Final Report
Groundwater Availability Model for the Dockum Aquifer

Report ___

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October 2008

Texas Water Development Board

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Abstract

This report documents the development of a three-dimensional groundwater model for the Dockum Aquifer in the Texas Panhandle, west Texas, and eastern New Mexico. The Dockum Aquifer is a minor aquifer in Texas with irrigation being the main water use. The groundwater availability model was developed using MODFLOW 2000 and consists of three layers. The upper layer rudimentarily represents the Ogallala Aquifer and other younger sediments overlying the Dockum Aquifer through general-head boundaries applied to the layer. The Dockum Aquifer was modeled as two layers with model layer 2 representing the upper portion of the Dockum Aquifer and model layer 3 representing the lower portion of the Dockum Aquifer. The model consists of 47,919 active grid cells in the layer representing the Ogallala/younger sediments, 48,078 active grid cells in the layer representing the upper portion of the Dockum Aquifer, and 54,273 active grid cells in the layer representing the lower portion of the Dockum Aquifer. The model grid for the Dockum Aquifer groundwater availability model corresponds directly to that for the Southern Ogallala groundwater availability model in the area where the two models overlap. The model incorporates the available information on structure, hydrostratigraphy, hydraulic properties, stream flow, recharge, and pumping for the Dockum Aquifer. The underlying data for these parameters are presented and discussed in detail.

The model is calibrated for two time periods, one representing steady-state conditions and the other representing transient conditions. The steady-state calibration considers the time period prior to 1950 which represents a period prior to significant development of the aquifer. The transient calibration period is from 1980 through 1997. The actual transient simulation consists of a steady-state period followed by a transient period beginning in 1950 to account for the development and associated impact on storage prior to the 1980 through 1997 calibration period. Both the steady-state and transient calibrations reproduced aquifer heads well and within the uncertainty in the head estimates.

A single model, consisting of a steady-state solution followed by a transient solution, was developed and, as such, all parameters common to the steady-state and transient time periods are identical. The geometric mean of the horizontal hydraulic conductivity is 0.19 feet per day for the upper portion of the Dockum Aquifer and 0.40 feet per day for the lower portion of the

Dockum Aquifer. The average recharge rate in the outcrop of the Dockum Aquifer is 0.15 inches per year during predevelopment and 0.58 inches per year during the transient calibration period. This change in average recharge is based on data and postulated to be primarily a result of land-use changes within the Dockum Aquifer outcrop as discussed in detail in Section 6.3.4. In the steady-state calibration period, cross-formational flow and recharge accounted for approximately 59 and 41 percent of the net aquifer inflow, respectively, and streams, evapotranspiration, and springs discharged approximately 54, 43, and 3 percent of the net aquifer outflow, respectively. At the end of the transient model period, recharge, flow from storage, and cross-formational flow accounted for 73, 14, and 13 percent of the net aquifer inflow, respectively, and streams, pumping, evapotranspiration, and springs discharged approximately 36, 34, 29 and 2 percent of the net aquifer outflow, respectively.

A sensitivity analysis was performed to determine which parameters have the most influence on model performance and calibration. For the steady-state calibration period, the most sensitive calibration parameter is the horizontal hydraulic conductivity of the lower portion of the Dockum Aquifer. Predevelopment heads in the upper portion of the Dockum Aquifer are also sensitive to the vertical hydraulic conductivity of the upper portion of the Dockum Aquifer. For the transient calibration period, the most sensitive calibration parameter is the horizontal hydraulic conductivity of the lower portion of the Dockum Aquifer. Transient heads in the upper portion of the Dockum Aquifer are also sensitive to the vertical hydraulic conductivity of the upper portion of the Dockum Aquifer.

The purpose of the Dockum Aquifer model is to provide a calibrated numerical model that can be used to assess groundwater availability in regional water plans and to assess the effects of various proposed water management strategies on the aquifer system. The applicability of the Dockum Aquifer model is limited to regional-scale assessments of groundwater availability (e.g., an area smaller than a county and larger than a square mile) due to the relatively large grid blocks (one square mile) over which pumping and hydraulic property data are averaged. At the scale of this model, it is not capable of predicting aquifer responses at a specific point such as a particular well. In addition to uncertainty in pumping and hydraulic property data, the model is limited to a first-order approach of coupling surface water and groundwater and does not provide a rigorous solution to surface-water flow in the region. The Dockum Aquifer groundwater availability model provides a documented, publicly-available, integrated tool for use by state planners, Regional Water Planning Groups, Groundwater Conservation Districts, Groundwater Management Areas, and other interested stakeholders.

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1.0 Introduction

The Texas Water Development Board (TWDB) has identified the major and minor aquifers in Texas on the basis of regional extent and amount of water produced. The major and minor aquifers are shown in Figures 1.0.1 and 1.0.2, respectively. General discussion of the major and minor aquifers is given in Ashworth and Hopkins (1995). Aquifers that supply large quantities of water over large areas of the state are defined as major aquifers and those that supply relatively small quantities of water over large areas of the state or supply large quantities of water over small areas of the state are defined as minor aquifers (Ashworth and Hopkins, 1995).

The focus of the study contained in this report is development of the groundwater availability model for the Dockum Aquifer, a minor aquifer in Texas (see Figure 1.0.2). Sections 1 through 5 document development of the conceptual model for the Dockum Aquifer. All aspects of the numerical modeling are discussed in Sections 6 through 9. Section 10 discusses the limitations of the model, Section 11 provides suggestions for future improvements to the model, and Section 12 presents conclusions.

Groundwater in the Dockum Group is fresh in parts of the outcrop areas (concentrations of dissolved solids less than 1,000 milligrams per liter) and brackish to brine in the subcrop areas (concentrations of dissolved solids greater than 1,000 milligrams per liter). The portion of the Dockum Group containing groundwater with a total dissolved solids concentration of less than 5,000 milligrams per liter make up the Dockum Aquifer as defined by Ashworth and Hopkins (1995). The Dockum Aquifer is present in all or parts of 46 Texas Panhandle and western counties. There has not been widespread use of the Dockum Aquifer because of poor water quality, low yields, declining water levels, and deep pumping depth. However, locally, the Dockum Aquifer can be an important source of groundwater for municipal, agricultural, and industrial uses (Bradley and Kalaswad, 2003). Groundwater use for the Dockum Aquifer in Texas was reported at 41,000 acre-feet per year in 1997 (TWDB, 2002) and 49,000 acre-feet per year in 2003 (TWDB, 2007a). The estimate of available fresh groundwater for the years 2010 and 2060 is reported as 406,138 and 248,720 acre-feet per year, respectively (TWDB, 2007a).

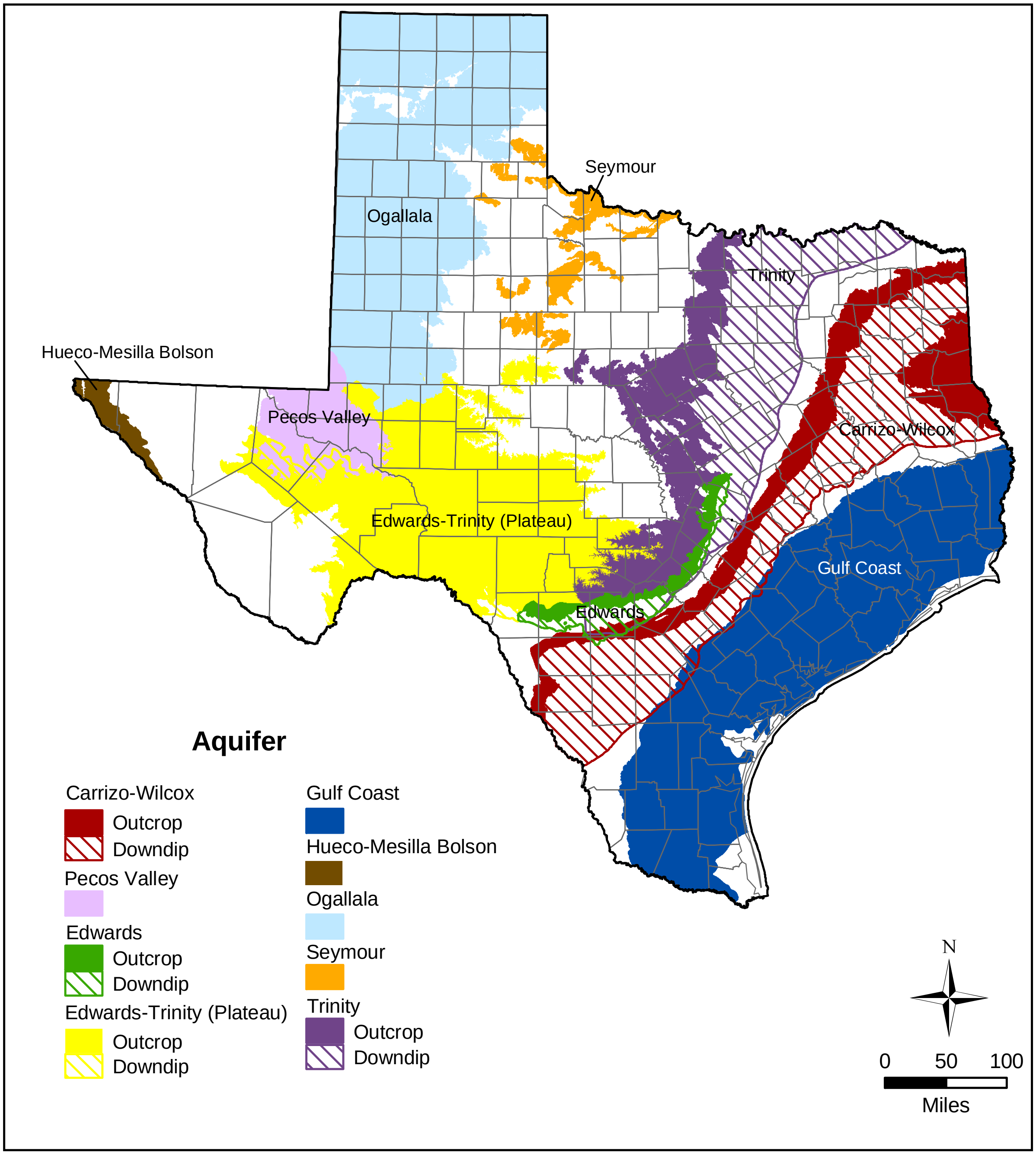
The modeling approach adopted for the Dockum Aquifer groundwater availability model was to represent the Dockum Aquifer with two layers. McGowen and others (1977) informally subdivided the Dockum Group into a lower sand-rich unit and an upper mud-rich unit. Production from the Dockum Aquifer is primarily from the lower unit. The upper unit acts primarily as a confining unit. The two model layers representing the Dockum Aquifer were defined with separate hydraulic characteristics.

The Texas Water Code codified the requirement for generation of a State Water Plan that allows for the development, management, and conservation of water resources and the preparation and response to drought, while maintaining sufficient water available for the citizens of Texas (TWDB, 2002). Senate Bill 1 and subsequent legislation directed the TWDB to coordinate regional water planning with a process based upon public participation. Also, as a result of Senate Bill 1, the approach to water planning in the state of Texas has shifted from a water-demand based allocation approach to a water-availability based approach.

Groundwater models provide a tool to estimate groundwater availability for various water use strategies and to determine the cumulative effects of increased water use and drought. A groundwater model is a numerical representation of the aquifer system capable of simulating historical conditions and predicting future aquifer conditions. Inherent to the groundwater model are a set of equations that are developed and applied to describe the primary or dominant physical processes considered to be controlling groundwater flow in the aquifer system. Groundwater models are essential to performing complex analyses and in making informed predictions and related decisions (Anderson and Woessner, 1992). As a result, development of groundwater availability models for the major and minor Texas aquifers is integral to the state water planning process. The purpose of the groundwater availability model program is to provide a tool that can be used to develop reliable and timely information on groundwater availability for the citizens of Texas and to ensure adequate supplies or recognize inadequate supplies over a 50-year planning period.

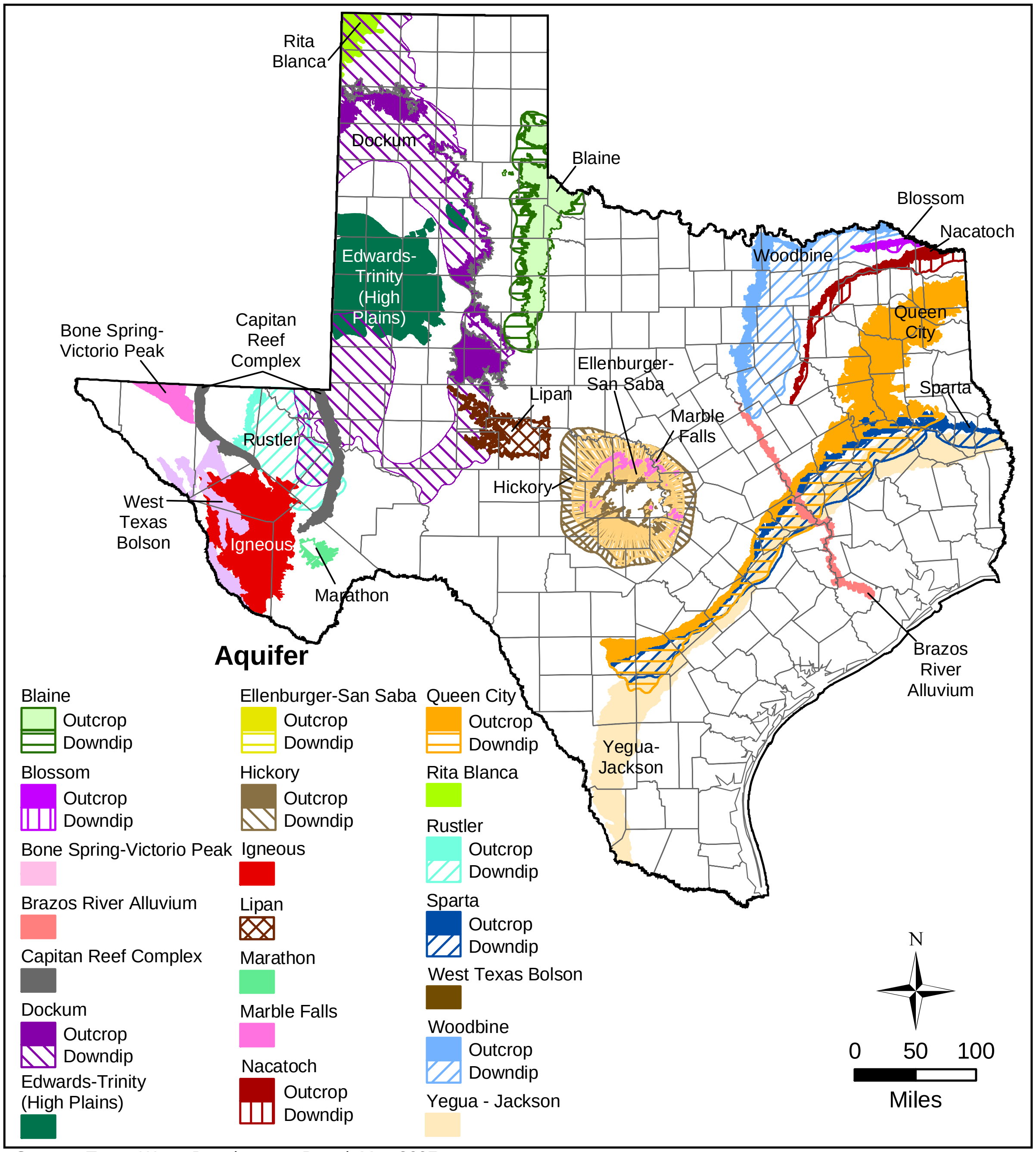
The Dockum Aquifer groundwater availability model was developed using a modeling protocol that is standard to the groundwater modeling industry. This protocol includes: (1) the development of a conceptual model for groundwater flow in the aquifer, including defining physical limits and properties, (2) model design, (3) model calibration, (4) sensitivity analysis, and (5) reporting. The conceptual model is a conceptual description of the physical processes governing groundwater flow in the aquifer system. Available data and reports for the model area were reviewed in the conceptual model development stage. Model design is the process used to translate the conceptual model into a physical model, in this case a numerical model of groundwater flow. This involves organizing and distributing model parameters, developing a model grid and model boundary conditions, and determining the model integration time scale. Model calibration is the process of modifying model parameters so that observed field measurements (e.g., water levels in wells) can be reproduced. The model was calibrated to steady-state conditions representing, as closely as possible, conditions in the aquifer prior to significant development and to transient aquifer conditions focused primarily on the time period from January 1980 through December 1997. Sensitivity analyses were performed on both the steady-state and transient portions of the model to offer insight to the uniqueness of the model and the impact of uncertainty in model parameter estimates.

Consistent with state water planning policy, the Dockum Aquifer groundwater availability model was developed with the support of stakeholders through stakeholder forums. The purpose of the groundwater availability models are to provide a tool for Regional Water Planning Groups, Groundwater Conservation Districts, River Authorities, and state planners for the evaluation of groundwater availability and to support the development of water management strategies and drought planning. The Dockum Aquifer groundwater availability model provides a tool for use in assessing water-planning strategies.



Source: Online: Texas Water Development Board, May 2007

Figure 1.0.1 Locations of major aquifers in Texas.



Source: Texas Water Development Board, May 2007

Figure 1.0.2 Locations of minor aquifers in Texas.

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2.0 Study Area

The Dockum Aquifer, classified as a minor aquifer in Texas, covers approximately 26,000 square miles in Texas. Much of the Dockum Aquifer underlies the Ogallala or Edwards-Trinity (High Plains) aquifers and overlies Permian-age deposits. Approximately 3,500 square miles of the Dockum Group in Texas is outcrop area and approximately 22,000 square miles is subcrop area for a total area of 25,500 square miles.

The location of the study area and the active model boundary for the Dockum Aquifer groundwater availability model are shown in Figures 2.0.1 and 2.0.2, respectively. Groundwater model boundaries are typically defined on the basis of surface or groundwater hydrologic boundaries. The lateral boundaries of the active model area are defined to include the extent of the Dockum Aquifer. Boundaries are generally assumed at the Dockum Aquifer boundary as defined by the TWDB. In areas extending outside of Texas, boundaries are generally placed along topographic highs or rivers since these features should behave as lateral no-flow boundaries. The model boundary, projected to plan view, is shown in report figures as a red line and provides the limits of the active model area. The report figures also show a dashed red line identified as the downdip aquifer limit. That line represents the downdip limit of the Dockum Aquifer as defined by the 5,000 milligrams per liter total dissolved solid concentration in Ashworth and Hopkins (1995). Although the portion of the Dockum Group containing groundwater with a total dissolved solids concentration of 5,000 milligrams per liter or greater is not considered to be part of the Dockum Aquifer, it was included in the Dockum Aquifer groundwater availability model.

The upper model boundary is defined as ground surface in the outcrop areas of the Dockum Aquifer. For the subsurface areas of the aquifer, the upper model boundary is defined as the top of the aquifers overlying the Dockum Group. The lower model boundary is defined as the base of the Dockum Group as defined by McGowen and others (1977).

Figure 2.0.3 shows the counties, roadways, cities, and towns included in the study area. All or part of 55 Texas counties and 11 New Mexico counties are included in the active model area. Of the 55 counties in Texas, the Dockum Group is not considered to be an aquifer (i.e., has groundwater with a total dissolved solids concentration of 5,000 milligrams per liter or greater) in nine of those counties. The locations of rivers, streams, lakes, and reservoirs in the study area are shown in Figure 2.0.4.

Figures 2.0.5 and 2.0.6 show the surface outcrop and downdip subcrop of the major and minor aquifers in Texas, respectively, in the active model area. Major aquifers located in the active model area include portions of the Ogallala, Pecos Valley, and Edwards-Trinity (Plateau) aquifers. Minor aquifers located in the active model area include the Dockum Aquifer, the Edwards-Trinity (High Plains) Aquifer, the Rita Blanca Aquifer, and portions of the Rustler and Capitan Reef Complex aquifers.

The active model area encompasses part of four Texas Regional Water Planning Groups (Figure 2.0.7). From north to south they are (1) the Panhandle Regional Water Planning Group (Region A), (2) the Llano Estacado Regional Water Planning Group (Region O), (3) the Brazos G Regional Water Planning Group (Region G), and (4) the Region F Regional Water Planning Group. The active model area includes all or part of 20 Groundwater Conservation Districts (Figure 2.0.8). Table 2.0.1 summarizes the Groundwater Conservation Districts in Texas in which the Dockum Aquifer is present. The study area intersects portions of Texas Groundwater Management Areas 1, 2, 3, 6, and 7 (Figure 2.0.9). The study area intersects four Texas river authorities: (1) the Red River Authority of Texas, (2) the Brazos River Authority, (3) the Upper Colorado River Authority, and (4) the Palo Duro River Authority (Figure 2.0.10).

