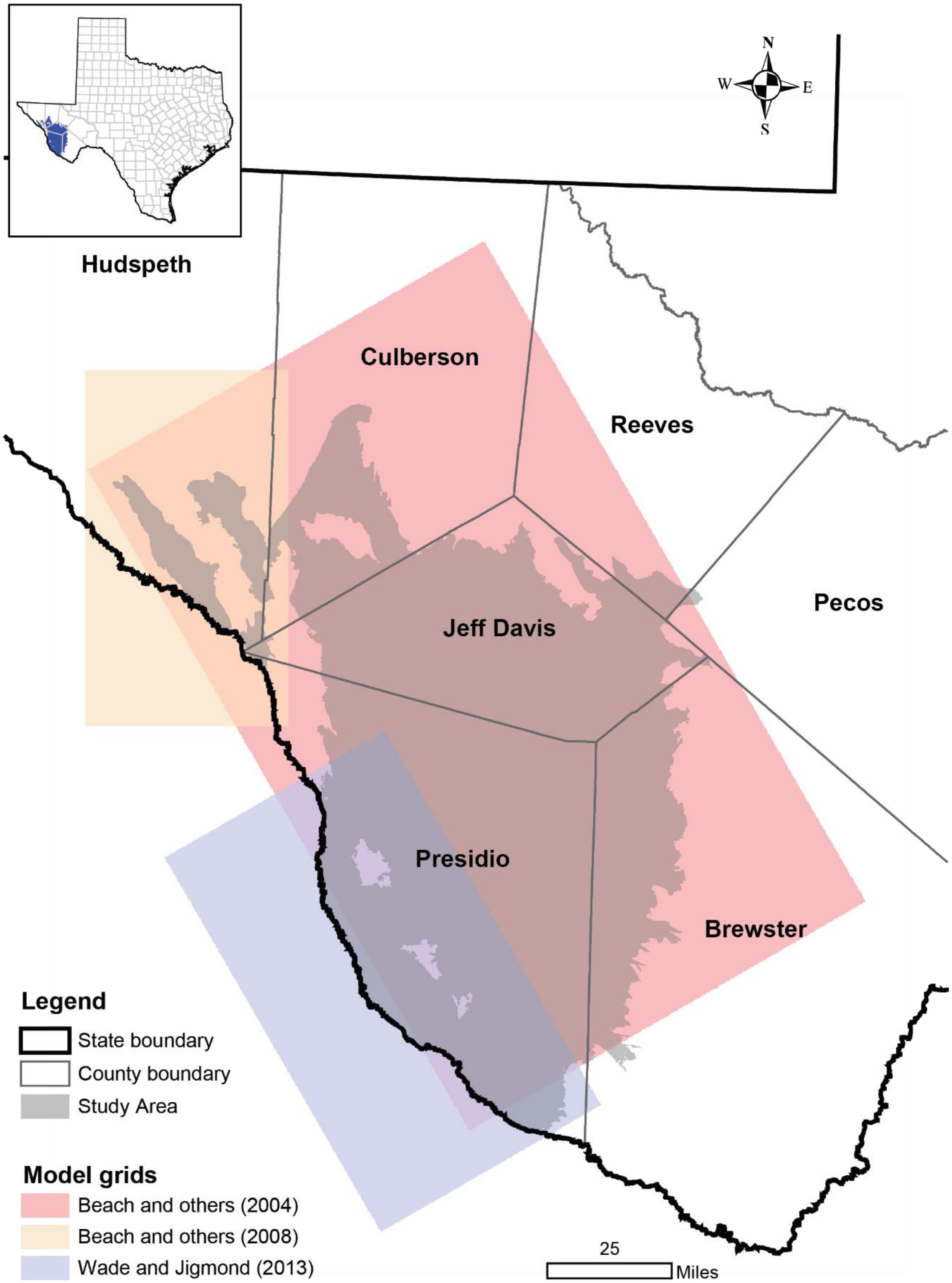


Figure 3.0.1. Approximate extents of previous model grids for models used for simulating groundwater flow through the Igneous and West Texas Bolsons aquifers.

4.0 HYDROLOGIC SETTING

The hydrologic setting is a description of the factors that contribute to the groundwater hydrology of the Igneous and West Texas Bolsons aquifers. These factors include the hydrostratigraphy, hydrogeologic framework, water levels, regional groundwater flow, recharge, surface-water bodies, hydraulic properties, discharge, and water quality.

4.1 Hydrostratigraphy and hydrostratigraphic framework

The Igneous and West Texas Bolsons aquifers (Figure 2.0.1) generally consist of the Tertiary igneous and quaternary alluvial sediments and rocks, respectively, that occur in the study area (Figure 4.1.1). The aquifers overlie several older Precambrian and Cretaceous rock units that also crop out in the adjacent mountains (Figure 2.2.1).

4.1.1 West Texas Bolsons Aquifer

The West Texas Bolsons Aquifer is composed of undifferentiated Quaternary alluvium derived from adjacent mountains (Figure 4.1.1). The aquifer consists of several basins that are connected in some cases. Alluvial fan deposits of sand, gravel, silt, and clays are found along the margins of the basin and typically become finer grained away from the mountains. Coarser grained deposits along the mountain front readily infiltrate recharge from stormwater runoff (Scanlon and others, 2001). Salt flats north of the Baylor Mountains and on the northern model boundary represent areas of groundwater discharge by evaporation (Boyd and Kreitler, 1986).

The top of the West Texas Bolsons Aquifer has elevations ranging from about 2,400 feet to more than 5,000 feet above mean sea level (Figure 4.1.2). The aquifer top represents land surface elevation, which is highest in the southeastern Ryan Flat adjacent to the Davis Mountains and lowest along the Rio Grande in the Presidio Bolson. Aquifer base elevations generally decrease towards the center of each basin (Figure 4.1.3). The aquifer base elevations range from elevations of more than 2,000 feet below mean sea level in the Presidio Bolson to more than 5,000 feet above mean sea level along the margins of the northernmost bolsons. The West Texas Bolsons Aquifer thickness is highly variable, ranging from less than 100 feet to more than 6,000 feet (Figure 4.1.4). In the study area, the West Texas Bolsons Aquifer is thickest along the Rio Grande, especially in the Presidio and Redford bolsons.

4.1.2 Igneous Aquifer

The Igneous Aquifer is composed of all contiguous Tertiary igneous formations that underlie the Davis Mountains and adjacent areas. These igneous rocks cover most of Presidio and Jeff Davis counties, western Brewster County, as well as small parts of the adjacent Culberson, Reeves, and Pecos counties.

The Igneous Aquifer is comprised of over 40 named volcanic units (Figure 2.2.1). Individual igneous formations are highly variable in nature and suggest varying forms of intrusive and extrusive volcanic activity interspersed with periods of low activity when erosional clastic sediments (volcaniclastics) accumulated.

The elevation of the top of the Igneous Aquifer ranges from about 2,500 to 8,000 feet above mean sea level (Figure 4.1.5). The aquifer top represents land surface except where it is overlain by Quaternary alluvium stratigraphic units. The estimated elevation of the base of the Igneous Aquifer varies from below 1,800 feet below mean sea level to about 6,000 feet above mean sea level (Figure 4.1.6). The lowest base elevations occur in western Jeff Davis County, coinciding with a graben that was infilled with alluvium to form Ryan Flat. The thickness of Tertiary igneous rocks has been estimated from geophysical and sample logs of prospective oil wells (Figure 4.1.7). Thickness ranges from 1,000 to 6,000 feet for most of the aquifer's areal extent. The aquifer thickness decreases along the outer edges as the volcanic rocks pinch out.

Era	System	Stratigraphy	Hydrostratigraphic Units	Model Layer
	Quaternary	Quaternary deposits Bolsons deposits	West Texas Bolsons Aquifer	1
Cenozoic	Tertiary	Undifferentiated volcanic rocks, tuffs, intrusive igneous rocks, and tuffaceous sedimentary rocks	Igneous Aquifer	2
Mesozoic	Cretaceous	Limestone, sandstone, quartzite, marl, and mudtone	Permian and Cretaceous hydrostratigraphic units	
Paleozoic	Permian			

Figure 4.1.1. Hydrostratigraphic chart for Igneous and West Texas Bolsons aquifers and underlying Mesozoic and Paleozoic stratigraphic units.

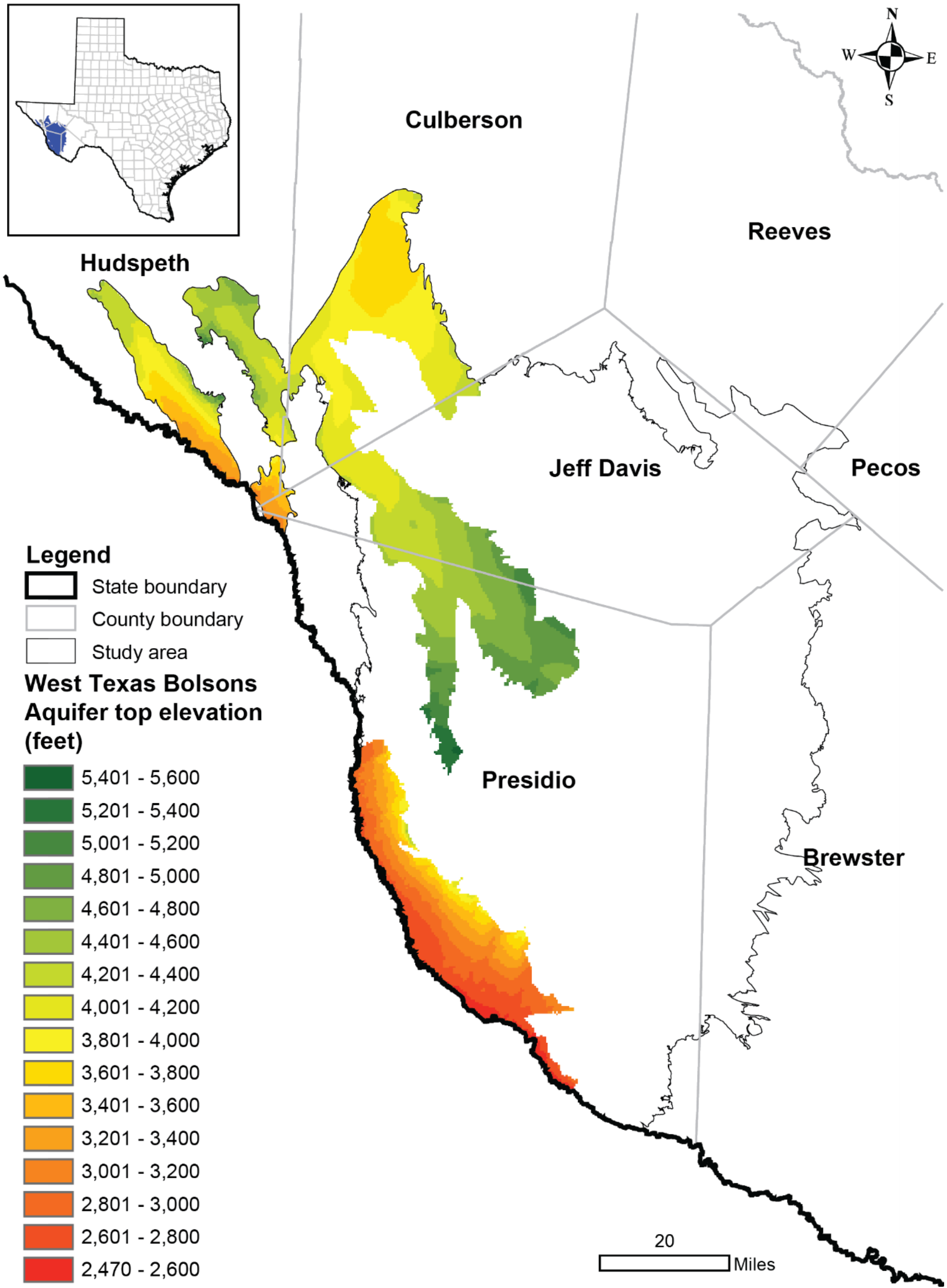


Figure 4.1.2. **The elevation (in feet relative to mean sea level) of the top of the West Texas Bolsons Aquifer (data from Beach and others, 2004, 2008; Wade and Jigmond, 2013).**

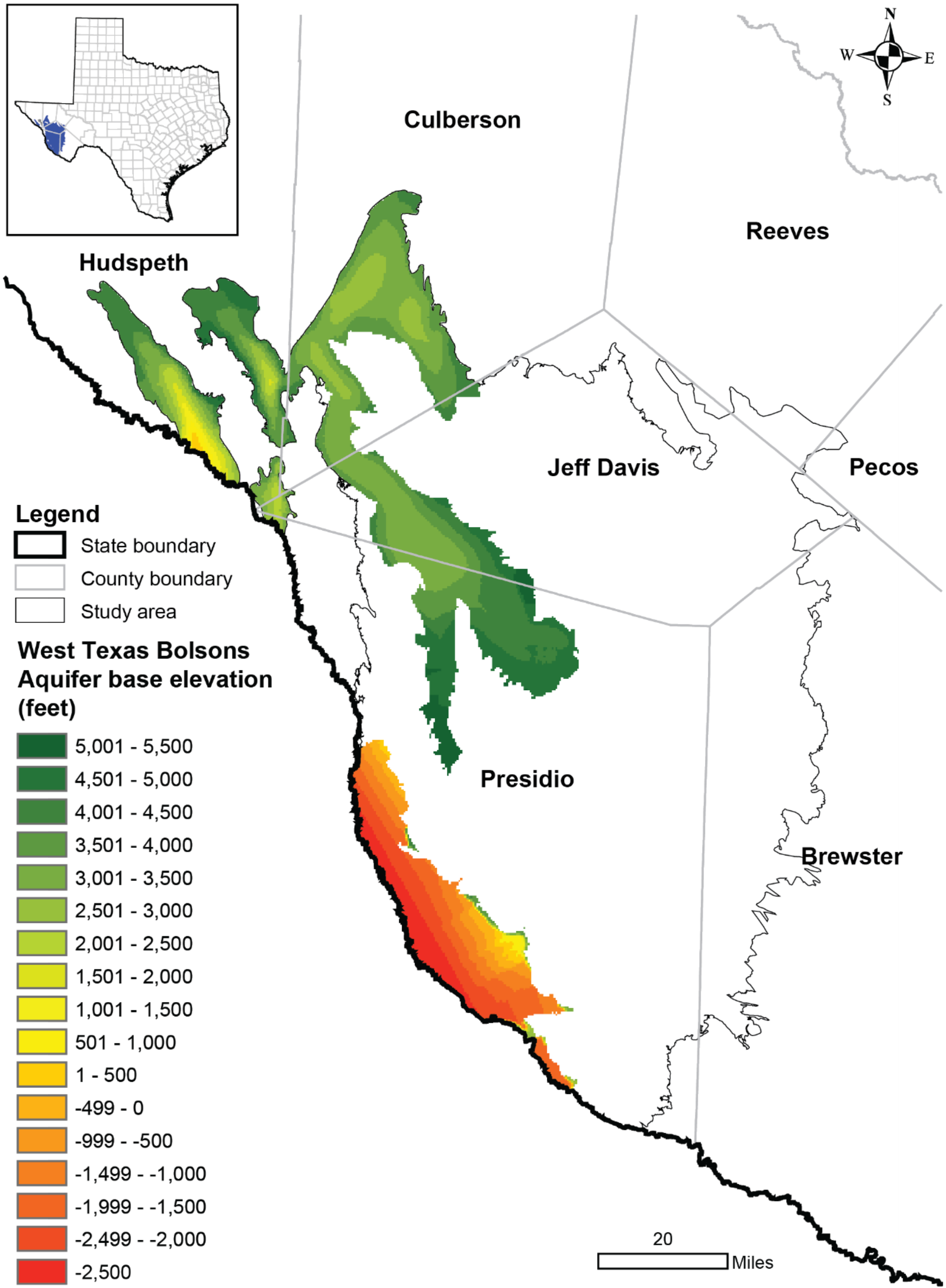


Figure 4.1.3. **The elevation (in feet relative to mean sea level) of the base of the West Texas Bolsons Aquifer (data from Beach and others, 2004, 2008; Wade and Jigmond, 2013).**

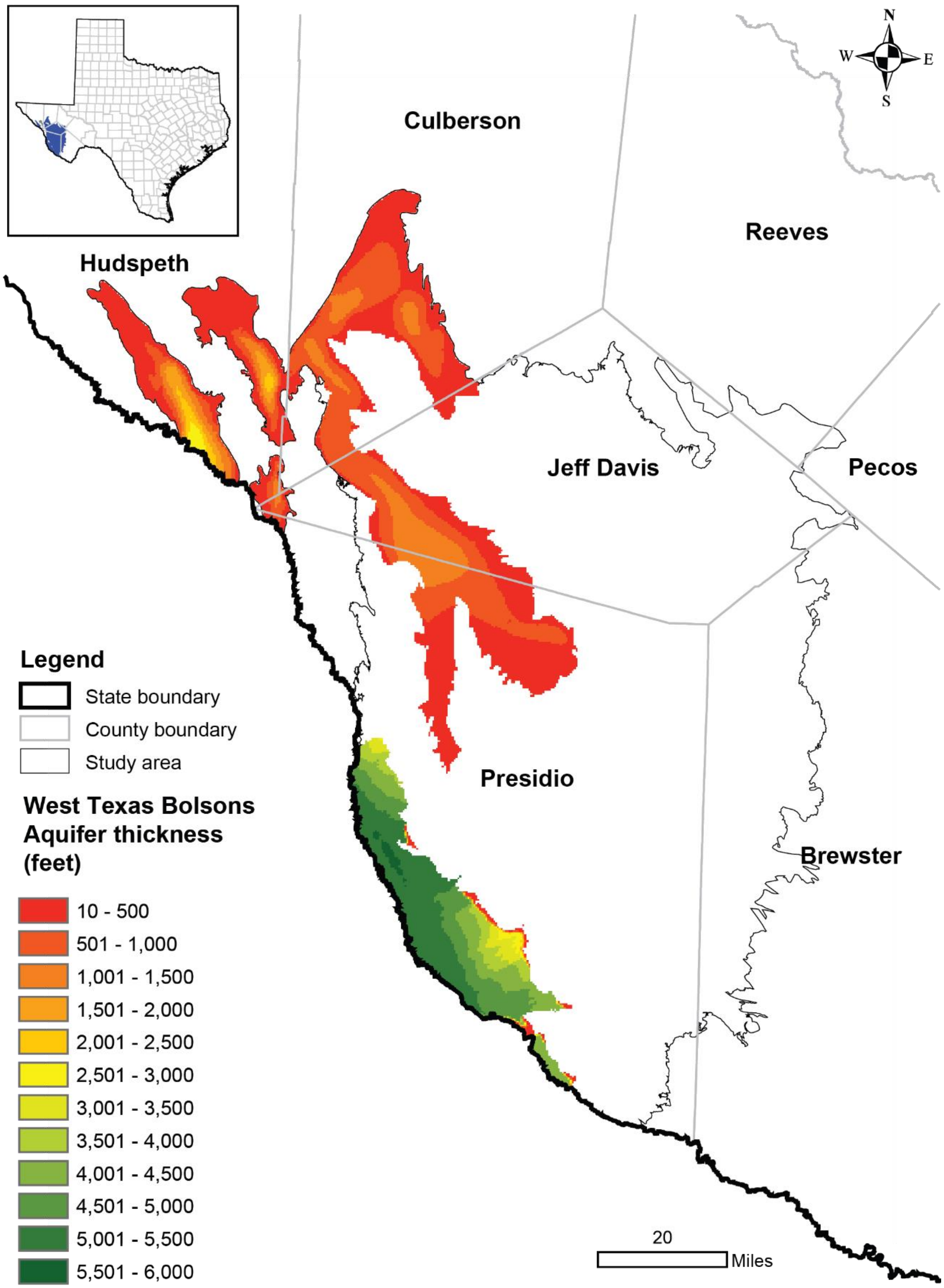


Figure 4.1.4. **Thickness (in feet) of the West Texas Bolsons Aquifer (data from Beach and others, 2004, 2008; Wade and Jigmond, 2013).**

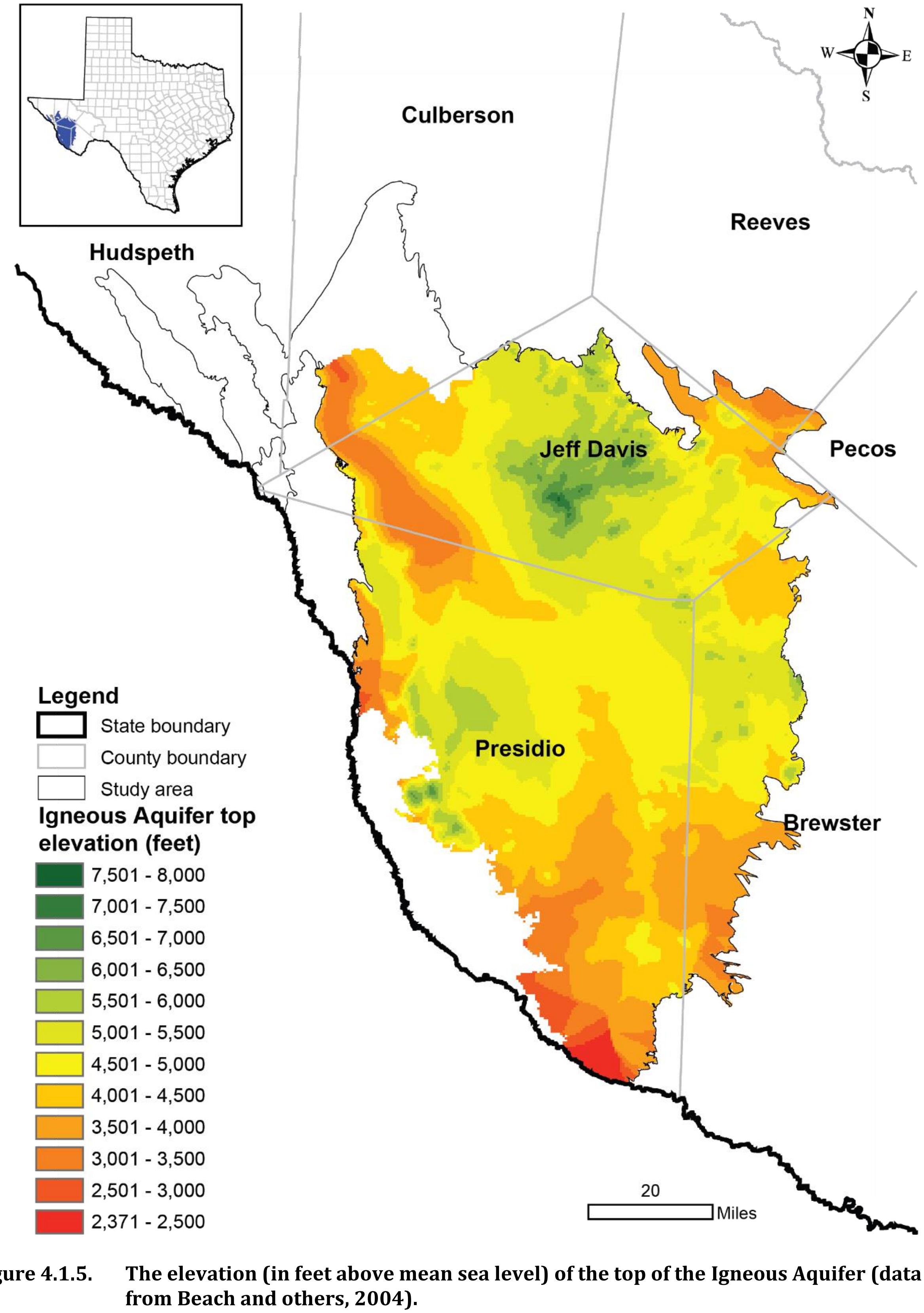


Figure 4.1.5. The elevation (in feet above mean sea level) of the top of the Igneous Aquifer (data from Beach and others, 2004).

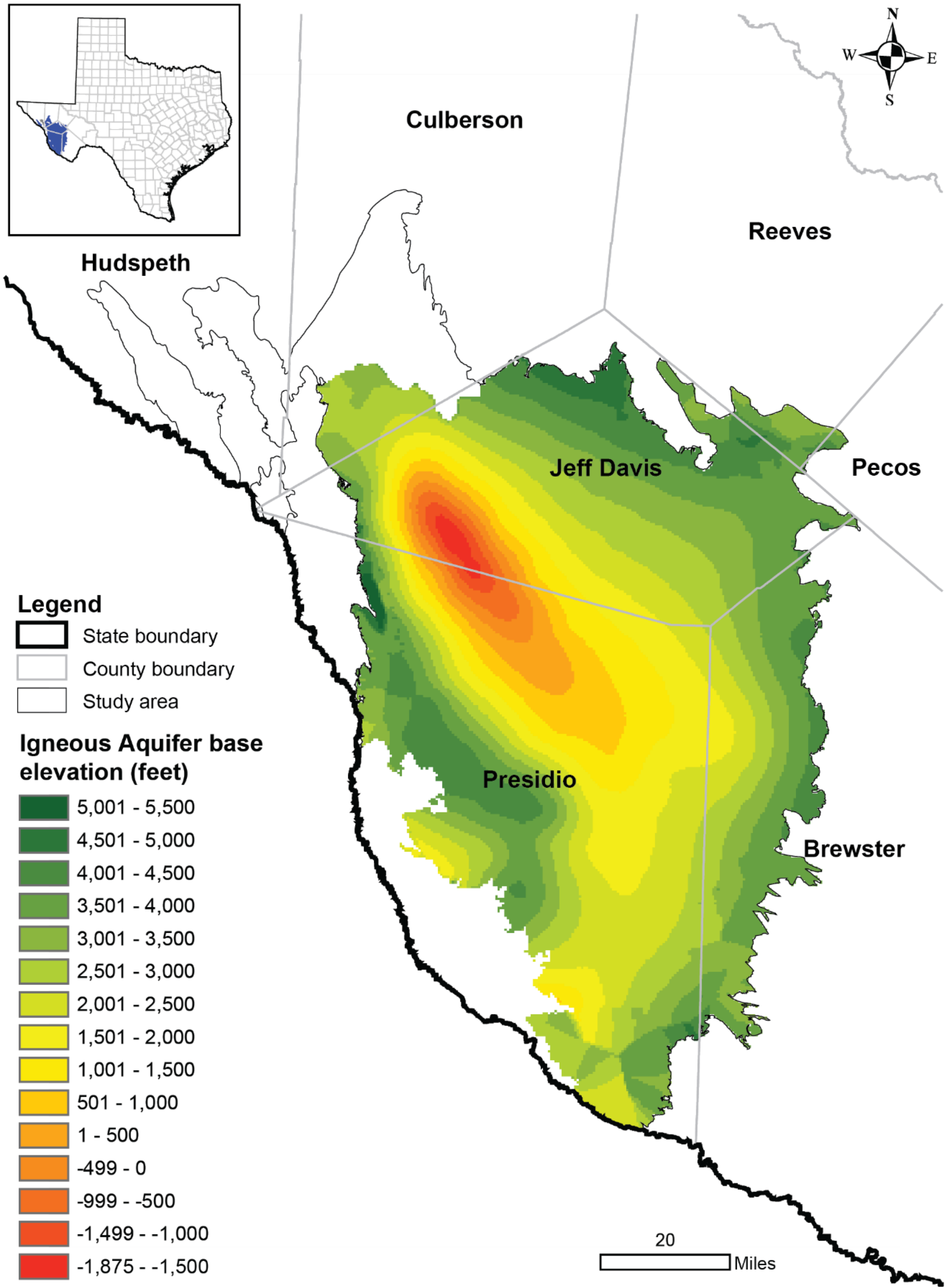


Figure 4.1.6. **The elevation (in feet above mean sea level) of the base of the Igneous Aquifer (data from Beach and others, 2004).**

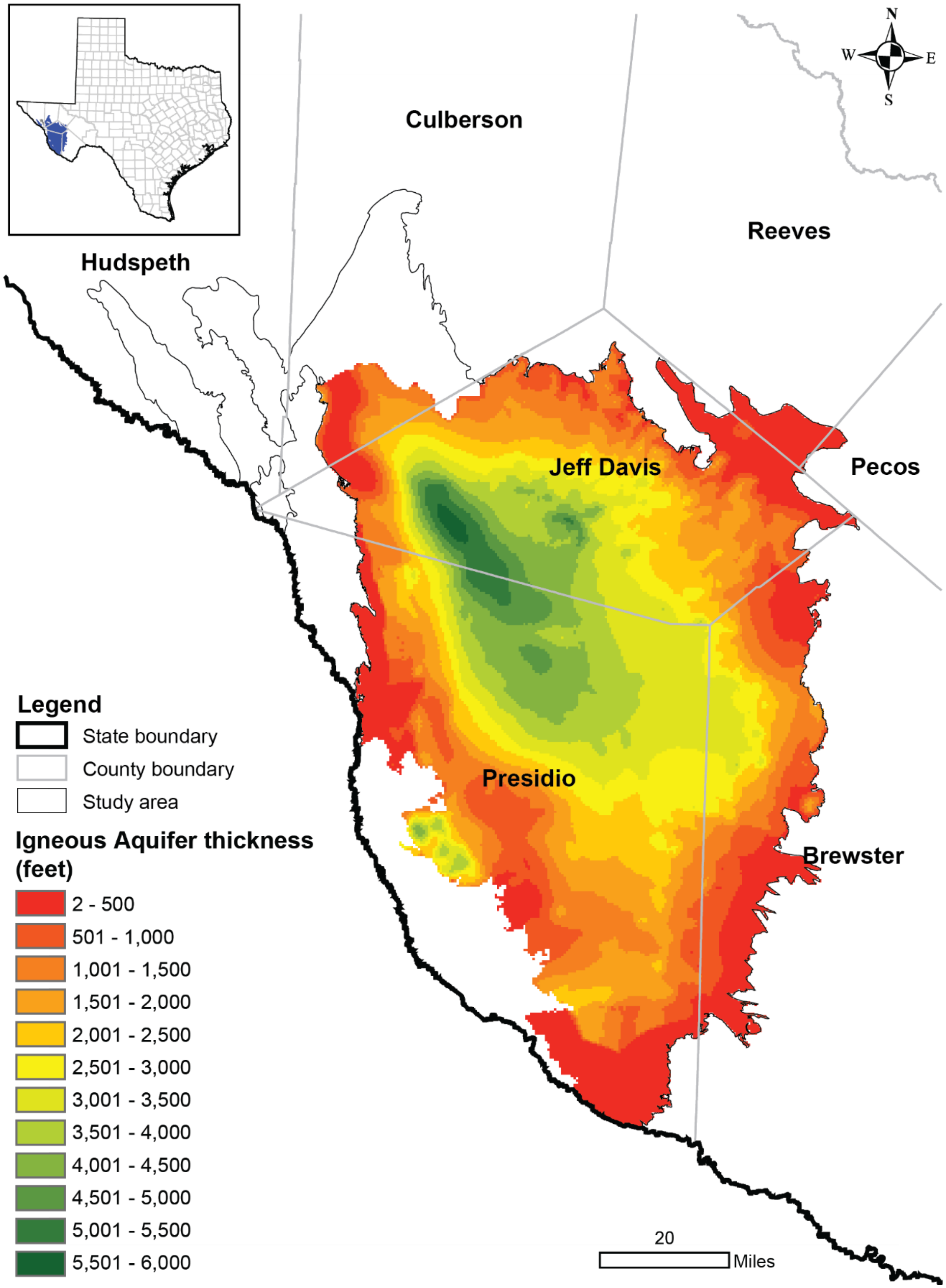


Figure 4.1.7. Thickness (in feet) of the Igneous Aquifer (data from Beach and others, 2004).

4.2 Water levels and regional groundwater flow

The TWDB Groundwater Database contains over 13,904 water-level measurements from 585 wells in the Igneous Aquifer and 558 wells in the West Texas Bolsons Aquifer taken between 1930 and 2022 (Figure 4.2.1; TWDB, 2022a). Figure 4.2.2 shows the temporal distribution of water-level data in the Igneous and West Texas Bolsons aquifers from 1950 through 2022.

In the Igneous Aquifer, the potentiometric surface slopes generally radiate outward from the Davis Mountains in central Jeff Davis County (Figures 4.2.3 and 4.2.4). In the West Texas Bolsons Aquifer, groundwater potentiometric surfaces suggest groundwater flow converges on the Rio Grande in the bolsons that interact with the river—the Green River Valley, Presidio Bolson, Redford Bolson, and Red Light Draw (Figures 4.2.5 and 4.2.6). The Eagle Flat is internally drained with no apparent discharge zones. In Eagle Flat, there is the possibility of groundwater inflow from the adjacent Lobo Flat and the possibility of groundwater discharge through inter-basin flow to Red Light Draw or Green River Valley (Darling, 1997). West Texas Bolsons Aquifer water-level measurements also indicate topographically driven inter-basin groundwater flow northward from Ryan Flat into Lobo Flat and then Wild Horse Flat. There are also indications of groundwater flow into Wild Horse Flat from Michigan Flat. It is quite likely that groundwater flows from Wild Horse Flat northward into the Salt Flat that is not included in the West Texas Bolsons Aquifer. In the Salt Flat, groundwater discharges by evapotranspiration, resulting in the occurrence of highly saline groundwater (Angle, 2001).

Water-level fluctuations observed in the Igneous and West Texas Bolsons aquifers (Figures 4.2.7 and 4.2.8) are aquifer responses to changes in pumping. Some hydrographs indicate effects of pumping resulting in gradual long-term water-level decline (for example, wells 5225209 and 5235711 in the Igneous Aquifer in Jeff Davis and Brewster counties, respectively, and well 4751719 in the West Texas Bolsons Aquifer of Culberson County). The declining water levels in these wells can be attributed to municipal pumping as they are located near Fort Davis, Alpine, and Van Horn, respectively. Igneous Aquifer well 5148604 and West Texas Bolsons Aquifer well 7430813, both located in Presidio County, display relatively constant water levels. West Texas Bolsons Aquifer wells 5110305 and 5110615 in Culberson County and well 5129805 in Presidio County display periods of drawdown followed by periods of recovery. The fluctuations in these wells reflect periodic irrigation of nearby croplands.

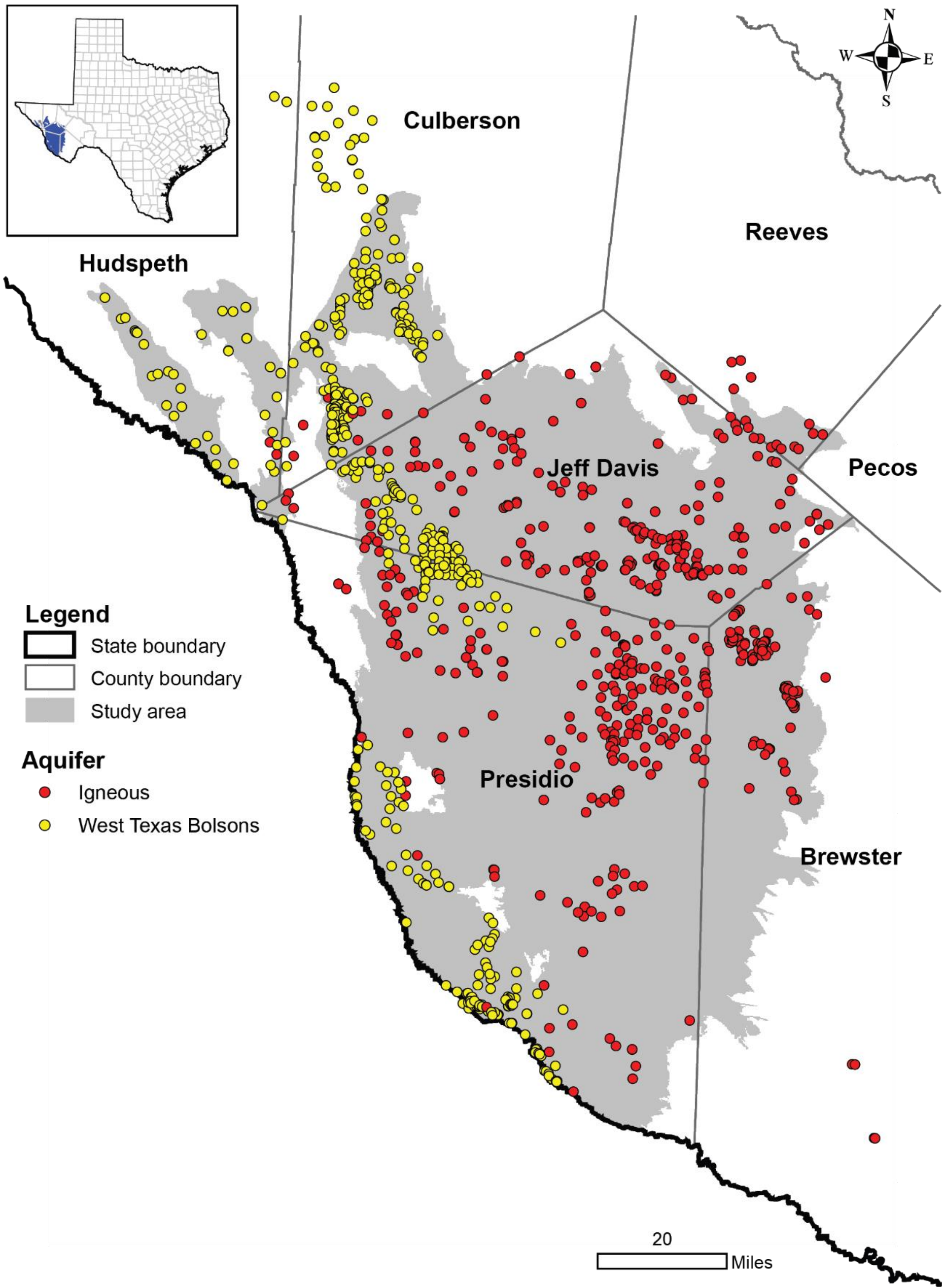


Figure 4.2.1. Water-level measurement locations for the Igneous and West Texas Bolsons aquifers (TWDB, 2022a).

