# CHAPTER 3
# WATER SUPPY ANALYSIS
# DRAFT June 2009

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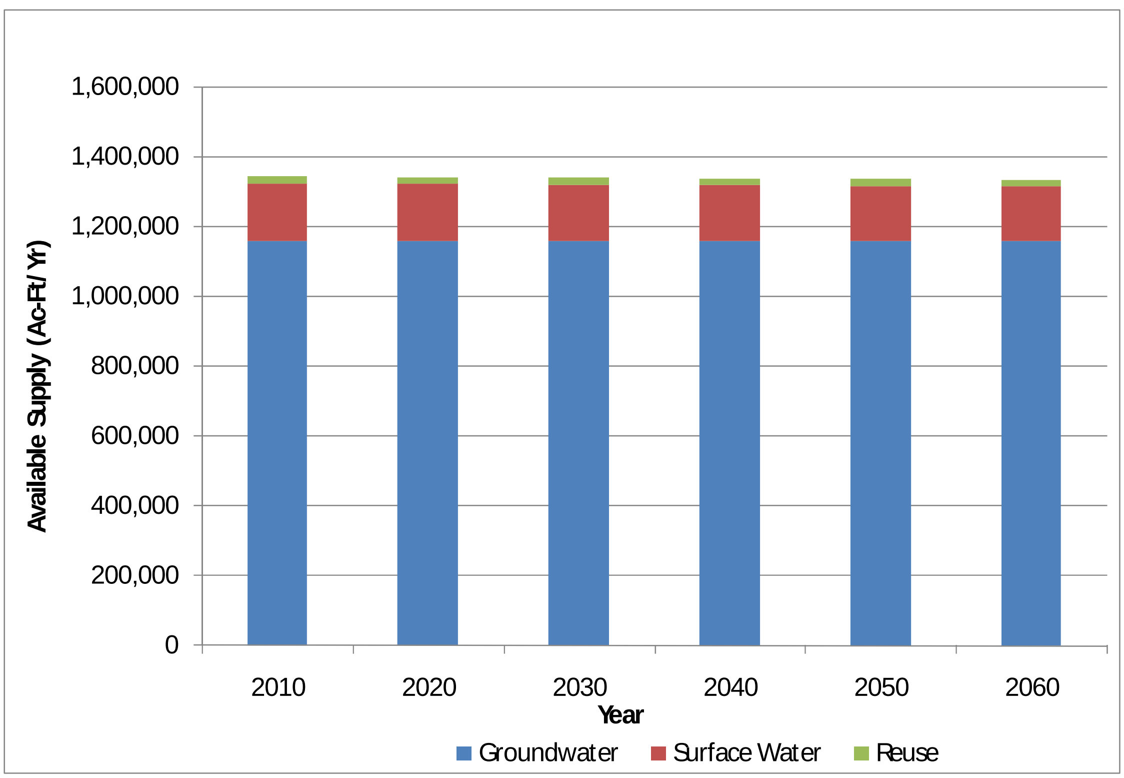
## Appendices

# 3 WATER SUPPLY ANALYSIS

In Region F, water comes from surface water sources such as run-of-the-river supplies and reservoirs, groundwater from individual wells or well fields, and from alternative sources such as reuse or desalination. Figure 3.1-1 shows the amount of water within Region F that is available for use. This supply generally does not include infrastructure or contract limitations, but does represent the amount of reliable supply that is currently available. Groundwater is the largest source of water supply available in Region F. Surface water supplies in Figure 3.1-1 are significantly reduced because of the assumptions used in the Colorado River Basin Water Availability Model (WAM) (see Section 3.2). A small amount of reuse is currently being used in the region.

**Figure 3.1-1**
**Water Availability by Source Type**



## 3.1 Existing Groundwater Supplies

Texas is in the midst of a Joint Planning initiative for groundwater. Joint Planning is conducted by the Groundwater Conservation Districts (GCDs) in the Groundwater Management Areas (GMAs) and is sometimes referred to as GMA planning. The counties in Region F fall in GMA-7, GMA-4, GMA-2, and GMA-8. The Texas Water Code now requires that RWPGs rely on the Managed Available Groundwater (MAG) estimates that are determined from the Desired Future Conditions (DFCs) in each GMA. Since the last planning cycle, the GCDs have been meeting in their respective GMAs to discuss approaches for determining DFCs and MAGs, and the TWDB has assisted the GMAs by running several model runs with the GAMs (known as "GAM runs") to help estimate the impacts from potential DFCs. However, at this time, the only MAG that has been determined is in GMA-8 for the Trinity Aquifer in Brown County. The TWDB documented this MAG in GAM Run 08-84mag. Therefore, the only groundwater availability that has been modified since the 2006 RWP is for the Trinity Aquifer in Brown County.

In 2004, groundwater sources supplied 338,000 acre feet of water, accounting for 63 percent of all water used in the region. Groundwater provides most of the irrigation water used in the region, as well as a significant portion of the water used for municipal and other purposes. Groundwater is primarily found in four major and seven minor aquifers that vary in quantity and quality (Figures 1.2-1 and 1.2-2). The following discussion describes each of these aquifers, including their current use and potential availability. Section 3.1.12 discusses the supply of brackish groundwater potentially available for desalination treatment.

From a planning perspective, groundwater availability should be defined based on locally accepted water use and management policy considerations. These management policy decisions are expressed in the rules and management plans of the various groundwater conservation districts in the region. Some districts consider recharge only, while other districts may consider recharge and an acceptable level of aquifer depletion over time. In some cases, groundwater availability may be limited by the economics of water treatment. For those counties in the region that are not governed by a groundwater conservation district, aquifer availability is based on historical use trends. Figure 1.3-4 shows the counties currently governed by groundwater conservation districts.

Groundwater availability by aquifer and river basin within each county is listed in Table 3.1-1. As discussed above, the availability volumes listed in this table represent an acceptable level of aquifer withdrawal in each county based on policy decisions that attempt to maintain water levels in the aquifers at desired levels (Figure 3.1-2). Also of consideration in much of the region is the desire to maintain aquifers such that springflow and associated base flow to rivers and streams are protected. It is, however, recognized that in times of severe drought, reduction in springflow and surface water flow will likely occur regardless of management policies.

With the exception of Brown County (Trinity Aquifer), for which groundwater availability was determined via a GAM run (GAM Run 08-84mag) by the TWDB, the quantification of groundwater availability considers both aquifer recharge and water held in storage in the aquifer matrix. Groundwater availability is defined by the following formula:

*Availability = Drought Year Recharge + Annual Supply from Storage*

The amount of water available from storage may be either 0 (no water from storage, limiting supply to recharge only), 75 percent of the recoverable volume in storage divided by 50 years, or 75 percent of the recoverable volume in storage divided by 100 years (see Figure 3.1-2).

For the 2006 Region F Water Plan, the draft Edwards-Trinity (Plateau) Groundwater Availability Model (ETPGAM) was used as a source to estimate recharge estimates for counties in Region F. At that time, the draft recharge estimates in the Edwards-Trinity (Plateau) GAM for the Edwards-Trinity aquifer were assumed to be one half of average annual recharge as provided. Since the 2006 Region F Water Plan was completed, the Edwards-Trinity (Plateau) GAM has been finalized. Therefore, the final recharge estimates from the ETPGAM were extracted from the model for each county and compared to the draft recharge estimates that were used in the last round of planning. The drought-of-record (DOR) recharge for the Edwards-Trinity (Plateau) aquifer for all of Region F that was estimated from the final ETPGAM was 290,000 af/yr, which is 60,920 af/yr less than the 350,920 af/yr calculated from the draft ETPGAM. The final DOR recharge equates to 83% of the DOR recharge that was estimated in the previous round of

**Table 3.1-1**
**Groundwater Availability in Region F**
(Values in Acre-Feet per Year)

| County | Aquifer | Basin | Annual Recharge During Drought [a] | Annual Supply from Storage | Annual Availability |
|---|---|---|---|---|---|
| Andrews | Cenozoic Pecos Alluvium | Rio Grande | 685 | 504 | 1,189 |
| | Dockum | Colorado | 0 | 905 | 905 |
| | | Rio Grande | 0 | 5,792 | 5,792 |
| | Ogallala | Colorado | 22,427 | 8,852 | 31,279 |
| | | Rio Grande | 3,293 | 1,040 | 4,333 |
| | Edwards-Trinity | Colorado | 4,205 | 435 | 4,640 |
| Borden | Dockum | Colorado | 0 | 117 | 117 |
| | Ogallala | Brazos | 0 | 108 | 108 |
| | | Colorado | 300 | 482 | 782 |
| Brown | Ellenburger-San Saba | Colorado | 0 | 0 | 0 |
| | Hickory | Colorado | 0 | 0 | 0 |
| | Trinity | Brazos | na | na | 28 |
| | Trinity | Colorado | na | na | 2,017 |
| Coke | Dockum | Colorado | 12 | 0 | 12 |
| | Edwards-Trinity | Colorado | 3,242 | 0 | 3,242 |
| Coleman | Ellenburger-San Saba | Colorado | 0 | 0 | 0 |
| | Hickory | Colorado | 0 | 0 | 0 |
| Concho | Edwards-Trinity | Colorado | 11,869 | 409 | 12,278 |
| | Hickory | Colorado | 0 | 14,299 | 14,299 |
| | Lipan | Colorado | 5,984 | 529 | 6,513 |
| Crane | Cenozoic Pecos Alluvium | Rio Grande | 2,537 | 0 | 2,537 |
| | Dockum | Rio Grande | 0 | 0 | 0 |
| | Edwards-Trinity | Rio Grande | 115 | 0 | 115 |
| Crockett | Dockum | Rio Grande | 0 | 0 | 0 |
| | Edwards-Trinity | Colorado | 636 | 0 | 636 |
| | | Rio Grande | 24,824 | 0 | 24,824 |
| Ector | Cenozoic Pecos Alluvium | Rio Grande | 1,059 | 1,845 | 2,904 |
| | Dockum | Colorado | 0 | 2,498 | 2,498 |
| | | Rio Grande | 0 | 3,479 | 3,479 |
| | Edwards-Trinity | Colorado | 9,027 | 1,103 | 10,130 |
| | | Rio Grande | 1,059 | 135 | 1,194 |
| | Ogallala | Colorado | 4,850 | 999 | 5,849 |
| Glasscock | Dockum | Colorado | 0 | 140 | 140 |
| | Ogallala | Colorado | 940 | 2,988 | 3,928 |
| | Edwards-Trinity | Colorado | 17,420 | 3,518 | 20,938 |

**Table 3.1-1: Groundwater Supplies in Region F (continued)**

| County | Aquifer | Basin | Annual Recharge During Drought [a] | Annual Supply from Storage | Annual Availability |
|---|---|---|---|---|---|
| Howard | Dockum | Colorado | 0 | 900 | 900 |
| | Edwards-Trinity | Colorado | 1,606 | 94 | 1,700 |
| | Ogallala | Colorado | 2,610 | 7,799 | 10,409 |
| Irion | Dockum | Colorado | 0 | 0 | 0 |
| | Edwards-Trinity | Colorado | 9,445 | 0 | 9,445 |
| Kimble | Edwards-Trinity | Colorado | 23,965 | 0 | 23,965 |
| | Ellenburger-San Saba | Colorado | 216 | 0 | 216 |
| | Hickory | Colorado | 0 | 0 | 0 |
| Loving | Cenozoic Pecos Alluvium | Rio Grande | 457 | 3,906 | 4,363 |
| | Dockum | Rio Grande | 0 | 860 | 860 |
| Martin | Ogallala | Colorado | 7,760 | 11,642 | 19,402 |
| | Edwards-Trinity | Colorado | 2,895 | 503 | 3,398 |
| Mason | Edwards-Trinity | Colorado | 3,205 | 623 | 3,828 |
| | Ellenburger-San Saba | Colorado | 3,537 | 1,113 | 4,650 |
| | Hickory | Colorado | 21,521 | 54,971 | 76,492 |
| McCulloch | Edwards-Trinity | Colorado | 7,735 | 514 | 8,249 |
| | Ellenburger-San Saba | Colorado | 3,596 | 12,926 | 16,522 |
| | Hickory | Colorado | 3,419 | 122,726 | 126,145 |
| Menard [b] | Edwards-Trinity | Colorado | 15,357 | 0 | 19,000 |
| | Ellenburger-San Saba | Colorado | 159 | 0 | 159 |
| | Hickory | Colorado | 0 | 0 | 34,000 |
| Midland | Dockum | Colorado | 0 | 45 | 45 |
| | Ogallala | Colorado | 3,270 | 1,397 | 4,667 |
| | Edwards-Trinity | Colorado | 18,082 | 1,313 | 19,395 |
| Mitchell | Dockum | Colorado | 8,744 | 5,274 | 14,018 |
| Pecos | Dockum | Rio Grande | 0 | 1,089 | 1,089 |
| | Cenozoic Pecos Alluvium | Rio Grande | 50,050 | 8,528 | 58,578 |
| | Edwards-Trinity | Rio Grande | 91,014 | 23,835 | 114,849 |
| | Capitan Reef | Rio Grande | 0 | 34,000 | 34,000 |
| Reagan | Dockum | Rio Grande | 0 | 54 | 54 |
| | Edwards-Trinity | Colorado | 19,522 | 9,364 | 28,886 |
| | | Rio Grande | 1,629 | 720 | 2,349 |
| Reeves | Dockum | Rio Grande | 0 | 3,065 | 3,065 |
| | Cenozoic Pecos Alluvium | Rio Grande | 40,099 | 20,421 | 60,520 |
| | Edwards-Trinity | Rio Grande | 11,909 | 41,936 | 53,845 |
| Runnels | Lipan | Colorado | 4,536 | 0 | 4,536 |
| Schleicher | Edwards-Trinity | Colorado | 12,204 | 0 | 12,204 |
| | | Rio Grande | 3,960 | 0 | 3,960 |

**Table 3.1-1: Groundwater Supplies in Region F (continued)**

| County | Aquifer | Basin | Annual Recharge During Drought [a] | Annual Supply from Storage | Annual Availability |
|---|---|---|---|---|---|
| Scurry | Dockum | Brazos | 7,898 | 1,940 | 9,838 |
| | | Colorado | 3,226 | 3,159 | 6,385 |
| Sterling | Dockum | Colorado | 0 | 0 | 0 |
| | Edwards-Trinity | Colorado | 5,168 | 0 | 5,168 |
| Sutton | Edwards-Trinity | Colorado | 9,349 | 0 | 9,349 |
| | | Rio Grande | 11,426 | 0 | 11,426 |
| Tom Green | Dockum | Colorado | 0 | 54 | 54 |
| | Edwards-Trinity | Colorado | 14,373 | 664 | 15,037 |
| | Lipan | Colorado | 24,916 | 12,570 | 37,486 |
| Upton | Cenozoic Pecos Alluvium | Rio Grande | 803 | 275 | 1,078 |
| | Dockum | Rio Grande | 0 | 797 | 797 |
| | Edwards-Trinity | Colorado | 6,745 | 1,303 | 8,048 |
| | | Rio Grande | 8,511 | 1,292 | 9,803 |
| Ward | Cenozoic Pecos Alluvium | Rio Grande | 5,984 | 11,304 | 17,288 |
| | Dockum | Rio Grande | 0 | 2,340 | 2,340 |
| | Capitan Reef | Rio Grande | 0 | 12,000 | 12,000 |
| Winkler | Cenozoic Pecos Alluvium | Rio Grande | 3,727 | 48,267 | 51,994 |
| | Dockum | Rio Grande | 0 | 10,746 | 10,746 |
| | Edwards-Trinity | Colorado | 423 | 94 | 517 |
| | Capitan Reef | Rio Grande | 0 | 15,000 | 15,000 |
| *Total* | | | *589,535* | *541,600* | *1,170,815* |

a. Drought recharge was assumed to be equal to one half of average annual recharge.
b. Supplies for Menard County are from the Menard County Underground Water District management plan.

planning. Crane, Reeves, Sterling and Winkler counties have higher recharge in the final ETPGAM than in the draft ETPGAM and the remaining counties have a lower recharge.

Because the joint planning process is still underway for all the GMAs in Region F that manage the Edwards-Trinity (Plateau) aquifer and because MAGs have not been determined across the region, the groundwater availability estimates for the Edwards-Trinity (Plateau) aquifer were not modified from the 2006 Region F Water Plan.

Recharge for other aquifers in the region, along with water in storage estimates, were retained from the 2006 *Region F Water Plan*. These recharge estimates were from previous studies by TWDB.

# Groundwater Availability Determination

## Region F Water Plan

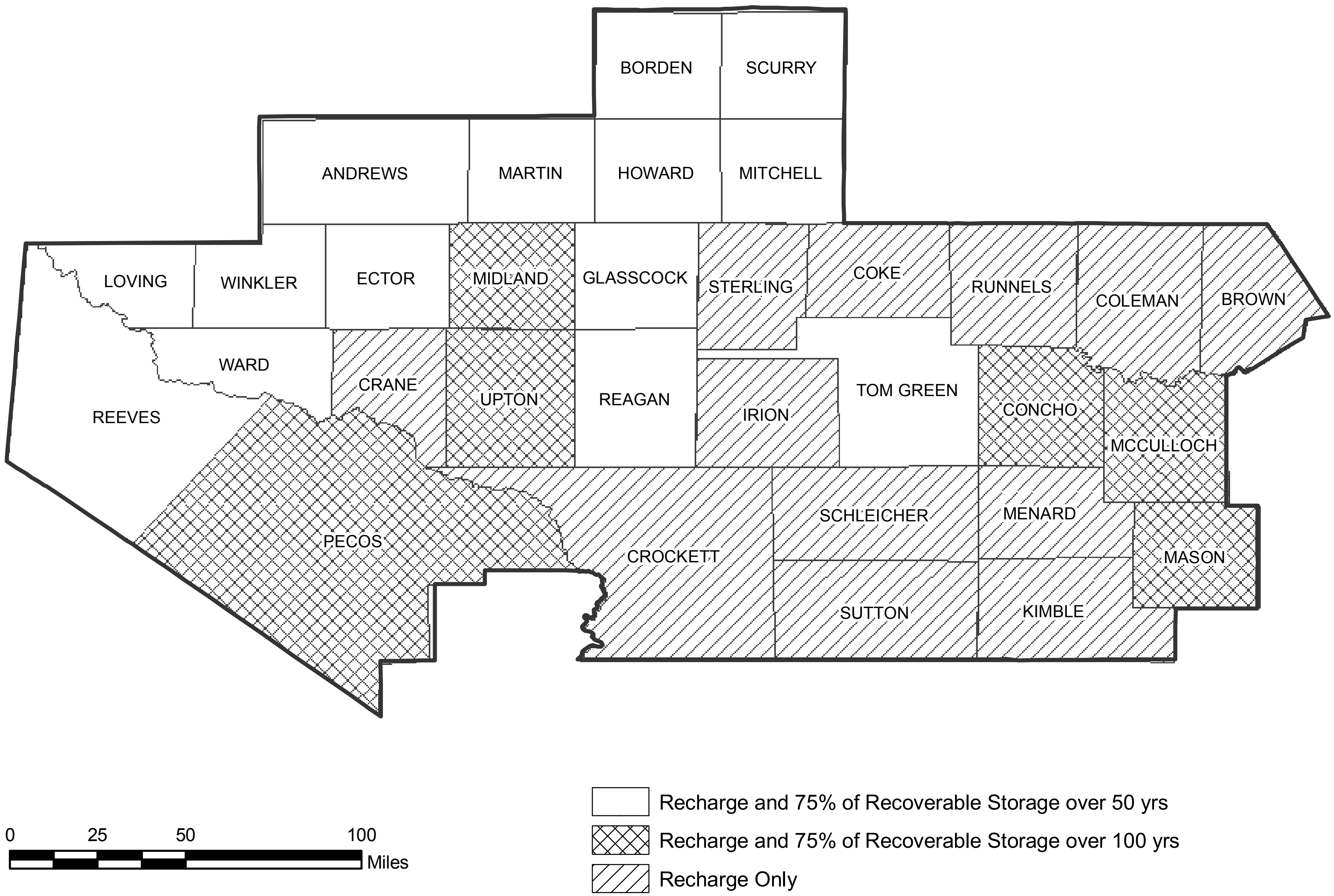



FIGURE 3.1-2

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### 3.1.1 Edwards-Trinity (Plateau) Aquifer

Extending from the Hill Country of Central Texas to the Trans-Pecos region of West Texas, the Edwards-Trinity (Plateau) aquifer is the largest aquifer in areal extent in Region F, occurring in 21 of the 32 Region F counties (Figure 3.1-3). This aquifer is comprised of water-bearing portions of the Edwards Formation and underlying formations of the Trinity Group, and is one of the largest contiguous karst regions in the United States. Regionally, this aquifer is categorized by the TWDB as one aquifer. However, in other parts of the state the Edwards and Trinity components are not hydrologically connected and are considered separate aquifers. The Trinity aquifer is also present as an individual aquifer in Eastern Brown County within Region F. More groundwater is produced from the Edwards-Trinity (Plateau) aquifer (approximately 34 percent) than any other aquifer in the region, three-fourths of which is used for irrigation and livestock watering. Many communities in the region use the aquifer for their public drinking-water supply as well.

The Edwards-Trinity (Plateau) aquifer is comprised of lower Cretaceous formations of the Trinity Group and limestone and dolomite formations of the overlying Edwards, Comanche Peak, and Georgetown. These strata are relatively flat lying, and located atop relatively impermeable pre-Cretaceous rocks. The saturated thickness of the entire aquifer is generally less than 400 feet, although the maximum thickness can exceed 1,500 feet. Recharge is primarily through the infiltration of precipitation on the outcrop, in particular where the limestone formations outcrop. Discharge is to wells and to rivers in the region. Groundwater flow in the aquifer generally flows in a south-southeasterly direction, but may vary locally. The hydraulic gradient averages about 10 feet/mile.