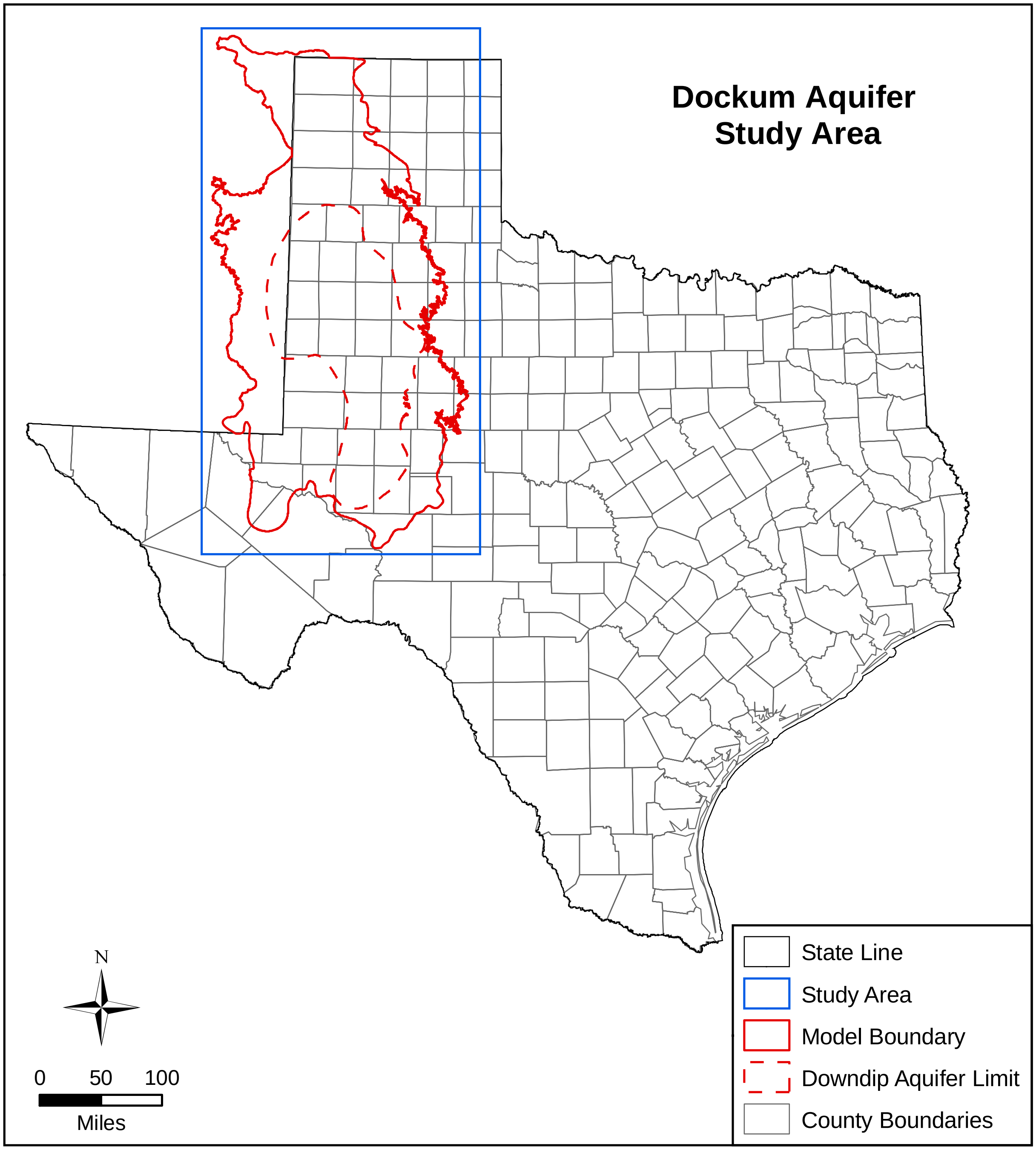
The major river basins in the study area are the Canadian, Red, Colorado, Brazos, and Rio Grande river basins (Figure 2.0.11). The Pecos River subbasin is contained within the Rio Grande River basin. Climate is the major control on flow in rivers and streams. The primary climatic factors are precipitation and evapotranspiration (water not available for recharge to the aquifer due to evaporation or use by the biological processes of plants). For all but the major rivers, flow in the rivers throughout the model area is generally episodic with extended periods of low flow or no flow conditions. Table 2.0.2 provides a listing of the river basins in the study area along with the river length in Texas, the river basin area in Texas, and the number of major reservoirs within the river basin in Texas.

Table 2.0.1 Texas Groundwater Conservation Districts in which the Dockum Aquifer is present.

Clear Fork Groundwater Conservation District	Middle Pecos Groundwater Conservation District
Coke County Underground Water Conservation District	North Plains Groundwater Conservation District
Emerald Underground Water Conservation District	Panhandle Groundwater Conservation District
Garza County Underground and Fresh Water Conservation District	Permian Basin Underground Water Conservation District
Glasscock Groundwater Conservation District	Salt Fork Underground Water Conservation District
High Plains Underground Water Conservation District No.1	Sandy Land Underground Water Conservation District
Irion County Water Conservation District	Santa Rita Underground Water Conservation District
Llano Estacado Underground Water Conservation District	South Plains Underground Water Conservation District
Lone Wolf Groundwater Conservation District	Sterling County Underground Water Conservation District
Mesa Underground Water Conservation District	Wes-Tex Groundwater Conservation District

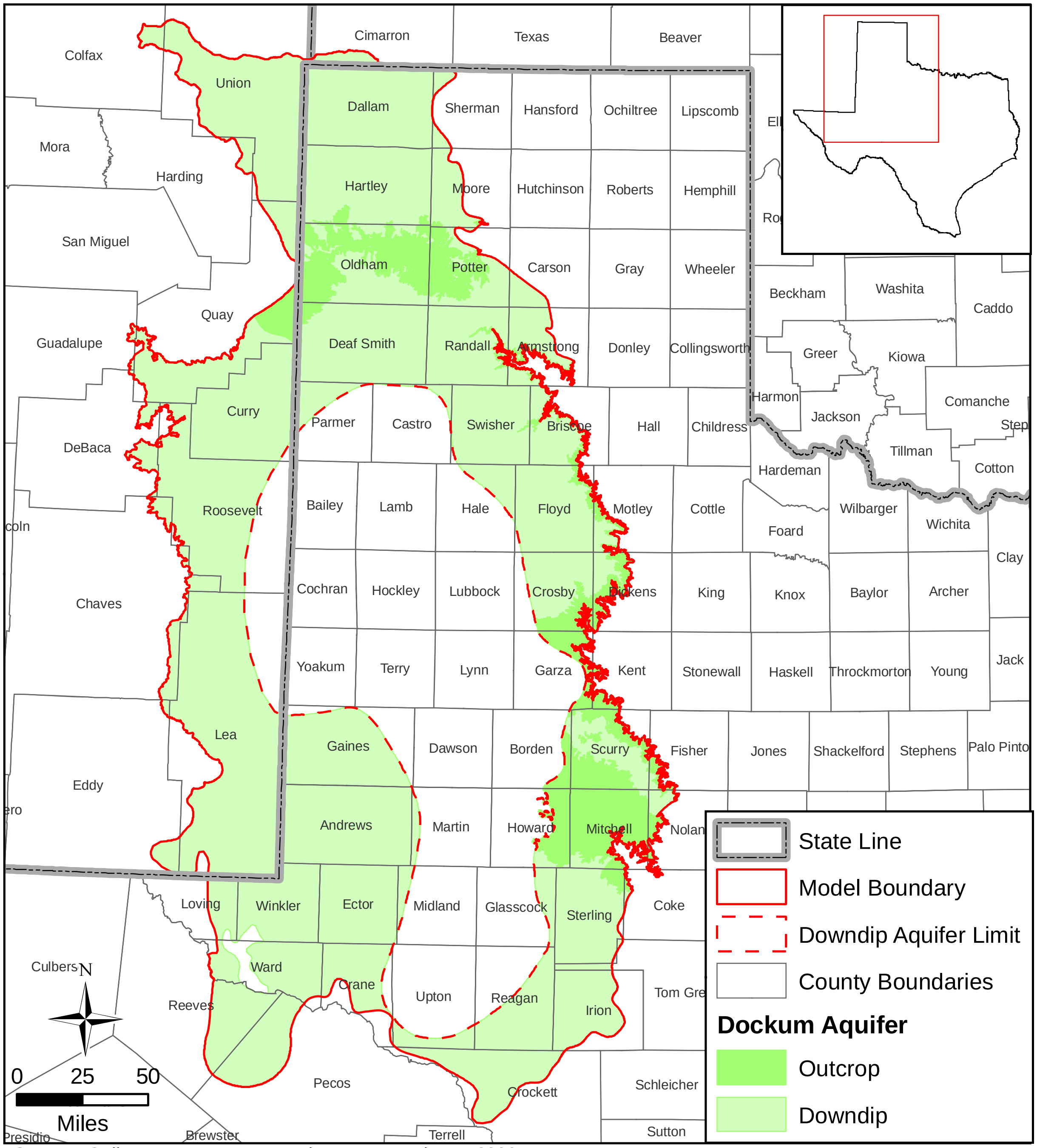
Table 2.0.2 River basins in the Dockum Aquifer groundwater availability model study area (University of Texas at Austin, 1996).

River Basin	Texas River Length (miles)	Texas River Basin Drainage Area (square miles)	Number of Major Reservoirs in Texas
Brazos	840	42,800	19
Canadian	200	12,700	2
Colorado	600	39,893	11
Red	680	30,823	7
Rio Grande	1,250	48,259	3



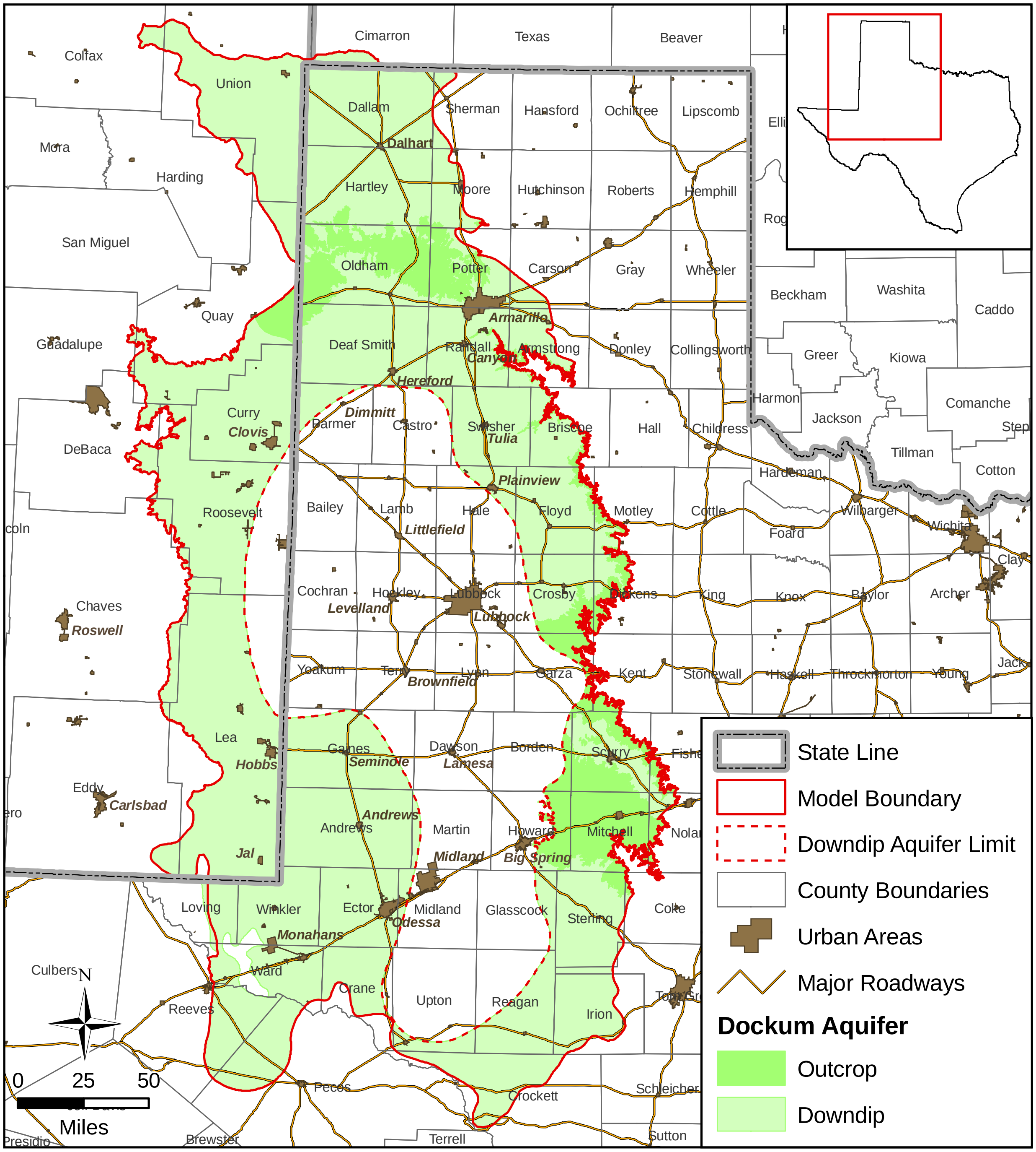
Source: N/A

Figure 2.0.1 Location of study area and Dockum Aquifer groundwater availability model.



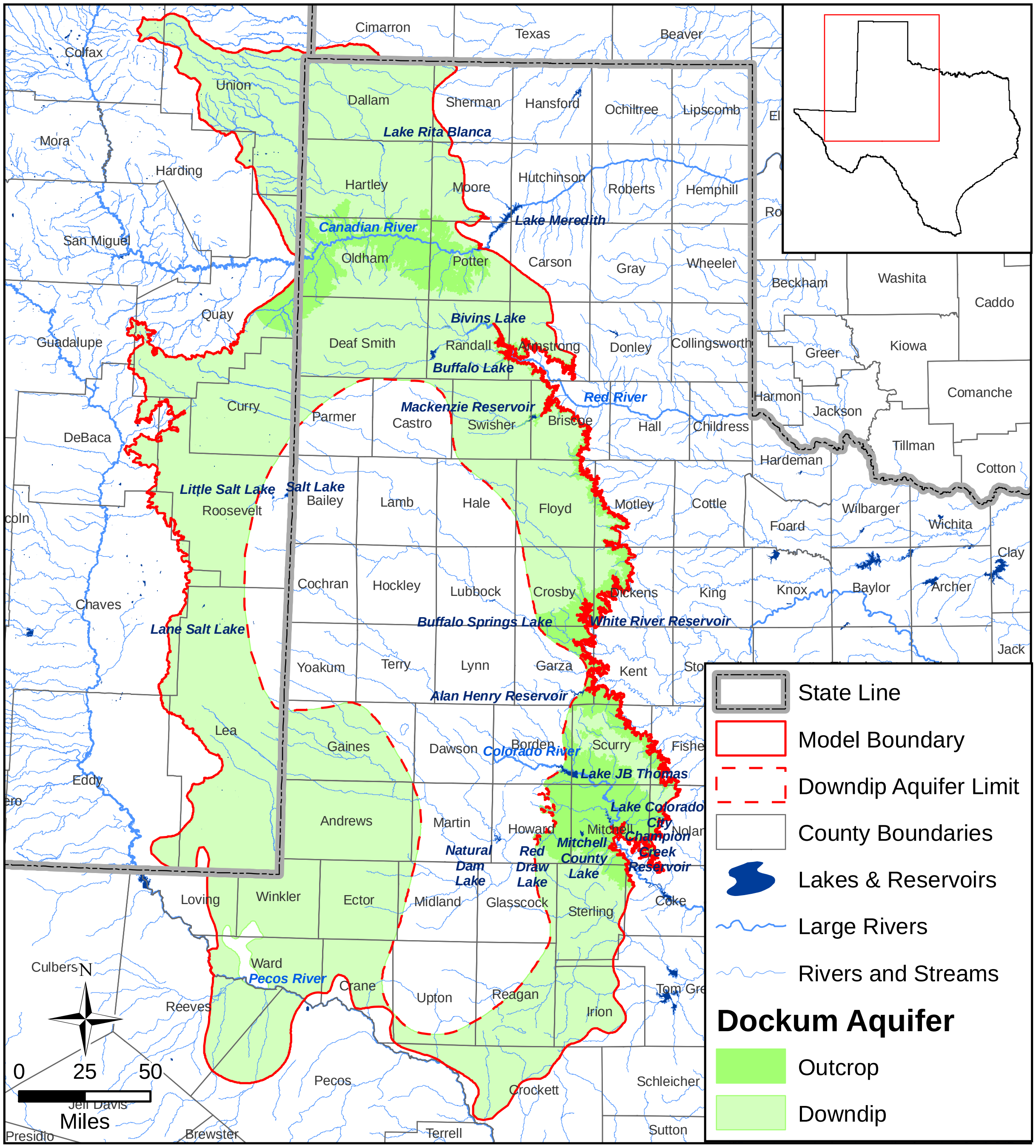
Source: Online: Texas Water Development Board, Aug 2006

Figure 2.0.2 Active model boundary for the Dockum Aquifer groundwater availability model.



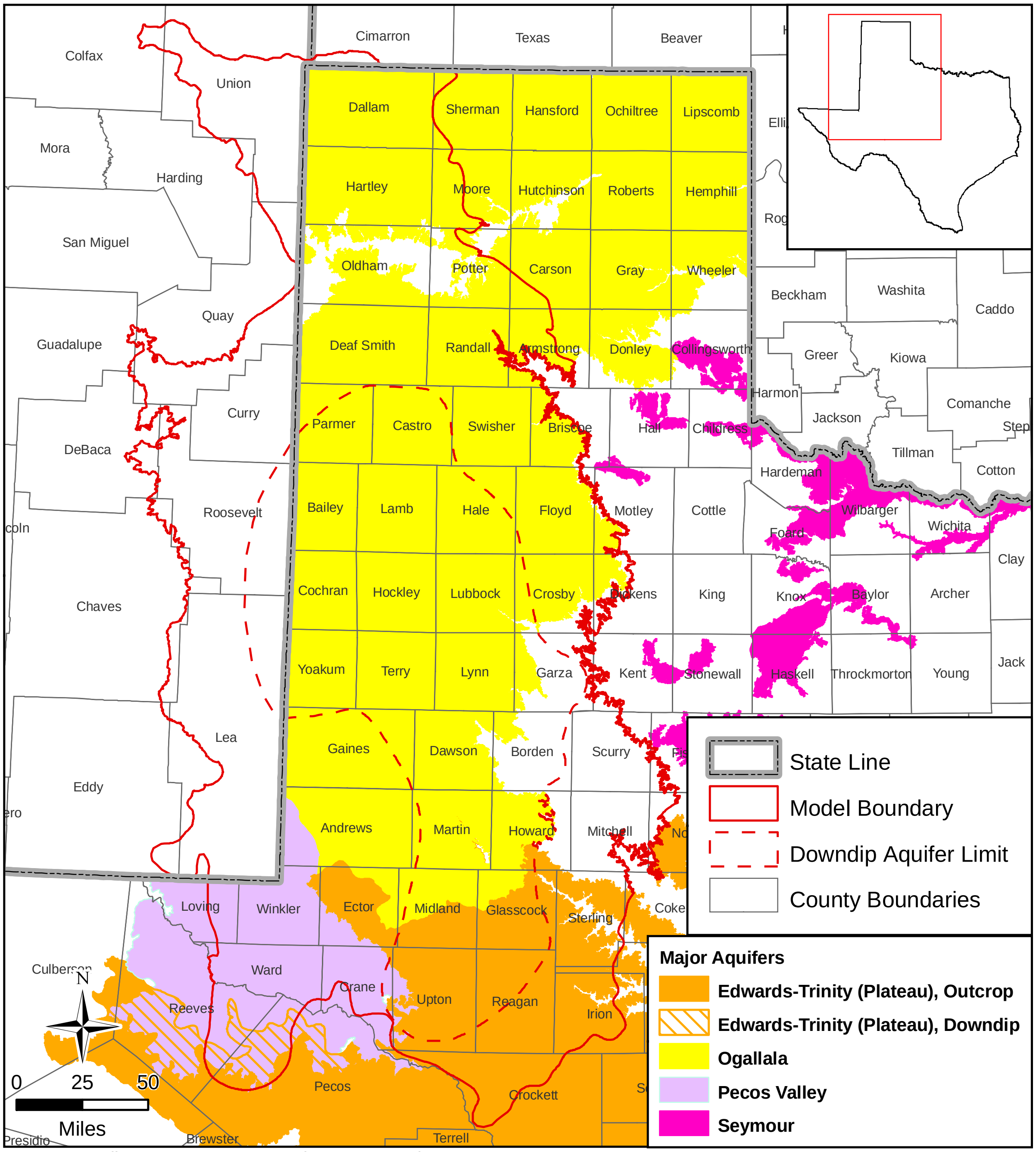
Source: Online: Texas Water Development Board, June 2006; New Mexico Resource GIS Program, June 2006

Figure 2.0.3 Location of study area showing county boundaries, cities, and major roadways.



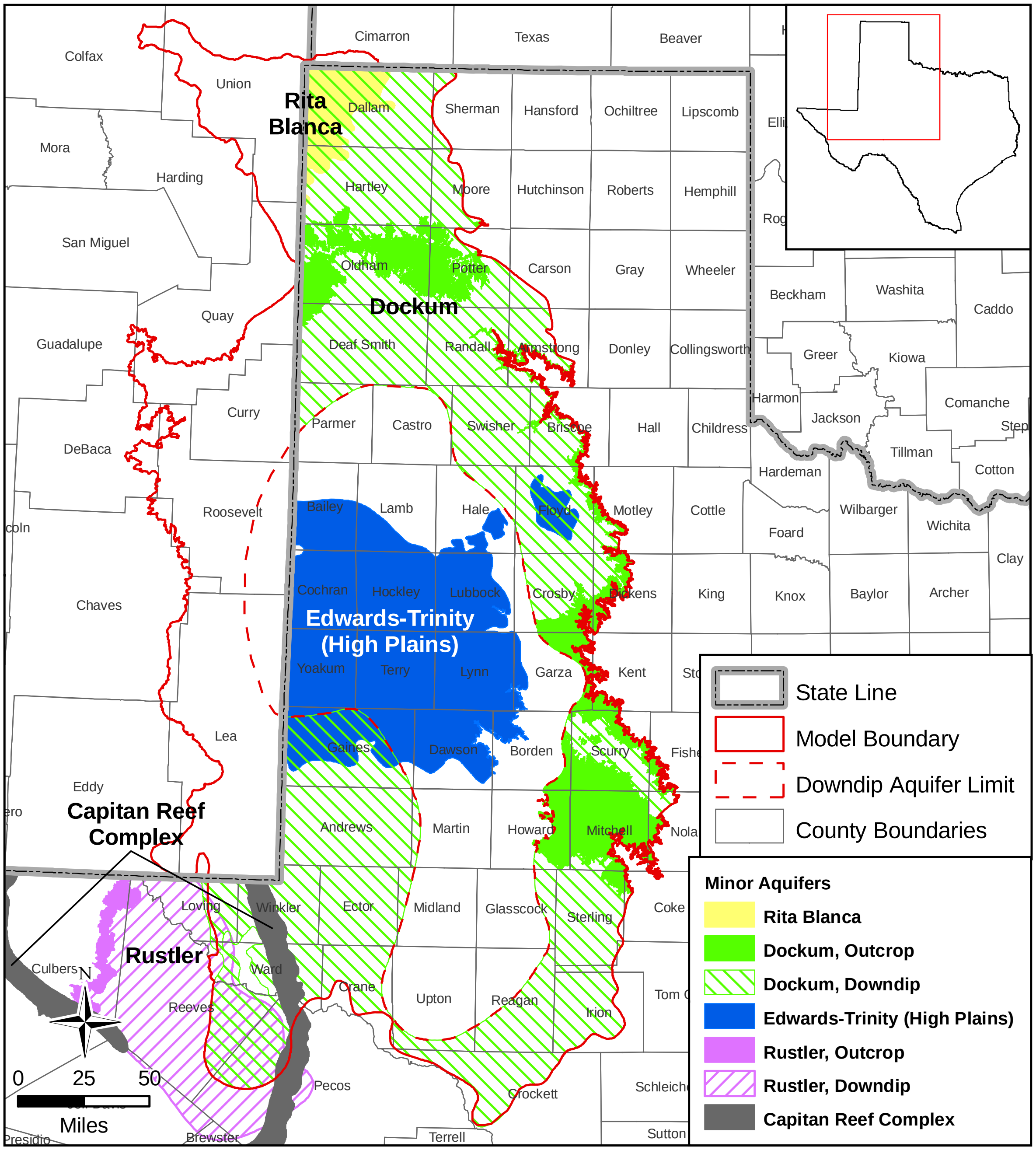
Source: Online: Texas Water Development Board, June 2006; USGS seamless, June 2006

Figure 2.0.4 Location of study area showing lakes and rivers.



