Conceptual Model: Capitan Reef Complex Aquifer of Texas

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Texas Water Development Board
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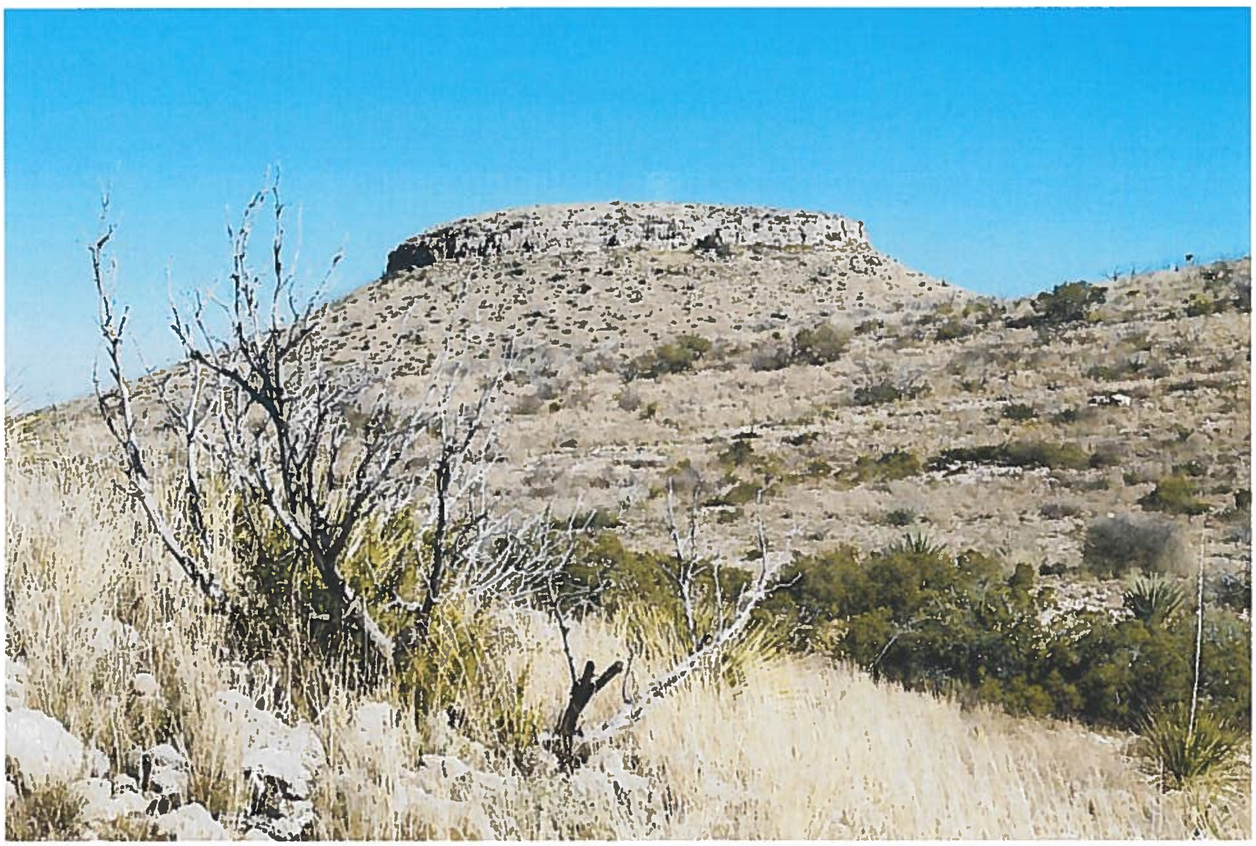

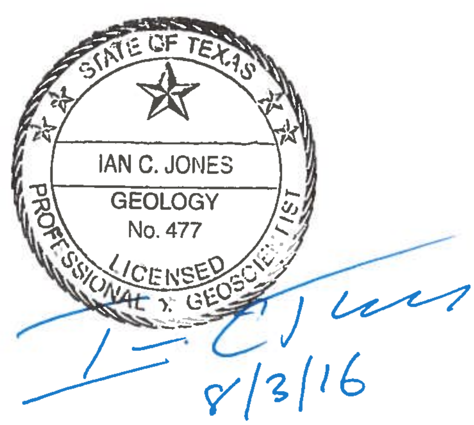

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Table of Contents

List of Figures

List of Tables

EXECUTIVE SUMMARY

The Capitan Reef Complex Aquifer is a minor aquifer located in the Trans-Pecos area of western Texas and southeastern New Mexico. The aquifer occurs in a horseshoe-shaped band of carbonate rocks exposed at the land surface where uplifted by tectonic processes but otherwise buried beneath younger sediments. The area of primary interest in this project is the eastern arm of the Capitan Reef Complex, extending from Brewster County through Pecos, Ward and Winkler counties in Texas to Lea County and part of Eddy County in New Mexico. This report documents the development of a conceptual model focusing primarily on the eastern arm of the Capitan Reef Complex Aquifer. We selected the eastern arm of the Capitan Reef Complex Aquifer because part of the western arm of the Capitan Reef Complex Aquifer is already included in the groundwater flow model for the Bone Spring-Victorio Peak Aquifer (Hutchison, 2008).

The Capitan Reef Complex Aquifer consists of the stratigraphic units of the Capitan Reef Complex that were deposited along the margins of the Delaware Basin. These stratigraphic units include the Carlsbad and Capitan limestones, and the Goat Seep Dolomite. The aquifer crops out in Brewster, Culberson, Hudspeth, and Pecos counties in Texas and in Eddy County in New Mexico. These outcrops coincide with areas of uplift that resulted in the formation of the Guadalupe, Apache, and Glass mountains. The Capitan Reef Complex Aquifer also occurs in subcrop only in parts of Jeff Davis, Pecos, Reeves, Ward, and Winkler counties in Texas and Lea County in New Mexico. The Capitan Reef Complex Aquifer generally dips towards the north and east. This is partially due to uplift that resulted in the formation of the previously mentioned mountain ranges that are located on the western and southern portions of the reef.

Available water level data show that groundwater flow in the Capitan Reef Complex Aquifer occurs parallel to the reef trends. Groundwater generally flows away from aquifer outcrop recharge zones towards deeper parts of the aquifer. Groundwater in the Capitan Reef Complex Aquifer likely naturally discharges by cross-formational flow through adjacent stratigraphic units. Discharge by any other mechanism is highly unlikely considering: (1) the lack of contact between the Capitan Reef Complex Aquifer and any surface-water bodies, such as, springs and rivers, and (2) the occurrence of artesian wells and water levels higher than those in overlying aquifers suggesting upward hydraulic gradients, especially in the eastern part of the aquifer.

Groundwater in the Capitan Reef Complex Aquifer is used primarily for oil and gas production in the northern and eastern parts of the aquifer, but is also used locally for livestock and irrigation. Sparse multi-year water-level data indicates static, declining, and fluctuating water levels in different parts of the Capitan Reef Complex Aquifer.

There is a general lack of hydraulic property data for the Capitan Reef Complex Aquifer. However, the data available show significant variability in the aquifer properties resulting from structural complexity within the basin, variability in lithology, and the effects of post-

depositional processes including karstification. Hydraulic conductivity values for the Capitan Reef Complex range from less than 0.01 feet per day to more than 500 feet per day and display no apparent spatial trends. The median hydraulic conductivity of the Capitan Reef Complex Aquifer is orders of magnitude higher than that of the adjacent basin and shelf stratigraphic units.

Water quality in the Capitan Reef Complex Aquifer is generally brackish to saline. Freshwater occurs in or adjacent to aquifer outcrops. In the subcrop, groundwater ranges from brackish to saline, with the highest salinity in the deepest parts of the aquifer—in Ward County, Texas and Lea County, New Mexico. Capitan Reef Complex Aquifer groundwater compositions range from calcium-magnesium-bicarbonate compositions to calcium-magnesium-sulfate compositions to sodium-chloride compositions, reflecting interaction with minerals—calcite, dolomite, gypsum, and halite—that occur within the Capitan Reef Complex and adjacent stratigraphic units.

Compositions of various isotopes in Capitan Reef Complex Aquifer groundwater indicate that: (1) most recharge to the aquifer occurs in the Guadalupe and Glass mountains aquifer outcrops, (2) relatively little recharge occurs in the Apache Mountains outcrop, and (3) rapid recharge to subcrop parts of the aquifer occurs south of the Delaware Mountains. Additionally, isotopes indicate that recharge to the Capitan Reef Complex Aquifer occurs under a wider range of altitude and climatic conditions in the western arm of the Capitan Reef Complex Aquifer than in the eastern arm. The data suggest that the groundwater flow system in the eastern arm of the aquifer is simple with a single recharge zone—the Glass Mountains aquifer outcrop.

The conceptual model of the eastern arm of the Capitan Reef Complex Aquifer is a simplified representation of the hydrogeological features—hydrostratigraphy, hydraulic properties, hydrologic boundaries, recharge, and discharge—that influence groundwater flow through the aquifer. The conceptual model for the eastern arm of the Capitan Reef Complex Aquifer—the basis used to construct a groundwater flow model—is composed of up to five model layers simulating groundwater flow through the Capitan Reef Complex Aquifer and overlying aquifers and confining units that occur within the Monument Draw Trough. This conceptual model is characterized by recharge to the aquifer outcrop in the Glass Mountains and limited inflow from the north margin the modeled area, groundwater flow into subcrop parts of the Capitan Reef Complex Aquifer, and discharge by upward flow through overlying aquifers.

1.0 INTRODUCTION

The Capitan Reef Complex Aquifer is a minor aquifer—one of nine major and 21 minor aquifers in Texas (Figures 1.0.1 and 1.0.2). The Texas Water Development Board defines a major aquifer as an aquifer that produces large amounts of water over a large area, and minor aquifers as aquifers that produce minor amounts of water over large areas or large amounts of water over small areas (George and others, 2011). The Capitan Reef Complex Aquifer meets the definition of a minor aquifer because (1) most of its extent is overlain by major aquifers—such as the Pecos Valley and Edwards-Trinity (Plateau) aquifers— that are more attractive to well drilling due to shallower depth, (2) it underlies a relatively small area that has a small population and little irrigation, and (3) poor water quality in most parts of the aquifer make it unattractive for most water uses. Historically, the Capitan Reef Complex Aquifer has been used for secondary recovery by the petroleum industry (White, 1987). Total pumping from the Texas portion of the Capitan Reef Complex Aquifer has ranged from a high of more than 15,000 acre-feet per year to less than 200 acre-feet per year during the period 1980 through 2008. This aquifer is important because drawdown in overlying major aquifers—especially the Pecos Valley Aquifer—can induce upward groundwater flow from the underlying aquifers such as the Capitan Reef Complex Aquifer (Jones, 2004). The Capitan Reef Complex Aquifer is also becoming more important as use of desalinated groundwater increases its potential as a groundwater source.

This report describes the aquifer data used to develop a conceptual model for the eastern arm of the Capitan Reef Complex Aquifer. This conceptual model will be the basis for the construction of a groundwater availability model for that portion of the Capitan Reef Complex Aquifer. Once this 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 Capitan Reef Complex Aquifer, (3) the hydrologic setting including hydrostratigraphy, geologic framework, groundwater hydrology, recharge, discharge, surface water, hydraulic properties, and water quality, and (4) the resultant conceptual model.

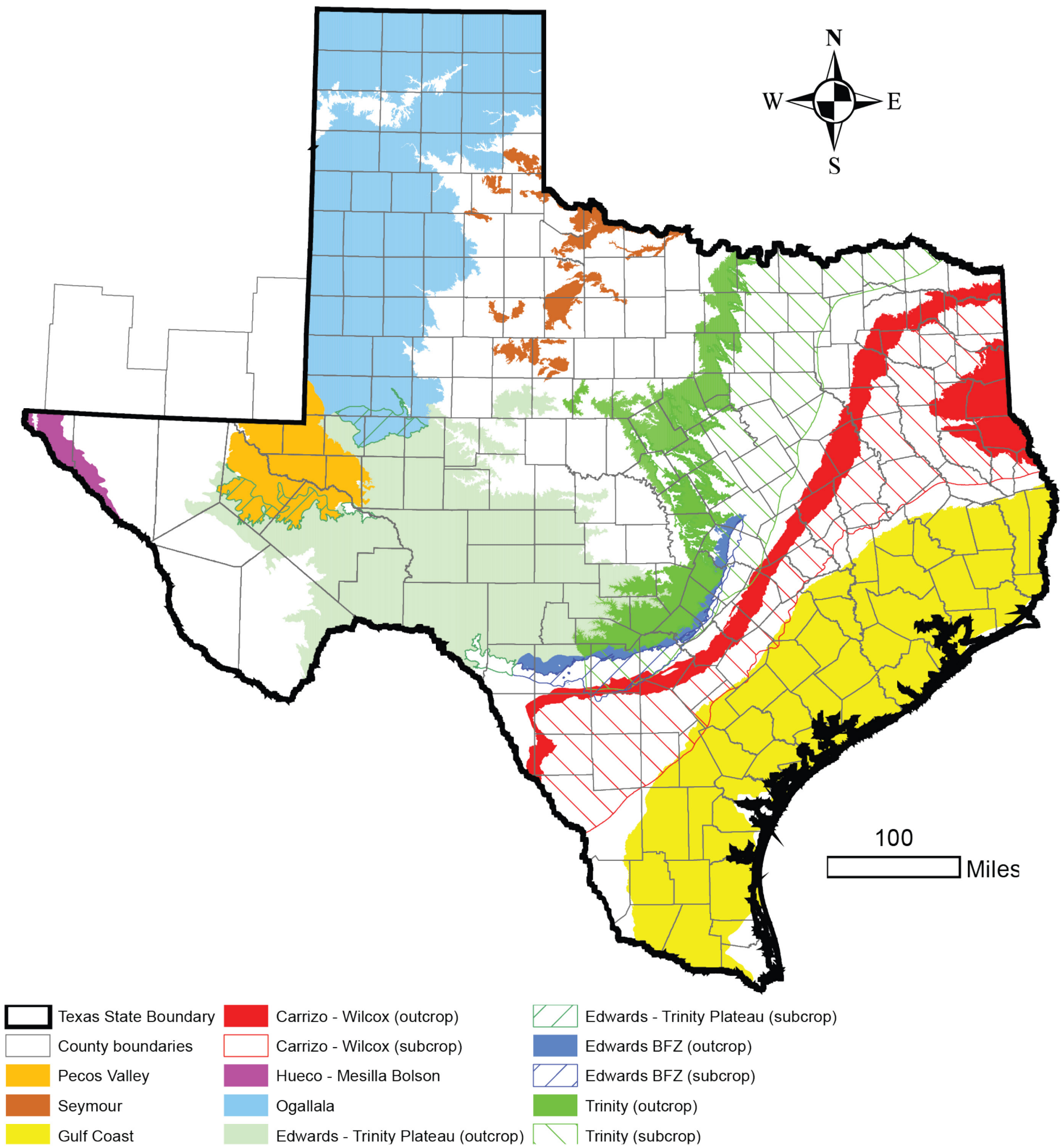


Figure 1.0.1. Locations of the major aquifers in Texas.

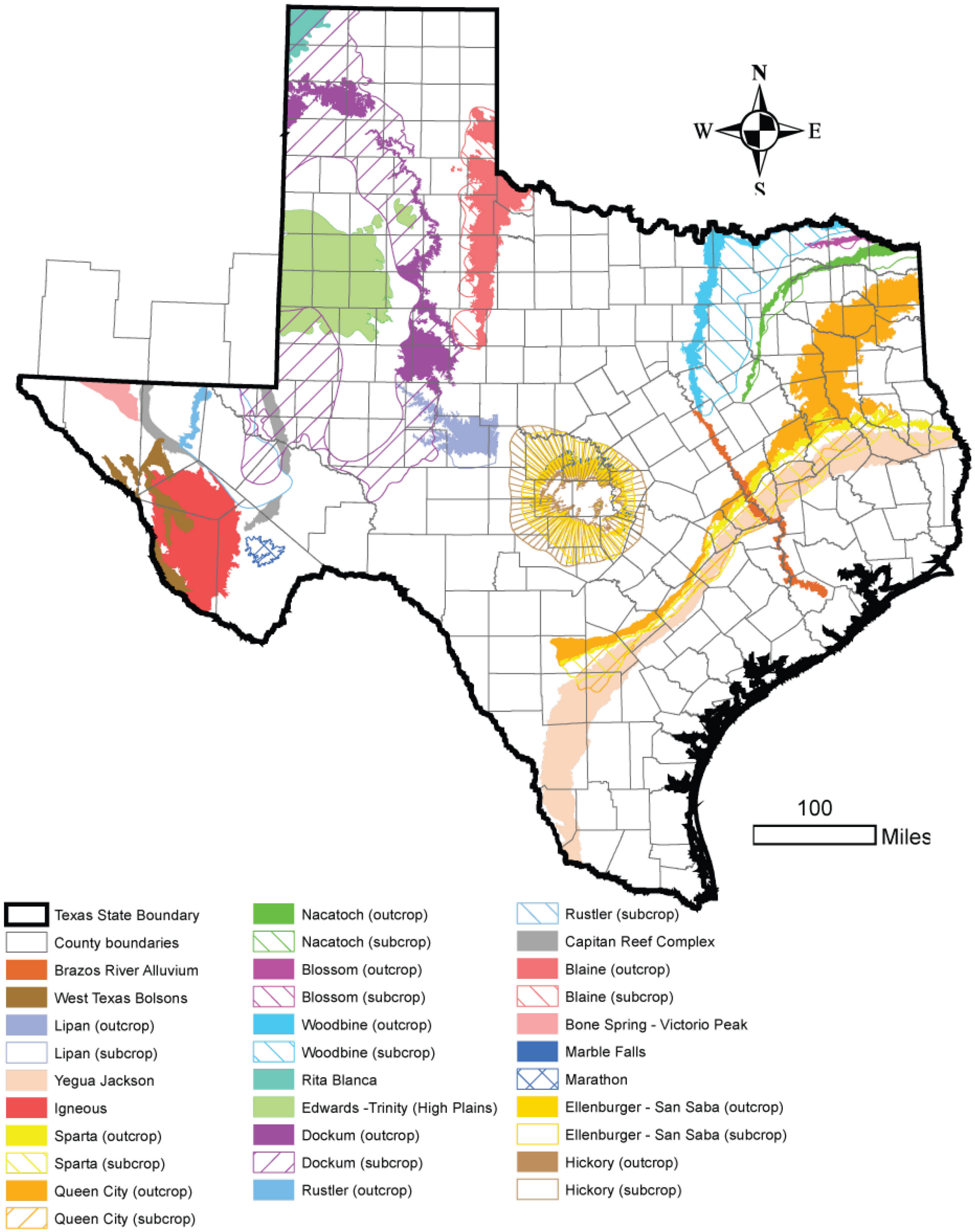


Figure 1.0.2. Locations of the minor aquifers in Texas.

2.0 STUDY AREA

The Capitan Reef Complex Aquifer occurs in outcrop and subcrop in a relatively narrow horseshoe-shaped band in the Trans-Pecos area of western Texas and southeastern New Mexico (Figure 2.0.1). The outcrops are located in the Guadalupe, Apache, and Glass mountains (Figure 2.0.2). The Capitan Reef Complex Aquifer boundaries used in this study were defined by work by Standen and others (2009). These alternative boundaries differ from the aquifer boundaries defined by the Texas Water Development Board (Figure 2.0.2). The alternative boundaries are used in this study because they are based on the most up-to-date data with regards to the spatial distribution of the Capitan Reef Complex.

Figure 2.0.3 shows the counties, major roadways, and cities in the study area. The Capitan Reef Complex Aquifer underlies eight counties in Texas and three counties in New Mexico. Cities overlying the Capitan Reef Complex Aquifer include Carlsbad in New Mexico, and Fort Stockton, Kermit, Monahans, Pyote, Wickett, and Wink in Texas. The locations of rivers, streams, lakes, and reservoirs in the study area are shown on Figure 2.0.4. The Pecos River and a few of its tributaries are the only perennial streams in the study area. The Pecos River—where it flows over Capitan Reef Complex Aquifer near Carlsbad, New Mexico—is the only perennial stream that interacts with the Capitan Reef Complex Aquifer. It should be noted that the Capitan Reef Complex does not crop out along the Pecos River channel.

Figures 2.0.5 and 2.0.6 show the major and minor aquifers that occur within the study area. Major aquifers occurring in the study area include parts of the Pecos Valley and Edwards-Trinity (Plateau) aquifers. In addition to the Capitan Reef Complex Aquifer, minor aquifers occurring in the study area include parts of the Dockum, Igneous, Rustler, and West Texas Bolsons aquifers.

The Capitan Reef Complex Aquifer underlies part of the Far West Texas Regional Water Planning Area and the Region F Regional Water Planning Area (Figure 2.0.7). The aquifer also underlies parts of the Middle Pecos Groundwater Conservation District, Brewster County Groundwater Conservation District, Jeff Davis County Underground Water Conservation District, Reeves County Groundwater Conservation District, and Culberson County Groundwater Conservation District (Figure 2.0.8). The Capitan Reef Complex Aquifer underlies portions of Groundwater Management Areas 3, 4, and 7 (Figure 2.0.9). The Capitan Reef Complex Aquifer does not occur within the boundaries of any river authority.

The Capitan Reef Complex Aquifer is contained wholly within the Rio Grande river basin (Figure 2.0.10). For all but the Pecos River and a few of its larger tributaries, rivers and streams in the study area are normally dry. When flow does occur in the smaller rivers and streams, it rarely reaches the Pecos River but rather seeps into the channel beds or spreads out over broad valleys (Ashworth, 1990).

Figure 2.0.1. Study area for the Capitan Reef Complex Aquifer. Aquifer boundaries are based on work by Standen and others (2009).

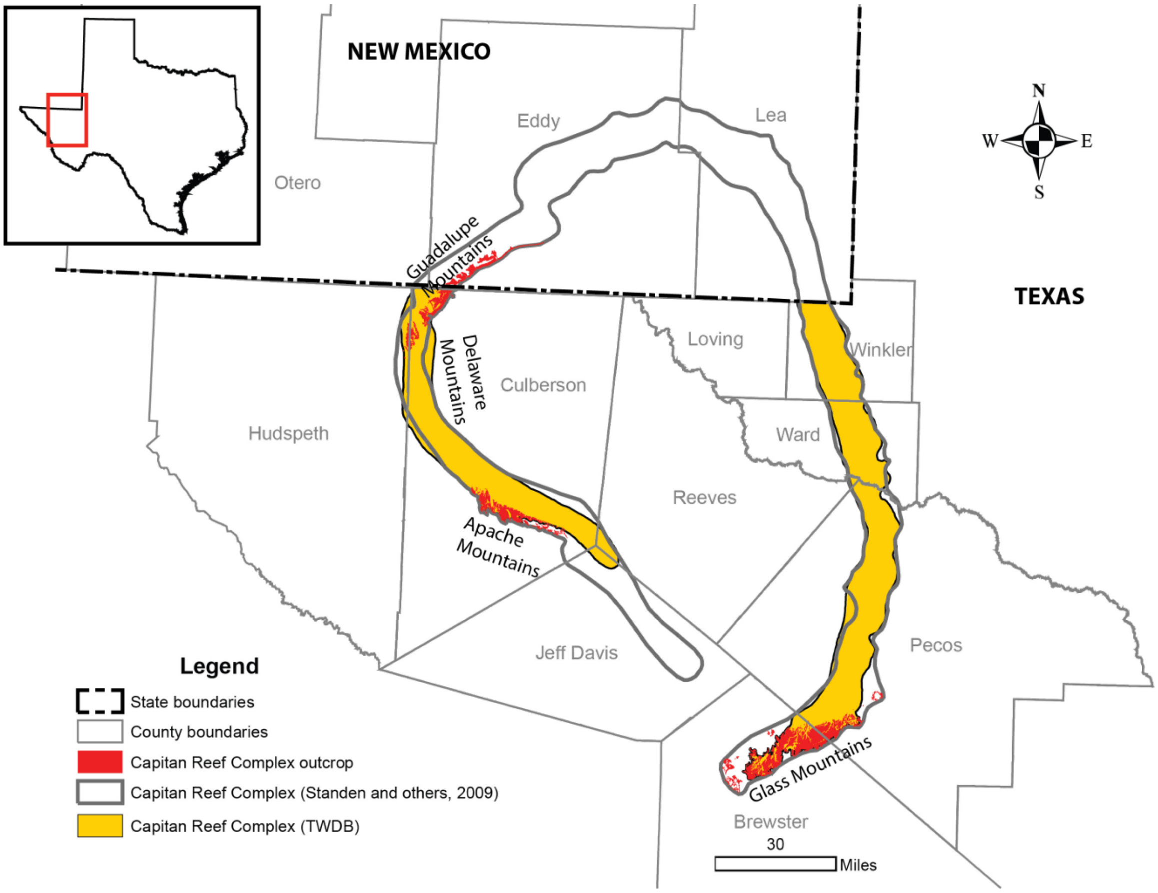


Figure 2.0.2. The official (Texas Water Development Board) and alternative boundaries of the Capitan Reef Complex Aquifer based on work done by Standen and others (2009) including the location of key mountain ranges in the study area.

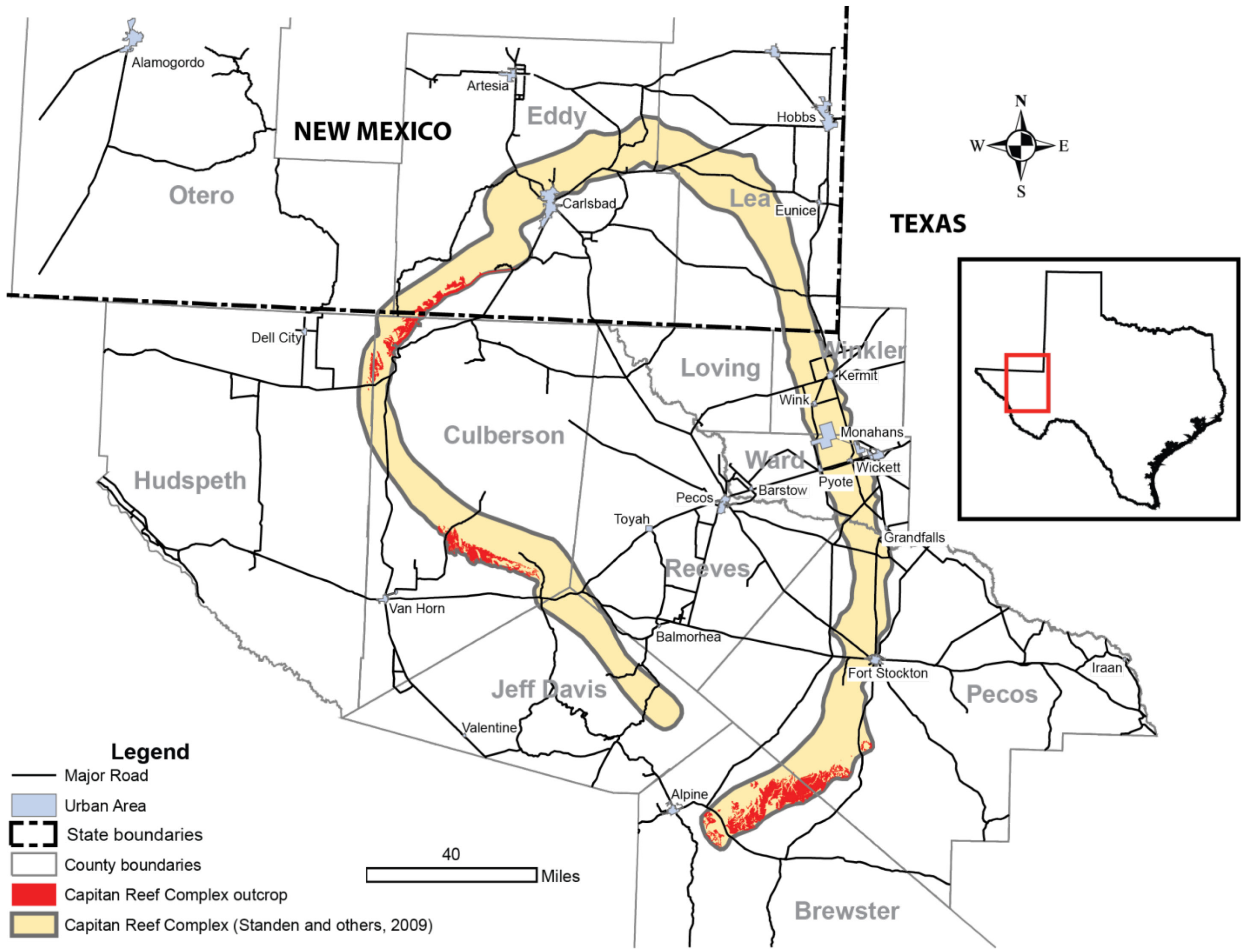


Figure 2.0.3. Cities and major roadways in the study area.

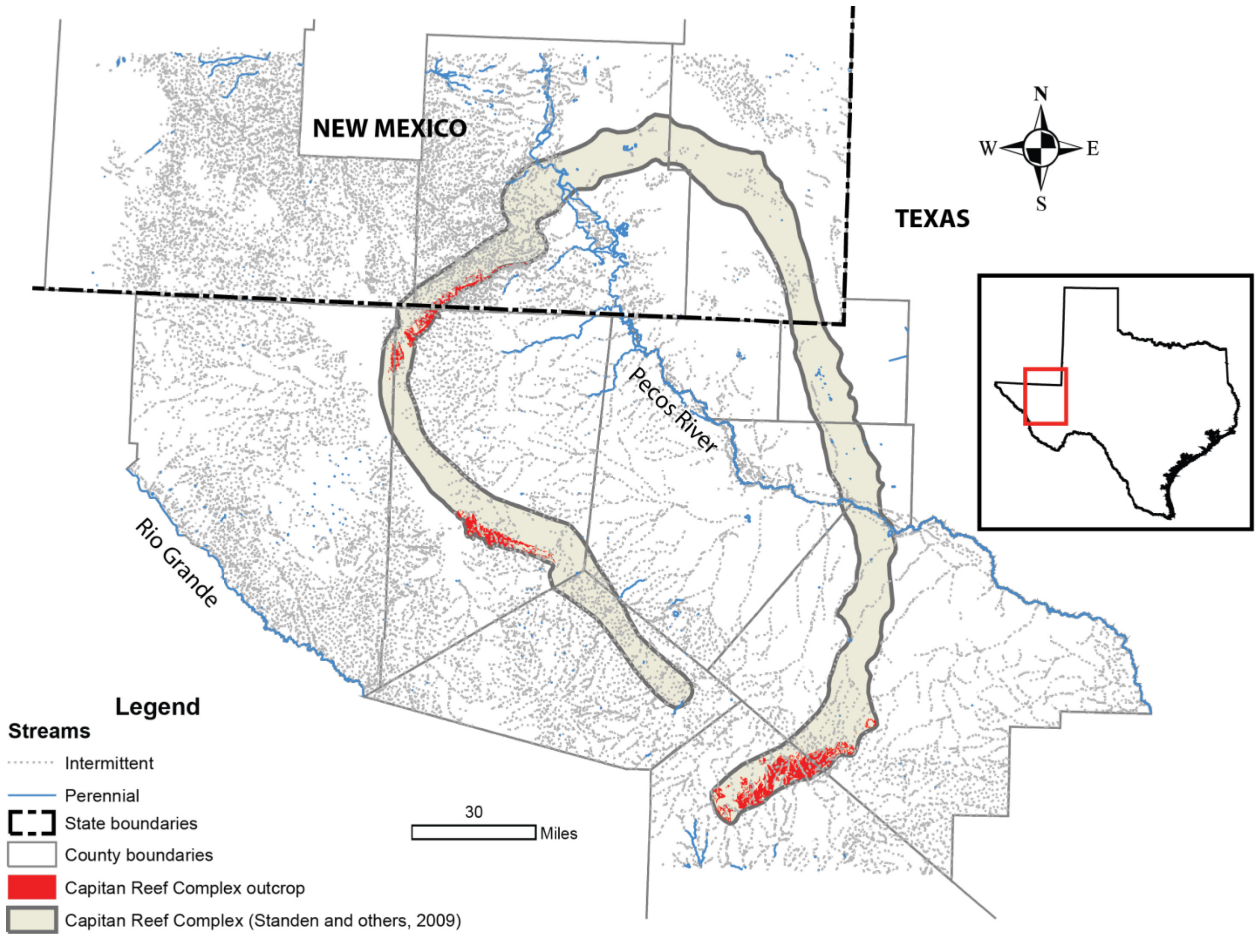


Figure 2.0.4. Rivers, streams, lakes, and reservoirs in the study area.

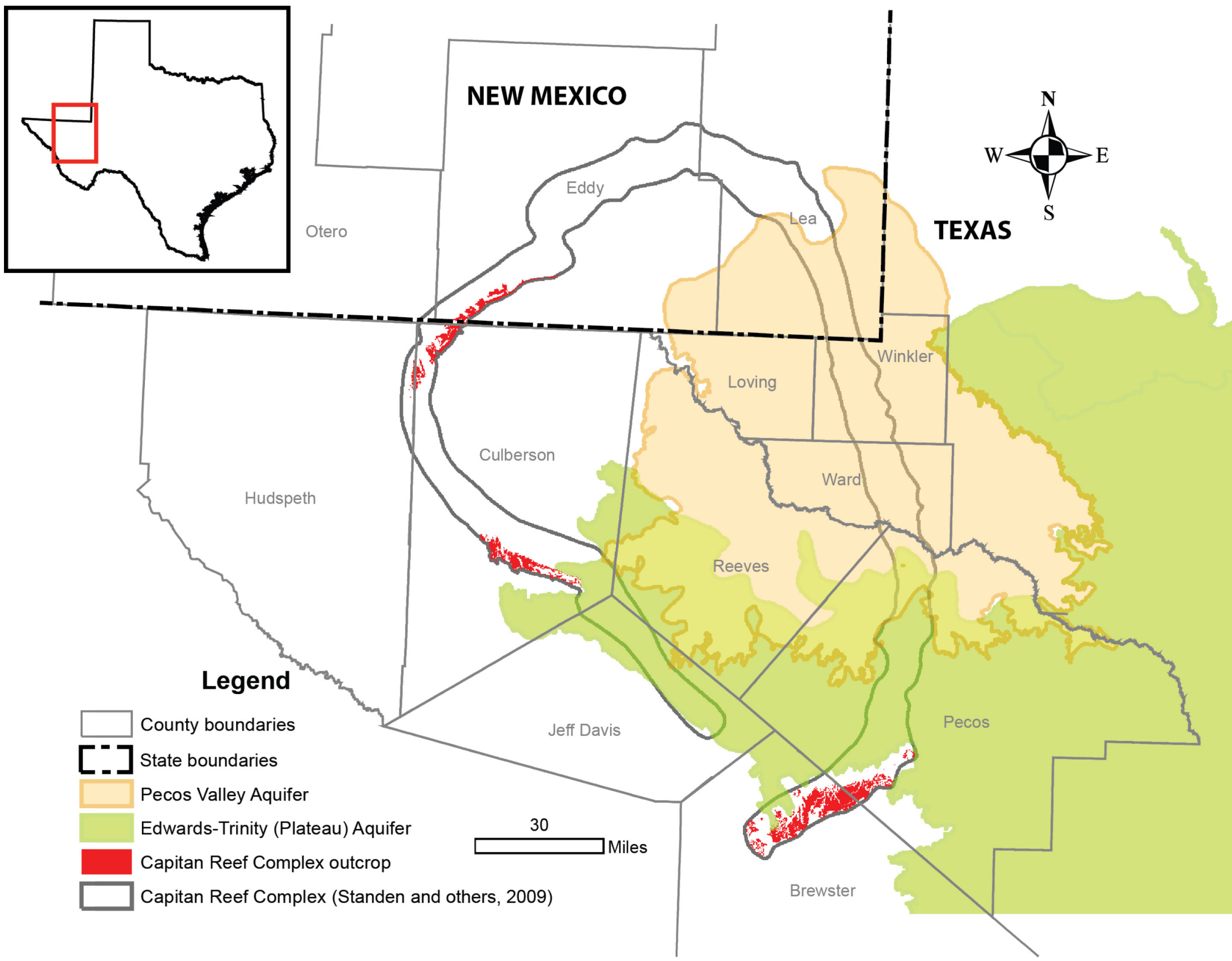


Figure 2.0.5. **Major aquifers in the study area.**

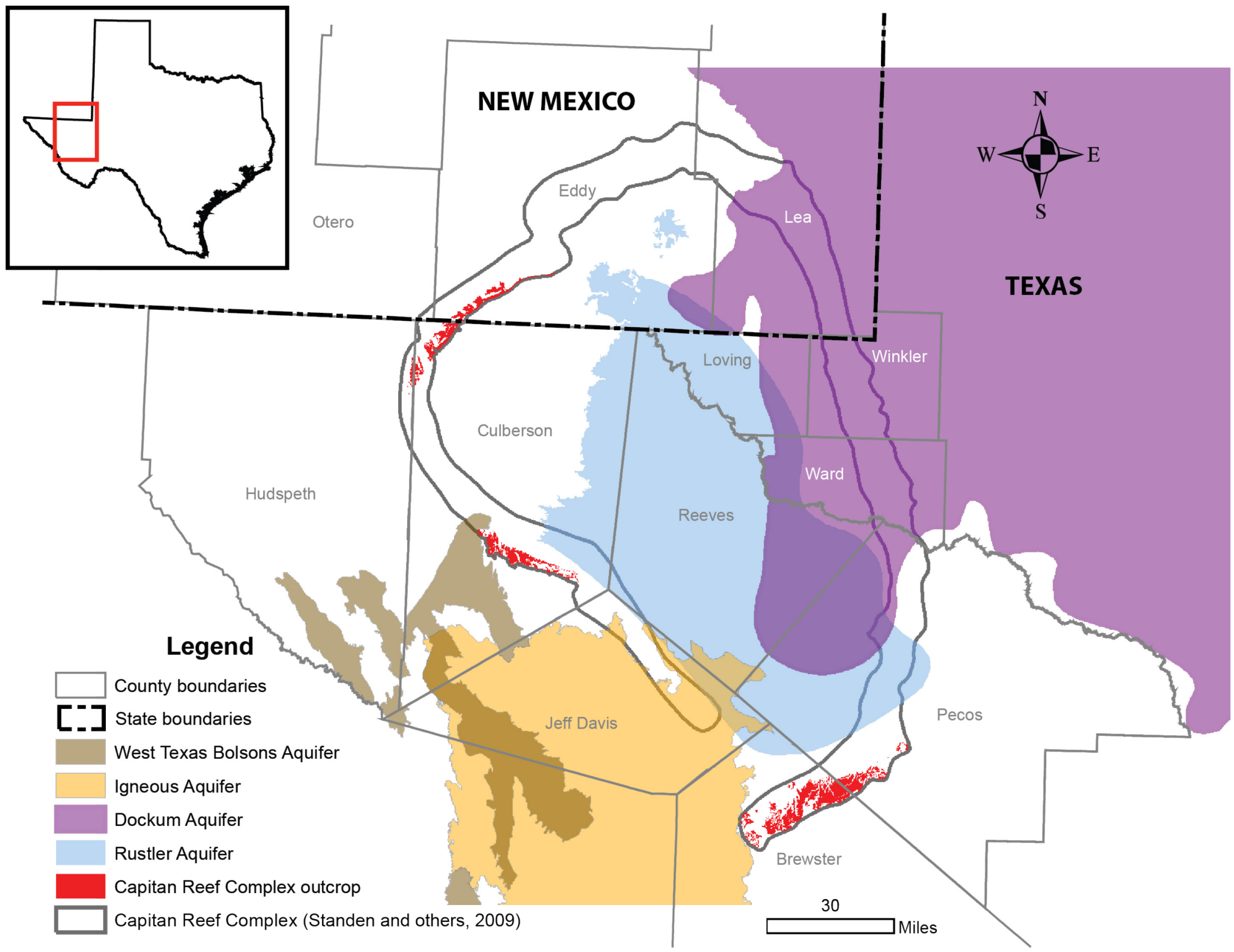


Figure 2.0.6. Minor aquifers in the study area.

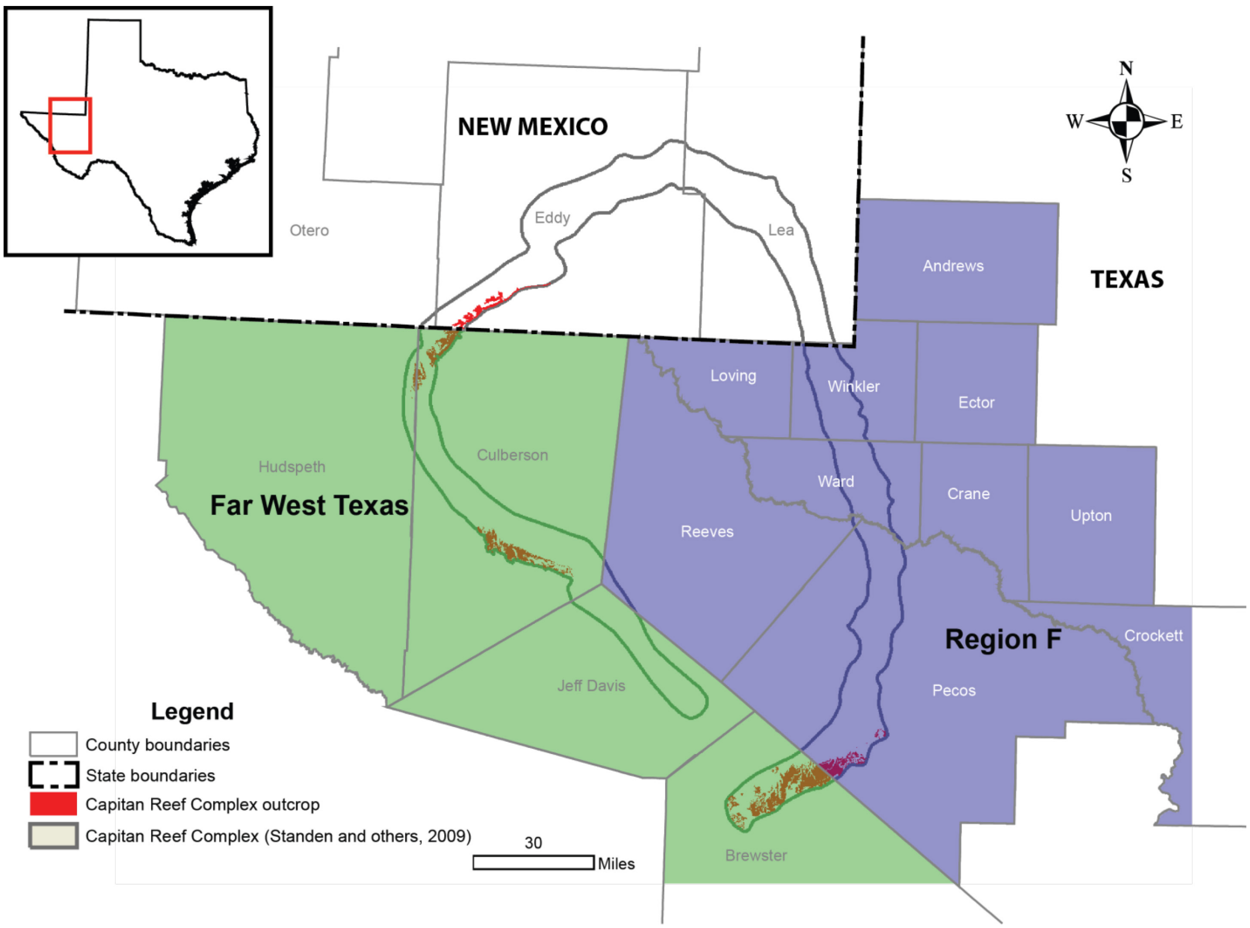


Figure 2.0.7. Texas regional water planning areas in the study area.

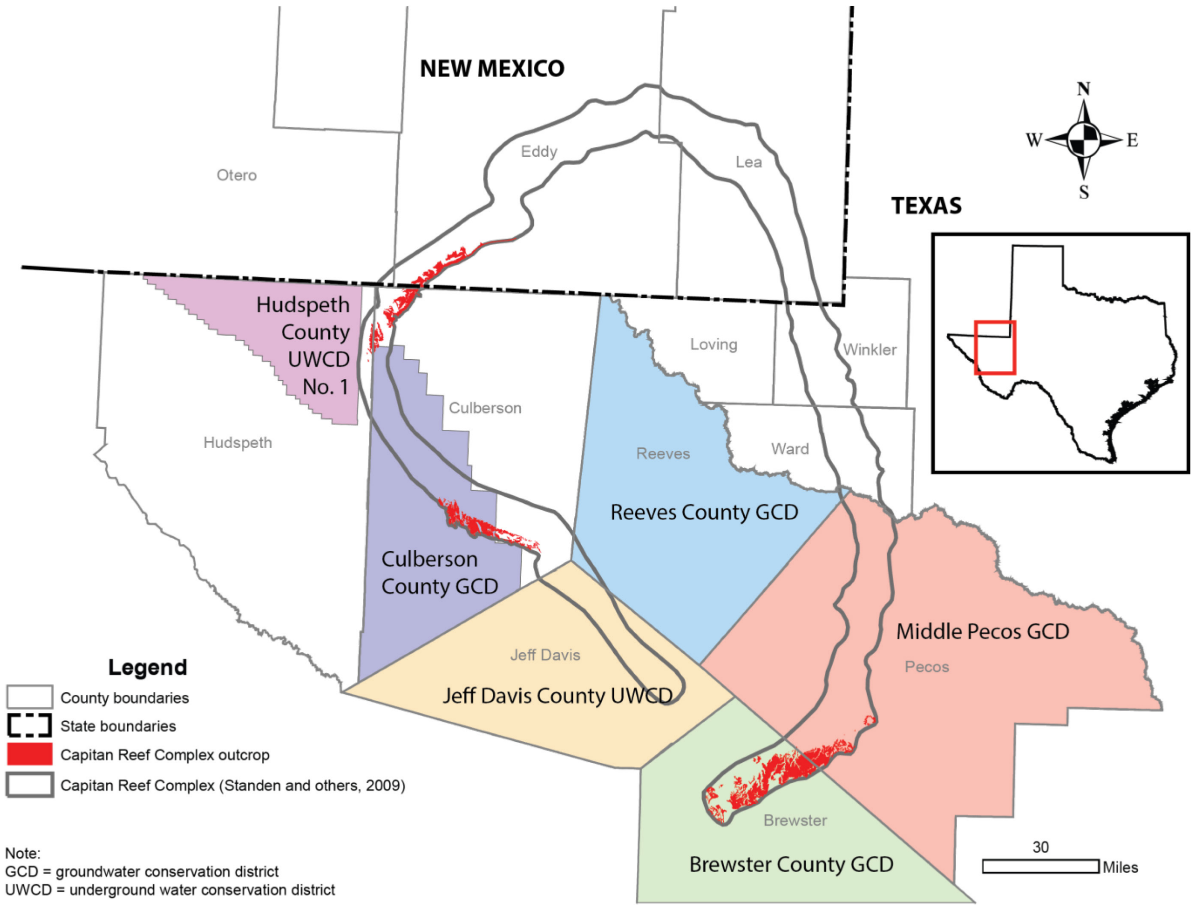


Figure 2.0.8. **Texas groundwater conservation districts in the study area as of February 2014.**

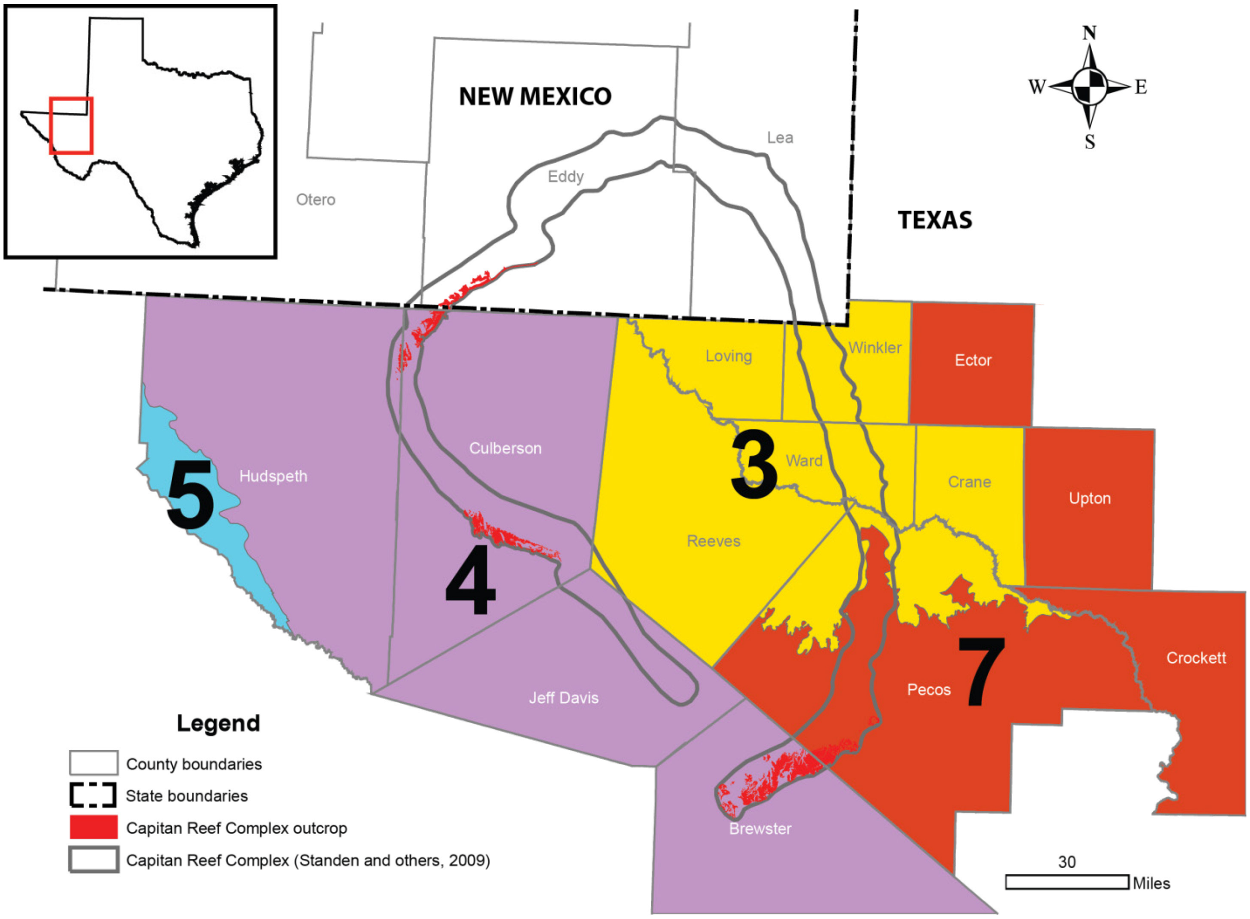


Figure 2.0.9. Texas groundwater management areas in the study area.

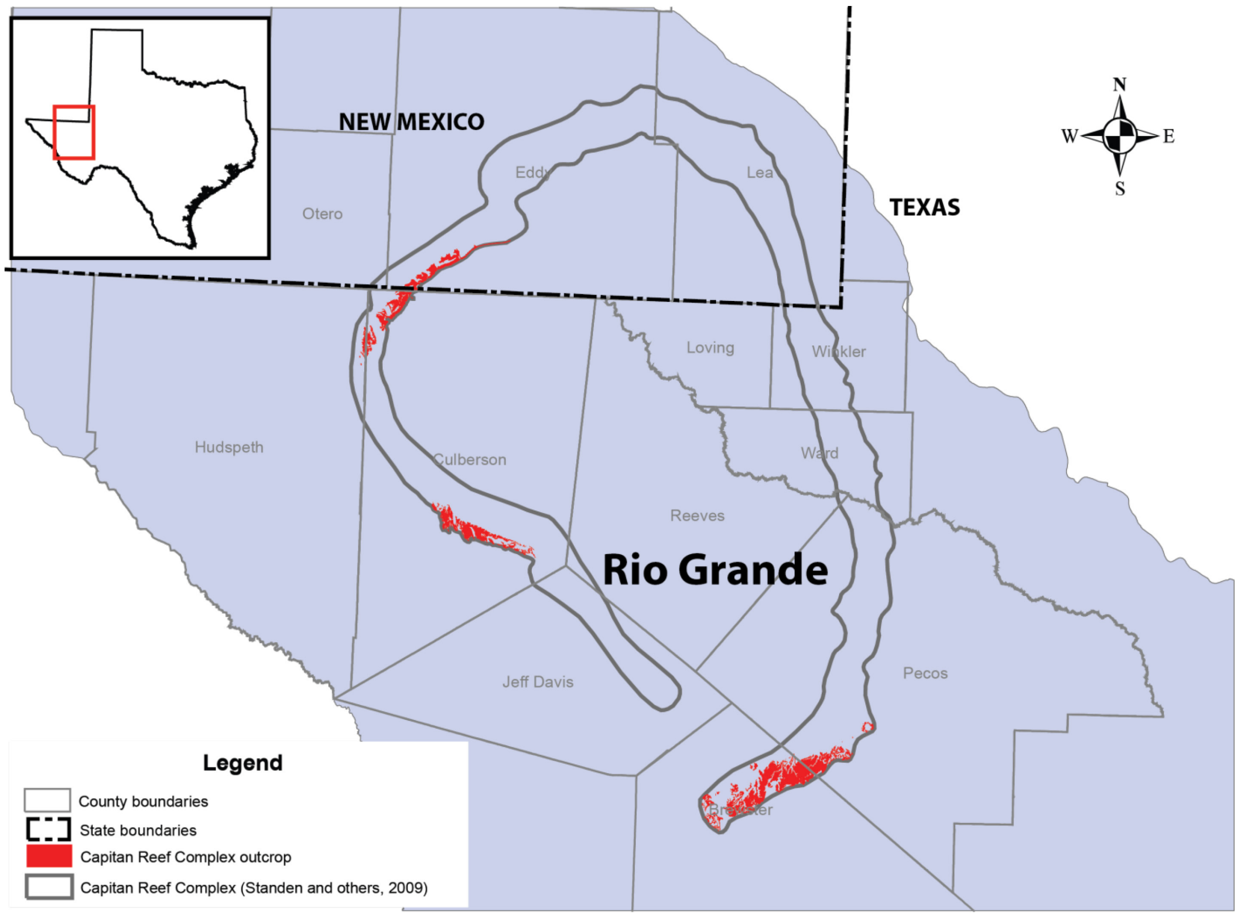


Figure 2.0.10. Major river basins in the study area.

2.1 Physiography and Climate

The study area includes parts of the Great Plains and Basin and Range physiographic provinces (Figure 2.1.1). In the study area, the Great Plains physiographic province consists of the Pecos Valley, Edwards Plateau, and High Plains sections, while the Basin and Range province consists of the Mexican Highland and Sacramento sections (United States Geological Survey, 2002). The Pecos Valley section is a long trough lying between the High Plains to the east and the Basin and Range to the west. Its topography varies from flat plains to rocky canyon lands. This section consists chiefly of the valley of the Pecos River. The Edwards Plateau also includes the Stockton Plateau located west of the Pecos River. The two parts of the Edwards Plateau are separated by the canyon of the Pecos River. The Stockton Plateau terminates against the mountains of the Mexican Highland section to the west. The High Plains are remnants of a former fluvial plain that stretched from the Rocky Mountain physiographic province located to the west—north of the study area. It is composed mostly of silt and sand with smaller quantities of gravel deposited by streams flowing eastward from the Rocky Mountains producing an extremely flat plain. The thickness of the unconsolidated material varies up to more than 500 feet (Leighty & Associates, Inc., 2001). Wermund (1996) describes the Basin and Range province in the study area as mountains peaks that rise abruptly from barren rock plains flanked by plateaus with nearly horizontal rocks less deformed than the adjacent mountains. The Mexican Highland is a section of the Basin and Range province that mostly occurs in Mexico but also extends along the Rio Grande. The Sacramento Section, located north of the Mexican Highland, is characterized by tilted plateaus (Leighty & Associates, Inc., 2001).

The Capitan Reef Complex Aquifer is located predominantly in the Chihuahuan Deserts Level III ecological region (Figure 2.1.2). However, parts of the aquifer also underlie the Arizona/New Mexico Mountains and High Plains ecological regions. The Chihuahuan Deserts region consists of desert grassland and desert scrub in the lowlands and low mountains and wooded vegetation in the higher mountains (United States Environmental Protection Agency, 2011a). A wide variety of plant and animal life can be found in this region. Texas Parks and Wildlife Department (2012) states that *"more rare and endemic species can be found in this region than in any other part of Texas."* The Capitan Reef Complex Aquifer crops out in the Guadalupe Mountains which is part of the Arizona/New Mexico Mountains region. The Arizona/New Mexico Mountains region has a variety of climates, depending on latitude and elevation, ranging from severe alpine climates to mid-latitude steppe and desert climates. In general, the region is marked by warm to hot summers and mild winters. Many intermittent streams and some perennial streams—both characterized by moderate to high gradients—occur in this ecological region (United States Environmental Protection Agency, 2011a). The High Plains region has a dry mid-latitude steppe climate. Historically, the High Plains region had mostly short and midgrass prairie vegetation. In the study area, the High Plains region has few to no streams. Surface water occurs in numerous playas that act as recharge areas for underlying aquifers (United States Environmental Protection Agency, 2011a).

Figure 2.1.3 provides a topographic map of the study area (Gesch and others, 2002). Land-surface elevation is greatest along an axis formed by a northwest-southeast oriented line of mountains—the Guadalupe, Delaware, Apache, Davis, Barilla, and Glass mountains—and generally decreases to the east and west to the Pecos River Valley and Salt Basin, respectively. Land-surface elevation in the footprint of the Capitan Reef Complex Aquifer varies from over 8,000 feet above mean sea level in the Guadalupe Mountains in Culberson and Eddy counties to about 2,000 feet above mean sea level at the Pecos River along the border of Ward and Pecos counties.

The climate in the study area, shown in Figure 2.1.4, is classified as subtropical arid over most of the Capitan Reef Complex Aquifer, continental steppe to the northeast, and mountain in the Guadalupe Mountains of Culberson County and the Davis Mountains in Jeff Davis County (Larkin and Bomar, 1983). The subtropical arid climate is the result of decreasing moisture content of air flowing inland from the Gulf of Mexico (Larkin and Bomar, 1983). This climate region is characterized by anomalous summertime rainfall associated with mountains. The continental steppe climate is the typical climate of the High Plains. It is a semi-arid climate characterized by large variations in daily temperatures, low relative humidity, and irregularly spaced moderate rainfall (Larkin and Bomar, 1983). The mountain climate is characterized by cooler temperatures, lower relative humidity, and mountainous precipitation anomalies typical of areas with orographic precipitation controls. This climate is associated with the highest mountain ranges in the region—the Davis and Guadalupe mountains—which include the highest mountain peaks in Texas (Larkin and Bomar, 1983). The average annual maximum air temperature in the study area ranges from a high of about 58 degrees Fahrenheit in the Pecos River Valley to a low of about 46 degrees Fahrenheit in the Guadalupe Mountains (Figure 2.1.5).

Figure 2.1.6 shows average annual precipitation for the period 1971 through 2000 (Oregon State University, 2006a). The highest annual precipitation of about 28 inches per year occurs in the Guadalupe Mountains in Culberson County and the lowest annual precipitation of less than 10 inches per year occurs in an adjacent part of the Salt Basin along the Culberson-Hudspeth county boundary.

Precipitation data are available at 23 Texas and 18 New Mexico stations within the study area (Figure 2.1.7). In general, measurements are not continuous on a month-by-month or year-by-year basis for the gages. Annual precipitation recorded at eight stations in the study area is shown in Figure 2.1.8. Figure 2.1.8 indicates wide interannual variation of precipitation, ranging from lows of about 5 inches to more than 25 inches per year. Figure 2.1.9 shows long-term average monthly variation in precipitation at eight gages in the study area. In the study area, monthly precipitation is generally highest during summer and early fall months—May through October.

The average annual net pan evaporation rate in the study area ranges from a high of 72 inches per year to a low of 55 inches per year and averages about 64 inches per year (Figure 2.1.10; Texas Water Development Board, 2012a). Average annual net pan evaporation is generally lowest in the southern part of the study area, increasing to the north and east. Pan evaporation rates significantly exceed the annual average precipitation. Monthly variations in lake surface evaporation are shown for seven locations in the study area (Figure 2.1.11; Texas Water Development Board, 2012a). These values represent the average of the monthly lake surface evaporation data from January 1954 through December 2011. Figure 2.1.11 shows that average lake evaporation peaks in June or July.

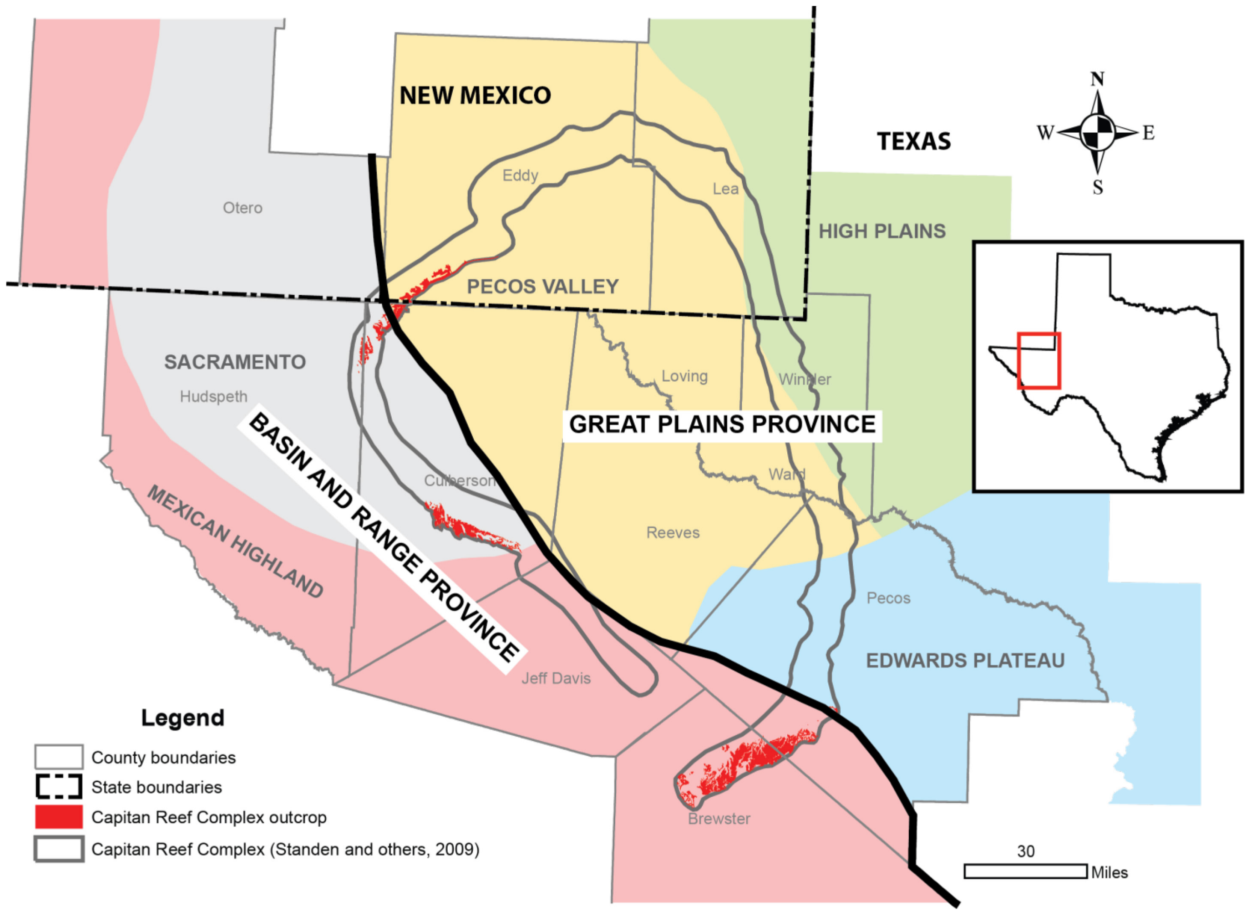


Figure 2.1.1. Physiographic provinces in the study area (United States Geological Survey, 2002).

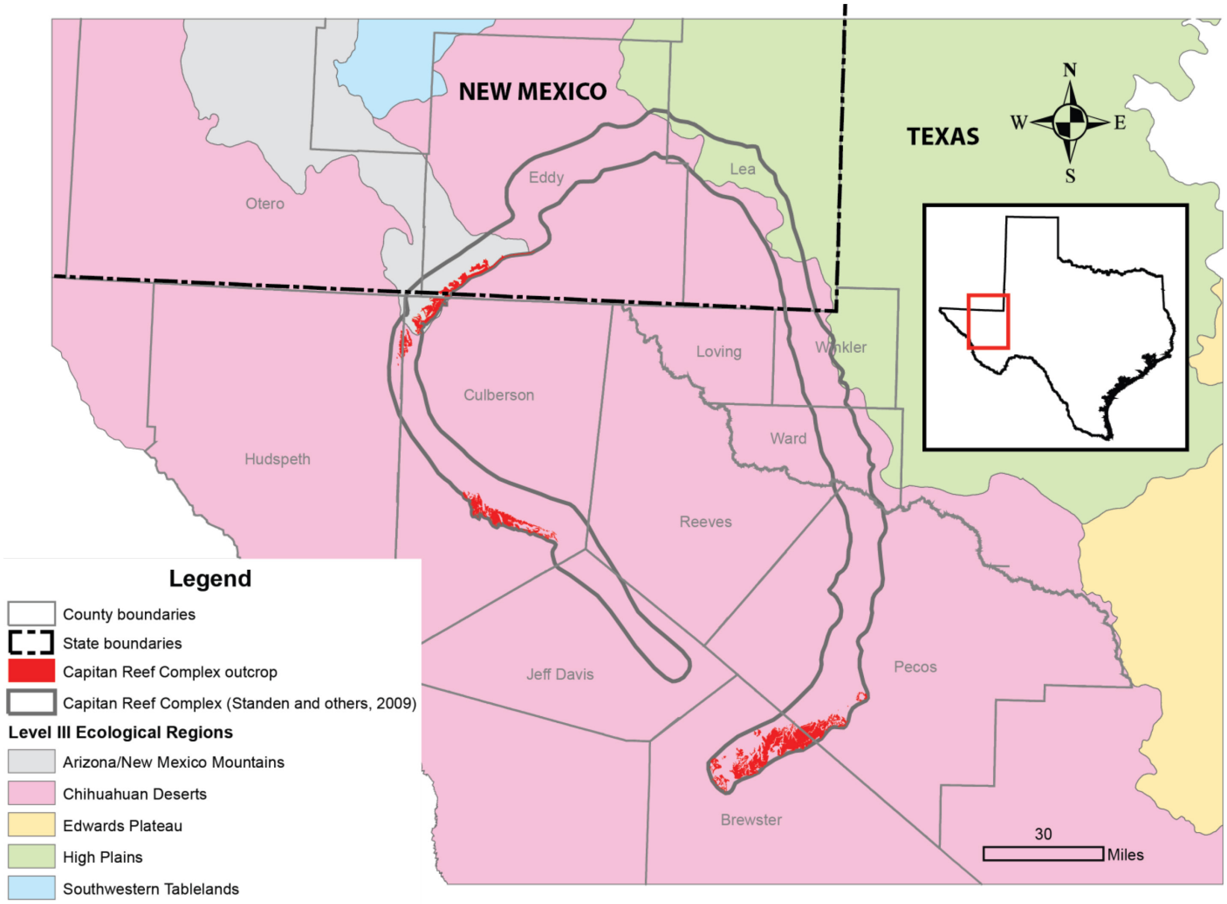


Figure 2.1.2. Level III ecological regions in the study area (United States Environmental Protection Agency, 2011b).