Long-term water-level declines have been observed in areas of heavy pumping, most notably in the Saint Lawrence irrigation district in Glasscock, Reagan, Upton, and Midland Counties, in the Midland-Odessa area in Ector County, and in the Belding Farm area in Pecos County. Figures 3.1-4, 3.1-5 and 3.1-6 show selected hydrographs for the Edwards-Trinity (Plateau) aquifer in Region F. As noted above, some areas have shown consistent water-level declines, as shown in Figure 3.1-4. In some cases, these declines have stopped due to cessation or reduction in pumpage, and are currently recovering. Figure 3.1-5 shows selected wells showing increases in water levels over time.

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# Edwards-Trinity Aquifer

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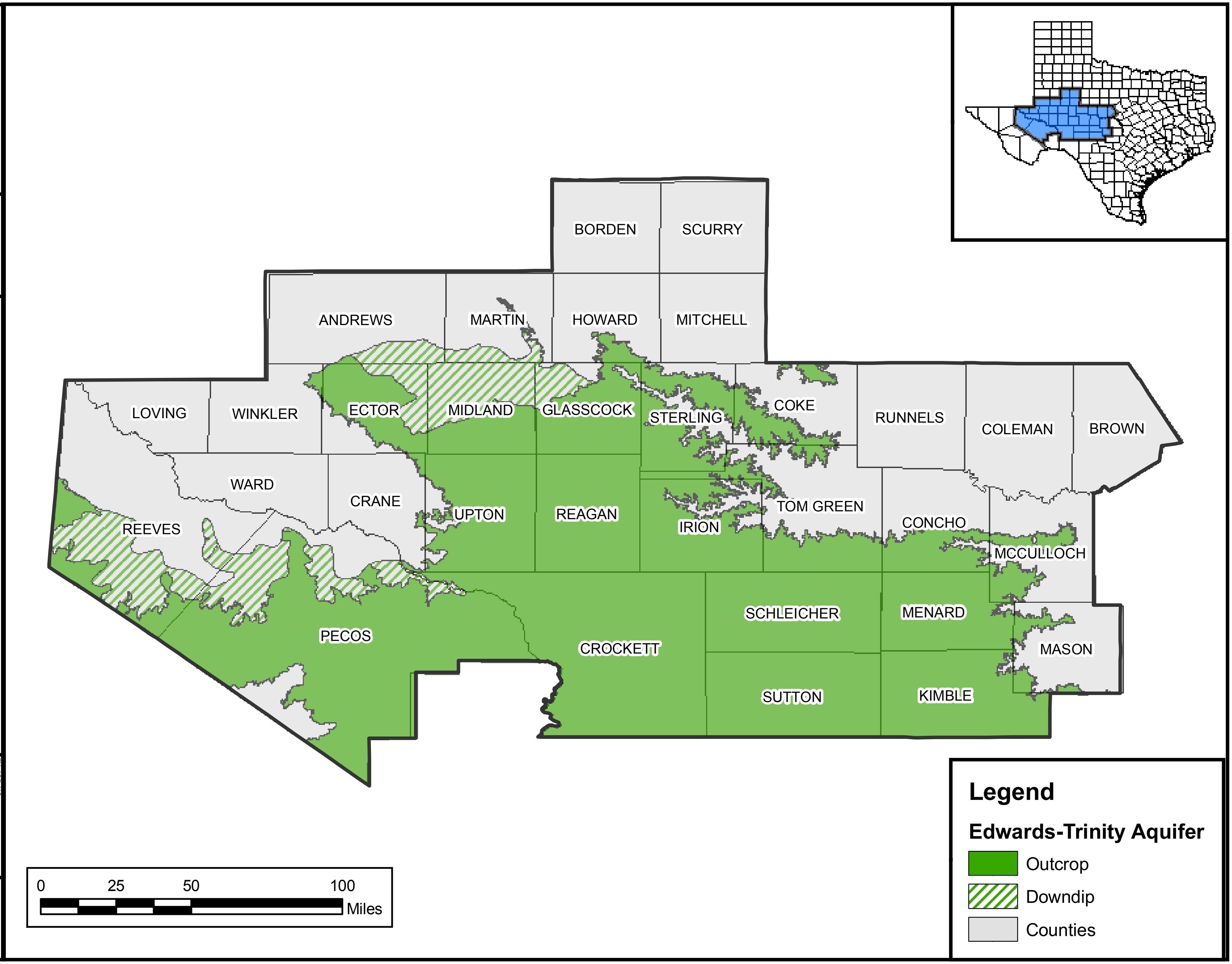


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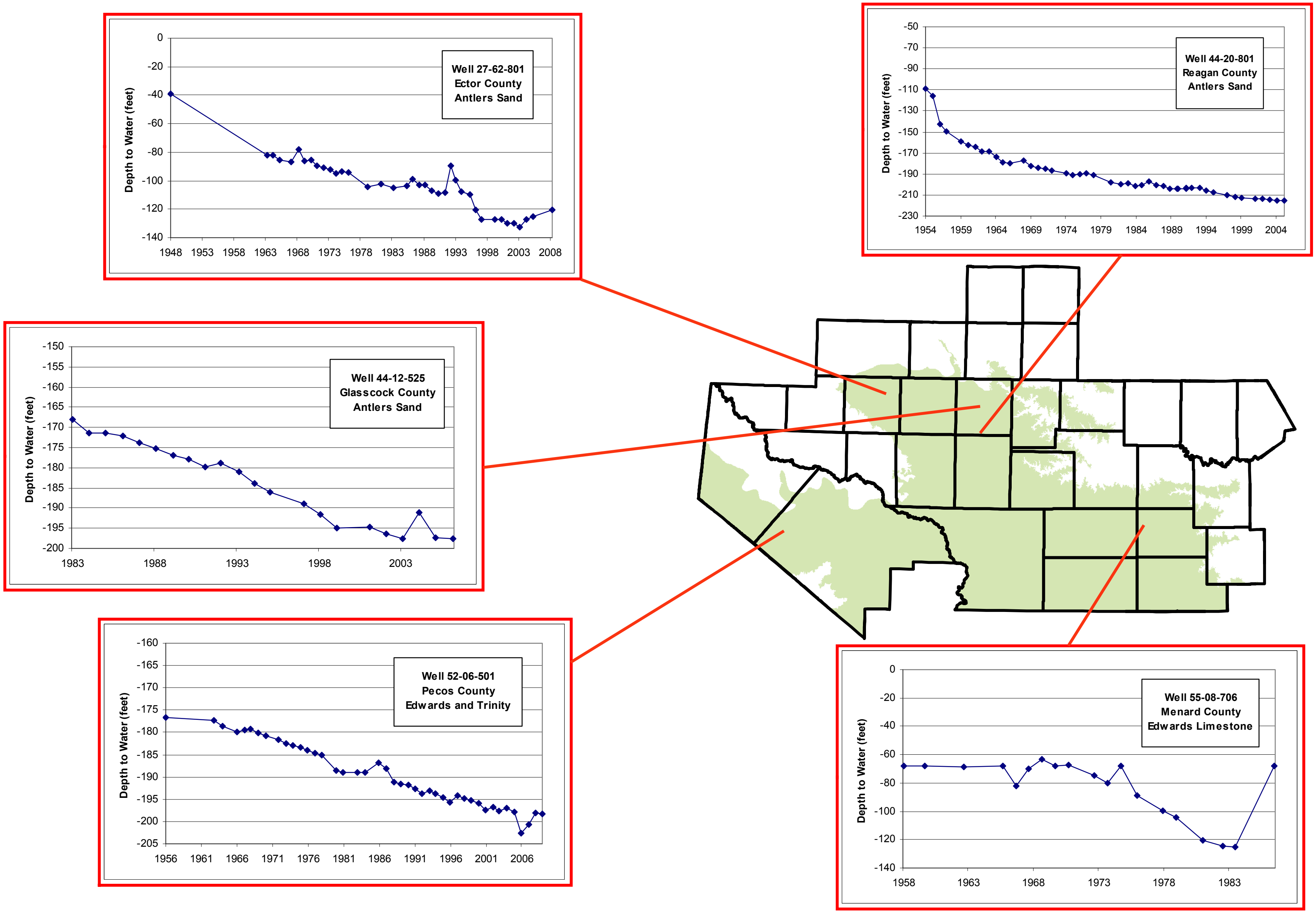
FIGURE 3.1-3

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# Selected Hydrographs from the Edwards-Trinity (Plateau) Aquifer Showing Declining Water Levels

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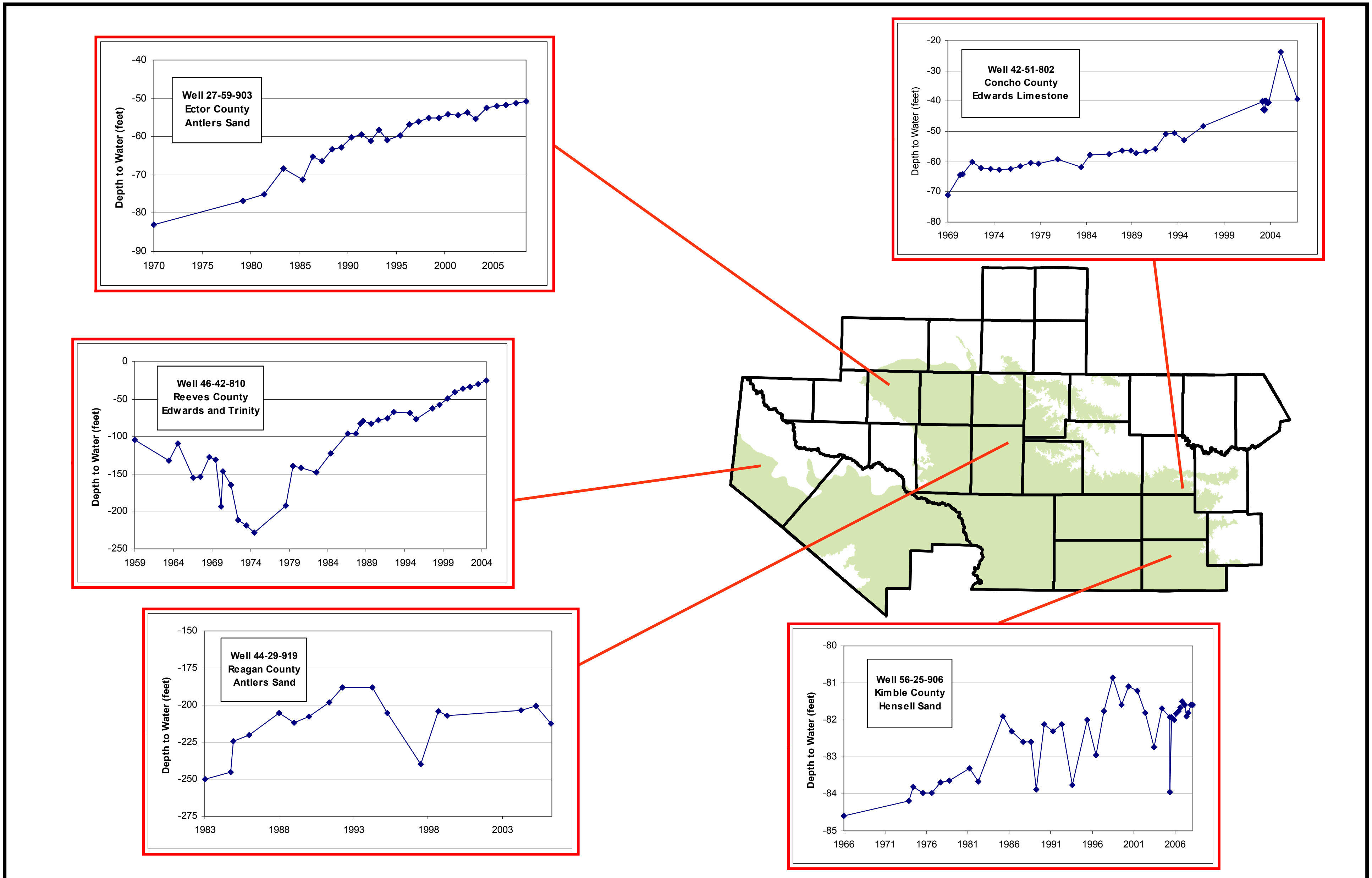
3.1-4
FIGURE

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# Selected Hydrographs from the Edwards-Trinity (Plateau) Aquifer Showing Rising Water Levels

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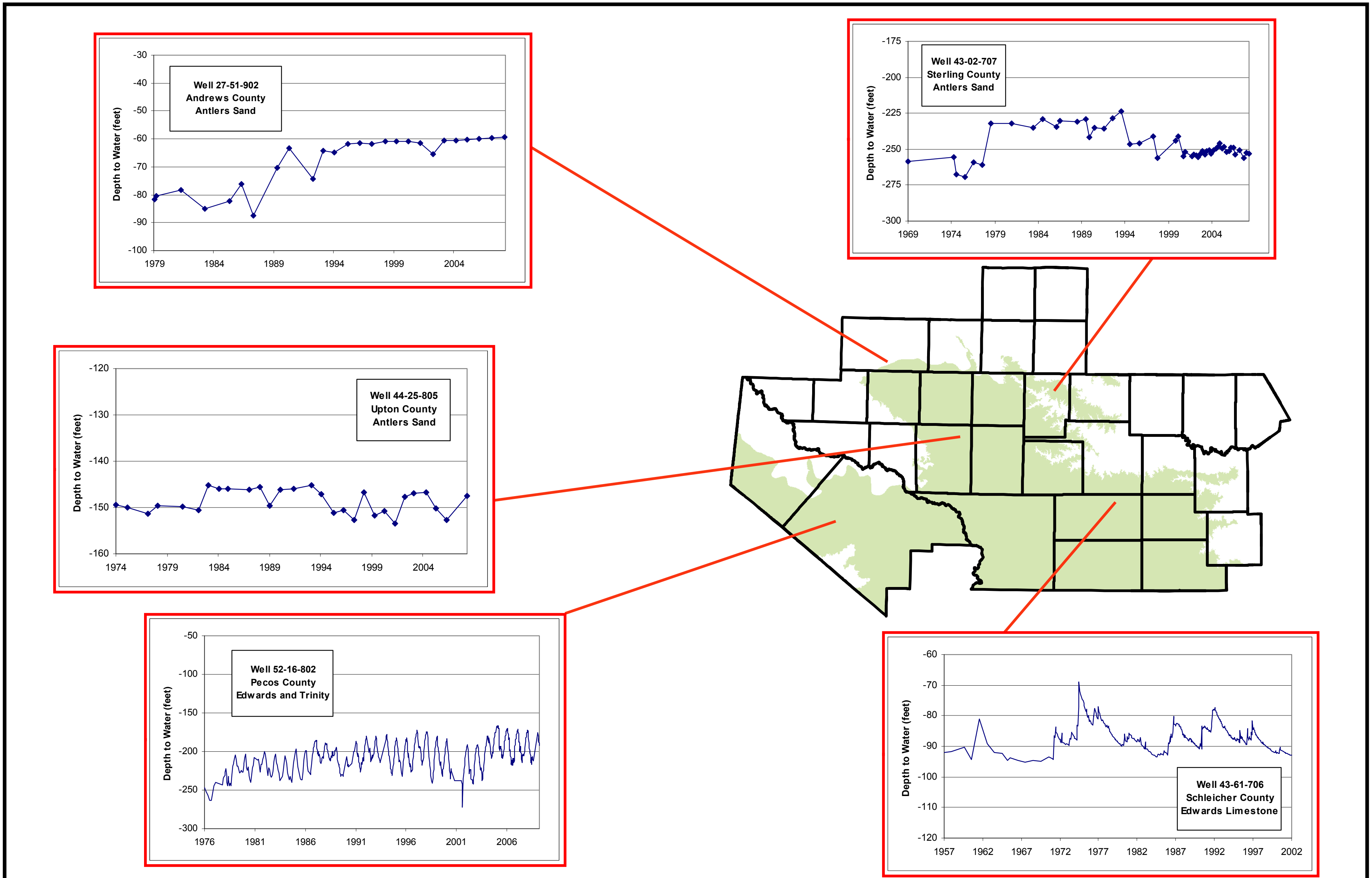
3.1-5
FIGURE

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## Selected Hydrographs from the Edwards-Trinity (Plateau) Aquifer Showing Stable Water Levels

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FIGURE 3.1-6

However, most Edwards-Trinity (Plateau) wells in the region show fairly stable water levels, or are slightly declining, as shown by the hydrographs in Figure 3.1-6. Well 52-16-802 in Pecos County (Figure 3.1-6) shows the water level variations throughout the year as pumpage increases in the summer and stops in the winter.

**Edwards Formation**

Groundwater is produced from the Edwards Formations portion of the Edwards-Trinity (Plateau) aquifer in a majority of the region. Groundwater in the Edwards and associated limestones occurs primarily in solution cavities that have developed along faults, fractures, and joints in the limestone. These formations are the main water-producing units in about two-thirds of the aquifer extent. The largest single area of pumpage from the Edwards portion of the aquifer in Region F is in the Belding Farms area of Pecos County.

Due to the nature of groundwater flow in the Edwards, it is very difficult to estimate aquifer properties for this portion of the Edwards-Trinity (Plateau) aquifer. However, based on aquifer characteristics of the Edwards elsewhere, wells producing from the Edwards portion of the Edwards-Trinity (Plateau) aquifer are expected to be much more productive than from the Trinity portion of the aquifer.

The chemical quality of the Edwards and associated limestones is generally better than that in the underlying Trinity aquifer. Groundwater from the Edwards and associated limestones is fairly uniform in quality, with water being a very hard, calcium bicarbonate type, usually containing less than 500 mg/l total dissolved solids (TDS), although in some areas the TDS can exceed 1,000 mg/l.

**Trinity Group**

Water-bearing units of the Trinity Group are used primarily in the northern third and on the southeastern edge of the aquifer. In most of the region, the Trinity is seldom used due to the presence of the Edwards above it, which produces better quality water at generally higher rates. In the southeast portion, the Trinity consists of, in ascending order, the Hosston, Sligo, Cow Creek, Hensell and Glen Rose Formations. In the north where the Glen Rose pinches out, all of the Trinity Group is referred to collectively as the Antlers Sand. The greatest withdrawal from the Trinity (Antlers) portion of the aquifer is in the Saint Lawrence irrigation area in Glasscock, Reagan, Upton and Midland Counties.

Reported well yields from the Trinity portion of the Edwards-Trinity (Plateau) aquifer commonly range from less than 50 gallons per minute (gpm) from the thinnest saturated section to rarely as much as 1,000 gpm, although higher yields occur in locations where wells are completed in jointed or cavernous limestone. Specific capacities of wells range from less than 1 to greater than 20 gpm/ft.

The water quality in the Trinity tends to be poorer than in the Edwards. Water from the Antlers is of the calcium bicarbonate/sulfate type and very hard, with salinity increasing towards the west. Salinities in the Antlers typically range from 500 to 1,000 mg/l TDS, although groundwater with greater than 1,000 mg/l TDS is common.

**Edwards-Trinity (Plateau) Aquifer Recharge**

Accurate recharge estimates are a key factor in estimating long-term groundwater availability in an aquifer system. The Edwards-Trinity (Plateau) aquifer covers all or parts of 21 of the 32 counties in Region F and provides water for many WUGs in the region. Therefore, in support of the aquifer availability analysis, a three-year study of the groundwater recharge in the Edwards portion of the aquifer was conducted. The goal of the study was to better understand the nature and timing of recharge events and to consider alternative methods of estimating recharge. This study entailed:

1. Design of monitoring well and rain gage networks in the study area,
2. Collection and evaluation of new and historical data to help estimate recharge characteristics,
3. Development of a rainfall-runoff model for the South Concho watershed in Tom Green and Schleicher Counties,
4. Documentation and discussion of data collection, recharge evaluation, statistical analyses, model development and results, and conclusions.

Monthly and (in some cases) daily water level and precipitation data were collected during 2003 and 2004, and in a few areas into 2005. Fifteen wells were monitored daily with transducers and about 100 wells were measured manually on a monthly basis. Precipitation data were assimilated from nine National Weather Service gages and over 60 volunteer-monitored gages. The project was performed within the boundaries of and with the assistance of groundwater conservation districts. Seven districts assisted in establishing the monitor well and rain gage networks, and collected and recorded the data used in the study:

- Glasscock Groundwater Conservation District

- Sterling County Underground Water Conservation District
- Irion County Water Conservation District
- Lipan-Kickapoo Water Conservation District (Tom Green, Concho, and Runnels Counties)
- Emerald Underground Water Conservation District (Crockett County)
- Plateau Underground Water Control and Supply District (Schleicher County)
- Sutton County Underground Water Conservation District

A full discussion of the study and the results are contained in a separately bound document titled *Evaluation of Edwards-Trinity (Plateau) Aquifer Recharge in a Portion of the Region F Planning Area*. Summary conclusions from the study include:

- Based on measured precipitation and groundwater levels, recharge of the Edwards-Trinity (Plateau) is highly variable both geographically and in time.
- Statistical evaluation of observed rainfall and water level data indicate that, because of the numerous factors that affect groundwater recharge, including temporal changes in precipitation, evapotranspiration, and geographic variations in hydrogeology and soils, a unique regional linear correlation between rainfall and recharge does not exist.
- Long periods of wet conditions in winter months tend to result in more recharge than similar periods in the summer due to the increased evapotranspiration and drier soil conditions in the summer.
- A South Concho watershed rainfall-runoff model developed for this study reproduced measured streamflow conditions relatively well and was helpful in identifying conditions that were conducive to increased groundwater recharge.
- Because the rainfall-runoff model accounts for temporal changes in precipitation, evapotranspiration and to some degree, geographic variations in hydrogeology and soils, model results were used to develop a relationship between annual precipitation and recharge for the South Concho watershed. The relationship can be used to estimate a "threshold" annual precipitation that results in groundwater recharge for the South Concho watershed. Due to the variability of factors impacting recharge potential, it is recommended that similar models be developed for individual watersheds.