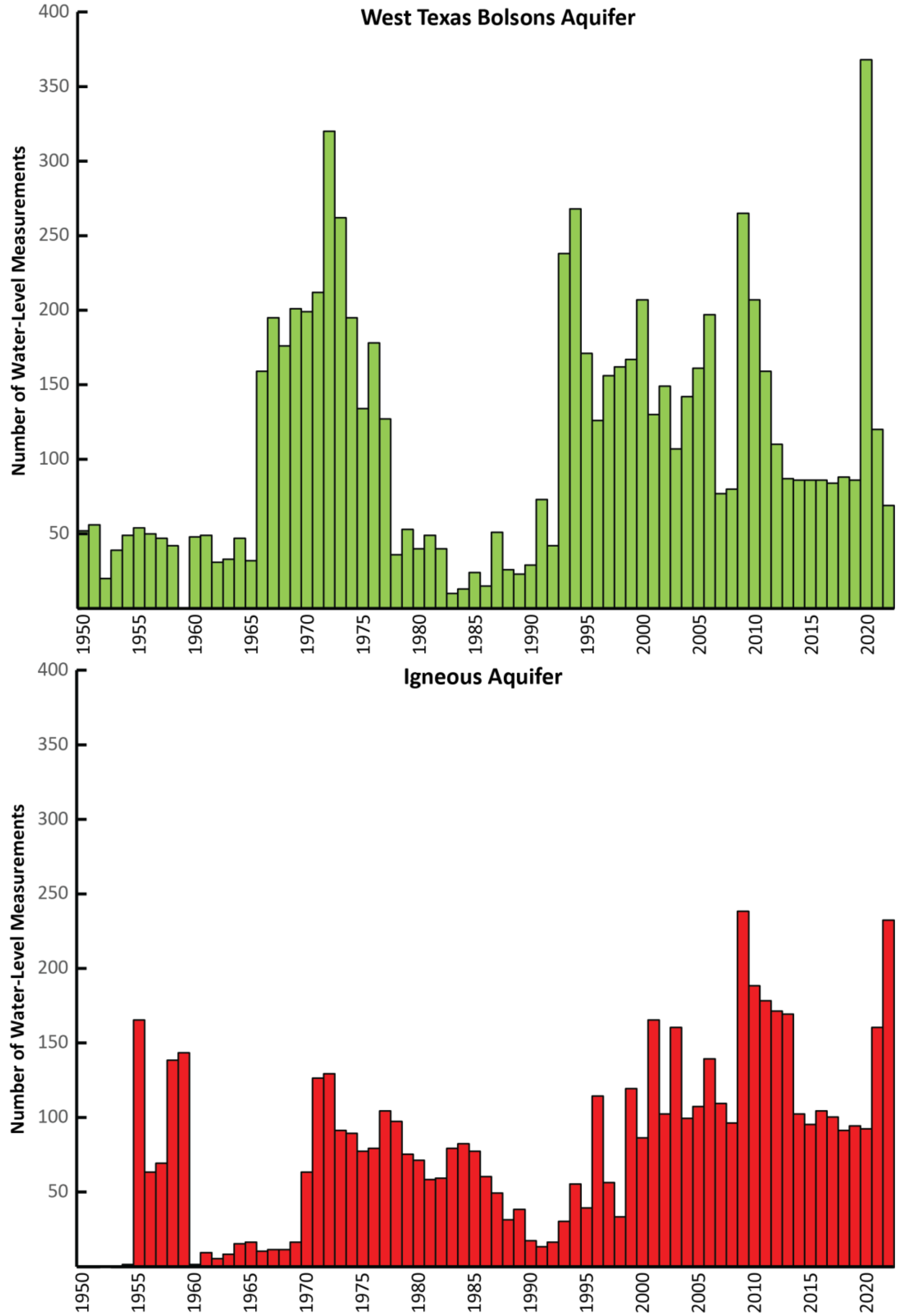


Figure 4.2.2. Temporal distribution of water-level measurements for 1950 to 2022 in the Igneous and West Texas Bolsons aquifers (TWDB, 2022a).

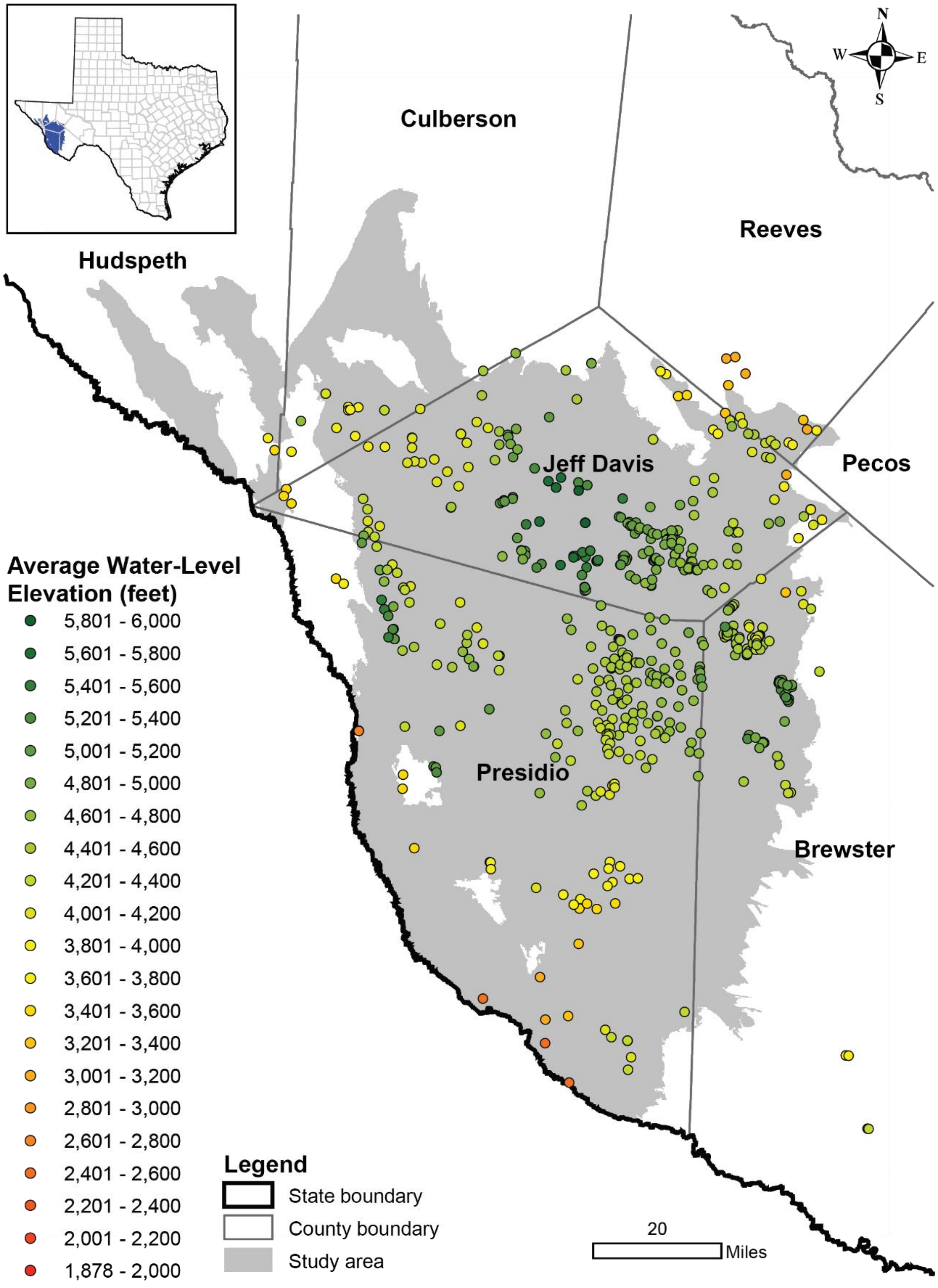


Figure 4.2.3. **Average water-level elevations (in feet above mean sea level) for wells completed in the Igneous Aquifer. This is based on water-level measurements mostly collected over the period 1940 to 2022 (TWDB, 2022a).**

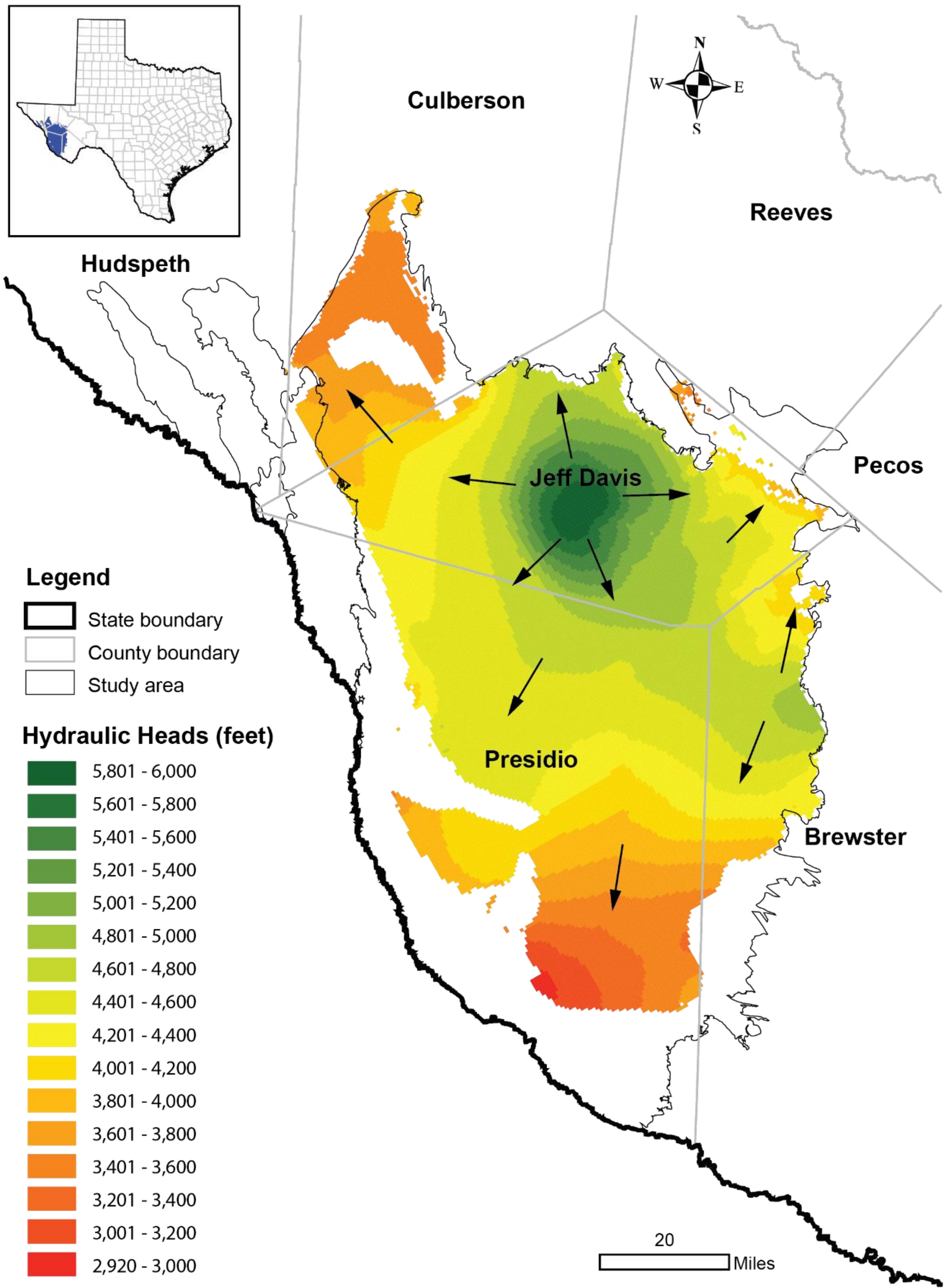


Figure 4.2.4. Simulated water levels for 2000 in the Igneous Aquifer (data from Beach and others, 2004). General direction of groundwater flow is shown by the black arrows.

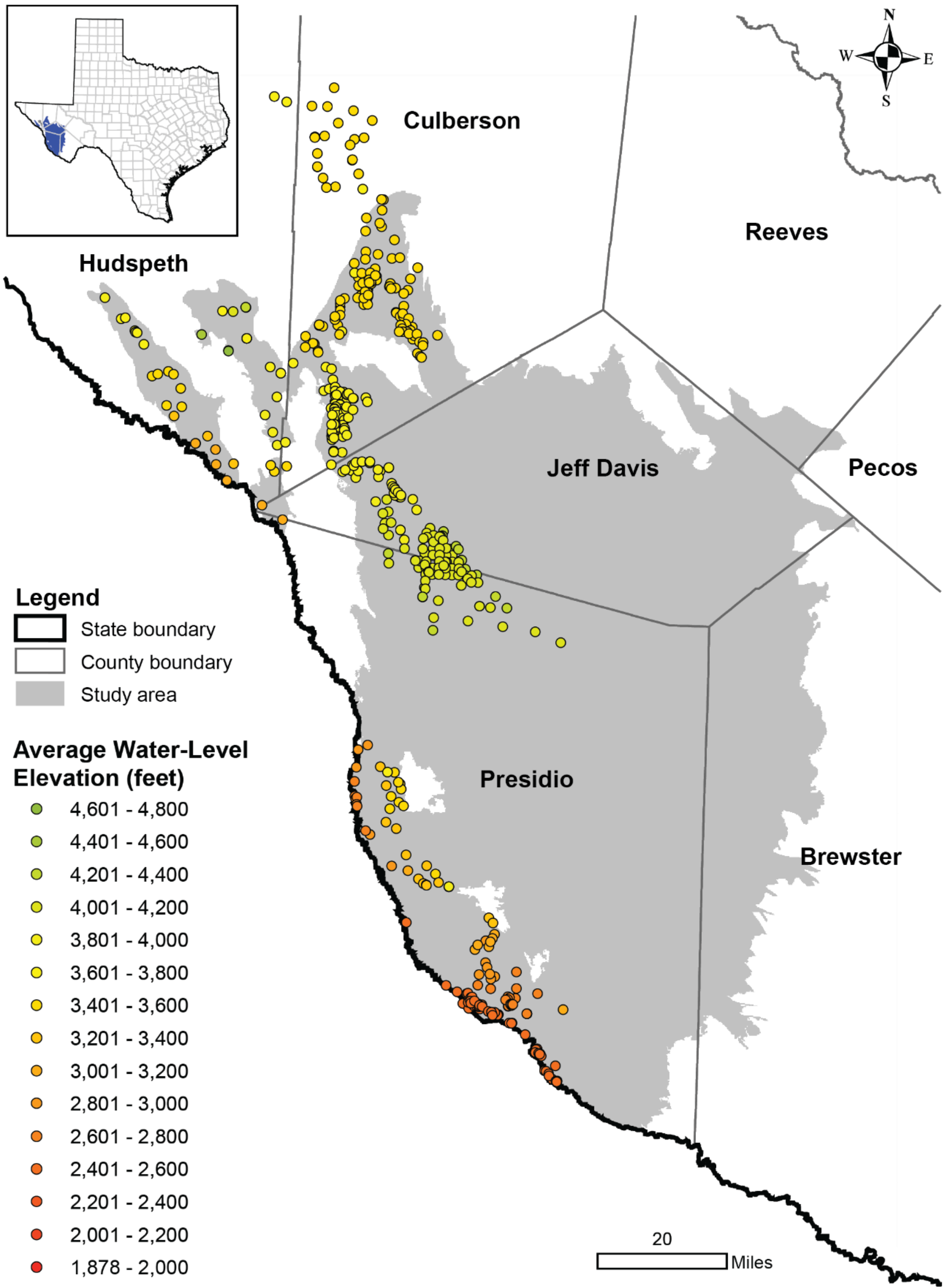


Figure 4.2.5. Average water-level elevations (in feet above mean sea level) for wells completed in the West Texas Bolson Aquifer. This is based on water-level measurements mostly collected over the period 1940 to 2022 (TWDB, 2022a).

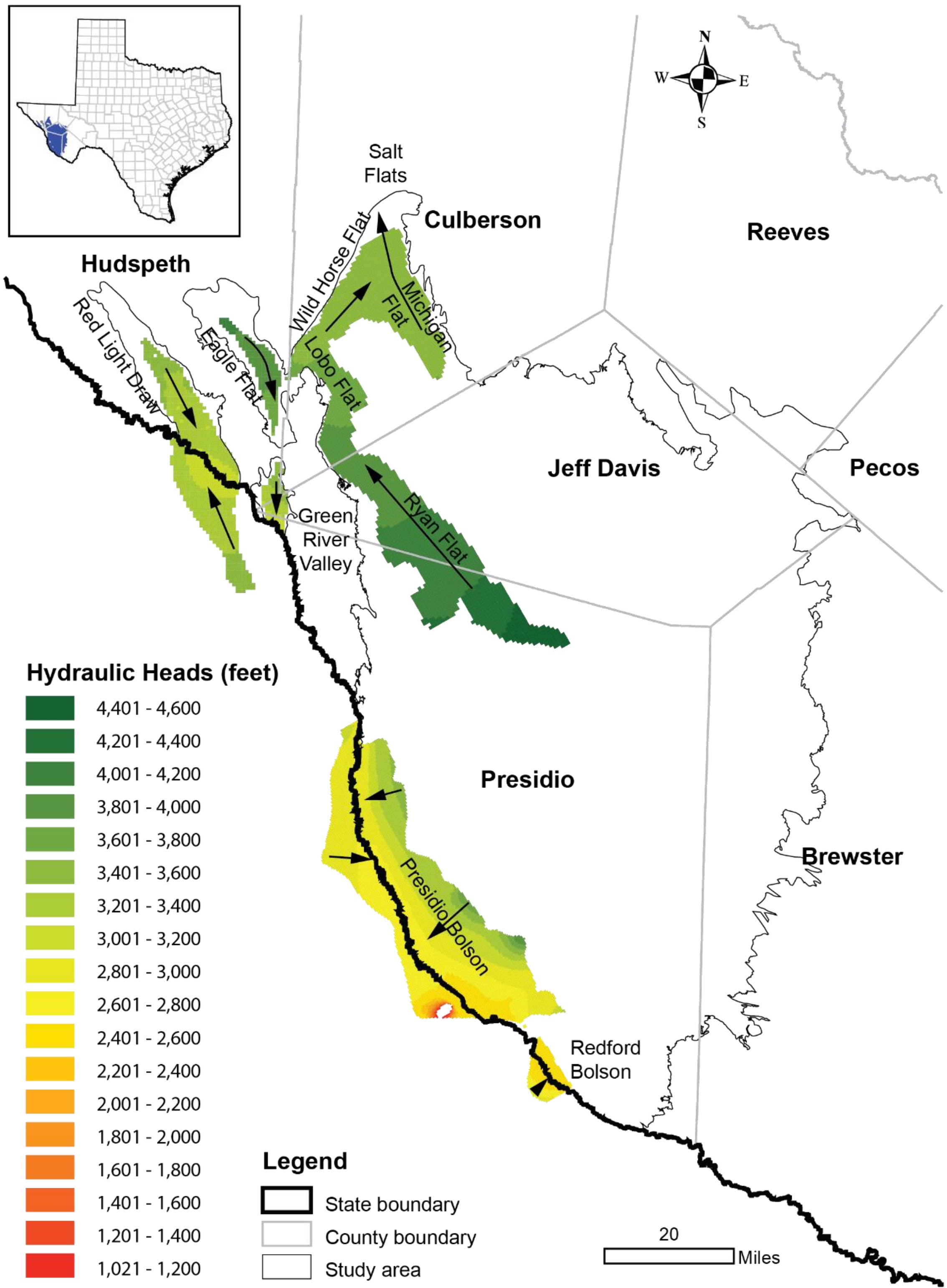


Figure 4.2.6. **Simulated water levels (in feet above mean sea level) for 2000 in the West Texas Bolsons Aquifer (data from Beach and others, 2004, 2008; Wade and Jigmond, 2013). General direction of groundwater flow is shown by the black arrows.**

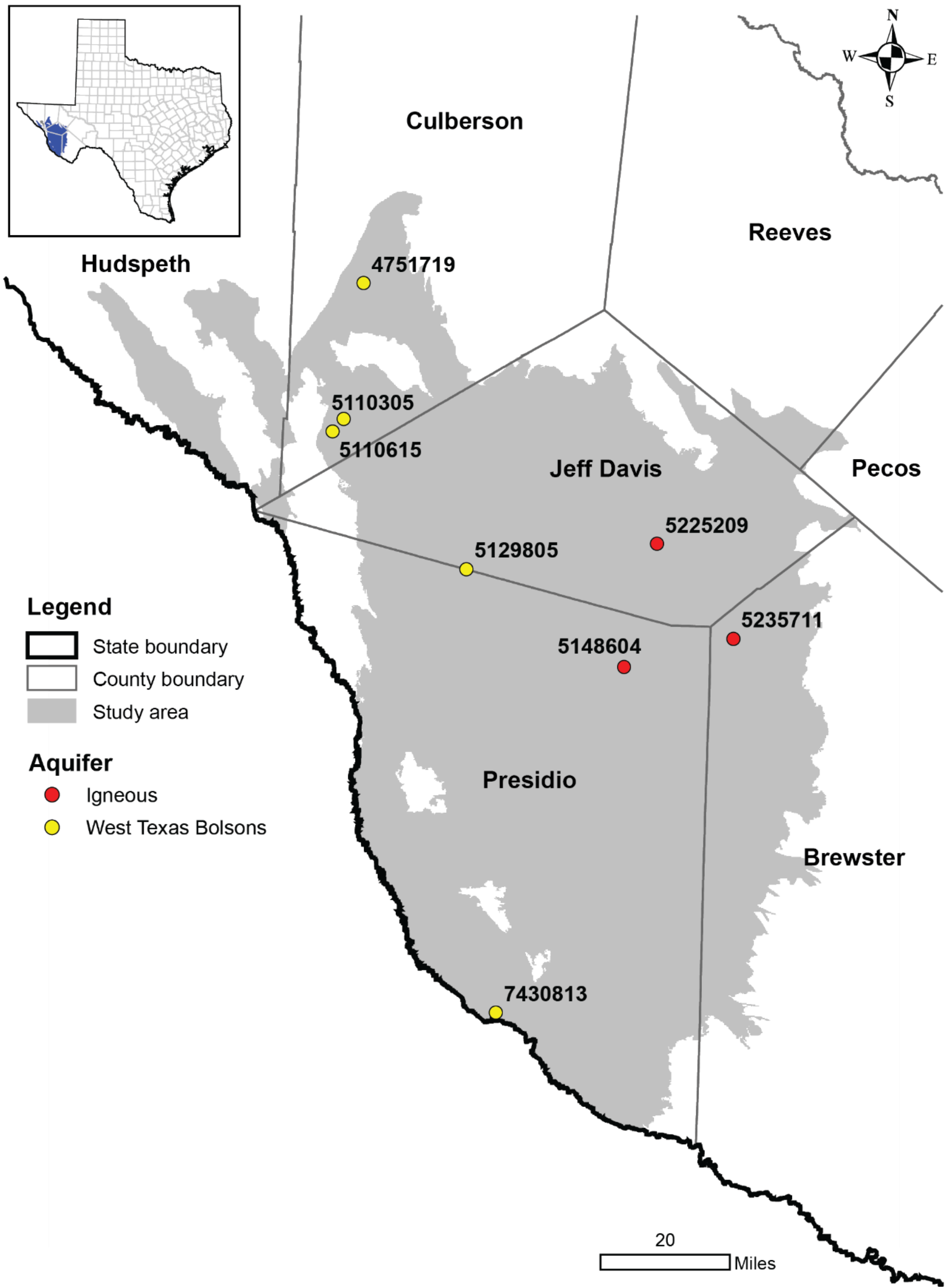
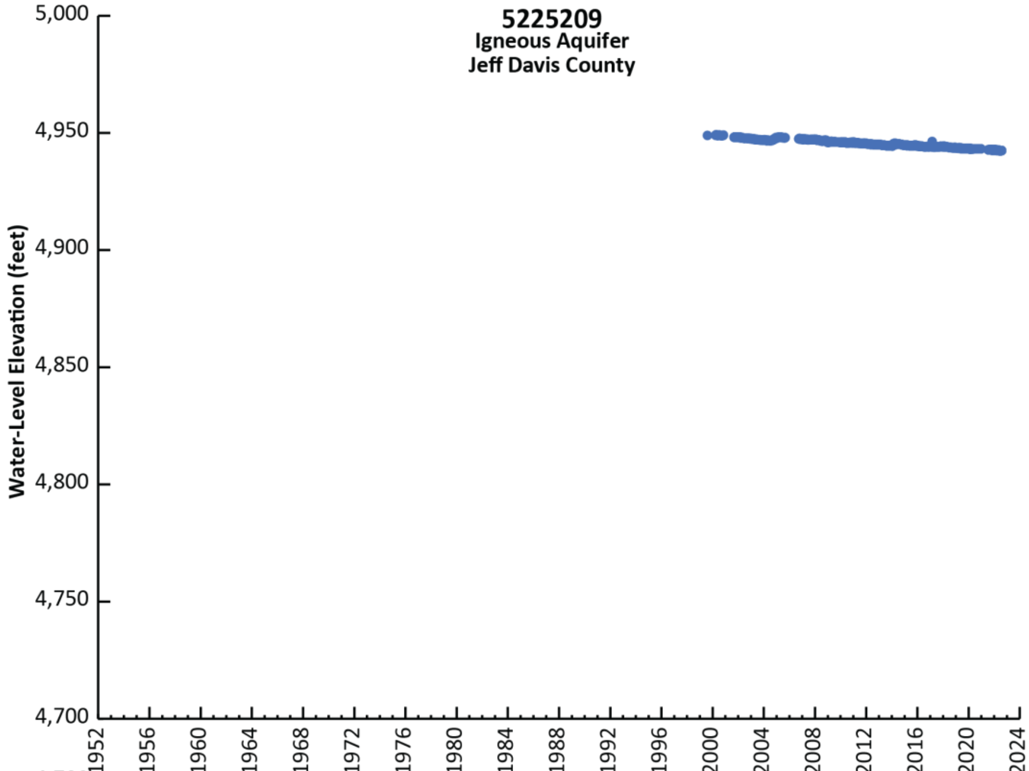


Figure 4.2.7. Locations of selected Igneous and West Texas Bolsons aquifers wells and associated state well number with transient water-level data (TWDB, 2022a).



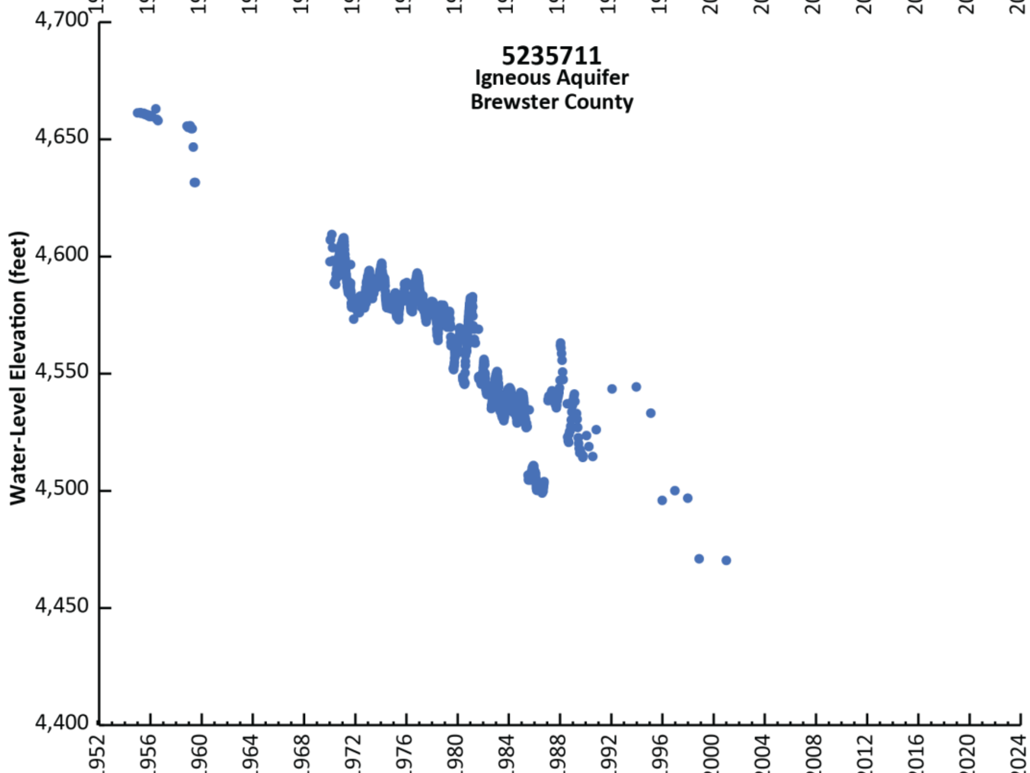
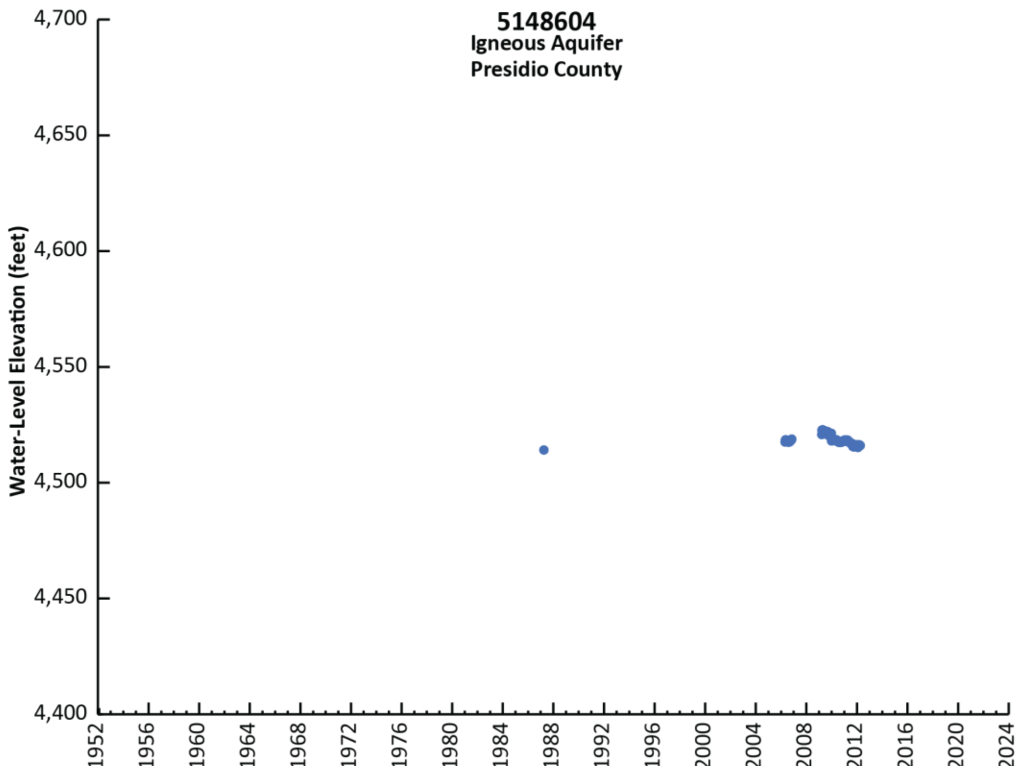


Figure 4.2.8. Hydrographs of transient water-level data (in feet above mean sea level) for the selected Igneous and West Texas Bolsons aquifers wells (TWDB, 2022a). See Figure 4.2.7 for locations.



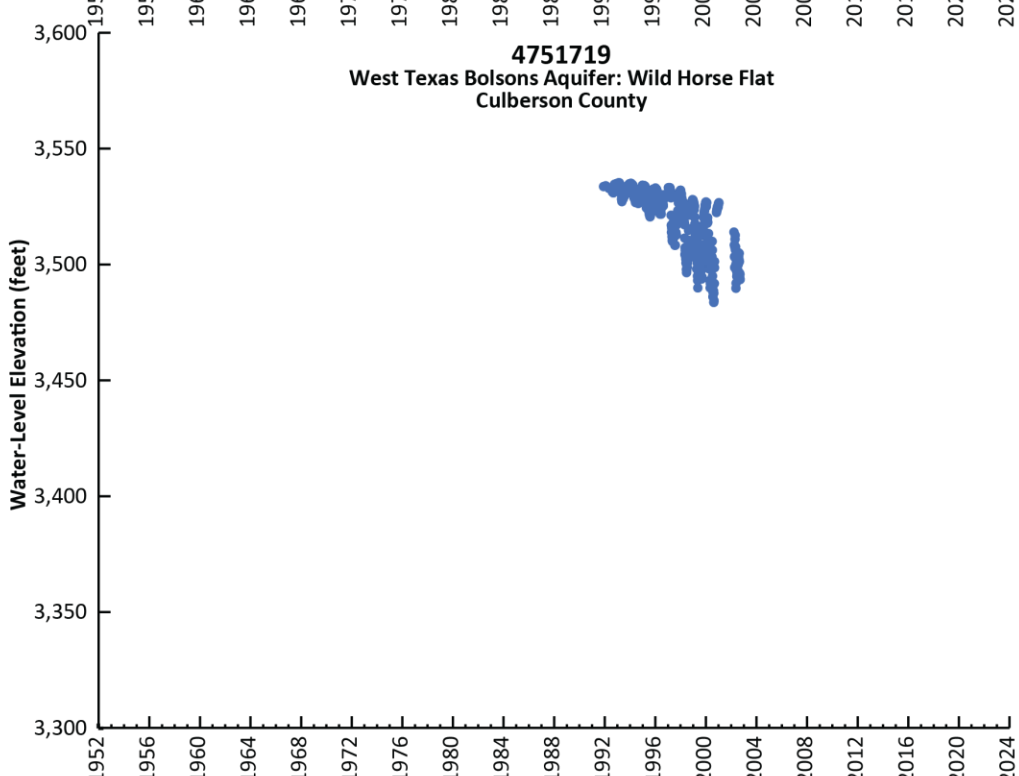
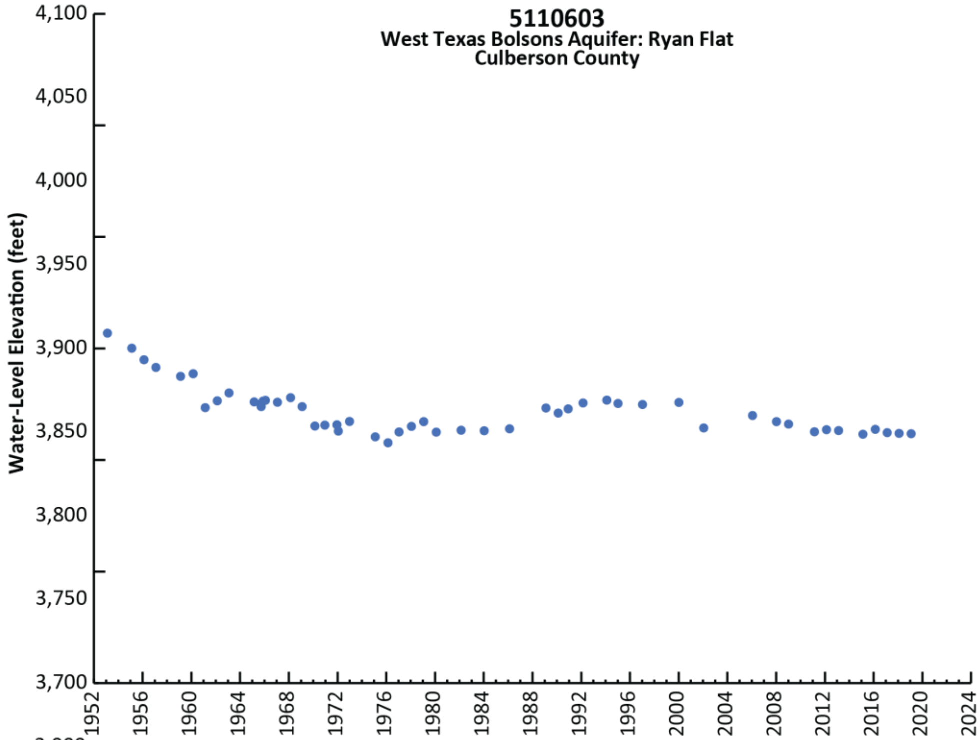


Figure 4.2.8 (continued). Hydrographs of transient water-level data (in feet above mean sea level) for the selected Igneous and West Texas Bolsons aquifers wells (TWDB, 2022a). See Figure 4.2.7 for locations.



