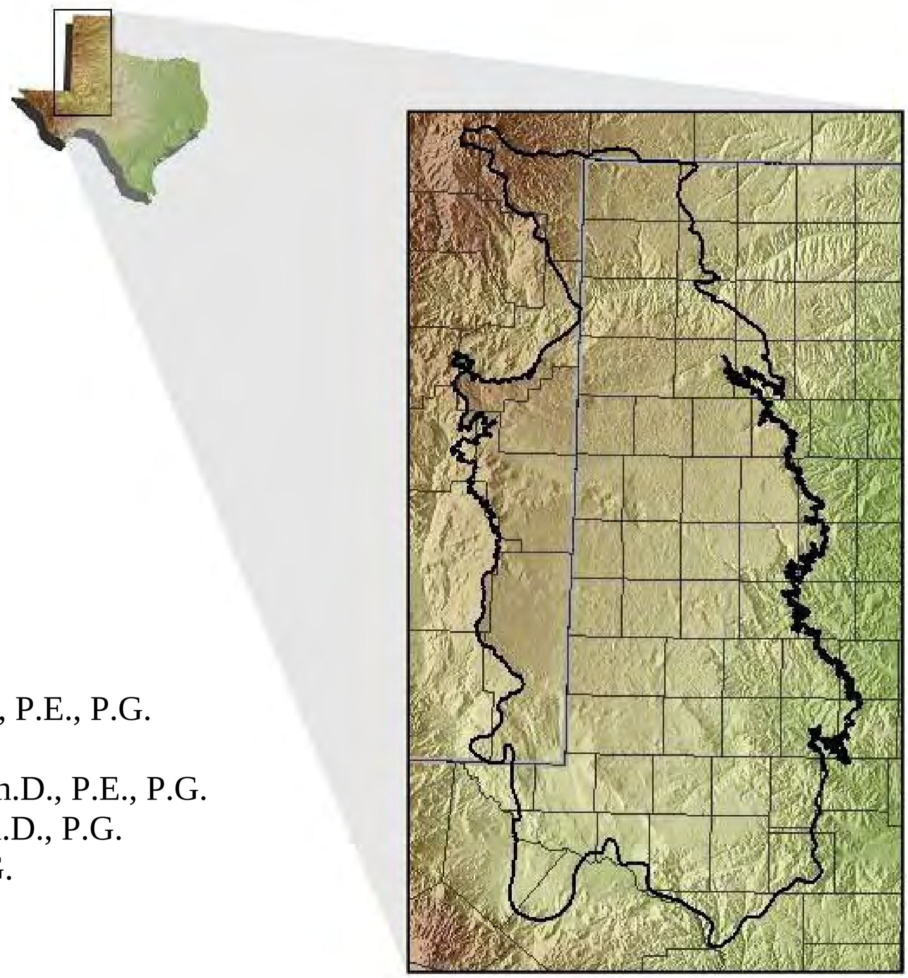
Final Report
Groundwater Availability Model for the Dockum Aquifer



Report ___

by
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October 2008

Texas Water Development Board

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Geoscientist and Engineering Seal

This report documents the work of the following Licensed Texas Geoscientists and Licensed Texas Professional Engineer:

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Dr. Pickens was the Project Manager for this work and was responsible for oversight on the project.

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Dr. Nicot was responsible for the evaluation of recharge to the Dockum Aquifer for the conceptual model.

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Bridget R. Scanlon, Ph.D., P.G.

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John B. Ashworth, P.G.

Mr. Ashworth was responsible for development of the geology and water quality for the Dockum Aquifer.

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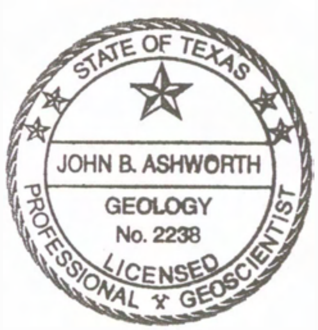
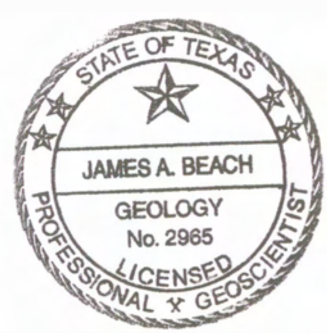


James Beach, P.G.

Mr. Beach was responsible for development of the Dockum Aquifer structure.

Signature — Date: 10/31/08



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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).

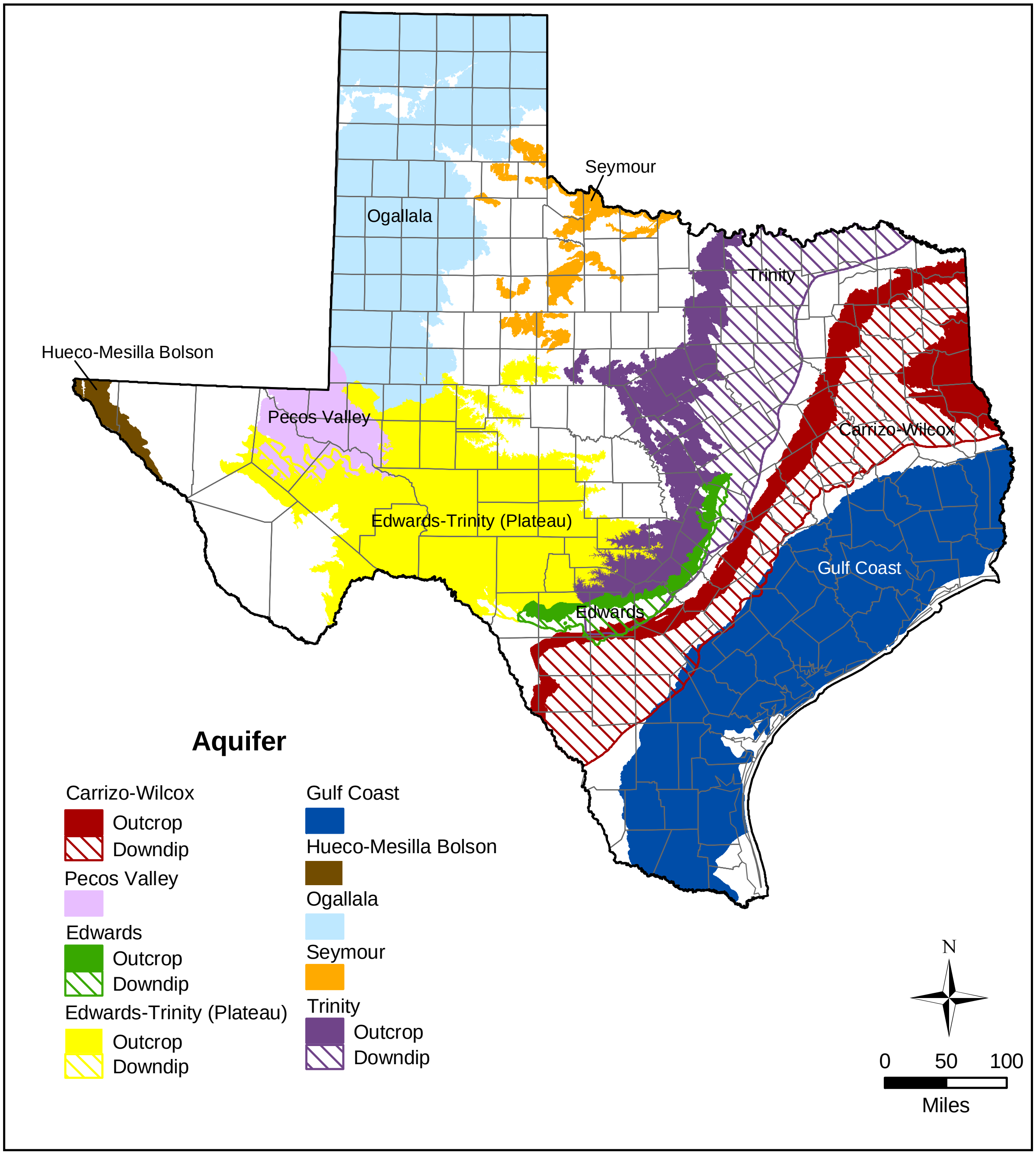
The modeling approach adopted for the Dockum Aquifer groundwater availability model was to represent the Dockum Aquifer with two layers. McGowen and others (1977) informally subdivided the Dockum Group into a lower sand-rich unit and an upper mud-rich unit. Production from the Dockum Aquifer is primarily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

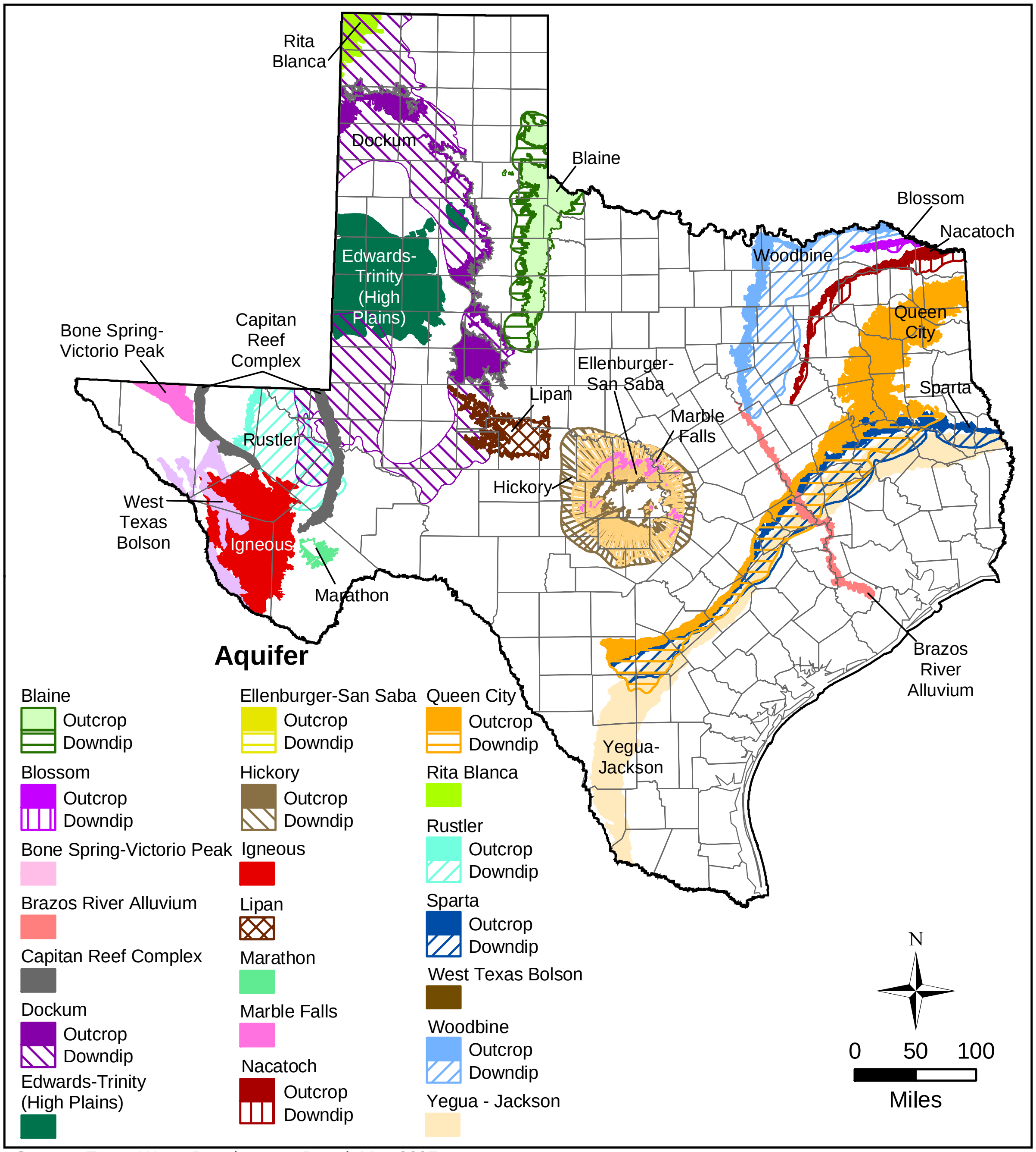
The Dockum Aquifer groundwater availability model was developed using a modeling protocol that is standard to the groundwater modeling industry. This protocol includes: (1) the development of a conceptual model for groundwater flow in the aquifer, including defining physical limits and properties, (2) 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

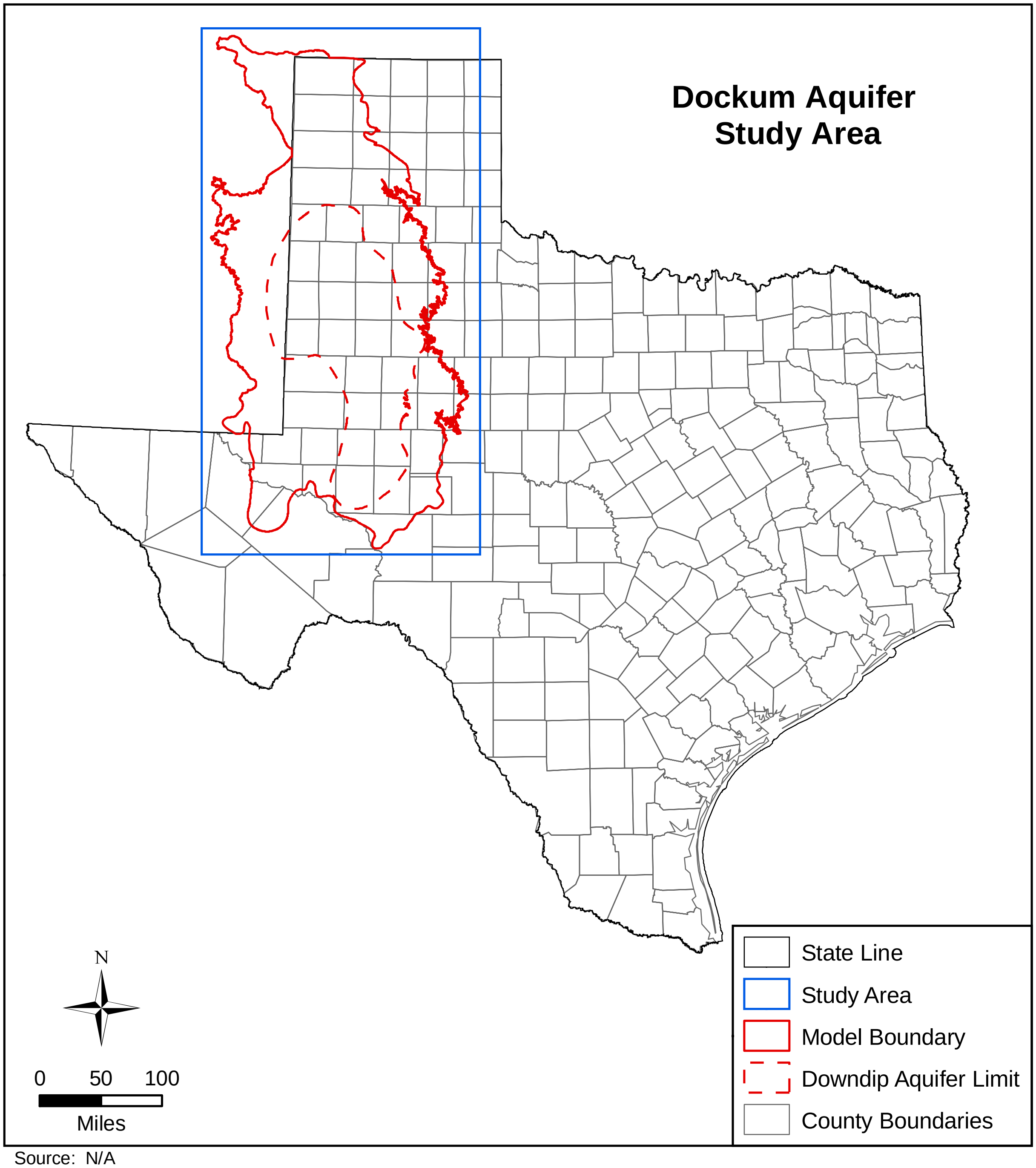
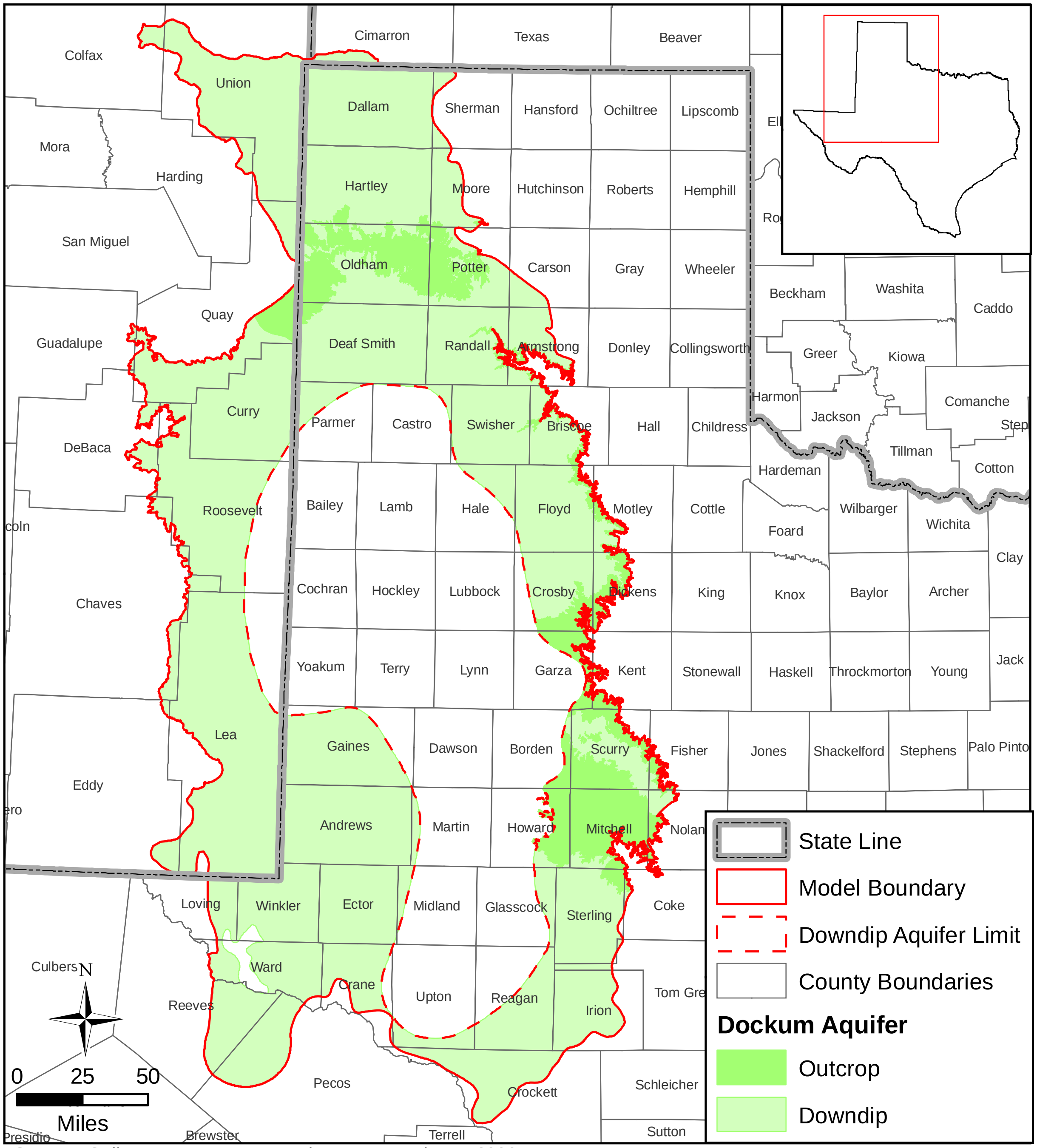
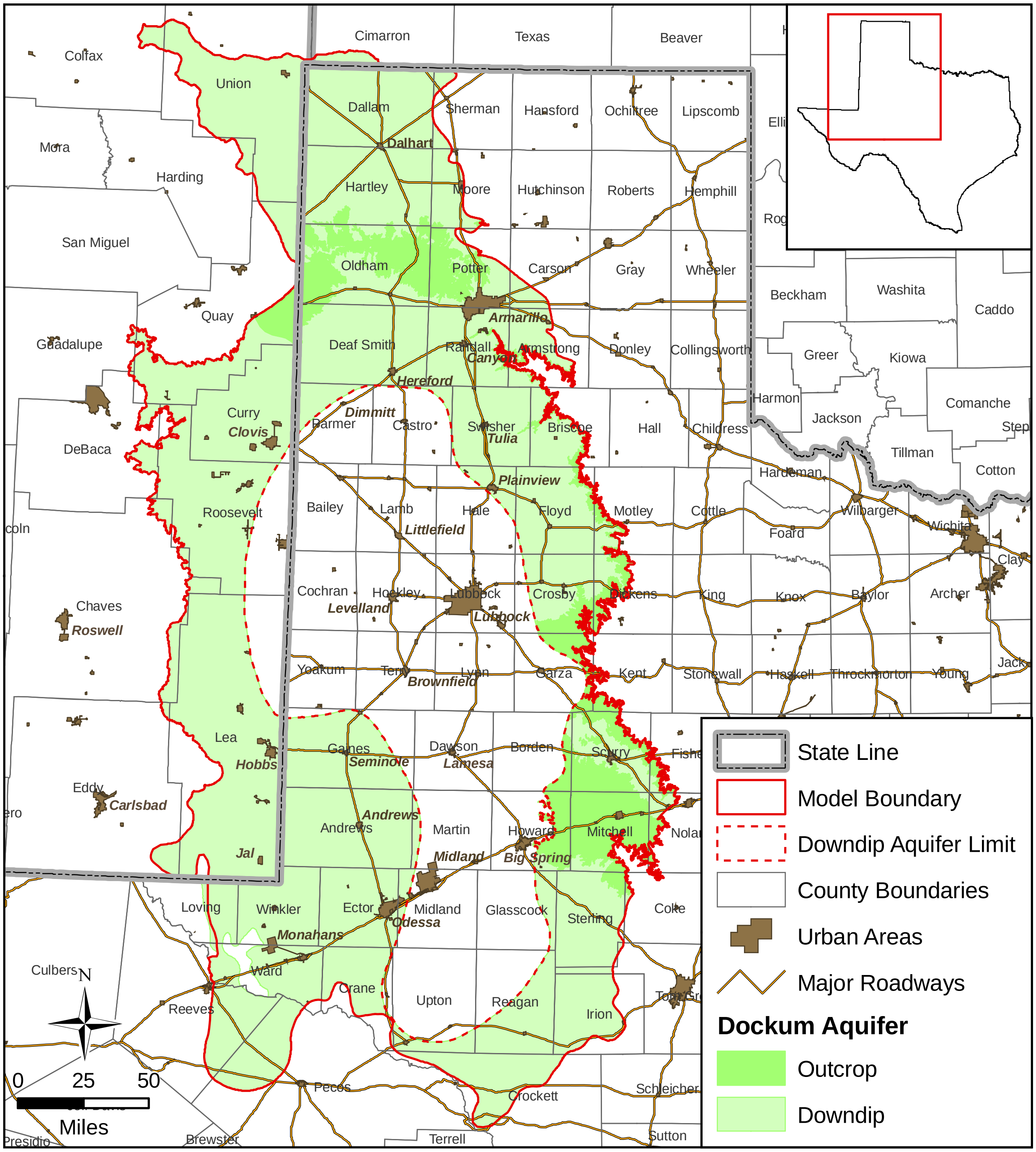


Figure 2.0.1 Location of study area and Dockum Aquifer groundwater availability model.



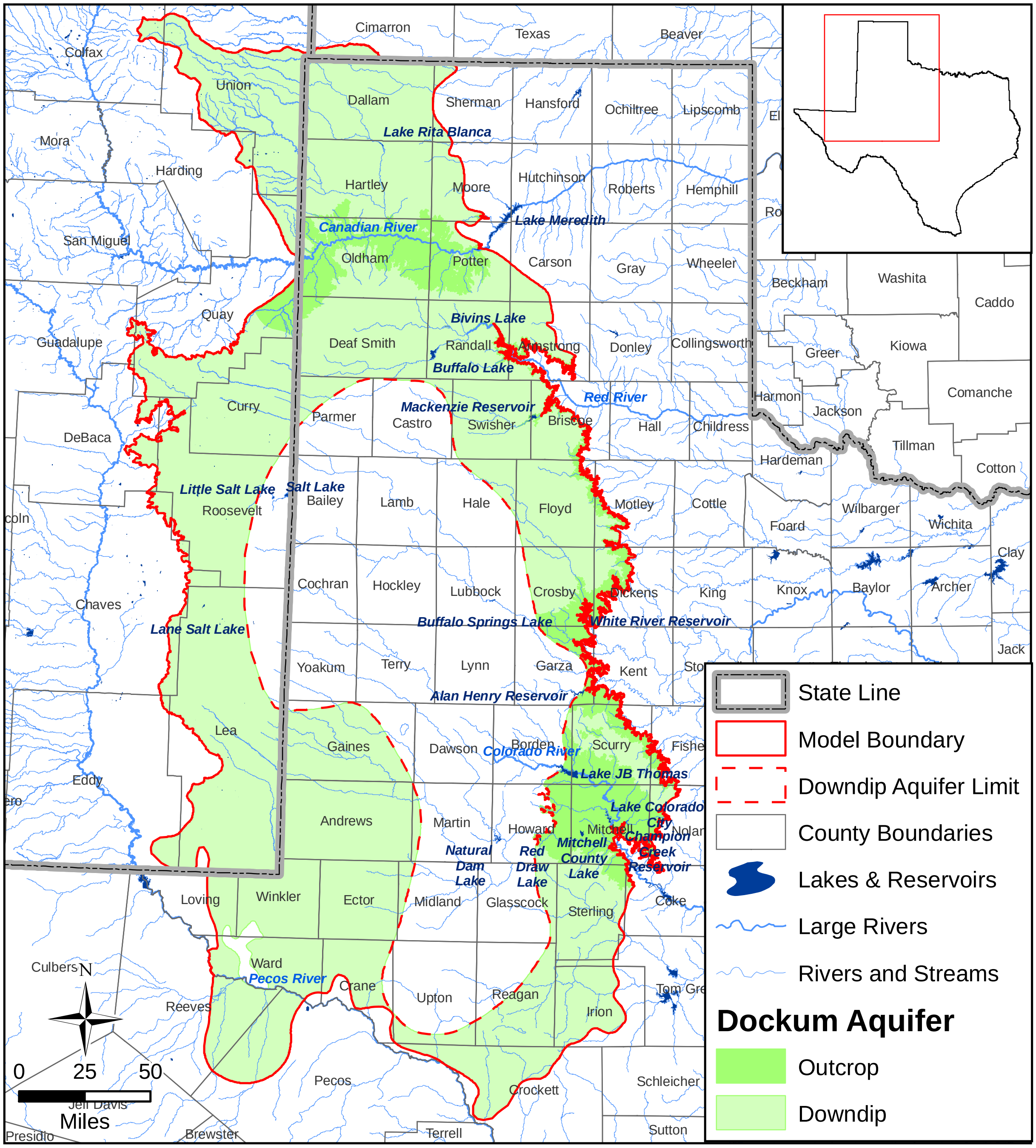
Source: Online: Texas Water Development Board, Aug 2006

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



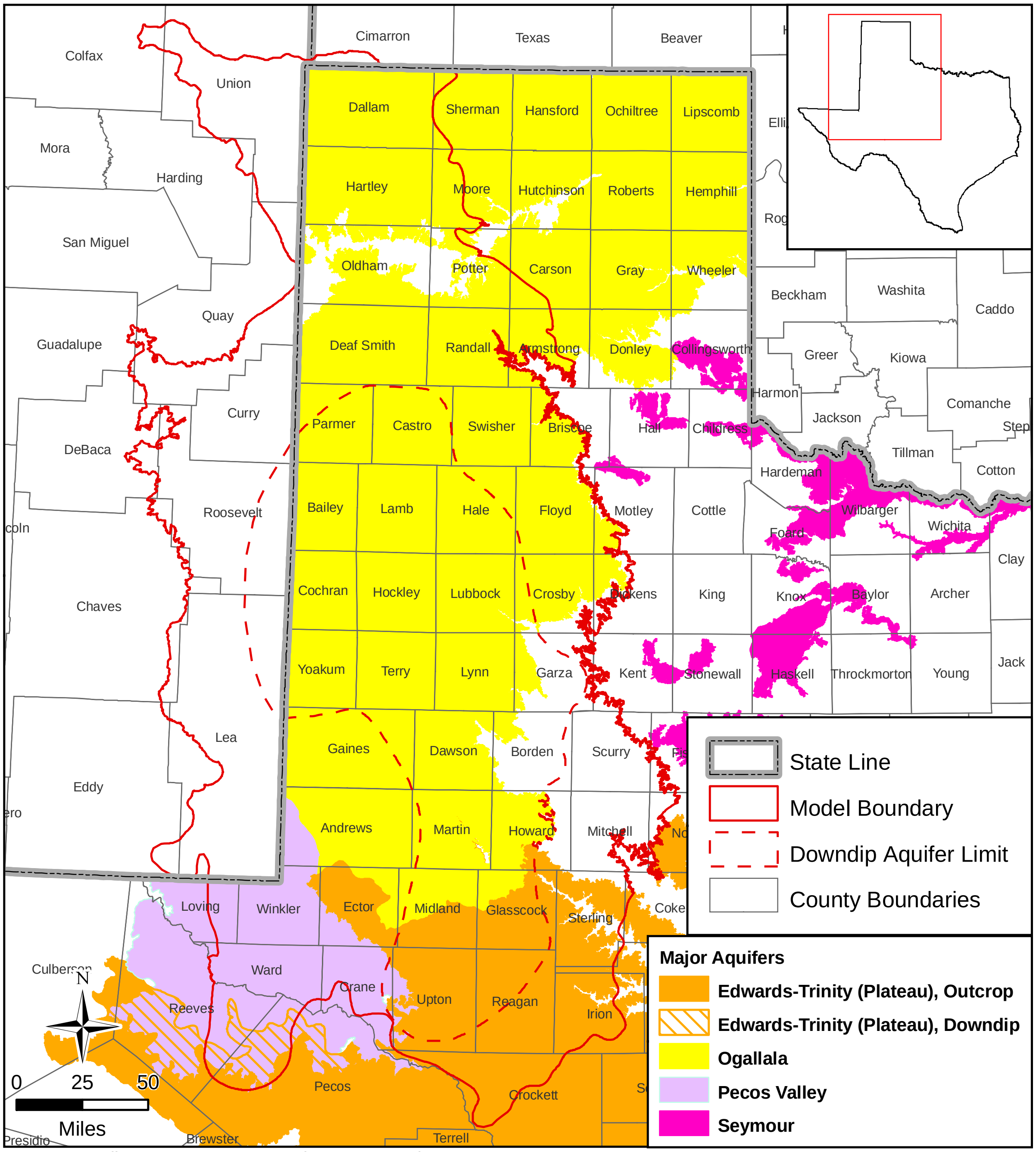
Source: Online: Texas Water Development Board, June 2006; New Mexico Resource GIS Program, June 2006

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



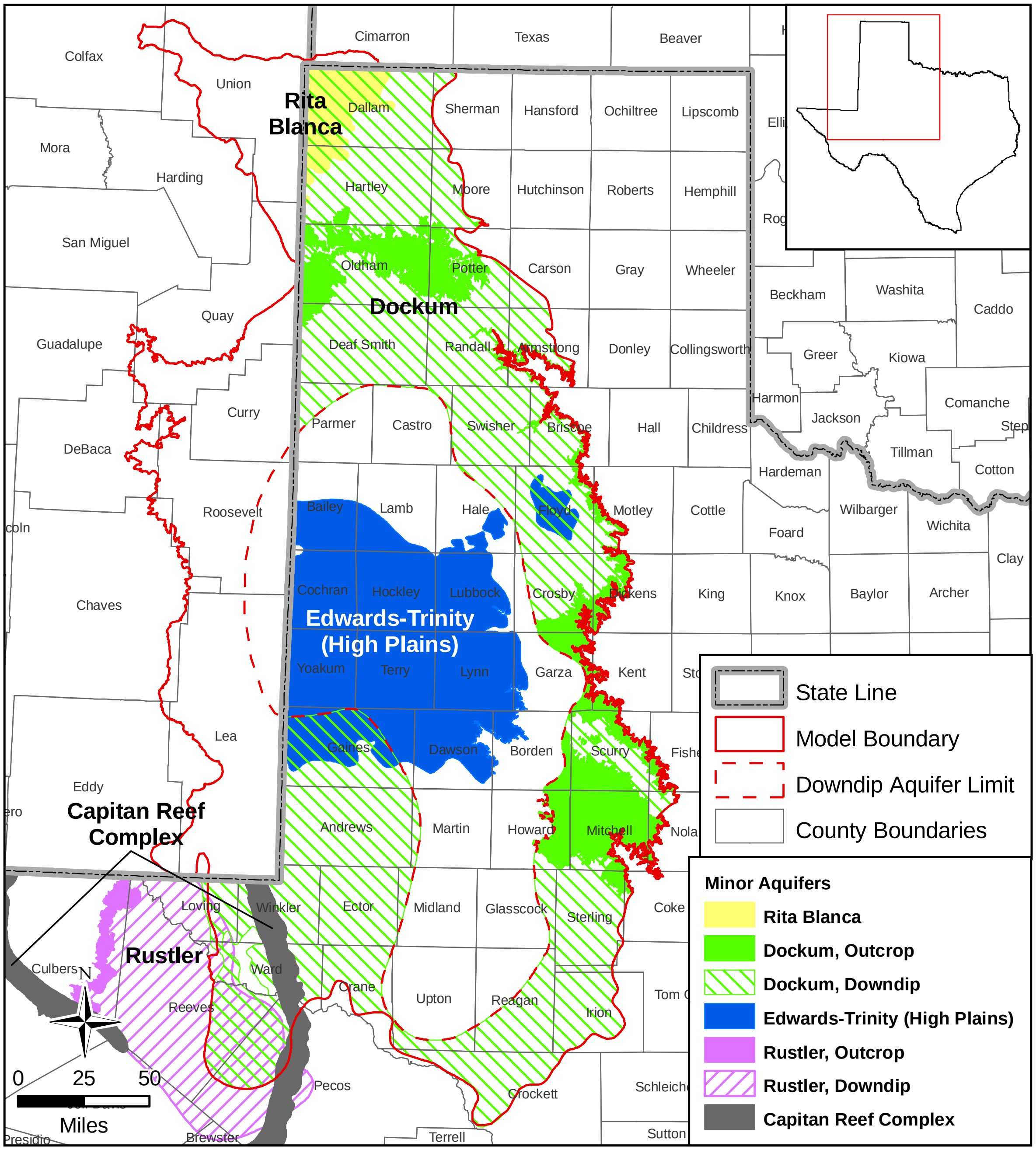
Source: Online: Texas Water Development Board, June 2006; USGS seamless, June 2006

Figure 2.0.4 Location of study area showing lakes and rivers.



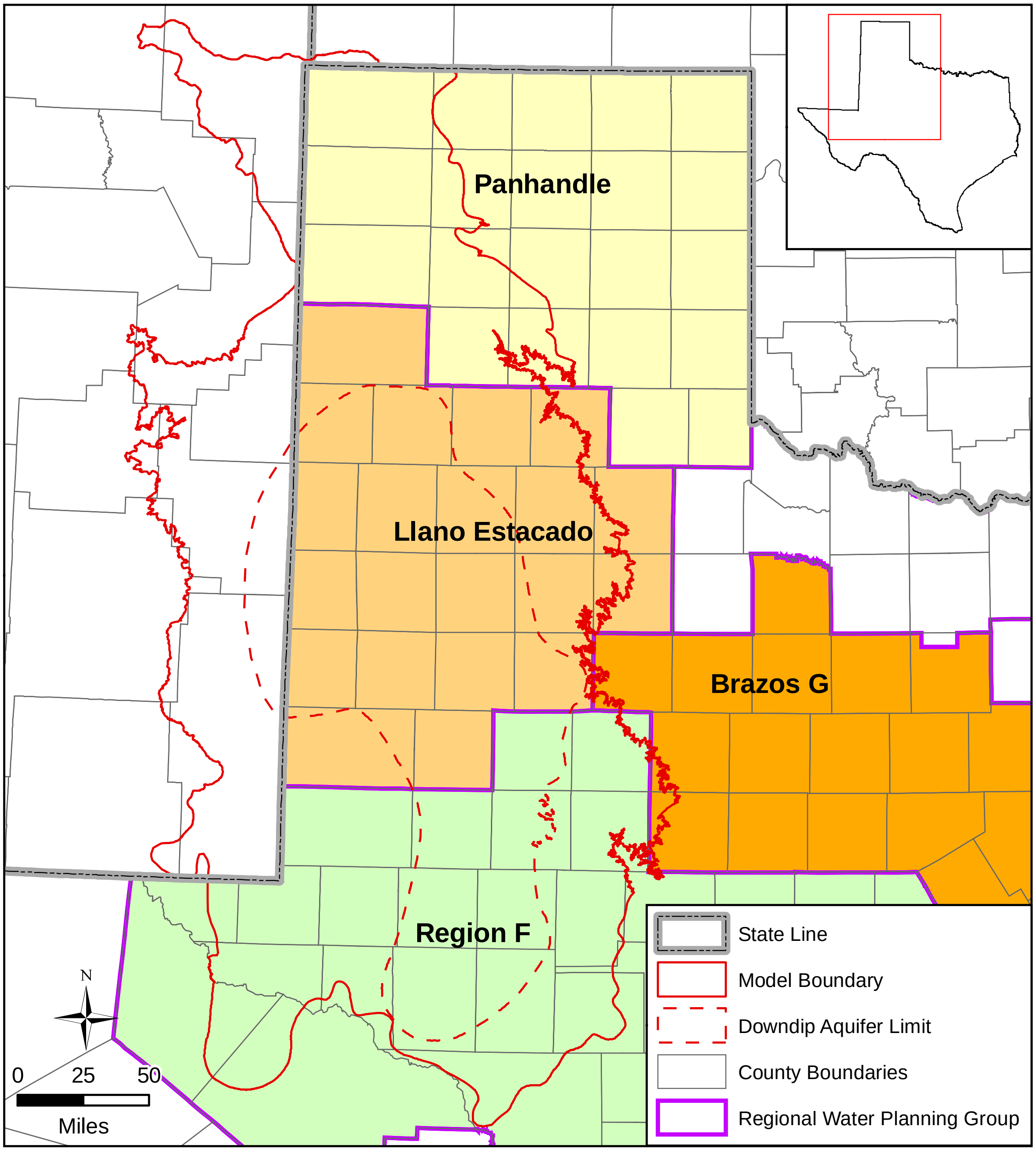
Source: Online: Texas Water Development Board, May 2007

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



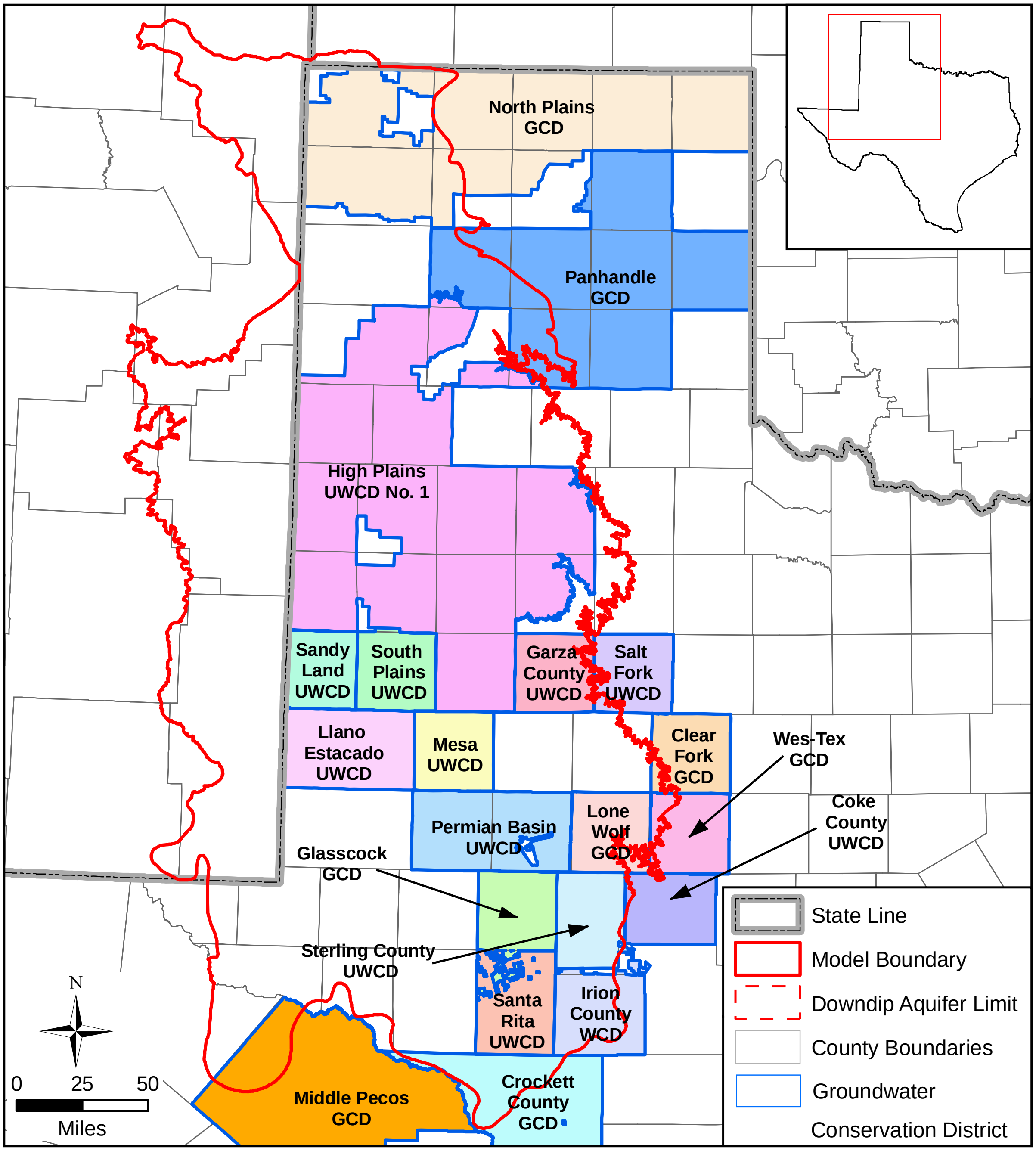
Source: Online: Texas Water Development Board, May 2007

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



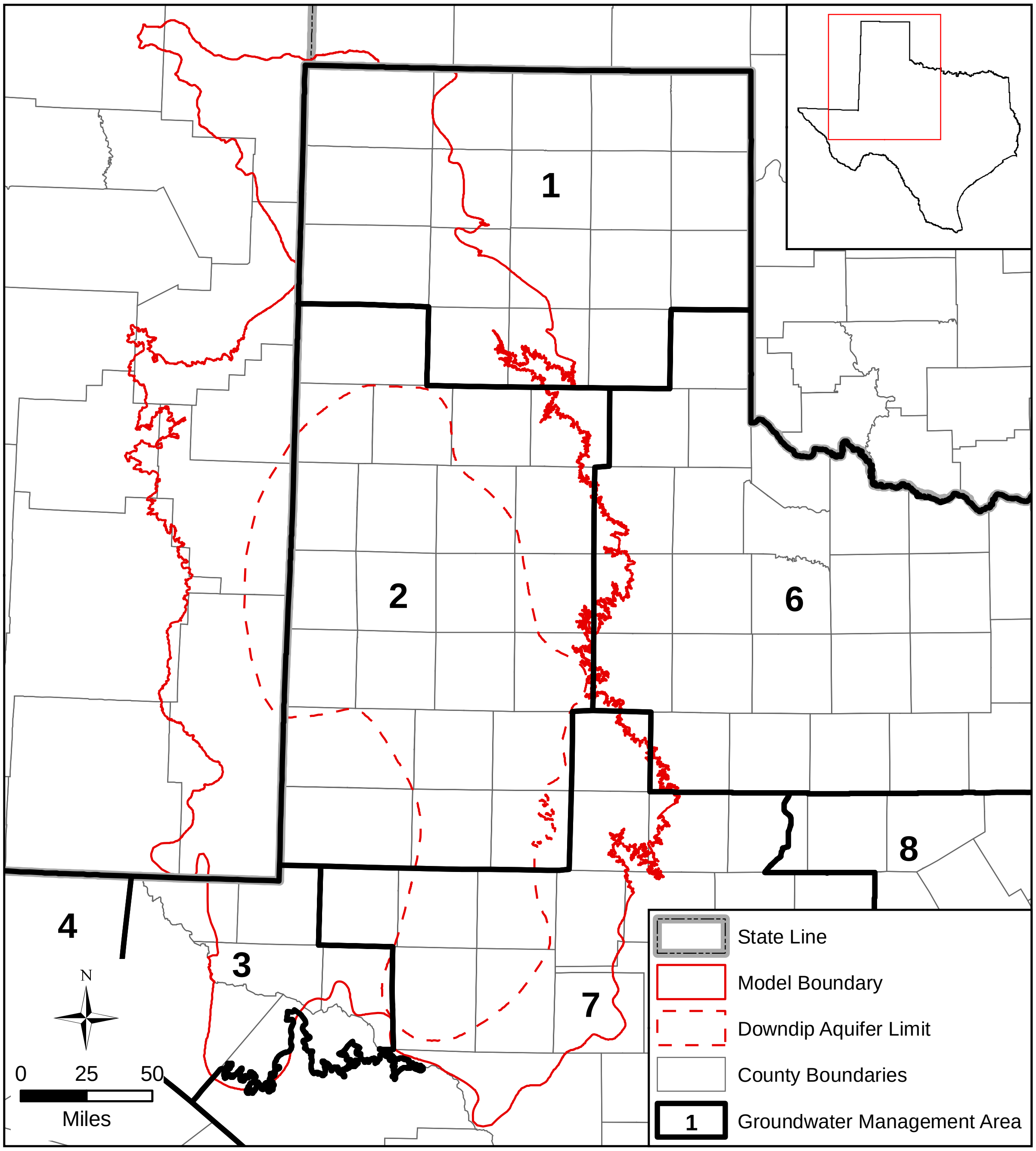
Source: Online: Texas Water Development Board, June 2006

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



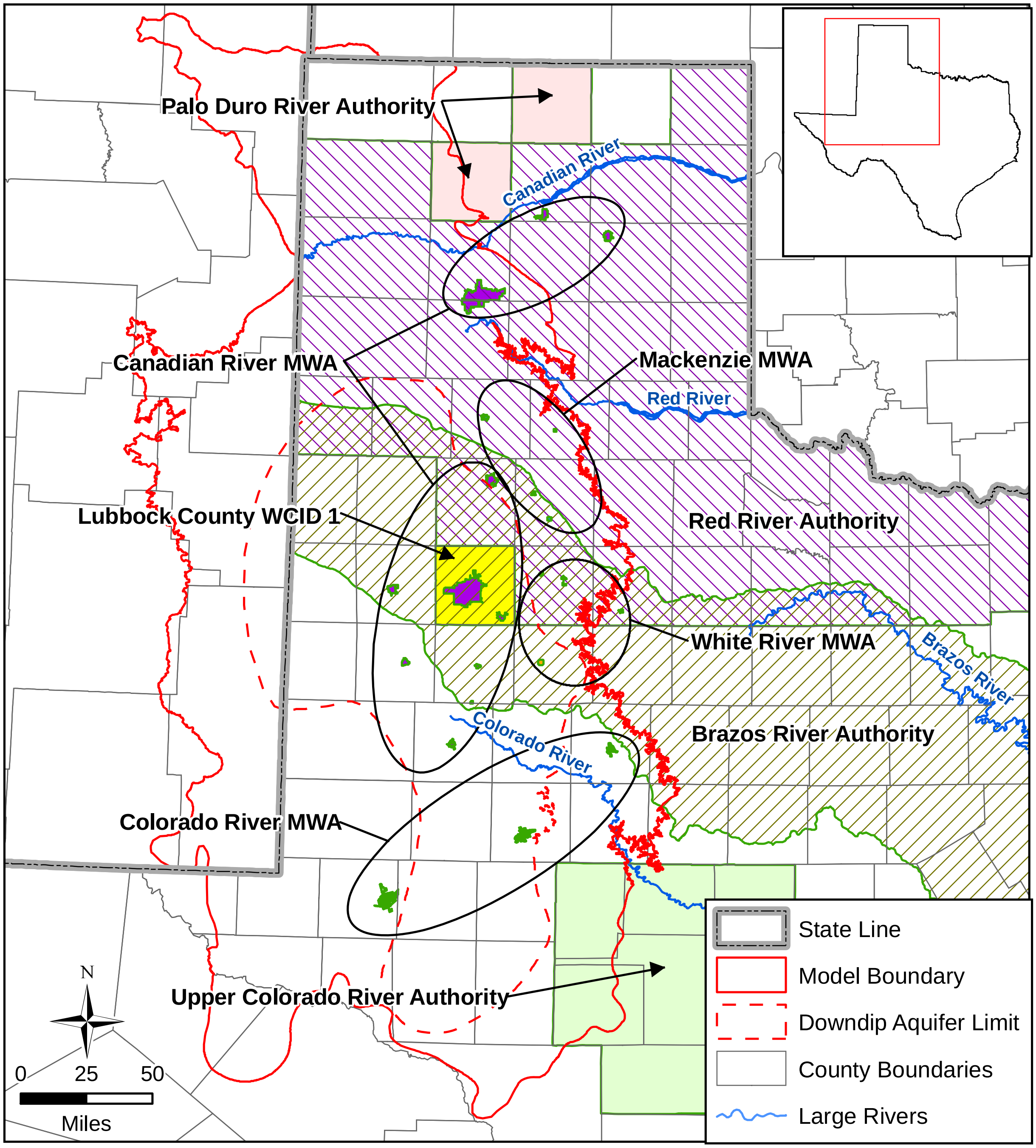
Source: Online: Texas Water Development Board, August 2008.

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



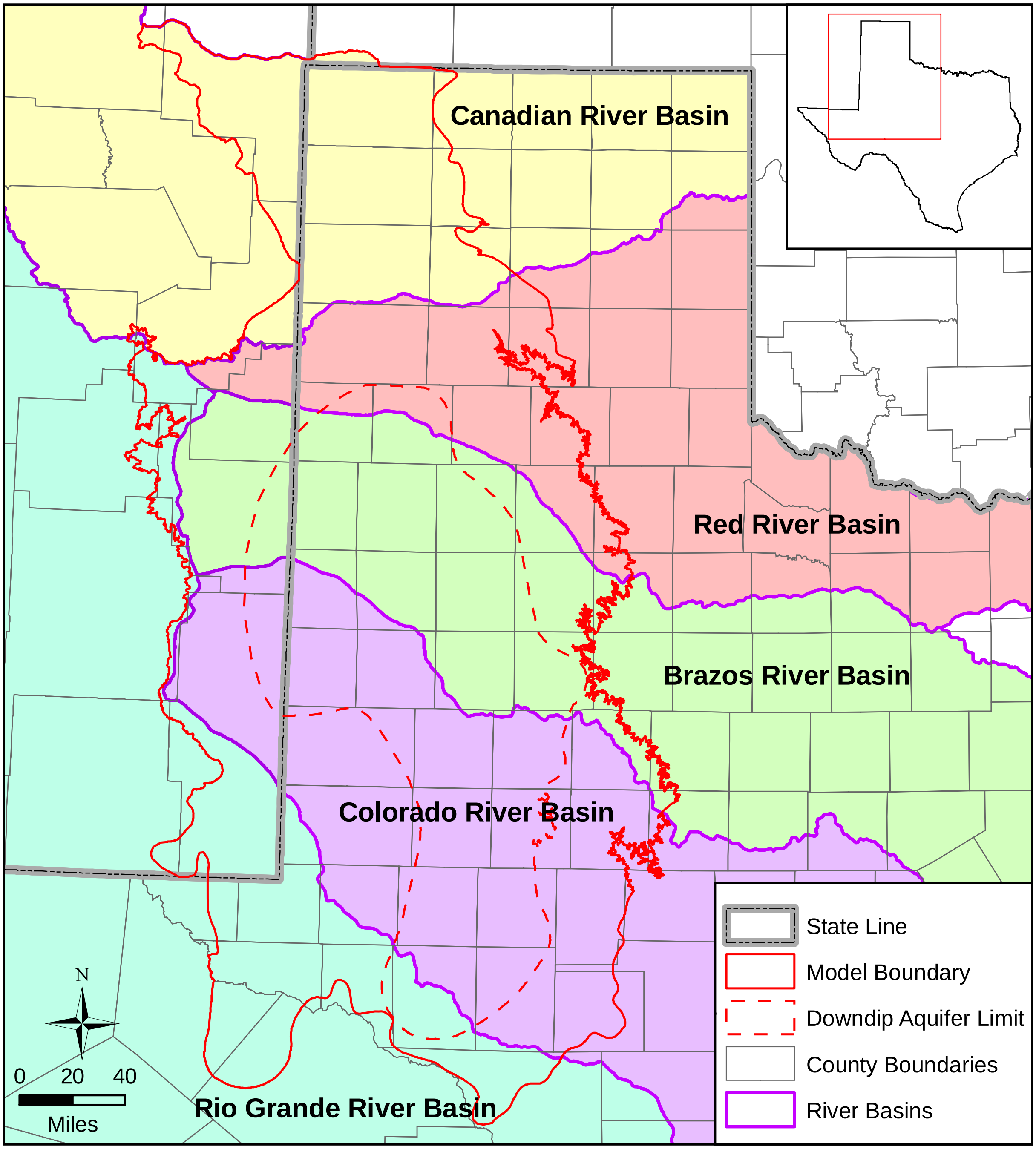
Source: Online: Texas Water Development Board, March 2007

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.

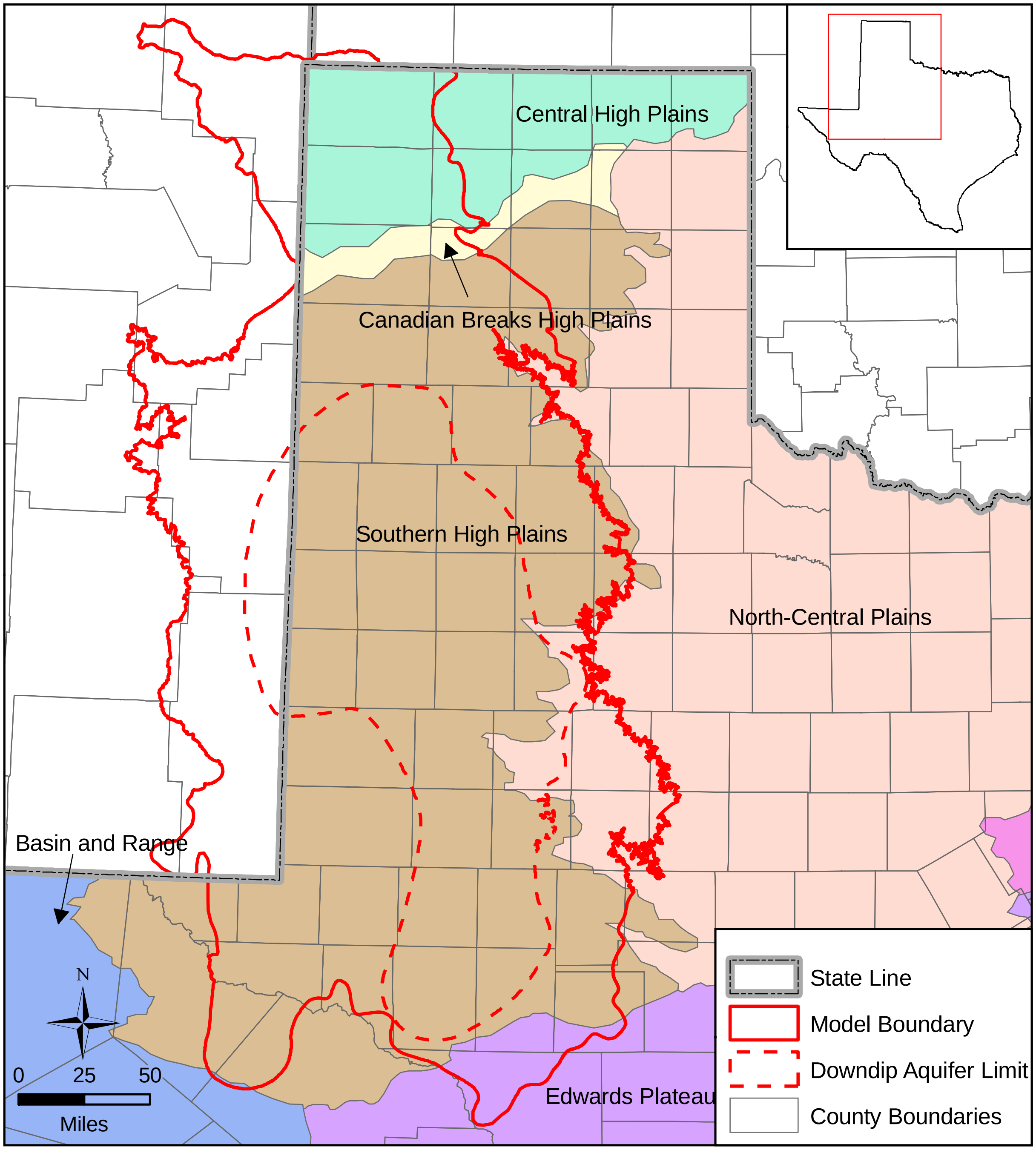
The climate in the active model area is classified predominantly as Continental Steppe (Larkin and Bomar, 1983) (Figure 2.1.4). This type of climate is typical of continent interiors. It is a semi-arid climate characterized by large variations in daily temperatures, low relative humidity, and irregularly 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.