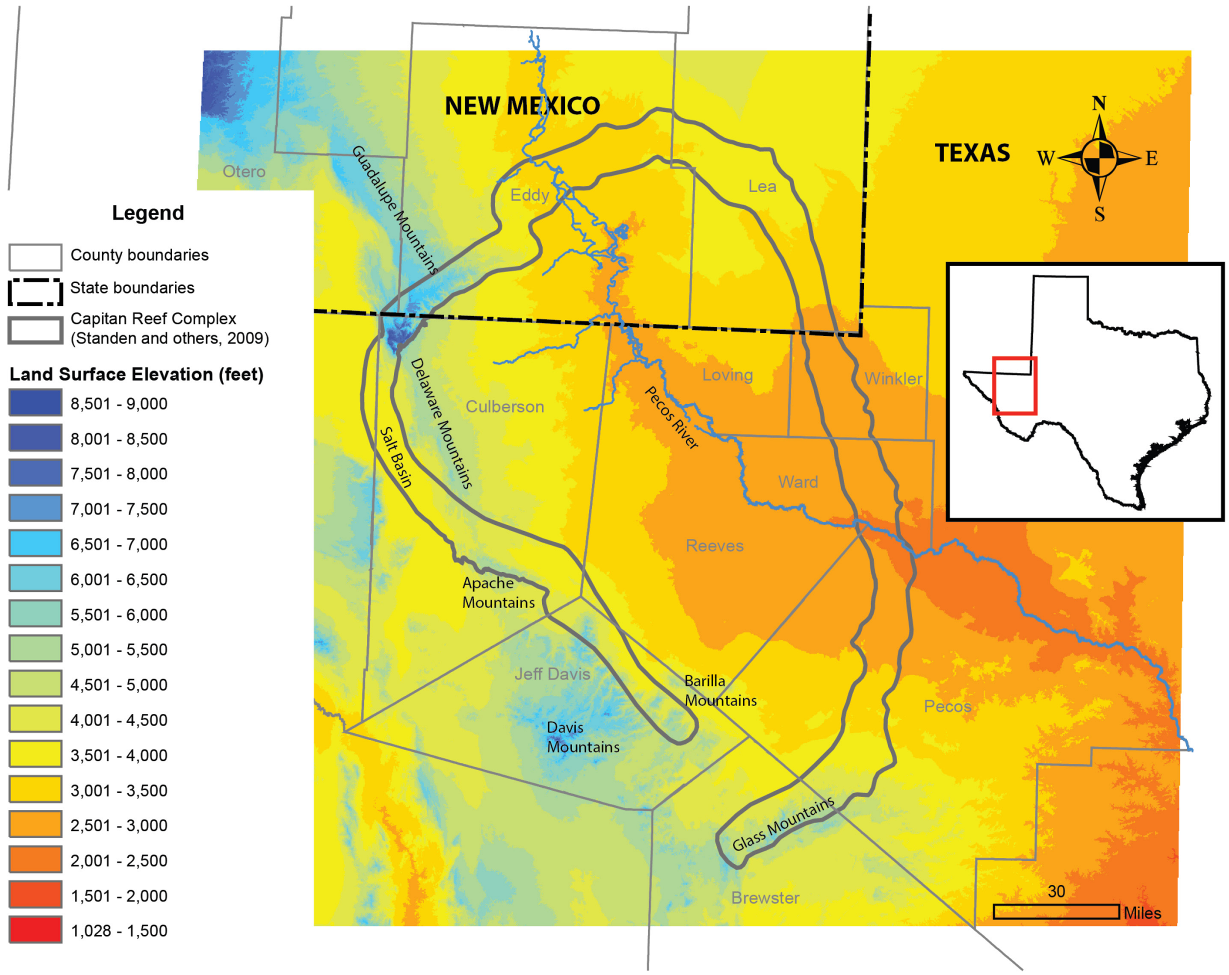


Figure 2.1.3. **Topographic map of the study area showing land surface elevation in feet above mean sea level. Based on data from Gesch and others (2002).**

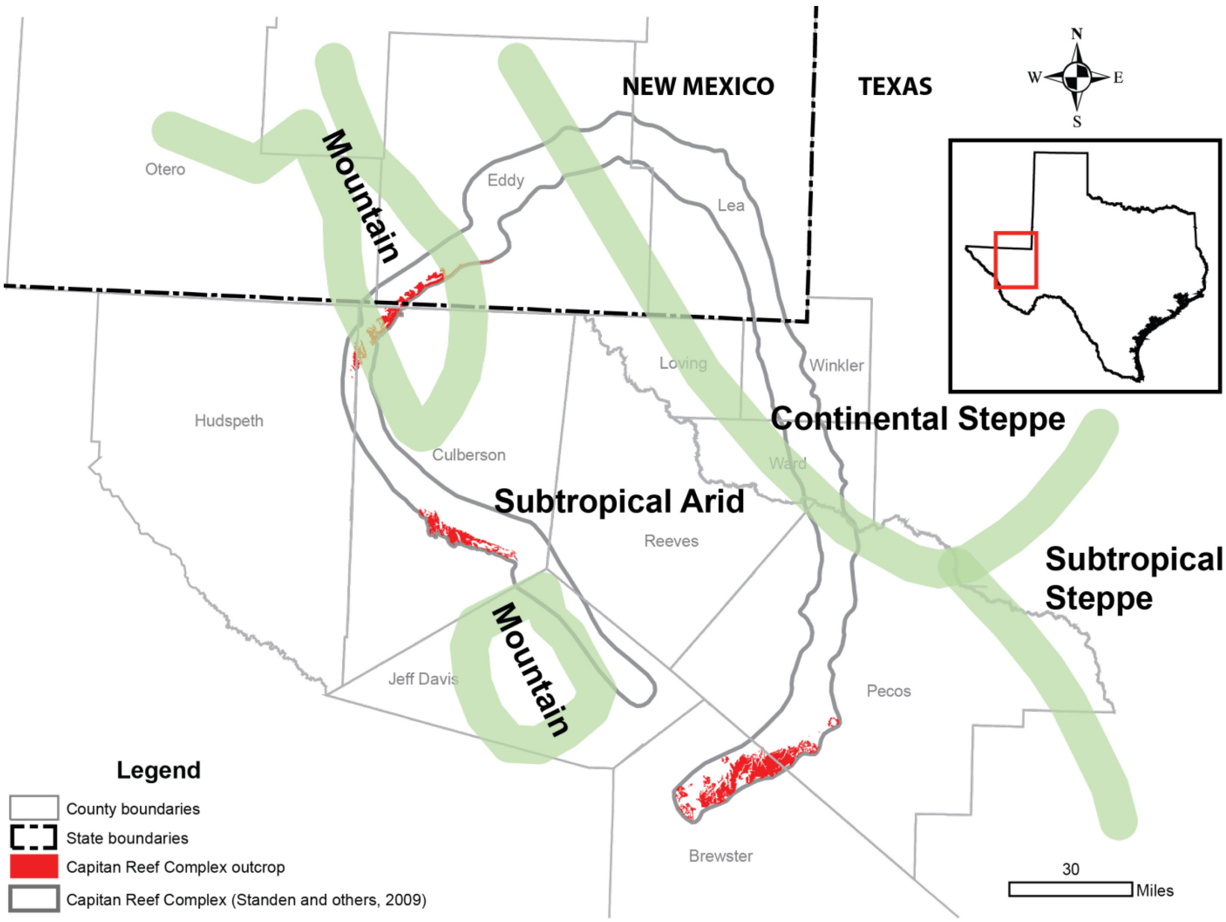


Figure 2.1.4. Climate classifications in the study area (modified from Larkin and Bomar, 1983).

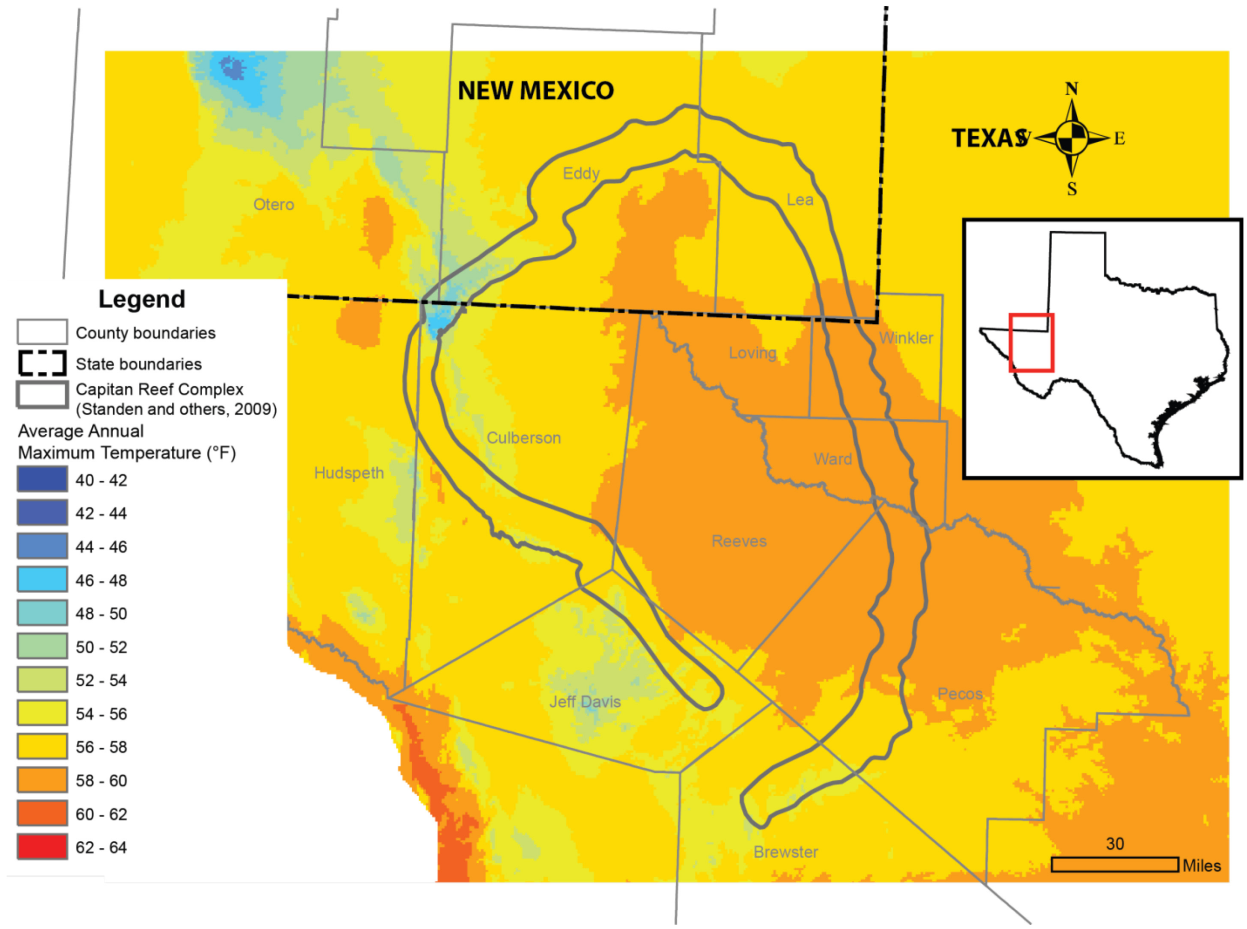


Figure 2.1.5. **Average annual air temperature in degrees Fahrenheit in the study area. Based on 1971 to 2000 PRISM data (Oregon State University, 2006b).**

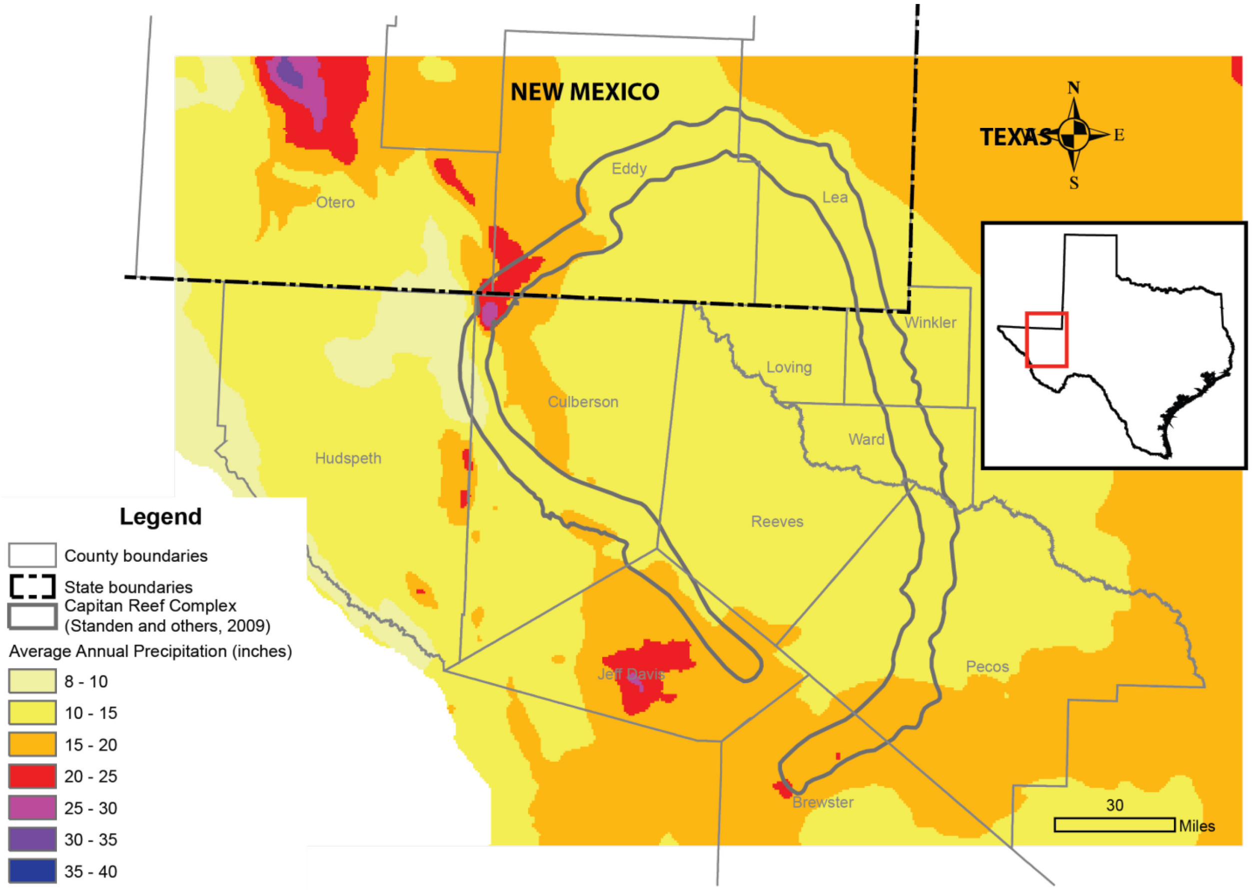


Figure 2.1.6. **Average annual precipitation in inches per year in the study area for the time period 1971 through 2000 (Oregon State University, 2006a).**

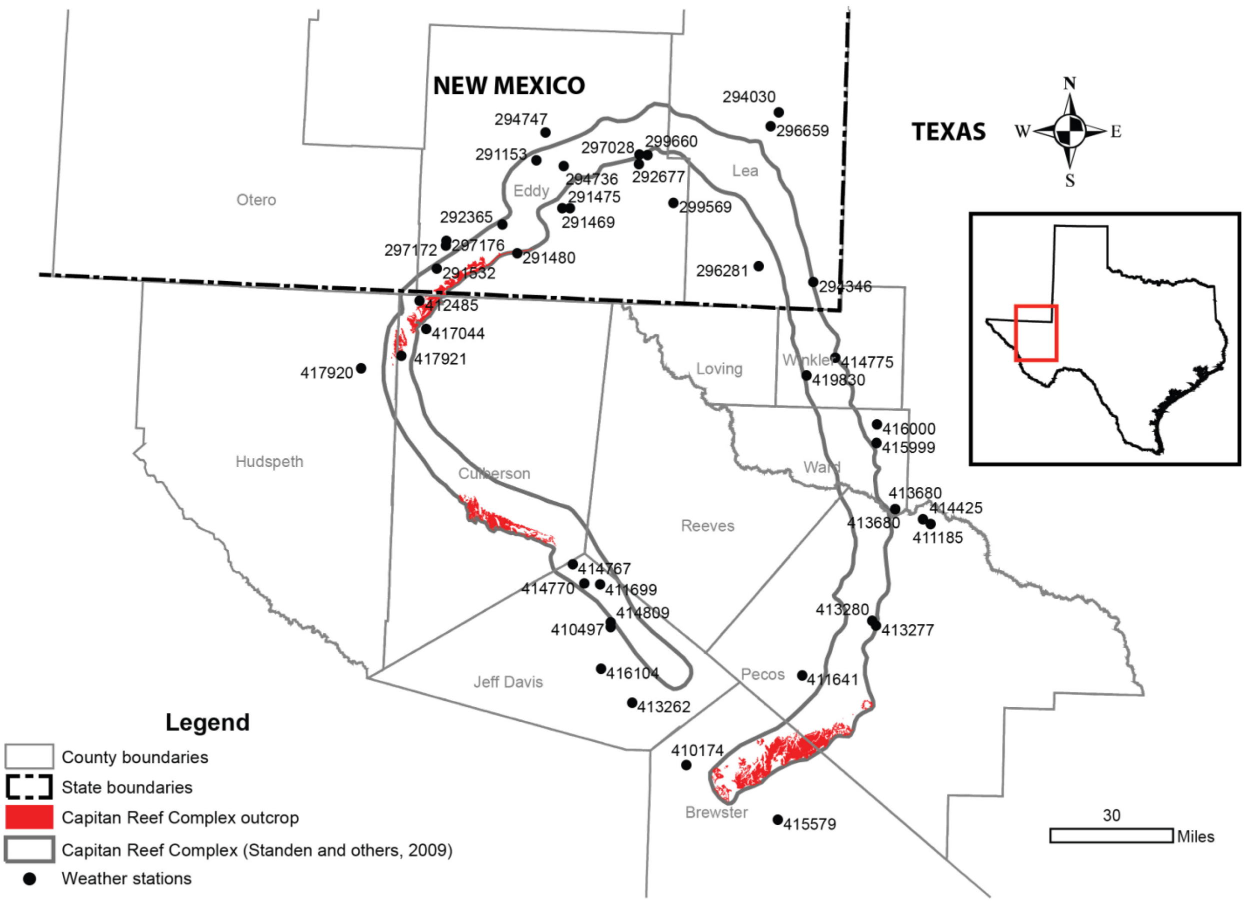


Figure 2.1.7. Location of precipitation gages in the study area (National Climatic Data Center, 2011).

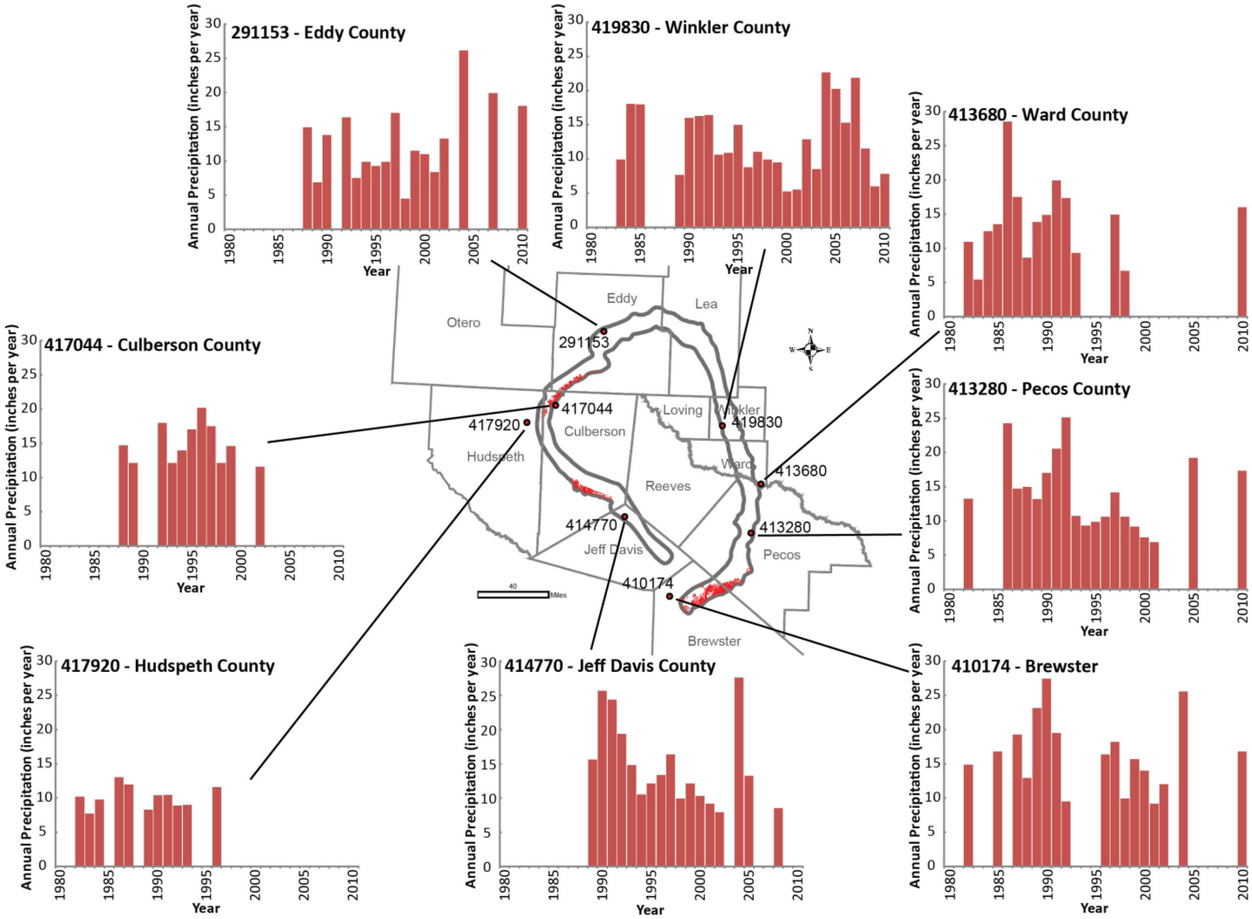


Figure 2.1.8. **Selected time series of annual precipitation in inches per year in the study area (National Climatic Data Center, 2011). Zero values indicate missing data.**

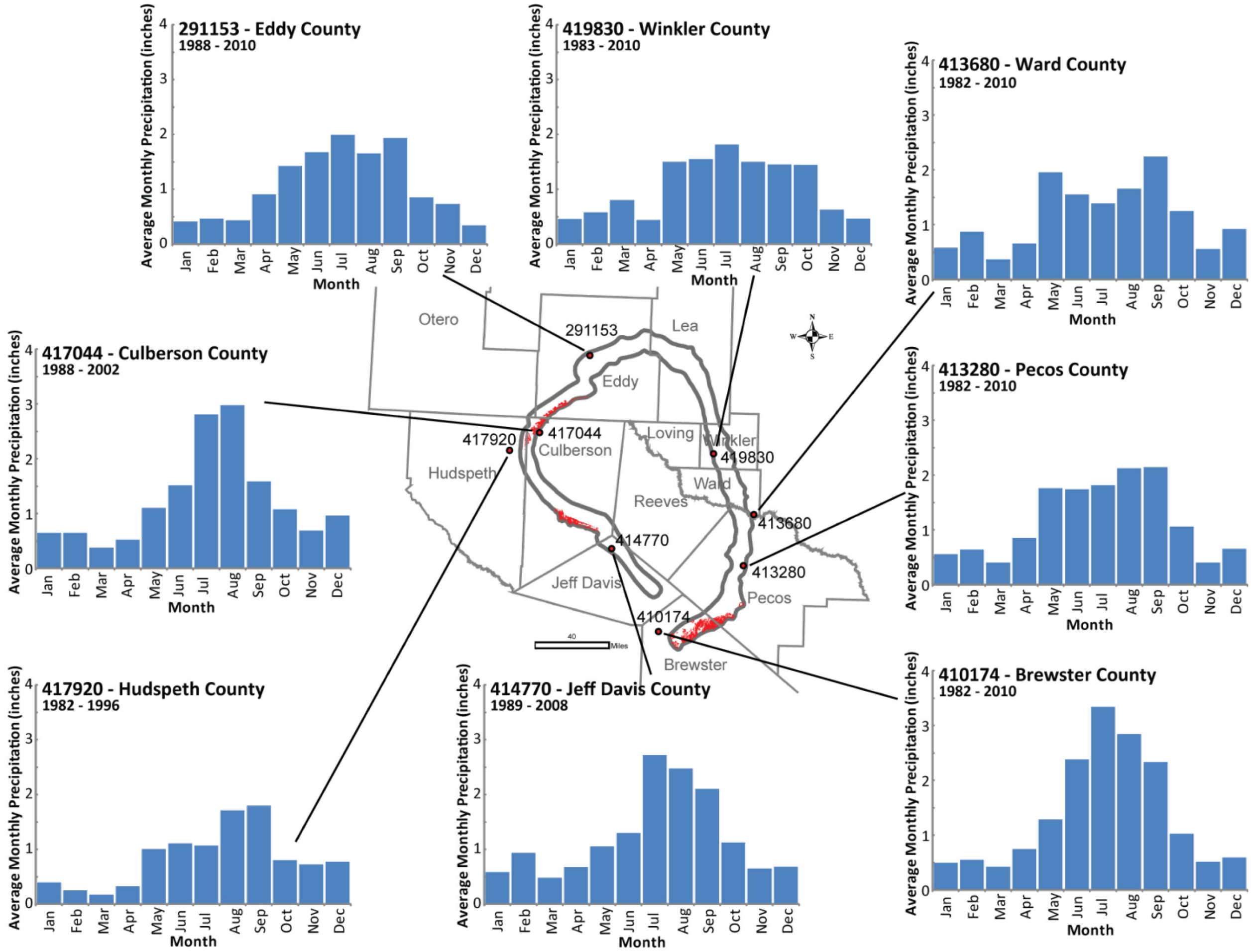


Figure 2.1.9. Selected time series of average monthly precipitation in inches per month in the study area (National Climatic Data Center, 2011).

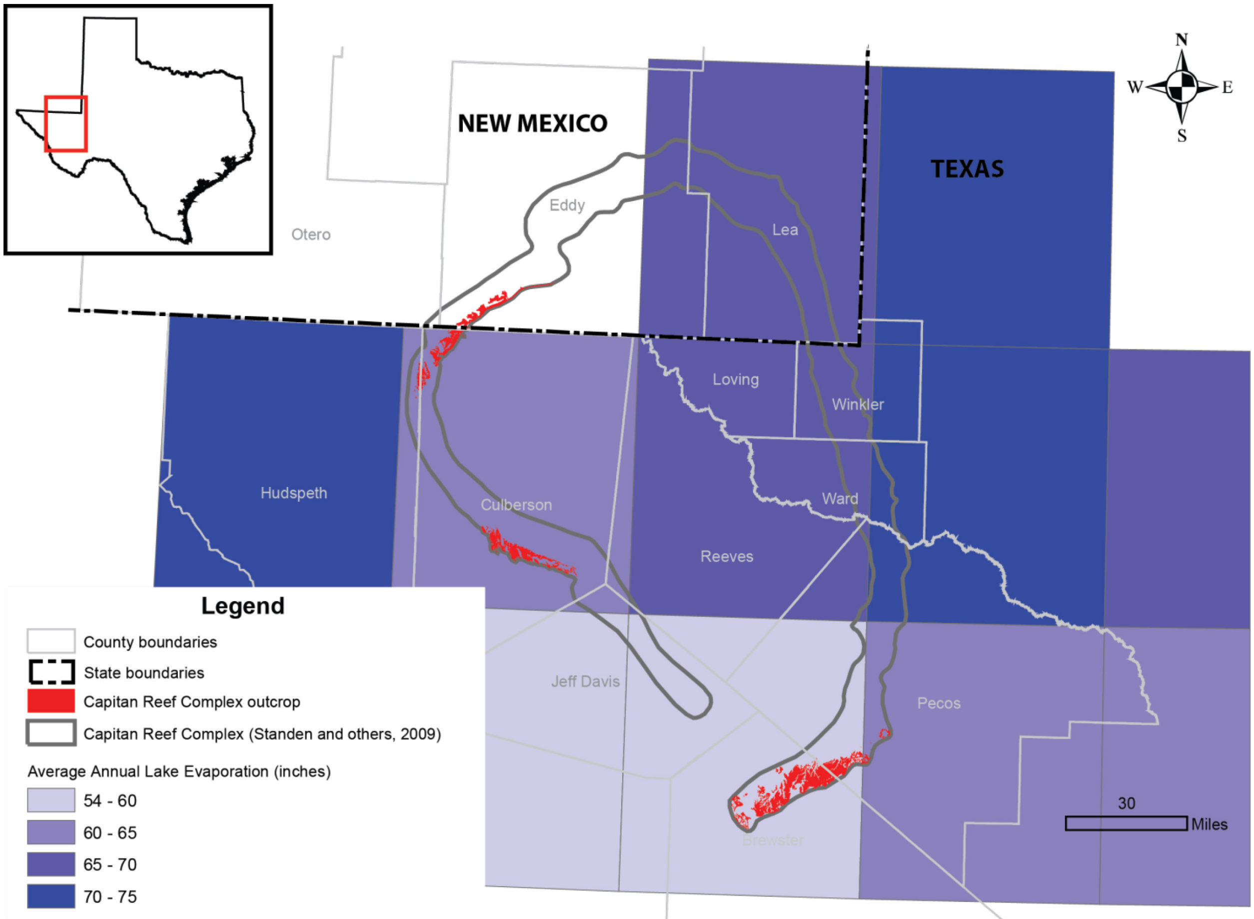


Figure 2.1.10. Average annual net pan evaporation rate in inches per year over the Texas portion of the study area (Texas Water Development Board, 2012a).

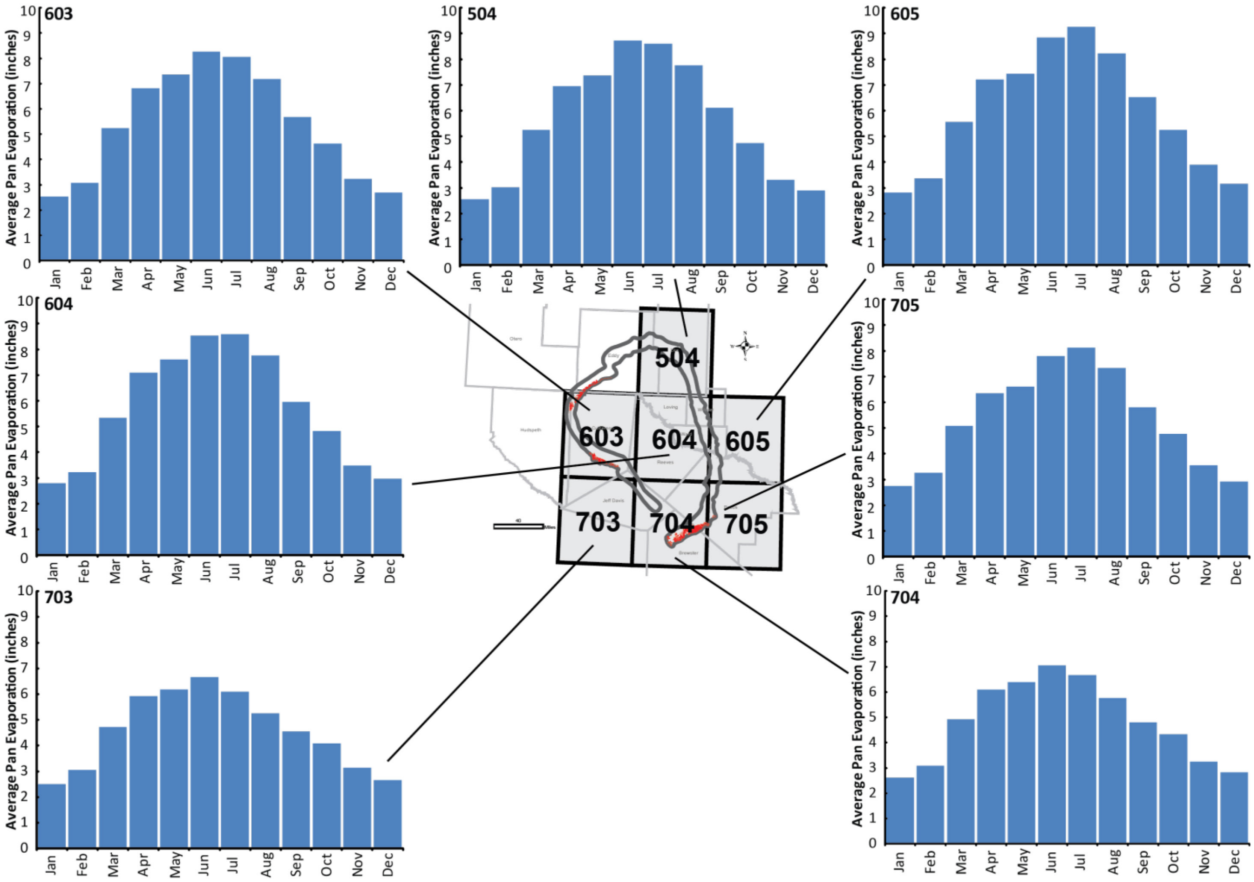


Figure 2.1.11. Average monthly lake surface evaporation in inches in selected map quadrangles in the study area (Texas Water Development Board, 2012a).

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 Capitan Reef Complex, including a description of geologic structural cross-sections through the study area.

2.2.1 Structural Setting

The structural setting for the study area is shown in Figure 2.2.1 (after Armstrong and McMillion, 1961). The primary structural features within the study area include the Delaware Basin, Central Basin Platform, Diablo Platform, Northwestern Shelf, Hovey Channel, and Sheffield Channel. The Capitan Reef Complex occurs along the margins of the Delaware Basin. This basin is surrounded by structural highs—the Northwest Shelf to the north, the Central Basin Platform to the east, the Diablo Platform to the west, and the Southern Shelf and Marathon Folded Belt to the south. The Delaware Basin is also connected to adjacent basins by the Hovey and Sheffield channels that connect the Delaware Basin to the Marfa and Midland basins, respectively.

The Delaware Basin—around which the Capitan Reef Complex formed—was a foreland basin formed when the Ouachita Mountains—located south and east of the study area—were uplifted as the southern supercontinent Gondwana collided with the supercontinent Laurasia during the Pennsylvanian period. This basin formed by subsidence that took place through the early and middle Permian—Leonardian and Guadalupian epochs. Rapid subsidence of the basin started in the middle Guadalupian Epoch of the upper Permian. Patch reefs responded by rapid—mostly vertical—growth, resulting in the deposition of the Goat Seep Dolomite reefs (Harris and others, 1997). The Capitan Reef Complex was built primarily from calcareous sponges and encrusting algae such as stromatolites and directly from seawater as a limey mud (Harris and others, 1997).

Sea level dropped as sedimentation continued to infill the Delaware Basin into the Ochoan epoch of the upper Permian, periodically cutting the basin off from its source of seawater. Part of the resulting brine became the deep-water evaporites of the overlying Castile and Salado formations (Harris and others, 1997). The Rustler Formation evaporites and dolomites represent the uppermost occurrence of evaporites in the Delaware Basin as the basin was finally in-filled and buried beneath non-marine sediments (Holt and Powers, 1990a, 1990b, 2011).

The Delaware Basin was filled at least to the top of Capitan Reef Complex and was mostly covered by dry land before the end of the Ochoan epoch. Rivers migrated over its surface and deposited the red silt and sand that now constitute the siltstone and sandstone of the Dewey Lake Formation and Dockum Group (McGowen and others, 1979; Harris and others, 1997). A karst topography developed as groundwater circulated in the buried Capitan Reef Complex limestone formations, dissolving away the rock to form voids and underground caverns, which were later destroyed by infill and erosion (Harris and others, 1997). Uplift associated with the Laramide Orogeny in the late Mesozoic and early Cenozoic resulted in the formation of the Guadalupe Mountains associated with a major fault zone—the Border Fault Zone (Figure 2.2.2). The mountain range forms the tilted upthrown side of the fault zone and the Salt Flat Bolson formed in the downthrown block (Figure 2.2.2). The Capitan Reef Complex was exposed above the surface, with the 8,000-foot-high El Capitan its most prominent feature. Other large outcrops that also formed were located in the Apache Mountains and Glass Mountains to the south (Harris and others, 1997). The Guadalupe Mountains high coincides with the upthrown—eastern—side of the Border Fault Zone. The Apache Mountains—another structural high in the Capitan Reef Complex—coincides with the upthrown side of the Stocks Fault. The relatively low area between the Border Fault Zone and the Stock Fault is a graben that forms part of the Salt Basin.

During the Late Cretaceous and Early Tertiary periods, the study area was uplifted and tilted slightly to the east. Subsequently, Late Tertiary Basin and Range block faulting formed the Guadalupe, Delaware, Apache, and Glass mountains and Patterson Hills. Major displacements of the Capitan Reef Complex by faulting are limited to the mountainous areas along the western and southern margins of the Delaware Basin (Figure 2.2.2). In addition to faults, the Capitan Reef Complex Aquifer has fissures parallel and perpendicular to the reef face.

Faults, fractures, and fissures play a very important role in local and regional groundwater flow patterns within the Capitan Reef Complex Aquifer. Tectonic events that occurred during the past three hundred million years—Ouachita orogeny, Laramide orogeny, and Basin and Range extension—have resulted in fracture patterns that control groundwater flow paths in the Capitan Reef Complex Aquifer (Uliana, 2000). Subsequent karstification of these fractures within the Capitan Reef Complex and overlying Cretaceous carbonates has produced highly permeable pathways for groundwater flow. Most of this karstification is associated with the Guadalupe Mountains, however, karstification also occurs in the Apache and Glass mountains and in the eastern and northern parts of the Capitan Reef Complex (Hill, 1999a). This karstification is influenced by the arrangement of stratigraphic units, degree of dolomitization, fracture patterns, and the occurrence of anticlines. Areas with large fault offsets may result in the stratigraphic alignment of more permeable Capitan Reef Complex carbonates with adjacent less permeable subsurface formations, such as the Delaware Mountain Group or Artesia Group. This juxtaposition of subsurface formations may significantly impact local and regional groundwater flow systems. Even in the absence of faulting, the Capitan Reef Complex Aquifer is surrounded both vertically and laterally by less permeable fore-reef and back-reef stratigraphic units that have the potential to restrict groundwater flow into and out of the Capitan Reef Complex Aquifer (White, 1987; Standen and others, 2009).

2.2.2 Surface Geology

Figure 2.2.3 is a geologic map of the study area. Over the majority of the study area, the predominant surficial deposits are Quaternary-age alluvial and eolian sediments. Permian and Cretaceous outcrops occur in the northwestern and southeastern parts of the study area, mostly associated with mountains, such as the Guadalupe, Delaware, Apache, and Glass mountains. The major outcrops of the Capitan Reef Complex occur in the Guadalupe, Apache, and Glass mountains.

2.2.3 Delaware Basin Stratigraphy

The Capitan Reef Complex forms a horseshoe-shaped feature along the margins of the Permian Delaware Basin and consists of massive fossiliferous white limestone (Figure 2.2.1). The Capitan Reef Complex combines the Goat Seep Dolomite, Capitan Limestone, and Carlsbad Limestone (Hiss, 1975) and grades into adjacent fore-reef and back-reef facies (Figure 2.2.4). The Capitan Reef Complex geologic model of fore-reef, reef, and back-reef facies was described in detail by King (1948) and by Melim and Scholle (1999).

The back-reef or shelf facies occur behind the reef complex. These facies are characterized by quartz sandstone and siltstone with carbonate and evaporite facies, and consist of the Artesia Group—the Grayburg, Queen, Seven Rivers, Yates, and Tansill formations (Figure 2.2.5). The Grayburg, Queen, and Yates formations contain more sandstone beds than the Seven Rivers and Tansill formations (Motts, 1968). Carbonate facies occurs adjacent to the Capitan Reef Complex while the evaporite facies occurs farther away. The boundary between the evaporite and carbonate facies shifts closer to the shelf margin in the younger formations of the Artesia Group from 15 to 20 miles from the shelf margin in the Queen Formation to about 5 to 10 miles in the Tansill Formation.

The fore-reef or basin facies consist of the Castile Formation and the Delaware Mountain Group. The Delaware Mountain Group is 2,700 to 3,500 feet thick and consists of the Brushy Canyon, Cherry Canyon, and Bell Canyon formations (Motts, 1968). The formations of the Delaware Mountain Group are predominantly sandstone with carbonate beds occurring in the Cherry Canyon and Bell Canyon formations. The Castile Formation consists of evaporites and thin beds of limestone, shale, and sandstone.

2.2.4 Capitan Reef Complex

The Capitan Reef Complex is exposed in outcrops in the Guadalupe Mountains (Eddy County, New Mexico and Culberson County, Texas), Patterson Hills (Culberson and Hudspeth counties, Texas), Apache Mountains (Culberson County, Texas), and Glass Mountains (Brewster and Pecos counties, Texas) (Figure 2.2.3). Geologic descriptions stem primarily from detailed mapping in the Guadalupe and Glass Mountains (King, 1930, 1948). Figures 2.2.6 through 2.2.9 show four representative cross-sections through the eastern arm of the Capitan Reef Complex. Figures 2.2.6 and 2.2.7 show east-west oriented cross-sections across the Capitan Reef Complex in Lea County, New Mexico and Pecos County, Texas, respectively, where the Capitan Reef Complex occurs in the subsurface. Figure 2.2.8 is a northwest-southeast oriented cross-section across the Capitan Reef Complex outcrop in the Glass Mountains of Brewster County, Texas. In this area, the Capitan Reef Complex dips towards the northwest, is overlain by Cretaceous sediments, and is cross-cut by faults and Tertiary igneous intrusions. Figure 2.2.9 is a cross-section approximately parallel to the trend of the eastern arm of the Capitan Reef Complex. This cross-section extends from Eddy County, New Mexico to the Glass Mountain Capitan Reef Complex outcrop near the boundary between Pecos and Brewster counties in Texas.

The arc-shaped reef structure of the Capitan Reef Complex is about 10 to 14 miles wide and is dissected by the Hovey Channel in Brewster County (Hill, 1996; Hiss, 1975). There is also some evidence suggesting another channel located in the western part of the Capitan Reef Complex (Hill, 1999b; 2006).

The Capitan Reef Complex is composed of massive white to gray fossiliferous limestone beds. The limestone beds grade from fore-reef to back-reef deposits. The gradation into fore-reef deposits is typically abrupt, with a defined geologic contact, whereas the gradation into back-reef deposits is more transitional, with difficult-to-identify geologic contacts (Hill, 1996; Hiss, 1975).

The rocks that make up the reef complex have been locally dissected by faults and consequently do not form one continuous aquifer but rather a series of disconnected highly permeable aquifers (Hill, 1996; Hiss, 1975) (Figure 2.2.2). For example, the uplifted Guadalupe Mountains divide the Capitan Reef Complex Aquifer into two separate disconnected aquifers, one that trends to the northeast and discharges to the Pecos River in New Mexico and one that originates along the western flank of the Guadalupe Mountains and flows south toward the Apache Mountains (Hiss, 1975; King, 1948).

Streams eroded away the softer sediment, lowering the ground level to its current position. Submarine canyons are incised in the Capitan Reef Complex along the northern and eastern margins of the Delaware Basin. Hiss (1975) identified 25 submarine canyons where the top of the Capitan Reef Complex is structurally low. These submarine canyons were eventually filled with low permeability material. Hiss (1975) believes that these submarine canyons restrict groundwater flow through the reef carbonates. Acidic groundwater excavated caves in the limestone of the higher areas, and eroded sediment helped fill any remaining Permian-aged caves. Unlike most other caves that are formed in limestone, the source of acidity that formed these caves was likely hydrogen sulfide and sulfide-rich brines freed by tectonic activity during the mid-Tertiary age. These acidic brines mixed with oxygenated groundwater, forming sulfuric acid. The Carlsbad Caverns and nearby modern caves started to form during this time below the water table. Additional uplift of the Guadalupe Mountains during the Pliocene and early Pleistocene epochs have enlarged Carlsbad Caverns and other nearby caves (Harris and others, 1997).

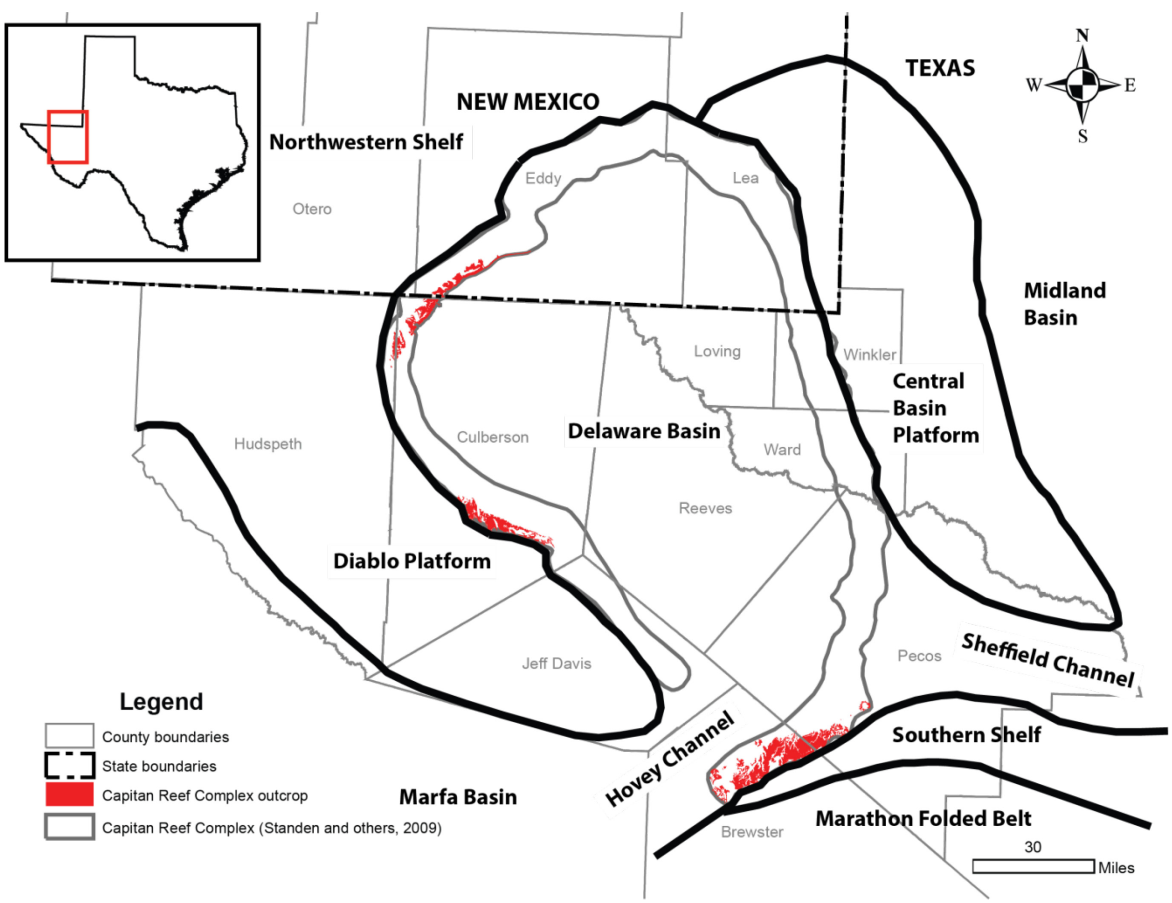


Figure 2.2.1. Major structural features in the study area (from Armstrong and McMillion, 1961).

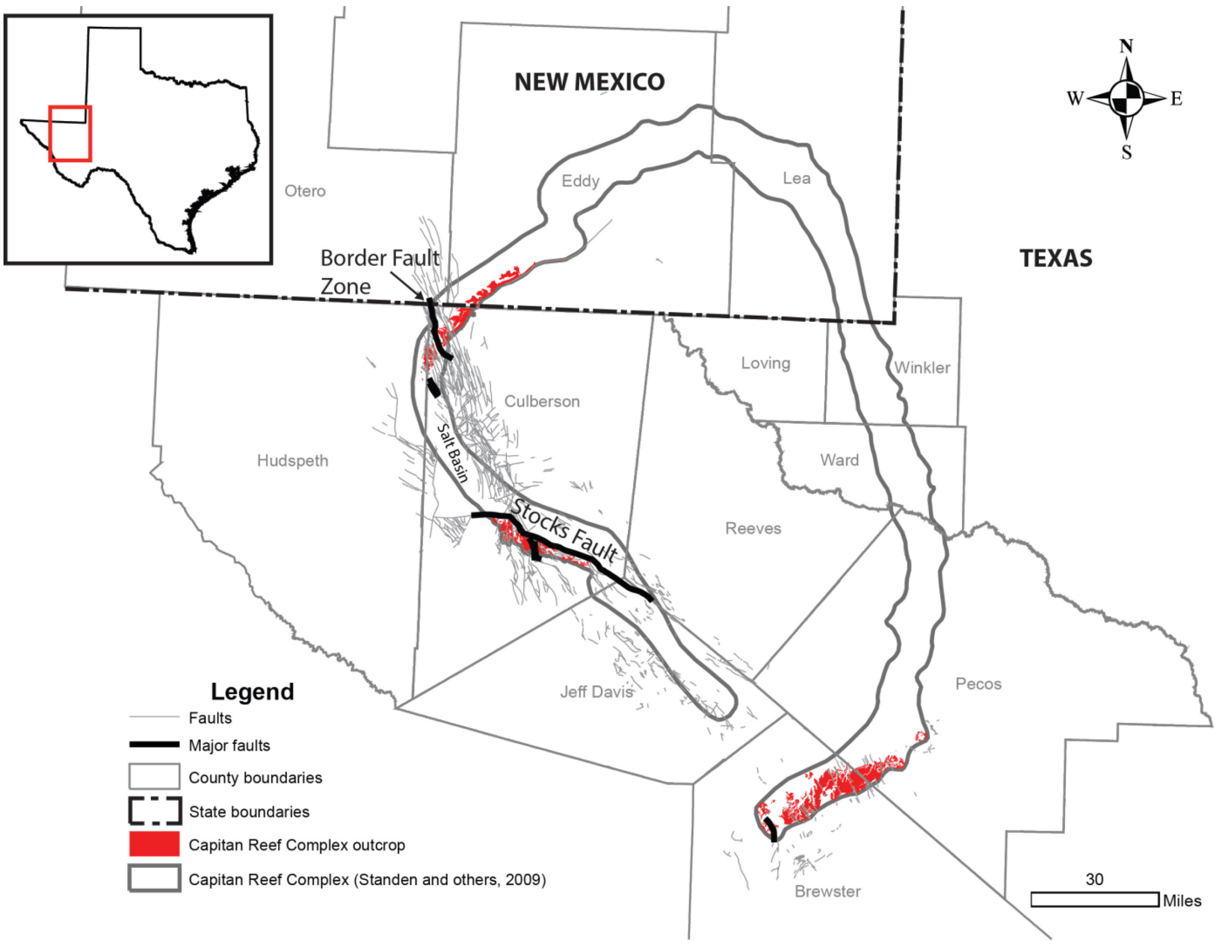


Figure 2.2.2. **Faults that cut through or lie adjacent to the Capitan Reef Complex Aquifer.**

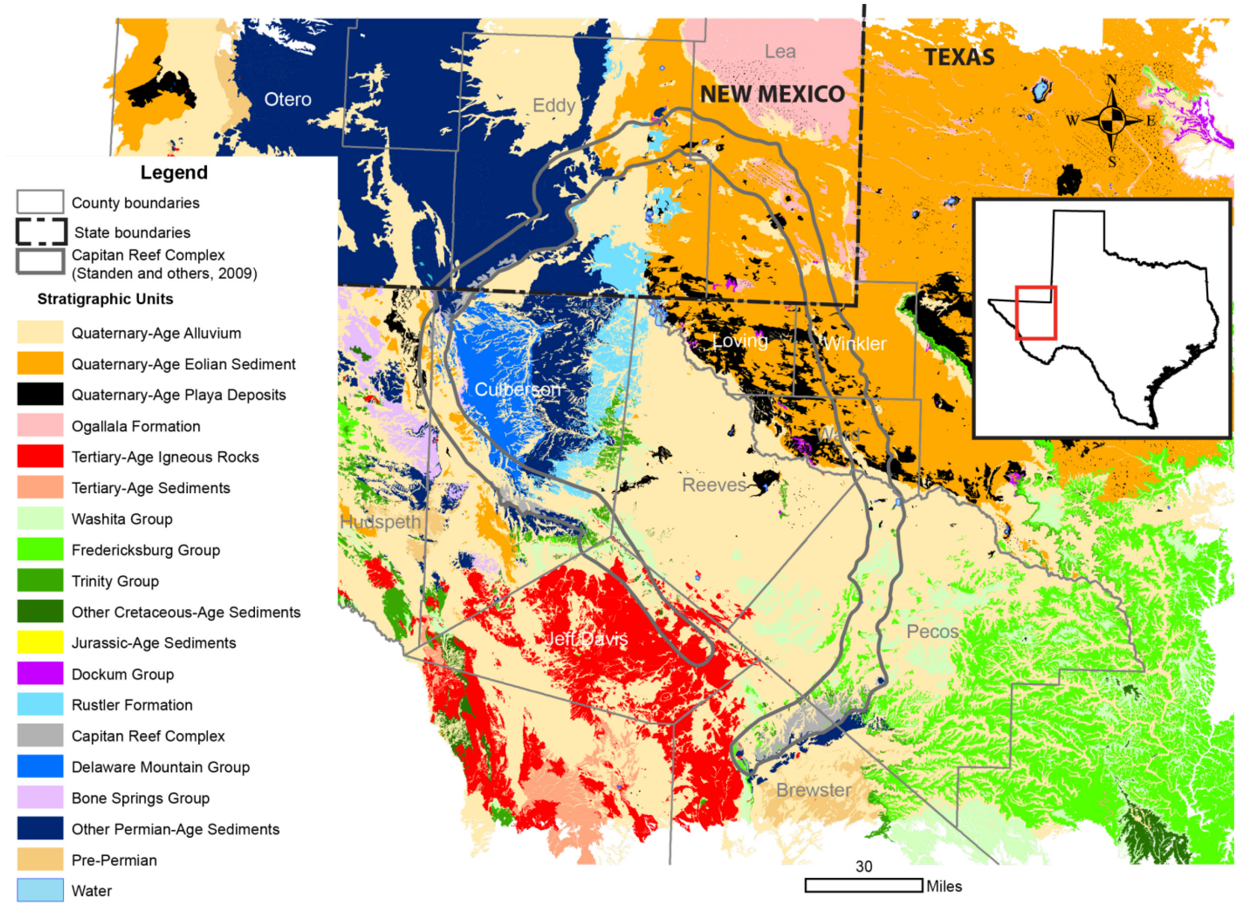


Figure 2.2.3. **Generalized surface geology in the study area.**

Summary of geologic formations and groups forming the Capitan Reef Complex and Delaware Basin

Period/Epoch or Series	Apache Mountains (Wood, 1968; Uliana, 2001)		Guadalupe Mountains (King, 1948; Hiss, 1975; Kerans and others, 1994; Kerans and Tinker, 1999)		Glass Mountains (Hill, 1999)		Delaware Basin
	Back Reef	**Reef**	**Back Reef**	**Reef**	**Back Reef**	**Reef**	
Quaternary to Tertiary	Quaternary Tertiary Deposits		Quaternary Tertiary Deposits		Quaternary Tertiary Deposits		Pecos Valley Alluvium
Cretaceous					Cretaceous		Edwards/Trinity Groups
Triassic							Dockum Group
Permian/Ochoan				Rustler [a] Salado [a] Castile [a]	Tessey		Rustler Salado Castile
Permian/ Guadalupian	Artesia Group: Tansill	*Capitan Reef Complex*: Capitan Limestone	Artesia Group: Tansill	*Capitan Reef Complex*: Carlsbad and Capitan Limestones	Gilliam	*Capitan Reef Complex*: Capitan Limestone	Delaware Mountain Group: Bell Canyon
	Artesia Group: Yates		Artesia Group: Yates				
	Artesia Group: Seven Rivers		Artesia Group: Seven Rivers				Cherry Canyon
	Munn		Queen/Grayburg	Goat Seep Dolomite	Vidrio		
	Cherry Canyon		Upper San Andres Lower San Andres (Brushy Canyon Equivalent)	Cherry Canyon	Word Formation (Cherry and Brushy Canyon Equivalent)		Brushy Canyon
	Cutoff Shale (Member of Bone Spring Limestone)						Pipeline Shale Member
Permian/ Leonardian	Yeso	Victorio Peak (Member of the Bone Spring Limestone)			Leonard and Hess Member of Leonard Formation		Bone Spring Limestone

Sources: From Standen and others (2009): Modified after King, 1948; Wood, 1968; Hiss, 1975; Uliana, 2001; Hill, 1999; Kerans and others, 1994; Kerans and Tinker, 1999.

[a] Formations overlie Capitan Reef Complex between the Guadalupe and Glass Mountains

Figure 2.2.4. Generalized stratigraphic column for the Capitan Reef Complex and overlying and underlying formations.

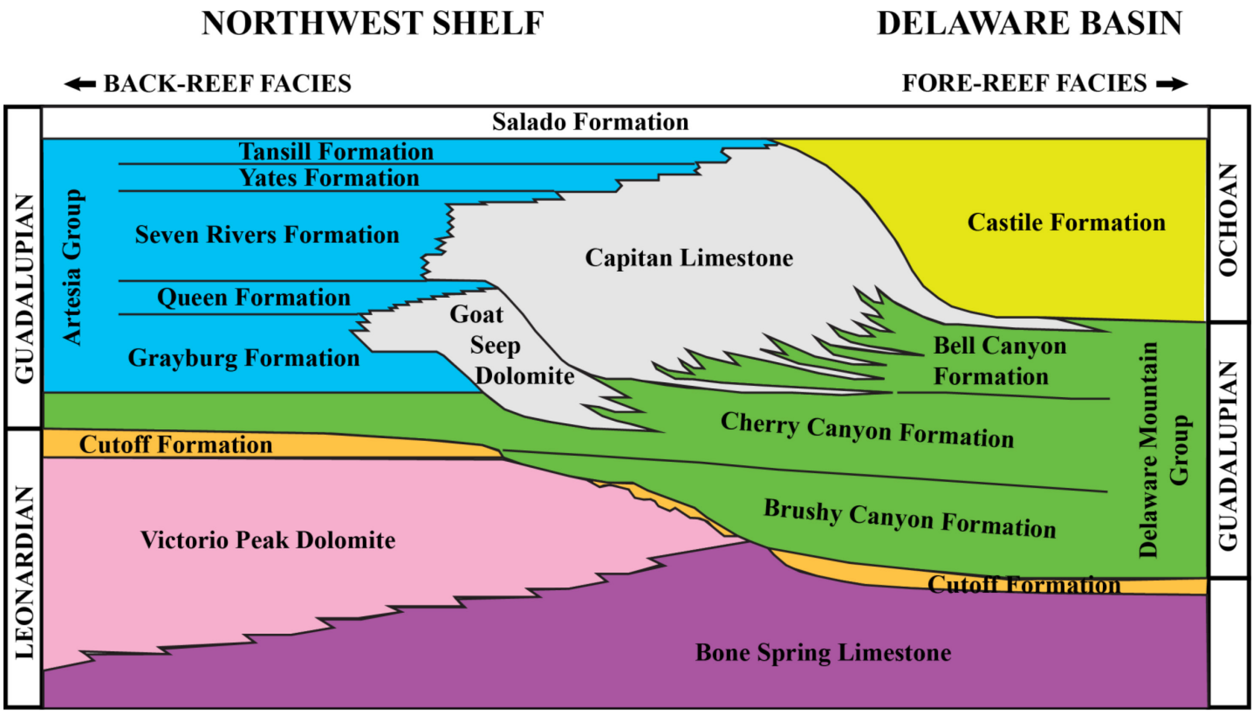
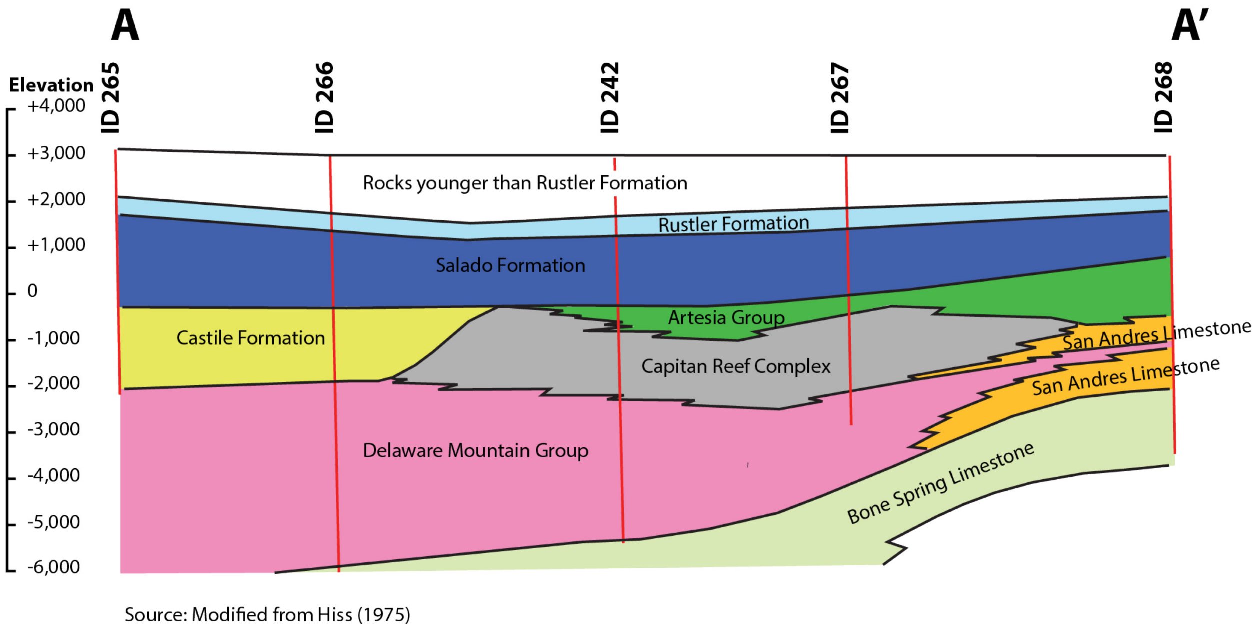


Figure 2.2.5. **Generalized cross-section through the Capitan Reef Complex and associated fore-reef and back-reef facies formations. Modified from Standen and others, 2009; Melim and Scholle, 1999).**



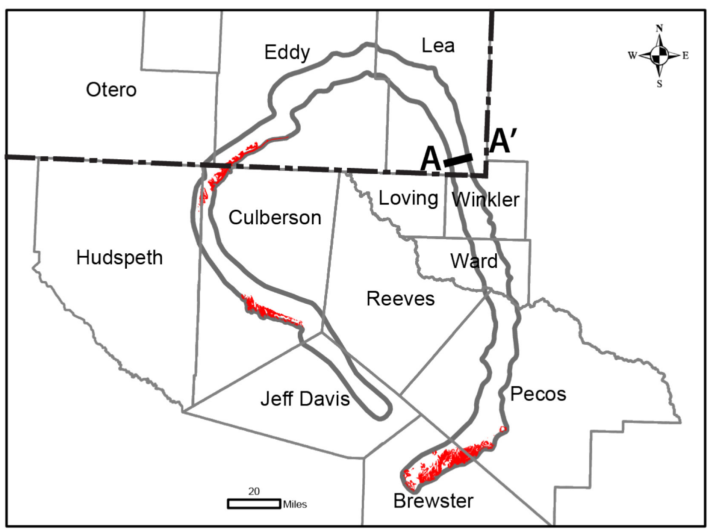
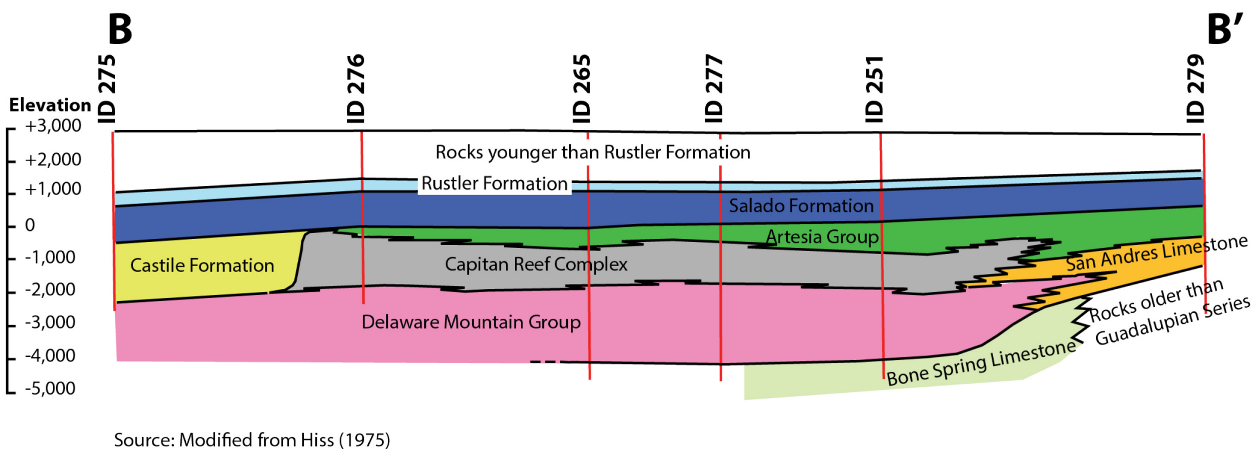


Figure 2.2.6. **A-A' cross-section through the Capitan Reef Complex in Lea County, New Mexico (modified from Standen and others, 2009; Hiss, 1975).**



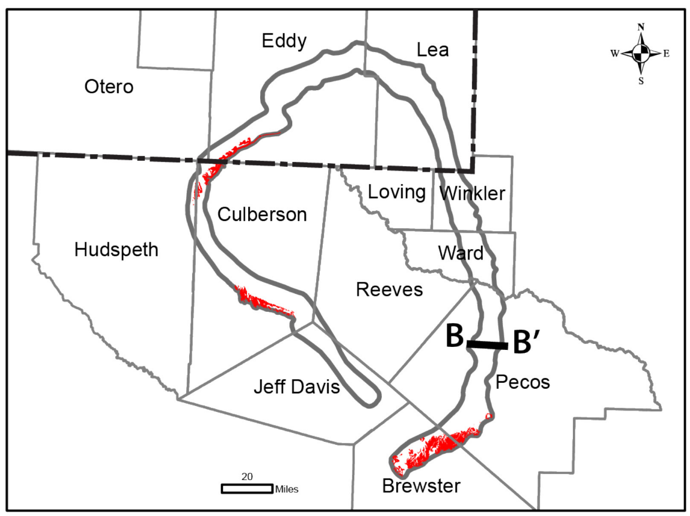


Figure 2.2.7. **B-B' cross-section through the Capitan Reef Complex in Pecos County, Texas (modified from Standen and others, 2009; Hiss, 1975).**

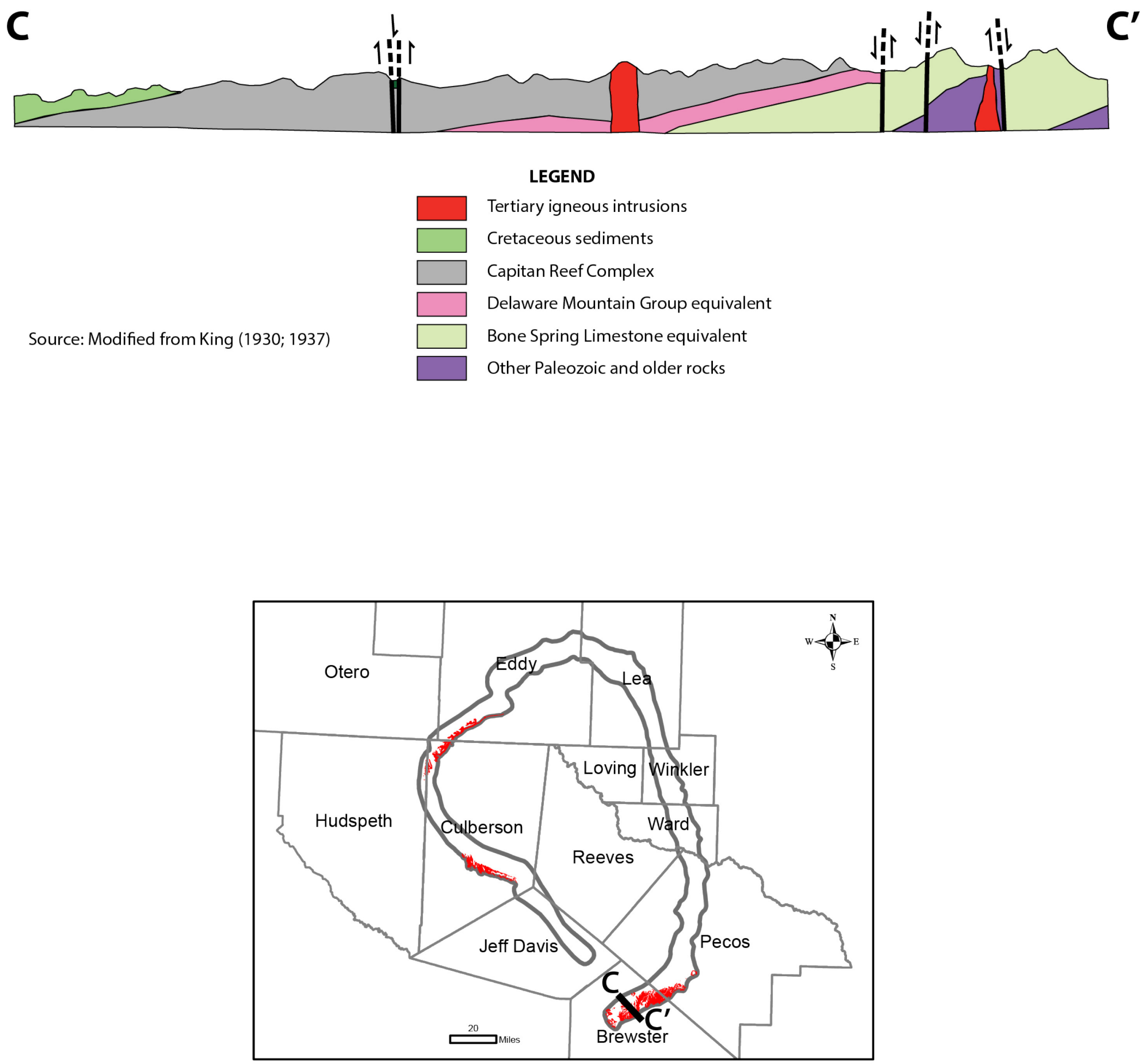


Figure 2.2.8. **C-C' cross-section through the Capitan Reef Complex outcrop in the Glass Mountains, Brewster County, Texas (modified from Standen and others, 2009; King, 1930; 1937).**

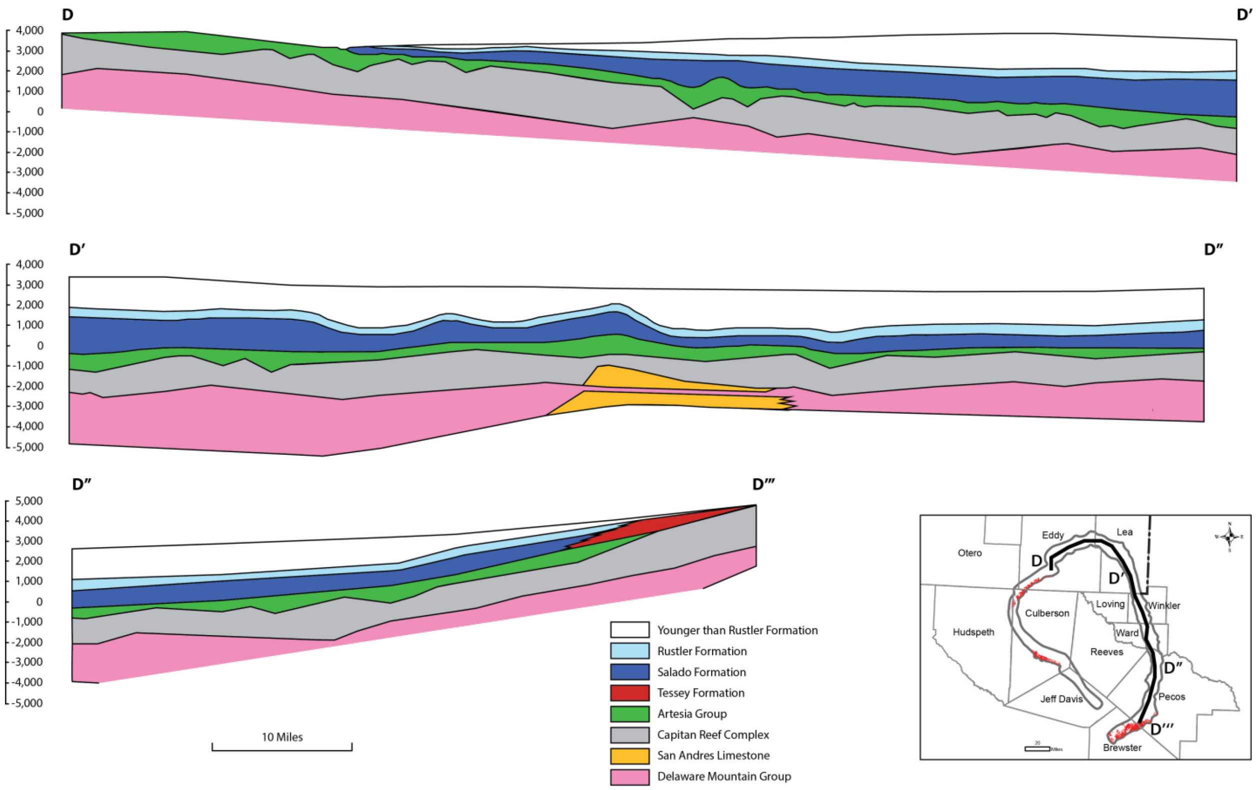


Figure 2.2.9. **D-D''' cross-section through the Capitan Reef Complex outcrop in the Glass Mountains, Brewster County, Texas (modified from Hiss, 1975).**

3.0 PREVIOUS WORK

There have been several studies of the stratigraphy, geologic framework, and hydrogeology of the Capitan Reef Complex—mostly by the United States Geological Survey and the University of Texas at Austin. Studies by King (1948), Hayes (1964), Wood (1965), and Bebout and Kerans (1993) described the geology of the Capitan Reef Complex outcrops in the Guadalupe and Apache mountains. Standen and others (2009) compiled work on the stratigraphy and geologic framework of the Capitan Reef Complex. Standen and others (2009) also used geophysical logs to define the elevations of the top and base of the Capitan Reef Complex and revise its spatial extents.