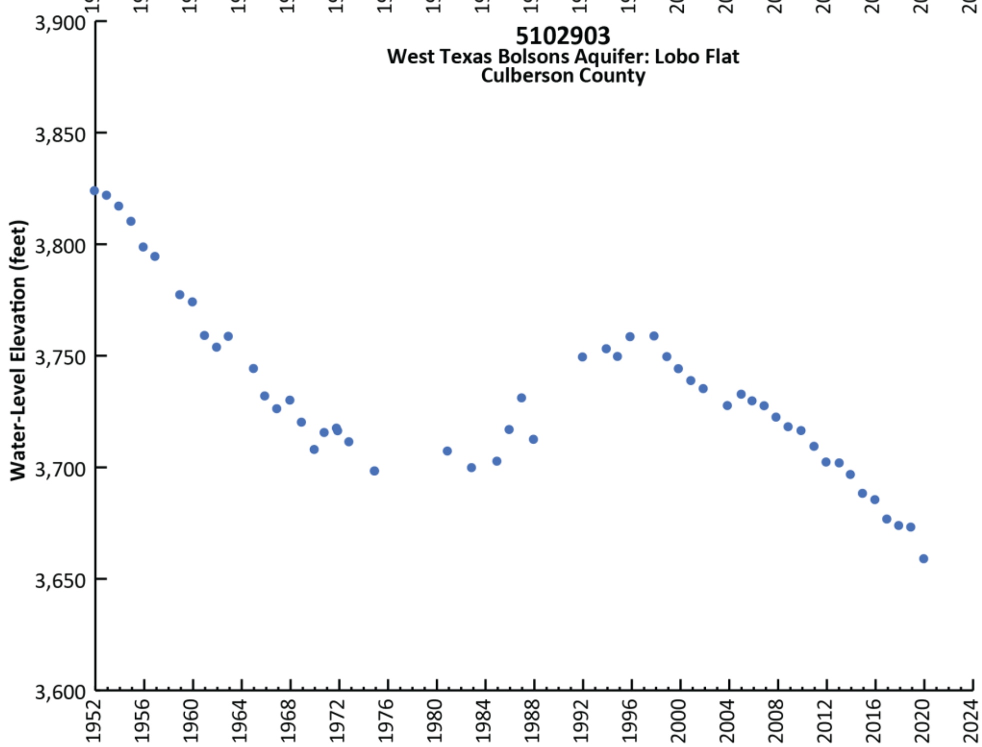
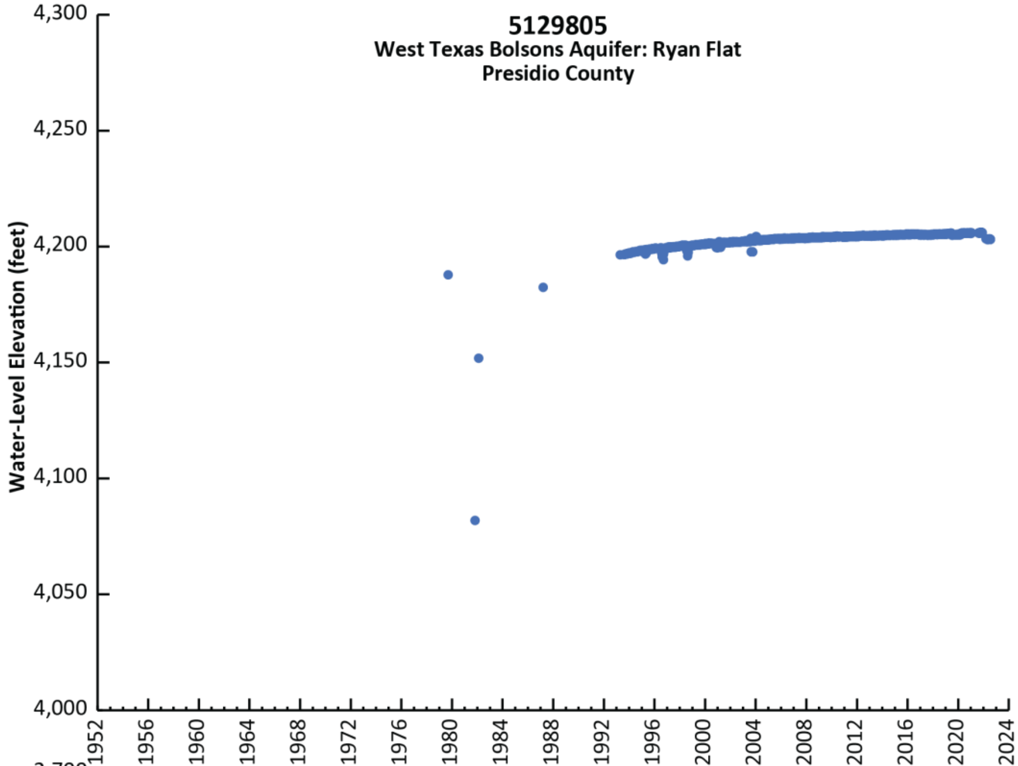


Figure 4.2.8 (continued). Hydrographs of transient water-level data (in feet above mean sea level) for the selected Igneous and West Texas Bolsons aquifers wells (TWDB, 2022a). See Figure 4.2.7 for locations.



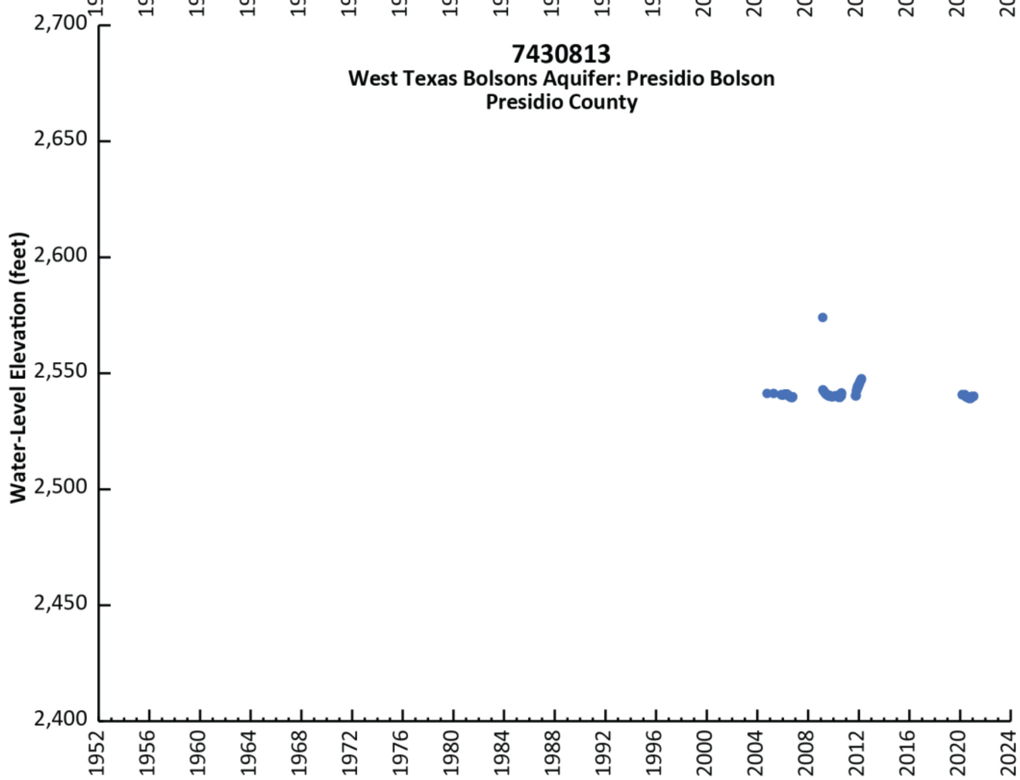


Figure 4.2.8 (continued). Hydrographs of transient water-level data (in feet above mean sea level) for the selected Igneous and West Texas Bolsons aquifers wells (TWDB, 2022a). See Figure 4.2.7 for locations.

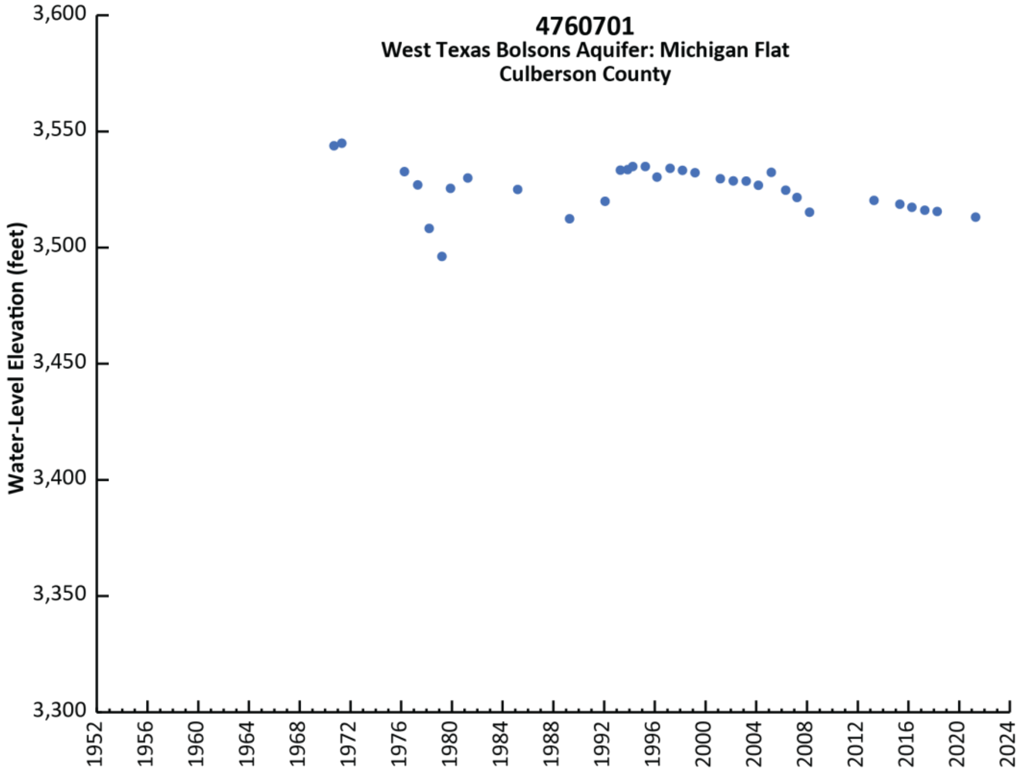


Figure 4.2.8 (continued). Hydrographs of transient water-level data (in feet above mean sea level) for the selected Igneous and West Texas Bolsons aquifers wells (TWDB, 2022a). See Figure 4.2.7 for locations.

4.3 Recharge

Recharge is defined as the processes involved in the addition of water to the water table (Jackson, 1997). In the Igneous and West Texas Bolsons aquifers study area, groundwater recharge primarily occurs by 1) infiltration of precipitation in the Eagle and Davis mountains, and 2) bolson-fringe recharge—also referred to as mountain front recharge—due to infiltration of storm-water runoff along intermittent streams in alluvial fans along the bolson margins (Gates and others, 1980; Scanlon and others 2001; Finch and Armour, 2001). Due to high evapotranspiration rates and low precipitation in the study area, little to no recharge occurs directly to the bolsons (Figure 4.3.1). The calibration results of previous models by Beach and others (2004, 2008) and Wade and Jigmond (2013), indicate that most of the recharge in the study area occurs in the Igneous Aquifer with relatively little in the West Texas Bolsons Aquifer (Figure 4.3.2).

Previous investigators have estimated recharge to the West Texas bolsons based on a percentage of precipitation and calculations of groundwater inflow (Hood and Scalapino, 1951; Gates and others, 1980; Cliett, 1994). A United States Geological Survey study in the late 1970s determined that one percent of the average annual precipitation should be used as the rate of recharge for the Basin and Range province of the Trans-Pecos Region (Gates and others, 1980). However, this method does not consider watershed characteristics that influence recharge, such as rock type or the feasibility of surface water to infiltrate into the groundwater system.

Isotopes, such as carbon-13, carbon-14, tritium, stable hydrogen, and oxygen in groundwater can be used to determine the spatial and seasonal distribution of recharge to an aquifer (See Sections 4.7.2 and 4.7.3). The tritium, carbon-13, and carbon-14 isotopic compositions of groundwater in the Igneous and West Texas Bolsons aquifers indicate recent recharge in the southernmost parts of the study area (in the southern portion of the Igneous Aquifer and in the Presidio Bolson of the West Texas Bolsons Aquifer). Elsewhere in the study area, groundwater isotopes indicate ancient recharge. Darling (1997) suggests that much of this recharge took place during the Pleistocene epoch—more than 10,000 years ago—at a time when the climate of the study area was wetter than it is today.

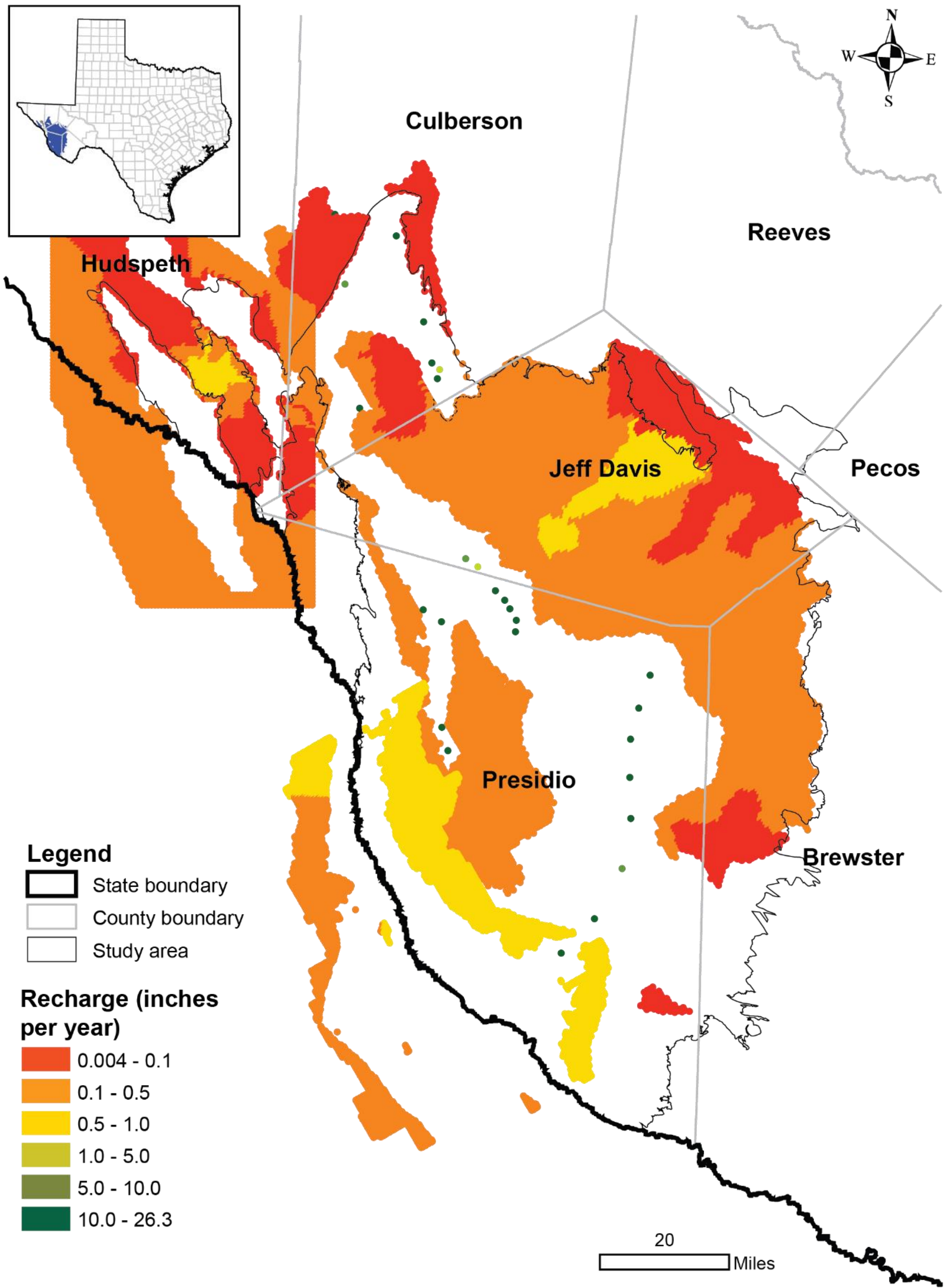


Figure 4.3.1. Spatial distribution of recharge in the Igneous and West Texas Bolsons aquifers study area in Beach and others (2004, 2008) and Wade and Jigmond (2013).

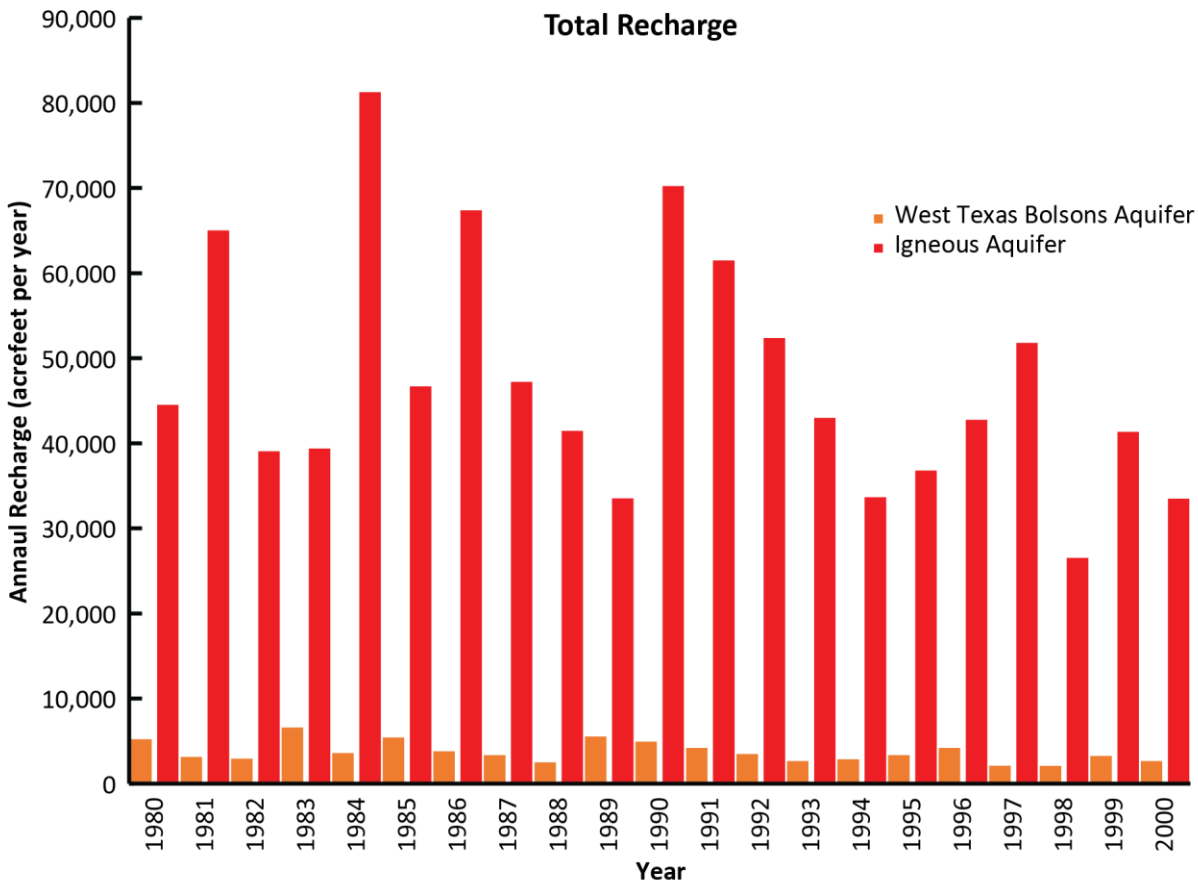


Figure 4.3.2. **Annual recharge to the Igneous and West Texas Bolsons aquifers from 1980 through 2000 (from Beach and others, 2004, 2008, and Wade and Jigmond, 2013).**

4.4 Surface-water bodies

Interaction between groundwater and surface water occurs primarily where surface water bodies—rivers, 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 Igneous and West Texas Bolsons aquifers study area lie completely within the Rio Grande watershed (Figure 2.0.10). Consequently, surface water in the study area either flows southward directly to the Rio Grande or in some cases toward the Pecos River and eventually to the Rio Grande. In the study area, there are only a few perennial streams, mostly located in the south (Figure 2.0.4). The overwhelming majority of streams are intermittent or ephemeral and only flow after heavy rainfall (Figure 4.4.1). In addition to surface water flow to the Rio Grande, some bolsons in the study area are topographically closed with no surface water outlet (Hibbs and Darling, 2005). Examples of closed basins include Eagle Flat, Ryan Flat, Lobo Flat, Michigan Flat, and Wild Horse Flat.

A streamflow study by the United States Geological Survey in 1932 indicated areas of streamflow loss balanced by areas of streamflow gain along Limpia Creek in Jeff Davis County (Figure 4.4.1; Slade and others, 2002). Limpia Creek is an intermittent stream.

4.4.2 Springs

Springs are locations where the water table intersects the ground surface (Figure 4.4.2). Spring data for the Igneous and West Texas Bolsons aquifers study area were found in the TWDB Groundwater Database (TWDB, 2022a), 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).

The identified springs mostly occur in the northern portion of the Igneous Aquifer along the margins of the Davis Mountains, and in the west associated with the Sierra Vieja and Chinati Mountains. Springs also occur in the West Texas Bolsons Aquifer, mostly in the Green River Valley and the Presidio Bolson. The springs with the highest reported discharge rates mostly occur along the western boundary of the study area associated with the Sierra Vieja, Chinati Mountains, and Presidio Bolson (Figure 4.4.3). Major springs—springs with reported spring discharge more than 100 cubic feet per second— are shown in Figure 4.4.2.

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 perennial natural lakes on the Igneous and West Texas Bolsons aquifers study area. However, Grayton Lake located within northern Eagle Flat only contains water occasionally after heavy rainfall events.

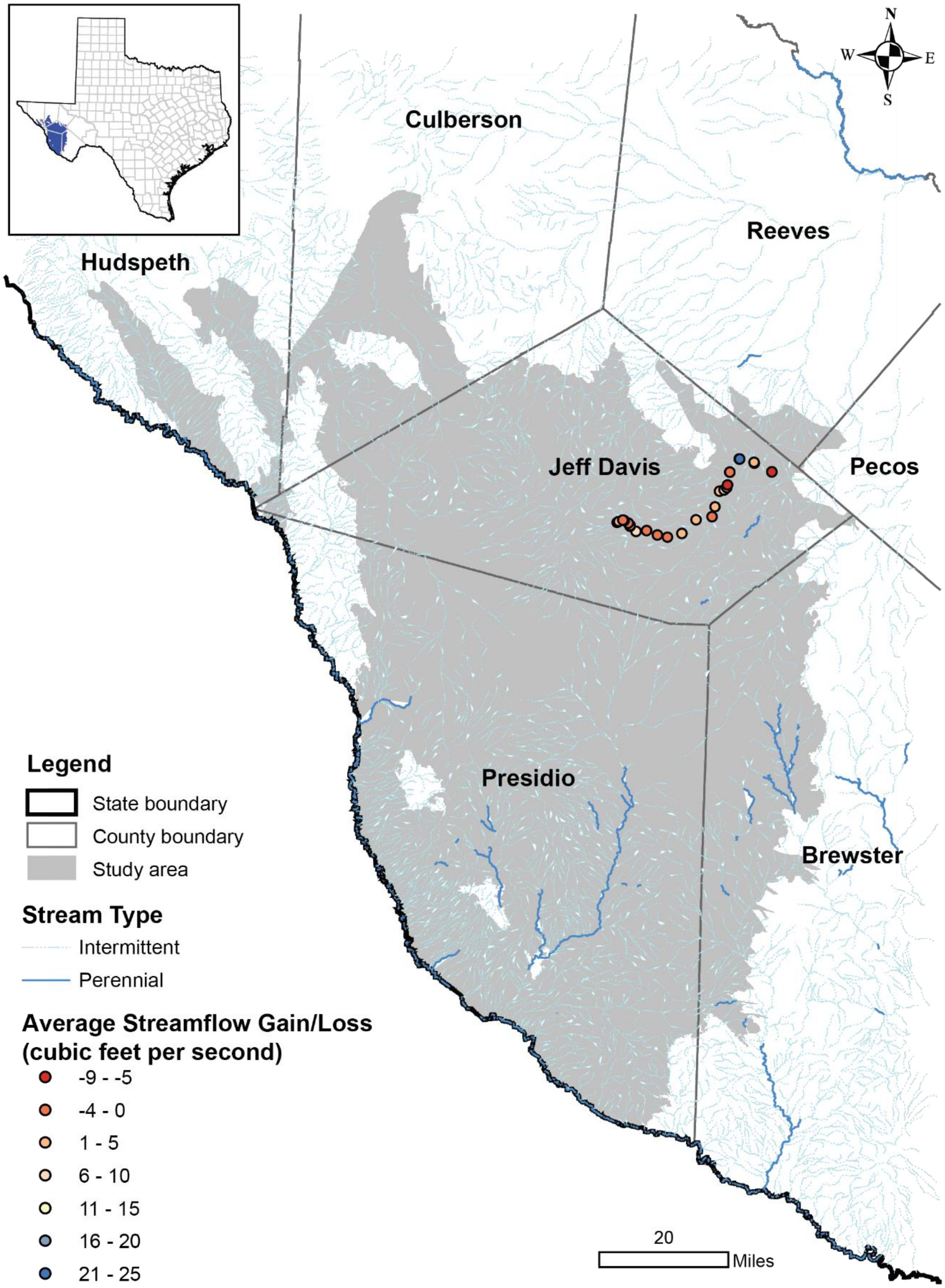


Figure 4.4.1. Streamflow gain-loss data from Slade and others (2002) along Limpia Creek. Negative values indicate losing streams while positive values indicate gaining streams.

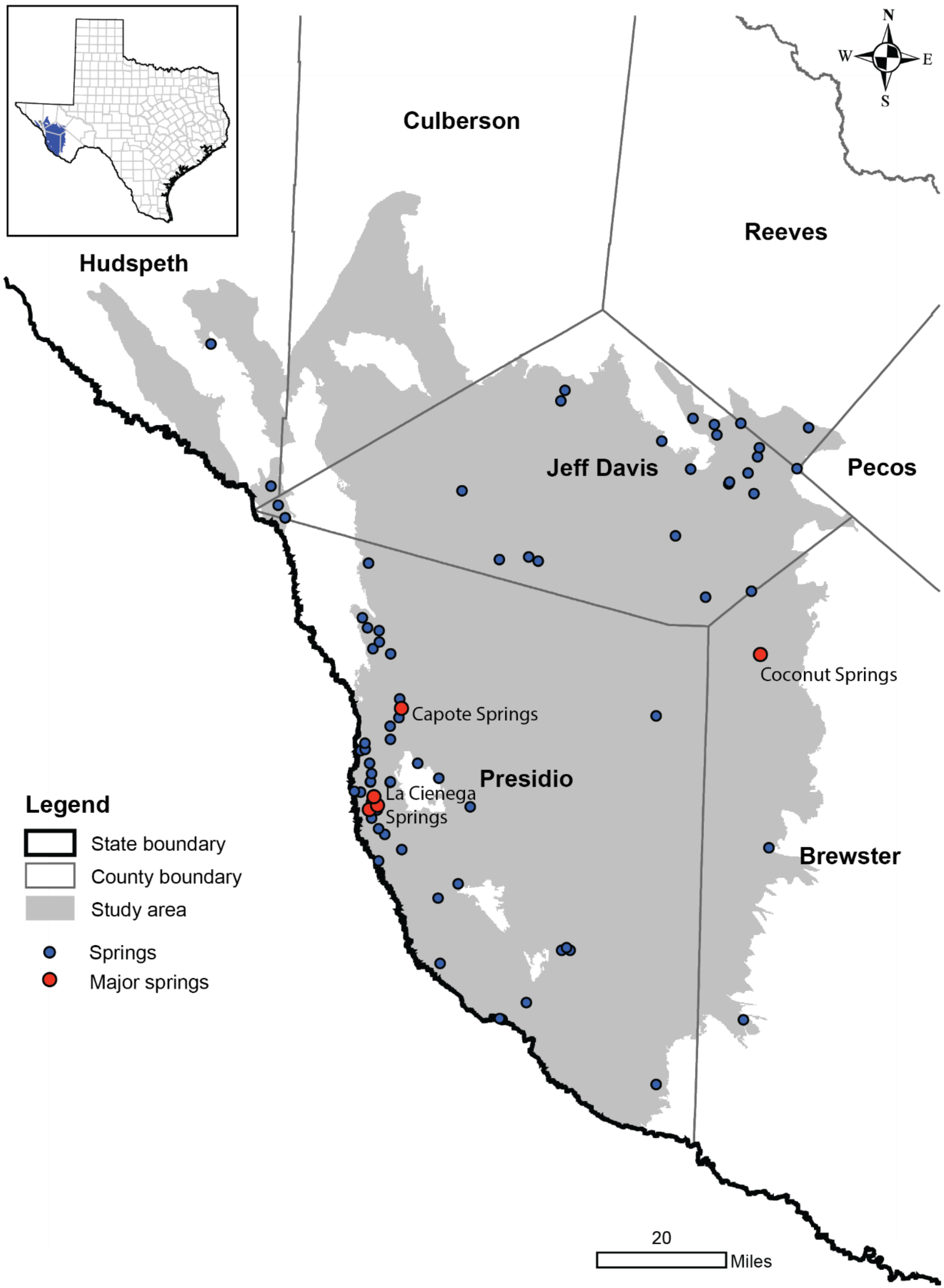


Figure 4.4.2. Locations of springs in the Igneous and West Texas Bolsons aquifers study area. (based on data from Brune, 2002 and Heitmuller and Reece, 2003).

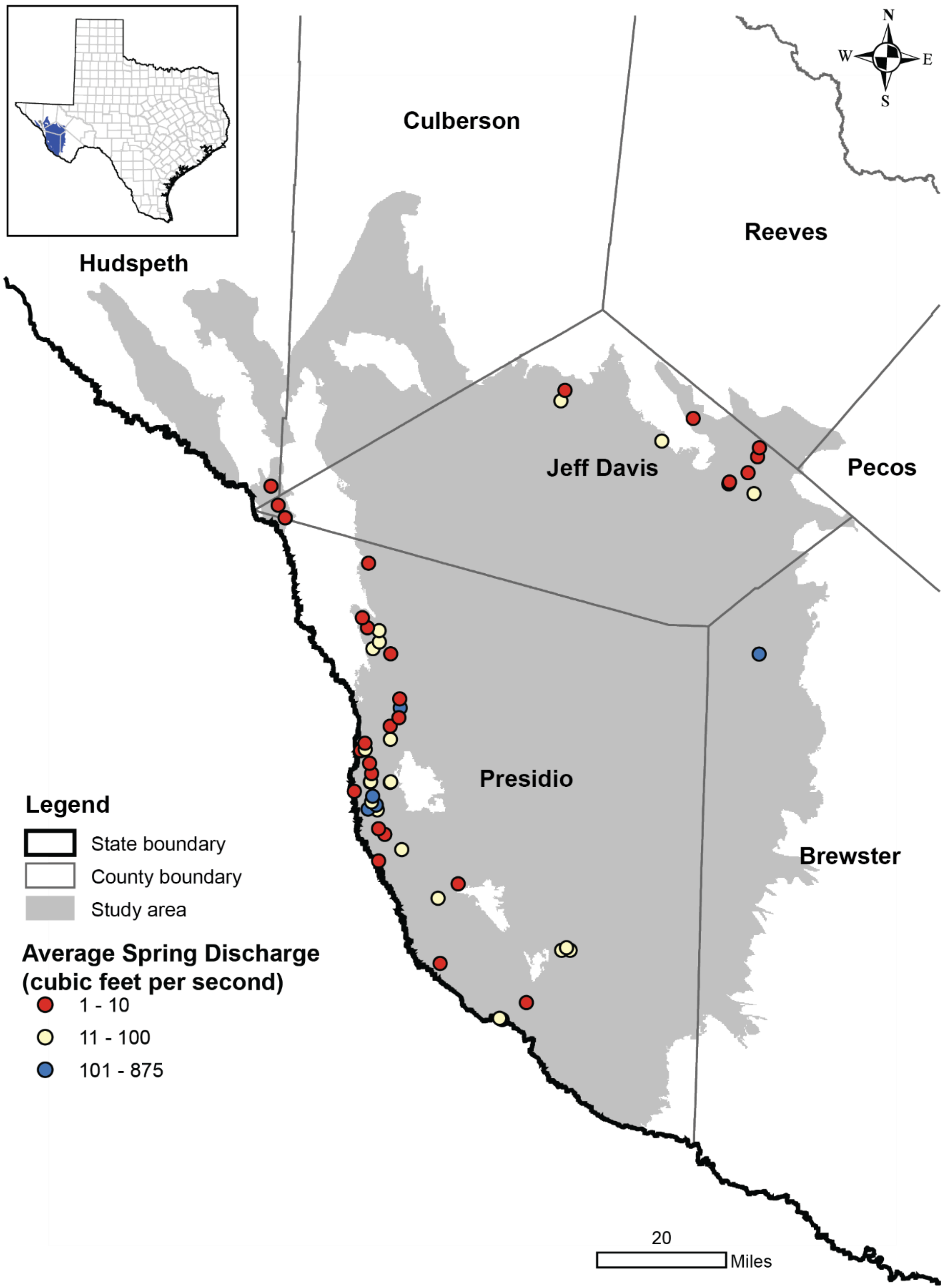


Figure 4.4.3. Spring discharge measurements in the Igneous and West Texas Bolsons aquifers study area.

4.5 Hydraulic properties

There is a paucity of hydraulic property data for the Igneous and West Texas Bolsons aquifers. The ability of the aquifer to transmit groundwater to a well varies greatly. Factors influencing the ability of an aquifer to transmit groundwater include aquifer lithology, sediment cementation, structural deformation, and fracturing. This section reviews the sources of available data describing the Igneous and West Texas Bolsons aquifers hydraulic properties. Several hydraulic properties are used to describe groundwater flow in aquifers. The properties discussed here are hydraulic conductivity and storativity.

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.

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.

4.5.1 Data sources

Development of hydraulic properties for the Igneous and West Texas Bolsons aquifers study area used multiple sources, including the Submitted Drillers Report Database and the TWDB Groundwater Database (Texas Department of Licensing and Regulation, 2022; TWDB, 2022a). The hydraulic property data for the Igneous and West Texas Bolsons aquifers are shown in Figures 4.5.1 through 4.5.4 and Table A1.

4.5.2 Hydraulic conductivity

There is little hydraulic conductivity data that are based on pumping tests for the Igneous and West Texas Bolsons aquifer study area. Hydraulic conductivity values in the Igneous Aquifer range between 0.1 and more than 2,500 feet per day, and median and geometric mean values are 10.3 feet per day and 23 feet per day, respectively (Figure 4.5.5). The spatial distribution of hydraulic conductivity in the Igneous Aquifer from the groundwater flow model by Beach and others (2004) shows lowest hydraulic conductivity in the Davis Mountains (Figure 4.5.2). Hydraulic conductivity values in the West Texas Bolsons Aquifer range between 0.5 and more than 2,400 feet per day, and median and geometric mean values are 13 feet per day and 12 feet per day, respectively (Figure 4.5.5). Most of the hydraulic conductivity data is derived from Lobo Flat, Michigan Flat, Ryan Flat, and Wild Horse Flat. Little or no data was obtained from the remaining bolsons that make up the West Texas Bolsons Aquifer. The spatial distribution of hydraulic conductivity in the West Texas Bolsons Aquifer from the groundwater flow model by Beach and others (2008) and Wade and Jigmond (2013) shows highest hydraulic conductivity in eastern bolsons—Lobo Flat, Michigan Flat, Ryan Flat, and Wild Horse Flat—and the lowest hydraulic conductivity occurs in the west and southern parts of the aquifer (Figure 4.5.4). In the Presidio and Redford bolsons, hydraulic conductivity increases along the Rio Grande. A small amount of hydraulic conductivity data is available from the Cretaceous stratigraphic units that underlie the bolsons. The hydraulic conductivity values in these Cretaceous stratigraphic units range between 0.01 and 280 feet per day, with median and geometric mean values of 0.3 feet per day and 0.9 feet per day, respectively (Figure 4.5.5).

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.

There is only one published storativity measurement in the Igneous and West Texas Bolsons aquifers study area, an aquifer test in a well (State Well Number 4854902) completed in the Cretaceous stratigraphic units below the bolsons. The aquifer test conducted in 1997 yielded a storativity of 4×10^{-3} (Beach and others, 2008). Specific yield, storativity, and porosity values previously used in the study area have been based on published ranges of 0.01 to 0.3, 5×10^{-5} to 5×10^{-3}, and 0 to 0.1, respectively (Freeze and Cherry, 1979). A narrower range of specific yield of 0.1 to 0.15 has been applied to the West Texas Bolsons Aquifer (Gates and others, 1980).

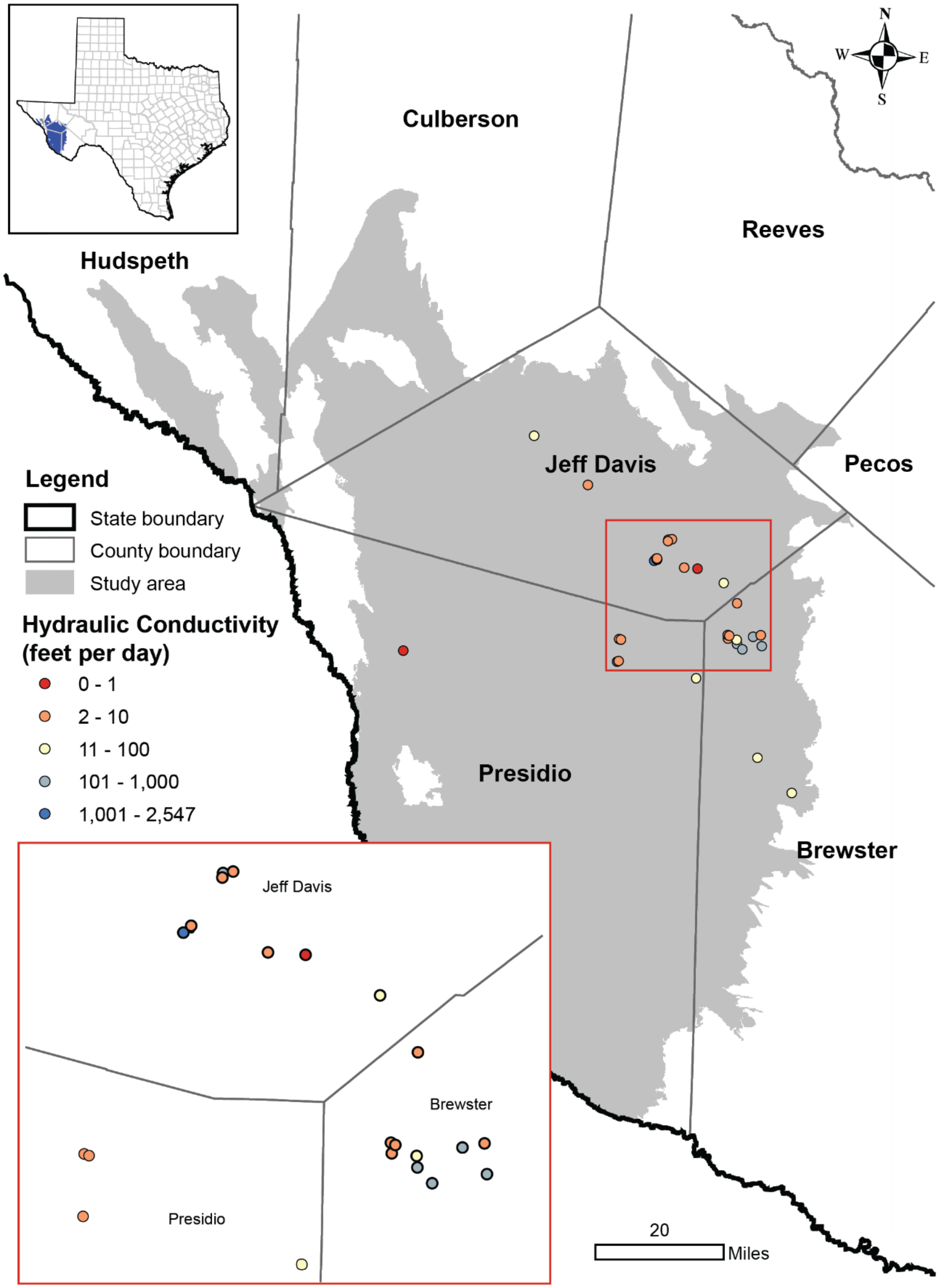


Figure 4.5.1. Hydraulic conductivity data for the Igneous Aquifer (data from TWDB, 2022a).