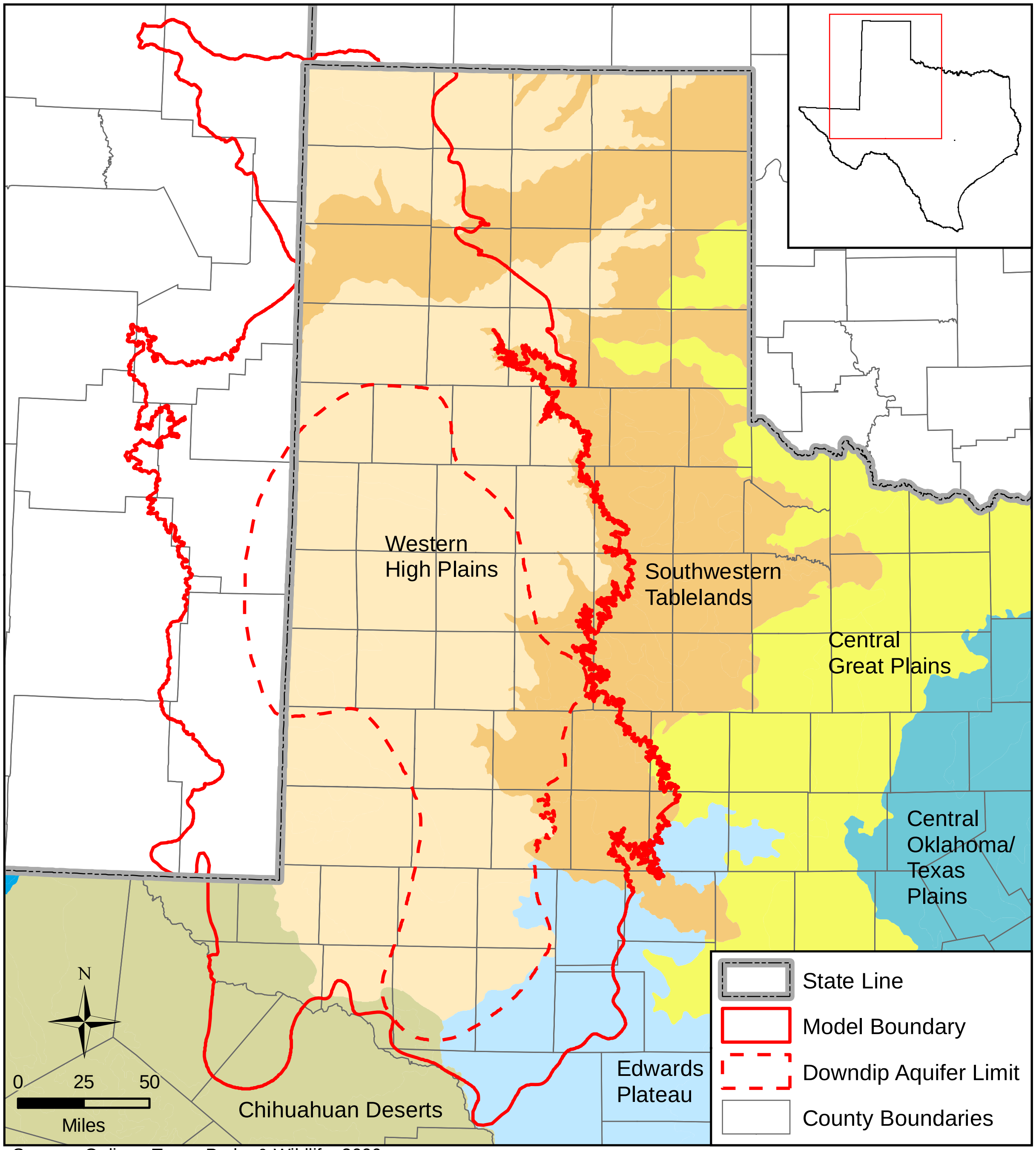
The Parameter-Elevation Regressions on Independent Slopes Model (PRISM) precipitation dataset developed and presented online by the Oregon Climate Service at Oregon State University (Oregon State University, 2002) provides a good distribution of average annual precipitation across the model area based 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).



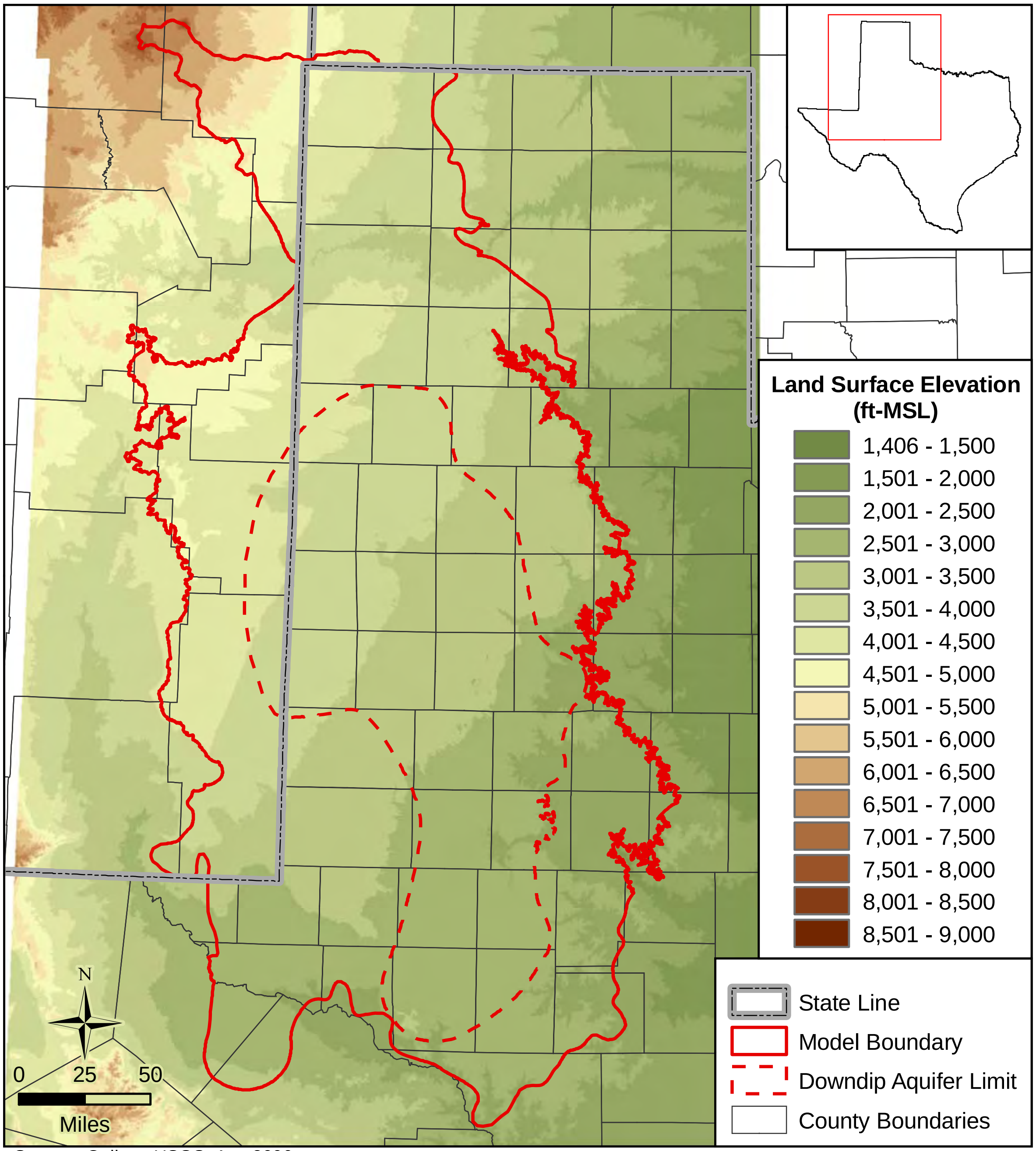
Source: Online: BEG, June 1996

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



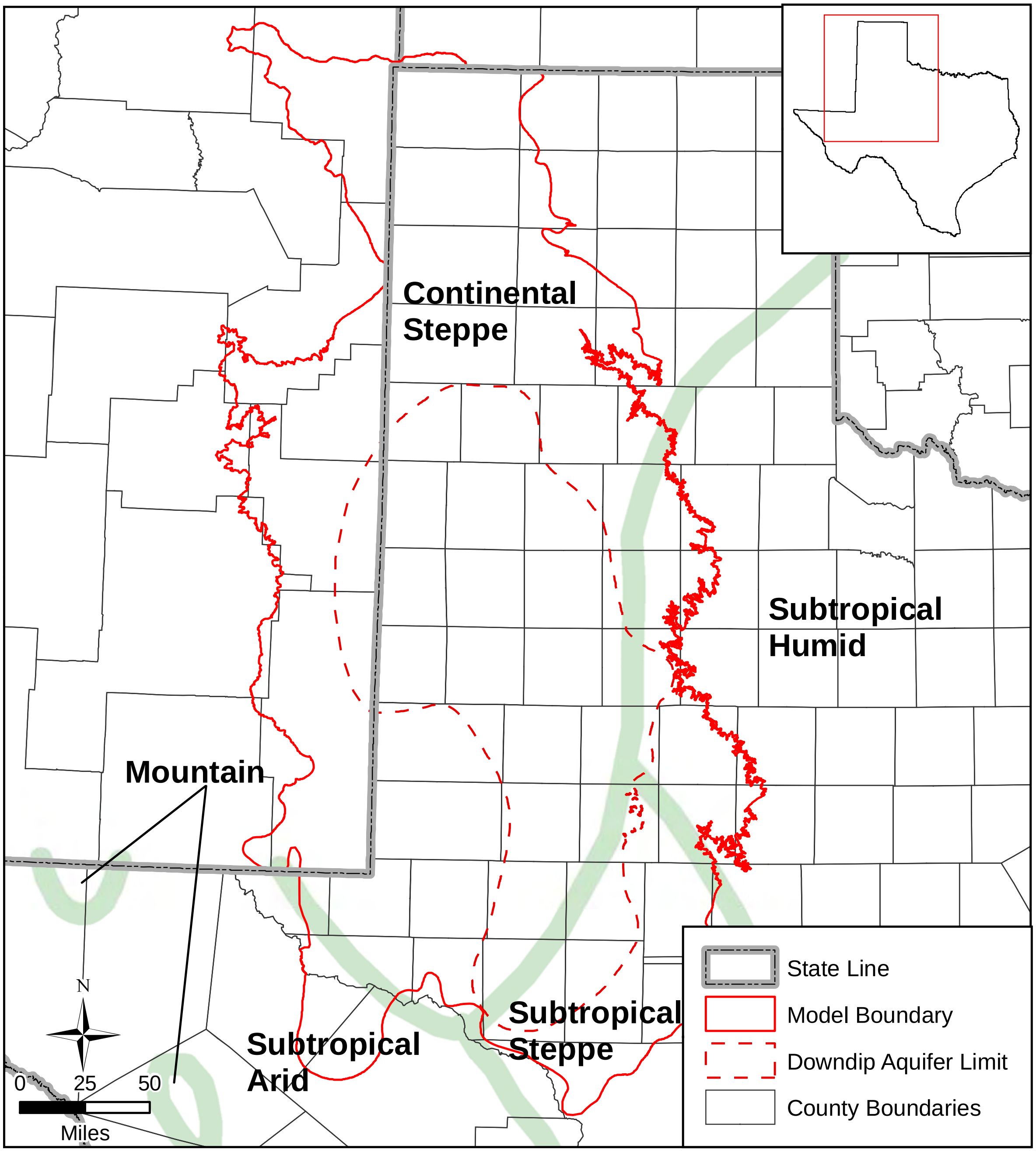
Source: Online: Texas Parks & Wildlife, 2006

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



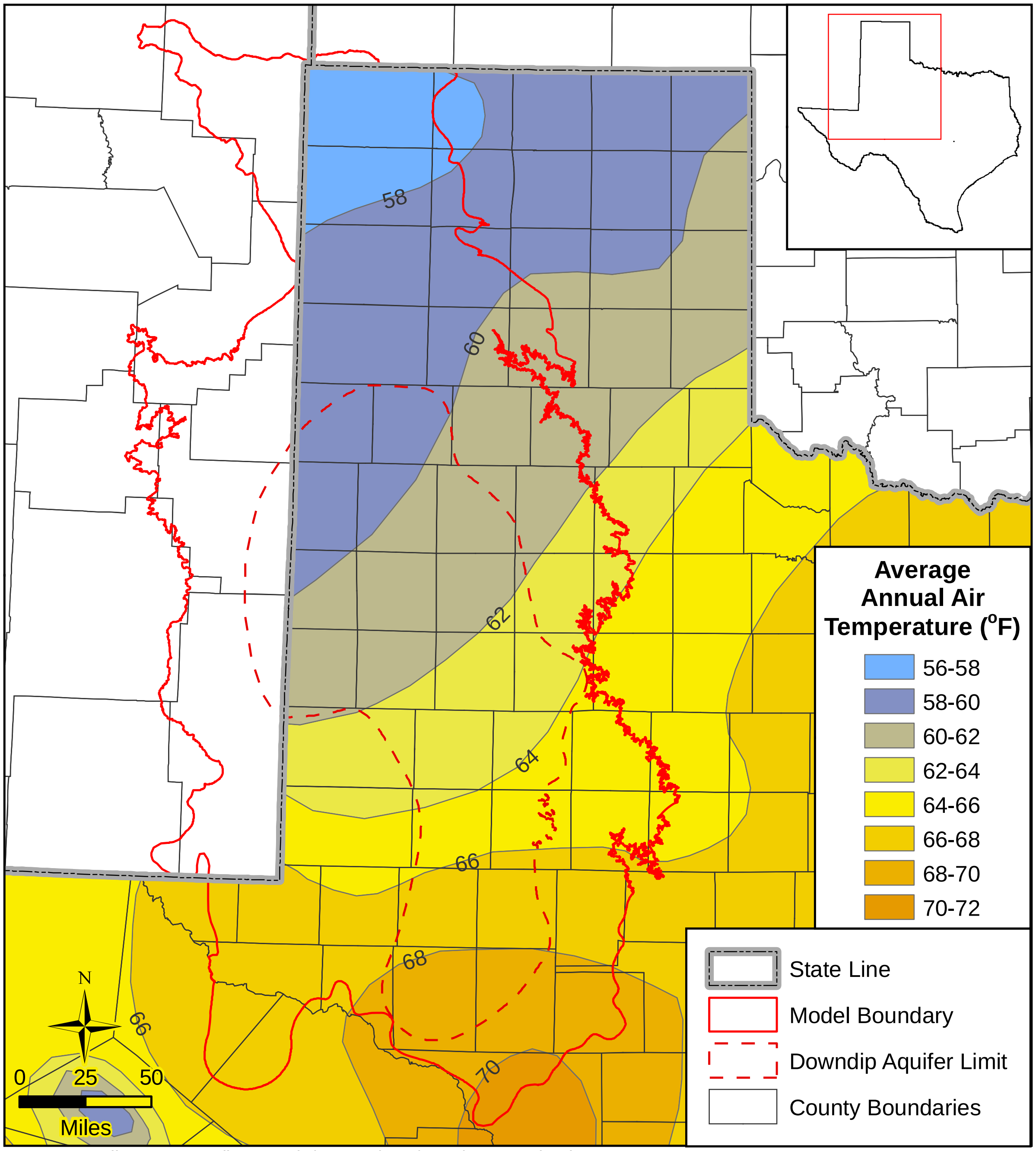
Source: Online: USGS, Aug 2006

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.

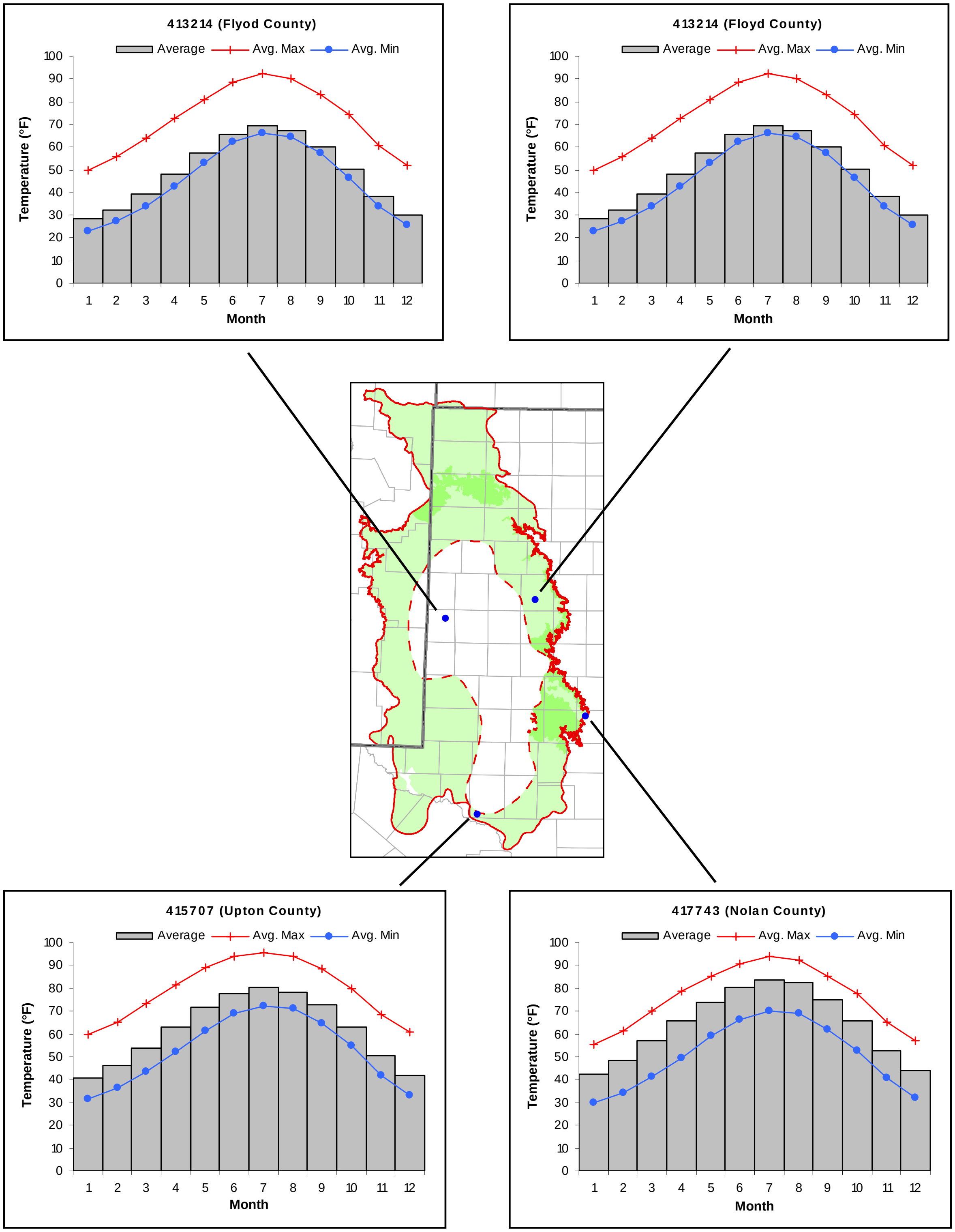
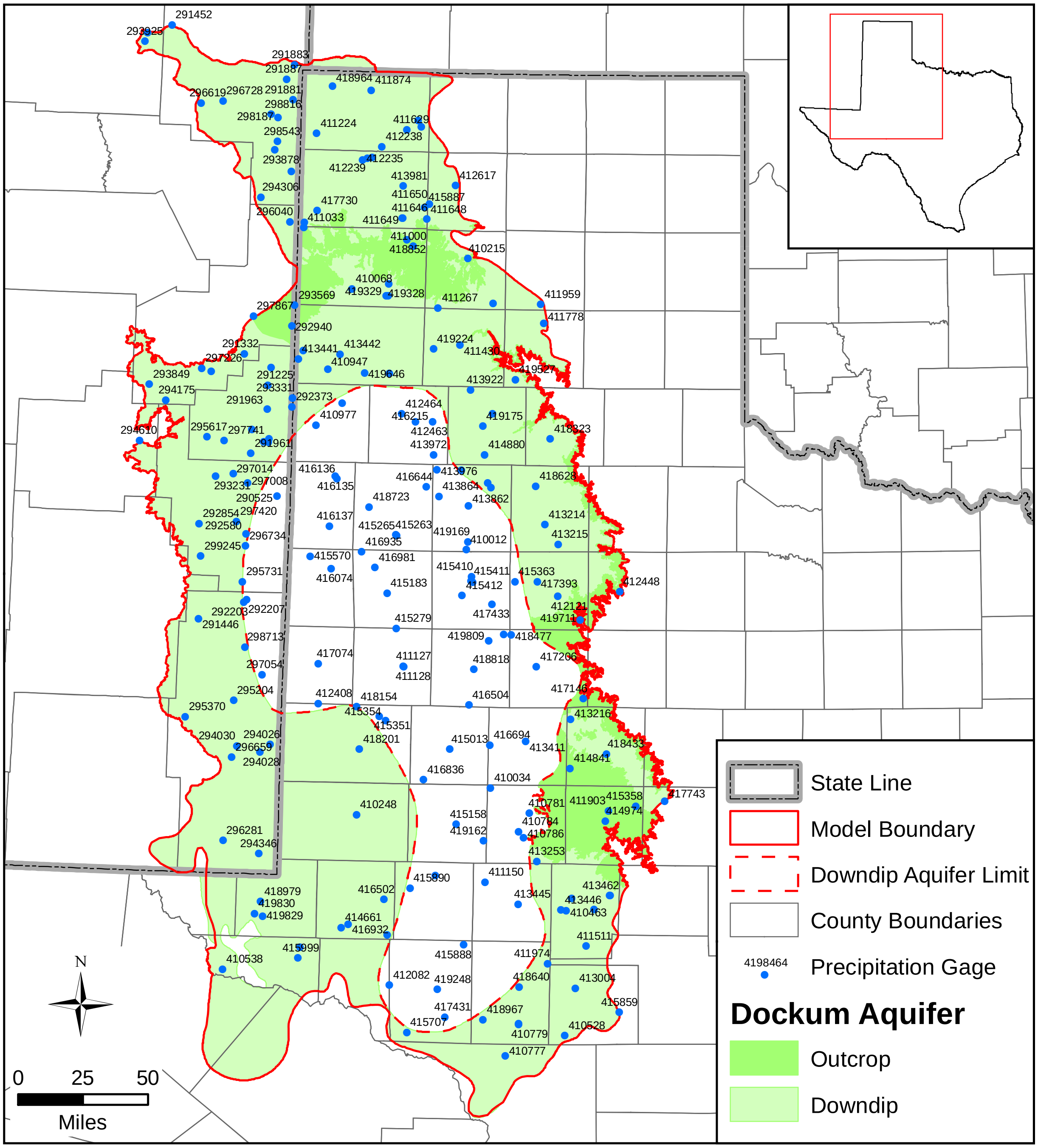


Figure 2.1.6 **Average, maximum, and minimum monthly temperatures in degrees Fahrenheit at selected locations in the study area calculated from daily temperatures reported by the National Climatic Data Center.**



Source: National Climatic Data Center, March 2003

Figure 2.1.7 Location of precipitation gages in the study area.

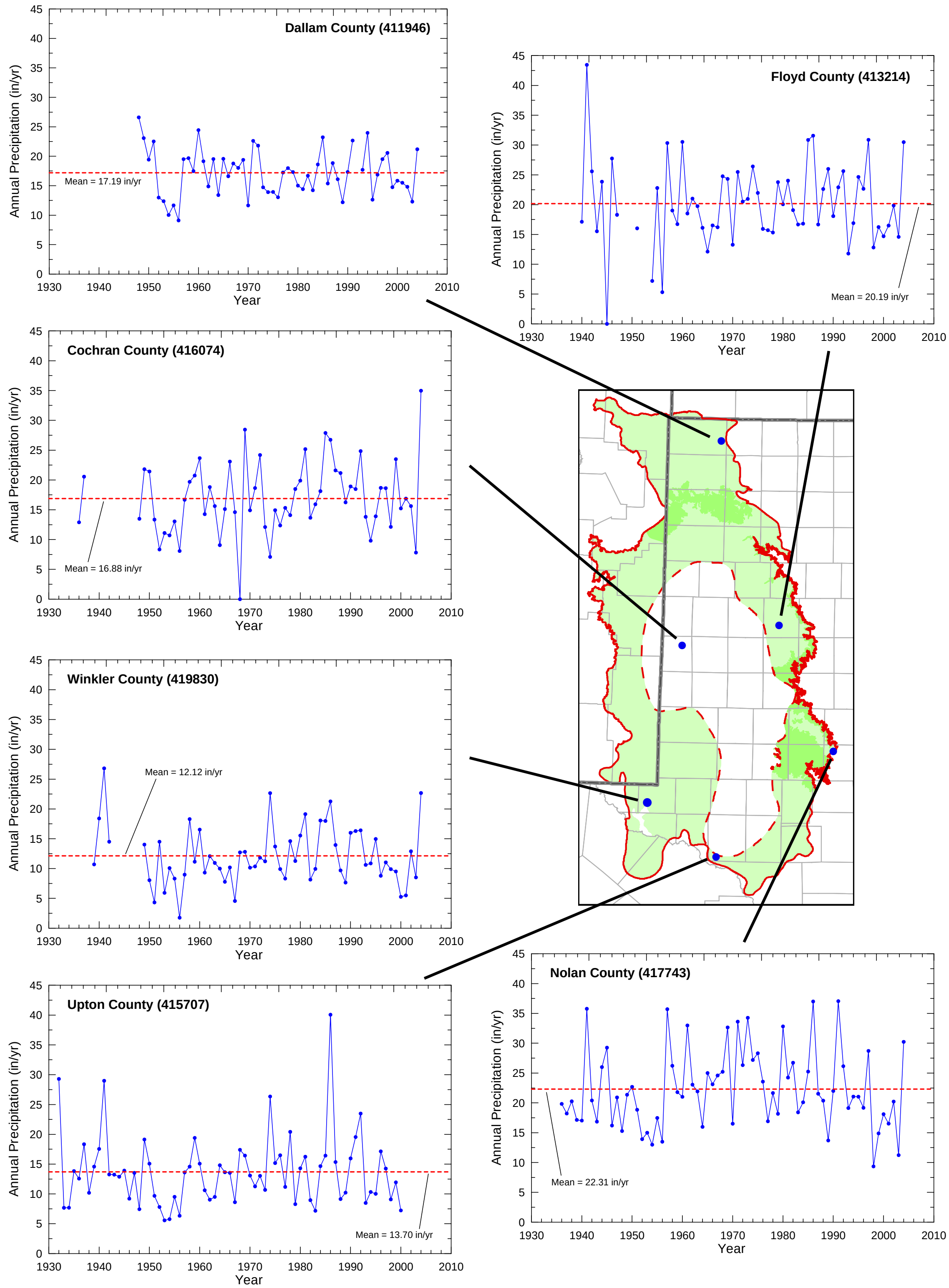
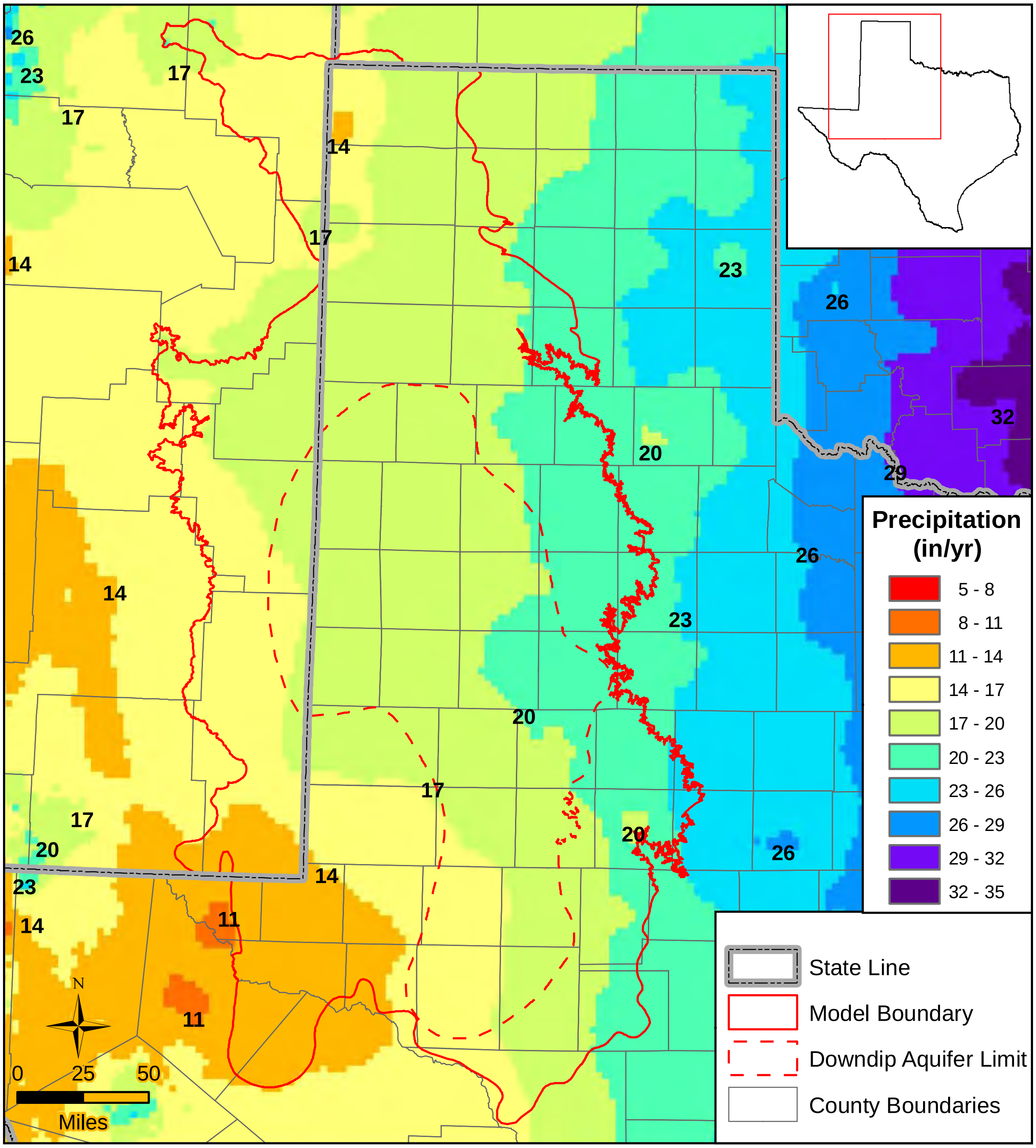
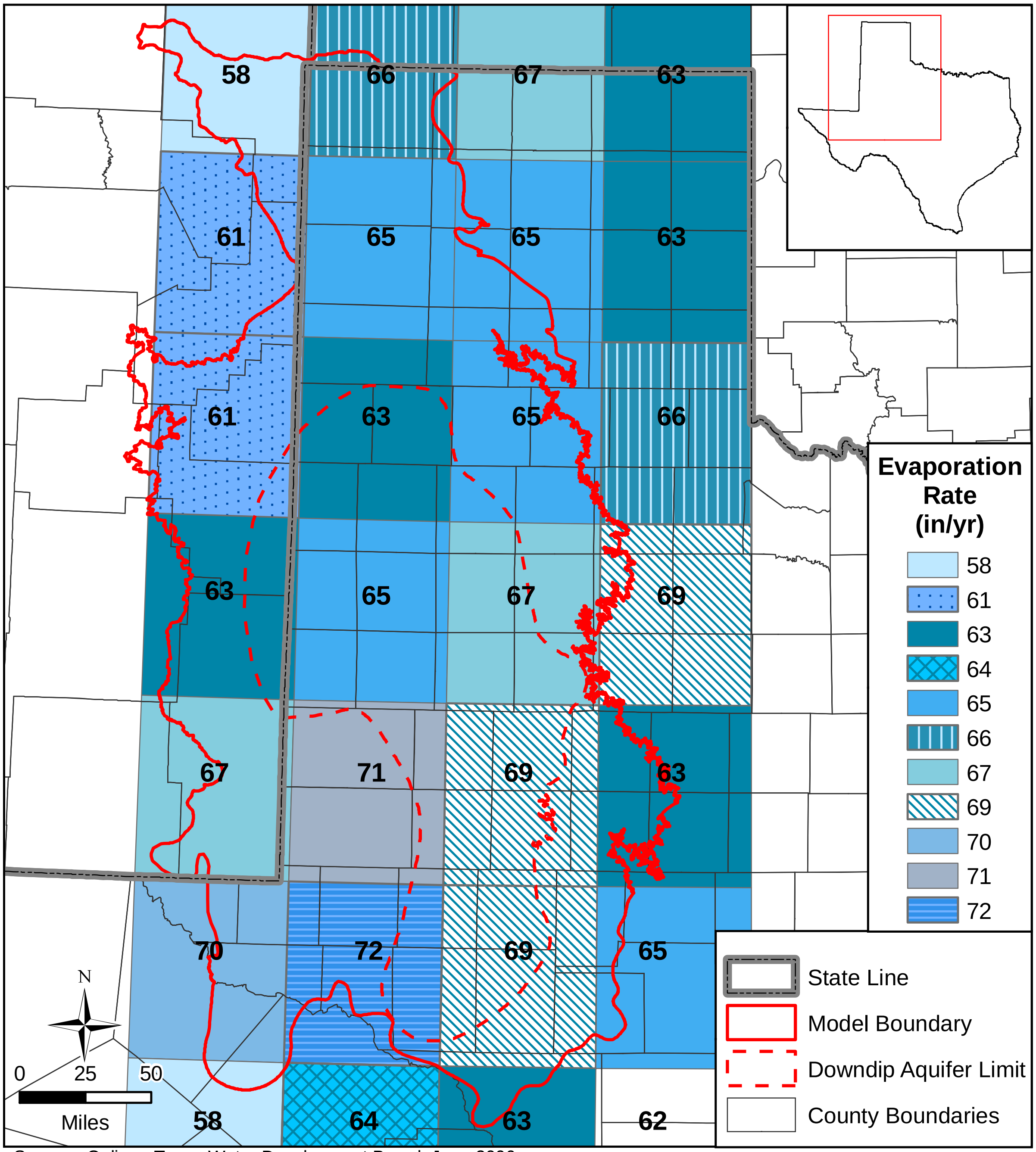


Figure 2.1.8 **Annual precipitation time series in inches per year at selected locations in the study area. (A discontinuous line indicates a break in the data. The dashed red line represents the mean annual precipitation).**



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.

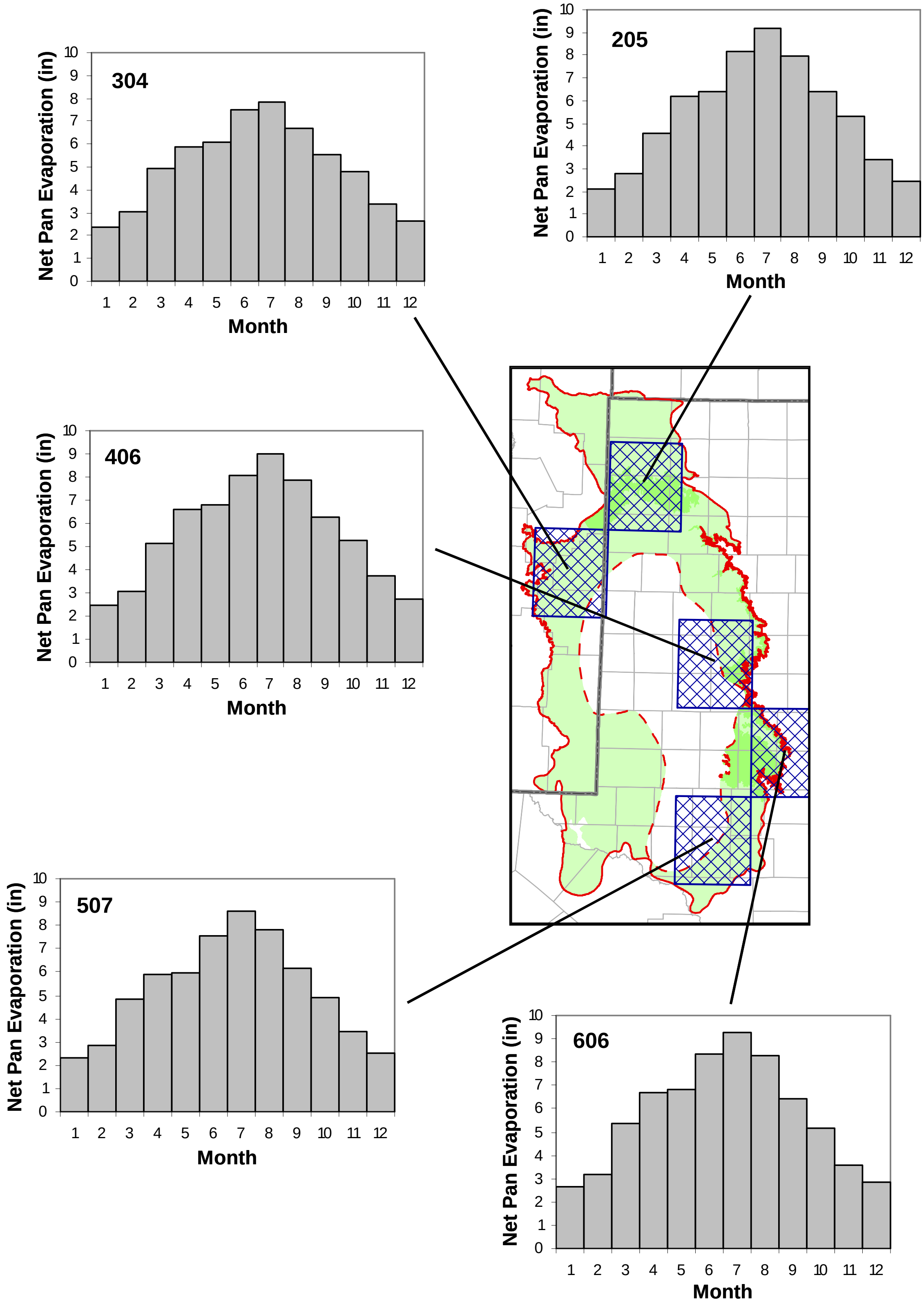


Figure 2.1.11 Average monthly lake surface evaporation in inches at selected locations in the study area.

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).

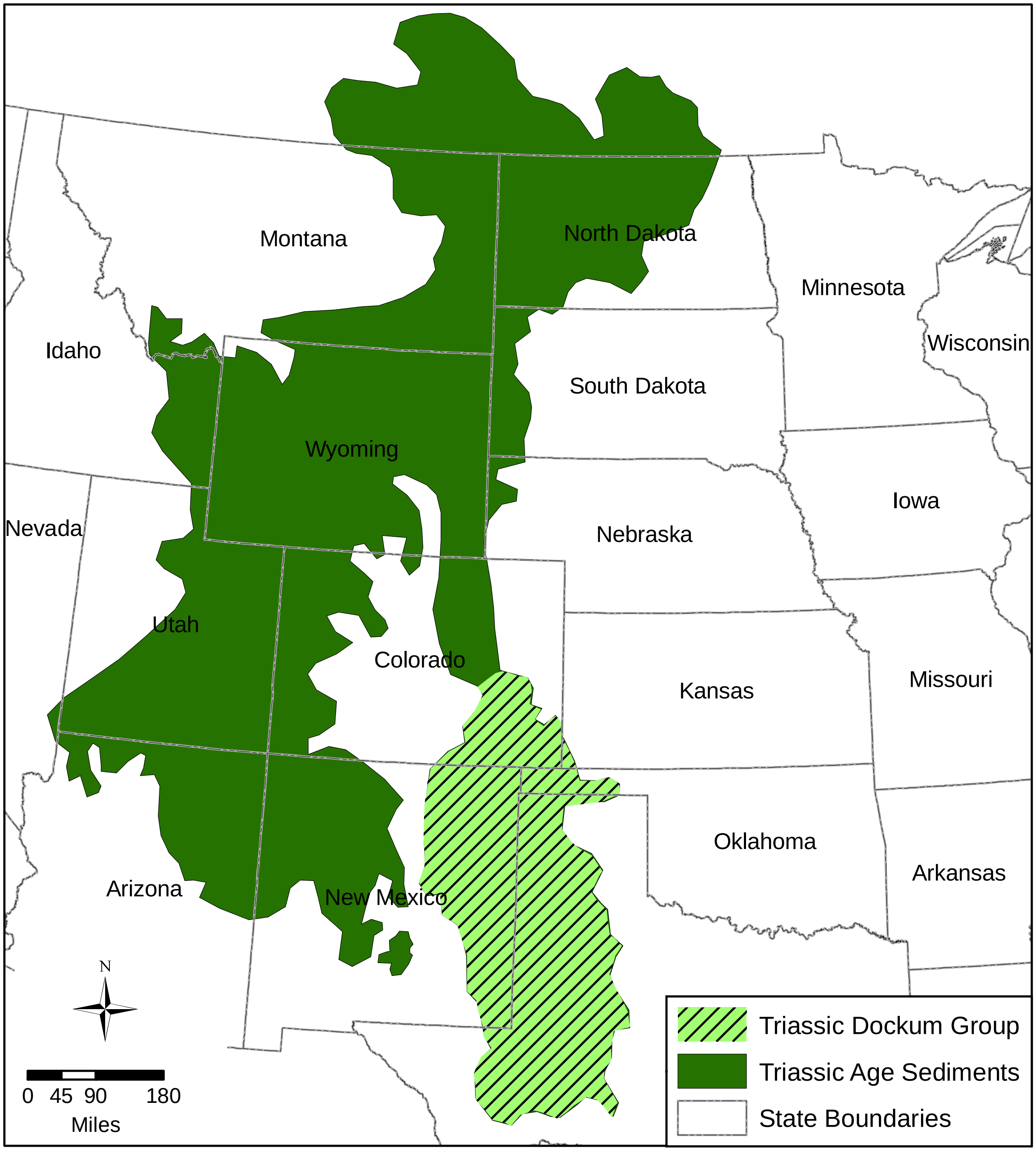
Pleistocene glacial melts in the southern Rocky Mountains possibly resulted in the release of a vast amount of water that poured across the High Plains enhancing the rapid headward erosion of both the Pecos and Canadian rivers and the westward retreat of the eastern caprock escarpment (Walker, 1978). 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>

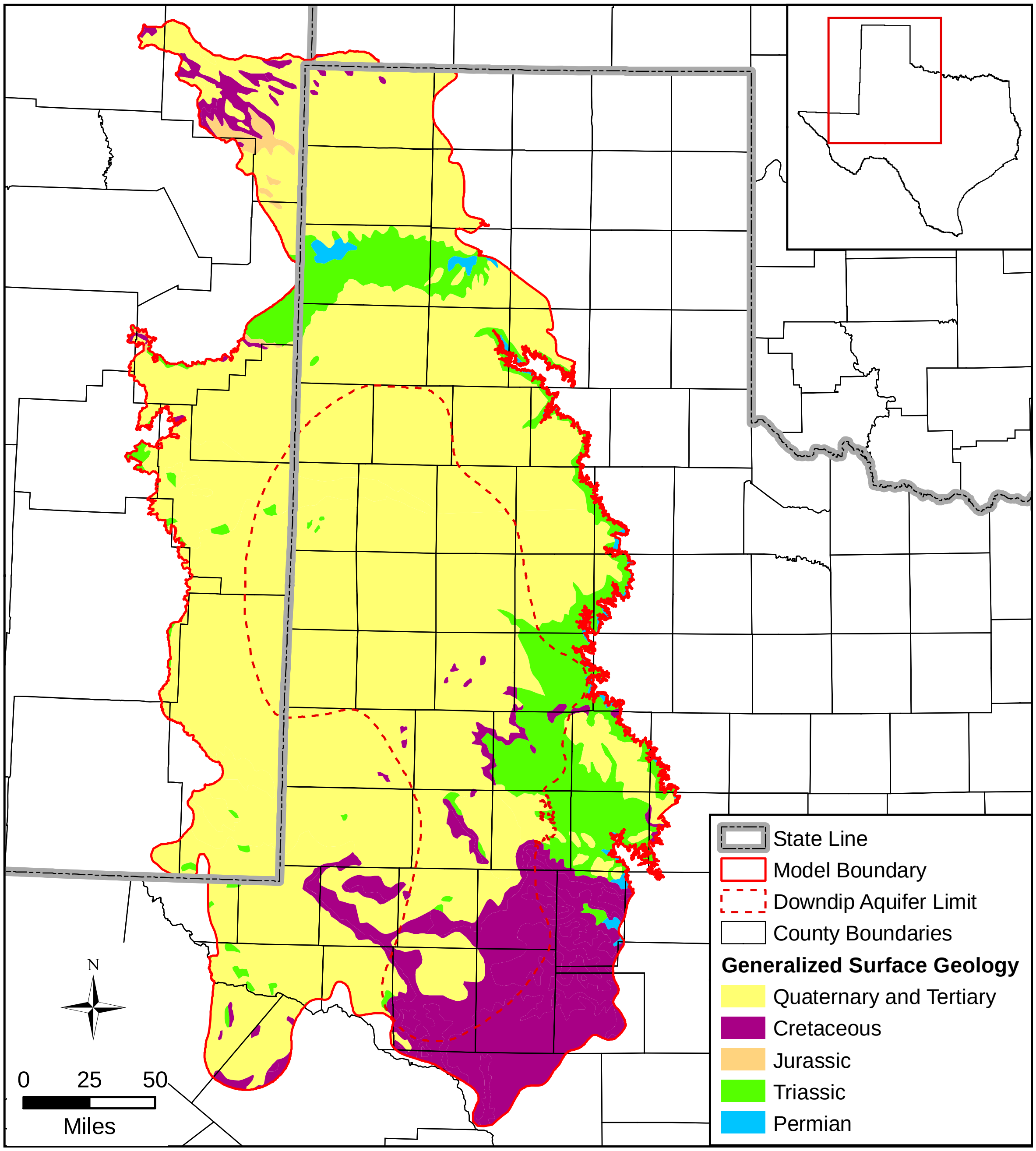
Table 2.2.2 Generalized stratigraphic section for the Dockum Group.

<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>



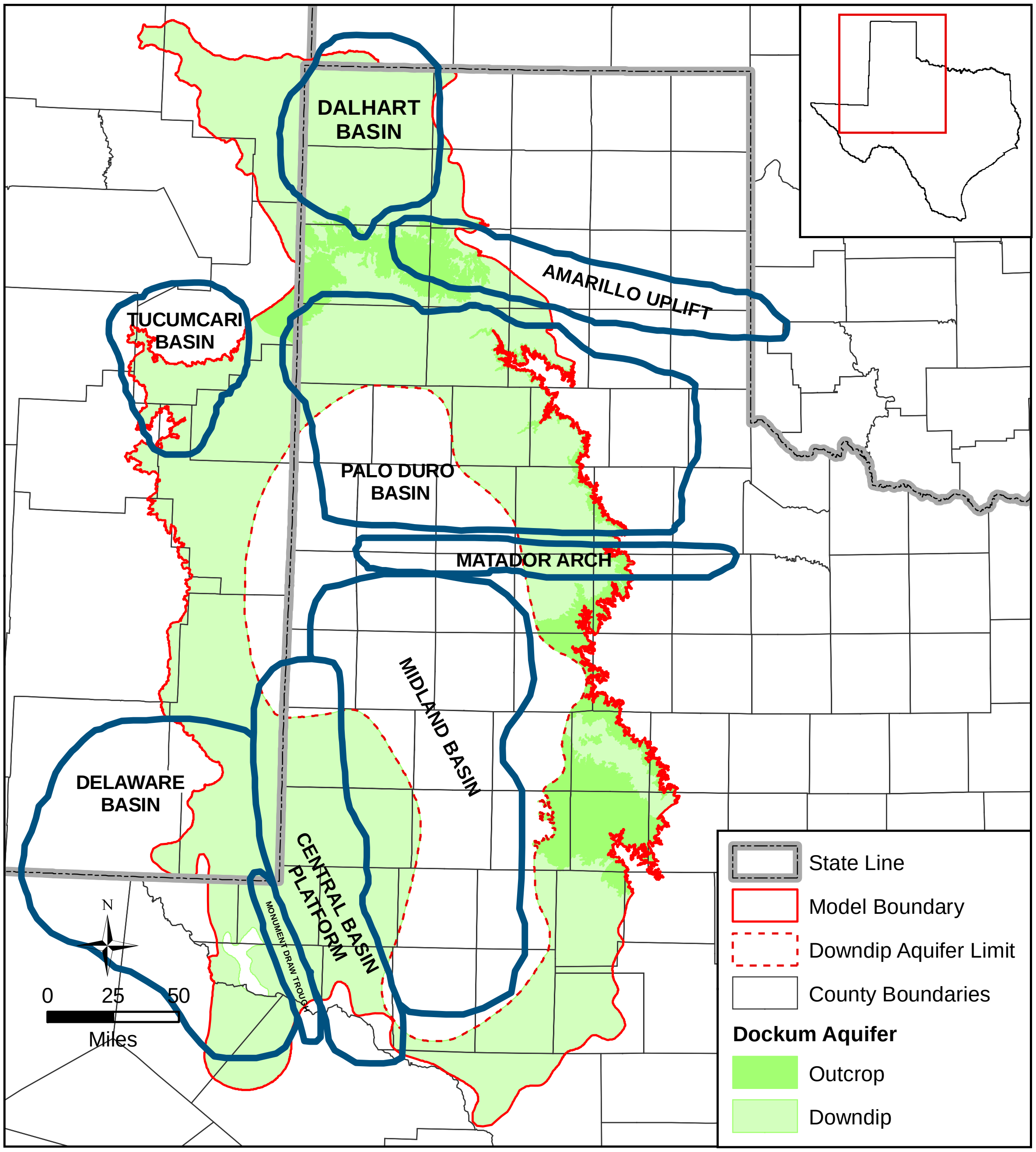
Adapted from McKee and others (1959)

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



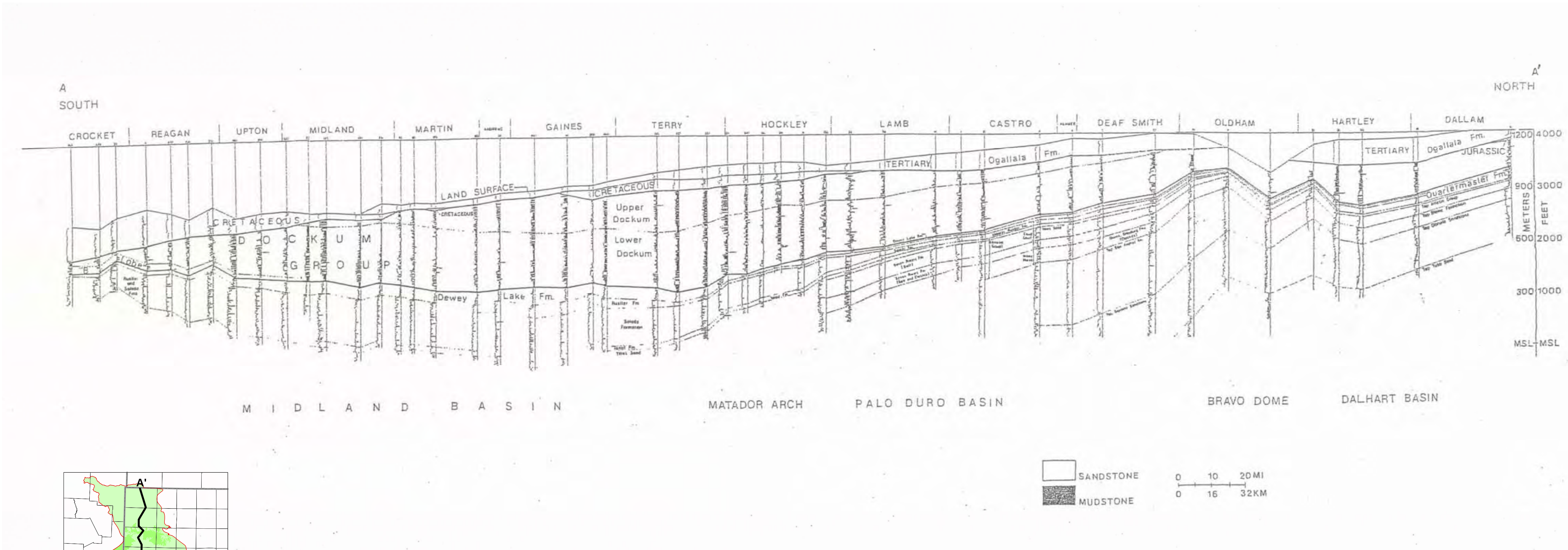
Source: Online: USGS Geology of the Conterminous United States at 1:2,500,000 Scale

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.



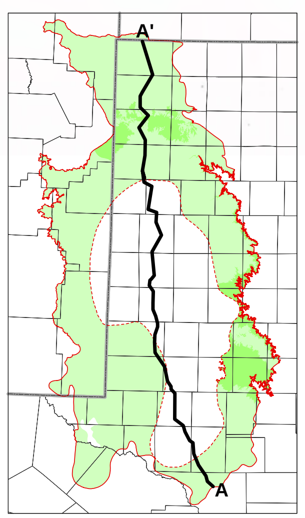


Figure 2.2.4 **South-north cross-section across the active model area (after McGowen and others, 1977).**

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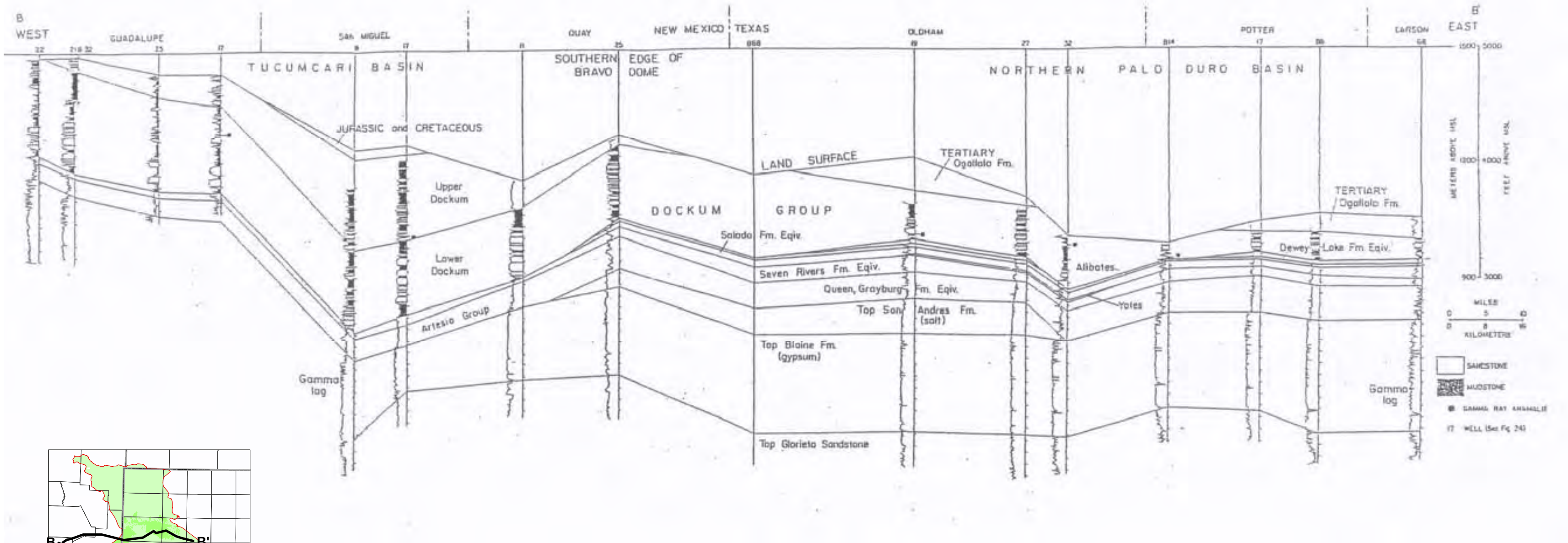

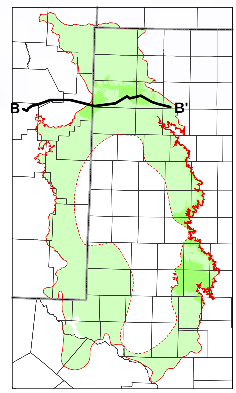

Figure 2.2.5 East-west cross-section across Guadalupe, San Miguel, and Quay counties, New Mexico and Oldham, Potter, and Carson counties, Texas (after McGowen and others, 1977).