Several studies investigating the hydrogeology of the Capitan Reef Complex Aquifer include Armstrong and McMillion (1961), White (1987), Hiss (1975; 1980), Richey and others (1985), Sharp (1989), Ashworth (1990), Brown (1997), Uliana (2001), Uliana and Sharp (2001), and INTERA (2013). The Brown (1997) study investigated water quality in the Capitan Reef Complex Aquifer. The groundwater flow system of the Capitan Reef Complex Aquifer has been documented in work by Hiss (1975; 1980), Uliana (2001), and Uliana and Sharp (2001).

Three groundwater flow models simulating groundwater flow in parts of the eastern arm of the Capitan Reef Complex Aquifer have been constructed (Figure 3.0.1). The first groundwater flow model simulates groundwater flow through the Capitan Reef Complex Aquifer and Pecos River alluvium near Carlsbad, New Mexico (Barroll and others, 2004). A simplified groundwater flow model was constructed by INTERA and Cook-Joyce (2012) simulating groundwater flow in part of the eastern arm of the Capitan Reef Complex Aquifer. The purpose of that model was to simulate the potential effects of a well field located in central Ward County. Despite its regional extent, this model was only calibrated based on water-level and pumping data from well fields located within Ward and Winkler counties. The third model simulated the effects of a pair of wells located in Lea County, New Mexico (Castiglia and others, 2013; INTERA, 2013). The groundwater flow models by Barroll and others (2004), INTERA and Cook-Joyce (2012) and Castiglia and others (2013) were constructed to address localized issues, groundwater flow along the Pecos River and potential effects of well fields, respectively. This contrasts with the proposed Texas Water Development Board groundwater availability model of the eastern arm of the Capitan Reef Complex Aquifer that will be designed to simulate groundwater flow between the Glass Mountains outcrop in Brewster County and where the Pecos River interacts with the aquifer near Carlsbad, New Mexico—a study area that includes the areas of interest of all three models.

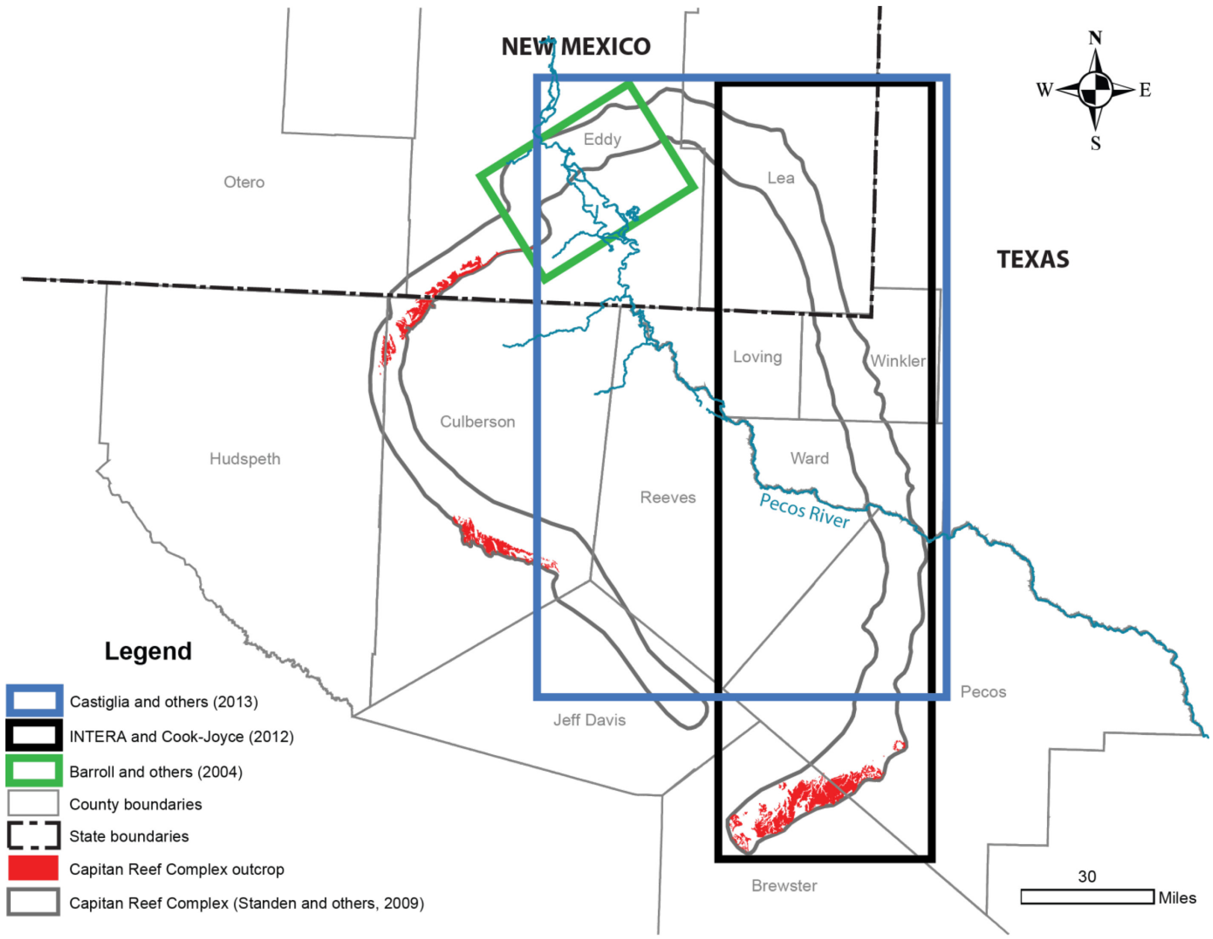


Figure 3.0.1. **Approximate extents of previous model grids for models used for simulating groundwater flow through the Capitan Reef Complex Aquifer.**

4.0 HYDROLOGIC SETTING

The hydrologic setting is a description of the factors that contribute to the groundwater hydrology of the Capitan Reef Complex Aquifer. These factors include the hydrostratigraphy, hydrogeologic framework, water levels and regional groundwater flow, recharge, surface-water bodies, hydraulic properties, discharge, and water quality.

4.1 Hydrostratigraphy and Hydrostratigraphic Framework

The Capitan Reef Complex Aquifer (Figure 2.0.2) is defined as Permian-age carbonate reef-forming rocks that were deposited on the margins of the Delaware Basin (Hiss, 1975). These limestone formations include the Capitan Limestone in the western, southern, and northern parts of the reef complex, and the Carlsbad Limestone and Goat Seep Dolomite in the north (Figure 4.1.1). In the south, the Tessey Limestone—a stratigraphic equivalent to the Salado and Castile formations—is a pathway for recharge to the underlying Capitan Reef Complex Aquifer. In the subsurface, the Capitan Reef Complex Aquifer is bounded laterally and vertically by aquitards made up of the fore-reef Delaware Mountain Group and back-reef Artesia Group. These stratigraphic units are in turn overlain by the evaporites of the Castile and Salado formations that also act as aquitards. Four aquifers—the Rustler, Dockum, Edwards-Trinity (Plateau), and Pecos Valley aquifers—overlie the aquitards.

The top of the Capitan Reef Complex Aquifer has elevations ranging from 1,500 feet below mean sea level to more than 8,000 feet above mean sea level. The top surface of the Capitan Reef Complex Aquifer shown in Figure 4.1.2 is a combination of subsurface top designations using geophysical logs and driller's reports, and 30-meter digital elevation model surface elevations of the Capitan Reef Complex Aquifer outcrops (Standen and others, 2009). Outcrop structural tops within the Capitan Reef Complex Aquifer were identified using the available digital Geological Atlas of Texas (Pearson, 2007). The subsurface top of the Capitan Reef Complex Aquifer is a combination of structural tops and erosional surfaces. Figure 4.1.3 shows the base of the Capitan Reef Complex Aquifer. The Capitan Reef Complex Aquifer base was created by subtracting the Capitan Reef Complex Aquifer thickness (Figure 4.1.4) from the top surface (Figure 4.1.2) using ArcGIS Spatial Analyst (Standen and others, 2009).

Figures 4.1.2 and 4.1.3 indicate that the Capitan Reef Complex Aquifer dips to the northeast with highest elevations associated with outcrops in the Guadalupe and Glass mountains and lowest elevations occurring in the subsurface in Lea, Winkler, Ward and northern Pecos counties. The thickest parts of the Capitan Reef Complex Aquifer occur in the Guadalupe Mountains and in the northern and eastern parts of the reef complex (Figure 4.1.4). The thickest parts of the aquifer occur on the fore-reef side of the Capitan Reef Complex. The thinnest parts of the Capitan Reef Complex Aquifer occur in the southern and back-reef parts of the reef complex.

The Capitan Reef Complex locally underwent erosion during the middle to late Guadalupian period. Hiss (1975) identified Capitan Reef Complex carbonate reef highs—thick carbonate intervals—alternating with erosional valleys—thin carbonate intervals—on the eastern arm of the Capitan Reef Complex (Figure 4.1.4). These erosional valleys extended from the Central Basin Platform, through the Capitan Reef Complex and toward the Delaware Basin (Figure 4.1.4). These erosional valleys were in-filled with silts, clays, and fine sands forming clastic channels overlying and adjacent to the Capitan Reef Complex limestone. In-filling with Cenozoic sediment is also associated with karstification along the fore-reef side of the Capitan Reef Complex (Hill, 1999a). Karstification in the Capitan Reef Complex is also attributed to the development of the overlying Monument Draw Trough through dissolution of overlying evaporites by groundwater discharging from the Capitan Reef Complex Aquifer accompanied by collapse of overlying sediment (Anderson and others, 1978; Anderson, 1981; Hill, 1999a). This process is likely responsible for the formation of the overlying Monument Draw Trough (Jones, 2001; 2004).

The elevations of the top and base of the Rustler Aquifer are shown in Figures 4.1.5 and 4.1.6. These figures indicate low areas coinciding with the Monument Draw and Pecos troughs that are most commonly associated with the overlying Pecos Valley Aquifer (Jones, 2001; 2004). These basins formed due to dissolution of the underlying Salado Formation. The Monument Draw Trough also coincides with the Capitan Reef Complex. The base of the Rustler Aquifer coincides with the top of the Salado Formation which is the top of the underlying aquitards that separate the Capitan Reef Complex Aquifer and the overlying Rustler Aquifer. Figure 4.1.7 shows that the Rustler Aquifer is thickest on the basin side of the Capitan Reef Complex—300 to 600 feet thick—while on the shelf side of the Capitan Reef Complex it thins to less than 100 feet.

Like the underlying Rustler Aquifer, the Dockum Aquifer top and base display low areas coinciding with the Monument Draw and Pecos troughs (Figures 4.1.8 and 4.1.9). The combined thickness of the Dockum Group and Dewey Lake Formation indicate an area of increased thickness coinciding with the Monument Draw Trough and underlying Capitan Reef Complex (Figure 4.1.10).

The Monument Draw and Pecos troughs are not apparent at land surface that forms the tops of the Edwards-Trinity (Plateau) and Pecos Valley aquifers (Figure 4.1.11). However, these basins are apparent as low areas at the base of the respective aquifers and as areas of increased thickness (Figures 4.1.12 and 4.1.13).

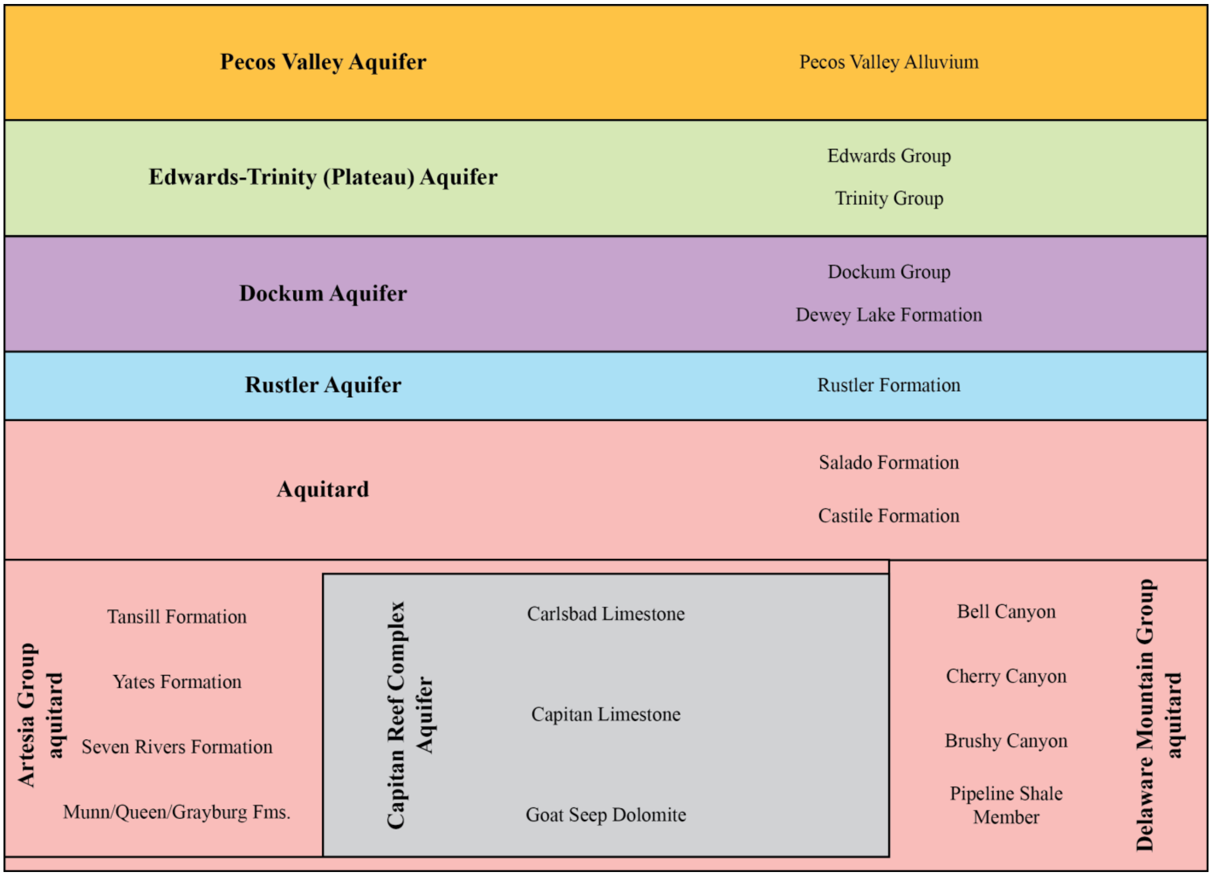


Figure 4.1.1. Hydrostratigraphic chart for down-dip portion of the Capitan Reef Complex and overlying and underlying formations.

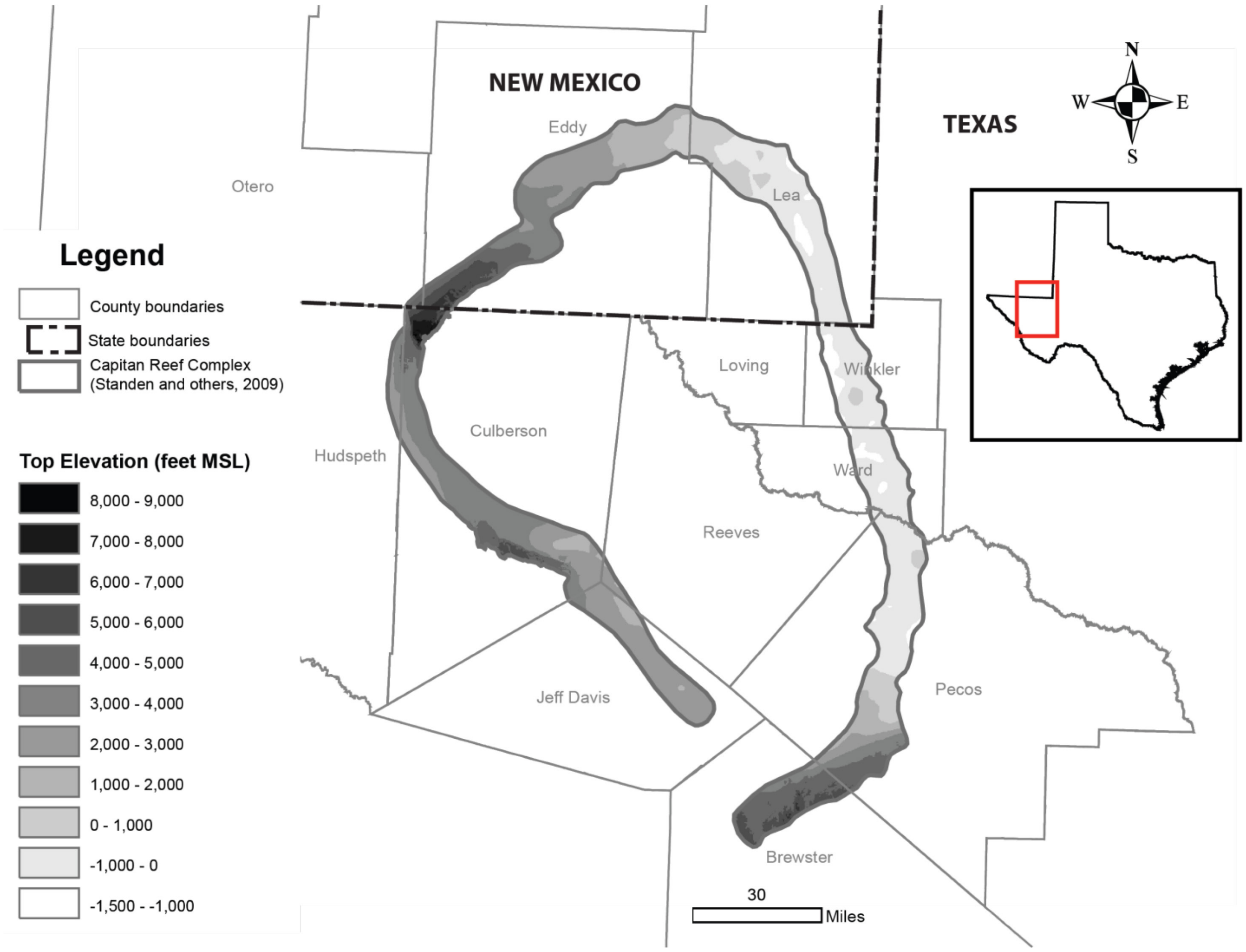


Figure 4.1.2. **The elevation (in feet above mean sea level (MSL)) of the top of the Capitan Reef Complex Aquifer (modified from Standen and others, 2009).**

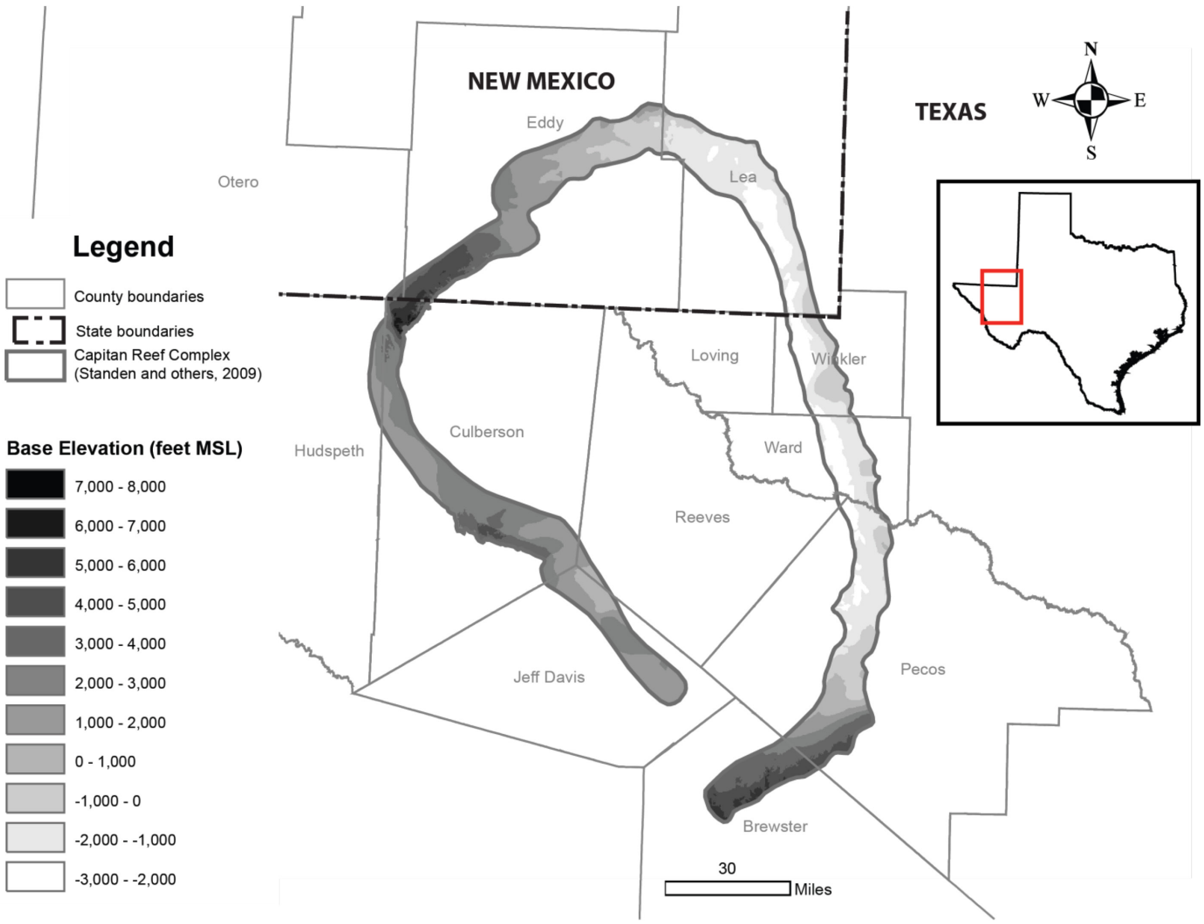


Figure 4.1.3. The elevation (in feet above mean sea level (MSL)) of the base of the Capitan Reef Complex Aquifer (modified from Standen and others, 2009).

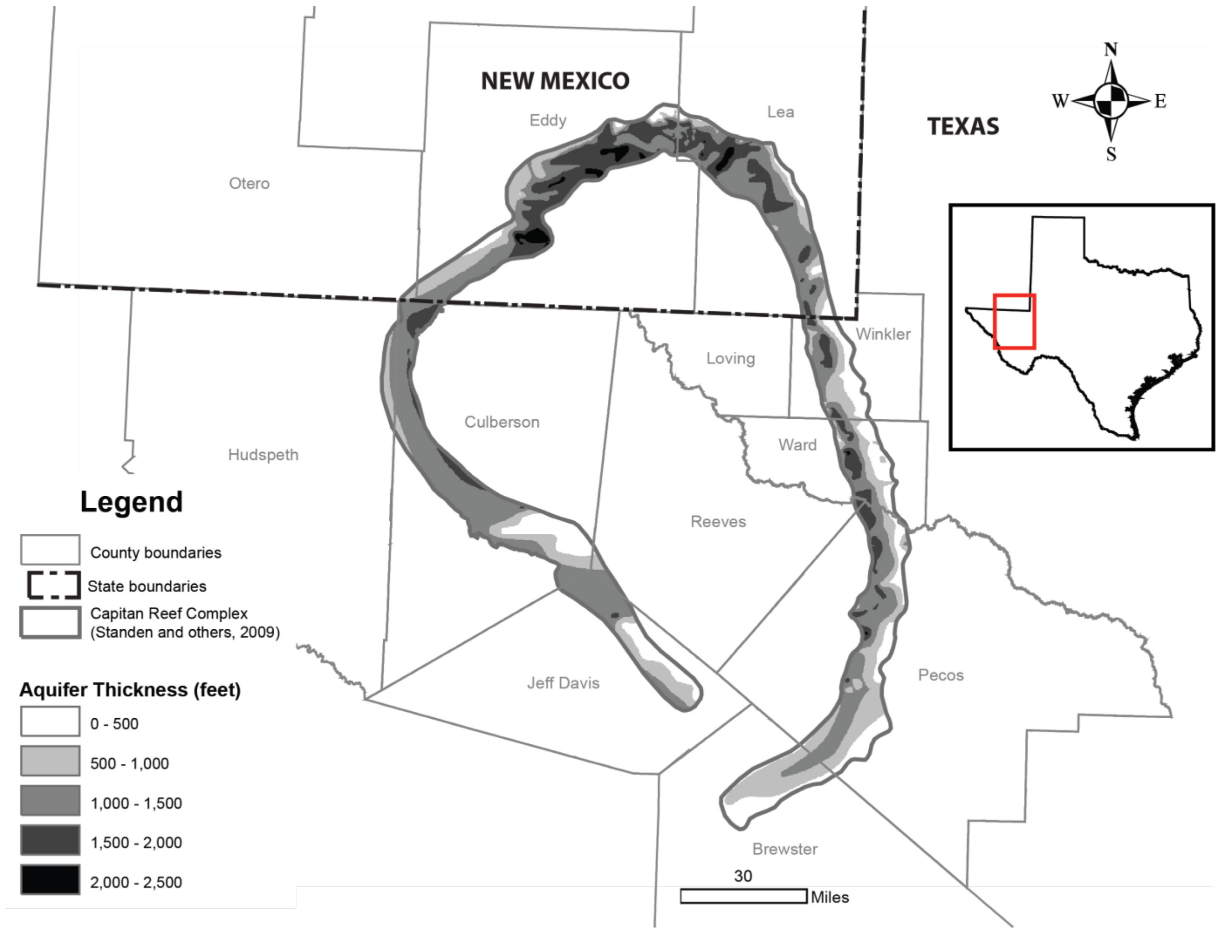


Figure 4.1.4. Thickness (in feet) of the Capitan Reef Complex Aquifer (modified from Standen and others, 2009).

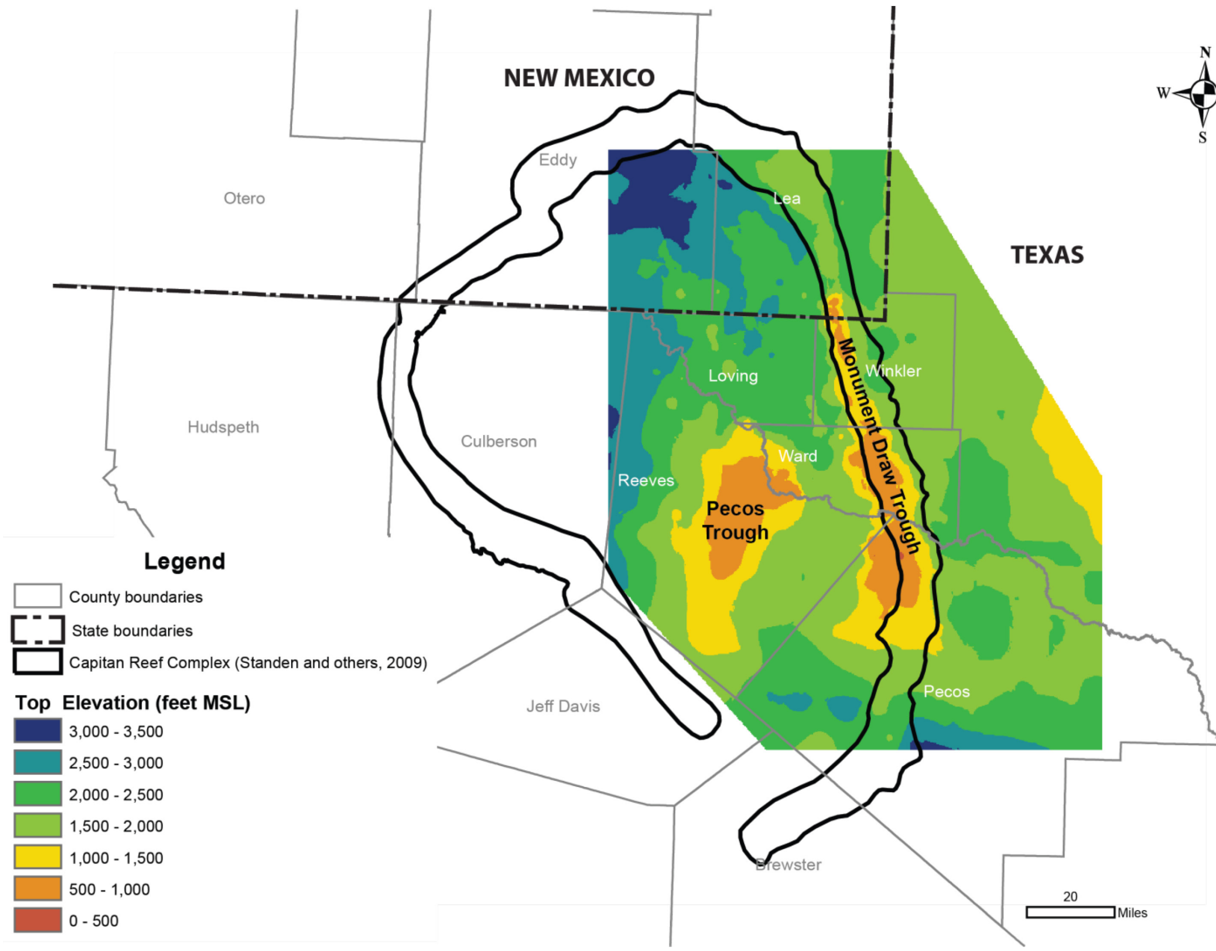


Figure 4.1.5. The elevation (in feet above mean sea level (MSL)) of the top of the Rustler Aquifer (based on data from Ewing and others, 2012).

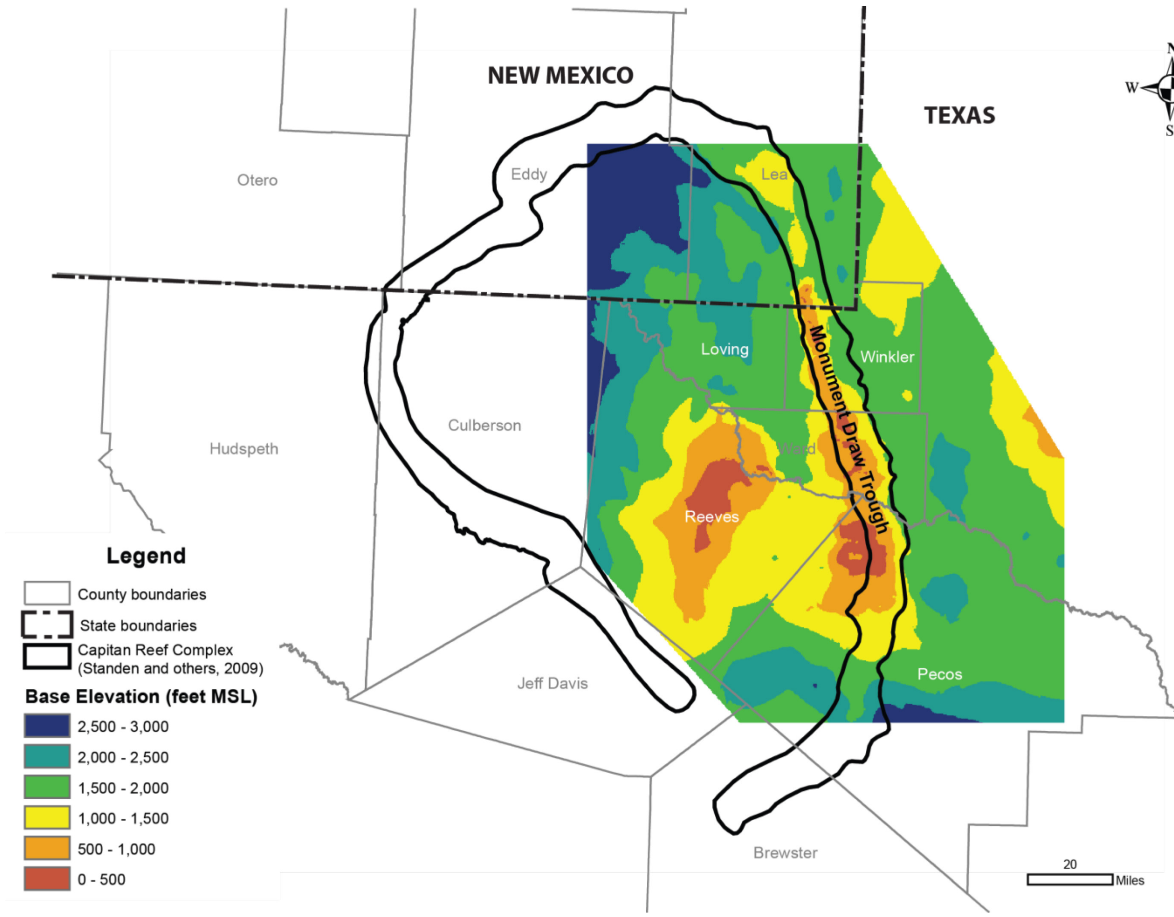


Figure 4.1.6. **The elevation (in feet above mean sea level (MSL)) of the base of the Rustler Aquifer (based on data from Ewing and others, 2012).**

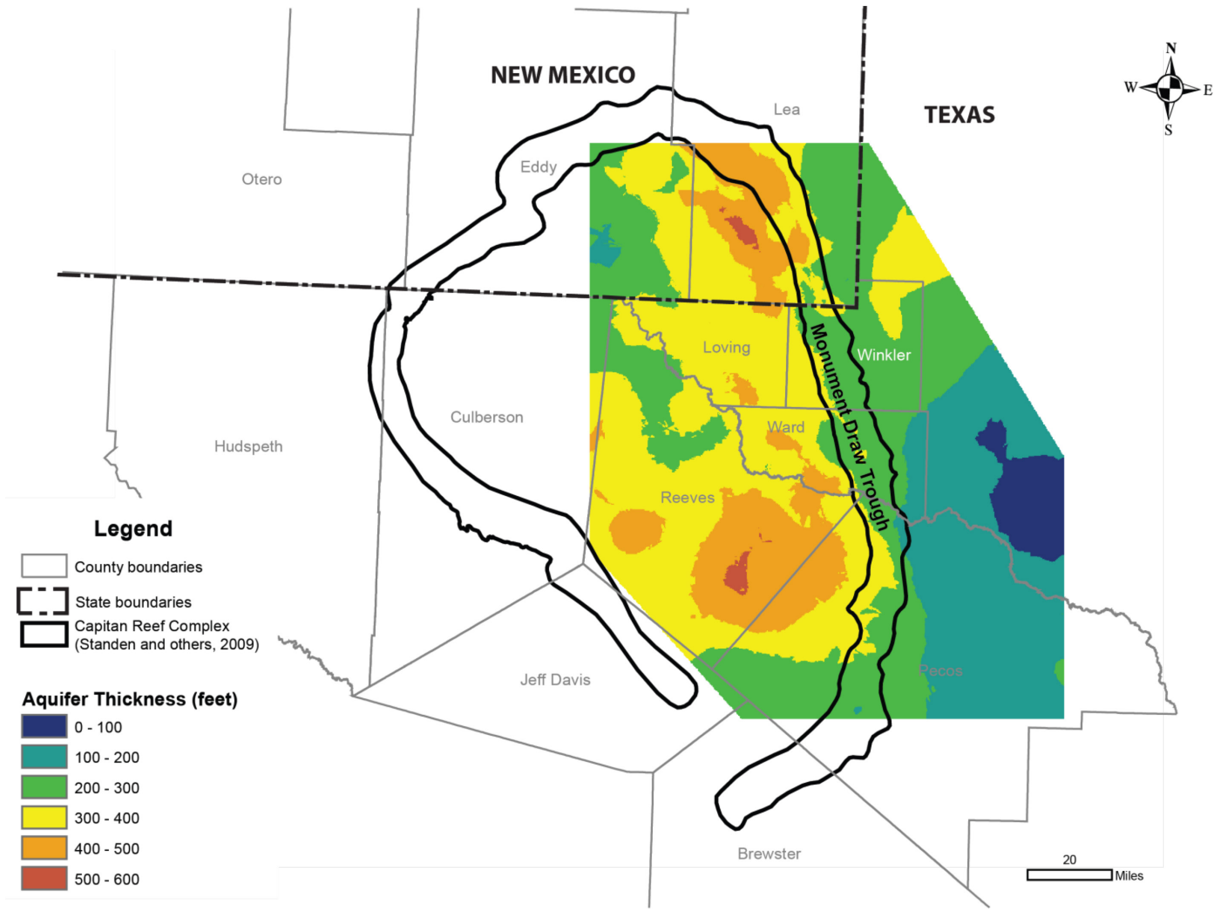


Figure 4.1.7. Thickness (in feet) of the Rustler Aquifer (based on data from Ewing and others, 2012).

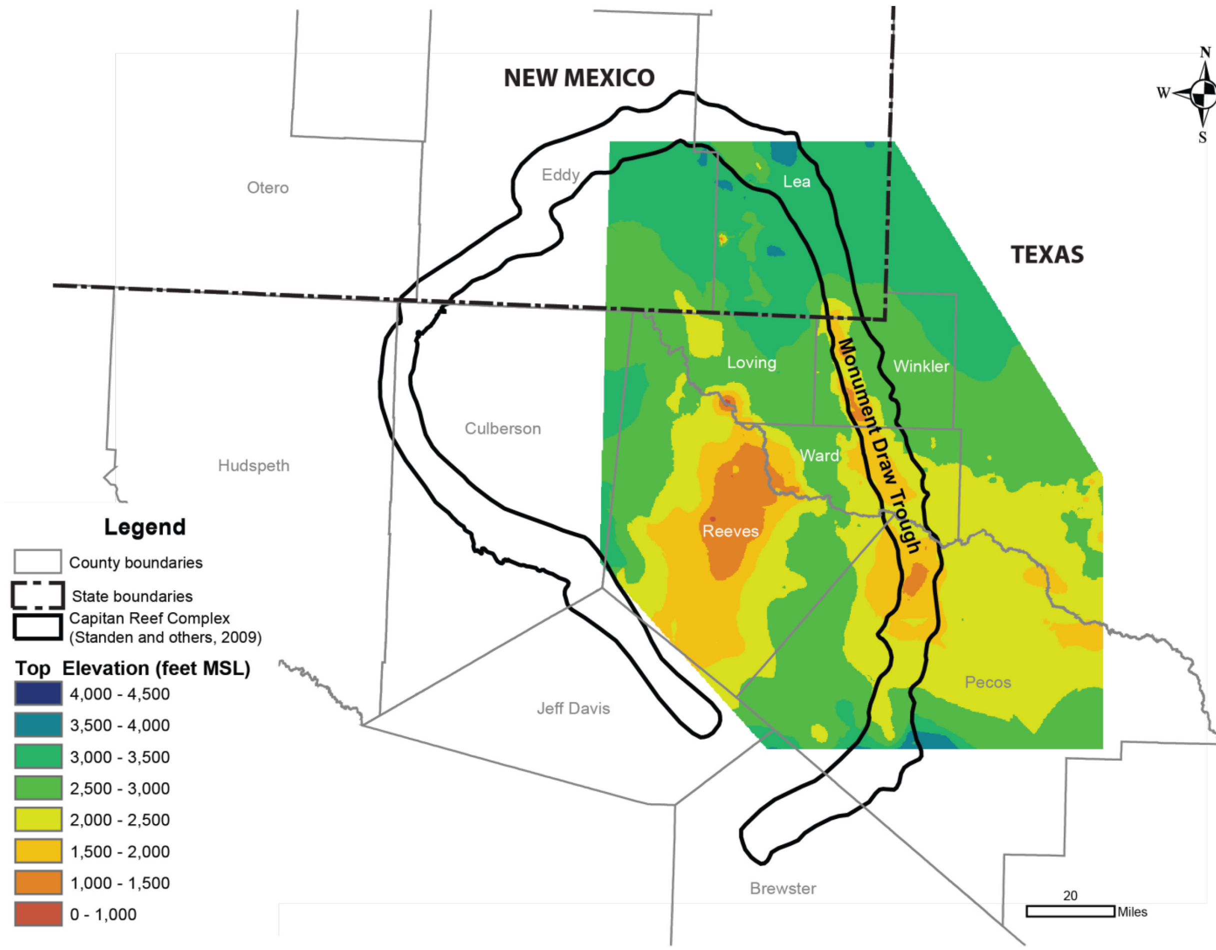


Figure 4.1.8. **The elevation (in feet above mean sea level (MSL)) of the top of the Dockum Aquifer (based on data from Ewing and others, 2008).**

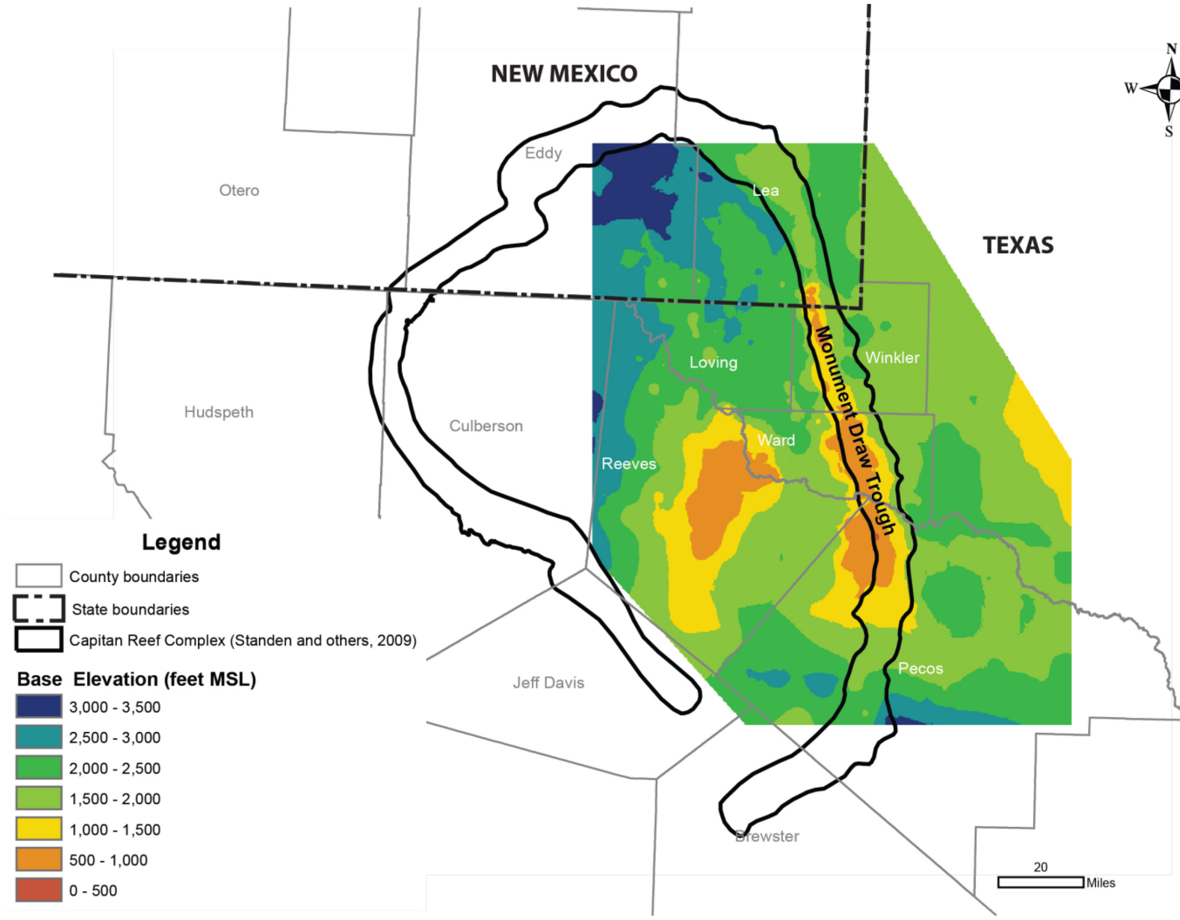


Figure 4.1.9. The elevation (in feet above mean sea level (MSL)) of the base of the combined Dewey Lake Formation and Dockum Aquifer (based on data from Ewing and others, 2008).

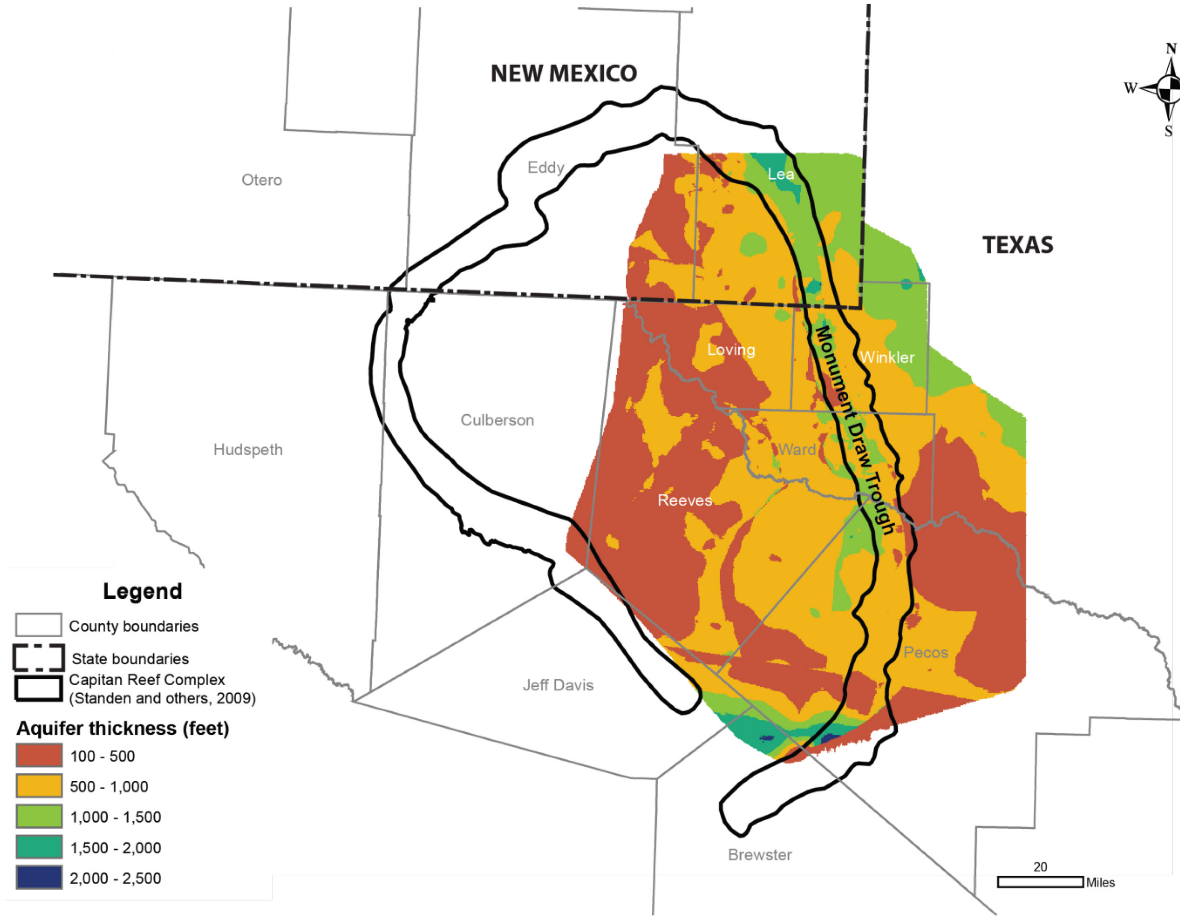


Figure 4.1.10. Total thickness (in feet) of the Dewey Lake Formation and the Dockum Aquifer (modified from Ewing and others, 2008).

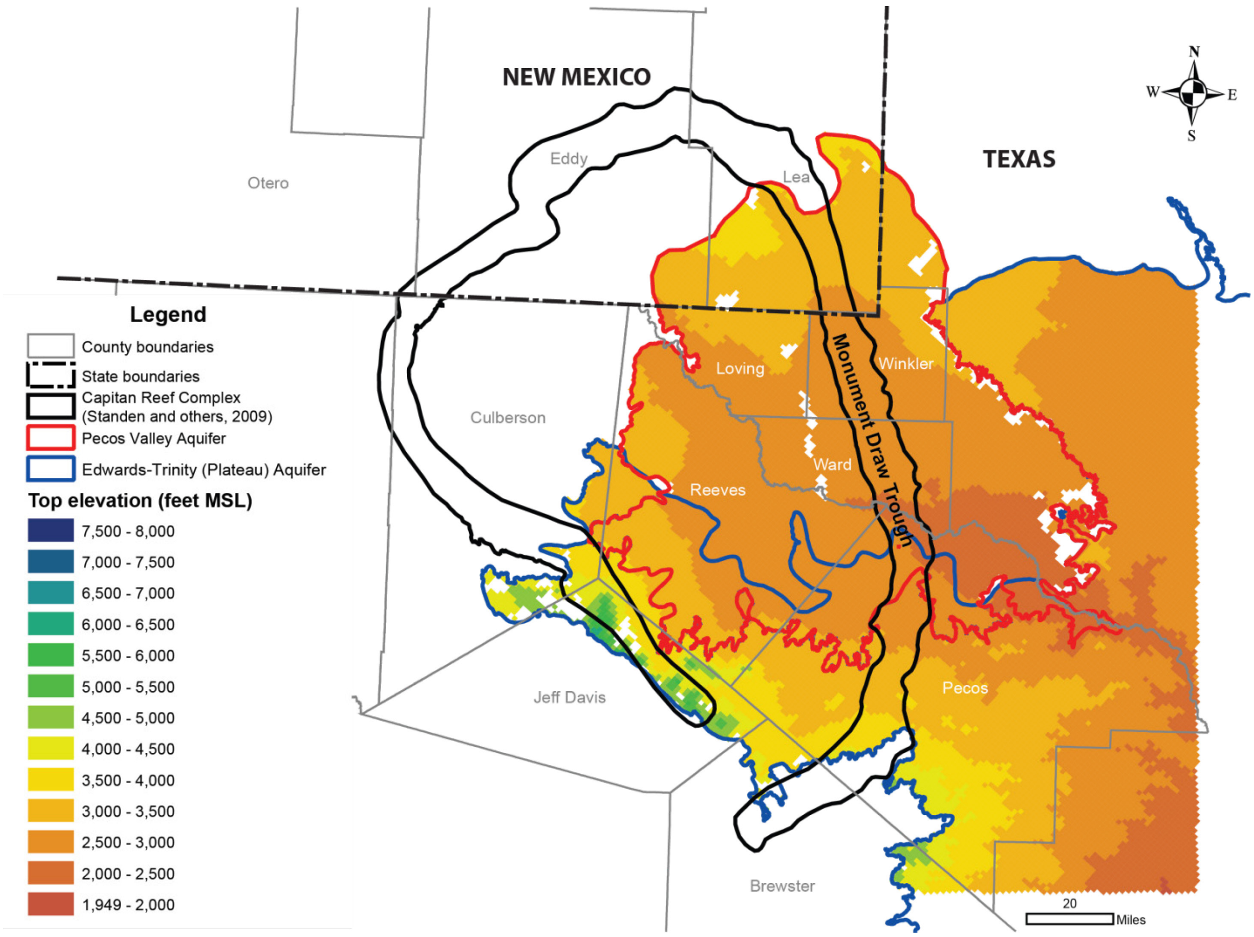


Figure 4.1.11. The elevation (in feet above mean sea level (MSL)) of the top of the Edwards-Trinity (Plateau) and Pecos Valley aquifers (modified from Hutchison and others, 2011).

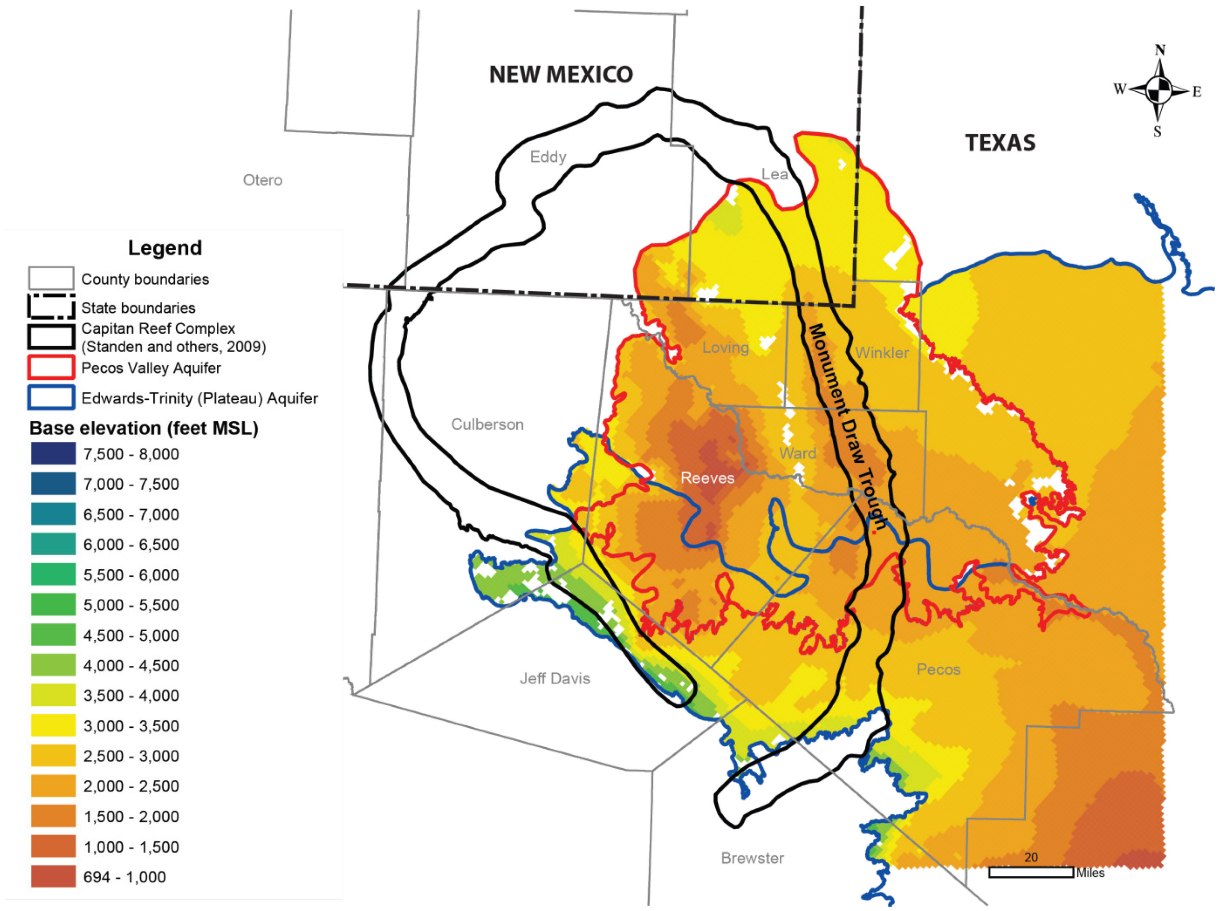


Figure 4.1.12. **The elevation (in feet above mean sea level (MSL)) of the base of the Edwards-Trinity (Plateau) and Pecos Valley aquifers (modified from Hutchison and others, 2011).**

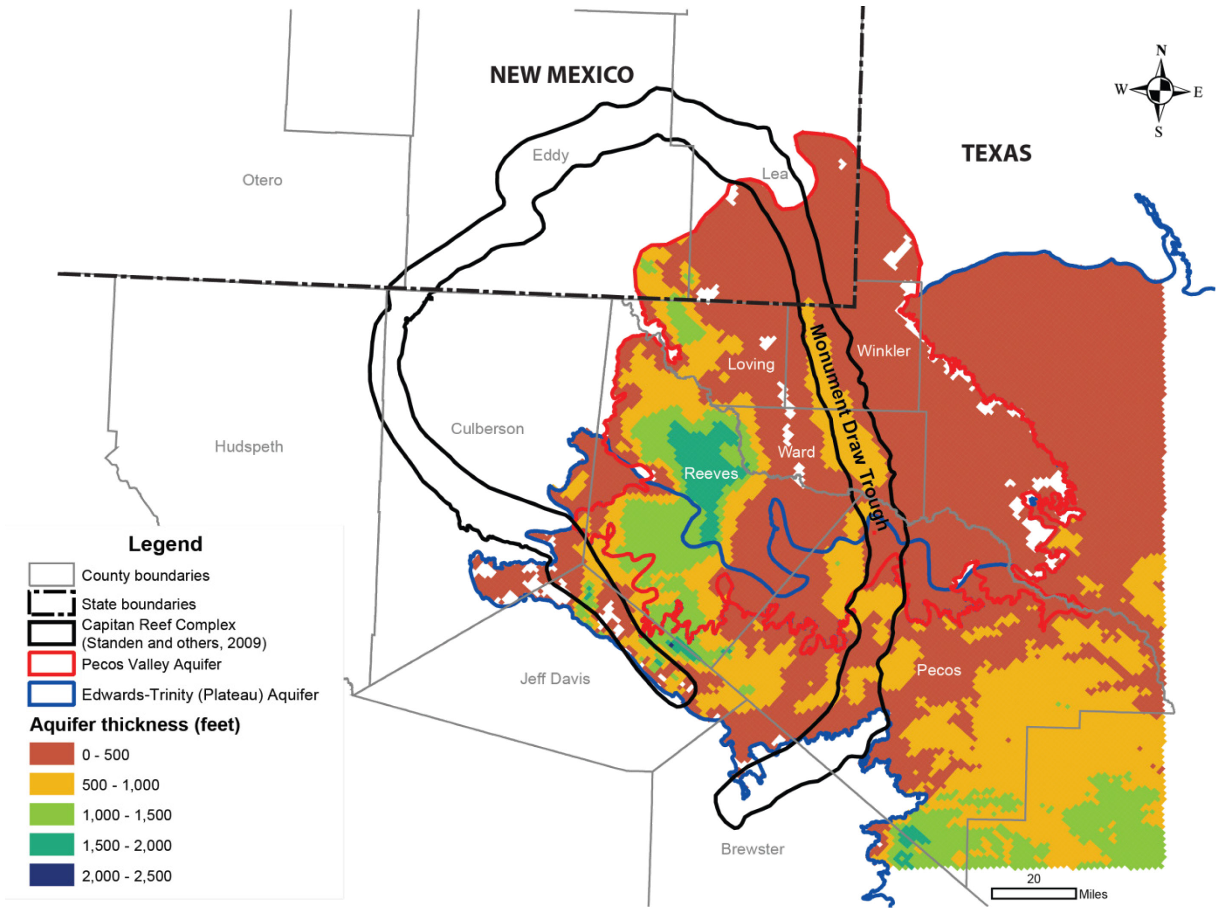


Figure 4.1.13. **Thickness (in feet) of the Edwards-Trinity (Plateau) and Pecos Valley aquifers (modified from Hutchison and others, 2011).**

4.2 Water Levels and Regional Groundwater Flow

Figure 4.2.1 illustrates regional groundwater flow paths for the Capitan Reef Complex Aquifer (Hiss, 1976; 1980; Uliana, 2001; Sharp, 2001). Hiss (1980) and Richey and others (1985) hypothesized that the uplift of the western side of the Delaware Basin—associated with the Border Fault Zone and the resultant formation of the Guadalupe Mountains—resulted in a topographic gradient for the regional groundwater flow system.