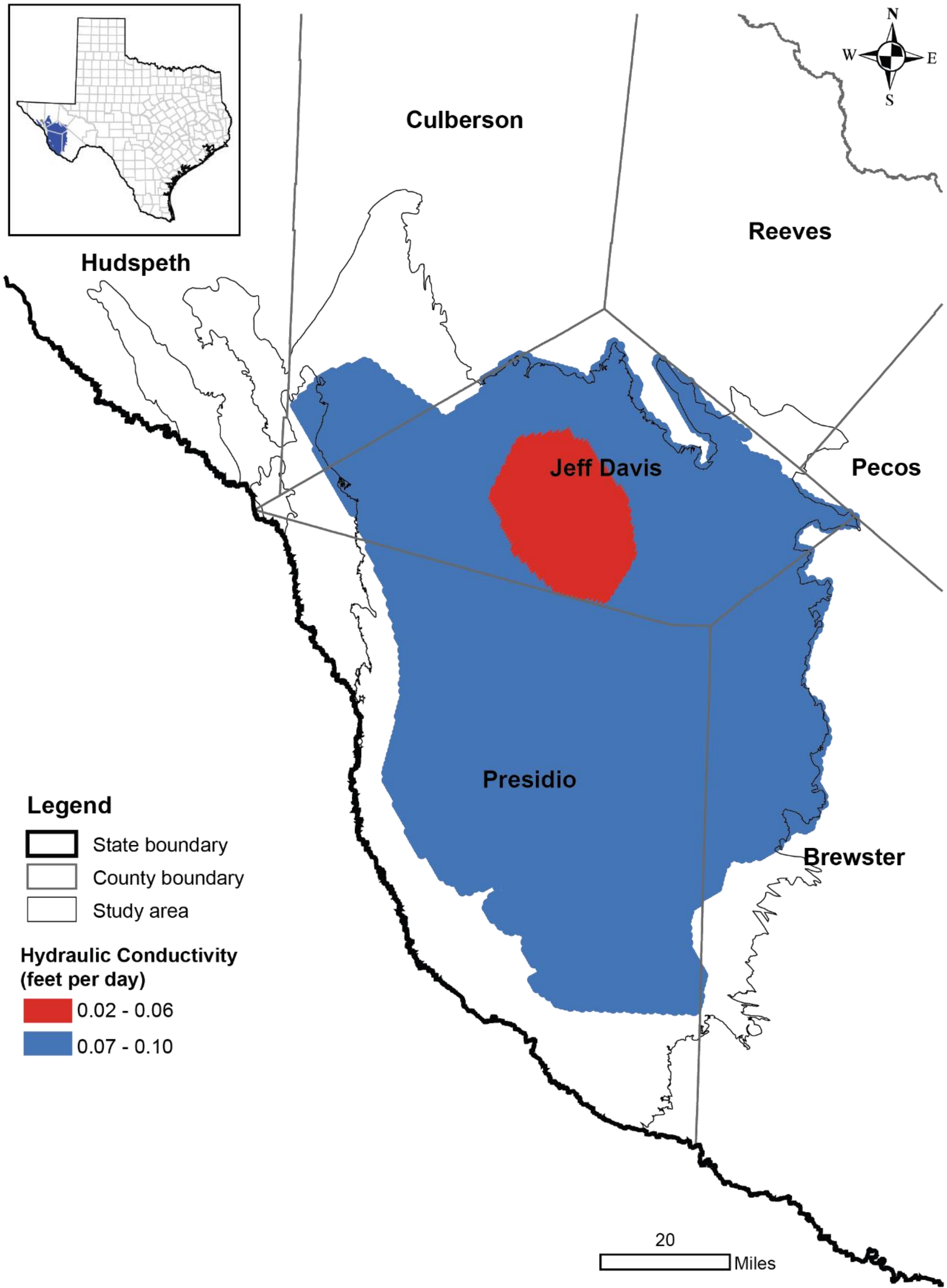


Figure 4.5.2. Hydraulic conductivity data for the Igneous Aquifer in the study area (based on data from Beach and others, 2004).

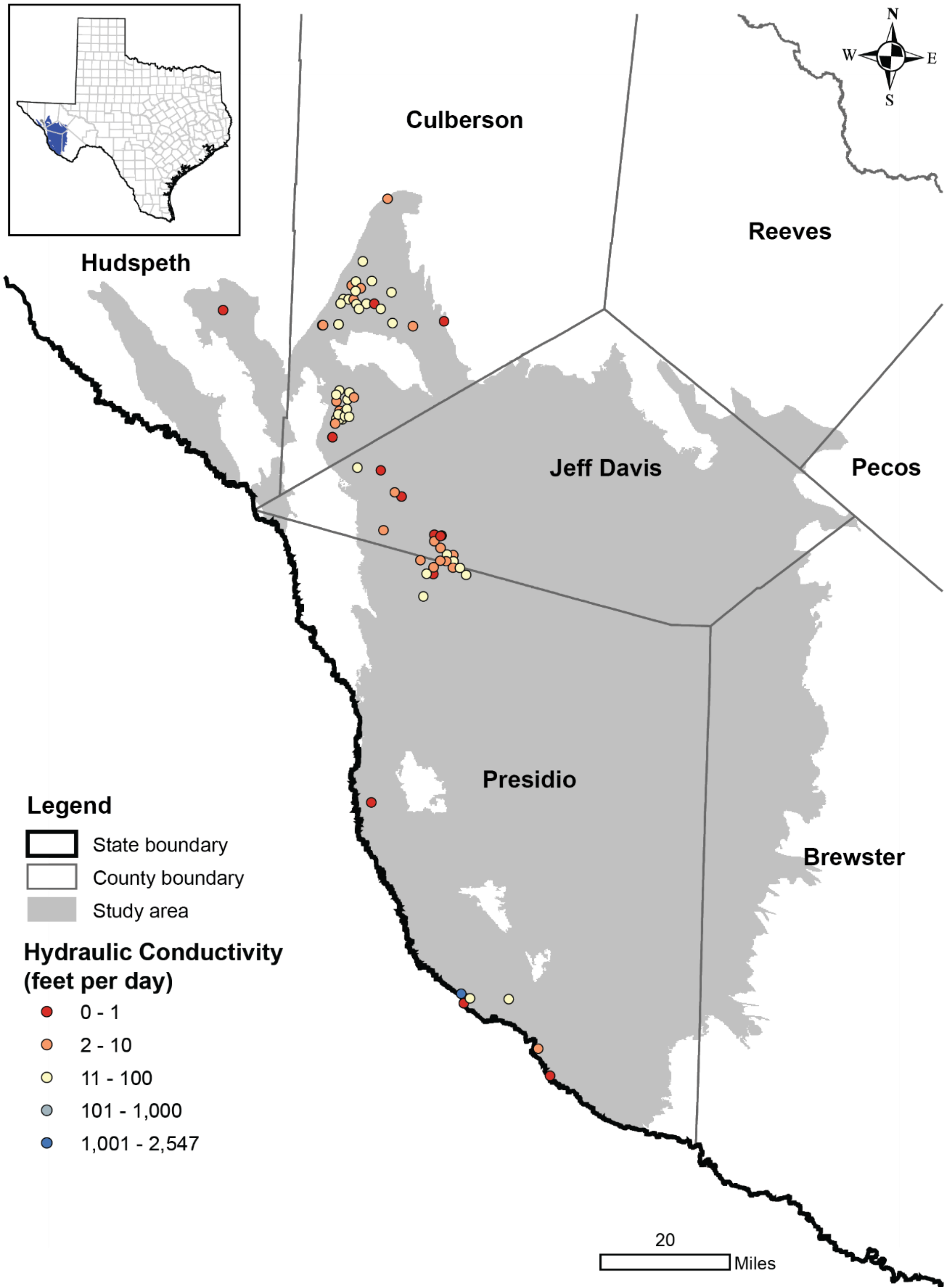


Figure 4.5.3. Hydraulic conductivity data for the West Texas Bolsons Aquifer (data from TWDB, 2022a).

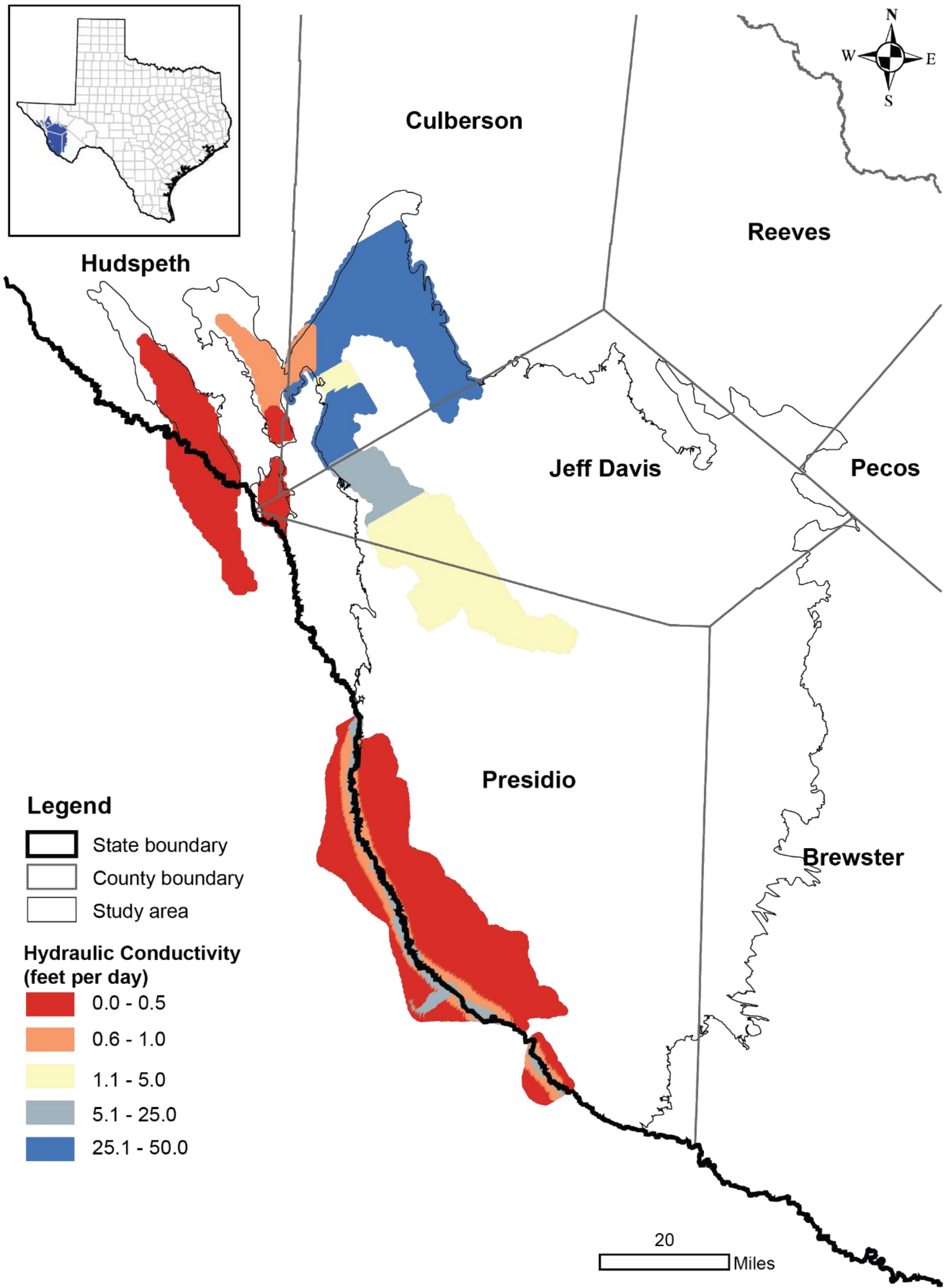


Figure 4.5.4. Hydraulic conductivity data for the West Texas Bolsons Aquifer in the study area (based on data from Beach and others, 2004, 2008; Wade and Jigmond, 2013).

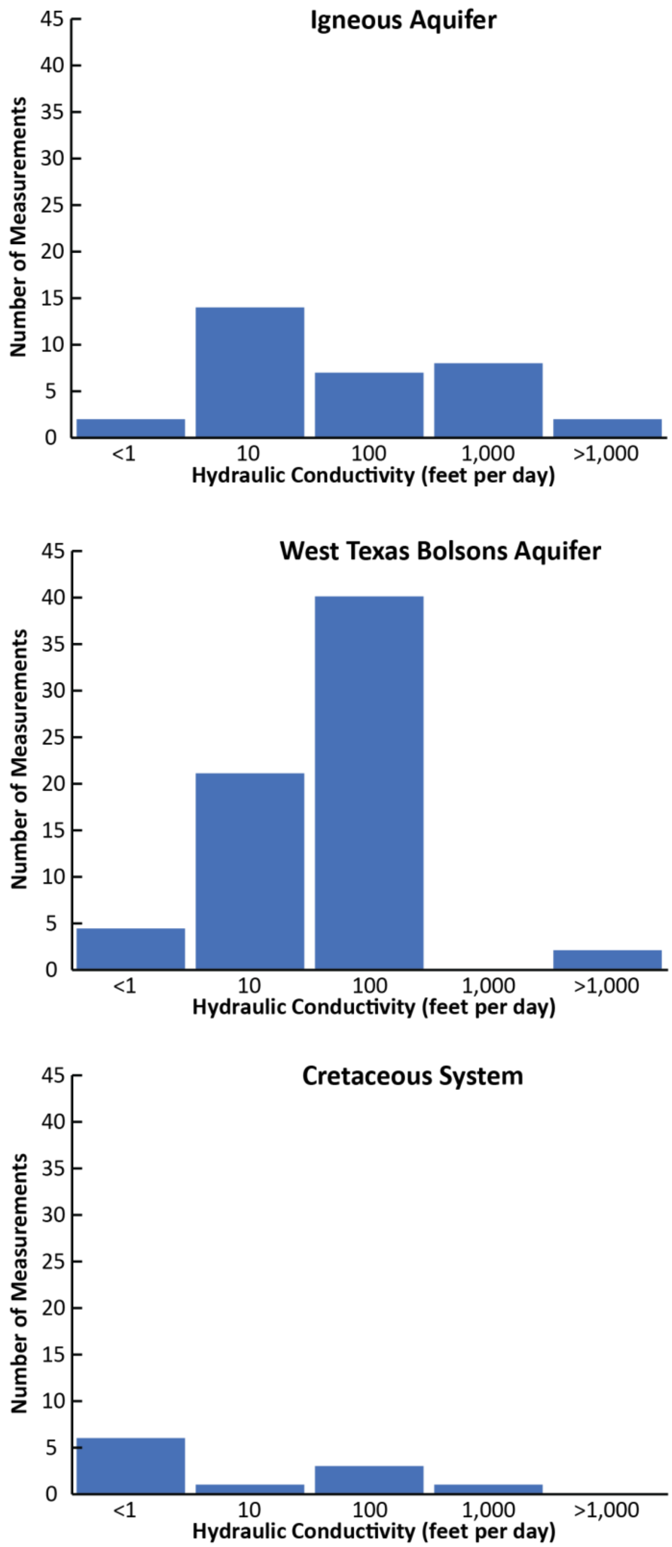


Figure 4.5.5. **Histogram of hydraulic conductivity data in feet per day for the Igneous and West Texas Bolsons aquifers and underlying Cretaceous rocks based on data from the hydraulic data indicated in Table A1 (data from Beach and others, 2004, 2008; Wade and others, 2011).**

4.6 Discharge

Discharge is the process 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 topography-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. In the Igneous and West Texas Bolsons aquifers, the most likely forms of discharge are stream and spring discharge and cross-formational flow in the subsurface. Groundwater discharge to surface water bodies is discussed in Sections 4.4.1 through 4.4.3. In a region with little surface runoff, most of the natural discharge from the Igneous and West Texas Bolsons aquifers is likely to take the form of discharge to the Rio Grande—the main perennial river in the study area (Figure 2.0.4). This form of discharge occurs where the respective aquifers intersect with the Rio Grande, for example, Red Light Draw, Green River Valley, Presidio Bolson and Redford Bolson. Alternatively, in the West Texas Bolsons Aquifer, groundwater discharge from Eagle Flat may take the form of cross-formational flow to Green River Valley through underlying stratigraphic units and groundwater discharges from Wild Horse Flat through lateral flow into the Salt Flat located to the north (Figure 4.2.6). Discharge via cross-formational flow is likely to occur in the Igneous Aquifer by upward discharge where it underlies the West Texas Bolsons Aquifer or Pecos Valley Aquifer.

4.6.2 Aquifer discharge through pumping

Estimates of groundwater pumping from the Igneous and West Texas Bolsons aquifers for the years 1980 through 2020 were obtained from the TWDB historical groundwater pumpage estimates (TWDB, 2022b). The six water-use categories defined in the TWDB database are municipal, manufacturing, steam electric generation, irrigation, mining, and livestock.

Potential areas for irrigation pumping from the Igneous and West Texas Bolsons aquifers study area are in the eastern and northern parts of the study area (Figure 4.6.1). This spatial distribution assumes that irrigation pumping 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). TWDB pumping data for the Igneous and West Texas Bolsons aquifers indicate irrigation pumping up to 4,486 acre-feet per year in the Igneous Aquifer and 88,648 acre-feet per year in the West Texas Bolsons Aquifer (Figure 4.6.2; Table A2).

Livestock pumping was distributed using land cover data obtained from the National Land Cover Dataset (Vogelmann and others, 1998a, 1998b). Livestock pumping is associated with grassland and scrubland land cover (Figure 4.6.1). These types of land cover are distributed over most of the land cover over the Igneous and West Texas Bolsons aquifers study area. Estimates of livestock pumping from the Igneous Aquifer has risen gradually from about 500 acre-feet per year in 1980 to about 750 acre-feet per year in 2020 (Figure 4.6.2; Table A3). In the West Texas Bolsons Aquifer, livestock pumping has declined from about 550 to 300 acre-feet per year over the same period.

Manufacturing, mining, steam electric power, and municipal pumping are spatially distributed based on known well locations (Figure 4.6.3). These wells tend to be clustered around the main municipalities in the study area—Alpine, Fort Davis, Marfa, Presidio, and Van Horn. TWDB pumping estimates (TWDB, 2022b) indicate manufacturing pumping from the Igneous and West Texas Bolsons aquifers is very low, totaling up to 24 acre-feet per year in the Igneous Aquifer and about 100 acre-feet per year in the West Texas Bolsons Aquifer (Figure 4.6.4; Table A4). Mining pumping estimates are less than 3 acre-feet per year (Figure 4.6.4; Table A5). Pumping estimates from the water use survey suggest that mining pumping from the study area occurs only in Hudspeth County and only from the West Texas Bolsons Aquifer. Municipal pumping from the Igneous and West Texas Bolsons aquifers are as high as 5,723 acre-feet per year and 2,158 acre-feet per year, respectively (Figure 4.6.5; Table A6). Most municipal pumping is from the Igneous Aquifer for the main municipalities in the study area—Alpine, Fort Davis and Marfa.

Steam electric power pumping took place in Culberson County from 1980 through 1997 (Figure 4.6.5; Table A7). This category of pumping declined rapidly between 1980 and 1990, starting at about 500 acre-feet per year in 1980 and was insignificant—fluctuating between 3 and less than 1 acre-feet per year—between 1990 and the last reported pumping in 1997. This pumping was most likely associated with power generation for the City of Van Horn.

Total pumping from the Igneous and West Texas Bolsons aquifers from 1980 through 2020 is shown in Table A8 and Figure 4.6.6. Total pumping from the Igneous Aquifer was relatively constant over the period fluctuating between 2,500 and 9,000 acre-feet per year. Total pumping from the West Texas Bolsons Aquifer is much higher, fluctuating between 15,000 and 60,000 acre-feet per year. The wide variation of pumping in the West Texas Bolsons Aquifer largely reflects variation of pumpage in Culberson County which accounts for the bulk of the pumpage from the aquifer (Figure 4.6.7). Figures 4.6.8 and 4.6.9 show the spatial distribution of pumping from the Igneous and West Texas Bolsons aquifers, respectively, from the groundwater availability models by Beach and others (2004, 2008) and Wade and Jigmond (2013). These figures show pumping in the Igneous Aquifer is highest in the vicinity of Alpine, Fort Davis, and Marfa. In the West Texas Bolsons Aquifer, pumping is highest along the Rio Grande in the Presidio and Redford Bolsons, and in Lobo, Michigan, Ryan, and Wild Horse Flat.

Municipal pumping is the main pumping category in the Igneous Aquifer and irrigation is the main pumping category in the West Texas Bolsons Aquifer (Figure 4.6.10). In the Igneous Aquifer, municipal pumping is the main category of pumping in Brewster County (Alpine), Jeff Davis County (Fort Davis), and Presidio County (Presidio) (Figure 4.6.11). Other pumping categories dominate in Hudspeth (livestock) and Culberson and Reeves (irrigation) counties where the Igneous Aquifer is a minor source of groundwater. Irrigation dominates pumping from the West Texas Bolsons Aquifer in Culberson and Jeff Davis counties while livestock and municipal pumping dominate pumping in Hudspeth and Presidio counties, respectively.

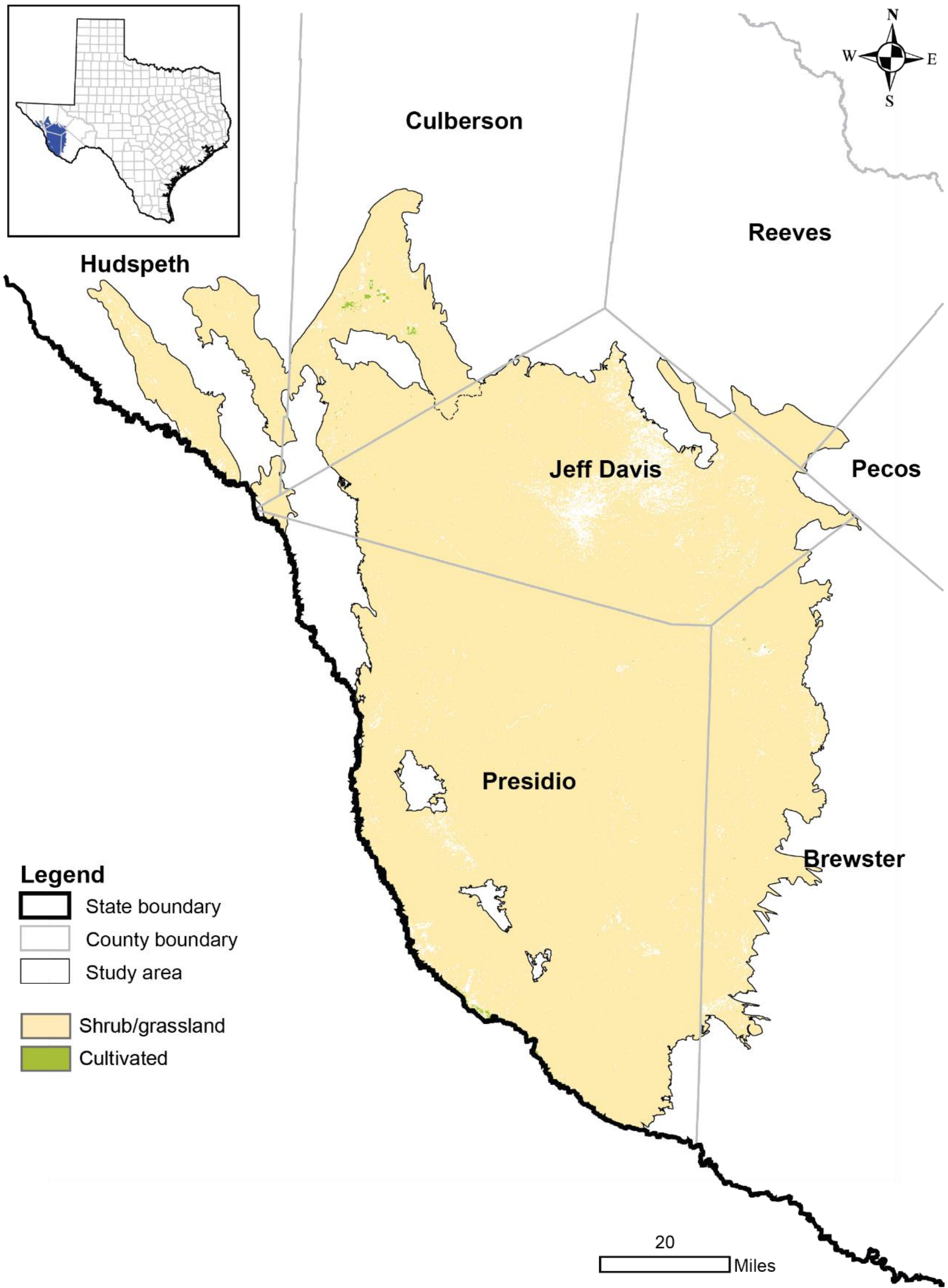
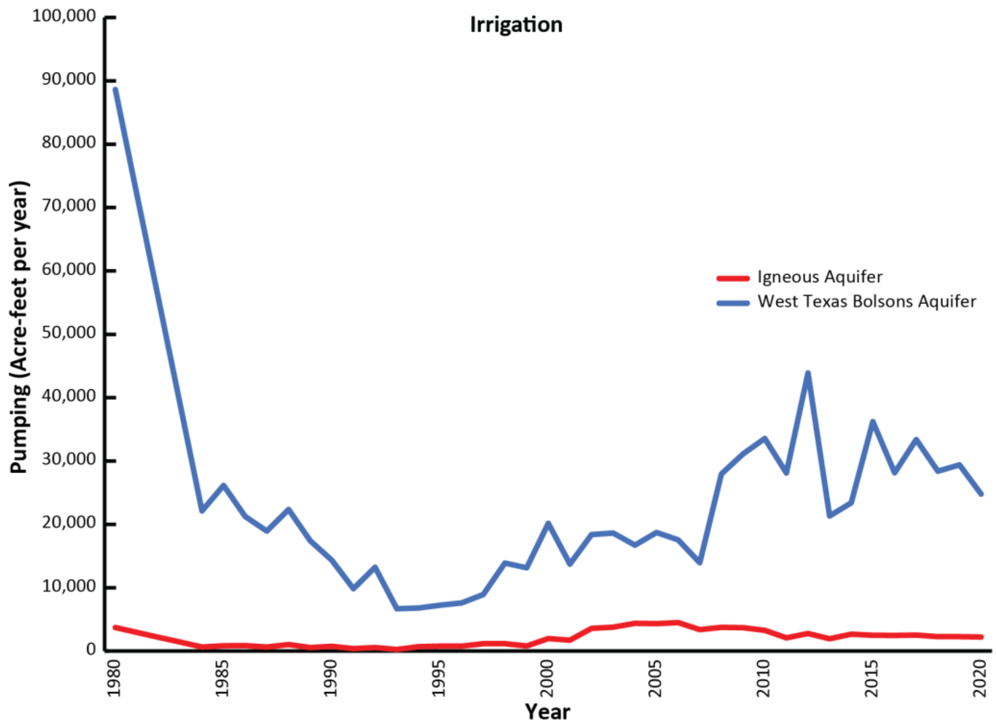


Figure 4.6.1. **Spatial distribution of irrigated and grassland and shrubland land cover from the National Land Cover Dataset throughout the study area (Vogelmann and others, 1998a, 1998b).**



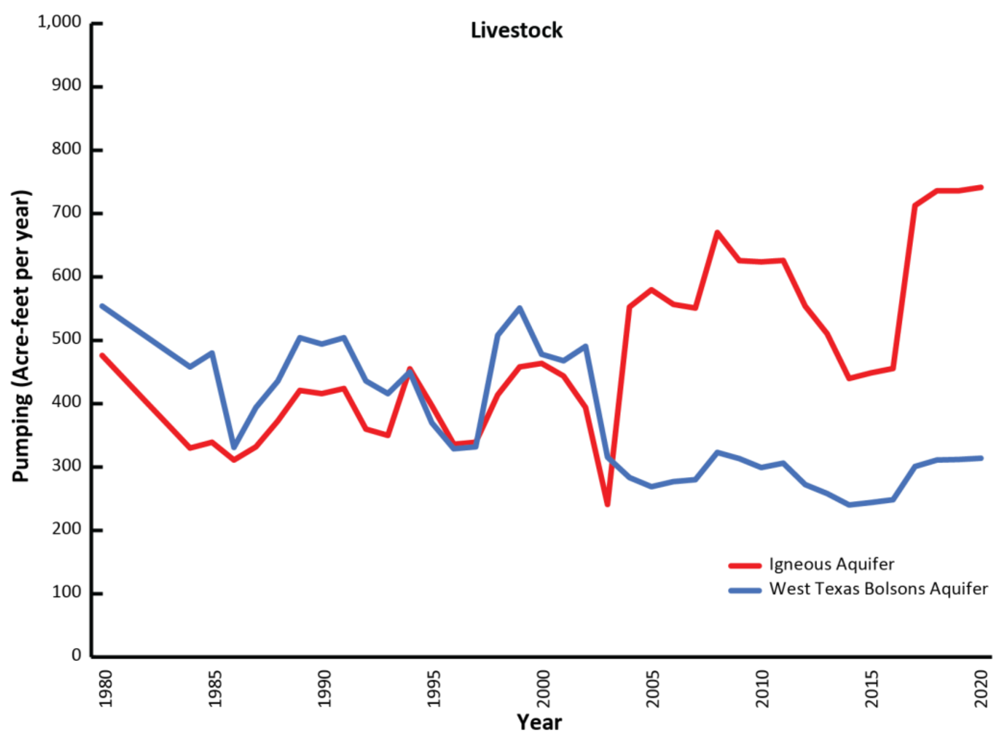


Figure 4.6.2. Estimated irrigation and livestock pumpage from the Igneous and West Texas Bolsons aquifers (data from TWDB, 2022b).

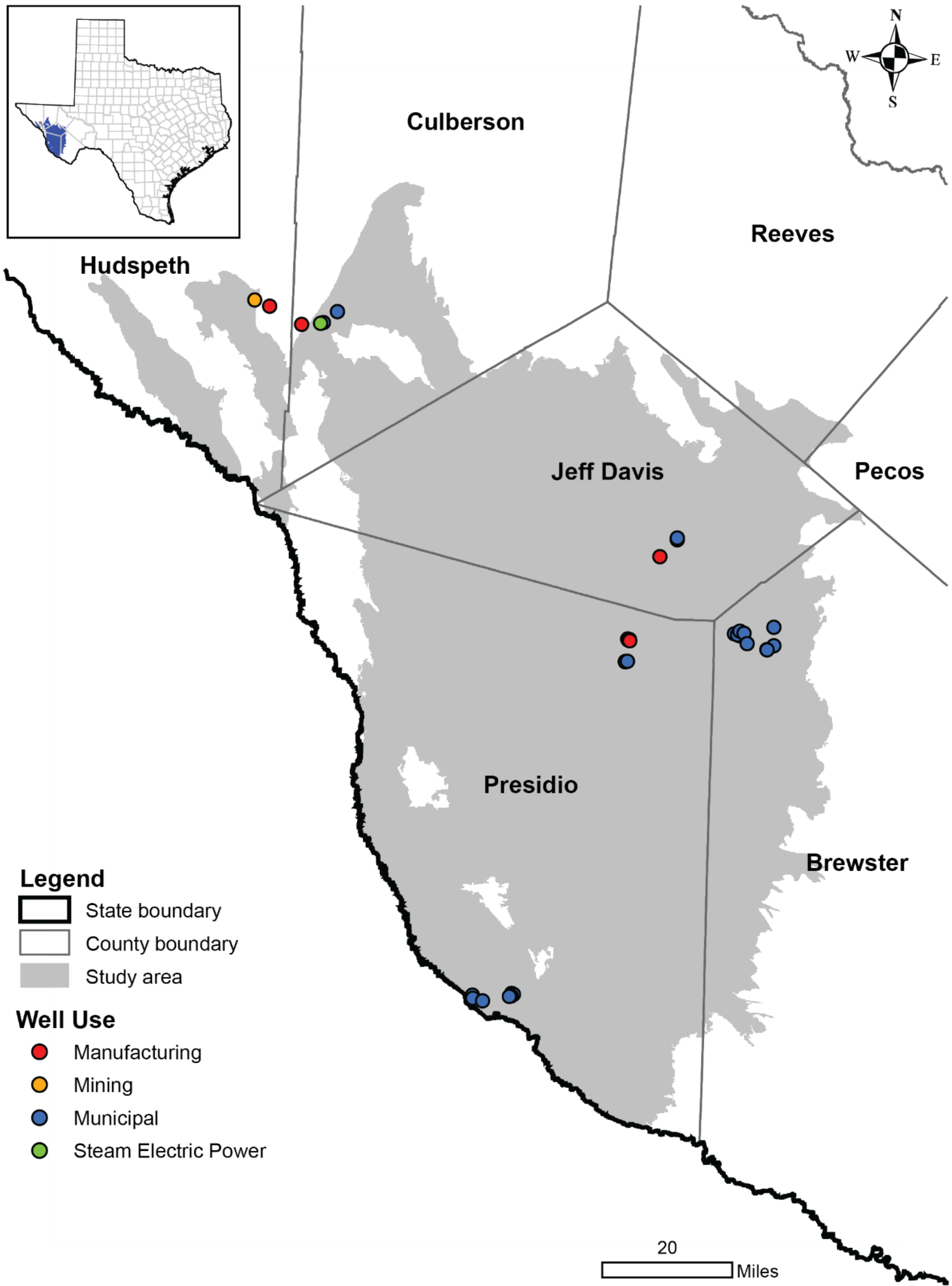
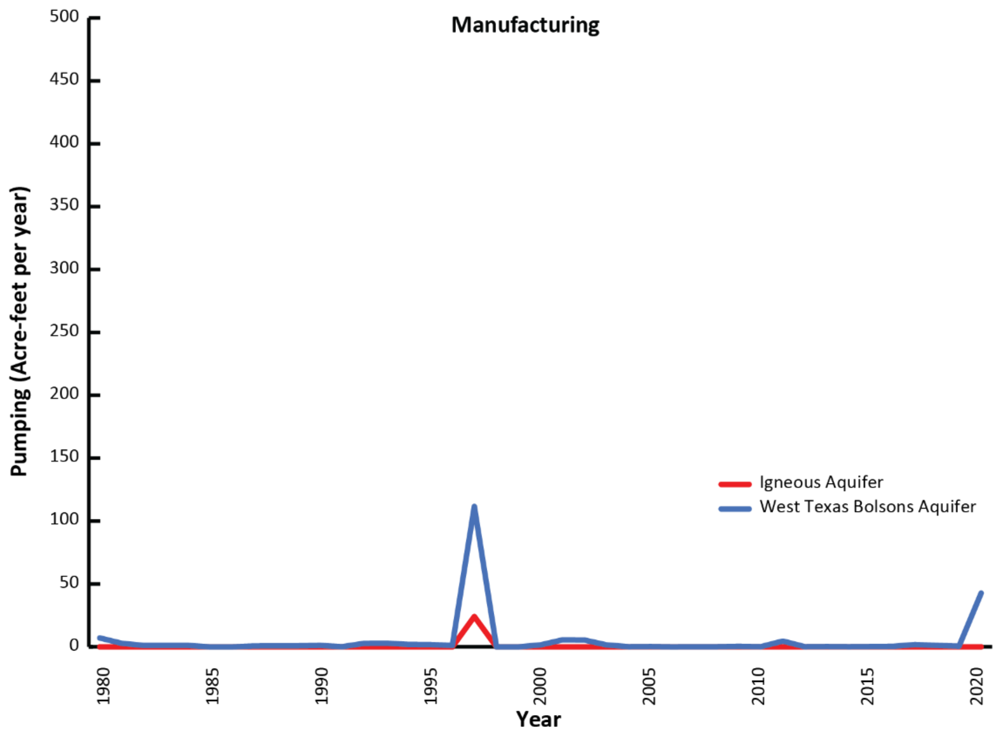


Figure 4.6.3. The spatial distribution of known manufacturing (industrial), mining, municipal (public supply), and steam electric power pumping (data from TWDB, 2022a).