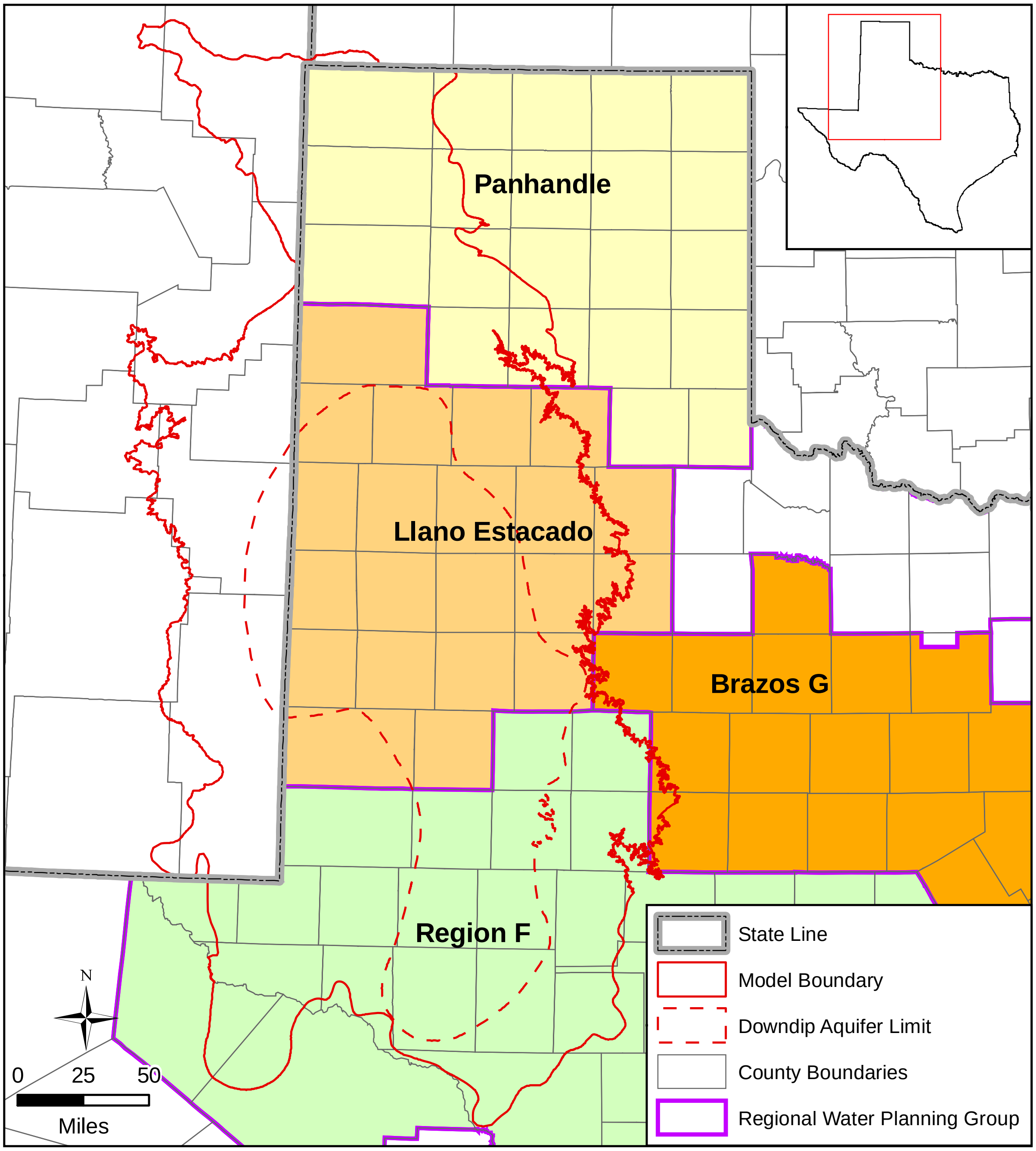
Source: Online: Texas Water Development Board, May 2007

Figure 2.0.5 Areal extents of Texas major aquifers in the study area.



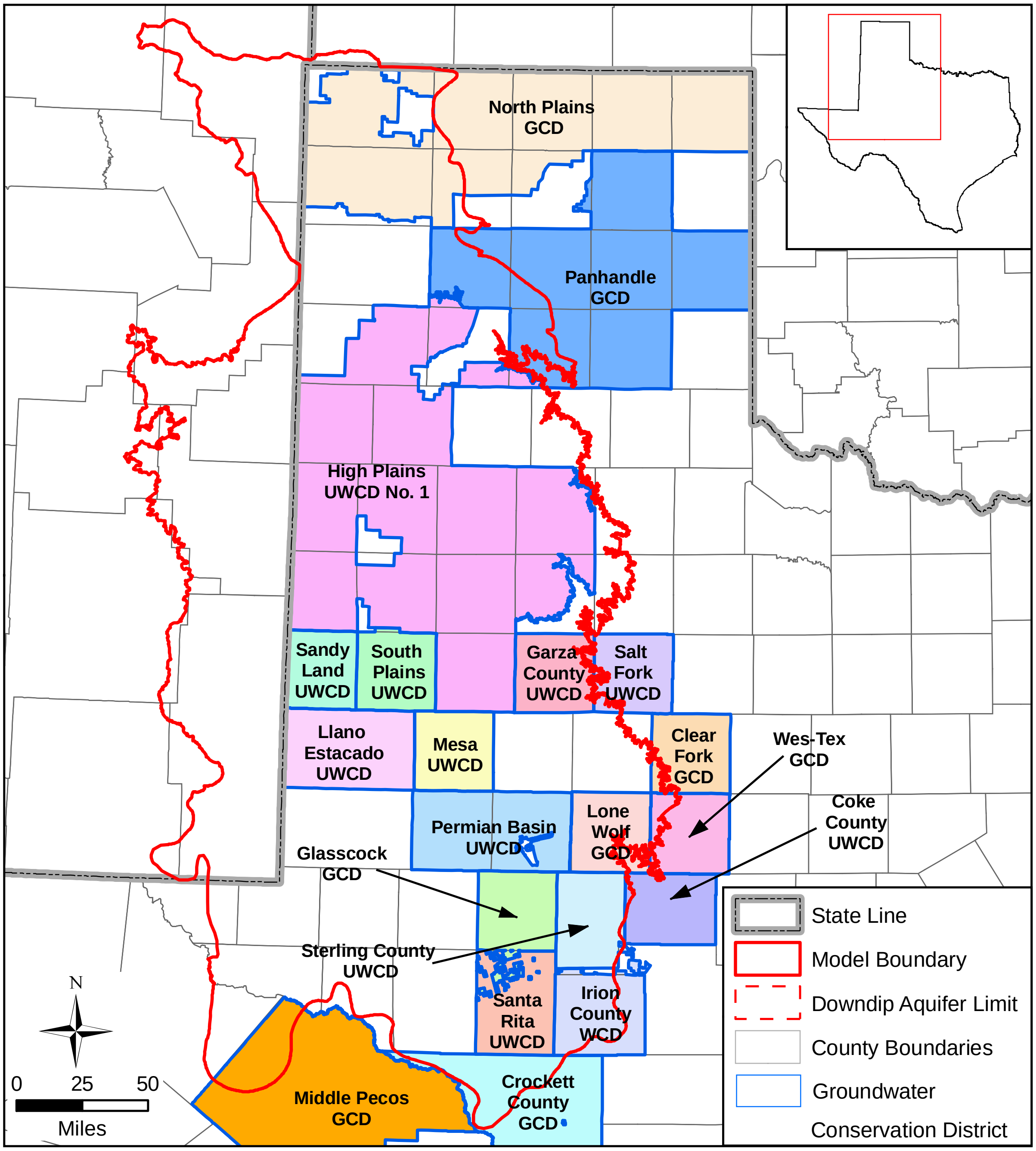
Source: Online: Texas Water Development Board, May 2007

Figure 2.0.6 Areal extents of Texas minor aquifers in the active model area.



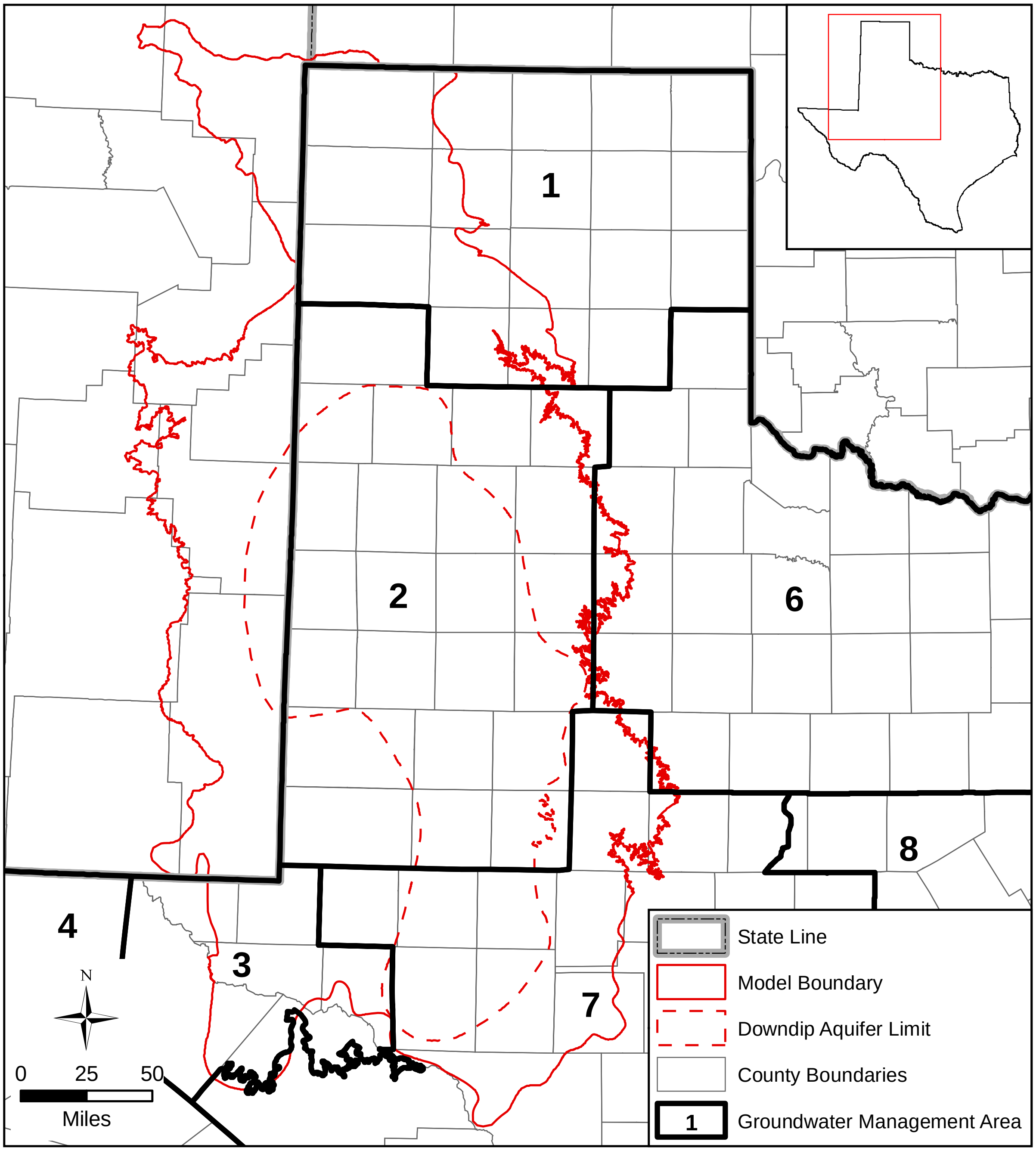
Source: Online: Texas Water Development Board, June 2006

Figure 2.0.7 Locations of Texas Regional Water Planning Groups in the study area.



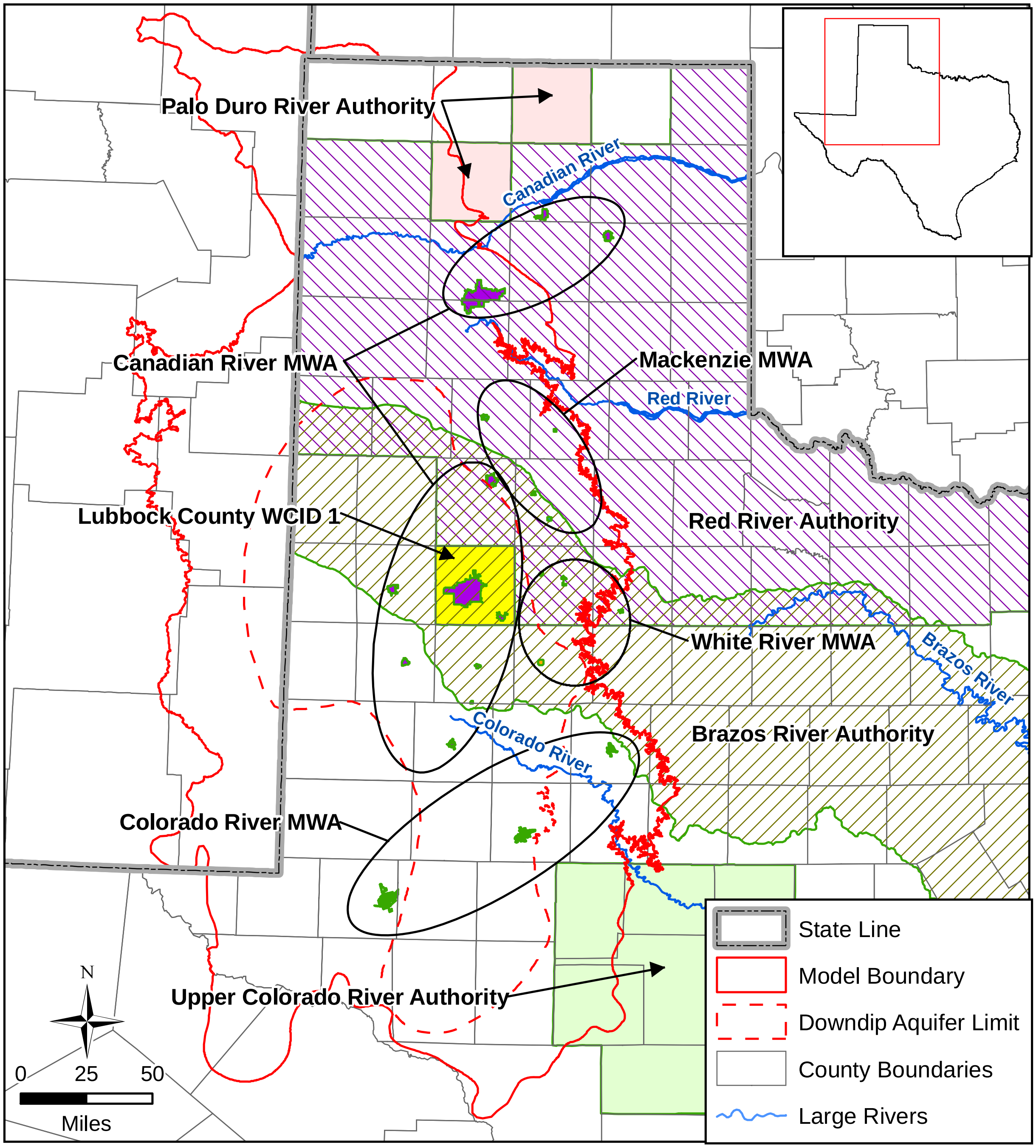
Source: Online: Texas Water Development Board, August 2008.

Figure 2.0.8 Locations of Texas Groundwater Conservation Districts in the study area.



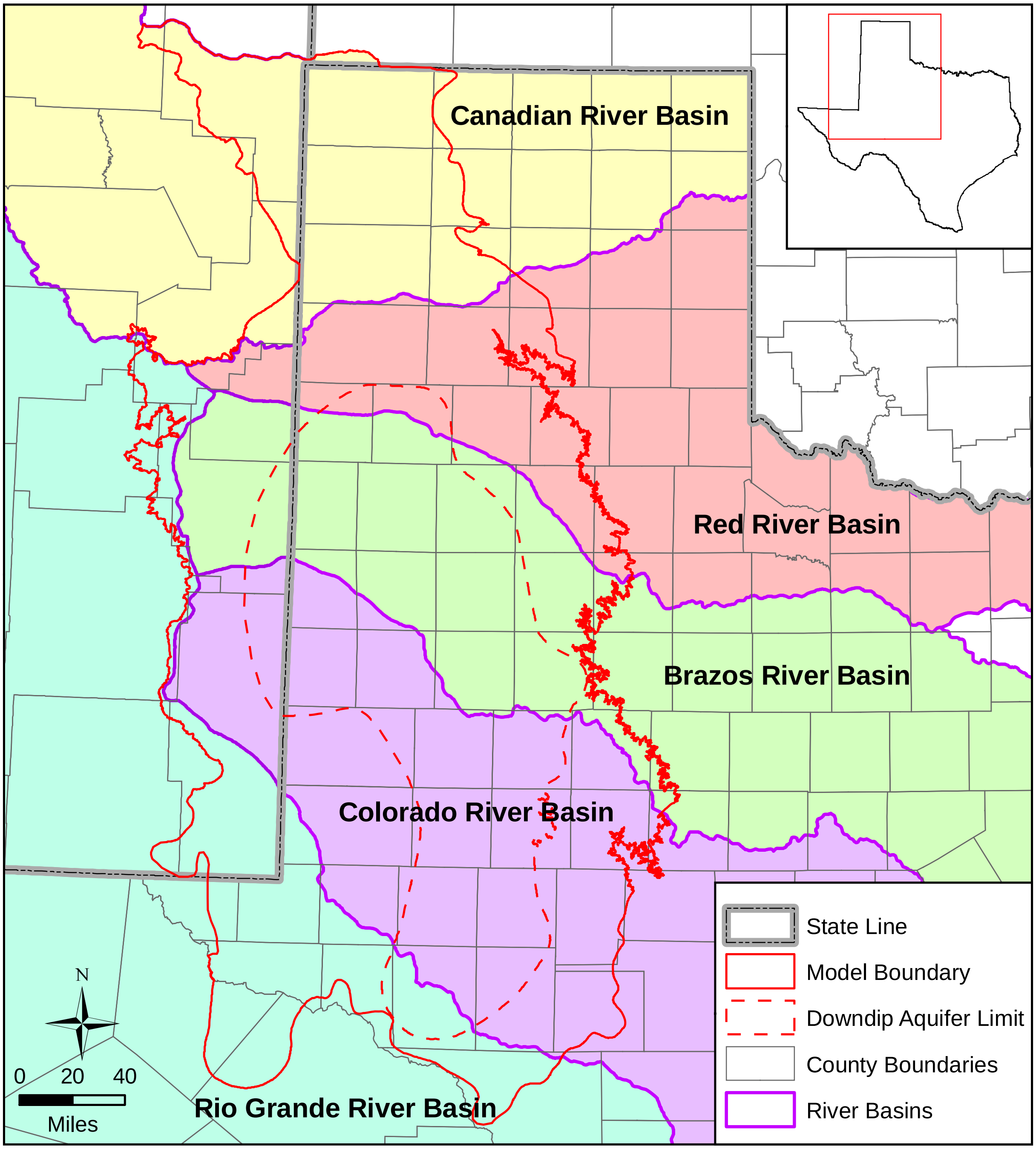
Source: Online: Texas Water Development Board, March 2007

Figure 2.0.9 Locations of Texas Groundwater Management Areas in the study area.



Source: Online: Texas Water Development Board, June 2006

Figure 2.0.10 Locations of River Authorities in the study area.



Source: Online: Texas Water Development Board, June 2006; New Mexico Resource GIS Program, June 2006

Figure 2.0.11 Major river basins in the study area.

2.1 Physiography and Climate

The study area is situated almost entirely in the High Plains physiographic province (Figure 2.1.1). The High Plains Province is subdivided into the Central High Plains, the Canadian Breaks High Plains, and the Southern High Plains. This province is described as "…a nearly flat plateau with an average elevation approximating 3,000 feet" (Wermund, 1996). Underlying the plain are extensive stream-laid sand and gravel deposits and local windblown sands and silts. The plains are essentially treeless and contain numerous playa lakes. Drainage on the High Plains is dominated by widespread, small, intermittent streams. The eastern boundary of the High Plains is a westward-retreating escarpment known as the caprock. This caprock is deeply notched by the headwaters of major rivers. Small portions of the study area are located in the North-Central Plains and in the Edwards Plateau physiographic provinces. The North-Central Plains are "an erosional surface that developed on upper Paleozoic formations…" (Wermund, 1996). This province consists of local prairies as well as hills and rolling plains. In the study area, the Edwards Plateau province a "mesalike land" where rainfall decreases to the west and "vegetation grades from mesquite juniper brush westward into creosote bush tarbush shrubs" (Wermund, 1996).