The Border Fault Zone forms a hydrologic divide between two regional groundwater flow systems: one that flows to the northeast from the recharge zone in the Guadalupe Mountains and one that flows to the south (Figure 4.2.1). Regional groundwater also flows northward away from the Glass Mountains—another heavily faulted, topographically high Capitan Reef Complex outcrop (Figure 4.2.1). The Stocks Fault (Figure 4.2.1) is a large fault system with more than 1,000 feet of throw that bounds the northern flank of the Apache Mountains. The fault is probably the result of dissolution of Delaware Basin evaporites north of the fault forming a graben—the Salt basin—between the Stocks Fault and Border Fault Zone (Wood, 1965; LaFave, 1987). The direction of greatest permeability is sub-parallel to the Stocks Fault (Sharp 2001; Uliana, 2000). Regional groundwater flow is probably fracture controlled and is believed to occur from Wild Horse Flat—located immediately west of the Apache Mountains—eastward through the basin sediments underneath the Apache Mountain Capitan Reef Complex outcrop or through the down-faulted Capitan Reef Complex along the northeastern side of the Stocks Fault and toward the Toyah Basin (LaFave, 1987; LaFave and Sharp, 1990; Uliana, 2000; Finch and Armour, 2001). Some of this groundwater may eventually discharge from the San Solomon Spring System located east of the Capitan Reef Complex Aquifer in Reeves and Jeff Davis counties (Chowdhury and others, 2004).

Regional groundwater flow in the Salt Basin portion of the Capitan Reef Complex is believed to occur from the downthrown side of the Border Fault Zone in the Guadalupe Mountains to the Apache Mountains and may not be influenced by the groundwater divides apparent in the overlying alluvial aquifer (Angle, 2001; Finch and Bennett, 2002).

The groundwater flow in the eastern portion of the Capitan Reef Complex Aquifer—east of the Border Fault Zone—has probably changed in response to the incision by the Pecos River above the Capitan Reef Complex Aquifer (Hiss, 1980; Uliana, 2001). This incision took place during the Pliocene—2 to 5 million years ago—when a period of regional uplift caused rivers to erode downward and upstream (Gutentag and others, 1984). The incision of the Pecos River induced groundwater discharge to the river and reduced eastward groundwater flow into the eastern arm of the Capitan Reef Complex Aquifer (Figure 4.2.2). The reduced groundwater flow is due to direct and indirect effects of the river. The direct effects occur along the Pecos River near Carlsbad, New Mexico where the Capitan Reef Complex Aquifer occurs at shallow depths. The indirect effects occur due to induced upward inter-aquifer flow related to discharge to the Pecos River from overlying aquifers, such as the Pecos Valley, Dockum, and Rustler aquifers.

Figure 4.2.3 shows water-level data from the eastern arm of the Capitan Reef Complex Aquifer and surrounding basin and shelf stratigraphic units—fore-reef and back-reef facies, respectively. The water-level contours suggest: (1) eastward groundwater flow across the Delaware Basin and in the Northwestern Shelf and the Central Basin Platform; (2) clockwise groundwater flow in the Capitan Reef Complex Aquifer in New Mexico; (3) counter-clockwise groundwater flow in the Capitan Reef Complex Aquifer in Brewster, Pecos, Ward and Winkler counties; and (4) groundwater convergence in Winkler County. Continuity of water-level contours in the Capitan Reef Complex Aquifer and the basin and shelf stratigraphic units west of the Pecos River in New Mexico suggest hydrologic connections between the stratigraphic units—groundwater flow is all part of the same flow system. Elsewhere, water-level contours indicate unrelated flow systems in the Delaware Basin and Capitan Reef Complex Aquifer—indicating that there is no hydrologic connection as suggested by Bjorklund and Motts (1959) and Motts (1968). Water-level contours suggest hydraulic connections between the Capitan Reef Complex Aquifer and the shelf stratigraphic units observed west of the Pecos River continue east of the Pecos River. The apparent convergence of groundwater flow in Winkler County suggests: (1) discharge by cross-formational flow into the adjacent Central Basin Platform; or (2) discharge by cross-formational flow through the overlying collapse feature that formed due to dissolution of the Salado

Formation, cuts through overlying aquifers—the Rustler and Dockum aquifers—and resulted in the formation of the Monument Draw Trough in the Pecos Valley Aquifer (Jones, 2001; 2004; 2008).

Water-level data from the Capitan Reef Complex Aquifer study area are sparse. A total of 206 wells in the Capitan Reef Complex Aquifer have at least one water-level measurement, with a median of two measurements (Figure 4.2.4). There are only 68 wells in New Mexico—mostly in Eddy County, adjacent to the Pecos River—and no water-level measurements in Winkler County, Texas. Figure 4.2.5 shows the temporal distribution of the Capitan Reef Complex Aquifer water-level data—mostly since 1960. About half of the wells in the deepest part of the Capitan Reef Complex Aquifer—northern Pecos County and Ward County— are artesian or flowing wells (Figure 4.2.6). Water-level data shown in Figure 4.2.7 generally agree with the groundwater flowpaths proposed by Hiss (1980). Highest water levels in the Capitan Reef Complex Aquifer occur in the Guadalupe Mountains, decreasing to the east and west. Water levels are also high in the Glass Mountains decreasing to the north and reaching minimum elevations in Ward County. Figures 4.2.8 through 4.2.10 show water-level data for the aquifers that overlie the Capitan Reef Complex Aquifer—the Rustler, Dockum, Edwards-Trinity (Plateau), and Pecos Valley aquifers. In the Rustler Aquifer, water-level data displayed in Ewing and others (2012) suggest groundwater flow trends from the west and south, converging on the Monument Draw Trough and Pecos River (Figure 4.2.8). Dockum Aquifer water-level data suggest groundwater flow gradients from northwest to southeast (Figure 4.2.9). Water-level data in the Edwards-Trinity (Plateau) and Pecos Valley aquifers in the Capitan Reef Complex Aquifer study area indicate groundwater flow converging on the Pecos River (Figure 4.2.10). The Pecos River is the main groundwater discharge zone for the largely surficial Edwards-Trinity (Plateau) and Pecos Valley aquifers in the study area. Additionally, water-level data for the Pecos Aquifer indicate a cone of depression in central Reeves County attributable to irrigation pumping (Jones, 2001; 2004).

Water-level comparisons were conducted where: (1) the Capitan Reef Complex Aquifer is overlain by other aquifers—the Pecos Valley, Edwards-Trinity (Plateau), Dockum, and Rustler aquifers, and (2) there were available water data from wells located within 5 miles of a Capitan Reef Complex Aquifer well (Figure 4.2.11). Figure 4.2.12 shows the results of this comparison conducted at the five Capitan Reef Complex Aquifer locations shown in Figure 4.2.11. Inter-aquifer water-level comparisons suggest that water levels in the Capitan Reef Complex Aquifer are generally higher than the water levels in the overlying aquifers. This suggests upward hydraulic gradients and groundwater flow from the Capitan Reef Complex Aquifer to the overlying aquifers.

Figure 4.2.13 shows the locations with the most water-level data in each county. The total number of measurements range from 3 in Pecos County, Texas to 516 in Eddy County, New Mexico. Figures 4.2.14 and 4.2.15 show hydrographs of the transient water-level data. The hydrographs indicate: (1) gradual water-level decline over time in the western part of the Capitan

Reef Complex Aquifer—Hudspeth and Culberson counties, (2) a net water-level rise in the eastern part of the aquifer—Pecos and Ward counties, and (3) relatively constant water levels in northern part of the aquifer—Eddy County.

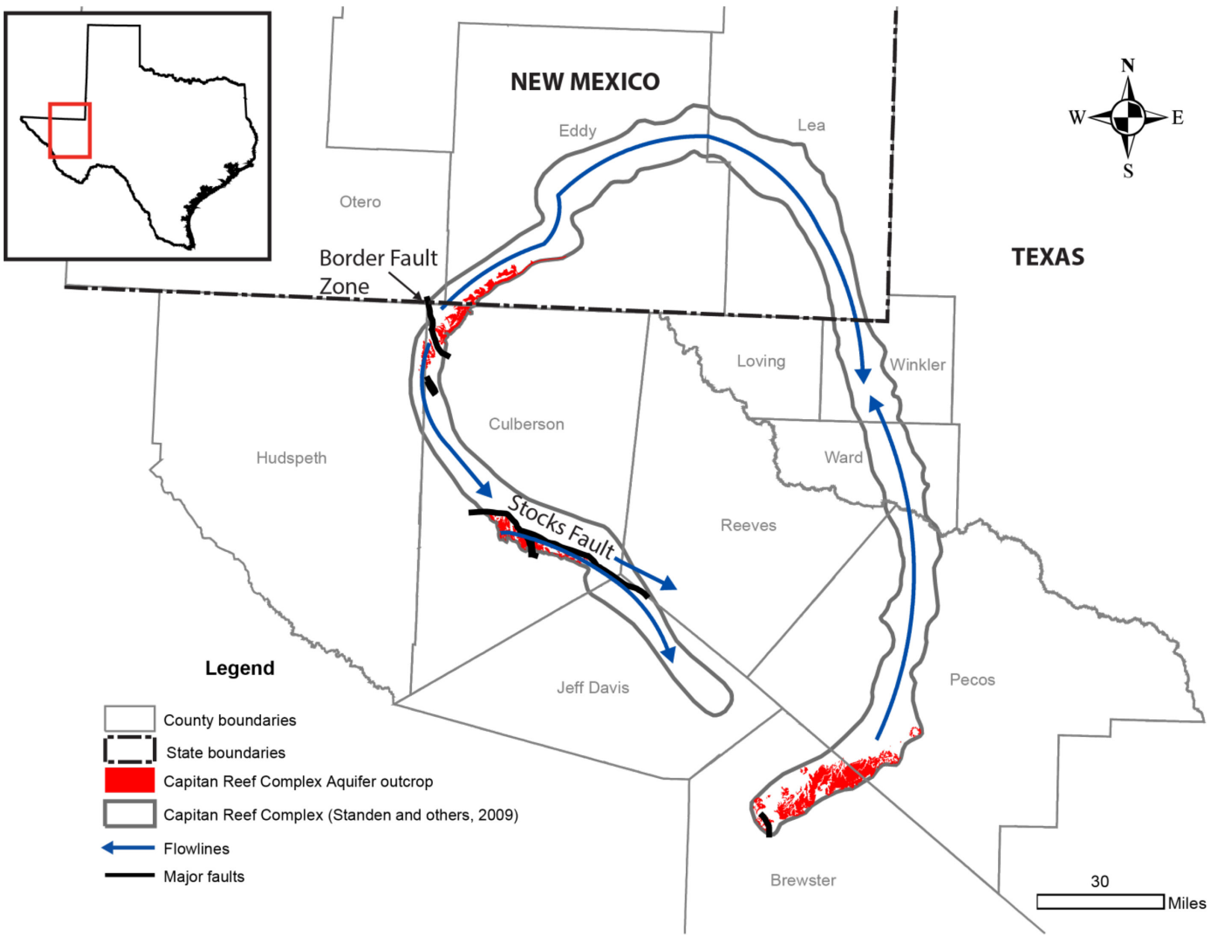


Figure 4.2.1. **Conceptual diagram of the proposed flow systems in the Capitan Reef Complex Aquifer based on work by Hiss (1980), Sharp (2001), and Uliana (2001).**

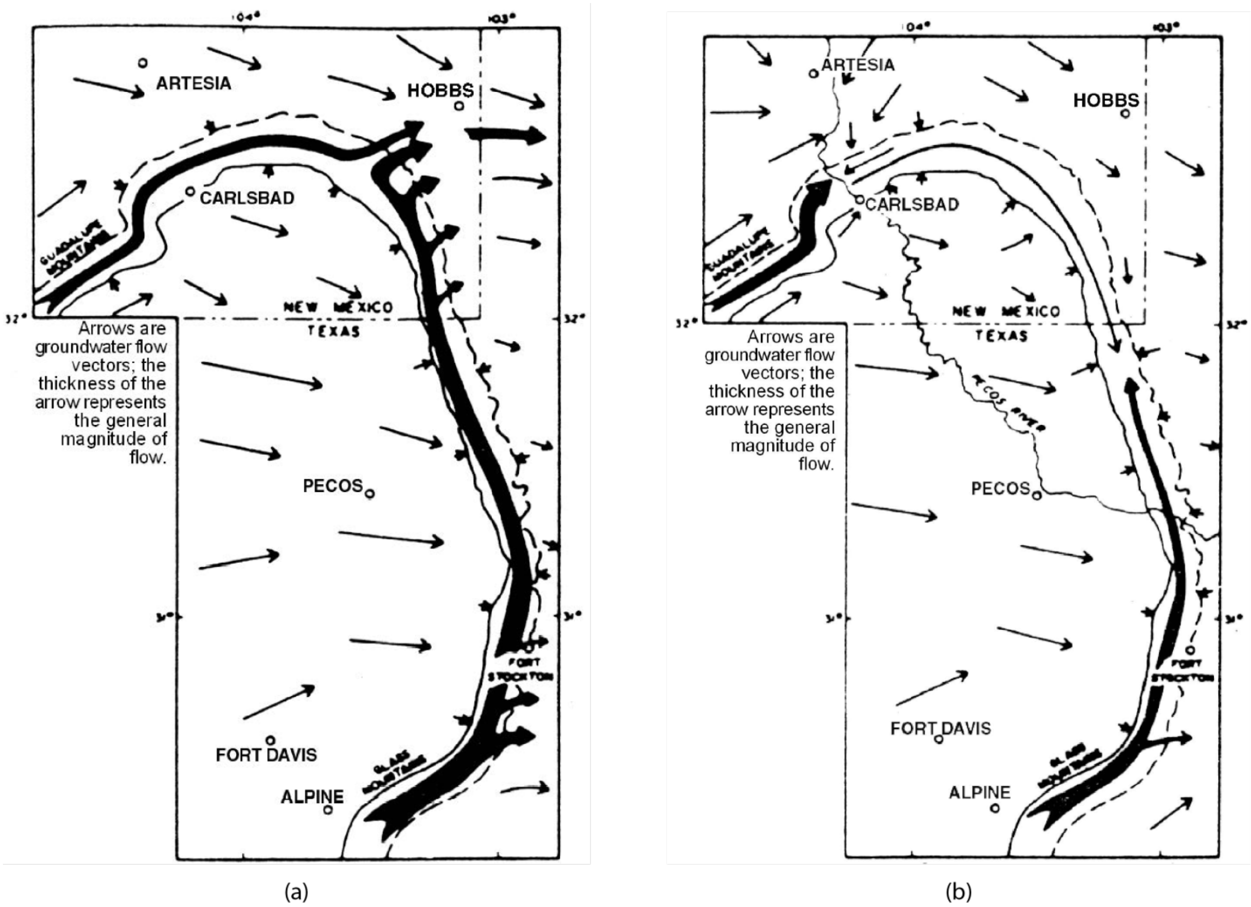


Figure 4.2.2. **Groundwater flowpaths through the eastern arm of the Capitan Reef Complex Aquifer have changed over time in response to the development of the Pecos River. These maps show groundwater flowpaths (a) prior to the incision of the Pecos River, and (b) after the incision of the Pecos River (Modified from Hiss (1980)).**

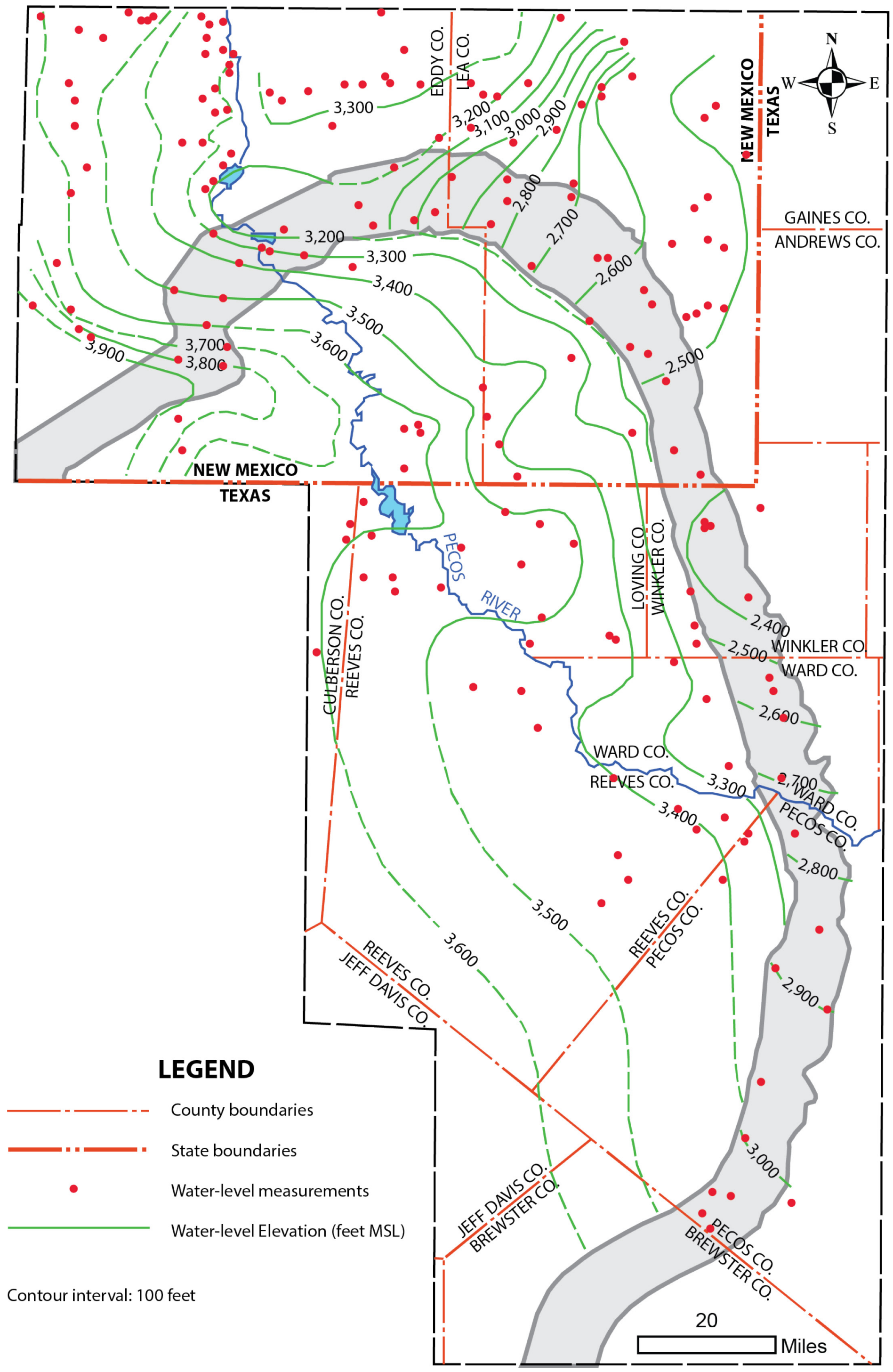


Figure 4.2.3. **Post-development water levels in the Capitan Reef Complex Aquifer and surrounding basin and shelf stratigraphic units (modified from Hiss, 1980). The continuity of water-level contours in the Capitan Reef Complex Aquifer and basin and shelf stratigraphic units in Eddy County indicate hydrologic connections that do not occur elsewhere.**

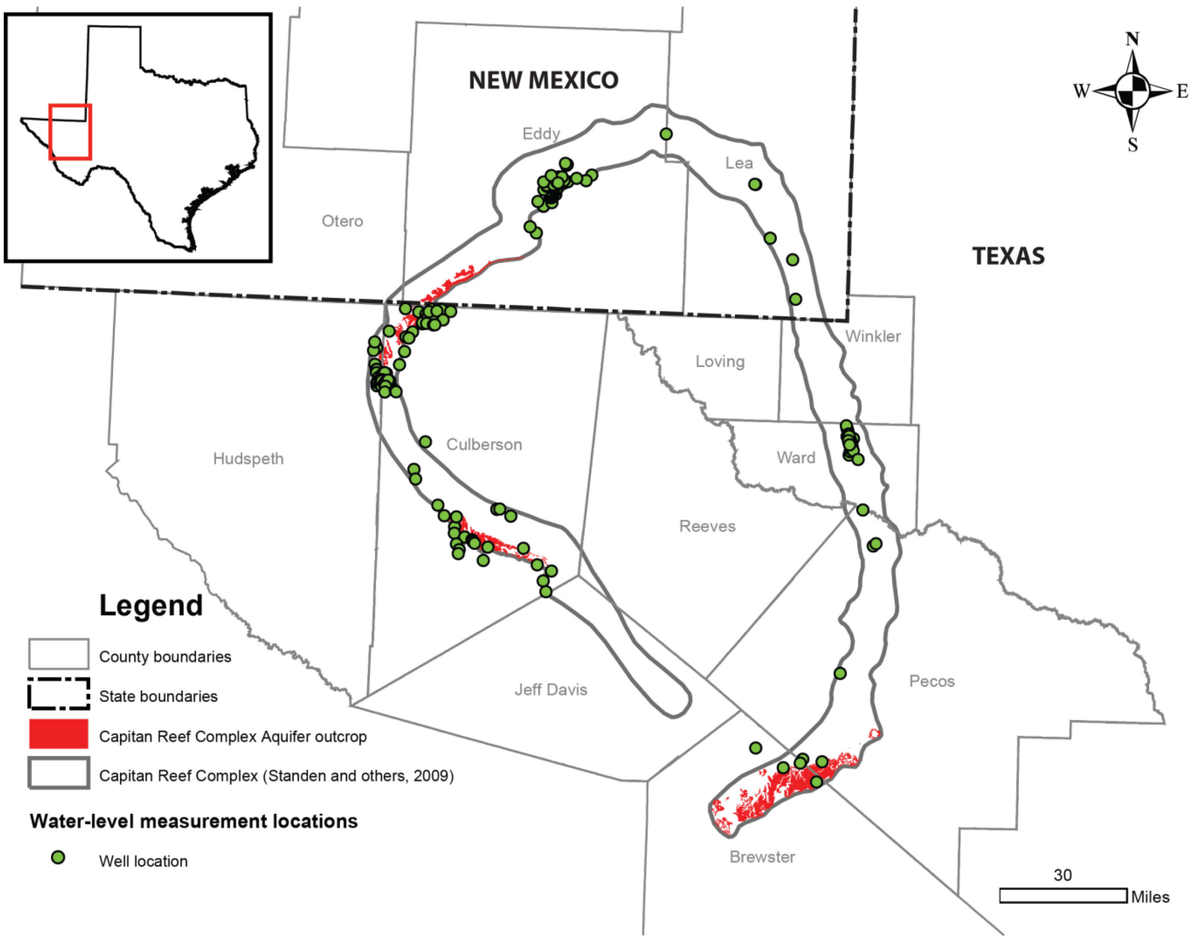


Figure 4.2.4. Water-level measurement locations for the Capitan Reef Complex Aquifer and adjacent areas (Texas Water Development Board, 2012b).

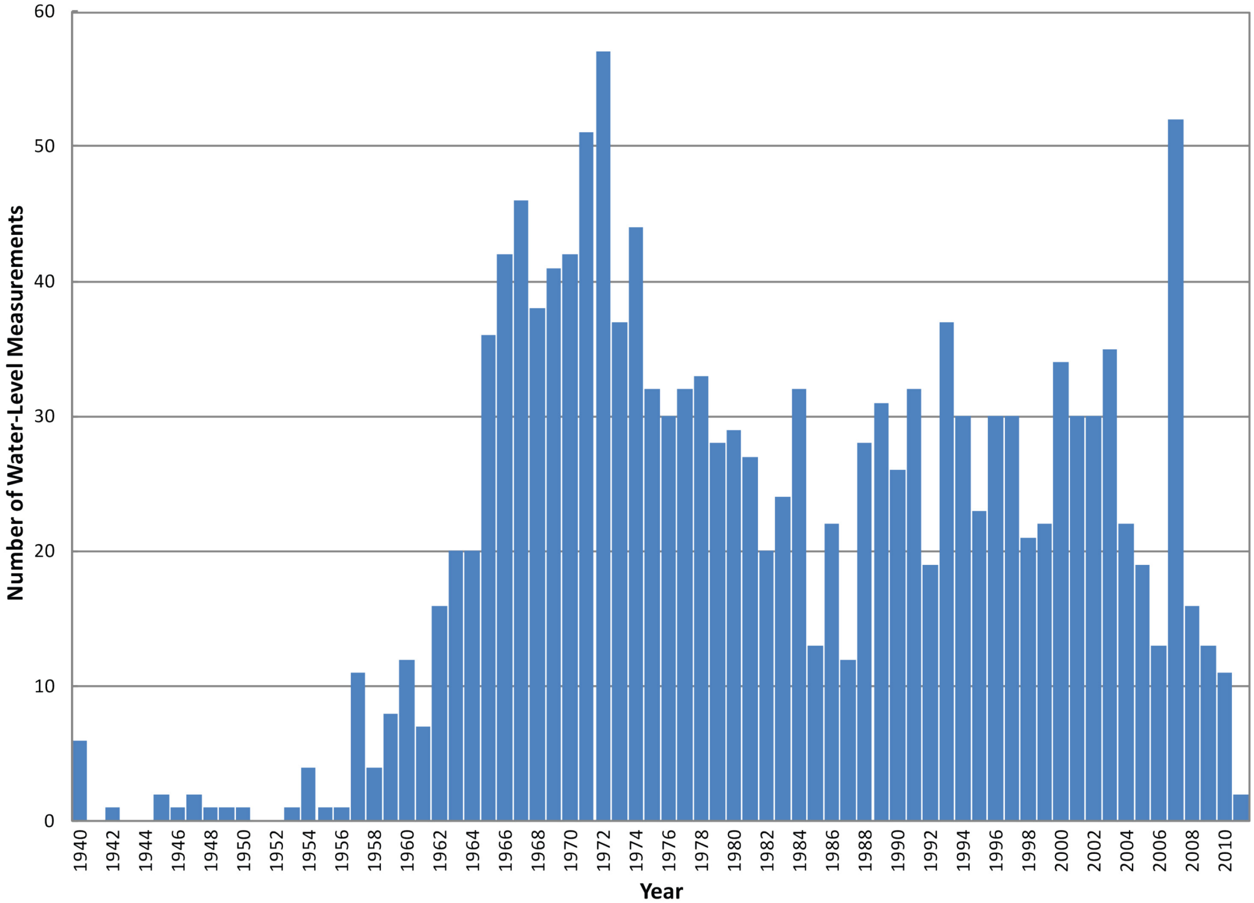


Figure 4.2.5. Temporal distribution of water-level measurements in the Capitan Reef Complex Aquifer (Texas Water Development Board, 2012b).

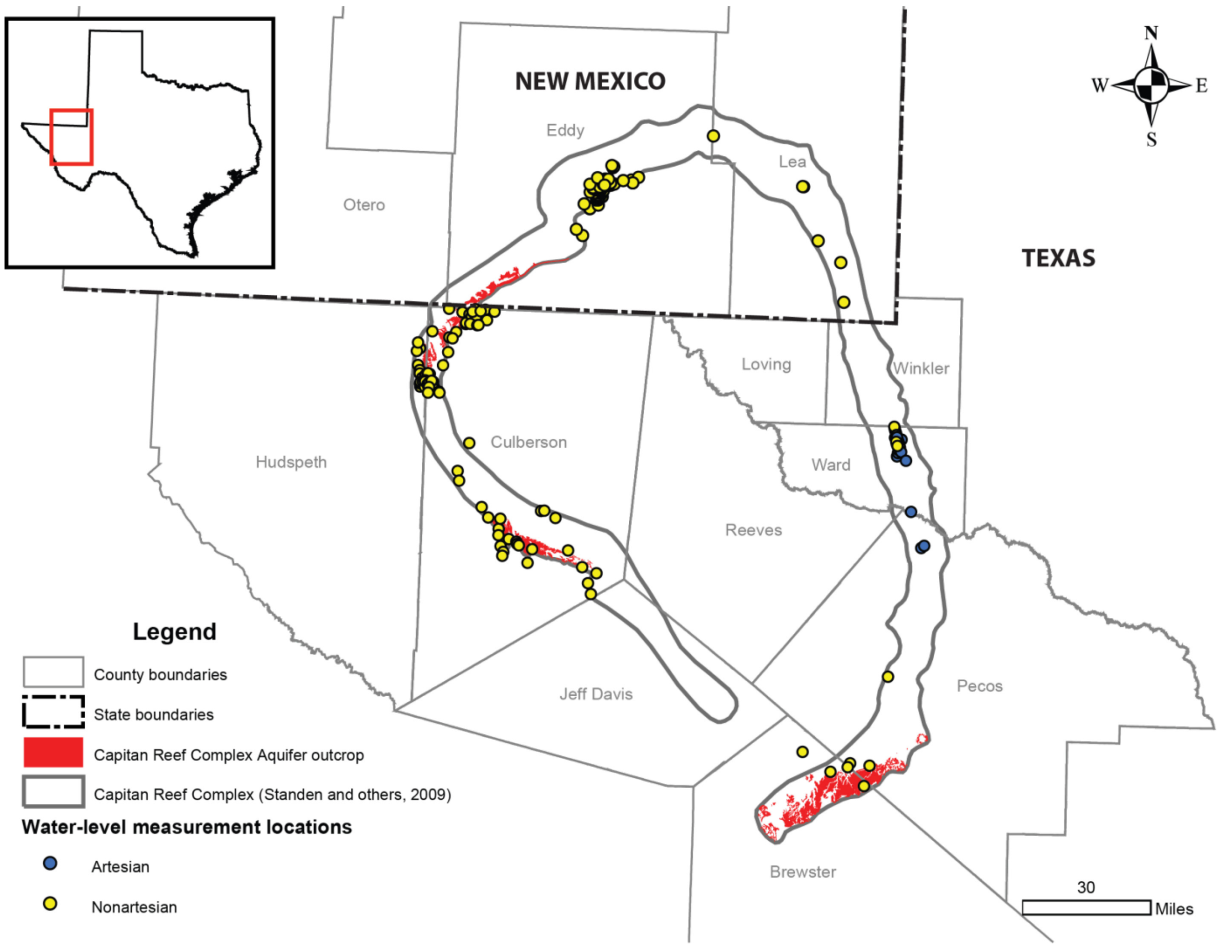


Figure 4.2.6. **Locations of Capitan Reef Complex Aquifer historically artesian and non-artesian wells (Texas Water Development Board, 2012b).**

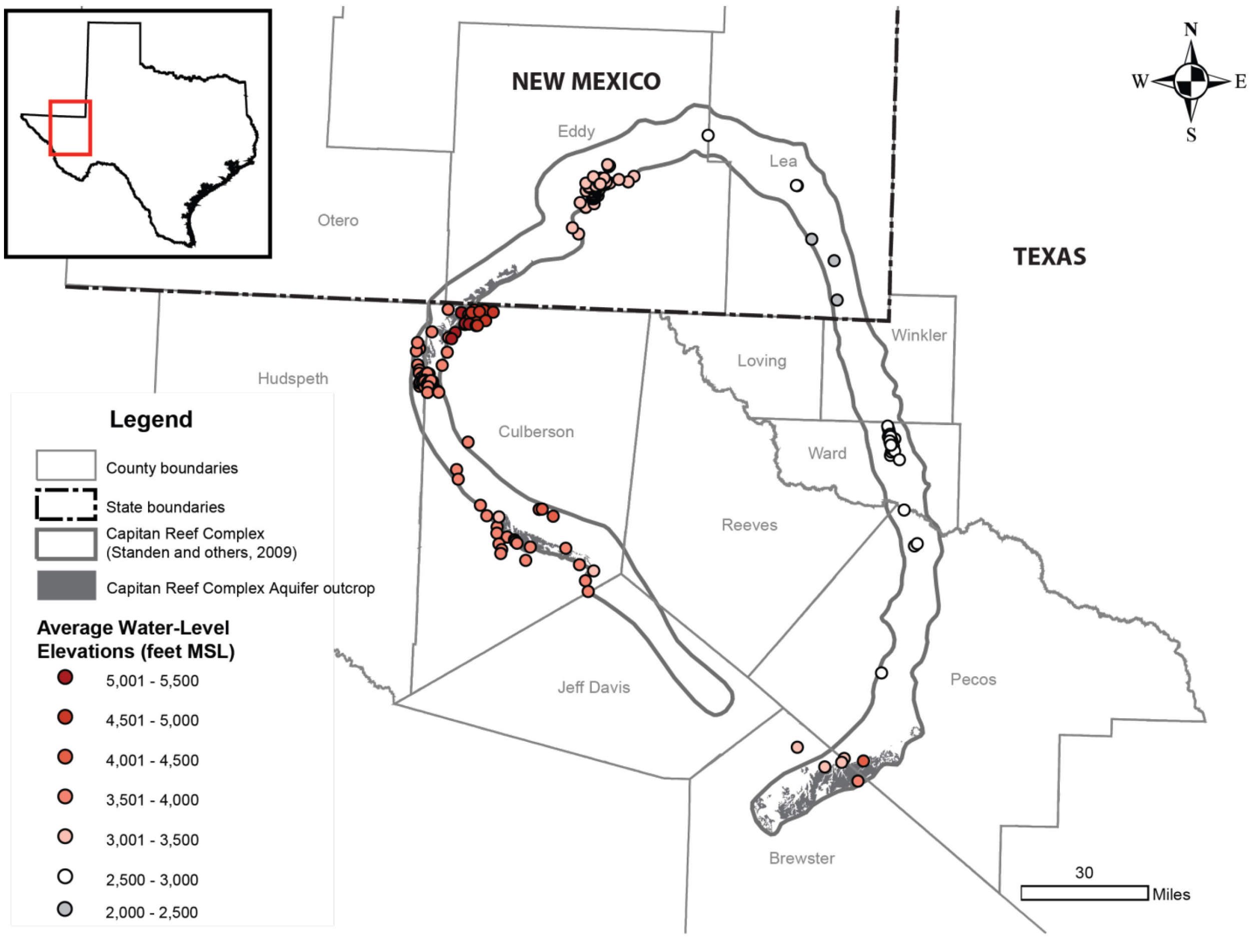


Figure 4.2.7. **Average water-level elevation (in feet above mean sea level (MSL)) for wells completed in the Capitan Reef Complex Aquifer (Texas Water Development Board, 2012b).**

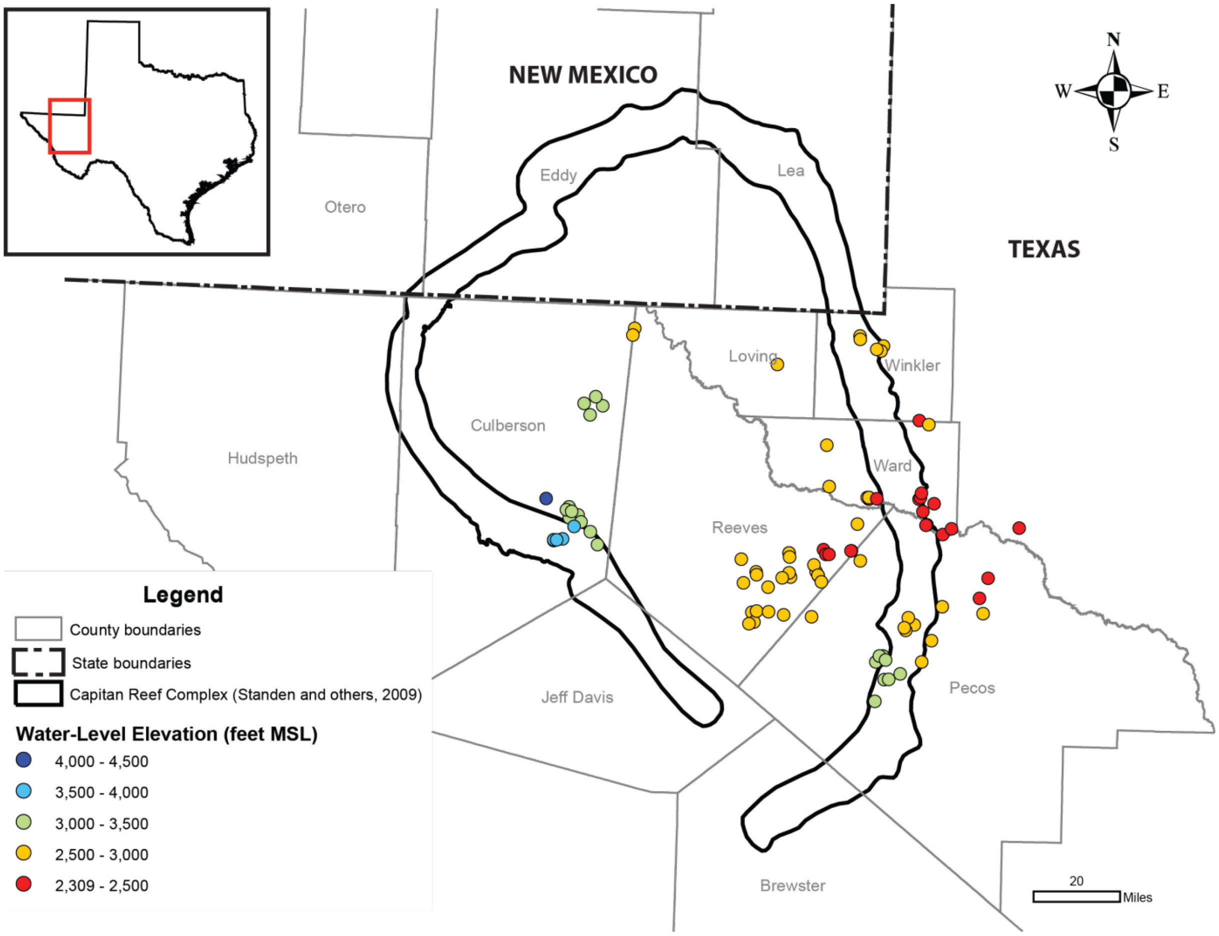


Figure 4.2.8. Average water-level elevation (in feet above mean sea level (MSL)) for wells completed in the Rustler Aquifer (Texas Water Development Board, 2012b).

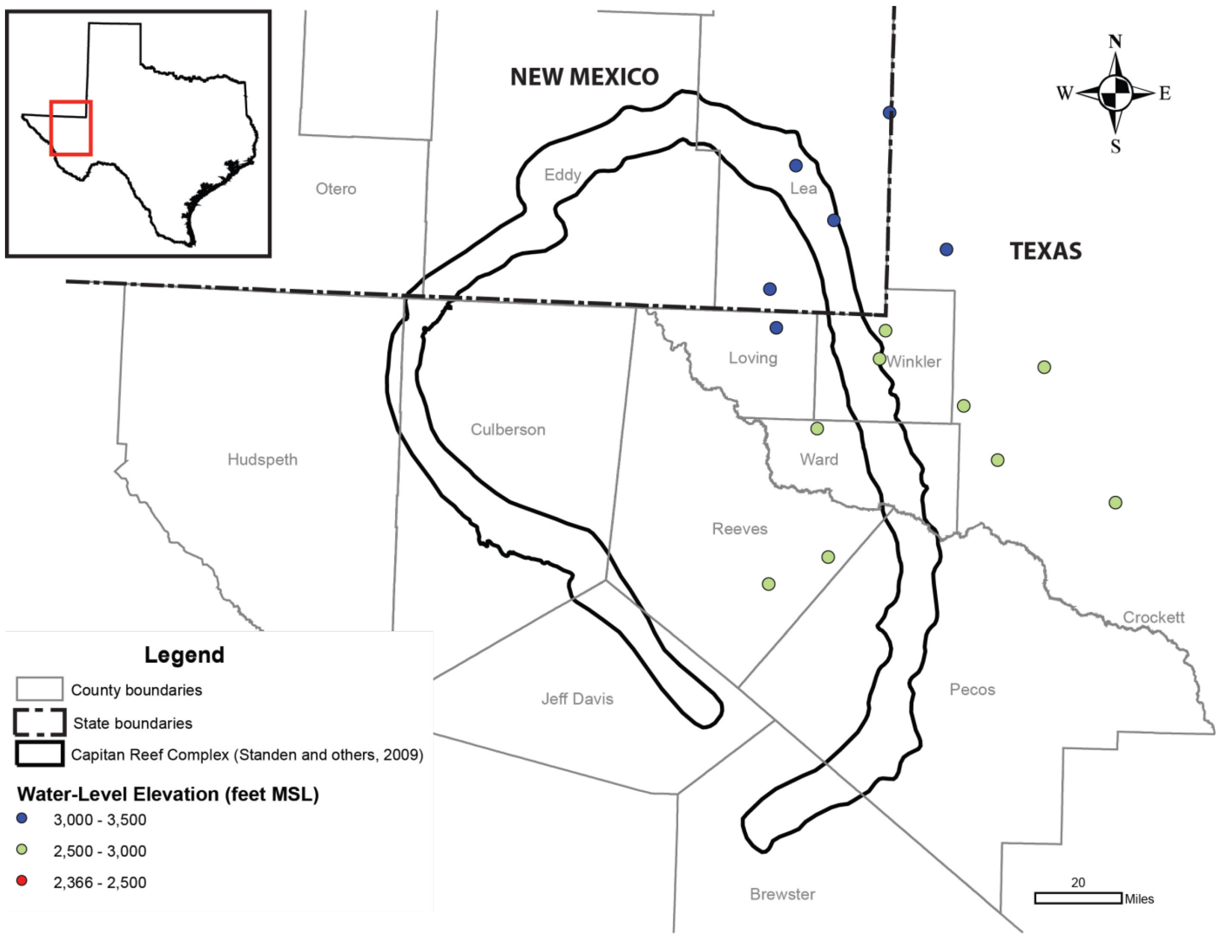


Figure 4.2.9. **Average water-level elevation (in feet above mean sea level (MSL)) for wells completed in the Dockum Aquifer (Texas Water Development Board, 2012b).**

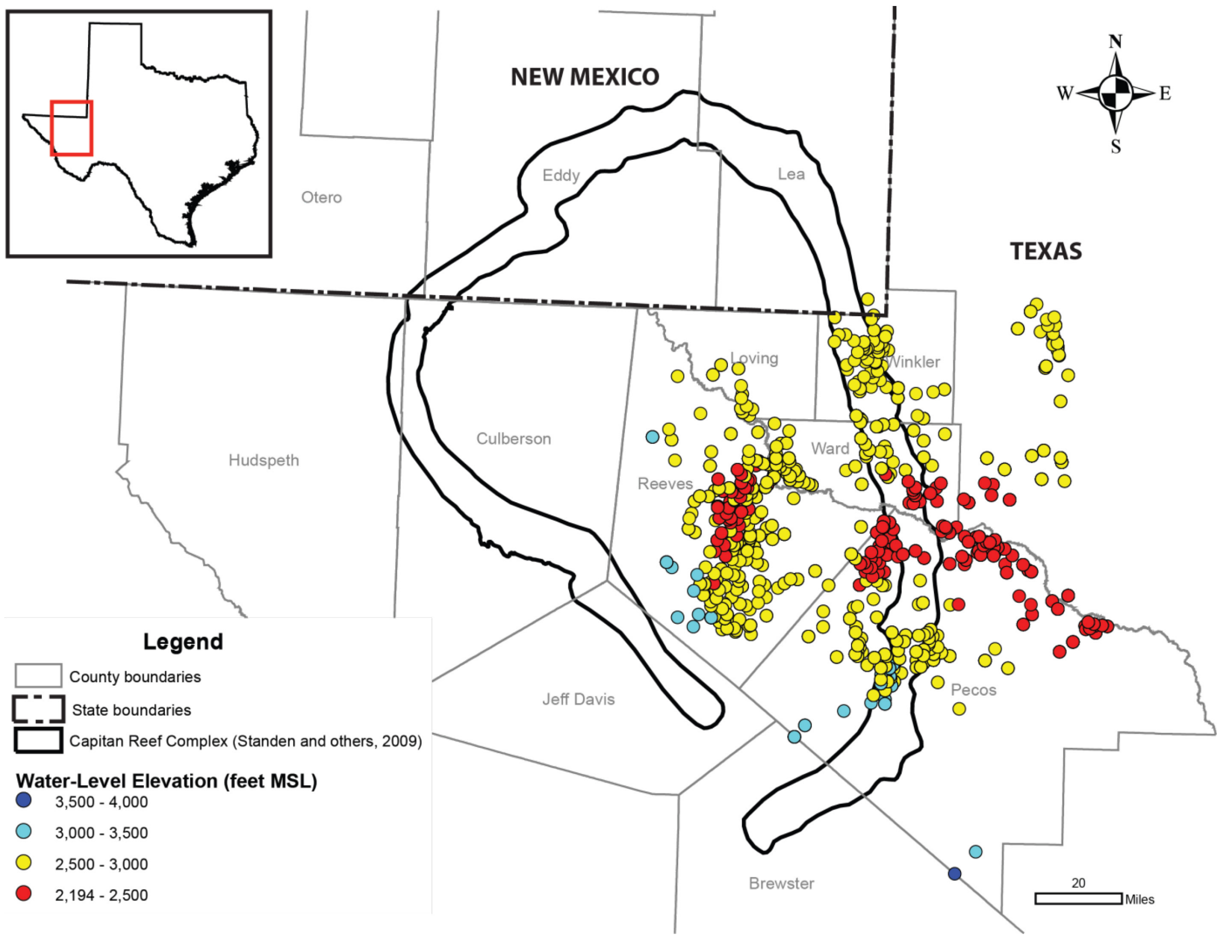


Figure 4.2.10. **Average water-level elevation (in feet above mean sea level (MSL)) for wells completed in the Edwards-Trinity (Plateau) and Pecos Valley aquifers (Ewing and others, 2012; Texas Water Development Board, 2012b).**

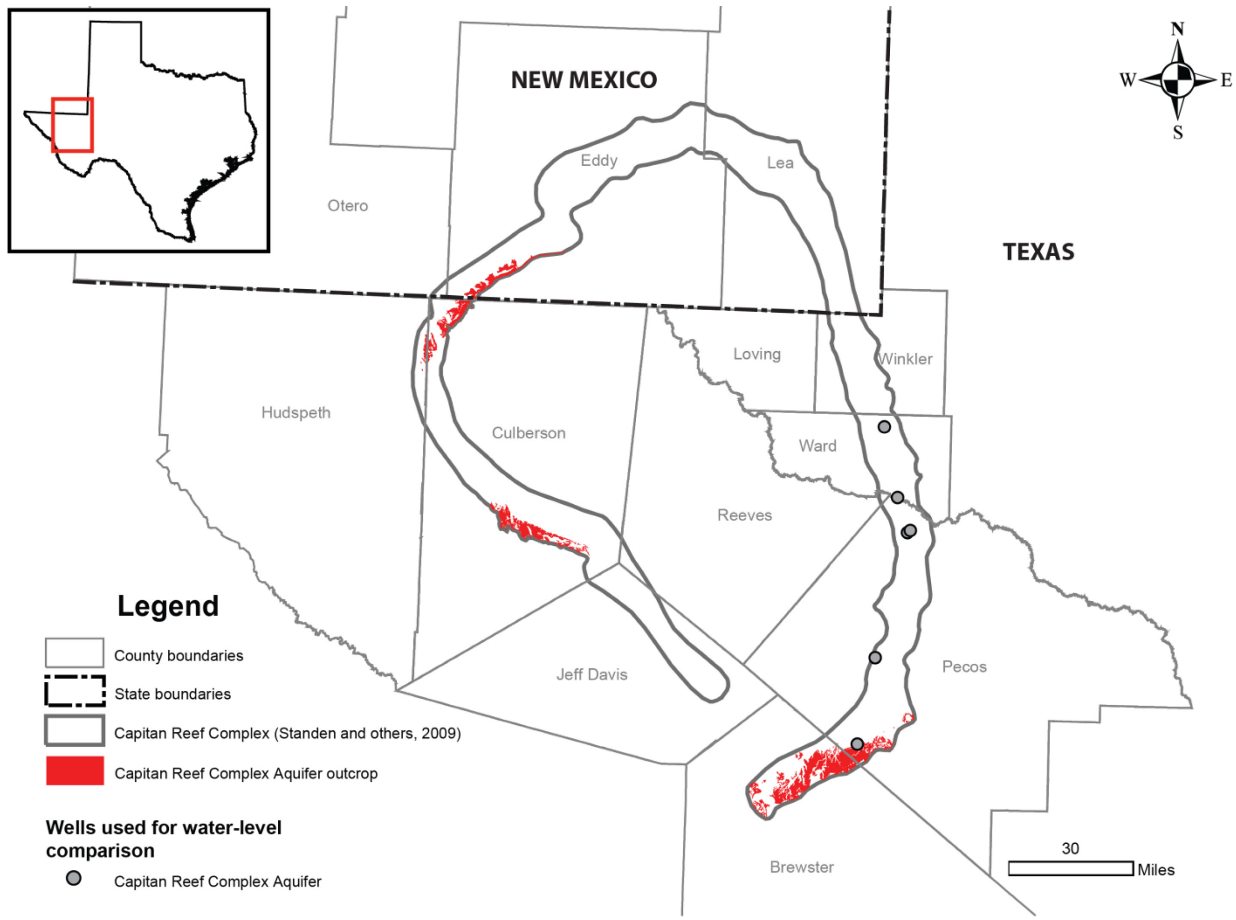
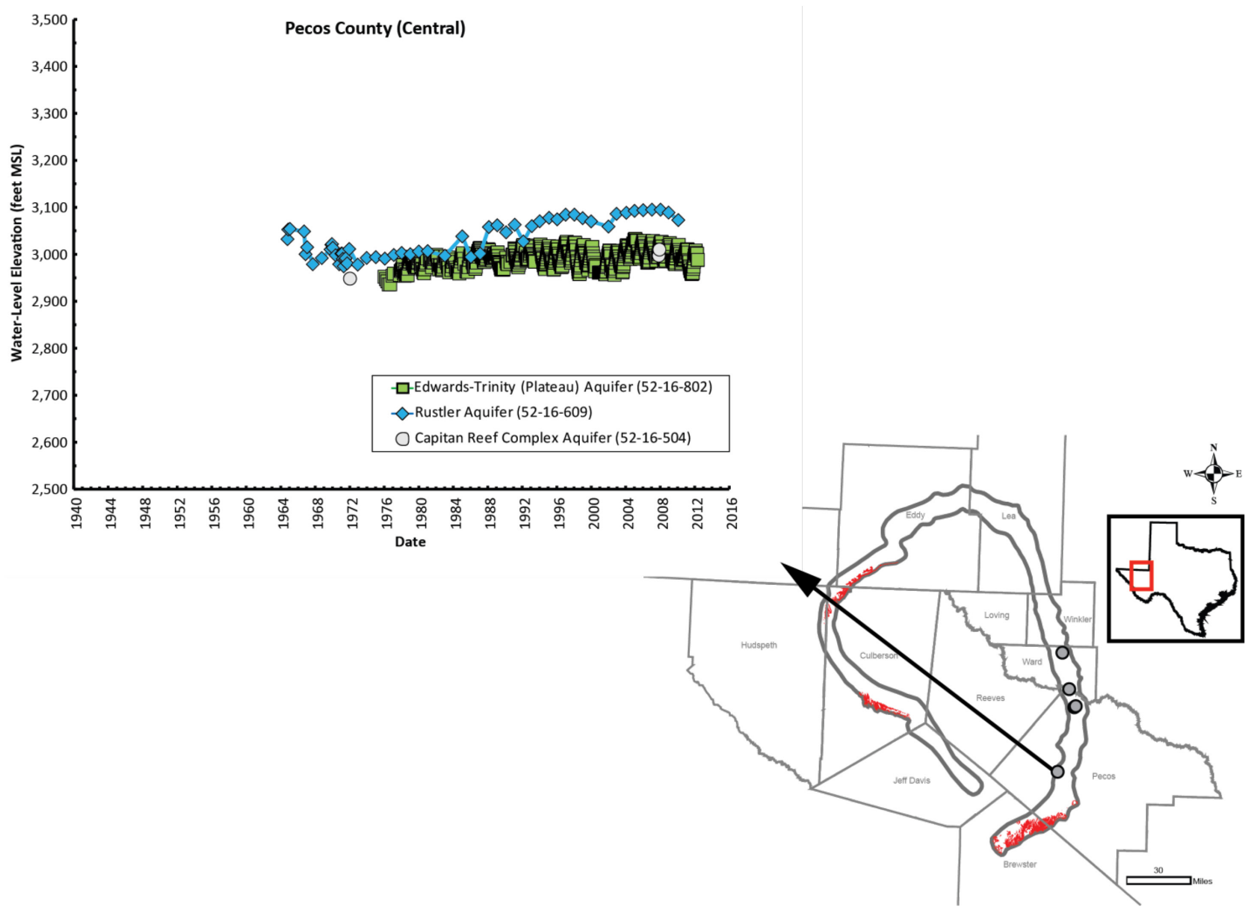
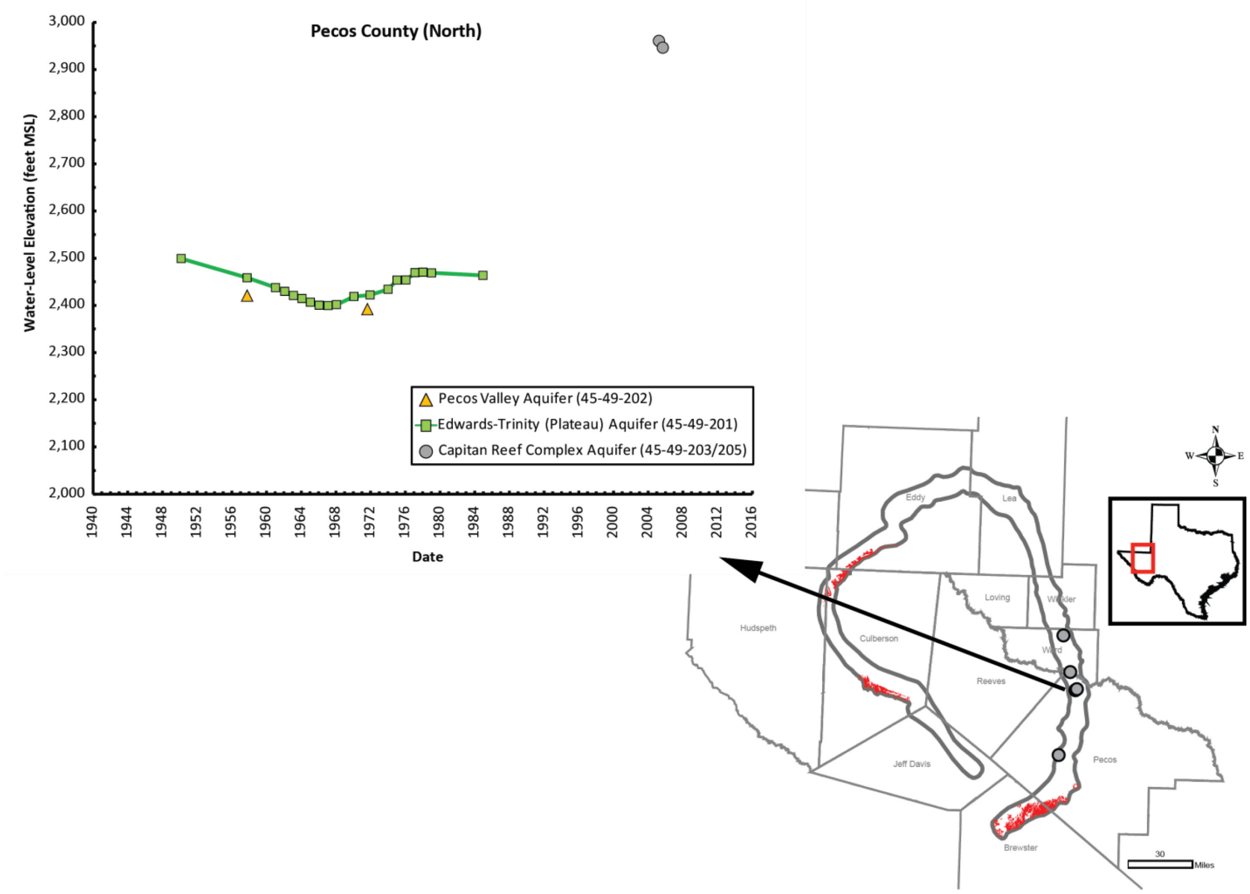


Figure 4.2.11. Locations of wells used for comparing water-level elevations between aquifers (Texas Water Development Board, 2012b).



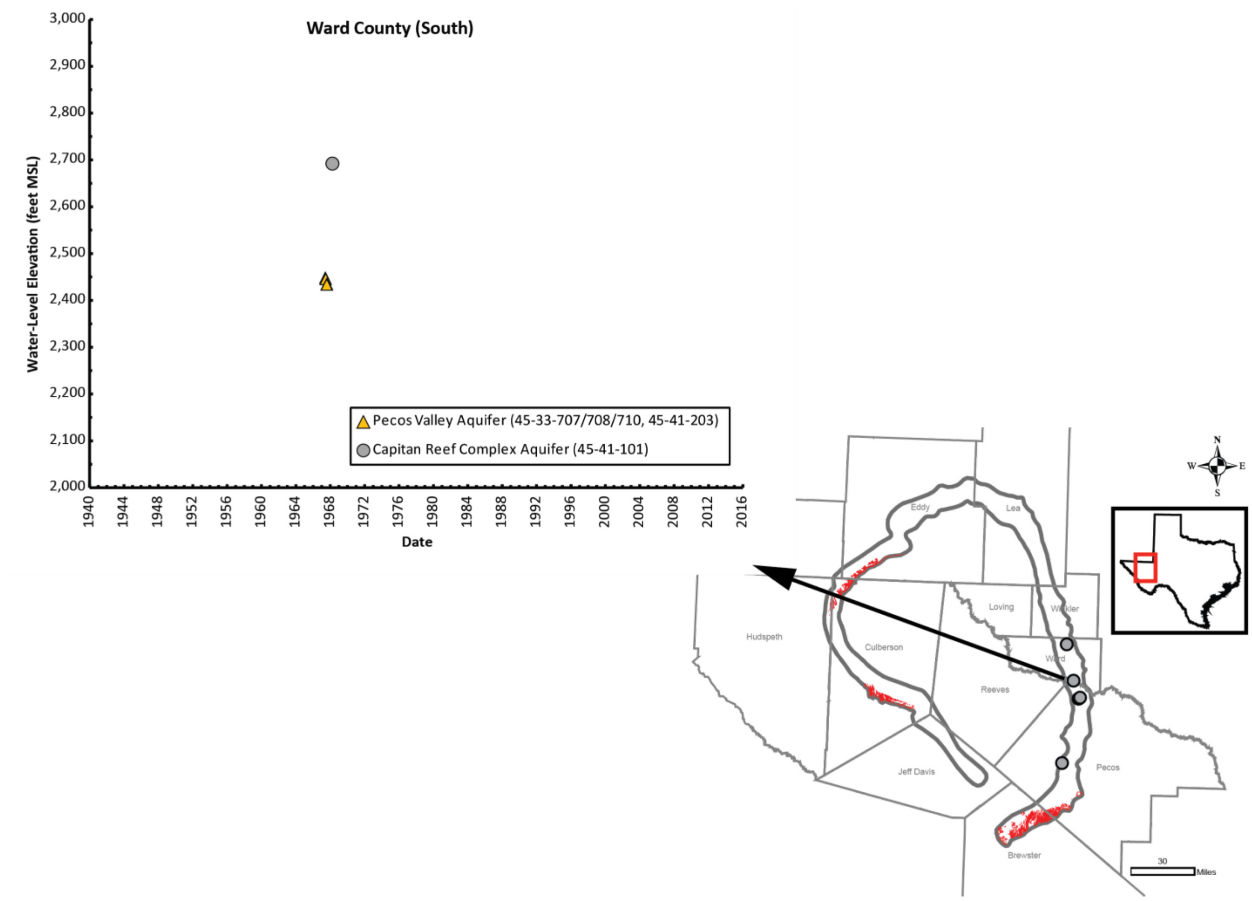
(A)

Figure 4.2.12. Comparison of water-level elevations (in feet above mean sea level (MSL)) in the Capitan Reef Complex and overlying Rustler, Dockum, Edwards-Trinity (Plateau), and Pecos Valley aquifers (Texas Water Development Board, 2012b).



(B)

Figure 4.2.12. (continued)



(C)

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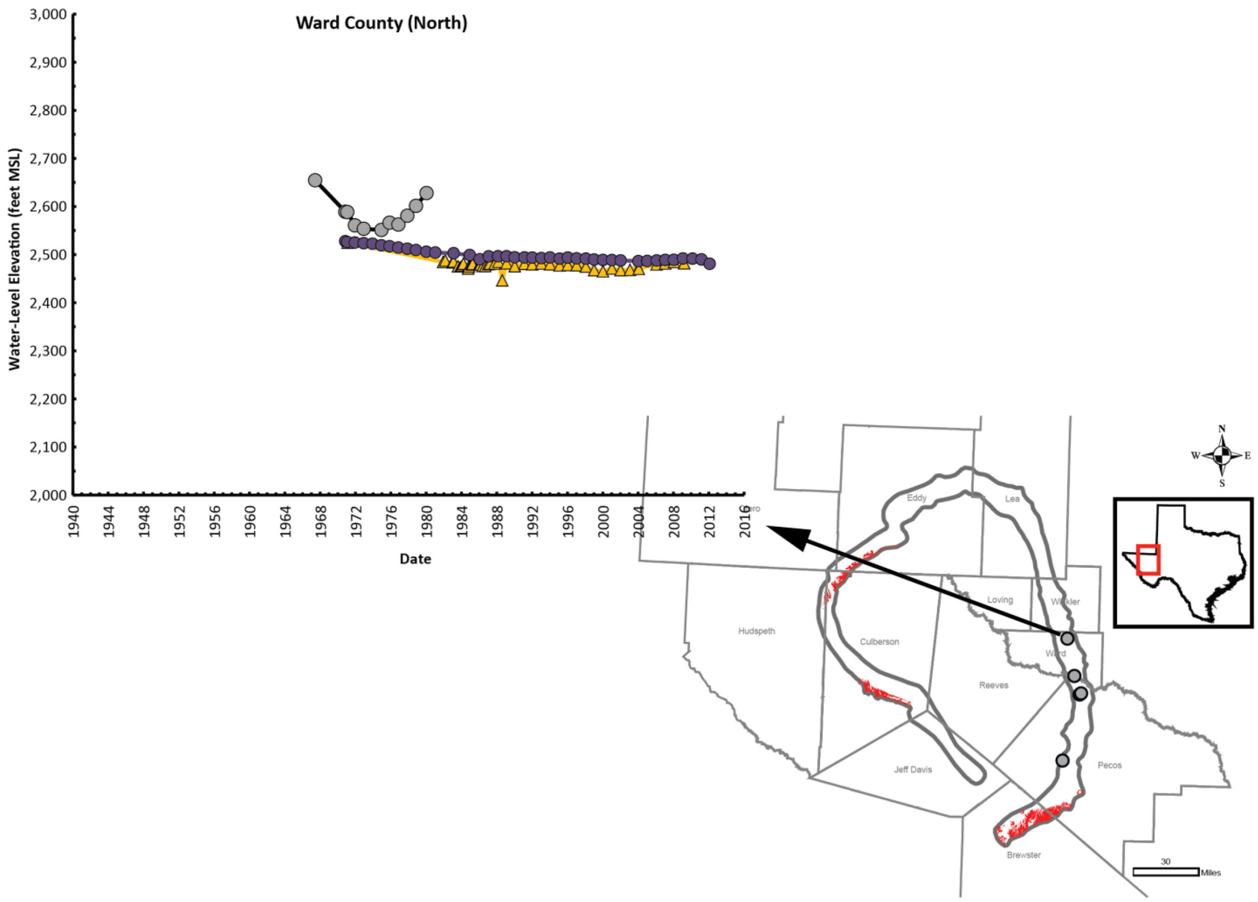

(D)

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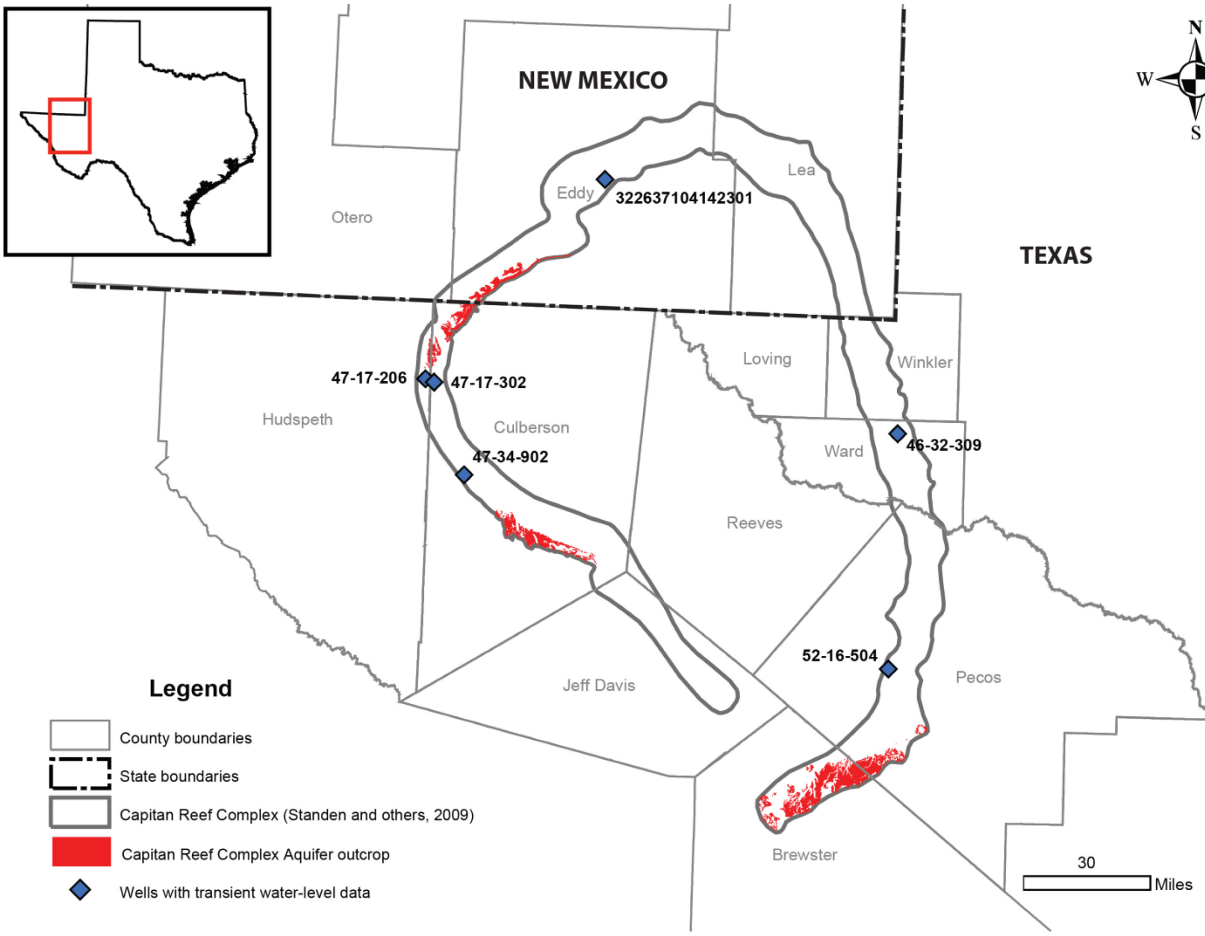


Figure 4.2.13. Locations of selected Capitan Reef Complex Aquifer wells with transient water-level data (Texas Water Development Board, 2012b; United States Geological Survey, 2012a).