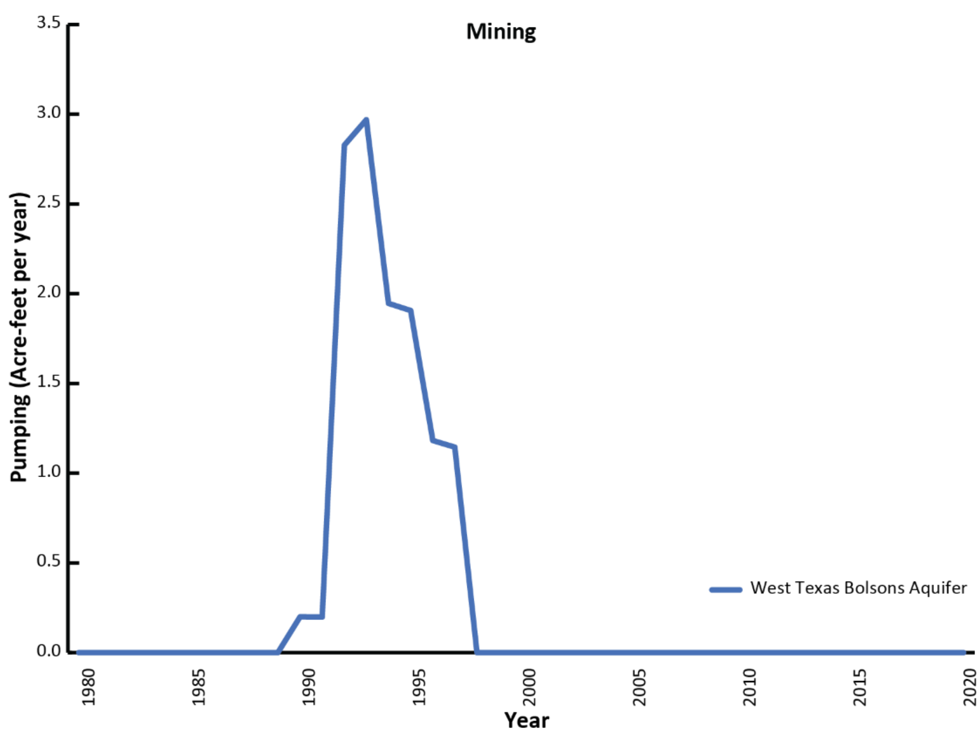


Figure 4.6.4. Estimated manufacturing and mining pumpage from the Igneous and West Texas Bolsons aquifers (data from TWDB, 2022b).

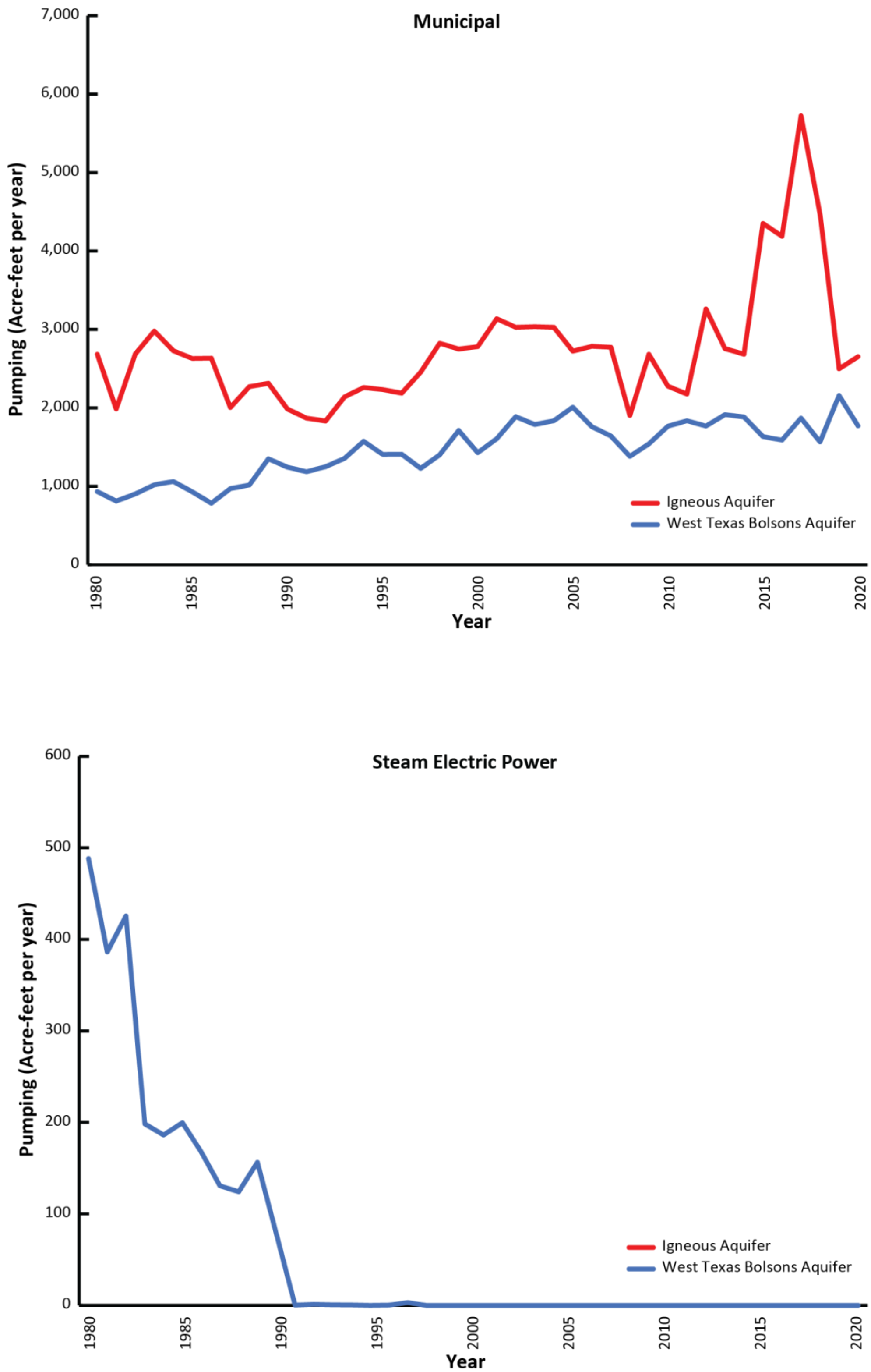


Figure 4.6.5. Estimated municipal and steam electric power pumpage from the Igneous and West Texas Bolsons aquifers (data from TWDB, 2022b).

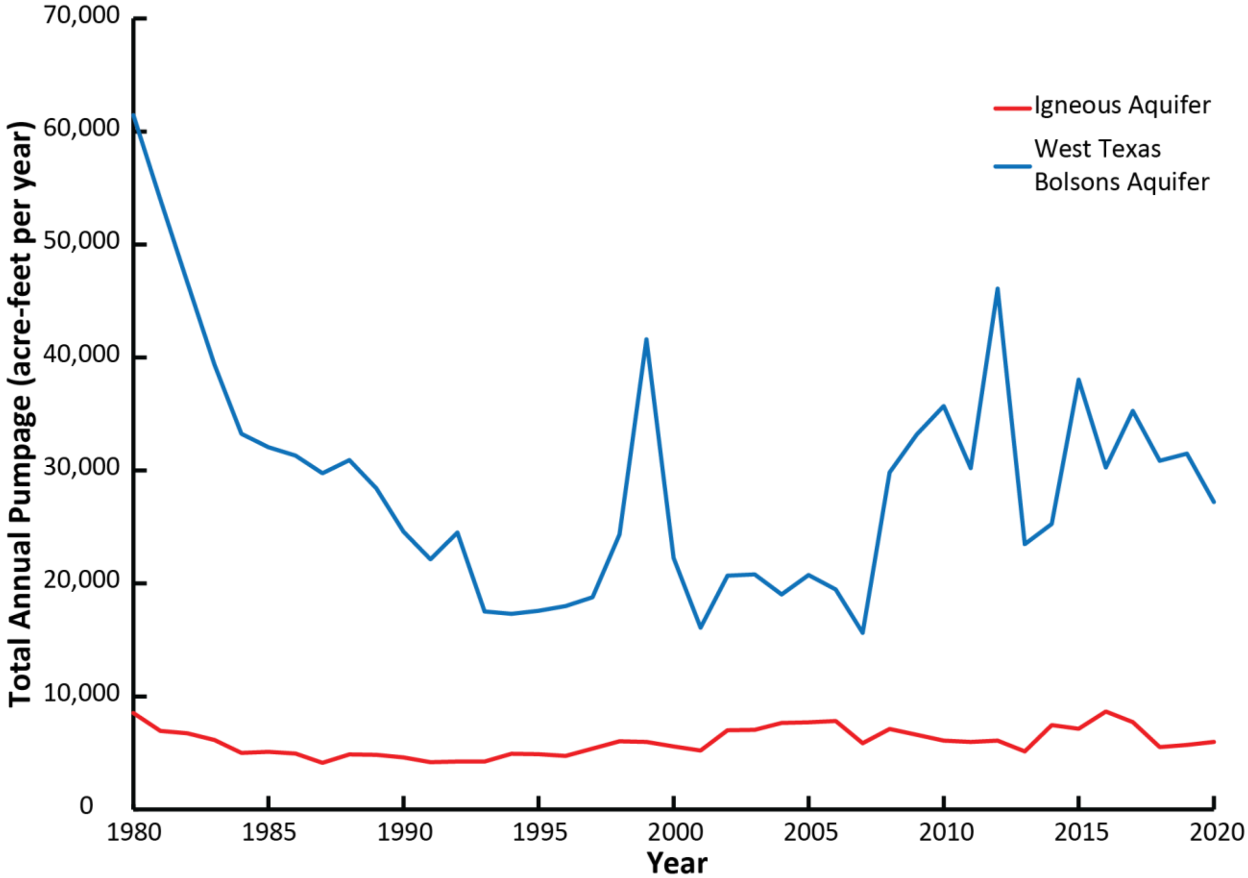


Figure 4.6.6. **Total estimated pumpage from the Igneous and West Texas Bolsons aquifers (data from TWDB, 2022b).**

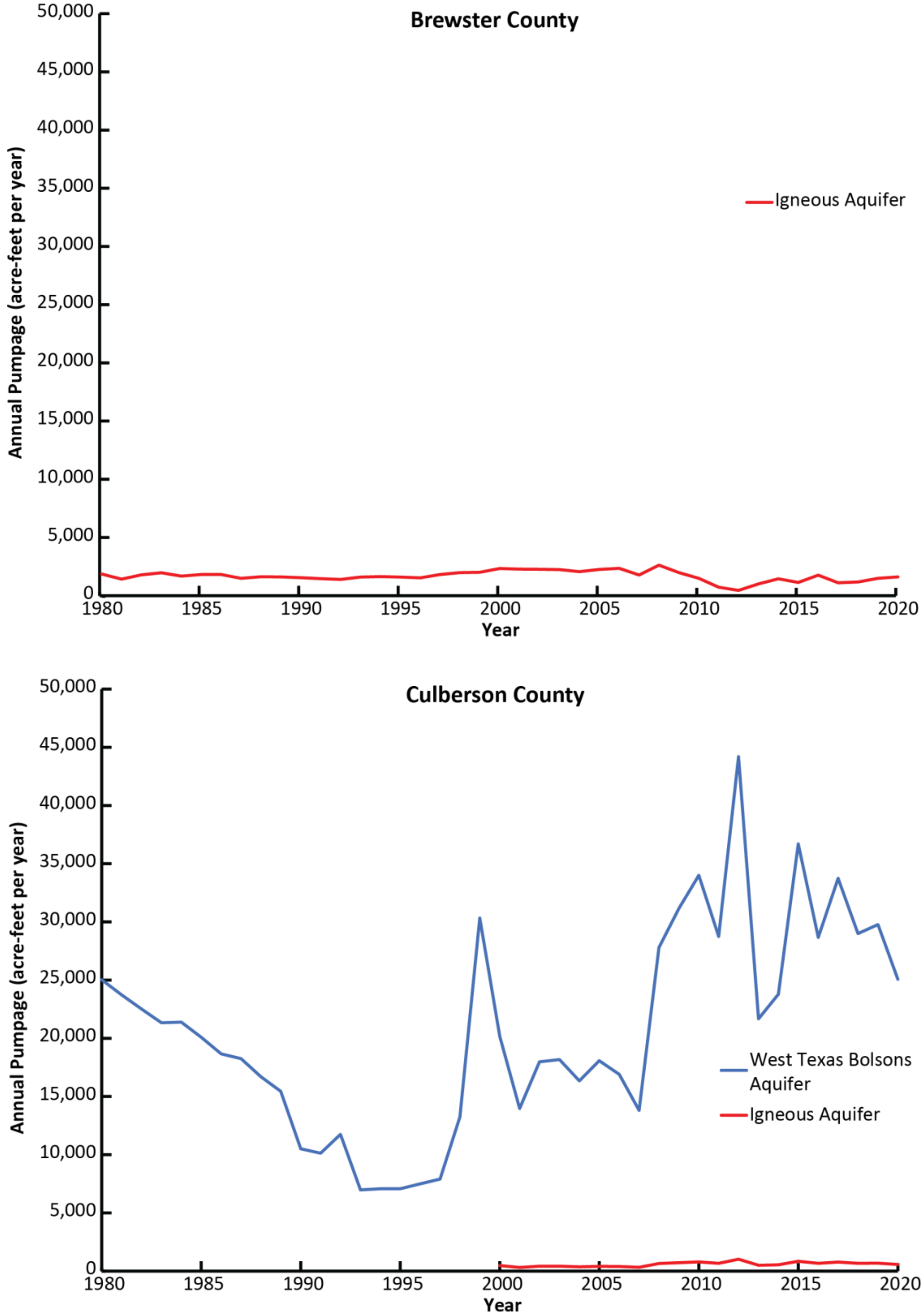
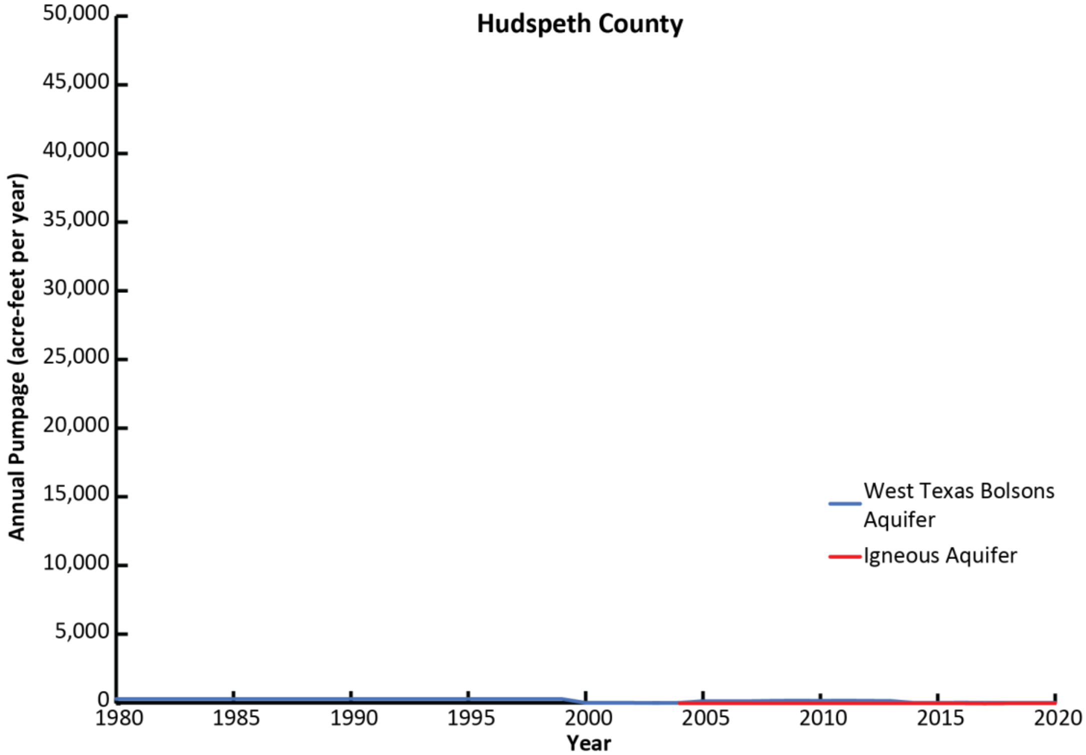


Figure 4.6.7. Total estimated pumpage for each of the counties in the Igneous and West Texas Bolsons aquifers study area (data from TWDB, 2022b).



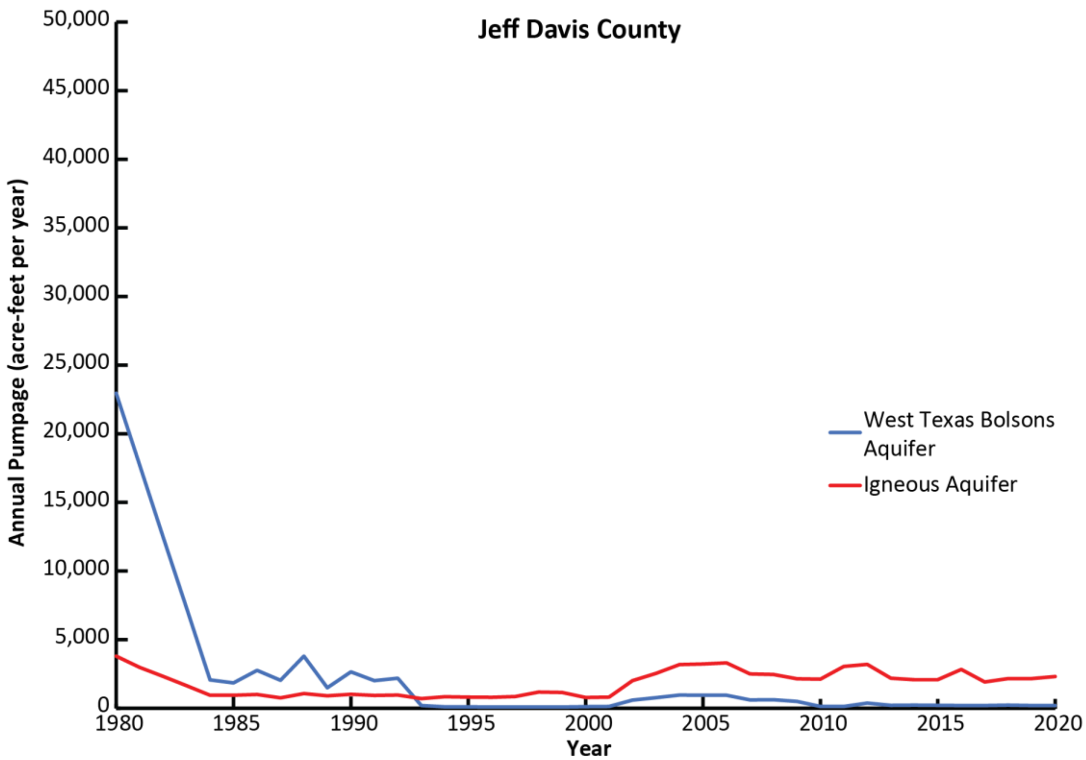
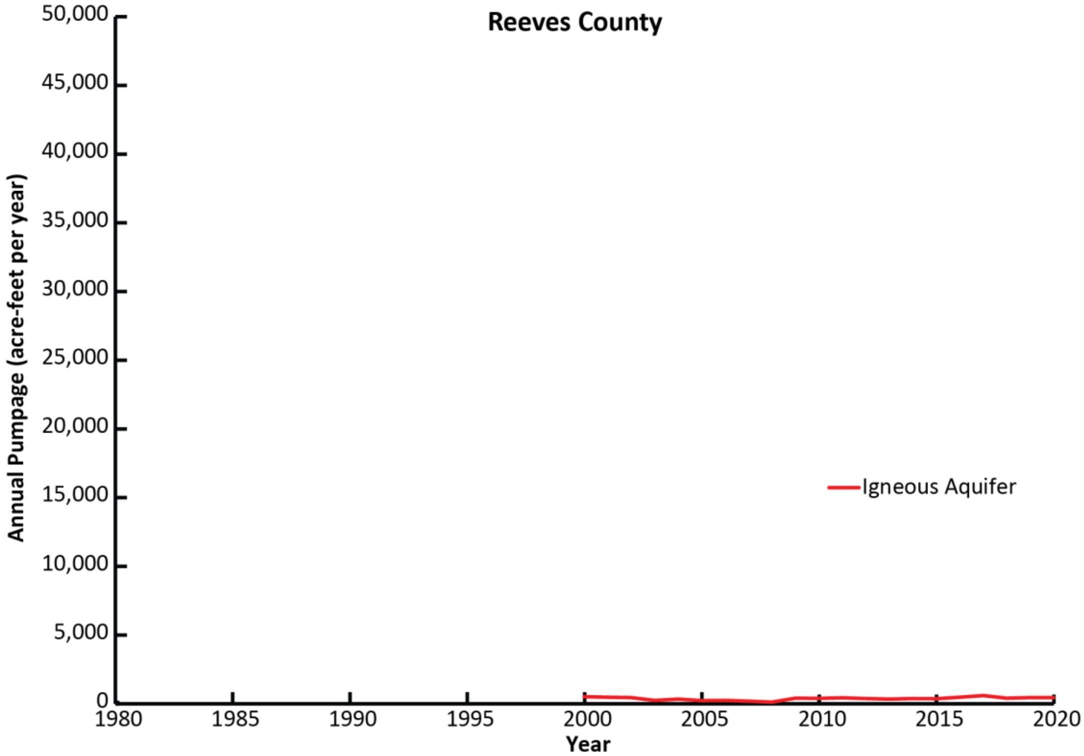


Figure 4.6.7. (continued). **Total estimated pumpage for each of the counties in the Igneous and West Texas Bolsons aquifers study area (data from TWDB, 2022b).**



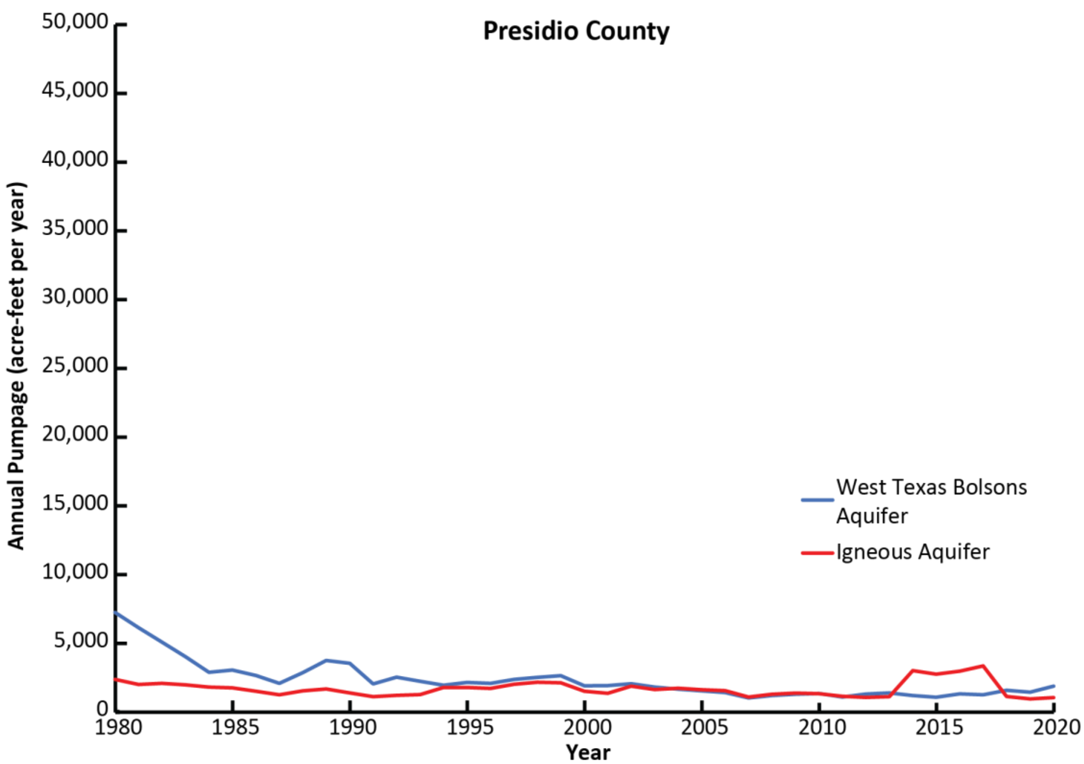


Figure 4.6.7. (continued). **Total estimated pumpage for each of the counties in the Igneous and West Texas Bolsons aquifers study area (data from TWDB, 2022b).**

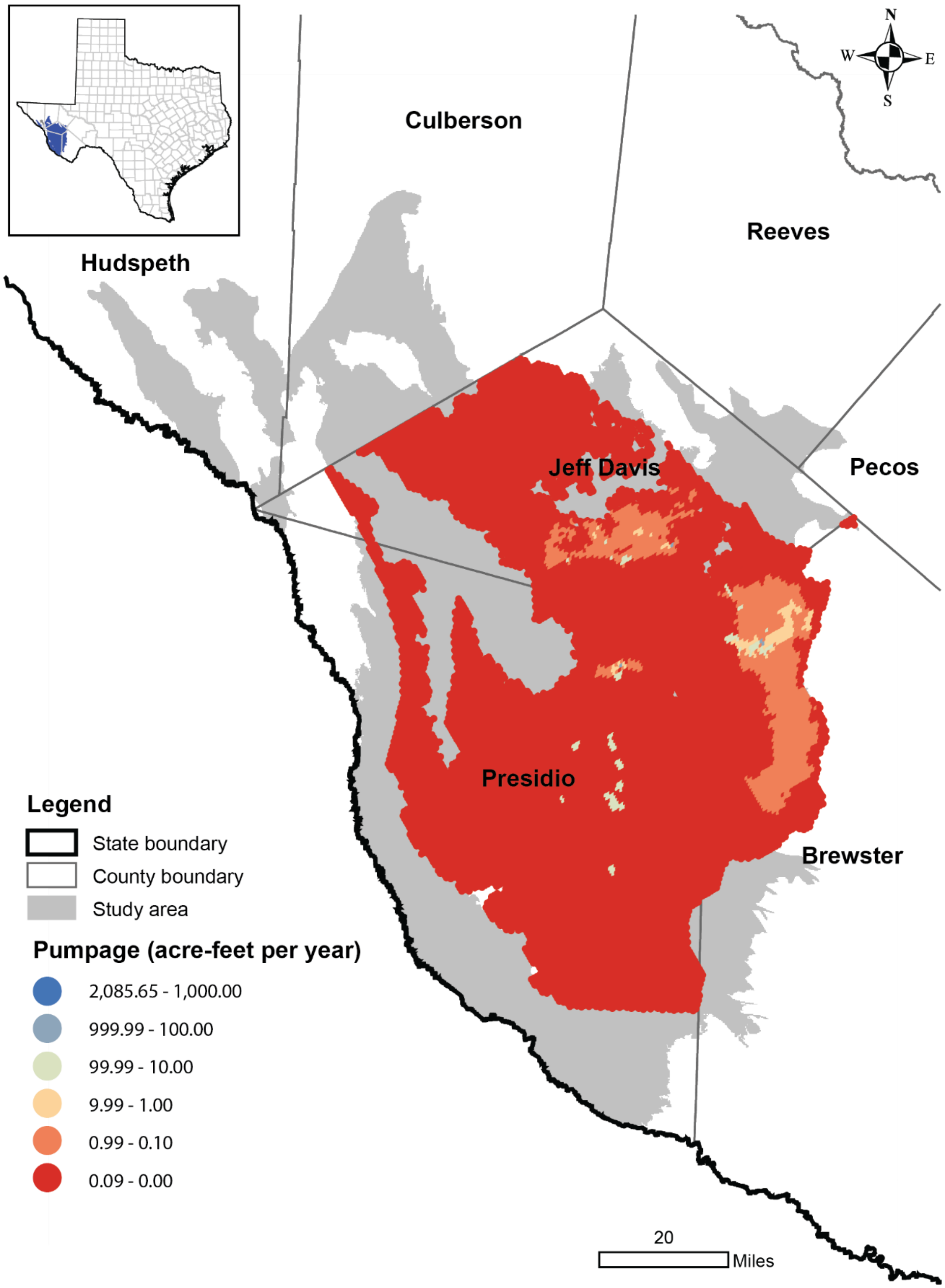


Figure 4.6.8. Total estimated pumpage from the Igneous Aquifer for the year 2000 (data from Beach and others, 2004).

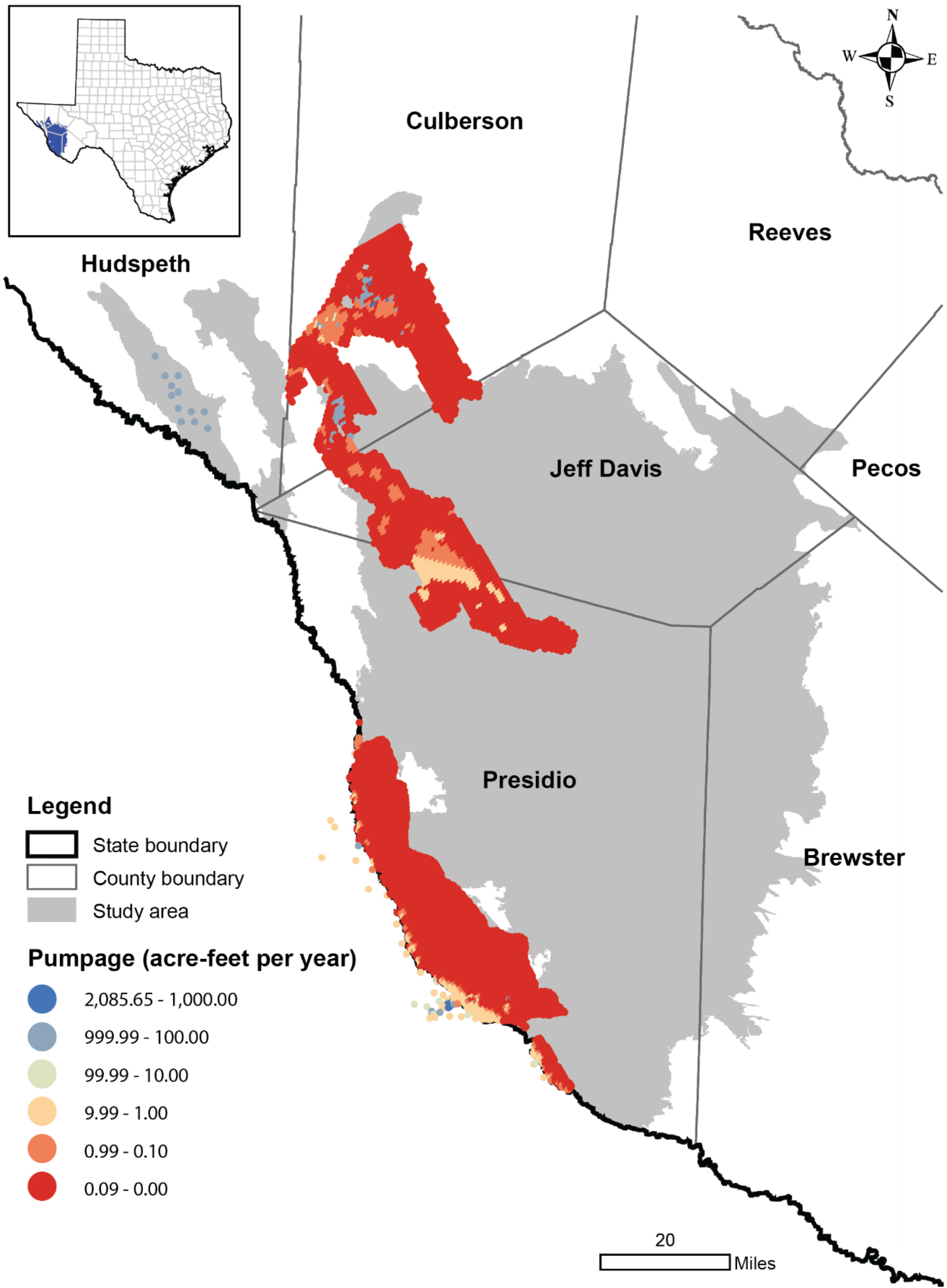


Figure 4.6.9. **Total estimated pumpage from the West Texas Bolsons Aquifer for the year 2000 (data from Beach and others, 2004, 2008 and Wade and Jigmond, 2013).**

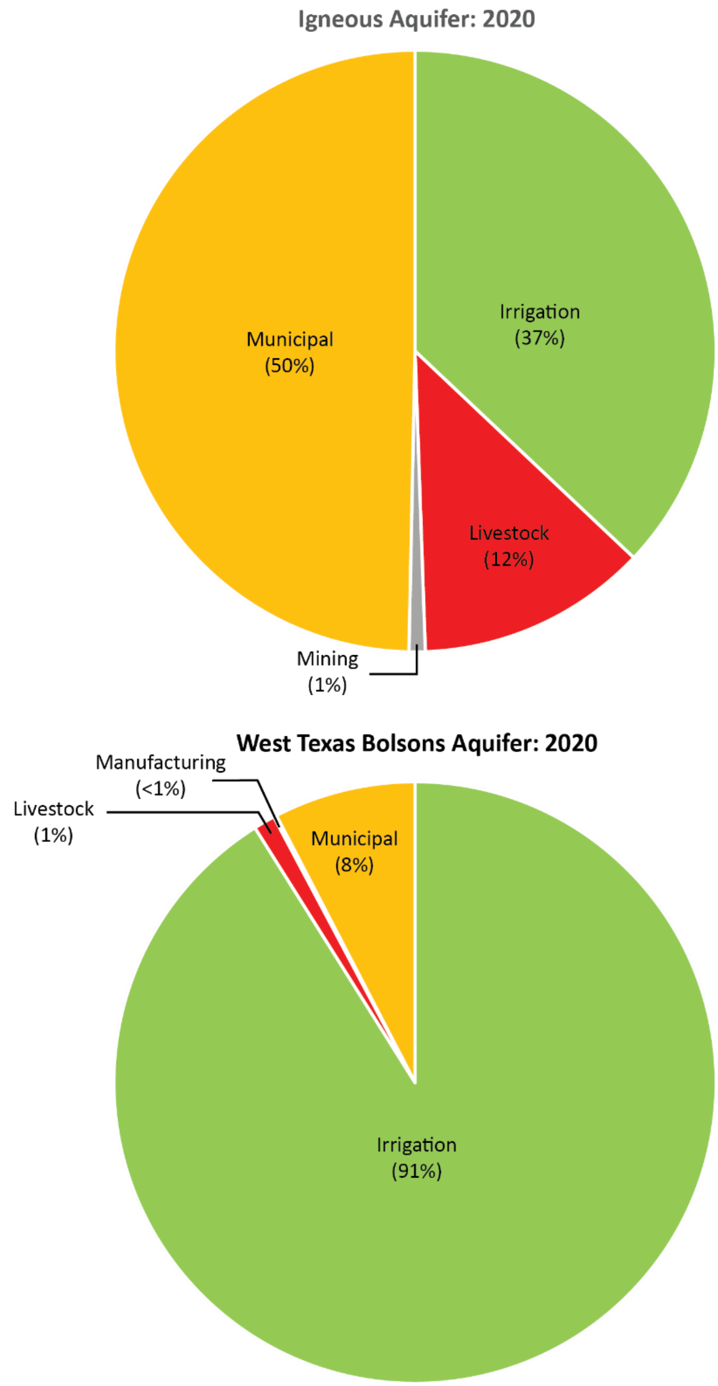


Figure 4.6.10. Pie charts showing relative amounts of pumping from steam electric power, irrigation, livestock, manufacturing, and municipal in the Igneous and West Texas Bolsons aquifers for the year 2020 (data from TWDB, 2022b).

Figure 4.6.11. Pie charts showing relative amounts of pumping from steam electric power, irrigation, livestock, manufacturing, and municipal in each of the counties that overlie the Igneous and West Texas Bolsons aquifers for the year 2020 (data from TWDB, 2022b).

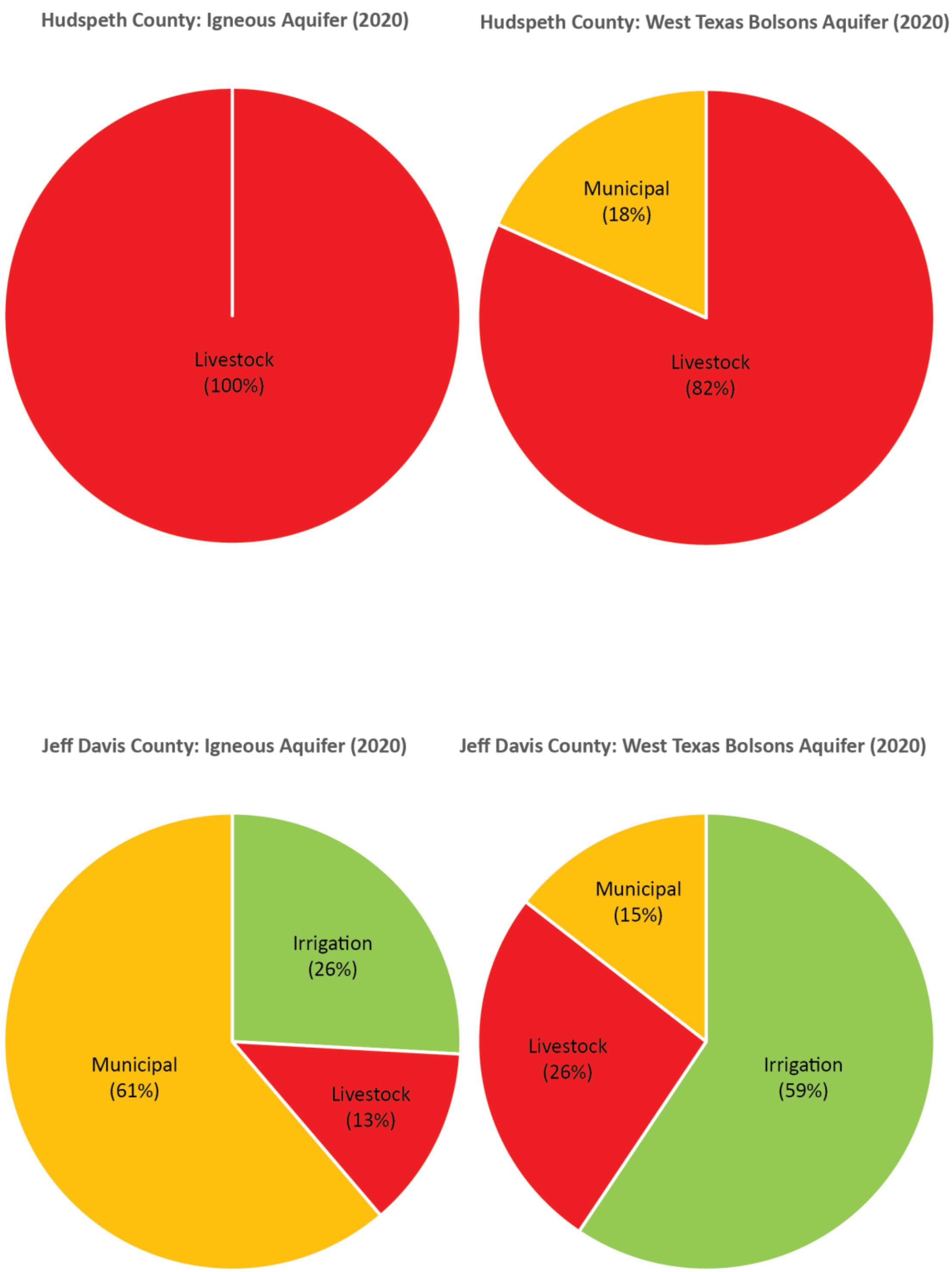


Figure 4.6.11. (continued). Pie charts showing relative amounts of pumping from steam electric power, irrigation, livestock, manufacturing, and municipal in each of the counties that overlie the Igneous and West Texas Bolsons aquifers for the year 2020 (data from TWDB, 2022b).