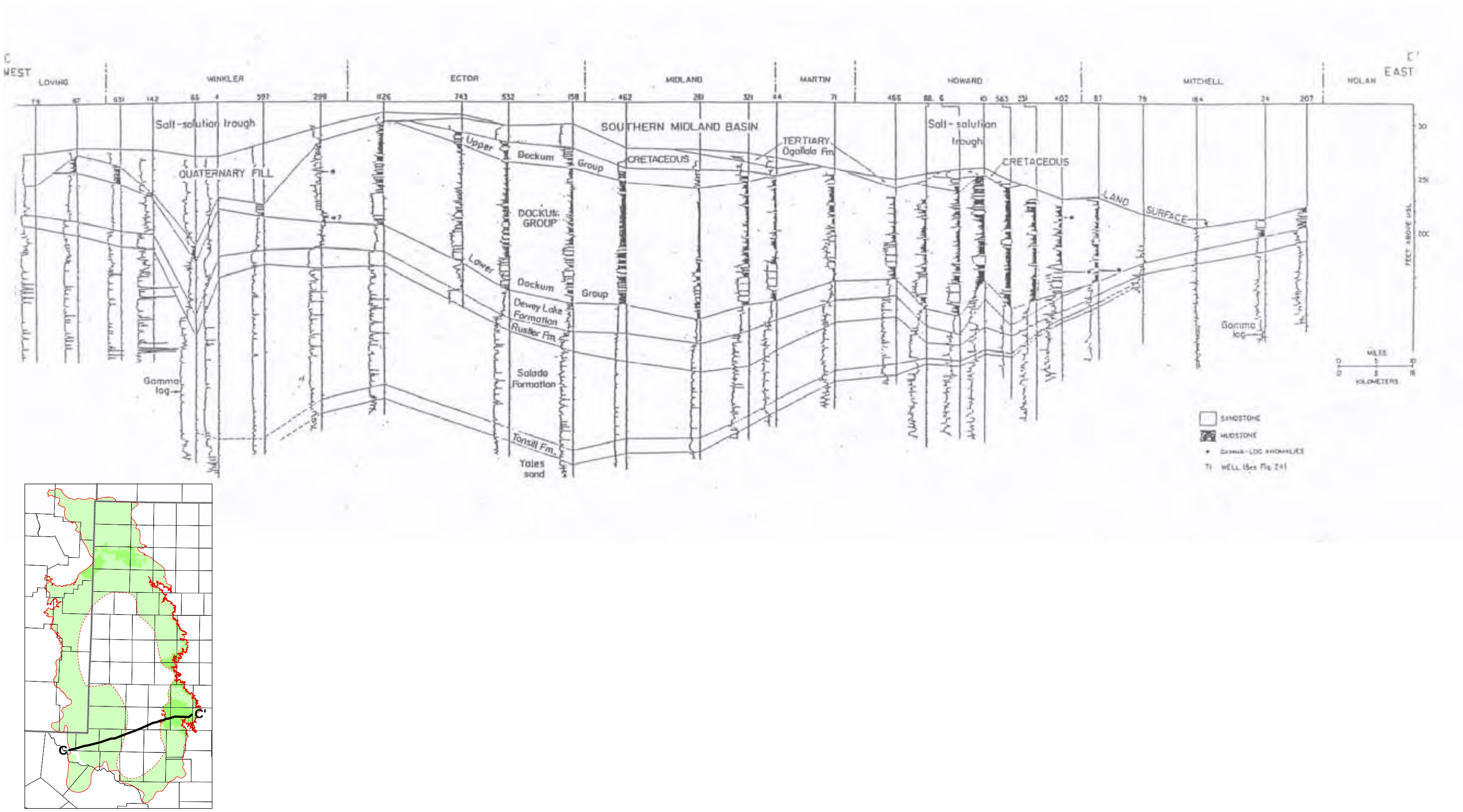

Figure 2.2.6 **East-west cross-section across Loving, Winkler, Ector, Midland, Martin, Howard, and Mitchell counties, Texas (after McGowen and others, 1977.**

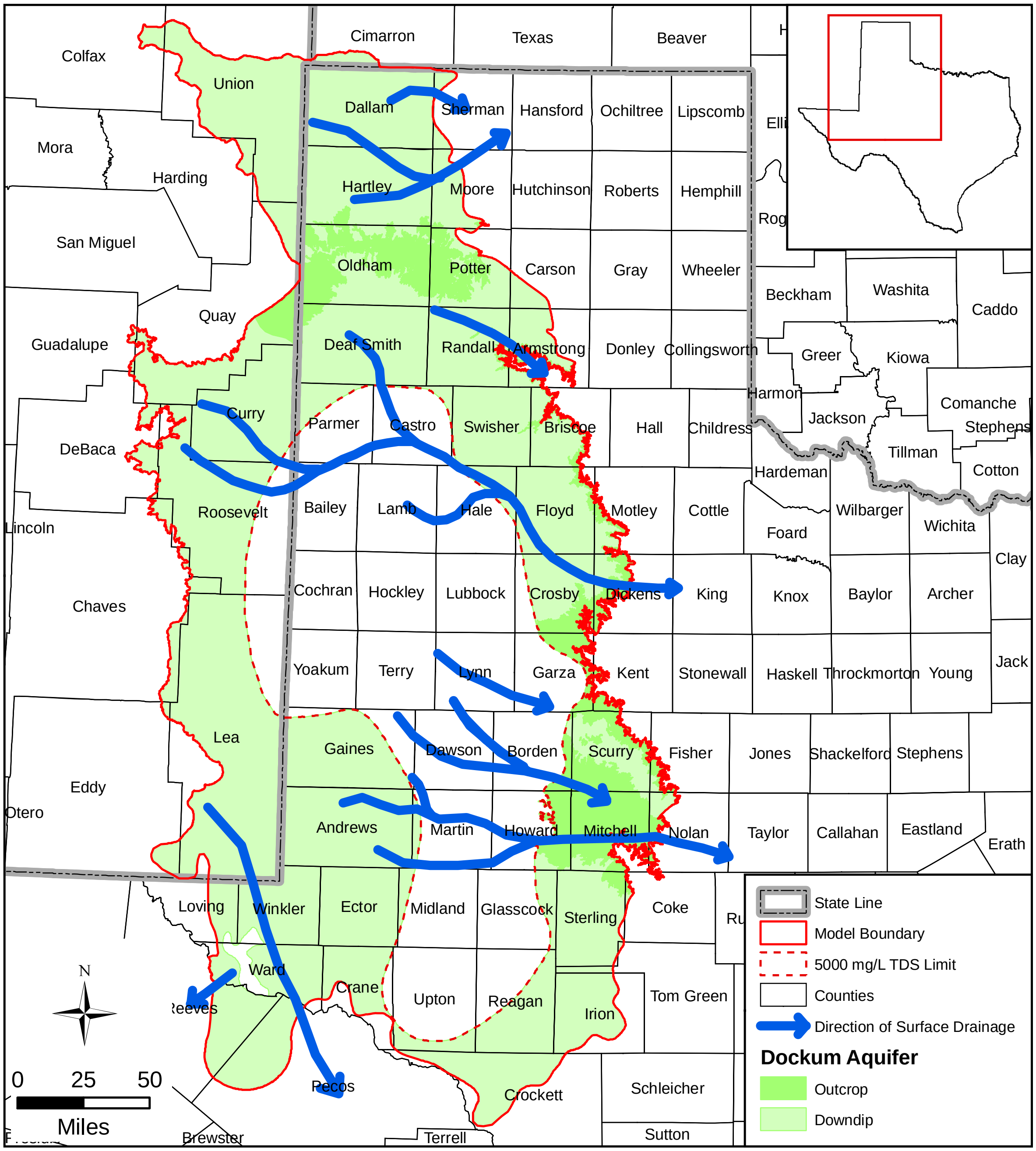

Figure 2.2.7 Post-depositional erosional patterns in the Dockum Group surface.

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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)

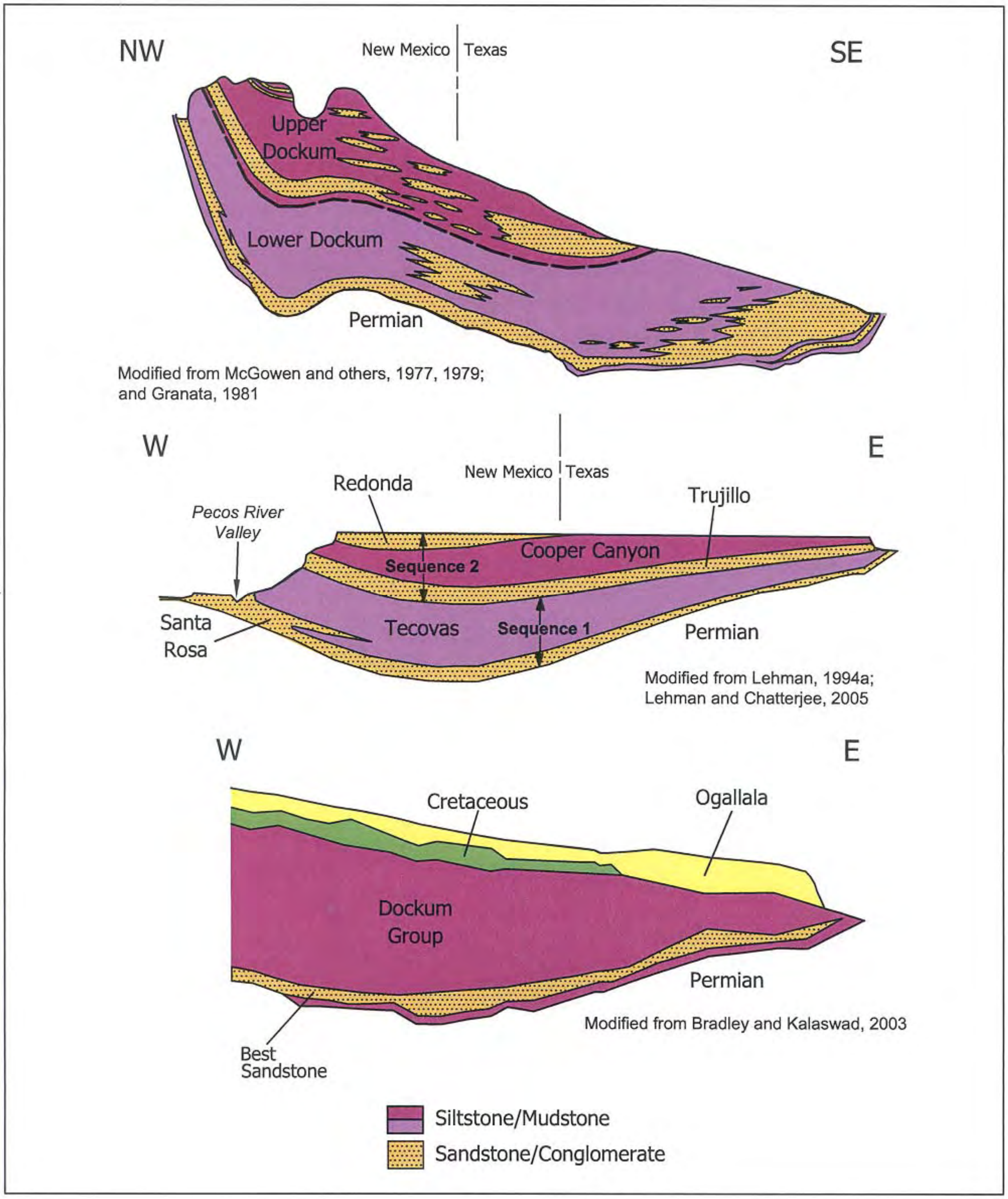

Figure 3.0.1 Schematic diagram of proposed stratigraphic sequences.

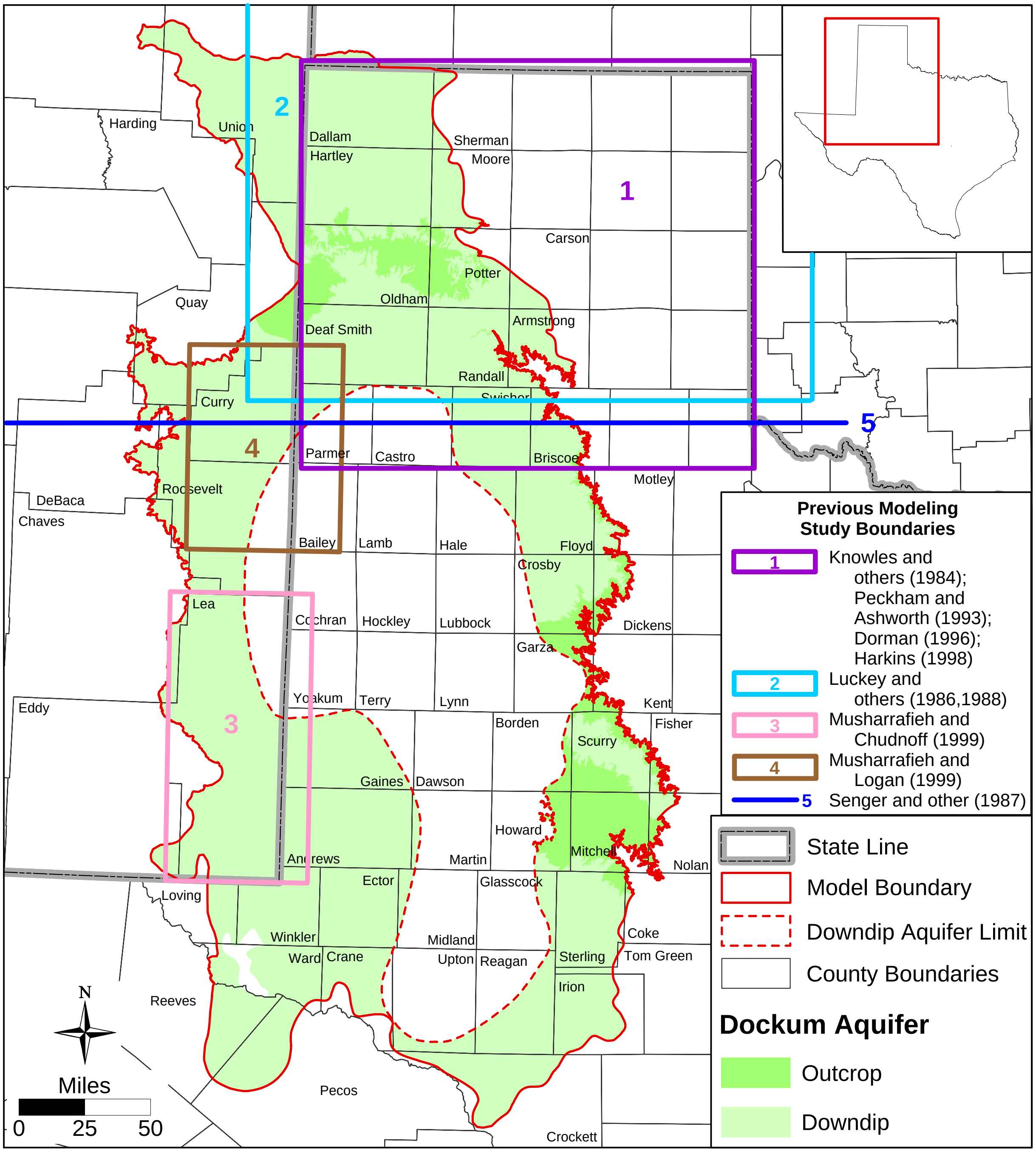

Figure 3.0.2 **Location of boundaries for previous modeling studies that included portions of the Dockum Group.**

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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.

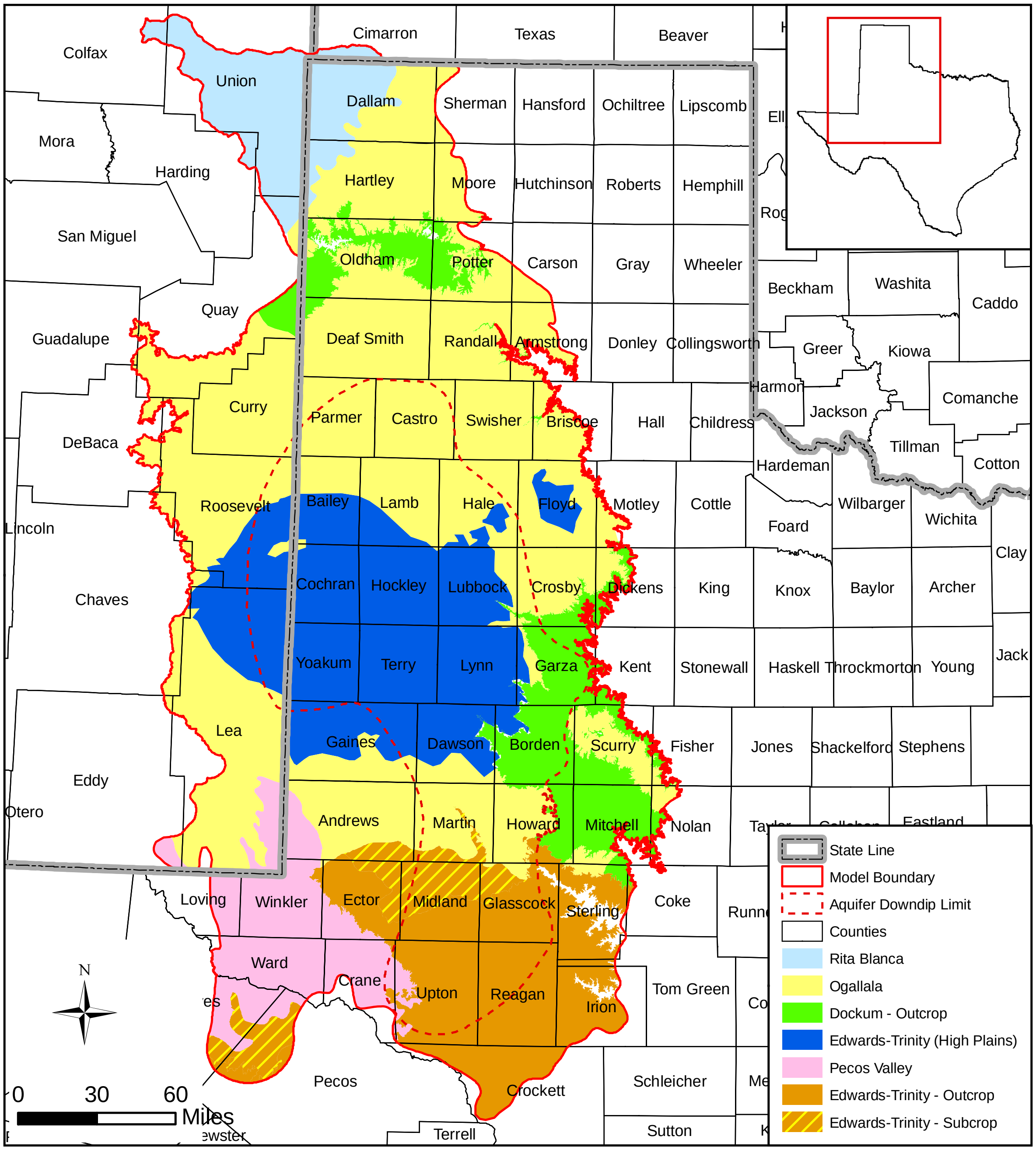
Johns (1989) distinguished four cyclic sequences in the lower portion of the Dockum Group each characterized by a mudstone base and coarsening upward sequence with more abundant sands, whereby the mudstone thickness increases toward the center of the Dockum Basin. The upper portion of the Dockum Group 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.

<table>
<tr><th colspan="2">McGowen and others (1977; 1979)</th><th colspan="2">Lehman (1994a; 1994b)</th><th>Model Layer</th></tr>
<tr><td rowspan="4">Dockum Group</td><td rowspan="2">Upper</td><td rowspan="4">Dockum Group</td><td>Cooper Canyon Formation</td><td rowspan="2">2</td></tr>
<tr><td>Trujillo Sandstone</td></tr>
<tr><td rowspan="2">Lower</td><td>Tecovas Formation</td><td rowspan="2">3</td></tr>
<tr><td>Santa Rosa Formation</td></tr>
</table>



Source: Adapted from Texas Water Development Board, Dec 2006

Figure 4.1.1 Aquifers directly overlying the Dockum Aquifer.

4.2 Structure

The Dalhart Basin, Amarillo Uplift, Palo Duro Basin, Matador Arch, Midland Basin, and Central Basin Platform are the main structural features underlying the Triassic-age sediments of the Dockum Group (see Figure 2.2.3). The base of the Dockum Group reflects the 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). McGowen and others (1977) state that sedimentation of the Dockum Group was not influenced by the Matador Arch, which appears to have been inactive during the late Triassic, or by the Central Basin Platform. Maximum preserved thickness of Dockum Group rocks occurs slightly west of center of the Midland Basin.

A small but dominate structural feature, a northwest-southeast oriented trough, is located in Lea County, New Mexico and Winkler, Ward, and Pecos counties, Texas (see Figure 2.2.3). This trough was formed by the dissolution of Permian-age salts and the collapse of overlying beds, including the Dockum Group (Garza and Wesselman, 1959). The width of the trough is about 5 to 10 miles in Winkler County. Maps of the top and bottom elevation of the Dockum Group (McGowen and others, 1977) indicate that the sides of the trough are very steep.

4.2.1 Data Source

The structure surfaces generated for the upper and lower portions of the Dockum Group are based on work presented in McGowen and others (1977). 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". Their upper and lower units were used as the basis for dividing the Dockum Group into two layers for modeling purposes. Using approximately 2,000 gamma-ray logs, McGowen and others (1977) developed elevation maps for the top and base of the Dockum Group, isopach maps for the upper, lower, and total Dockum Group, and sand percent maps for the upper and lower portions of the Dockum Group. These structure maps were adopted as the basis for developing the structural surfaces for the Dockum Aquifer for use in the Dockum Aquifer groundwater availability model.

McGowen and others (1977) defined the base of the Dockum Group on gamma logs as "the base of any muds (high radioactivity response) immediately underlying [the] lowest Dockum sandstone …, or conversely as the top of the siltstone interval (intermediate radioactivity response) immediately overlying the Permian evaporate section". Looking at "average vertical sections", they identified two low frequency cycles of lithology, which they used to differentiate between the upper and lower portions of the Dockum Group. The lower portion of the Dockum Group is preserved throughout the extent of Dockum Group sedimentation but the upper portion of the Dockum Group is preserved over a smaller extent.

McGowen and others (1977) provide isopach and sand percent maps for both the upper and lower portions of the Dockum Group. However, the lateral extent of the upper portion of the Dockum Group on the isopach and sand percent maps is greater than the extent indicated on their cross-sections. For example, the isopach and sand percent maps show the upper portion of the Dockum Group extending north of the Canadian River, while the two north-south cross-sections show the upper portion of the Dockum Group pinching out south of the Canadian River. For this reason, the upper portion of the Dockum Group was not considered a separate hydrogeologic unit north of the Canadian River in development of the Dockum Aquifer structure for the groundwater availability model. The extent of the upper portion of the Dockum Group south of the Canadian River was determined based on the approximate locations of pinch-outs of the upper portion of the Dockum Group in the McGowen and others (1977) cross sections. Figure 6 of McGowen and others (1977) shows the locations of their cross-sections, which consist of three north-south cross-sections, five generally east-west cross-sections, and one northwest-southeast cross-section. Using these cross-sections, a lateral boundary for the upper portion of the Dockum Group was estimated.

The specific data from McGowen and others (1977) used to develop the structural surfaces for the Dockum Aquifer where the elevations of the base of the Dockum Group, the elevations of the top of the Dockum Group, the lower Dockum Group isopach, and the percent sandstone maps for the upper and lower portions of the Dockum Group. In the outcrop areas, the top of the Dockum Group from McGowen and others (1977) was replaced with the National Elevation Database data. McGowen and others (1977) did not provide a map of the elevations for the base of the upper portion of the Dockum Group. Therefore, one was created using the elevations for the base of the Dockum Group and the isopach map for the lower portion of the Dockum Group.

4.2.2 Construction of the Structural Surfaces

The three maps from McGowen and others (1977) used to develop the structural surfaces for the Dockum Aquifer were:

- Figure 5. Structure map, base of Dockum Group,
- Figure 14. Elevation on top of Dockum Group, and
- Figure 7. Isopach map, lower part of Dockum Group.

The steps used to generate the surfaces consisted of scanning each of the McGowen and others (1977) figures. The scanned images were then georeferenced. The contour lines on the scanned images were then digitized and assigned the appropriate attribute (e.g., elevation or thickness). A raster dataset on a quarter-mile grid spacing was created from the digitized contour lines using the ESRI Spatial Analyst topo-to-raster algorithm. Contour lines were then generated using the raster data and compared to the digitized contour lines. If the contour lines generated from the raster data did not match the digitized contour lines, additional contour lines and/or point data coverages were developed to help constrain the algorithm. Additional points and/or lines were added to the constraining shapefile until the digitized contour lines were reproduced.

The first surface developed was the elevation of the base of the Dockum Group. The process described above was used to recreate the base elevation as shown in Figure 5 of McGowen and others (1977). An additional polyline shapefile was created to help force the topo-to-raster algorithm to reproduce the digitized contours in a few areas. After many iterations, the process yielded contours that compared very well to the original digitized contour lines.

The second surface developed was the elevation of the top of the Dockum Group. Using the process described above, the top elevation as documented in Figure 14 of McGowen and others (1977) was recreated. For this surface, an additional point shapefile was also developed to help force the topo-to-raster algorithm to reproduce the digitized contours. After several iterations, the process yielded contours that compared very well to the original digitized contour lines. Where the Dockum Group outcrops, the interpolated surface for the top of Dockum Group was replaced by the land surface elevation. The land surface elevation was estimated by averaging all of the 30-meter National Elevation Database data in each quarter-mile gridblock in the outcrop of the raster dataset created from the digitized contour lines.

Once the top and bottom elevation surfaces were created, the total thickness of the Dockum Group was calculated by subtracting the top elevation surface from the base elevation surface. This calculation yielded several areas where the top surface was lower than the base surface. The overlap areas were located mainly near the edges of the Dockum Group and in the trough in Winkler and Ward counties. There are several sources of potential error that could have caused the overlap. These include errors in the original maps in McGowen and others (1977), georeferencing errors, digitizing errors, errors made in the assignment of contour line values, and interpolation errors.

Across most of the Dockum Group area, the top and base structure maps in McGowen and others (1977) are shown with 100-foot contour intervals. In the trough area, however, they used 500-foot contours, presumably due to the steep nature of the trough feature. Because the contour interval in the trough area is large, it was difficult to determine the source of the errors causing the overlap of the top and base elevation surfaces. To reduce the overlap, minor adjustments were made to the digitized contour lines for the top and base elevations in the trough area. After these adjustments, there were still a few areas near the edges of the Dockum Group where the top surface was lower than the base surface. In these areas as well as in areas with a thickness of less than 50 feet, a minimum thickness of 50 feet was assigned by lowering the base surface.

The final top and base elevations for the Dockum Aquifer are shown in Figures 4.2.1 and 4.2.2, respectively. These figures, and all subsequent figures in this section, show the locations of the wells with gamma-ray logs used by McGowen and others (1977) to develop their structure maps. The top elevations indicate that the surface of the Dockum Aquifer is relatively smooth, sloping from northwest to southeast, with the exception of the trough area in Winkler and Ward counties. The base elevations reflect the influence of the deep Midland Basin in the central and south-central portions of the model area and the shallower Dalhart Basin in the area of Hartley County. The relatively smooth nature of the base elevations from the center of the Midland Basin to the north and from the center of the basin to the southwest suggests that sedimentation of the Dockum Group was not influenced by Matador Arch and the Central Basin Platform, respectively. The higher elevations in Oldham and Potter counties reflect the influence of the Amarillo Uplift.

The isopach map for the lower portion of the Dockum Group provided in McGowen and others (1977) has contours at a 200-foot interval. To improve the interpolation of the isopach, estimated locations for odd numbered 100-foot interval contour lines were hand drawn and digitized to help force the interpolation routine to reproduce the original isopach. Although this approach may introduce error because the original thickness data were not available to guide the location of the added contours, it was determined that this error was preferred over an error caused strictly by the mathematical interpolation. For the isopach of the lower portion of the Dockum group, an additional point shapefile was also developed to help force the topo-to-raster algorithm reproduce the digitized contours. After several iterations, the process yielded contours that compared very well to the digitized contour lines. In order to avoid problems during modeling, the minimum thickness of the lower portion of the Dockum Group was assigned a value of 50 feet. The thicknesses of the lower portion of the Dockum Group are shown in Figure 4.2.3. This figure shows an anomalous thickening of the lower portion of the Dockum Group just beyond the extent of the upper portion of the Dockum Group in Deaf Smith and Randall counties. This thickening is an edge effect associated with the margin of the upper portion of the Dockum Group and is a result of the inconsistency in the areal extent of the upper portion of the Dockum Group as reported in McGowen and others (1977). These anomalously thick areas were not removed because that would have required deviating from the structure data given in McGowen and others (1977). As shown in Figure 4.2.3, the lower portion of the Dockum Group is thickest in the Midland Basin and thins to the southwest, south, and east. The lower portion of the Dockum Group also thins to the north over the Amarillo Uplift and then thickens slightly in the Dalhart Basin.

McGowen and others (1977) did not provide a map of the elevations for the top of the lower portion of the Dockum Group. Therefore, that surface was created by adding the thicknesses for the lower portion of the Dockum Group to the elevations for the base of the Dockum Group. The elevations for the top of the lower portion of the Dockum Group, in areas where both the upper and lower portions of the Dockum Group are present, are shown in Figure 4.2.4. In the remaining portion of the model area, the top of the lower portion of the Dockum Group is coincident with the top of the Dockum Group. In general, the top of the lower portion of the Dockum Group is a smooth surface sloping from the northwest to the southeast, with the lowest elevations over the Midland Basin.

As stated in Section 4.2.1, the lateral extent of the upper portion of the Dockum Group is less than that of the lower portion of the Dockum Group and was defined based on its extent identified on the cross-sections in McGowen and others (1977) in the northern part of the model area. The thickness of the upper portion of the Dockum Group was calculated by subtracting the elevations for the top of the lower portion of the Dockum Group from the elevations for the top of the Dockum Group. The resulting thicknesses for the upper portion of the Dockum Group are shown in Figure 4.2.5. The upper portion of the Dockum Group is thickest in its central and west-central areas and thins outward in the north, east, and south directions. A thin trough is observed in Roosevelt County, New Mexico and a thick ridge is observed in Quay County, New Mexico.

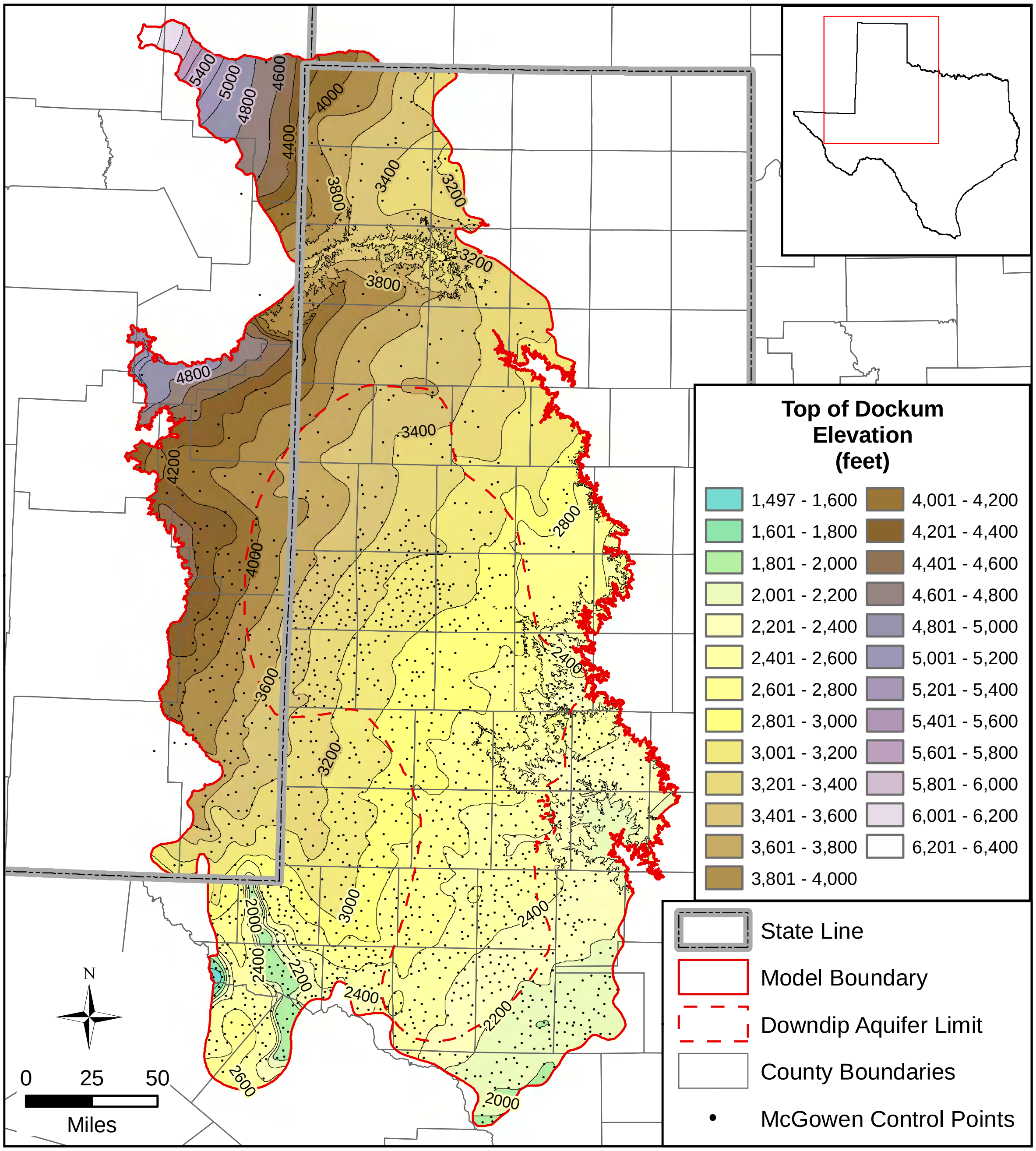
4.2.3 Net Sand Thickness Maps

The net sand thicknesses for the upper and lower portions of the Dockum Group were determined using the sandstone percent maps provided by McGowen and others (1977) and the thicknesses developed as described above. The sandstone percent map for the lower portion of the Dockum Group provided in Figure 20 in McGowen and others (1977) was contoured at a 20-percent interval. To improve the interpolation of the map, estimated locations for odd numbered 10-percent contour lines were hand drawn and digitized to help force the interpolation routine to reproduce the original map. Although this approach may introduce error because the original sand percent data was not available to guide the location of the added contours, it was determined that this error was preferred over an error caused strictly by the mathematical interpolation. The sandstone percent map for the upper portion of the Dockum Group provided in Figure 26 of McGowen and others (1977) is contoured at 10-percent intervals; therefore, no further refinement was made to the percent sandstone contours for the upper portion of the Dockum Group.

Using the process outlined in Section 4.2.2, sandstone percent maps for the upper and lower portions of the Dockum Group that reproduced the percent sand maps in McGowen and others

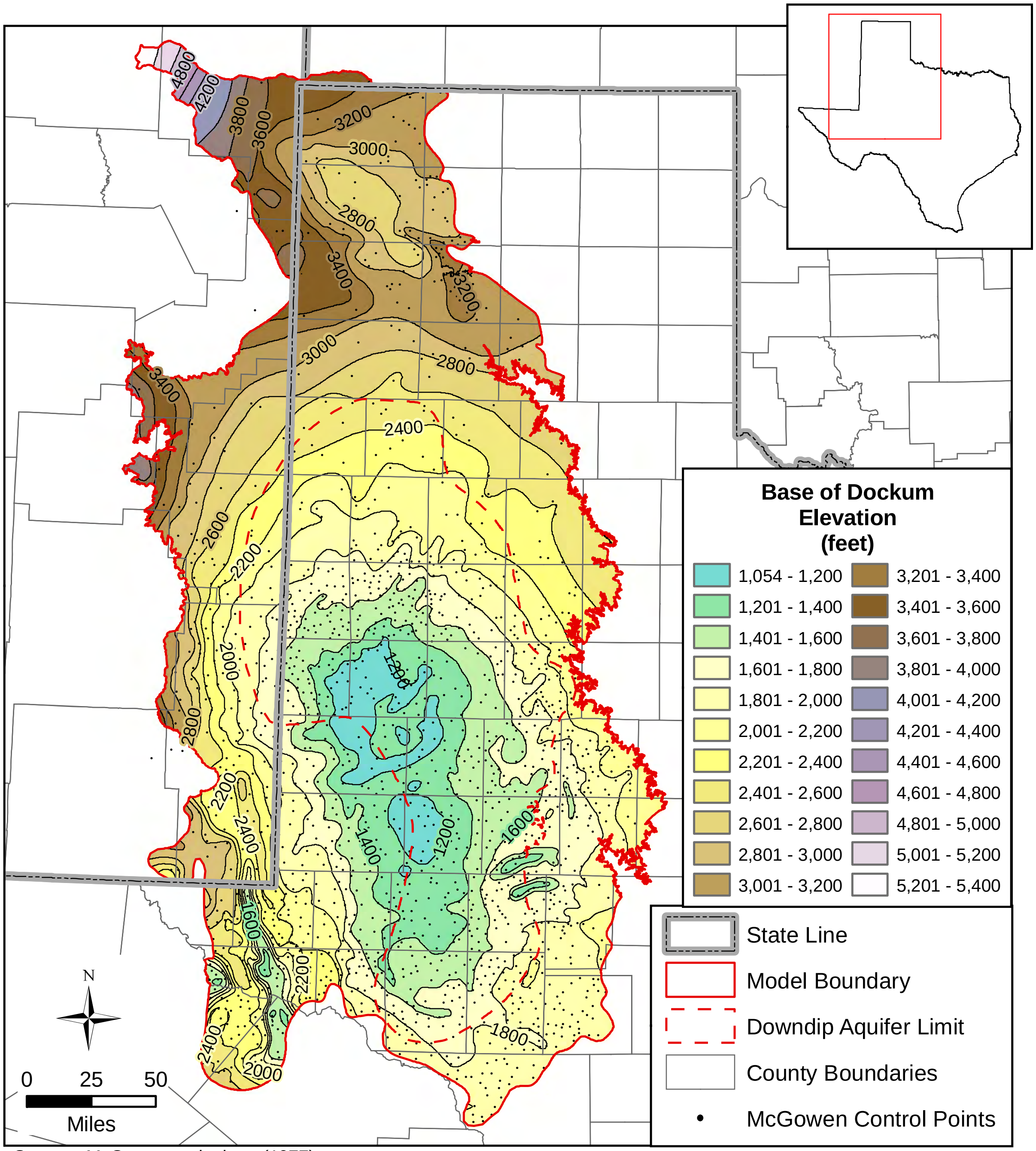
(1977) were developed. Net sand thickness maps were generated for the upper and lower portions of the Dockum Group by multiplying the percent sand maps by the estimated total thickness maps. As with the isopach map for the upper portion of the Dockum Group, the sand percent map for the upper portion of the Dockum Group provided by McGowen and others (1977) extends beyond the extent of the upper portion of the Dockum Group as shown on their cross-sections. Therefore, creation of the net sand thickness map for the upper portion of the Dockum Group clipped the data to the lateral extent of the upper portion of the Dockum Group as estimated from the cross-sections.

The net sand thickness maps for the upper and lower portions of the Dockum Group are shown in Figures 4.2.6 and 4.2.7, respectively. The maximum net sand thickness of 450 feet for the upper portion of the Dockum Group is observed on the western side of the Midland Basin in Yoakum County, Texas. The maximum net sand thickness of 550 feet for the lower portion of the Dockum Group is observed in the southern part of the model area in Upton County, Texas.



Source: McGowen and others (1977)

Figure 4.2.1 Top of Dockum Aquifer.



Source: McGowen and others (1977)

Figure 4.2.2 Base of Dockum Aquifer.

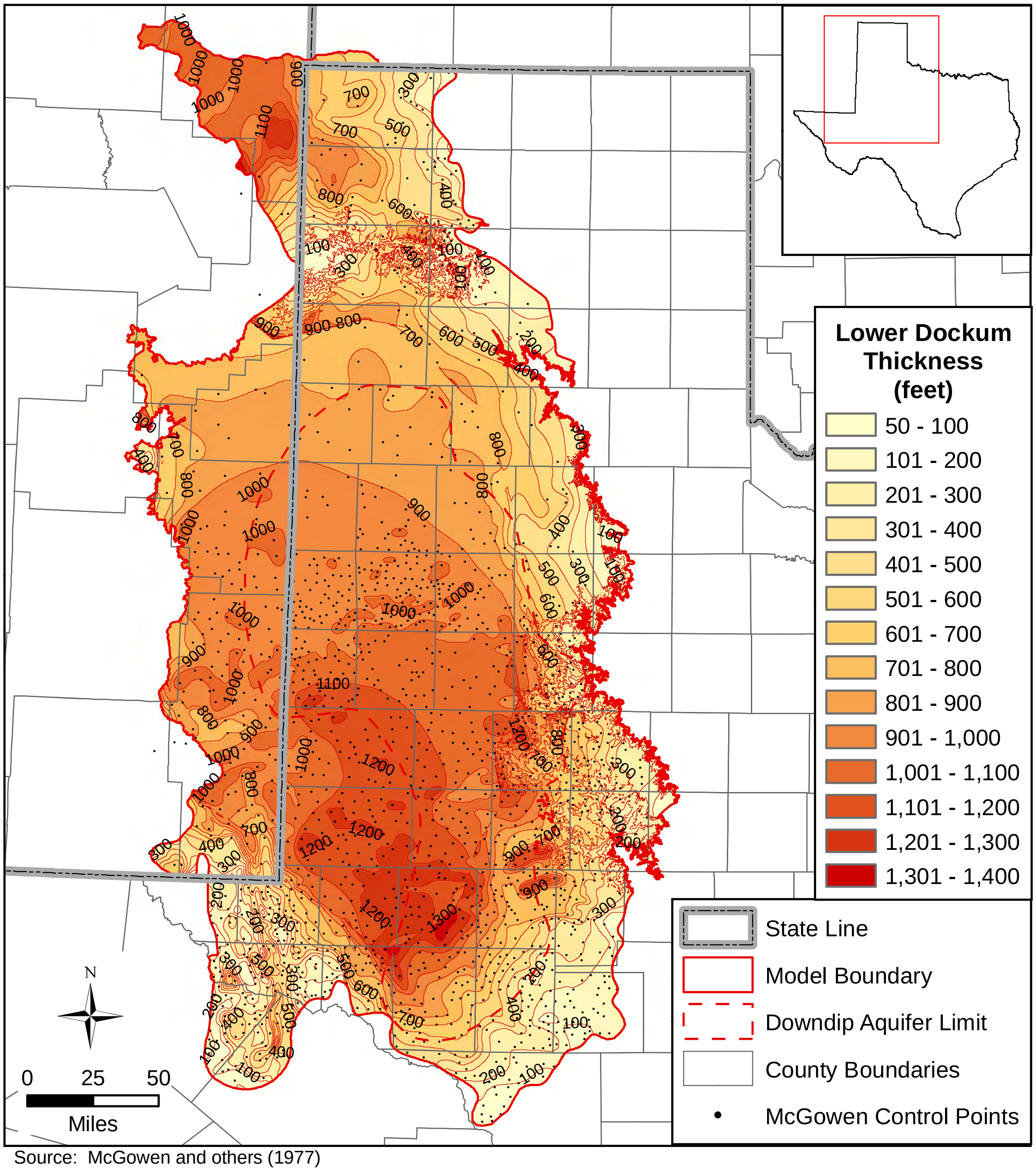
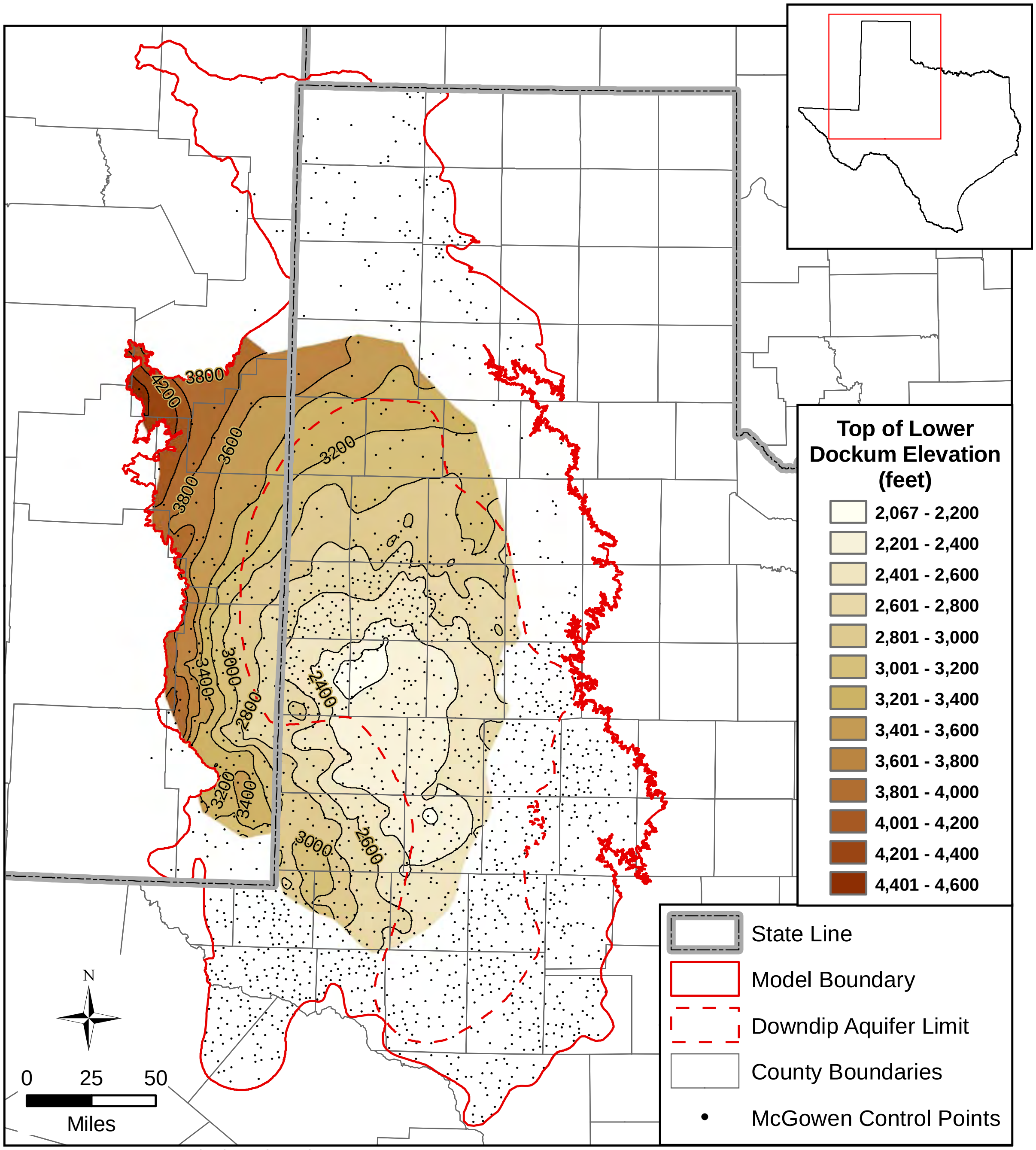
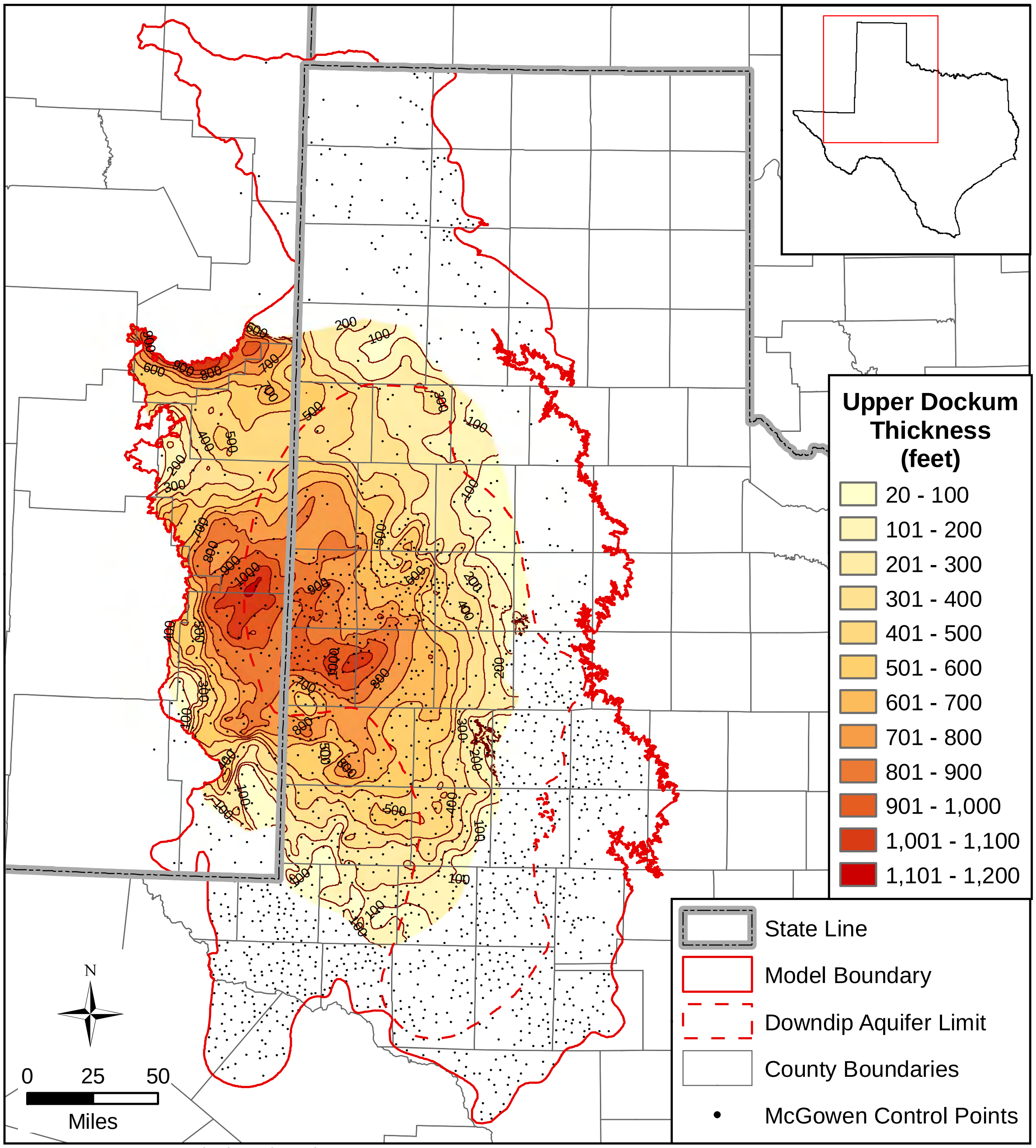


Figure 4.2.3 Thickness of the lower portion of the Dockum Aquifer.



Source: McGowen and others (1977)

Figure 4.2.4 **Top of the lower portion of the Dockum Aquifer at locations where the upper portion of the Dockum Aquifer is present.**



Source: McGowen and others (1977)

Figure 4.2.5 Thickness of the upper portion of the Dockum Aquifer.

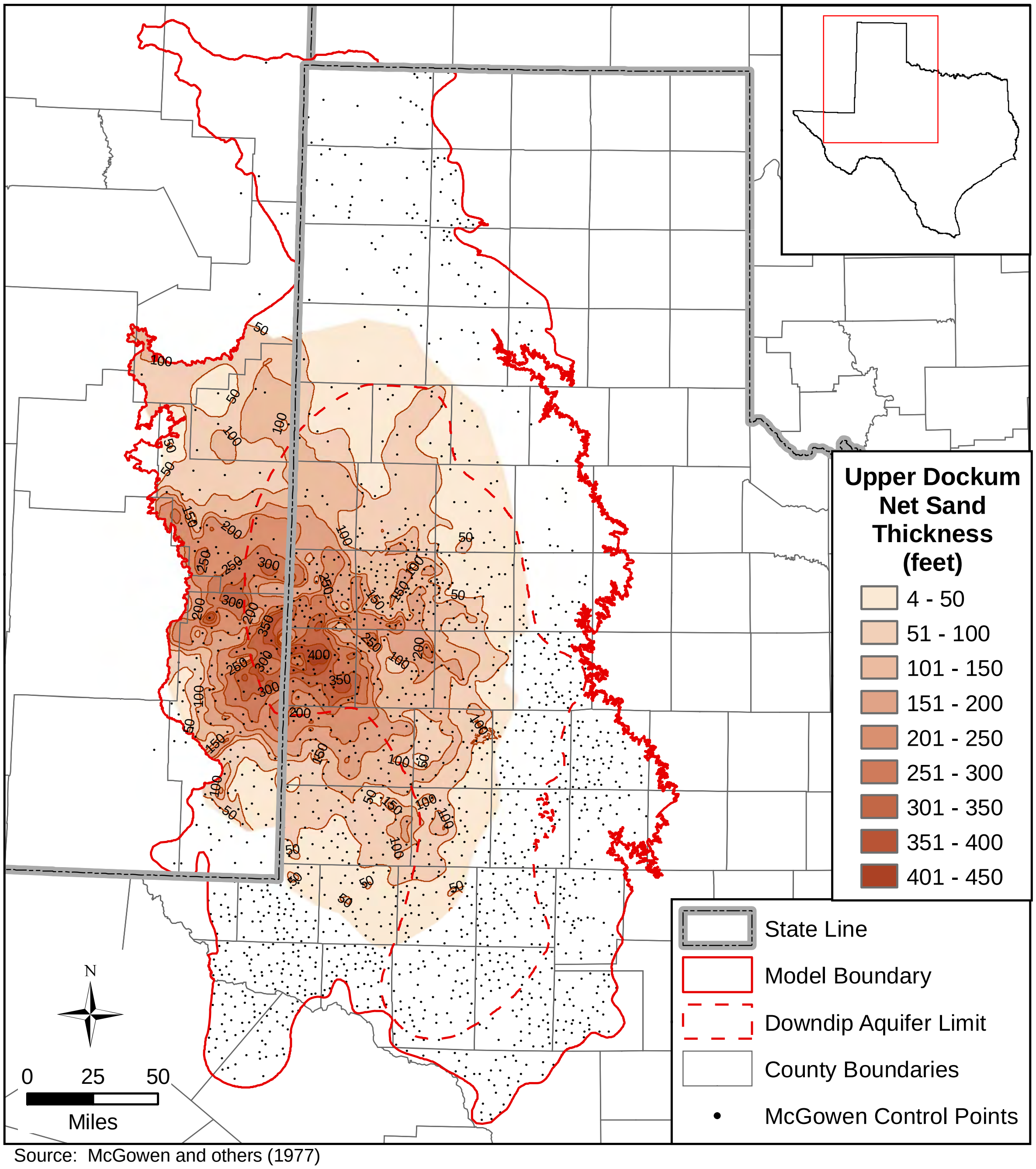
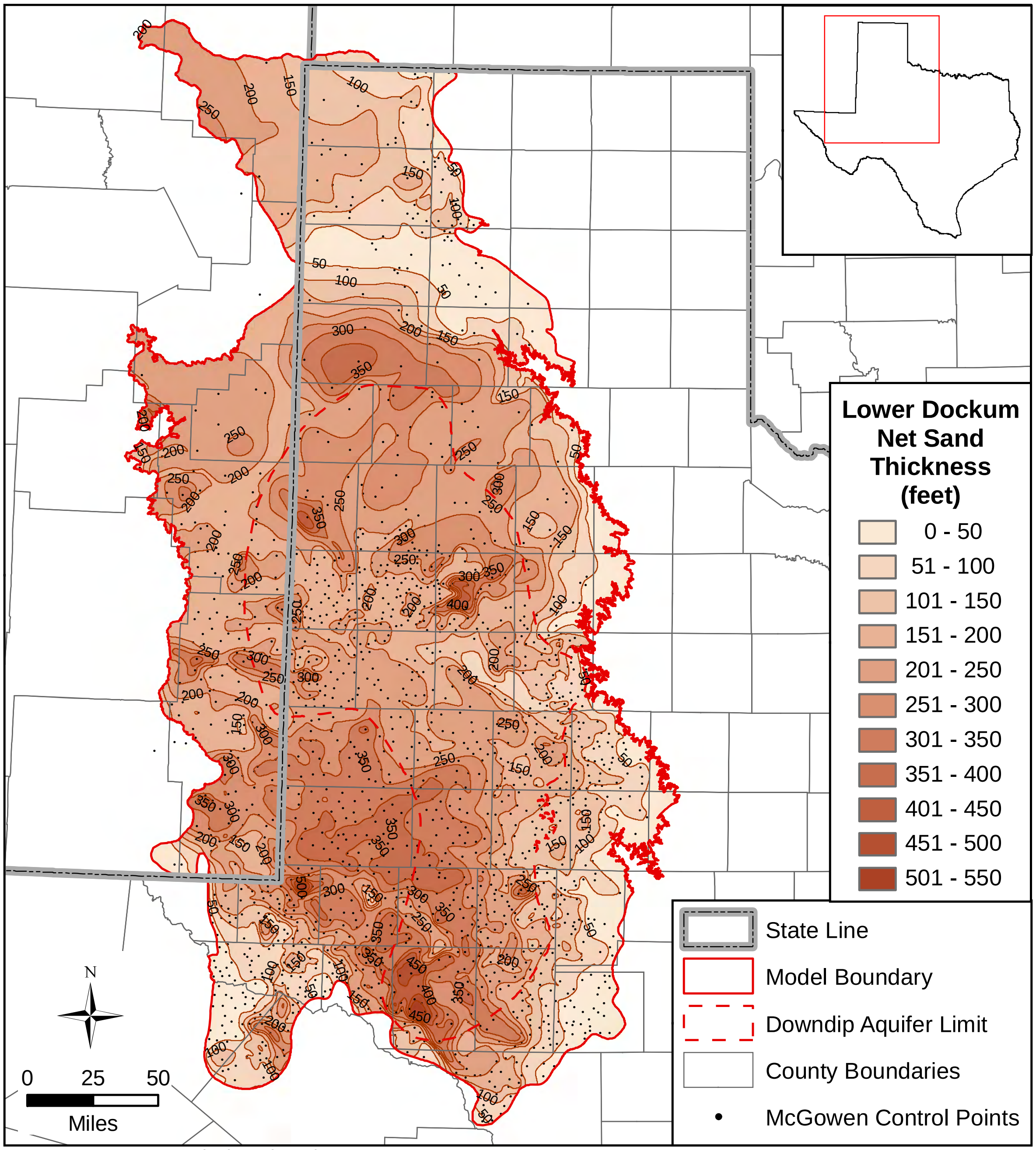


Figure 4.2.6 Net sand thickness of the upper portion of the Dockum Aquifer.



Source: McGowen and others (1977)

Figure 4.2.7 Net sand thickness of the lower portion of the Dockum Aquifer.

4.3 Water Level and Regional Groundwater Flow

An extensive literature search was conducted to understand regional groundwater flow and transient water level trends in the Dockum Aquifer. The literature search included a review of available reports by the various past and present Texas state agencies responsible for water resources, the Bureau of Economic Geology, and the New Mexico Bureau of Mines and Mineral Resources. In addition, water-level data provided by the TWDB on their website, obtained from the Panhandle Groundwater Conservation District, found in Texas Commission on Environmental Quality well records, found in New Mexico county reports, and obtained from the United States Geological Survey were used to (1) develop water-level elevation contours for the steady-state period, considered representative of predevelopment conditions, the start time for the transient model calibration period (January 1980), the middle time for the transient model calibration period (January 1990), and the end of the transient model (December 1997); (2) investigate transient water-level trends; and (3) investigate cross-formational flow.

The sources for the water-level data used for the Dockum Aquifer in Texas are the TWDB website (TWDB, 2007b) and the Panhandle Groundwater Conservation District. New Mexico data were obtained from the United States Geological Survey and found in New Mexico county reports. Locations and hydrostratigraphic units for Texas wells with water-level data in the Dockum Aquifer and in the Dockum Aquifer combined with an overlying or underlying aquifer are shown in Figure 4.3.1. A summary of the aquifer codes assigned to these wells along with the number of wells associated with each aquifer code is provided in Table 4.3.1. The locations for New Mexico wells with water-level data in the Dockum Aquifer are also shown in Figure 4.3.1. Some of the New Mexico data fall outside of the active model area because the entire Dockum Aquifer in New Mexico is not included in the Dockum Aquifer groundwater availability model.

According to the water-level data on the TWDB website, a total of 8,340 individual water-level measurements have been taken in 2,114 wells completed into the Dockum Aquifer or the Dockum Aquifer combined with an overlying or underlying aquifer. An additional 1,679 individual water-level measurements in 274 wells was provided by the Panhandle Groundwater Conservation District. The number of wells with water-level measurements in counties containing the Dockum Aquifer varies significantly as illustrated in Figure 4.3.2. The counties with the greatest number of wells are Mitchell, Potter, and Scurry. These are also counties where the Dockum Aquifer occurs in outcrop. Counties located in the central portion of the Dockum Group, beyond the downdip aquifer limit, contain few to no wells completed into the Dockum Group. The number of water-level measurements in counties containing the Dockum Aquifer also varies significantly as illustrated in Figure 4.3.3. The counties with large numbers of water-level measurements are those where the Dockum Aquifer outcrops (Mitchell, Scurry, Potter, Oldham, and Howard) as wells as Winkler and Ward counties in west Texas and Armstrong and Carson counties along the north-eastern boundary of the active model area. Very few water-level measurements have been made within the central part of the Dockum Group where there are few wells and the total dissolved solids concentrations in the groundwater is high.