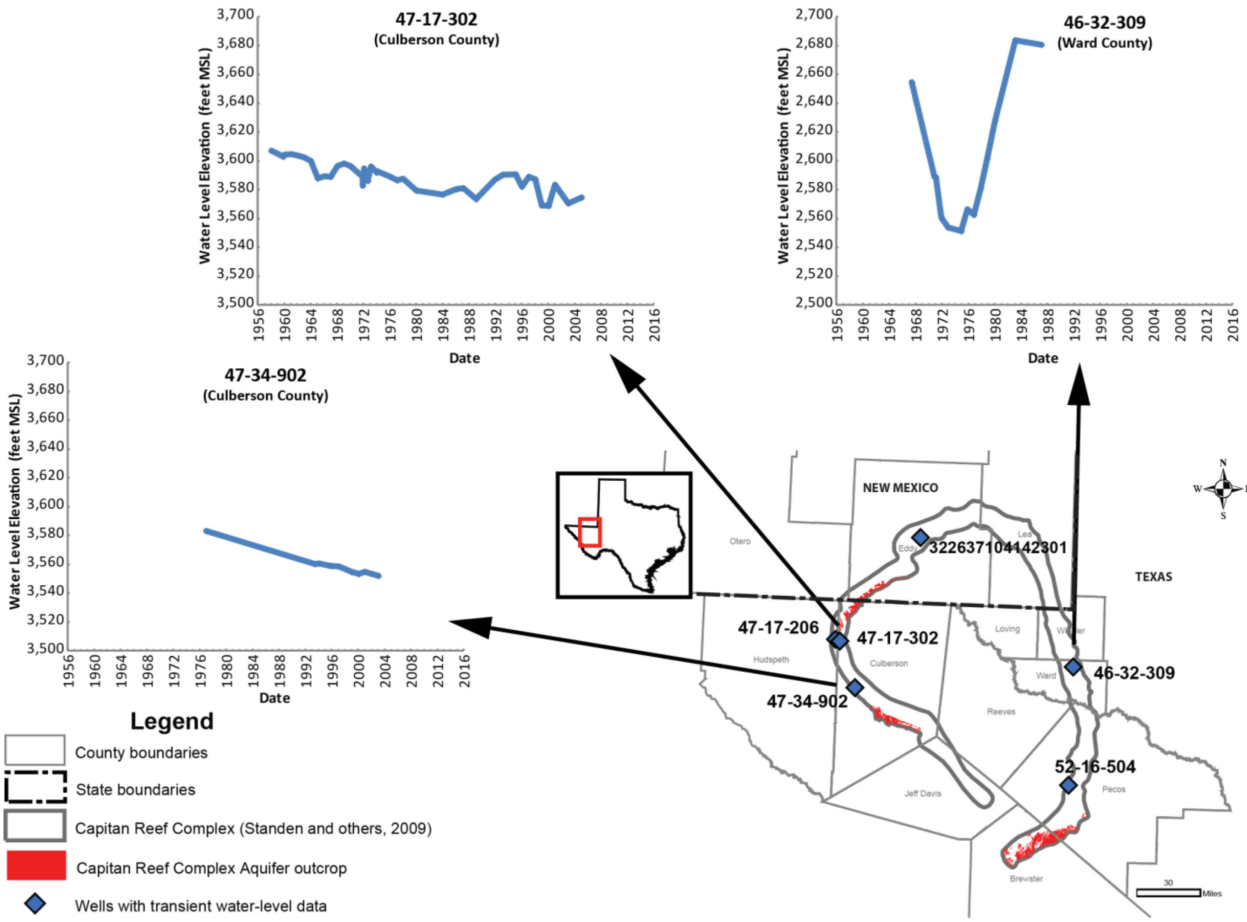


Figure 4.2.14. Hydrographs of transient water-level data (in feet above mean sea level (MSL)) for Capitan Reef Complex Aquifer wells in Culberson and Ward counties (Texas Water Development Board, 2012b).

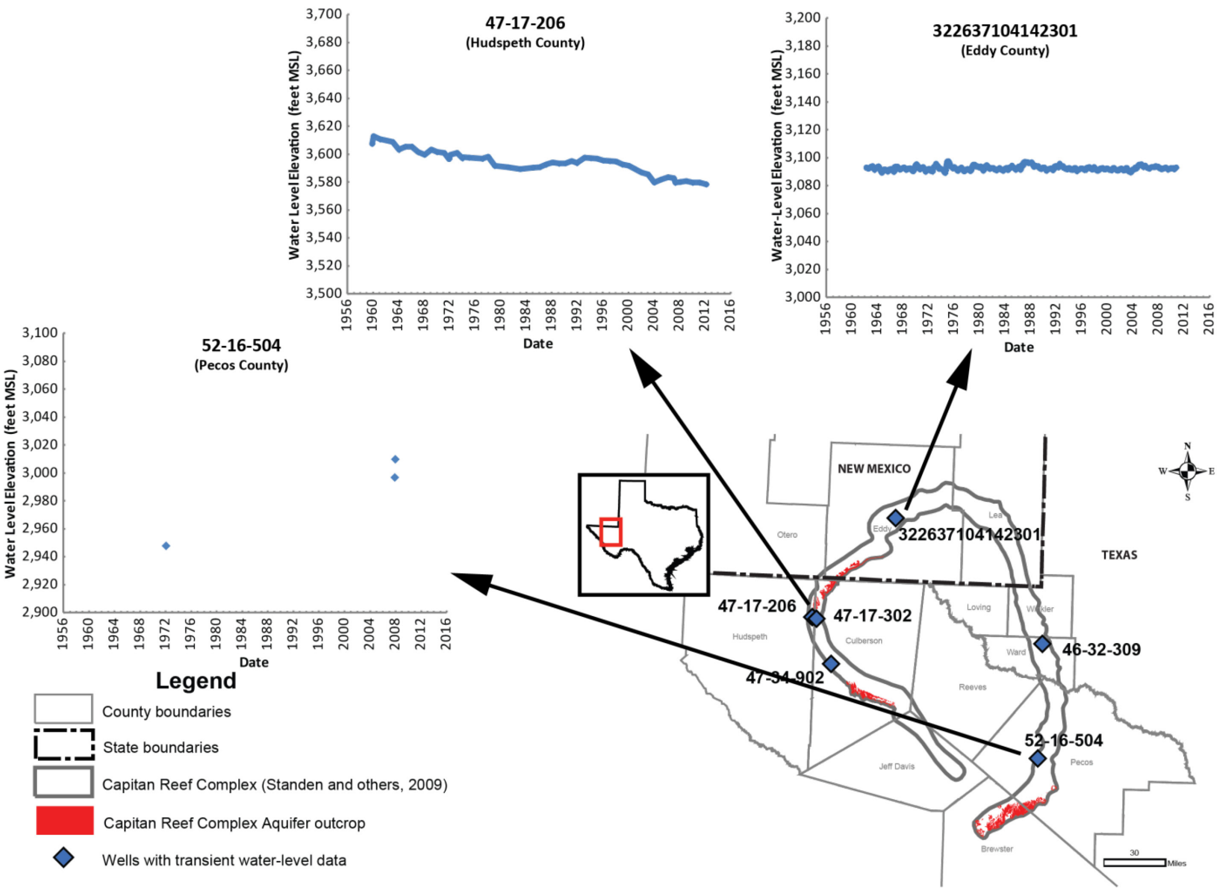


Figure 4.2.15. Hydrographs of transient water-level data (in feet above mean sea level (MSL)) for Capitan Reef Complex Aquifer wells in Hudspeth and Pecos counties in Texas and Eddy County in New Mexico (Texas Water Development Board, 2012b; United States Geological Survey, 2012a).

4.3 Recharge

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

During a rainfall event, some of the precipitation: (1) runs off through streams, (2) is taken up through evapotranspiration, and (3) the remainder—if any—infiltrates into the soil and rock and recharges the underlying aquifer. The potential for the occurrence of recharge to the Capitan Reef Complex Aquifer is greater where it is exposed at land surface (see Figure 4.3.1) compared to areas where infiltrating water must pass through overlying units. Faults and karst dissolution features potentially facilitate recharge by acting as pathways for rapid infiltration of water both where the Capitan Reef Complex Aquifer crops out and where it is confined by overlying aquifers or aquitards—rocks that do not transmit useable amounts of water and thus do not meet the criteria to be aquifers. Recharge to the Capitan Reef Complex Aquifer is potentially topographically controlled, with higher recharge in the areas of higher elevation where the amount of precipitation is highest and the evaporative potential is least (Figures 2.1.3 and 2.1.6).

Isotopes in groundwater, such as carbon-13, carbon-14, tritium, and stable hydrogen and oxygen can be used to determine the spatial and seasonal distribution of recharge to an aquifer (See Section 4.7). The carbon-13 and carbon-14 isotopic compositions of Capitan Reef Complex Aquifer groundwater indicate recharge zones in the Guadalupe and Glass mountains but little recharge in the Apache Mountains—all areas where the aquifer crops out. The carbon-13 and carbon-14 isotopic compositions also indicate recharge associated with faults near the southern margin of the Delaware Mountains. Groundwater tritium compositions indicate that the most recent recharge to the Capitan Reef Complex Aquifer occurred near the southern margin of the Delaware Mountains. The stable oxygen and hydrogen isotopes indicate a relatively simple flow system in the eastern arm of the Capitan Reef Complex Aquifer with a single recharge zone. In the west, there is a more complex system where recharge takes place under a range of conditions.

Ewing and others (2012) estimated potential recharge to the Capitan Reef Complex Aquifer in the Glass Mountains in the range of 1,090 to 14,210 acre-feet per year during their study of the Rustler Aquifer. These estimates are based on assumed recharge factors—percentages of average annual precipitation—ranging from 0.77 percent to 10 percent. These highest recharge factors were justified by the occurrence of karst features in the Glass Mountains that have the potential to facilitate rapid infiltration of large amounts of recharge water. INTERA (2013) estimated recharge to the outcrop of the Capitan Reef Complex Aquifer in the Glass Mountains of 0 to 2.69 inches per year and averaging 0.63 inches per year. Finch (2014) estimated recharge to the Capitan Reef Complex Aquifer outcrop in the Glass Mountains based on daily precipitation. The resultant recharge estimate was 2.56 inches per year or 18 percent of the average annual precipitation. There are some other studies of recharge in arid environments that have some relevance to the Capitan Reef Complex Aquifer (Hibbs and Darling, 1995; Hibbs and others, 1998; Stone and others, 2001; Beach and others, 2004; Wilson and Guan, 2004; Berger and others, 2008). However, these studies are not directly applicable to the Capitan Reef Complex Aquifer.

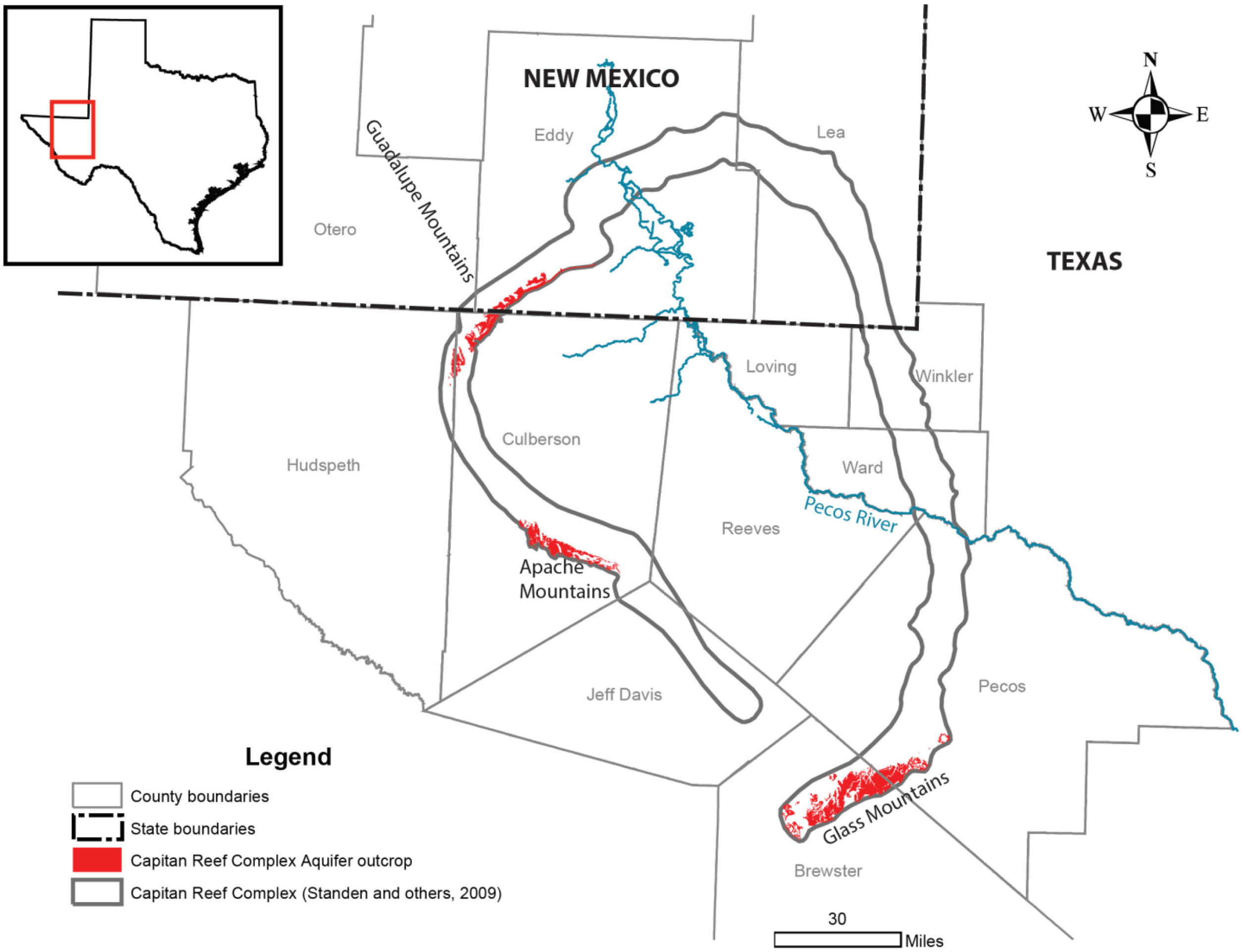


Figure 4.3.1. **Capitan Reef Complex Aquifer outcrop regions where the potential for recharge is assumed to be the greatest.**

4.4 Rivers, Streams, Springs, and Lakes

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

4.4.1 Rivers and Streams

Interaction between groundwater and rivers and streams depends on the relative elevations of the water table and the stream stage. In losing streams, the water table is below the elevation of the stream stage, and the gradient causes water to flow from the stream into the aquifer. In gaining streams, the water table is above the elevation of the stream stage and consequently water flows from the aquifer into the stream.

No existing studies were found to describe river gain/loss in the Capitan Reef Complex Aquifer outcrop. This is not surprising because there are very few perennial water bodies in the study area (Figure 2.0.4). The unproductive search for existing studies included a review of gain/loss studies in Texas completed by Slade and others (2002). Determination of streamflow gain or loss in the Pecos River where it crosses the Capitan Reef Complex Aquifer is difficult because of the presence of a reservoir—Lake Avalon—that disrupts natural flow through the river. Comparison of streamflow at upstream and downstream locations on the Capitan Reef Complex Aquifer footprint—Stations 08401500 and 08405200, respectively—suggest mostly declining streamflow across the outcrop (Figure 4.4.1). This contradicts findings by Hiss (1980) who reported aquifer discharge along the river. The declining streamflow may be explained by increasing storage in Lake Avalon and the fact that due to the presence of the reservoir located between the two gaging stations, the Pecos River does not flow naturally (also see Section 4.4.3).

4.4.2 Springs

Springs are locations where the water table intersects the ground surface. Spring data for the Capitan Reef Complex Aquifer were found in the Texas Water Development Board groundwater database (Texas Water Development Board, 2012b), 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). Only one spring identified as discharging from the Capitan Reef Complex Aquifer was located from the three data sources—Frijoles Spring—located in the Guadalupe Mountains (Figure 4.4.2). A second spring—Carlsbad Springs—is located in New Mexico. Discharge from Carlsbad Springs to the Pecos River is reported to include groundwater discharge from the Capitan Reef Complex Aquifer in addition to groundwater from the overlying Artesia Group (Bjorklund, 1958; Thomas, 1963; Texas Department of Water Resources, 1978).

There is very little spring discharge data available for springs discharging from the Capitan Reef Complex Aquifer. Spring discharge from Frijoles Spring was reported as less than 2 gallons per minute (Texas Water Development Board, 2012b). It should be noted that Carlsbad Springs receives water from multiple sources in addition to the Capitan Reef Complex Aquifer (Bjorklund, 1958; Cox, 1967; Texas Department of Water Resources, 1978). These sources include Lake Avalon, return-flow from nearby irrigated farmland, and discharge from overlying stratigraphic units. Reported discharge rates from Carlsbad Springs range from 30 cubic feet per second to 100 cubic feet per second (Bjorklund, 1958).

4.4.3 Lakes and Reservoirs

Typically, interaction between an aquifer and a lake or reservoir is restricted to the outcrop area of an aquifer where the lake or reservoir lies directly on the aquifer. There are no natural lakes or reservoirs in the outcrop of the Capitan Reef Complex Aquifer. However, there is thought to be interaction between the Capitan Reef Complex Aquifer and Lake Avalon, which is located on the

Pecos River overlying the Capitan Reef Complex Aquifer (Figure 4.4.3). Bjorklund (1958) and Cox (1967) discuss the interaction of Lake Avalon, the Capitan Reef Complex Aquifer, and Carlsbad Springs. They found that water seeps from Lake Avalon, recharging the underlying Capitan Reef Complex Aquifer and rapidly discharges back into the Pecos River downstream through the Carlsbad Springs. Bjorklund (1958) suggested that the net effect of seepage from Lake Avalon on discharge at Carlsbad Springs lags by one to three months. These effects are superimposed upon effects associated with fluctuations of the water levels in the Capitan Reef Complex Aquifer.

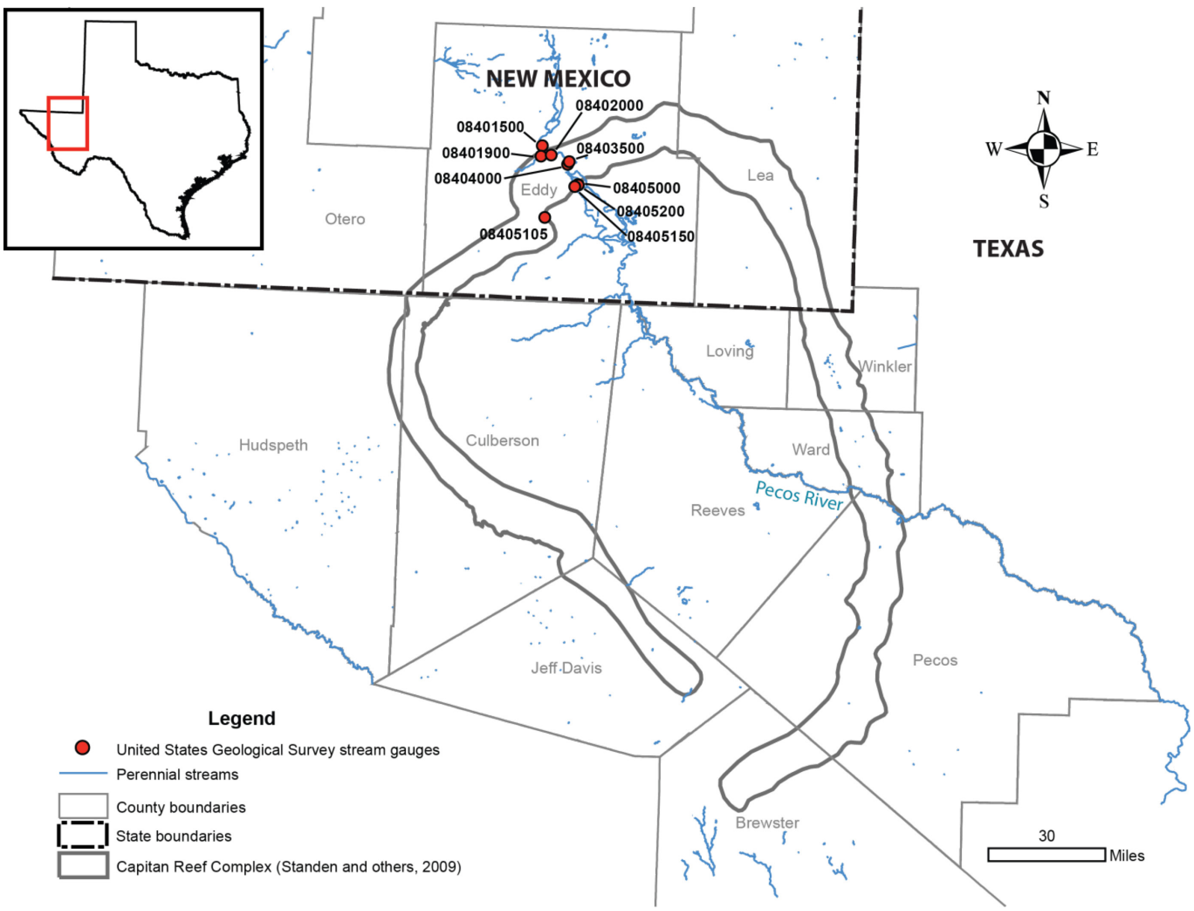


Figure 4.4.1. **Locations of and hydrographs from stream gauges along the Pecos River (United States Geological Survey, 2012b).**

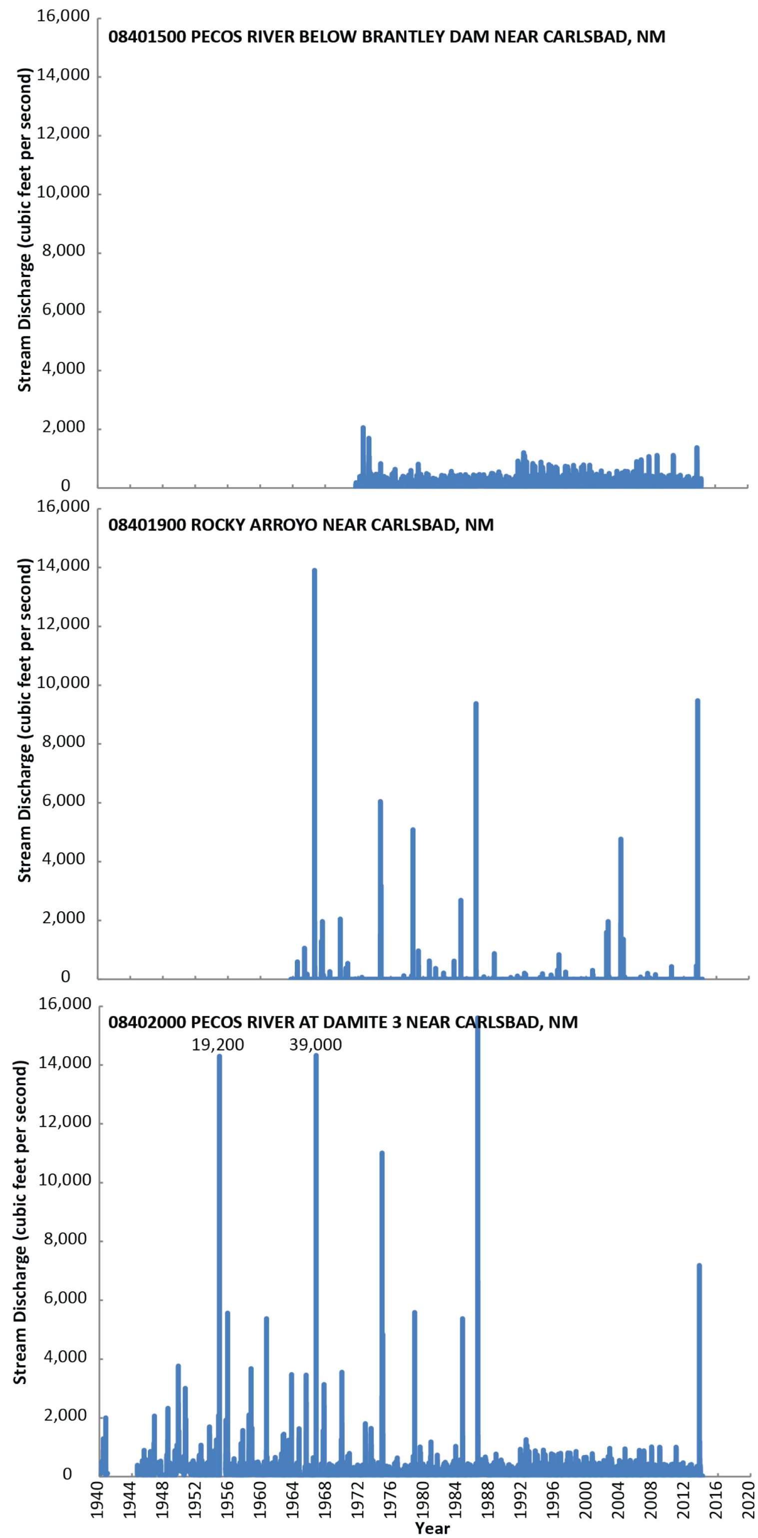
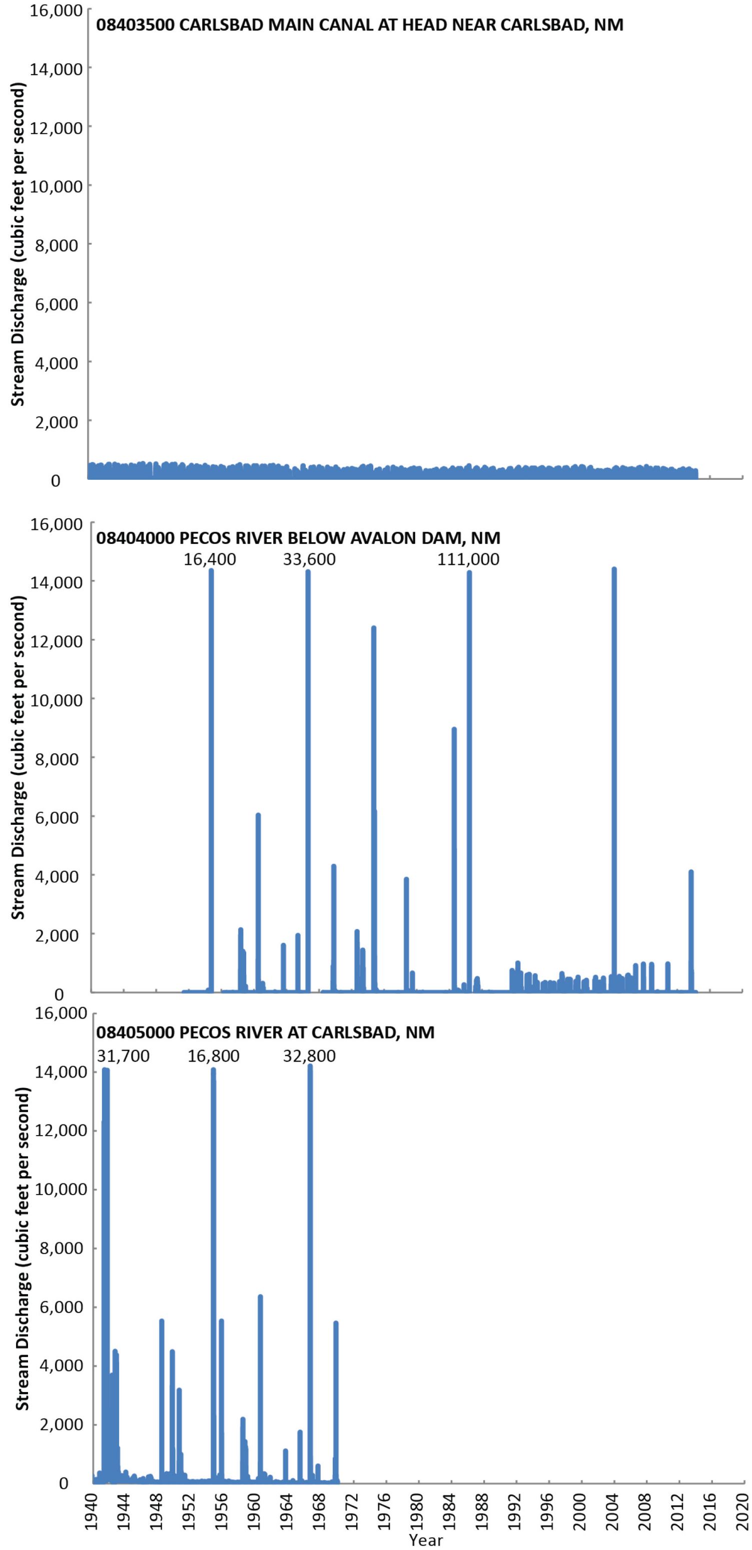


Figure 4.4.1. (continued).



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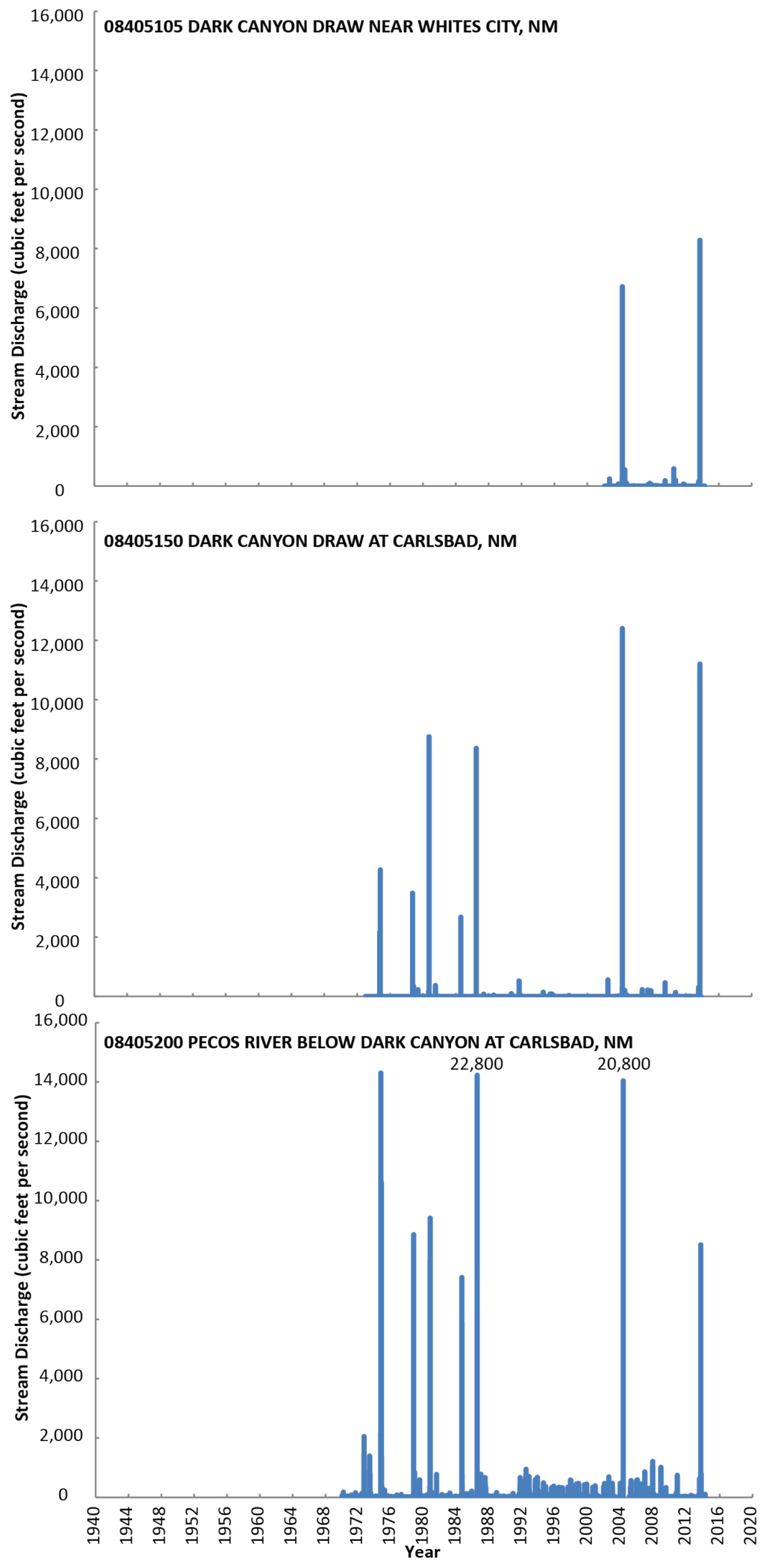


Figure 4.4.1. (continued).

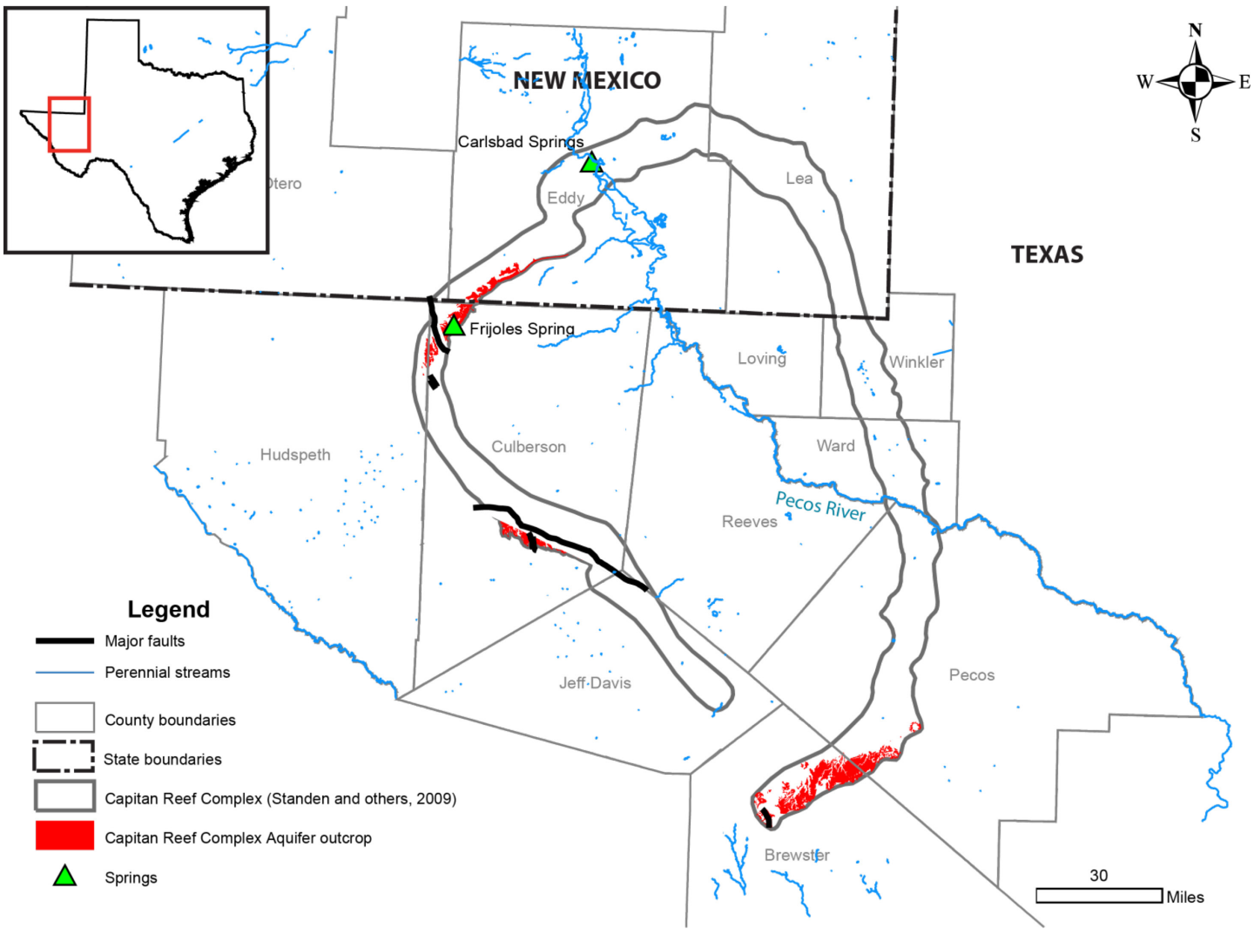


Figure 4.4.2. Locations of springs flowing from the Capitan Reef Complex Aquifer (Texas Department of Water Resources, 1978; Heitmuller and Reece, 2003).

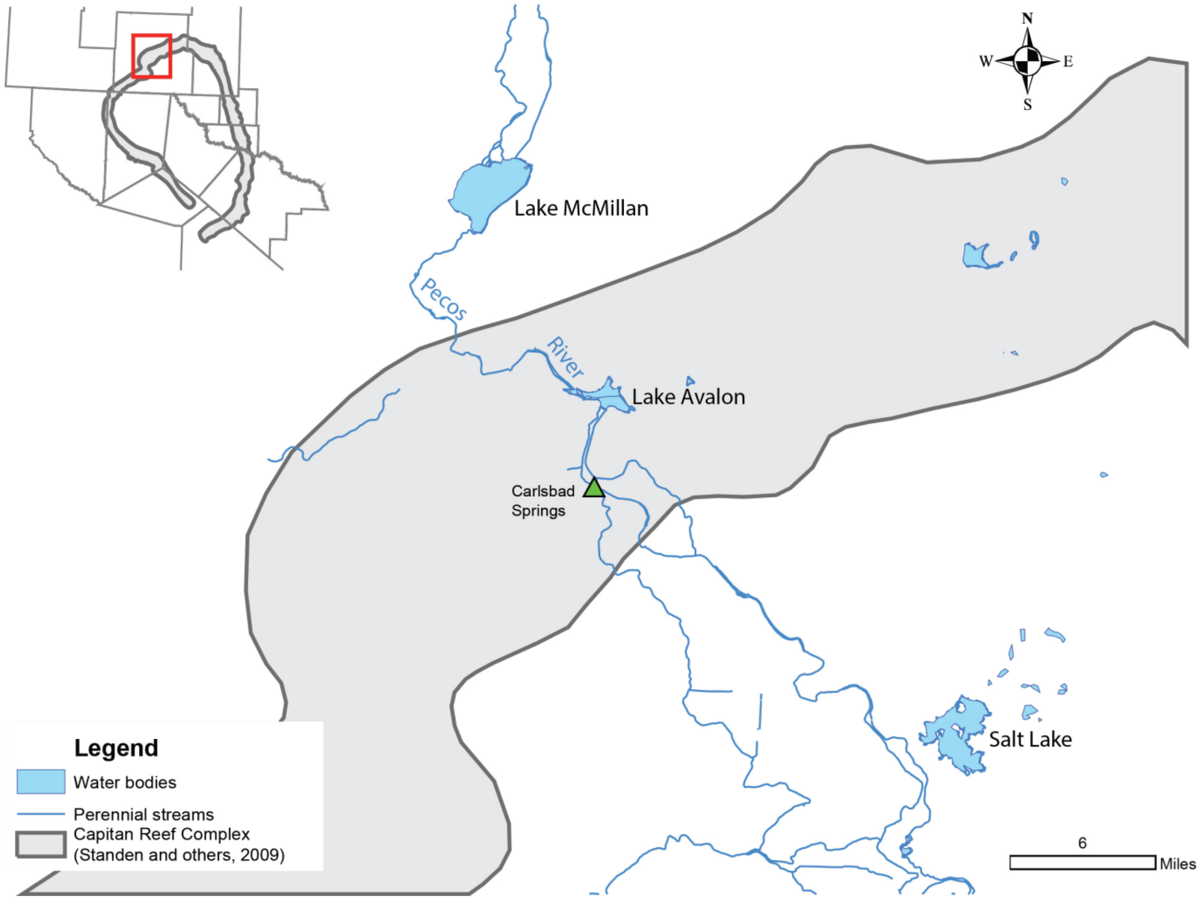


Figure 4.4.3. Reservoirs located along the Pecos River including where it intersects with the Capitan Reef Complex Aquifer near Carlsbad, New Mexico.

4.5 Hydraulic Properties

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

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

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

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

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

4.5.1 Data Sources

Development of hydraulic properties for the Capitan Reef Complex Aquifer in the study area used multiple sources: Brackbill and Gaines (1964); Richey and others (1985); Myers (1969); Hiss (1973; 1975); Christian and Wuerch (2012); Huff (1997); Garber, and others (1989); INTERA (2012); and specific capacity data from drillers' logs on the Texas Water Development Board website (Texas Water Development Board, 2012b).

Little is known regarding the hydraulic properties of the Capitan Reef Complex Formation in Texas and most of it is semi-quantitative information such as reports of well productivity. Brackbill and Gaines (1964) reported a permeability value of 6 darcies—equivalent to a hydraulic conductivity of 17 feet per day—in Winkler County. Reported well yields in the Capitan Reef Complex Aquifer vary from about 3 gallons per minute up to 6,200 gallons per minute, with a median yield of about 390 gallons per minute (Texas Water Development Board, 2012b). This suggests a wide range of hydraulic conductivity in the aquifer.

The hydraulic property data for the Capitan Reef Complex in New Mexico and Texas are shown in Figure 4.5.1 and Table 4.5.1. Using all sources available, 38 estimates of specific capacity, 7 estimates of transmissivity, 15 estimates of hydraulic conductivity, and 2 estimates of storativity were found for the Capitan Reef Complex Aquifer. INTERA (2012) reports storativity estimates for two wells based on different methodologies.

4.5.2 Calculation of Hydraulic Conductivity from Specific Capacity

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

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

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

where:

s = drawdown in the well [L],

Q = pumping rate [L3/T],

T = transmissivity [L2/T],

t = time [T],

r = radius of the well [L], and

S = storativity [--].

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

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

For a given specific capacity, transmissivity can be solved iteratively. Table 4.5.2 provides specific capacity and calculated transmissivity and hydraulic conductivity data for Capitan Reef Complex Aquifer wells. Transmissivity was calculated using the iterative method outlined by Equation 4.5.2 and assuming a storativity value of 0.0005. Hydraulic conductivity was calculated by dividing the transmissivity by the well screen length or in the absence of screen information by the thickness of the Capitan Reef Complex Aquifer indicated in Figure 4.1.4.

The estimated hydraulic conductivity values for the Capitan Reef Complex Aquifer range from 0.009 to 517 feet per day, with a median of 3 feet per day (Figures 4.5.2 and 4.5.3). A model by INTERA (2012) divided the eastern arm of the Capitan Reef Complex Aquifer into eight zones with horizontal hydraulic conductivities ranging from 0.005 feet per day to 20 feet per day. Highest hydraulic conductivity in the Capitan Reef Complex Aquifer is associated with karstification of the limestone (Motts, 1968).

Hiss (1975) found that the hydraulic conductivity of the stratigraphic units in the fore-reef Delaware Basin—the Castile Formation and Delaware Mountain Group—are much less than the Capitan Reef Complex Aquifer. The Castile Formation and most units within the Delaware Mountain Group transmit only limited amounts of water (Motts, 1968). Consequently, it is expected that inter-aquifer flow between the Capitan Reef Complex Aquifer and the fore-reef Delaware Basin is limited. The differences in water quality in the Delaware Basin and the Capitan Reef Complex Aquifer adds more evidence that hydrologic interaction is limited (Hiss, 1980). Hydraulic property data for the Delaware Mountain Group indicate hydraulic conductivity in the range of 0.01 to 0.04 feet per day with a average of 0.02 feet per day—much less than the Capitan Reef Complex Aquifer (Hiss, 1975; Huff, 1997).

West of where the Pecos River intersects with the Capitan Reef Complex Aquifer in New Mexico, the back-reef or shelf stratigraphic units of the Artesia Group locally have hydraulic conductivities similar to the Capitan Reef Complex Aquifer (Hiss, 1975; 1980). However, east of the Pecos River, the Artesia Group is readily distinguishable from the Capitan Reef Complex Aquifer in terms of hydraulic properties and water quality (Hiss, 1975). The hydraulic conductivity of the Artesia Group correlates to the mineralogy and texture. The carbonate facies generally have low hydraulic conductivity, except near the boundary with the Capitan Reef Complex. The evaporite facies generally have moderate hydraulic conductivity. The overall hydraulic conductivity of the Artesia Group is several orders of magnitude lower east of the Pecos River than west and is generally one to two orders of magnitude lower than the Capitan Reef Complex Aquifer (Motts, 1968; Hiss, 1980). Consequently, one can deduce significant interaction between the Artesia Group and the Capitan Reef Complex Aquifer west of the Pecos River and limited interaction to the east. Hydraulic property data for the Artesia Group indicate hydraulic conductivity in the range of up to 0.9 feet per day with a median of 0.006 feet per day—much less than the Capitan Reef Complex (Figure 4.5.4; Hiss, 1975; Huff, 1997).

Hydraulic conductivity data from the aquifers overlying the Capitan Reef Complex Aquifer—the Rustler, Dockum, Edwards-Trinity (Plateau), and Pecos Valley aquifers—were obtained from their respective groundwater availability model or alternative model reports (Ewing and others, 2012; Ewing and others, 2008; Hutchison and others, 2011). In the Rustler Aquifer, hydraulic conductivity lies in the range of 0.001 to 1,000 feet per day with an average of about 1 foot per day (Figure 4.5.5). Some of the highest hydraulic conductivities in the Rustler Aquifer occur where the underlying Salado Formation has been partially removed by dissolution—which occurs where the Rustler Aquifer overlies the Capitan Reef Complex Aquifer. Dockum Aquifer hydraulic conductivity adjacent to the Capitan Reef Complex Aquifer lies in the range 0.3 to 300 feet per day which is typical for the rest of the Dockum Aquifer (Figures 4.5.6 and 4.5.7). At the regional scale, hydraulic conductivity ranges in the Edwards-Trinity (Plateau) and Pecos Valley aquifers are 30 to 80 feet per day and 5 to 29 feet per day, respectively (Figure 4.5.8).

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.

INTERA (2012) storativity estimates in two wells range from 1.58×10^{-4} to 2.43×10^{-5} and 4.78×10^{-5} to 5.52×10^{-7}, respectively, using several different methods. A wide range of storage values—storativity and specific yield—would be expected in the Capitan Reef Complex Aquifer because it is composed of a complex mixture of different carbonate rock types and additionally displays varying degrees of karstification (Garber and others, 1989). A study of a core extending from the Salado Formation to the top of the Cherry Canyon Formation in the Delaware Group—including entire thickness of the Capitan Formation—in Eddy County, New Mexico, indicates porosity in the Capitan Reef Complex Aquifer of up to 15 percent (Garber and others, 1989).

Table 4.5.1. Hydraulic property data from wells shown in Figure 4.5.1, located within the Capitan Reef Complex Aquifer. T= transmissivity, K = hydraulic conductivity, Q = well discharge, SC = specific capacity.

Map	Well No.	Location	Latitude	Longitude	Source	County	Date	T (ft^2/d)	K (ft/d)	Q (gpm)	SC (gpm/ft)
1	4717317		31.7436	-104.9164	Myers, 1969	Culberson	10/28/1965	16,000	148	2,000	58
2	21.27.05.414	T21S R27E Sec05 414	32.5057	-104.2044	Hiss, 1973	Eddy	8/12/1969		2.4	85	
3	21.28.30.14123	T21S R28E Sec30 14123	32.4558	-104.1247	Hiss, 1973	Eddy	8/9/1961		16	100	
4	4632309		31.6056	-103.0367	White, 1971	Ward	6/28/1957			780	10
5	4632307		31.5989	-103.0336	White, 1971	Ward	6/28/1957			640	7.3
6	4632305		31.6042	-103.0208	White, 1971	Ward	6/28/1957			704	7.3
7	4632306		31.5894	-103.0389	White, 1971	Ward	2/20/1957			288	2.5
8	4632308		31.5917	-103.0306	White, 1971	Ward	2/20/1957			655	8.9
9	4632610		31.5592	-103.0333	White, 1971	Ward	2/20/1957			375	3.4
10	4632611		31.5778	-103.0261	White, 1971	Ward	6/28/1957			435	3.8
11	4632901		31.5333	-103.0006	White, 1971	Ward	7/11/1962			1,310	13
12	21.34.24	T21S R34E Sec 24	32.4652	-104.4238	Hiss, 1975	Lea	1/14/1965		3.0	240	
13	21.35.14	T21S R35E Sec 14	32.4797	-103.3382	Hiss, 1975	Lea	7/8/1962		1.7	270	
13	21.35.14	T21S R35E Sec 14	32.4797	-103.3382	Hiss, 1975	Lea	10/15/1966		3.5		
13	21.35.14	T21S R35E Sec 14	32.4797	-103.3382	Hiss, 1975	Lea	12/14/1966		1.9	328	
13	21.35.14	T21S R35E Sec 14	32.4797	-103.3382	Hiss, 1975	Lea	12/15/1966		1.4		
14	24.36.4	T24S R36E Sec 04	32.2467	-103.2697	Hiss, 1975	Lea	2/28/1968		24	550	
14	24.36.4	T24S R36E Sec 04	32.2467	-103.2697	Hiss, 1975	Lea	2/28/1968		25	550	
15	24.36.16	T24S R36E Sec 16	32.2175	-103.2697	Hiss, 1975	Lea	10/4/1967		4.4	504	
16	4717321		31.7264	-104.8839	Christian/Wuerch, 2012	Culberson	11/21/1971	179,591		1,600	195
17	5238301		30.4753	-103.2633	TWDB, 2012b	Brewster					0.04
18	4702801		31.9147	-104.8017	TWDB, 2012b	Culberson					0.01
19	4703206		31.9597	-104.6819	TWDB, 2012b	Culberson					0.19
20	4709903		31.7650	-104.9164	TWDB, 2012b	Culberson					16.8
21	4710401		31.8006	-104.8478	TWDB, 2012b	Culberson					0.85
22	4718402		31.7081	-104.8581	TWDB, 2012b	Culberson					3
23	4734603		31.4461	-104.7725	TWDB, 2012b	Culberson					22
24	4734902		31.4139	-104.7650	TWDB, 2012b	Culberson					52
25	4743503		31.3278	-104.6714	TWDB, 2012b	Culberson					7
26	4752301		31.2150	-104.5292	TWDB, 2012b	Culberson					5
27	4752601		31.2083	-104.5256	TWDB, 2012b	Culberson					44
28	4752602		31.2033	-104.5189	TWDB, 2012b	Culberson					12
29	4709201		31.8550	-104.9425	TWDB, 2012b	Hudspeth					10
30	4709207		31.8453	-104.9550	TWDB, 2012b	Hudspeth					428
31	4709208		31.8744	-104.9519	TWDB, 2012b	Hudspeth					1.3
32	4717204		31.7336	-104.9344	TWDB, 2012b	Hudspeth					6.5
33	4717208		31.7361	-104.9367	TWDB, 2012b	Hudspeth					12
34	142		32.4260	-104.2773	NMOSE, 2012	Eddy	8/19/1954				147
35	143		32.4027	-104.2497	NMOSE, 2012	Eddy	8/20/1954				381
36	151		32.4252	-104.2504	NMOSE, 2012	Eddy	10/29/1939				275
37	153		32.2924	-104.3460	NMOSE, 2012	Eddy	7/29/1955				0.87
38	154		32.3899	-104.2732	NMOSE, 2012	Eddy	4/6/1955				419
39	155		32.3624	-104.2971	NMOSE, 2012	Eddy	6/2/1955				14.10
40	171		32.3972	-104.2626	NMOSE, 2012	Eddy	2/27/1942				6.40
41	172		32.3972	-104.2626	NMOSE, 2012	Eddy	8/18/1954				32.40
42	229		32.4082	-104.2669	NMOSE, 2012	Eddy	8/20/1954				138
43	230		32.3928	-104.2884	NMOSE, 2012	Eddy	6/2/1955				90
44	250		32.1803	-104.3782	NMOSE, 2012	Eddy	12/8/1954				18.30
45	314		32.4540	-104.1293	NMOSE, 2012	Eddy	1/1/1961	6,700			
46		El Capitan SWS			Brackbill & Gaines, 1964	Winkler			17		
47	ICP	Ochoa SOP Mine			Castiglia & others, 2013	Lea		6,993	6.9	491	
48	4549203		31.2397	-102.9311	TWDB, 2012b	Pecos	8/17/2010	17,200			
49	ICP-WS-01		32.2405	-103.3393	INTERA, 2012	Lea	2/8/2012	7,999	8.0		
50	ICP-WS-02		32.2446	-103.3392	INTERA, 2012	Lea	6/9/2012	723	0.7		

Table 4.5.2. Specific capacity data and calculated hydraulic conductivity based on Equation 4.5.2 for wells in the Capitan Reef Complex Aquifer. The map number refers to location numbers in Figure 4.5.1.

Map	Well Number	County	Specific Capacity (gpm/ft)	Drawdown (ft)	Pump Rate (gpm)	Time (h)	Well Diameter (in)	Screen Length (ft)	Transmissivity (ft^2/d)	Hydraulic Conductivity (ft/d)
17	5238301	Brewster	0.04	82	5	5	8	839	9.5	0.011
18	4702801	Culberson	0.01	364	4	161	6	220	2.0	0.009
19	4703206	Culberson	0.19	25	5	2.5	4	60	35.1	0.58
20	4709903	Culberson	16.8	39	656	8	16	375	3,961	10.56
21	4710401	Culberson	0.85	20	17	24	8	799	193.0	0.24
1	4717317	Culberson	58	34	2,000	24	16	70	16,162	231
16	4717321	Culberson	219	7.3	1,600	12	16	564	62,485	110.8
22	4718402	Culberson	3	104	279	12	12	1,513	593	0.39
23	4734603	Culberson	22	103	2,250	24	14	192	5,739	29.9
24	4734902	Culberson	52	49	2,550	23	14	61	14,387	236
25	4743503	Culberson	7	83	550	36	14	321	1,654	5.15
26	4752301	Culberson	5	82	379	2.5	18	550	878	1.60
27	4752601	Culberson	44	9	396	51	18	155	12,256	79.1
28	4752602	Culberson	12	88	1,100	27	18	309	3,087	9.99
29	4709201	Hudspeth	10	3	30	4	6	204	2,480	12.16
30	4709207	Hudspeth	428	3.5	1,500	4	14	234	121,035	517
31	4709208	Hudspeth	1.3	19	25	24	7	135	314	2.33
32	4717204	Hudspeth	6.5	88	570	24	18	830	1,515	1.83
33	4717208	Hudspeth	12	168	2,000	24	18	1,540	2,907	1.89
6	4632305	Ward	7.3	97	778	5	13	178	1,781	10.01
7	4632306	Ward	2.5	113	288	24	13	713	584	0.82
5	4632307	Ward	7.3	88	640	5	10	3,100	1,668	0.54
8	4632308	Ward	8.9	74	655	24	13	564	2,214	3.93
4	4632309	Ward	10	78	780	5	13	455	2,258	4.96
9	4632610	Ward	3.5	110	385	5	13	799	728	0.91
10	4632611	Ward	3.8	115	435	5	13	596	792	1.33
11	4632901	Ward	13	101	1,310	4	9	1,096	3,097	2.83
34	142	Eddy	147	10	1,470	8	12		40,347	23.06
35	143	Eddy	381	7	2,670	8	16		107,029	61.16
36	151	Eddy	275	3	833	8	12		78,271	44.73
37	153	Eddy	0.87	23	20	1	12		125	0.07
38	154	Eddy	419	1	419	8	6		131,482	75.13
39	155	Eddy	14.10	17	240	1	8		2,947	1.68
40	171	Eddy	6.40	25	160	5	12		1,368	0.78
41	172	Eddy	32.40	18	550	5	13		7,291	4.17
42	229	Eddy	138	7	1,238	8	14		48,188	27.54
43	230	Eddy	90	23	350	1	12		3,085	1.76
44	250	Eddy	18.30	6	110	54	12		4,981	2.85

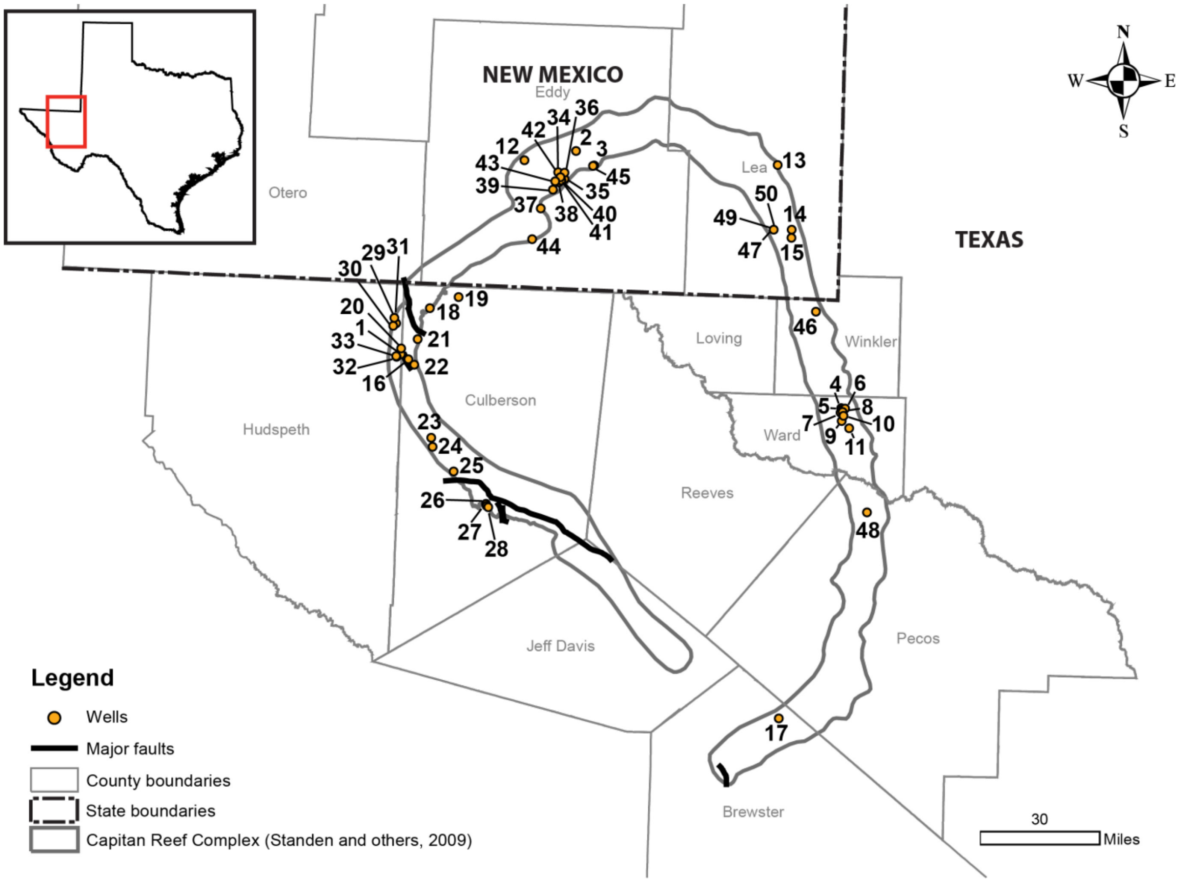


Figure 4.5.1. Hydraulic property data locations for the Capitan Reef Complex Formation in Texas and New Mexico. The numbers refer to wells in Table 4.5.1 and includes references for the source of data.

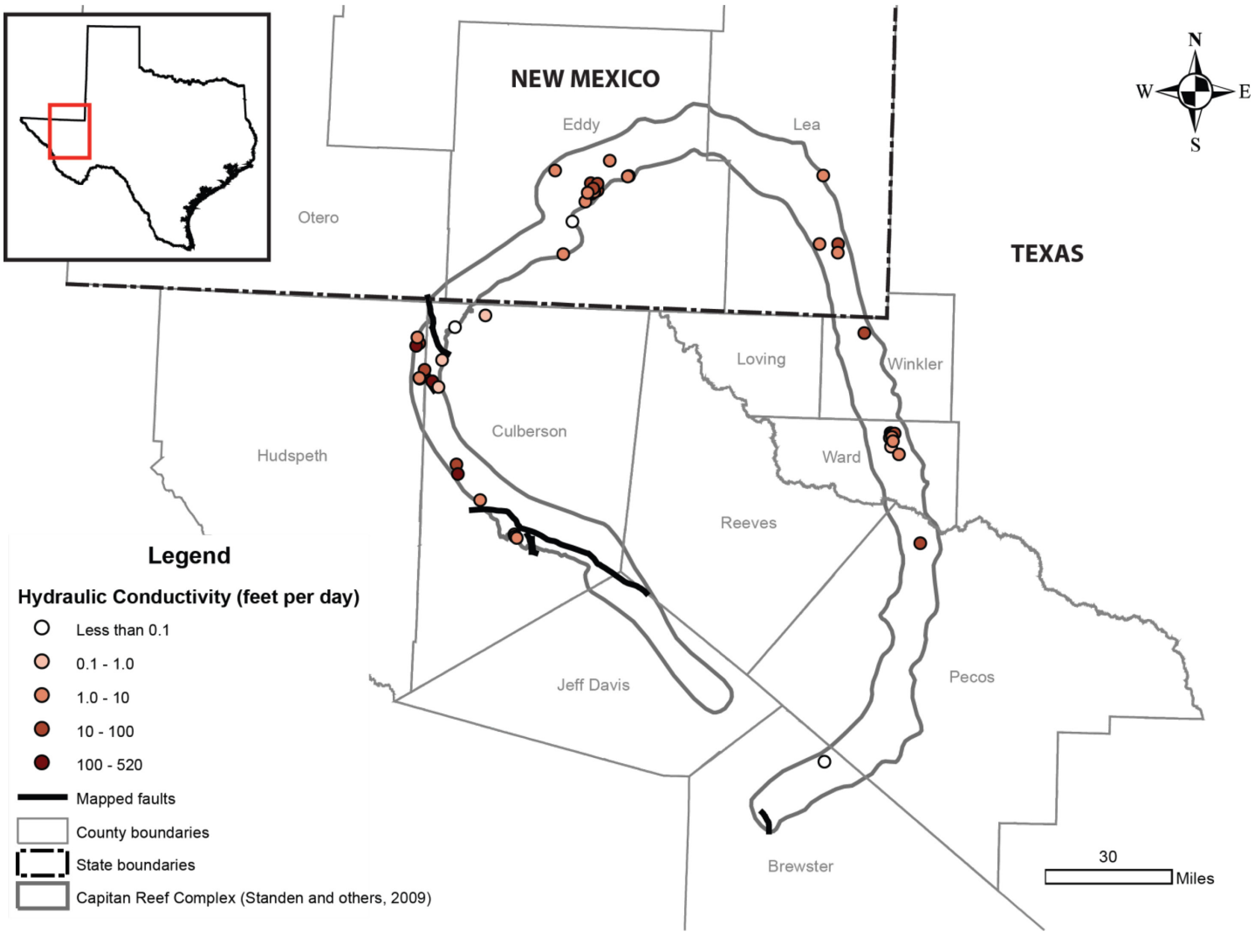


Figure 4.5.2. **Hydraulic conductivity data for the Capitan Reef Complex Aquifer in Texas and New Mexico (see Table 4.5.1 for references of the source of data).**

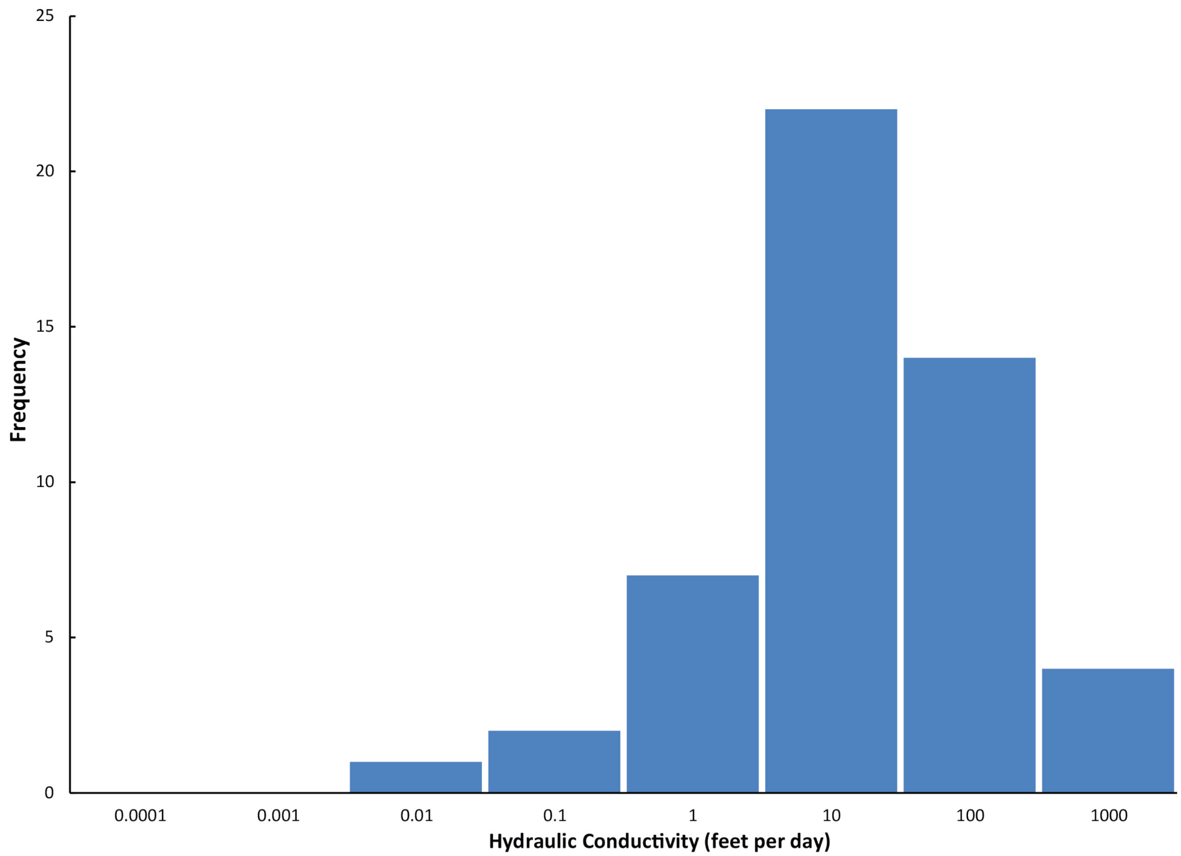


Figure 4.5.3. Histogram of hydraulic conductivity data in feet per day for the Capitan Reef Complex Aquifer based on data from the sources indicated in Table 4.5.1.