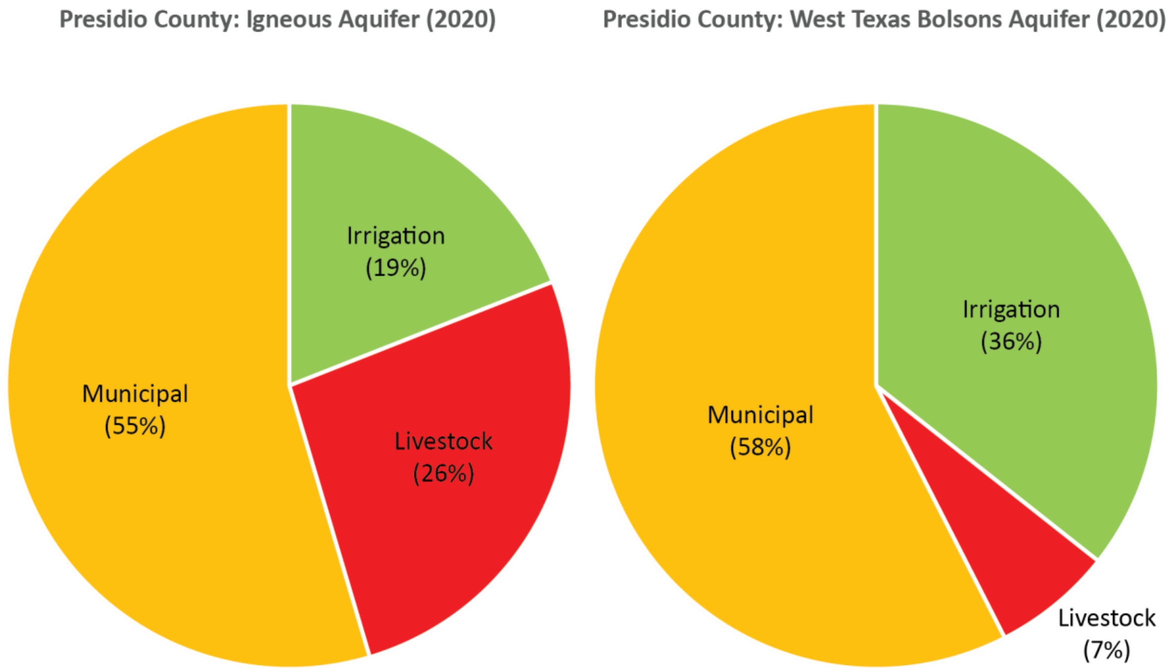


Figure 4.6.11. (continued). Pie charts showing relative amounts of pumping from steam electric power, irrigation, livestock, manufacturing, and municipal in each of the counties that overlie the Igneous and West Texas Bolsons aquifers for the year 2020 (data from TWDB, 2022b).

4.7 Water quality

The Igneous Aquifer has fresh groundwater that is generally less saline than the overlying West Texas Bolsons Aquifer. This section is a discussion of the major element and isotopic compositions of groundwater in the Igneous and West Texas Bolsons aquifers with implications for determination of groundwater flow through and recharge to the respective aquifers.

4.7.1 Major elements

Figures 4.7.1 and 4.7.2 show total dissolved solids concentrations in the Igneous and West Texas Bolsons aquifers groundwater. Fresh groundwater—total dissolved solids less than 1,000 milligrams per liter—occurs throughout the aquifers. Slightly saline groundwater—total dissolved solids of 1,000 milligrams per liter to 3,000 milligrams per liter—occur mostly in the West Texas Bolsons Aquifer, in the Presidio and Redford bolsons, and in the north in the Lobo Flat Michigan Flat, and Wild Horse Flat. Moderately saline groundwater—total dissolved solids of 3,000 milligrams per liter to 10,000 milligrams per liter—occurs in the Salt Flat, north of the West Texas Bolsons Aquifer. These higher groundwater salinities can be attributed to discharge through evaporation in a closed basin (Boyd and Kreitler, 1986; Angle, 2001).

Groundwater in the Igneous and West Texas Bolsons aquifers display a wide range of geochemical compositions (Figure 4.7.3). Igneous Aquifer groundwater compositions range from calcium-magnesium-bicarbonate to sodium-bicarbonate compositions. West Texas Bolsons Aquifer groundwater has a wider range of compositions, from calcium-magnesium to sodium and bicarbonate to sulfate-chloride. These compositional ranges are determined by geochemical processes that take place as the groundwater flows through the aquifer interacting with volcanic or alluvial aquifer rock and mixing with groundwater inflows from surrounding stratigraphic units.

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 tends to have more negative carbon-13 compositions reflecting recent contact with the soil. With increasing groundwater residence in the aquifer, increasing effects of water-rock interaction results in the groundwater taking on more positive carbon-13 isotopic compositions, reflecting those of the aquifer rock. This process is apparent in the Igneous and West Texas Bolsons aquifers where groundwater carbon-13 compositions indicate areas of relatively recent recharge (Figures 4.7.4 and 4.7.5). In the Igneous Aquifer, more negative groundwater carbon-13 compositions—about -15 to -8 per mil—indicate relatively recent recharge along the margins of the aquifer with older groundwater in the central parts of the aquifer. Carbon-13 isotopes in the West Texas Bolsons Aquifer indicate relatively recent recharge only in Ryan Flat and Presidio Bolson. Indications are that the groundwater in Red Light Draw and Eagle Flat, and possibly Lobo, Michigan, and Wild Horse Flat is very old.

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 Igneous and West Texas Bolsons aquifers, carbon-14 activity is generally highest—up to 1.0 fraction modern carbon—where recharge occurs, and lowest—less than 0.2 fraction modern carbon—where there is no recharge and almost all the groundwater carbon-14 has decayed (Figures 4.7.6 and 4.7.7). The groundwater carbon-14 in the study area has the similar indications to carbon-13—recent recharge along the margins of the Igneous Aquifer and Presidio Bolson of the West Texas Bolsons Aquifer. This similarity is due to the fact that both isotopic compositions change over time. Carbon-14 due to radioactive decay and carbon-13 due to water-rock interaction processes (Figure 4.7.8).

Groundwater tritium behaves like carbon-14 (Figure 4.7.9). 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 and is therefore more sensitive to more recent recharge than carbon-14 (Clark and Fritz, 1997). High tritium activity indicates the most recent recharge. In the Igneous and West Texas Bolsons aquifers, the groundwater tritium activity ranges between 0 and 7 Tritium Units (Figures 4.7.10 and 4.7.11). Most groundwater samples in the study area display tritium activity less than 1.0 suggesting little recharge to the aquifer within the past 50 years. The few groundwater samples with relatively high tritium activity tend to occur along the margins of the aquifers, suggesting relatively recent recharge.

Groundwater stable hydrogen ($\delta^{2}H$) and oxygen ($\delta^{18}O$) isotopic compositions represent the ratios of stable hydrogen isotopes (H and ^{2}H) and stable oxygen isotopes (^{16}O and ^{18}O) in groundwater relative to the composition of standard mean ocean water (Clark and Fritz, 1997). These isotope ratios are expressed as the relative difference in parts per thousand (per mil). Groundwater stable hydrogen and oxygen isotopic compositions reflect the composition of the precipitation that recharged the aquifer, which may vary spatially or temporally in response to factors such as elevation, temperature, and amount of precipitation (Dansgaard, 1964; Fontes and Olivry, 1977; Fontes, 1980; Gonfiantini, 1985; Scholl and others, 1996). Consequently, the hydrogen and oxygen isotopic compositions of groundwater can be used as an indicator of the conditions under which recharge to the aquifer occurred. Figure 4.7.12 shows groundwater hydrogen and oxygen isotopic compositions in the Igneous and West Texas Bolsons aquifers.

Groundwater stable hydrogen and oxygen isotopic compositions in the Igneous Aquifer range between -60 to -40 per mil and -8 to -4 per mil, respectively. Groundwater stable hydrogen and oxygen isotopic compositions in the West Texas Bolsons Aquifer range between -70 to -40 per mil and -9 to -6 per mil, respectively. Stable hydrogen and oxygen isotope compositions are generally slightly below the Global Meteoric Water Line—the average relationship between stable hydrogen and oxygen isotopic compositions in precipitation around the world—but follow the same trend (Craig, 1961). The average stable hydrogen and oxygen isotope composition for the Igneous Aquifer is further up the Global Meteoric Water Line than the average West Texas Bolsons Aquifer composition. This difference can be explained by Figure 4.7.13 which shows the groundwater stable oxygen isotopic trends across the study area. Stable oxygen isotopic compositions tend to become increasingly negative from southeast to northwest, with the highest values occurring in the southern Igneous Aquifer and the Presidio Bolson, and the lowest values occurring in the northern and westernmost bolsons—Eagle Flat and Red Light Draw of the West Texas Bolsons Aquifer.

4.7.3 Implications for recharge based on major element and isotopic compositions in groundwater

The most likely effects influencing the range of groundwater stable oxygen isotopic compositions in the Igneous and West Texas Bolsons aquifers are the temperature and/or the amount of precipitation. Higher precipitation amounts and/or lower temperatures produce more negative isotopic compositions in the precipitation and resultant groundwater.

Figure 4.7.14 shows the variation of groundwater stable oxygen isotopic compositions with groundwater carbon-14 compositions in the study area, where carbon-14 is a representation of time. Carbon-14 compositions around 1 represent recent recharge within the last 25 years, while compositions approaching 0 indicate on average recharge several thousand years ago during the Pleistocene epoch. Figure 4.7.14 indicates the most ancient groundwater in the study area occurs in the Green River Valley, Red Light Draw, and the Salt Basin which is made up of Lobo Flat, Michigan Flat, Ryan Flat, and Wild Horse Flat. This groundwater tends to be characterized by stable oxygen isotopic compositions below -7 per mil.

The most recently recharged groundwater in the Presidio Bolson and Igneous Aquifer are characterized by stable oxygen isotopic compositions above -7 per mil. This relationship between the apparent age of the groundwater and stable oxygen isotopic composition is related to the climatic differences between the Pleistocene when the study area was cooler and wetter than it currently is today. The conclusion that can be made from Figures 4.7.13 and 4.7.14 is that most recharge in the western and northern bolsons of the West Texas Bolsons Aquifer occurred during the Pleistocene. Elsewhere in the study area, especially in the Igneous Aquifer and the Presidio Bolson of the West Texas Bolsons Aquifer, the aquifers are characterized by a mixture of Pleistocene and modern recharge.

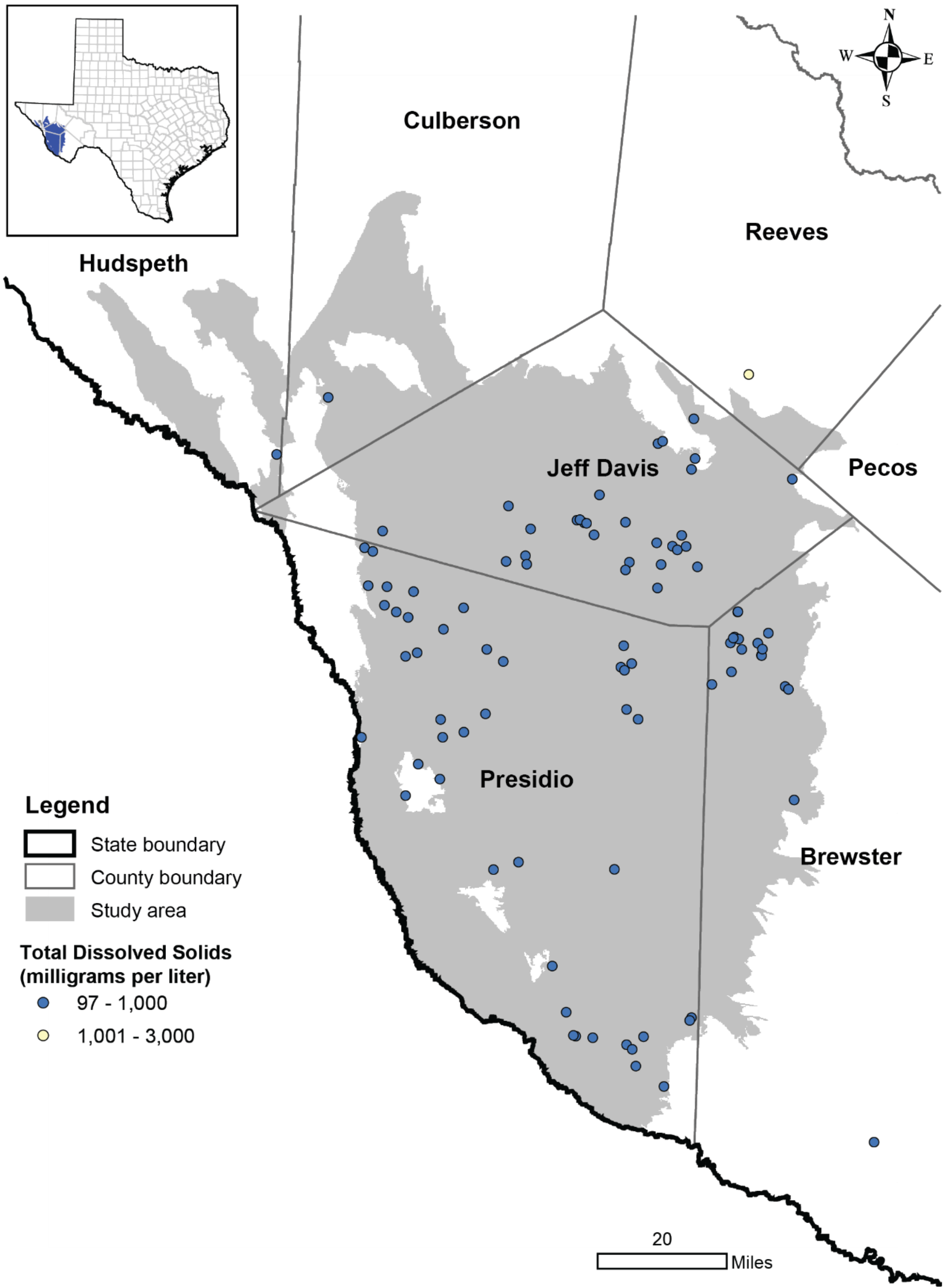


Figure 4.7.1. **Total dissolved solids concentration (in milligrams per liter) in the Igneous Aquifer (data from TWDB, 2022a).**

Figure 4.7.2. **Total dissolved solids concentration (in milligrams per liter) in the West Texas Bolsons Aquifer (data from TWDB, 2022a).**

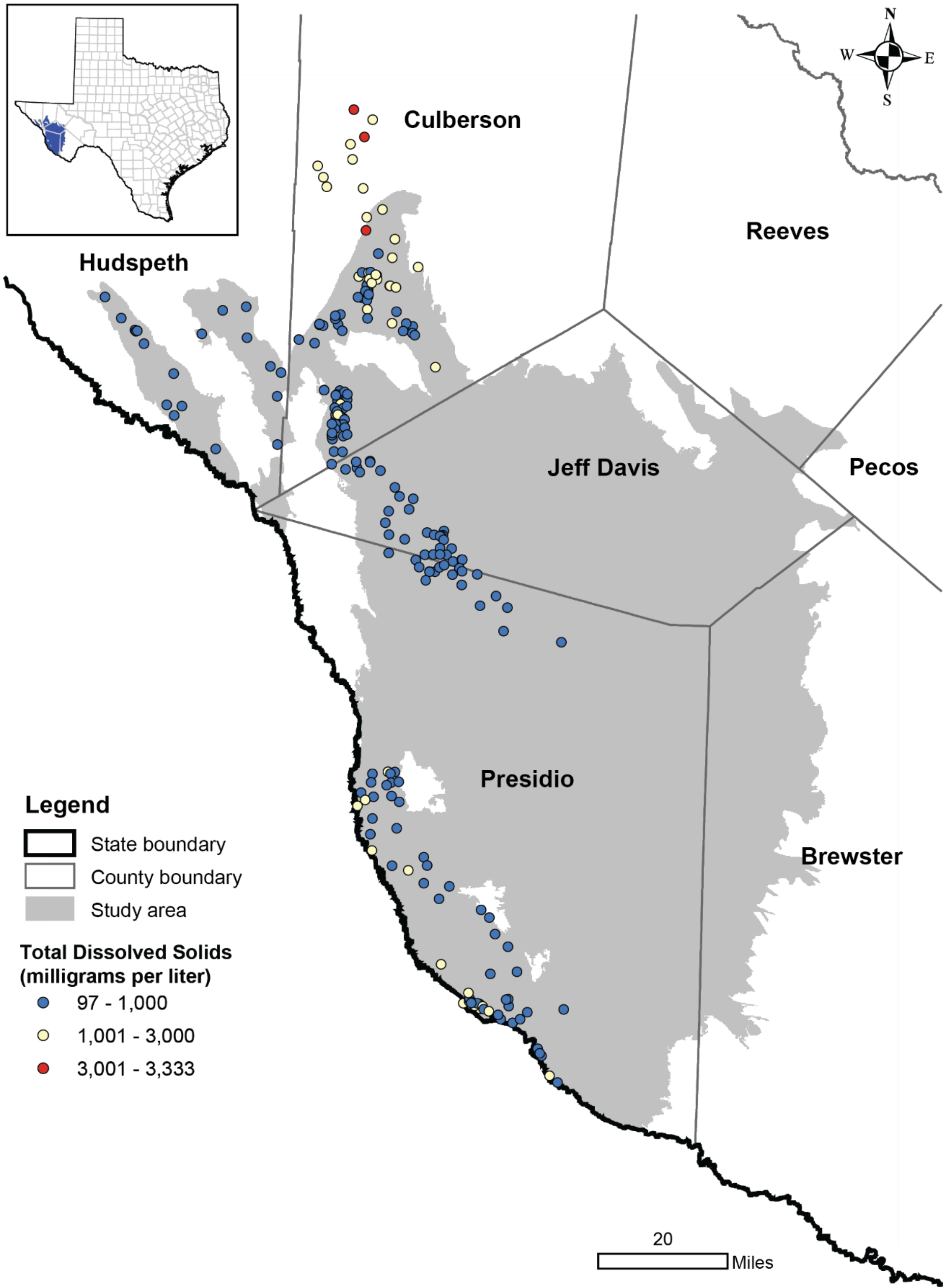


Figure 4.7.2. Total dissolved solids concentration (in milligrams per liter) in the West Texas Bolsons Aquifer (data from TWDB, 2022a).

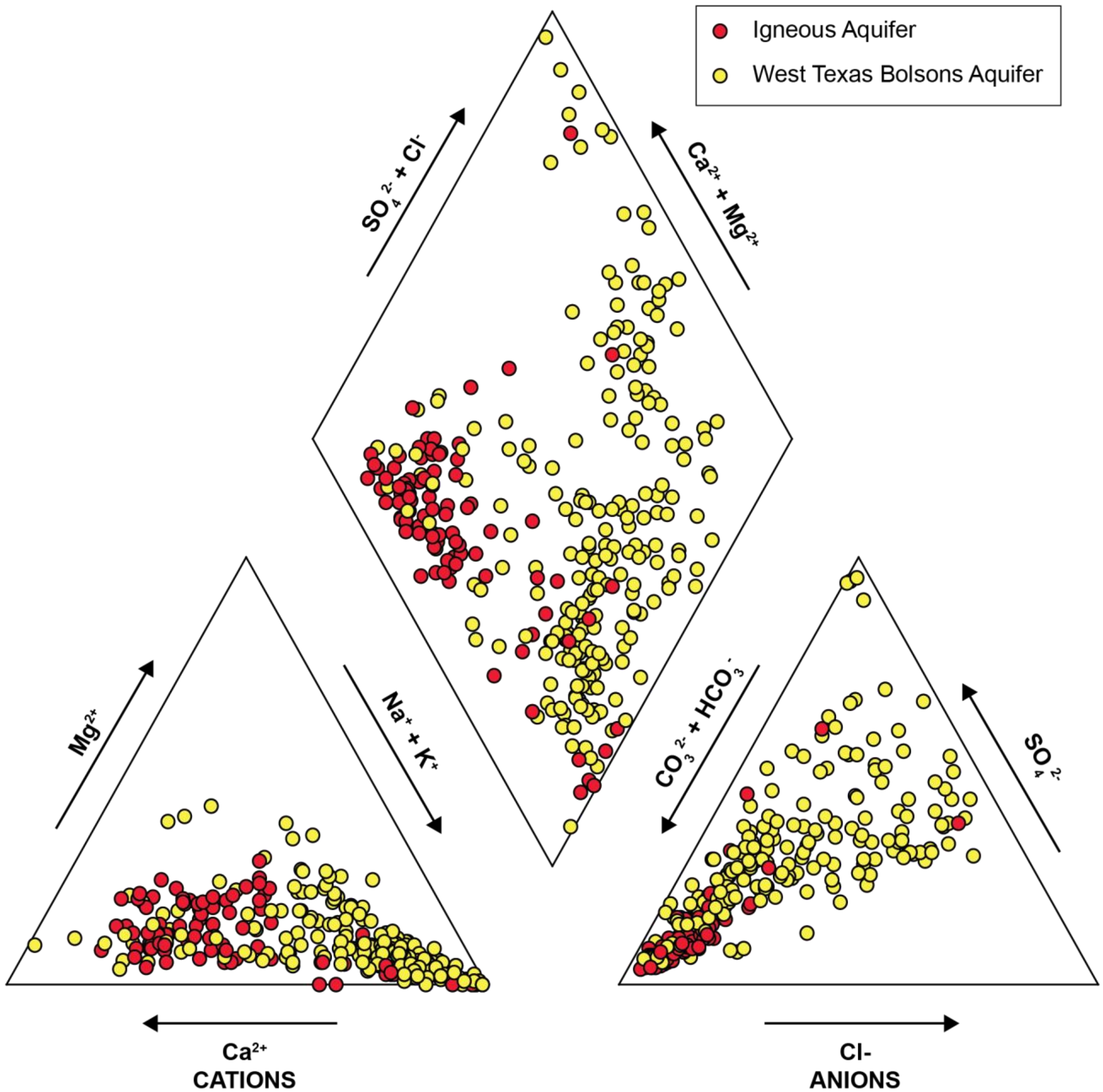


Figure 4.7.3. **A Piper diagram showing the range of groundwater compositions in the Igneous Aquifer (red dots) and the overlying West Texas Bolsons Aquifer (yellow dots) (data from TWDB, 2022a).**

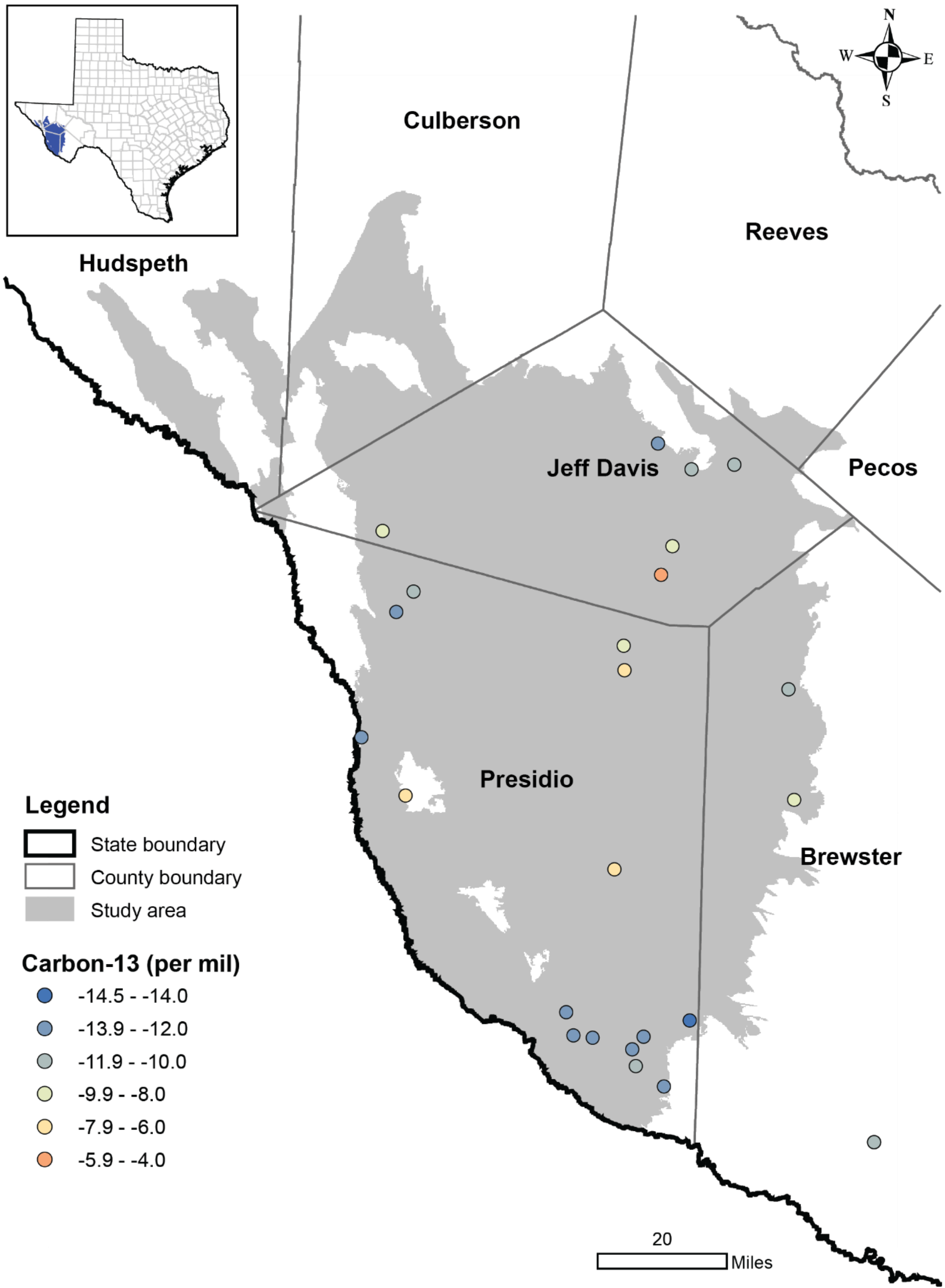


Figure 4.7.4. Groundwater carbon-13 isotopes (in per mil) in the Igneous Aquifer (data from TWDB, 2022a).

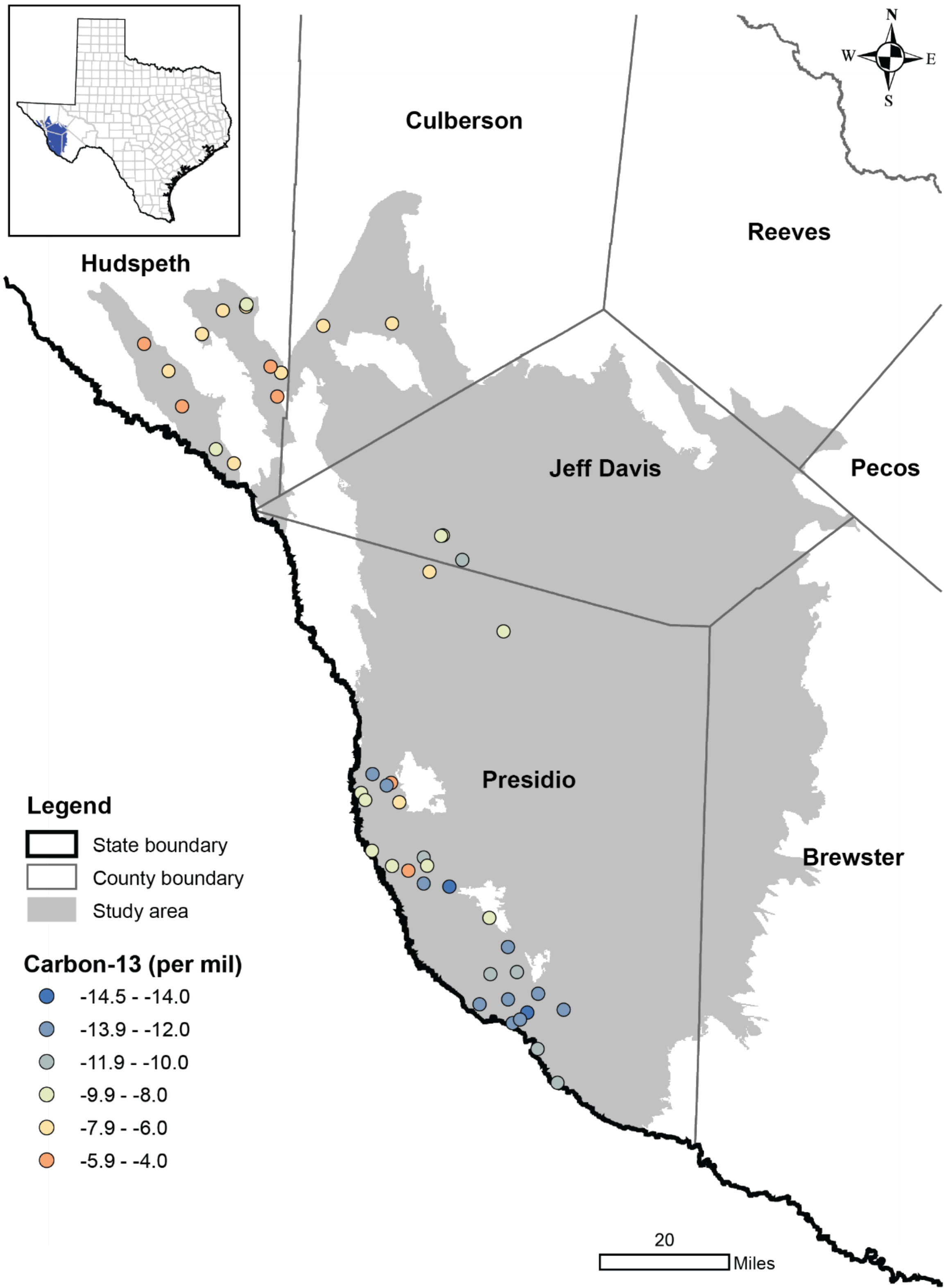


Figure 4.7.5. Groundwater carbon-13 isotopes (in per mil) in the West Texas Bolsons Aquifer (data from TWDB, 2022a).

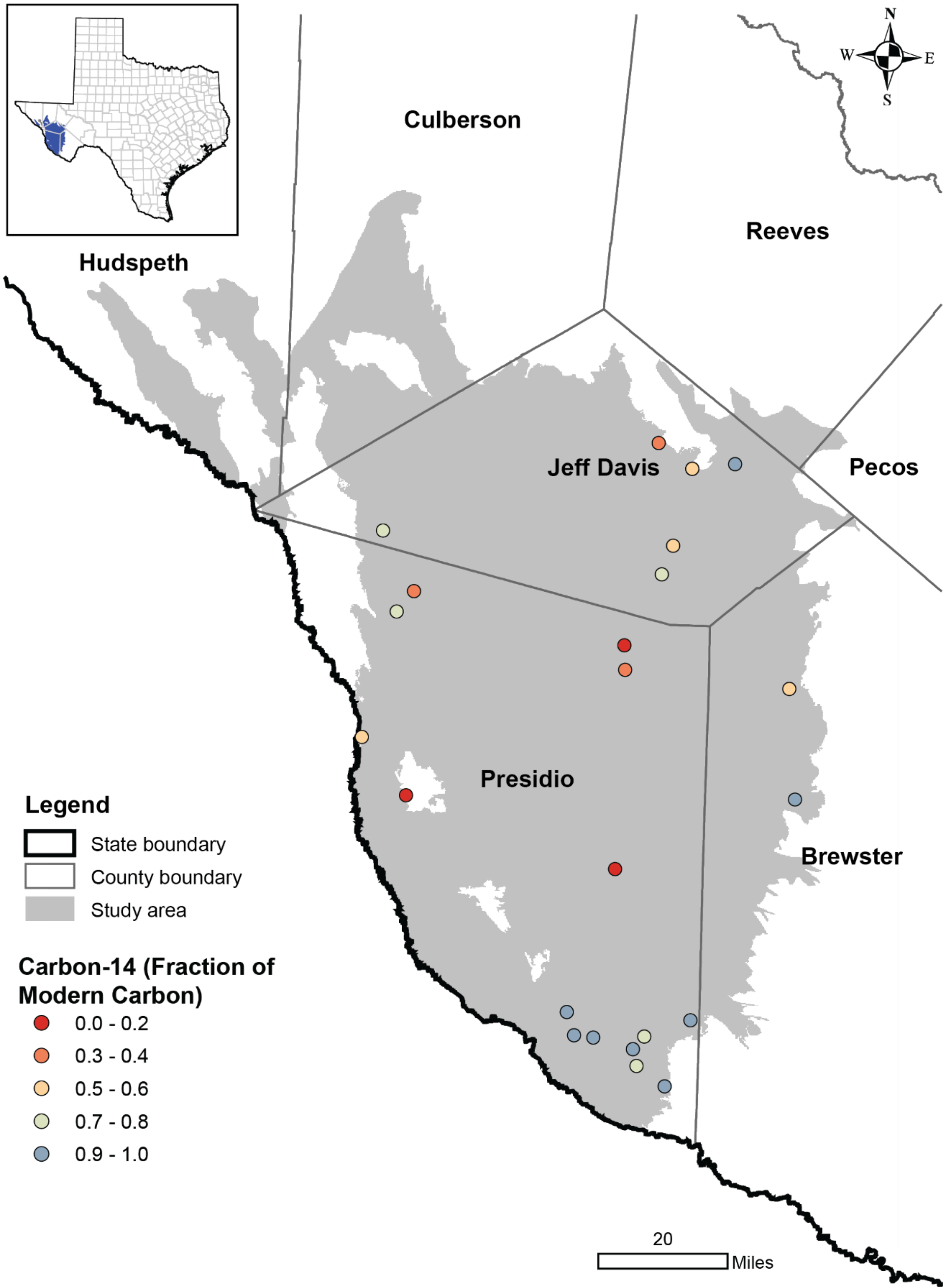


Figure 4.7.6. **Groundwater carbon-14 (in fraction of modern carbon) in the Igneous Aquifer (data from TWDB, 2022a).**

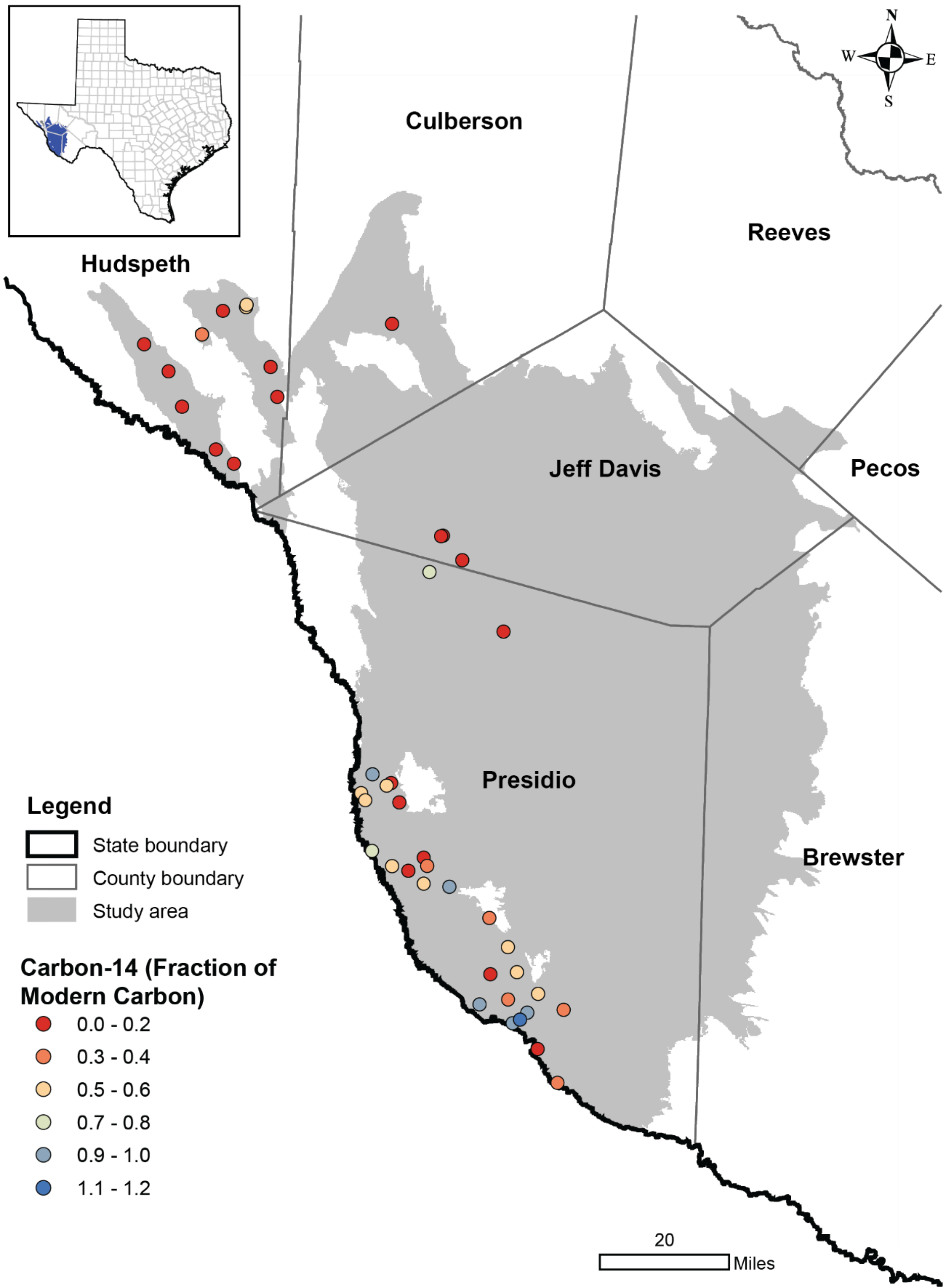


Figure 4.7.7. Groundwater carbon-14 (in fraction of modern carbon) in the West Texas Bolsons Aquifer (data from TWDB, 2022a).