In addition to varying by location, the frequency of water-level measurements has also varied with time (Figure 4.3.4). Note that the y-axis scale is 0 to 350 measurements for the Dockum Aquifer temporal distribution of water-level measurements and 0 to 150 measurements for all other measurements, and the x-axis scale is from 1900 to 2005. Figure 4.3.4 shows that many more water-level measurements have been made in wells completed into the Dockum Aquifer alone than wells completed into the Dockum Aquifer combined with an overlying or underlying aquifer. The first water-level measurement for a well completed only into the Dockum Aquifer reported on the TWDB website is in 1930 in Randall County and the greatest number of measurements were made in 1963, 1964, and 1961, predominantly in Mitchell County.

4.3.1 Regional Groundwater Flow

Groundwater within the Dockum Aquifer occurs under water-table conditions in the outcrop areas and confined or semi-confined conditions in the downdip areas. In some areas, sands in the lower portion of the Dockum Aquifer are semi-confined by mudstones in the upper portion of the Dockum Aquifer. Flow in the outcrop areas is controlled by topography with groundwater flowing locally toward the Colorado River or its principal tributaries in Mitchell County (Shamburger, 1967) and toward the Canadian River in Oldham and Potter counties. Bradley and Kalaswad (2003) state that groundwater in the Dockum Aquifer generally moves to the east and southeast.

The sparse water-level data in the Dockum Aquifer suggest southeastward groundwater flow (see Section 4.3.2). However, the spatial distribution of groundwater salinity, which shows higher salinity in the central portion of the aquifer and lower salinity at the aquifer margins (see Section 4.8), indicates that this may not be the case. Groundwater flow is most likely negligible in the center of the Dockum Aquifer and thus, is likely limited to the aquifer margins. Some groundwater flow to and from the Dockum Aquifer occurs vertically across formations (see Section 4.3.5). The conceptual model of groundwater flow in the Dockum Aquifer is provided in Section 5.0.

4.3.2 Predevelopment Conditions for the Dockum Aquifer

Predevelopment conditions are defined as those existing in the aquifer prior to any disturbances of natural groundwater flow due to artificial discharge via pumping. Literature information on the historical development of the Dockum Aquifer is sparse. County reports exist for only a few of the counties in which the Dockum Aquifer is located and most of those reports focus on the overlying Ogallala Aquifer.

The following information on well development in the Dockum Aquifer was obtained from date drilled and primary water use data found on the TWDB website. Note that there is some uncertainty with this information because a drill date is not available for every well and many of the early wells are identified as unused, so the original purpose for drilling the well is unknown. The first documented well in the Dockum Aquifer was completed in 1850 in Ward County. Two other wells are documented as being completed in the 1800s; another well in Ward County and one in Reagan County. This early well in Reagan County was completed into both the Dockum Aquifer and the overlying Antlers Sand. Most of the wells completed into the Dockum Aquifer in the late 1800s and early 1900s were used for domestic and stock purposes. The first wells identified with a use other than domestic or stock are public supply wells completed in 1926 in Mitchell and Scurry counties. Wells for industrial purposes were first completed into the Dockum Aquifer in 1930 and 1932 in Winkler and Ward counties, respectively. These wells were used in conjunction with the oil industry and were completed into both the Dockum and Pecos Valley aquifers. The first wells identified as irrigation wells were completed into the Dockum Aquifer in 1936 in Nolan County. Until 1953, all Dockum Aquifer irrigation wells were located in Mitchell, Nolan, or Scurry counties. Based on the available data from the

TWDB website, the order of the decades during which irrigation wells were completed into the Dockum Aquifer from the most number of wells to the least number of wells is 1970s, 1960s, 1950s, 1980s, 1990s, 1940s, and 1930s.

Dates of water-level measurements from the TWDB website indicate that the first water level was measured in a Dockum Aquifer well in 1908 in Garza County. This well was completed into both the Dockum Aquifer and overlying alluvium sediments. Measured water levels were not reported again in a Dockum Aquifer well until 1930 in Randall County. See Figure 4.3.4 for the frequency of water-level measurements in Dockum Aquifer wells after this time.

Predevelopment water-level elevations were generated for both the upper portion of the Dockum Aquifer, model layer 2, and the lower portion of the Dockum Aquifer, model layer 3. Because early measurements are not available for many portions of the aquifer, the predevelopment water-level elevations were generated using the maximum water levels measured in individual wells. The maximum values could be unusually high in some cases if they were measured during wet periods, however, they were considered the best data for use. In areas where numerous water-level measurements are available, the maximum from all the wells was selected for use, unless that value seemed significantly different from expected values based on the overall trend of the data. The water-level elevation contours for the predevelopment period are shown in Figures 4.3.5 and 4.3.6 for the upper and lower portions of the Dockum Aquifer, respectively. Note that contour lines on these figures are restricted to areas with data. The predevelopment contours were used as a general guideline in calibrating the steady-state model. The calibration targets for the steady-state model are given in Table 4.3.2.

In both the upper and lower portions of the Dockum Aquifer, predevelopment water levels are higher in the northwest and lower in the southeast. The predevelopment contours show flow in the lower portion of the Dockum Aquifer toward the Canadian River in Oldham and Potter counties. Flow towards the Colorado River and its tributaries in Mitchell County is indicated in the predevelopment contours. In Ward and Winkler counties in the southwestern portion of the model area, the predevelopment contours in the lower portion of the Dockum Aquifer suggest flow towards the Monument Draw Trough. Predevelopment water-level elevations in the upper portion of the Dockum Aquifer are higher than those in the lower portion of the Dockum

Aquifer. The magnitude of the differences between predevelopment water-level elevations in the upper and lower portions of the Dockum Aquifer is greatest in New Mexico and decreases towards the southeast. This observation is based on a very limited number of data points in the central portion of both the upper and lower parts of the aquifer.

4.3.3 Water-Level Elevations for Model Calibration

Transient model calibration considers the time period from January 1, 1980 to December 31, 1997. Water-level data obtained from the TWDB website, provided by the Panhandle Groundwater Conservation District, found in Texas Commission on Environmental Quality well records, and provided by the United States Geological Survey for New Mexico were used to develop water-level elevation contours for the start of calibration (January 1, 1980), the middle of the calibration period (January 1, 1990), and at the end of calibration (December 31, 1997). These contours aided in assessing the transient model's ability to represent observed conditions.

Water-level data are not available at regular time intervals in every well. Therefore, the coverage of water-level data for a particular month or even a year is very sparse. Since the amount of water-level data available for the times of interest were not sufficient to develop contours, data for the year of interest and for two years prior to and two years after the year of interest were used. If a well had only one water-level measurement during that time, that measurement was used. If a well had several water-level measurements during that time, the average of the water levels was used.

Figures 4.3.7 and 4.3.8 show the water-level elevations for the upper and lower portions of the Dockum Aquifer, respectively, at the start of model calibration (January 1, 1980). Due to a lack of data in the central and southern areas, the water-level elevations could not be contoured in the upper portion of the Dockum Aquifer. Therefore, Figure 4.3.7 shows posted values rather than contour lines. Data were sufficient to contour the water-level elevations in the lower portion of the Dockum Aquifer (see Figure 4.3.8). Contour lines on this figure are restricted to areas with data. In the lower portion of the Dockum Aquifer, a large cone of depression defined by a well in eastern Andrews County is apparent and small cones of depression are found in Mitchell, Scurry, Garza, Oldham, and eastern Deaf Smith-western Randall counties. The size of the large cone of depression defined by the well in eastern Andrews County is probably overstated due to the lack of data surrounding this well.

Figures 4.3.9 and 4.3.10 show the water-level elevations for the upper and lower portions of the Dockum Aquifer, respectively, for January 1, 1990. Due to a lack of data in the southern area, water-level elevations could not be contoured for the upper portion of the Dockum Aquifer. Therefore, Figure 4.3.9 shows posted values rather than contour lines. Data were sufficient to contour the water-level elevations for the lower portion of the Dockum Aquifer (see Figure 4.3.10). Contour lines in this figure are restricted to areas with data. In the lower portion of the Dockum Aquifer, the large cone of depression defined by the well in eastern Andrews County on the 1980 contours is absent. This is because no data were collected in that Andrews County well after 1982. A small cone of depression is observed in the lower portion of the Dockum Aquifer in Randall County. The differences in the locations of cones of depression in the lower portion of the Dockum Aquifer between 1980 and 1990 are most likely a function of where water-level measurements where taken for each time period rather than any significant changes in the character of aquifer pumpage.

Figures 4.3.11 and 4.3.12 show the water-level elevations for the upper and lower portions of the Dockum Aquifer, respectively, for the end of the model calibration period (December 31, 1997). Due to a lack of data in the central and southern area, water-level elevations could not be contoured for the upper portion of the Dockum Aquifer. Therefore, Figure 4.3.11 shows posted values rather than contour lines. Data were sufficient to contour the water-level elevations for the lower portion of the Dockum Aquifer (see Figure 4.3.12). Contour lines in this figure are restricted to areas with data. A small cone of depression in the lower portion of the Dockum Aquifer is seen in Borden County and also in Gaines County. Again, the differences in the locations of cones of depression in the lower portion of the Dockum Aquifer between 1990 and 1997 may be due to variations in locations of water-level measurements rather than to significant changes in the character of pumping in the aquifer.

4.3.4 Transient Water Levels

Figure 4.3.13 shows the locations for which transient water-level data were obtained from the TWDB website. These locations are defined as those that have at least ten water-level measurements over time. Transient data are available for 10 wells completed into the upper portion of the Dockum Aquifer and 230 wells completed into the lower portion of the Dockum Aquifer. In most cases, the transient data include measurements during the transient model calibration period of 1980 through 1997. Generation of hydrographs of the transient data assumed that the aquifer codes given on the TWDB website accurately represent the aquifer(s) into which the wells are completed. Most of the hydrographs shown in Figures 4.3.14 through 4.3.20 are plotted with a 100-foot elevation difference on the y-axis. In some cases, the difference in water-level elevations was greater than 100 feet and the y-axis had to be expanded. In all cases, the interval between grid lines on the y-axis is 10 feet.

Seven of the wells completed into the upper portion of the Dockum Aquifer with transient water-level data show less than a 15 feet change over time periods ranging from 15 to 40 years. Two other wells, which are both completed into the upper portion of the Dockum Aquifer and the overlying Ogallala Aquifer, show a decline in water level. One well, located in Deaf Smith County, shows about a 40-foot decline over a period of 12 years and the other well, located in Swisher County, shows a 63-foot decline over a period of 30 years. One of the wells, which is completed into the upper portion of the Dockum Aquifer and located in Deaf Smith County, shows water-level fluctuations of about 50 feet over a 40-year time period. Figure 4.3.14 shows example hydrographs for wells completed into the upper portion of the Dockum Aquifer or into the upper portion of the Dockum Aquifer and the overlying Ogallala Aquifer.

Table 4.3.3 summarizes the transient water-level data for wells completed into the lower portion of the Dockum Aquifer and the Ogallala Aquifer, to the lower portion of the Dockum Aquifer only, and into the lower portion of the Dockum Aquifer and the Pecos Valley Aquifer. These data are summarized as to whether the overall trend in the observed water levels is decreasing, stable, or increasing. The overall trend is taken as the overall change from the first water-level measurement to the last water-level measurement. Therefore, wells with increasing and decreasing trends may not have had constant increasing or decreasing water levels. In the same way, wells with a stable trend may have had variable water levels with time, but from first measurement to last measurement the water level is nearly the same (i.e., within 30 feet). Almost all of the hydrographs have at least a 20-year record and most have measurements through 2000. A number of counties have no entries in this table because there are no transient water-level data in those counties.

For wells completed into both the lower portion of the Dockum Aquifer and the Ogallala Aquifer, the transient data indicate that the water level has decreased over time in 67 percent of those wells, increased over time in 13 percent of the wells, and remained relatively stable in 21 percent of the wells (see Table 4.3.3). The decrease in water level with time is most dramatic in Moore County where water levels have declined over 120 feet in time periods ranging from 20 to 45 years. There are also wells in Moore County, however, that show only about a 10-foot decline in water level over a 20-year period. In several counties, the water level in wells completed into the lower portion of the Dockum Aquifer and the Ogallala Aquifer have not declined, but rather have remained stable or increased. The highest increase is about 40 feet in a well in Randall County but, typically, increases are on the order of 10 feet. Example hydrographs for wells completed into the lower portion of the Dockum Aquifer and the Ogallala Aquifer are shown in Figures 4.3.15 and 4.3.16.

For wells completed to only the lower portion of the Dockum Aquifer, the transient data indicate that the water level has decreased over time in 31 percent of those wells, increased over time in 47 percent of the wells, and remained relatively stable in 22 percent of the wells (see Table 4.3.3). The typical decline in water level is between 5 and 20 feet with only a few wells showing a greater than 30-foot decline. The largest declines are about 120 feet observed in a well located in Deaf Smith County and about 100 feet observed in a well located in Ector County. In the outcrop areas in Mitchell, Nolan, and Scurry counties, there are more wells with increasing or stable water levels than with decreasing water levels. The largest increase in water level is about 80 feet observed in a well in Nolan County. Example hydrographs for wells completed only into the lower portion of the Dockum Aquifer can be found in Figures 4.3.15 through 4.3.20.

For wells completed into the lower portion of the Dockum Aquifer and the overlying Pecos Valley Aquifer, the transient data indicate that the water level has decreased over time in 39 percent of the wells, increased over time in 17 percent of the wells, and remained relatively stable in 44 percent of the wells (see Table 4.3.3). The largest declines in water level are 50 to 120 feet observed in wells located in Pecos and Reeves counties. In these two counties, only declining water levels have been observed in wells completed into the lower portion of the Dockum Aquifer and the Pecos Valley Aquifer. The observed increases in water level are in the range of 15 to 20 feet and occur in wells located in Ward and Winkler counties. Wells with stable water levels have been observed in these two counties as well as in Sterling County. Example hydrographs for wells completed into the lower portion of the Dockum Aquifer and the Pecos Valley Aquifer can be found on Figures 4.3.19 and 4.3.20.

An attempt was made to analyze the transient water-level data for the upper and lower portions of the Dockum Aquifer with respect to seasonal fluctuations. This analysis could not be performed, however, because measurements of water levels at a frequency sufficient for evaluation of seasonal changes were not taken in any well completed into the Dockum Aquifer.

4.3.5 Cross-Formational Flow

An exercise was conducted to investigate cross-formational flow between the Dockum Aquifer and the underlying Permian-age rock and the overlying Ogallala, Rita Blanca, Edwards-Trinity (High Plains), Pecos Valley, and Edwards-Trinity (Plateau) aquifers. At several places within the active model area, wells completed separately into the Dockum Aquifer and into overlying aquifers or the underlying Permian-age sediments share a similar ground-surface location. The wells at these locations were used to assess upward or downward hydraulic gradients indicative of cross-formational flow to or from the Dockum Aquifer. This analysis did not include wells completed across multiple aquifers.

Figures 4.3.21 through 4.3.23 show water-level elevations for wells completed into the Dockum Aquifer and wells completed into the overlying Ogallala Aquifer having similar ground-surface locations. These figures show that water levels in the Dockum and Ogallala aquifers are at similar elevations in Castro, Crosby, Floyd, Hartley, Moore, Oldham, and northeastern Randall counties suggesting hydraulic connection between the two aquifers in these locations. Wells in the northwestern portion of Deaf Smith County show the water-level elevation in the Dockum Aquifer about 15 feet higher than that in the Ogallala Aquifer, while wells in the north-central and southeastern portion of the county show water-level elevations in the Ogallala Aquifer over 300 feet higher than those in the Dockum Aquifer. Wells in southwestern Randall County show water-level elevations in the Ogallala Aquifer over 60 feet higher than those in the Dockum Aquifer. In Swisher County, a comparison of two wells shows water-level elevations in the Ogallala Aquifer about 300 feet higher than those in the Dockum Aquifer. Based on two wells in each county, the water-level elevation in the Ogallala Aquifer is about 600 feet higher than in the Dockum Aquifer in Gaines County and about 1,000 feet higher in Andrews County. In general, the locations at which the water-level elevation in the Ogallala and Dockum aquifers are similar are locations where the upper portion of the Dockum Aquifer is missing and the Ogallala Aquifer lies directly on the lower portion of the Dockum Aquifer.

At locations where the water-level elevation in the Ogallala Aquifer is higher than in the Dockum Aquifer, a potential exists for downward vertical flow from the Ogallala Aquifer to the Dockum Aquifer. The fact that the water levels are significantly different suggests that, in these areas, vertical hydraulic connection between these two aquifers is poor. This conclusion is supported by the fact that the groundwater in the Dockum Aquifer in these areas is, in general, isotopically and chemically different from the groundwater in the Ogallala Aquifer (Dutton and Simpkins 1986; Nativ, 1988). The locations with water-level elevations in the Ogallala Aquifer significantly higher than in the Dockum Aquifer lie, in general, within areas where the upper portion of the Dockum Aquifer is present. The lack of communication between the Ogallala and Dockum aquifers in these areas is likely due to the presence of low permeability mudstones in the upper portion of the Dockum Aquifer restricting downward flow. In addition to this explanation, Dutton and Simpkins (1986) also suggest that the high difference in water-level elevation "might reflect … a decrease of ground water stored in the Dockum Group due to the present lack of substantial recharge and the continuation of discharge in springs and seeps along the Eastern Caprock Escarpment and the western part of the Rolling Plains." Because of the large differences in water-level elevations, cross-formational flow from the Ogallala Aquifer to the Dockum Aquifer must be much less than the present recharge rate to the Ogallala Aquifer of 0.188 inches per year (Dutton and Simpkins, 1986).

Based on comparisons in hydraulic head and water chemistry, Nativ (1988) states that upward flow from the Dockum Aquifer to the Ogallala Aquifer is likely in some areas. These areas include Crosby, northwest Deaf Smith, Dickens, Garza, Howard, and Parmer counties. Nativ (1988) also states that it is possible that upward flow from the Dockum Aquifer to the Ogallala

Aquifer occurs at other areas along the escarpment although this can not be verified because the potentiometric surface of the Dockum Aquifer is poorly known in these areas. Water-level elevations in Deaf Smith and Oldham counties (see Figure 4.3.21) also show a potential for upward flow from the Dockum Aquifer into the Ogallala Aquifer.

Figure 4.3.24 shows water-level elevations for wells completed into the Dockum Aquifer and wells completed into the Pecos Valley Aquifer having similar ground-surface locations. At four of the six locations, the water-level elevations are similar in both aquifers suggesting that they are hydraulically connected at those locations. Garza and Wesselman (1959) state that the Pecos Valley and Dockum aquifers are in hydraulic communication in some parts of Winkler County. In these areas, precipitation percolates into the Pecos Valley Aquifer and then flows into the Dockum Aquifer. The amount of cross-formation flow from the Pecos Valley Aquifer to the Dockum Aquifer will be less than the amount of recharge to the Pecos Valley Aquifer. Through model calibration, Anaya and Jones (2004) estimate that recharge to the Pecos Valley Aquifer north of the Pecos River is about 3 percent of the annual precipitation in the area.

At one location in Pecos County, the water-level elevation in the Dockum Aquifer is about 150 feet higher than that in the Pecos Valley Aquifer suggesting the potential for upward flow from the Dockum Aquifer to the Pecos Valley Aquifer. This location is very near the Monument Draw Trough where the Dockum Aquifer subcrops to the Pecos Valley Aquifer. It is expected that the Dockum Aquifer discharges to the Pecos Valley Aquifer along the trough. At this location, however, the total dissolved solids concentration of groundwater in the Dockum Aquifer is much higher than that of groundwater in the Pecos Valley Aquifer indicating that the rate of this discharge is very slow. This is consistent with the observation of a large head difference between the two aquifers. At many other locations along the Monument Draw Trough, the total dissolved solids concentration of groundwater in the Dockum Aquifer is about the same as that of groundwater in the Pecos Valley Aquifer. The assessment of potential discharge from the Dockum Aquifer to the Pecos Valley Aquifer at these locations is not possible, however, due to a lack of wells with similar locations but completed separately into the two aquifers.

At a location in Ward County, the water-level elevation in the Pecos Valley Aquifer ranges from about 50 to 120 feet higher than that in the Dockum Aquifer suggesting little communication between the aquifers at this location. Garza and Wesselman (1959) state that, in some areas of Winkler County, the Chinle Formation of the upper portion of the Dockum Aquifer is present and hydraulically separates the Santa Rosa Formation of the lower portion of the Dockum Aquifer from the Pecos Valley Aquifer. Mudstones in the Chinle Formation likely act as a confining layer restricting downward flow.

Similar surface locations for wells completed into the Dockum Aquifer and wells completed into overlying sediments of Cretaceous age were found at nine locations (Figures 4.3.25 and 4.3.26). In Gaines County, a well completed into the Cretaceous system appears to have a water-level elevation about 800 feet higher than a nearby well completed into the Dockum Aquifer. This comparison is uncertain, however, because the dates of the measurements in each well are not the same (see Figure 4.3.25).

Comparisons between the Antlers Sand of the Trinity Group in the Edwards-Trinity (Plateau) Aquifer and the Dockum Aquifer can be made at several locations (see Figures 4.3.25 and 4.3.26). In Sterling and Upton counties, the water-level elevation in the Antlers Sand is about 10 to 125 feet higher than in the Dockum Aquifer. In Reagan County, the situation is reversed, with the water-level elevation in the Dockum Aquifer about 15 to 20 feet higher than in the Antlers Sand. In Ector County, one well-pair shows very similar water-level elevations in both aquifers. A visual comparison of the predevelopment water-level elevations for the lower portion of the Dockum Aquifer (see Figure 4.3.6) and interpolated water-level elevations for the Trinity Group from the Edwards-Trinity (Plateau) and Cenozoic Pecos Alluvium groundwater availability model (Anaya and Jones, 2004) shows water-level elevations in the Trinity Group 300 to 400 feet higher than those in the Dockum Aquifer. A well pair in Crockett County shows water-level elevations in the Cretaceous system about 60 feet higher than those in the Dockum Aquifer.

Nativ and Gutierrez (1988) state that the potentiometric surface of Cretaceous aquifers in the Texas Panhandle is higher than that of the Dockum Aquifer suggesting the possibility of downward flow from the Cretaceous or Edwards-Trinity (High Plains) Aquifer to the Dockum Aquifer. They indicate, however, that this cannot be verified using chemical or isotopic data because of the limited number of wells completed into the Dockum Aquifer in this area.

Although not mentioned by Nativ and Gutierrez (1988), it is likely that mudstones of the upper portion of the Dockum Aquifer probably limit downward flow from the Edwards-Trinity (High Plains) Aquifer to the Dockum Aquifer as they limit downward flow from the Ogallala Aquifer to the Dockum Aquifer where they are present. Fallin (1989) states that vertical leakage from the Edwards-Trinity (High Plains) Aquifer to the Dockum Aquifer "occurs at isolated locations, particularly in parts of Borden, Cochran, Dawson, Floyd, and Yoakum Counties, Texas, and in Lea and Roosevelt Counties, New Mexico, where coarse-grained fluvial-deltaic deposits occur in the upper parts of the Late Triassic [Dockum] section".

Walker (1979) indicates that the Santa Rosa Sandstone of the lower portion of the Dockum Aquifer is in hydraulic communication with the overlying Edwards-Trinity (Plateau) Aquifer in parts of Crockett, Irion, Reagan, and Sterling counties. Chemical analyses of groundwater from several Dockum Aquifer wells in Sterling County suggest "some groundwater movement from the limestone-dominated Edwards-Trinity (Plateau) Aquifer into the Dockum Aquifer" (Bradley and Kalaswad, 2003). The amount of cross-formational flow from the Edwards-Trinity (Plateau) Aquifer to the Dockum Aquifer will most likely be much less than the amount of recharge to the Edwards-Trinity (Plateau) Aquifer. Through model calibration, Anaya and Jones (2004) estimate that recharge to the Edwards-Trinity (Plateau) Aquifer, where it overlies the Dockum Aquifer, ranges from 1 to 3 percent of the annual precipitation.

A comparison between water-level elevations in the Dockum Aquifer to those in the underlying Permian-age sediments could be conducted for six locations (Figure 4.3.27). In every instance, the water-level elevation in the Dockum Aquifer is higher than that in the Permian-age sediments, with the difference ranging from less than 10 feet to over 50 feet along the eastern margin of the Dockum Aquifer and is over 100 feet in Loving County located in the southwestern portion of the active model area. These comparisons suggest a potential for downward flow from the Dockum Aquifer to the underlying Permian-age sediments.

Evaluation of the cross-formational flow of groundwater from or to overlying and underlying formations is uncertain because there is limited information available. The role of cross-formational flow in the overall conceptualization of groundwater flow in the Dockum Aquifer is discussed in Section 5.0.

Table 4.3.1 Summary of aquifer codes for wells completed into the Dockum Aquifer and the Dockum Aquifer combined with an overlying or underlying aquifer.

TWDB Aquifer Code	Description	Number of Wells from the TWDB Database	Number of Wells from the Panhandle Groundwater Conservation District
100CPDG	Cenozoic Pecos Alluvium and Dockum Formation	231	0
110CPDR	Cenozoic Pecos Alluvium and Dockum and Rustler Formations	1	0
110AVDK	Alluvium and Dockum Formation	9	0
121OGDK	Ogallala Formation and Dockum Formation	287	173
218ASDB	Antlers Sand and Dockum Formation	88	0
218EDAD	Edwards and Associated Limestones, Antlers Sand, and Dockum Formation	11	0
231DCKM	Dockum Formation	1455	99
231DCKP	Dockum Formation and Permian Rocks	32	2

Table 4.3.2 Target values for calibration of the steady-state model to predevelopment conditions.

Well Number or Location	County	Measurement Date	Observed Water-Level Elevation (feet)	Source of Observed Data
Upper portion of the Dockum Aquifer				
335720103521801	Chaves	2/17/1994	4696.0	United States Geological Survey
334312103452201	Chaves	2/3/1994	4385.0	United States Geological Survey
332224103455601	Chaves	1/17/1961	4464.0	United States Geological Survey
28-17-5	Dawson	7/30/1996	2951.1	Texas Commission on Environmental Quality well records
908301	Deaf Smith	11/3/2005	4432.0	TWDB website
1001601	Deaf Smith	11/2/2005	4275.0	TWDB website
10-10-8	Deaf Smith	5/1/1971	4074.4	Texas Commission on Environmental Quality well records
45-05-5	Ector	7/4/1977	2999.7	Texas Commission on Environmental Quality well records
45-21-5	Ector	12/5/1973	2978.3	Texas Commission on Environmental Quality well records
330741103052701	Lea	1/14/1994	3810.0	United States Geological Survey
325424103113301	Lea	4/19/1993	3753.0	United States Geological Survey
323608103073501	Lea	9/30/1993	3570.0	United States Geological Survey
T21SR33E28	Lea	6/30/1954	3690.0	New Mexico County Report
T24SR33E23	Lea	11/27/1953	3565.0	New Mexico County Report
23-19-5	Lubbock	2/12/1999	3206.4	Texas Commission on Environmental Quality well records
23-36-7	Lubbock	2/22/1999	3062.2	Texas Commission on Environmental Quality well records
45-07-5	Midland	11/10/1973	2861.1	Texas Commission on Environmental Quality well records
45-16-5	Midland	1/18/1978	2734.6	Texas Commission on Environmental Quality well records
10-19-5	Parmer		4010.0	Texas Commission on Environmental Quality well records
10-26-5	Parmer		4142.9	Texas Commission on Environmental Quality well records
10-28-5	Parmer	12/16/1970	4028.8	Texas Commission on Environmental Quality well records
345350104033601	Quay	3/3/1977	5358.0	United States Geological Survey
344940103410501	Quay	7/30/1955	4889.0	United States Geological Survey
344514104064001	Quay	1/7/1977	5144.0	United States Geological Survey
344407103523901	Quay	4/30/1987	4803.0	United States Geological Survey
343929104012401	Quay	8/23/1955	4922.0	United States Geological Survey
344012103452801	Quay	8/20/1955	4702.0	United States Geological Survey
1016702	Randall	12/10/1998	3811.0	TWDB website
341132103004401	Roosevelt	8/15/1992	3970.0	United States Geological Survey
Lower portion of the Dockum Aquifer				
2750201	Andrews	10/11/1979	3233.8	TWDB website
1106803	Armstrong	4/1/1993	3135.9	TWDB website
1106906	Armstrong	4/1/1993	3156.2	TWDB website
1104501	Armstrong	3/30/1966	3198.0	TWDB website
1105601	Armstrong	11/15/1979	3202.7	TWDB website
1105304	Armstrong	10/19/2000	3251.3	TWDB website
661401	Armstrong	10/29/1954	3298.8	TWDB website

Table 4.3.2, continued

Well Number or Location	County	Measurement Date	Observed Water-Level Elevation (feet)	Source of Observed Data
Lower portion of the Dockum Aquifer, continued				
1148103	Briscoe	9/23/1981	2644.2	TWDB website
1139904	Briscoe	9/17/1981	2790.8	TWDB website
1121604	Briscoe	9/21/1981	3002.1	TWDB website
1130201	Briscoe	9/16/1946	3066.0	TWDB website
1024307	Castro	6/30/1964	3576.5	TWDB website
4528702	Crane	12/20/1954	2632.0	TWDB website
4460803	Crockett	9/27/1995	2366.0	TWDB website
2340402	Crosby	6/18/1996	2377.7	TWDB website
2339501	Crosby	1/6/1977	2454.1	TWDB website
2331501	Crosby	7/18/2000	2716.6	TWDB website
2316802	Crosby	12/13/1983	2760.4	TWDB website
2315603	Crosby	1/31/1975	2782.0	TWDB website
343315103102701	Curry	4/20/1994	3988.0	United States Geological Survey
02-35-5	Dallam	11/12/1979	4116.6	Texas Commission on Environmental Quality well records
02-41-5	Dallam	2/17/1968	4417.2	Texas Commission on Environmental Quality well records
750702	Deaf Smith	5/20/1980	4112.0	TWDB website
2226105	Dickens	12/6/1967	2477.1	TWDB website
2226101	Dickens	9/16/1947	2480.2	TWDB website
2226202	Dickens	11/30/1944	2481.0	TWDB website
2226201	Dickens	8/17/1995	2482.4	TWDB website
2226102	Dickens	11/30/1935	2493.0	TWDB website
2226104	Dickens	12/11/1997	2504.2	TWDB website
2210831	Dickens	6/3/1983	2527.0	TWDB website
2217902	Dickens	2/20/1946	2527.0	TWDB website
2210830	Dickens	6/3/1983	2530.9	TWDB website
2217601	Dickens	9/15/1988	2540.6	TWDB website
2210829	Dickens	5/18/1983	2552.8	TWDB website
2218701	Dickens	9/29/1967	2625.8	TWDB website
2218103	Dickens	5/18/1983	2633.7	TWDB website
2209401	Dickens	7/9/1966	2673.0	TWDB website
2209701	Dickens	6/30/1966	2723.0	TWDB website
4519101	Ector	12/7/1966	2707.2	TWDB website
4513201	Ector	12/15/1970	2880.6	TWDB website
2927601	Fisher	9/12/1989	2357.5	TWDB website
1156103	Floyd	11/21/1968	2662.0	TWDB website
1156801	Floyd	12/11/1968	2737.7	TWDB website
1156104	Floyd	11/22/1968	2741.2	TWDB website
1155301	Floyd	11/21/1968	2754.0	TWDB website
1156106	Floyd	11/22/1968	2765.2	TWDB website
1164202	Floyd	12/13/1968	2794.8	TWDB website
1155302	Floyd	11/21/1968	2804.9	TWDB website
1164209	Floyd	12/14/1968	2804.9	TWDB website
1164503	Floyd	12/14/1968	2815.6	TWDB website
1164802	Floyd	12/16/1968	2820.3	TWDB website
1164212	Floyd	12/14/1968	2823.9	TWDB website

Table 4.3.2, continued

Well Number or Location	County	Measurement Date	Observed Water-Level Elevation (feet)	Source of Observed Data
Lower portion of the Dockum Aquifer, continued				
1156503	Floyd	11/25/1968	2834.2	TWDB website
1156805	Floyd	9/6/1938	2835.5	TWDB website
1156701	Floyd	12/2/1938	2874.7	TWDB website
1155210	Floyd	7/20/2000	2897.4	TWDB website
1155803	Floyd	1/11/2001	2930.1	TWDB website
1155201	Floyd	12/12/1963	2942.5	TWDB website
1147501	Floyd	12/10/1968	2972.8	TWDB website
2364402	Garza	3/5/1982	2330.2	TWDB website
2346201	Garza	12/29/1960	2338.1	TWDB website
2348101	Garza	6/28/1976	2385.0	TWDB website
07-14-3	Hartley		3538.5	Texas Commission on Environmental Quality well records
07-06-1	Hartley	6/11/1996	3775.0	Texas Commission on Environmental Quality well records
07-03-3	Hartley		3859.3	Texas Commission on Environmental Quality well records
07-02-8	Hartley	1/23/1984	3865.5	Texas Commission on Environmental Quality well records
02-60-7	Hartley		3951.5	Texas Commission on Environmental Quality well records
02-59-9	Hartley		4072.7	Texas Commission on Environmental Quality well records
719501	Hartley	2/14/1980	3648.3	TWDB website
726101	Hartley	7/14/1983	3658.2	TWDB website
2838601	Howard	8/8/1961	2244.7	TWDB website
2829903	Howard	6/3/1936	2265.6	TWDB website
2855101	Howard	9/23/1986	2333.5	TWDB website
2828805	Howard	1/16/1990	2620.2	TWDB website
4341303	Irion	8/9/1940	2148.8	TWDB website
2364901	Kent	8/21/1995	2301.3	TWDB website
323942103035901	Lea	5/25/1993	3449.0	United States Geological Survey
T23SR36E16	Lea	1952	3315.0	New Mexico County Report
T21SR34E13	Lea	1943	3455.0	New Mexico County Report
T26SR34E6	Lea	7/23/1954	3188.1	New Mexico County Report
4605404	Loving	1/9/1979	3032.0	TWDB website
2942601	Mitchell	1/21/1964	2105.2	TWDB website
2934818	Mitchell	3/7/1979	2112.0	TWDB website
2934501	Mitchell	5/15/1946	2127.0	TWDB website
2934414	Mitchell	12/31/1963	2170.9	TWDB website
2934904	Mitchell	12/2/1959	2171.3	TWDB website
2935511	Mitchell	12/31/1963	2202.8	TWDB website
2832903	Mitchell	6/30/1963	2202.9	TWDB website
2943802	Mitchell	11/9/1975	2203.8	TWDB website
2839901	Mitchell	6/30/1963	2210.6	TWDB website
2934307	Mitchell	5/31/1963	2224.0	TWDB website
2840103	Mitchell	7/20/1960	2239.3	TWDB website
2832703	Mitchell	6/30/1963	2245.5	TWDB website

Table 4.3.2, continued

Well Number or Location	County	Measurement Date	Observed Water-Level Elevation (feet)	Source of Observed Data
Lower portion of the Dockum Aquifer, continued				
2926901	Mitchell	6/4/1963	2295.9	TWDB website
2926802	Mitchell	3/3/1961	2308.6	TWDB website
2927802	Mitchell	3/31/1963	2341.7	TWDB website
2927902	Mitchell	10/7/1981	2373.1	TWDB website
2856902	Mitchell	10/31/1962	2564.7	TWDB website
2210203	Motley	1/31/1969	2496.0	TWDB website
2210202	Motley	1/31/1969	2497.0	TWDB website
2202101	Motley	10/23/1939	2547.2	TWDB website
2209303	Motley	11/3/1959	2570.4	TWDB website
2209301	Motley	11/3/1959	2575.0	TWDB website
2201302	Motley	5/31/1967	2578.0	TWDB website
2201905	Motley	11/3/1959	2583.4	TWDB website
2201913	Motley	11/8/1979	2602.0	TWDB website
2201904	Motley	12/1/1977	2607.7	TWDB website
2201912	Motley	10/27/1939	2612.7	TWDB website
1156502	Motley	11/25/1968	2648.1	TWDB website
2201909	Motley	12/6/1974	2648.2	TWDB website
2209101	Motley	10/22/1981	2680.8	TWDB website
2201801	Motley	10/26/1939	2694.2	TWDB website
2201501	Motley	12/18/1968	2694.7	TWDB website
2201205	Motley	12/20/1968	2695.2	TWDB website
2201301	Motley	10/9/1968	2703.6	TWDB website
1164303	Motley	12/12/1968	2708.7	TWDB website
2201201	Motley	10/31/1966	2710.0	TWDB website
2201203	Motley	12/17/1968	2715.8	TWDB website
2201702	Motley	11/8/1979	2731.7	TWDB website
1164601	Motley	9/24/1968	2736.5	TWDB website
2201204	Motley	5/31/1966	2737.0	TWDB website
2201701	Motley	12/19/1968	2742.7	TWDB website
2201105	Motley	12/17/1968	2746.8	TWDB website
2201402	Motley	10/25/1939	2751.5	TWDB website
2201401	Motley	11/1/1939	2766.1	TWDB website
1164301	Motley	12/12/1968	2775.7	TWDB website
1164901	Motley	10/10/1968	2781.6	TWDB website
2308302	Motley	6/15/1937	2799.8	TWDB website
2308602	Motley	9/30/1939	2801.0	TWDB website
2308901	Motley	6/30/1966	2803.0	TWDB website
2308601	Motley	10/31/1939	2805.9	TWDB website
1164904	Motley	10/31/1959	2816.0	TWDB website
2936108	Nolan	7/19/1983	2319.3	TWDB website
2943602	Nolan	1/5/1993	2331.1	TWDB website
2936208	Nolan	5/16/1991	2336.8	TWDB website
2944205	Nolan	10/15/1987	2361.4	TWDB website
2936107	Nolan	12/1/1981	2369.1	TWDB website
2936704	Nolan	1/31/1963	2371.6	TWDB website
2936824	Nolan	12/15/1972	2385.0	TWDB website
07-38-9	Oldham	Mar-76	3514.0	Texas Commission on Environmental Quality well records

Table 4.3.2, continued

Well Number or Location	County	Measurement Date	Observed Water-Level Elevation (feet)	Source of Observed Data
Lower portion of the Dockum Aquifer, continued				
07-23-7	Oldham	2/12/1999	3528.1	Texas Commission on Environmental Quality well records
07-55-2	Oldham	6/5/1971	3730.6	Texas Commission on Environmental Quality well records
07-46-8	Oldham	2/1/1989	3822.9	Texas Commission on Environmental Quality well records
07-50-6	Oldham		4085.8	Texas Commission on Environmental Quality well records
737101	Oldham	4/5/1974	3503.0	TWDB website
734501	Oldham	12/8/1988	3614.7	TWDB website
726301	Oldham	10/16/1977	3651.0	TWDB website
746901	Oldham	3/20/1973	3693.3	TWDB website
725201	Oldham	10/1/1968	3740.0	TWDB website
743501	Oldham	12/6/1987	3878.1	TWDB website
832601	Oldham	11/1/2005	3906.6	TWDB website
743401	Oldham	12/12/2001	3909.2	TWDB website
742901	Oldham	1/11/1977	3911.2	TWDB website
651102	Potter		3432.3	TWDB website
650401	Potter	12/17/2002	3511.1	TWDB website
642903	Potter	9/6/1979	3516.5	TWDB website
641701	Potter	10/31/1975	3528.0	TWDB website
659901	Randall	11/7/2005	3285.6	TWDB website
1102701	Randall	1/4/1980	3514.6	TWDB website
1016802	Randall	11/12/1963	3573.0	TWDB website
1016104	Randall	12/11/2002	3574.8	TWDB website
4436809	Reagan	5/10/1983	2465.8	TWDB website
4427804	Reagan	3/30/1966	2528.5	TWDB website
4654601	Reeves	1/29/1959	2628.7	TWDB website
4661101	Reeves	12/9/1948	2768.5	TWDB website
341655103182801	Roosevelt	2/28/1993	4020.0	United States Geological Survey
341514103402101	Roosevelt	2/3/1994	4105.0	United States Geological Survey
2831301	Scurry	7/23/1970	2210.7	TWDB website
2832301	Scurry	3/9/1971	2234.6	TWDB website
2832207	Scurry	9/23/1986	2239.3	TWDB website
2917308	Scurry	9/25/1970	2284.0	TWDB website
2917601	Scurry	4/18/1975	2287.0	TWDB website
2918401	Scurry	10/31/1969	2300.0	TWDB website
2917209	Scurry	7/13/1983	2315.4	TWDB website
2909705	Scurry	2/10/1961	2321.8	TWDB website
2901601	Scurry	7/23/1957	2323.4	TWDB website
2917402	Scurry	1/21/1993	2324.2	TWDB website
2909905	Scurry	6/1/1971	2335.0	TWDB website
2909707	Scurry	8/12/1978	2345.0	TWDB website
2910601	Scurry	7/20/1983	2395.1	TWDB website
2927703	Scurry	2/14/1961	2395.6	TWDB website
2824201	Scurry	11/24/1967	2404.0	TWDB website

Table 4.3.2, continued

Well Number or Location	County	Measurement Date	Observed Water-Level Elevation (feet)	Source of Observed Data
Lower portion of the Dockum Aquifer, continued				
2824304	Scurry	4/26/1978	2416.0	TWDB website
2815302	Scurry	3/16/1961	2576.1	TWDB website
4408604	Sterling	6/22/1976	2439.0	TWDB website
T31NR34E11	Union		4681.0	New Mexico County Report
T31NR33E12	Union	11/14/1955	4815.0	New Mexico County Report
T31NR32E13	Union	11/15/1955	5103.0	New Mexico County Report
T32NR31E34	Union	12/5/1955	5263.0	New Mexico County Report
4539904	Upton	3/19/1966	2619.0	TWDB website
4630201	Ward	10/2/1967	2728.2	TWDB website
4616213	Winkler	10/31/1953	2806.0	TWDB website
4608512	Winkler	1/14/1982	2888.0	TWDB website

Table 4.3.3 Summary of transient water-level data for wells completed into the lower portion of the Dockum Aquifer.

County	Lower portion of the Dockum Aquifer and Ogallala Aquifer Wells			Lower portion of the Dockum Aquifer Wells			Lower portion of the Dockum Aquifer and Pecos Valley Aquifer Wells		
	Overall Decrease	Overall Stable	Overall Increase	Overall Decrease	Overall Stable	Overall Increase	Overall Decrease	Overall Stable	Overall Increase
Andrews				1					
Armstrong		2	3	1	2	2			
Bailey									
Borden				1		1			
Briscoe			1						
Carson	2	1							
Castro									
Cochran									
Crane						1			
Crockett									
Crosby		2		1					
Dallam	7	2							
Dawson									
Deaf Smith	3			1		1			
Dickens					1	1			
Ector				1					
Fisher						1			
Floyd					1				
Gaines									
Garza			1			1			
Glasscock									
Hale									
Hartley	2								
Hockley									
Howard						2			
Irion									
Kent				1					
Lamb									
Loving				1	1				
Lubbock									
Lynn									
Martin									
Midland									
Mitchell				4	10	28			
Moore	19	2		1	1				
Motley	1		1	4	1				
Nolan				3	1	7			
Oldham	3	1		3	3	1			

Table 4.3.3, continued

County	Lower portion of the Dockum Aquifer and Ogallala Aquifer Wells			Lower portion of the Dockum Aquifer Wells			Lower portion of the Dockum Aquifer and Pecos Valley Aquifer Wells		
	Overall Decrease	Overall Stable	Overall Increase	Overall Decrease	Overall Stable	Overall Increase	Overall Decrease	Overall Stable	Overall Increase
Parmer	2								
Pecos							5		
Potter				1	1				
Randall	3	3	2	2	1	1			
Reagan									
Reeves				10	1		2		
Scurry				4	4	19			
Sherman									
Sterling					1	1		2	
Swisher				1		1			
Terry									
Upton						1			
Ward				3	3			4	1
Winkler				4	1	3		2	2
Yoakum									
Total	42	13	8	48	33	72	7	8	3
Percentage	67	21	13	31	22	47	39	44	17

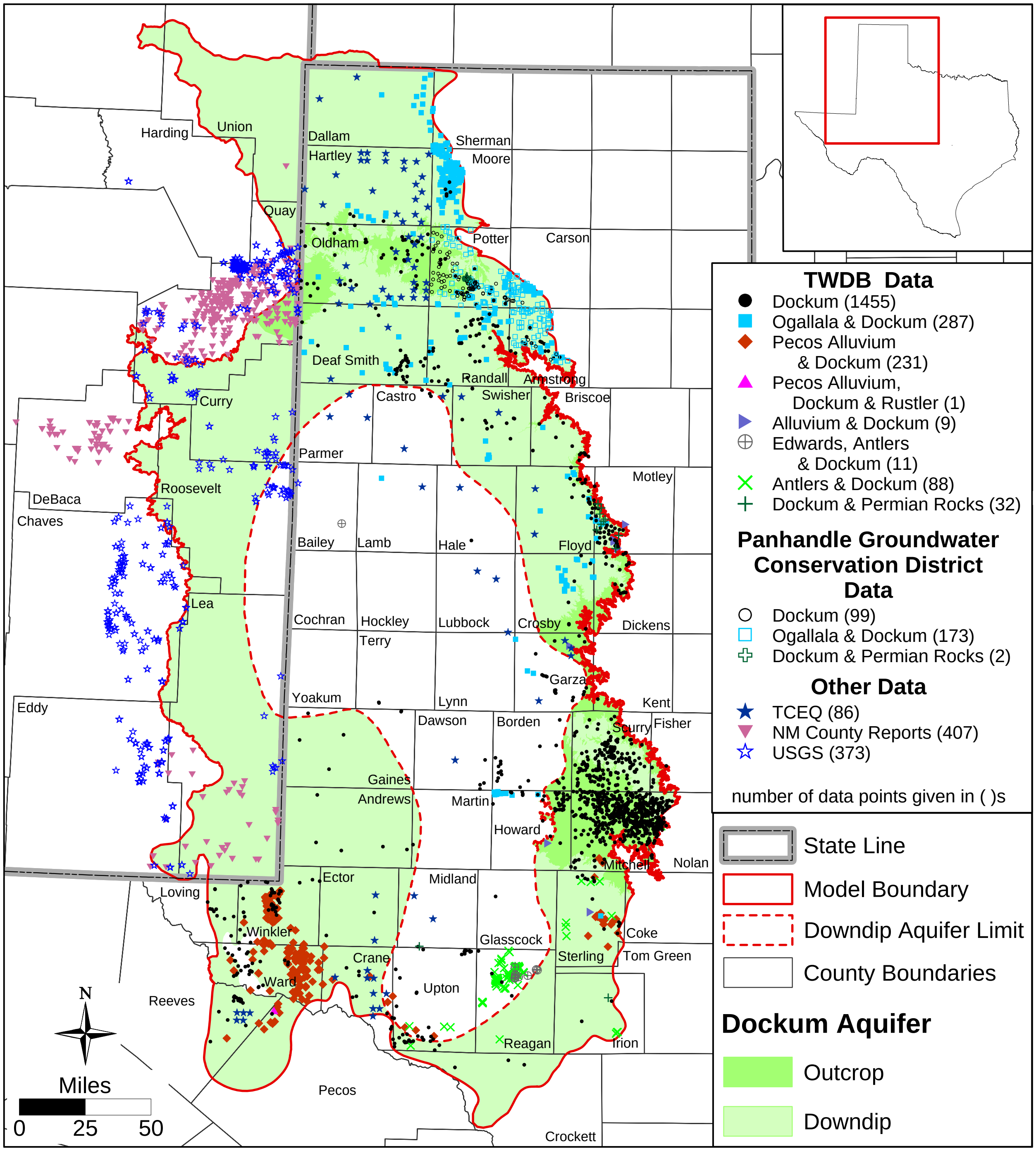


Figure 4.3.1 Water-level measurement locations for the Dockum Aquifer.

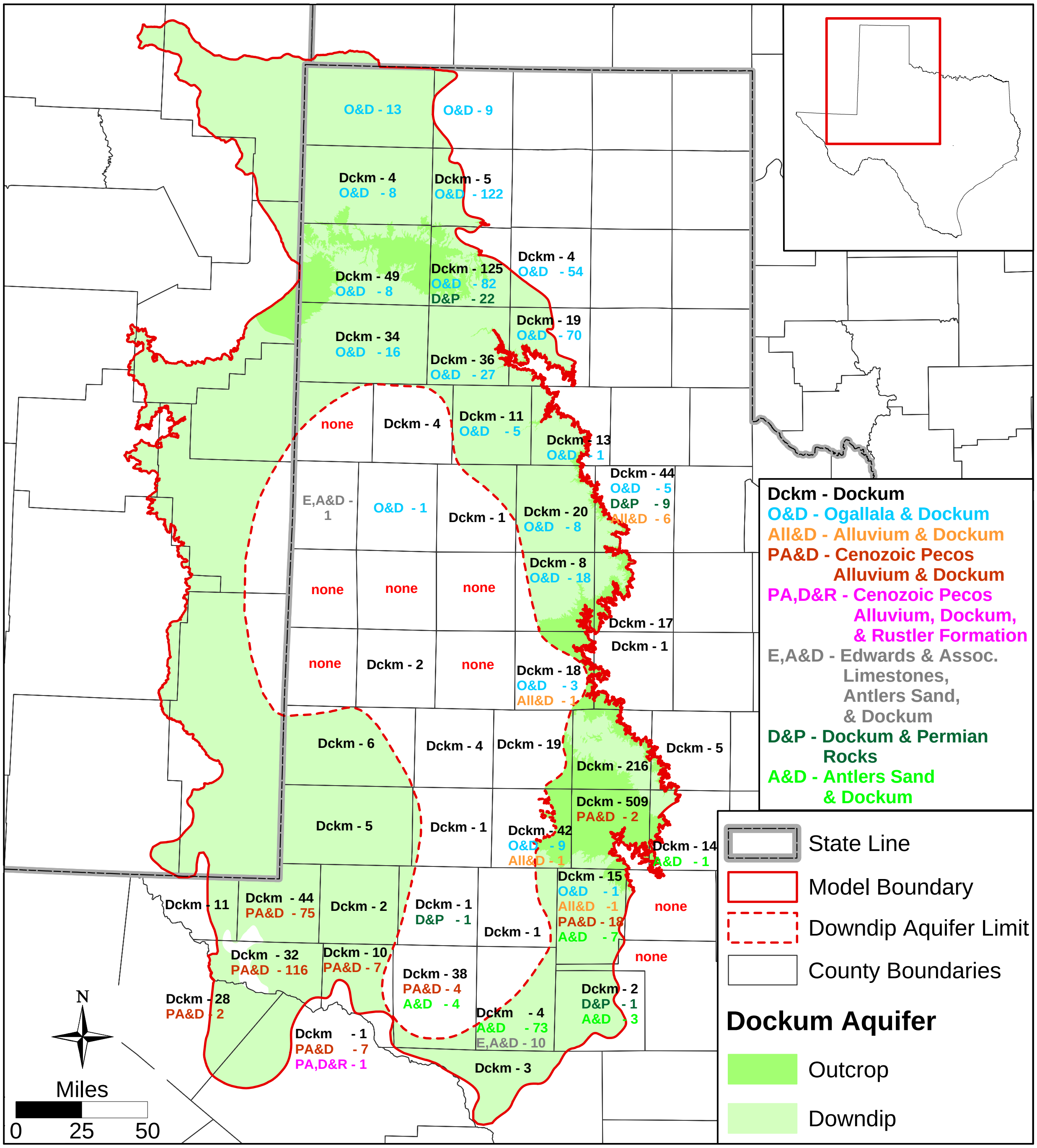


Figure 4.3.2 **Number of wells in Texas by county completed into the Dockum Aquifer and the Dockum Aquifer combined with an overlying or underlying aquifer.**

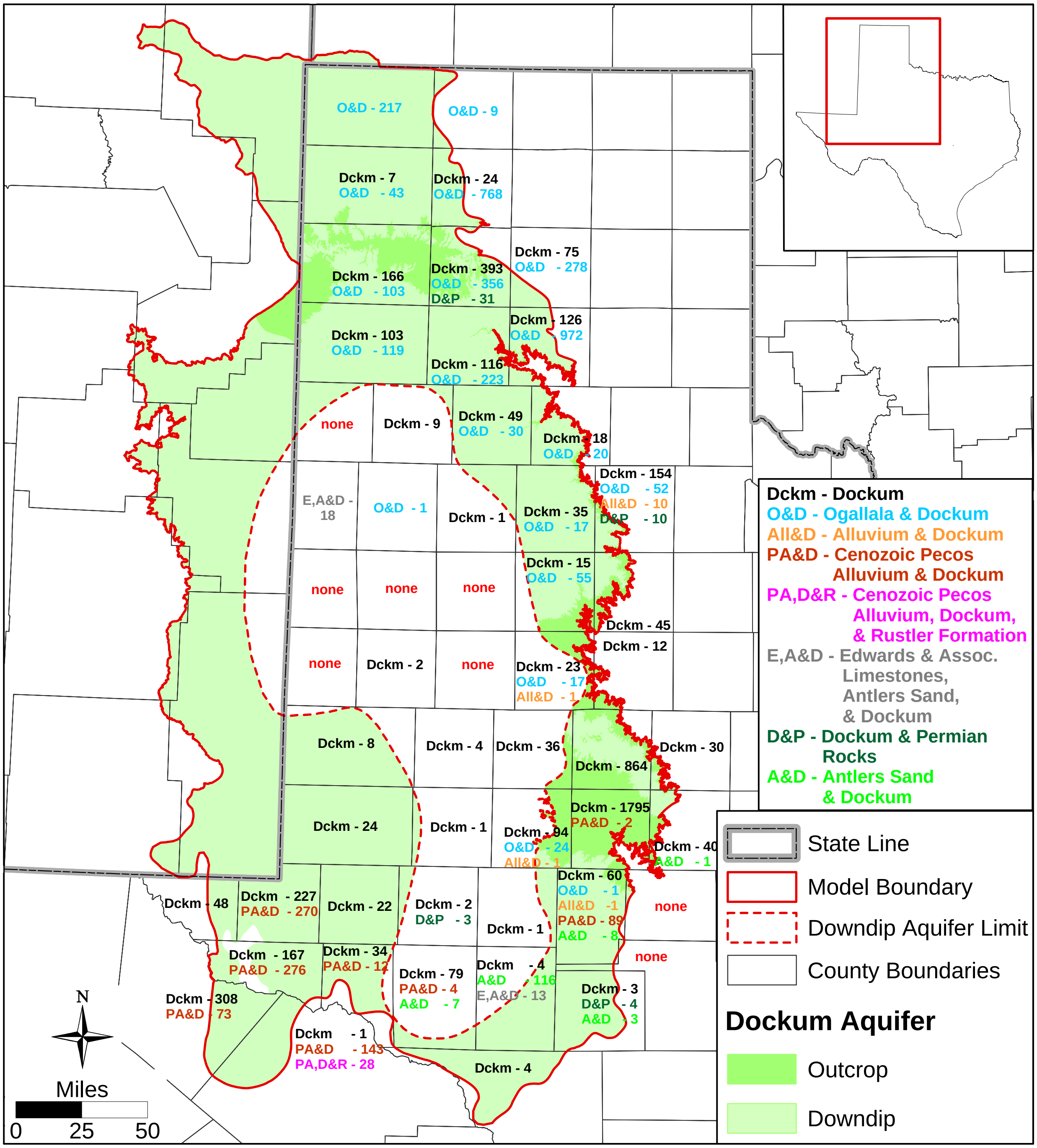


Figure 4.3.3 **Number of water-level measurements in Texas by county for wells completed into the Dockum Aquifer and the Dockum Aquifer combined with an overlying or underlying aquifer.**

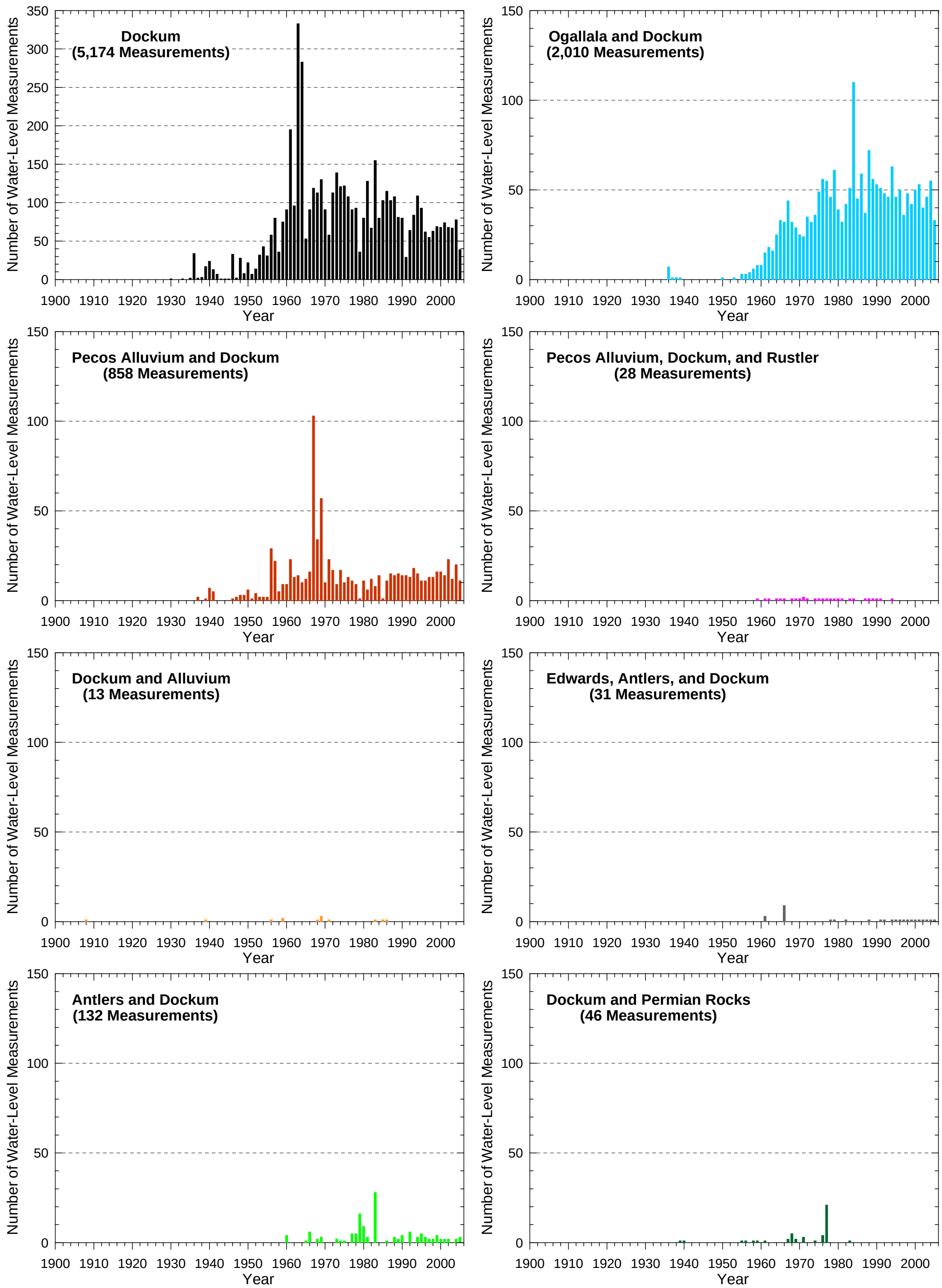


Figure 4.3.4 Temporal distribution of water-level measurements in Texas for wells completed into the Dockum Aquifer and the Dockum Aquifer combined with an overlying or underlying aquifer.