A large portion of the study area is located within the waving grasslands of the High Plains ecological region (Figure 2.1.2), which has an estimated coverage of 20 million acres in Texas (Texas Parks and Wildlife, 2006). The High Plains ecological region is classified as a "…mixed plain and short-grass prairie…" (Texas Parks and Wildlife, 2006). Vegetation is highly variant and location dependent. Some of the natural vegetation in this region has been replaced by introduced species. The introduction of crops in the region has changed its original character. Parts of the study area are located in the Southwestern Tablelands, Edwards Plateau, and Chihuahuan Deserts ecological regions. The Southwestern Tablelands is an elevated tableland consisting of subhumid grassland and semiarid grazing land. The Edwards Plateau ecological region is a rugged, semiarid region containing over 100 endemic Texas plants. The Chihuahuan Deserts ecological region "…comprises broad basins and valleys bordered by sloping alluvial fans and terraces" (United States Environmental Protection Agency, 2002). The central and western portions of the region contain isolated mesas and mountains. This region supports a wide variety of plants, ranging from arid grass and shrubs to oak-juniper woodlands, and animals, ranging from hummingbirds to bighorn sheep.

Figure 2.1.3 provides a topographic map of the study area. Generally, the surface elevation decreases from northwest to southeast across the active model area. The ground-surface elevation varies from over 7,400 feet above mean sea level at the northwest boundary of the model area to less than 2,100 feet above mean sea level in the southeast along the Colorado River valley. The Canadian and Pecos rivers have created valleys that are over 100 feet lower than the surrounding ground.

The climate in the active model area is classified predominantly as Continental Steppe (Larkin and Bomar, 1983) (Figure 2.1.4). This type of climate is typical of continent interiors. It is a semi-arid climate characterized by large variations in daily temperatures, low relative humidity, and irregularly spaced rainfall of moderate amounts (Larkin and Bomar, 1983). In general, most rainfall occurs between April and October. Typically, summers are hot and winters, although mild, are the most severe in Texas. The very eastern, southeastern, southern, and southwestern portions of the study area are in the Subtropical climate. This climate is caused by the onshore flow of air from the Gulf of Mexico. Air from the Gulf decreases in moisture content as it travels across the state. Intrusion of continental air into the Gulf maritime air occurs seasonally and affects the moisture content of the air. The Subtropical classification is subdivided based on the moisture content of the air. The subdivisions Subhumid, Steepe, and Arid are applied over the study area.

The average annual temperature in the study area ranges from a high of 72 degrees Fahrenheit in the south to a low of 56 degree Fahrenheit in the northwest (Figure 2.1.5). Monthly variations in temperature are shown in Figure 2.1.6 for four locations in the study area. This figure shows monthly average, maximum, and minimum temperatures. These monthly temperatures were calculated by first averaging average, maximum, and minimum daily temperatures from the National Climatic Data Center to get average monthly values. This was done for every month from January 1971 through December 2001. For each month, the average values for the years 1971 through 2001 were then averaged to obtain the monthly values shown in Figure 2.1.6.

Precipitation data are available at over 130 Texas and 50 New Mexico stations within the model boundary (Figure 2.1.7) from as early as 1898 through the present. Measurement of precipitation at most gages began in the 1940s. In general, measurements are not continuous on a month by month or year by year basis for the gages. Annual precipitation recorded at six stations within the active model area is shown in Figure 2.1.8. These gages show an extensive drought in the early 1950s. Several of the gages also show a recent drought from about 1998 to 2002.

The Parameter-Elevation Regressions on Independent Slopes Model (PRISM) precipitation dataset developed and presented online by the Oregon Climate Service at Oregon State University (Oregon State University, 2002) provides a good distribution of average annual precipitation across the model area based on the period from 1971 to 2000. Figure 2.1.9 provides a raster data post plot of the Parameter-Elevation Regression on Independent Slopes Model average annual precipitation across the model study area. Generally, the average annual precipitation decreases from the east to the west and from a high of 23.6 inches at the eastern model boundary to a low of 10.5 inches in the southwest.

Average annual net pan evaporation rate in the active model area ranges from a high of 72 inches per year to a low of 58 inches per year (Figure 2.1.10). The pan evaporation rate significantly exceeds the annual average rainfall, with the greatest rainfall deficit (approximately 59 inches per year) occurring in the southwestern portion of the active model area. Monthly variations in lake surface evaporation are shown in Figure 2.1.11 for five locations in the study area. These values represent the average of the monthly lake surface evaporation data for January 1954 through December 2004 (TWDB, 2008).

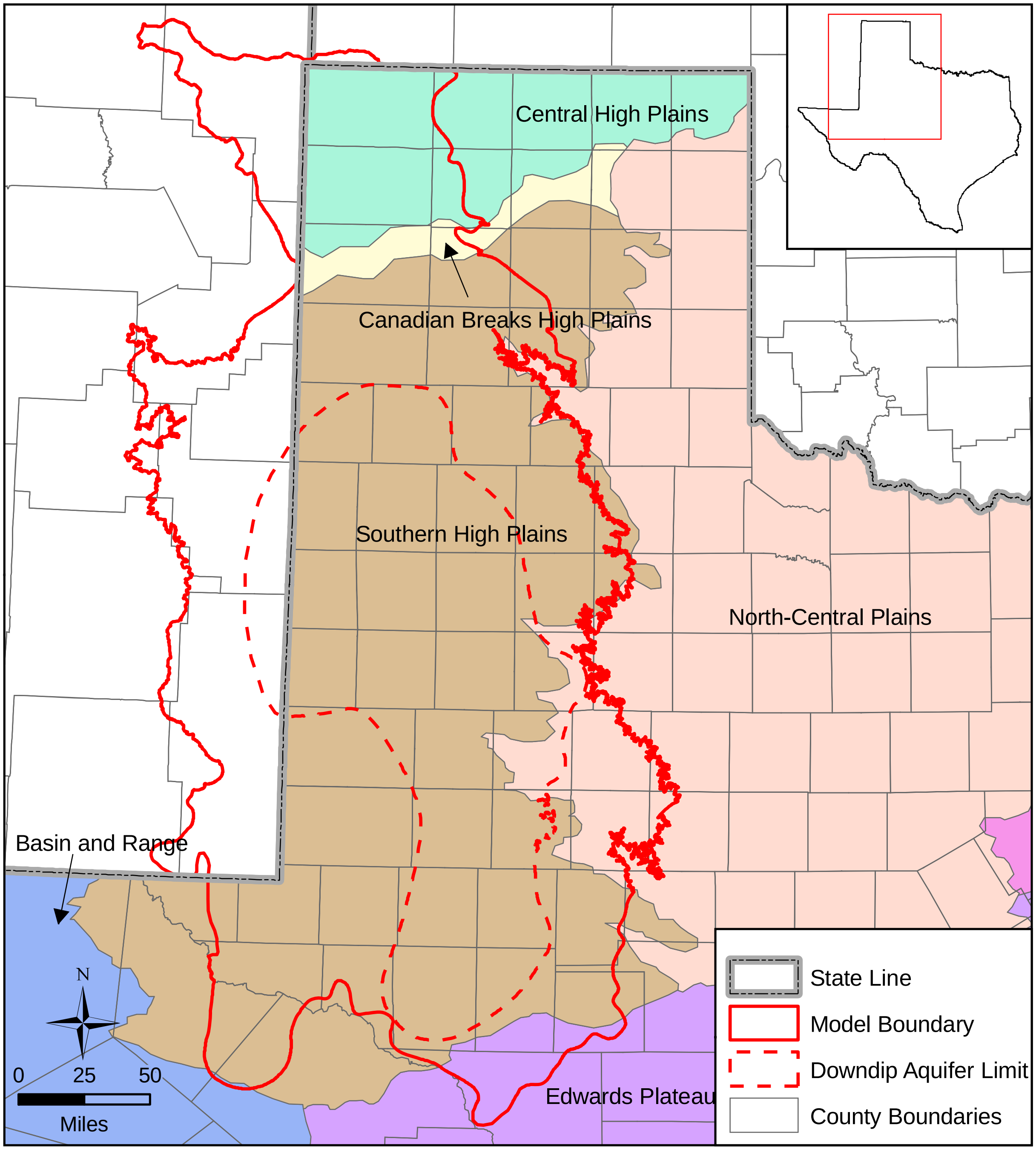
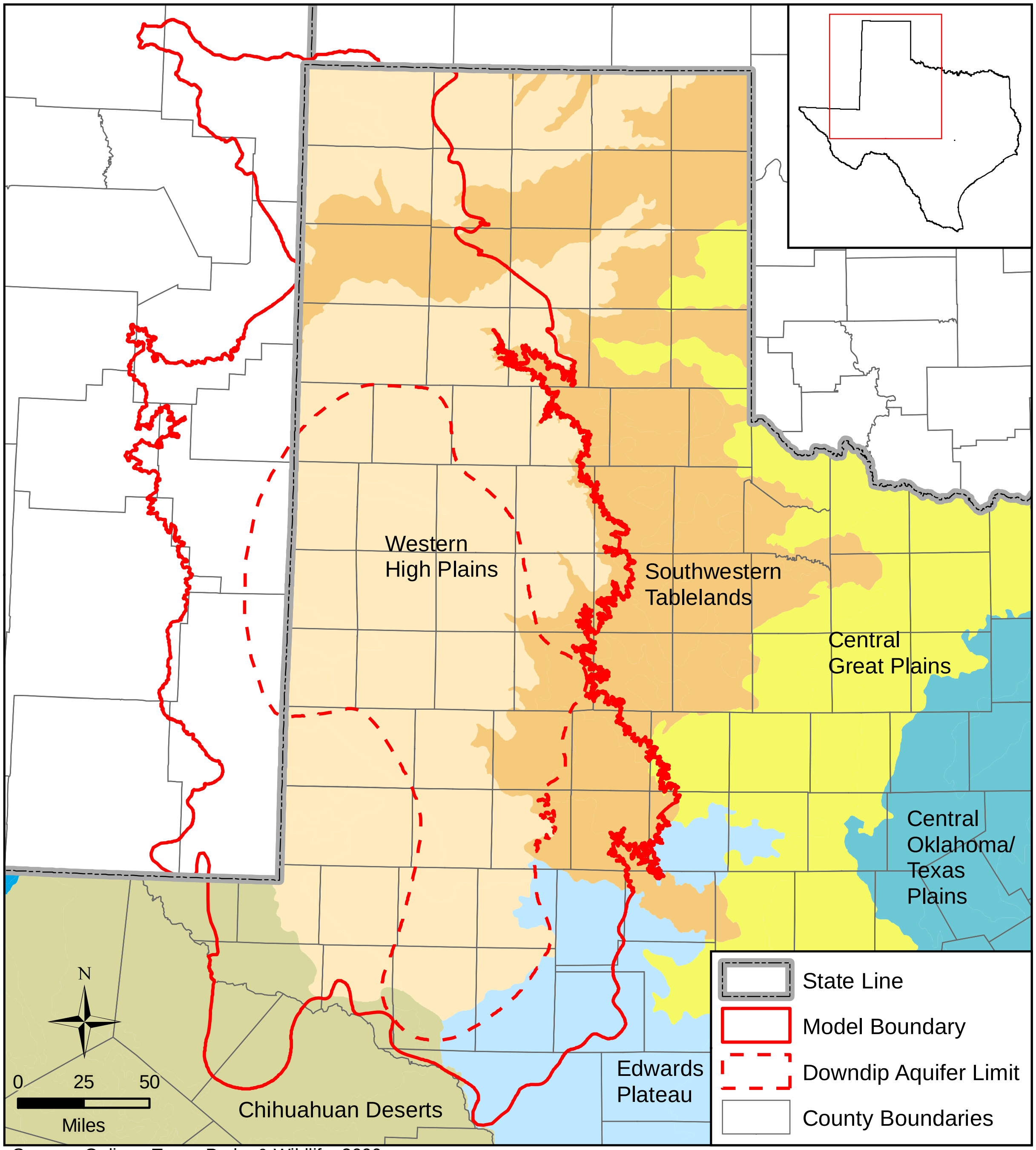
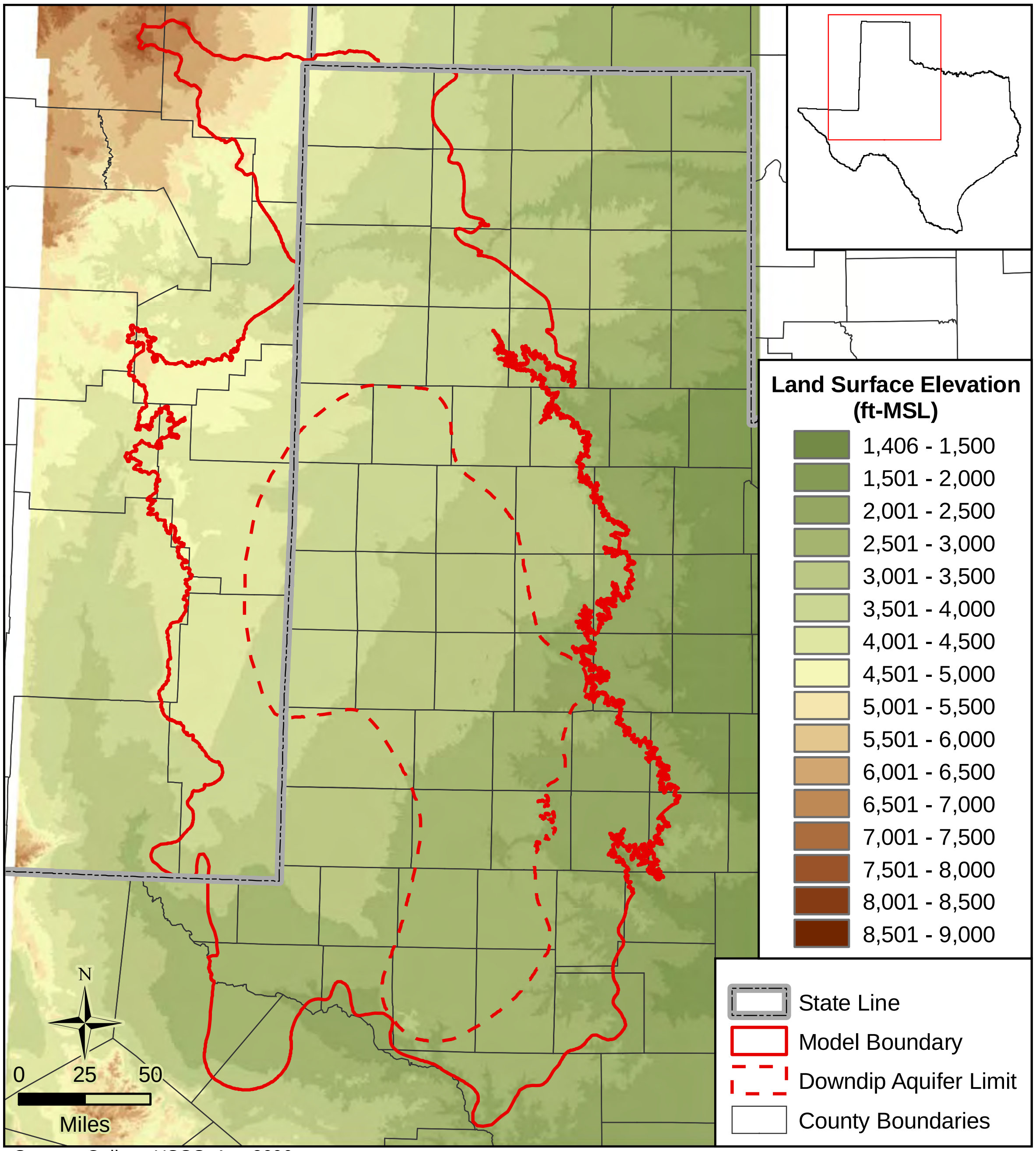


Figure 2.1.1 Physiographic provinces in the Texas portion of the study area.



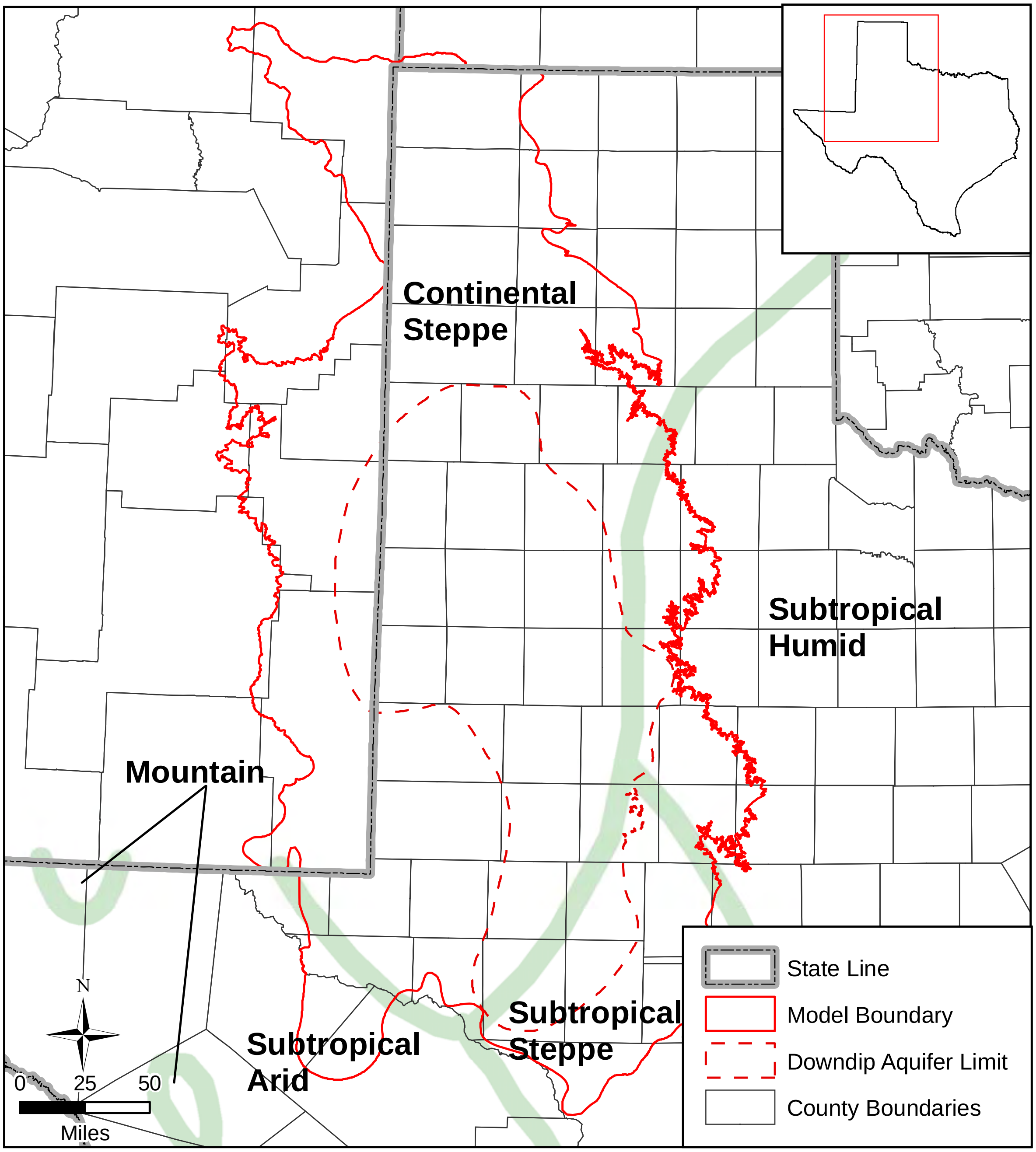
Source: Online: Texas Parks & Wildlife, 2006

Figure 2.1.2 Level III ecological regions in the Texas portion of the study area.



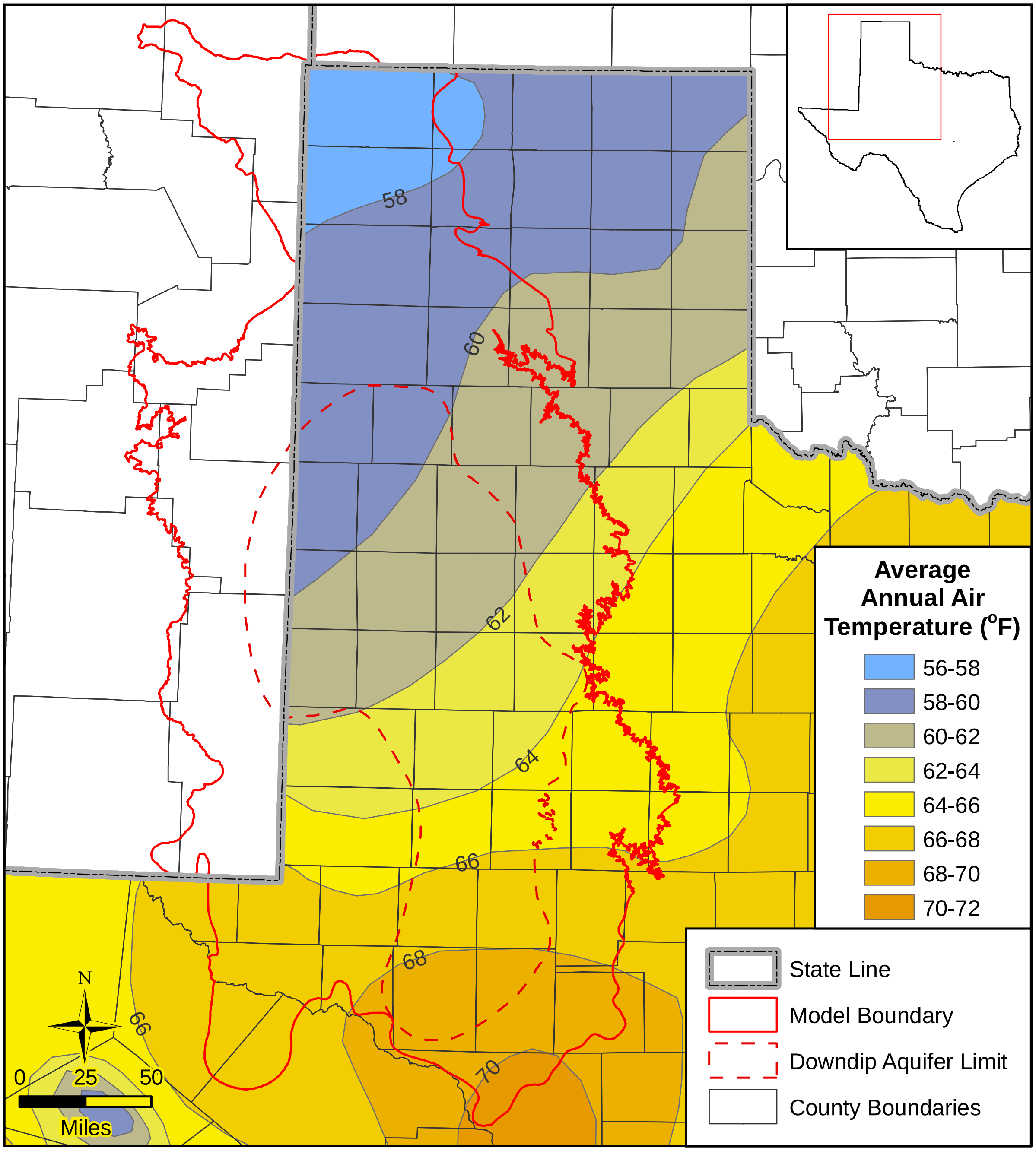
Source: Online: USGS, Aug 2006

Figure 2.1.3 Topographic map of the study area showing land surface elevation in feet above mean sea level.