### 3.1.2 Ogallala Aquifer

The Ogallala is one of the largest sources of groundwater in the United States, extending from South Dakota to the Southern High Plains of the Texas Panhandle. In Region F, the aquifer occurs in seven counties in the northwestern part of the region including Andrews, Borden, Ector, Howard, Glasscock, Martin and Midland Counties (Figure 3.1-7). The aquifer provides approximately 20 percent of all groundwater used in the region. The formation is hydrologically connected to the underlying Edwards-Trinity (Plateau) aquifer in southern Andrews and Martin Counties, and northern Ector, Midland and Glasscock Counties.

In Region F, agricultural irrigation and livestock consumption account for approximately two-thirds of the total use of Ogallala groundwater. Municipal use accounts for approximately 20 percent. Most of the withdrawals from the aquifer occur in Midland, Martin, and Andrews Counties.

The Ogallala is composed of coarse to medium grained sand and gravel in the lower strata grading upward into fine clay, silt and sand. Recharge occurs principally by infiltration of precipitation on the surface and to a lesser extent by upward leakage from underlying formations. Highest recharge infiltration rates occur in areas overlain by sandy soils and in some playa lake basins. Groundwater in the aquifer generally moves slowly in a southeastwardly direction. Water quality of the Ogallala in the Southern High Plains ranges from fresh to moderately saline, with dissolved solids averaging approximately 1,500 mg/l.

### 3.1.3 Cenozoic Pecos Alluvium Aquifer

The Cenozoic Pecos Alluvium aquifer is located in the upper part of the Pecos River Valley of West Texas in Andrews, Crane, Crockett, Ector, Loving, Pecos, Reeves, Upton, Ward and Winkler Counties (Figure 3.1-8). Consisting of up to 1,500 feet of alluvial fill, the Cenozoic Pecos Alluvium occupies two hydrologically separate basins: the Pecos Trough in the west and the Monument Draw Trough in the east. The aquifer is hydrologically connected to underlying water-bearing strata, including the Edwards-Trinity in Pecos and Reeves Counties, the Triassic Dockum in Ward and Winkler Counties, and the Rustler in Reeves County.

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# Ogallala Aquifer

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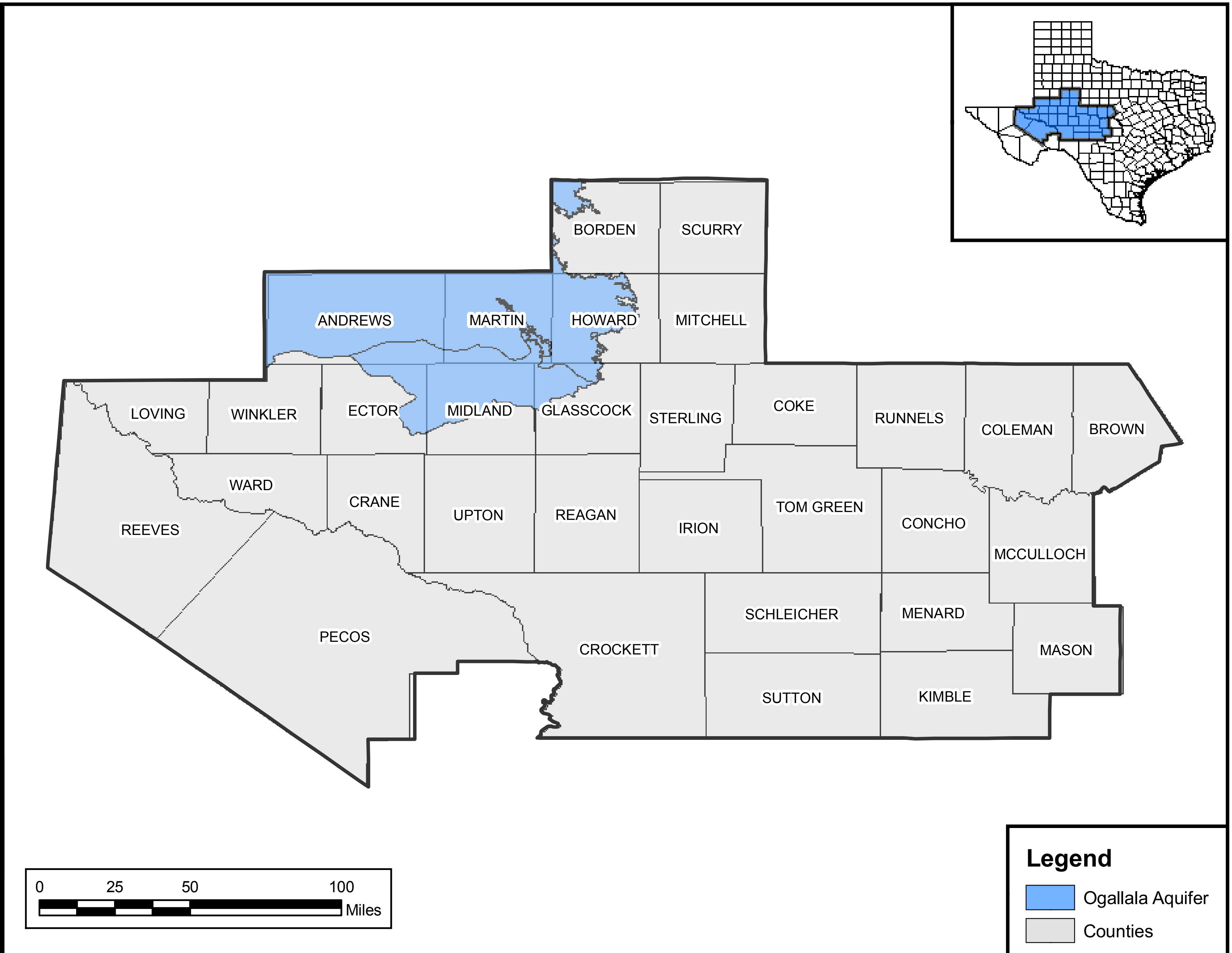
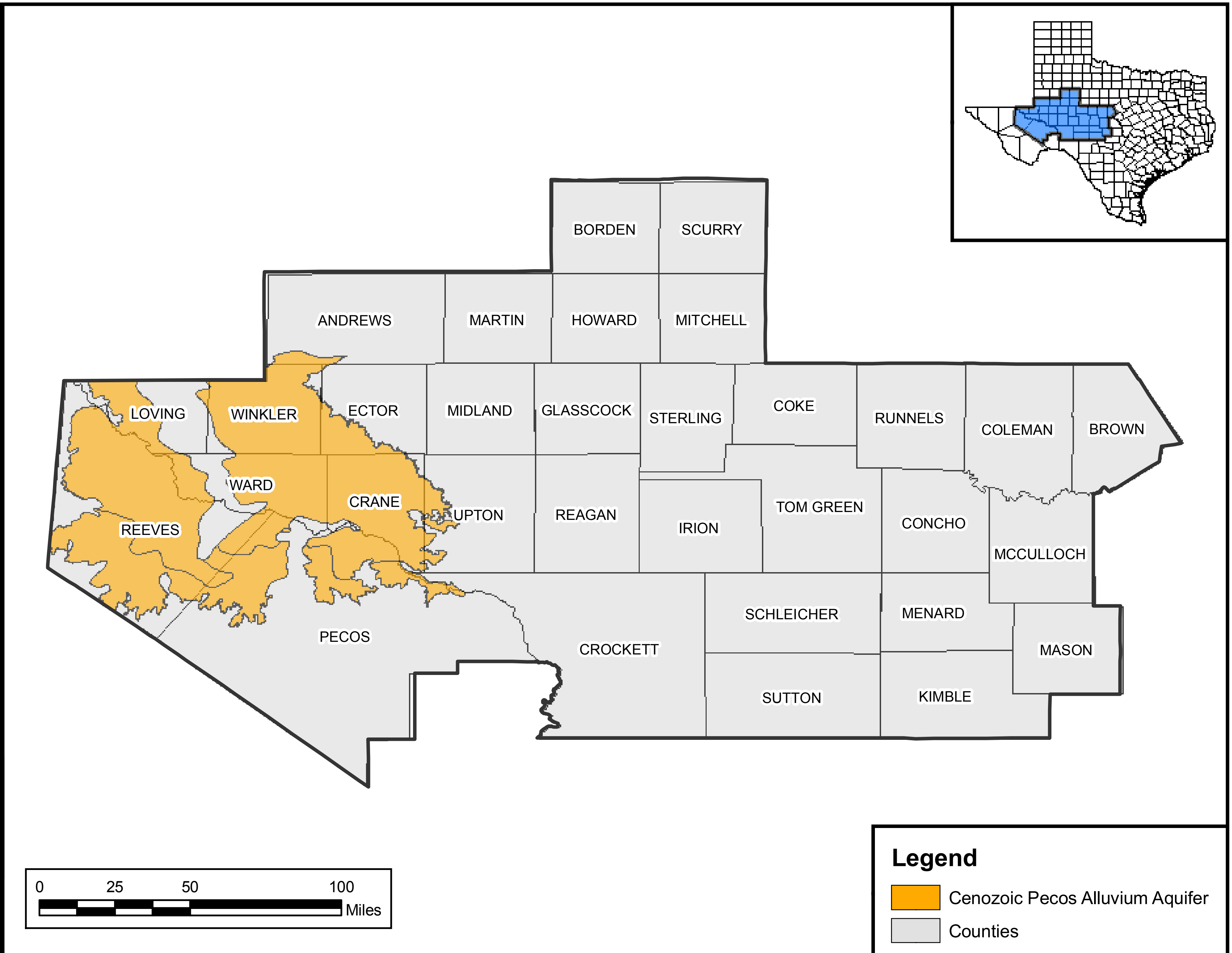
FIGURE 3.1-7







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# Cenozoic Pecos Alluvium Aquifer

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FIGURE 3.1-8

The western basin (Pecos Trough) contains poorer quality water and is used most extensively for irrigation of salt-tolerant crops. The eastern basin (Monument Draw Trough) contains relatively good quality water that is used for a variety of purposes, including industrial use, power generation, and public water supply.

The Cenozoic Pecos Alluvium is the second most used aquifer in the region, representing approximately 31 percent of total groundwater use. Agricultural related consumption (irrigation and livestock) accounts for approximately 80 percent of the total, while municipal consumption and power generation account for about 15 percent of aquifer use. Lateral subsurface flow from the Rustler aquifer into the Cenozoic Pecos Alluvium has significantly affected the chemical quality of groundwater in the overlying western Pecos Trough aquifer. Most of this basin contains water with greater than 1,000 mg/l TDS, and a significant portion is above 3,000 mg/l TDS. The eastern Monument Draw Trough is underlain by the Dockum aquifer but is not as significantly affected by its quality difference. Water levels in the past fifty years have generally been stable. However, in Reeves and Pecos Counties water levels have dropped an average of 80 feet.

### 3.1.4 Trinity Aquifer

The Trinity aquifer is a primary groundwater source for eastern Brown County (Figure 3.1-9). Small isolated outcrops of Trinity Age rocks also occur in south central Brown County and northwest Coleman County. However, these two areas are not classified as the contiguous Trinity aquifer by the TWDB and the TWDB did not estimate a groundwater availability for the Trinity Aquifer in Coleman County. Agricultural related consumption (irrigation and livestock) accounts for approximately 80 percent of the total withdrawal from the aquifer.

The Trinity was deposited during the Cretaceous Period and is comprised of (from bottom to top) the Twin Mountains, Glen Rose and Paluxy Formations. In western Brown and Coleman Counties, the Glen Rose is thin or missing and the Paluxy and Twin Mountains coalesce to form the Antlers Sand. The Paluxy consists of sand and shale and is capable of producing small quantities of fresh to slightly saline water. The Twin Mountains formation is composed of sand, gravel, shale, clay and occasional conglomerate, sandstone and limestone beds. It is the principal aquifer and yields moderate to large quantities of fresh to slightly saline water. Maximum thickness of the Trinity aquifer is approximately 200 feet in this area.

# Trinity Aquifer

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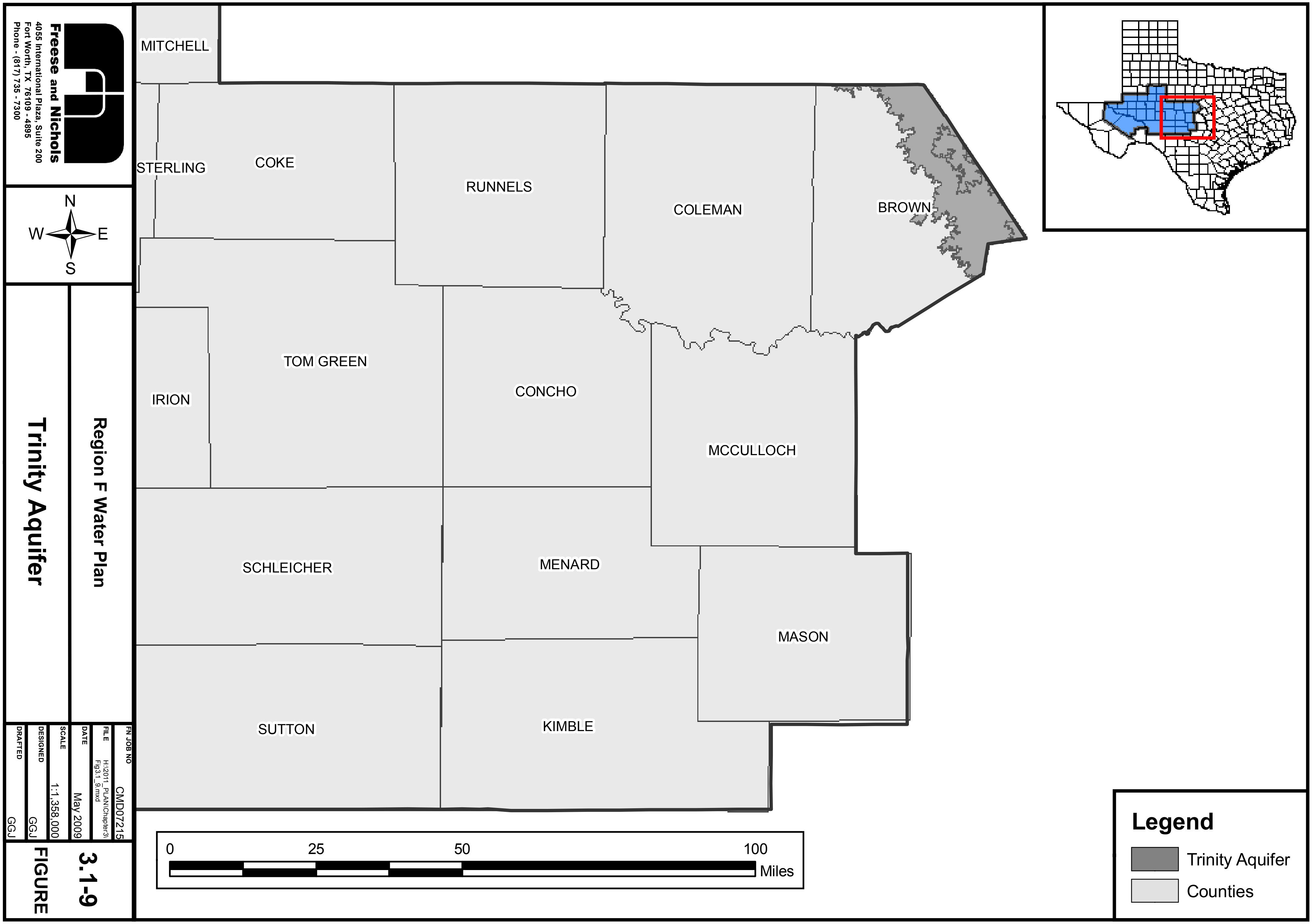


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FIGURE 3.1-9

Trinity aquifer water quality is acceptable for most municipal, industrial, and irrigation purposes. Dissolved solids range from approximately 150 to over 7,000 mg/l in Brown County; however, most wells have dissolved solids concentrations of less than 1,000 mg/l. The potential for updip movement of poor quality water exists where large and ongoing water level declines have reversed the natural water level gradient and have allowed water of elevated salinity to migrate back updip toward pumpage centers.

### 3.1.5 Dockum Aquifer

The Dockum aquifer is used for water supply in 12 counties in Region F, including Andrews, Crane, Ector, Howard, Loving, Mitchell, Reagan, Reeves, Scurry, Upton, Ward and Winkler Counties (Figure 3.1-10). The Dockum outcrops in Scurry and Mitchell Counties, and elsewhere underlies rock formations comprising the Ogallala, Edwards-Trinity, and Cenozoic Pecos Alluvium. Although the Dockum aquifer underlies much of the region, its low water-yielding potential and generally poor quality results in its classification as a minor aquifer.

Most Dockum water used for irrigation is withdrawn in Mitchell and Scurry Counties, while public supply use of Dockum water occurs mostly in Reeves and Winkler Counties. Elsewhere, the aquifer is used extensively for oil field water flooding operations.

The primary water-bearing zone in the Dockum Group, commonly called the "Santa Rosa", consists of up to 700 feet of sand and conglomerate interbedded with layers of silt and shale. The Santa Rosa abuts the overlying Trinity aquifer along a defined corridor that traverses Sterling, Irion, Reagan and Crockett Counties. Within this corridor, the Trinity and Dockum are hydrologically connected, thus forming a thicker aquifer section. A similar hydrologic relationship occurs in Ward and Winkler Counties, where the Santa Rosa unit of the Dockum is in direct contact with the overlying Cenozoic Pecos Alluvium aquifer. Local groundwater reports use the term "Allurosa" aquifer in reference to this combined section of water-bearing sands.

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# Dockum Aquifer

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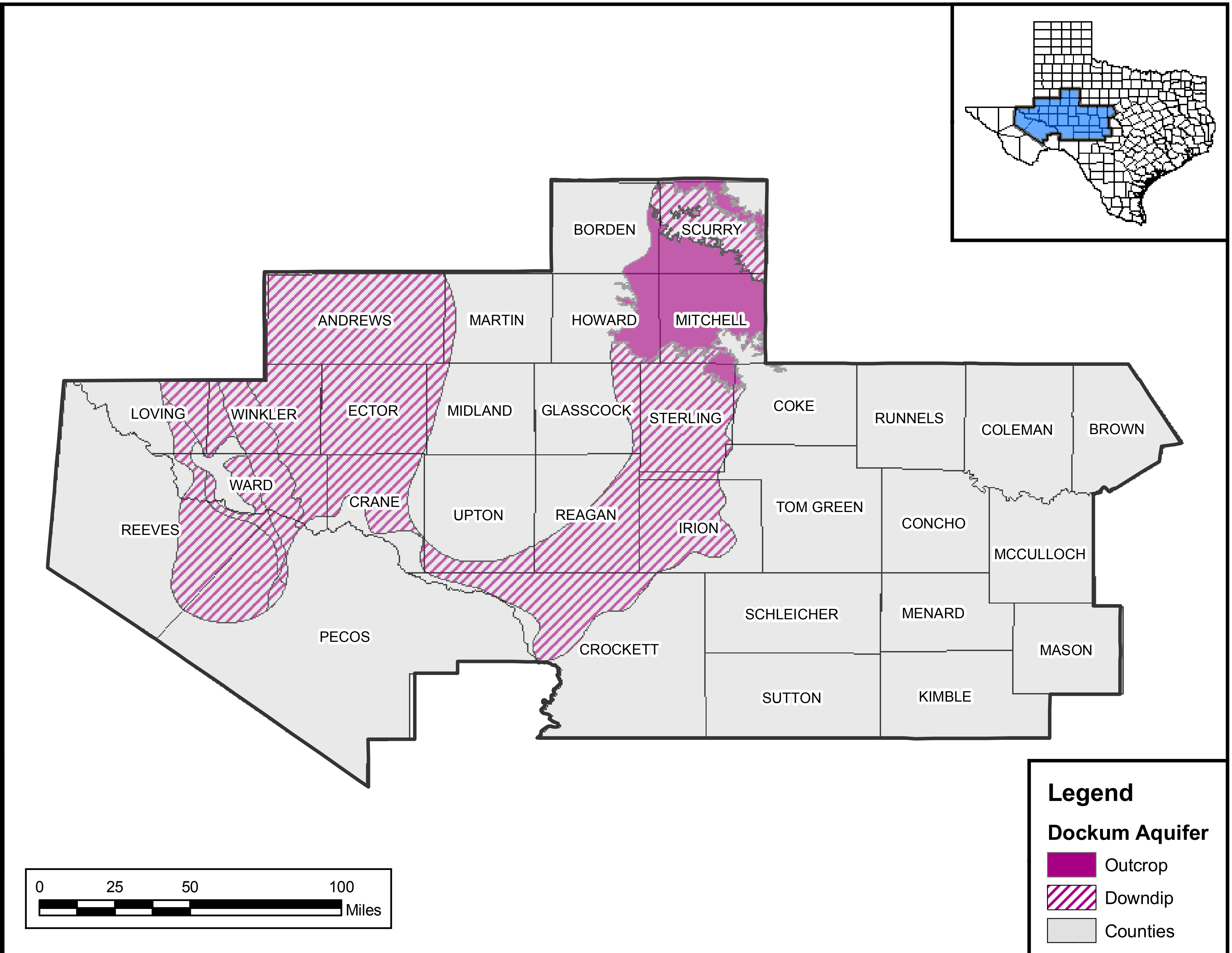
FIGURE 3.1-10



Recharge to the Dockum primarily occurs in Scurry and Mitchell Counties where the formation outcrops at the land surface. As discussed in the previous paragraph, recharge potential also occurs where water-bearing units of the Trinity and Cenozoic Pecos Alluvium directly overlie the Santa Rosa portion of the Dockum. Elsewhere, the Dockum is buried deep below the land surface, is finer grained, and receives very limited lateral recharge. Groundwater pumped from the aquifer in these areas will come directly from storage and will result in water level declines.