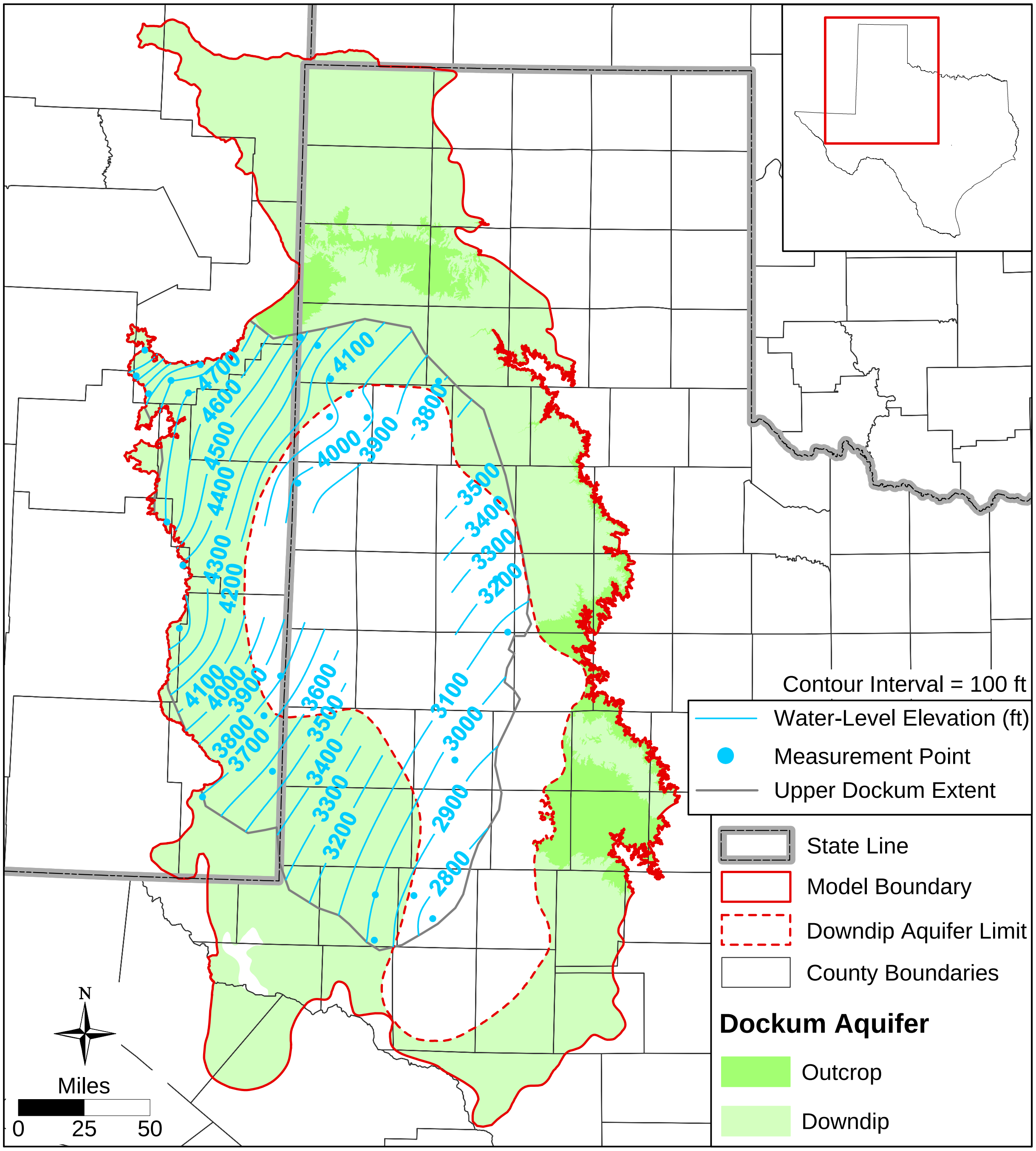


Figure 4.3.5 **Estimated water-level elevation contours in feet for predevelopment conditions in the upper portion of the Dockum Aquifer.**

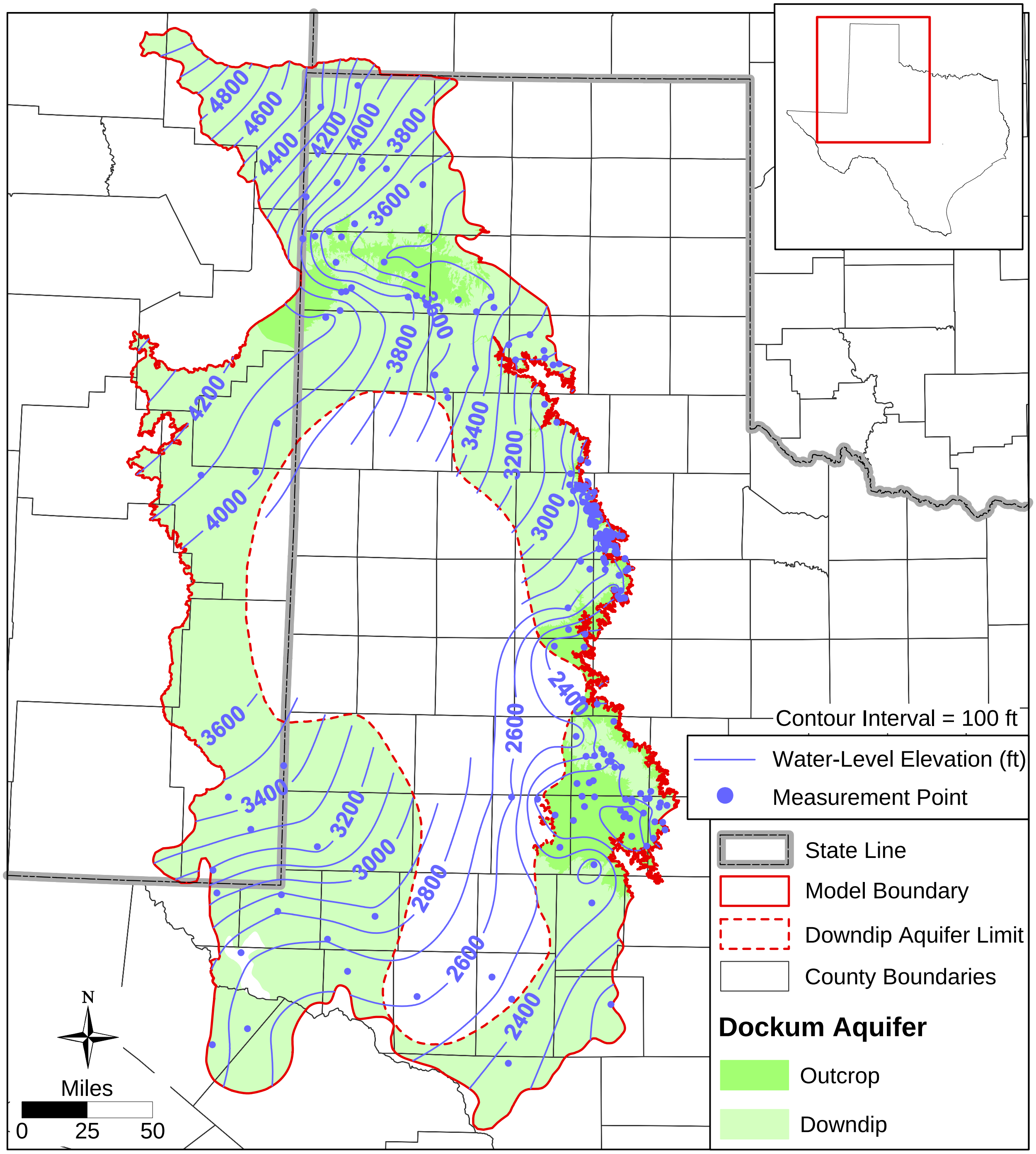


Figure 4.3.6 **Estimated water-level elevation contours in feet for predevelopment conditions in the lower portion of the Dockum Aquifer.**

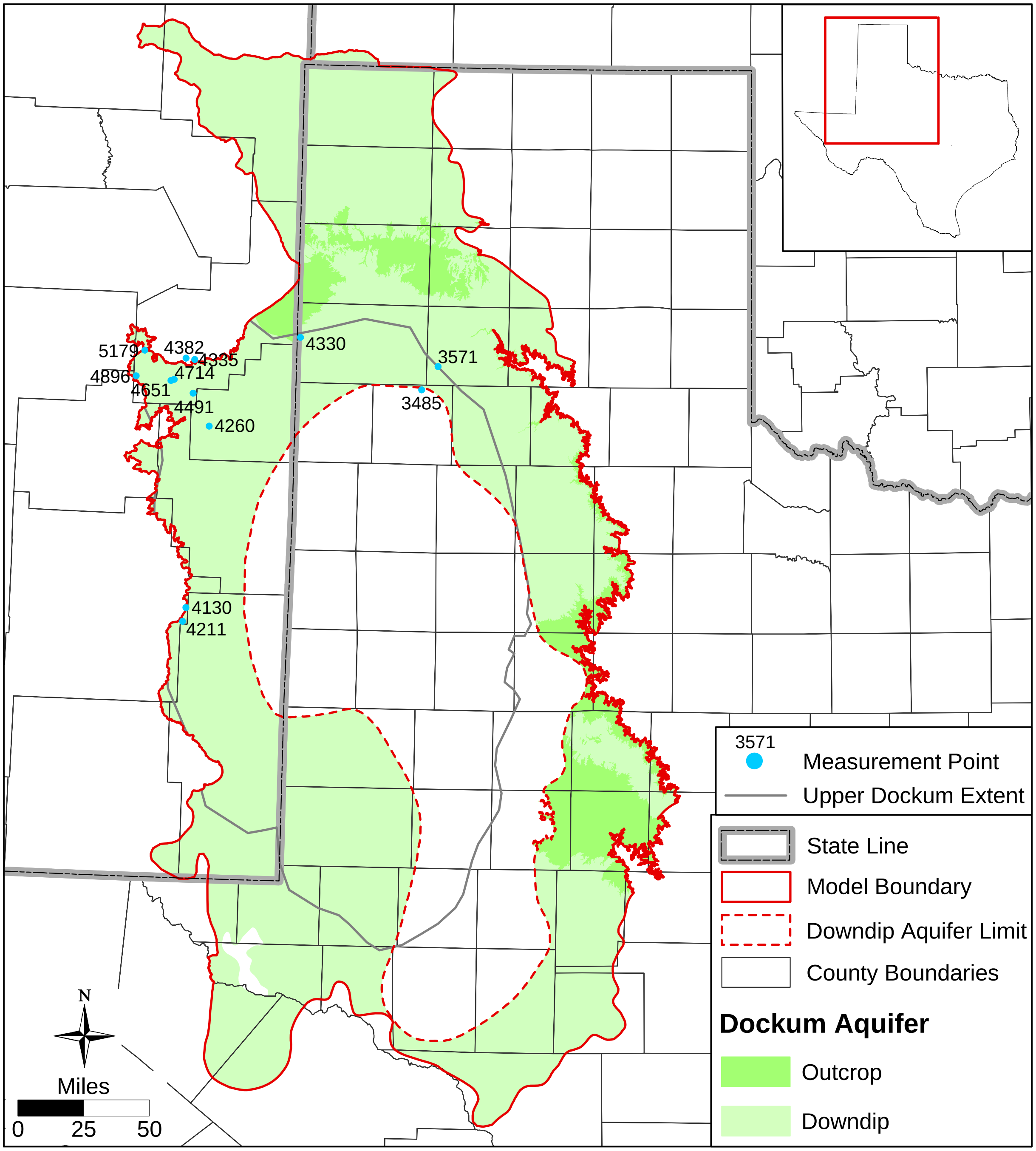


Figure 4.3.7 Water-level elevations in feet for the upper portion of the Dockum Aquifer at the start of model calibration (January 1980).

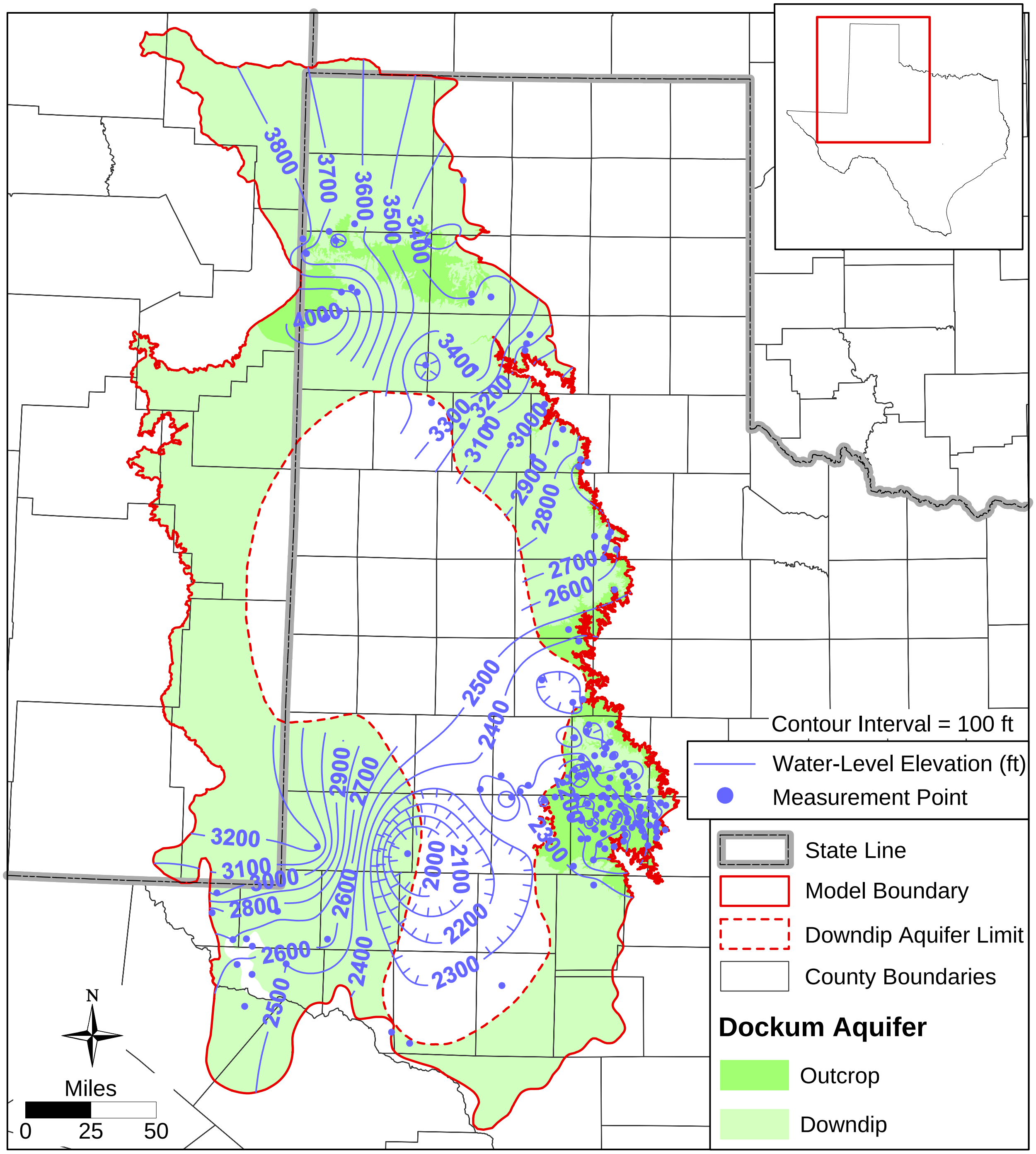


Figure 4.3.8 **Water-level elevation contours in feet for the lower portion of the Dockum Aquifer at the start of model calibration (January 1980).**

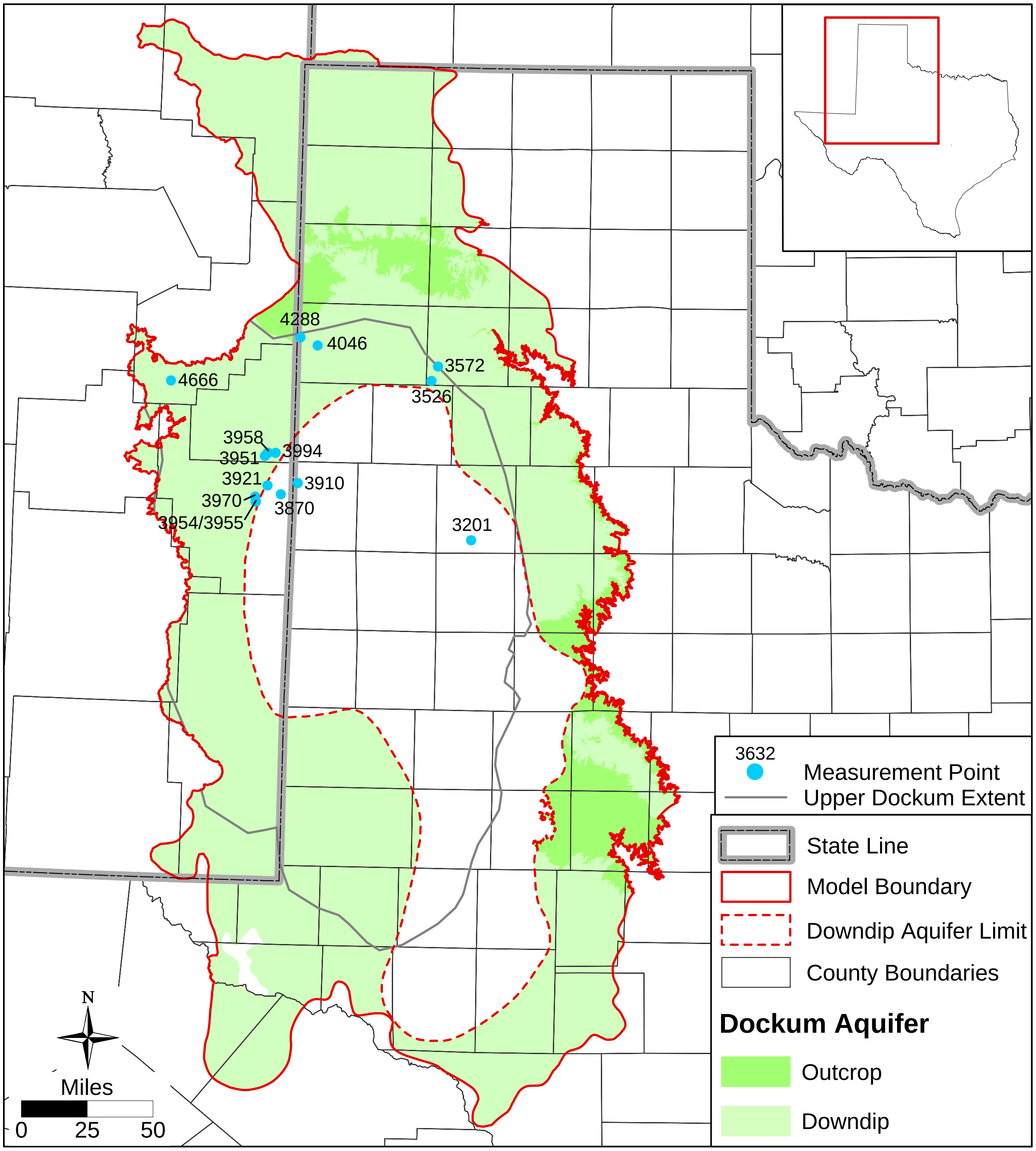


Figure 4.3.9 Water-level elevations in feet for the upper portion of the Dockum Aquifer at the middle of model calibration (January 1990).

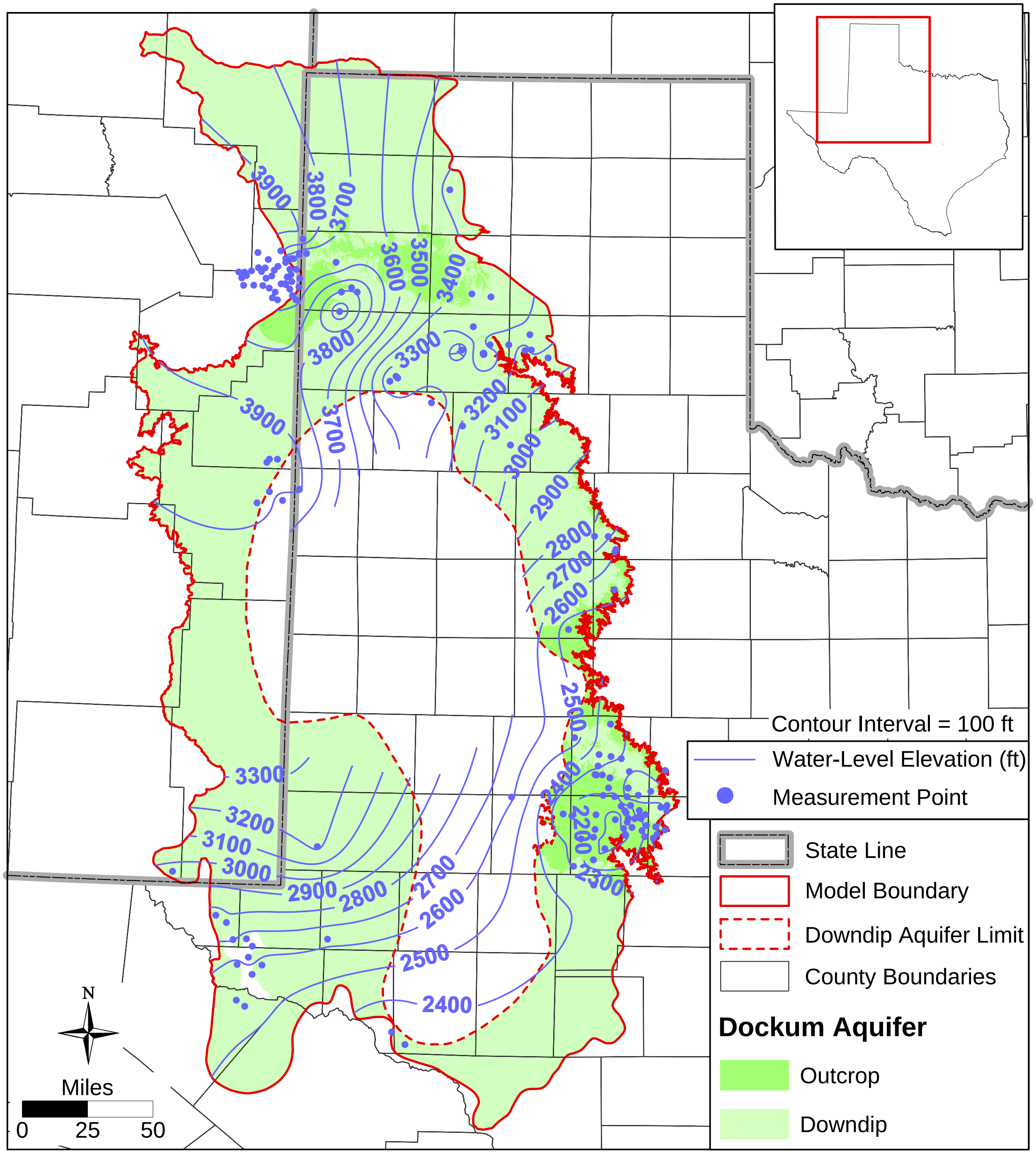


Figure 4.3.10 **Water-level elevation contours in feet for the lower portion of the Dockum Aquifer at the middle of model calibration (January 1990).**

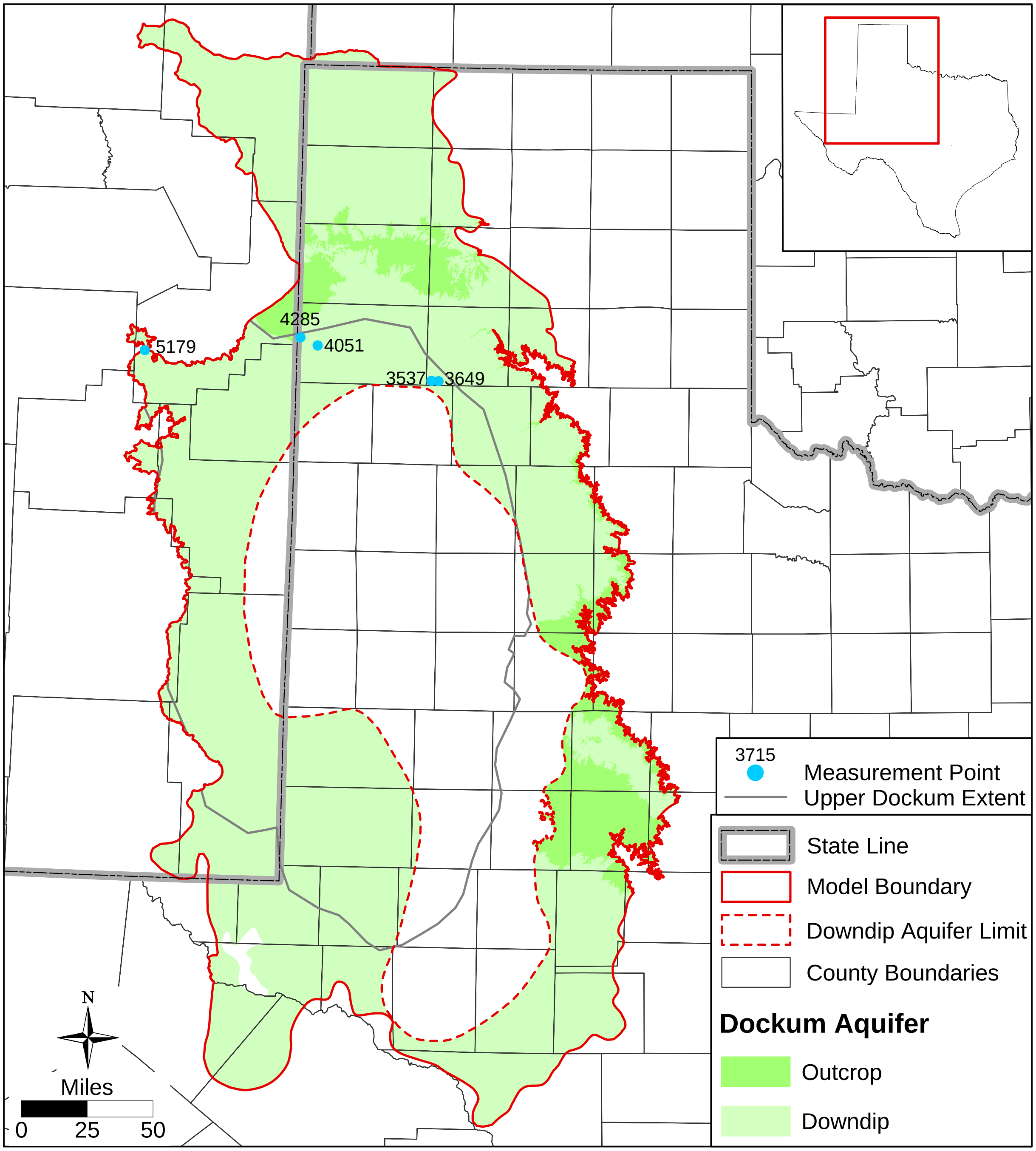


Figure 4.3.11 **Water-level elevations in feet for the upper portion of the Dockum Aquifer at the end of model calibration (December 1997).**

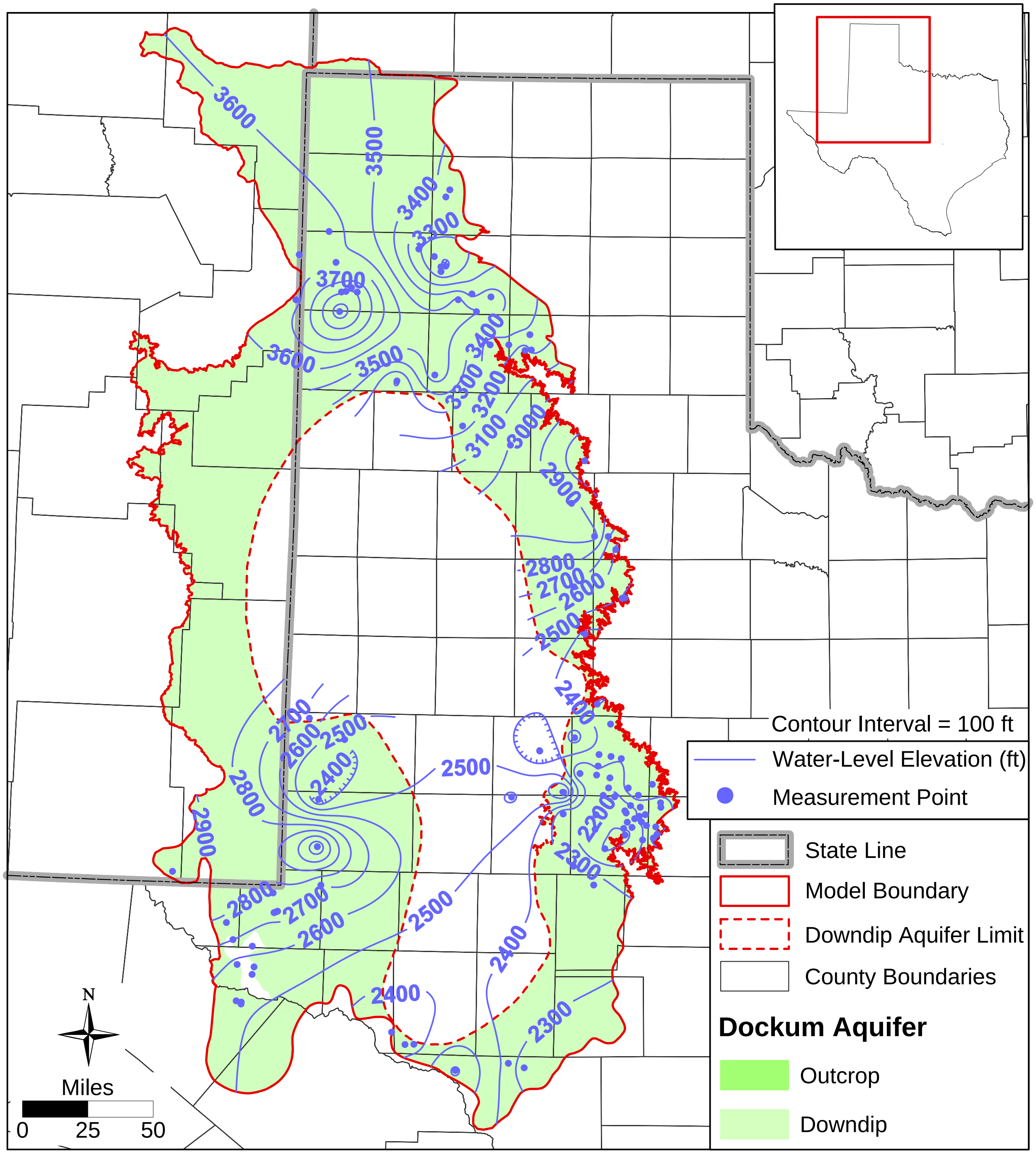


Figure 4.3.12 **Water-level elevation contours in feet for the lower portion of the Dockum Aquifer at the end of model calibration (December 1997).**

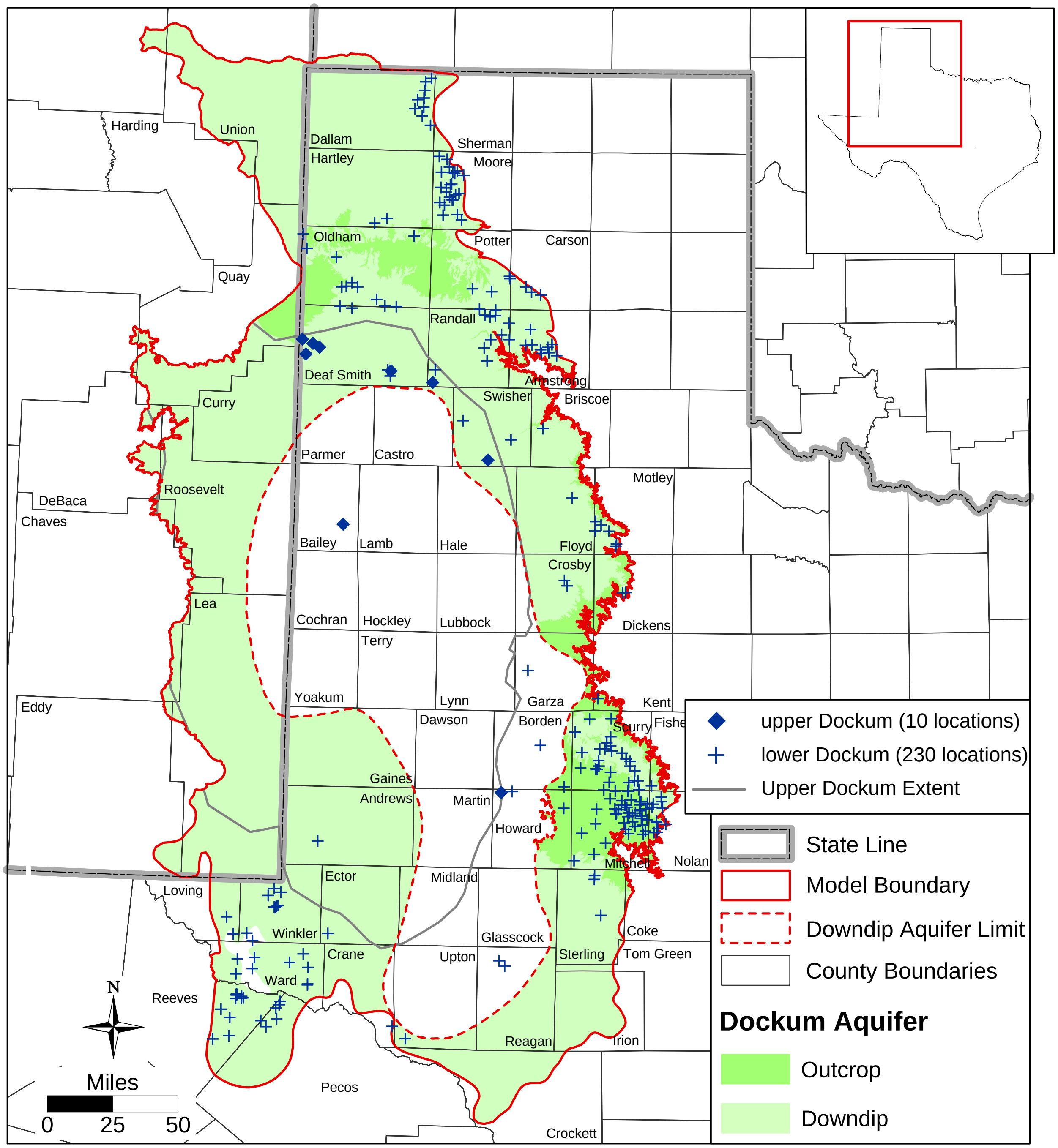


Figure 4.3.13 Locations in Texas with transient water-level data in the upper and lower portions of the Dockum Aquifer.

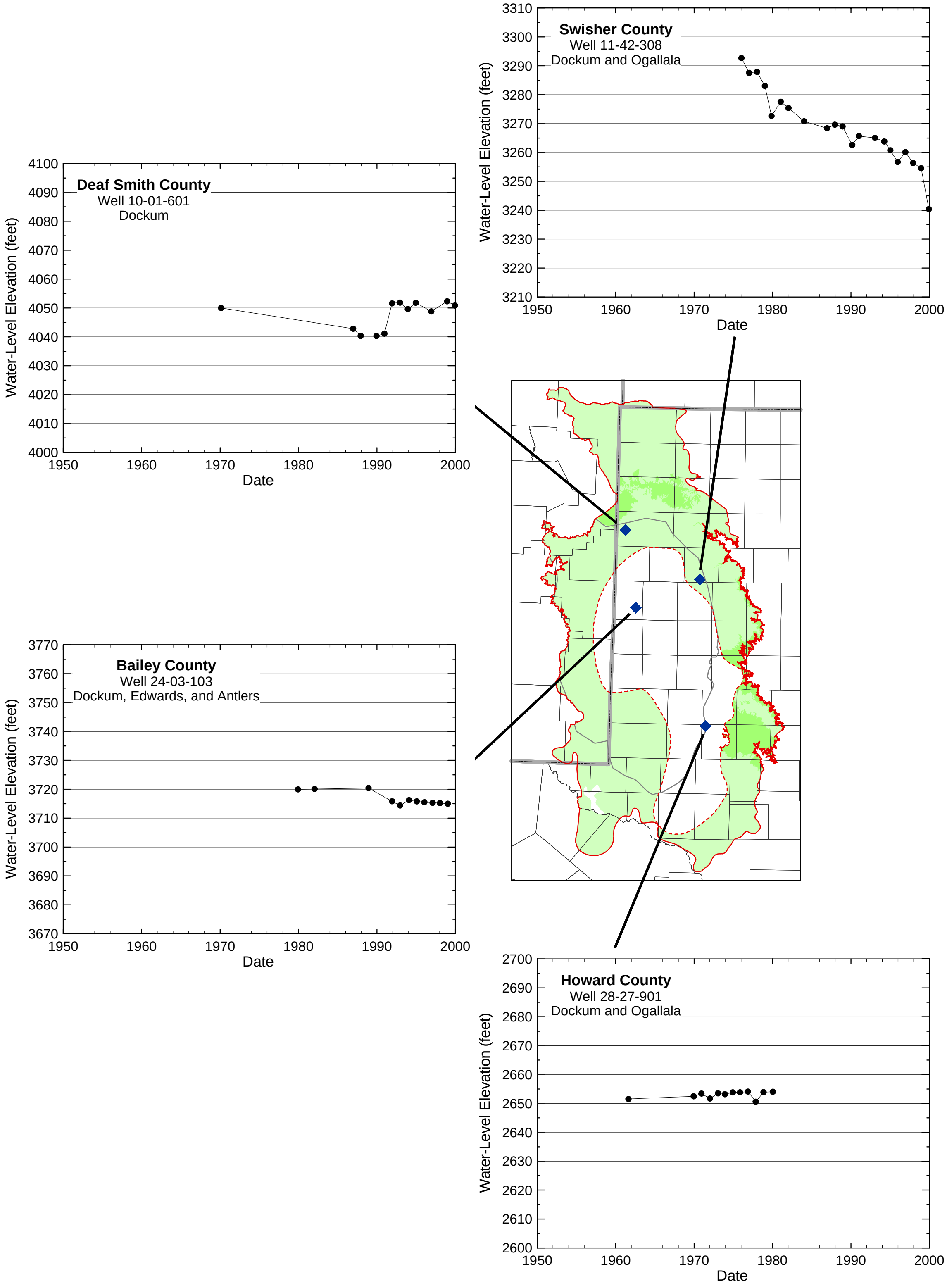


Figure 4.3.14 **Example hydrographs for wells completed into the upper portion of the Dockum Aquifer and into the upper portion of the Dockum Aquifer combined with an overlying aquifer.**

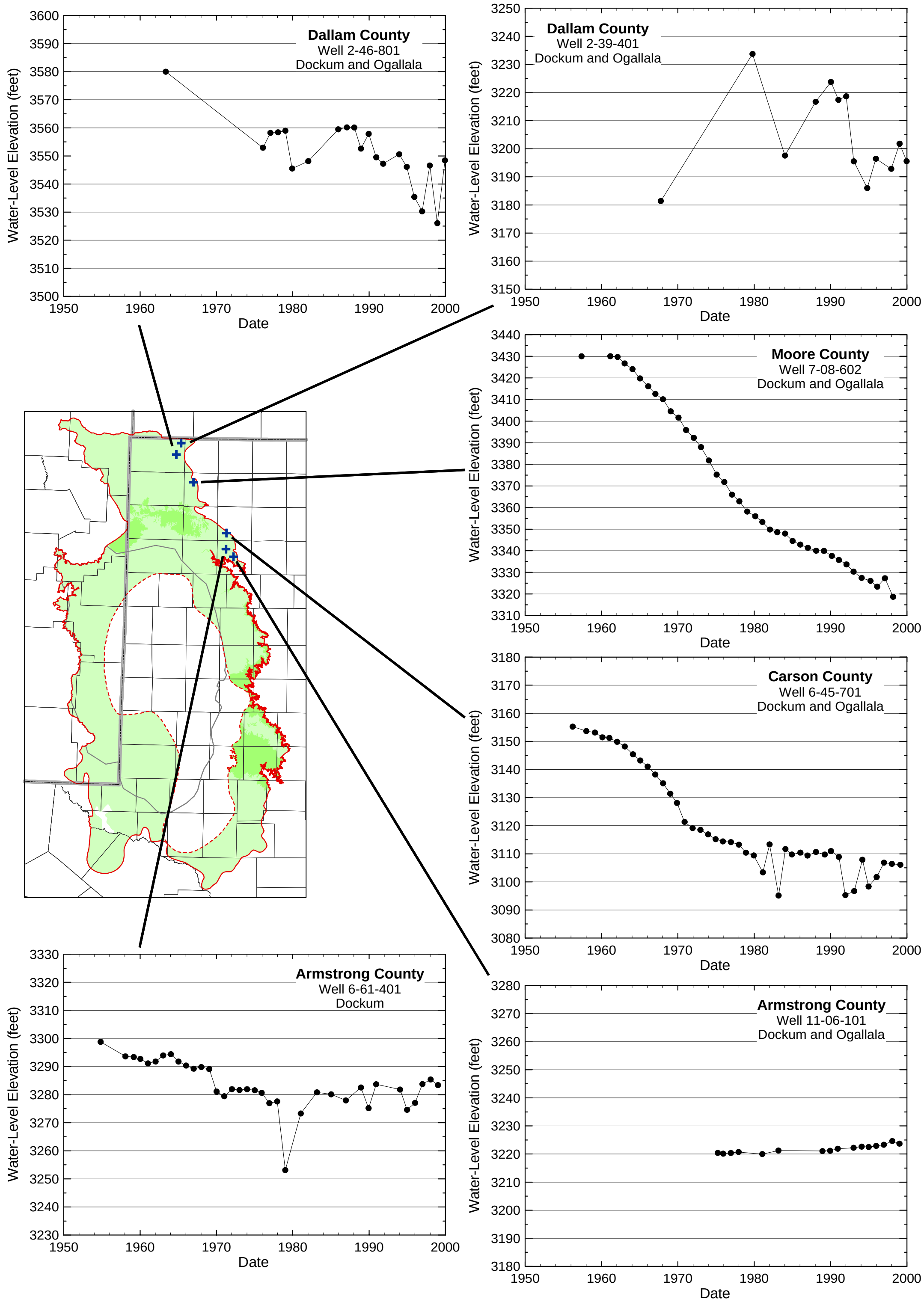


Figure 4.3.15 **Example hydrographs for wells completed into the lower portion of the Dockum Aquifer and into the lower portion of the Dockum Aquifer and the Ogallala Aquifer in Armstrong, Dallam, Carson, and Moore counties.**

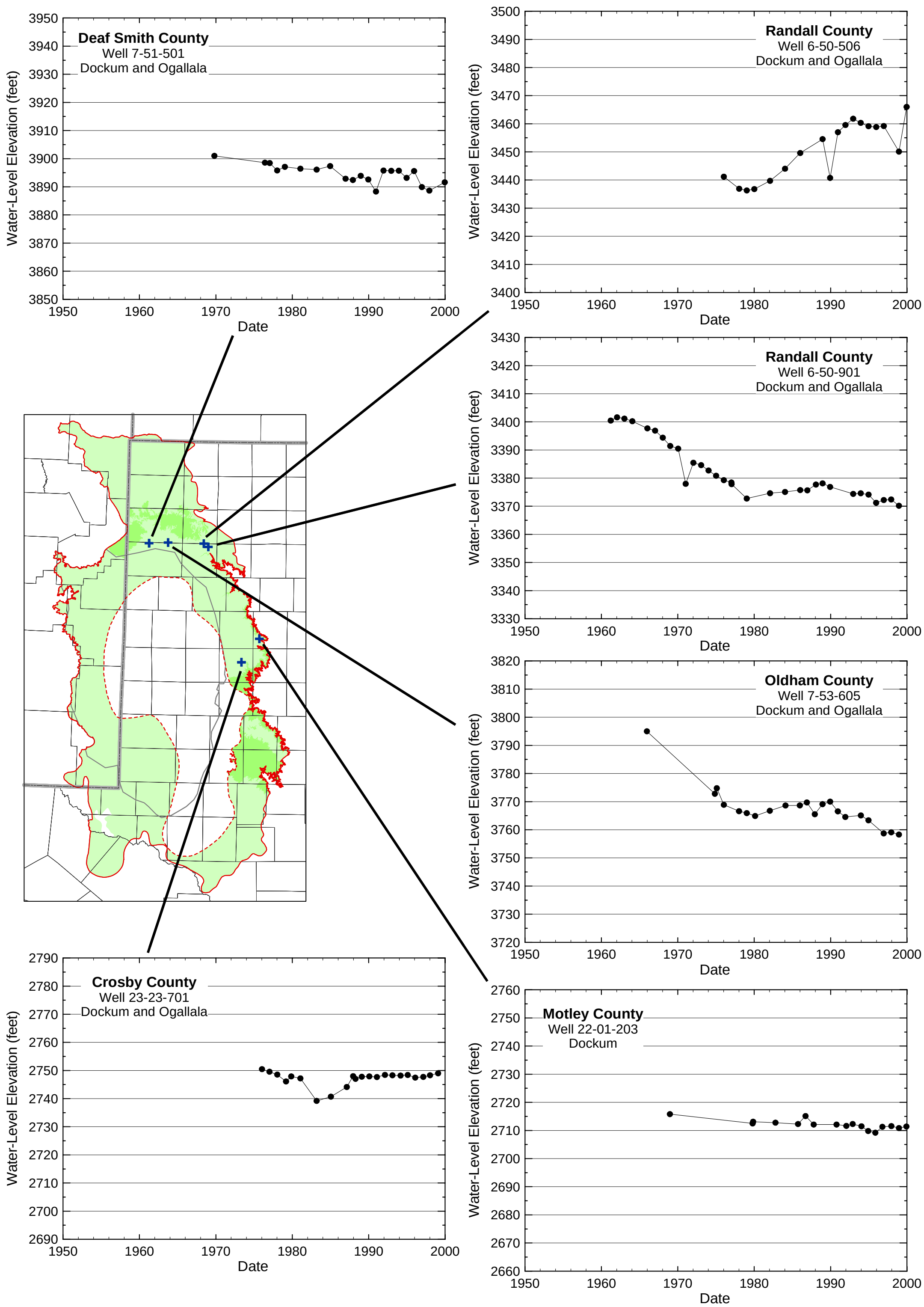


Figure 4.3.16 **Example hydrographs for wells completed into the lower portion of the Dockum Aquifer and into the lower portion of the Dockum Aquifer and the Ogallala Aquifer in Crosby, Deaf Smith, Motley, Oldham, and Randall counties.**

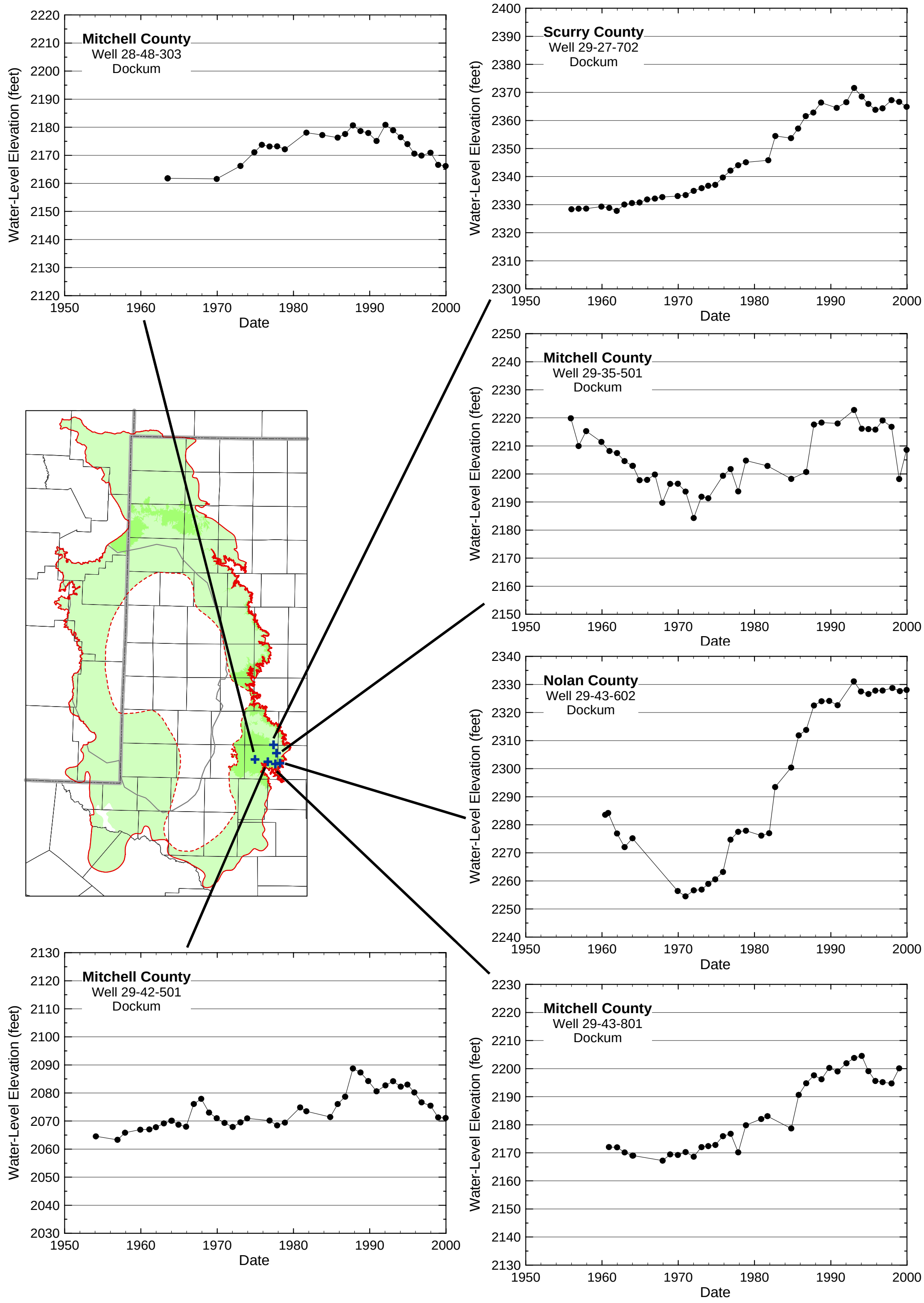


Figure 4.3.17 **Example hydrographs for wells completed into the lower portion of the Dockum Aquifer in Mitchell, Nolan, and Scurry counties.**

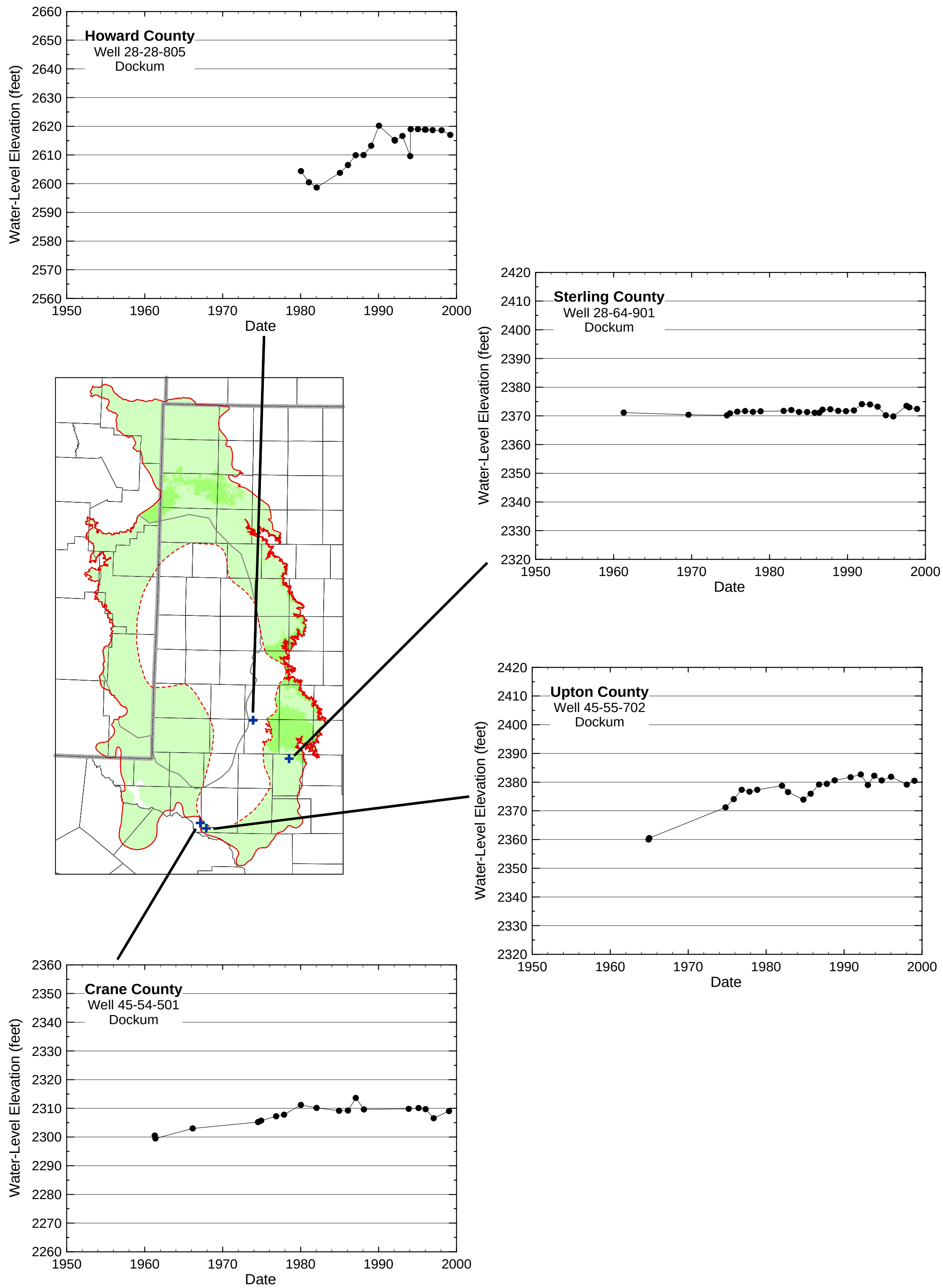


Figure 4.3.18 Example hydrographs for wells completed into the lower portion of the Dockum Aquifer in Crane, Howard, Sterling, and Upton counties.