Source: Online: Larkin and Bomar (1983)

Figure 2.1.4 Climate classifications in the Texas portion of the study area.



Source: Online: www.csdl.tamu.edu/FLORA/taes/tracy/map2NF.html

Figure 2.1.5 Average annual air temperature in degrees Fahrenheit for the Texas portion of the study area.

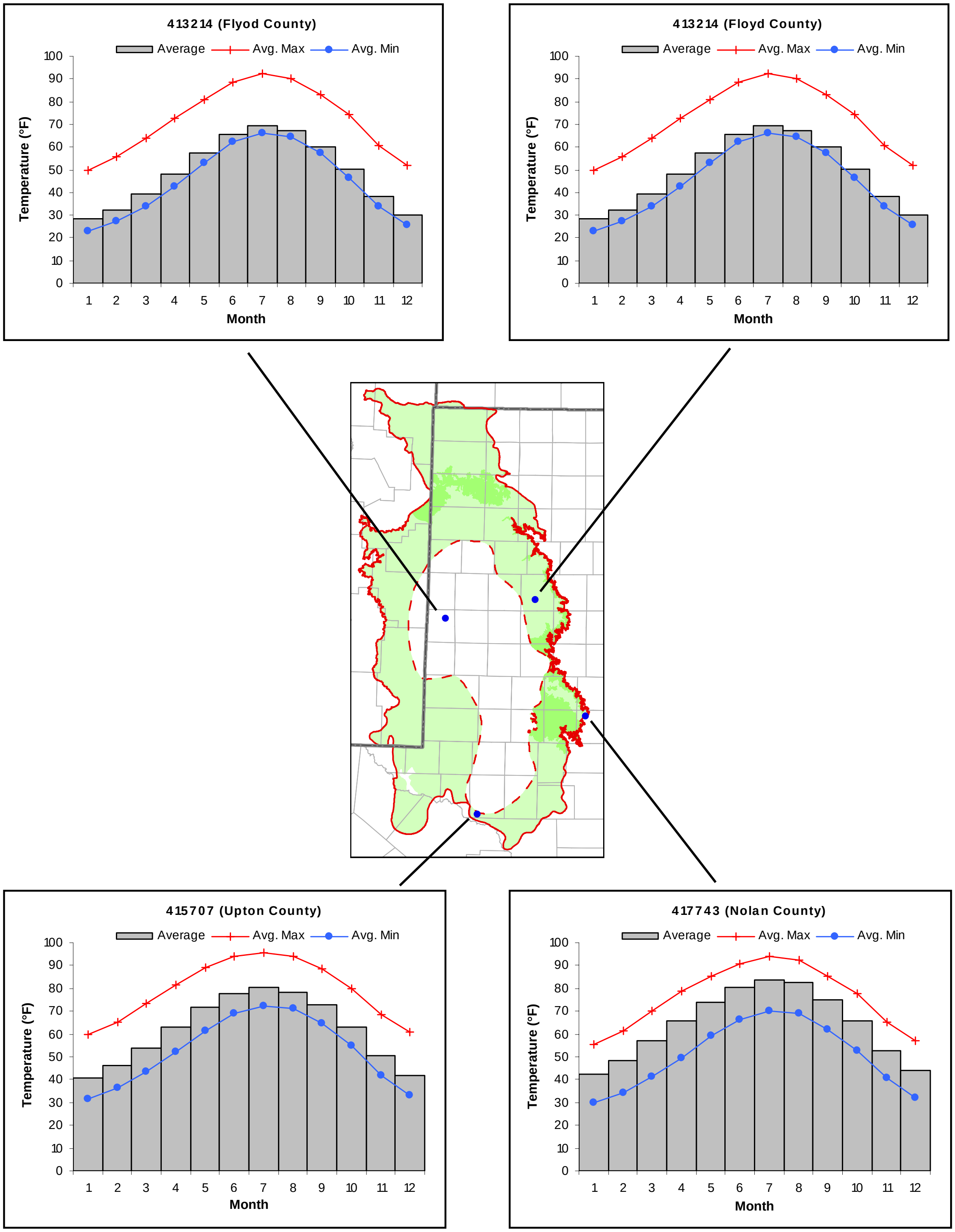
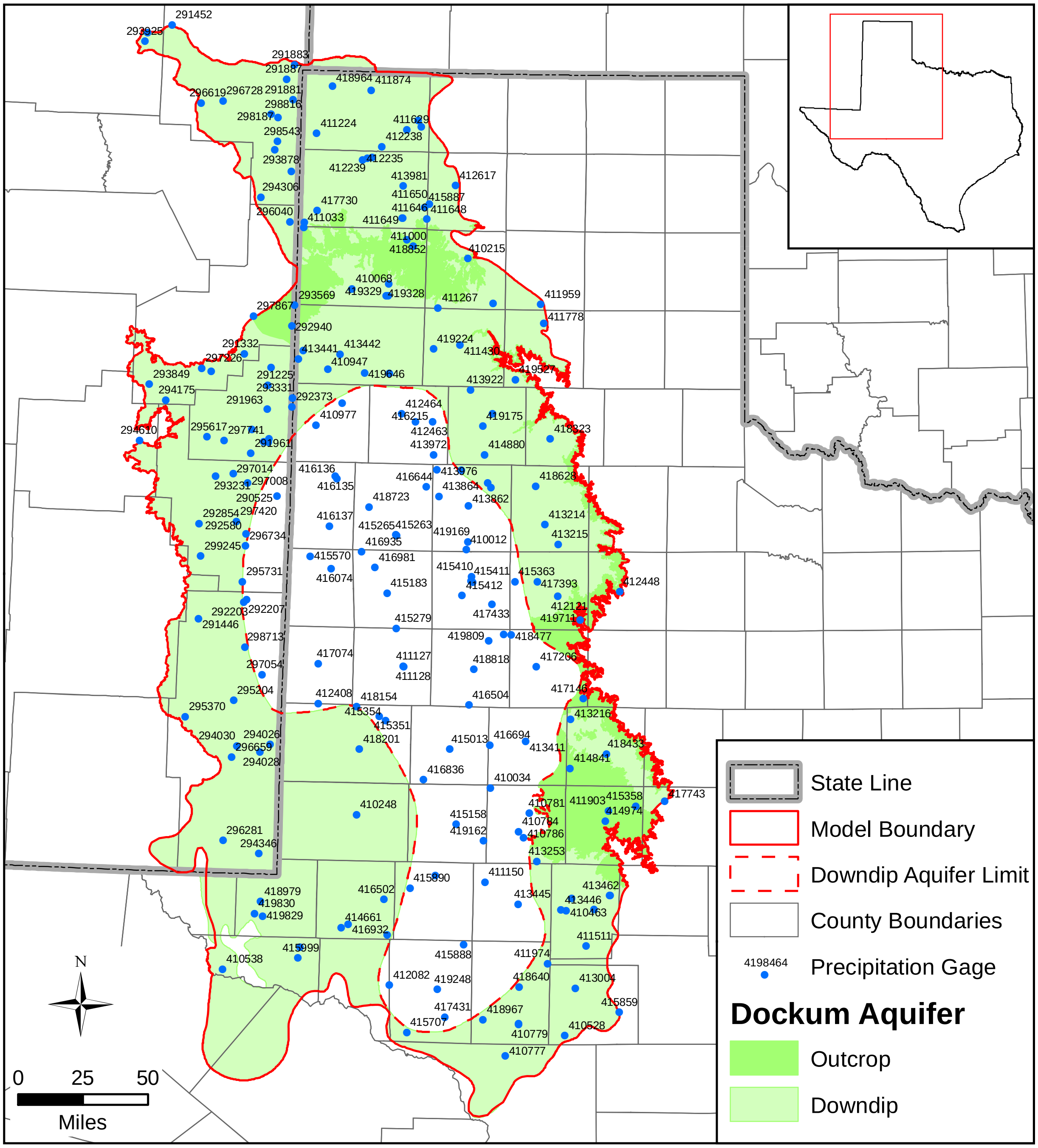


Figure 2.1.6 Average, maximum, and minimum monthly temperatures in degrees Fahrenheit at selected locations in the study area calculated from daily temperatures reported by the National Climatic Data Center.



Source: National Climatic Data Center, March 2003

Figure 2.1.7 Location of precipitation gages in the study area.

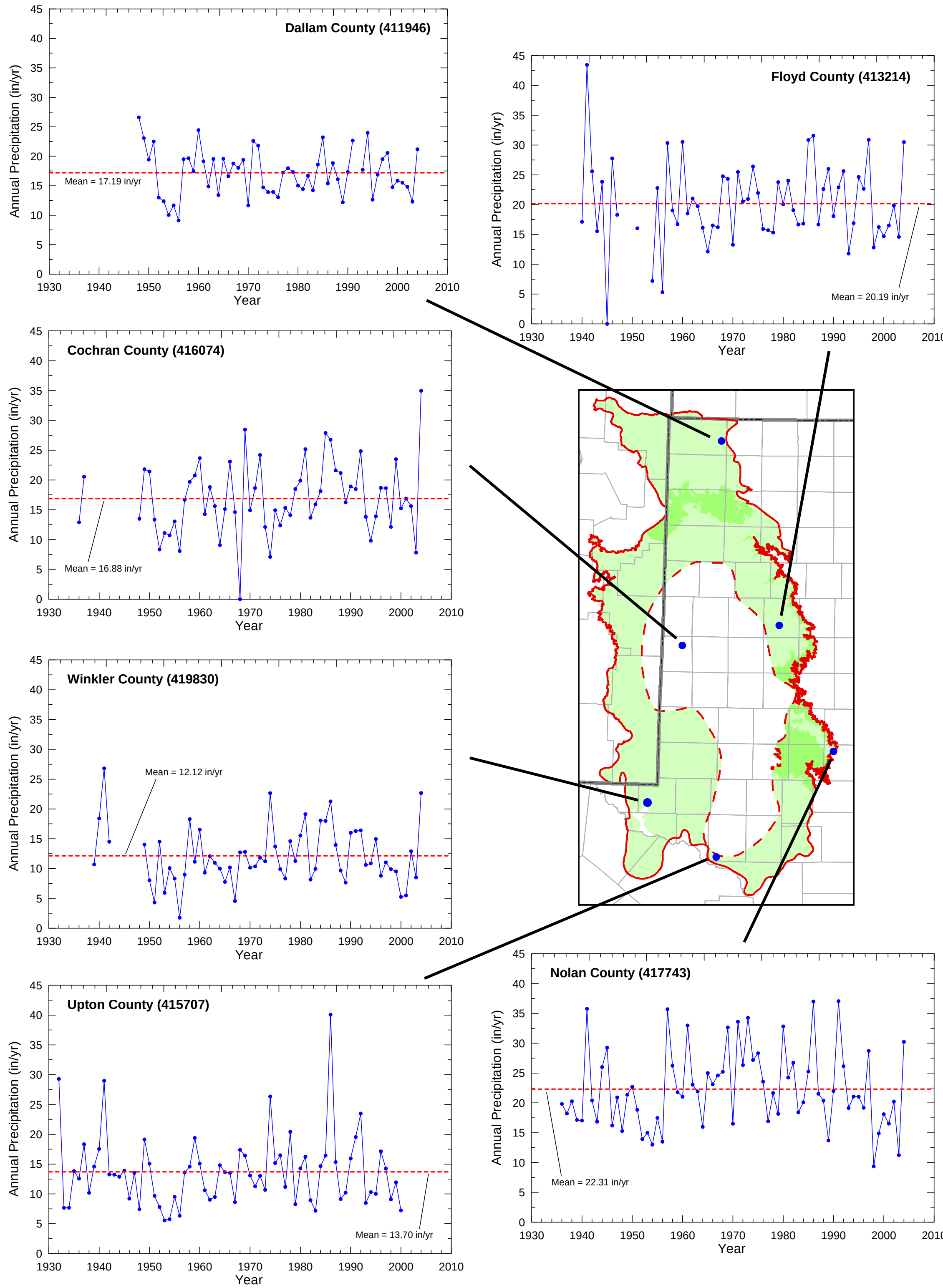
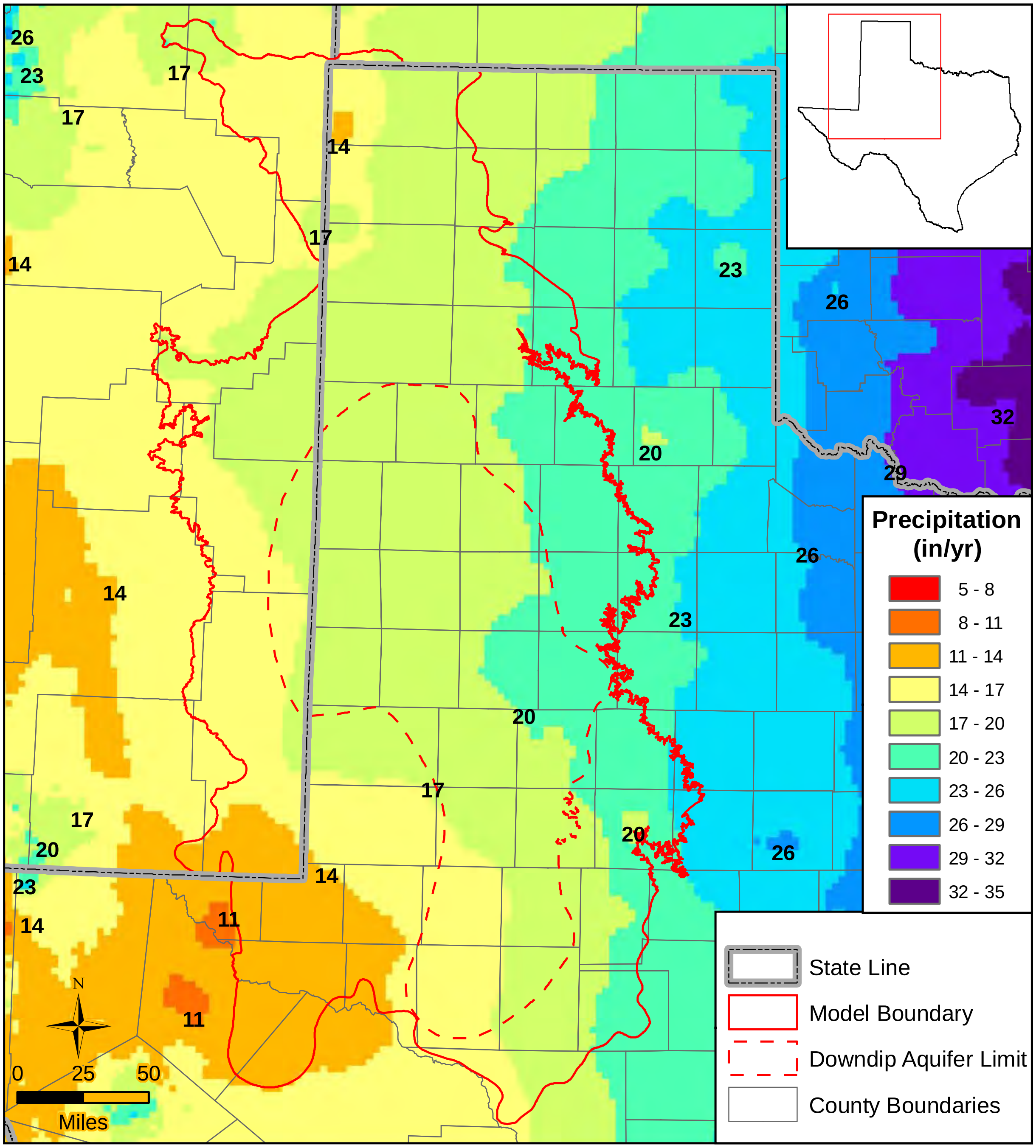
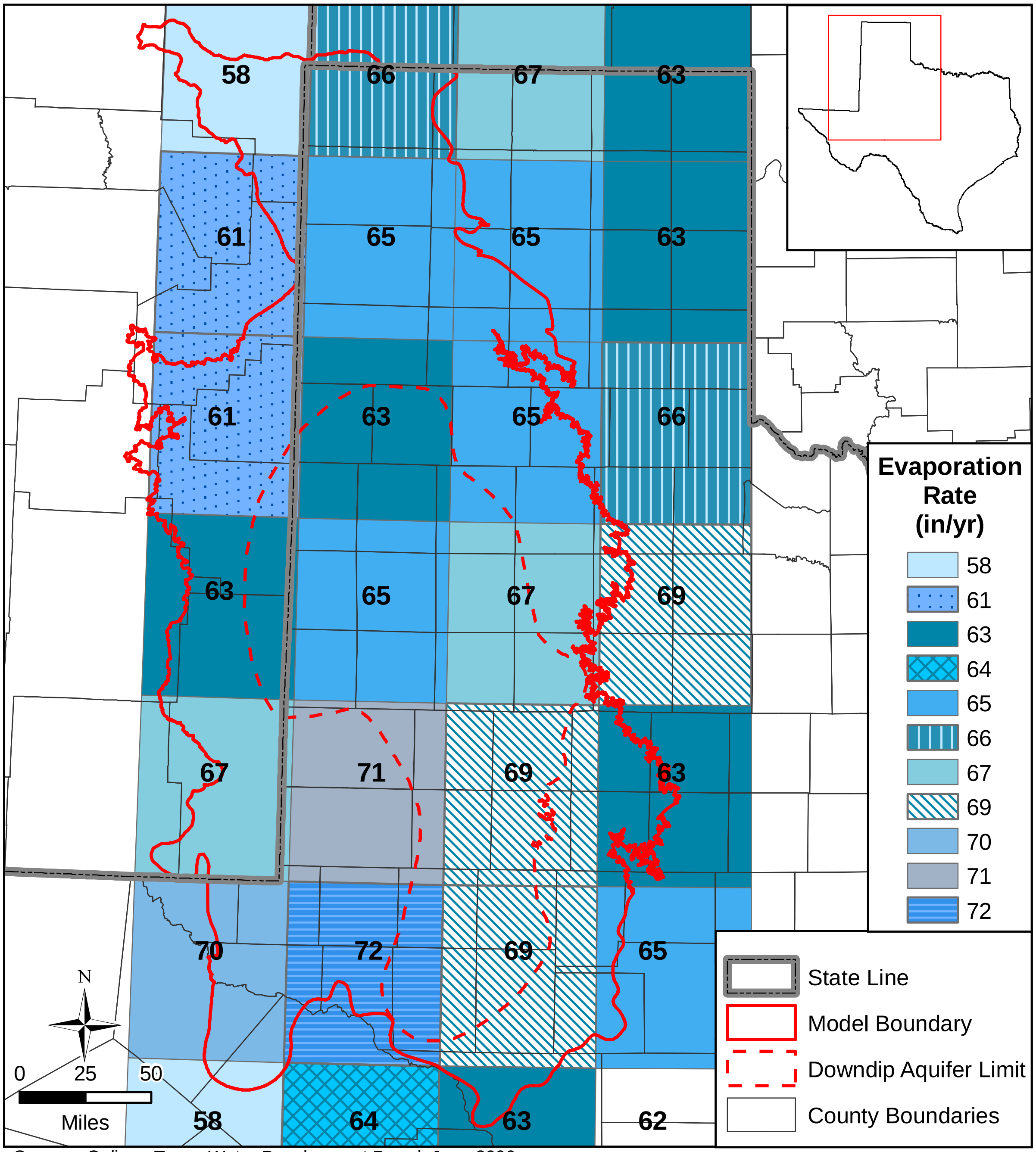


Figure 2.1.8 Annual precipitation time series in inches per year at selected locations in the study area. (A discontinuous line indicates a break in the data. The dashed red line represents the mean annual precipitation).



Source: Online: Oregon State University's Spacial Climate Analysis Service

Figure 2.1.9 Average annual precipitation in inches per year over the study area.



Source: Online: Texas Water Development Board, June 2006

Figure 2.1.10 Average annual net pan evaporation rate in inches per year over the study area.

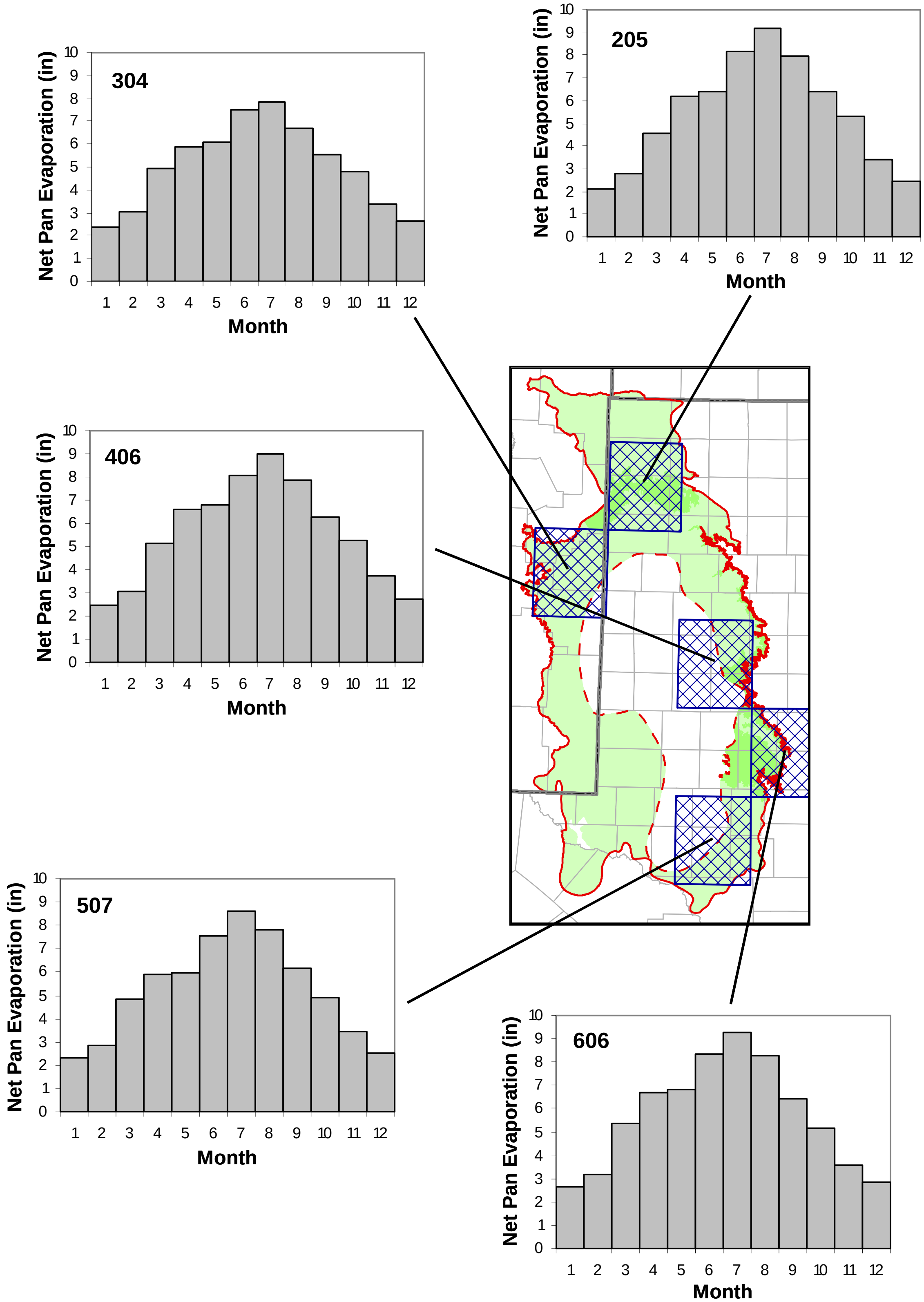


Figure 2.1.11 Average monthly lake surface evaporation in inches at selected locations in the study area.