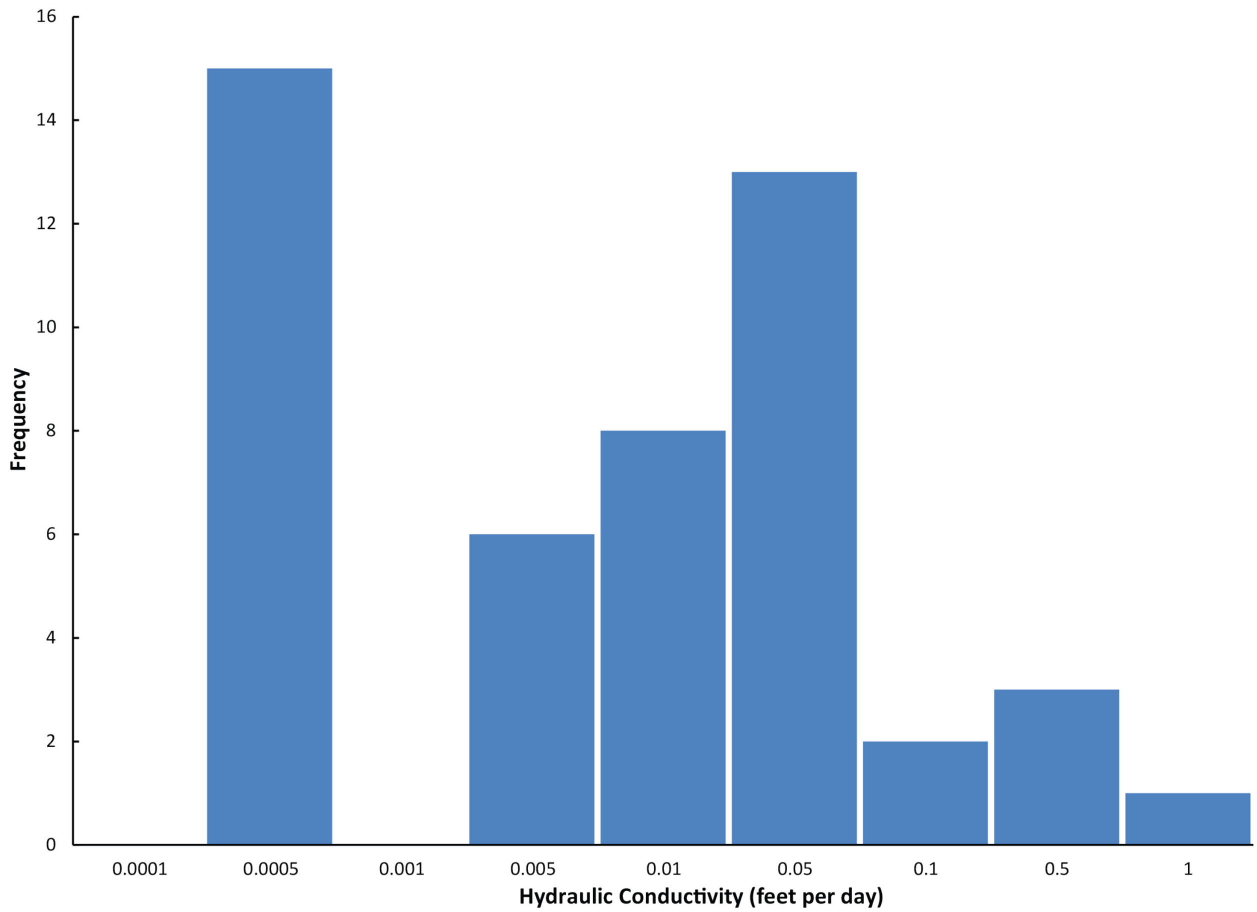


Figure 4.5.4. Histogram of hydraulic conductivity data in feet per day for the Artesia Group based on data from Huff (1997).

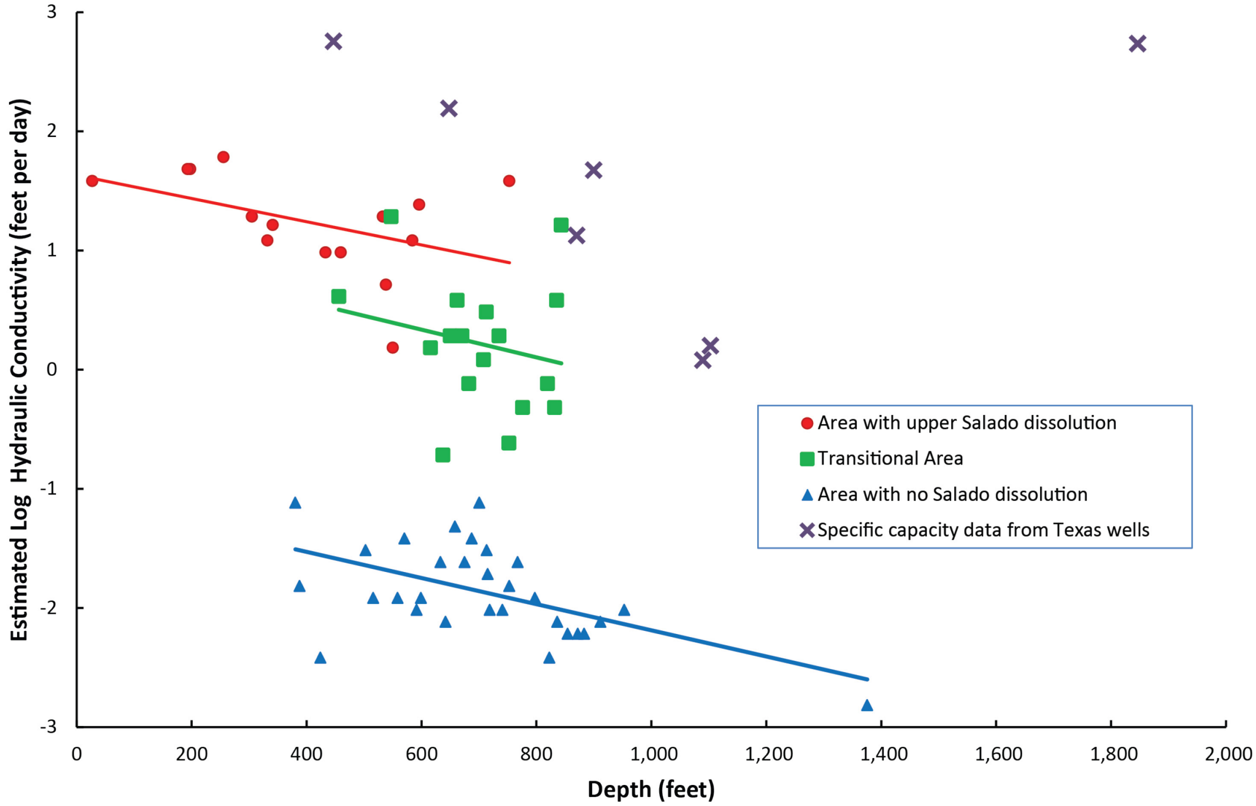


Figure 4.5.5. Hydraulic conductivity data for the Rustler Aquifer in Texas and New Mexico (from Ewing and others, 2012).

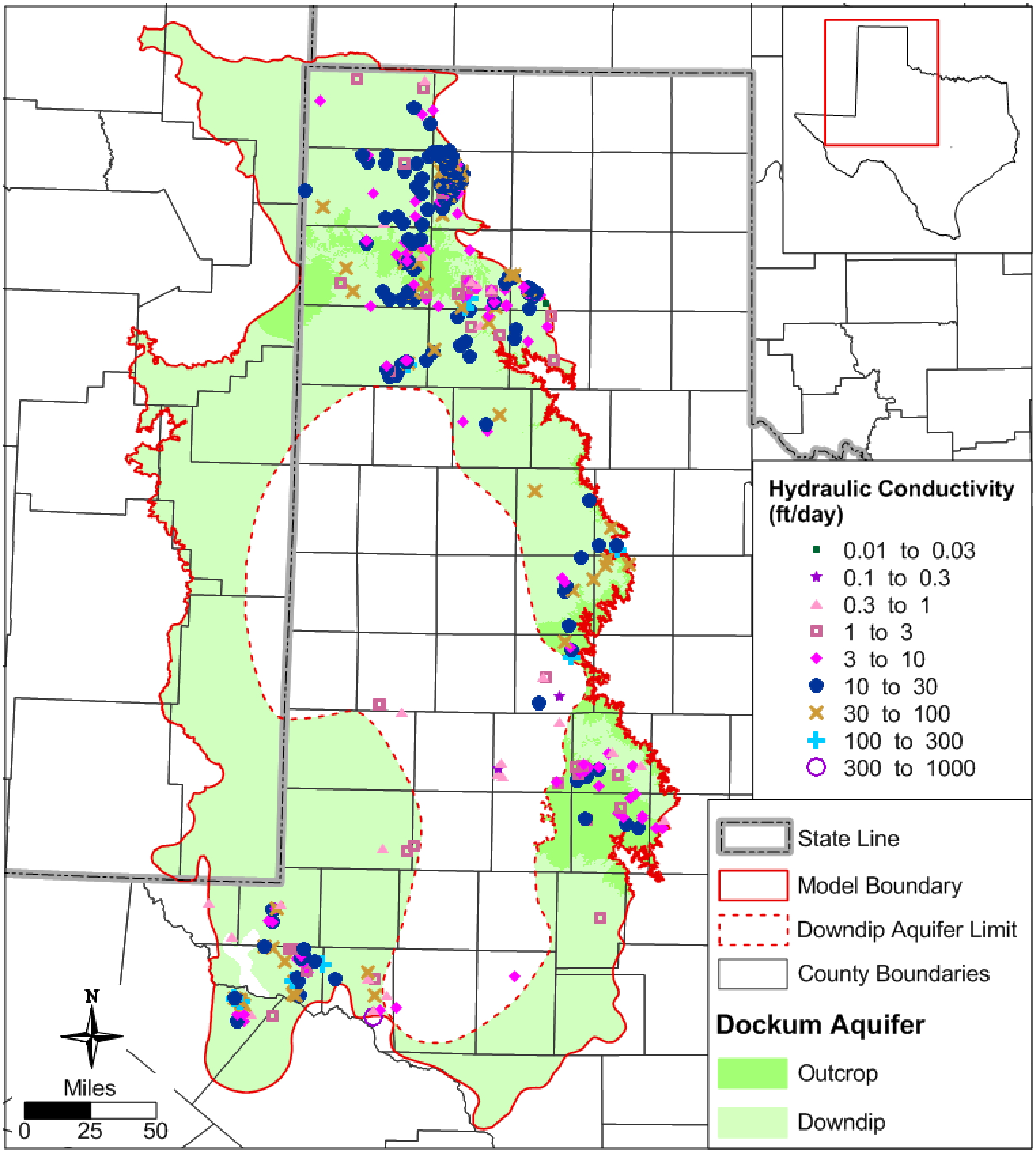


Figure 4.5.6. Hydraulic conductivity data for the Dockum Aquifer in Texas and New Mexico (from Ewing and others, 2008).

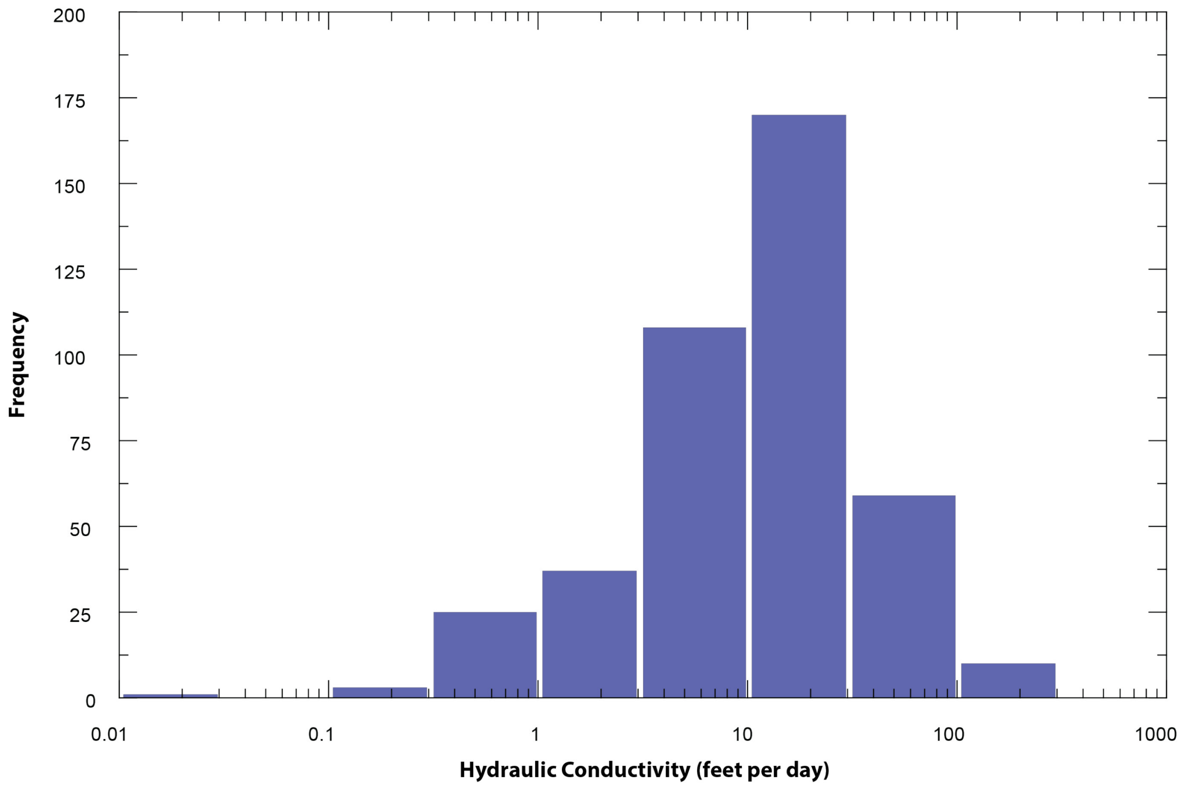


Figure 4.5.7. Histogram of hydraulic conductivity data in feet per day for the Dockum Aquifer (modified from Ewing and others, 2008).

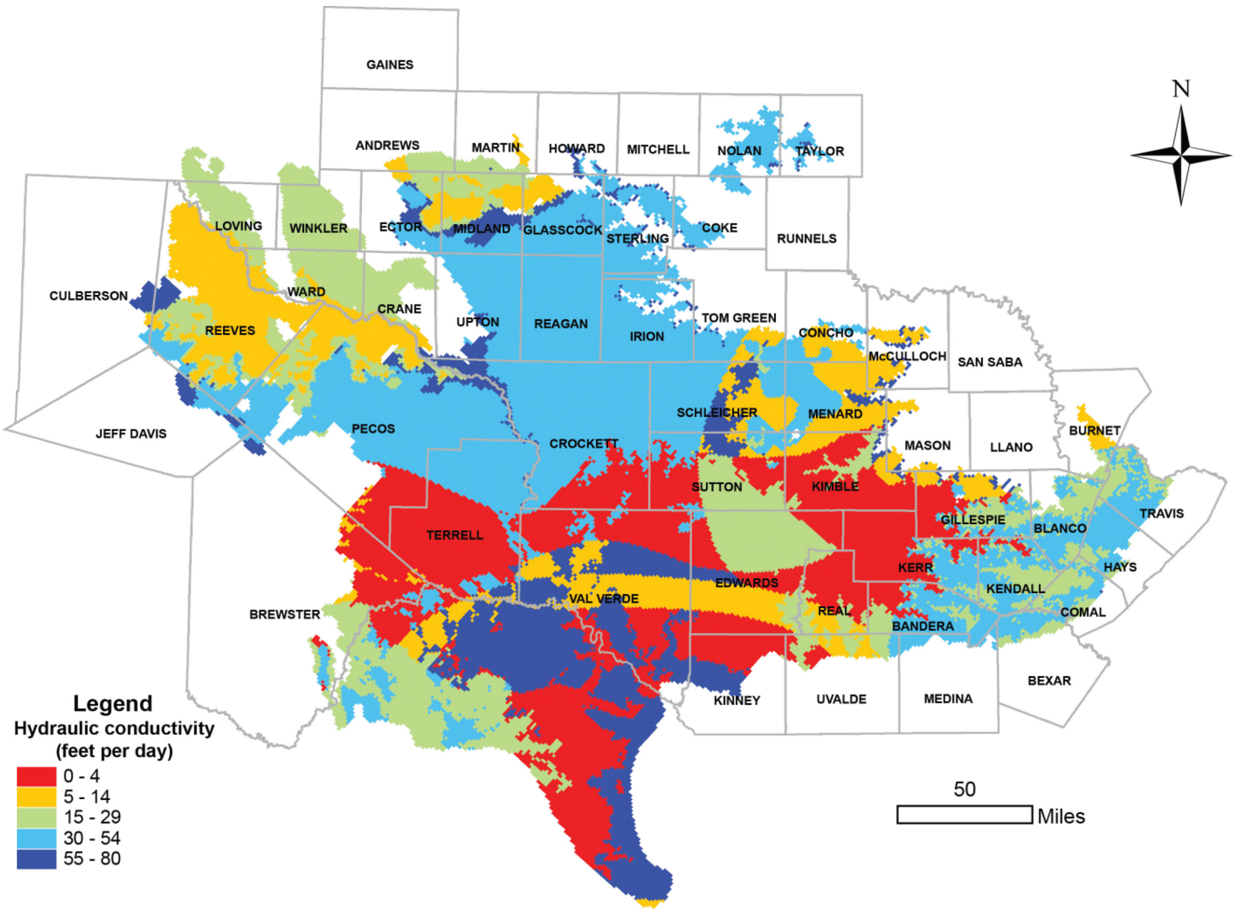


Figure 4.5.8. **Hydraulic conductivity data for the Edwards-Trinity and Pecos Valley aquifers in Texas and New Mexico (From Hutchison and others, 2011).**

4.6 Discharge

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

4.6.1 Natural Aquifer Discharge

In a typical topographically-driven flow system, percolation of precipitation results in recharge at the water table, which flows from topographic highs and discharges at topographic lows through streams and springs and groundwater evapotranspiration. Water that moves down-dip eventually discharges upward through cross-formational flow. In the Capitan Reef Complex Aquifer, the most likely forms of discharge are spring discharge and cross-formational flow in the subsurface.

Discharge through spring discharge to Frijoles Spring and baseflow from the Capitan Reef Complex Aquifer to the Pecos River in New Mexico is discussed in Sections 4.4.1 through 4.4.3. This discharge limits eastward groundwater flow into the eastern arm of the Capitan Reef Complex Aquifer (Figure 4.2.2).

Discharge via cross-formational flow is mentioned in Section 4.2. Cross-formational flow is likely the largest form of discharge from the Capitan Reef Complex Aquifer considering the limited access to perennial streams and wetlands—sites for baseflow and evapotranspiration discharge from the aquifer—where the aquifer crops out. Evidence supporting cross-formational flow as the main form of discharge are: (1) few perennial streams crossing aquifer outcrops; (2) northward and southward flow paths converging in Winkler and Ward counties; (3) the occurrence of artesian wells and springs like the Diamond Y Spring that discharge water derived from underlying aquifers (Veni, 1991; Boghici and Van Broekhoven, 2001); and (4) Capitan Reef Complex Aquifer water levels that are consistently higher than water levels in overlying aquifers (Figures 4.2.1, 4.2.3, 4.2.6, 4.2.12). This cross-formational discharge is likely a combination of discharge to the back-reef Artesia Group and vertical discharge to overlying aquifers. The collapse structure that resulted from the dissolution of the overlying Salado Formation and resultant subsidence of the overlying stratigraphic units acts as a potential pathway for upward groundwater flow through—and mixing with—Rustler, Dockum, and Pecos Valley aquifer groundwater. This collapse structure is responsible for the formation of the Monument Draw Trough in the Pecos Valley Aquifer (Jones, 2001; 2004) and also approximately coincides with the eastern arm of the Capitan Reef Complex Aquifer (Figure 4.6.1).

4.6.2 Aquifer Discharge through Pumping

Estimates of groundwater pumping from the Capitan Reef Complex Aquifer throughout Texas for the years 1980 through 2008 were obtained from the Texas Water Development Board historical water use estimates. The six water-use categories defined in the Texas Water Development Board database are municipal, manufacturing, steam electric generation, irrigation, mining, and livestock. Rural domestic pumping is likely to be very small relative to the other pumping categories because of low population, poor water quality, aquifer depth, and the fact that the Capitan Reef Complex Aquifer is overlain by other aquifers that have better water quality and are consequently more attractive sources of groundwater. Water use estimates for the Capitan Reef Complex Aquifer indicate pumping from Brewster, Culberson, Hudspeth, Pecos, and Ward counties, and no pumping in Winkler County.

In the groundwater availability model for the Capitan Reef Complex Aquifer, pumping data for overlying aquifers—Rustler, Dockum, Edwards-Trinity (Plateau), and Pecos Valley aquifers—will be derived from the respective groundwater availability models (Ewing and others, 2008; 2012; Hutchison and others, 2011). It will be assumed that due to low groundwater yield and poor water quality issues that pumping from the non-aquifer stratigraphic units in the study area—the Artesia and Delaware Mountain groups, and the Castile and Salado formations—is insignificant.

The Texas Water Development Board water use survey indicates that mining pumpage is primarily attributable to oil and gas operations. Figure 4.6.2A shows the spatial distribution of oil and gas wells drilled since 1928 that penetrate the Capitan Reef Complex Aquifer. These wells—

mostly located on the eastern arm of the Capitan Reef Complex—were used to extract or explore for oil and gas in underlying stratigraphic units including the Wolfcamp, Spraberry, Canyon, Clear Fork, San Andres, and Grayburg formations (Nicot and others, 2012). In some cases, the Capitan Reef Complex Aquifer is used as a source of water for use in oil and gas well fields (Brackbill and Gaines, 1964). It is likely that petroleum-related pumping from the Capitan Reef Complex Aquifer will vary with oil and gas activity (Figure 4.6.2B). Figure 4.6.2B shows wide fluctuations in the number of oil and gas wells drilled per year. Over the period 2000 to 2010, the number of oil and gas wells penetrating the Capitan Reef Complex Aquifer per year varied from a high of 288 wells in 2006 to a low of 55 wells in 2002. However, there is a general trend towards increased drilling over time. Thus it is expected that petroleum-related pumping is gradually rising over time with the number of oil and gas wells in the area. Hiss (1975) estimated petroleum-related pumping from the Capitan Reef Complex Aquifer by decade and county. These estimates vary from average pumping of 10 acre-feet per year in Eddy County, New Mexico in the 1950s to about 15,000 acre-feet per year in Winkler County, Texas in the 1960s.

Nicot and others (2011; 2012) indicate that there are five categories of petroleum-related pumping—well completion in tight formations, enhanced oil recovery, waterflooding, drilling, and hydraulic fracturing. The term tight-formation completion refers to hydraulic fracturing of low permeability reservoir rock to increase oil and/or gas production. Enhanced oil recovery is a term for techniques that increase the amount of oil that can be extracted from an oil reservoir. Waterflooding is the injection of water into and oil or gas reservoirs in order to maintain pressure. The water used for drilling oil and gas wells that is reported in Nicot and others (2011) is an estimate based on informal discussions with practicing field engineers. Hydraulic fracturing refers to water used to fracture source rocks, such as shales, in order to extract gas. Hydraulic fracturing water use is subdivided into use and consumption. Water use refers to the amount of water used regardless of the water source, while water consumption excludes recycled and reused water. In the study area, there is no petroleum-related pumping in Brewster, Hudspeth, and Jeff Davis counties (Table 4.6.1). Overall, highest petroleum-related pumping occurs in Pecos County, although the highest rates of water consumption related to hydraulic fracturing occur in Ward County (Figure 4.6.3).

Irrigation pumping from the Capitan Reef Complex Aquifer is likely to be minimal considering issues of aquifer depth, groundwater quality, and the occurrence of alternative sources of irrigation water. Texas Water Development Board pumping data for the Capitan Reef Complex Aquifer indicate irrigation pumping up to 8,600 acre-feet per year—mostly in Culberson, Hudspeth, and Pecos counties (Figure 4.6.4; Table 4.6.2).

Livestock pumping was distributed using land cover data obtained from the National Land Cover Dataset (Vogelman and others, 1998a; 1998b). We assume that livestock pumping is associated with grassland and scrubland land cover (Figure 4.6.5A). These types of land cover account for almost all of the land cover over the Capitan Reef Complex Aquifer; however, livestock pumping is unlikely to occur much beyond the Capitan Reef Complex outcrops. Figure 4.6.5B shows the area most likely to be used for livestock pumping—where the depth to the Capitan Reef Complex Aquifer is less than 600 feet—the average depth of livestock wells pumping from the aquifer. Estimates of livestock pumping from the Capitan Reef Complex Aquifer are low, less than 100 acre-feet per year (Table 4.6.3).

Manufacturing and municipal pumping are spatially distributed based on known well locations (Figure 4.6.6). Texas Water Development Board pumping data indicates very little municipal pumping and almost no manufacturing and steam electric pumping from the Capitan Reef Complex Aquifer (Tables 4.6.4 and 4.6.5). Estimated pumping from the Texas Water Development Board water use survey indicates total municipal pumping from the Capitan Reef Complex Aquifer in the range of 1 to 20 acre-feet per year and no manufacturing pumping since 1982.

Rural domestic pumping—which consists primarily of unreported domestic water use—is assumed to: (1) be related to the population density in non-urban areas (Figure 4.6.7A), and (2) occur only in and adjacent to the Capitan Reef Complex Aquifer outcrops—in an area defined by an aquifer depth less than 900 feet which is the average depth of Capitan Reef Complex Aquifer domestic wells (Figure 4.6.7B). Capitan Reef Complex Aquifer rural domestic pumping is expected to be very small because most parts of the aquifer with this category of pumping have population densities of 0 to 1 persons per square mile (Figure 4.6.7). Rural domestic pumping estimates are based partially on per capita water usage rate estimates (Table 4.6.6). Estimates of per capita water use vary from 110 gallons per day to as high as 500 gallons per day. The highest estimates—based on county-wide municipal pumping and urban populations—are probably high because they also incorporate some commercial pumping that use “city water.”

Table 4.6.1. County-wide estimates of different categories of petroleum-related pumping in the Texas portion of the study area. The data was taken from Nicot and others (2011; 2012).

County	Tight Formation Completion (acre-feet)	Enhanced Oil Recovery (acre-feet)	Waterfloods (acre-feet)		Drilling (acre-feet)	Hydraulic Fracturing Use (acre-feet)	Hydraulic Fracturing Consumption (acre-feet)
	2008	1995	2008	2010	2008	2011	2011
Brewster	0	0	0	0	0	0	0
Culberson	12	0	115	160	0	166	33
Hudspeth	0	0	0	0	0	0	0
Jeff Davis	0	0	0	0	0	0	0
Pecos	183	162	267	315	206	110	22
Ward	67	9	13	15	84	568	114
Winkler	14	47	87	105	57	62	12

Table 4.6.2. Estimates of Capitan Reef Complex Aquifer irrigation pumping in the Texas portion of the study area. The data—expressed in acre-feet—was taken from Texas Water Development Board (2012c).

Year	County					
	Brewster	Culberson	Hudspeth	Pecos	Ward	Winkler
1980	0	60	2,800	0	0	0
1981	0	50	2,125	0	0	0
1982	0	41	1,449	0	0	0
1983	0	31	774	0	0	0
1984	0	21	98	0	0	0
1985	0	25	80	0	0	0
1986	0	19	37	0	0	0
1987	0	20	40	0	0	0
1988	0	19	46	0	0	0
1989	0	14	81	0	0	0
1990	0	9	42	0	0	0
1991	0	9	43	0	0	0
1992	0	11	33	0	0	0
1993	0	6	97	0	0	0
1994	0	0	2,797	0	0	0
1995	0	0	2,224	0	0	0
1996	0	0	2,084	0	0	0
1997	0	0	2,094	0	0	0
1998	0	0	2,436	0	0	0
1999	0	0	3,701	0	0	0
2000	0	0	3,532	0	0	0
2001	0	0	3,121	0	0	0
2002	0	0	2,769	0	0	0
2003	0	0	2,463	0	0	0
2004	0	3,151	2,828	918	0	0
2005	0	3,594	2,363	888	0	0
2006	0	3,366	1,522	1,337	0	0
2007	0	2,749	1,766	1,179	0	0
2008	0	5,651	1,713	1,229	0	0

Table 4.6.3. Estimates of Capitan Reef Complex Aquifer livestock pumping in the Texas portion of the study area. The data—expressed in acre-feet—was taken from Texas Water **Development Board (2012c).**

Year	County					
	Brewster	Culberson	Hudspeth	Pecos	Ward	Winkler
1980	0	41	11	0	0	0
1981	0	38	11	0	0	0
1982	0	36	10	0	0	0
1983	0	33	10	0	0	0
1984	0	30	9	0	0	0
1985	0	33	5	0	0	0
1986	0	28	3	0	0	0
1987	0	44	5	0	0	0
1988	0	47	5	0	0	0
1989	0	47	5	0	0	0
1990	0	46	5	0	0	0
1991	0	47	5	0	0	0
1992	0	31	6	0	0	0
1993	0	29	6	0	0	0
1994	0	26	8	0	0	0
1995	0	21	6	0	0	0
1996	0	23	5	0	0	0
1997	0	25	5	0	0	0
1998	0	34	9	0	0	0
1999	0	37	9	0	0	0
2000	0	33	8	0	0	0
2001	0	30	8	0	0	0
2002	0	47	8	0	0	0
2003	0	25	6	0	0	0
2004	21	50	6	14	0	0
2005	27	41	5	15	0	0
2006	25	47	6	17	0	0
2007	27	53	6	13	0	0
2008	30	55	6	15	0	0

Table 4.6.4. Estimates of Capitan Reef Complex Aquifer manufacturing pumping in the Texas portion of the study area. The data—expressed in acre-feet—was taken from Texas Water Development Board (2012c).

Year	County					
	Brewster	Culberson	Hudspeth	Pecos	Ward	Winkler
1980	0	0	1.00	0	0	0
1981	0	0	0.75	0	0	0
1982	0	0	0.50	0	0	0
1983	0	0	0.25	0	0	0
1984	0	0	0	0	0	0
1985	0	0	0	0	0	0
1986	0	0	0	0	0	0
1987	0	0	0	0	0	0
1988	0	0	0	0	0	0
1989	0	0	0	0	0	0
1990	0	0	0	0	0	0
1991	0	0	0	0	0	0
1992	0	0	0	0	0	0
1993	0	0	0	0	0	0
1994	0	0	0	0	0	0
1995	0	0	0	0	0	0
1996	0	0	0	0	0	0
1997	0	0	0	0	0	0
1998	0	0	0	0	0	0
1999	0	0	0	0	0	0
2000	0	0	0	0	0	0
2001	0	0	0	0	0	0
2002	0	0	0	0	0	0
2003	0	0	0	0	0	0
2004	0	0	0	0	0	0
2005	0	0	0	0	0	0
2006	0	0	0	0	0	0
2007	0	0	0	0	0	0
2008	0	0	0	0	0	0

Table 4.6.5. Estimates of Capitan Reef Complex Aquifer municipal pumping in the Texas portion of the study area. The data—expressed in acre-feet—was taken from Texas Water Development Board (2012c).

Year	County					
	Brewster	Culberson	Hudspeth	Pecos	Ward	Winkler
1980	0	10	2	0	0	0
1981	0	11	2	0	0	0
1982	0	11	2	0	0	0
1983	0	12	1	0	0	0
1984	0	12	1	0	0	0
1985	0	10	1	0	0	0
1986	0	8	1	0	0	0
1987	0	9	1	0	0	0
1988	0	9	1	0	0	0
1989	0	7	1	0	0	0
1990	0	5	1	0	0	0
1991	0	5	1	0	0	0
1992	0	5	1	0	0	0
1993	0	6	1	0	0	0
1994	0	0	1	0	0	0
1995	0	5	1	0	0	0
1996	0	5	1	0	0	0
1997	0	4	1	0	0	0
1998	0	5	1	0	0	0
1999	0	6	1	0	0	0
2000	0	4	1	0	0	0
2001	0	4	1	0	0	0
2002	0	4	1	0	0	0
2003	0	4	1	0	0	0
2004	3	12	4	0	0	0
2005	3	12	4	0	0	0
2006	3	13	4	0	0	0
2007	3	10	3	0	0	0
2008	3	11	3	0	0	0

Table 4.6.6. County-wide estimates of rural domestic pumping in the Capitan Reef Complex Aquifer study area. The data was obtained from the United States Department of Commerce (2013).

County	Rural Population (2000)	Rural Domestic Pumpage (2000) (acre-feet)
Brewster	2,085	257
Culberson	386	48
Eddy	10,091	1,243
Hudspeth	2,911	359
Jeff Davis	2,031	250
Lea	8,595	1,059
Loving	67	8
Otero	15,204	1,873
Pecos	6,587	811
Reeves	1,454	179
Ward	1,871	230
Winkler	215	26

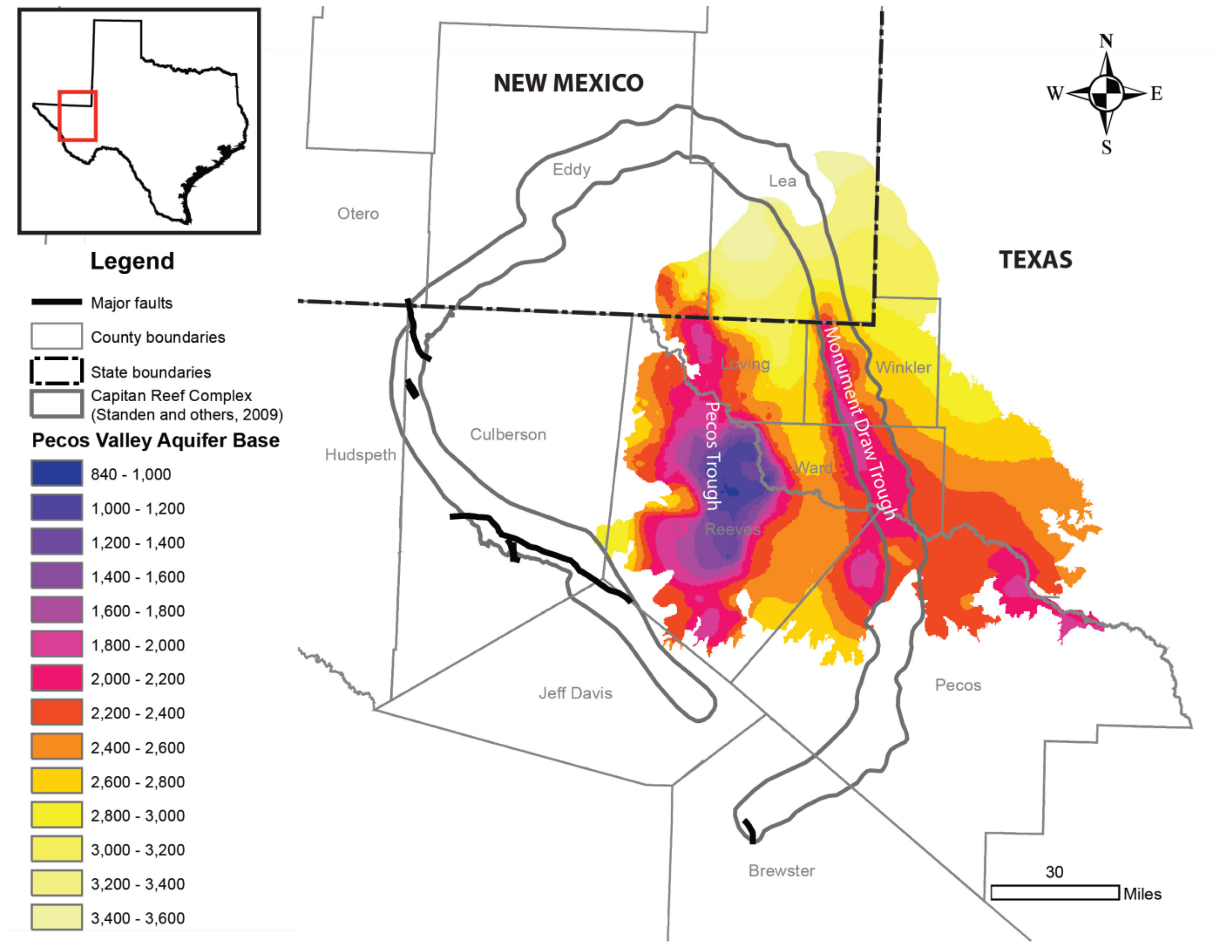
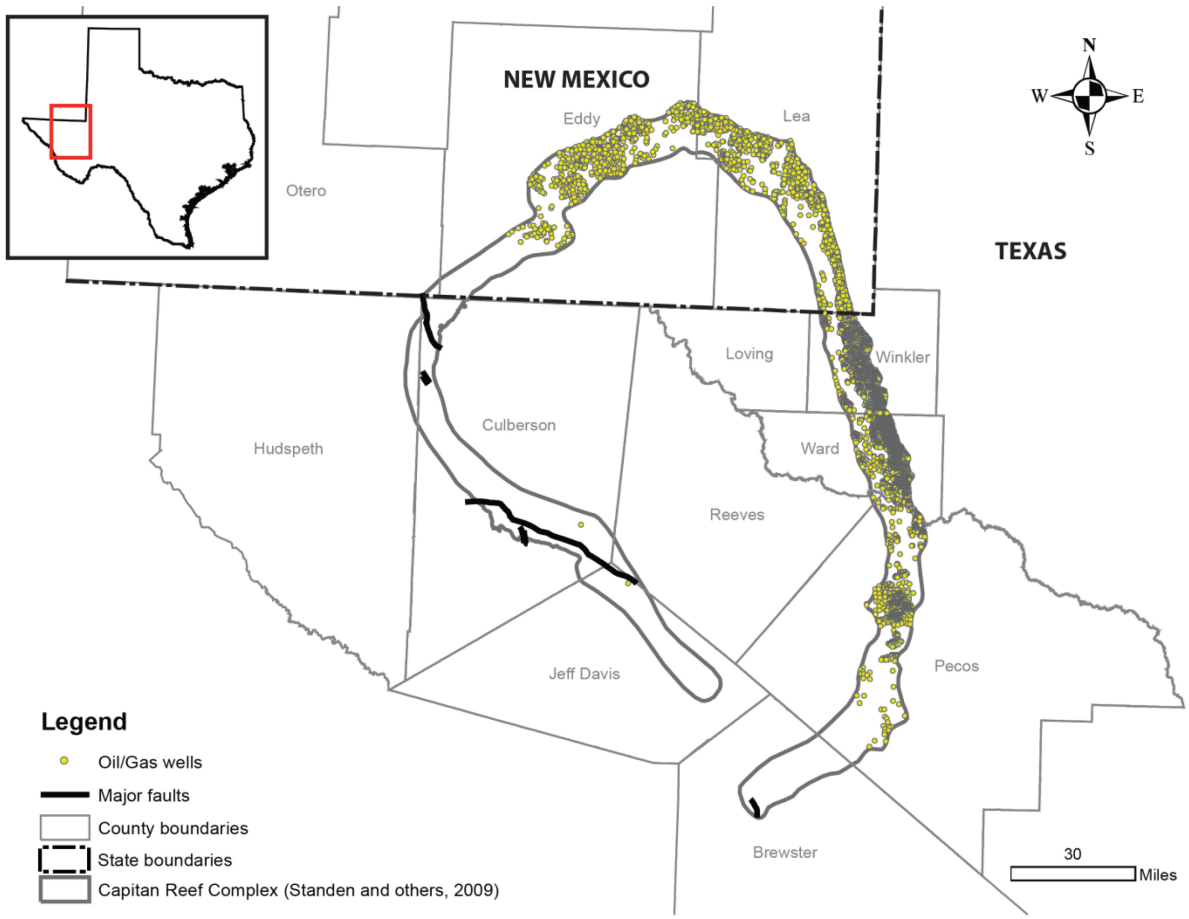
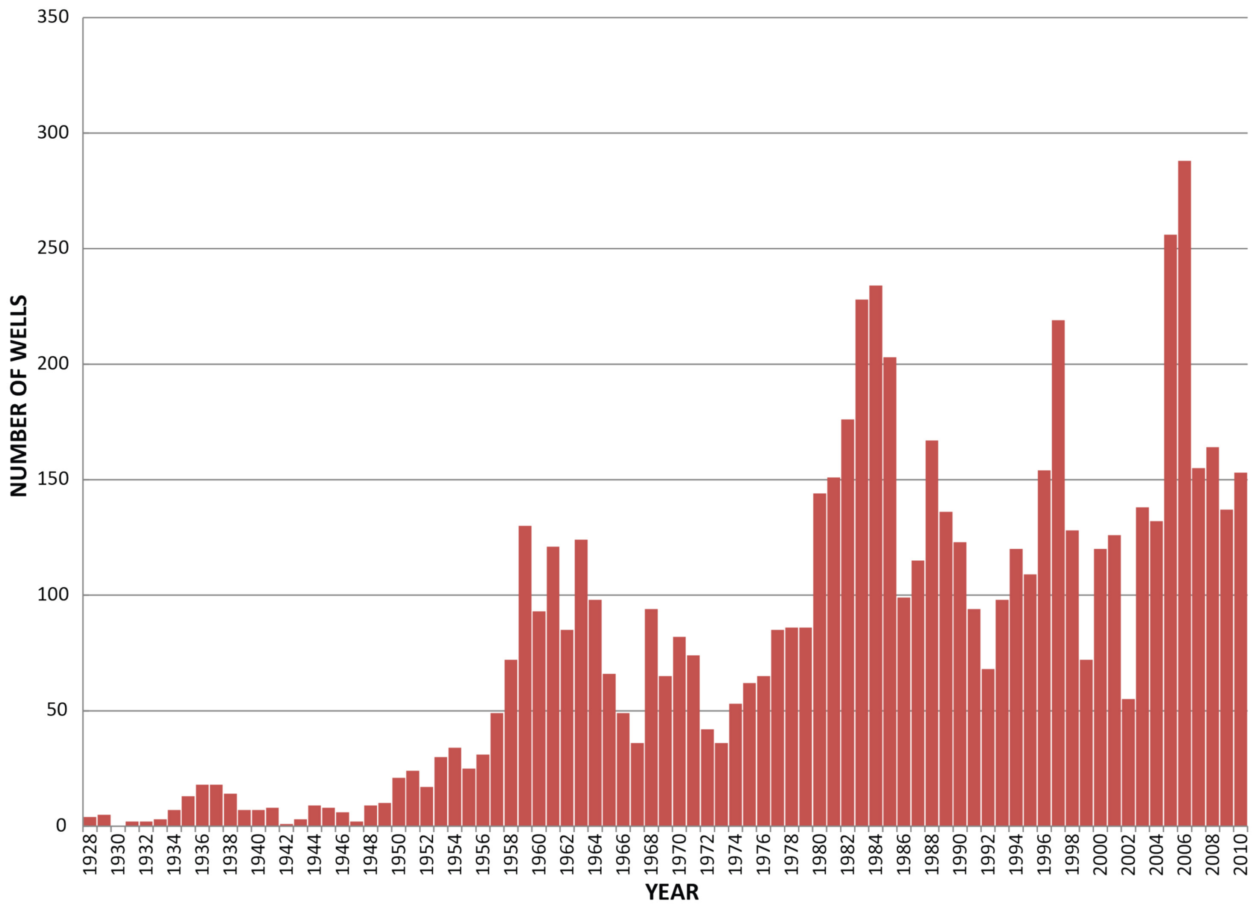


Figure 4.6.1. **The eastern arm of the Capitan Reef Complex Aquifer coincides with the Monument Draw Trough of the overlying Pecos Valley. The formation of the Monument Draw Trough is the result of dissolution of the Salado Formation—a stratigraphic unit overlying the Capitan Reef Complex—and consequent collapse of overlying stratigraphic units. This collapse structure potentially forms a pathway for upward discharge of groundwater. (Pecos Valley Aquifer base data from Hutchison and others, 2011).**



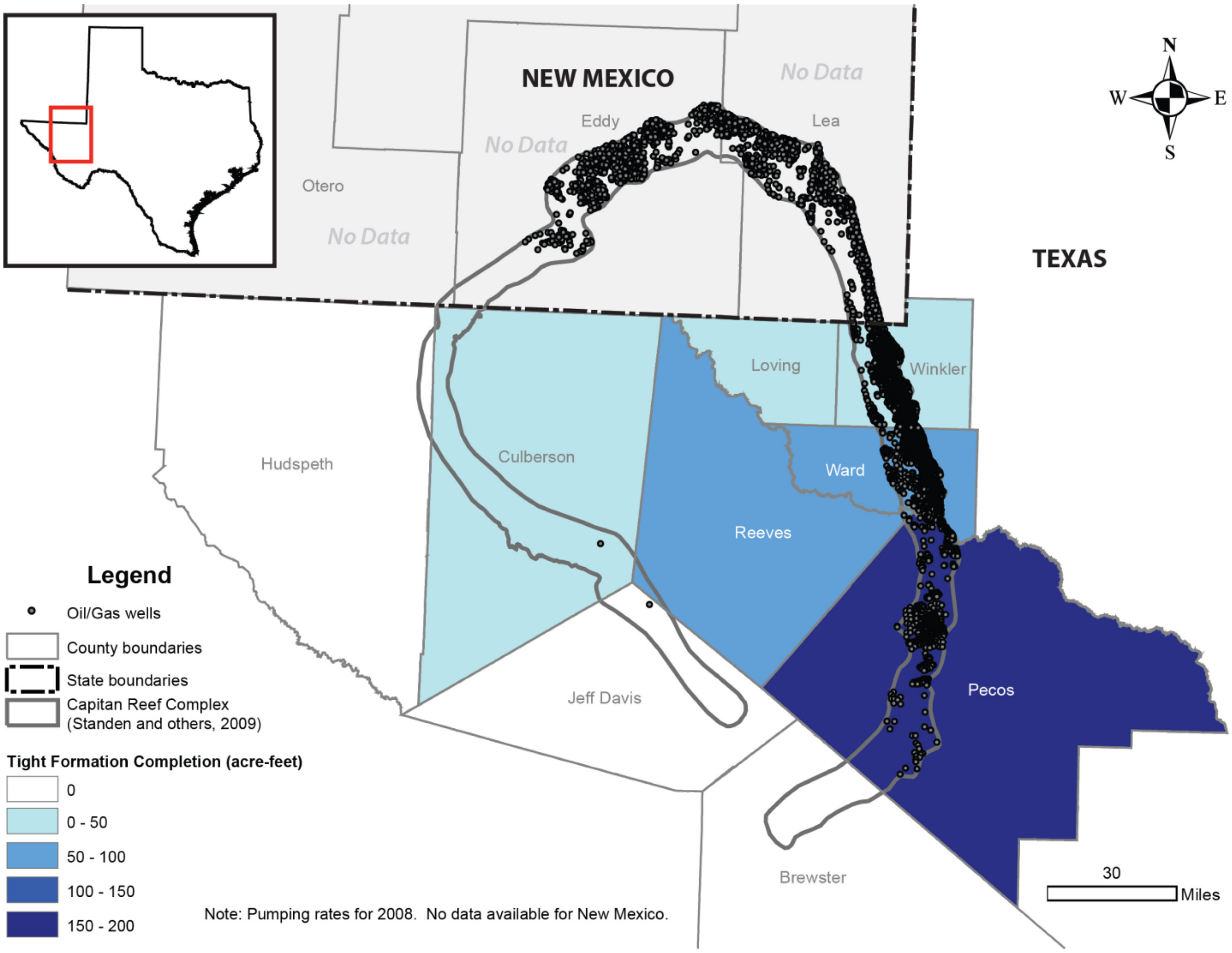
(A)

Figure 4.6.2. Spatial (A) and temporal (B) distribution of oil and gas wells penetrating the Capitan Reef Complex Aquifer (Railroad Commission of Texas, 2012; New Mexico Energy, Minerals and Natural Resources Department, 2012).



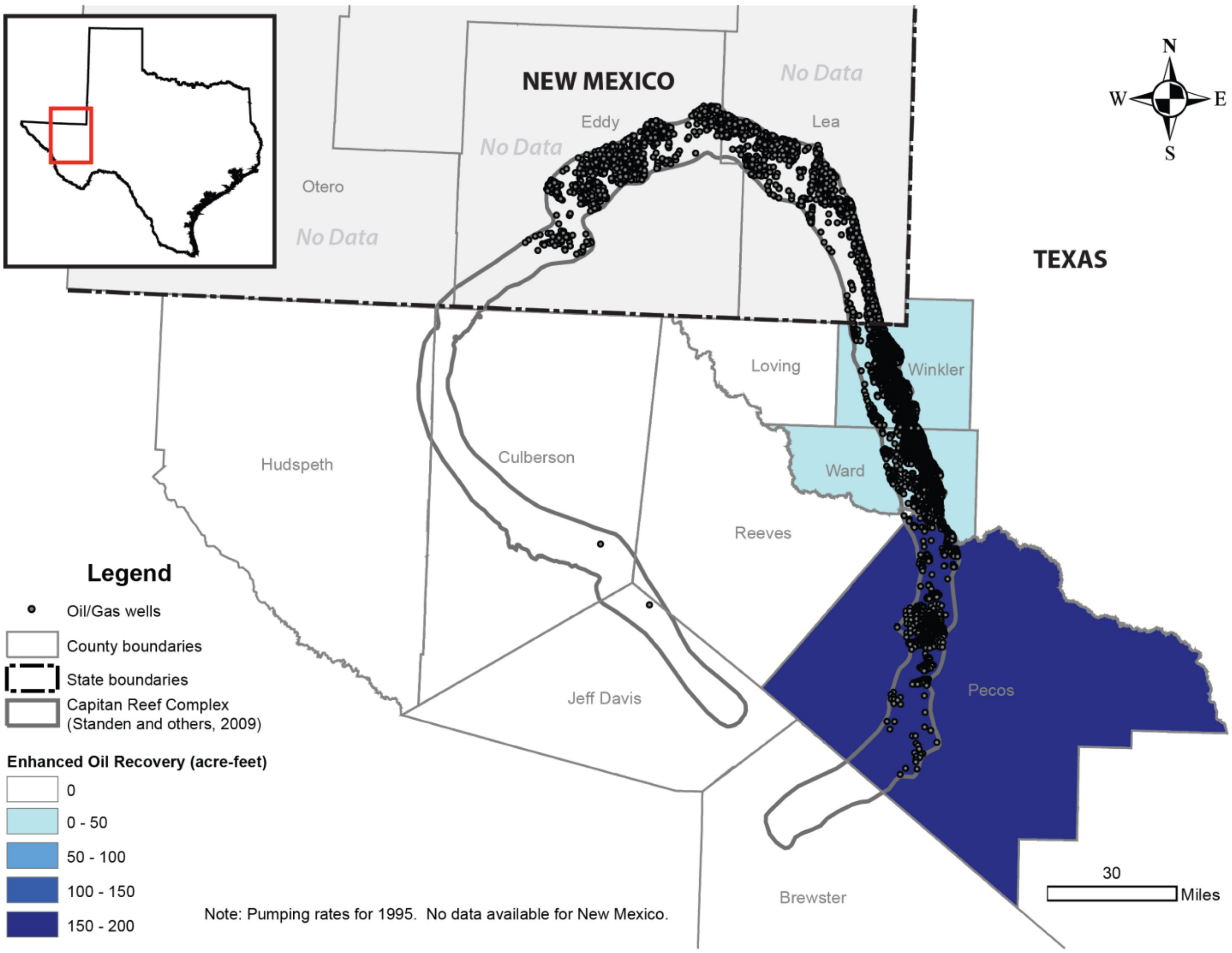
(B)

Figure 4.6.2. (continued)



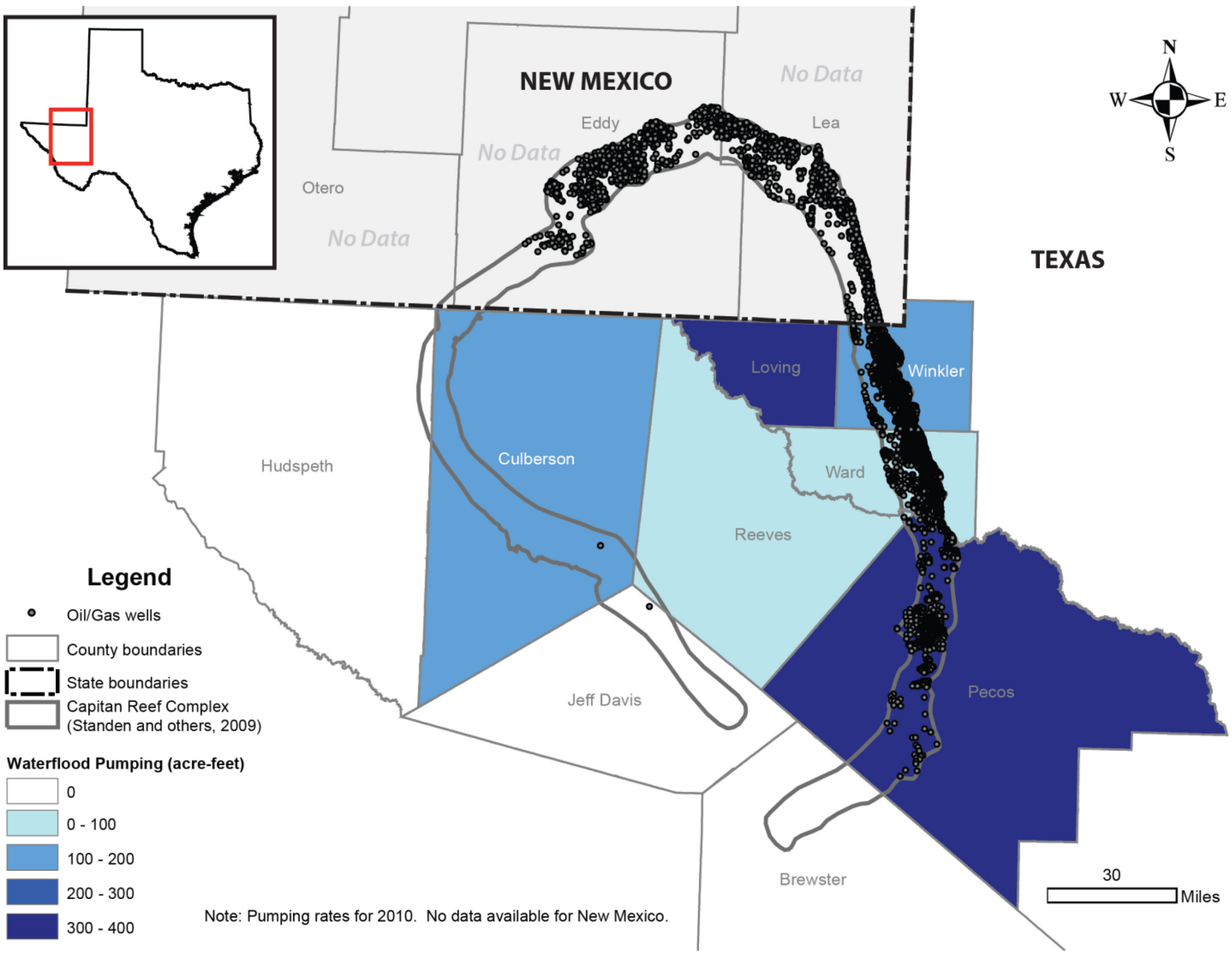
(A)

Figure 4.6.3. Petroleum-related pumping in counties adjacent to the Capitan Reef Complex Aquifer from Nicot and others (2011; 2012). This pumping falls under five categories: (A) tight-formation completion, (B) enhanced oil recovery, (C) waterflooding, (D) drilling, and (E) hydraulic fracturing consumption.



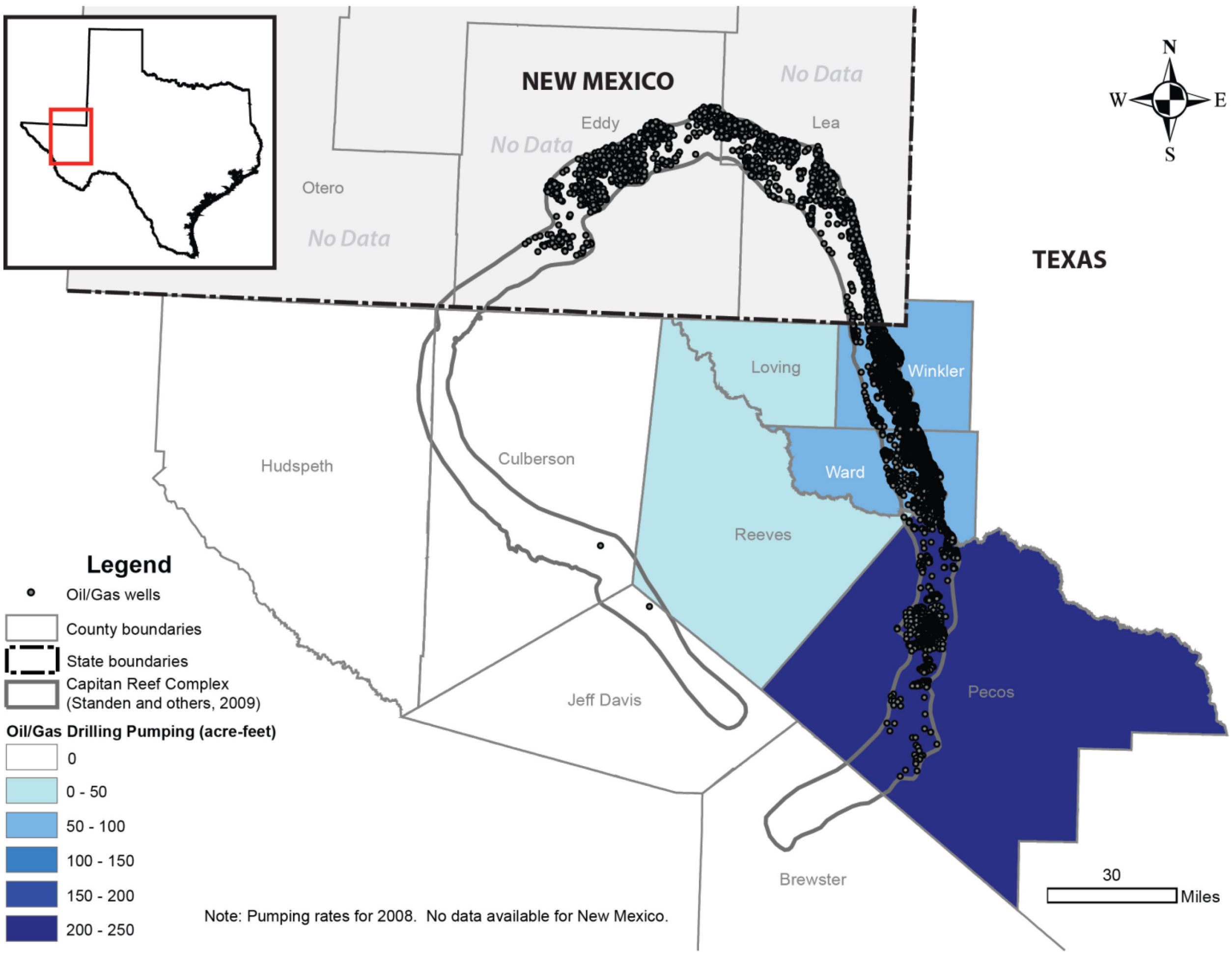
(B)

Figure 4.6.3. (continued).



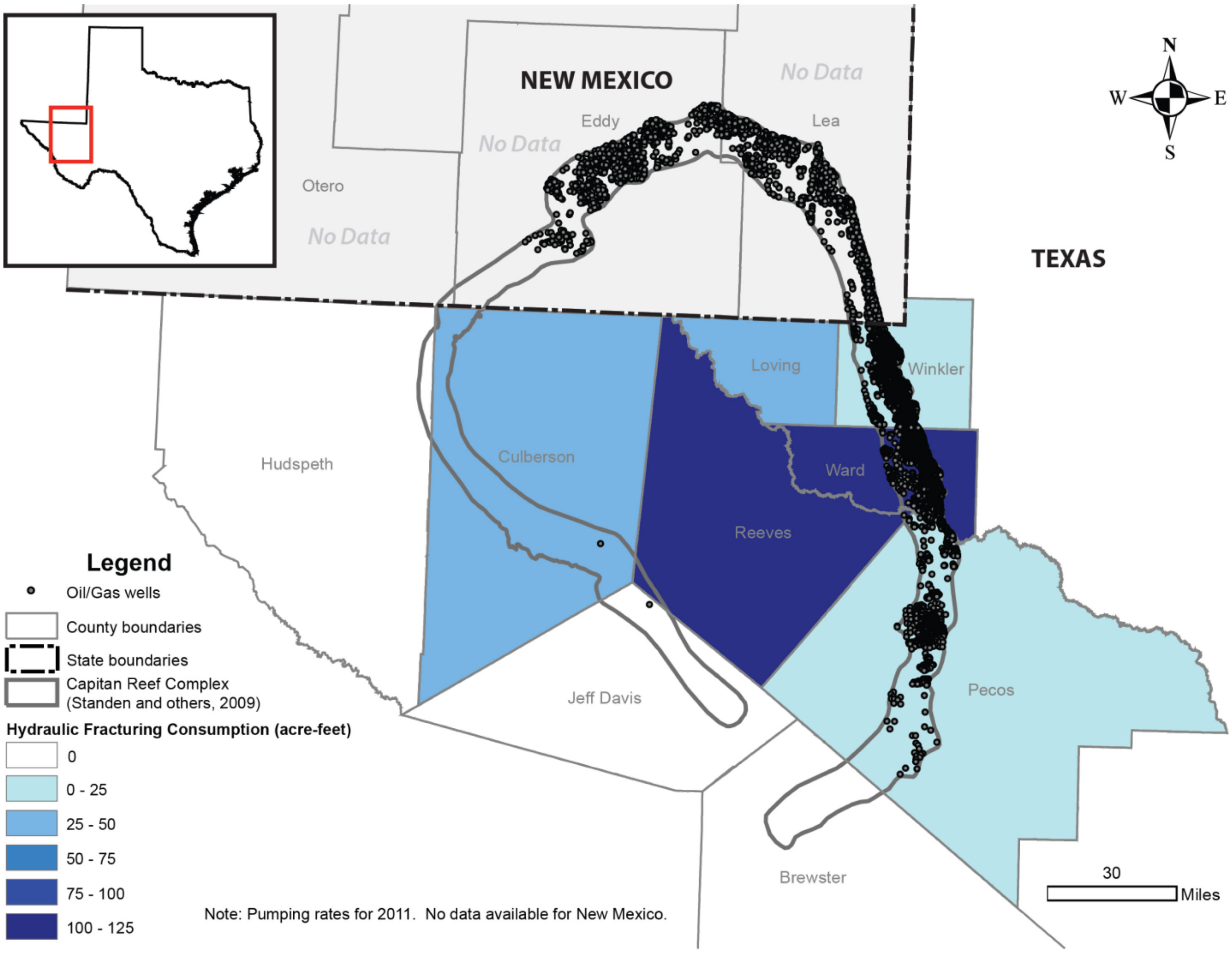
(C)

Figure 4.6.3. (continued).



(D)

Figure 4.6.3. (continued).



(E)

Figure 4.6.3. (continued).