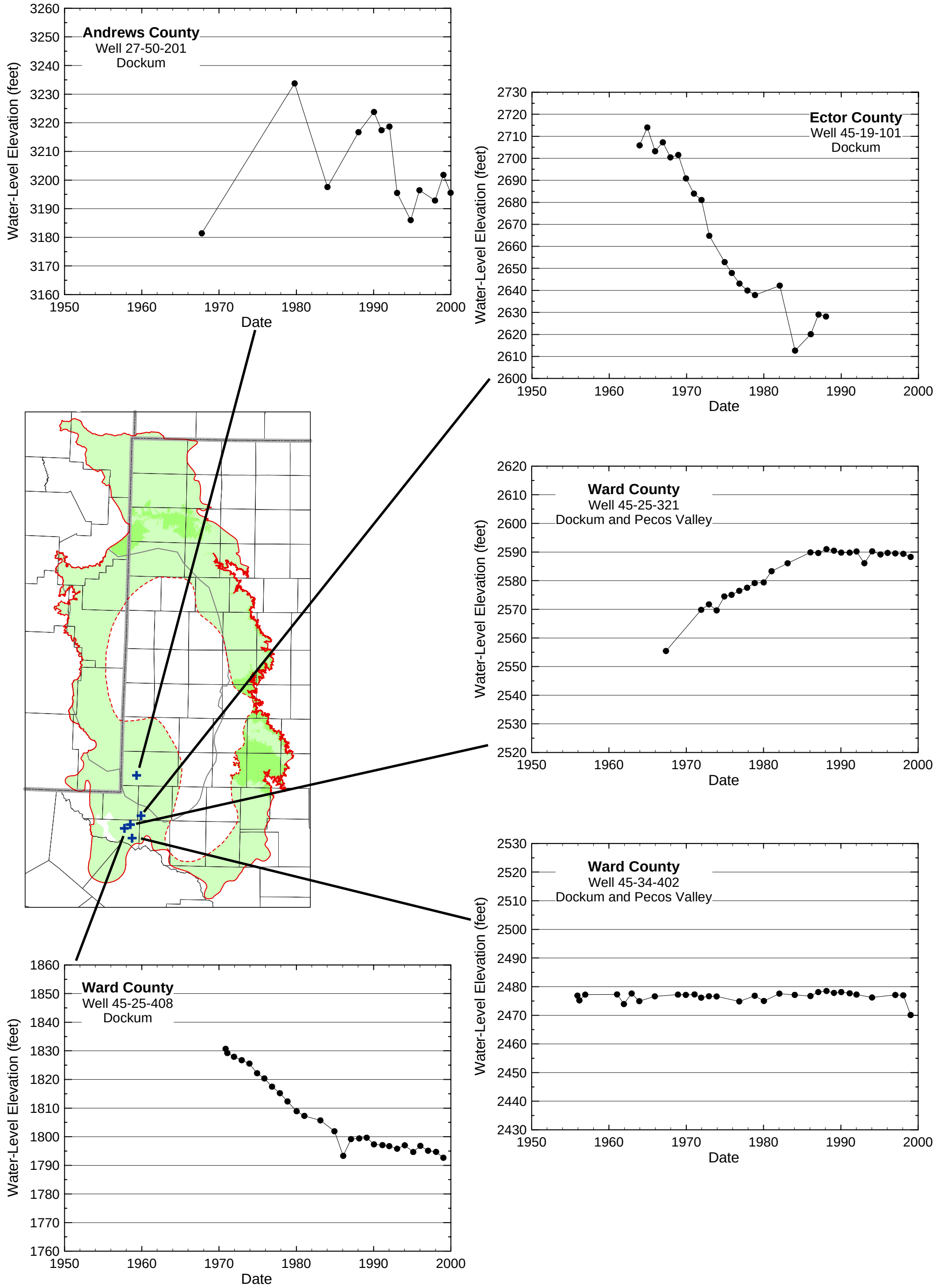


Figure 4.3.19 **Example hydrographs for wells completed into the lower portion of the Dockum Aquifer and into the lower portion of the Dockum Aquifer and the Pecos Valley Aquifer in Andrews, Ector, and Ward counties.**

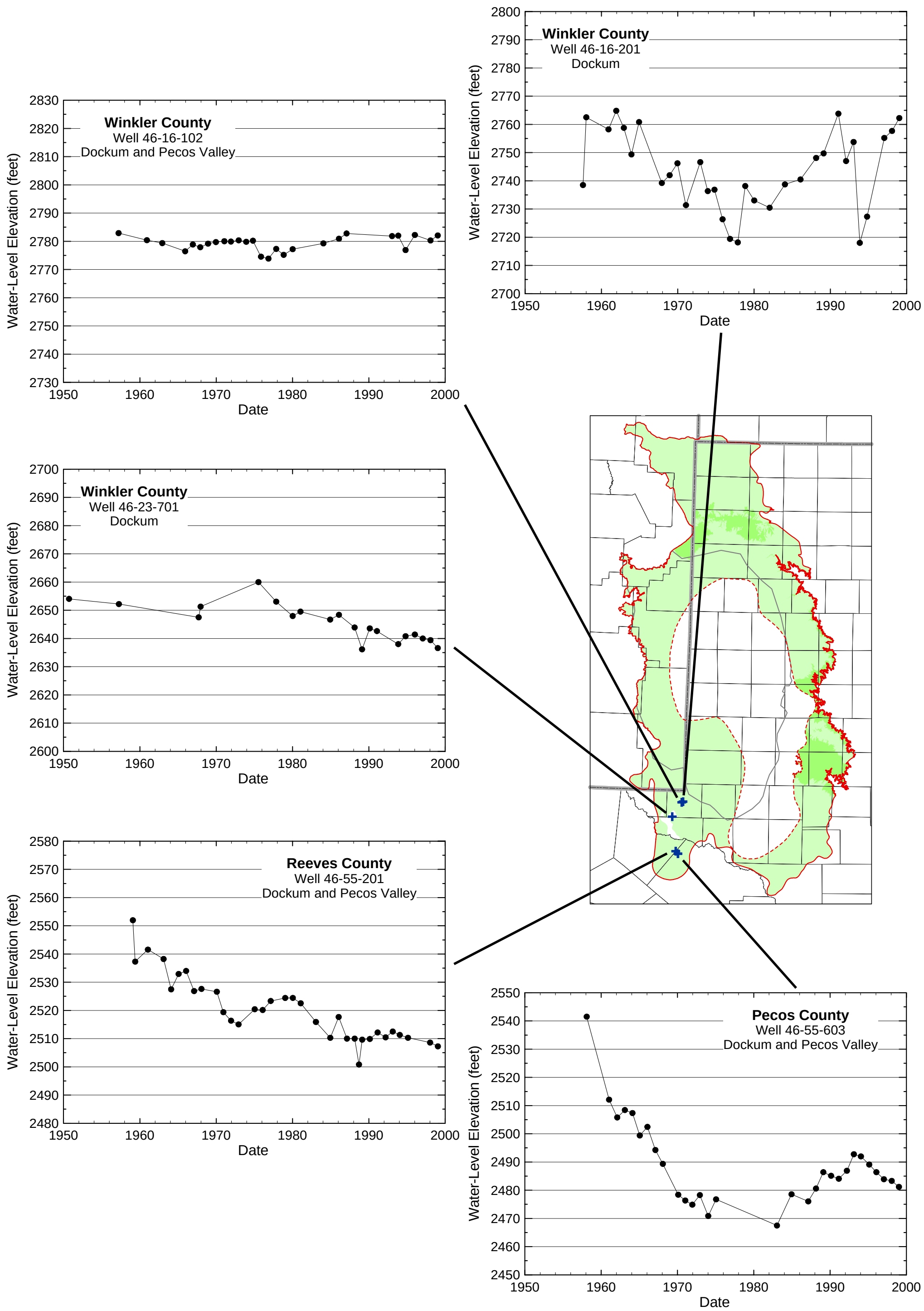


Figure 4.3.20 **Examples hydrographs for wells completed into the lower portion of the Dockum Aquifer and into the lower portion of the Dockum Aquifer and the Pecos Valley Aquifer in Pecos, Reeves, and Winkler counties.**

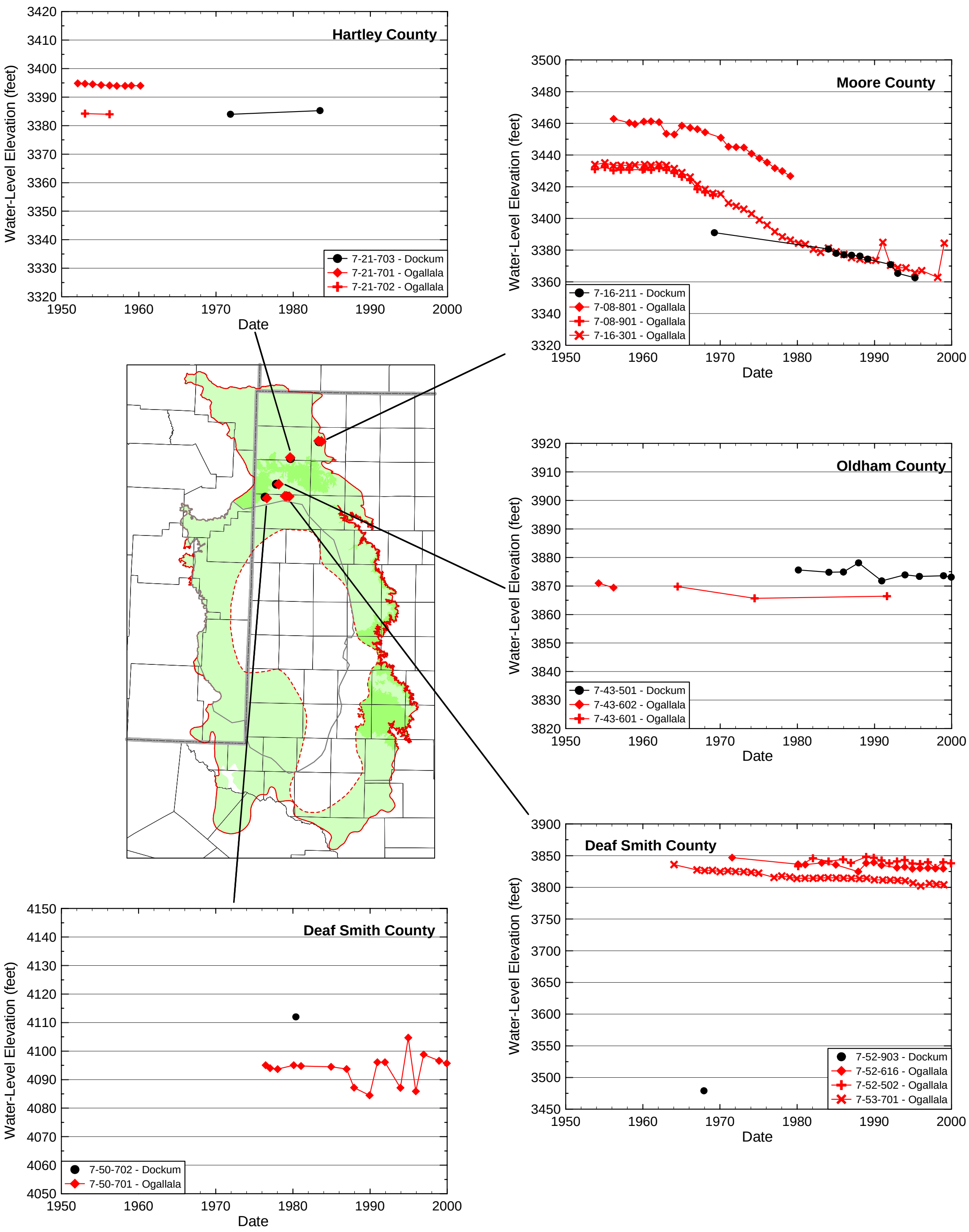


Figure 4.3.21 Comparison of water-level elevations in the Dockum Aquifer and in the overlying Ogallala Aquifer in Deaf Smith, Hartley, Moore, and Oldham counties.

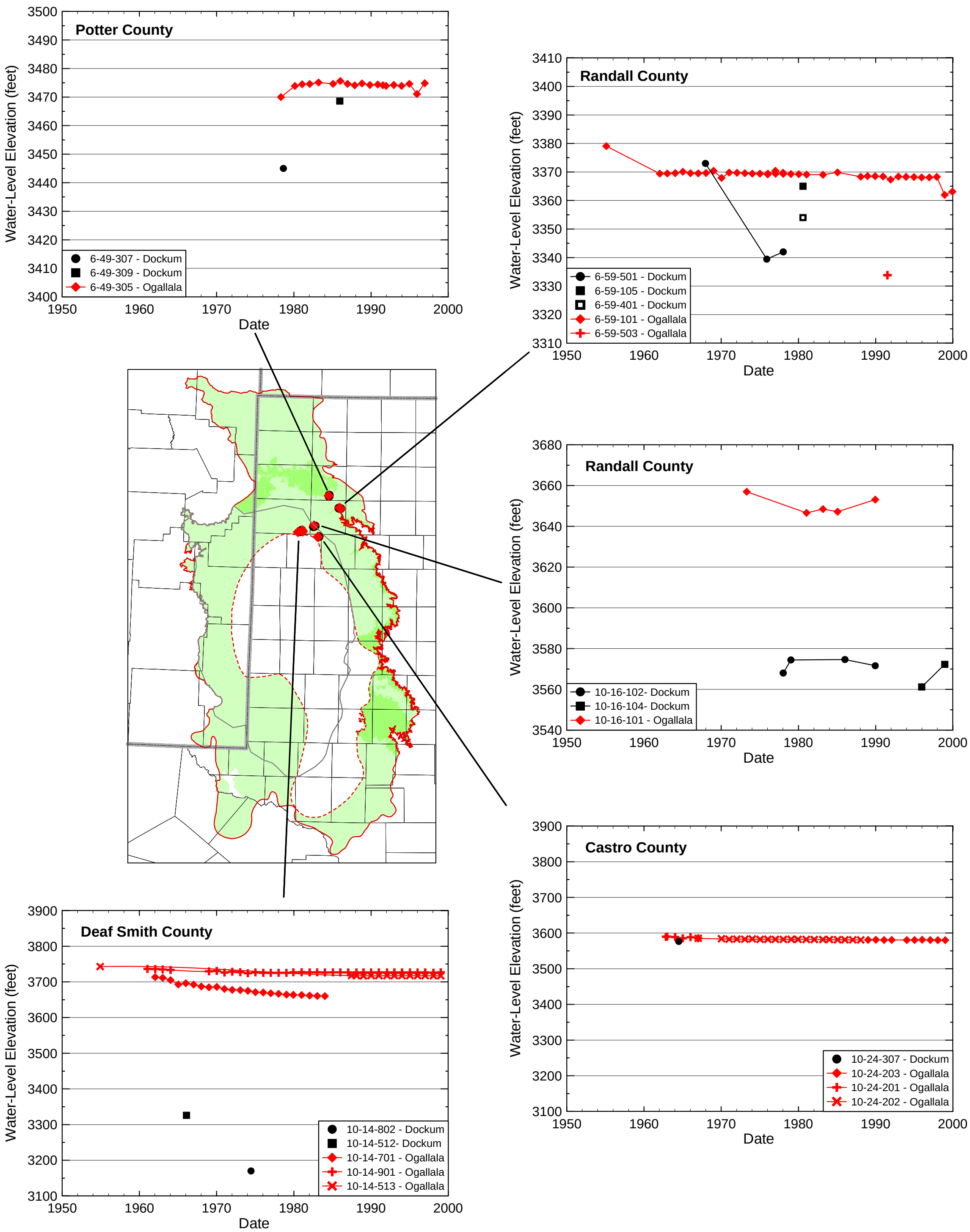


Figure 4.3.22 Comparison of water-level elevations in the Dockum Aquifer and in the overlying Ogallala Aquifer in Deaf Smith, Castro, Potter, and Randall counties.

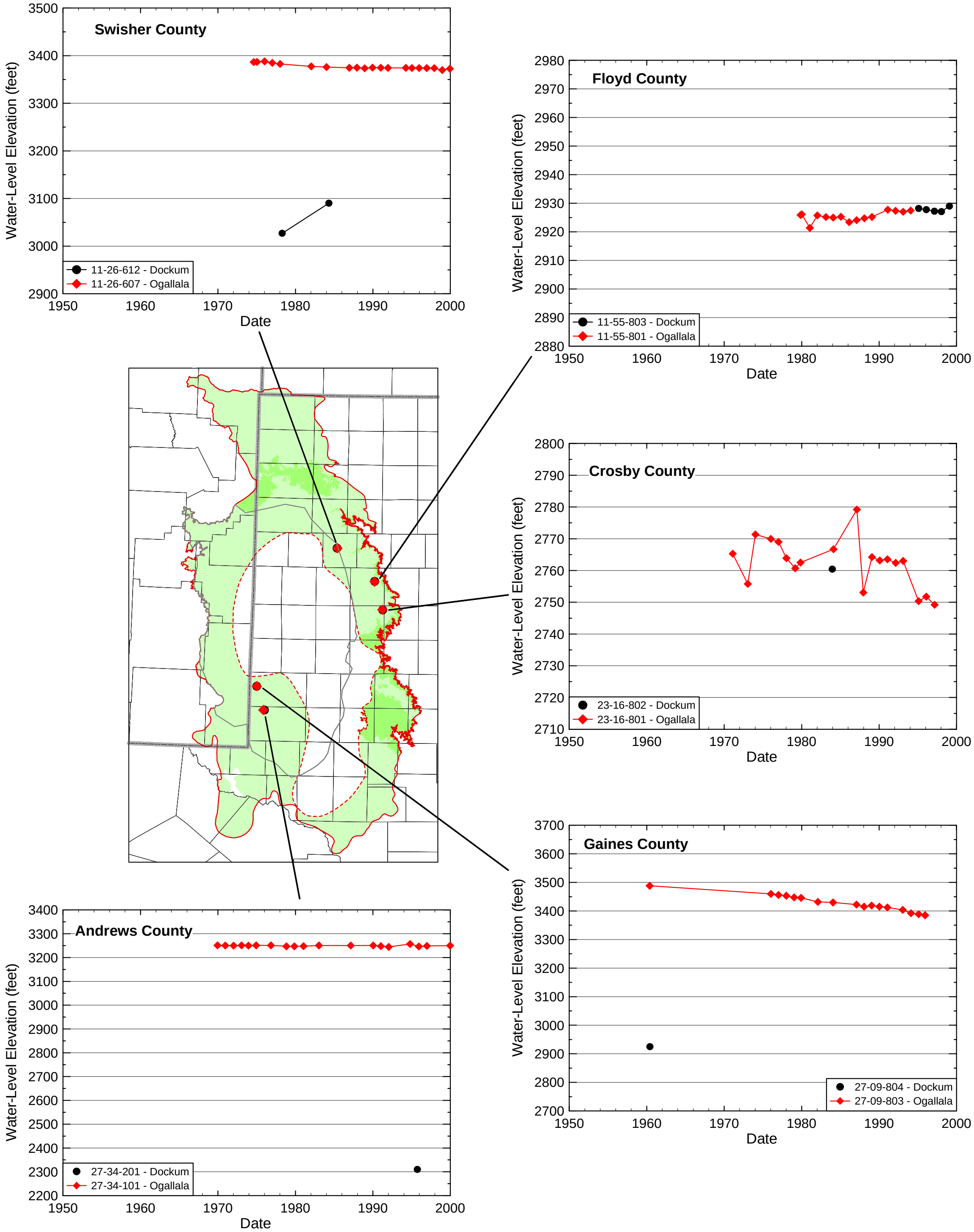


Figure 4.3.23 Comparison of water-level elevations in the Dockum Aquifer and in the overlying Ogallala Aquifer in Andrews, Crosby, Floyd, Gaines, and Swisher counties.

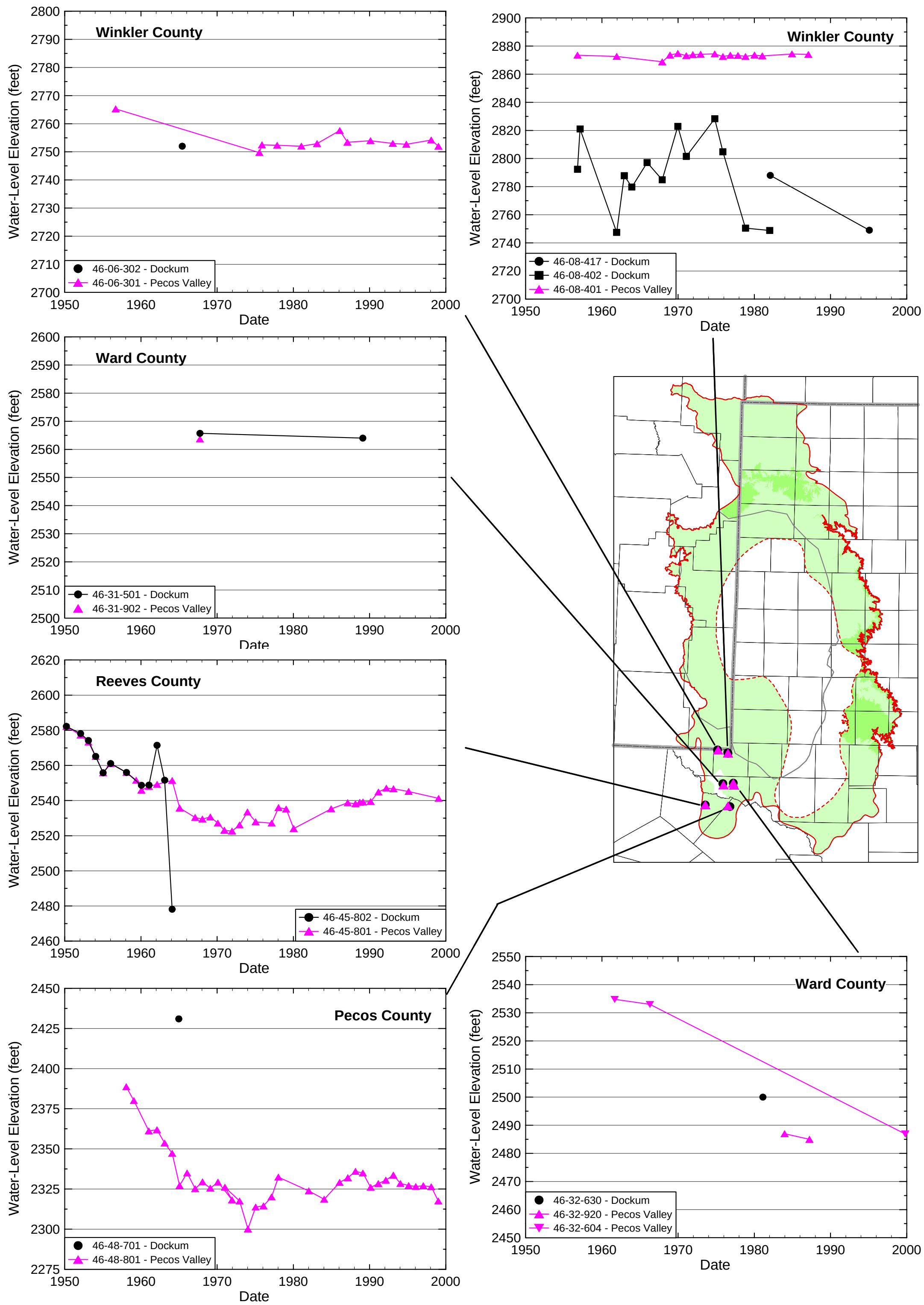


Figure 4.3.24 **Comparison of water-level elevations in the Dockum Aquifer and in the overlying Pecos Valley Aquifer in Pecos, Reeves, Ward, and Winkler counties.**

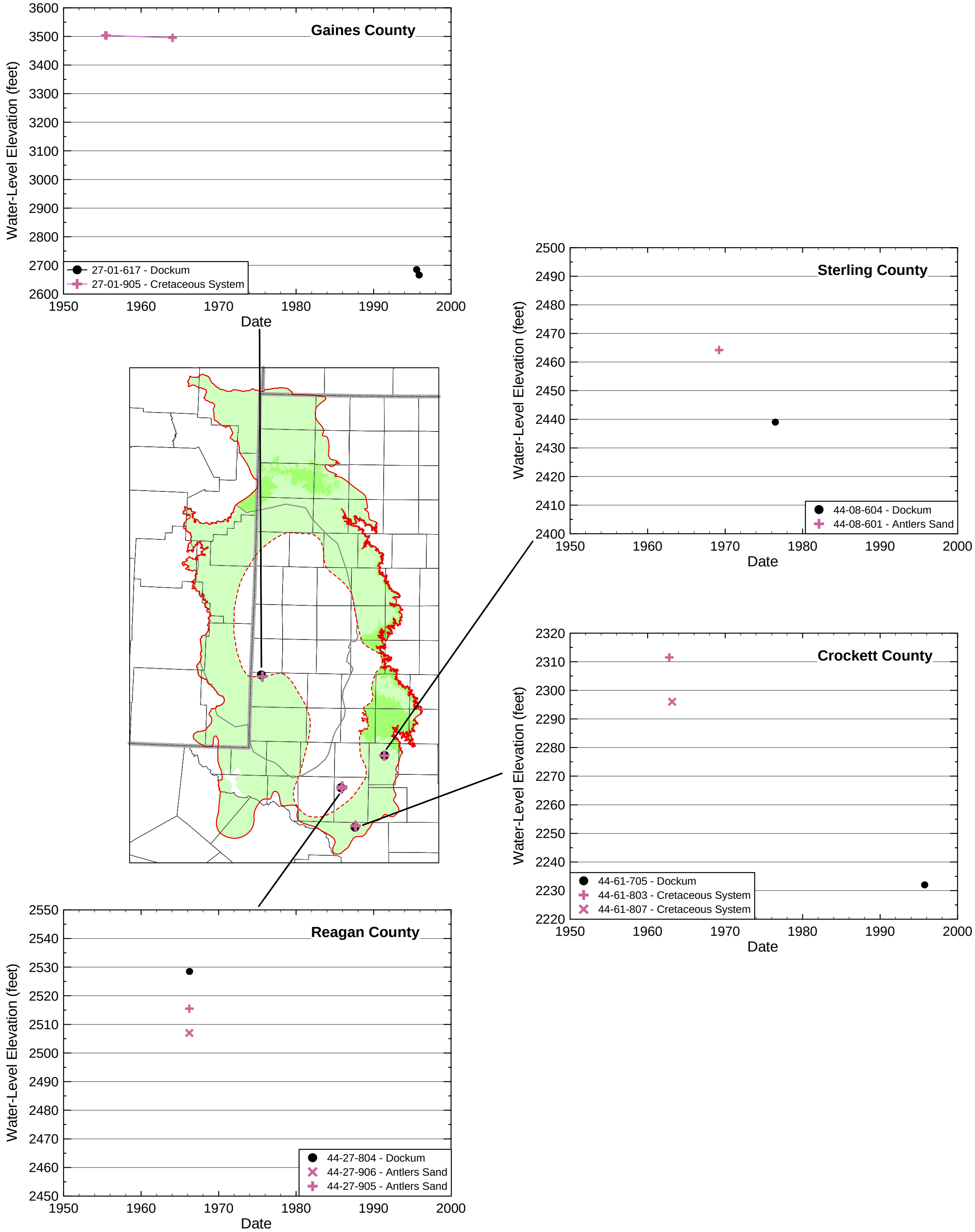


Figure 4.3.25 Comparison of water-level elevations in the Dockum Aquifer and in the overlying Cretaceous-age sediments in Crockett, Gaines, Reagan, and Sterling counties.

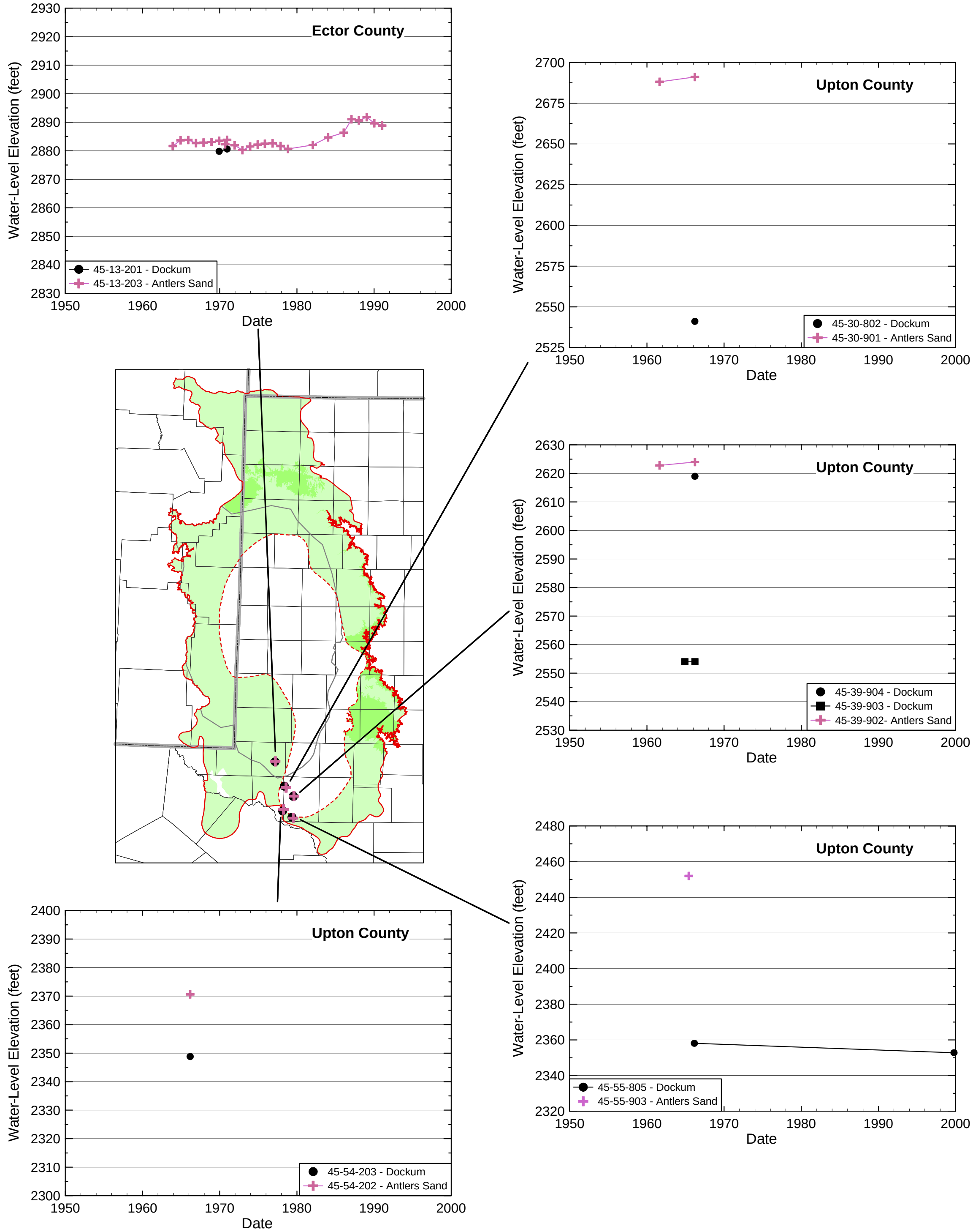


Figure 4.3.26 Comparison of water-level elevations in the Dockum Aquifer and in the overlying Cretaceous-age sediments in Ector and Upton counties.

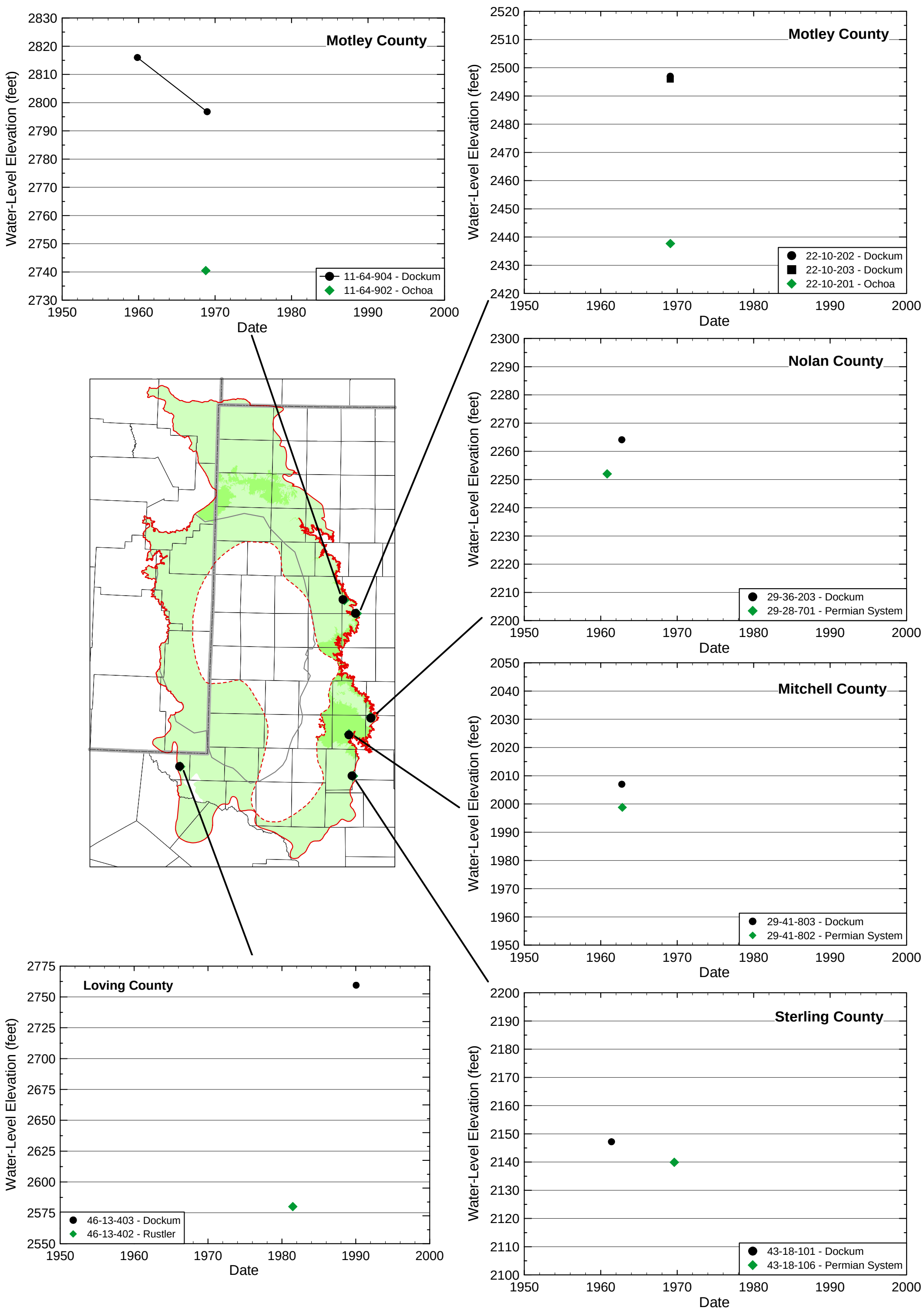


Figure 4.3.27 Comparison of water-level elevations in the Dockum Aquifer and in the underlying Permian-age sediments in Loving, Mitchell, Motley, Nolan, and Sterling counties.

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4.4 Recharge

Recharge can be defined as water that enters the saturated zone at the water table (Freeze, 1969). Recharge is a complex function of rate and volume of precipitation, soil type, water level, soil moisture, topography, and evapotranspiration (Freeze, 1969). Potential sources for recharge to the water table include precipitation, irrigation return flow, and stream or reservoir leakage. Precipitation and irrigation return flow are generally considered to be diffuse sources of recharge, while stream or reservoir leakage are considered to be focused sources of recharge. Man-made reservoirs in the aquifer outcrop may provide the potential for focused recharge in the active model area. However, because the reservoirs are located in topographically low areas and on clayey soils, it is expected that recharge to the aquifer associated with the reservoirs is small and subject to evapotranspiration and discharge to streams.

During a rainfall event (or irrigation event), some of the water may run off to small streams and surface features and some of the water infiltrates to the soil (a small fraction of the water that infiltrates to the soil may become interflow, but this process is neglected as inconsequential in this discussion). Much of the infiltrating water evaporates while still near the surface or is taken up by vegetation in the vadose zone (i.e., evapotranspiration). If enough water infiltrates to satisfy the moisture deficit of the soil and the vegetation in the vadose zone, then the remaining water will reach the water table.

The groundwater system in the outcrop can often act as a classical topographically-driven recharge/discharge system, where recharge primarily occurs in the areas of higher elevation and discharge occurs in the areas of lower elevation through streams, seeps, and groundwater evapotranspiration. The recharge to the water table that discharges relatively quickly does not have a significant impact on the deeper, confined aquifer system. Conceptually, recharge can be divided into two different types, "shallow" recharge that discharges relatively quickly through baseflow and other surficial discharge components, and "deep" recharge which moves into the confined system and exits through cross-formation flow or pumping.

The Dockum Aquifer outcrops in two main areas: along the Canadian River in Oldham and Potter counties in the northern portion of the model area and in Borden, Crosby, Dawson, Dickens, Garza, Howard, Kent, Mitchell, Nolan, and Scurry counties in the south-central portion of the eastern side of the model area (Figure 4.4.1). In the western portion of this area (Borden, Dawson, and Garza counties), the groundwater in the Dockum Aquifer has a total dissolved solids concentration greater than 5,000 milligrams per liter. This high value suggests negligible recharge in this portion of the outcrop. This conclusion is supported by the high clay content of the soil in this area. In the remainder of this report, the portion of the outcrop along the Canadian River is referred to as the Canadian River outcrop area, the portion of the outcrop in Howard, Mitchell, and Scurry counties is referred to as the Colorado River outcrop area, and the portion of the outcrop where the groundwater has a high total dissolved solids concentration is referred to as the high total dissolved solids outcrop (see Figure 4.4.1).

Because of the configuration and location of the outcrop areas of the Dockum Aquifer, all recharge to the Dockum is considered to be shallow recharge with none expected to reach the confined portions of the aquifer. The Colorado River outcrop area and all outcrops located along the eastern edge of the aquifer are located in the downgradient portion of the aquifer. Therefore, it is not possible for recharge in these areas to move into the confined portions of the aquifer. In the Canadian River outcrop area, flow is towards the Canadian River and its tributaries, so all recharge entering the aquifer moves toward the rivers and streams and not downdip.

Dutton and Simpkins (1986) propose an origin for the groundwater in the lower portion of the Dockum Group. They suggest that the part of the lower portion of the Dockum Group located in the deeper parts of the depositional basin were recharged by precipitation on higher elevation outcrops in New Mexico during the Pleistocene. These sandy outcrops were then eroded from the Pecos Plains and Pecos River valley, thus, cutting off recharge. Figure 4.4.2 illustrates hypothetical flow paths in the Dockum Group presented by Dutton and Simpkins (1986) for conditions before and after erosion of Dockum Group outcrop due to erosion of the Pecos River valley.

4.4.1 Diffuse Recharge

Diffuse sources of recharge are precipitation and irrigation return flow. This section discusses literature estimates of diffuse recharge for the Dockum Aquifer, develops estimates of diffuse predevelopment and current recharge, and discusses irrigation return flow.

4.4.1.1 Literature Estimates

There are few published recharge estimates for the Dockum Aquifer (Table 4.4.1). Bradley and Kalaswad (2003) estimated that the total annual recharge, including cross-formational flow, in the confined sections of the aquifer is approximately 31,000 acre-feet. Details were not given regarding the methodology used to obtain this value, but they describe the source of the recharge as predominately precipitation. This volume of water translates to about 0.16 inches per year of recharge if distributed over 2.32 million acres, which is the approximate area of Dockum Aquifer outcrop assumed to be taking recharge (i.e., the Canadian and Colorado river outcrop areas). In a regional water plan for the Panhandle Regional Planning Commission, Freese and Nichols (2006) estimate effective recharge to the Dockum Aquifer at 23,500 acre-feet per year. They state this recharge is “primarily limited to outcrop areas”. Using the approximate area of the Dockum Aquifer outcrop, 23,500 acre-feet per year translates to a recharge rate of about 0.12 inches per year. Although the Freese and Nichols (2006) report is for the Panhandle Regional Planning Commission, there is no indication that the reported effective recharge is for the Panhandle portion of the aquifer only. However, if the effective recharge reported by Freese and Nichols (2006) is for the Panhandle portion of the aquifer only, the estimated recharge rate would be higher than the value of 0.12 inches per year calculated using the total outcrop area. The difference between the recharge rates calculated from the annual recharge estimates in Bradley and Kalaswad (2003) and Freese and Nichols (2006) could be due to two factors. The first is the fact that the estimated annual recharge reported in Bradley and Kalaswad (2003) includes cross-formation flow and the value in Freese and Nichols (2006) does not. The second is the uncertainty in the area of outcrop over which the estimate recharge reported in Freese and Nichols (2006) is applicable.

Bounding estimates of recharge to the Dockum Aquifer can be inferred by (1) examination of recharge information from similar aquifers/formations in the vicinity (mostly Ogallala and Seymour aquifers) for comparison purposes and (2) compiling general statements about the aquifer from a diverse array of publications. An important aspect of recharge is land use, particularly land use changes. The impact of land use on recharge is well documented in Texas (e.g., Scanlon and others, 2005). Recharge for the Ogallala Aquifer ranges from low values or zero beneath natural interdrainage rangeland areas to higher values (about 1 inch per year in the Dawson County region) beneath cropland areas (Scanlon and others, 2005).

Recharge information from aquifers/formations in the vicinity of the Dockum Aquifer were reviewed for comparison purposes. For predevelopment conditions, the Ogallala Aquifer groundwater availability model used about 0.03 inches per year of recharge in Borden, Dawson, Garza, and Howard counties west of the Dockum high total dissolved solids outcrop area, and 0.007 to 0.085 inches per year immediately south of the Dockum Canadian River outcrop area in Oldham and Potter counties (Blandford and others, 2003). For current land use conditions (postdevelopment conditions), the Ogallala Aquifer groundwater availability model used 2.0, 1.75, and 1.5 inches per year on non-irrigated agriculture for high, medium, and low soil permeability, respectively, in Borden, Dawson, Garza, and Lynn counties, which are located west and northwest of the Colorado River outcrop area. Those counties have recently experienced significant water table rises in the Ogallala Aquifer (Blandford and others, 2003; Scanlon and others, 2005). The Ogallala Aquifer groundwater availability model used a recharge rate of zero to 0.5 inches per year in Oldham and Potter counties just south of the Dockum Canadian River outcrop area for postdevelopment conditions (Blandford and others, 2003). In the Seymour Aquifer groundwater availability model, the portions of the Seymour Aquifer located in Fisher and Kent counties just northeast of Scurry County were assigned a recharge rate between 1 and 2 inches per year (Ewing and others, 2004). The permeability of the Dockum Aquifer is less than that of the Ogallala or Seymour aquifers. Therefore, recharge to the Dockum Aquifer is expected to be less than recharge to either of these two aquifers.

4.4.1.2 Estimation of Predevelopment Recharge

Scanlon and others (2002) describe several techniques to estimate recharge. Techniques applied to the High Plains Aquifer include vertical distribution of chloride and/or tritium in soil water and comparison of chloride concentration in groundwater to that of rain water (Blandford and others, 2003). Unsaturated zone chloride data and bomb pulse tritium data can be used to quantify water fluxes in the unsaturated zone and ultimately recharge rates. Those two techniques are not currently applicable to the Dockum Aquifer due to lack of data. However, an estimate of the regional historical recharge on the time scale of centuries can be made using the following equation (Blandford and others, 2003):

$$R = \frac{P \times Cl_P}{Cl_{GW}} \tag{4.4.1}$$

where R is the regional historical recharge, P is the amount of precipitation, Cl_P is the chloride concentration in the precipitation and dry deposition (only common source of chloride in shallow aquifers), and Cl_{GW} is the chloride concentration in the groundwater. This approach makes the assumption that all chloride in the saturated zone comes from infiltration and none from brine contamination or halite dissolution. Due to the possibility of chloride in the Dockum Aquifer from sources other than precipitation, this analysis was applied using only samples having a total dissolved solids concentration of less than 500 milligrams per liter. Recharge numbers estimated using Equation 4.4.1 are inferred from the current aquifer chemical composition which averages, in a complex manner, precipitation and processes of the past centuries.

Average precipitation in Mitchell, Scurry, and neighboring counties is approximately 20 inches per year. Chloride concentration in rain water (including dry deposition) is estimated to be 0.32 milligrams per liter in this area (Scanlon and others, 2002). The chloride concentration of groundwater in the Dockum Aquifer varies from 1 to 82 milligrams per liter for samples having a total dissolved solids concentration of less than 500 milligrams per liter from wells with a depth of less than 200 feet. Using the oldest sample from these wells (Figure 4.4.3), the median chloride concentration is 34 milligrams per liter, which yields an estimated historical recharge over the entire Colorado River outcrop area of 0.19 inches per year. This recharge value lies within the range proposed by Scanlon and others (2005) using a saturated zone modeling approach. Scanlon and others (2005) used a supraregional approach at the state level and derived a recharge rate of 0.08 to 0.20 inches per year for the Colorado River outcrop area.

A few playas are present in the footprint of the Dockum Aquifer outcrop and in the footprint of the Ogallala Formation "island" overlying the Dockum Aquifer subcrop in Scurry County (Figure 4.4.4). This Ogallala Formation “island” is essentially unsaturated and allows direct recharge to the Dockum Aquifer. Using a variety of field techniques, Scanlon and Goldsmith (1997) estimated flux through a playa on the Ogallala Aquifer at 60 to 120 millimeters per year. About 50 playas have been mapped in the Ogallala Formation "island" covering approximately 2,923 acres or 0.82 percent of the surface area. Mullican and others (1997) show through modeling that focusing recharge at playa locations only and distributing the volume of recharge in the playas across the entire outcrop area have the same impact for the aquifer. On the Ogallala Formation "island", recharge is estimated to be in the 0.02 to 0.04 inches per year range. The high end of this range is more likely because precipitation in Scurry County is higher than the average precipitation over the entire Ogallala Aquifer.

In the Canadian River outcrop area, precipitation is estimated to be 17 inches per year and contain 0.2 milligrams per liter chloride (Scanlon and others, 2002). Using the oldest samples having a total dissolved solids concentration of less than 500 milligrams per liter from wells with a depth of less than 200 feet (Figure 4.4.5), the median chloride concentration is 17 milligrams per liter, resulting in an estimated predevelopment recharge rate of 0.2 inches per year. The supraregional approach by Scanlon and others (2003) yielded a recharge value of less than 0.08 inches per year for the Canadian River outcrop area.

4.4.1.3 Estimation of Current Recharge

The impact of land use on recharge has been well documented across the world including the Texas Panhandle (e.g., Scanlon and others, 2005; Blandford and others, 2003). Ewing and others (2004) report that water levels in the Seymour Aquifer, including the portion of the aquifer in Fisher County, which is located just east of Scurry County, rose after settlers cleared the land. An increase in the quality of the water in the Seymour Aquifer (i.e., change from ‘gyp’ to fresh water) was also noted. A study on the Ogallala Aquifer in Dawson County by Scanlon and others (2005) documented in detail the impact of land use on recharge. In the Ogallala Aquifer groundwater availability model, the recharge rate for postdevelopment was determined to be higher than for predevelopment in the croplands but was the same elsewhere (Blandford and others, 2003).

A crude analysis of the average water-table elevation through time gives some qualitative insights into recharge. This analysis used all data available from the TWDB database, not just data for wells with multiple observations. In the Colorado River outcrop area, the regional rise in the water table may be as much as 60 feet on average in the past 50 years (Figure 4.4.6a). Assuming a specific yield of 15 percent, this translates into an additional volume of slightly more than 2.2 inches per year. This includes recovery, impact of land use changes, and other processes such as irrigation return flow and recharge from losing segments of the Colorado River and its tributaries. This approach is, on average, valid if wells are relatively uniformly distributed across the area of interest for most years and if most wells exhibit the same behavior (rising or declining). Both of these criteria are generally satisfied in the Colorado River outcrop area. Using the same approach in the Canadian River outcrop area shows that water levels have remained much more stable (Figure 4.4.6b) although the uncertainty level and noise in the data is much higher because of the larger elevation relief.

For wells with a linear water-level rise in the Colorado River outcrop area, recharge can be estimated as the amount of water-level rise divided by the time period of the rise times the specific yield. For wells with an initial water-table depth of less than 100 feet, the estimated recharge ranges from 0.7 to 4.3 inches per year (Figure 4.4.7). The median of these data is 1.6 inches per year, the geometric average is 1.7 inches per year, and the mode is between 0.6 and 1.2 inches per year. These wells generally correspond to cropland areas (Figure 4.4.8) with enhanced recharge as noted above.

The linear rises in water level observed in wells located in the Colorado River outcrop area are not seen in wells in the Canadian River outcrop area. In addition, there is very little cropland area on the Canadian River outcrop area (Figure 4.4.9). As a result of no major land use changes in the Canadian River outcrop area, there has been no increased recharge. Therefore, the recharge determined for this area under predevelopment conditions is also applicable for current (postdevelopment) conditions.

4.4.1.4 Irrigation Return Flow

Irrigation is practiced in both the Colorado and Canadian River outcrop areas. Based on the amount of groundwater pumped for irrigation purposes, irrigation in the Canadian River outcrop area is significantly less than in the Colorado River outcrop area (see Section 4.7). Irrigation return flow can be a significant source of recharge, depending on the concentration of irrigation activities and the type of crops being grown. In general, current agricultural practices for most crops include balancing irrigation with plant evapotranspiration requirements (e.g., Allen and others, 1998), so that the amount of irrigation water likely to move beyond the root zone to the water table below can be very small under good management practices. It is expected that some percent of the total groundwater pumped to supply irrigation water over the Dockum Aquifer outcrop makes its way back to the water table as shallow groundwater recharge.

4.4.2 Rejected Recharge

Rejected recharge is the concept that some water that reaches the water table as recharge in the unconfined part of the aquifer does not travel downdip into the confined part of the aquifer. It discharges instead as springs or evapotranspiration and/or into streams and rivers. For the Dockum Aquifer, rejected recharge is essentially the only component of total recharge due to the configuration and location of the outcrop areas. The Colorado River outcrop area and all outcrops located along the eastern edge of the aquifer are located in the downgradient portion of the aquifer. Therefore, it is not possible for recharge in these areas to move into the confined portions of the aquifer. In the Canadian River outcrop area, flow is towards the Canadian River and its tributaries, so all recharge entering the aquifer moves toward the rivers and streams and not downdip.

4.4.3 Focused Recharge

Reservoirs, lakes, rivers, and streams provide a potential site of focused recharged. Although there are no natural lakes in the outcrop of the Dockum Aquifer, there are nine reservoirs providing potential areas of focused recharge. For a complete description of the reservoirs in the study area, see Section 4.5.3. Reservoirs, by necessity are constructed in topographic lows and are typically located in clayey soils. As a result, it is expected conceptually that any shallow recharge to the groundwater that occurs as a result of these reservoirs would be small and have a high potential for discharge through evapotranspiration and stream discharge.

Recharge to the Dockum Aquifer by streams is limited to the outcrop areas. For a complete description of streams and rivers in the study area, see Section 4.5.1. One method for determining stream-aquifer interaction is through streamflow gain/loss studies. Section 4.5.1 summarizes the results of 11 gain/loss studies intersecting the Dockum Aquifer in the Colorado River outcrop area.

There are no gain/loss studies reported in the Canadian River outcrop area. Because the area of the watershed for the Canadian River is much larger than the area of Dockum outcrop along the river, it was felt that a baseflow separation study on the river gages would not provide information relevant to the Dockum Aquifer.

4.4.4 General Methodology for Recharge Implementation

Recharge in the model for steady-state conditions was estimated based on groundwater chloride data for wells with a total dissolved solids concentration of less than 500 milligrams per liter and for transient conditions was estimated based on water level rises. The estimated recharge was distributed spatial based on a recharge elevation model. A complete discussion of the implementation of recharge in the model can be found in Section 6.3.4.

Table 4.4.1 Summary of recharge rate estimates.

County/Area	Land use	Aquifer	Recharge (inches per year)	Technique	Reference
Literature Estimates					
All Dockum outcrops, could also include cross-formational flow		Dockum	0.16 (31,000 acre-feet)	not reported	Bradley and Kalaswad (2003)
All Dockum outcrops		Dockum	0.12 (23,500 acre-feet per year)	not reported	Freese and Nichols (2006)
Borden, Dawson, Garza, and Howard counties - Predevelopment	Grassland and shrubland	Ogallala	~0.03	groundwater numerical modeling	Blandford and others (2003)
Oldham and Potter counties - Predevelopment	Grassland and shrubland	Ogallala	0.007 to 0.085	groundwater numerical modeling	Blandford and others (2003)
Borden, Dawson, Garza, and Lynn counties - Postdevelopment	Non-irrigated cropland	Ogallala	1.5 to 2.0	groundwater numerical modeling	Blandford and others (2003)
Oldham and Potter counties - Postdevelopment	Grassland and shrubland	Ogallala	0 to 0.5	groundwater numerical modeling	Blandford and others (2003)
Fisher County and Kent County, both next to Scurry County	not reported	Seymour	1 to 2	groundwater numerical modeling	Ewing and others (2004)
Dockum Aquifer – Colorado River outcrop area					
All of the Colorado River outcrop area - Predevelopment	Grassland and shrubland	Dockum	0.19	saturated zone chloride mass balance	This report
All of the Colorado River outcrop area –Predevelopment		Dockum	0.08 to 0.2	unsaturated zone numerical modeling	Scanlon and others (2003)
Scurry County - Predevelopment		Dockum	0.02 to 0.04	Water budget on playas	This report
All of the Colorado River Outcrop area - Postdevelopment		Dockum	2.2	regional water level rise	This report
Sandy areas (Nolan and eastern Mitchell counties) - Postdevelopment	Cropland	Dockum	Geom. Average = 1.7 Median = 1.6 Range = 0.7 to 4.3	linear water level rises in individual wells	This report

Table 4.4.1, continued

County/Area	Land use	Aquifer	Recharge (inches per year)	Technique	Reference
Dockum Aquifer – Canadian River outcrop area					
All of the Canadian River outcrop area- Predevelopment and Postdevelopment	Grassland and shrubland	Dockum	0.2	saturated zone chloride mass balance	This report
All of the Canadian River outcrop area		Dockum	<0.08	unsaturated zone numerical modeling	Scanlon and others (2003)

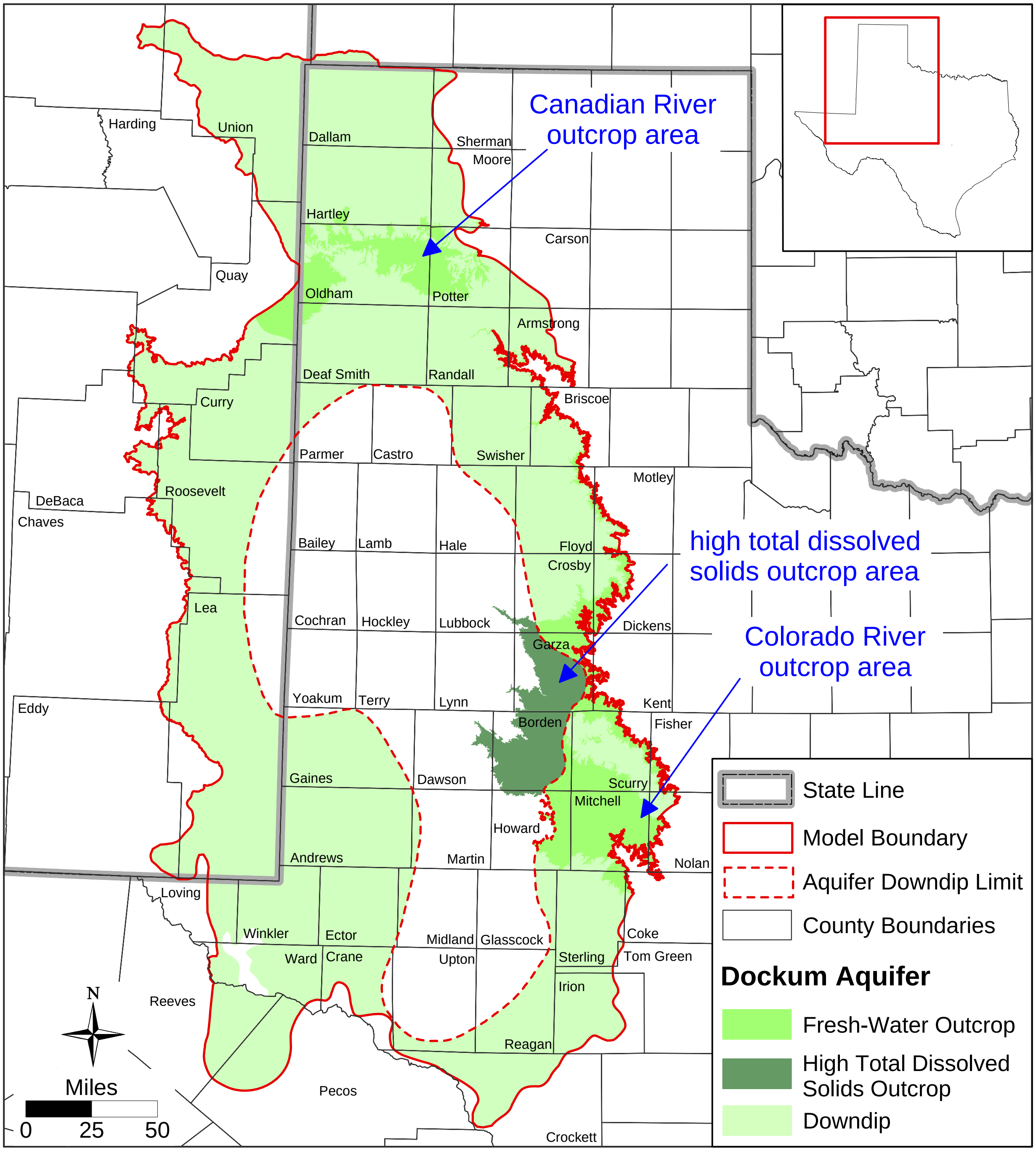


Figure 4.4.1 **Dockum Aquifer outcrop areas.**

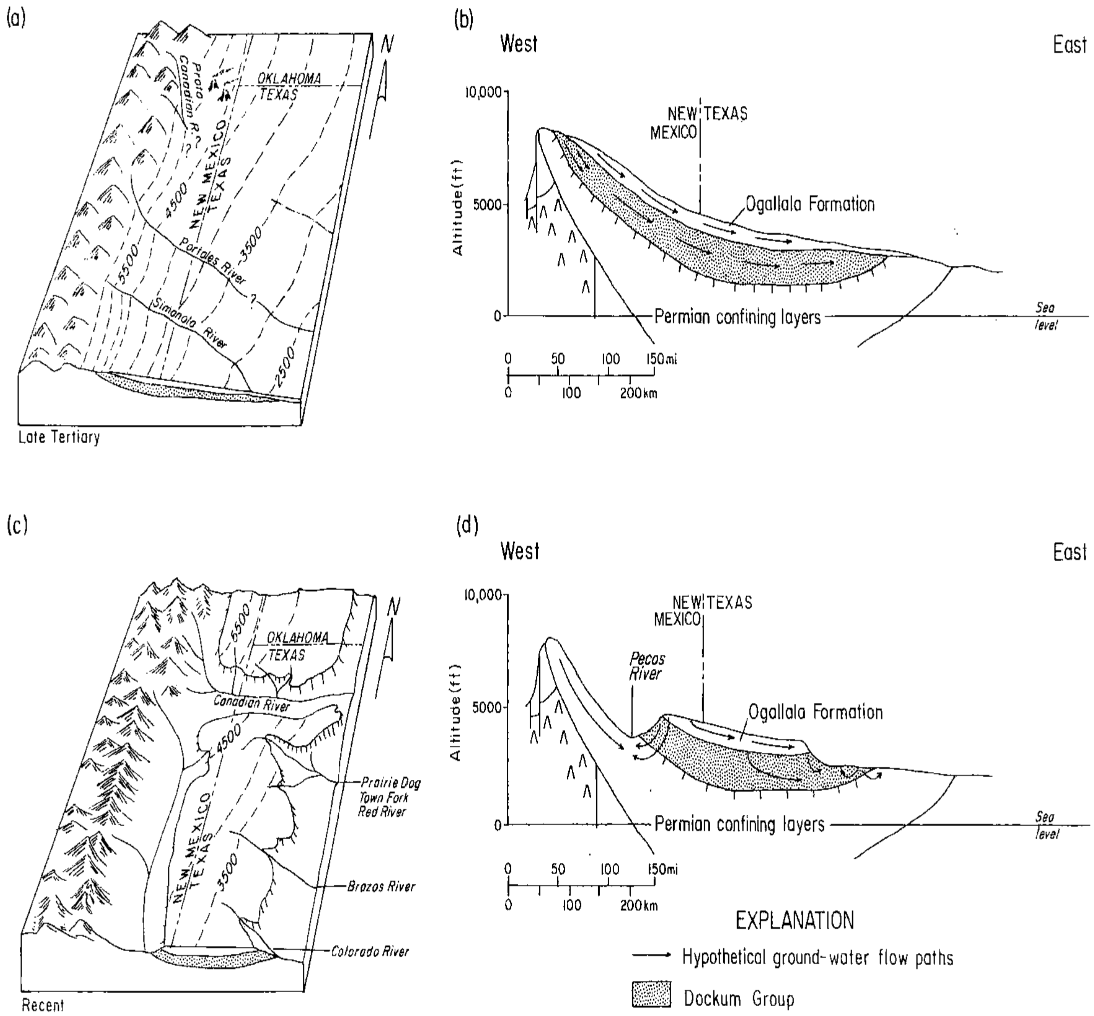


Figure 4.4.2 **Hypothetical block diagrams and regional flow paths of groundwater flow in the Dockum Group (a and b) before and (c and d) after development of the Pecos River valley (from Dutton and Simpkins, 1986).**

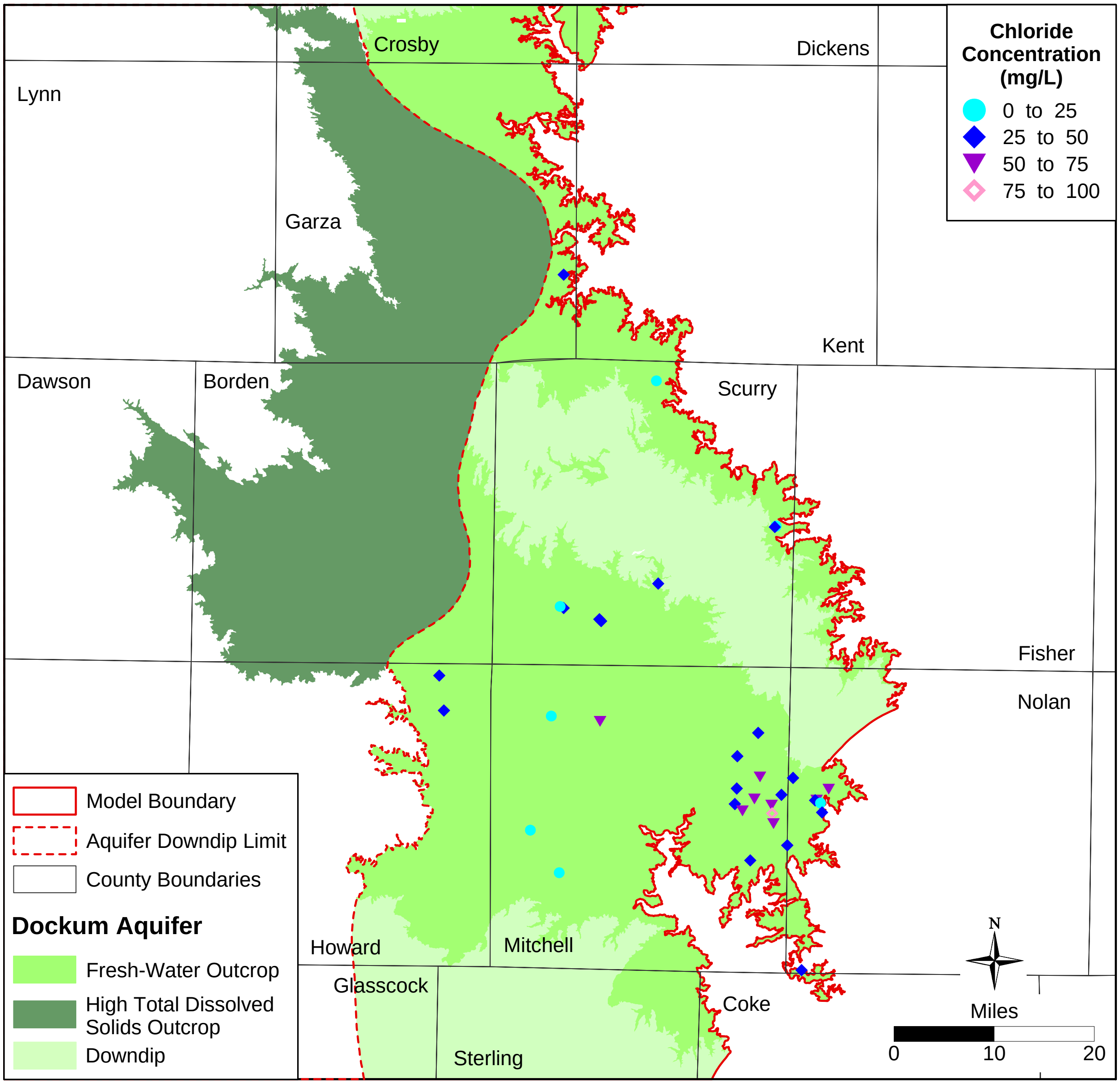


Figure 4.4.3 **Dockum Aquifer chloride concentration in milligrams per liter in the Colorado River outcrop area for samples with a total dissolved solids concentration of less than 500 milligrams per liter from wells with a depth of less than 200 feet.**

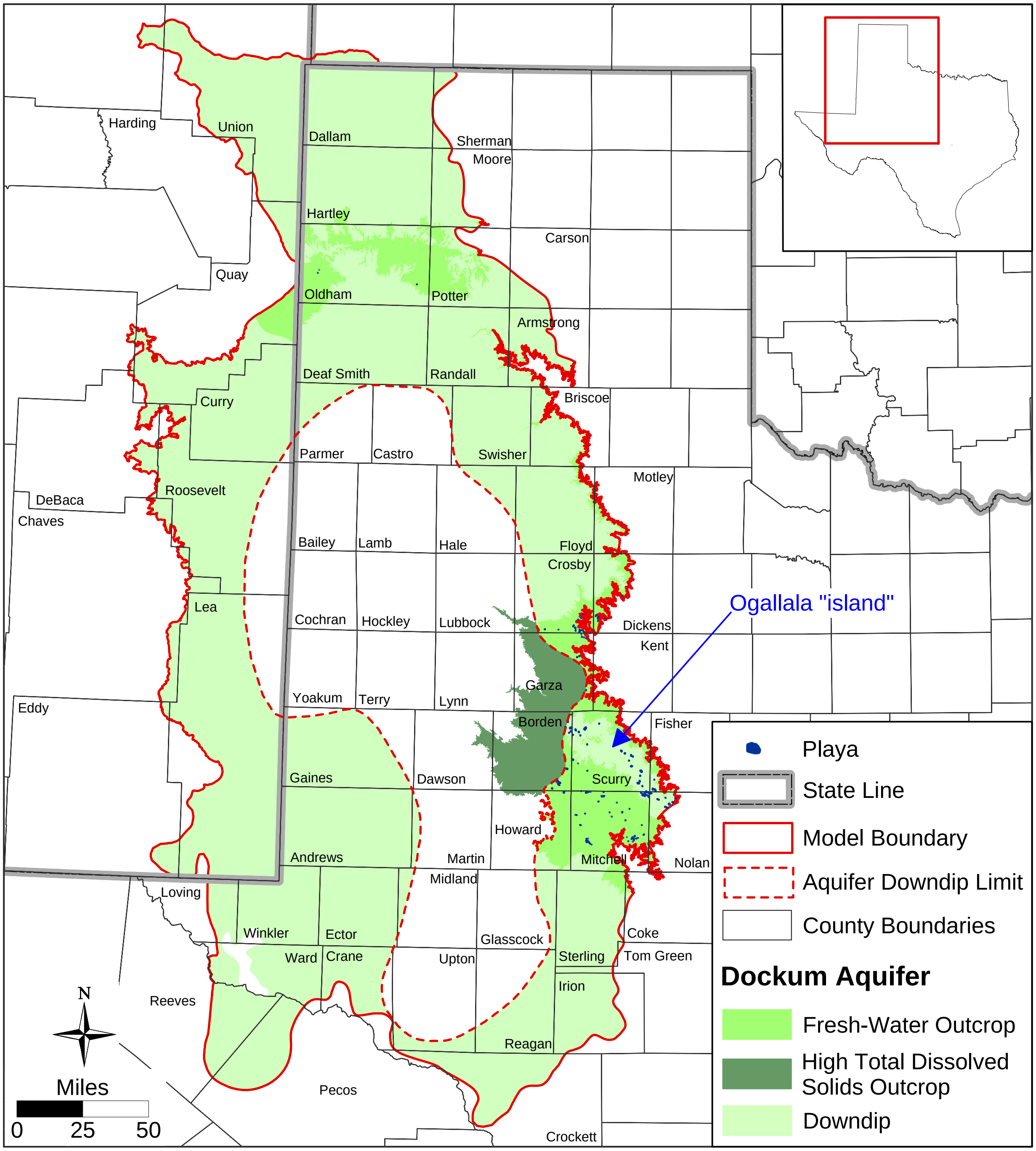


Figure 4.4.4 Playa locations in the Dockum Aquifer outcrop and the Ogallala Formation “island”.