2.2 Geology

A mid-continent trough persisted from earlier Mesozoic times and provided the environment for the deposition of Triassic-age sediments from the southern border of Canada to the Southern High Plains of the Texas Panhandle and eastern New Mexico (McKee and others, 1959) (Figure 2.2.1). In their southernmost extent, only the upper one-third of Triassic time is represented by the presence of non-marine redbeds of the Dockum Group, which accumulated in a series of basins underlying parts of Texas, New Mexico, Colorado, Kansas, and Oklahoma. Elsewhere in Texas, equivalent Triassic-age sediments (Eagle Mills Formation) were deposited in the newly forming Gulf of Mexico (Antoine and others, 1974).

For the purpose of this report, only the modeled portion of the Dockum Group that occurs in the Texas Panhandle, eastern New Mexico, and the Oklahoma Panhandle is further discussed. Surface exposures of the Dockum Group are primarily restricted to the Canadian River valley, which separates the Southern High Plains from the Northern High Plains (The University of Texas at Austin, Bureau of Economic Geology, 1969; 1983), and the eastern escarpment of the Southern High Plains or Llano Estacado. Elsewhere, the Dockum Group outcrops are identifiable in the Pecos River valley in Texas and New Mexico. In their subsurface extent, units of the Dockum Group are sandwiched between older underlying Permian-age strata and younger overlying Jurassic-, Cretaceous-, and Tertiary-age formations (Table 2.2.1). Today, the Tertiary-age Ogallala Formation and modern day soils cover most of the Dockum Group and limited exposures of underlying geologic units are visible in drainages (Figure 2.2.2).

2.2.1 Tectonic History and Dockum Group Structure

In parts of Texas, New Mexico, and Oklahoma, Triassic-age sediments of the Dockum Group accumulated in pre-existing late-Paleozoic mid-continent structural basins that include from north to south the Dalhart, Tucumcari, Palo Duro (a northern extension of the Midland Basin), Midland, and Delaware basins. These structural features, and an approximate outline of their extent, are shown in Figure 2.2.3. Of these, the Midland Basin had the greatest influence in terms of areal extent. Granata (1981) refers to this entire sediment catchment area as the "Dockum Basin". Positive structural features separating these basins include the Amarillo Uplift, Matador Arch, and the Central Basin Platform (see Figure 2.2.3).

The base of the Dockum Group reflects structural features that affected deposition. Net sandstone and isopach maps indicate renewed influence of individual basement structures on deposition during the Triassic in the Palo Duro Basin (Johns, 1989). The maximum preserved thickness of Dockum Group rocks, which is approximately 2,000 feet, occurs slightly west of center of the Midland Basin. The top of Dockum Group is a relatively smooth surface indicative of the final filling of the ancestral basins.

2.2.2 Dockum Group Deposition Environment

The initiation of Dockum Group sedimentation was apparently the result of a shift from an arid Permian climate toward a more humid Triassic climate and a rejuvenation of some Paleozoic structural elements (Asquith and Cramer, 1975), including the opening of the Gulf of Mexico, uplift in part of the Ouachita Tectonic Belt, and renewed subsidence of the "Dockum Basin". The Dockum Group consists of complex terrigeneous clastic and lacustrine sediments ranging from mudstone to conglomerate that peripherally filled mid-continent basins that were preserved in the ancestral post-Permian topography. As arid Permian conditions gradually gave way to more humid conditions of the Triassic, a period of erosion followed throughout much of the area, thus forming an unconformity that separates Permian and Triassic strata. However, in some areas, the contact is gradational, as sedimentation was probably continuous from Permian into Triassic (McGowen and others, 1979).

Beyond this basic premise, researchers have differed on mode of deposition (facies) and stratigraphic subdivisions. Two basic depositional models prevail, one postulating a fluvial-deltaic deposition in a lacustrine environment and the other suggesting a dominant alluvial process with minor lacustrine influences. McGowen and others (1977) and Granata (1981) recognized two low frequency, fining-upward cycles of lithology recognizable throughout the basin despite differing source areas and inferred the cyclicity to be due to climatic and/or tectonic variation. McGowen and others (1979) describe the Dockum Group as deltaic and lacustrine sediments deposited in a large inland lake confined in pre-existing Paleozoic structural basins. Researchers note that the Dockum Basin was filled from all directions and that no basin outlet is indicated by net sandstone maps and depositional axes as additional support of the large lake basin hypothesis. These depositional facies represent a shift from the underlying Permian evaporates and terrigeneous clastics deposited in shallow hypersaline tidal flats and sabkhas.

Johns (1989) recognized four cyclic sequences in the lower part of the Dockum Group, each characterized by a mudstone base and coarsening upward sequence with more abundant sands. The mudstone thickness increases toward the center of the depositional basin. The upper part of the Dockum Group characteristically consists of more isolated sands embedded in predominantly mudstone.

In opposition to the large inland lake (lacustrine) depositional concept, Lucas and Anderson (1992) describe Dockum Group strata as mainly fluvial (deposited by rivers) in origin. They conclude that the siltstones and mudstones were deposited on floodplains, interfluves, and small ponds.

Lehman (1994a; 1994b) and Lehman and Chatterjee (2005) follow the fluvial deposition concept and characterize the Dockum Group strata as comprising two major upward-fining alluvial-lacustrine depositional sequences; a basal sequence and an upper sequence. Both depositional sequences described by Lehman and Chatterjee (2005) are comprised largely of two typical alluvial facies associations, stream channel and overbank facies. Lacustrine facies accumulated in local flood-plain depressions likely resulting from subsidence over areas of underlying salt dissolution. Lehman and Chatterjee (2005) suggest that the change in mineralogical composition, and presumed sediment source areas between the two Dockum Group depositional sequences and the differences in paleocurrent orientations between them, indicate that these strata are the product of two distinct sediment dispersal systems. An upward change in mineralogical composition was also noted by Johns and Hovorka (1984) with basal sands being similar to underlying Permian units and stratigraphically higher sandstones containing more rock fragments indicating schist, gneiss, phyllite, and other metamorphic source rocks.

Petrographic and paleocurrent evidence indicate that the highly quartzose sediment composition of the basal alluvium sequence was derived mostly from the north, northeast, and east of the current outcrop belt (Riggs and others, 1996). Thickness of this sequence is greatest on the western extent of the Dockum Group and thins to the south and east. The thicker, more laterally extensive upper sequence consists of highly micaceous alluvium with abundant metamorphic rock fragments indicating a basement metamorphic rock source of the Ouachita orogenic belt to the south and southeast (Long and Lehman, 1993; 1994). The unconformity between the two sequences, the difference in mineralogical composition and presumed source area, differences in paleocurrent orientation, and intervening episodes of local deformation indicate that the sequences are of tectonic origin.

2.2.3 Dockum Group Stratigraphy

Dockum Group sediment sources were initially predominantly terrigenous Paleozoic rocks from surrounding highlands in New Mexico, Oklahoma, and central Texas and subsequently, as erosion progressed, basement rocks of various types; thus generating variable mineralogical content in different parts of the Dockum Basin. Although both Dockum Group and Permian-age strata are primarily red in color, Dockum Group rocks are sufficiently unique in color complexity, mineralogy, and facies geometry to be discernable from the underlying Permian-age strata. Sand beds in the lower part of the Dockum Group are highly quartzose (Riggs and others, 1996), while sand beds in the upper part are highly micaceous with abundant metamorphic rock fragments (Long and Lehman, 1993, 1994; Johns and Hovorka, 1984).

Dockum Group stratigraphy has been described in detail at numerous locations by previous researchers (see Section 3.0) and various attempts have been made to correlate stratigraphic units laterally across the Dockum Basin. Compressed cross-sections used by Johns (1989) to identify genetic sequences represents a correlation of sandstone beds across the Palo Duro Basin.

For this study, the stratigraphic nomenclature from Lehman (1994a; 1994b) is adopted (Table 2.2.2). The formations of the Dockum Group are, from oldest to youngest, the Santa Rosa Formation, the Tecovas Formation, the Trujillo Sandstone, and the Cooper Canyon Formation. The lowermost Santa Rosa Formation consists of extensive sandstone and conglomerate beds and the overlying Tecovas Formation consists of variegated mudstones and siltstones. The Trujillo Sandstone consists of massive crossbedded sandstones and conglomerates and the uppermost Cooper Canyon Formation consists of mudstone with some siltstone, sandstone, and conglomerate.

2.2.4 Post-Dockum Group Deposition, Structure, and Tectonic Events

As the western basins filled, the lowering margins of the newly formed Gulf of Mexico rapidly shifted centers of deposition eastward, thus bringing the period of Triassic Dockum Group deposition in the southwest to a close. Deposition of younger formations of Jurassic-, Cretaceous-, and finally Tertiary-age subsequently buried Dockum Group strata, which was exposed at the surface once again in more recent times by erosion around the basin periphery and in the Canadian River valley. See Figure 2.2.2 for the age and distribution of rocks directly overlying the Dockum Group. The geologic cross-sections presented in Figures 2.2.4 through 2.2.6 illustrate the structural configuration of the Dockum Group and overlying younger and underlying older stratigraphic units.

Dockum Group rocks have been subjected to several episodes of erosion as indicated by the overlying stratigraphy, which have produced a generally uniform southeasterly dipping surface and eventual truncation along its eastern margin (Granata, 1981). A pre-Jurassic erosional surface, preserved in New Mexico, is relatively minor; while pre-Cretaceous erosion had a more widespread effect on the upper surface of the Dockum Group. Probably during late Jurassic, eastern parts of the Dockum Group were being deeply eroded and transported into the Gulf (Granata, 1981). Figure 2.2.7 illustrates a number of erosional patterns discernable in the Dockum Group surface.

At the end of the Cretaceous Period, the Laramide Orogeny resulted in the uplift of the southern Rocky Mountains, eastward tilting of pre-existing strata underlying the Southern High Plains, and the regression of Cretaceous seas that had covered the American southwest. A network of southeasterly flowing streams carved canyons in the newly exposed subareal Cretaceous surface and underlying Dockum Group strata (Brand, 1952; Walker, 1978).

A major flow-through system (referred to as the *Clovis Paleovalley* by Gustavson and Winkler, 1988) is evident from Clovis, New Mexico east and southeastward through Castro, Crosby, Floyd, Hale, and Parmer counties, Texas. Finch and Wright (1970) describe a northwest-southeast trending lineament based on straight stream segments and alignment of small playa lake basins on the current Ogallala Formation topography that directly overlies the Clovis Paleovalley structure. Finch and Wright (1970) refer to this structural trend as the *Running Water Draw – White River Lineament* and postulate a post-Ogallala Formation fault displacement of up to 100 feet.

Lineaments are linear physiographic features in the land surface that suggest structural control. Finley and Gustavson (1981) used remote sensing data to identify predominant lineament patterns on the High Plains and in adjacent formations. Due to the lack of identifiable faults in the Texas Panhandle, they determined that the lineaments are most likely the surface expression of underlying joints or overlie basement structures. Although not as well defined as lineaments patterns on the High Plains, lineament patterns common in formations adjacent to the High Plains (Cretaceous, Triassic, and Permian) exhibit an orientation of north-south to northeast-southwest. A High Plains lineament orientation of northwest-southeast is most prominently defined by aligned playa lake depressions and surface drainages. In outcrop, moderately consolidated sandstones show better developed jointing than do the associated siltstones and mudstones. These lineament/joint patterns likely influenced both active Dockum Group depositional directions and post-Dockum Group surface drainage patterns.

The solution of salt beds in underlying Permian formations has also locally impacted overlying formations. A major drainage feature is evident in the deep solution trough located west of the Central Basin Platform from Lea County, New Mexico through Winkler and Ward counties, Texas (see Figure 2.2.3). This trough is known as the Monument Draw Trough and can be seen in the cross-section shown in Figure 2.2.6. Elsewhere, localized collapse sinks are manifested as land-surface depressions (Reeves and Reeves, 1996).

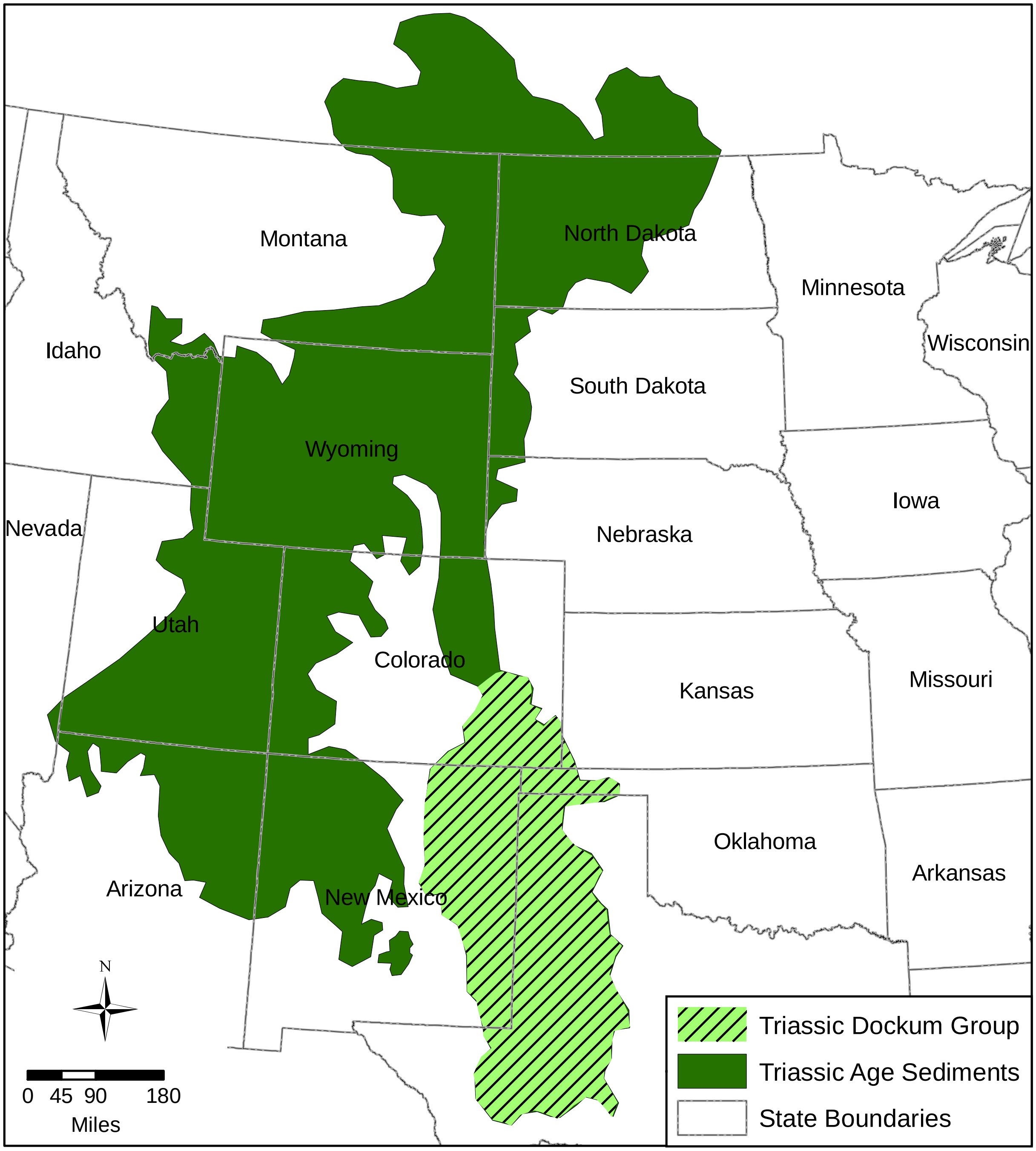
Pleistocene glacial melts in the southern Rocky Mountains possibly resulted in the release of a vast amount of water that poured across the High Plains enhancing the rapid headward erosion of both the Pecos and Canadian rivers and the westward retreat of the eastern caprock escarpment (Walker, 1978). Ancestral Brazos, Leon, Canadian, Pecos, Red, and Colorado rivers thus reshaped the post-Cretaceous landscape prior to eventually depositing hundreds of feet of silt, sand, and gravel of the Ogallala Formation. Today, erosion continues in the river valleys and along the eastern escarpment where Dockum Group strata are presently exposed.

Table 2.2.1 Hydrogeologic units in the Dockum Basin.

<table>
<tr><th>Era</th><th>System</th><th>Series</th><th>Group</th><th>Formation</th><th>Aquifer</th></tr>
<tr><td rowspan="2">Cenozoic</td><td>Quaternary</td><td></td><td></td><td>Pecos Valley Alluvium</td><td>Pecos Valley</td></tr>
<tr><td>Tertiary</td><td>Late Miocene to Pliocene</td><td></td><td>Ogallala</td><td>Ogallala</td></tr>
<tr><td rowspan="12">Mesozoic</td><td rowspan="6">Cretaceous</td><td rowspan="6"></td><td>Washita</td><td>Duck Creek</td><td rowspan="6">Edwards-Trinity (High Plains)</td></tr>
<tr><td rowspan="4">Fredericksburg</td><td>Kiamichi</td></tr>
<tr><td>Edwards</td></tr>
<tr><td>Comanche Peak</td></tr>
<tr><td>Walnut</td></tr>
<tr><td>Trinity</td><td>Antlers</td></tr>
<tr><td rowspan="2">Jurassic</td><td rowspan="2"></td><td rowspan="2"></td><td>Morrison</td><td rowspan="2">Rita Blanca</td></tr>
<tr><td>Exeter</td></tr>
<tr><td rowspan="4">Triassic</td><td rowspan="4"></td><td rowspan="4">Dockum</td><td>Cooper Canyon</td><td rowspan="4">Dockum</td></tr>
<tr><td>Trujillo</td></tr>
<tr><td>Tecovas</td></tr>
<tr><td>Santa Rosa</td></tr>
<tr><td rowspan="2">Paleozoic</td><td rowspan="2">Permian</td><td>Ochoa</td><td></td><td>Dewey Lake</td><td rowspan="2"></td></tr>
<tr><td>Guadalupe</td><td></td><td>Rustler</td></tr>
</table>

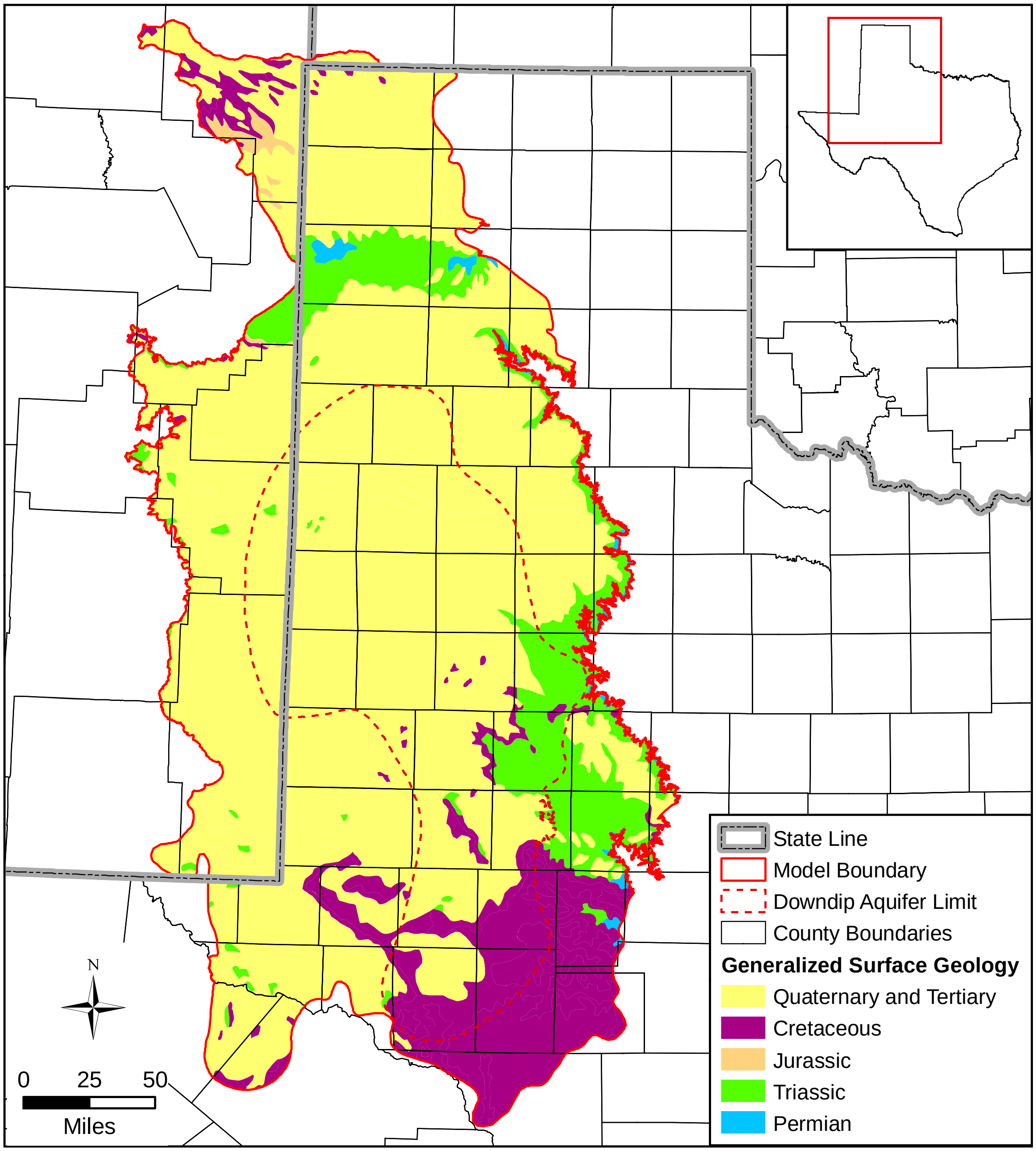
Table 2.2.2 Generalized stratigraphic section for the Dockum Group.