The chemical quality of water from the Dockum aquifer ranges from fresh in outcrop areas to very saline in the deeper central basin area. Groundwater pumped from the aquifer in Region F has average dissolved solids ranging from 558 mg/l in Winkler County to over 2,500 mg/l in Andrews, Crane, Ector, Howard, Reagan and Upton Counties.

### 3.1.6 Hickory Aquifer

The Hickory aquifer is located in the eastern portion of Region F and outcrops in Mason and McCulloch Counties (Figure 3.1-11). Besides these two counties, this aquifer also supplies groundwater to Concho and Menard Counties. The Hickory Sandstone Member of the Cambrian Riley Formation is composed of some of the oldest sedimentary rocks in Texas. Irrigation and livestock account for approximately 80 percent of the total pumpage, while municipal water use accounts for approximately 18 percent. Mason County uses the greatest amount of water from the Hickory aquifer, most of which is used for irrigation.

In most northern and western portions of the aquifer, the Hickory Sandstone Member can be differentiated into lower, middle and upper units, which reach a maximum thickness of 480 feet in southwestern McCulloch County. Block faulting has compartmentalized the Hickory aquifer, which locally limits the occurrence, movement, productivity, and quality of groundwater within the aquifer.

Hickory aquifer water is generally fresh, with dissolved solids concentrations ranging from 300 to 500 mg/l. Much of the water from the Hickory aquifer exceeds drinking water standards for alpha particles, beta particles and radium particles in the downdip portion of the aquifer. The middle Hickory unit is believed to be the source of alpha, beta and radium concentrations in excess of drinking water standards. The water may also contain radon gas. The upper unit of the

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# Hickory Aquifer

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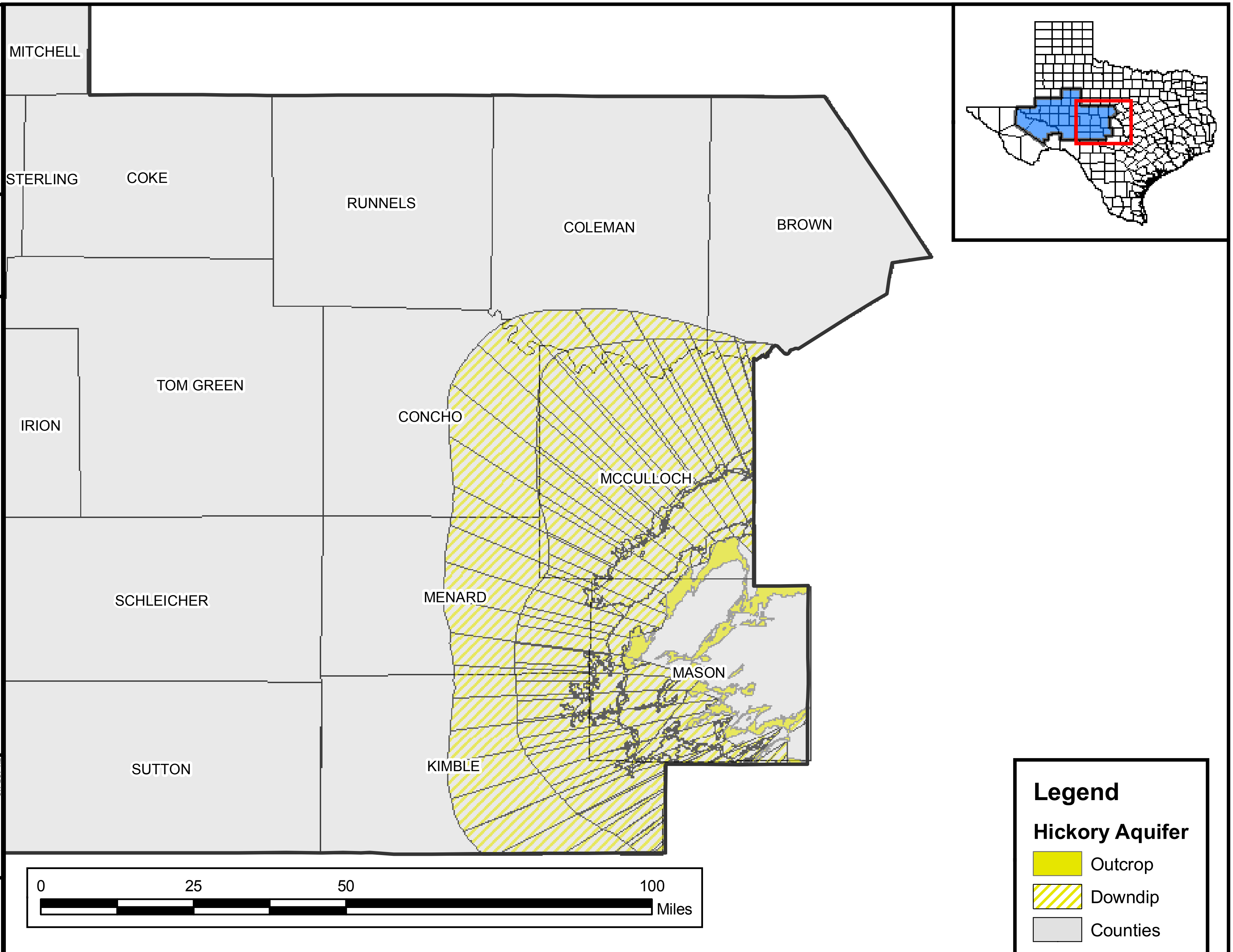
FIGURE 3.1-11



Hickory aquifer produces groundwater containing concentrations of iron in excess of drinking water standards. Wells in the shallow Hickory and the outcrop areas have local concentrations of nitrate in excess of drinking water standards.

Yields of large-capacity wells usually range between 200 and 500 gpm. Some wells have yields in excess of 1,000 gpm. Highest well yields are typically found northwest of the Llano Uplift, where the aquifer has the greatest saturated thickness.

### 3.1.7 Lipan Aquifer

The Lipan aquifer occurs in Concho, Runnels and Tom Green Counties (Figure 3.1-12). The aquifer is principally used for irrigation, with limited rural domestic and livestock use. The Lipan aquifer is comprised of saturated alluvial deposits of the Leona Formation and the updip portions of the underlying Choza Formation, Bullwagon Dolomite, and Standpipe Limestone of Permian-age that are hydrologically connected to the Leona. Total thickness of the Leona alluvium ranges from a few feet to about 125 feet. However, most of the groundwater is contained within the underlying Permian units.

Typical irrigation practice in the area is to withdraw water held in storage in the aquifer during the growing season with expectation of recharge recovery during the winter months. The Lipan-Kickapoo Water Conservation District controls overuse by limiting well density.

Groundwater in the Leona Formation ranges from fresh to slightly saline and is very hard, while water in the underlying updip portions of the Choza, Bullwagon and Standpipe tends to be slightly saline. The chemical quality of groundwater in the Lipan aquifer generally does not meet drinking water standards but is suitable for irrigation. In some cases Lipan water has TDS concentrations in excess of drinking water standards due to influx of water from lower formations. In other cases the Lipan has excessive nitrates because of agricultural activities in the area. Well yields generally range from 20 to 500 gpm with the average well yielding approximately 200 gpm.

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# Lipan Aquifer

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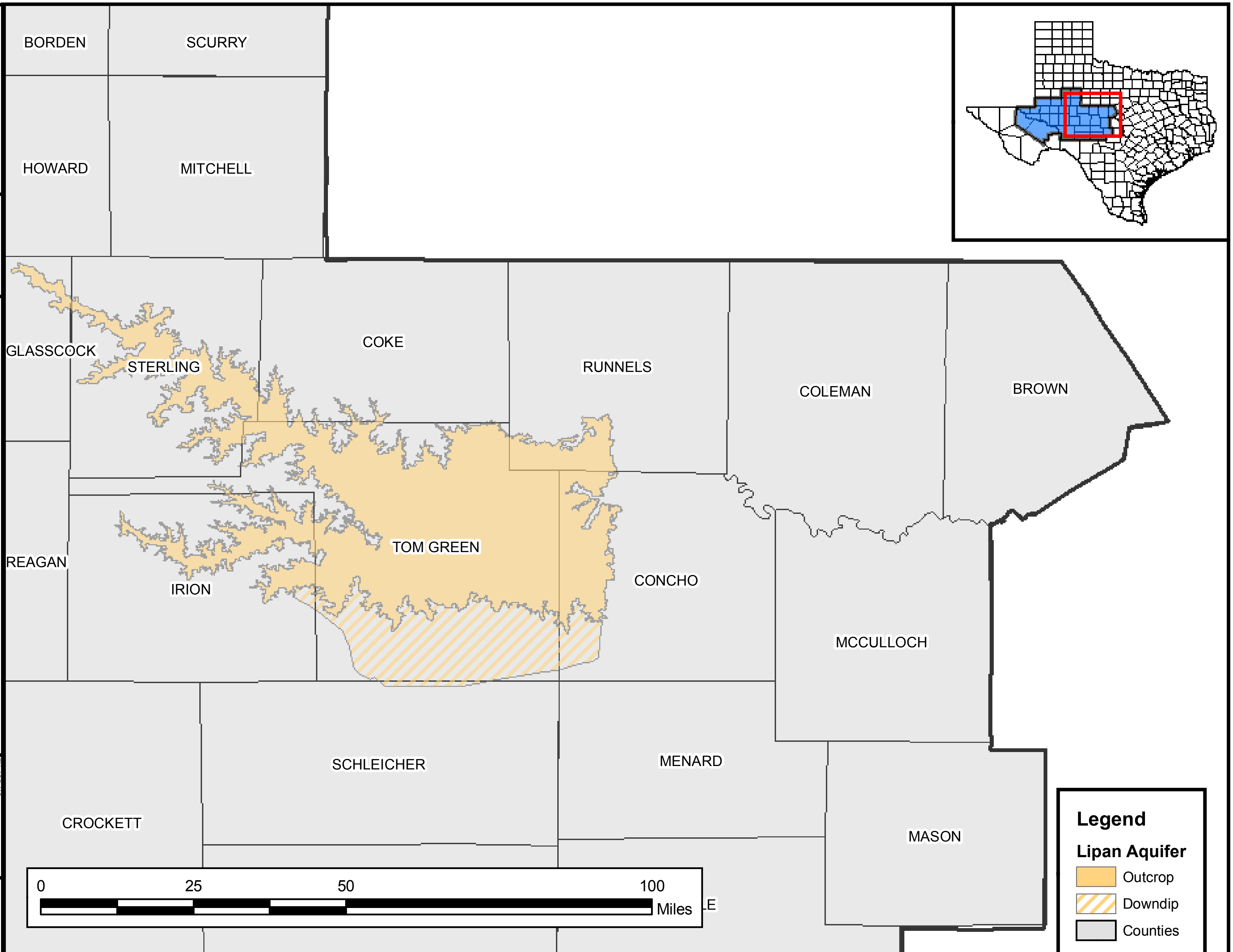
FIGURE 3.1-12



Most of the water in the Lipan aquifer is brackish due to the dissolution of gypsum and other minerals from the aquifer matrix. Additionally, irrigation return flow has concentrated minerals in the water through evaporation and the leaching of natural salts from the unsaturated zone.

### 3.1.8 Ellenburger-San Saba Aquifer

Including the downdip boundary as designated by the TWDB, the Ellenburger-San Saba aquifer occurs in Brown, Coleman, Kimble, Mason, McCulloch and Menard Counties within Region F (Figure 3.1-13). Currently, most pumpage from the aquifer occurs in McCulloch County. In Brown and Coleman Counties, the aquifer is present in only the extreme southern part, and most of the aquifer in this area contains water in excess of 1,000 mg/l TDS. The downdip boundary of the aquifer, which represents the extent of water with less than 3,000 mg/l TDS, is roughly estimated due to lack of data.

The Ellenburger-San Saba aquifer is comprised of the Cambrian-age San Saba member of the Wilberns Formation and the Ordovician-age Ellenburger Group, which includes the Tanyard, Gorman and Honeycut Formations. Discontinuous outcrops of the aquifer generally encircle older rocks in the core of the Llano Uplift. The maximum thickness of the aquifer is about 1,100 feet. In some areas, where the overlying beds are thin or absent, the Ellenburger-San Saba aquifer may be hydrologically connected to the Marble Falls aquifer. Local and regional block faulting has significantly compartmentalized the Ellenburger-San Saba, which locally limits the occurrence, movement, productivity, and quality of groundwater within the aquifer.

Water produced from the aquifer has a range in dissolved solids between 200 and 3,000 mg/l, but is usually less than 1,000 mg/l. The quality of water deteriorates rapidly away from outcrop areas. Approximately 20 miles or more downdip from the outcrop, water is typically unsuitable for most uses. All the groundwater produced from the aquifer is inherently hard.

Principal use from the aquifer is for livestock supply in Mason and McCulloch Counties, and a minor amount in Menard County. Maximum yields of large-capacity wells generally range between 200 and 600 gpm, most other wells typically yield less than 100 gpm.

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# Ellenburger-San Saba Aquifer

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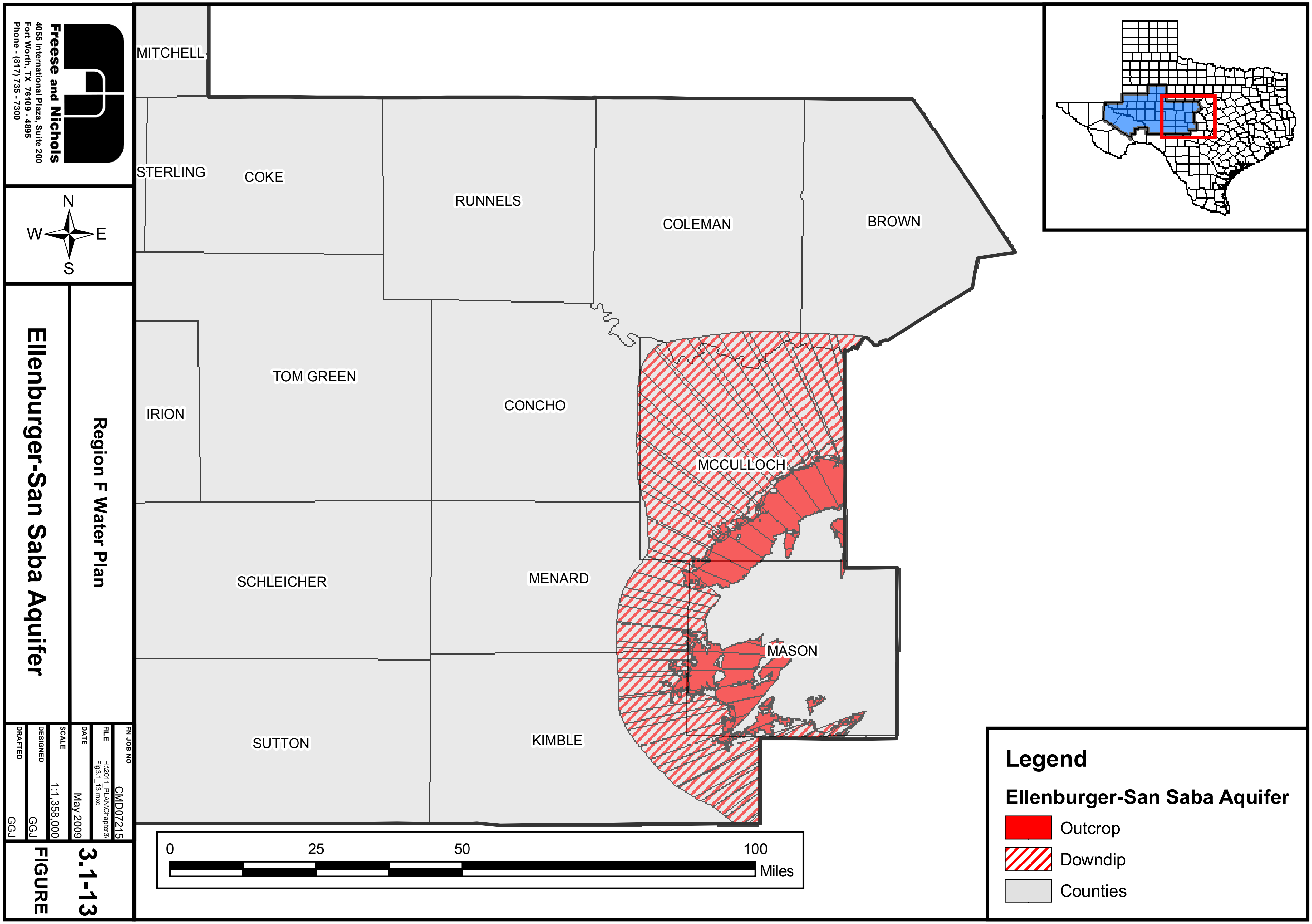

### 3.1.9 Marble Falls Aquifer

The Marble Falls is the smallest aquifer in the region, occurring in very limited outcrop areas in Kimble, Mason and McCulloch Counties (Figure 3.1-14). Groundwater in the aquifer occurs in fractures, solution cavities, and channels in the limestones of the Marble Falls Formation of the Pennsylvanian-age Bend Group. Where underlying beds are thin or absent, the Marble Falls and Ellenburger-San Saba aquifers may be hydrologically connected.

A limited amount of well data suggests that water quality is acceptable for most uses only in wells located on the outcrop and in wells that are less than 300-feet deep in the downdip portion of the aquifer. The downdip artesian portion of the aquifer is not extensive, and water becomes significantly mineralized within a relatively short distance downdip from the outcrop area. Most water produced from the aquifer occurs in Mason County, with lesser amounts in McCulloch County.

### 3.1.10 Rustler Aquifer

The Rustler Formation outcrops outside of Region F in Culberson County, but the majority of its downdip extent occurs in Loving, Pecos, Reeves and Ward Counties (Figure 3.1-15). The Rustler Formation consists of 200 to 500 feet of anhydrite and dolomite with a basal zone of sandstone and shale deposited in the ancestral Permian-age Delaware Basin. Water is produced primarily from highly permeable solution channels, caverns and collapsed breccia zones.

Groundwater from the Rustler Formation may locally migrate upward, impacting water quality in the overlying Edwards-Trinity and Cenozoic Pecos Alluvium aquifers. The Rustler is primarily used for livestock watering and a minor amount of irrigation, mostly in Pecos County.

Throughout most of its extent, the Rustler is relatively deep below the land surface, and generally contains water with dissolved constituents (TDS) well in excess of 3,000 mg/l. Only in western Pecos, eastern Loving and southeastern Reeves Counties has water been identified that contains less than 3,000 mg/l TDS. The dissolved-solids concentrations increase down gradient, eastward into the basin, with a shift from sulfate to chloride as the predominant anion. No groundwater from the Rustler aquifer has been located that meets drinking water standards.