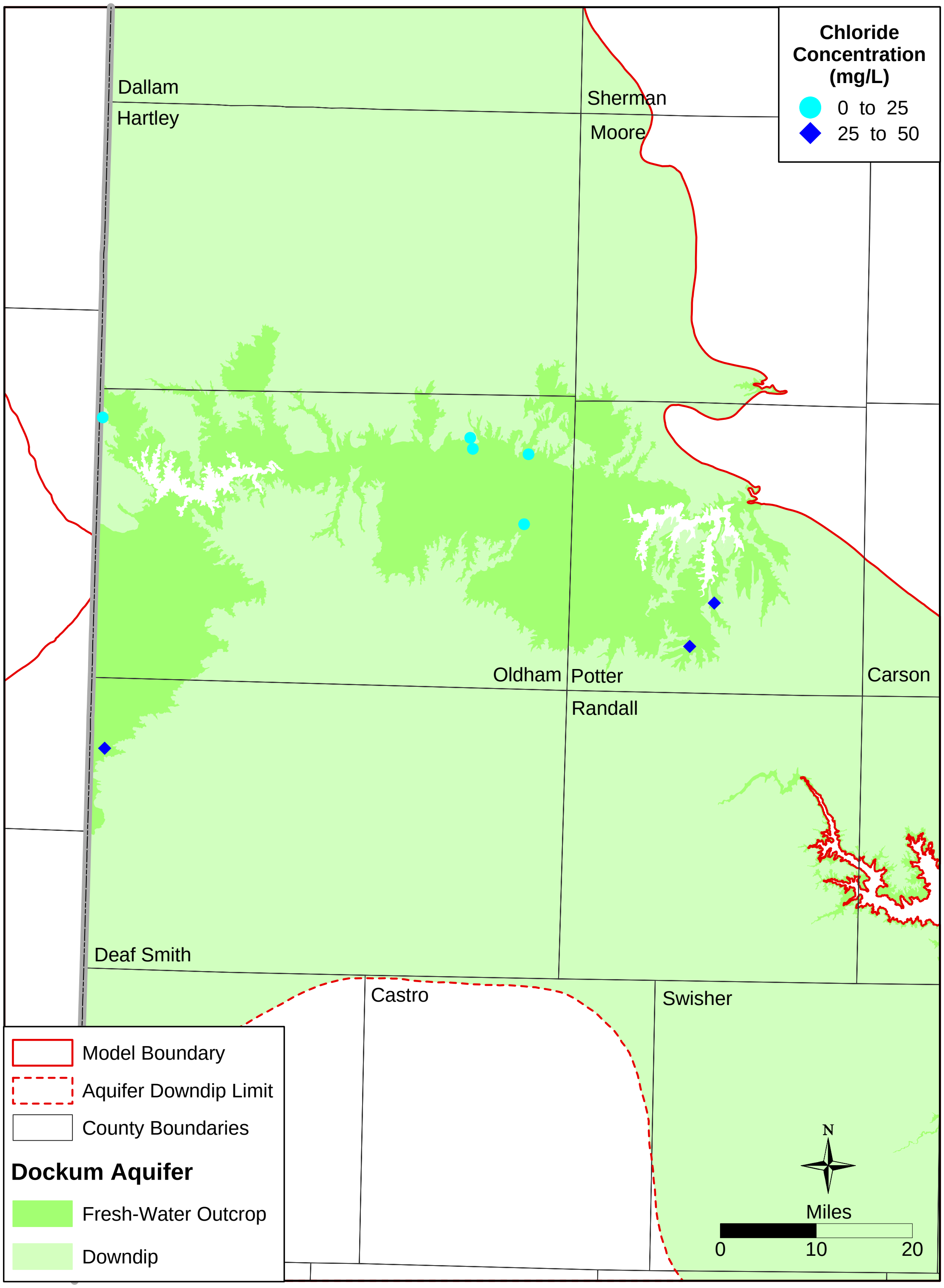
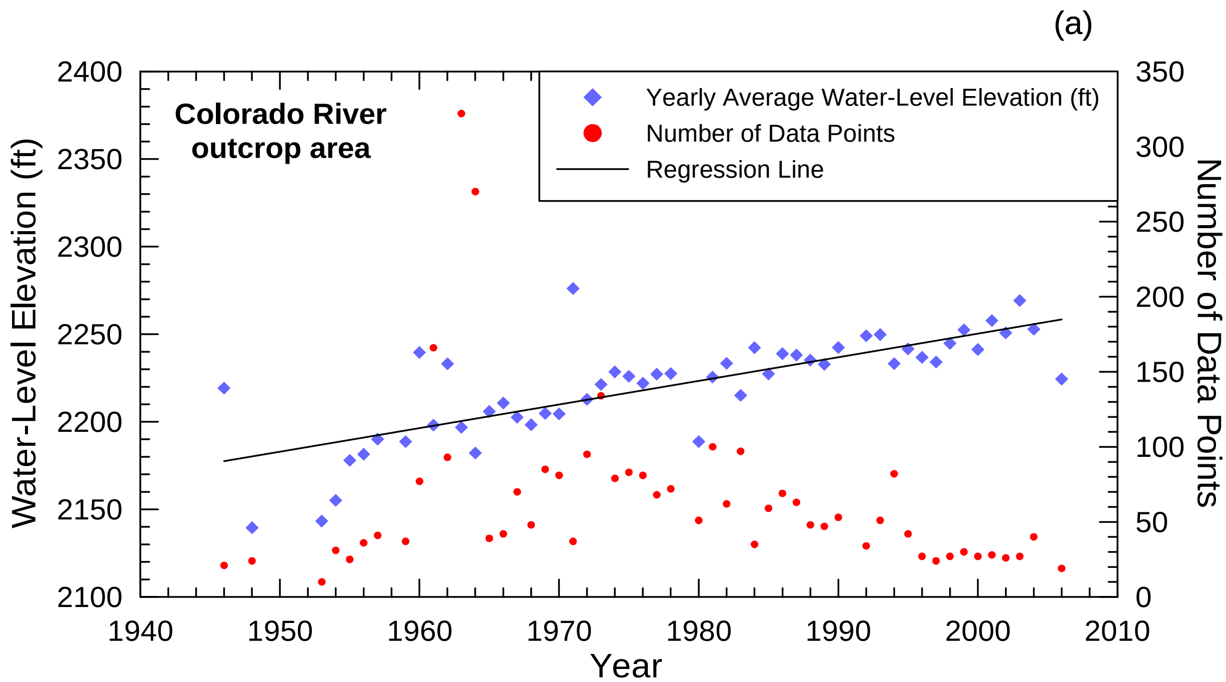


Figure 4.4.5 Dockum Aquifer chloride concentration in milligrams per liter in the Canadian River outcrop area for samples with a total dissolved solids concentration of less than 500 milligrams per liter from wells with a depth of less than 200 feet.



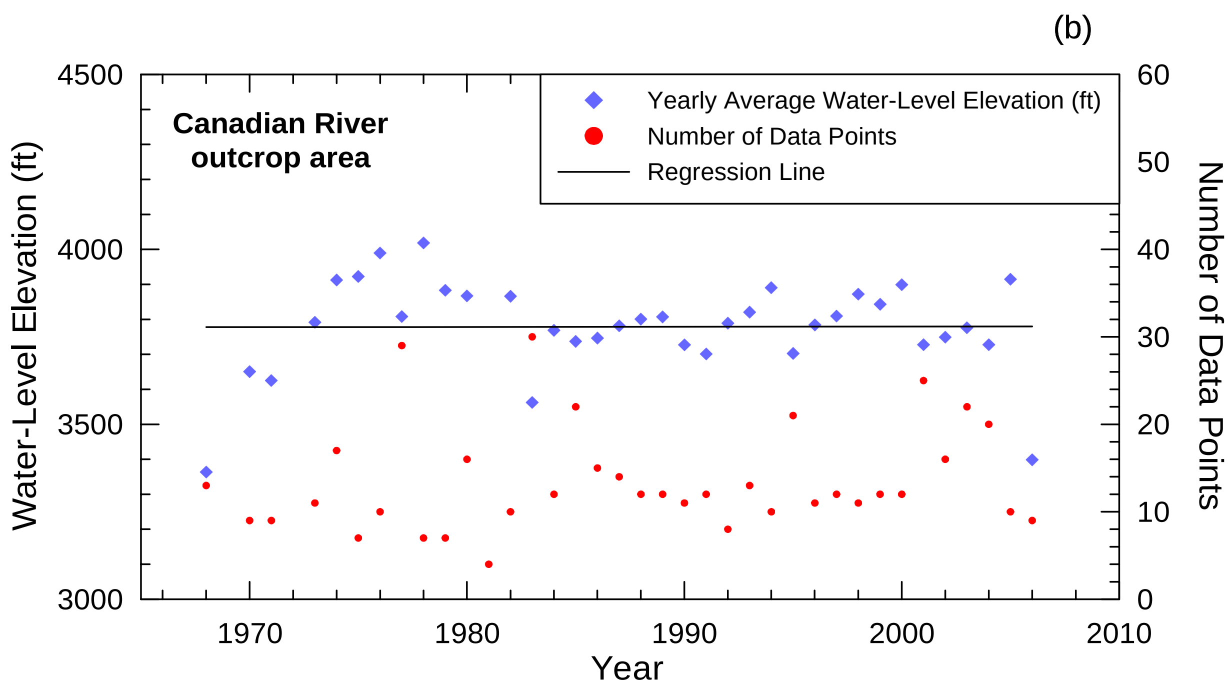


Figure 4.4.6 **Average regional water level in feet in (a) the Colorado River outcrop area and (b) the Canadian River outcrop area.**

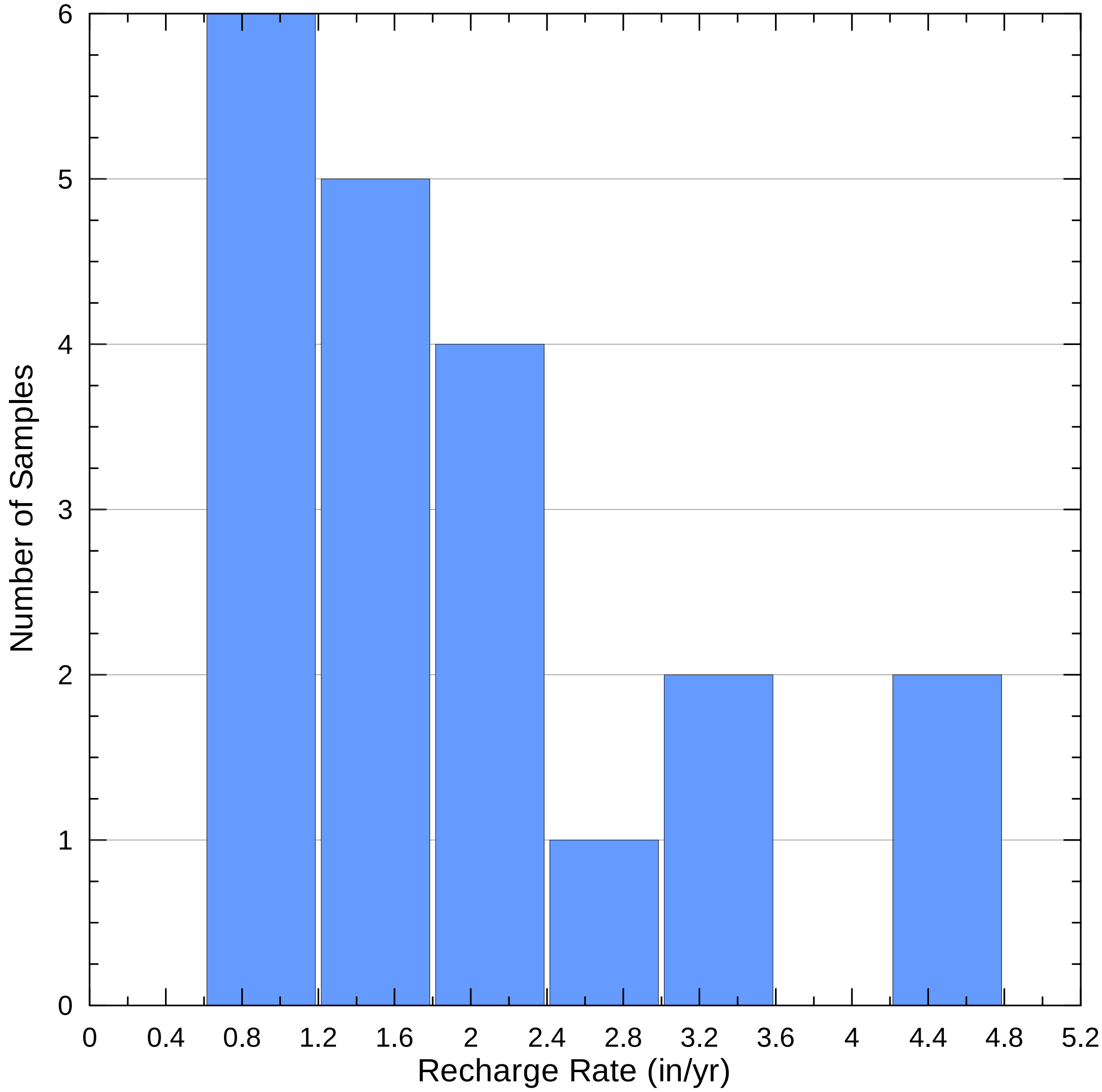


Figure 4.4.7 Histogram of recharge rates in inches per year calculated from linear increases in water level observed in wells in the Colorado River outcrop area.

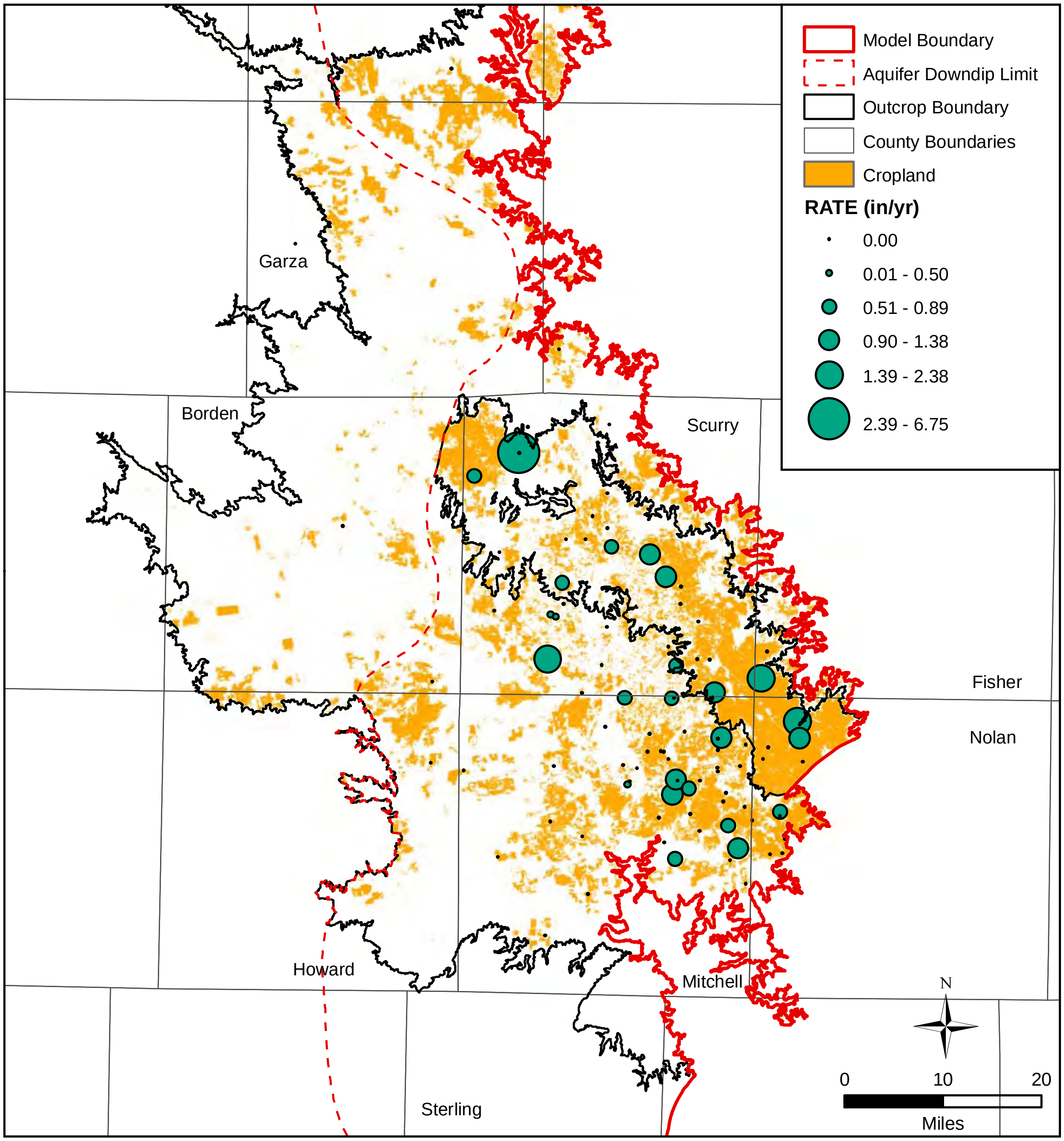


Figure 4.4.8 Rates of linear water-level rises in inches per year and spatial distribution of cropland in the Colorado River outcrop area.

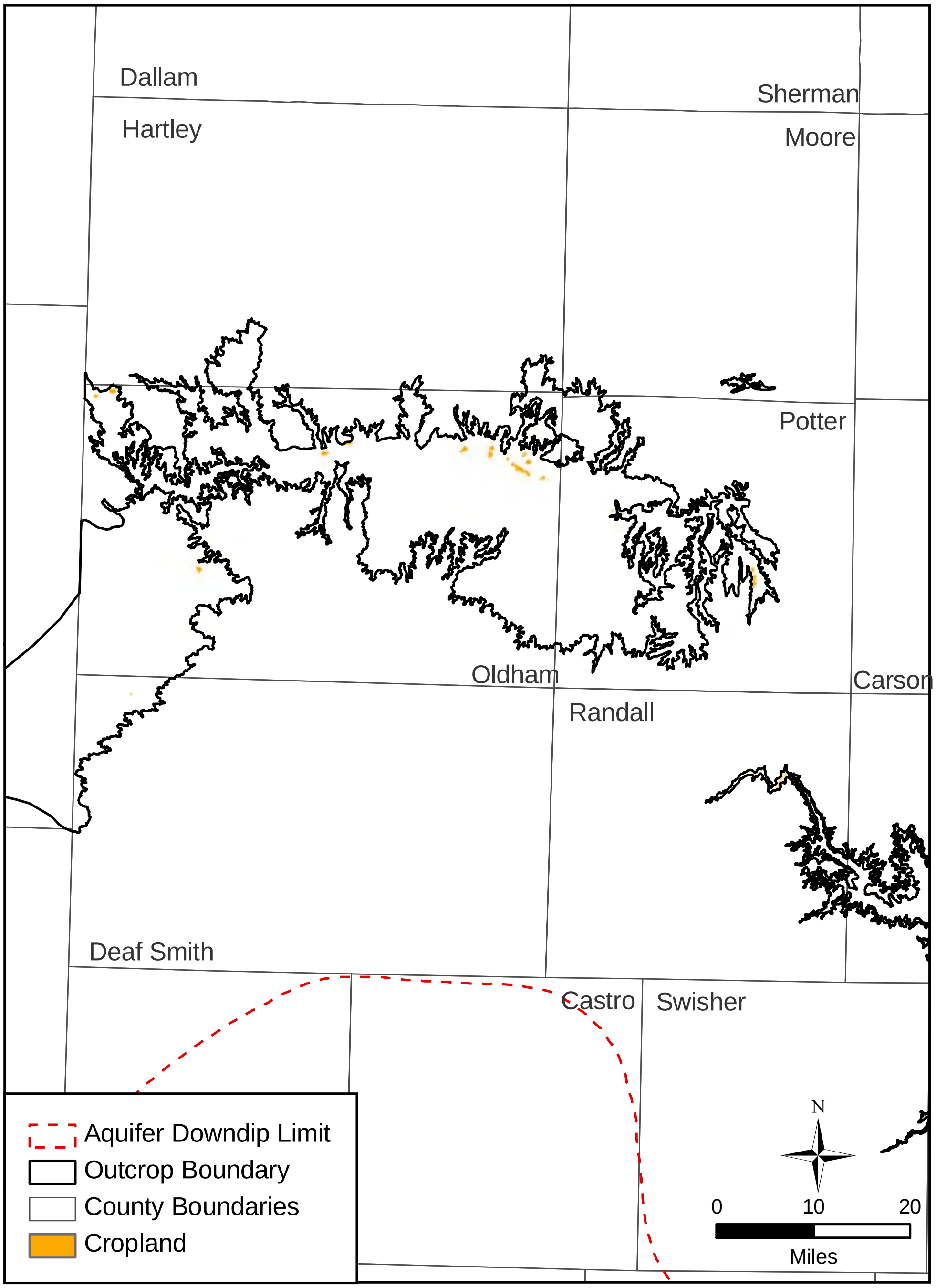


Figure 4.4.9 **Spatial distribution of cropland in the Canadian River outcrop area.**

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4.5 Rivers, Streams, Springs, and Lakes

The interaction between groundwater and surface water occurs at the locations of rivers, streams, springs, and lakes. Rivers and streams can either lose water to the underlying aquifer, resulting in aquifer recharge, or gain water from the underlying aquifer, resulting in aquifer discharge. Discharge from an aquifer also occurs where the water table intersects the ground surface at springs or seeps. Lakes can provide a potential site of focused recharge.

4.5.1 Rivers and Streams

Three major streams, the Canadian, Red, and Colorado rivers (Figure 4.5.1) and numerous smaller streams (see Figure 2.0.4) intersect the study area. Only rivers and streams intersecting the outcrop of the Dockum Aquifer provide a means of aquifer discharge or recharge. Figures 4.5.2 and 4.5.3 show the locations of stream gages in the Canadian River outcrop area and the Colorado River and high total dissolved solids outcrop areas, respectively, where stream flow and elevation data are collected. Figure 4.5.4 shows hydrographs for the two streamflow gages in the Canadian River outcrop area. Figure 4.5.5 shows hydrographs for selected streamflow gages in the Colorado River and high total dissolved solids outcrop areas.

Base flow in a river or stream is the contribution of groundwater to gaining reaches of a stream. After runoff from storm events has drained away, the natural surface-water flow that continues is predominately base flow from groundwater. Streams can have an intermittent base flow with flow during wet periods and low or no flow during dry periods. Larger streams and rivers might have a perennial base flow. Direct exchange between surface and groundwater is limited to the outcrop.

Stream-aquifer interaction can be quantified by conducting gain/loss studies. Slade and others (2002) compiled the results of 366 gain/loss studies conducted since 1918 on 249 individual stream reaches throughout Texas. They document 11 gain/loss studies that intersect the Dockum Aquifer in the Colorado River outcrop area. The following discussion deals only with the portions of the studies that intersected the Dockum Aquifer. The locations of these studies, and stream gage locations along the reaches of the river studied, are shown on Figure 4.5.6. The characteristics of the gain/loss studies are summarized in Table 4.5.1.

Three studies where performed on Beals Creek (37, 38, and 39) in February 1986, December 1986, and February-March 1989, respectively. Study 37 indicates no significant gain or loss from the stream to the Dockum Aquifer and studies 38 and 39 indicate gaining conductions indicative of aquifer discharge to the stream. The river gain on the Dockum Aquifer outcrop was 100.4 acre-feet per year per mile of river during study 38 and 59.2 acre-feet per year per mile of river during study 39. Table 4.5.1 shows that flow in the downstream gage on Beals Creek (gage 08123800) was very low during study 37 and significantly higher during studies 38 and 39.

Eight studies (42 - 48 and 52), conducted between February 1968 and March 1989, included approximately the same reach of the Colorado River on the Dockum Aquifer outcrop. The earliest three studies, one conducted in 1968 and two conducted in 1975, indicate gaining conditions, with gains of 30.0, 163.1, and 101.4 acre-feet per year per mile of river for studies 52, 45, and 46, respectively. The latter five studies, conducted in 1976, 1986, 1987, and 1989, indicate losing conditions, indicative of aquifer recharge, with losses ranging from 34 to 240 acre-feet per year per mile of river. The flow data for the gages along the study area (see Table 4.5.1) show the highest flow rates during studies 43 and 44, which also show the highest stream losses. This is consistent with an observation given in Shamburger (1967) that states "In the South Fork Champion Creek area in Nolan County, one well is reported to be capable of supplying 15 to 20 percent more sprinklers after sustained heavy runoff to the creek". This suggests recharge of the Dockum Aquifer during high flow conditions on the river. The gage flow data for the remaining studies conducted on the Colorado River in the Dockum Aquifer outcrop do not show a clear trend between stream flow and stream gain/loss.

Slade and others (2002) do not identify any gain/loss studies conducted in the Canadian River outcrop area. Because the area of the watershed for the Canadian River is much larger than the area of Dockum Aquifer outcrop along the river, it was felt that a baseflow separation study on these gages would not provide information relevant to the Dockum Aquifer. A comparison of flow at the two gages (Figure 4.5.7) indicates very similar flow rates from about 1969 (start of the record for upstream gage 07227470) to late 1971, slightly lower flow at the upstream gage than at the downstream gage from late 1971 to mid-1976, and then similar flow from mid-1976 to the end of the record in late 1977 for the upstream. The period during which flow is higher at the downstream gage may indicate a gaining stream or may indicate additional flow from tributaries entering the Canadian River between the two gages. In summary, the flow rates and fluctuations for these two gages are consistent and, therefore, no apparent recharge to or discharge from the Dockum Aquifer occurs along this reach of the Canadian River.

The stream routing package for MODFLOW (Prudic, 1988) was used to implement rivers and streams into the Dockum Aquifer groundwater availability model. A detailed discussion of that implementation is provided in Section 6.3.3.

4.5.2 Springs

Springs are locations where the water table intersects the ground surface. Springs typically occur in topographically low areas in river valleys or in areas of the outcrop where hydrogeologic conditions preferentially reject recharge. Three sources were used to find spring data for the Dockum Aquifer: the TWDB well website, a database of Texas springs compiled by the United States Geological Survey and reported in Heitmuller and Reece (2003), and Brune (2002). Figure 4.5.8 shows the locations of springs flowing from the Dockum Aquifer. Only springs identified as flowing from the Dockum Aquifer or the Dockum Aquifer combined with an overlying or underlying formation are included in this figure.

The literature review identified 90 springs or groups of springs issuing from the Dockum Aquifer. The majority of the springs are located along the eastern escarpment and in the Canadian and Colorado river outcrop areas. Of these, 17 springs do, or at one time did, discharge at a rate greater than 100 gallons per minute. Six are located in Briscoe County, six also in Floyd County, two in Motley County, and one each in Crosby, Potter, and Scurry counties. The available measured spring flow rates range from the springs being dry to a high of 97.1 liters per second (1,539 gallons per minute; 3.43 cubic feet per second) at Roaring Springs in Motley County. Brune (2002) states that Roaring Springs is a natural beauty spot with the discharge water falling over a ledge below the spring into a pool. Initially, the falls could be heard about a mile away, but in 1975 they could be heard only about a quarter of a mile away (Brune, 2002). A hydrograph of discharge from Roaring Springs, which issues from the Dockum Aquifer, shown in Figure 4.5.9 indicates a decline in discharge from about 1945 to about 1960 but relatively stable discharge since that time to the end of the record in 1994. Figure 4.5.9 also shows a hydrograph of discharge from Chicken Springs, which is the source of Chicken Creek, located in Potter County. Note that the time scale for this hydrograph is 1940 to 1980. This spring flows from the Dockum and Ogallala aquifers. Discharge from Chicken

Springs steadily declined between about 1956 and 1962 and remained relatively stable from 1962 to 1980.

Throughout much of the state, including the study area, spring flows have shown a general decline over time. Most information regarding spring declines for minor springs is anecdotal and undocumented. Table 4.5.2 shows that two or more flow measurements are available for 19 Dockum Aquifer springs. Of those 19, three show an increase in flow over time, two show stable flow over time, and 14 show declining flow over time. The flow from several springs has stopped and the springs have become dry or flow has reduced such that the springs are now just seeps. Brune (2002) notes that declining water levels due to pumping has resulted in reduced flow in many of the Dockum Aquifer springs.

Springs were implemented in the Dockum Aquifer groundwater availability model with drain boundary conditions. A detailed discussion of that implementation is provided in Section 6.3.3.

4.5.3 Lakes and Reservoirs

There are no natural lakes in the study area. However, nine reservoirs occur in the outcrop of the Dockum Aquifer. Table 4.5.3 lists the names, owners, area, and year impounded for these reservoirs in the active model area. Figure 4.5.10 shows the locations of the reservoirs and the historical lake stage elevations for three of the reservoirs. The hydrograph for Lake Meredith shows elevation fluctuations from about 2,877 to 2,915 feet above mean sea level with an average value of about 2,895 feet above mean sea level. The hydrograph for White River Reservoir shows fairly constant elevations until about 1992 and then declines of about 10 to 15 feet up until 2000. The hydrograph for Lake JB Thomas shows relatively constant elevations around 2,255 feet above mean sea level from 1954 to 1963 and then an overall decrease in the lake level of about 35 feet up until about 1970. From about 1970 to 1994, the elevation of Lake JB Thomas fluctuated about 20 feet about an average level of around 2,225 feet above mean sea level. The reservoirs located in outcrop areas provide potential locations for focused recharge to or discharge from the underlying Dockum Aquifer. Reservoirs, by necessity, are constructed in topographic lows and are usually located on clayey soil to reduce leakage. As a result, it is expected conceptually that groundwater interaction with the reservoirs is negligible. Therefore, reservoirs were not included in the Dockum Aquifer groundwater availability model.

Table 4.5.1 Summary of the portions of streamflow gain/loss studies that intersect the Dockum Aquifer outcrop in the Colorado River outcrop area (after Slade and others, 2002).

Study Number	Study Date(s)	Flow at Gage (cfs)				River Gain or Loss[a] (cfs)	Reach Length (mi)	Gain or Loss per Mile Reach[a] (cfs)	Gain or Loss per Mile Reach[a] (AFY/mi)
Gain-Loss Studies on Beals Creek									
		8123720		**8123800**					
		regulated		**unregulated**					
37	2/24/1986	0.01		0.11		-0.01	46.1	0.000	-0.16
38	12/9/1986	1.4		9.6		6.38	46.1	0.138	100.40
	12/10/1986	0.18		8.8					
39	2/27/1989			6.6		3.76	46.1	0.082	59.17
	2/28/1989			7.2					
	3/1/1989			6.4					
Gain-Loss Studies on the Colorado River									
		8117995	**8119500**	**8120700**	**8121000**				
		unregulated	**regulated**	**regulated**	**regulated**				
52	4/8/1968		3.3	2.8	3.1	2.30	55.8	0.041	29.90
45	2/14/1975		0.43	7.0	11	7.98	35.5	0.225	163.08
46	11/13/1975		0.22	3.2	6.7	4.96	35.5	0.14	101.36
47	1/20/1976		0.36	3.8	0.17	-2.24	35.5	-0.063	-45.78
48	3/2/1976		0.31	4.2	0.2	-2.25	35.5	-0.063	-45.98
42	2/24/1986		0.34	4.5	0.17	-2.92	62.5	-0.047	-33.89
	2/25/1986		0.35	4.8	0.23				
	2/26/1986		0.34	5.2	0.24				
43	1/6/1987		2.5	20	24	-20.68	62.5	-0.331	-240.04
	1/7/1987		2.5	19	24				
	1/8/1987		2.5	18	24				
	1/9/1987		2.5	22	26				
44	2/27/1989	2.0	1.6	14	13	-11.06	62.5	-0.177	-128.38
	2/28/1989	1.8	1.6	13	1.3				
	3/1/1989	1.8	1.6	13	0.92				

NOTE: Regulated - at least 10 percent of the contributing drainage area is controlled by at least one reservoir.
Unregulated - less than 10 percent of the contributing drainage area in controlled by a reservoir.

[a] Negative values reflect losses and positive values reflect gains.

cfs = cubic feet per second   mi = mile   AFY/mi = acre-feet per year per mile

Table 4.5.2 Summary of springs flowing from the Dockum Aquifer or the Dockum Aquifer combined with an overlying aquifer.

County	Spring Name/Number	Formation	Elevation (feet)	Max flow (lps)	Max flow (gpm)	Max flow (cfs)	Max flow (AFY)	Date of Max	Min flow (lps)	Min flow (gpm)	Min flow (cfs)	Min flow (AFY)	Date of Min	Number of Measure-ments	Source
Armstrong	Dripping Springs	Dockum		**0.95**	15	0.03	24	1940	**seeps**				8/1978	2	Brune (2002)
Armstrong	Harrell Springs	Dockum		**0.63**	10	0.02	16	1940	**dry**				8/1978	2	Brune (2002)
Armstrong	Hidden Springs	Dockum		**1.9**	30	0.07	49	8/11/1978						1	Brune (2002)
Briscoe	Cottonwood and Red Rock Springs	Dockum		**26.3**	417	0.93	673	7/10/1979						1	Brune (2002)
Briscoe	11-21-302	Dockum	2180	6.3	**100**	0.22	161	1946						1	United States Geological Survey
Briscoe	11-21-303	Dockum	3150	5.0	**80**	0.18	129	1946						1	United States Geological Survey
Briscoe	11-21-304	Dockum	3050	3.2	**50**	0.11	81	1946						1	United States Geological Survey
Briscoe	11-21-305	Dockum	2050	12.6	**200**	0.45	323	1946						1	United States Geological Survey
Briscoe	11-21-306	Dockum	3040	12.6	**200**	0.45	323	1946						1	United States Geological Survey
Briscoe	11-21-308	Dockum	3040	15.8	**250**	0.56	404	1946						1	United States Geological Survey
Briscoe	11-47-201	Dockum	2770	18.9	**300**	0.67	484	10/19/1967	0.6	**10**	0.022	16	1938	2	United States Geological Survey
Briscoe	11-47-302	Dockum	2705	0.2	**3**	0.01	5	1969						1	TWDB website/ United States Geological Survey
Briscoe	11-47-504	Dockum	2855	0.2	**3**	0.01	5	1938						1	United States Geological Survey
Briscoe	11-47-505	Dockum	2800	5.7	**90**	0.20	145	1967	5.2	**83**	0.185	134	1938	2	United States Geological Survey
Briscoe	11-47-602	Dockum												0	TWDB website/ United States Geological Survey
Crosby	C Bar Springs	Dockum		**19**	301	0.67	486	1938	**0.5**	8	0.018	13	4/1977	2	Brune (2002)
Crosby	L7 Springs	Dockum		**3.5**	55	0.12	90	1938	**0.05**	0.8	0.002	1.3	4/1977	3	Brune (2002)
Dickens	Boggey Creek Spring	Dockum		0.9	**15**	0.03	24	1938						1	TWDB website/ United States Geological Survey
Dickens	Browning Springs	Dockum		**trickle**										0	Brune (2002)
Dickens	22-10-401	Dockum	2513	1.0	**16**	0.04	26	1969						1	United States Geological Survey

Table 4.5.2, continued

County	Spring Name/Number	Formation	Elevation (feet)	Max flow (lps)	Max flow (gpm)	Max flow (cfs)	Max flow (AFY)	Date of Max	Min flow (lps)	Min flow (gpm)	Min flow (cfs)	Min flow (AFY)	Date of Min	Number of Measure-ments	Source
Dickens	22-17-501	Dockum	2660	0.02	**0.25**	0.00	0	1938						1	United States Geological Survey
Dickens	22-18-801	Dockum	2490	0.9	**15**	0.03	24	1967						1	United States Geological Survey
Dickens	22-18-802	Dockum	2440	0.5	**8**	0.02	13	1967	0.2	**3**	0.007	5	1938	2	United States Geological Survey
Dickens	22-25-201	Dockum	2485	0.2	**2.5**	0.01	4	1969						1	United States Geological Survey
Dickens	22-25-202	Dockum	2485	0.28	**4.5**	0.01	7	1938	0.22	**3.5**	0.008	6	1969	2	United States Geological Survey
Dickens	nr	Dockum		**0.2**	3	0.01	5	8/11/1979						1	Brune (2002)
Floyd	Blue Hole Springs	Dockum		12.7	**202**	0.45	326	1968						1	TWDB website/ United States Geological Survey
Floyd	Cold Springs	Dockum		0.6	**10**	0.02	16	nr	**dry**				1968	2	TWDB website/ United States Geological Survey
Floyd	Dripping Springs	Dockum		0.1	**2**	0.00	3	1968						1	TWDB website/ United States Geological Survey
Floyd	Mud Spring	Dockum		0.9	**15**	0.03	24	1968						1	TWDB website/ United States Geological Survey
Floyd	Turkey Creek Falls Spring	Dockum		3.7	**58**	0.13	94	1968						1	TWDB website/ United States Geological Survey
Floyd	Watercress Pool	Dockum		7.3	**115**	0.26	186	1968						1	United States Geological Survey
Floyd	11-55-202	Dockum & Ogallala	2960	0.6	**10**	0.02	16	1938						1	TWDB website/ United States Geological Survey
Floyd	11-55-203	Dockum & Ogallala	2960	0.3	**5**	0.01	8	1938						1	TWDB website/ United States Geological Survey
Floyd	11-55-204	Dockum	2940	12.2	**193**	0.43	312	1968						1	United States Geological Survey
Floyd	11-55-206	Dockum	2940	0.8	**12**	0.03	19	nr						1	United States Geological Survey
Floyd	11-55-303	Dockum	2870	3.2	**50**	0.11	81	1938	1.2	**19**	0.042	31	1968	2	TWDB website/ United States Geological Survey
Floyd	11-56-214	Dockum	2820	0.1	**2**	0.00	3	nr						1	United States Geological Survey

Table 4.5.2, continued

County	Spring Name/Number	Formation	Elevation (feet)	Max flow (lps)	Max flow (gpm)	Max flow (cfs)	Max flow (AFY)	Date of Max	Min flow (lps)	Min flow (gpm)	Min flow (cfs)	Min flow (AFY)	Date of Min	Number of Measure-ments	Source
Floyd	11-56-504	Dockum	2680	0.4	**6**	0.01	10	1938						1	United States Geological Survey
Floyd	11-56-505	Dockum	2720	0.6	**9**	0.02	15	1938						1	United States Geological Survey
Floyd	11-56-506	Dockum	2800	0.2	**3**	0.01	5	1938						1	United States Geological Survey
Floyd	11-56-806	Dockum & Ogallala	2820	7.9	**125**	0.28	202	1938						1	United States Geological Survey
Floyd	11-56-807	Dockum	2740	0.9	**15**	0.03	24	1938						1	United States Geological Survey
Floyd	11-56-809	Dockum	2680	0.02	**0.25**	0.00	0	1938						1	United States Geological Survey
Floyd	11-64-203	Dockum	2785	2.8	**45**	0.10	73	1968						1	United States Geological Survey
Floyd	11-64-204	Dockum	2790	0.3	**5**	0.01	8	1968						1	United States Geological Survey
Floyd	11-64-205	Dockum	2800	2.2	**35**	0.08	57	1968						1	United States Geological Survey
Floyd	11-64-206	Dockum	2770	0.6	**10**	0.02	16	1968						1	United States Geological Survey
Floyd	11-64-208	Dockum	2790	9.3	**147**	0.33	237	1968						1	United States Geological Survey
Floyd	11-64-210	Dockum & Ogallala	2845	2.5	**40**	0.09	65	1937	2.2	**35**	0.078	57	1968	2	United States Geological Survey
Floyd	11-64-216	Dockum	2730	7.9	**125**	0.28	202	1968						1	United States Geological Survey
Garza	Barnum Springs	Dockum							**dry**				6/1979	1	Brune (2002)
Garza	Garza Springs	Dockum							**seep**				6/2/1979	1	Brune (2002)
Garza	Llano Springs	Dockum							**dry**				after 1940	0	Brune (2002)
Garza	Rocky Springs	Dockum												0	Brune (2002)
Garza	OS Springs	Dockum							**wet-weather seeps**				6/1978	1	Brune (2002)
Garza	nr	Dockum							**seeps**				6/5/1979	1	Brune (2002)
Hartley	7-19-101	Dockum & Ogallala												0	TWDB website
Kent	Elkins Springs	Dockum		**0.07**	1.1	0.00	2	8/16/1979						1	Brune (2002)
Kent	Mackenzie Springs	Dockum							**seeps**				8/16/1979	1	Brune (2002)

Table 4.5.2, continued

County	Spring Name/Number	Formation	Elevation (feet)	Max flow (lps)	Max flow (gpm)	Max flow (cfs)	Max flow (AFY)	Date of Max	Min flow (lps)	Min flow (gpm)	Min flow (cfs)	Min flow (AFY)	Date of Min	Number of Measure-ments	Source
Mitchell	28-40-811	Dockum												0	United States Geological Survey
Mitchell	29-25-702	Dockum												0	United States Geological Survey
Mitchell	29-43-113	Dockum		0.3	**5**	0.01	8	nr						1	TWDB website/ United States Geological Survey
Mitchell	29-49-801	Dockum		0.8	**12**	0.03	19	nr						1	TWDB website
Motley	Roaring Springs	Dockum	2510	97.1	**1539**	3.43	2485	1946	23.5	**373**	0.831	602	11/9/1966	152	TWDB website/ United States Geological Survey/Brune (2002)
Motley	11-64-602	Dockum	2680	4.7	**75**	0.17	121	nr						1	United States Geological Survey
Motley	11-64-604	Dockum & Ogallala	2885	8.8	**140**	0.31	226	nr						1	United States Geological Survey
Motley	11-64-909	Dockum & Ogallala	2755	1.9	**30**	0.07	48	1968	0.6	**10**	0.022	16	1938	2	TWDB website/ United States Geological Survey
Motley	11-64-910	Dockum & Ogallala	2765	2.5	**40**	0.09	65	1968						1	TWDB website/ United States Geological Survey
Motley	12-57-803	Dockum	2640	2.3	**37**	0.08	60	1968						1	United States Geological Survey
Motley	22-01-303	Dockum	2575	0.3	**4**	0.01	6	1968						1	TWDB website/ United States Geological Survey
Motley	22-01-503	Dockum & Ogallala	2698	2.4	**37.5**	0.08	61	1938	2.37	**37.5**	0.084	61	1968	2	United States Geological Survey
Motley	22-01-504	Dockum	2660	0.8	**12.5**	0.03	20	1938	0.79	**12.5**	0.028	20	1968	2	United States Geological Survey
Motley	22-09-104	Dockum & Ogallala	2685	2.8	**45**	0.10	73	1968						1	United States Geological Survey
Oldham	Brown's Camp Springs	Dockum		**2.5**	40	0.09	64	5/1977						1	Brune (2002)
Oldham	Chisum Springs	Dockum		**1.9**	30	0.07	49	5/5/1977						1	Brune (2002)
Oldham	Ojo Caballo or Horse Spring	Dockum		**0.063**	1.00	0.00	2	1938	**0.04**	0.57	0.001	0.9	1977	2	Brune (2002)
Oldham	nr	Dockum		**1.7**	27	0.06	44	1938	**seeps**				5/1977	2	Brune (2002)

Table 4.5.2, continued

County	Spring Name/Number	Formation	Elevation (feet)	Max flow (lps)	Max flow (gpm)	Max flow (cfs)	Max flow (AFY)	Date of Max	Min flow (lps)	Min flow (gpm)	Min flow (cfs)	Min flow (AFY)	Date of Min	Number of Measure-ments	Source
Potter	Bonita or Pretty Springs	Dockum & Ogallala		**4.6**	73	0.16	118	7/4/1978						1	Brune (2002)
Potter	Chicken Springs	Dockum & Ogallala		**96**	1522	3.39	2457	1956	**18**	285	0.636	461	1974	26	Brune (2002)
Potter	Pitcher Springs	Dockum		**3.3**	52	0.12	84	7/6/1978						1	Brune (2002)
Potter	Quail Feather Springs	Dockum		**2.7**	43	0.10	69	7/6/1978						1	Brune (2002)
Potter	Sandoval Springs	Dockum		**0.72**	11	0.03	18	7/1978						1	Brune (2002)
Potter	Spring Cove Springs	Dockum & Alluvium												0	Brune (2002)
Randall	CCC Springs	Dockum	3199	**0.38**	6.0	0.01	10	5/11/1937	**0.05**	0.8	0.002	1.3	8/11/1978	2	Brune (2002)
Scurry	Dripping Springs	Dockum		**0.7**	11	0.02	18	12/15/1975						1	Brune (2002)
Scurry	Camp Springs	Dockum	2231	**57**	904	2.01	1459	4/8/1924	**0.13**	2.1	0.005	3	6/14/1975	3	Brune (2002)
Scurry	nr	Dockum							**seeps**				12/1975	1	Brune (2002)
Scurry	28-24-701	Dockum	2240	0.6	**9**	0.02	15	1961						1	TWDB website/ United States Geological Survey

Note: Bolded information reflects values and text given in the data source.
United States Geological Survey = Heitmuller and Reece (2003)

Max = maximum Minimum = minimum lps = liters per second
gpm = gallons per minute cfs = cubic feet per second AFY = acre-feet per year

Table 4.5.3 Characteristics of reservoirs in the Texas portion of the study area.

Reservoir Name	Owner/Controlling Authority	Area (acres)	Date Impounded
Alan Henry Reservoir	City of Lubbock	2,880	1993
Bivins Lake	City of Amarillo	379	1926
Buffalo Lake	U.S. Fish and Wildlife Service	1,900	1938
Buffalo Springs Lake	Lubbock County Water Control and Improvement District No. 1	241	1960
Champion Creek Reservoir	Texas Utilities Generating Co.	1,560	1959
Lake Colorado City	Texas Utilities Generating Co.	1,612	1949
Lake JB Thomas	Colorado River Municipal Water District	7,820	1952
Lake Meredith	Canadian River Municipal Water Authority	17,320	1965
Lake Rita Blanca	U.S. Soil Conservation Service	524	1941
Mackenzie Reservoir	Mackenzie Municipal Water Authority	896	1974
Mitchell County Lake	Colorado River Municipal Water District	1,463	1991
Natural Dam Lake	Wilkinson Ranch and Colorado River Municipal Water District		
Red Draw Lake	Colorado River Municipal Water District	374	1985
White River Reservoir	White River Municipal Water District	1,808	1963

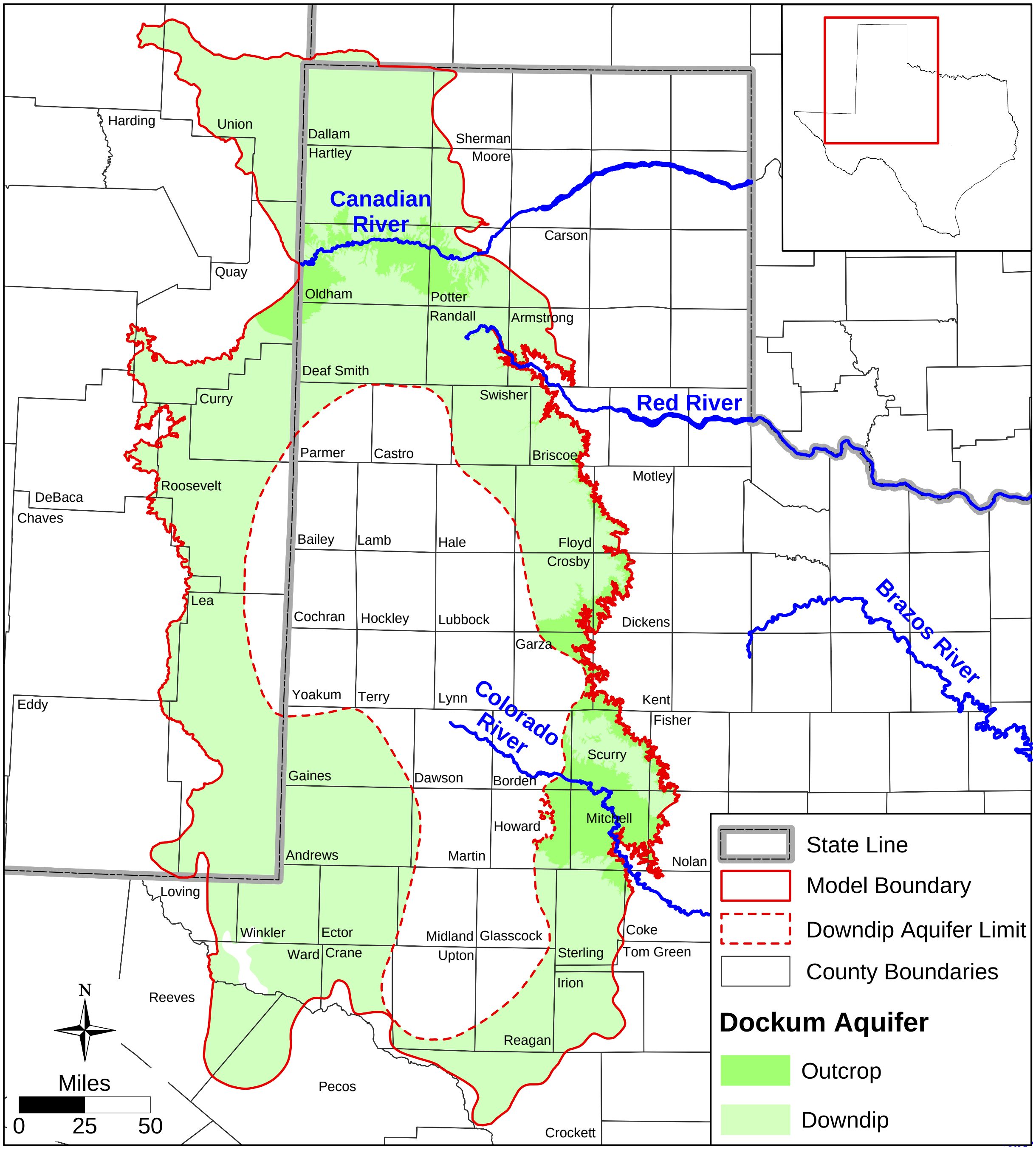

Figure 4.5.1 Major rivers in the Texas portion of the study area.