<table>
<tr><th>Group</th><th>Formation</th><th>General Description</th></tr>
<tr><td rowspan="4">Dockum</td><td>Cooper Canyon</td><td>reddish-brown to orange siltstone and mudstone with lenses of sandstone and conglomerate</td></tr>
<tr><td>Trujillo</td><td>gray, brown, greenish-gray, fine to coarse-grained sandstone and sandy conglomerate with thin gray and red shale interbeds</td></tr>
<tr><td>Tecovas</td><td>variegated, sometimes sandy mudstone with interbedded fine to medium-grained sandstone</td></tr>
<tr><td>Santa Rosa</td><td>red to reddish-brown sandstone and conglomerate</td></tr>
</table>



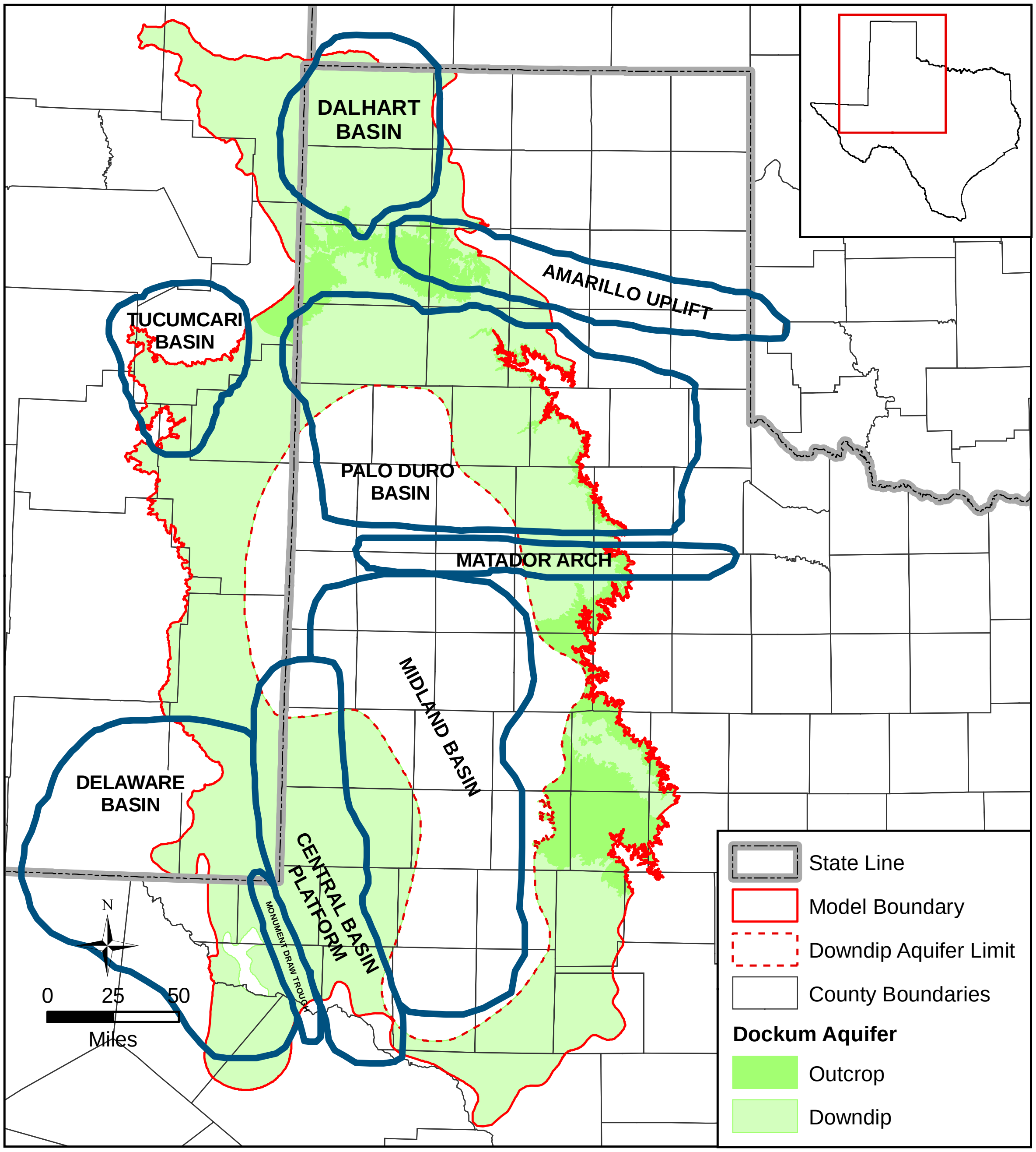
Adapted from McKee and others (1959)

Figure 2.2.1 Extent of Triassic-age sediments in the central continental corridor.



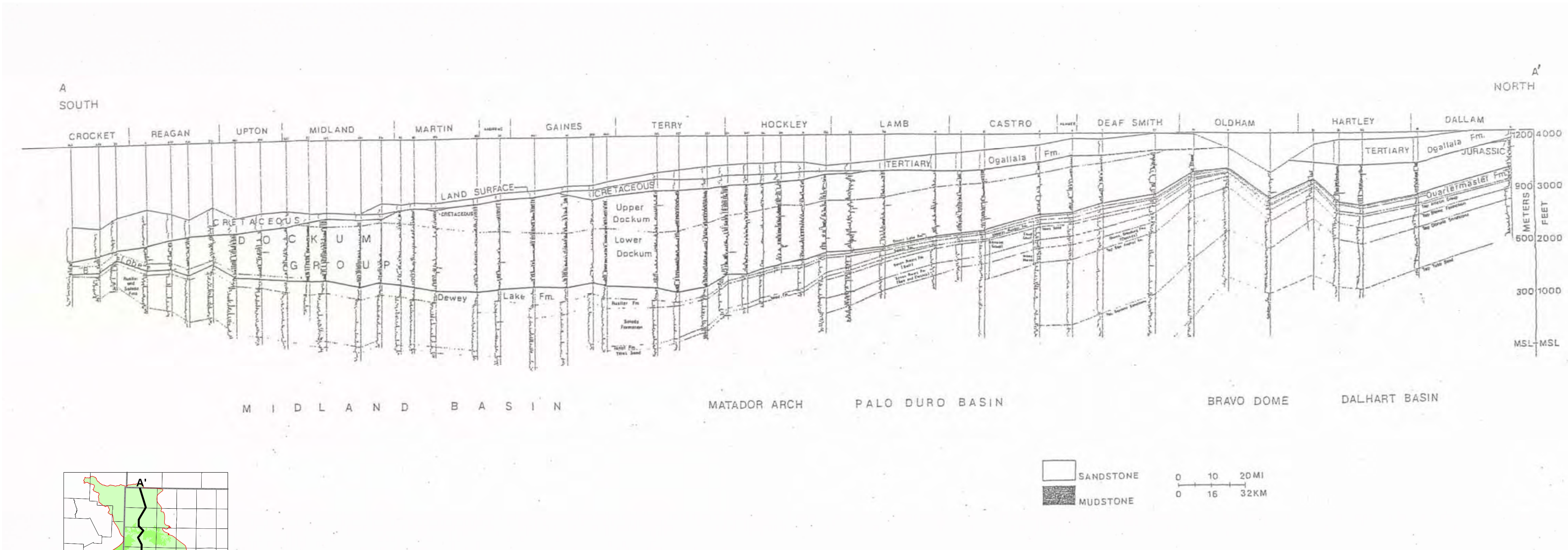
Source: Online: USGS Geology of the Conterminous United States at 1:2,500,000 Scale

Figure 2.2.2 Surface geology of the active model area.



Source: Adapted from Senger and others (1987) and Online: Encyclopedia Britannica, Inc., 2007

Figure 2.2.3 Major structural features in the active model area and an approximate outline of their extent.



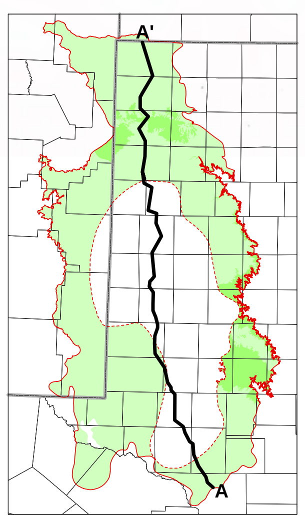


Figure 2.2.4 South-north cross-section across the active model area (after McGowen and others, 1977).

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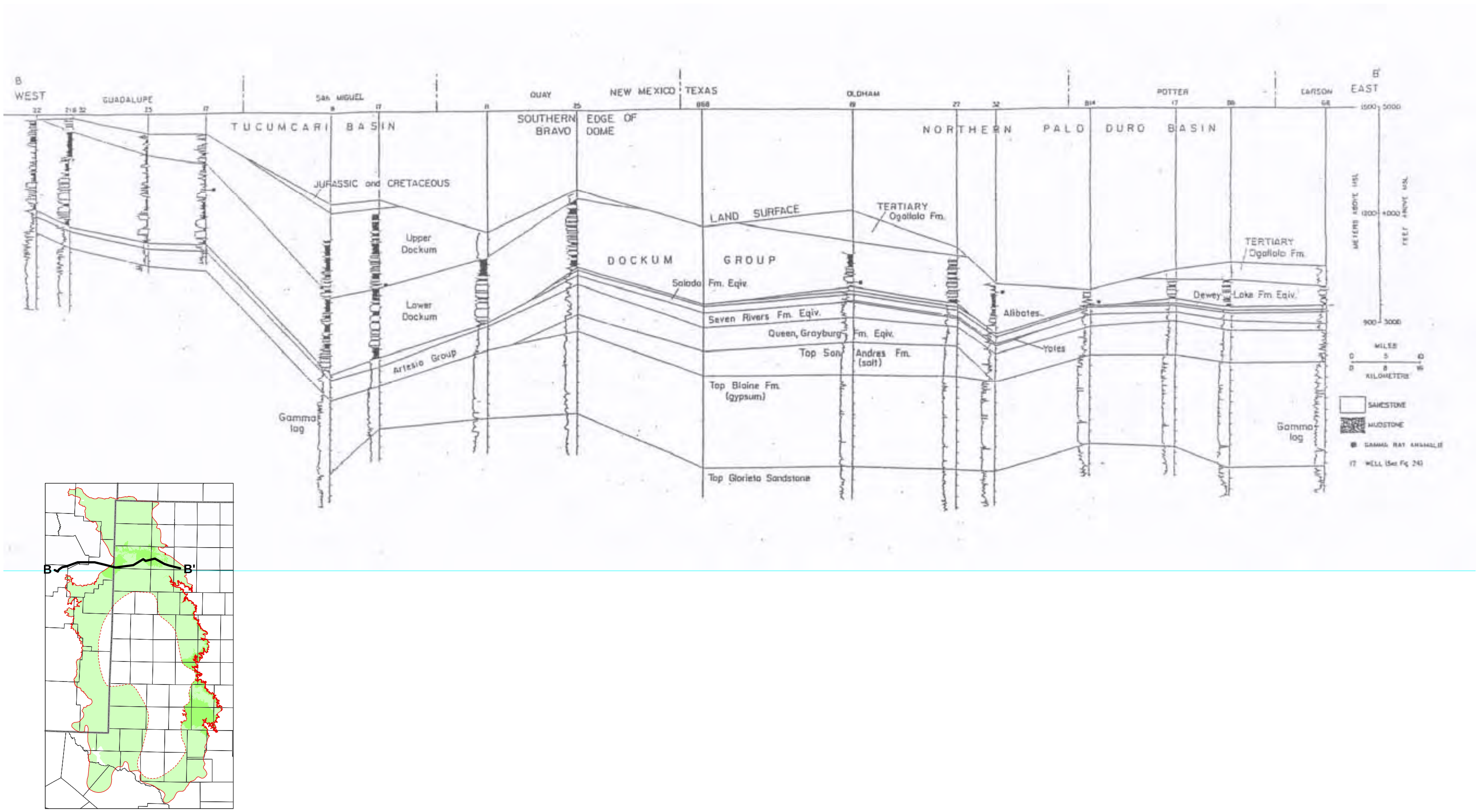

Figure 2.2.5 **East-west cross-section across Guadalupe, San Miguel, and Quay counties, New Mexico and Oldham, Potter, and Carson counties, Texas (after McGowen and others, 1977).**

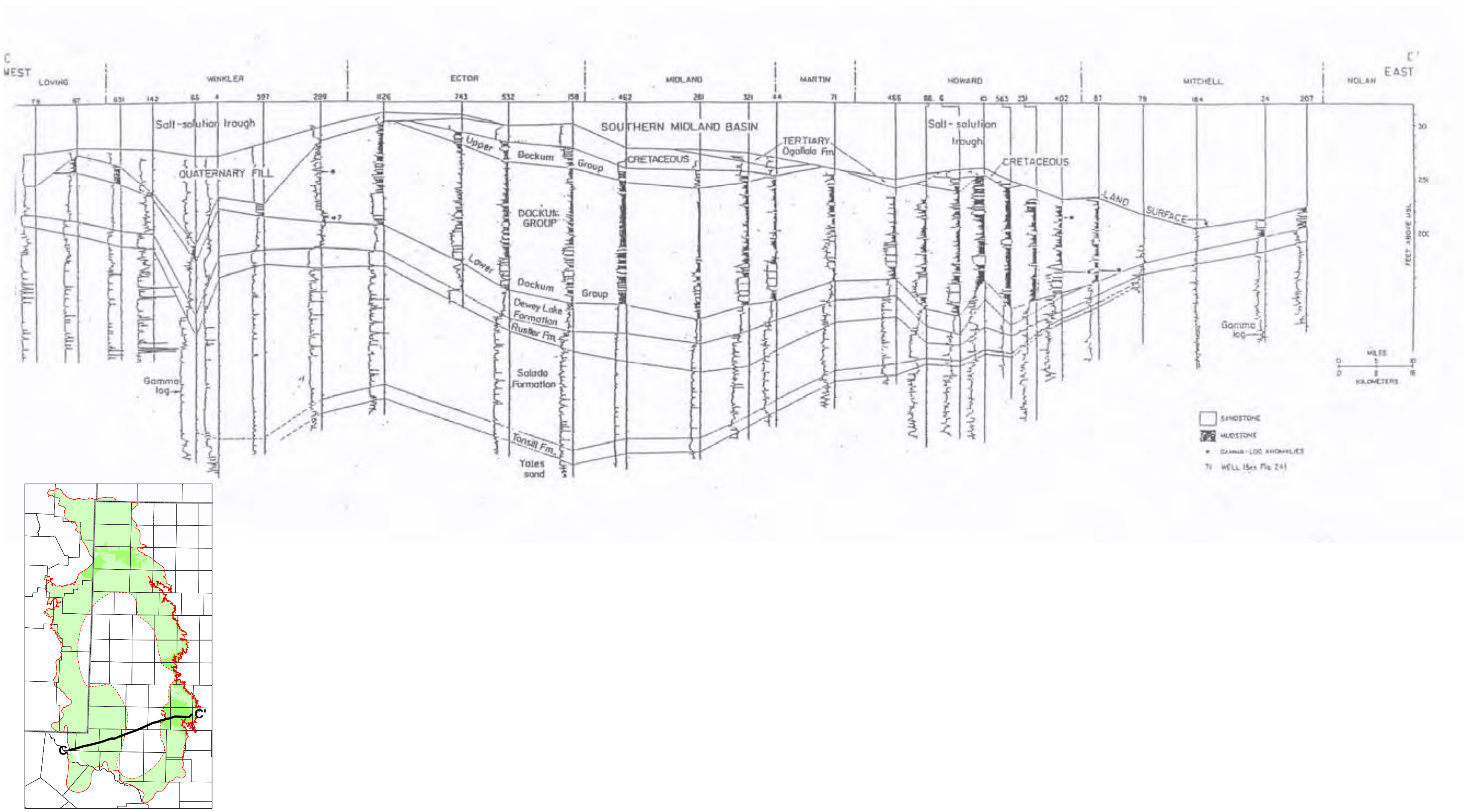

Figure 2.2.6 **East-west cross-section across Loving, Winkler, Ector, Midland, Martin, Howard, and Mitchell counties, Texas (after McGowen and others, 1977.**

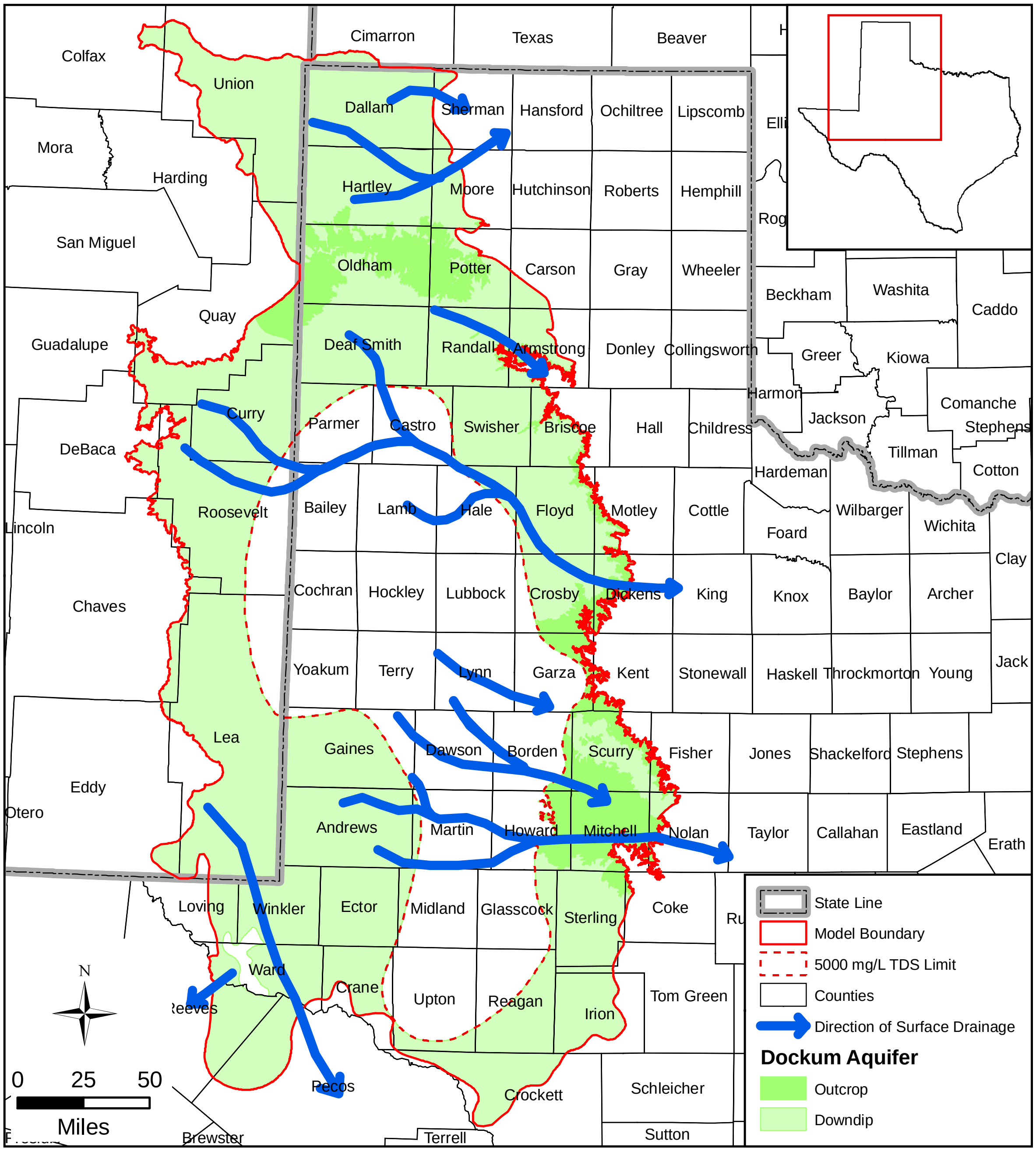

Figure 2.2.7 Post-depositional erosional patterns in the Dockum Group surface.

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3.0 Previous Investigations

The Triassic-age Dockum Group in western Texas and eastern New Mexico has been the subject of numerous studies. A majority of the studies relate to the depositional history and/or lithostratigraphic correlations of the Dockum Group. W.F. Cummins (1890) described and named outcropping redbeds in western Dickens County, Texas the “Dockum beds”; the following year he stated their age as Triassic (Cummins, 1891). Since then, numerous researchers have studied Dockum Group outcrops along the eastern margin of the Texas Panhandle and the Canadian River valley into eastern New Mexico. In more recent times, researchers have evaluated geophysical logs from wells drilled through the Dockum Group, and have attempted to piece together its subsurface stratigraphy. Each researcher recognized locally identifiable stratigraphic sequences and often assigned a name to each. A generalized summary of Dockum Group nomenclature is presented in Table 3.0.1.

Gould (1907) first subdivided the Dockum (Group) in the Canadian River valley in the Texas Panhandle into a basal shale or mudstone unit that he named the Tecovas Formation and an upper sandstone and shale unit he named the Trujillo Formation. Drake (1891) studied the Dockum Group outcrop from Big Spring to Amarillo, Texas and westward to Tucumcari, New Mexico. His correlations were later reexamined by Hoots (1926), Darton (1928), and Adams (1929), who introduced such names as Chinle and Santa Rosa into the stratigraphic complexity. Adkins (1932) also mentioned other localized stratigraphic names such as Barstow, Quito, Camp Springs, Dripping Springs, and Taylor.