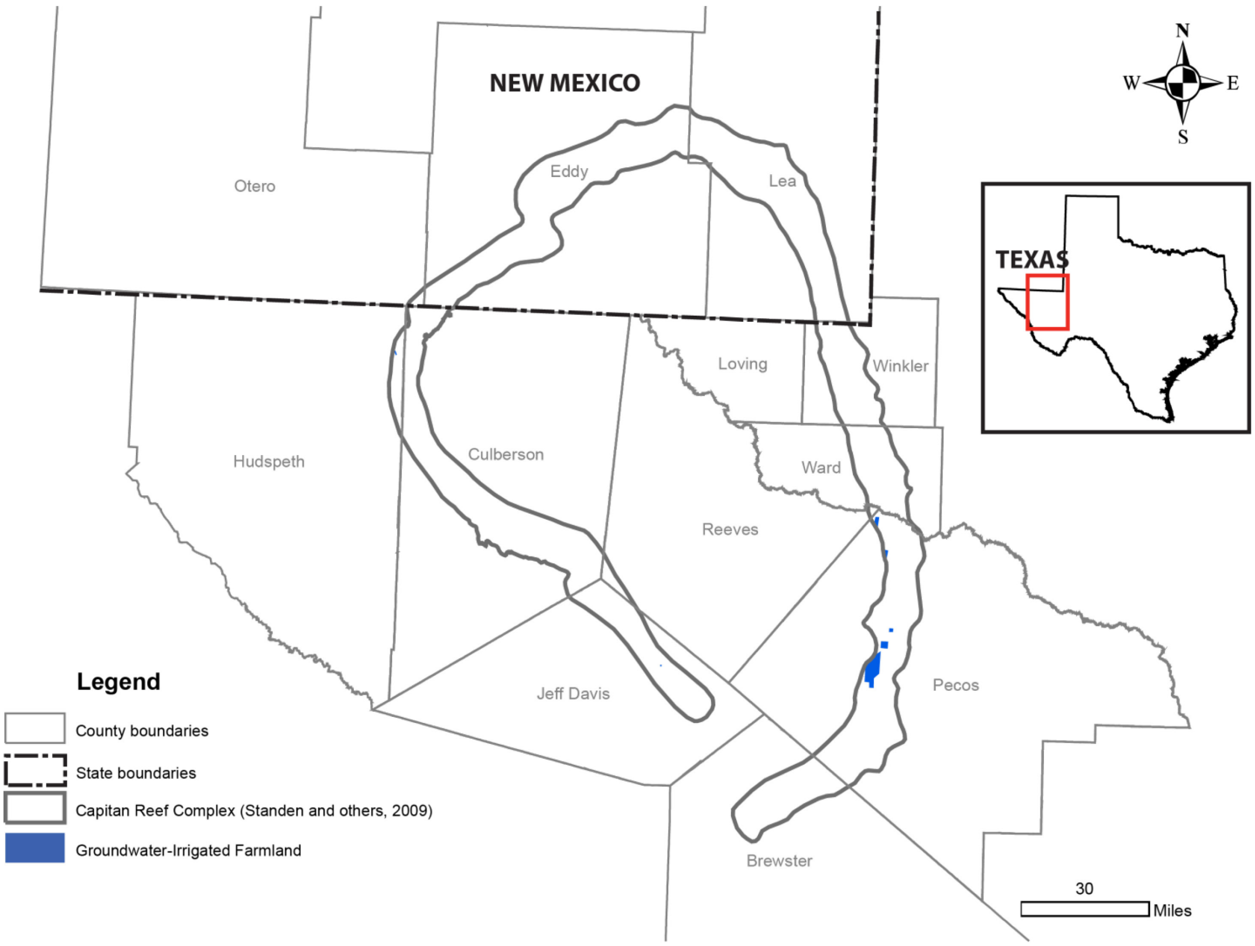
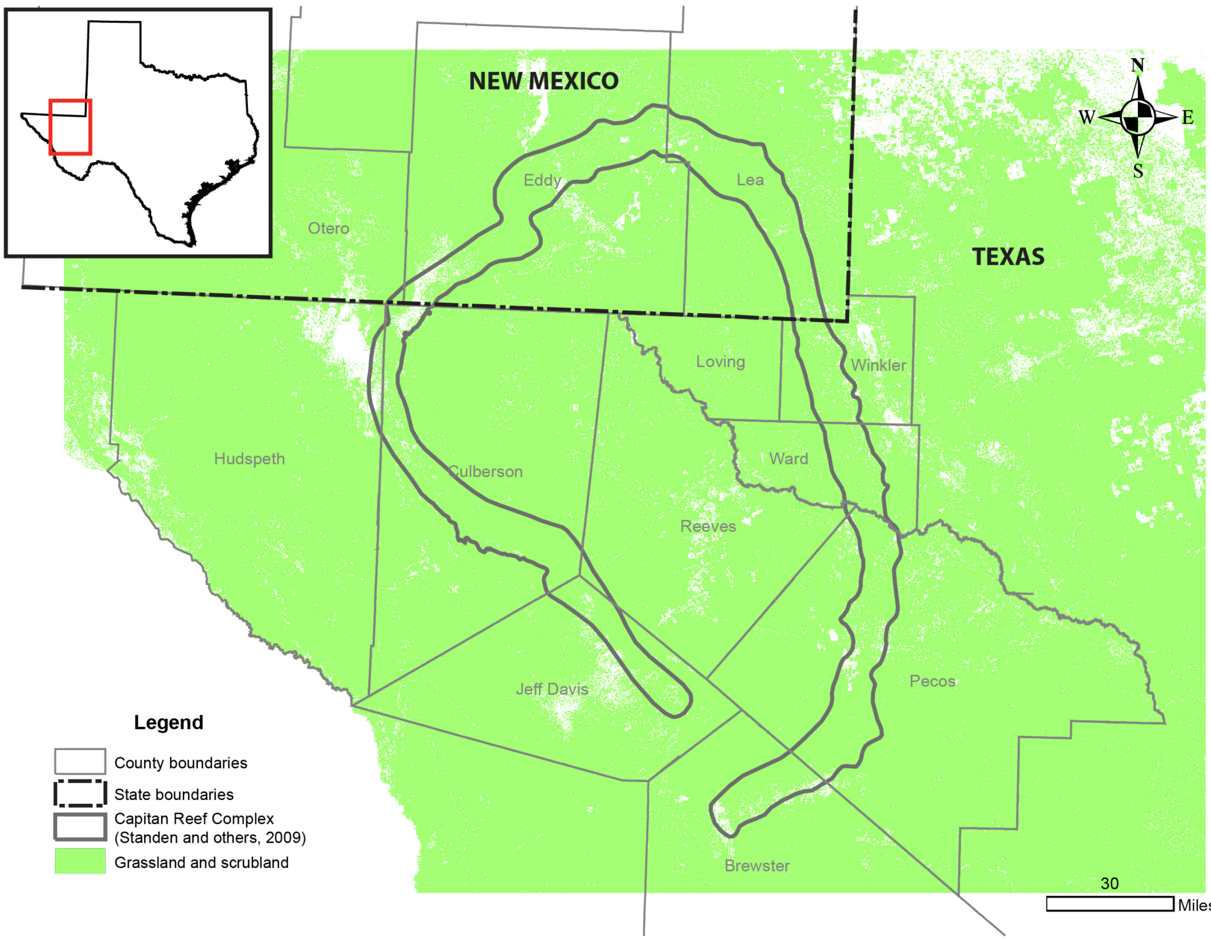
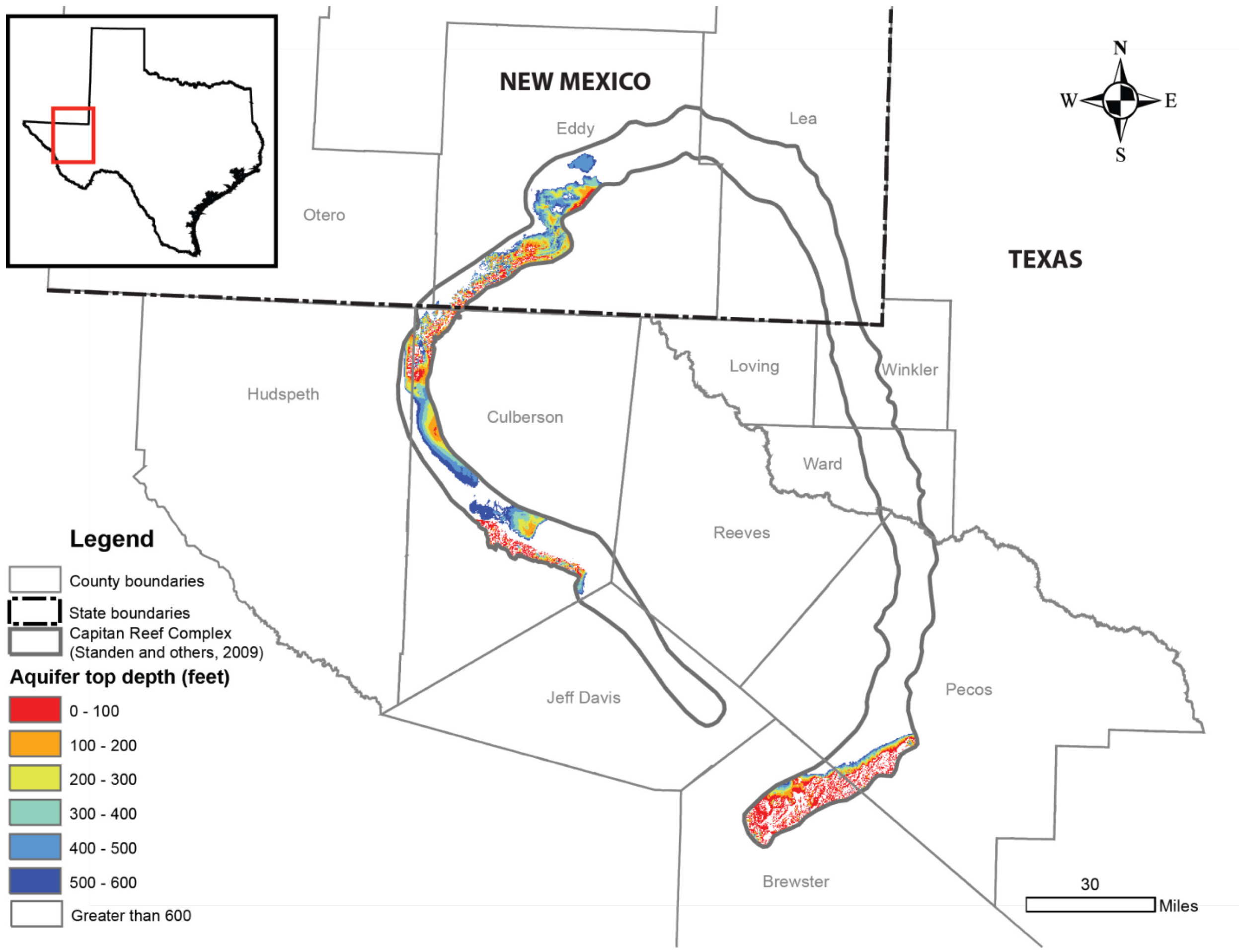


Figure 4.6.4. Spatial distribution of groundwater-irrigated farmland overlying the Capitan Reef Complex Aquifer.



(A)

Figure 4.6.5. **The spatial distribution of livestock pumping (A) based grassland and scrubland land cover from the National Land Cover Dataset throughout the study area (Vogelman and others, 1998a; 1998b) and (B) the portion of the Capitan Reef Complex Aquifer that would potentially be used for livestock pumping based on the combination of depth to the top of the aquifer and an average Capitan Reef Complex Aquifer livestock well depth of 600 feet. Livestock pumping will be distributed in model cells that include the shallow zones in (Figure 4.6.5B).**



(B)

Figure 4.6.5. (continued).

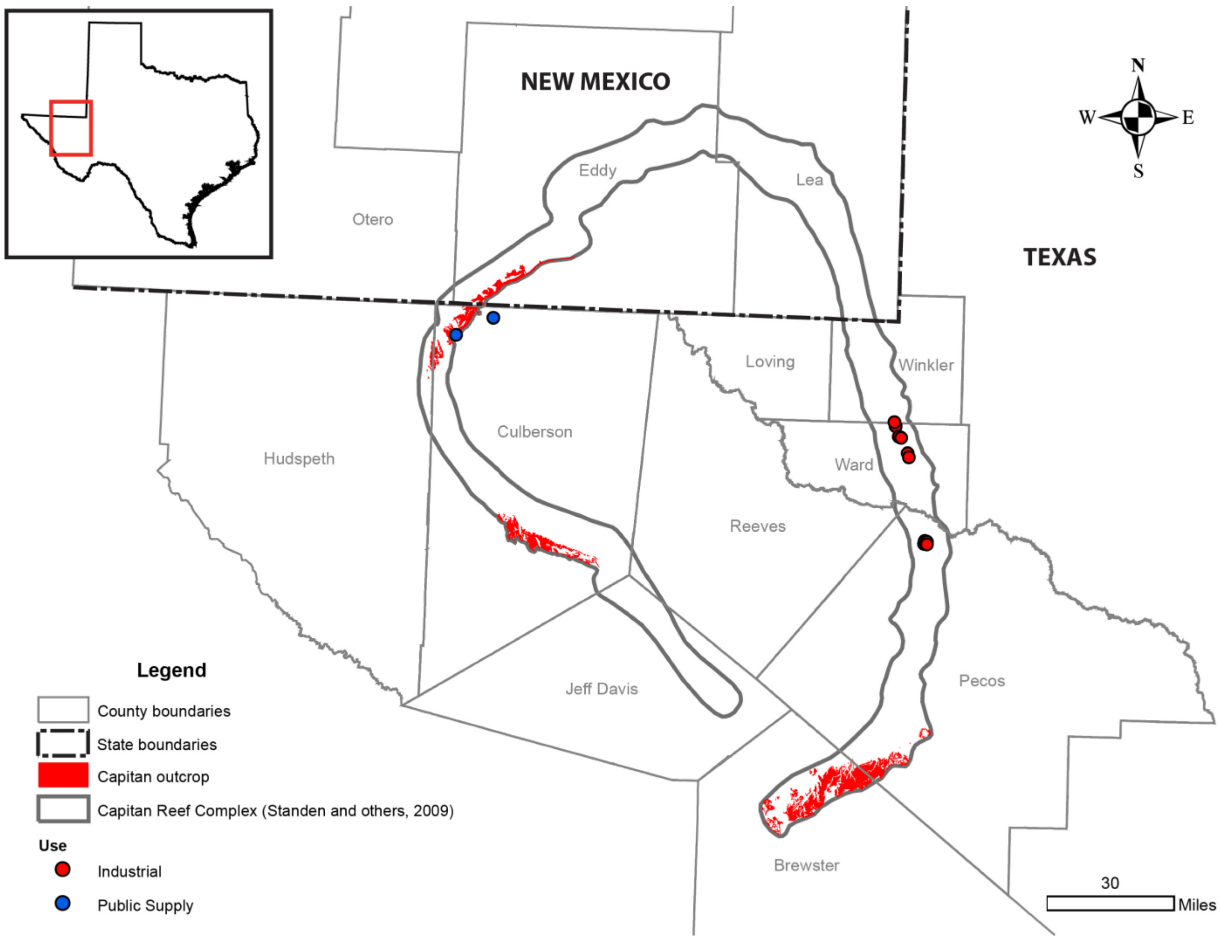
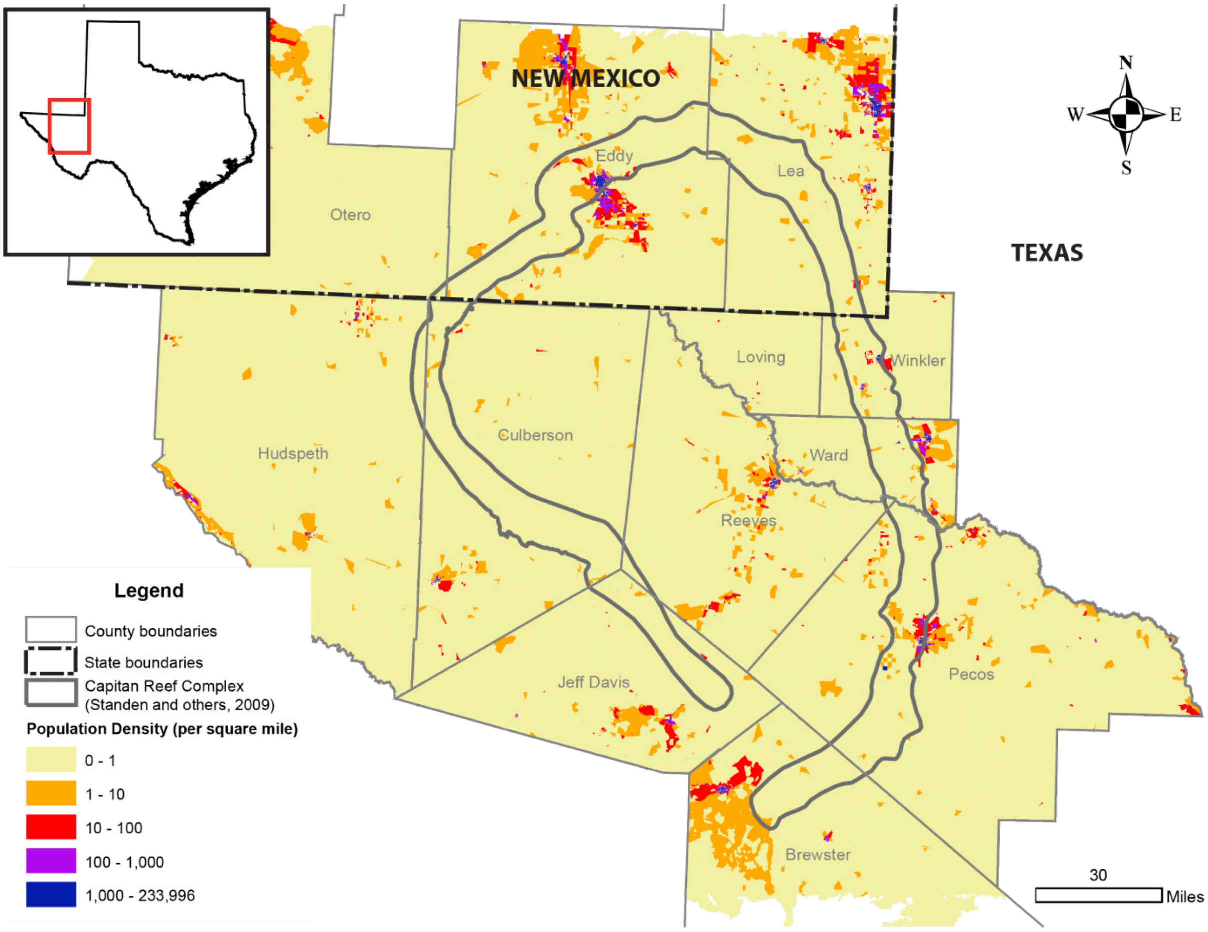
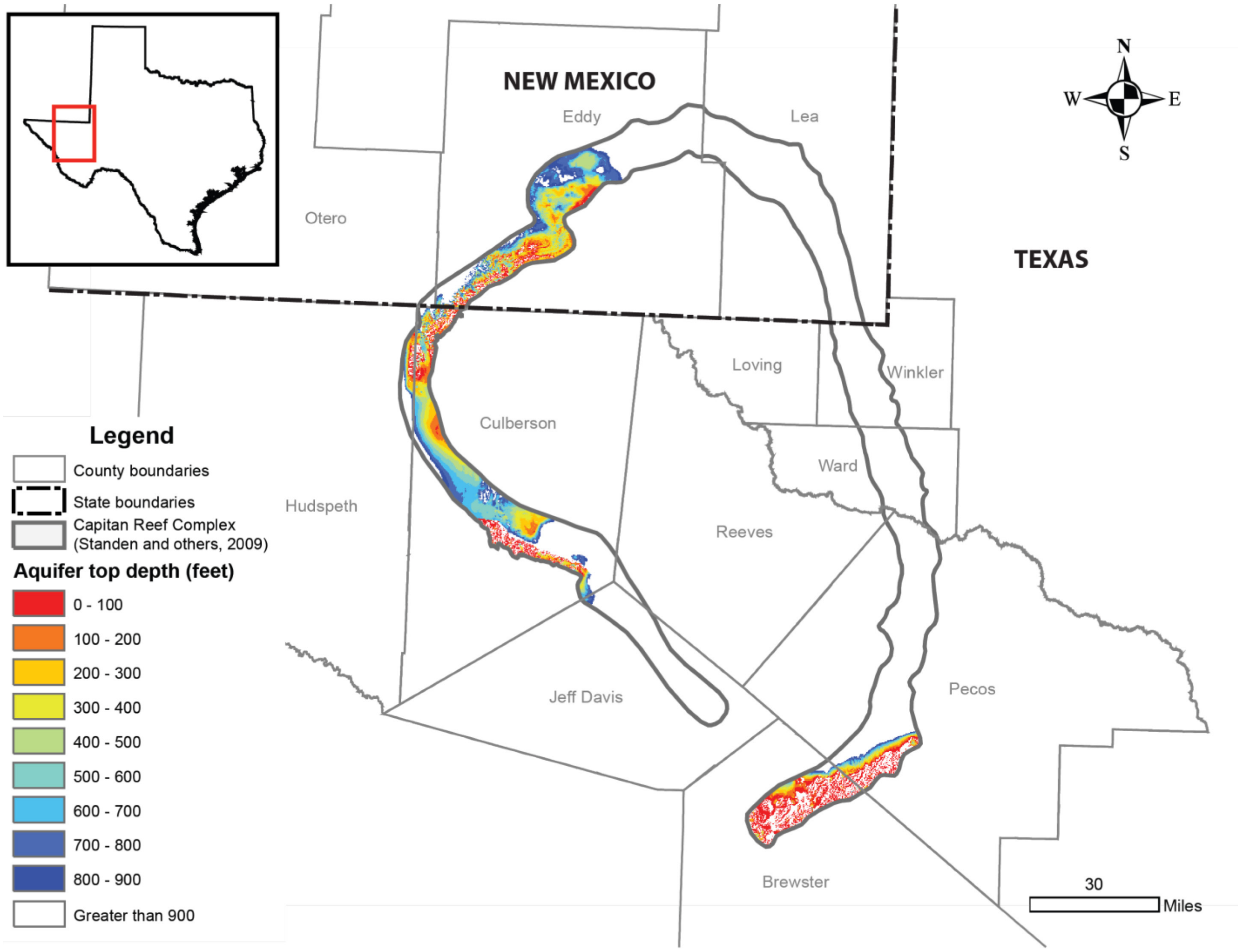


Figure 4.6.6. **The spatial distribution of manufacturing (industrial) and municipal (public supply) pumping. Manufacturing and public supply pumping will be distributed in model cells that coincide with the well locations.**



(A)

Figure 4.6.7. Population density in the Capitan Reef Complex Aquifer study area (A). Rural domestic pumping in the Capitan Reef Complex Aquifer is distributed based on the rural population over the aquifer and the combination of depth to the top of the aquifer and an average Capitan Reef Complex Aquifer domestic well depth of 900 feet (B). Rural domestic pumping will be distributed in model cells that include the shallow zones in (Figure 4.6.7B).



(B)

Figure 4.6.7. (continued).

4.7 Water Quality

The Capitan Reef Complex Aquifer generally has slightly to very saline groundwater (Brown, 1997).

4.7.1 Major Elements

In some parts of the Capitan Reef Complex Aquifer, concentrations of total dissolved solids, chloride, fluoride, and sulfate exceed applicable water quality standards. High concentrations of these constituents occur in both eastern and western parts of the aquifer in Texas, with especially high concentrations in Texas occurring in Pecos, Ward, and Winkler counties (Brown, 1997). Iron and manganese concentrations exceeding their respective water quality standards occur in the western extent of the aquifer.

Figure 4.7.1 shows total dissolved solids concentrations in Capitan Reef Complex Aquifer groundwater. The occurrence of fresh groundwater—total dissolved solids less than 1,000 milligrams per liter—is restricted to aquifer outcrops in Brewster, Culberson, Hudspeth, and Pecos counties and possibly also southern Eddy County. In areas where the Capitan Reef Complex Aquifer occurs at depth, groundwater varies from slightly saline to brine with a range of total dissolved solids of 1,000 milligrams per liter to greater than 100,000 milligrams per liter. The most saline groundwater occurs in Eddy and Lea counties in New Mexico. Groundwater salinity generally increases as groundwater flows away from the outcrops where recharge occurs, reaching a maximum in the northernmost parts of the aquifer.

Groundwater in the Capitan Reef Complex Aquifer displays a wide range of geochemical compositions (Figure 4.7.2). Groundwater compositions range from calcium-magnesium to sodium compositions and bicarbonate to sulfate to chloride compositions. These compositional ranges represent geochemical processes that take place as the groundwater flows through the aquifer interacting with aquifer rock and mixing with groundwater inflows from surrounding stratigraphic units (Figure 4.7.3). These compositions indicate groundwater interaction with calcite, dolomite, gypsum, and halite, minerals that occur within the Capitan Reef Complex and adjacent stratigraphic units. Groundwater interaction with dolomite and calcite would produce calcium-magnesium-bicarbonate compositions, gypsum would produce calcium-sulfate compositions, and halite would produce sodium-chloride compositions. In the Capitan Reef Complex Aquifer, groundwater with calcium-magnesium-bicarbonate compositions occur in or adjacent to Capitan Reef Complex outcrops in the Guadalupe and Glass mountains. Groundwater with calcium-magnesium-sulfate compositions occur in deeper parts of the aquifer in northern Pecos County while calcium-sulfate groundwater compositions occur adjacent to the Delaware Mountains in Culberson County. Groundwater with sodium-calcium-chloride and sodium-chloride-sulfate compositions occur in the New Mexico portion of the aquifer. Capitan Reef Complex Aquifer groundwater with sodium-chloride compositions are associated with some of the most saline groundwater in the aquifer—occurring in Eddy, Lea, and Ward counties. Figure 4.7.4 shows changes in groundwater composition that take place in the eastern arm of the

Capitan Reef Complex Aquifer extending from Brewster County, north through Pecos, Ward and Winkler counties in Texas and Lea County and eastern Eddy County in New Mexico. Northward, groundwater compositions change from calcium-magnesium-bicarbonate and calcium-magnesium-sulfate compositions in Brewster County and southern Pecos County to sodium-potassium-chloride compositions in Ward, Winkler, Lea, and Eddy counties. This pattern of geochemical composition changes suggests increasing inputs from halite dissolution as the groundwater flows away from the Glass and Guadalupe mountain recharge zones. These changes in groundwater compositions are also accompanied by increasing total dissolved solids concentrations.

4.7.2 Isotopes

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

Groundwater carbon-13 isotopic compositions ($\delta^{13}C$) represent the ratios of stable carbon isotopes—^{12}C and ^{13}C—in groundwater relative to the composition of a standard—PDB 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 reflect relative carbon inputs from interaction with soil and aquifer rock. Groundwater near recharge zones tend to have more negative carbon-13 compositions reflecting recent contact with the soil. As the groundwater flows through the aquifer—away from the recharge zone—water-rock interaction results in the groundwater taking on more positive carbon-13 isotopic compositions reflecting those of the aquifer rock. This trend is most apparent in the eastern part of the Capitan Reef Complex Aquifer where carbon-13 isotopic compositions range from -10.7 per mil in the aquifer outcrop in Brewster County to -3.6 per mil in northern Pecos County (Figure 4.7.5). Negative groundwater carbon-13 compositions also indicate recharge in the Guadalupe Mountains outcrop but relatively little recharge in the Apache Mountains outcrop of the Capitan Reef Complex. On the other hand, low groundwater carbon-13 compositions in the subsurface adjacent to the southern margin of the Delaware Mountains in Culberson County suggest that recent recharge has occurred there.

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 Capitan Reef Complex Aquifer, carbon-14 activity is generally highest—up to 100 percent modern carbon—where the aquifer crops out and recharge occurs, and lowest in the subcrop where there is no recharge and almost all of the groundwater carbon-14 has decayed (Figure 4.7.6). This figure shows the trend of decreasing groundwater carbon-14 activity northwards from the Glass Mountains outcrop of Brewster County and southern Pecos County. The spatial distribution of carbon-14 activity in the Capitan Reef

Complex Aquifer suggests that recharge zones occur in the aquifer outcrops in the Guadalupe and Glass mountains, and near the southern margin of the Delaware Mountains, while there is little recharge in the Apache Mountains outcrop—as suggested by groundwater carbon-13.

Groundwater tritium behaves like carbon-14. The difference is that tritium has a faster decay rate with a half-life of 12.3 years compared to 5,730 years for carbon-14 (Clark and Fritz, 1997). High tritium activity indicates the most recent recharge. In the Capitan Reef Complex Aquifer, the groundwater tritium activity ranges between 0 and 5 tritium units (Figure 4.7.7). However, except for a well in Culberson County with tritium activity in excess of 4 tritium units, most groundwater tritium activity is 0.1 tritium units or less. This indicates that there is very little recent recharge to the aquifer. This most recent recharge is limited to an area near the southern margin of the Delaware Mountains.

Groundwater stable hydrogen (δ^2H) and oxygen ($\delta^{18}O$) isotopic compositions represent the ratios of stable hydrogen isotopes—H and ^2H—and stable oxygen isotopes—^{16}O and ^{18}O—in groundwater relative to the composition of standard mean ocean water (Clark and Fritz, 1997). These isotope ratios are expressed as the relative difference in parts per thousand—per mil. Groundwater stable hydrogen (δ^2H) and oxygen ($\delta^{18}O$) isotopic compositions reflect the composition of the precipitation that recharged the aquifer. Consequently, the hydrogen and oxygen isotopic compositions of groundwater can be used as an indicator of the conditions under which recharge to the aquifer occurred. Figures 4.7.8 and 4.7.9 show groundwater hydrogen and oxygen isotopic compositions in the Capitan Reef Complex Aquifer. Groundwater stable hydrogen and oxygen isotopic compositions in the Capitan Reef Complex Aquifer lie in the ranges -71 to -43 per mil and -10 to -7 per mil, respectively. There are no apparent isotopic composition trends along groundwater flowpaths. The well located adjacent to the southern margin of the Delaware Mountains that is associated with recent recharge based on its groundwater carbon-13, carbon-14, and tritium compositions also has stable hydrogen and oxygen isotopic compositions that are more distinct—much higher—than other locations in the Capitan Reef Complex Aquifer. Stable hydrogen and oxygen isotope compositions generally lie along the Global Meteoric Water Line—the average relationship between stable hydrogen and oxygen isotopic compositions in precipitation around the world (Craig, 1961). Figure 4.7.10 shows Capitan Reef Complex Aquifer groundwater stable hydrogen and oxygen isotopic compositions relative to the Global Meteoric Water Line. The lowest stable hydrogen and oxygen groundwater isotopic compositions occur in the Guadalupe, Apache, and Glass mountains (Figures 4.7.8 and 4.7.9). The highest stable hydrogen and oxygen groundwater isotopic compositions occur just south of the Delaware Mountains. The range of groundwater stable hydrogen and oxygen isotopic compositions is narrower in the eastern arm of the Capitan Reef Complex Aquifer—Brewster, Pecos, Ward, and Winkler counties—than in the west—Culberson and Hudspeth counties (Figure 4.7.11).

4.7.3 Implications for Recharge Based on Groundwater Isotopic Compositions

The range of stable hydrogen and oxygen isotopic compositions can be influenced by temperature, altitude, amount of precipitation, and water-rock interaction effects (Dansgaard, 1964; Fontes and Olivry, 1977; Scholl and others, 1996; Gonfiantini, 1985; Fontes, 1980). The most likely effects influencing the range of groundwater stable hydrogen and oxygen isotopic compositions in the Capitan Reef Complex Aquifer are the altitude and amount effects. The altitude effect would result in groundwater with lower stable hydrogen and oxygen isotopic compositions—such as in the Guadalupe Mountains—due to recharge taking place at higher elevations. Conversely, recharge occurring at lower elevations would be characterized by higher stable hydrogen and oxygen isotopic compositions. Higher precipitation amounts produce more negative isotopic compositions in the precipitation and resultant groundwater. Note that more precipitation (Figure 2.1.6) also occurs at higher elevations (Figure 2.1.3) such as the Guadalupe Mountains; consequently, it would be difficult to differentiate between the impacts of the amount and elevation effects on groundwater stable hydrogen and oxygen isotopic compositions. The influence of these two effects can explain the difference in the ranges of groundwater stable hydrogen and oxygen isotopic compositions observed in the eastern and western arms of the Capitan Reef Complex Aquifer. The narrower range of groundwater stable hydrogen and oxygen isotope compositions in the eastern arm of the Capitan Reef Complex Aquifer can be explained as the product of a single recharge zone in the outcrops in the Glass Mountains. The wider range of compositions in the western side of the Capitan Reef Complex Aquifer—Culberson and Hudspeth counties—represent recharge under a range of conditions of climate and elevation. The relatively low groundwater stable hydrogen and oxygen compositions in northern Culberson County and Hudspeth County can be attributed to recharge in or adjacent to the Guadalupe Mountains—the highest mountains in Texas (Figure 4.7.12). The wide range of groundwater compositions in southern Culberson County represent a wide range of recharge conditions varying from recharge at higher elevations in the Apache Mountains—the lowest values—to recharge taking place at lower elevations in the valley between the Apache and Delaware mountains—the higher values (Figure 4.7.12).

An alternative explanation for the highest groundwater stable hydrogen and oxygen isotopic compositions in the western arm of the Capitan Reef Complex Aquifer is recent recharge in a climate that is warmer and drier than Pleistocene climate—a pattern that has been observed in other aquifers in the region (Darling, 1997). This explanation is supported by the carbon-14 and tritium data. These data indicate that about half of the groundwater samples collected from the Capitan Reef Complex Aquifer have apparent ages in excess of 10,000 years—carbon-14 of less than 25 percent modern carbon—suggesting recharge during the Pleistocene. Most groundwater carbon-14 apparent ages are in excess of 5,000 years. The highest groundwater stable hydrogen and oxygen isotopic compositions in the western arm of the Capitan Reef Complex Aquifer are associated with very high carbon-14 compositions—approaching 100 percent modern carbon—and the highest tritium concentration, indicating very recent recharge. This groundwater occurs in the subcrop part of the Capitan Reef Complex Aquifer near the southern margin of the

Delaware Mountains and is probably the result of recharge due to rapid infiltration down fractures.

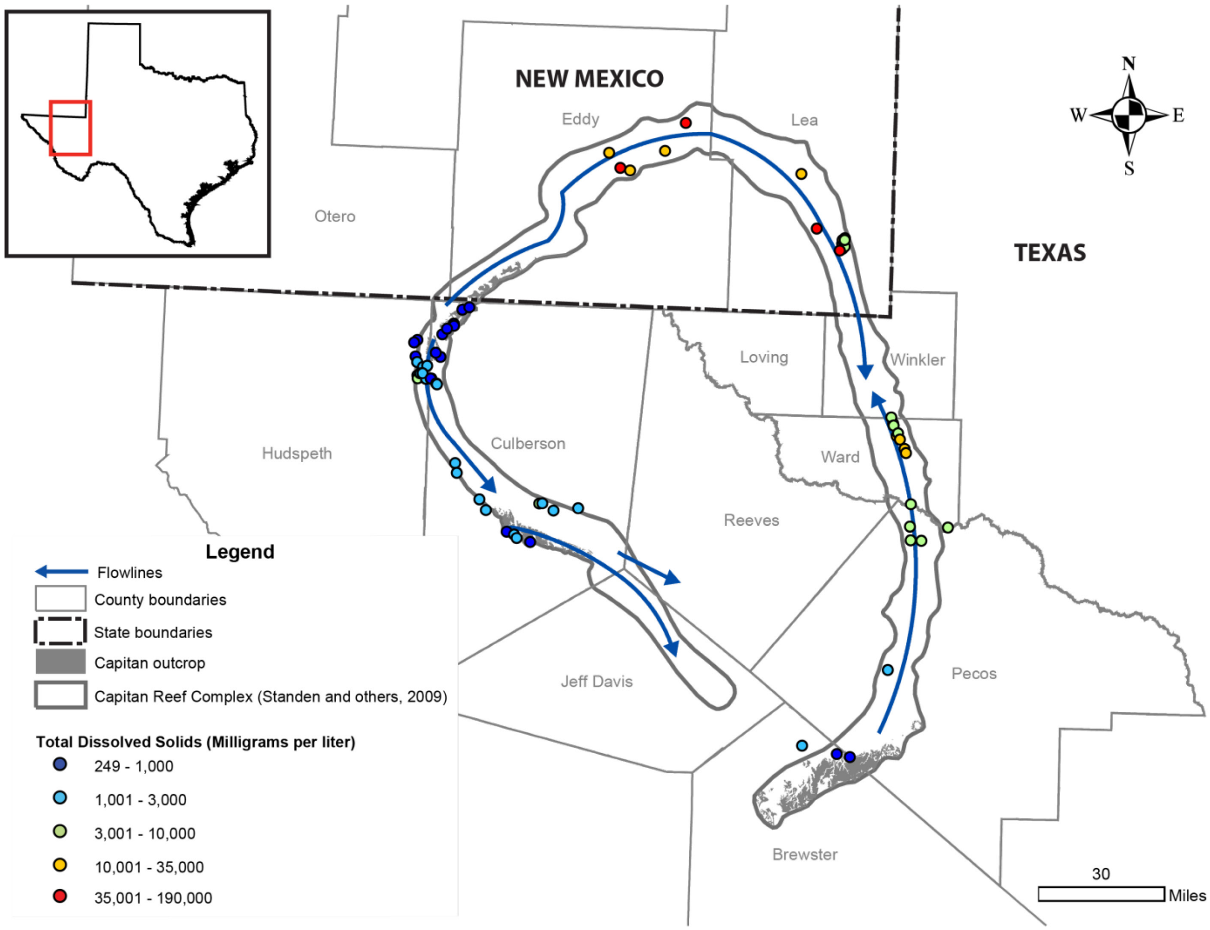


Figure 4.7.1. Total dissolved solids concentration (in milligrams per liter) in the Capitan Reef Complex Aquifer (Data from Hiss, 1973; Texas Water Development Board, 2012b; New Mexico Office of the State Engineer, 2014).

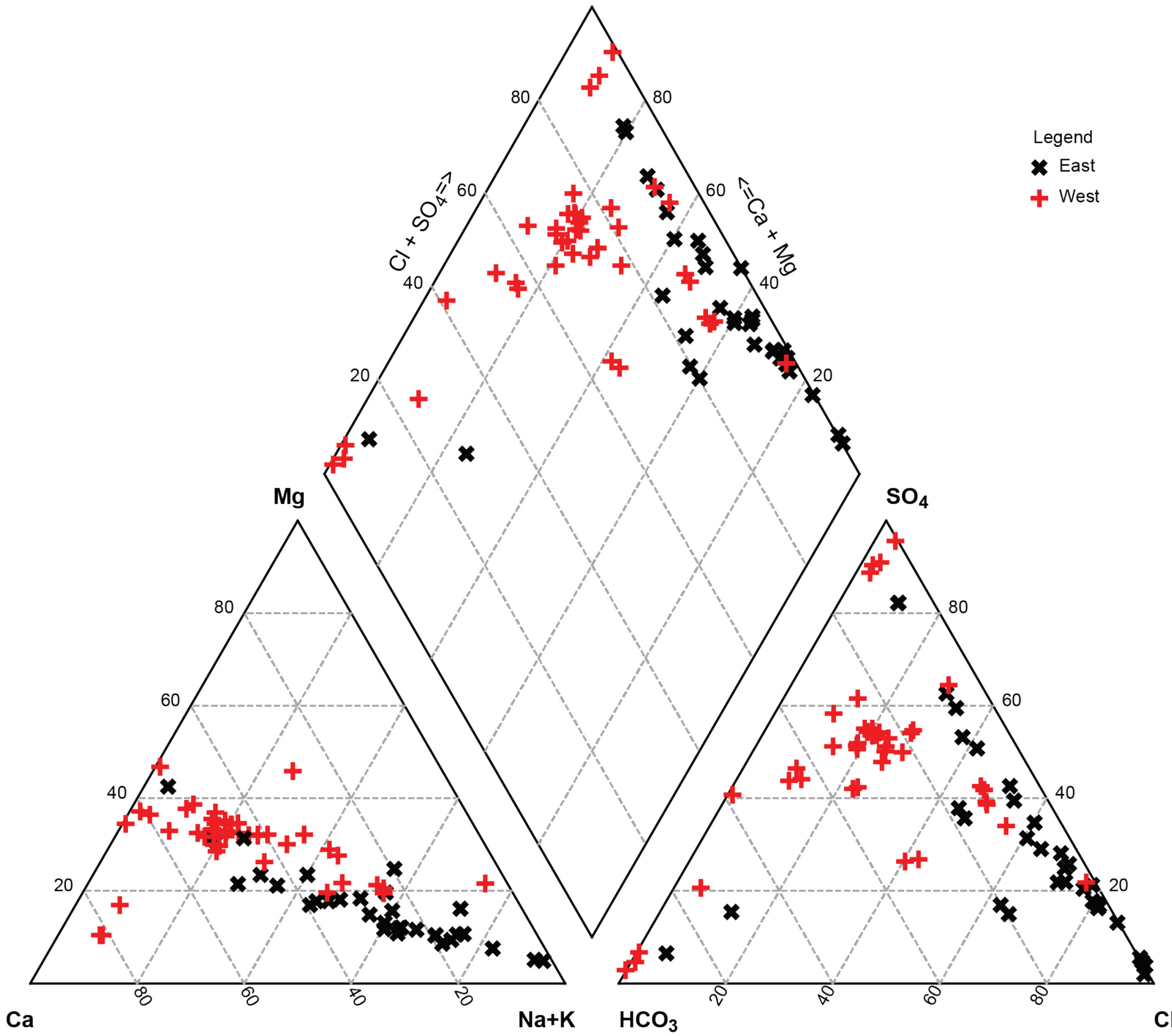


Figure 4.7.2. A Piper diagram showing the range of groundwater compositions in the eastern (Brewster, Pecos, Ward and Winkler counties) and the western (Culberson and Hudspeth counties) parts of the Capitan Reef Complex Aquifer (Data from Hiss, 1973; Texas Water Development Board, 2012b; New Mexico Office of the State Engineer, 2014).

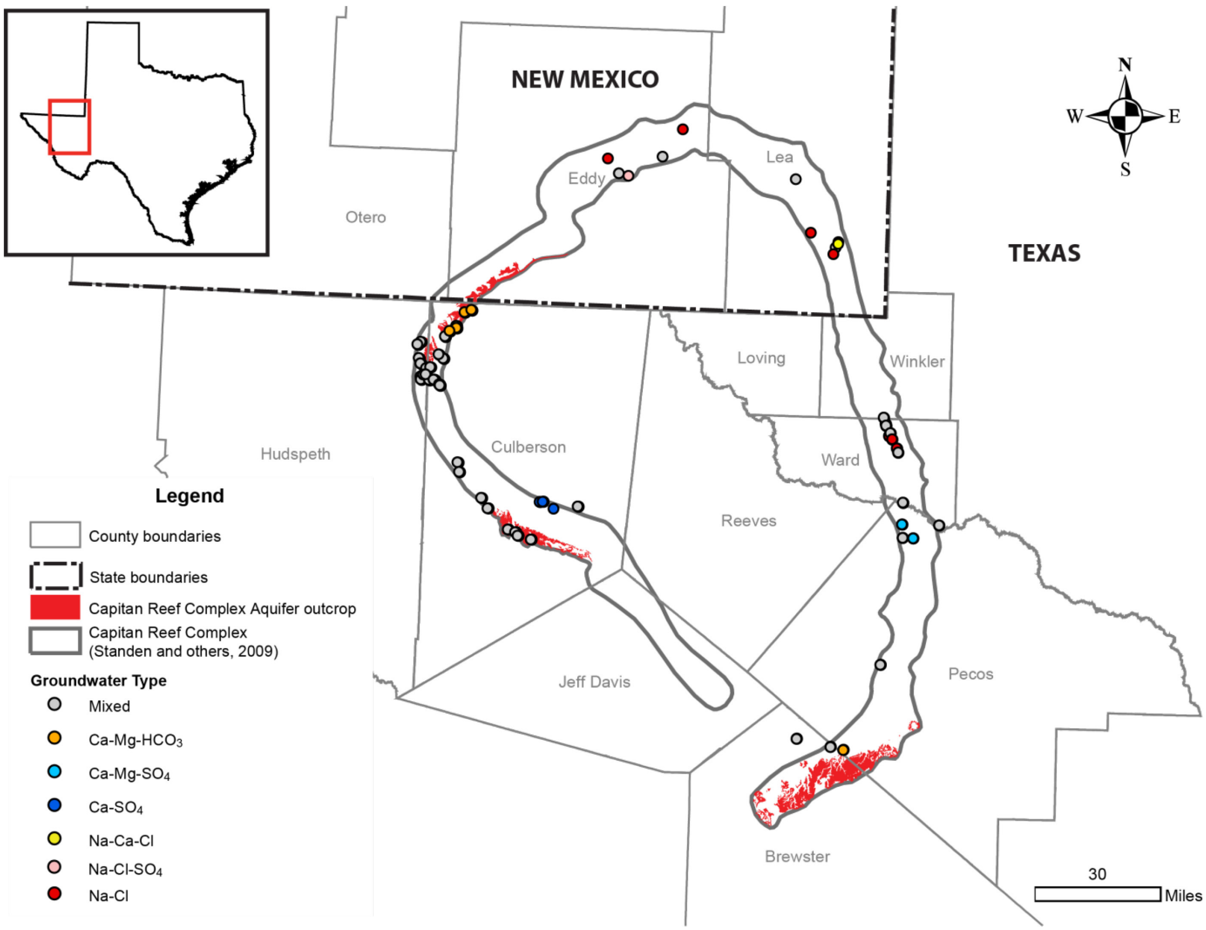


Figure 4.7.3. Groundwater types in the Capitan Reef Complex Aquifer (Data from Hiss, 1973; Texas Water Development Board, 2012b; New Mexico Office of the State Engineer, 2014).

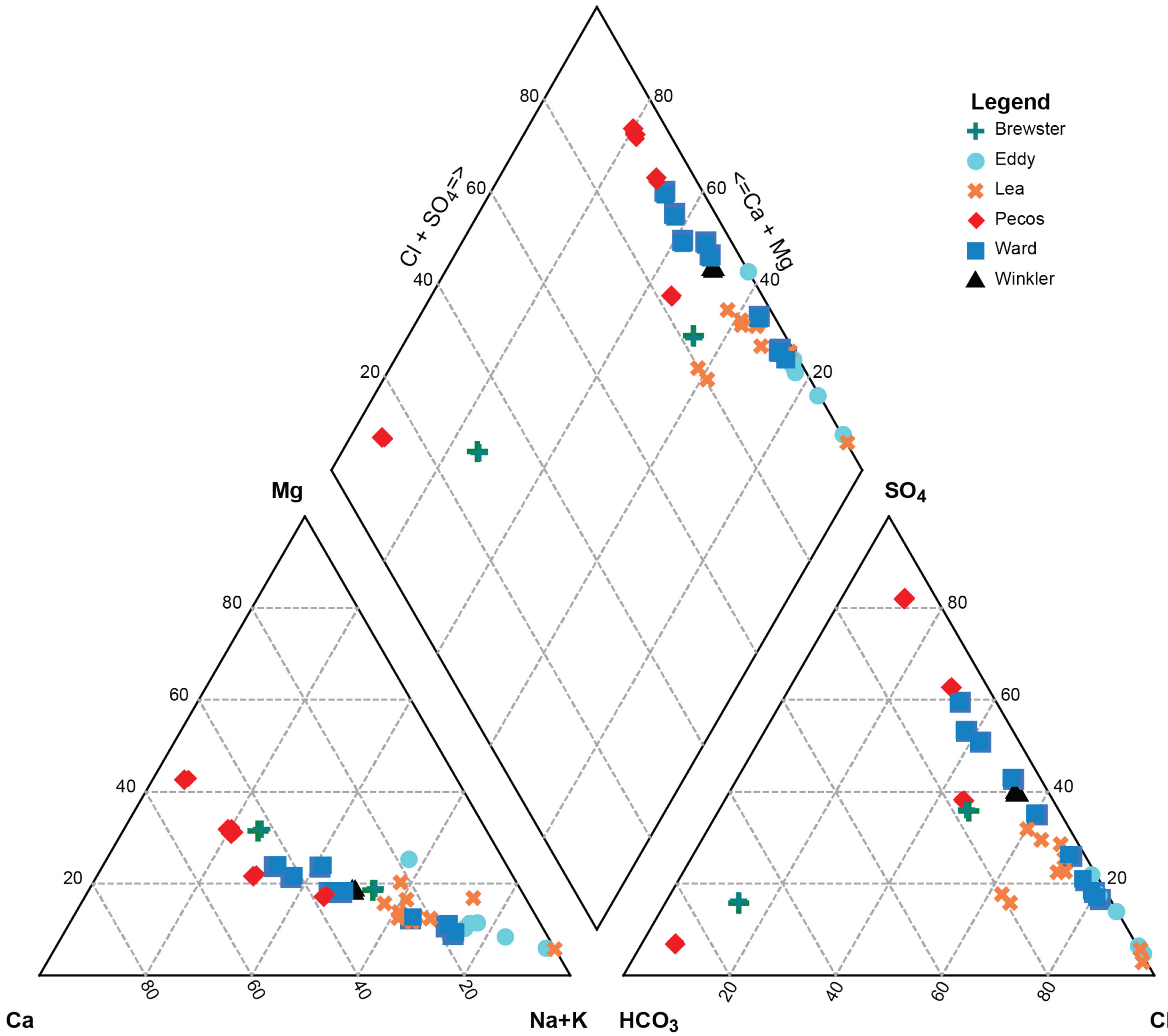


Figure 4.7.4. A Piper diagram showing the range of groundwater compositions in counties of the eastern (Brewster, Pecos, Ward, and Winkler counties) part of the Capitan Reef Complex Aquifer (Data from Hiss, 1973; Texas Water Development Board, 2012b; New Mexico Office of the State Engineer, 2014).

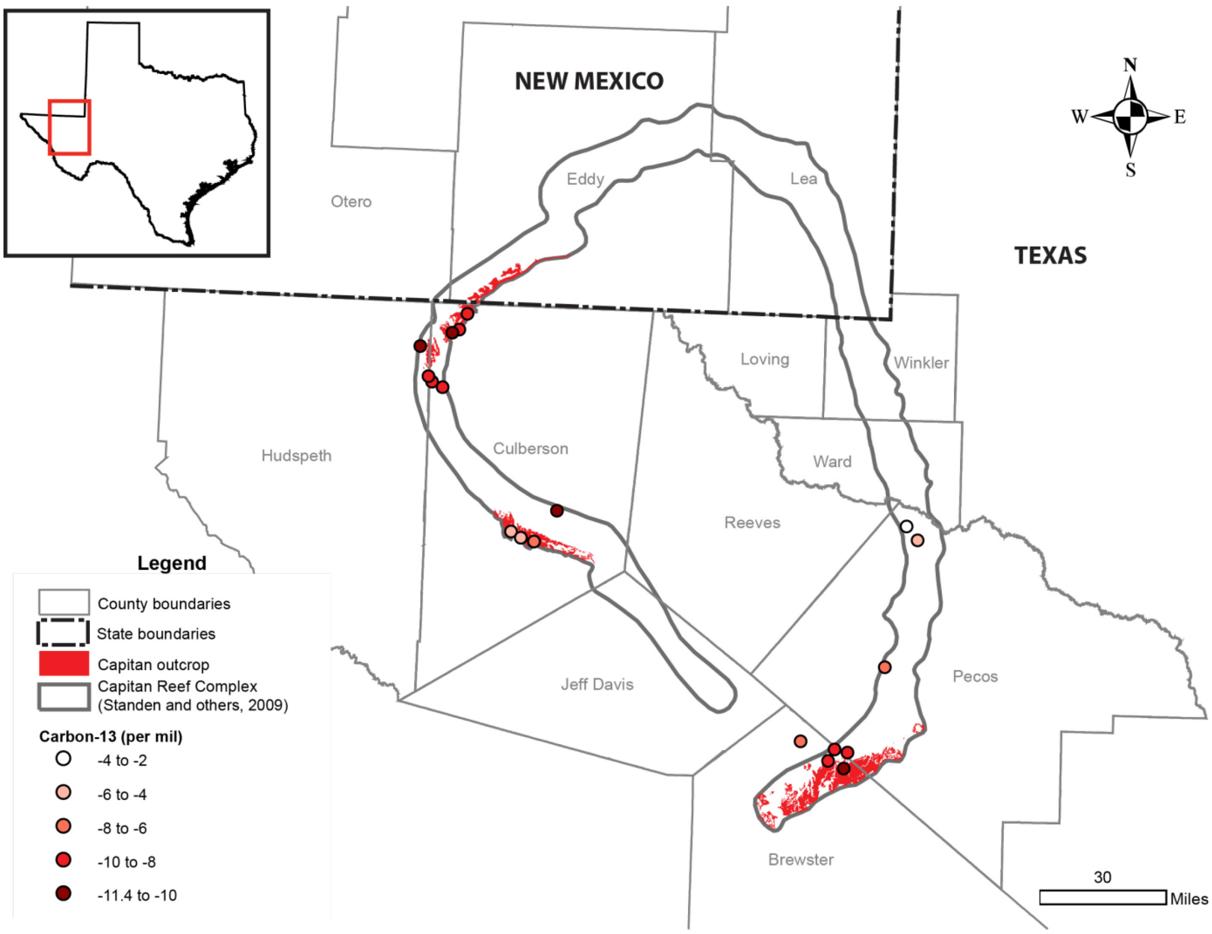


Figure 4.7.5. **Groundwater Carbon-13 isotopes (in per mil) in the Capitan Reef Complex Aquifer (Data from Texas Water Development Board, 2012b).**

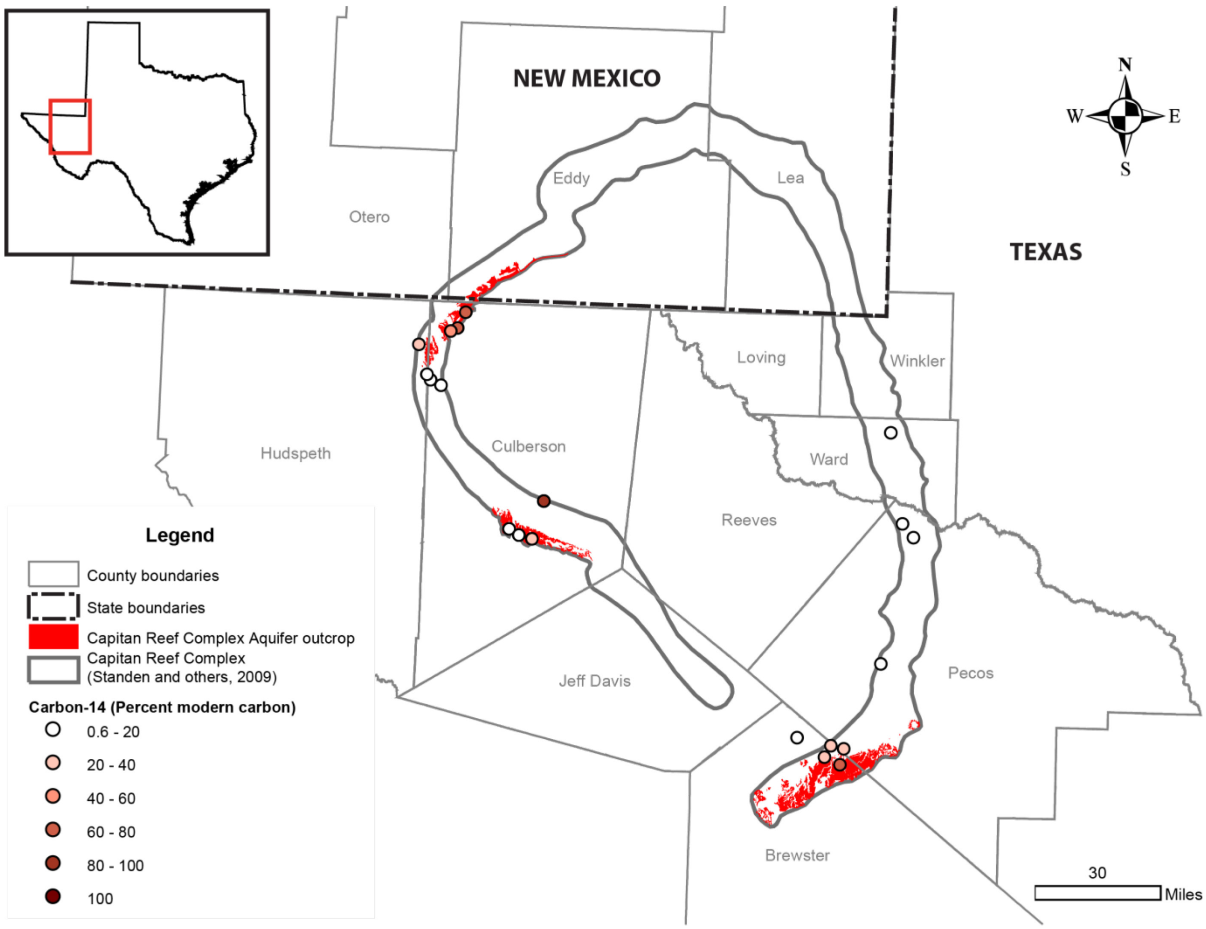


Figure 4.7.6. Groundwater Carbon-14 (in percent modern carbon) in the Capitan Reef Complex Aquifer (Data from Texas Water Development Board, 2012b).

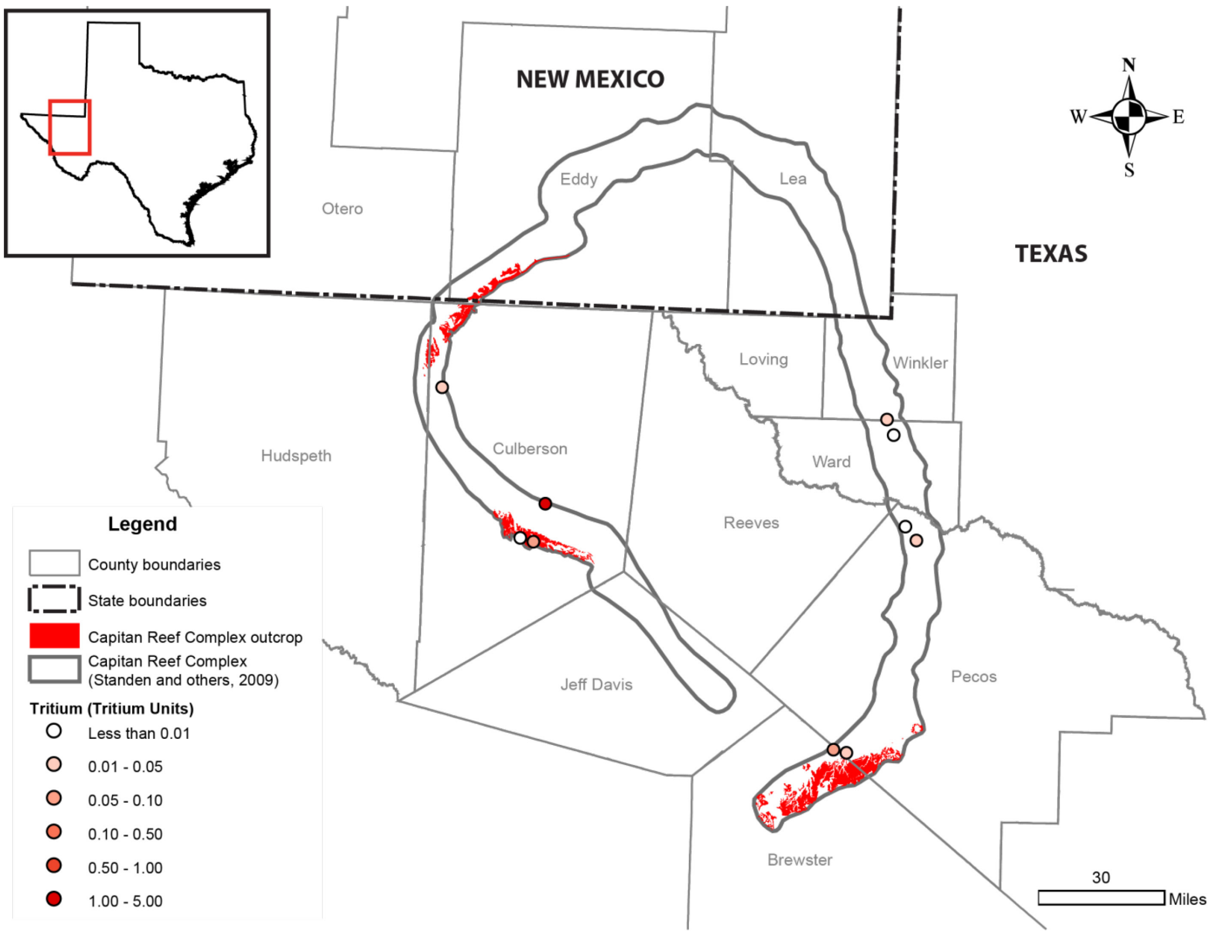


Figure 4.7.7. Groundwater tritium (in Tritium Units) in the Capitan Reef Complex Aquifer (Data from Texas Water Development Board, 2012b).

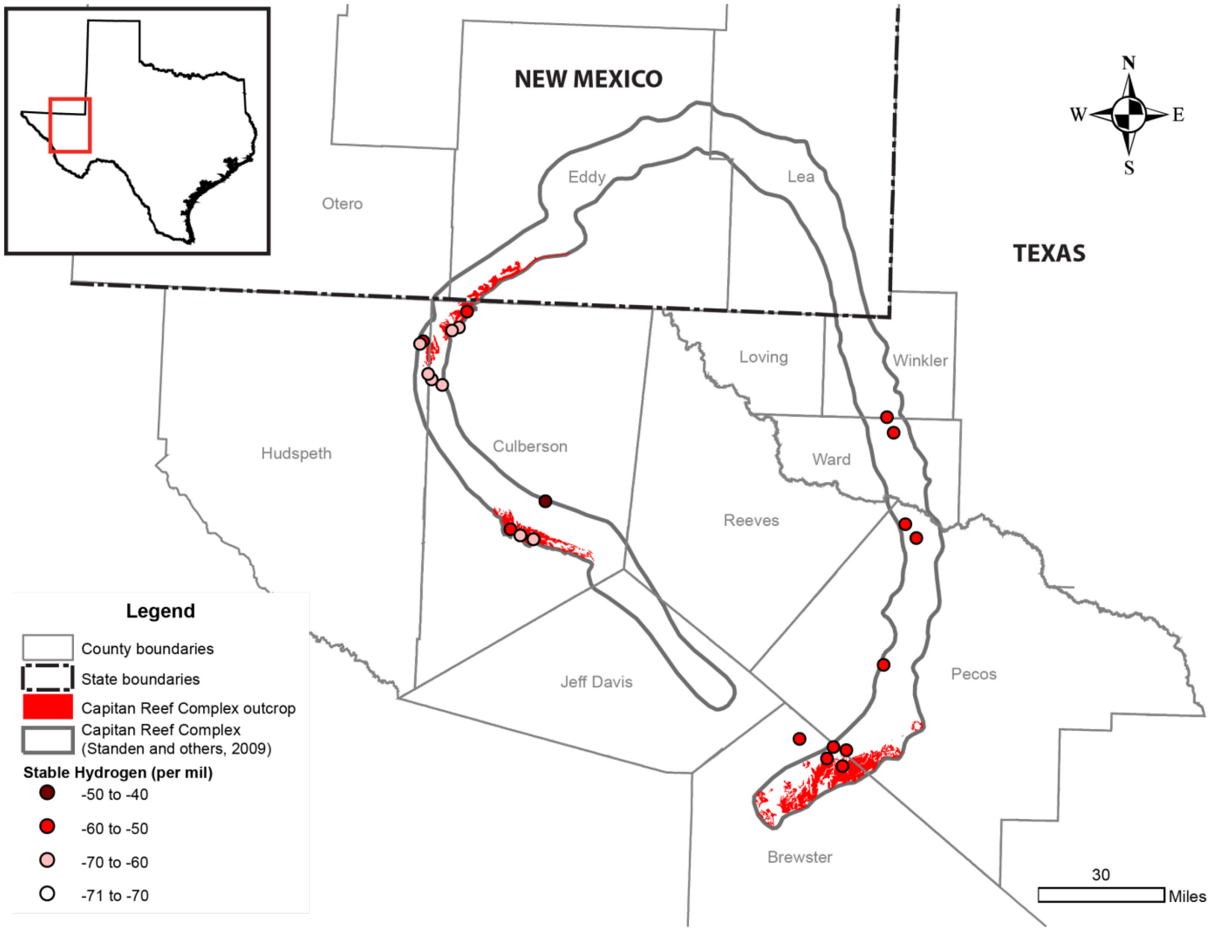


Figure 4.7.8. Groundwater stable hydrogen isotopes (δ^2H, in per mil) in the Capitan Reef Complex Aquifer (Data from Texas Water Development Board, 2012b).

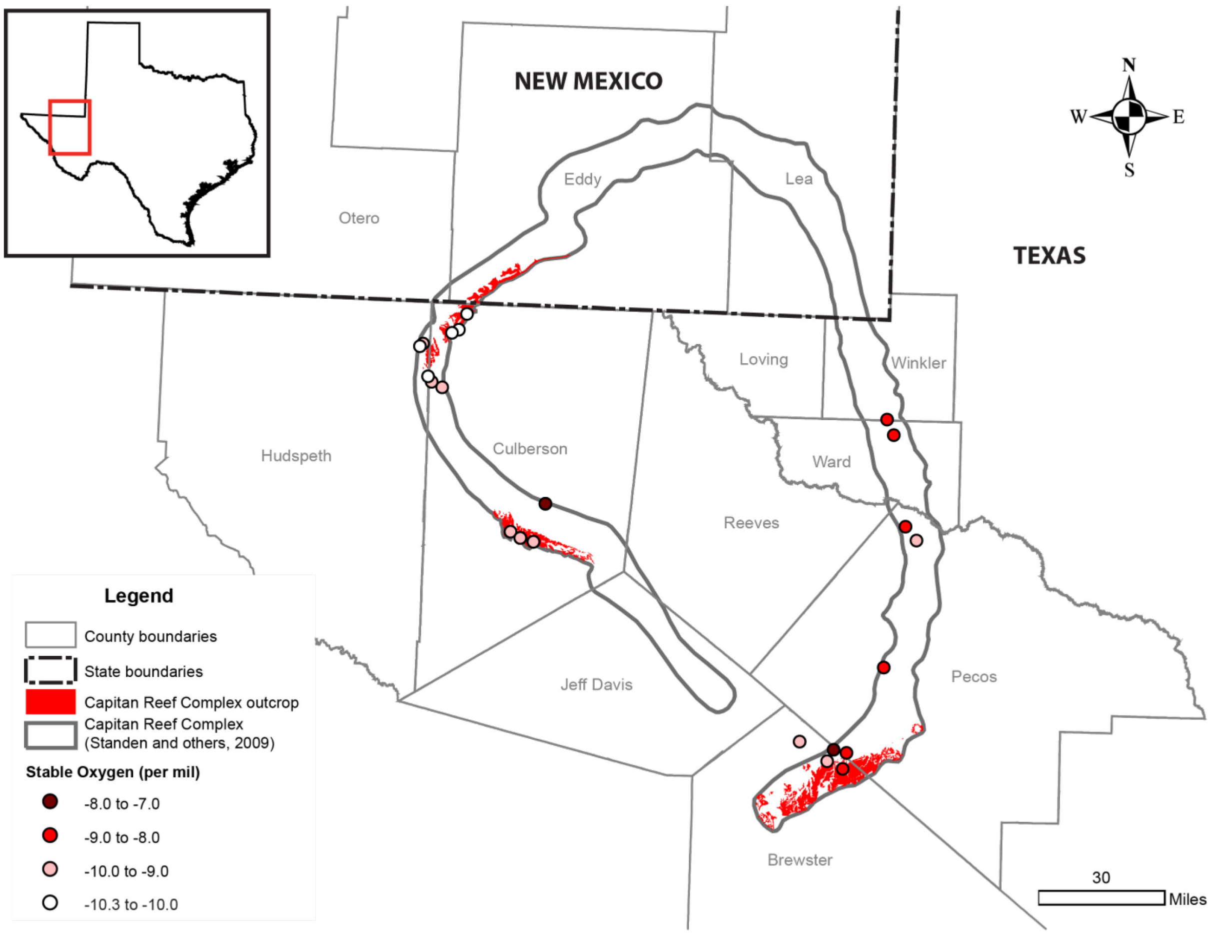


Figure 4.7.9. Groundwater stable oxygen isotopes ($\delta^{18}O$, in per mil) in the Capitan Reef Complex Aquifer (Data from Texas Water Development Board, 2012b).

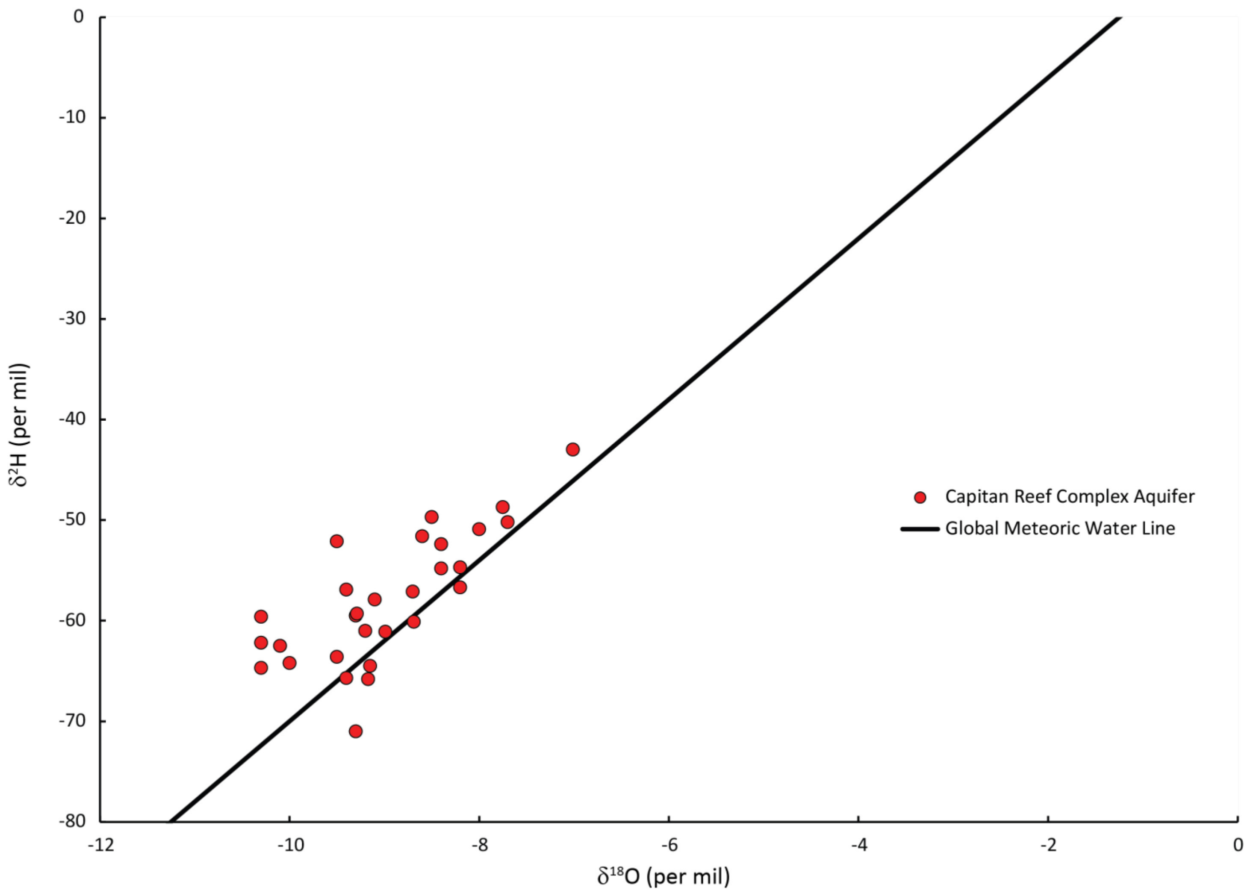


Figure 4.7.10. Capitan Reef Complex Aquifer groundwater stable hydrogen and oxygen isotopes (in per mil) relative to the Global Meteoric Water Line (Data from Texas Water Development Board, 2012b).