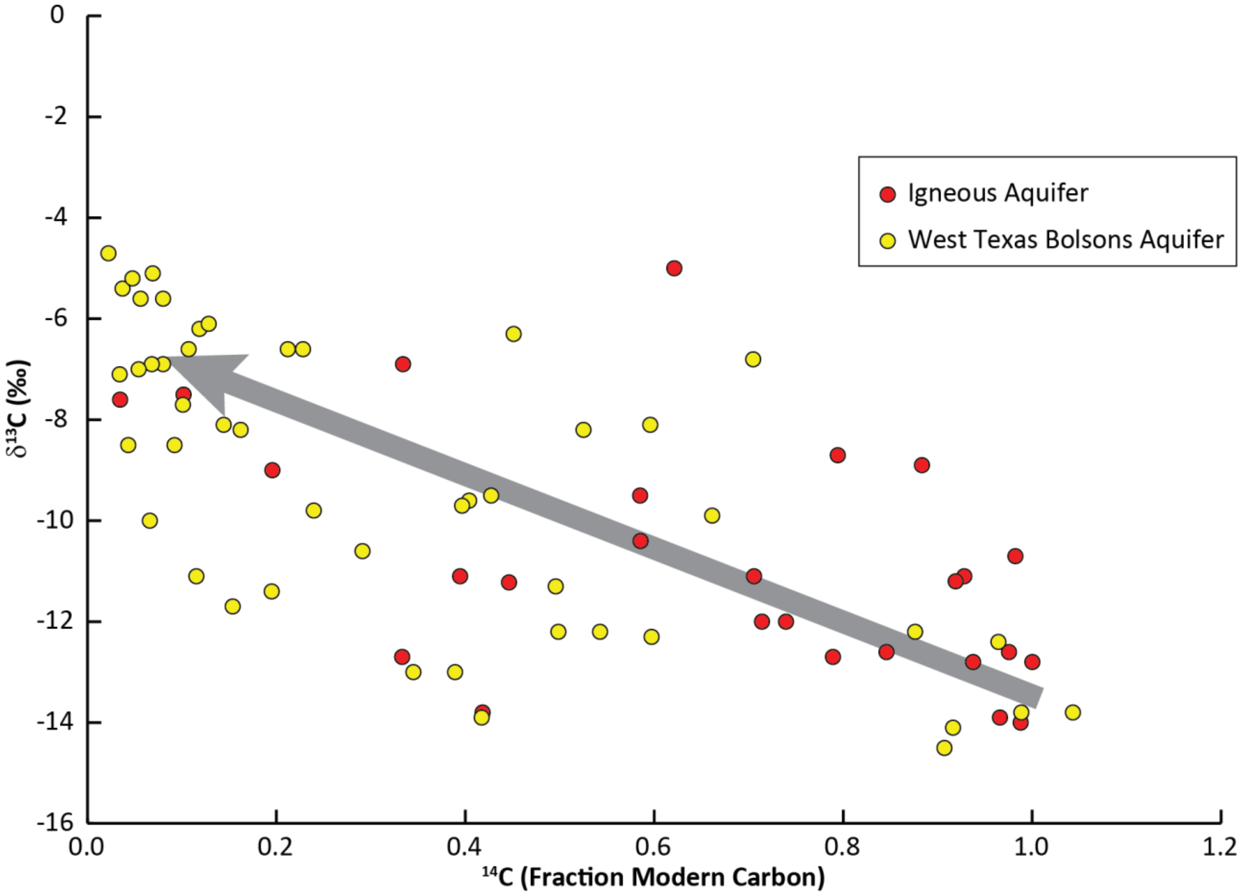


Figure 4.7.8. Groundwater carbon-13 and carbon-14 isotopes in the Igneous and West Texas Bolsons aquifers. The arrow indicates down-gradient groundwater compositions (data from TWDB, 2022a).

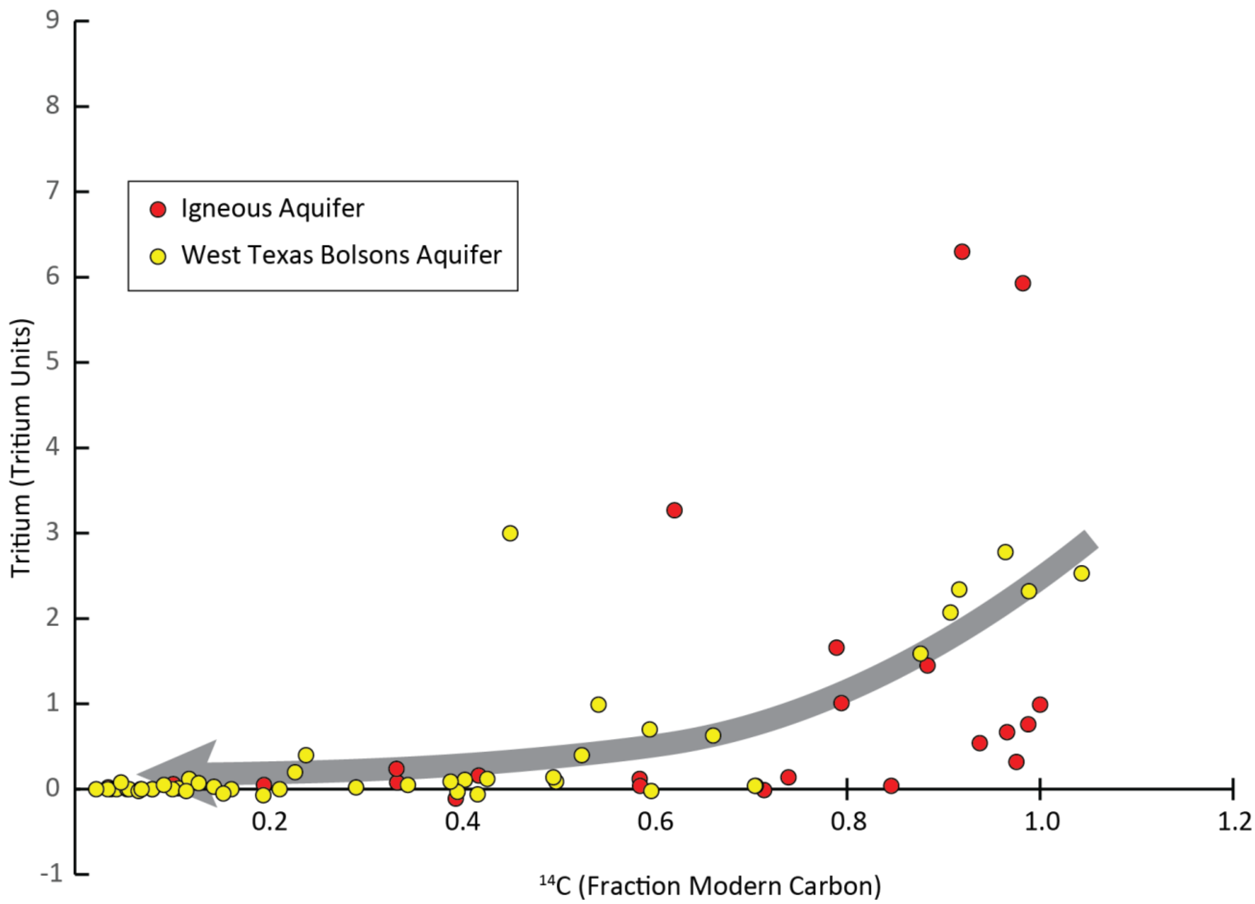


Figure 4.7.9. Groundwater tritium and carbon-14 isotopes in the Igneous and West Texas Bolsons aquifers. The arrow indicates down-gradient groundwater compositions (data from TWDB, 2022a).

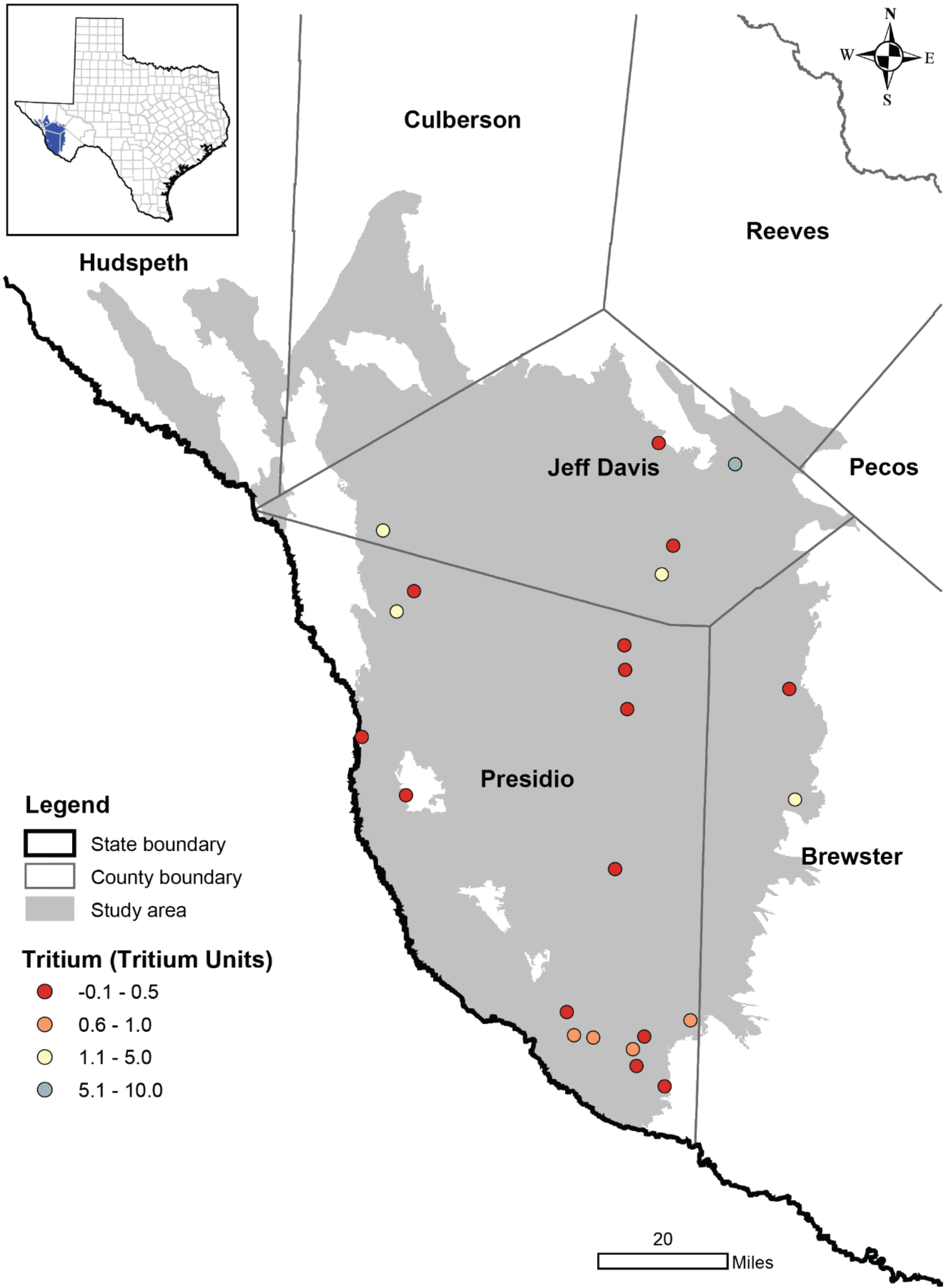


Figure 4.7.10. Groundwater tritium (in Tritium Units) in the Igneous Aquifer (data from TWDB, 2022a).

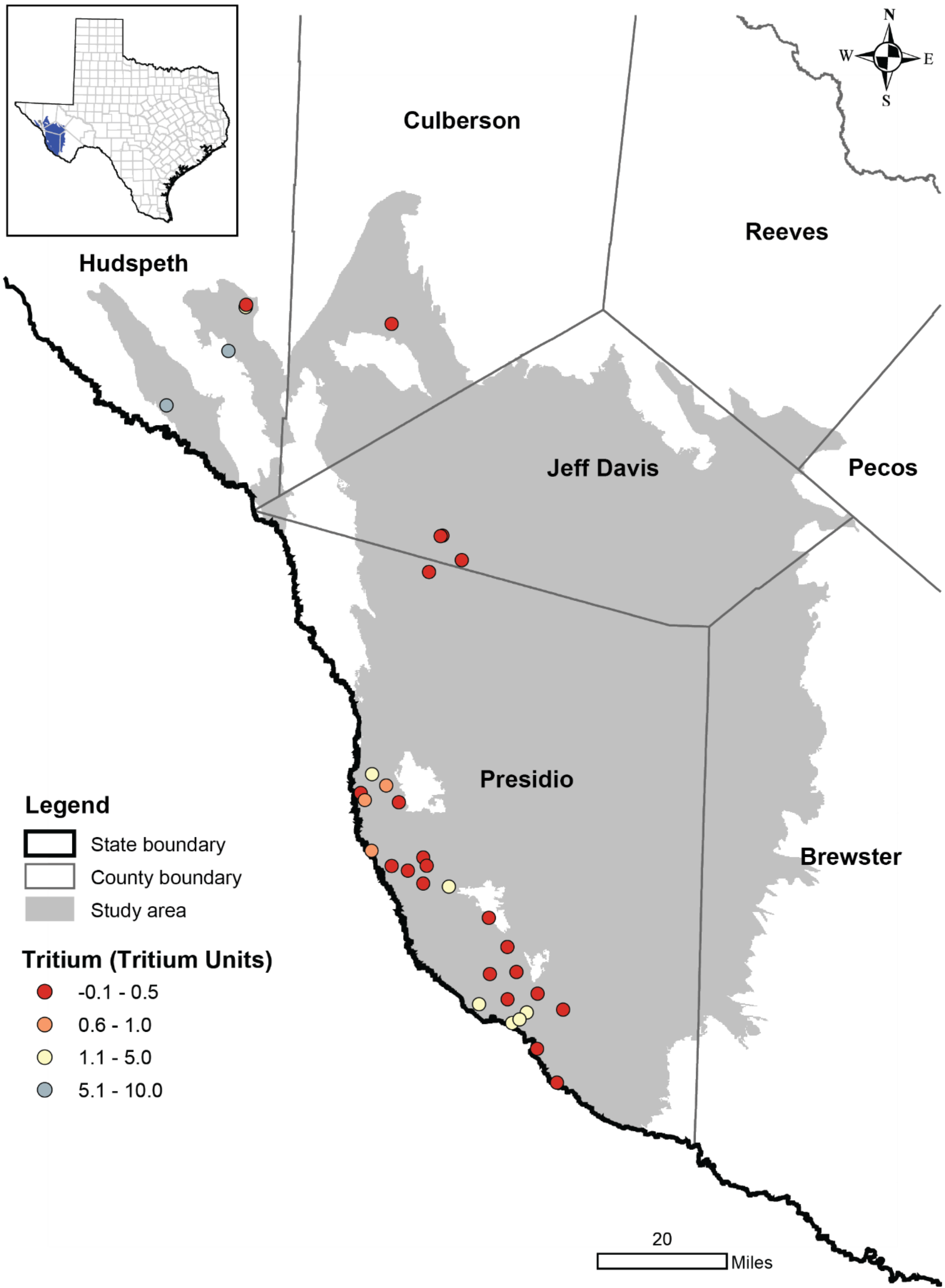


Figure 4.7.11. Groundwater tritium (in Tritium Units) in the West Texas Bolsons Aquifer (data from TWDB, 2022a).

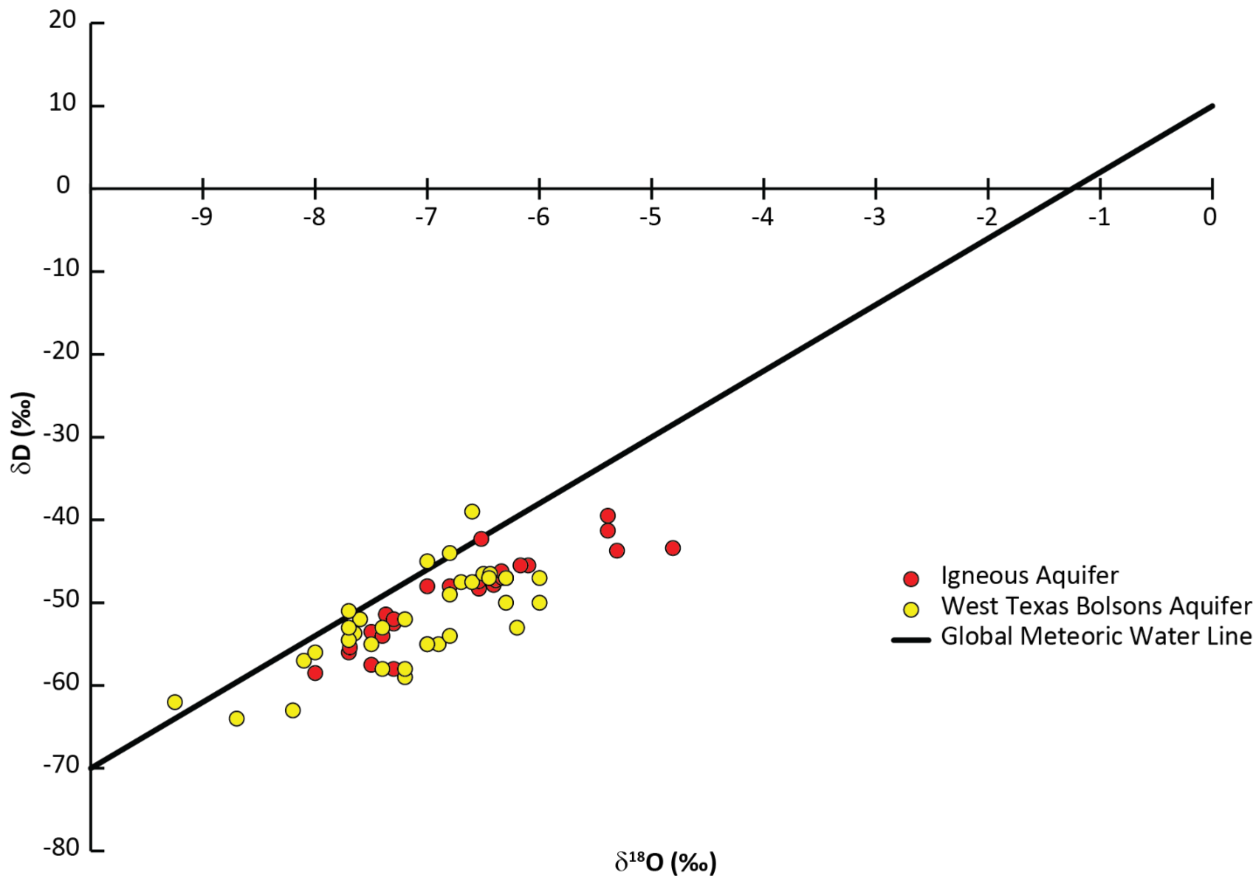


Figure 4.7.12. Groundwater stable oxygen isotopes ($\delta^{18}O$, in per mil) and stable hydrogen isotopes ($\delta^{2}H$, in per mil) in the Igneous and West Texas Bolsons aquifers (data from TWDB, 2022a).

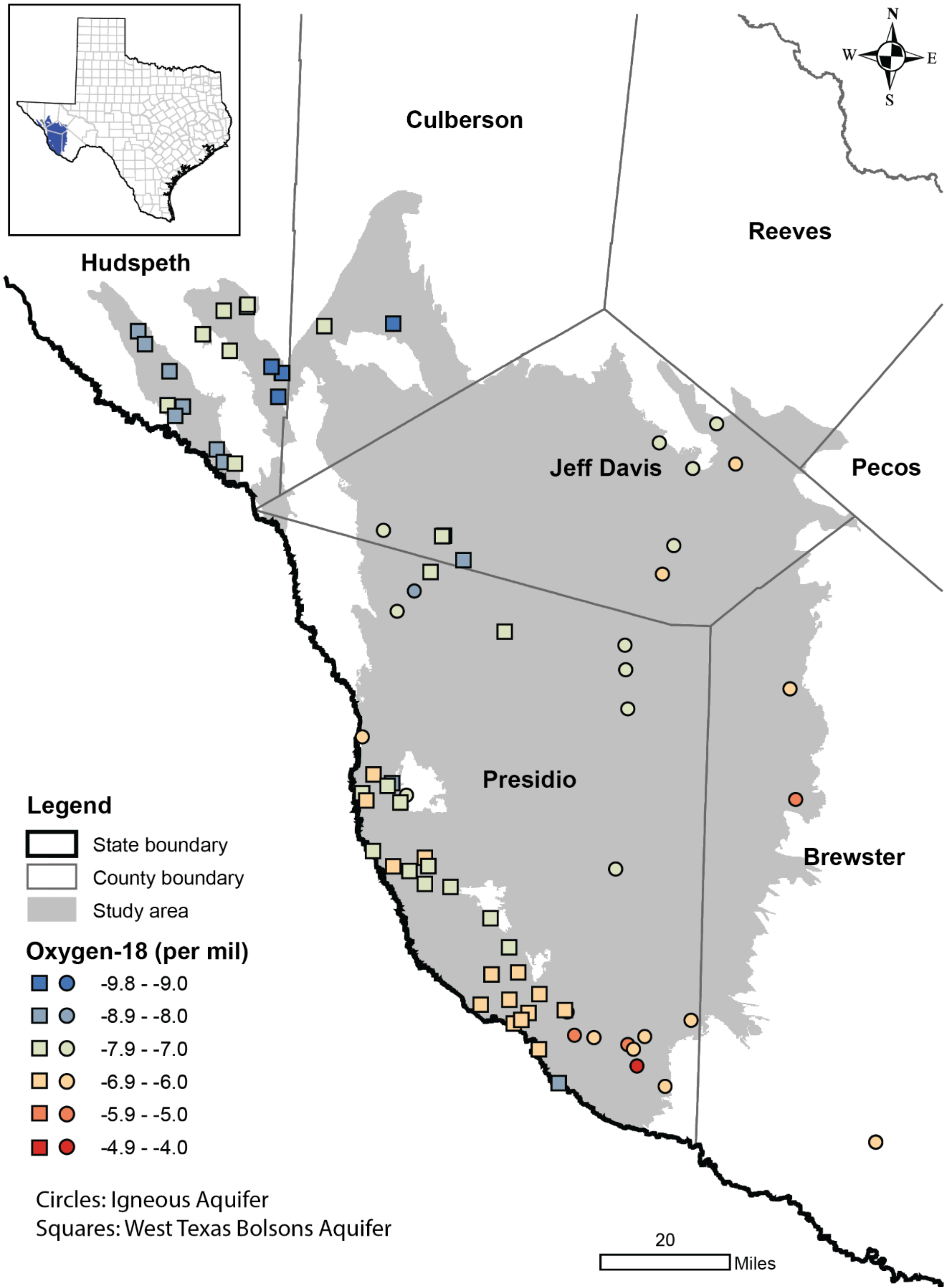


Figure 4.7.13. Groundwater stable oxygen isotopes ($\delta^{18}O$, in per mil) in the Igneous and West Texas Bolsons aquifers (data from TWDB, 2022a).

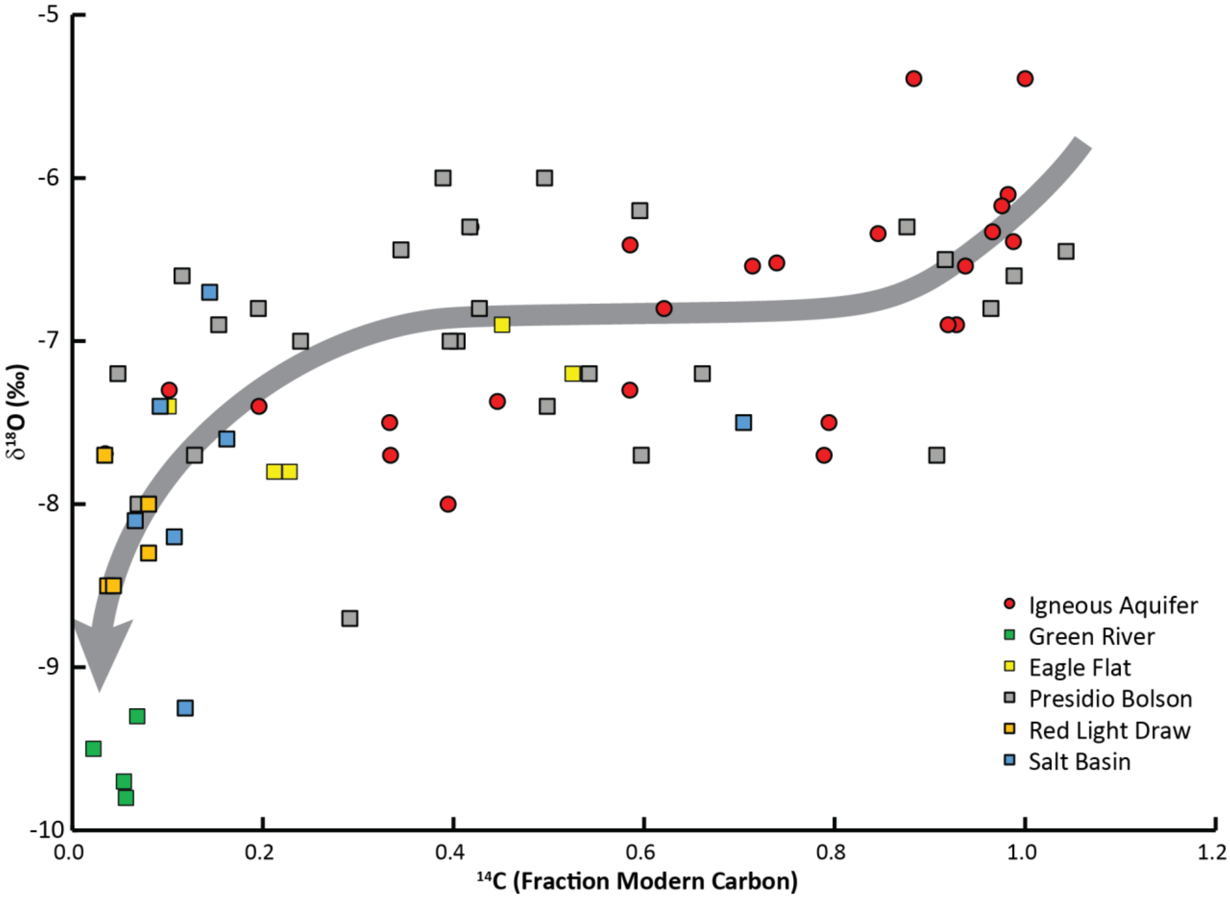


Figure 4.7.14. Groundwater stable oxygen and carbon-14 isotopes in the Igneous and West Texas Bolsons aquifers. The arrow indicates increasing groundwater age compositions (data from TWDB, 2022a).

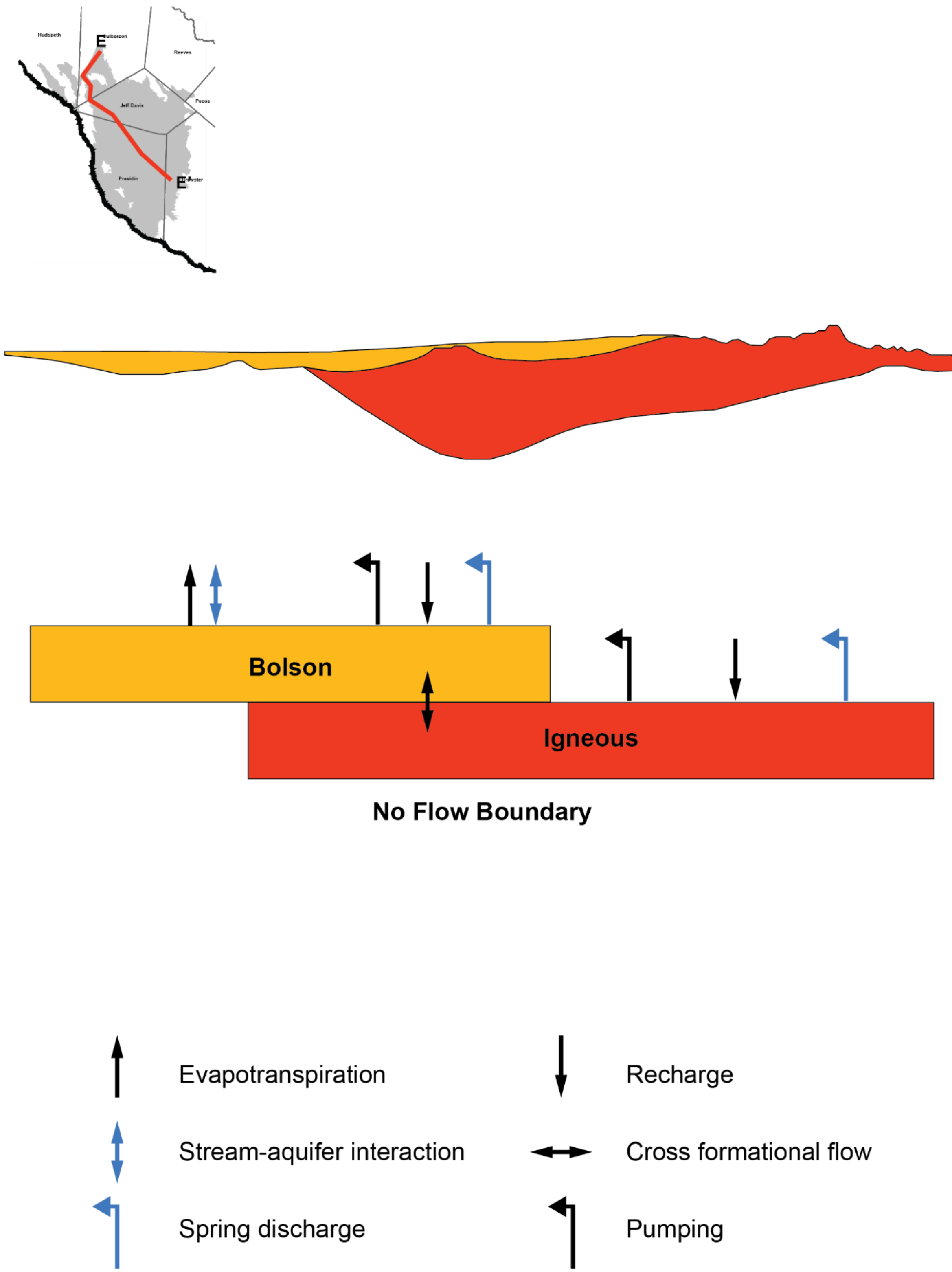
5.0 CONCEPTUAL MODEL OF GROUNDWATER FLOW IN THE IGNEOUS AND WEST TEXAS BOLSONS AQUIFERS

The conceptual model of groundwater flow in the Igneous and West Texas Bolsons aquifers 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 these aquifers. It includes the hydrostratigraphy, hydrogeologic framework, hydraulic properties, hydrologic boundaries, recharge, and discharge.

The Igneous and West Texas Bolsons aquifers extend over most of Jeff Davis and Presidio counties and include parts of Brewster, Culberson, Hudspeth, and Reeves counties. The Igneous Aquifer and West Texas Bolsons Aquifer are composed of the Tertiary volcanic and overlying Quaternary alluvium, respectively, that occur in the study area (Figure 2.2.1).

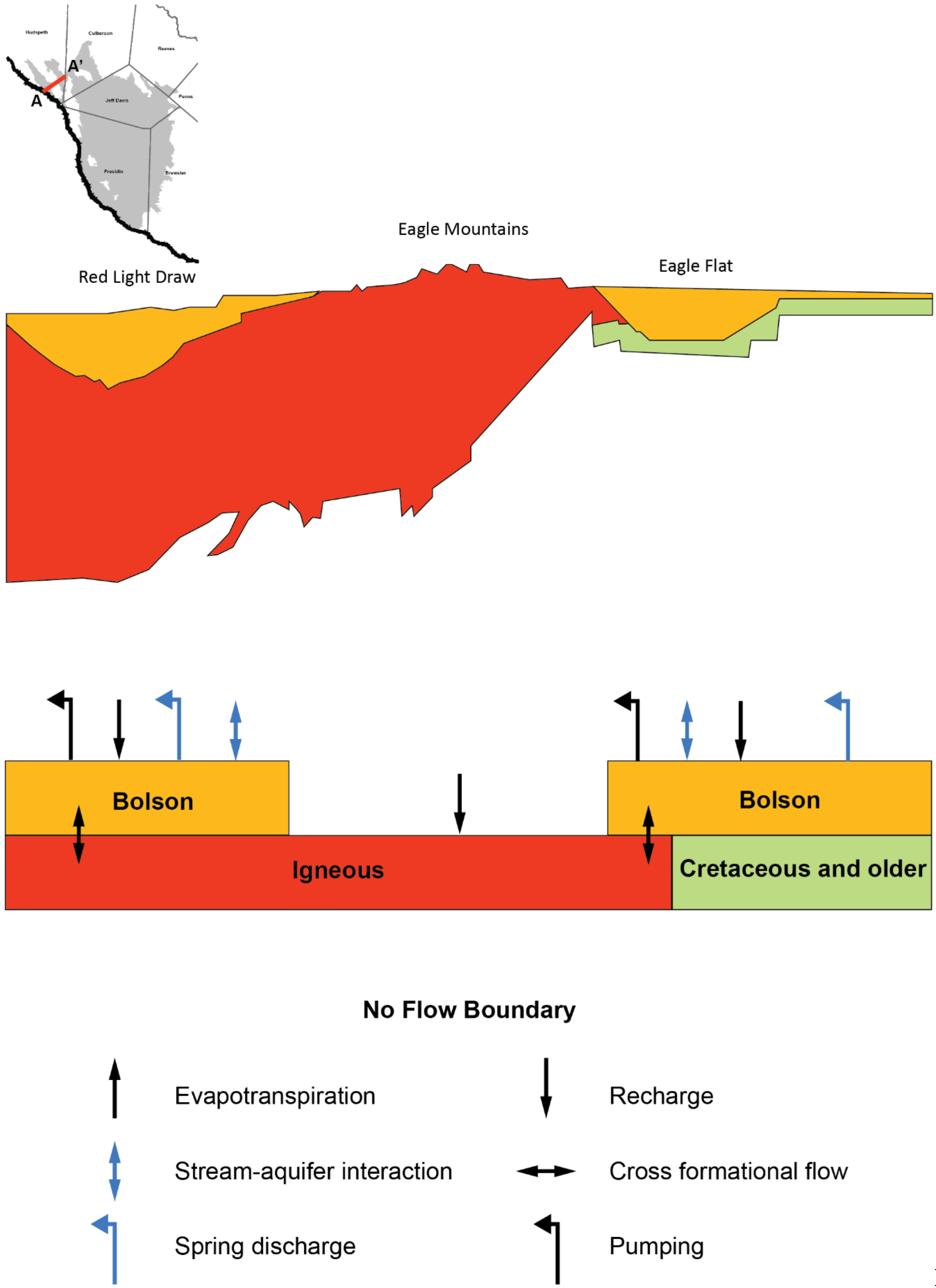
TWDB groundwater level data (Beach and others, 2004; TWDB, 2022a) indicate that groundwater flow through the Igneous Aquifer generally radiates from the Davis Mountains (Figure 4.2.4). Beach and others (2004, 2008), Wade and Jigmond (2013), and TWDB (2022a) indicate that in the West Texas Bolsons Aquifer, groundwater flow converges on the Rio Grande in the Green River Valley, Presidio Bolson, Red Light Draw, and Redford Bolson (Figure 4.2.6). The remaining bolsons are closed basins. There is no apparent surface water discharge in Eagle Flat. In the Salt Basin—Ryan Flat, Lobo Flat, Michigan Flat, and Wild Horse Flat—groundwater flows northward from one bolson to the next, eventually discharging by evapotranspiration in the salt flats located north of the study area. The Igneous and West Texas Bolsons aquifers recharge by infiltration of precipitation or resultant runoff along the margins of the mountains in the study area as noted in Sections 4.3 and 4.7.2. Groundwater isotopes indicate that most groundwater in the Igneous and West Texas Bolsons aquifer is ancient, characteristic of recharge during the Pleistocene epoch. Evidence of recent recharge is restricted to the Presidio Bolson portion of the West Texas Bolsons Aquifer and southernmost parts of the Igneous Aquifer.