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# Marble Falls Aquifer

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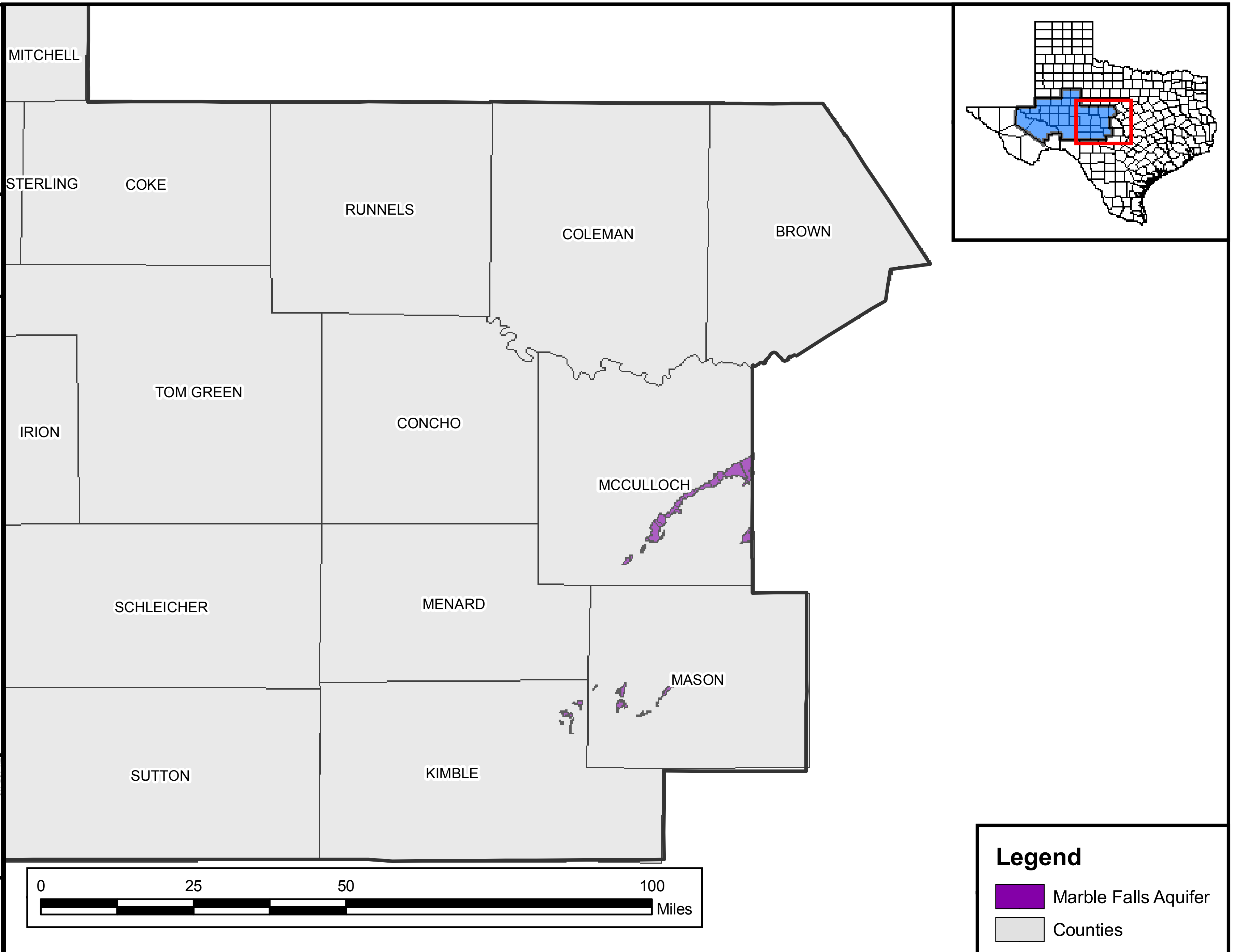
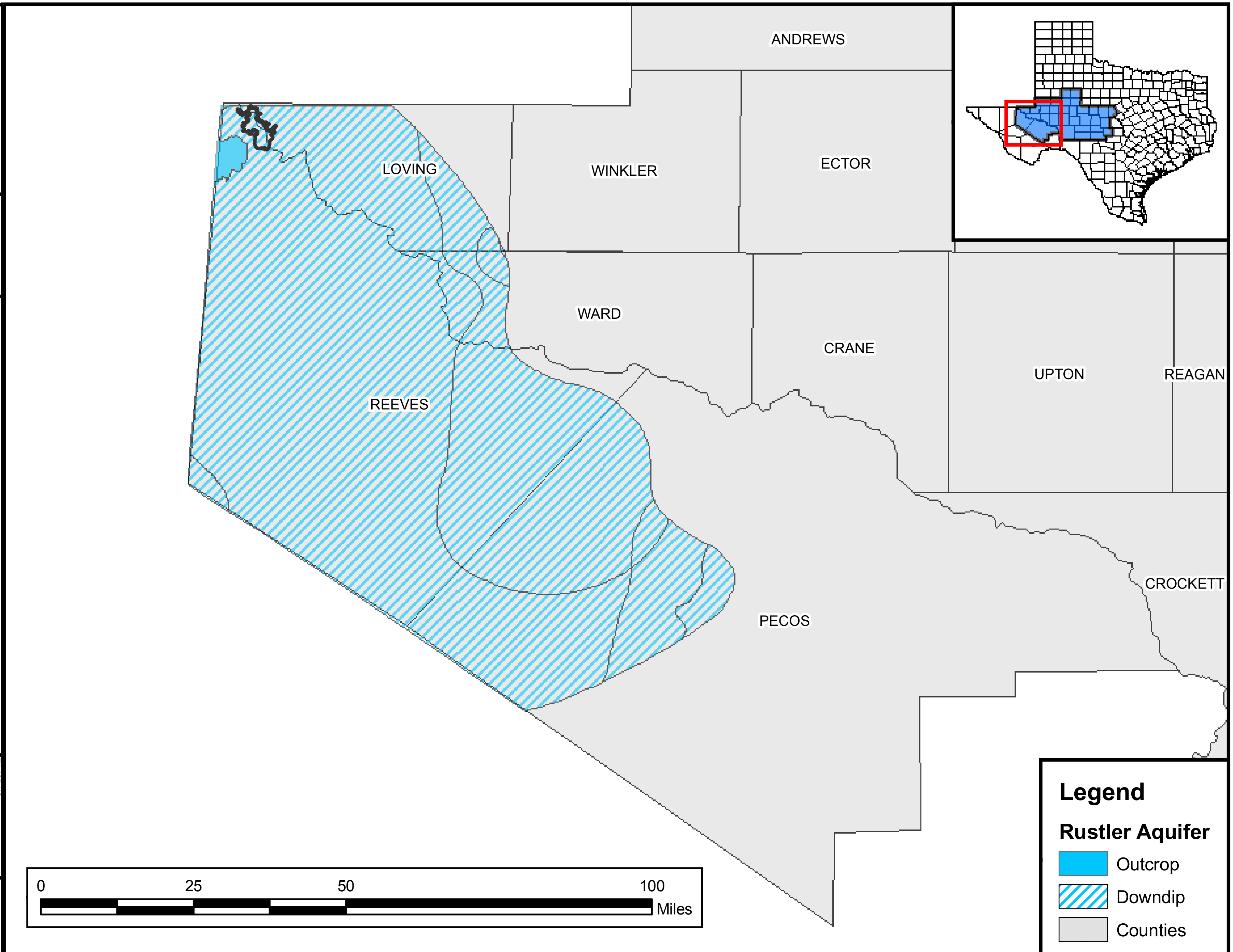
FIGURE 3.1-14



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# Rustler Aquifer

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FIGURE 3.1-15

### 3.1.11 Capitan Reef Aquifer

The Capitan Reef formed along the margins of the ancestral Delaware Basin, an embayment covered by a shallow sea in Permian time. In Texas, the reef parallels the western and eastern edges of the basin in two arcuate strips 10 to 14 miles wide and is exposed in the Guadalupe, Apache and Glass Mountains. From its exposure in the Glass Mountains in Brewster and southern Pecos Counties, the reef plunges underground to a maximum depth of 4,000 feet in northern Pecos County. The reef trends northward into New Mexico where it is a major source of water in the Carlsbad area.

The aquifer is composed of up to 2,000 feet of massive, vuggy to cavernous dolomite, limestone and reef talus. Water-bearing formations associated with the aquifer system include the Capitan Limestone, Goat Sheep Limestone, and most of the Carlsbad facies of the Artesia Group, which includes the Grayburg, Queen, Seven Rivers, Yates and Tansill Formations. The Capitan Reef aquifer underlies the Cenozoic Pecos Alluvium, Edwards-Trinity (Plateau), Dockum and Rustler aquifers in Pecos, Ward and Winkler Counties (Figure 3.1-16).

The aquifer generally contains water of marginal quality, with TDS concentrations ranging between 3,000 and 22,000 mg/l. High salt concentrations in some areas are probably caused by migration of brine waters injected for secondary oil recovery. The freshest water is located near areas of recharge where the reef is exposed at the surface. Yields of wells commonly range from 400 to 1,000 gpm.

Most of the groundwater pumped from the aquifer has historically been used for oil reservoir water-flooding operations in Ward and Winkler Counties. A few irrigation wells have also tapped the aquifer in Pecos County. Otherwise, very little reliance has been placed on this aquifer due to its depth, limited extent, and marginal quality. The Capitan Reef aquifer may be a potential of brackish water supply for desalination treatment.

# Capitan Reef Aquifer

Region F Water Plan

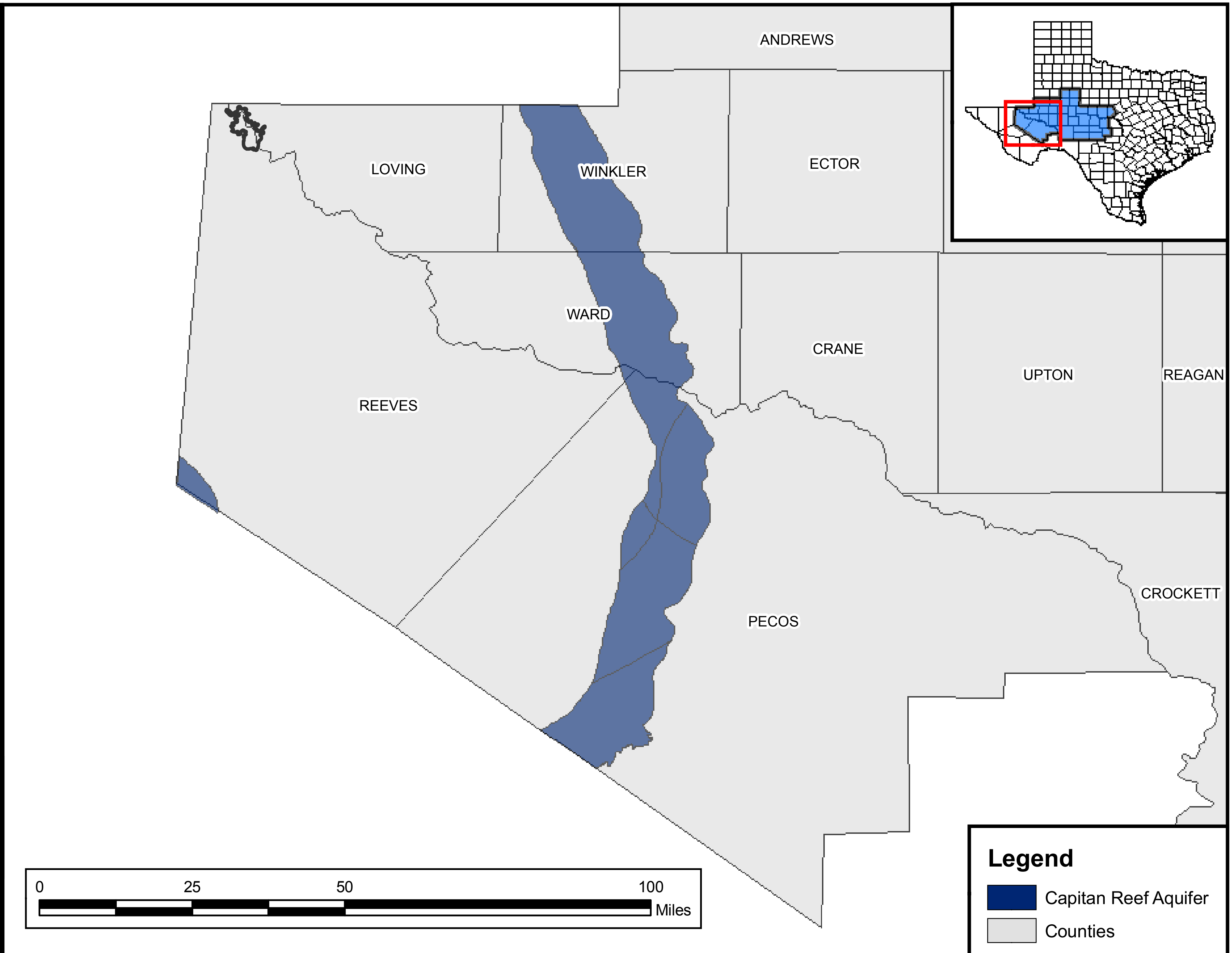


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FIGURE 3.1-16

### 3.1.12 Brackish Groundwater Availability

Additional supplies of water in Region F may be obtained from the desalination of existing brackish or saline water sources. Desalination technology is improving, and costs are continuing to decrease, meaning more brackish groundwater supplies may become economically feasible to use as a water supply to meet regional water demands.

Many of the major and minor aquifers in Region F contain significant quantities of groundwater with TDS concentrations ranging between 1,000 and 5,000 mg/l. While some of this water is currently being used for agricultural and industrial purposes, much of it remains unused.

It is unlikely that desalination will be sufficiently economical to be a significant supply for end uses such as irrigated agriculture.

Although extensive brackish and saline water occurs in the deep, typically hydrocarbon-producing formations throughout Region F, for the most part these are not effective water supplies for meeting regional water demands. Many of these formations typically produce groundwater with very high salinities and are found at depths too great to be economically feasible as a water supply. It should be noted that most of the deeper, hydrocarbon-producing formations do have some potential to produce brackish groundwater at reasonable rates from shallower depths in and near where they outcrop, which for many of these units is in the eastern third of the region. If areas in or near the outcrop area of any of these deeper units are to be targeted, additional data and study on a site-specific basis will be required.

Additional information on brackish water supplies may be found in Appendix 3A in the 2006 Region F Water Plan.

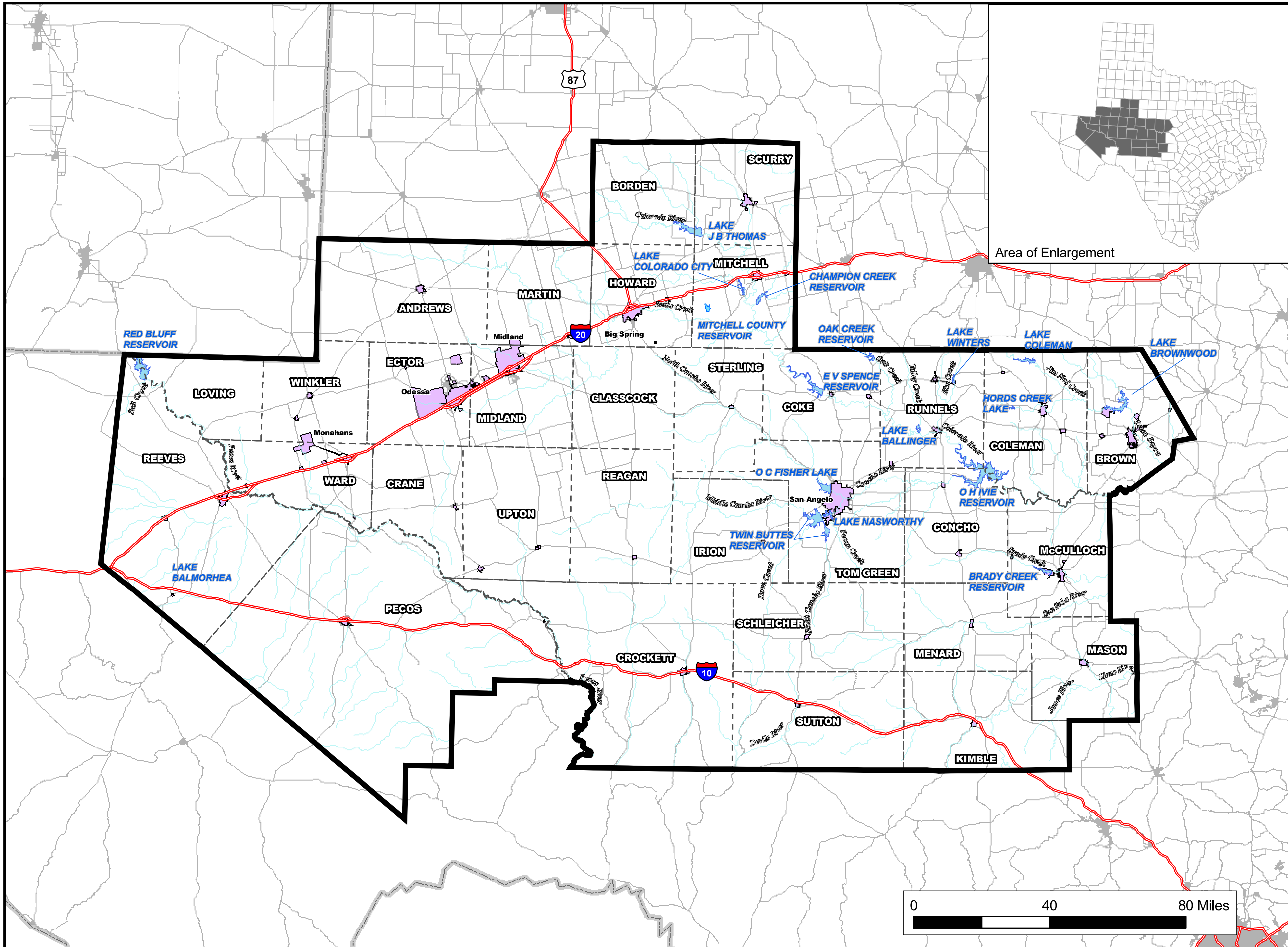
## 3.2 Existing Surface Water Supplies

In the year 2004, approximately 198,000 acre-feet of surface water was used in Region F, supplying 37 percent of the water supply in the region. Surface water from reservoirs provides most of the municipal water supply in Region F. Run-of-the-river water rights are used primarily for irrigation. Table 3.2-1 shows information regarding the 18 major reservoirs in Region F. Figure 3.2-1 shows the location of these reservoirs. Additional information regarding water

**Table 3.2-1**
**Major Reservoirs in Region F[a]**

| Reservoir Name | Basin | Stream | County(ies) | Water Right Number(s) | Priority Date | Permitted Conservation Storage (Acre-Feet) | Permitted Diversion (Acre-Feet per Year) | Owner | Water Rights Holder(s) |
|---|---|---|---|---|---|---|---|---|---|
| Lake J. B. Thomas | Colorado | Colorado River | Borden and Scurry | CA-1002 | 08/05/1946 | 204,000 | 30,000[b] | CRMWD | CRMWD |
| Lake Colorado City | Colorado | Morgan Creek | Mitchell | CA-1009 | 11/22/1948 | 29,934 | 5,500 | TXU | TXU |
| Champion Creek Reservoir | Colorado | Champion Creek | Mitchell | CA-1009 | 04/08/1957 | 40,170 | 6,750 | TXU | TXU |
| Oak Creek Reservoir | Colorado | Oak Creek | Coke | CA-1031 | 04/27/1949 | 30,000 | 10,000 | City of Sweetwater | City of Sweetwater |
| Lake Coleman | Colorado | Jim Ned Creek | Coleman | CA-1702 | 08/25/1958 | 40,000 | 9,000 | City of Coleman | City of Coleman |
| E. V. Spence Reservoir | Colorado | Colorado River | Coke | CA-1008 | 08/17/1964 | 488,760 | 43,000 [b] | CRMWD | CRMWD |
| Mitchell County Reservoir | Colorado | Off-channel | Mitchell | | 2/14/1990 | 27,266 | | | |
| Lake Winters | Colorado | Elm Creek | Runnels | CA-1095 | 12/18/1944 | 8,347 | 1,755 | City of Winters | City of Winters |
| Lake Brownwood | Colorado | Pecan Bayou | Brown | CA-2454 | 09/29/1925 | 114,000 | 29,712 | Brown Co. WID | Brown Co. WID |
| Hords Creek Lake | Colorado | Hords Creek | Coleman | CA-1705 | 03/23/1946 | 7,959 | 2,240 | COE | City of Coleman |
| Lake Ballinger / Lake Moonen | Colorado | Valley Creek | Runnels | CA-1072 | 10/04/1946 | 6,850 | 1,000 | City of Ballinger | City of Ballinger |
| O. H. Ivie Reservoir | Colorado | Colorado River | Coleman, Concho and Runnels | A-3866<br>P-3676 | 02/21/1978 | 554,340 | 113,000 | CRMWD | CRMWD |
| O. C. Fisher Lake | Colorado | North Concho River | Tom Green | CA-1190 | 05/27/1949 | 80,400[c] | 80,400 | COE | Upper Colorado River Authority |
| Twin Buttes Reservoir | Colorado | South Concho River | Tom Green | CA-1318 | 05/06/1959 | 170,000[c] | 29,000 | U.S. Bureau of Reclamation | City of San Angelo |
| Lake Nasworthy | Colorado | South Concho River | Tom Green | CA-1319 | 03/11/1929 | 12,500 | 25,000 | City of San Angelo | City of San Angelo |
| Brady Creek Reservoir | Colorado | Brady Creek | McCulloch | CA-1849 | 09/02/1959 | 30,000 | 3,500 | City of Brady | City of Brady |
| Red Bluff Reservoir | Rio Grande | Pecos River | Loving and Reeves | CA-5438 | 01/01/1980 | 300,000 | 292,500 | Red Bluff WPCD | Red Bluff WPCD |
| Lake Balmorhea | Rio Grande | Toyah Creek | Reeves | A-0060<br>P-0057 | 10/05/1914 | 13,583 | 41,400 | Reeves Co WID #1 | Reeves Co WID #1 |
| *Total* | | | | | | *2,158,136* | *723,757* | | |

a. A major reservoir has more than 5,000 acre-feet of storage.
b. Total diversions under CA 1002 and CA 1008 limited to 73,000 acre-feet per year. CA 1008 allows up to 50,000 acre-feet per year of diversion. For purposes of this table, the limitation is placed on CA 1008.
c. Permitted storage reported is for water conservation storage. UCRA has permission to use water from the sediment pool.




# Figure 3.2-1

## Major Reservoirs

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rights and historical water use may be found in Chapter 1. A comprehensive list of Region F water rights may be found in Appendix 3A.

All surface water supplies in this chapter are derived from Water Availability Models (WAMs) developed by the Texas Commission on Environmental Quality (TCEQ). The TWDB requires the use of the Full Authorization Run (Run 3) of the approved TCEQ WAM for each basin as the basis for water availability in regional water planning[1]. Three WAM models are available in Region F: (a) the Colorado WAM, which covers most of the central and eastern portions of the region, (b) the Rio Grande WAM, which covers the Pecos Basin, and (c) the Brazos WAM. There are approximately 493,000 acre-feet of permitted diversions in the Colorado Basin in Region F, more than half of the permitted diversions in the region. There are 416,158 acre-feet of permitted diversions in the Rio Grande Basin. There is one water right in the Brazos Basin in Region F with a permitted diversion of 63 acre-feet per year.