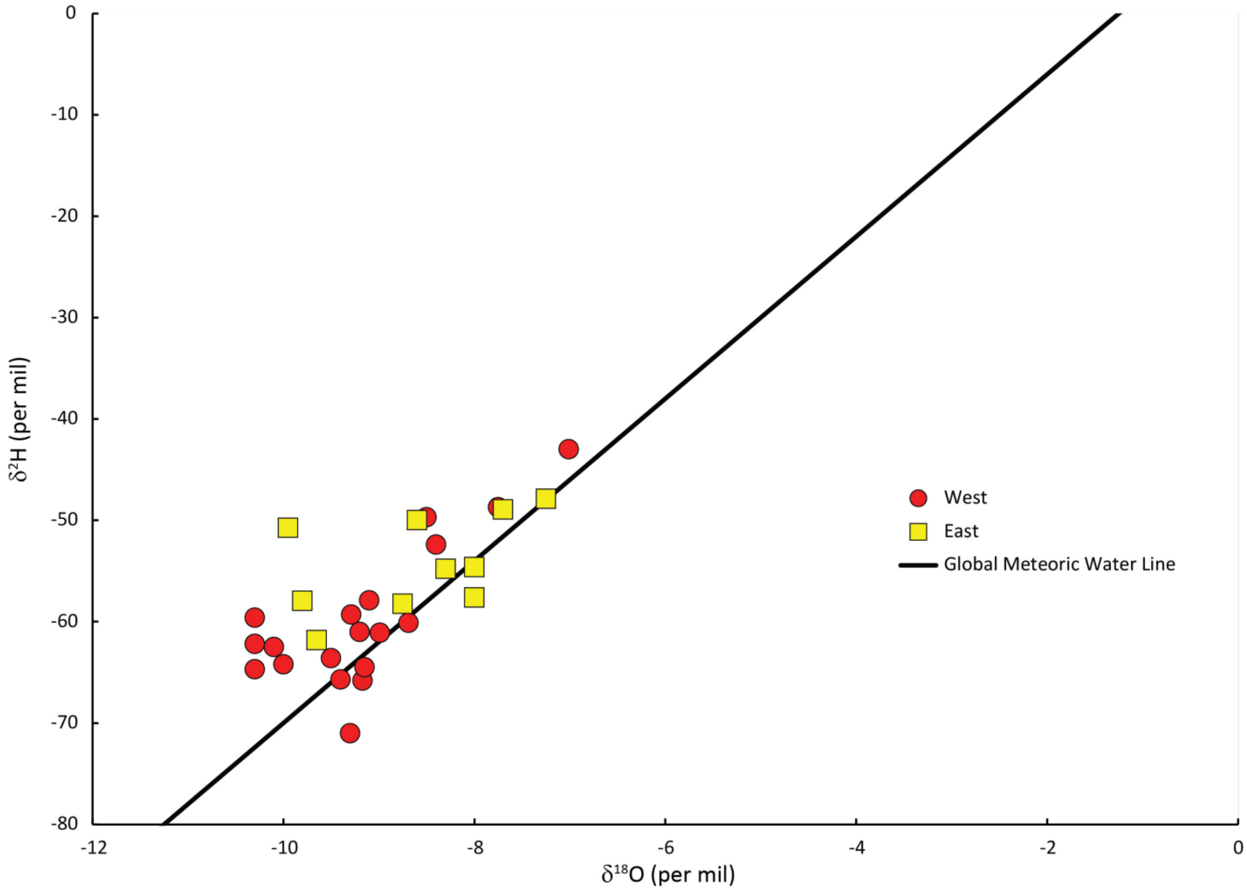
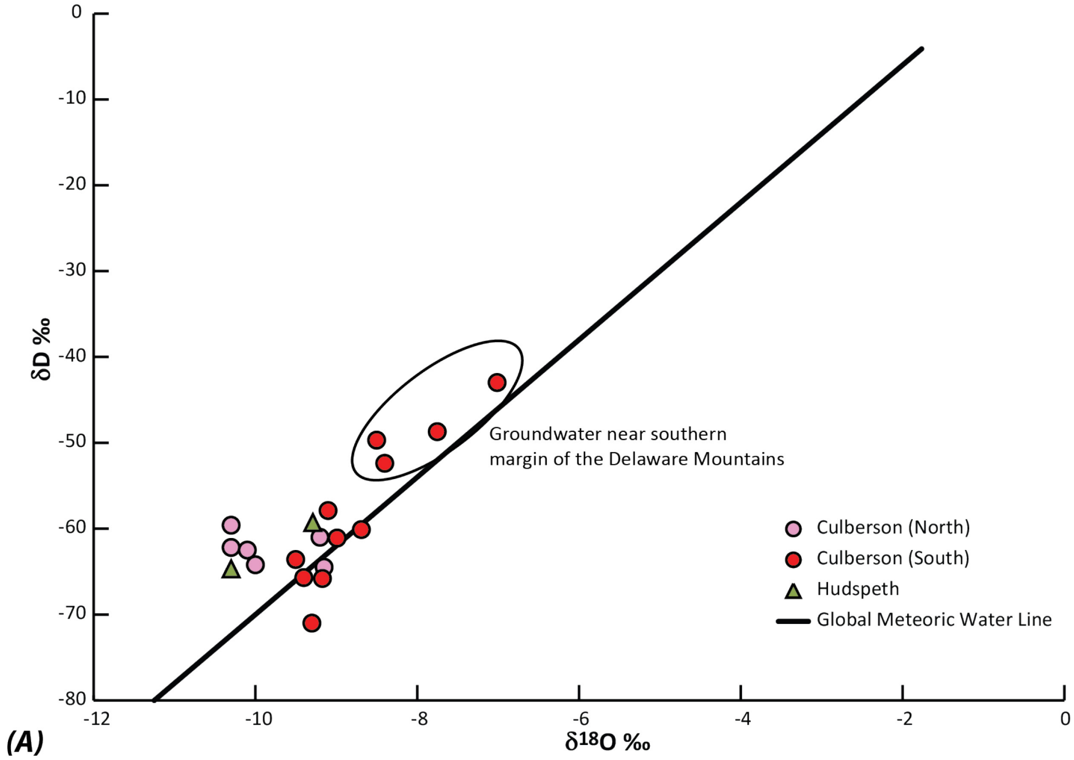


Figure 4.7.11. Comparison of groundwater stable hydrogen and oxygen isotopes (in per mil) in the eastern and western arms of the Capitan Reef Complex Aquifer of Texas (Data from Texas Water Development Board, 2012b).



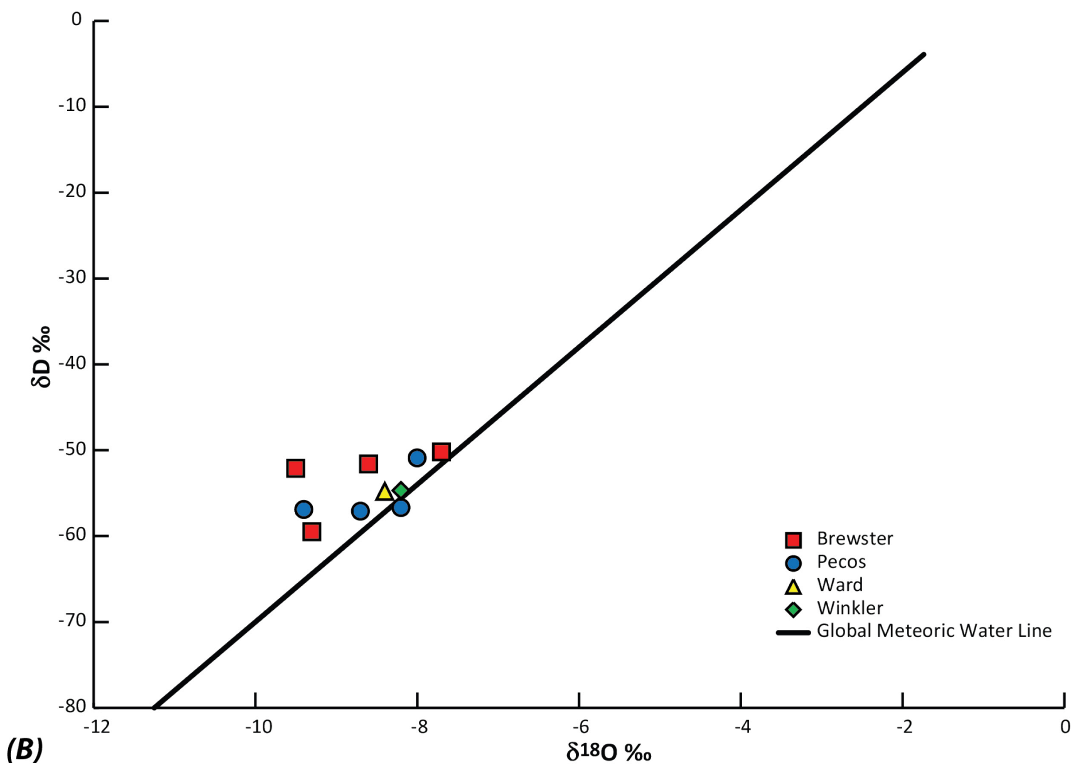


Figure 4.7.12. **Comparison of groundwater stable hydrogen and oxygen isotopes (in per mil) in the eastern (A) and western (B) arms of the Capitan Reef Complex Aquifer of Texas by county (Data from Texas Water Development Board, 2012b).**

5.0 CONCEPTUAL MODEL OF GROUNDWATER FLOW IN THE EASTERN ARM OF THE CAPITAN REEF COMPLEX AQUIFER

The conceptual model of groundwater flow in the eastern arm of the Capitan Reef Complex Aquifer is based on the hydrogeologic setting, described in Section 4.0. The conceptual model is a simplified representation of the hydrogeological features that govern groundwater flow in the aquifer. It includes the hydrostratigraphy, hydrogeologic framework, hydraulic properties, hydrologic boundaries, recharge, and discharge. In this study, only the eastern arm of the Capitan Reef Complex Aquifer is included in the conceptual model. The western arm of the Capitan Reef Complex Aquifer was excluded because parts of the western arm are included in the groundwater model of the Bone Spring-Victorio Peak Aquifer by Hutchison (2008).

The Capitan Reef Complex Aquifer is located in the Trans-Pecos region of western Texas and southeastern New Mexico. The boundaries of the eastern arm of the Capitan Reef Complex Aquifer used in this study were defined by Standen and others (2009) and differ slightly from the official Texas Water Development Board boundaries in Brewster and Pecos counties. The Capitan Reef Complex Aquifer is composed of the Capitan Limestone, Carlsbad Limestone, and Goat Seep Dolomite although of these stratigraphic units, only the Capitan Limestone occurs within the eastern arm of the aquifer (Figure 2.2.4).

The Capitan Reef Complex is bounded—vertically and laterally—by back-reef deposits of the Artesia Group and fore-reef deposits of the Delaware Group and Castile Formation. The Capitan Reef Complex is also overlain by the Salado Formation, a largely rock salt stratigraphic unit. The Salado Formation overlying the Capitan Reef Complex is thinned as a result of dissolution that resulted in the formation of the overlying Monument Draw Trough (Richey and others, 1985).

Work by Hiss (1976; 1980), Uliana (2001), and Sharp (2001) indicates groundwater flow through the Capitan Reef Complex Aquifer parallel to the reef trend and diverging from the main aquifer outcrops—the Guadalupe, Apache, and Glass mountains (Figure 4.2.1). Groundwater apparently converges in the northeastern part of the aquifer—possibly in Winkler County. Groundwater in the eastern arm of the Capitan Reef Complex Aquifer likely recharges by infiltration of precipitation where the aquifer crops out—the Glass Mountains—as noted in Section 4.7 (Figure 5.0.1). Discharge from the Capitan Reef Complex Aquifer likely takes the form of cross-formational flow through the back-reef stratigraphic units and overlying aquifers. Groundwater discharge by vertical cross-formational flow is supported by the fact that Capitan Reef Complex Aquifer water levels are generally higher than water levels in overlying aquifers, indicating an upward hydraulic gradient (Section 4.2). It is also possible for the Capitan Reef Complex Aquifer to discharge by cross-formational flow to adjacent fore- and back-reef deposits, especially the back-reef deposits which (1) have higher hydraulic conductivity values than the fore-reef deposits and (2) there is more evidence of hydrologic connections with the back-reef deposits than the fore-reef deposits (Figure 4.2.3).

In the aquifers overlying the eastern arm of the Capitan Reef Complex Aquifer, groundwater flow generally converges on the Monument Draw Trough which coincides with the Capitan Reef Complex (Figure 5.0.1; Ewing and others, 2008; 2012; Hutchison and others, 2011). Groundwater flow in the surficial Edwards-Trinity (Plateau) and Pecos Valley aquifers also converges on the Pecos River—a major discharge zone for both aquifers (Anaya and Jones, 2009; Hutchison and others, 2011).

The schematic diagram in Figure 5.0.2A is a conceptual block diagram illustrating aquifer contact relationships and sources and sinks of groundwater in the eastern arm of the Capitan Reef Complex Aquifer and overlying aquifers. Constructing the Groundwater Availability Model for the eastern arm of the Capitan Reef Complex Aquifer will require up to five model layers simulating groundwater flow through the Capitan Reef Complex Aquifer and the overlying aquifers and geologic formations within the Monument Draw Trough. The lowermost model layer would represent: (1) the Capitan Reef Complex Aquifer which is exposed at land surface in the Glass Mountains and (2) adjacent parts of the Artesia and Delaware Mountain groups (Figure 5.0.2B). Active cells in the model grid would extend from the Glass Mountains in the south and north to where the Capitan Reef Complex Aquifer footprint intersects with the Pecos River near Carlsbad, New Mexico. Other layers will simulate groundwater flow through the overlying Rustler, Dockum, Edwards-Trinity (Plateau), and Pecos Valley aquifers. There is the possibility that additional layers may be used to simulate the Artesia Group, and Salado, and Castile formations that act as confining units. In the eastern arm of the Capitan Reef Complex Aquifer, the Artesia Group pinches out and is absent along the western side of the aquifer. The Salado Formation and possibly the Castile Formation are thinned due to dissolution by groundwater discharging from the Capitan Reef Complex Aquifer in northern Pecos County and Winkler and Ward counties resulting in the formation of the Monument Draw Trough through collapse of overlying stratigraphic units and infilling by alluvial and eolian sediments (Figure 4.6.1; Synder and others, 1982; Jones, 2001; 2004). The Monument Draw Trough collapse structure would facilitate upward discharge of groundwater from the Capitan Reef Complex Aquifer through the Salado and Castile formations through breccia pipes (Figure 5.0.3; Hill, 1996; 1999a) that contributes to (1) saline groundwater discharging from Diamond Y Springs that is located directly over the Capitan Reef Complex Aquifer footprint and (2) pumping-induced deteriorating groundwater quality observed in the Pecos Valley Aquifer (Veni, 1991; Jones, 2004). An alternative strategy that can be used is to simulate the presence of the confining units by restricting vertical groundwater flow between the aquifers they separate.

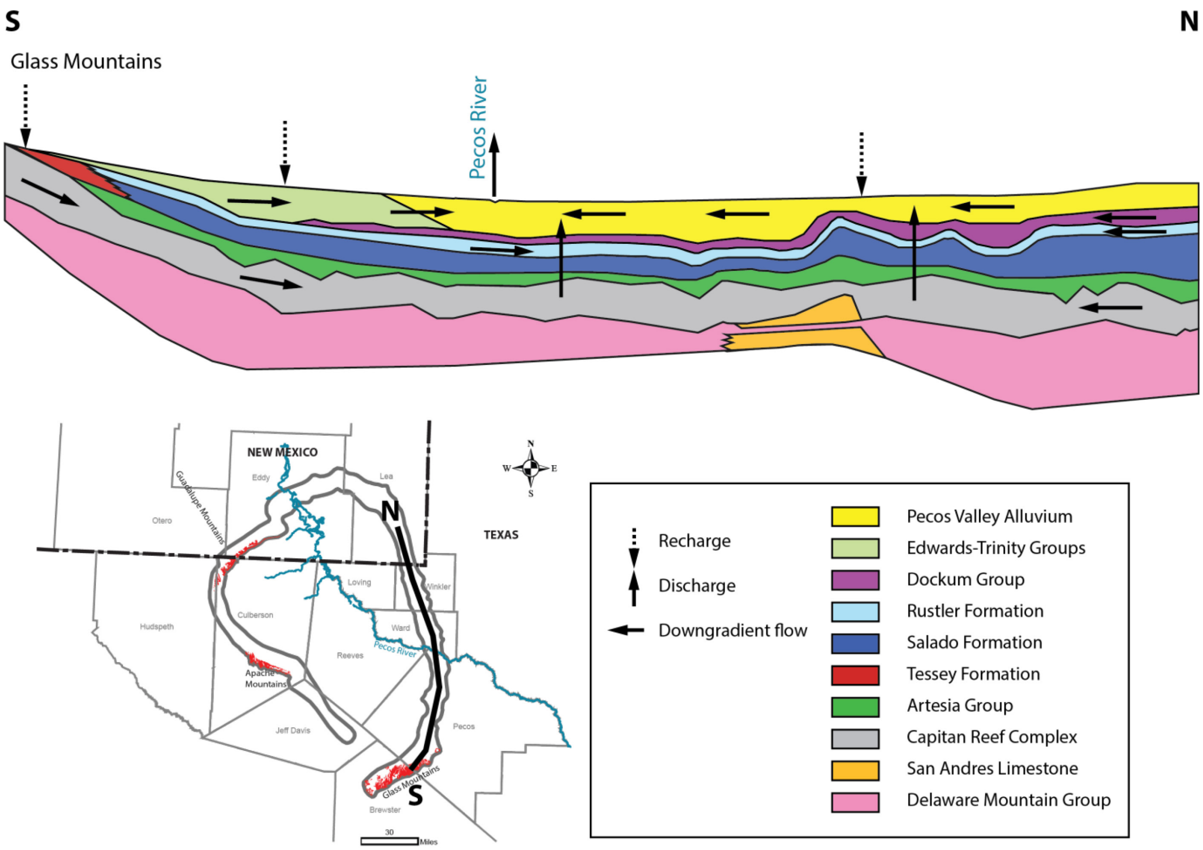
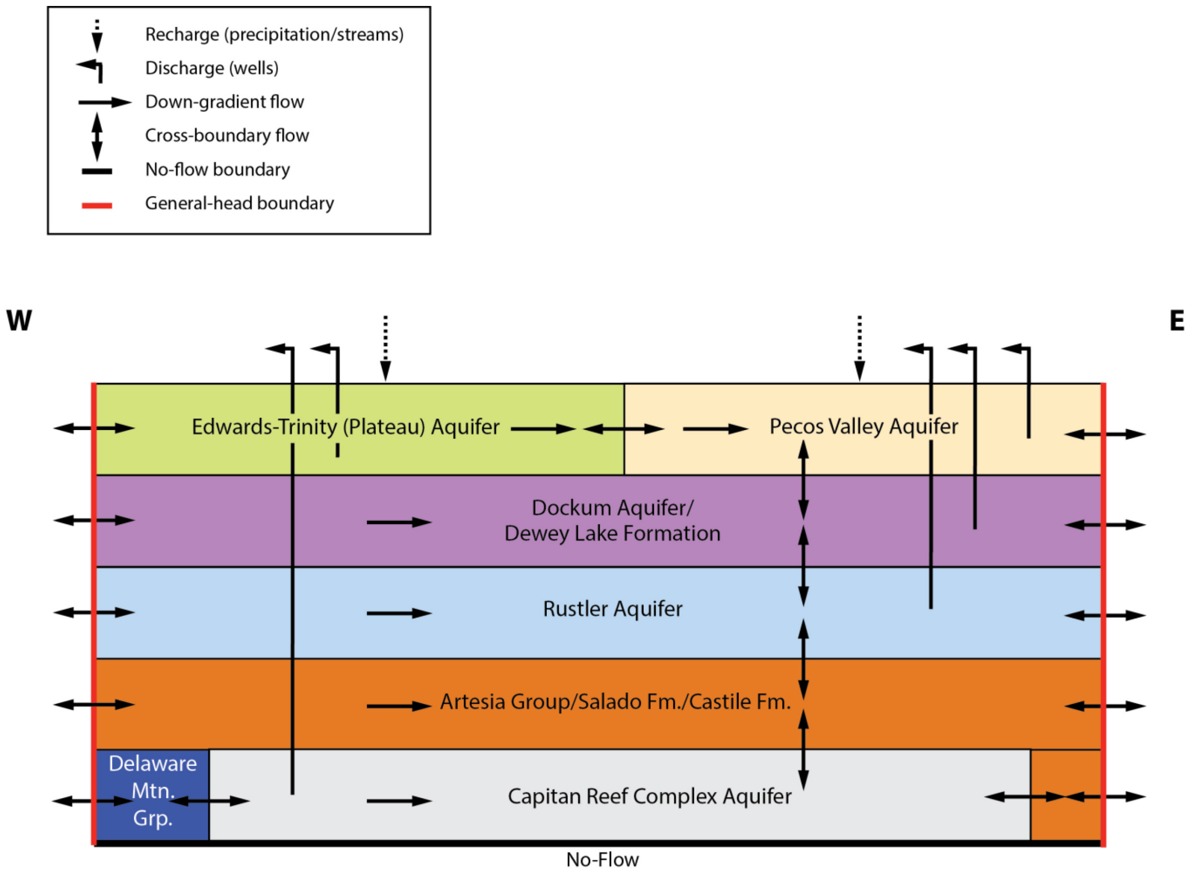
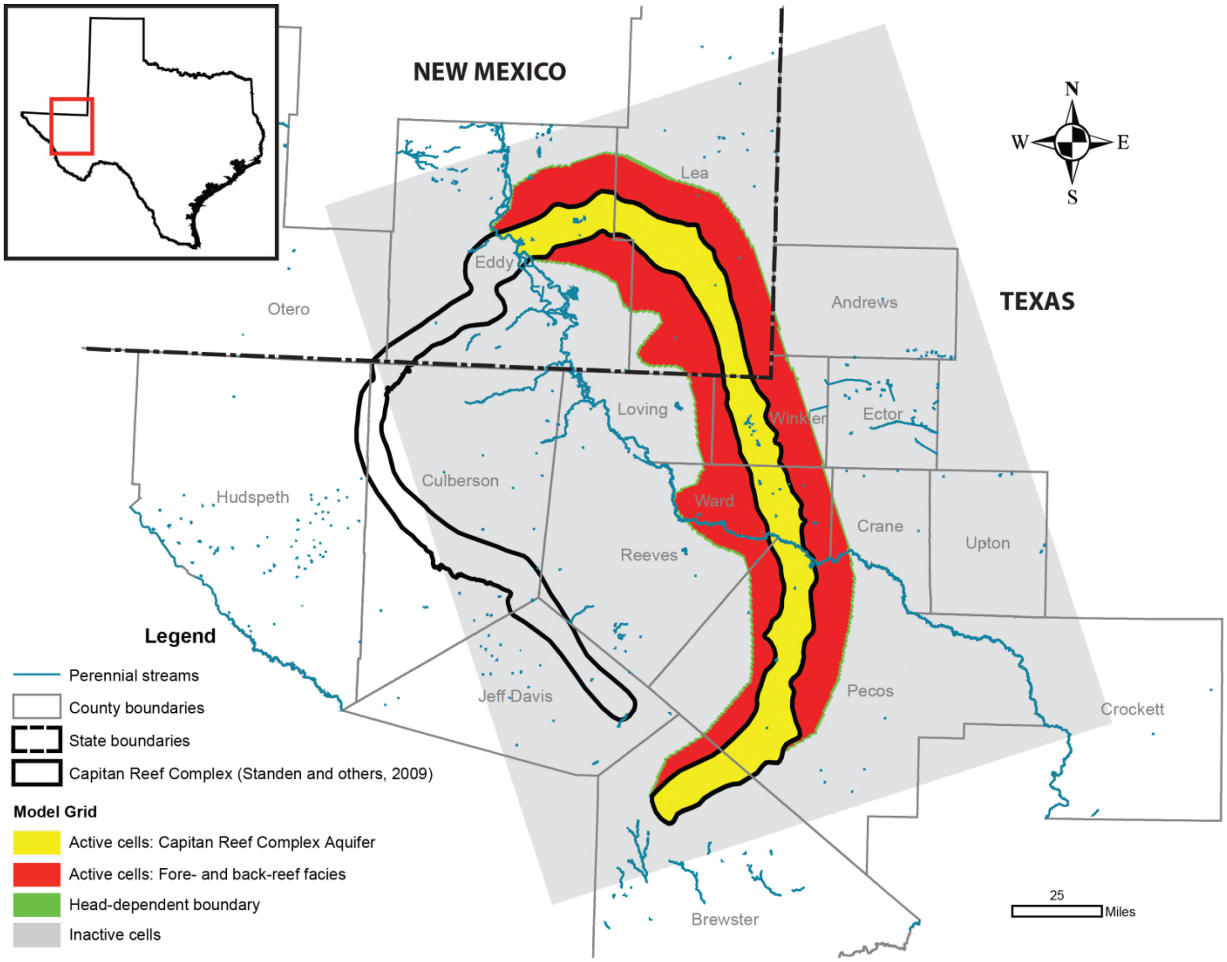


Figure 5.0.1. **Schematic cross-section through the Capitan Reef Complex Aquifer Groundwater Availability Model study area.**



(A)

Figure 5.0.2. **Conceptual groundwater flow model for the Capitan Reef Complex Aquifer Groundwater Availability Model. (A) cross-sectional view and (B) map view.**



(B)

Figure 5.0.2. (continued).

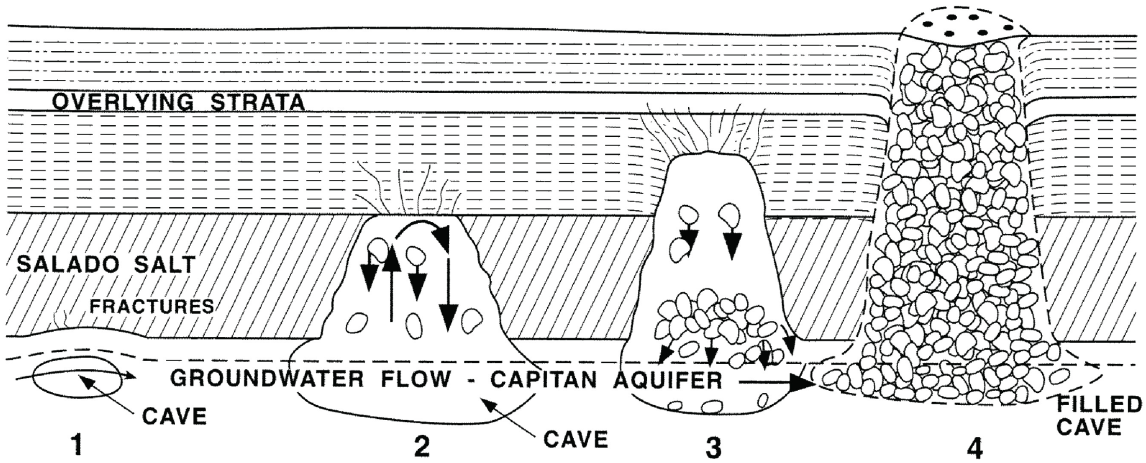


Figure 5.0.3. **The development of breccia pipes through karstification in the Capitan Reef Complex Aquifer and subsequent collapse of overlying stratigraphic units produce potential pathways for upward cross-formational groundwater discharge from the Capitan Reef Complex Aquifer. (From Hill, 1996; 1999a).**

6.0 ACKNOWLEDGEMENTS

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APPENDIX A. CONCEPTUAL MODEL REPORT COMMENTS AND RESPONSES

General Comments

1. It does not seem necessary to include detailed information in the conceptual model about the western arm of the Capitan Reef Complex Aquifer, if the Texas Water Development Board is only building a model of the eastern arm.

A conceptual model report for the entire Capitan Reef Complex Aquifer was done because (1) there is no conceptual model report for the western arm of the aquifer even though parts of it will be included in the groundwater availability model for the Bone Spring-Victorio Peak Aquifer, and (2) it provides the flexibility to allow us to extend the groundwater availability model for the eastern arm of the aquifer westward if deemed necessary at a later date.

2. Discharge is considered to occur as vertical flow from the confined Capitan Reef Complex Aquifer in Winkler County. This is in disagreement with Hiss (1975) and other studies, which describe discharge as occurring as lateral flow to the shelf margin aquifer. See comments below.

Discharge from the Capitan Reef Complex Aquifer in Winkler County is possible by both lateral cross-formational flow into the back-reef stratigraphic units as well as vertical cross-formational flow through overlying aquifers. The collapse structure formed by dissolution in the Salado Formation along with the resultant collapse of overlying stratigraphic units has formed a relatively high hydraulic conductivity pathway for upward discharge from the Capitan Reef Complex Aquifer. This high hydraulic conductivity is apparent in both groundwater availability models for the Rustler and Dockum aquifers.

3. The geologic framework from Hiss (1975) and Standen and others (2009) do not include the Tessey Limestone directly north and northeast of the Glass Mountains. Wilshire and others (1976) and other geologic studies provide the geologic analyses needed to modify the thickness and top and bottom elevations of the Capitan Reef Complex Aquifer north of the Glass Mountains. Adding the Tessey Limestone will significantly increase the recharge area, aquifer thickness, and storage in the unconfined portion of the Capitan Reef Complex Aquifer.

The Tessey Formation will be included in the model as a boundary condition influencing recharge to the Capitan Reef Complex Aquifer. Explicit inclusion of the Tessey Formation may be considered in future updates to the model.

4. The west to east trending fault zone defining the northern boundary of Subdomain 5 in Ewing and others (2012; Figure 4.2.10) is potentially a major boundary that limits groundwater flow from the unconfined portion of the aquifer to the down dip confined portion of the Capitan Reef Complex Aquifer. The fault system has also been identified by Bumgarner and others (2012; Figure 11).

There is no evidence to suggest that there is a regional-scale flow barrier to north-south groundwater flow in the Capitan Reef Complex or Edwards-Trinity (Plateau) aquifers. The Rustler Aquifer Groundwater Availability Model conceptual model shows groundwater from the Glass Mountains outcrop which includes the Tessey Limestone—a stratigraphic equivalent to the Rustler Formation—into the Rustler Aquifer.

Section 1.0 INTRODUCTION

Page 3. 1st paragraph, bullet (3): Implying the Capitan Reef Complex Aquifer has poor quality water throughout the aquifer may be misleading, as the Capitan Reef Complex Aquifer is known to have potable groundwater in the unconfined portions at or near the formation outcrop.

Added the phrase "in most parts of the aquifer" to indicate that potable groundwater exists in some parts of the aquifer.

Page 3. 1st paragraph, 2nd sentence: As determined from Hiss (1975), historical total pumping from 1954 to 1970 was 306,500 acre-feet (18,039 acre-feet per year average).

Revised the sentence to specify that the pumping rates applied only to the Texas portion of the aquifer for the period 1980 through 2008.

Figure 1.0.2 should show the entire Capitan Reef Complex Aquifer outline.

Figure 1.0.2 only shows the Texas portions of the respective minor aquifers.

Section 2.1 Physiography and Climate

Page 18: 3rd and 4th paragraphs would benefit from an analysis of daily precipitation and evaporation statistics. Daily data are extremely important for understanding and calculating recharge.

Daily data would probably not be applicable to the spatial and temporal scale of the proposed groundwater availability model which will be regional-scale with 1-year stress periods.

Section 2.2 Geology

Consider restructuring Section 2.2 so it contains the following:

- 2.2.1 Structural Setting
- 2.2.2 Surface Geology
- 2.2.3 Delaware Basin Stratigraphy
- 2.2.4 Capitan Reef Complex
- 2.2.5 Geologic units overlying Capitan Reef Complex Aquifer

The section does not include discussion of overlying geologic units.

Recommended Section 2.2.5 would be extremely important for understanding recharge and discharge for the Capitan Reef Complex Aquifer.

Discussion of the overlying stratigraphic units can be found in other reports referenced throughout this report.

Section 2.2.1 Structural Setting

No time periods are given for the various structural elements discussed in this section. The Delaware Basin is the primary structural feature that influenced the formation of the Capitan Reef Complex Aquifer, however, there are several structural elements that formed after the Delaware Basin that should be discussed (Monument-Belding Trough, tectonic event that formed the Glass Mountains, major fault zones, and Sierra Madera astrobleme). Some of the written parts of Section 2.2.3 belong in 2.2.1.

The Monument Draw Trough is discussed in Section 4. and, the uplift that resulted in the formation of the Capitan Reef Complex Aquifer outcrops including the Glass Mountains and major fault zones are discussed in Section 2.2.3. The Sierra Madera astrobleme is small relative to the model area. We will have to investigate the effects of the astrobleme on the regional flow system during model construction and calibration.

Section 2.2.3 Capitan Reef Complex Aquifer and Delaware Basin Stratigraphy

This section should be divided into two sections: Delaware Basin Stratigraphy and Capitan Reef Complex. Furthermore, several paragraphs in Section 2.2.3 belong in Section 2.2.1.

This section has been subdivided as suggested and several paragraphs moved to the Structural Setting section.

The Delaware Basin stratigraphy from oldest to youngest should discuss Permian carbonates of Leonardian (prior to deposition of Capitan Reef) and Guadalupian periods (during deposition of Capitan Reef), and post deposition of Capitan Reef and filling of Delaware Basin with evaporates, Rustler Formation, Triassic red beds, Cretaceous rocks, and alluvium.

The primary focus of this report is on the Capitan Reef Complex; consequently, other stratigraphic units—especially underlying units—are discussed in limited detail.

Page 30: The discussion of geologic units confuses formations from different areas. The formation names that make up the Capitan Reef Complex Aquifer are different for the Capitan, Glass, and Apache Mountains. The formations that consist of the Capitan Reef Complex Aquifer from the Glass Mountains and the eastern arm of the Reef include Capitan Limestone, Tessey Formation, Gilliam Formation, Vidrio Formation, and the Word and San Andres Formations (where hydraulically connected).

Figure 2.2.4 has been revised to clarify the relationships between the various formations that occur in the Glass Mountains. Please note that even though they may be hydraulically connected, we do not consider the Tessey Formation—an equivalent to the Castile and Salado formations, Gilliam, Vidrio, Word and San Andres formations to be part of the Capitan Reef Complex Aquifer. Interaction between these formations and the Capitan Reef Complex Aquifer will be simulated in the model.

The compositional differences between the formations that make up the Capitan Reef Complex Aquifer are not discussed. For example, the Tessey Formation is a massive limestone lacking fossils that grades northward from the Glass Mountains into the Rustler, Salado, and Castile Formations. The Capitan Formation is fossiliferous reef mound. Both formations have undergone karstification and are hydraulically connected.

At the regional scale, compositional differences among the stratigraphic units that make up the Capitan Reef Complex Aquifer and adjacent units such as the Tessey Formation is of secondary importance considering the variability over short distances that are small compared to the likely cell size that will be used in the groundwater flow model.

Figures 2.2.2, 2.2.4, 2.2.5, 2.2.6, and 2.2.7 should use formation colors standardized by the United States Geological Survey.

The colors used in Figure 2.2.2—a simplified surface geology map—are loosely based on the United States Geological Survey colors; however, exceptions are made in some cases to provide contrast necessary for important stratigraphic units to be distinguishable from other stratigraphic units of similar age on such a small map. It is not practical to use the standardized colors in Figures 2.2.4 through 2.2.7 because almost all of the stratigraphic units in the cross-sections are Permian and would therefore have very similar colors that may not be distinguishable.

Figure 2.2.3 lists the Bissett Conglomerate as Triassic, but it has been designated as Cretaceous (see Fort Stockton Sheet, and Wilcox (1989)).

Figure 2.2.3 is now Figure 2.2.4. As a result of revisions, the Bissett Conglomerate no longer appears on this figure.

Cross sections and fence diagrams from Wilshire and others (1972) should be considered in the Capitan Reef Complex Aquifer conceptual model report.

The report by Wilshire and others (1972) is highly localized and does not include information that does not appear elsewhere.

Section 3.0 PREVIOUS WORK

Page 41, 2nd and 3rd paragraphs: The report accurately describes the previous modeling work by both Barroll et al. (2004) and INTERA and Cook-Joyce (2012). However, missing from this discussion is mention of the calibrated groundwater flow model developed for the eastern limb of the Capitan aquifer described by INTERA (2013).

We revised the text to include mention of this model.

The report states on page 41 that the Board's interest is to "..simulate groundwater flow between the Glass Mountains outcrop in Brewster County and where the Pecos River interacts with the aquifer near Carlsbad, New Mexico—a study area that includes the areas of interest of both models." Given this interest, the model described in INTERA (2013) is brought to the Boards attention because it is a model that simulates flow between the Glass Mountains and the Pecos River and does so by adopting the model described by Barroll and others (2004) to evaluate impacts on the Pecos River. Because the Board's objective and area of interest is directly in line with the objective and area of interest of the model described in INTERA (2013), a discussion of this previous work would be an important addition to the section that describes previous work. Though Appendix B of INTERA (2013) is referenced in Section 4.3 of the subject report on recharge, in Section 3.0 there is no mention of the model described in the body of INTERA (2013). Therefore, the Board may wish to add to Section 3.0 a discussion of the model described in INTERA (2013) to recognize a calibrated groundwater flow model that has recently been developed for the eastern limb of the Capitan Reef Complex Aquifer.

Based on figures in the INTERA (2013) groundwater flow model report, the model domain does not include the Glass Mountains that occur in southern Pecos County and extend into Brewster County. Instead the model uses a specified flux boundary to simulate recharge inflow from the Glass Mountains. The Texas Water Development Board requirements for a groundwater availability model is to explicitly simulate groundwater flow within the official aquifer boundaries in Texas, part of which is excluded from the INTERA (2013) model.

It should be noted that the work by Hill (1996) is the most comprehensive summary of geology, stratigraphy, structure, hydrology, and formation of caves and karst in the Capitan Reef Complex Aquifer.

Hill (1996) is referenced in this report.

More information on the model by INTERA and Cook-Joyce (2012) should be presented if this model will be relied on to complete the Capitan Reef Complex Aquifer Groundwater Availability Model (GAM).

The model by INTERA and Cook-Joyce (2012) is listed only as an example of existing models in the study.

Section 4.0 HYDROLOGIC SETTING

This section would benefit from a discussion of karst features in the Capitan Reef Complex Aquifer. A good reference would be Hill (1996). Hill (1996) states *"Water moves through the Capitan primarily along the upper and basinward sides of the carbonate aquifer units where a zone of high porosity exist (Gail, 1974). This zone is located along the contact of the reef and fore-reef facies exactly in the same position as are many of the cave passages in the Guadalupe Mountains… Breaks in drilling have indicated true cavernous zones in some places."*

Mention of karstification in the Capitan Reef Complex Aquifer occurs throughout the text. We revised the text slightly to include additional information on karst processes in the Capitan Reef Complex.

Section 4.1 Hydrostratigraphy

Page 43, 2nd paragraph, 3rd sentence: The fore-reef and back reef formations are reversed. The fore-reef is the Delaware Mountain Group, and the back-reef is the Artesia Group. Furthermore, it should be clarified that the aquitards overlying the Capitan Reef Complex Aquifer do not exist in the Capitan Reef Complex Aquifer outcrop area and directly down dip, and that the formations overlying the Capitan Reef Complex Aquifer changes from the Glass Mountains down dip to the north. In Pecos County, from south to north, the Capitan Reef Complex Aquifer is overlain by the Bissett Formation, Rustler Formation, salt beds of the Castile formation, and then the Artesia Group.

The text has been revised in response to this comment.

The Artesia Group along the northern portion of the eastern arm is not considered an aquitard, but rather part of the shelf aquifer with similar hydraulic properties to the Capitan Reef Complex Aquifer (Hiss, 1975).

Text has been added to clarify that the hydraulic connection between the Capitan Reef Complex Aquifer and back-reef stratigraphic units observed west of the Pecos River also exists to the east.

Page 43, 3rd and 4th paragraphs: It has been discovered that the Tessey Formation was not included when Standen and others (2009) defined the top elevation and thickness of the Capitan Reef Complex Aquifer. Hiss (1975) used geophysical logs to pick the top of the Capitan Formation and did not include the Tessey Formation as part of the Capitan Formation (see Hiss, 1975; Figure 6). Standen and others (2009) carried over this same approach. The Tessey Formation needs to be included in defining the Capitan Reef Complex Aquifer framework for the model to be representative.

The Tessey Formation will be simulated as a boundary condition in the groundwater availability model for the Capitan Reef Complex Aquifer. Explicit simulation of the groundwater flow *through the Tessey Formation is not considered at this time because of the absence of aquifer property, water-level, and other hydrologic data.*

Figure 4.1.1: The title should state Hydrostratigraphic chart of the Capitan Reef Complex Aquifer for the down dip portion of the eastern arm.

The figure caption has been revised in response to the comment.

Figures 4.1.2 through 4.1.4 do not include the Tessey Limestone. Slight modifications to the geologic structure of the Capitan Reef Complex Aquifer are needed south of Belding to include the Tessey Limestone. Aquifer thickness of the Capitan Reef Complex Aquifer will increase by more than 500 feet when the Tessey Limestone is included.

As mentioned before in response to other comments, the Tessey Formation will be simulated as a boundary condition in the groundwater availability model for the Capitan Reef Complex Aquifer and may be incorporated in future updates of the model.

4.2 Water Levels and Regional Groundwater Flow

In the last paragraph on page 58, the report suggests that the post-development potentiometric surface that shows a convergence of groundwater flow in Winkler County may be caused by either discharge into the Central Basin Platform or to overlying aquifers. It is suggested the Board also consider the effects of groundwater pumping from well fields in Winkler County that resulted in an excess of 700 feet of drawdown in the Capitan aquifer. INTERA (2013) conceptualizes the pumping in Winkler County to have reversed the flow in the aquifer between Winkler County and the northern end of the aquifer from a northerly to a southerly flow direction. It seems more likely that this convergence in Winkler County is primarily a result of pumping over several decades in the mid-20th century, although some discharge to the back-reef units and/or overlying aquifers under non-pumping conditions is also possible, though less likely the cause based upon our analysis.

We are unsure of the source of water-level data that Hiss used to develop the flow regimes in Figure 27 of INTERA (2013). It is therefore speculative where the point of convergence between eastward groundwater flow from the Guadalupe Mountains and Pecos River and northward groundwater flow from the Glass Mountains would be located before and after the Pecos River incision and if it moved in post-development times. One would question whether pumping in one of many well fields in the Capitan Reef Complex Aquifer would have the ability to completely change the aquifer flow system.

The report states on Page 59 that "[t]here are only two wells in New Mexico—both in Eddy County—and no water-level measurements in Lea County, New Mexico…" please also consider the water levels measured in groundwater wells ICP-WS-01 (CP-01056) and ICP-WS-02 (CP-

01057), which are discussed on page 5 of INTERA (2013). These water-supply wells were drilled in early 2012 by ICP in Lea County, NM as part of the Ochoa Project.

That statement refers to the data available at the time the draft report was written. These additional wells do not change the fact that water-level data is sparse and therefore an issue in model calibration.

In addition to the data mentioned in the previous comment, water levels have been measured on a quarterly basis since November 2012 from seven wells previously described in Hiss (1975). These measurements have been collected by the U.S. Geological Survey for the Bureau of Land Management Carlsbad Field Office. Measurements have been recorded from the North Cedar Hills Unit 1, City of Carlsbad Well 13 (La Huerta East Well), City of Carlsbad Test Well 3 (Miller-Nix-Yates 1), South Wilson Deep Unit 1, North Custer Mountain Unit 1, Federal Davison 1, and Southwest Jal Unit 1 monitoring wells described in Hiss (1975). The data show that the water levels in wells east of the West Laguna Submarine canyon have rebounded hundreds of feet since some of the last measurements were recorded in 1980. Given the importance of these data, the Board is encouraged to contact Mr. David Herrell of the BLM Carlsbad Field Office to discuss the data. Mr. Herrell can be reached at (575) 234-5972 and has been provided with a copy of these comments.

We will contact the Bureau of Land Management to obtain this water-level data and incorporate as appropriate.

It is assumed that the water-level measurements presented in Figure 4.2.3 are from during or before the 1980's, closer in time to when this area of the Capitan Reef Complex Aquifer was stressed due to pumping to supply water flooding projects. Since pumping has stopped, recent observations (e.g., United States Geological Survey/Bureau of Land Management measurements) indicate a rebound in water levels in Lea County as far south as the Southwest Jal Unit 1 well near the Texas-New Mexico state line. The report shows a rapid rebound in well 46-32-309 in Figure 4.2.14, also after records indicate pumping of the Capitan Reef Complex Aquifer for water flooding projects ceased. The convergence that is evident in the data presented by Hiss (1980) seems more likely to be caused primarily from pumping rather than the two options suggested in this draft report based upon our analysis. We would recommend that the Board consider and discuss this third option as well.

Figure 4.2.3 is modified from Hiss (1980) but the original map appeared in Hiss (1975; Figure 23). The water levels in Figure 4.2.3 were measured over a period of time ranging from the 1950s through the early 1970s. It is difficult to make inferences on regional-scale changes in aquifer water levels based on a single well. The water-level rebound observed on well 46-32-309 during the late 1970s does not correspond with a period of increasing oil and gas drilling but it does coincide with similar water-level responses observed in overlying aquifers that correspond to changes in non-petroleum related pumping. The available water-level and pumping data are *insufficient to support groundwater convergence due to pumping in an aquifer that has no surficial discharge zone and therefore must discharge through cross-formational flow.*

Figures 4.2.13 and 4.2.14: Please consider adding to these figures information presented in Figure 28 and Appendix C in INTERA (2013) for additional wells with transient data in Lea County and Eddy County, New Mexico.

We add these water-level data if they provide additional information to the figures.

Figure 4.2.2 and the 3rd paragraph on Page. 58 do not seem pertinent to the conceptual model. Figure 4.2.3 presents the post development water levels in the Capitan Reef aquifer modified from the work originally developed by Hiss (1975, Figure 23). Hiss (1975) divided the water levels into various groups: 1) head measured in basin aquifers where the hydraulic communication with the Capitan Reef was poor, 2) head measured in the Capitan and shelf aquifers where the communication is good between Capitan Reef Complex Aquifer and shelf aquifers, and 3) head measured in shelf aquifer where hydraulic communication is poor with the Capitan Reef Complex Aquifer. These are important hydraulic distinctions that have been removed in Figure 4.2.3.

Figure 4.2.2 and the associated discussion in the text discuss the influence of the Pecos River—the proposed northern boundary of the groundwater availability model—on the groundwater flow system of the Capitan Reef Complex Aquifer and is therefore relevant to the conceptual model. Hiss classified the water-level contours into three groups. The modified map only shows water levels in the Capitan Reef Complex Aquifer and surrounding shelf and basin stratigraphic units and is not intended to indicate hydraulic connectivity. Hydraulic connections between the Capitan Reef Complex Aquifer and the basin and shelf stratigraphic units are discussed in the text.

Hiss (1975) and Hill (1996, p. 263) discuss the potentiometric trough in the northern part of the eastern arm of the Capitan Reef Complex Aquifer. Groundwater west of the trough flows toward the Pecos River, and groundwater east of the trough flows toward the Hobbs channel where groundwater discharges from the Capitan Reef Complex Aquifer.

In the text, we discuss groundwater discharge by lateral cross-formational flow in addition to vertical cross-formational flow.

It is important to note that the post development water levels are about 200 feet lower than predevelopment water levels (Hiss, 1975). Therefore, it is recommended to include the predevelopment water levels for the Eastern Arm of the Capitan Reef Complex Aquifer developed by Hiss (1975, Figure 22).

The pre-development water levels shown in Figure 22 of Hiss (1975) are identical to the post-development water levels in Figure 3 in Hiss (1980)—the source of Figure 4.2.3 in this report.

Including the pre-development water levels from Figure 2 in Hiss (1980) is not appropriate due to numerous errors such as intersecting contours and numerous contours that are not based on actual water-level data.

Page 58, 4th paragraph: The convergence of groundwater elevation contours in Winkler County is a result of lateral eastward flow (discharge) to the shelf aquifer, and Capitan Reef Complex Aquifer pumping from Winkler and Ward Counties that occurred between 1960 and 1970. There is no evidence that discharges from the Capitan Reef Complex Aquifer occurred through 2,000 feet of aquitard into the overlying Monument Draw Trough collapse feature in Winkler County. However, it may be possible that some vertical flow occurs from the Capitan Reef Complex Aquifer to the Rustler Formation locally where sink holes have formed (see discussion in Hill, 1996).

The convergence of southward and northward groundwater flow in the Capitan Reef Complex Aquifer in Winkler County results from multiple factors. Vertical cross-formational flow cannot be ruled out considering: 1) the amount of subsidence that took place due to the dissolution of the overlying Salado Formation (Jones, 2001; 2004; 2008), 2) the coincidence of the Capitan Reef Complex Aquifer and the Monument Draw Trough, 3) the relatively high hydraulic conductivity zones in the overly Rustler and Dockum aquifers (Ewing and others, 2008; 2012) that coincide with the Monument Draw Trough and would provide a pathway for upward groundwater flow, and 4) the vertical hydraulic gradients between the Capitan Reef Complex Aquifer and overly aquifers.

The cited references (Jones, 2001, 2004, and 2008) stated *"Cross-formational flow from underlying saline Permian aquifers is also enhanced due to increasing municipal and industrial pumpage in the Monument Draw Trough portion of the Pecos Valley Aquifer (Jones, 2004)."* This statement is in reference to municipal pumping in central Ward County, where there appears to be a correlation between increasing total dissolved solids with pumping over time. Under heavy pumping conditions at the City of Pecos Ward well field, the total dissolved solids increased about 150 milligrams per liter over a 12-year period (see Jones, 2004, Figure 6-13). A review of water quality data from the area of wells used to construct Jones (2004) Figure 6-13 suggests these slight increases in total dissolved solids could also be attributed to capture of shallow groundwater directly east or south of the pumping wells. This captured groundwater may be elevated in total dissolved solids resembling sodium-chloride type water from oil field brine impacts.

It is difficult to conclude that groundwater salinity changes over time that have a direct relationship with water-level decline are related to oil field brine contamination based on only three wells and without enough spatially distributed data to indicate shallow sources of oil field brine contamination.

Hill (1996, p. 263) states “Some of the water in the Capitan Aquifer of the Glass Mountains moves eastward before reaching a point west of Fort Stockton, and the remainder of the water apparently moves northward along the reef to finally exit the basin via the Hobbs channel.” Researchers have performed a detailed analysis of geophysical logs (API 49532997, 49532160, and 49532177) from wells drilled into the Winkler County portion of the Monument Draw Trough and found that several thousand feet of evaporate beds overlie the Capitan Reef Complex Aquifer, thereby reducing the likelihood for vertical flow into the Santa Rosa Sandstone (Dockum) or Pecos Valley alluvium aquifers. Furthermore, there are no water quality data in the shallow aquifers to support the concept of discharge from the Capitan Reef Complex Aquifer via vertical cross formational flow.

The Monument Draw Trough collapse structure extends into New Mexico and coincides with the Capitan Reef Complex. The Monument Draw Trough is described as a series of coalesced collapse features—breccia pipes—similar to sinkholes (Meyer and others, 2012). These breccia pipes can transmit groundwater vertically from the Capitan Reef Complex Aquifer through the Salado Formation to overlying aquifers and are apparent in the structure of the Rustler Formation (Hiss, 1976). Over the Capitan Reef Complex Aquifer the Salado Formation is much thinner than elsewhere due to dissolution by groundwater derived from the Capitan Reef Complex Aquifer. Because of the occurrence of these breccia pipes, the occurrence of several hundred feet of evaporite beds over the Capitan Reef Complex Aquifer is unlikely to prevent vertical groundwater discharge. The concept of vertical groundwater flow from the Capitan Reef Complex Aquifer to overlying aquifers is also supported by other authors, such as Hiss (1976) and Veni (1991) who associated this flow with surface discharge from Diamond Y Springs. Additional evidence of extensive cross-formational flow can be seen in the overlapping geochemical and isotopic compositions of groundwater in the Capitan Reef Complex and overlying aquifers.

Figure 4.2.12(a) compares water level elevations between the Edwards-Trinity (52-32-701) and Capitan Reef Complex Aquifer (52-40-101) aquifers. Well 52-40-101 is a hand dug well on a hillside at the old Sanderson Camp on the La Escalera Ranch; researchers performed a field check of this well during April 2014 and found it to be related to a localized perched groundwater system. The aquifer designation for 52-32-701 is not accurate. Based on researchers’ field check, this well is located on the mapped portion of the Capitan Reef Complex Aquifer and drilled into the Capitan Reef Complex Aquifer, and is therefore not an Edwards Trinity well. The water level from 52-32-701 (owner’s name is Pump Jack Well, also JJ-17 in B6016) is representative of the Capitan Reef Complex Aquifer.

We deleted Figure 4.2.12(a) and adjusted the other associated figures as appropriate.

Figure 4.2.12(a-e): It is difficult to see the difference in head due to the y-axis scale.

We revised these figures using a smaller y-axis range.

4.3 Recharge

Page 78, 2nd paragraph: This section should include the concept of recharge to karst terrains, and present some type of analysis and estimate of recharge that relates to the observed conditions in the Glass Mountains and Sierra Madera. Based on researchers' analysis of precipitation data for the area, recharge is not significantly controlled by topography as stated in this paragraph.

We added text mentioning karst features as potential pathways for recharging water to the aquifer. Topography plays a role in recharge to the Capitan Reef Complex Aquifer because the aquifer outcrops—potential recharge zones—all coincide with mountains, such as the Guadalupe, Apache, and Glass mountains. One would expect that the role played by topography in influencing amounts of recharge would be greater in the high relief of the Guadalupe Mountains than in the Glass Mountains. We also revised the text to incorporate recharge estimates from Finch (2014).

Page 79, 1st paragraph: There is a lot of reliance on age-dating of groundwater to make inferences about recharge to the Capitan Reef Complex Aquifer. The validity of isotope analysis depends on well construction and representative section of aquifer sampled.

In this case, groundwater isotopes are used qualitatively—comparing changes in the groundwater isotopic composition in different parts of the aquifer. This indicates relatively ages of groundwater and conditions under which recharge occurred. Comparison of groundwater isotopic compositions in the Capitan Reef Complex and overlying aquifers indicate overlapping composition ranges in all of the aquifers in the study area.

INTERA (2013) and Ewing and others (2012) recharge estimates are weakly supported by data and analysis. Researchers' analysis of recharge for the Glass Mountain area uses daily precipitation statistics and outcrop characteristics.

We revised the text to incorporate recharge estimates from Finch (2014).

4.4 Rivers, Streams, Springs, and Lakes

Page 81, Section 4.4.1: It is suggested the Board consider the discussion presented on page 14 of Barroll et al. (2004), which indicates that groundwater still flows from the Capitan Reef Complex Aquifer into the alluvial aquifer and into the Pecos River. It is further suggested the Board also consider the influence of discharge through pumping for municipal, industrial, and irrigation uses along this reach in addition to the presence of Lake Avalon.

Please note that the Pecos River near Carlsbad, New Mexico is peripheral to this project which is primarily focused on the Texas portion of the aquifer. Groundwater discharge from underlying aquifers, including the Capitan Reef Complex Aquifer, is discussed in Section 4.4.2.

4.5 Hydraulic Properties

Page 88, Section 4.5.1: There are estimates of specific capacity, transmissivity, hydraulic conductivity and storativity presented in INTERA (2012) that are not mentioned in this section. Estimates for each property are provided in INTERA (2012) based on both single well tests and aquifer testing. It is suggested that the number of estimates for each property be updated and that the statement in the last paragraph of this section ".. no estimates of storativity were found for the Capitan Reef Complex Aquifer." be revised It is also suggested that Figure 4.5.1 and Table 4.5.1 be updated to include the data presented in INTERA (2012), as they represent recent results for hydraulic property data in the area of interest.

The text and applicable figure and table have been revised to include these hydraulic property data.

Page 88, Section 4.5.2: Please consider adding to this section the estimate of horizontal hydraulic conductivity presented in INTERA (2012). This estimate, which was obtained from an aquifer test that was completed using two wells that fully penetrated the thickness of the Capitan Reef Complex Aquifer, could be useful to both the conceptual and numerical models of this aquifer.

The report states on page 89 that "A model by INTERA and Cook-Joyce (2012) used a uniform horizontal hydraulic conductivity of 20 feet per day and a vertical hydraulic conductivity of 2 feet per day." In place of this statement, it is suggested that the Board consider discussing the more recent approach described in INTERA (2013) where eight (8) zones of hydraulic conductivity were established through model calibration. Doing so would acknowledge the variability in hydraulic conductivity recognized in previous modeling work for the CRCA.

The text was revised to replace discussion of the INTERA and Cook-Joyce (2012) model with INTERA (2013).

Page 91, Section 4.5.3: As stated a comment above, the storativity value discussed in INTERA (2013) and presented in INTERA (2012) can be referenced as a Capitan Reef Complex Aquifer storativity value based on recent field tests.

The text was revised to include the storativity data.

There is a reported transmissivity for a well in Pecos County (45-49-203, Enstor-Waha WW Site) that is not listed in Table 4.5.2 (horizontal hydraulic conductivity is about 24.8 feet/day).

We added this well to Table 4.5.1 and Figure 4.5.1.

Between 1955 and 1970 significant volumes of water were pumped from the Capitan Reef Complex Aquifer in Lea County, New Mexico and Winkler and Ward Counties, Texas. The pumping caused widespread drawdown from Lea County to the Glass Mountains (Hiss, 1975). This type of aquifer response would imply high transmissivity in a confined karst type aquifer.

The hydraulic property data in this report suggest that the transmissivity in the Capitan Reef Complex Aquifer is much higher than in the surrounding fore- and back-reef stratigraphic units.

There is a good description of regional hydraulic conductivity distribution by Hiss (1975), where he states "hydraulic conductivity of the Capitan aquifer probably averages 5.0 feet/day in most of Southern Lea County, New Mexico, but appears to increase progressively southward to an estimated 10.0 feet/day near the Pecos-Brewster County line. The hydraulic conductivity in the Glass Mountains is probably very high because of the numerous small caverns developed in this area."

The data in Figure 4.5.2 do not support the Hiss (1975) statement; however, we will take it under consideration during model calibration.

4.6 Discharge

Page 102-123, Section 4.6.2: Because historic records indicate that pumping of groundwater from the Capitan Reef Complex Aquifer for water flooding projects began in earnest in the 1950's (see Figure 38 of Hiss, 1975), it is suggested that the report discussion be expanded to capture these pre-1980 uses. To our knowledge, pumping-rate data are not available outside of Hiss (1975) for many of the major groundwater well fields in Lea County, New Mexico and Ward and Winkler Counties that supplied water for secondary oil recovery projects. For example, major groundwater well fields developed in the Capitan Reef Complex Aquifer included the Jal, Dollarhide, El Capitan, Grisham-Hunter, Wink, O'Brien, and Wicket well fields. Though pumping data are not available, Hiss (1975) does provide hydraulic heads associated with these stresses, with data available from 1967 through 1972. Although the discussion of this early period may be lacking specificity in terms of pumping volumes, we believe the potential importance of pumping in the pre-1980 period warrants discussion.

Because the domain of the conceptual model includes Eddy and Lea County, New Mexico, it is suggested that the discussion in this section be expanded to include discharge through pumping that occurs in New Mexico. Expanding the discussion to include New Mexico would be appropriate given the extent of the model and the different uses of the Capitan Reef Complex Aquifer compared to Texas. For example, the report states "Irrigation pumping from the Capitan Reef Complex Aquifer is likely to be minimal considering issues of aquifer depth, groundwater quality, and the occurrence of alternative sources of irrigation water." It is assumed that this statement is intended to only apply to a discussion of pumping in Texas, but suggest clarification given that much pumping from the Capitan Reef Complex Aquifer for irrigated agriculture occurs in Eddy County, New Mexico. Consider, for example, the present water uses for the Capitan Underground Water Basin discussed in the Lower Pecos Valley Regional Water Plan (PVWUA, 2001).

We added mention of the pumping estimates from Hiss (1975) to the text.

4.6.1 Natural Aquifer Discharge largely discusses upward discharge through cross formational flow, and neglects the data and analysis by Hiss (1975) supporting lateral cross formational flow from the Capitan Reef Complex Aquifer to the shelf aquifer to the east. Hiss (1975) wrote "Stratigraphically, the Capitan Aquifer is adjacent to, and partly enclosed by, the basin and shelf aquifers. Because of the position and the relatively higher transmissivity, it functions either as a drain or as a source of water for the shelf and basin aquifers, depending on the relative differences in head between the aquifers….. Water in the Capitan Aquifer on the east side of the ground-water divide moved eastward toward a point northeast of Eunice, where it then flowed into the San Andres Limestone and other formations in the Artesia Group as noted above."

Term 'cross-formational flow' refers to groundwater discharge from the Capitan Reef Complex Aquifer to adjacent stratigraphic units irrespective of whether that flow is lateral or vertical. Discharge by lateral cross-formational flow is discussed in Section 4.2. Figure 4.2.3 indicates little interaction between the Capitan Reef Complex Aquifer and basin stratigraphic units and data supporting interaction between the Capitan Reef Complex Aquifer and the shelf stratigraphic units is limited to the New Mexico portion of the study area. However there is a lot of hydrologic, structural geologic, and geochemical data supporting vertical cross-formational flow discharge.

See comments for Section 4.2.

See response above.

4.6.2 Aquifer Discharge through Pumping

The report only includes pumping from 1980 to 2008, when the heaviest pumping occurred from Ward and Winkler County between 1950 and 1970. Researchers have compiled pumping and water level data to assist with model development and calibration.

We would welcome any pumping and water-level data that you have to aid in model development and calibration. The period—1980 through 2008—is the period for which the most readily available pumping data is available. However, we will not restrict the model calibration period to this period of time.

4.7 Water Quality

It is suggested the publically available groundwater quality data from the Jal Water System of Lea County, New Mexico be added to the discussion. The system consisted of seven wells that once supplied water for oil flooding projects and are now plugged and abandoned.

We included New Mexico groundwater quality in Figures 4.7.1 through 4.7.4 and revised the text where appropriate.

Fresh water in the Capitan Reef Complex Aquifer is not restricted to the outcrop area, but instead to the unconfined aquifer area. Researchers have developed a map showing the distribution of water quality in the Capitan Reef Complex Aquifer using data from Hiss (1976) and John Shomaker and Associates Inc. (2014).

In this report, we assume that outcrop and unconfined areas of the Capitan Reef Complex Aquifer are synonymous.

Figure 4.7.2 nicely separates data points between east and west Capitan Reef Complex Aquifer. A plot of sulfate versus chloride for the east Capitan Reef Complex Aquifer data points would further support the change in chemistry along the groundwater flow path down dip from the Glass Mountains to Ward County.

A plot of sulfate versus chloride would not provide additional information that is not apparent in Figure 4.7.2.

Page 125, 2nd paragraph: It would appear that using Carbon isotopes for analysis of age dating the Capitan Reef Complex Aquifer would be complicated by carbonate rocks and carbonate geochemistry.

We are not using carbon-14 for quantitative age dating. That would require complex corrections to address the issues that you pointed out in this comment. Instead, we are using carbon-14 qualitatively to compare carbon-14 concentrations at different locations along flow paths. We assume the principle of decreasing carbon-14 with increasing average groundwater residence time in the aquifer.

5.0 CONCEPTUAL MODEL OF GROUNDWATER FLOW IN THE AQUIFER

Page 140: It is acknowledged that communication is possibly occurring between the Capitan Reef Complex Aquifer and overlying aquifers in the area of the Monument Draw Trough where the Salado Formation is absent. However, a more important control on historical groundwater flow direction that would explain this convergence of flow in Winkler County is the large volume of pumping that occurred in that area before and during those water-level measurements (e.g., see Brackbill and Gaines, 1964; Hoestenbach, 1982).

The interpretation of sparse data throws a lot of certainty on the location(s) of flow convergence in the Capitan Reef Complex Aquifer inferred in Hiss (1975). One needs to ask whether pumping over the past 50 years was enough to dramatically change the flow system in the Capitan Reef Complex Aquifer.

Page 142, Figure 5.0.1.: An explanation in the legend of what each arrow indicates is currently missing for dashed vs. solid lines. Assuming that the arrows indicate the direction (and magnitude?) of groundwater flow, the vertical flow of water through the Salado Formation into the overlying Rustler, Dockum, and Pecos Alluvial Aquifers is questionable. For example, Beauheim et al. (1991) report that the hydraulic conductivity of the overlying halite and anhydrite intervals of the Salado Formation are extremely low compared to other rock types, interpreted to be on the order of 1.2×10^{-9} to 3.5×10^{-6} m/day. However, the graphic shows water moving through the Salado with arrows the same size or larger than some of the arrows that depict horizontal movement. The size of the arrows may mislead readers to believe that size corresponds to flow rate, which is presumably not the intention of this figure.

We revised the figure in response to this comment. Groundwater discharge through the Salado Formation likely occurs through breccia pipes which would have hydraulic conductivity values much higher than undisturbed halite and anhydrite. The arrows in this figure indicate general directions of flow and should not be interpreted to indicate flow magnitudes.

Perhaps the section title should be rephrased to CONCEPTUAL MODEL OF GROUNDWATER IN THE EASTERN ARM OF THE CAPITAN REEF COMPLEX AQUIFER.

We revised the title of this chapter to "The Conceptual Model of Groundwater Flow in the Eastern Arm of the Capitan Reef Complex Aquifer".

Page 140, 2nd paragraph: The boundaries and geometry of the Capitan Reef Complex Aquifer on the north end of the Glass Mountains will change from Hiss (1975) and Standen and others (2009) if the Tessey Limestone is included with the Capitan Formation. The eastern arm does not contain Carlsbad Limestone or Goat Seep Limestone.

The Standen and others (2009) boundaries for the Capitan Reef Complex Aquifer include the Tessey Formation.

Page 140, 4th paragraph: The primary path for discharge is stated as upward cross formational flow. However, this conclusion is not fully supported by the data and analysis from Hiss (1975) and Hill (1996).

We revised this paragraph slightly, but it already included discussion of cross-formational flow discharge through back-reef stratigraphic units. Evidence for vertical cross-formational flow discharge is discussed in this paragraph.

Figure 5.01 is a great depiction of the conceptual model, but the formation thicknesses are not proportional making the flow paths misleading. It would help to illustrate the aquitards in Figure 5.01 and the transition from unconfined to confined aquifer system.

We revised Figure 5.0.1 based on Figure 2.2.9 to better represent formation thicknesses.

Page 141, 2nd paragraph, 5th sentence: Geophysical log analysis has shown that the salt beds of Salado and Castile are not absent in the Monument Draw Trough. The Dewey Lake redbeds act as a significant aquitard separating groundwater flow in the Permian rocks from the overlying formations. It is my understanding that dissolution of the Castile Formation happened slow enough for contemporaneous subsidence and filling of the Monument Draw Trough. As a result, the overlying Salado salt beds and Dewey Lake redbeds remained intact (deformed without faulting and fracturing), and continued to act as confining layers.

We revised the paragraph to more accurately describe the Salado Formation and the mechanism for vertical cross-formational flow from the Capitan Reef Complex Aquifer to the overlying aquifers through the formation of breccia pipes through the Salado and Castile formations. Please note: that in the Monument Draw Trough, the overlying aquifers—the Rustler and Dockum aquifers—are characterized by relatively high hydraulic conductivities probably caused by fracturing associated with subsidence (Ewing and others, 2008; 2012). Also, because of the subsidence the Rustler Formation within the Monument Draw is disconnected from the rest of the formation (Ewing and others, 2012).