McGowen and others (1975; 1977; 1979) and Granata (1981) analyzed Triassic strata in terms of genetic facies that compose depositional systems. For the purpose of developing sandstone distribution maps, they subdivided the Dockum Group into a mud-rich “Upper Dockum Unit” and a sand-rich “Lower Dockum Unit”. These units were characterized as informal and were not intended to be construed as being of stratigraphic status. Hart and others (1976) also divided the Dockum Group in the western Oklahoma Panhandle into upper and lower units.

Johns (1989), working in the Palo Duro Basin area, described the depositional origin of Dockum Group rocks, mapped the distribution of major lithofacies, and determined the influences controlling sandstone thickness. The lower portion of the Dockum Group of McGowen and others (1977) is distinguished by four cyclic, coarsening upward sequences with more abundant sands, while more isolated sands embedded in predominantly mudstone characterizes the upper portion of the Dockum Group.

Lucas and Anderson (1992; 1993; 1994; 1995) suggested a revision of the Dockum from Group status (Chinle being the new group name) to formation status and identified a number of localized member subdivisions. Lehman (1994a; 1994b) defined the Dockum with Group status, subdivided into four formations in Texas (Santa Rosa Sandstone, Tecovas Formation, Trujillo Sandstone, and Cooper Canyon Formation).

Bradley and Kalaswad (2003) support the stratigraphic divisions of Lehman (1994a; 1994b); however, they refer in their cross-sections to the "Best Sandstone", which represents the most prolific parts of the aquifer developed in the lower and middle sections of the Dockum Group where coarse-grained sediments predominate. They also note that locally, any water-bearing sandstone within the Dockum Group is typically referred to as the Santa Rosa Aquifer. Figure 3.0.1 schematically illustrates in cross-sectional view the nomenclature divisions for the Dockum Group used by McGowen and others (1977; 1979) and Granata (1981), Lehman (1994a) and Lehman and Chatterjee (2005), and Bradley and Kalaswad (2003).

The occurrence and resources of groundwater in several counties in the active model area have been reported by past and present Texas state agencies responsible for water resources and the New Mexico Bureau of Mines and Mineral Resources (Table 3.0.2). A summary of the hydrogeochemistry and water resources of the lower Dockum Group in west Texas and eastern New Mexico is reported in Dutton and Simpkins (1986). Dutton and Simpkins (1986) and Dutton (1995) present a source for the isotopically light δD and $\delta^{18}O$ composition of the groundwater found in the Dockum Group. That source is "probably… precipitation during the Pleistocene at elevations of 6,000 to greater than 7,000 ft … in Dockum Group sandstones, that were later eroded from the Pecos Plains and Pecos River valley" (Dutton and Simpkins, 1986). The most recent summary report on groundwater resources of the Dockum Group is provided by Bradley and Kalaswad (2003).

Several models of the High Plains Aquifer have been developed (Knowles and others, 1984; Luckey and others, 1986, 1988; Peckham and Ashworth, 1993; Dorman 1996; Harkins, 1998; Musharrafieh and Chudnoff, 1999; Musharrafieh and Logan, 1999). The grid extent of these models is shown in Figure 3.0.2. These models, which consisted of a single model layer representing the High Plains Aquifer, included the Dockum Group as part of the High Plains Aquifer where it is hydraulically connected to the overlying Ogallala Formation but did not include the remainder of the underlying Dockum Group. Several models of the Ogallala Aquifer have also been developed (Dutton and others, 2001; Blandford and others, 2003; Dutton, 2004). These models consisted of one layer representing the Ogallala Aquifer and did not include the Dockum Group.

Senger and others (1987) developed a two-dimensional, cross-section model of the Palo Duro Basin (see Figure 3.0.2). Their model extended from ground surface to the base of the basement aquiclude underlying the Deep-Basin Brine Aquifer and explicitly included the Dockum Group. The purpose of their modeling was to "characterize regional ground-water flow paths as well as to investigate causes of underpressuring below the Evaporite aquitard, to evaluate mechanisms of recharge and discharge to and from the Deep-Basin Brine Aquifer, and to examine transient effects of erosion and hydrocarbon production". Earlier modeling of the Palo Duro Basin by INTERA (1984) and Wironjanagud and others (1986) combined the Ogallala Formation and Dockum Group into a single model layer. Based on observed head differences between these two units, Senger and others (1987) separated the Ogallala Formation and Dockum Group into individual layers in an effort to reproduce the observed head differences. Although the Dockum Group was included, the major focus of the modeling presented in Senger and others (1987) was the Permian Evaporite aquitard, a potential host strata for a high-level nuclear waste disposal site during the 1980s, and the underlying Deep-Basin Brine Aquifer.

The Dockum Aquifer groundwater availability model presents the first three-dimensional numerical model focused on only the Dockum Group in Texas.

Table 3.0.1 Summary of Triassic Dockum Group nomenclature (modified from Bradley and Kalaswad, 2003).

<table>
<tr><th>Author</th><th>Cummins (1890)</th><th>Gould (1907)</th><th>Hoots (1926)</th><th>Darton (1928)</th><th>Adams (1929)</th><th>McGowen and others (1975; 1977; 1979)</th><th>Hart and others (1976)</th><th>Granata (1981)</th><th colspan="3">Lucas and Anderson (1992; 1993; 1994; 1995)</th><th colspan="2">Lehman (1994a; 1994b)</th></tr>
<tr><td>Region</td><td>Southern High Plains Texas & New Mexico</td><td>Northern Texas Panhandle</td><td>Southern Texas Panhandle</td><td>Eastern New Mexico</td><td>Southern Texas Panhandle</td><td>Southern High Plains Texas & New Mexico</td><td>Oklahoma Panhandle</td><td>Northeastern New Mexico</td><td colspan="3"></td><td colspan="2">Southern High Plains Texas & New Mexico</td></tr>
<tr><td rowspan="6">Dockum subunit distinctions vertically</td><td rowspan="6">Dockum Redbeds</td><td>(thin or absent)</td><td rowspan="3">Upper red clay</td><td rowspan="3">Chinle Formation</td><td rowspan="3">Chinle Formation</td><td rowspan="3">Upper Dockum[2]</td><td rowspan="3">Upper Dockum[2]</td><td>Redonda Formation</td><td rowspan="6">Chinle Group</td><td rowspan="6">Dockum Formation</td><td rowspan="2">Bull Canyon Member</td><td rowspan="3">Sequence 2</td><td>Redonda Formation[1]</td></tr>
<tr><td rowspan="2">Trujillo sandstone and shale</td><td rowspan="2">Chinle Formation</td><td>Cooper Canyon Formation</td></tr>
<tr><td>Trujillo Member</td><td>Trujillo Sandstone</td></tr>
<tr><td rowspan="3">Tecovas basal shale</td><td rowspan="2">Basal red clay and sandstone</td><td rowspan="2">Santa Rosa Sandstone</td><td rowspan="2">Santa Rosa Sandstone</td><td rowspan="3">Lower Dockum[2]</td><td rowspan="3">Lower Dockum[2]</td><td rowspan="3">Santa Rosa Sandstone</td><td>Tecovas Member</td><td rowspan="3">Sequence 1</td><td rowspan="2">Tecovas Formation</td></tr>
<tr><td>Colorado City Member</td></tr>
<tr><td>(generally absent)</td><td>(generally absent)</td><td>Basal shales</td><td>Camp Springs Member</td><td>Santa Rosa Sandstone</td></tr>
</table>

(1) in New Mexico only
(2) not intended as a formal stratigraphic name
Dockum is considered a group designation by all researchers except Lucas and Anderson.
Lateral stratigraphic correlation between units depicted on this table is not intended.
Bradley and Kalaswad (2003) refer to the more prolific parts of the Dockum Aquifer as simply the "Best Sandstone".

Table 3.0.2 Summary of county reports for the active model area.

County	Report Number	Citation
Texas Counties		
Borden	M016	Ellis (1949)
Briscoe	R167	Popkins (1973)
	R313	Nordstrom and Fallin (1989)
Carson	B5802	Gard (1958)
	B6102	Long (1961)
	B6402	McAdoo and others (1964)
Crockett	R047	Iglehart (1967)
Dallam	R315	Christian (1989)
Dickens	R158	Cronin (1972)
Ector	B5210	Knowles (1952)
Floyd	R165	Smith (1973)
Gaines	R015	Rettman and Leggat (1966)
Hall	R167	Popkins (1973)
Hale	B6010	Cronin and Wells (1960)
	R313	Nordstrom and Fallin (1989)
Kent	R158	Cronin (1972)
Lamb	B5704	Leggat (1957)
Loving	R317	Ashworth (1990)
Lynn	B5207	Leggat (1952)
Midland	R312	Ashworth and Christian (1989)
Mitchell	R050	Shamburger (1967)
Motley	R165	Smith (1973)
Nolan	R050	Shamburger (1967)
Pecos	B6106V1	Armstrong and McMillion (1961a)
	B6106V2	Armstrong and McMillion (1961b)
	R317	Ashworth (1990)
Reagan	R312	Ashworth and Christian (1989)
Reeves	M226	Knowles (1947)
	B6214V1	Ogilbee and Wesselman (1962)
	R317	Ashworth (1990)
Swisher	R313	Nordstrom and Fallin (1989)
Upton	R078	White (1968)
	R312	Ashworth and Christian (1989)
Ward	R125	White (1971)
	R317	Ashworth (1990)
Winkler	B5916	Garza and Wesselman (1959)
	R317	Ashworth (1990)
New Mexico Counties		
De Baca	Ground-Water Report 10	Mourant and Shomaker (1970)
Eddy	Ground-Water Report 3	Hendrickson and Jones (1952)
Lea	Ground-Water Report 6	Nicholson and Clebsch (1961)
Quay	Ground-Water Report 9	Berkstresser and Mourant (1966)
Union	Ground-Water Report 8	Cooper and Davis (1967)

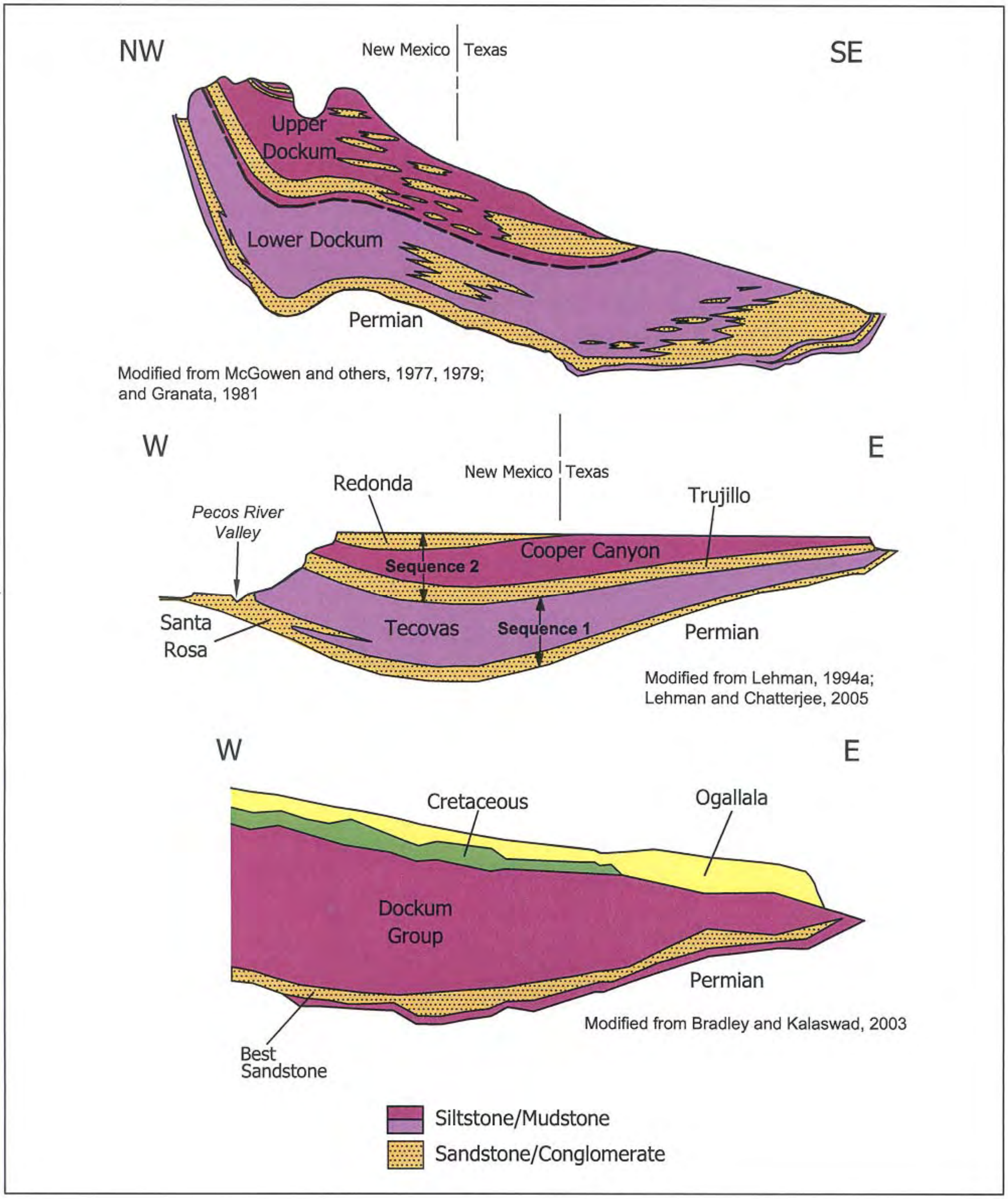

Figure 3.0.1 Schematic diagram of proposed stratigraphic sequences.

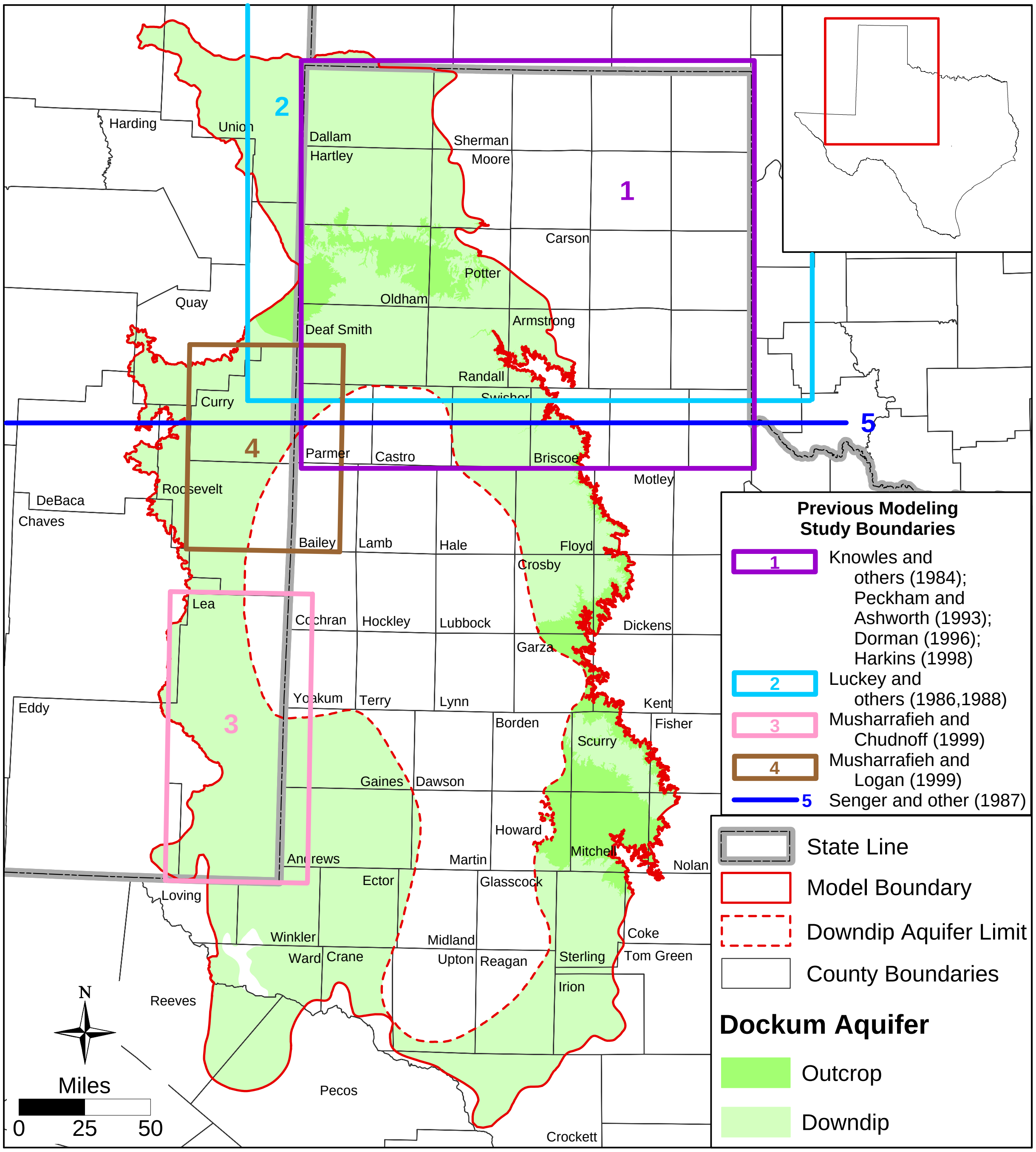

Figure 3.0.2 Location of boundaries for previous modeling studies that included portions of the Dockum Group.

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4.0 Hydrogeologic Setting

The hydrogeologic setting of the Dockum Aquifer is defined by the hydrostratigraphy, hydraulic properties, structure, regional groundwater flow, surface and groundwater interaction, and recharge and discharge. The characterization of the hydrogeologic setting is based on previous geologic and hydrologic studies in the area and compilation and analyses of structure maps, hydraulic properties, water-level data, spring and stream flow data, and climatic information.

4.1 Hydrostratigraphy

The Dockum Aquifer is a confined or partially confined aquifer located in the Panhandle of Texas and in a small area of west Texas and eastern New Mexico. The TWDB defines the Dockum Aquifer as the portion of the Dockum Group containing groundwater having a total dissolved solids concentration of less than 5,000 milligrams per liter (Ashworth and Hopkins, 1995). Although the entire Dockum Group is not considered to be the Dockum Aquifer, it was included in the Dockum Aquifer groundwater availability model. The TWDB and its predecessor agencies originally designated the aquifer with the Dockum Group as the Santa Rosa Aquifer based on common use. When it became apparent that wells were drawing water from sand beds other than the actual Santa Rosa Formation within the Dockum Group, the TWDB changed the aquifer nomenclature to the Dockum Aquifer to avoid any confusion as to the origin of the groundwater.

The Dockum Group consists of gravel, sandstone, siltstone, mudstone, shale, and conglomerates. Bradley and Kalaswad (2003) describe the lowermost Santa Rosa Formation as sandstone and conglomerate, the overlying Tecovas Formation as mudstone with interbedded sandstones, the Trujillo Formation as sandstone and sandy conglomerate with shale interbeds, and the uppermost Cooper Canyon Formation as siltstone and mudstone with sandstone lenses, and conglomerate (see Table 2.2.2). Individual sandstones within the Dockum Group range in thickness from a few feet to about 50 feet, are often lens-shaped and, thus, discontinuous and difficult to correlate in the subsurface. The sand units are separated by sandy shale units that range in thickness from about 50 to 100 feet.

Groundwater located in the sandstone and conglomerate units within the Dockum Group sedimentary sequence is recoverable with the highest yields coming from the coarsest-grained deposits located at the middle and base of the group. Typically, the water-bearing sandstones in the Dockum Group are locally referred to as the Santa Rosa Aquifer. The fine-grained deposits form less permeable areas within the Dockum Group.

Johns (1989) distinguished four cyclic sequences in the lower portion of the Dockum Group each characterized by a mudstone base and coarsening upward sequence with more abundant sands, whereby the mudstone thickness increases toward the center of the Dockum Basin. The upper portion of the Dockum Group indicates fewer, more isolated sands embedded in predominately mudstone. This overall pattern leads to two distinct hydrostratigraphic units, which will be modeled as two separate layers within the Dockum Group. These two layers will correspond to the lower "sand-rich" portion of the Dockum Group and the upper "mud-rich" portion of the Dockum Group as reported in McGowen and others (1977; 1979) (Table 4.1.1). In general, sandstones in the lower portion of the Dockum Group are more continuous and yield more water than those in the upper portion of the Dockum Group, and the overall percentage of sandstone is higher in the lower portion of the Dockum Group than in the upper portion of the Dockum Group.

The Dockum Group is everywhere underlain by Permian-age formations generally consisting of siltstone, mudstone, and evaporate beds. The solution of thick sections of evaporate has resulted in structurally collapsed features within overlying formations in localized areas. Although some of the Permian-age formation may contain groundwater of generally poor quality, they were not included in the Dockum Aquifer groundwater availability model.

The Dockum Group is overlain by five aquifers (Figure 4.1.1). These are the Rita Blanca Aquifer in the northwest, the Edward-Trinity (High Plains) Aquifer in the central area, the Edwards-Trinity (Plateau) Aquifer in the southeast and south-central area, the Pecos Valley Aquifer in the southwest, and the Ogallala Aquifer in the remaining areas. The Dockum Aquifer is hydraulically connected to the Pecos Valley Aquifer due to direct contact between the basal sands of the Dockum Group and alluvial sediments of the Pecos Valley Aquifer. The Dockum Aquifer is also hydraulically connected to the Ogallala Aquifer in some areas of the northeastern and eastern portions of the model area. In the remaining areas, which make up the majority of the model area, little hydraulic connection between the Dockum Aquifer and overlying aquifers is observed. A more detailed discussion of the relationship between the Dockum Aquifer and overlying aquifers is provided in Section 4.3.5. The overlying aquifers were included as the uppermost layer (layer 1) in the model (see Section 6.2).

Table 4.1.1 Dockum Group stratigraphy and model layers.

McGowen and others (1977; 1979)		Lehman (1994a; 1994b)		Model Layer
Dockum Group	Upper	Dockum Group	Cooper Canyon Formation	2
			Trujillo Sandstone	
	Lower		Tecovas Formation	3
			Santa Rosa Formation	