Table 3.2-2 compares the firm yields of the 17 major reservoirs in Region F developed prior to the WAMs to the yields from the TCEQ WAM[2]. Table 3.2-3 provides a similar comparison for the run-of-the river supplies. The supplies derived using the WAMs are very different from those assumed in previous planning. Total supplies from reservoirs are about 75 percent of that determined by methods prior to the WAMs. Total run-of-the-river supplies are about one third of the supplies in the previous planning. Nearly all of the supply reductions are associated with sources in the Colorado Basin.

The reason for this change is that previous studies made significantly different assumptions about the availability of water supplies in the Colorado Basin. The WAMs assume that priority of diversion and storage determines water availability regardless of geographic location, the type of right, or purpose of use. Previous water analyses generally assumed that municipal reservoir supplies in the Colorado Basin were not subject to priority calls by senior water rights. If any water was passed to senior downstream water rights holders it was only for diversions and not to maintain permitted storage.

TWDB requires the use of the TCEQ WAM for regional water planning even though the Colorado WAM uses many assumptions that are very different than the way that the basin has historically been operated. More detailed information about these assumptions may be found in

**Table 3.2-2**
**Comparison of Firm Yields of Region F Reservoirs under Different Planning Assumptions**
(Values in Acre-Feet per Year)

| Reservoir Name | Basin | Firm Yield Prior to WAM [a] | WAM Firm Yield [b] | WAM Safe Yield |
|---|---|---|---|---|
| Lake J. B. Thomas | Colorado | 9,900 | 20 | 0 |
| E. V. Spence Reservoir | Colorado | 38,776 | 6,170 | 560 |
| O. H. Ivie Reservoir | Colorado | 96,169 | 85,150 | 67,700 |
| Lake Colorado City | Colorado | 4,550 | 0 | 0 |
| Champion Creek Reservoir | Colorado | 4,081 | 10 | 0 |
| Oak Creek Reservoir | Colorado | 5,684 | 5 | 0 |
| Lake Coleman | Colorado | 8,822 | 5 | 0 |
| Lake Winters/ New Lake Winters | Colorado | 1,407 | 0 | 0 |
| Lake Brownwood | Colorado | 41,800 | 47,200 [d] | 33,500 [d] |
| Hords Creek Lake | Colorado | 1,425 | 0 | 0 |
| Lake Ballinger / Lake Moonen | Colorado | 3,566 | 30 | 0 |
| O. C. Fisher Lake | Colorado | 2,973 | 0 | 0 |
| Twin Buttes Reservoir | Colorado | 8,900 | 10 [d] | 0 |
| Lake Nasworthy | Colorado | 7,900 | | |
| Brady Creek Reservoir | Colorado | 2,252 | 0 | 0 |
| Red Bluff Reservoir | Rio Grande | 31,000 | 41,725 [d] | 33,600 [d] |
| Lake Balmorhea | Rio Grande | 182 | 0 | 0 |
| *Total* | | *269,387* | *180,325* | *135,360* |

a Firm Yield Prior to WAM is from the 2001 Water Plan are for year 2000 sediment conditions
b WAM yields are for original sediment conditions except where noted.
c Individual yields not computed in the Colorado WAM report
d WAM yield using year 2000 sediment conditions at reservoir

Appendix 3C of the 2006 Region F Water Plan. It is the opinion of the Region F Water Planning Group that the Colorado WAM does not give a realistic assessment of water supplies for planning purposes because it ignores the historical operation of the basin and previous agreements among water right holders. Using the WAM for water supply planning tends to

**Table 3.2-3**
**Comparison of Run-of-the-River Supplies under Different Planning Assumptions** [a]
(Values in Acre-Feet per Year)

| County | Previous Planning Supplies[b] | WAM Supplies | Increase (Decrease) in Yield |
|---|---|---|---|
| Andrews | 125 | 0 | (125) |
| Borden | 145 | 0 | (145) |
| Brown | 3,256 | 778 | (2,478) |
| Coke | 275 | 48 | (227) |
| Coleman | 2,326 | 31 | (2,295) |
| Concho | 727 | 263 | (464) |
| Crane | 1,434 | 0 | (1,434) |
| Crockett | 361 | 0 | (361) |
| Ector | 1,800 | 23 | (1,777) |
| Howard | 24 | 0 | (24) |
| Irion | 1,980 | 580 | (1,400) |
| Kimble | 3,502 | 1,488 | (2,014) |
| Loving | 0 | 0 | 0 |
| Martin | 550 | 0 | (550) |
| Mason | 0 | 0 | 0 |
| McCulloch | 550 | 128 | (422) |
| Menard | 3,792 | 3,238 | (554) |
| Midland | 1,400 | 0 | (1,400) |
| Mitchell | 235 | 15 | (220) |
| Pecos | 0 | 4,444 | 4,444 |
| Reagan | 0 | 0 | 0 |
| Reeves | 182 | 0 | (182) |
| Runnels | 5,500 | 771 | (4,729) |
| Schleicher | 0 | 0 | 0 |
| Scurry | 1,170 | 69 | (1,101) |
| Sterling | 0 | 48 | 48 |
| Sutton | 475 | 8 | (467) |
| Tom Green | 15,839 | 3,454 | (12,385) |
| Upton | 0 | 0 | 0 |
| Ward | 0 | 0 | 0 |
| Winkler | 0 | 0 | 0 |
| *Total* | *45,648* | *15,386* | *(30,262)* |

a Does not include unpermitted supplies for livestock or diverted water from CRMWD chloride projects

b. Previous planning values are taken from the 1997 and 2001 State Water Plans overestimate available supplies in the lower Colorado River Basin, while underestimating available supplies in the upper basin.

In order to address these water supply issues, a joint modeling effort was conducted with the Lower Colorado Regional Water Planning Group (Region K) as part of the development of the 2006 regional water plans. This modeling effort analyzed the impact of subordination of major senior water rights in the lower Colorado Basin to major water rights in Region F, as well as subordination of major Region F water rights to each other. The subordination strategy and the results of the subordination modeling are described in Chapter 4.

For this plan update, Region K refined the modeling efforts in the Lower Colorado River Basin for use in the 2011 Region K regional water plan. As a special study, Region F monitored the Region K modeling and provided input (See Appendix xx). The special study found that the Region K model assumes that less water is passed from Region F to Region K than shown in the subordination model used for the 2006 water plans,. This results in showing more water available in Region F. Region F decided to retain the water availability analyses and subordination strategy used in the 2006 water plan, including water provider agreements and system operations. This approach should not have an impact to the supplies in Region K as determined by the new Region K “cutoff” model. Since overall supplies in Region F would likely be higher if assumptions similar to the Region K model were used, the water availability analysis performed for the 2006 Region F plan should be conservative. While there are some differences between the models, the use of the two models in this round of planning should not impact the overall balance of water between the two regions. Therefore supplies from the 2006 Region F plan were retained.

## 3.3 Alternative Water Supplies

This section highlights sources of water that have not traditionally been used for water supply, but which could potentially be a significant resource for consideration in future water planning. In Region F, these sources include desalination of brackish water (groundwater and surface water) and reclaimed water.

This section provides information about the current status of alternative water supplies in Region F. Information on brackish groundwater sources may be found in Section 3.1.12. Potential strategies using brackish water or reuse may be found in Chapter 4.

### 3.3.1 Desalination

Desalination processes are used to treat water for use as a public water supply, or for non-potable uses sensitive to the salt content of the water. Desalination can be defined as any process that removes salts from water.[3] The Texas secondary drinking water standard for chloride is 300 mg/l. Consumers can generally detect a salty taste in water that has chloride concentration above about 250 mg/l. However, because chloride is only one component of the dissolved solids typically present in water, the specific taste threshold for TDS is difficult to pinpoint.[4] The Texas secondary drinking water standard for TDS is 1,000 mg/l. Although secondary standards are recommended limits and not required limits, TWDB will not fund a municipal project that uses a water source with TDS greater than 1,000 mg/l unless desalination is part of the planned treatment process, greatly increasing the cost of new water supplies. Region F believes that this policy should be revised allowing for local conditions such as the economy, availability of water, community concerns for the aesthetic of water, and technologies such as point-of use on a voluntary basis.

Water is considered brackish if the total dissolved solids (TDS) range from 1,000 mg/l to 10,000 mg/l. Brackish waters have historically not been considered a water supply source except in limited applications. Until recently desalination of brackish waters was too expensive to be a feasible option for most public water suppliers. However, the costs associated with desalination technology have declined significantly in recent years, making it more affordable for communities to implement. If an available source of brackish water is nearby, desalination can be as cost-effective as transporting better quality water a large distance. In some areas, there is less competition for water from brackish sources because very little brackish water is currently used for other purposes, making it easier to develop brackish sources.

Two factors significantly impact the cost-effectiveness of desalination: water quality and concentrate disposal. Treatment costs are directly correlated to the quality of the source water and can vary significantly depending on the constituents in the water. Use of brackish waters with higher ranges of TDS may not be cost-effective. The presence of other constituents, such as calcium sulfate, may also impact the cost-effectiveness of desalination. The disposal of brine waste from the desalination process can be a significant portion of the costs of a project. The least expensive option is discharge to a receiving body of water or land application. However, a suitable receiving body with acceptable impacts to the environment may not be available. Disposal of concentrate by deep well injection is sometimes a practical and cost-effective method for large-scale desalination projects in Region F.

If the native water quality in the injection zone is 10,000 mg/l or less, then the underground reservoir is classified as an Underground Source of Drinking Water (USDW) and will likely require a Class V Authorization supplemented with portions of a Class I application. Therefore the time and cost for permitting can be substantial. However, the disposal of water from oil field operations, which is similar or worse in quality to the reject from desalination, requires a Class II permit from the Railroad Commission of Texas, which has a less intensive permitting process. Non-hazardous desalination concentrate can be injected into a Class II well without any additional permitting if it is used for secondary recovery. Non-hazardous desalination concentrate can also be injected into a Class I well under a general permit. The TCEQ is currently working to implement a more streamlined permitting process for desalination concentrate. TWDB Report 366, *Please Pass the Salt: Using Oil Fields for the Disposal of Concentrate from Desalination*, provides significant detail regarding the potential for injecting desalination concentrate into oil fields[5].

TWDB through a contract with the Bureau of Economic Geology developed a database of the desalination facilities operating in Texas in 2005. The information in the database was obtained through surveys and correspondence with the plant operators. Facilities placed in operation after 2005 are not included in the database. According to the data posted on the TWDB website, a total of about 6.6 million gallons of water per day (MGD) is desalinated on a regular basis in Region F by municipal, commercial and industrial facilities.[6] It should be noted that not all of the source water for the desalination activities is considered brackish water, and some desalination facilities are used to treat the water for other constituents such as radionuclides. The current TWDB list of desalination facilities does not distinguish between brackish source waters and source waters classified as fresh water.

A major treatment facility for brackish water currently operating in Region F is at Fort Stockton. Fort Stockton draws water from the Edwards-Trinity Aquifer that must be treated to reduce TDS to acceptable levels. The Fort Stockton plant consists of microfiltration (MF) and ultraviolet (UV) disinfection pretreatment, followed by RO and chlorination. Feed water with a TDS concentration of approximately 1,400 mg/l is blended with RO permeate at a ratio of 60:40. The maximum capacity of the RO permeate stream is approximately 3.8 MGD. Currently, the Fort Stockton facility produces approximately 7.0 MGD blended water, at 800 mg/l TDS. Concentrate streams are disposed of using evaporation ponds. Future plans for the Fort Stockton facility include the possible installation of a dedicated treatment train for the city's industrial customers.[7,8]

Other current users of desalination facilities include the City of Brady, Midland Country Club and Water Runner, Inc in Midland. In addition, the Millersview-Doole Water Supply Corporation (MDWSC) is building a RO desalination plant with an initial capacity of approximately 1.5 MGD. The MDWSC will use Lake Ivie as a water source, which has TDS levels ranging from 1,100 to 1,500 mg/l. Ultimately, the City of Brady and MDWSC plants plan to expand to 3.0 MGD each.[9,10]

Other industrial and commercial users in the region also desalinate water for various uses. However, the TWDB database does not report any user with a treatment facility smaller than 0.025 million gallons per day. At this time, it is not feasible to estimate how much of the industrial and commercial desalination utilizes a brackish water source.

### 3.3.2 Use of Reclaimed Water

Reclaimed water can be defined as any water that has already been used for some purpose, and is used again for another purpose instead of being discharged or otherwise disposed. Although water initially used for agricultural and industrial purposes can be reclaimed, this discussion will focus on reuse of treated municipal wastewater effluent. Reclaimed water has been used for agricultural irrigation and some industrial purposes for many years. Additionally its use has recently gained a level of public acceptance that allows water managers to readily implement other reuse strategies. Although there is still public resistance to the notion of the reuse of wastewater effluent for potable water supply, there is increasingly widespread use of reclaimed water for agricultural and industrial purposes and for irrigation of parks and landscaping. The use of reclaimed water requires development of the infrastructure necessary to transport the treated effluent to secondary users. For some uses, the wastewater may be difficult to treat to the required standard.

The TWDB notes three important advantages of the use of reclaimed water:

- Effluent from municipal wastewater plants is a drought-proof supply.
- Treated effluent is the *only* source of water that automatically increases as economic and population growth occurs in the community.
- The source of treated effluent is usually located near the intended use, not at some yet-to-be developed, distant reservoir or well field.[11]

The use of reclaimed water can occur directly or indirectly. Direct use is typically defined as use of the effluent before it is discharged, under arrangements set up by the generator of the wastewater. Indirect reuse occurs when the effluent is discharged to a stream and later diverted from the stream for some purpose, such as municipal, agricultural or industrial supply. Indirect reuse is sometimes difficult to quantify because the effluent becomes mixed with the waters of the receiving body. A water rights permit may be needed to enable the diversion of the effluent from the stream.

A number of communities in Region F have direct wastewater reuse programs in place, utilizing municipal wastewater effluent for landscape irrigation or for industrial or agricultural purposes. The major municipal reuse programs in Region F are listed in Table 3.3-1. Smaller programs (less than 0.1 MGD) are also reported in Concho, Howard, Irion, Martin, and Reagan counties.

**Table 3.3-1**
**Recent Reuse Quantities in Region F**

| City | County | Use | Year 2000 | | Year 2001 | | Year 2002 | |
|---|---|---|---|---|---|---|---|---|
| | | | (MGD) | (Ac-Ft/Yr) | (MGD) | (Ac-Ft/Yr) | (MGD) | (Ac-Ft/Yr) |
| Midland | Midland | Irrigation | 10.7 | 12,000 | 11.3 | 12,700 | 11.3 | 12,700 |
| San Angelo | Tom Green | Irrigation | 7.6 | 8,500 | 8.2 | 9,200 | 7.6 | 8,500 |
| Odessa | Ector | Industrial Irrigation | 3.2 | 3,600 | 3.4 | 2,800 | 3.3 | 3,700 |
| Monahans | Ward | Irrigation | no data | no data | 0.6 | 670 | 0.6 | 670 |
| Andrews | Andrews | Irrigation | 0.5 | 560 | no data | no data | no data | no data |
| Winters | Runnels | Irrigation | 0.2 | 220 | 0.2 | 220 | 0.2 | 220 |
| Snyder | Scurry | Irrigation | no data | no data | 0.1 | 110 | 0.1 | 110 |
| *TOTAL* | | | *22.2* | *24,880* | *23.8* | *26,700* | *23.1* | *25,900* |

Source of Data: TWDB reuse database [12]

One of the Region F special studies completed in 2008 was the Municipal Conservation Survey. This survey offered detail on the conservation practices, including water reuse of select cities in Region F. The cities of Andrews, Eden, and Odessa reported using wastewater effluent for municipal irrigation and/or industrial purposes. Midland and San Angelo currently reuse their effluent for non-municipal purposes. Only two cities, Odessa and San Angelo provided more recent reuse data. This data is summarized in Table 3.3-2.

Teleconferences with several cities provided insight into current and future plans to expand water reuse. The City of Menard is currently trying to fund a wastewater treatment plant that would provide wastewater reuse for golf course irrigation. In addition to current reuse practices, Midland wants to provide Midland College with 100,000 gallons per day of reuse water for landscape irrigation by constructing an interceptor unit. The City of Odessa already provides reuse water for industrial, irrigation and residential irrigation users. The city is exploring options to offer reuse water for irrigation to additional facilities which are in the vicinity of existing reuse pipelines. San Angelo has historically used reuse water to irrigate city-owned farms or has sold the effluent to other irrigators.

**Table 3.3-2**
**Reuse Water Sales in Region F**

| City | County | Use | Year 2005 | | Year 2006 | | Year 2007 | |
|---|---|---|---|---|---|---|---|---|
| | | | (MGD) | (Ac-Ft/Yr) | (MGD) | (Ac-Ft/Yr) | (MGD) | (Ac-Ft/Yr) |
| San Angelo | Tom Green | Irrigation | 8.2 | 9,181 | 7.0 | 7,798 | 8.2 | 9,215 |
| Odessa | Ector | Industrial Irrigation | 2.9 | 3,228 | 3.0 | 3,332 | 2.4 | 2,741 |

a. The amount of reuse water provided for industrial purposes is approximately 47% of the total amount reported. The City has a contract to provide 3 MGD of reuse water for industrial purposes.
b. The reported MGD is average daily use.

For planning purposes only the reuse for Midland, San Angelo and Odessa will be considered as a current supply. It is uncertain whether the TWDB considered reuse projects that are used to irrigate city properties and park facilities as a source when developing demands for the cities. To be conservative, it will be assumed that the demands for the cities in Region F do not include the existing municipal irrigation demands for reuse supplies. Reuse supplies developed beyond what is currently being used may be considered as a water management strategy.

## 3.4 Currently Available Supplies for Water User Groups

Summary tables in Appendix 3B present the currently available water available for each water user group (WUG), arranged by county. (Water user groups are cities with populations greater than 500, water suppliers who serve an average of at least 0.25 million gallons per day (MGD) annually, “county other” municipal uses, and countywide manufacturing, irrigation, mining, livestock, and steam electric uses.) Unlike the overall water availability figures in Sections 3.1 and 3.2, currently available supplies are limited by the ability to deliver and/or use water. These limitations may include firm yield of reservoirs, well field capacity, aquifer characteristics, water quality, water rights, permits, contracts, regulatory restrictions, raw water delivery infrastructure and water treatment capacities where appropriate. Currently available supplies in each county are shown in Table 3.5-1. The total of the currently available supply by use type is shown in Figure 3.5-1.

Historical water use from TWDB provides the basis for livestock water availability. Surface water supplies for livestock in Region F come primarily from private stock ponds, most of which are exempt under §11.142 of the Texas Water Code and do not require a water right. In addition, a significant portion of the mining demand in Brown and Crane Counties appears to be based on recirculated surface water from exempt sources. Therefore, a supply to meet the demand is assumed to come from exempt sources to prevent an unwarranted shortage.

## 3.5 Currently Available Supplies for Wholesale Water Providers

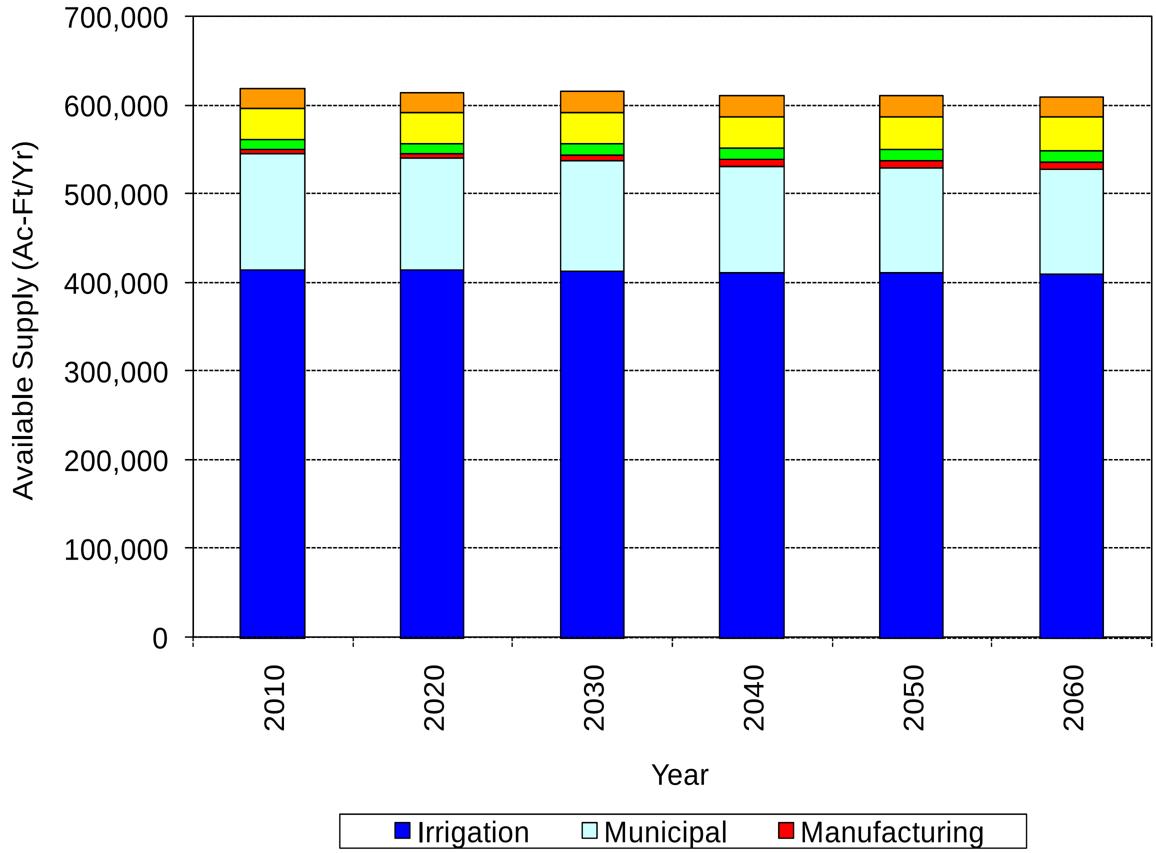
There are seven designated wholesale water providers in Region F. A wholesale water provider has wholesale water contracts for 1,000 acre-feet per year or is expected to contract for 1,000 acre-feet per year or more over the planning period. Similar to the currently available supply for water user groups, the currently available supply for each wholesale water provider is limited by the ability to deliver water to end-users. These limitations include firm yield of reservoirs, well field capacity, aquifer characteristics, water quality, water rights, permits, contracts, regulatory restrictions and infrastructure. A summary of currently available supplies for each wholesale water provider is included in Table 3.5-2 and Appendix 3C. Brief descriptions of the supply sources are presented below.