Figure 5.0.1 is two cross-sections through the study area and proposed conceptual block diagrams illustrating aquifer contact relationships and sources and sinks of groundwater in the Igneous and West Texas Bolsons aquifers and the underlying stratigraphic units. The conceptual model block diagram differs from the conceptual models used in the previous groundwater availability models of the Igneous and West Texas Bolsons aquifers by Beach and others (2004, 2008) and Wade and Jigmond (2013) which were all three-layer models. The proposed conceptual model is a two-layer model representing the West Texas Bolsons Aquifer (Layer 1) and the Igneous Aquifer and the underlying non-aquifer stratigraphic units (Layer 2). The non-aquifer stratigraphic units underly the three westernmost bolsons—Red Light Draw, Eagle Flat, and Green River Valley—and the Presidio and Redford bolsons.



A

Figure 5.0.1. **Schematic cross-section and conceptual groundwater flow model for the Igneous and West Texas Bolsons aquifers groundwater availability model.**



B

Figure 5.0.1. (continued). Schematic cross-section and conceptual groundwater flow model for the Igneous and West Texas Bolsons aquifers groundwater availability model.

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 acknowledge staff who reviewed and otherwise contributed to this conceptual model report.

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APPENDIX A. AQUIFER DATA TABLES

Table A1. Hydraulic property data from wells shown in Figures 4.5.1 through 4.5.3.

Well Number	County	Aquifer	Latitude	Longitude	Hydraulic Conductivity (feet per day)
4845602	Hudspeth	Cretaceous System	31.3053	-105.4069	31
4845603	Hudspeth	Cretaceous System	31.2992	-105.3975	17
4853801	Hudspeth	Cretaceous System	31.1419	-105.4417	279
4853802	Hudspeth	Cretaceous System	31.1436	-105.4414	13
4853803	Hudspeth	Cretaceous System	31.1478	-105.4417	0.33
4854503	Hudspeth	Cretaceous System	31.1675	-105.3264	7
4854902	Hudspeth	Cretaceous System	31.1450	-105.2622	0.05
4854903	Hudspeth	Cretaceous System	31.1361	-105.2850	0.06
4854904	Hudspeth	Cretaceous System	31.1397	-105.2542	0.01
4862301	Hudspeth	Cretaceous System	31.1133	-105.2672	0.01
4863101	Hudspeth	Cretaceous System	31.1000	-105.2222	0.34
4864502	Hudspeth	West Texas Bolsons	31.0658	-105.0831	0.54
7403305	Presidio	West Texas Bolsons	29.9931	-104.6475	0.45
7429604	Presidio	West Texas Bolsons	29.5689	-104.3889	1,977
7429606	Presidio	West Texas Bolsons	29.5786	-104.3992	2,356
7429612	Presidio	West Texas Bolsons	29.5575	-104.3917	0.98
7429617	Presidio	West Texas Bolsons	29.5686	-104.3769	30
7430606	Presidio	West Texas Bolsons	29.5706	-104.2783	13
7439202	Presidio	West Texas Bolsons	29.4636	-104.1992	2
7439904	Presidio	West Texas Bolsons	29.4047	-104.1664	0.52
4743503	Culberson	West Texas Bolsons	31.3279	-104.6713	6
4750901	Culberson	West Texas Bolsons	31.1332	-104.7547	5
4751403	Culberson	West Texas Bolsons	31.1874	-104.7283	45
4751717	Culberson	West Texas Bolsons	31.1421	-104.7441	11
4751718	Culberson	West Texas Bolsons	31.1279	-104.7302	5
4751807	Culberson	West Texas Bolsons	31.1451	-104.7030	23
4758309	Culberson	West Texas Bolsons	31.1026	-104.7744	11
4758310	Culberson	West Texas Bolsons	31.1024	-104.7608	15
4758311	Culberson	West Texas Bolsons	31.0924	-104.7813	38
4758502	Culberson	West Texas Bolsons	31.0428	-104.8256	11
4758505	Culberson	West Texas Bolsons	31.0431	-104.8236	9
4758602	Culberson	West Texas Bolsons	31.0462	-104.7838	26
4758602	Culberson	West Texas Bolsons	31.0462	-104.7838	33
4759102	Culberson	West Texas Bolsons	31.0946	-104.7147	28
4759116	Culberson	West Texas Bolsons	31.1024	-104.7472	9
4759117	Culberson	West Texas Bolsons	31.0921	-104.7405	30

Table A1. (continued). Hydraulic property data from wells shown in Figures 4.5.1 through 4.5.3.

Well Number	County	Aquifer	Latitude	Longitude	Hydraulic Conductivity (feet per day)
4759120	Culberson	West Texas Bolsons	31.1210	-104.7438	20
4759209	Culberson	West Texas Bolsons	31.0843	-104.6766	18
4759307	Culberson	West Texas Bolsons	31.1215	-104.6513	13
4759404	Culberson	West Texas Bolsons	31.0821	-104.7335	14
4759603	Culberson	West Texas Bolsons	31.0540	-104.6449	71
4760404	Culberson	West Texas Bolsons	31.0490	-104.5922	5
5102906	Culberson	West Texas Bolsons	30.9004	-104.7738	68
5102918	Culberson	West Texas Bolsons	30.8762	-104.7810	5
5102923	Culberson	West Texas Bolsons	30.8901	-104.7824	79
5102926	Culberson	West Texas Bolsons	30.8810	-104.7527	28
5103702	Culberson	West Texas Bolsons	30.8968	-104.7483	18
5103703	Culberson	West Texas Bolsons	30.8862	-104.7363	2
5110306	Culberson	West Texas Bolsons	30.8549	-104.7719	10
5110309	Culberson	West Texas Bolsons	30.8363	-104.7644	38
5110316	Culberson	West Texas Bolsons	30.8476	-104.7644	36
5110317	Culberson	West Texas Bolsons	30.8501	-104.7616	14
5110321	Culberson	West Texas Bolsons	30.8363	-104.7797	40
5110322	Culberson	West Texas Bolsons	30.8363	-104.7713	11
5110328	Culberson	West Texas Bolsons	30.8471	-104.7747	39
5110331	Culberson	West Texas Bolsons	30.8435	-104.7574	23
5110332	Culberson	West Texas Bolsons	30.8599	-104.7524	61
5110624	Culberson	West Texas Bolsons	30.8268	-104.7816	3
5111106	Culberson	West Texas Bolsons	30.8429	-104.7463	11
5119104	Jeff Davis	West Texas Bolsons	30.7313	-104.7194	16
5120404	Jeff Davis	West Texas Bolsons	30.6804	-104.6210	3
5127302	Jeff Davis	West Texas Bolsons	30.5954	-104.6460	4
5128303	Jeff Davis	West Texas Bolsons	30.5901	-104.5149	1
5128606	Jeff Davis	West Texas Bolsons	30.5760	-104.5144	2
5128803	Presidio	West Texas Bolsons	30.5324	-104.5483	9
5128903	Presidio	West Texas Bolsons	30.5035	-104.5135	1
5128904	Presidio	West Texas Bolsons	30.5182	-104.5138	3
5128907	Presidio	West Texas Bolsons	30.5035	-104.5308	15
5129403	Jeff Davis	West Texas Bolsons	30.5471	-104.4644	3

Table A1. (continued). Hydraulic property data from wells shown in Figures 4.5.1 through 4.5.3.

Well Number	County	Aquifer	Latitude	Longitude	Hydraulic Conductivity (feet per day)
5129404	Jeff Davis	West Texas Bolsons	30.5474	-104.4805	14
5129406	Jeff Davis	West Texas Bolsons	30.5615	-104.4977	2
5129702	Jeff Davis	West Texas Bolsons	30.5332	-104.4635	29
5129704	Jeff Davis	West Texas Bolsons	30.5324	-104.4821	2
5129705	Jeff Davis	West Texas Bolsons	30.5329	-104.4969	9
5129706	Presidio	West Texas Bolsons	30.5188	-104.4641	10
5129806	Presidio	West Texas Bolsons	30.5043	-104.4296	87
5129808	Presidio	West Texas Bolsons	30.5188	-104.4463	12
5136601	Presidio	West Texas Bolsons	30.4529	-104.5363	33
52431	Brewster	Igneous	30.3631	-103.7131	228
52358	Brewster	Igneous	30.3800	-103.6725	571
51244	Jeff Davis	Igneous	30.7052	-104.1130	10
52428	Presidio	Igneous	30.2836	-103.8156	21
52358	Brewster	Igneous	30.3736	-103.7369	8
52253	Jeff Davis	Igneous	30.5872	-103.8994	280
52604	Brewster	Igneous	30.1103	-103.6508	27
52359	Brewster	Igneous	30.3839	-103.6525	8
52253	Jeff Davis	Igneous	30.5900	-103.9000	721
51145	Jeff Davis	Igneous	30.8103	-104.2572	12
52267	Jeff Davis	Igneous	30.5286	-103.8564	3
52608	Brewster	Igneous	30.0350	-103.5597	10
52253	Jeff Davis	Igneous	30.5914	-103.8908	7
52268	Jeff Davis	Igneous	30.5278	-103.8219	0.40
52255	Jeff Davis	Igneous	30.5419	-103.9344	2,547
52255	Jeff Davis	Igneous	30.5442	-103.9272	19
52255	Jeff Davis	Igneous	30.5450	-103.9275	7
52255	Jeff Davis	Igneous	30.5467	-103.9294	325
52255	Jeff Davis	Igneous	30.5475	-103.9275	1
52433	Brewster	Igneous	30.3597	-103.6494	127
52432	Brewster	Igneous	30.3511	-103.6992	222
74142	Presidio	Igneous	29.8558	-104.3256	753
52343	Jeff Davis	Igneous	30.4978	-103.7525	41
52253	Jeff Davis	Igneous	30.5864	-103.9006	5

Table A1. (continued). Hydraulic property data from wells shown in Figures 4.5.1 through 4.5.3.

Well Number	County	Aquifer	Latitude	Longitude	Hydraulic Conductivity (feet per day)
51483	Presidio	Igneous	30.3646	-104.0178	9
52431	Brewster	Igneous	30.3722	-103.7142	79
52431	Brewster	Igneous	30.3819	-103.7381	6
52354	Brewster	Igneous	30.4539	-103.7161	3
51483	Presidio	Igneous	30.3634	-104.0133	7
52357	Brewster	Igneous	30.3803	-103.7339	6
51445	Presidio	Igneous	30.3200	-104.5731	0.10
51486	Presidio	Igneous	30.3142	-104.0208	1,808
51486	Presidio	Igneous	30.3153	-104.0167	2

Table A2. Estimates of Igneous and West Texas Bolsons aquifers irrigation pumping. The data—expressed in acre-feet per year (AFY)—was taken from Texas Water Development Board (2022b).

Igneous Aquifer						
Year	Brewster	Culberson	Hudspeth	Jeff Davis	Presidio	Reeves
1980	0.0			3,120	600	
1981	38			2,409	506	
1982	75			1,697	412	
1983	113			986	318	
1984	150			274	224	
1985	351			244	239	
1986	351			373	152	
1987	351			273	35	
1988	351			514	163	
1989	84			193	289	
1990	106			352	289	
1991	106			268	31	
1992	106			291	163	
1993	116			21	130	
1994	0.0			132	575	
1995	0.0			120	656	
1996	0.0			120	672	
1997	0.0			120	1,059	
1998	0.0			120	1,065	
1999	0.0			120	704	
2000	191	451		395	542	392
2001	137	301		433	513	353
2002	137	396		1,623	1,085	331
2003	177	401		2,184	869	137
2004	186	351		2,683	930	229
2005	339	400		2,700	791	117
2006	598	374		2,709	687	117
2007	873	306		1,820	317	78
2008	867	629		1,776	490	0.0
2009	657	702		1,463	605	276
2010	1,236	769		455	574	254
2011	418	648		467	256	292
2012	137	1,010		1,118	264	247

Table A2. (continued). **Estimates of Igneous and West Texas Bolsons aquifers irrigation pumping. The data—expressed in acre-feet per year (AFY)—was taken from Texas Water Development Board (2022b).**

Igneous Aquifer						
Year	Brewster	Culberson	Hudspeth	Jeff Davis	Presidio	Reeves
2013	146	485		718	382	207
2014	679	533		840	358	252
2015	259	831		794	388	230
2016	407	644		692	396	336
2017	309	767		604	379	474
2018	433	651		588	317	287
2019	506	669		667	128	322
2020	513	558		610	195	339

West Texas Bolsons Aquifer						
Year	Brewster	Culberson	Hudspeth	Jeff Davis	Presidio	Reeves
1980		50,868	3,500	22,880	11,400	
1981		42,401	2,625	17,660	9,331	
1982		33,934	1,750	12,440	7,263	
1983		25,467	875	7,220	5,194	
1984		17,000	0.0	2,000	3,125	
1985		21,055	0.0	1,784	3,324	
1986		16,406	0.0	2,722	2,113	
1987		16,462	0.0	2,000	494	
1988		16,321	0.0	3,758	2,272	
1989		11,993	0.0	1,410	4,028	
1990		7,751	0.0	2,572	4,028	
1991		7,471	0.0	1,958	429	
1992		8,832	0.0	2,128	2,259	
1993		4,737	0.0	152	1,809	
1994		5,583	0.0	59	1,150	
1995		5,885	0.0	53	1,313	
1996		6,196	0.0	53	1,344	
1997		6,751	0.0	53	2,119	
1998		11,702	0.0	53	2,131	
1999		11,702	0.0	53	1,407	

Table A2. (continued). Estimates of Igneous and West Texas Bolsons aquifers irrigation pumping. The data—expressed in acre-feet per year (AFY)—was taken from Texas Water Development Board (2022b).

West Texas Bolsons Aquifer						
Year	**Brewster**	**Culberson**	**Hudspeth**	**Jeff Davis**	**Presidio**	**Reeves**
2000		19,361		45	759	
2001		12,936		60	735	
2002		16,995		513	888	
2003		17,208		727	711	
2004		15,058		917	761	
2005		17,174		899	647	
2006		16,083		902	562	
2007		13,136		564	260	
2008		27,004		561	401	
2009		30,169		441	495	
2010		33,033		62	469	
2011		27,845		67	209	
2012		43,376		315	216	
2013		20,845		177	313	
2014		22,908		195	293	
2015		35,714		178	318	
2016		27,655		165	324	
2017		32,932		146	310	
2018		27,962		162	259	
2019		28,758		144	502	
2020		23,980		145	659	

Table A3. Estimates of Igneous and West Texas Bolsons aquifers livestock pumping. The data—expressed in acre-feet per year (AFY)—was taken from Texas Water Development Board (2022b).

Igneous Aquifer						
Year	Brewster	Culberson	Hudspeth	Jeff Davis	Presidio	Reeves
1980	280			96	100	
1981	248			90	102	
1982	215			84	105	
1983	183			77	107	
1984	150			71	109	
1985	140			76	123	
1986	183			57	71	
1987	220			44	68	
1988	244			50	79	
1989	241			78	102	
1990	238			77	101	
1991	243			78	103	
1992	180			78	102	
1993	180			68	102	
1994	266			66	123	
1995	239			56	102	
1996	202			56	78	
1997	207			54	78	
1998	207			79	128	
1999	234			84	140	
2000	224	17		72	128	23
2001	202	15		77	128	21
2002	165	24		73	112	20

Table A3. (continued) Estimates of Igneous and West Texas Bolsons aquifers livestock pumping. The data—expressed in acre-feet per year (AFY)—was taken from Texas Water Development Board (2022b).

Igneous Aquifer						
Year	**Brewster**	**Culberson**	**Hudspeth**	**Jeff Davis**	**Presidio**	**Reeves**
2003	86	13		54	74	14
2004	79	14	6	240	198	17
2005	103	11	5	239	202	20
2006	93	13	6	228	192	25
2007	103	15	6	239	174	16
2008	112	15	6	299	224	14
2009	102	14	7	268	217	18
2010	109	13	6	282	205	9
2011	107	13	7	284	207	9
2012	93	13	5	251	184	8
2013	109	14	5	201	167	14
2014	88	14	5	183	138	13
2015	89	14	5	186	140	13
2016	91	15	5	190	142	13
2017	139	13	4	291	261	6
2018	144	13	4	299	270	6
2019	144	13	4	299	270	6
2020	144	13	4	304	270	6

Table A3. (continued) Estimates of Igneous and West Texas Bolsons aquifers livestock pumping. The data—expressed in acre-feet per year (AFY)—was taken from Texas Water Development Board (2022b).

West Texas Bolsons Aquifer						
Year	**Brewster**	**Culberson**	**Hudspeth**	**Jeff Davis**	**Presidio**	**Reeves**
1980		181	68	100	205	
1981		169	64	94	204	
1982		156	61	87	203	
1983		144	57	81	201	
1984		131	53	74	200	
1985		145	30	79	226	
1986		124	18	58	131	
1987		195	28	46	125	
1988		208	31	52	145	
1989		205	31	81	187	
1990		201	30	79	184	
1991		205	30	81	188	
1992		134	35	81	186	
1993		127	33	71	185	
1994		113	45	69	223	
1995		92	34	59	185	
1996		99	30	59	141	
1997		106	29	56	141	
1998		144	51	82	231	
1999		155	55	88	253	
2000		123	51	75	229	

Table A3. (continued) Estimates of Igneous and West Texas Bolsons aquifers livestock pumping. The data—expressed in acre-feet per year (AFY)—was taken from Texas Water Development Board (2022b).

West Texas Bolsons Aquifer						
Year	**Brewster**	**Culberson**	**Hudspeth**	**Jeff Davis**	**Presidio**	**Reeves**
2001		111	48	80	229	
2002		168	45	76	202	
2003		91	35	56	133	
2004		85	55	50	93	
2005		70	54	50	95	
2006		80	59	48	90	
2007		90	58	50	82	
2008		93	62	63	105	
2009		85	70	56	102	
2010		80	64	59	96	
2011		80	69	60	97	
2012		80	53	53	86	
2013		90	48	42	78	
2014		88	50	38	65	
2015		90	49	39	66	
2016		91	51	40	67	
2017		80	37	61	123	
2018		83	38	63	127	
2019		83	39	63	127	
2020		83	40	64	127	

Table A4. Estimates of Igneous and West Texas Bolsons aquifers manufacturing pumping. The data—expressed in acre-feet per year (AFY)—was taken from Texas Water Development Board (2022b).

Igneous Aquifer						
Year	Brewster	Culberson	Hudspeth	Jeff Davis	Presidio	Reeves
1997				24		

West Texas Bolsons Aquifer						
Year	Brewster	Culberson	Hudspeth	Jeff Davis	Presidio	Reeves
1980		6	1			
1981		0.0	3			
1982		0.0	1			
1983		0.0	1			
1984		0.0	1			
1985		0.0	0.0			
1986		0.0	0.0			
1987		0.0	1			
1988		0.0	1			
1989		0.0	1			
1990		0.0	1			
1991		0.0	0.2			
1992		0.0	3			
1993		0.0	3			
1994		0.0	2			
1995		0.0	2			
1996		0.0	1			
1997		0.0	1		110	
1998		0.0	0.0			

Table A4. (continued). Estimates of Igneous and West Texas Bolsons aquifers manufacturing pumping. The data—expressed in acre-feet per year (AFY)—was taken from Texas Water Development Board (2022b).

West Texas Bolsons Aquifer						
Year	Brewster	Culberson	Hudspeth	Jeff Davis	Presidio	Reeves
1999		0.0	0.0			
2000		0.4	1			
2001		5	1			
2002		4	1			
2003		1	1			
2004		0.2				
2005		0.4				
2006		0.1				
2007		0.2				
2008		0.2				
2009		0.5				
2010		0.2				
2011		5				
2012		0.1				
2013		0.3				
2014		0.2				
2015		0.3				
2016		0.4				
2017		2				
2018		1				
2019		1				
2020		43				

Table A5. Estimates of Igneous Aquifer mining pumping. The data—expressed in acre-feet per year (AFY)—was taken from Texas Water Development Board (2022b).

West Texas Bolsons Aquifer						
Year	**Brewster**	**Culberson**	**Hudspeth**	**Jeff Davis**	**Presidio**	**Reeves**
1990			0.2			
1991			0.2			
1992			2.8			
1993			3.0			
1994			1.9			
1995			1.9			
1996			1.2			
1997			1.1			

Table A6. **Estimates of Igneous and West Texas Bolsons aquifers municipal pumping. The data—expressed in acre-feet per year (AFY)—was taken from Texas Water Development Board (2022b).**

Igneous Aquifer						
Year	**Brewster**	**Culberson**	**Hudspeth**	**Jeff Davis**	**Presidio**	**Reeves**
1980	1,594			116	975	
1981	1,091			101	795	
1982	1,511			127	1,048	
1983	1,713			156	1,110	
1984	1,458			157	1,114	
1985	1,458			164	1,008	
1986	1,481			163	991	
1987	1,015			151	839	
1988	1,128			168	975	
1989	1,224			197	893	
1990	1,108			170	707	
1991	1,015			157	696	
1992	993			163	676	
1993	1,204			178	760	
1994	1,265			200	794	
1995	1,233			214	787	
1996	1,203			219	766	
1997	1,547			210	698	
1998	1,750			255	819	
1999	1,750			232	769	
2000	1,750			251	781	
2000	1,974			355	808	
2001	1,985			349	693	

Table A6. (continued). Estimates of Igneous and West Texas Bolsons aquifers municipal pumping. The data—expressed in acre-feet per year (AFY)—was taken from Texas Water Development Board (2022b).

Igneous Aquifer						
Year	Brewster	Culberson	Hudspeth	Jeff Davis	Presidio	Reeves
2002	2,019			360	657	
2003	2,025			344	659	
2004	1,839			305	580	
2005	1,855			329	600	
2006	1,712	3		413	641	4
2007	844	2		482	571	3
2008	1,695	2		431	552	4
2009	1,270	2		465	524	15
2010	189	2		1,430	526	28
2011	245	2		2,335	649	30
2012	274	2		1,868	582	29
2013	806	2		1,311	538	27
2014	729	1		1,107	2,491	22
2015	834	1		1,141	2,189	23
2016	1,308	1		1,987	2,404	22
2017	704	1		1,063	2,680	24
2018	642	0.1		1,320	512	24
2019	868	0.1		1,238	522	25
2020	956	0.2		1,444	559	11

Table A6. (continued). Estimates of Igneous and West Texas Bolsons aquifers municipal pumping. The data—expressed in acre-feet per year (AFY)—was taken from Texas Water Development Board (2022b).

West Texas Bolsons Aquifer						
Year	Brewster	Culberson	Hudspeth	Jeff Davis	Presidio	Reeves
1980		614	74		246	
1981		562			251	
1982		592			312	
1983		661			358	
1984		722			340	
1985		584			346	
1986		414			370	
1987		653			318	
1988		647			370	
1989		827			525	
1990		747			498	
1991		693			493	
1992		767			483	
1993		825			532	
1994		934			641	
1995		657			750	
1996		763			646	
1997		611			618	
1998		716			686	
1999		957			755	
2000		575			853	

Table A6. (continued). Estimates of Igneous and West Texas Bolsons aquifers municipal pumping. The data—expressed in acre-feet per year (AFY)—was taken from Texas Water Development Board (2022b).

2000		677	0.3	35	895	
2001		926	0.3	33	931	
2002		812	0.2	42	933	
2003		867	0.3	37	932	
2004		1,194	0.3	37	777	
2005		835	114	38	773	
2006		743	121	38	740	
2007		578	120	35	650	
2008		697	143	41	660	
2009		912	143	47	663	
2010		889	142	52	753	
2011		819	143	53	753	
2012		741	142	52	979	
2013		734	140	40	971	
2014		790	2	34	807	
2015		890	1	33	665	
2016		923	7	39	900	
2017		728	10	41	787	
2018		943	13	39	1,162	
2019		926	14	39	792	
2020		963	9	36	1,064	

Table A7. Estimates of West Texas Bolsons Aquifer steam electric power pumping expressed in acre-feet per year (AFY).

West Texas Bolsons Aquifer						
Year	Brewster	Culberson	Hudspeth	Jeff Davis	Presidio	Reeves
1980		488				
1981		386				
1982		426				
1983		198				
1984		186				
1985		200				
1986		168				
1987		131				
1988		124				
1989		156				
1990		78				
1991		0.4				
1992		1				
1993		1				
1994		1				
1995		0.1				
1996		0.4				
1997		3				

Table A8. Estimates of Igneous and West Texas Bolsons aquifers total pumping expressed in acre-feet per year (AFY).

Igneous Aquifer						
Year	Brewster	Culberson	Hudspeth	Jeff Davis	Presidio	Reeves
1980	1,874			3,332	1,675	0
1981	1,376			2,599	1,403	1
1982	1,801			1,908	1,564	0
1983	2,008			1,219	1,535	0
1984	1,758			502	1,447	0
1985	1,949			484	1,370	
1986	2,015			593	1,214	
1987	1,586			468	942	
1988	1,723			732	1,217	
1989	1,549			468	1,284	
1990	1,452			599	1,097	
1991	1,364			503	830	
1992	1,279			532	941	
1993	1,500			267	992	
1994	1,531			398	1,492	
1995	1,472			390	1,545	
1996	1,405			395	1,516	
1997	1,754			384	1,835	
1998	1,957			454	2,012	
1999	1,984			436	1,613	
2000	4,139	468		1,072	2,259	415
2001	2,324	317		859	1,334	373
2002	2,320	419		2,056	1,854	352
2003	2,288	413		2,582	1,602	151
2004	2,103	364	6	3,227	1,707	246
2005	2,297	411	5	3,268	1,593	137
2006	2,402	390	6	3,351	1,520	146
2007	1,819	322	6	2,541	1,063	96
2008	2,674	646	6	2,506	1,266	17
2009	2,029	718	7	2,196	1,345	309
2010	1,534	784	6	2,168	1,305	290
2011	769	663	7	3,086	1,112	332
2012	504	1,025	5	3,237	1,030	284
2013	1,062	501	5	2,231	1,087	247
2014	1,495	548	5	2,130	2,986	287
2015	1,183	846	5	2,122	2,718	266
2016	1,806	659	5	2,869	2,943	372

Table A8. (continued). Estimates of Igneous and West Texas Bolsons aquifers total pumping expressed in acre-feet per year (AFY).

Igneous Aquifer						
Year	Brewster	Culberson	Hudspeth	Jeff Davis	Presidio	Reeves
2017	1,151	780	4	1,957	3,320	504
2018	1,219	664	4	2,207	1,099	317
2019	1,518	683	4	2,204	920	354
2020	1,613	572	4	2,358	1,024	356

West Texas Bolsons Aquifer						
Year	Brewster	Culberson	Hudspeth	Jeff Davis	Presidio	Reeves
1980		52,157	3,643	22,980	11,851	
1981		43,517	2,692	17,754	9,786	
1982		35,107	1,812	12,527	7,777	
1983		26,470	933	7,301	5,753	
1984		18,039	54	2,074	3,665	
1985		21,984	30	1,863	3,896	
1986		17,112	18	2,780	2,614	
1987		17,441	29	2,046	937	
1988		17,301	32	3,810	2,787	
1989		13,181	32	1,491	4,740	
1990		8,778	31	2,651	4,710	
1991		8,369	30	2,039	1,110	
1992		9,735	38	2,209	2,928	
1993		5,690	36	223	2,526	
1994		6,630	47	128	2,014	
1995		6,634	36	112	2,248	
1996		7,058	31	112	2,131	
1997		7,471	30	133	2,989	
1998		12,562	51	135	3,048	
1999		12,814	55	141	2,415	
2000		20,737	52	155	2,736	
2001		13,976	49	173	1,895	
2002		17,979	46	631	2,023	
2003		18,167	36	820	1,777	
2004		16,337	56	1,005	1,631	
2005		18,079	168	987	1,515	
2006		16,906	180	988	1,392	

Table A8. (continued). Estimates of Igneous and West Texas Bolsons aquifers total pumping expressed in acre-feet per year (AFY).

West Texas Bolsons Aquifer						
Year	**Brewster**	**Culberson**	**Hudspeth**	**Jeff Davis**	**Presidio**	**Reeves**
2007		13,804	178	649	991	
2008		27,794	206	664	1,166	
2009		31,167	213	545	1,260	
2010		34,003	206	173	1,319	
2011		28,750	212	179	1,059	
2012		44,197	195	419	1,281	
2013		21,670	188	259	1,362	
2014		23,786	52	268	1,165	
2015		36,694	51	250	1,049	
2016		28,669	59	244	1,291	
2017		33,741	48	248	1,219	
2018		28,989	51	264	1,548	
2019		29,767	53	246	1,421	
2020		25,069	49	245	1,849	

APPENDIX B. SPRING DATA TABLE

Table B1. List of springs in the Igneous and West Texas Bolsons aquifers study area shown in Figure 4.4.3—taken from Heitmuller and Reece (2003). Spring discharge expressed in gallons per minute.

Spring Name	Latitude	Longitude	Geological Unit	Average Discharge
Ruidosa Hot Spring 1	30.0389	-104.5994	Bolson deposits	34
Capote Springs	30.2044	-104.5817	Gill Brecchia	875
Mesquite Spring	30.6833	-104.9375	Bolson deposits	7
UW-74-30-901	29.5233	-104.2894	Young Quaternary deposits	90
UW-74-30-804	29.5247	-104.2942	Fresno Formation	33
UW-74-30-805	29.5256	-104.2958		22
Rabago y Teran Springs	29.5628	-104.2297	Old Quaternary deposits	6
Chupadera Springs	29.6422	-104.4528	Bolson deposits	6
Cottonwood Springs	29.6819	-104.1447	Perdiz Conglomerate	14
Alamo Springs	29.6825	-104.1233	Rawls Formation	15
Alamo Springs	29.6881	-104.1328	Rawls Formation	22
La Cienaga Springs	29.7861	-104.4647	Old Quaternary deposits	33
Spencer Springs	29.8203	-104.4150	Chinati Mountains Group	10
San Jose Spring	29.8639	-104.6206	Young Quaternary deposits	2
Indian Spring	29.8911	-104.5625	Intrusive igneous rocks	15
UW-74-04-403	29.9228	-104.6072	Bolson deposits	3
Section 32 Spring	29.9350	-104.6236	Bolson deposits	9
Shannon Spring	29.9767	-104.6294	Bolson deposits	15
UW-74-03-303	29.9772	-104.6528	Young Quaternary deposits	280
UW-74-03-302	29.9872	-104.6322	Bolson deposits	120
Torres Springs	29.9936	-104.6444	Bolson deposits	27
La Cienega Springs	30.0061	-104.6422	Bolson deposits	107
UW-51-59-802	30.0156	-104.6897	Bolson deposits	1

Spring Name	Latitude	Longitude	Geological Unit	Average Discharge
Negley Springs (south)	30.0375	-104.6500	Old Quaternary deposits	54
Negley Springs (north)	30.0386	-104.6494	Old Quaternary deposits	25
Ruidosa Hot Spring 2	30.0397	-104.5983	Bolson deposits	35
Sanguijuela Springs	30.0564	-104.6478	Young Quaternary deposits	2
Chupadera Pila Spring	30.0792	-104.6542	Bolson deposits	3
Rancho Spring	30.1061	-104.6781	Bolson deposits	4
La Cienaga seepage area	30.1092	-104.6669	Bolson deposits	29
Ranchita Spring	30.1233	-104.6681	Young Quaternary deposits	4
Nixon Spring	30.1339	-104.6033	Colmena Tuff	31
Adobe Ruin Spring	30.1633	-104.6050	Colmena Tuff	4
Mexican Springs	30.1825	-104.5836	Old Quaternary deposits	5
Vasquez Spring	30.2244	-104.5836	Ojinaga Formation	4
UW-51-44-401	30.3236	-104.6114	San Carlos Sandstone	3
McComb Spring	30.3333	-104.6575	Chambers Tuff	15
Headquarters Spring	30.3486	-104.6417	Capote Mountain Tuff	17
Coconut Spring	30.3531	-103.6669	Fan deposits	224
Musgrave Canyon Spring	30.3736	-104.6439	Bracks Rhyolite	22
Coldwater Spring	30.3786	-104.6736	Bracks Rhyolite	9
White Spring	30.4008	-104.6883	Chambers Tuff	4
Upper Z-H Canyon Spring	30.5222	-104.6783	Bracks Rhyolite	3
Ash Spring	30.6144	-104.8972	Bolson deposits	4
PS-51-25-302	30.6144	-104.8975	Bolson deposits	4
Catclaw Spring	30.6419	-104.9167	Old Quaternary deposits	3
Horse Thief Spring	30.7086	-103.6936	Landslide deposits	50
Alamo Spring	30.7283	-103.7594	Fan deposits	3
Pecan Spring	30.7325	-103.7578	Landslide deposits	2

Spring Name	Latitude	Longitude	Geological Unit	Average Discharge
Big Spring	30.7539	-103.7106	Landslide deposits	2
Dutchover Spring	30.7900	-103.6875	Star Mountain Rhyolite	2
Head Spring	30.8103	-103.6836	Star Mountain Rhyolite	3
Orchard Spring	30.8178	-103.9356	Star Mountain Rhyolite	20
Augustine Spring	30.8703	-103.8572	Alluvium	10
Patterson Spring	30.8983	-104.1997	Adobe Canyon	50
PS-51-07-502	30.9222	-104.1906	Adobe Canyon	10

APPENDIX C. CONCEPTUAL MODEL REPORT COMMENTS AND RESPONSES

General Comments

None.

Specific Comments

Comment 1: Section 1.0, report page 3, 2nd paragraph, 2nd sentence states:

> *This conceptual model will be the basis for updating the groundwater availability model for the Igneous and West Texas Bolsons aquifers. 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.*

There is no explanation of why the TWDB is combining the three previous conceptual models and Groundwater Availability Models (GAM) into one model. Why would this will be better than what already exist? Why not update the existing models with more current data? Will the larger model be simplified with a coarser model grid?

The text was revised in response to this comment. The updated model will combine the previous three models simulating the Igneous Aquifer and different parts of the West Texas Bolsons Aquifer into a single model. The advantage of a single model is that it facilitates aquifer-wide calculations and better simulates groundwater flow between aquifers. Updating the model will also incorporate more recent data. The updated model will not utilize a coarser model grid.

Comment 2: How will a more regional model be a better tool than what already exists to evaluate the effects of pumping, drought, and different water management scenarios?

The advantage of a single model is that it facilitates aquifer-wide calculations and better simulates groundwater flow between aquifers.

Comment 3: Section 2.1, report page 18 and Figure 2.1.10 regarding average annual lake evaporation.

Can results of evapotranspiration be reported in addition to average annual lake evaporation? There are no "lakes" in the study area; furthermore, it is unknown how the average annual lake evaporation numbers will be used in the conceptual model. Calculations of evapotranspiration from online tools such as "open ET" would be more applicable to the study area since most of the groundwater is used for irrigated agriculture. Also, average annual lake evaporation significantly varies according to the size and depth of water body, which is not specified.

The format of this conceptual model report follows the Groundwater Availability Model (GAM) standards (https://www.twdb.texas.gov/groundwater/models/other-download.asp) that outline the procedures for constructing and documenting a TWDB groundwater availability model. The conceptual model report is a description of the geology and hydrology of the study area and is the basis for the input data for the model. However, not all the data presented in the conceptual model report will be used in the model. For example, lake (pan) evaporation which is described in the report per GAM standards will not be an input parameter in the model. Losses to evapotranspiration are taken into consideration when estimating recharge.

Comment 4: Section 4.2, report page 53, last paragraph, and Figures 4.2.7 and 4.2.8 regarding water-level fluctuations.

There is no reference if the hydrographs on Figure 4.2.8 represent observation wells or pumping wells. Also, it would be informative to have at least two hydrographs for each bolson, because groundwater pumping significantly varies between bolsons.

The water-level data in the TWDB groundwater database reflects non-pumping conditions. Some bolsons in the west Texas Bolsons Aquifer, such as Eagle Flat, Green River Valley, and Red Light Draw, do not have sufficient water-level data to construct hydrographs.

Comment 5: The 4th sentence in the last paragraph on report page 53 states West Texas Bolsons Aquifer wells 5110305 and 5110615 in Culberson County and well 5129805 in Presidio County display periods of drawdown followed by periods of recovery. This is not necessarily true, for example, drawdown in Lobo Flat has been near continuous with little to no recovery.

If irrigation pumping is relatively consistent, then the drawdown will be nearly continuous.

Comment 6: There are better water level datasets representative of Lobo Flat water-level fluctuations, for example see 51-02-903, 51-02-926, 51-10-323, and 51-10-603.

Figure 4.2.8 has been revised in response to this comment.

Comment 7: Will the hydrographs presented on Figure 4.28 be used for model calibration? If so, see Comment 6.

The wells indicated in Comment 6 are part of the calibration target dataset.

Comment 8: Section 4.4.2, report page 68, and Figure 4.42 regarding springs.

A list of springs, flow rate, and geologic unit would be helpful. There are other sources for springs that should be incorporated, such as those investigated by Sul Ross State University (e.g., Weathers, M.Z.)

A list of springs and spring discharge data was added to the report as Appendix B.

Comment 9: Section 4.6.2, report page 79, regarding aquifer discharge through pumping.

The largest component of pumping from the Igneous aquifer may be from domestic (exempt) wells rather than municipal wells. This is a component of groundwater discharge that has been overlooked and may have the greatest effect where ranches have been subdivided around Marfa, Fort Davis, and Alpine.

Estimation of rural domestic pumping from the Igneous Aquifer based on population indicated that it is much lower than estimates of municipal pumping. For the year 2010, rural domestic pumping is estimated to be 425 acre-feet per year compared to 2,175 acre-feet per year of municipal pumping.

Comment 10: Might consider incorporating municipal wells for Balmorhea that are in Jeff Davis County.

The municipal wells for Balmorhea located in Jeff Davis County are not applicable because one is a spring and the other located in alluvium that is not related to the West Texas Bolsons Aquifer.

Comment 11: What is pumpage (acre per year) on Figures 4.6.8 and 4.6.9? This does not seem to be a volume per unit time quantity.

Revised figures 4.6.8 and 4.6.9 in response to this comment.