**Table 3.5-1**
**Summary of Currently Available Supply to Water Users by County[a]**
(Values in Acre-Feet per Year)

| County | Year 2010 | Year 2020 | Year 2030 | Year 2040 | Year 2050 | Year 2060 |
|---|---|---|---|---|---|---|
| Andrews | 25,761 | 25,761 | 25,761 | 26,249 | 26,239 | 26,226 |
| Borden | 2,316 | 2,317 | 2,316 | 2,316 | 2,316 | 2,316 |
| Brown | 21,694 | 21,784 | 21,787 | 21,752 | 21,764 | 21,821 |
| Coke | 2,094 | 2,072 | 2,345 | 2,307 | 2,288 | 2,253 |
| Coleman | 2,906 | 2,891 | 2,888 | 2,886 | 2,885 | 2,881 |
| Concho | 7,001 | 6,994 | 7,032 | 7,021 | 6,909 | 6,909 |
| Crane | 3,969 | 4,097 | 4,159 | 4,201 | 4,258 | 4,323 |
| Crockett | 5,980 | 5,997 | 6,006 | 6,014 | 6,022 | 6,030 |
| Ector | 48,121 | 44,770 | 53,358 | 54,244 | 55,272 | 55,608 |
| Glasscock | 24,906 | 24,906 | 24,906 | 24,906 | 24,906 | 24,906 |
| Howard | 14,040 | 13,722 | 16,332 | 15,897 | 15,646 | 15,294 |
| Irion | 2,331 | 2,331 | 2,325 | 2,316 | 2,309 | 2,305 |
| Kimble | 2,749 | 2,746 | 2,746 | 2,746 | 2,746 | 2,746 |
| Loving | 667 | 667 | 666 | 666 | 666 | 666 |
| Martin | 14,949 | 14,949 | 14,949 | 15,022 | 14,760 | 14,496 |
| Mason | 18,097 | 18,096 | 18,097 | 18,097 | 18,097 | 18,097 |
| McCulloch | 9,644 | 9,737 | 9,889 | 9,941 | 9,790 | 9,889 |
| Menard | 4,650 | 4,647 | 4,646 | 4,646 | 4,646 | 4,646 |
| Midland | 58,331 | 58,133 | 45,989 | 41,081 | 40,880 | 40,660 |
| Mitchell | 7,882 | 7,872 | 7,858 | 7,838 | 7,821 | 7,793 |
| Pecos | 91,772 | 91,792 | 91,801 | 91,800 | 91,796 | 91,782 |
| Reagan | 28,950 | 28,950 | 28,950 | 28,950 | 28,950 | 28,950 |
| Reeves | 74,003 | 74,248 | 74,438 | 74,583 | 74,736 | 74,872 |
| Runnels | 4,854 | 4,859 | 4,899 | 4,899 | 4,825 | 4,856 |
| Schleicher | 4,921 | 4,910 | 4,903 | 4,898 | 4,894 | 4,897 |
| Scurry | 11,139 | 11,019 | 11,697 | 11,538 | 11,451 | 11,324 |
| Sterling | 2,187 | 2,225 | 2,240 | 2,244 | 2,236 | 2,247 |
| Sutton | 4,884 | 4,879 | 4,879 | 4,874 | 4,873 | 4,872 |
| Tom Green | 74,516 | 74,295 | 74,186 | 73,972 | 73,449 | 73,226 |
| Upton | 10,543 | 10,547 | 10,549 | 10,551 | 10,552 | 10,554 |
| Ward | 16,950 | 16,283 | 16,081 | 15,924 | 15,759 | 15,609 |
| Winkler | 16,768 | 16,768 | 16,768 | 16,768 | 16,768 | 16,768 |
| *Total* | *619,575* | *615,264* | *615,446* | *611,147* | *610,509* | *609,822* |

a. Currently available supply reflects the most limiting factor affecting water availability to users in the region. These limitations include firm yield of reservoirs, well field capacity, aquifer characteristics, water quality, water rights, permits, contracts, regulatory restrictions, raw water delivery infrastructure and water treatment capacities

**Figure 3.5-1**
**Supplies Currently Available to Water User Groups by Type of Use**




*Colorado River Municipal Water District (CRMWD).* CRMWD supplies raw water from Lake J.B. Thomas, E.V. Spence Reservoir, and O.H. Ivie Reservoir, and well fields in Ward, Martin, Scurry and Ector Counties. Water for oil and gas production, which is classified as a mining use, is supplied from several chloride control projects. CRMWD owns and operates more than 600 miles of 18-inch to 60-inch water transmission lines to provide water to its member cities and customers[13].

*Brown County Water Improvement District Number One (BCWID).* BCWID owns and operates Lake Brownwood, as well as raw water transmission lines that supply the District's water treatment facilities, irrigation customers and the City of Early. BCWID operates two water treatment facilities in the City of Brownwood which together have a combined capacity of 16 mgd[14]. Other customers divert water directly from the lake.

**Table 3.5-2**
**Currently Available Supplies for Wholesale Water Providers**
(Values in Acre-Feet per Year)

| Water Provider | Source | 2010 | 2020 | 2030 | 2040 | 2050 | 2060 |
|---|---|---|---|---|---|---|---|
| BCWID | Lake Brownwood [a] | 29,712 | 29,712 | 29,712 | 29,712 | 29,712 | 29,712 |
| | | | | | | | |
| CRMWD | Lake Ivie [b] | 66,350 | 65,000 | 63,650 | 62,300 | 60,950 | 59,600 |
| | Spence Reservoir [b] | 560 | 560 | 560 | 560 | 560 | 560 |
| | Thomas Reservoir [b] | 0 | 0 | 0 | 0 | 0 | 0 |
| | Ward Co. Well Field [c] | 5,200 | 0 | 0 | 0 | 0 | 0 |
| | Martin Co. Well Field | 1,035 | 1,035 | 1,035 | 1,035 | 1,035 | 1,035 |
| | Ector Co. Well Field | 423 | 423 | 423 | 423 | 423 | 423 |
| | Scurry Co. Well Field | 900 | 900 | 900 | 900 | 900 | 900 |
| | | | | | | | |
| Great Plains Water System | Andrews and Gaines Counties Well Fields [d] | 5,220 | 5,220 | 5,220 | 5,220 | 5,220 | 5,220 |
| | | | | | | | |
| City of Odessa | CRMWD System [b] | 13,439 | 13,191 | 20,793 | 20,778 | 21,177 | 21,047 |
| | Ector Co. Well Field (CRMWD) | 423 | 423 | 423 | 423 | 423 | 423 |
| | Ward Co. Well Field (CRMWD) | 4,800 | | | | | |
| | Direct Reuse | 3,000 | 3,150 | 3,300 | 3,450 | 3,600 | 3,750 |
| | | | | | | | |
| UCRA | O.C. Fisher Reservoir [b] | 0 | 0 | 0 | 0 | 0 | 0 |
| | Mountain Creek Reservoir [b] | 0 | 0 | 0 | 0 | 0 | 0 |
| | | | | | | | |
| City of San Angelo | Twin Buttes/ Nasworthy [b] | 0 | 0 | 0 | 0 | 0 | 0 |
| | O.C. Fisher Reservoir [b] | 0 | 0 | 0 | 0 | 0 | 0 |
| | Spence Reservoir [e] | 0 | 0 | 0 | 0 | 0 | 0 |
| | Lake Ivie [f] | 10,974 | 10,751 | 10,528 | 10,304 | 10,081 | 9,858 |
| | Concho River | 642 | 642 | 642 | 642 | 642 | 642 |
| | Direct Reuse - Irrigation | 8,500 | 8,500 | 8,500 | 8,500 | 8,500 | 8,500 |

Table 3.5-2 (Continued)

| **Water Provider** | **Source** | **2010** | **2020** | **2030** | **2040** | **2050** | **2060** |
|---|---|---|---|---|---|---|---|
| University Lands | CRMWD Ward Co Well Field [c] | 5,200 | 0 | 0 | 0 | 0 | 0 |
| | Midland Paul Davis Well Field [g] | 4,722 | 4,722 | 4,722 | 0 | 0 | 0 |
| | City of Andrews Well Field [h] | 671 | 708 | 730 | 0 | 0 | 0 |
| | | | | | | | |
| *Total Wholesale Providers* | | *161,771* | *144,937* | *151,138* | *144,247* | *143,223* | *141,670* |

a Yield of Lake Brownwood limited by water right.
b Safe yield from the Colorado WAM. See subordination strategy for actual supply used in planning.
c Contract between CRMWD and University Lands expires in 2019.
d Region F supplies only.
e Supplies from Spence Reservoir currently not available to the City of San Angelo pending rehabilitation of Spence pipeline.
f For planning purposes supplies limited to 16.54 percent of the safe yield of Ivie Reservoir.
g Contract between University Lands and the City of Midland expires in 2035. Current supplies estimated at 4,722 acre-feet per year.
h Contract between University Lands and the City of Andrews expires in 2033. Current supplies estimated at 20% of the city’s demands.

*Upper Colorado River Authority (UCRA).* The UCRA owns water rights in O.C. Fisher Reservoir in Tom Green County and Mountain Creek Lake in Coke County. O.C. Fisher supplies are contracted to the Cities of San Angelo and Miles, and Mountain Creek Lake supplies are contracted to the City of Robert Lee.

*Texland Great Plains Water System, Ltd.* The Texland Great Plains Water System (Great Plains) provides water to customers in Region F from the Ogallala Aquifer in Andrews County in Region F and Gaines County in Region O. Great Plains owns an extensive pipeline system that has historically provided water primarily for oil and gas operations, although a small amount of municipal water has been supplied to rural Ector County as well. The provider's largest customer is a steam electric operation in Ector County.

*City of Odessa*. The City of Odessa is a CRMWD member city. As a member city, all of Odessa's future needs will be provided from CRMWD sources. The City of Odessa sells treated water to the Ector County Utility District, and treated effluent to industrial users and municipal irrigation users.

*City of San Angelo*. The City of San Angelo's sources of supply are Lake O.C. Fisher (purchased from Upper Colorado River Authority), Twin Buttes Reservoir, Lake Nasworthy, local surface water rights, O.H. Ivie Reservoir (purchased from CRMWD), and E.V. Spence Reservoir (purchased from CRMWD). The city owns several run-of-the river water rights on the Concho River which enable the city to make use of uncontrolled supplies from the Concho River. San Angelo owns and operates a raw water transmission line from Spence Reservoir and a 5-mile water transmission line from a pump station on the CRMWD Ivie pipeline just north of the city. The city also owns an undeveloped well field in McCulloch County. San Angelo supplies raw water to the power plant located on Lake Nasworthy. The city provides treated water to the City of Miles and to rural customers in Tom Green County. Treated wastewater from the city is currently used for irrigation.

*University Lands.* University Lands manages properties belonging to the University of Texas System in West Texas. University Lands does not directly supply water; CRMWD, the City of Midland and the City of Andrews have developed water well fields on property managed by University Lands. The well fields produce water from the Cenozoic Pecos Alluvium aquifer in Ward County and the Ogallala aquifer in Martin and Andrews Counties.

## 3.6 Impact of Drought on Region F

During the past century, recurring drought has been a natural part of Texas' varying climate, especially in the arid and semi-arid regions of the state. An old saying about droughts in west Texas is that "droughts are continual with short intermittent periods of rainfall."[15] Droughts, due to their complex nature, are difficult to define and understand, especially in a context that is useful for communities that must plan and prepare for drought. Drought directly impacts the availability of ground and surface water supplies for agricultural, industrial, municipal, recreational, and designated aquatic life uses. The location, duration, and severity of drought determine the extent to which the natural environment, human activities, and economic factors are impacted.

Geography, geology and climate vary significantly from east to west in Region F. Ecoregions within Region F vary from the Edwards Plateau to the east, Central Great and Western High Plains in the central and northern portions of the region, and Chihuahuan Deserts to the west. Annual rainfall in Region F ranges from an average of more than 28 inches in the east to slightly more than 10 inches in the west. Likewise, the annual gross reservoir evaporation rate ranges from 60 inches in the east to approximately 75 inches in the western portion of the region. Extended periods of drought are common in the region, with severe to extreme droughts having occurred in the 1950s, 1990s, and early 2000s.

### 3.6.1 Drought Conditions

Numerous definitions of drought have been developed to describe drought conditions based on various factors and potential consequences. In the simplest of terms, drought can be defined as "a prolonged period of below-normal rainfall." However, the *State Drought Preparedness Plan*[16] provides more specific and detailed definitions:

- *Meteorological Drought.* A period of substantially diminished precipitation duration and/or intensity that persists long enough to produce a significant hydrologic imbalance.
- *Agricultural Drought.* Inadequate precipitation and/or soil moisture to sustain crop or forage production systems. The water deficit results in serious damage and economic loss to plant and animal agriculture. Agricultural drought usually begins after meteorological drought but before hydrological drought and can also affect livestock and other agricultural operations.
- *Hydrological Drought.* Refers to deficiencies in surface and subsurface water supplies. It is measured as streamflow, and as lake, reservoir, and groundwater levels. There is

usually a lack of rain or snow and less measurable water in streams, lakes, and reservoirs, making hydrological measurements not the earliest indicators of drought.

- *Socioeconomic Drought.* Occurs when physical water shortages start to affect the health, well-being, and quality of life of the people, or when the drought starts to affect the supply and demand of an economic product.

These definitions are not mutually exclusive, and provide valuable insight into the complexity of droughts and their impacts. They also help to identify factors to be considered in the development of appropriate and effective drought preparation and contingency measures.

Droughts have often been described as “insidious by nature.” This is mainly due to several factors:

- Droughts cannot be accurately characterized by well-defined beginning or end points.
- Severity of drought-related impacts is dependent on antecedent conditions, as well as ambient conditions such as temperature, wind, and cloud cover.
- Droughts, depending on their severity, may have significant impacts on human activities; and human activities during periods of drought may exacerbate the drought conditions through increased water usage and demand.

Furthermore, the impact of a drought may extend well past the time when normal or above-normal precipitation returns.

Various indices have been developed in an attempt to quantify drought severity for assessment and comparative purposes. One numerical measure of drought severity that is frequently used by many federal and state government agencies is the Palmer Drought Severity Index (PDSI). It is an estimate of soil moisture that is calculated based on precipitation and temperature. The PDSI ranges from +6.0 for the wettest conditions to –6.0 for the driest conditions. A PDSI of –3.99 to –3.0 is termed “severe drought” and a PDSI of –6.0 to –4.0 is described as “extreme drought”. The Texas Water Development Board (TWDB) uses the PDSI to monitor wet/dry conditions in Texas. In 2000, all counties of Region F experienced at least some periods of severe or extreme drought. However, the PDSI is an indicator of an agricultural drought only. It has little relationship with a hydrological drought.

### 3.6.2 Drought of Record and Recent Droughts in Region F

In general, the drought of record is defined as the worst drought to occur in a region during the entire period of meteorological record keeping. For most of Texas, the drought of record occurred from 1950 to 1957. During the 1950s drought, many wells, springs, streams, and rivers went dry and some cities had to rely on water trucked in from other areas to meet drinking water demands. By the end of 1956, 244 of the 254 Texas counties were classified as disaster areas due to the drought, including all of the counties in Region F.

During the past decade, most regions of Texas have experienced droughts resulting in diminished water supplies for agricultural and municipal use, decreased flows in streams and reservoirs, and significant economic loss. Droughts of moderate to extreme conditions occurred in 1996, 1998, and 2000 in various regions of the state, including Region F. The worst year during the recent drought was 2000, when most Region F counties experienced extreme drought for the entire growing season.

**Meteorological Drought in Region F**

Meteorological drought is characterized by below-normal precipitation for an extended period of time. Figures 3.6-1 and 3.6-3 show the historical annual precipitation totals for Midland and San Angelo for the period from 1951 to 2007. As is typical in Texas, the average annual precipitation in Region F increases from west to east. Midland is further west, and averages about 14 inches a year over the period shown. San Angelo averages about 19 inches of precipitation per year. The patterns of wet and dry years have some general correlation, but can vary significantly. Figures 3.6-2 and 3.6-4 show the rainfall variation from the annual average for the two locations. For both the 1950's drought and the recent drought, annual rainfall is significantly below average for an extended number of years. The current drought appears more severe than the 1950's drought. Ten of the last fifteen years show rainfall less than the historic average. This occurred at no other time in the period of record.

**Hydrological Drought in Region F**

Available water supplies for municipal and agricultural use have been a major concern in the region since the end of the 19th century. During the past 80 years, eighteen major reservoirs have been constructed for water storage, recreation and flood control throughout Region F. Table 3.2-1 summarizes pertinent data for these reservoirs, including conservation storage capacities. The locations of these reservoirs are shown on Figure 3.2-1.

**Figure 3.6-1**
**Annual Precipitation at Midland, Texas from 1951 to 2007**

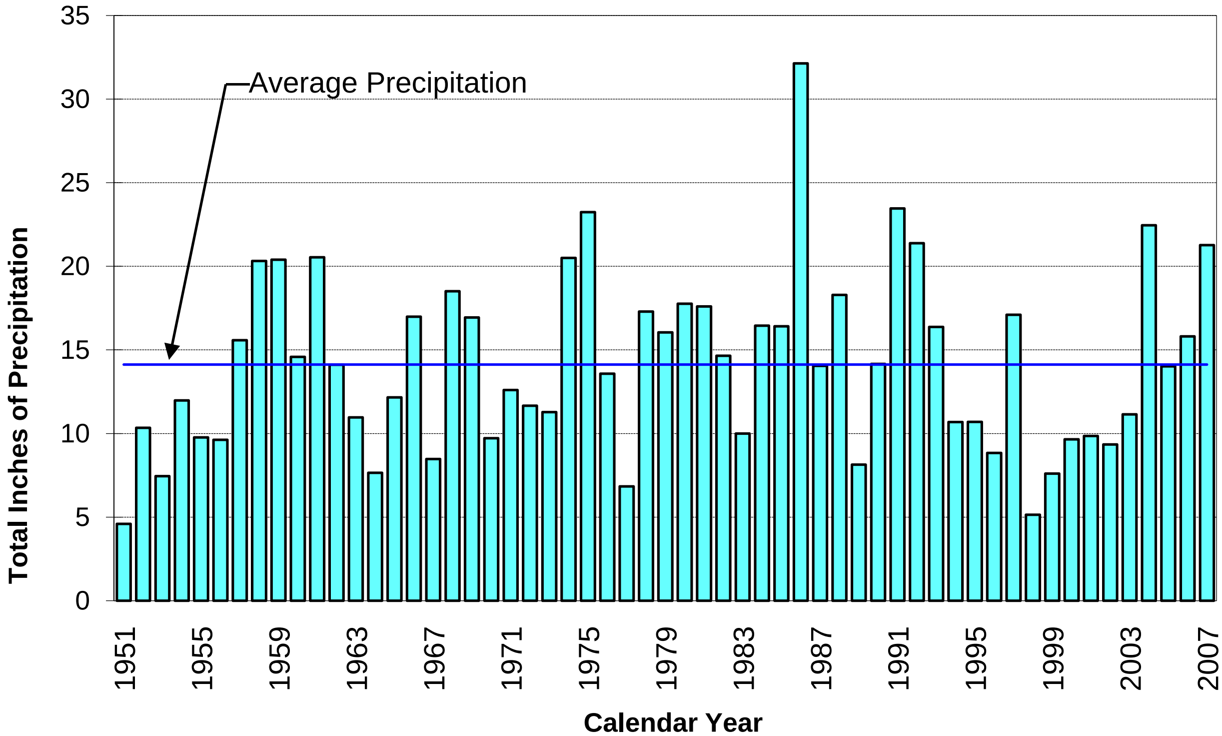
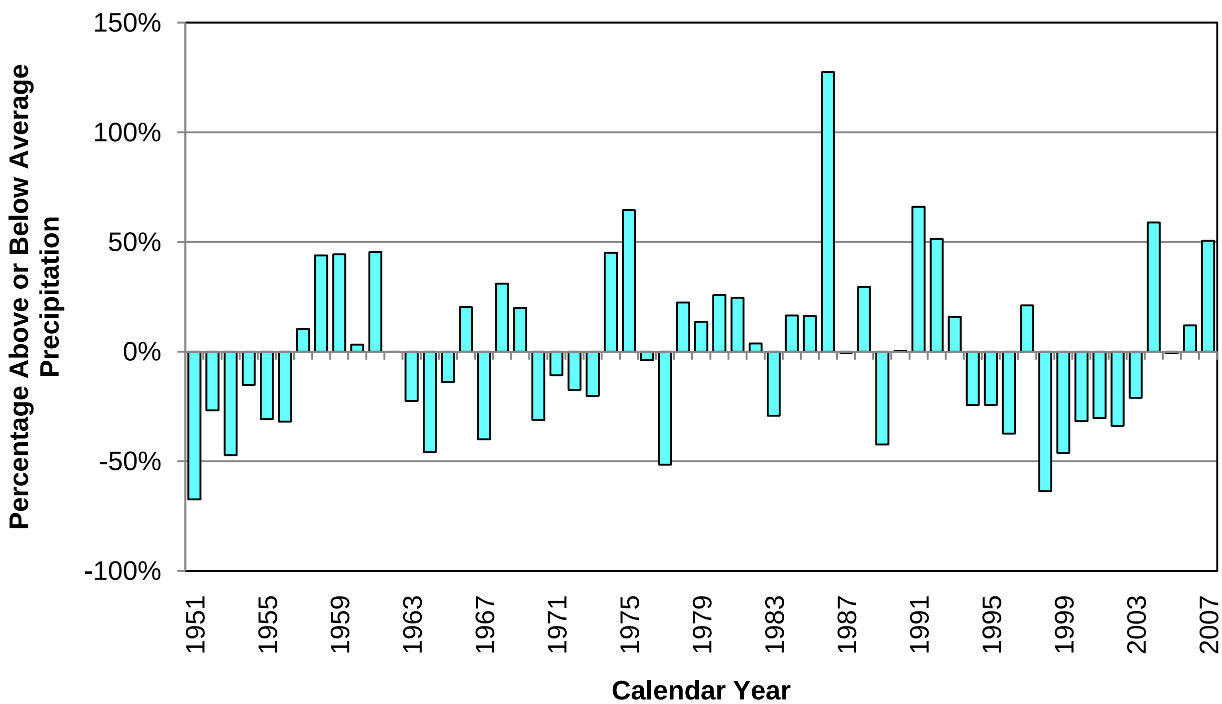



**Figure 3.6-2**
**Precipitation Variation from Average at Midland, Texas from 1951 to 2007**




Data for Figures 3.6-1 and 3.6-2 are from the National Climate Data Center, Station ID #5890

**Figure 3.6-3**
**Annual Precipitation at San Angelo, Texas from 1951 to 2007**

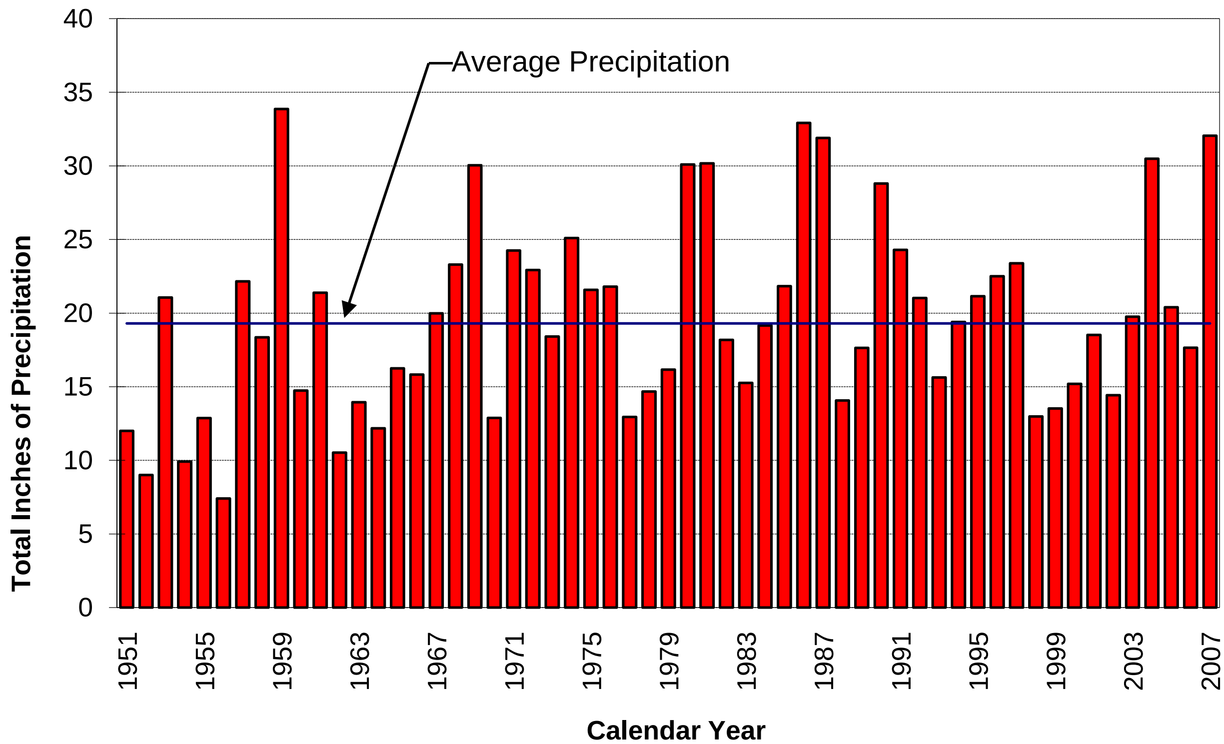
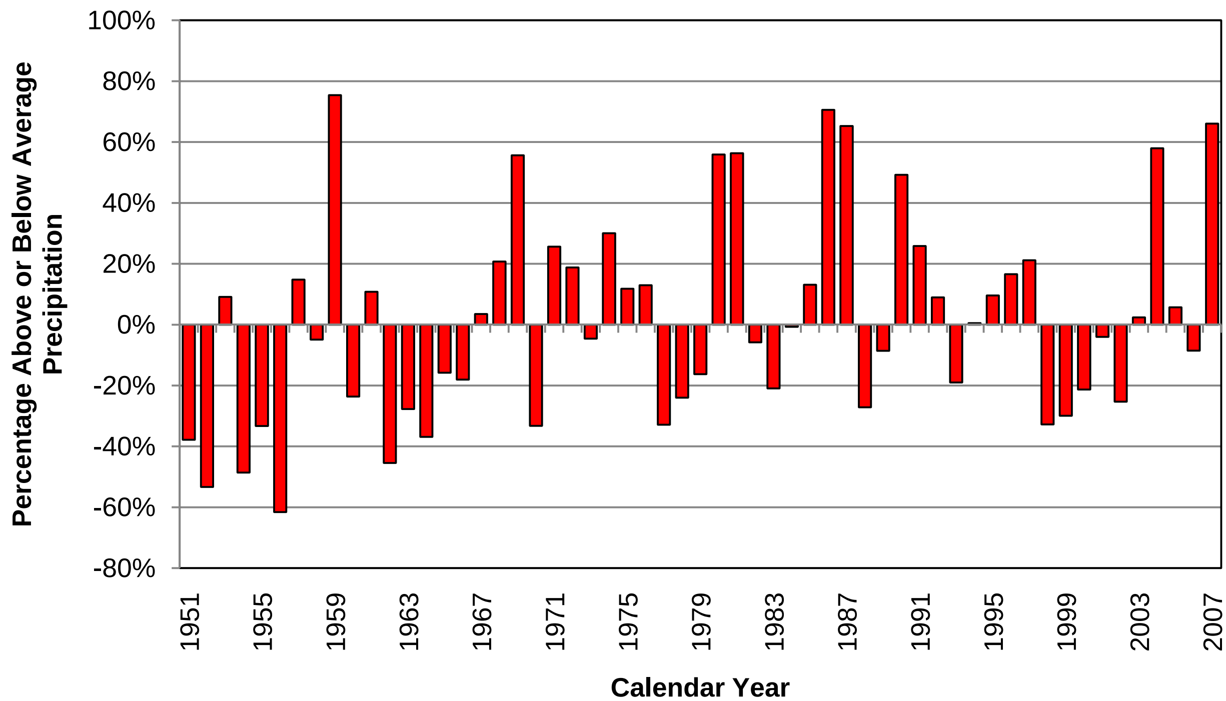



**Figure 3.6-4**
**Precipitation Variation from Average at San Angelo, Texas from 1951 to 2007**




Data for Figures 3.6-3 and 3.6-4 are from the National Climate Data Center, Station ID #5890

Frequent and extended hydrological droughts have occurred in almost every decade since 1940. The most severe droughts occurred in the 1950s, 1960s, 1980s and the late 1990s through early 2000. The most recent drought is quite possibly the worst hydrologic drought experienced in that period.

According to TWDB records, reservoir levels in Region F have generally decreased over the past ten to fifteen years. For some reservoirs the recent above average rainfall has had little impact to reservoir storage. A summary of major reservoirs in the region follows:

- O.H. Ivie Reservoir experienced a sharp decrease in storage in 1996, recovered in 1997 and then experienced a steady decline until hitting a low of about 30% capacity in 2004. The reservoir began to recover late in 2004 with additional rainfall in the watershed. The highest storage in 2005 was about 55% with the level declining to about 40% by the beginning of 2007. The reservoir recovered quickly in 2007 but in May 2009 was only 50% full.
- Levels at E.V. Spence Reservoir began a general decline in 1992 and hit a low of less than 10% capacity in 2002. By January 2005, the reservoir levels rose to 18% of capacity. However, by May 2009 the reservoir level reached its lowest point of 8.6% capacity.
- Levels at O.C. Fisher and Twin Buttes Reservoirs also declined in the past 10 years, both hitting critically low levels. In January 2005, levels at O.C. Fisher and Twin Buttes were only at 6% of storage capacity. By the end of 2005 the level in O.C. Fisher had increased to 15% but since then the storage has steadily been declining. From the January 2005 low, the Twin Buttes Reservoir had increased to 25% by May 2009.
- Lake Brownwood, in the northeastern corner of Region F, suffered two to three years of declining water levels in the late 1990's. It hit a low of about 50% in 2000, but recovered by late 2002 to levels above 90%. In 2005 the level started to decline and reached a low of 60% by 2007. By May 2009 the reservoir level had increased to 74% capacity.
- Red Bluff Reservoir, on the Pecos River at the western edge of Region F, dropped from a high of about 50% capacity in 1992 to a low of about 10% in 2001, but had recovered to a 39% level by 2005. In May 2009 the reservoir had declined to 25%.

These data indicate the degree of drought in Region F during the past 10 to 15 years and the percent recovery in five of the region's major reservoirs. By the end of the 1990's, many Region F reservoirs were at their lowest recorded levels. However, for the same period, the TWDB reported the statewide reservoir storage level at approximately 90 percent of capacity. The reported statewide reservoir storage level in the late 1990's indicates that many reservoirs in other regions of the state were at or near 100 percent of capacity and drought conditions were not occurring in these regions.

**Agricultural Drought in Region F**

Because a substantial portion of water used in Region F is for agriculture, a drought can result in serious economic losses to farmers and ranchers. During the 1950's drought, many Texas ranchers and farmers incurred increased levels of debt or were forced to abandon their operations. Some ranchers singed the spines off of prickly pear cactus so their cattle would have something to eat. Ranch debt reached a high of $3 billion and 143 rural counties statewide experienced a population decline during the drought.[17] In Region F, the population declined in 18 of the region's 32 counties between 1950 and 1960.

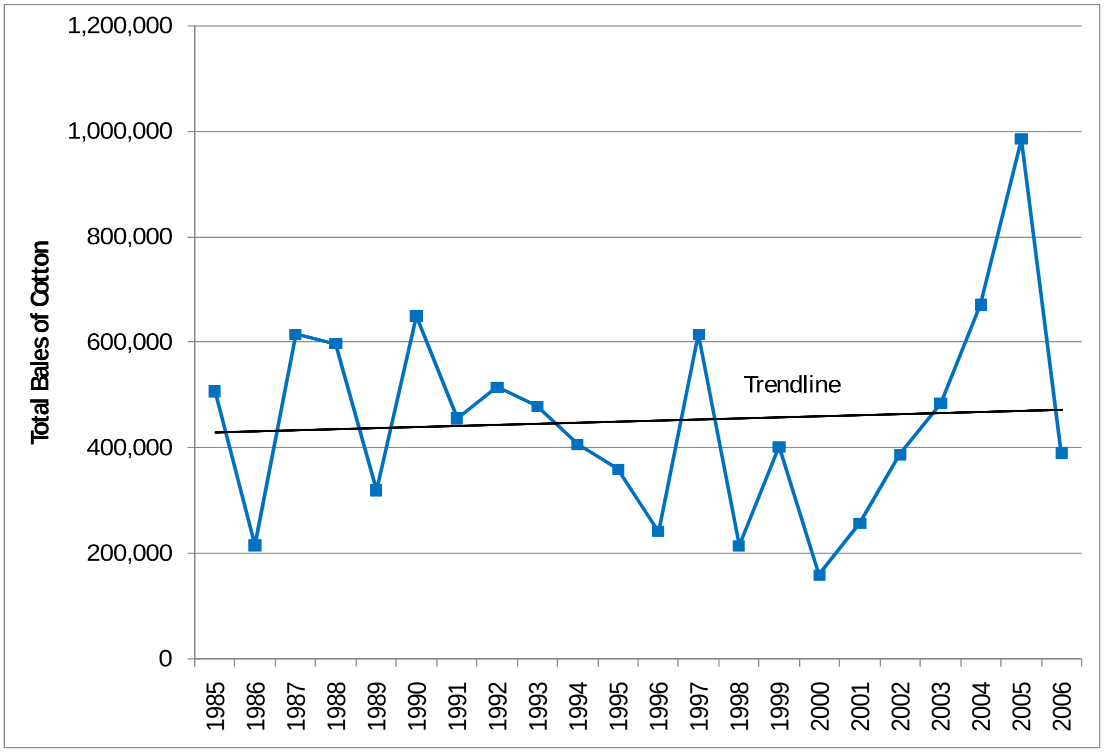
Agricultural drought can occur even when calendar-year precipitation totals are not abnormally low, especially if the rainfall is inadequate during the growing season. Researchers at the Texas A&M University Sonora Experiment Station report that the precipitation during the growing season averaged only about 7 inches per year during the 1990's, compared to a long-term average of 15 inches. Researchers also calculated the PDSI for the Sonora station and noted that the period from August 1999 through September 2000 had the lowest continuous PDSI values for any 12-month or greater time period since the 1950's drought.

Annual production of agricultural crops can be used as an indicator of impacts due to droughts. Various factors, such as market demand and production costs, can also play a significant role with respect to the number of acres planted and harvested for specific crops. However, a decline in crop production over a prolonged period may indicate an impact of drought.

In general, cotton is a good indicator of agricultural drought impacts in Region F because it is the major agricultural crop in the region and it can be grown with or without irrigation. Between 1951 and 1958, the number of acres planted in cotton statewide declined by 57 percent and the number of acres harvested declined by 55 percent. More recently crop productions have fluctuated considerably, with a low of less than 200,000 bales of cotton produced in 2000 to a high of nearly 1 million bales in 2005. Figure 3.6-5 shows a graph of annual Region F cotton production from 1985 to 2006.

During this period, winter wheat crops in Region F were not as seriously impacted by the drought, because the precipitation deficits were more pronounced during the warmer months. Livestock production was also impacted by the drought. During the hot, dry summer of 2000,

**Figure 3.6-5**
**Annual Cotton Production in Region F from 1985 to 2006**




large grass die-offs occurred in parts of west Texas. The drought was severe enough to even cause some live oak trees to die.[18]

**Socio-Economic Drought in Region F**

As presented previously, drought can have a significant and prolonged impact on the economy and social fabric within a region. Region F is not an exception to this fact. The drought of record in the 1950's produced drastic decreases in the annual production values for agriculture and livestock. At the same time, census data indicate that thousands of rural residents in Region F migrated from rural county areas to the main metropolitan centers in the region. This type of migration can have a significant impact on the demographics, health, and social needs in both rural and municipal settings.

Much of the economic activity in Region F has historically been associated with the oil and gas industry. In the past few years that industry has experienced volatile ups and downs with changing markets. Cities in Region F have been actively seeking new industries to balance the uncertainty in the oil and gas sector, but the recent drought and its impacts on water supplies has hindered that process. Rural communities need new business and industries to replace the agricultural sector and population losses. The Governor's Office, Texas Department of Agriculture, and the U.S. Department of Agriculture are trying to promote and assist rural areas. These efforts are hindered due to availability of water and the cost of securing and producing water that meets water quality standards.

### 3.6.3 Potential Environmental Impacts of Drought in Region F

Increasing water supply demand for municipal and agricultural uses, the encroachment of invasive brush (e.g., mesquite, Ashe juniper, and salt cedar), and extended drought conditions during the 1990's, have resulted in a net decrease in water supplies available to sustain designated aquatic life uses in areas of the region. Combined with reservoir construction on the Concho and Colorado Rivers, the quantity of water available to maintain instream flows has declined. However, the Texas Parks and Wildlife Department (TPWD) and U.S. Fish and Wildlife Service (USFWS) are collaborating to determine instream flow levels necessary to maintain designated aquatic life uses.

In December 2004, the USFWS issued a revised Biological Opinion[19] concerning the status of threatened aquatic species. The Biological Opinion changes the magnitude of required releases from the E.V. Spence and O.H. Ivie Reservoirs under certain conditions. These changes will result in a decrease in the volume of mandatory releases from the two reservoirs, especially during periods of extended drought and low reservoir levels.

These reduced flows and the elimination of mandatory water releases during periods of no inflow to the reservoirs will provide relief to the water suppliers and their users, especially during periods of low rainfall or extended drought. In the Biological Opinion, USFWS has determined that these reduced flows are not likely to jeopardize the continued existence of threatened species, nor likely to destroy or adversely impact designated critical habitat for the species.

### 3.6.4 Impacts of Recent Drought on Water Supply

The Colorado WAM uses naturalized flows from 1940 through 1998. As a result, the WAM does not include most of a major drought in Region F. Indications are that for many reservoirs the recent drought may be more severe than previous droughts, potentially lowering the available supply from the reservoirs.

To assess the potential impact of the recent drought on water supplies in Region F, historical gauge flows at key locations in Region F were developed covering the period from 1999 through 2004. These flows were incorporated into a special simplified version of the Colorado WAM (MiniWAM). The MiniWAM includes only major reservoirs in Region F and the City of Junction's run-of-the-river right. Flows from 1940 through 1998 are based on the modeled flows available to these water rights. Impacts of the new drought on reservoir yields in Region F using WAM Run 3 (no subordination) are negligible due to the low yields of the reservoirs. Impacts are more readily seen with the subordination strategy, which is discussed in Section 4.2.3. With subordination, the analysis showed that most of the Colorado Basin Reservoirs in Region F have experienced new drought-of-record conditions as a result of the current drought. More detailed information on the impact of drought may be found in Appendix 4E in the 2006 Region F Water Plan.

## 3.7 List of References

[1] Texas Water Development Board: General Guidelines for Regional Water Plan Development, September 2008.

[2] R.J. Brandes Company et al.: Water Availability Modeling for the Colorado/Brazos-Colorado Basin, prepared for the Texas Natural Resources Conservation Commission, December 2001.

[3] Krishna, Hari J., Introduction to Desalination Technologies, included in Chapter 2 of The Future of Desalination in Texas, Volume 2: Technical Papers, Case Studies, and Desalination Technology Resources, TWDB, available at http://www.twdb.state.tx.us/desalination/desal/Volume2Main.asp and accessed on 2/28/2005.

[4] Viessman, Warren, Jr. and Hammer, Mark J., Water Supply and Pollution Control, Fourth Edition, Harper & Row, New York, 1985, pg. 230.

[5] TWDB. Report 366, *Please Pass the Salt: Using Oil Fields for the Disposal of Concentrate from Desalination,* Date.

[6] TWDB Desalination Database, available at http://www.twdb.state.tx.us/iwtdesaldb/dbStart.aspx

[7] Mickley, Michael C., Membrane Concentrate Disposal: Practices and Regulations, report prepared for the U.S. Department of Interior, Bureau of Reclamation, September 2001.

[8] Phone conversation with Cindy Hollander, City of Fort Stockton, 2/22/05.

[9] Phone conversation with Derrick Turner of Jacoby Martin, design engineer for the Brady and MDWSC treatment plants, January 2005.

[10] Phone conversation with Rufus Beam, City of Brady, 1/21/2005.

[11] Krishna, Hari J., "Water Reuse in Texas", TWDB, available at http://www.twdb.state.tx.us/assistance/conservation/Municipal/Reuse/ReuseArticle.asp and accessed 2/21/05.

[12] TWDB reuse database, available at http://www.twdb.state.tx.us/assistance/conservation/Municipal/Reuse/Reuse.asp and accessed 2/23/05.

[13] Colorado River Municipal Water District: *District Operations.* Available online at www.crmwd.org/op.htm.

[14] Brown County Water Improvement District No. 1: *About the Brown County WID #1*. Available online at http://www.bcwid.org/About/Facilities/Treatment.cfm.

[15] Word, Jim, quoted by Hamilton, Cliff, in "Is the drought over? Experts won't know until late summer", Odessa American, January 12, 2005.

[16] Drought Preparedness Council: *State Drought Preparedness Plan*, January 2001.

[17] Votteler, Todd H., Ph.D., "Texas Water", Texas Water Foundation, article accessed at http://www.texaswater.org/water/drought/drought2.htm, March 2005.

[18] Personal communication from Butch Taylor, Sonora Experiment Station, Texas A&M Agricultural Extension Service, Feb. 11, 2005.

[19] United States Department of the Interior Fish and Wildlife Service, Biological Opinion (2-15-F-2004-0242) to U.S. Army Corps of Engineers, Fort Worth District, regarding the Concho water snake, Austin, December 3, 2004.