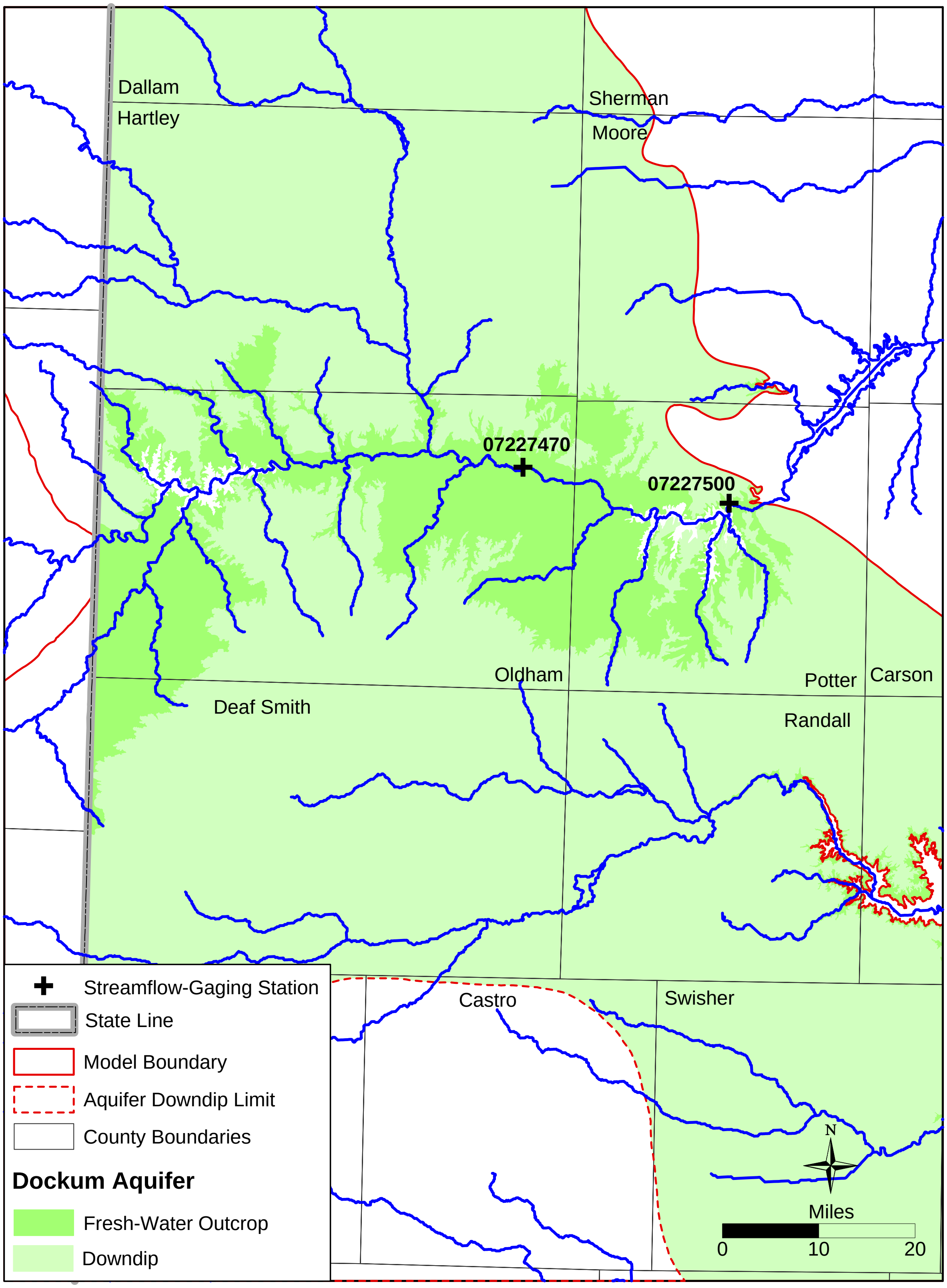

Figure 4.5.2 **Streamflow gage locations in the Canadian River outcrop area.**

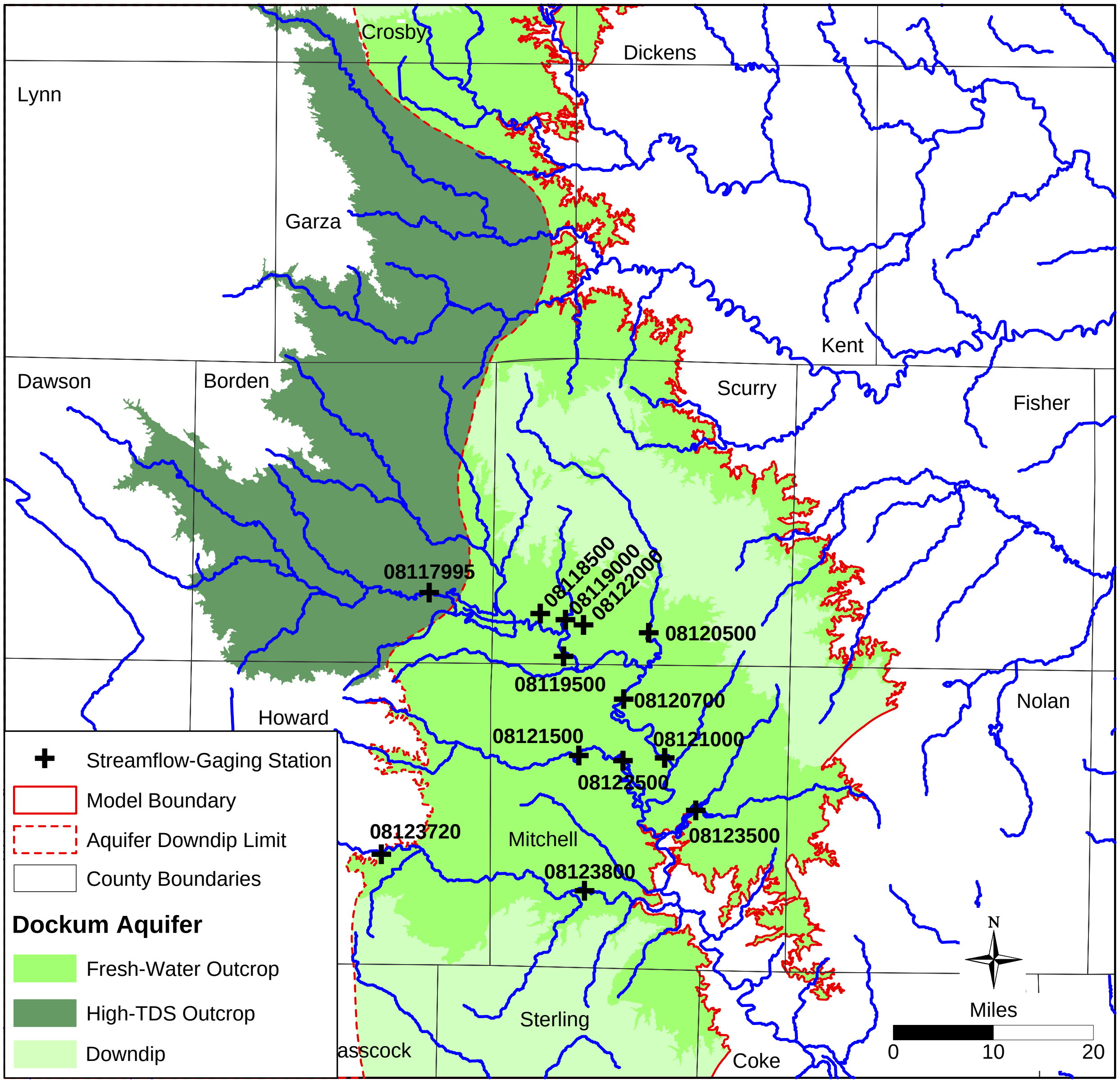

Figure 4.5.3 Streamflow gage locations in the Colorado River and high total dissolved solids outcrop areas.

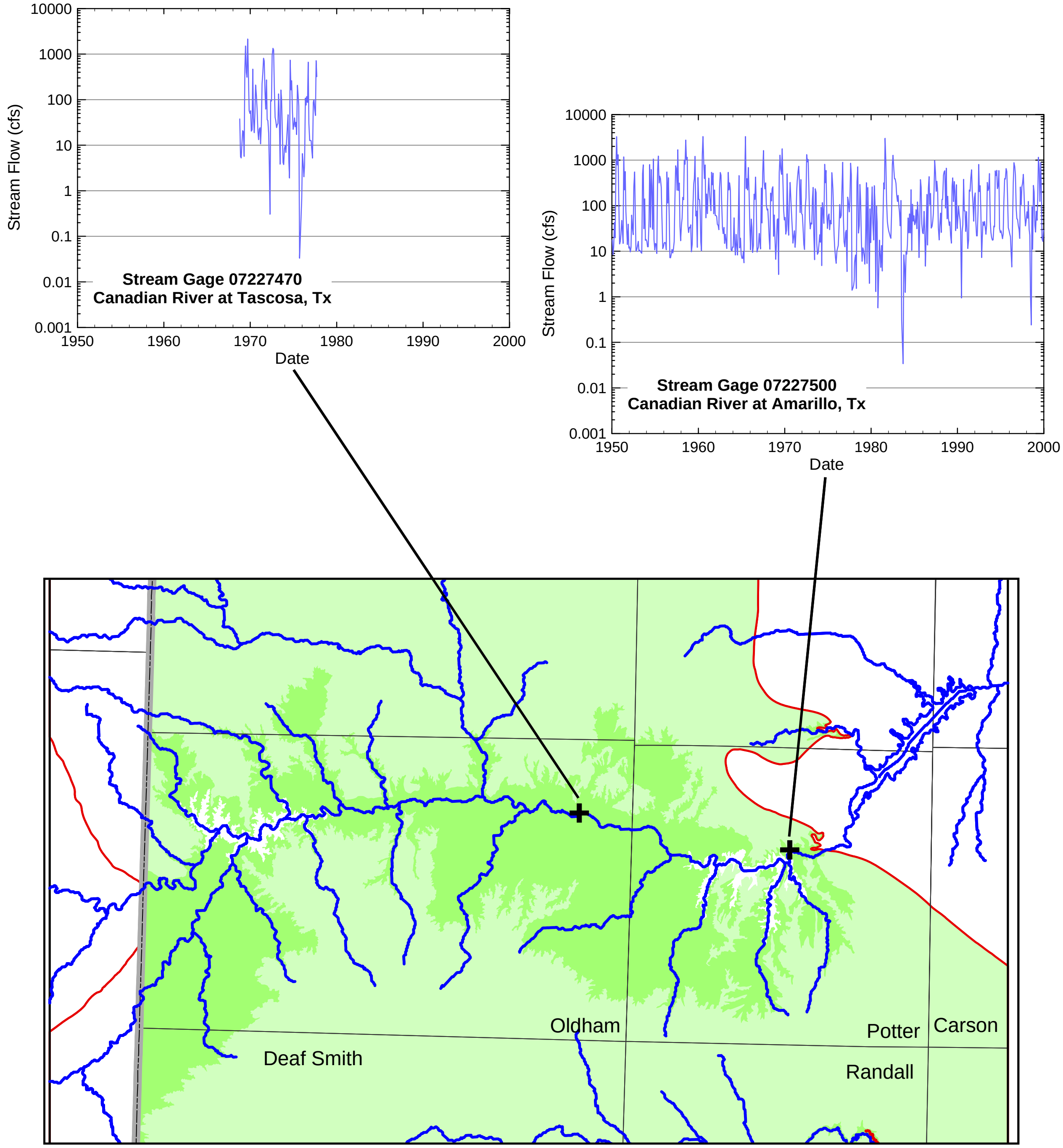

Figure 4.5.4 Hydrographs of streamflow in cubic feet per second for the gages in the Canadian River outcrop area.

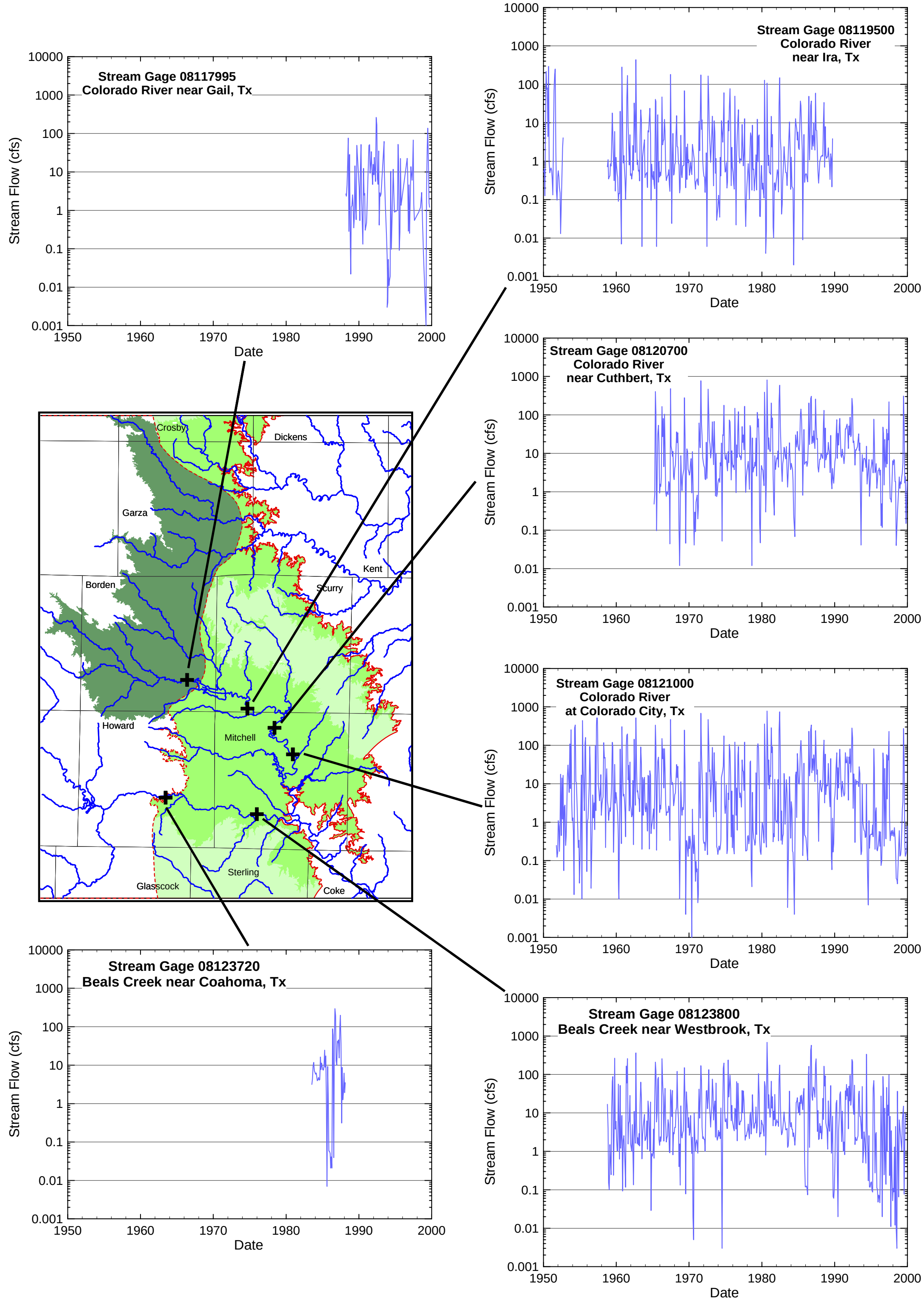

Figure 4.5.5 Hydrographs of streamflow in cubic feet per second for selected gages in the Colorado River and high total dissolved solids outcrop areas.

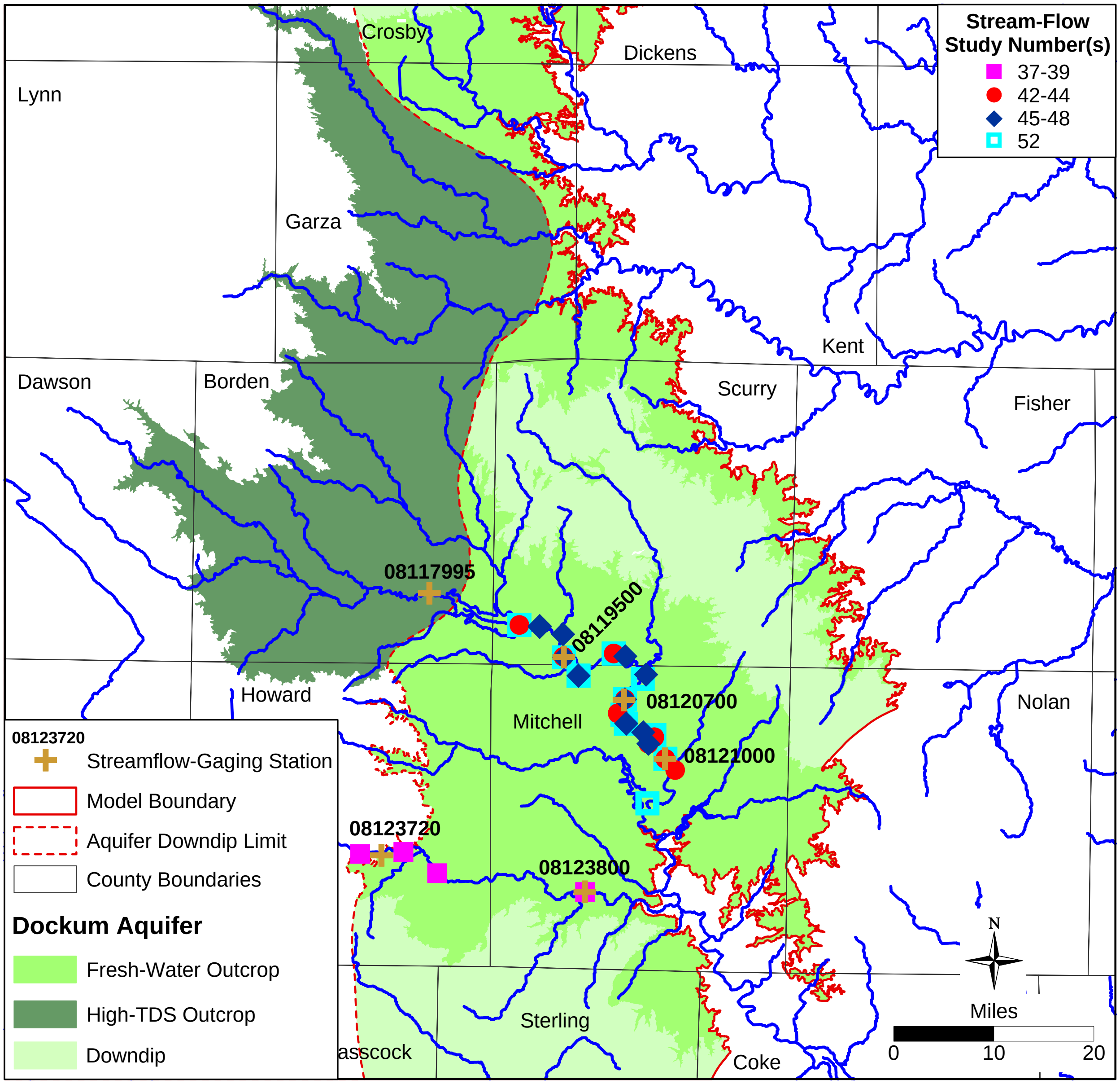

Figure 4.5.6 **Locations of the portions of streamflow gain/loss studies that intersect the Dockum Aquifer in the Colorado River outcrop area.**

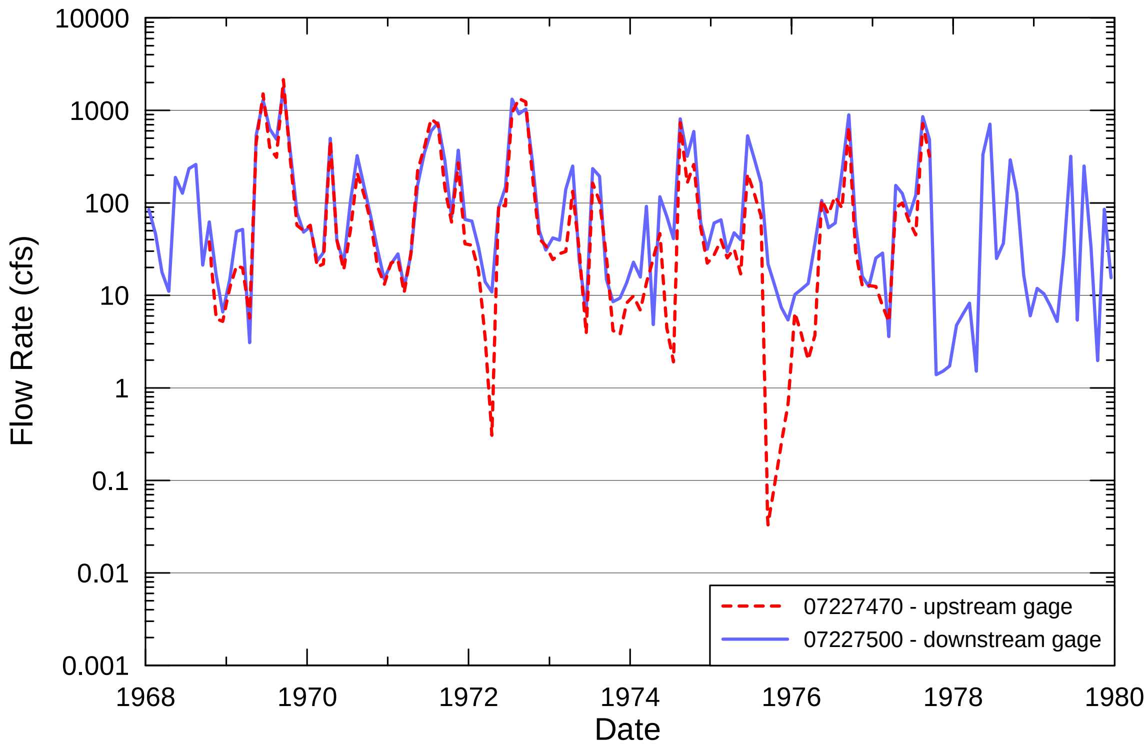

Figure 4.5.7 Comparison of streamflow in cubic feet per second from the gages in the Canadian River outcrop area.

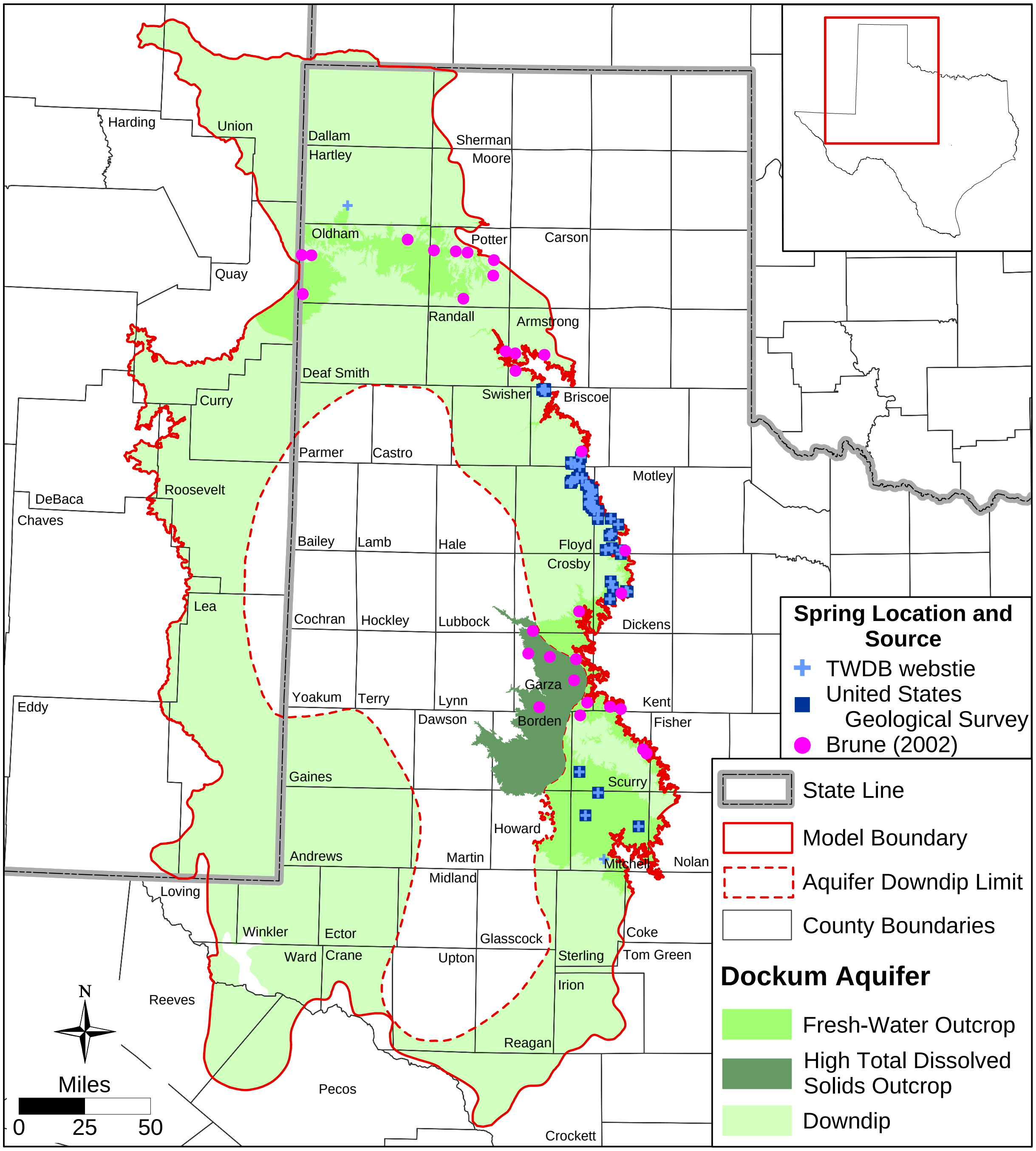

Figure 4.5.8 **Locations in Texas of springs from the Dockum Aquifer or from both the Dockum Aquifer and an overlying aquifer.**

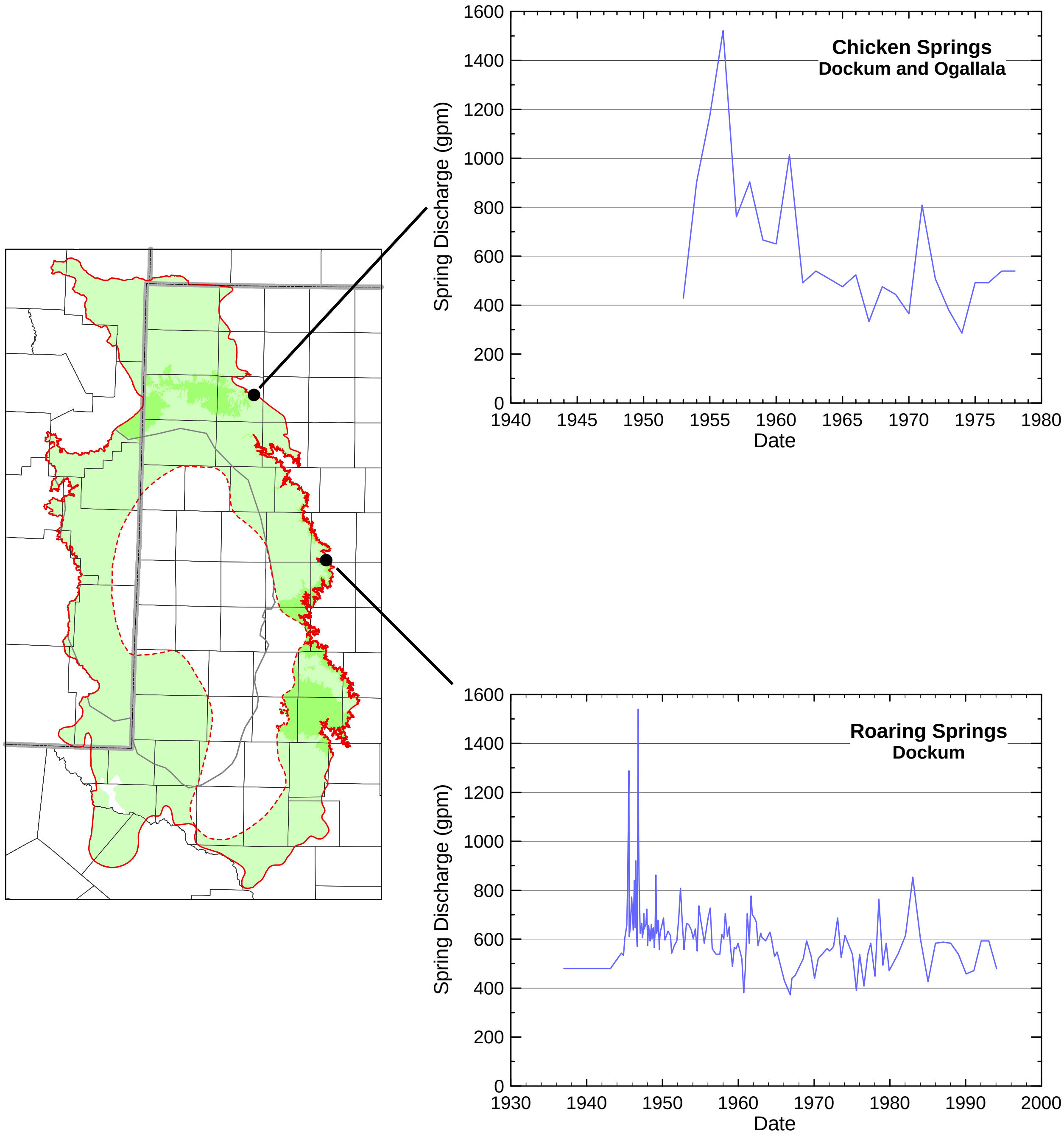

Figure 4.5.9 Hydrographs of discharge in gallons per minute for selected springs.

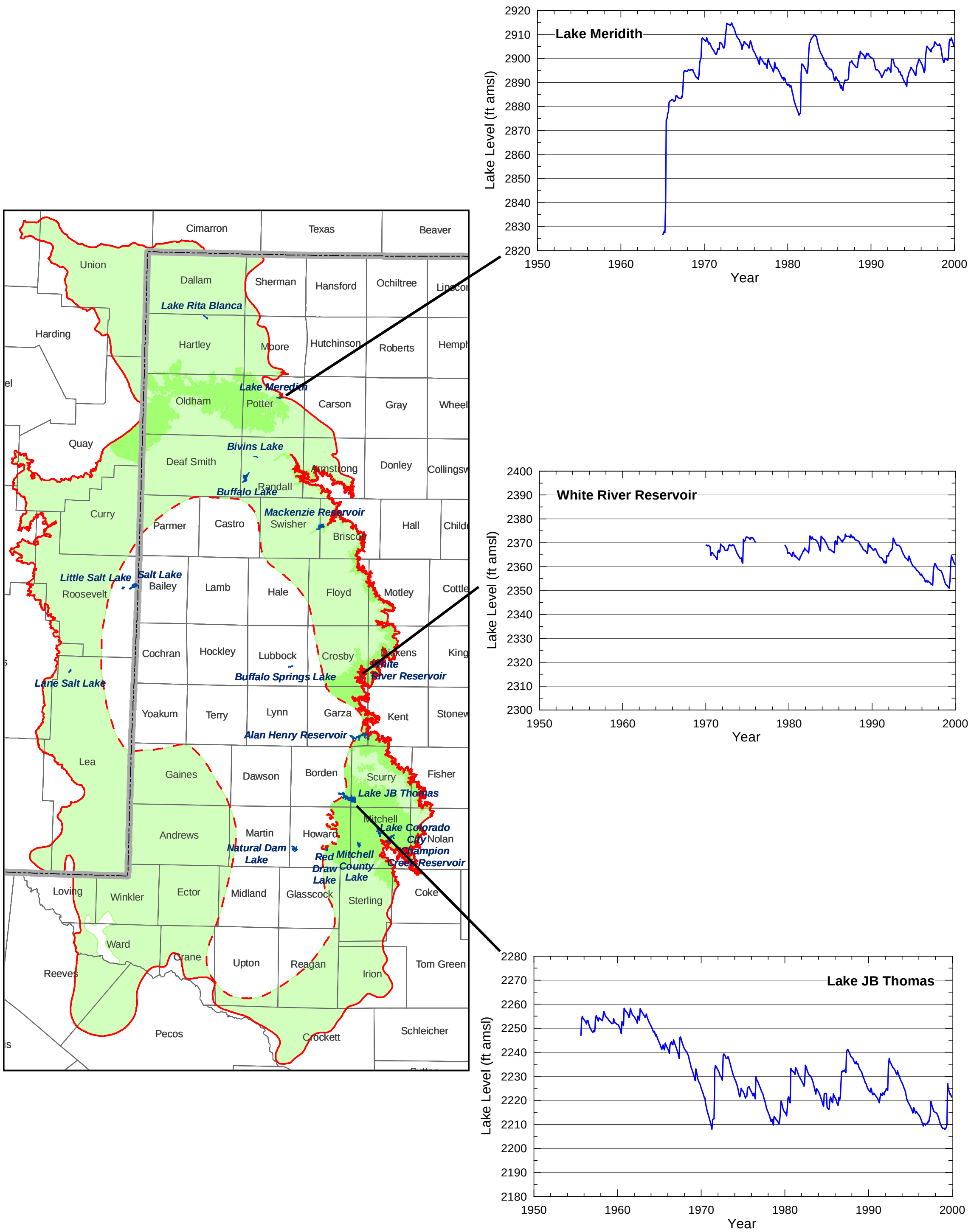

Figure 4.5.10 **Reservoirs in the active model area and hydrographs in feet above mean sea level for selected reservoirs in the Dockum Aquifer outcrop.**

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4.6 Hydraulic Properties

The ability of the Dockum Aquifer to transmit water is dependent on the type of sediment and its lateral continuity. The most porous and permeable sediments are those consisting of coarse-grained deposits and the less permeable sediments are those consisting of fine-grained deposits. Because the type of sedimentation in the Dockum Aquifer varies significantly, so does the ability of the aquifer to transmit water. This variation can be observed over small distances due to the heterogeneity of the aquifer.

Several hydraulic properties are used to describe groundwater flow in aquifers. The properties discussed here are hydraulic conductivity, transmissivity, coefficient of storage or storativity, and specific capacity. Each of these terms is briefly described below.

Hydraulic Conductivity - The measure of the ease with which groundwater can flow through an aquifer. Higher hydraulic conductivity indicates that the aquifer will allow more water movement under the same hydraulic gradient. Units for hydraulic conductivity may be expressed in feet per day or gallons per day per square foot.

Transmissivity - This term is closely related to hydraulic conductivity and refers to the product of the hydraulic conductivity times the effective aquifer thickness. Transmissivity describes the ability of groundwater to flow through the entire thickness of an aquifer. As the thickness of the aquifer increases, the transmissivity increases for a given hydraulic conductivity. Units for transmissivity may be expressed in square feet per day or gallons per day per foot.

Storativity - Also referred to as the coefficient of storage, this term describes the volume of water a confined aquifer will release when the water level in an aquifer is lowered. Storativity is a dimensionless parameter.

Specific Capacity - This parameter reflects the efficiency of a well and an aquifer to produce water to the well. Specific capacity is dependent on both the properties of the aquifer as well as the efficiency of the well. Specific capacity is expressed in terms of gallons per minute per foot of drawdown in the well.

4.6.1 Data Sources

Development of hydraulic properties for the Dockum Aquifer in Texas used transmissivities, specific capacities, and storage coefficients reported in Bradley and Kalaswad (2003) and found on the TWDB website; transmissivity and specific capacity reported in Dutton and Simpkins (1986); storativity reported in Myers (1969); transmissivity and storage reported in Garza and Wesselman (1959); and specific capacity data from Texas Commission on Environmental Quality well records. Typically, specific capacity values were not reported in the data on the TWDB website and on Texas Commission on Environmental Quality well records but, rather, were calculated from well yield and drawdown reported in the sources. Much of the data in Bradley and Kalaswad (2003) and Dutton and Simpkins (1986) are also found on the TWDB website.

Data from the TWDB website were taken for wells identified as being completed into the Dockum Aquifer and for wells completed into another aquifer as well as the Dockum Aquifer. These latter data were used because few wells are completed only into the Dockum Aquifer in the northern portion of the study area where most wells completed into the Dockum Aquifer are also completed into the Ogallala Aquifer, and in the southwestern portion of the study area where many wells are completed into both the Dockum Aquifer and the Pecos Valley Aquifer.

Search of the Texas Commission on Environmental Quality well records involved overlaying the Texas Commission on Environmental Quality well location grid on the Dockum Aquifer. For the majority of wells contained in the Texas Commission on Environmental Quality records, locations are identified only at the Texas Commission on Environmental Quality grid-block level, which is a 2.5-minute by 2.5-minute area. The locations of the centroids of these areas are readily available and were converted to groundwater availability model coordinates. Since individual well locations were not easily determined, all well data contained within a single grid bock were averaged and assigned to the location of the centroid of the block. The Texas Commission on Environmental Quality well records do not include the aquifer in which the wells are completed. Therefore, the depth of the screened interval, or the total well depth when screen data were not available, was compared to the top and bottom depths of the Dockum Aquifer to determine whether the well is completed into the Dockum Aquifer. The search of Texas Commission on Environmental Quality well records focused on areas in the Dockum Aquifer where (1) the Dockum Group is defined as an aquifer by the TWDB, (2) few data from other sources are available, and (3) significant pumping of the aquifer occurs.

Few hydraulic property data were found for the Dockum Aquifer in New Mexico. A couple of specific capacity measurements in Lea County, New Mexico were found in the Lea County report (Nicholson and Clebsch, 1961). However, no data regarding the characteristics of the aquifer or the lithology in the wells were found for these wells, so these data were not used. Reports for DeBaca, Eddy, Quay, and Union counties in New Mexico did not contain hydraulic property data for the Dockum Aquifer. Although Dutton and Simpkins (1986) discuss water levels and water quality for the Dockum Aquifer in New Mexico, they do not include any hydraulic property data.

A detailed review of the well yield and drawdown data on the TWDB website and Texas Commission on Environmental Quality well records was conducted to evaluate the reliability of the reported values. The review revealed some data that did not appear reliable and, therefore, those data were not used to determine hydraulic properties for the Dockum Aquifer. In such cases, the data were determined to be unreliable because the reported drawdown resulted in pumping water levels that were deeper than the total well depth or deeper than the reported depth of the pump. Well yield and drawdown are available from the TWDB website and Texas Commission on Environmental Quality well records for both pumping and bailing tests. Although pumping tests provide more accurate specific capacity data than do bailing tests, data from both types of tests were used because the overall amount of data is low for the Dockum Aquifer and bailing tests provide the only data in many portions of the aquifer.

The locations of hydraulic property data for the Dockum Aquifer are illustrated in Figure 4.6.1. Permeability data are available at one location each in Deaf Smith, Motley, and Upton counties. Transmissivity data are available at 45 locations and storativity data are available at 13 locations. Specific capacity data are available at 293 locations from pumping tests and at 61 locations from bailing tests in the TWDB database, and were found at 44 locations from pumping tests and 31 locations from bailing tests in the Texas Commission on Environmental Quality well records. Both transmissivity and specific capacity data are available at 45 coincident locations.

4.6.2 Calculation of Hydraulic Conductivity from Specific Capacity

Because specific capacity is relatively easy to measure, requiring knowledge of only the pumping rate and drawdown, it is commonly reported in well records. However, hydraulic conductivity is a more useful parameter than specific capacity for regional groundwater modeling. A methodology presented in Mace (2001) was used to estimate hydraulic conductivity from specific capacity.

Transmissivity can be determined from an empirical relationship relating transmissivity and specific capacity, provided benchmarking measurements of both transmissivity and specific capacity exist at the same location. For the Dockum Aquifer, transmissivity and specific capacity were measured at 45 coincident locations. From these paired values, an empirical correlation relating transmissivity to specific capacity was established for the Dockum Aquifer as depicted in Figure 4.6.2. The high coefficient of determination (R^2) of 0.89 indicates good correlation between the transmissivity and specific capacity data. The relationship shown in Figure 4.6.2 was used to estimate transmissivity at locations where only specific capacity was measured.

Typically, hydraulic conductivity is calculated as transmissivity divided by the screen length. For the Dockum Aquifer, however, using the screen length would result in underestimates of the hydraulic conductivity because the screen intervals usually consist of both sand and clay/shale layers. In many instances, the clay/shale layers constitute a significant percentage of the total screened interval. Therefore, an estimate of the sand thickness within the screened intervals, based on review of the lithologic logs, was used to calculate the sand hydraulic conductivity from transmissivity rather than using the entire screen thickness. The sand thickness ranged anywhere from 3 to 100 percent of the screen thickness and averaged 67 percent. In instances where the lithology of the screen interval could not be determined (9 percent of the time), the sand thickness was assumed to be 67 percent of the screen interval.

4.6.3 Analysis of the Hydraulic Conductivity Data

Figure 4.6.3 shows histograms of the sand hydraulic conductivity data for the upper and lower portions of the Dockum Aquifer. Note that the horizontal scale on the figures is logarithmic. Figure 4.6.3 indicates that the data are close to lognormally distributed in both the upper and lower portions of the Dockum Aquifer. A statistical summary of the sand hydraulic conductivity data is provided in Table 4.6.1.

The overall summary statistics for sand hydraulic conductivity for the upper and lower portions of the Dockum Aquifer are relatively similar. This result is unexpected since the upper portion of the Dockum Aquifer generally exhibits more fine-grained material and more limited lateral extent of sand lenses. The similar statistics may be the result of the small sample size for the upper portion of the Dockum Aquifer as well as the potential for data reporting to be biased because it is more likely that a specific capacity will be reported for wells that exhibit higher flow rates (and higher hydraulic conductivities) than for wells that exhibit poor flow rates (and lower hydraulic conductivities). In addition, all wells with specific capacity data for the upper portion of the Dockum Aquifer are completed into both the upper portion of the Dockum Aquifer and the overlying Ogallala Aquifer. In general, the percentage of the wells completed into the upper portion of the Dockum Aquifer is much less than the percentage completed into the Ogallala Aquifer. It is likely that the sand hydraulic properties are dominated by the Ogallala Aquifer and, thus, the calculated sand hydraulic conductivities are biased to values representative of the Ogallala Aquifer rather than the upper portion of the Dockum Aquifer. Based on the mud-rich character of the upper portion of the Dockum Aquifer, the hydraulic conductivity at a well completed into only the upper portion of the Dockum Aquifer is presumed to be lower than that for a well completed into only the Ogallala Aquifer. Therefore, the sand hydraulic conductivities calculated for the upper portion of the Dockum Aquifer are probably biased high.

The spatial distribution of the sand hydraulic conductivity data is given in Figures 4.6.4 and 4.6.5 for the upper and lower portions of the Dockum Aquifer, respectively. The majority of the data are located around the outer edges in the upper portion of the Dockum Aquifer. The majority of the data in the lower portion of the Dockum Aquifer are located within the portion of the Dockum Group defined as an aquifer by the TWDB. Figure 4.6.5 shows significant short-scale variability in the lateral distribution of the sand hydraulic conductivity values in the lower portion of the Dockum Aquifer.

4.6.4 Correlation of Hydraulic Conductivity to Depth and Net Sand Thickness

Since the 1960s, many authors have presented data and evaluations that identify and utilize a relationship that shows permeability or hydraulic conductivity decreasing with increasing depth in geologic and hydrogeologic investigations. This reduction in permeability with depth is discussed generally in the context of porosity reduction (and correlated permeability reduction with porosity reduction) with depth as a consequence of compaction, cementation, and/or geochemical processes for unfractured formations and as a consequence of fewer fractures present and fracture closure at higher in-situ stresses for fractured formations.

Crossplots of log transformed sand hydraulic conductivity versus well depth for the upper and lower portions of the Dockum Aquifer are provided in Figures 4.6.6a and 4.6.7a, respectively. In the lower portion of the Dockum Aquifer, the majority of the data are for wells with a depth of less than 800 feet and only a dozen or so data are for wells deeper than 800 feet. The shallow data show a large range in values while the deep data show a narrow range. It is likely that the values for the deep data represent high-end values because wells at these depths are not tested unless they produce at some threshold level. In order to evaluate whether a trend with depth is observed, the data for both the upper and lower portions of the Dockum Aquifer were averaged every 50 feet (Figures 4.6.6b and 4.6.7b, respectively). Decreasing hydraulic conductivity with depth is not observed in the data for the upper portion of the Dockum Aquifer data (see Figure 4.6.6b) but is observed in the data for the lower portion of the Dockum Aquifer (see Figure 4.6.7b)

Crossplots of log transformed sand hydraulic conductivity versus net sand thickness for the upper and lower portions of the Dockum Aquifer are provided in Figure 4.6.8. No apparent correlation between sand hydraulic conductivity and net sand thickness is observed for either the upper or lower portions of the Dockum Aquifer. Notice that the net sand thicknesses are larger for the lower portion of the Dockum Aquifer than for the upper portion of the Dockum Aquifer.

4.6.5 Variogram Analysis of Horizontal Hydraulic Conductivity

The spatial relationship and continuity of the sand hydraulic conductivity data can be described using variogram analysis. Variograms quantify the spatial correlation and variability of a dataset [for detailed background information on geostatistics, refer to Isaaks and Srivastava (1989)].

Typical hydrogeologic properties show some spatial correlation indicated by less variance between observations that are closer together and more variance between data points that are farther apart. As the distance between measurements increases, the variance typically approaches a constant value, or sill, that represents the variance of the dataset as a whole. This distance where the variogram reaches the sill is called the range or correlation length of the dataset. Theoretically, the variance between data points at zero distance apart should be zero; however, discontinuity with the origin of the variogram, or nugget effect, may indicate short-scale variability and potential measurement errors within the dataset. Variogram analysis can also be used to characterize anisotropy within a dataset. Spatial continuity or correlation of the data is greatest along the primary axis or direction of the anisotropy. Specifying a direction for the calculation of omnidirectional and directional variograms allows the user to identify changes in correlation length, if present, with the maximum range indicating the direction of the anisotropy. For a detailed explanation of directional variogram terminology and calculation, see Deutsch and Journel (1992).

A variogram analysis was conducted for data for both the upper portion of the Dockum Aquifer and the lower portion of the Dockum Aquifer. At several locations, the tested interval included both the upper and lower portions of the Dockum Aquifer. Data from those locations were included in both layers. The data subset from the upper portion of the Dockum Aquifer is sparsely populated consisting of only 19 data points. Data for the lower portion of the Dockum Aquifer are available at 414 locations.

The variogram analyses were completed on logarithmically transformed sand hydraulic conductivity data. The variograms for the data subsets for the upper and lower portions of the Dockum Aquifer are shown in Figure 4.6.9. Lag widths and total lag distances were selected based on the spacing of the data within each dataset and relative continuity of the experimental variograms compared to various lag widths and distances. The lag widths for measurements for the upper portion of the Dockum Aquifer were 40,000 feet and a total lag distance of 240,000 feet, while the measurements for the lower portion of the Dockum Aquifer showed better continuity at shorter lag widths of 20,000 feet and a total distance of 400,000 feet. To delineate any directional trends in the data, the azimuth tolerance for the experimental variograms was limited to 70 degrees and the azimuth direction varied in 10-degree increments.

Primary trends in the data are usually located along the azimuth direction where the range of the experimental variogram is the greatest and shows the best continuity. For the lower portion of the Dockum Aquifer, a slight trend is observed at approximately north 20 degrees west, and the search direction for the calculation of the experimental variogram was oriented in this direction. Because of the limited amount of data associated with the upper portion of the Dockum Aquifer, discontinuity at greater distances in the experimental variogram is observed for the sand hydraulic conductivities for the upper portion of the Dockum Aquifer.

Figure 4.6.9 also shows the model variogram fits for each of the datasets. A spherical model was selected to fit both datasets. The equation for the spherical model is:

$$\gamma(h) = \begin{Bmatrix} C_0 + C_1(1.5\frac{h}{A} - 0.5\left(\frac{h}{A}\right)^3) & h < A \\ C_0 + C_1 & h \geq A \end{Bmatrix} \tag{4.6.1}$$

where C_0 is the nugget, C_1 is the scale (sill minus nugget), A is the range parameter, and h is the lag distance. Using the spherical model, the range of the upper portion of the Dockum Aquifer was estimated to be 110,000 feet and the sill was 0.2 combined with a nugget of 0.05. For the sand hydraulic conductivities for the lower portion of the Dockum Aquifer, the range of the spherical model was 220,000 feet and the sill was 0.31 with a nugget of 0.08.

4.6.6 Spatial Distribution of Horizontal Hydraulic Conductivity

Using the spherical variogram models described above, the sand hydraulic conductivity data were kriged to areas defining the limits of the upper and lower portions of the Dockum Aquifer. The kriging grids for both the upper and lower portions of the Dockum Aquifer interpolation used regularly-spaced grid nodes at every 25,000 feet that bounded the limits defined by the structure. Using these coarsely spaced grids allowed the interpretation of general regional trends in the data and smoothed some of the short-scale heterogeneity as a result of the declustering effect on closely spaced data within the kriging algorithm. The resulting spatial distributions for the sand hydraulic conductivities in the upper and lower portions of the Dockum Aquifer are shown in Figures 4.6.10 and 4.6.11, respectively.

The distribution of kriged sand hydraulic conductivities for the upper portion of the Dockum Aquifer ranged from 0.41 to 20 feet per day with a mean value of 8.1 feet per day. The overall distribution of the sand hydraulic conductivities in the upper portion of the Dockum Aquifer is strongly influenced by individual data locations indicating the limited number of measurements compared to the interpolation space. The distribution for the upper portion of the Dockum Aquifer tends towards the global mean of the distribution in the western portions of the study area because of the lack of data in this area. In the distribution for the lower portion of the Dockum Aquifer, the range of kriged sand hydraulic conductivities was 0.59 to 61 feet per day with a mean of 6.6 feet per day. This mean for the lower portion of the Dockum Aquifer is significantly lower than the mean of the dataset and is a result of the declustering effect of the kriging, where the lower values in the deeper and central portions of the lower portion of the Dockum Aquifer provide significant influence over the interpolation to grid nodes in this area. This trend in the interpolation is supported, though, by the decreasing trend in sand horizontal hydraulic conductivity with depth as shown in Figure 4.6.7. For the lower portion of the Dockum Aquifer, higher sand hydraulic conductivities produce a strong linear feature in the northern portion of the study area along the same trend (north 20 degrees west) noted in the variogram. The data for the upper portion of the Dockum Aquifer in the northern portion of the study area also suggest this trend. However, limited data for this part of the upper portion of the Dockum Aquifer and the fact that all data are for wells completed in both the Dockum and Ogallala aquifers prohibits conclusions regarding this apparent feature.

The sand hydraulic conductivity distributions shown in Figures 4.6.10 and 4.6.11 for the upper and lower portions of the Dockum Aquifer, respectively, were multiplied by the sand fraction for the upper and lower portions of the Dockum Aquifer, respectively, to produce initial effective horizontal hydraulic conductivity fields for the Dockum model layers (see Section 6.4). These fields were modified during model calibration taking into account data from pumping, water levels, and water quality as well as the notion of a high bias. The final calibrated hydraulic conductivity fields are discussed and presented in Section 8.1.2.

4.6.7 Vertical Hydraulic Conductivity

Data for the vertical hydraulic conductivity in the Dockum Aquifer were not found during the literature review. The stratified nature of the sediments in the Dockum Aquifer will likely result in some degree of anisotropy in hydraulic conductivity. While horizontal hydraulic conductivity is dominated by the higher permeable sediments, vertical hydraulic conductivity is dominated by the lower permeability strata and tends to be lower than the horizontal hydraulic conductivity. Domenico and Schwartz (1998) list horizontal and vertical hydraulic conductivities for material similar to sediments in the study area. The ratio between the horizontal and vertical values ranges from two to ten. This range is the same as that reported in Freeze and Cherry (1979) for core samples on fluvial deposits. Freeze and Cherry (1979) state that, for fluvial deposits, the ratio between horizontal and vertical hydraulic conductivity for core samples is less than the ratio that will be observed at larger scales.

It is generally accepted that groundwater models provide the best means for estimating vertical hydraulic conductivity at a regional scale (Anderson and Woessner, 1992). The only model that has included the Dockum Aquifer explicitly is that of Senger and others (1987). Although their model focused on the Deep Brine Aquifer of the Palo Duro Basin, Texas, they explicitly included the Ogallala and Dockum aquifers. They found that a vertical hydraulic conductivity in the Dockum Aquifer that was four orders of magnitude less than the horizontal hydraulic conductivity was required to simulate the head differences observed between the Ogallala and Dockum aquifers.

To provide insight into expected vertical hydraulic conductivity ranges, Table 4.6.2 provides a scoping analysis for both horizontal and vertical hydraulic conductivity. Two hydrostratigraphic units are considered, one with 80 percent sand and 20 percent clay (more typical of an aquifer) and one with 20 percent sand and 80 percent clay (more typical of a confining unit). The scoping analysis assumes that the sand hydraulic conductivity is equal to 5 feet per day and the clay hydraulic conductivity is equal to 3×10^{-6} feet per day [average shale from Freeze and Cherry (1979)]. The horizontal hydraulic conductivity is calculated as the weighted arithmetic average. The vertical hydraulic conductivity is calculated as both the weighted geometric mean and the weighted harmonic mean assuming that the correct value falls between these two averages. Based on this scoping analysis, the vertical anisotropy in the aquifer units would be expected to range from about 10 to 100,000.

Vertical hydraulic conductivity values for the Dockum Aquifer were estimated using literature values for sand and clay, and the percentage of sand in the upper and lower portions of the Dockum Aquifer (see Section 6.4.1). With respect to overlying aquifers, the leakance between layers will most likely be dominated by the vertical hydraulic conductivity in the Dockum Aquifer since it is expected to be much lower than the vertical hydraulic conductivity of overlying aquifers. The final vertical hydraulic conductivity was determined through calibration of the model (see Section 8.1.2).

4.6.8 Storativity

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

A literature review was conducted for storativity of the Dockum Aquifer (Table 4.6.3). Storativity ranged from 5×10^{-5} to 2×10^{-3} with a geometric mean equal to 1.6×10^{-4}. Figure 4.6.12 shows the locations of well specific storativity values and a histogram of those values. The literature review found no estimates of specific yield for the Dockum Aquifer. Domenico and Schwartz (1998) list values of specific yield that range from 0.03 to 0.28 for material similar to the sediments in the study area. Lohman (1972) gives 0.1 to 0.3 as general limits for the specific yield of unconfined aquifers. Implementation of storativity in the model is discussed in Section 6.4.2.

Table 4.6.1 Summary statistics for the sand horizontal hydraulic conductivity data in feet per day for the Dockum Aquifer.

Statistic	Value
upper portion of the Dockum Aquifer	
Number of Samples	19
Arithmetic Mean	14.4
Median	10.2
Geometric Mean	7.9
Standard Deviation K	11.7
Standard Deviation $Log_{10}(K)$	0.66
lower portion of the Dockum Aquifer	
Number of Samples	414
Arithmetic Mean	22.1
Median	12.3
Geometric Mean	10.4
Standard Deviation K	38.4
Standard Deviation $Log_{10}(K)$	0.58

Table 4.6.2 Hydraulic conductivity scoping analysis.

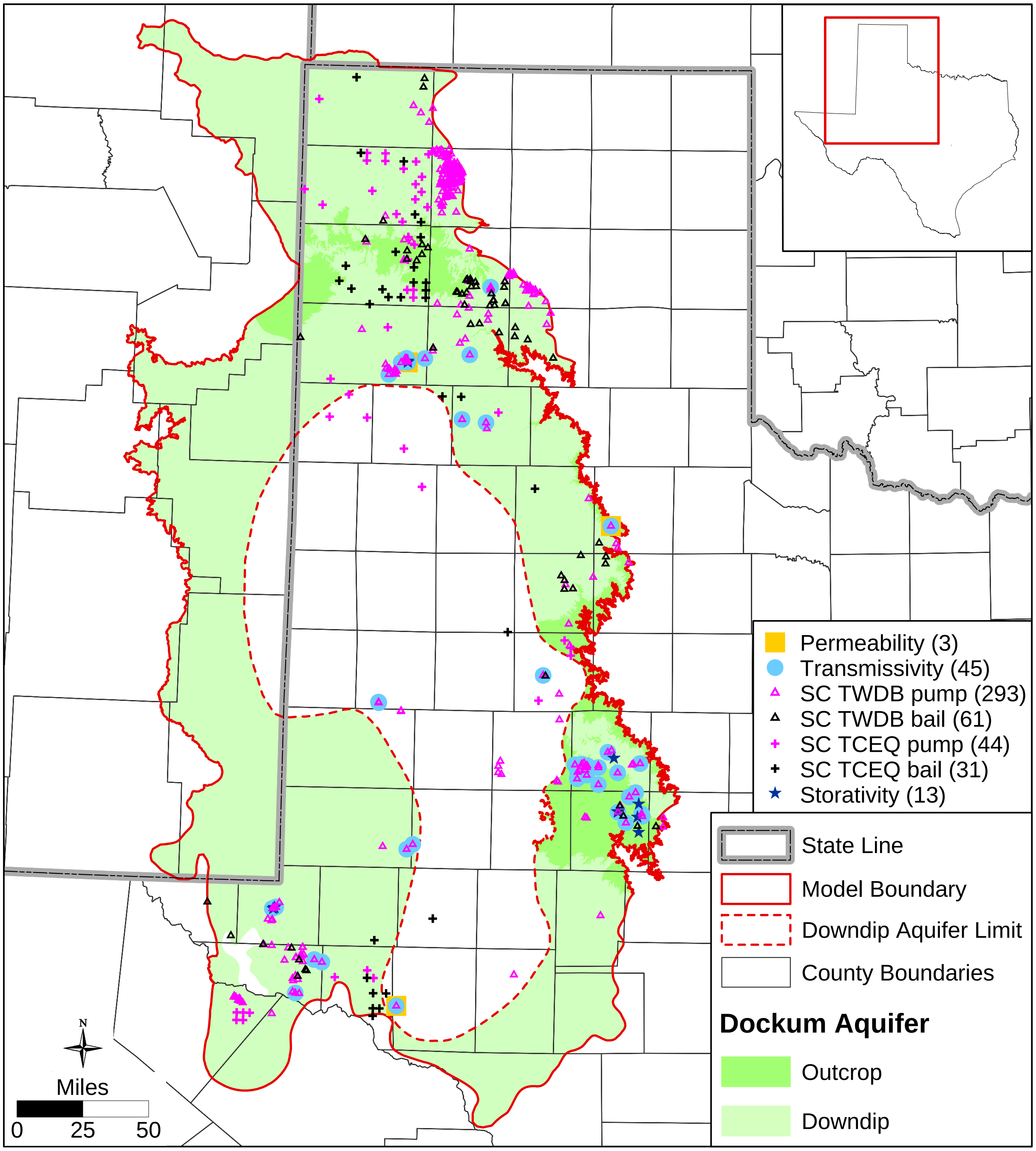
Lithology	Horizontal K (feet per day)[1]	Vertical K (feet per day)[2]	Vertical K (feet per day)[3]
80 percent sand 20 percent clay	4	2.8×10^{-1}	1.5×10^{-5}
20 percent sand 80 percent clay	1	5.3×10^{-5}	3.7×10^{-6}

Notes:
Hydraulic conductivity of clay = 3×10^{-6} feet per day [median shale clay; Freeze and Cherry, (1979)]
Hydraulic conductivity of sand assumed to be 5 feet per day
[1] arithmetic average
[2] weighted geometric average
[3] weighted harmonic average

Table 4.6.3 Summary of literature estimates of storativity for the Dockum Aquifer.

County	Aquifer	Well Number	Storativity	Reference
Deaf Smith	Dockum	1006802	1×10^{-4}	TWDB database
Deaf Smith	Dockum	1014202	1×10^{-4}	TWDB database, Myers (1969) Bradley & Kalaswad (2003)
Deaf Smith	Dockum	2934709	5.0×10^{-5} (1)	Bradley & Kalaswad (2003)
Deaf Smith	Dockum	2934716	6.8×10^{-5} (2)	Bradley & Kalaswad (2003)
Mitchell	Dockum	2934714	8×10^{-5}	Shamburger (1967)
Mitchell	Dockum	2935437	1.3×10^{-4}	Bradley & Kalaswad (2003)
Mitchell	Dockum	2935712	4.4×10^{-4}	Shamburger (1967) Bradley & Kalaswad (2003)
Mitchell	Dockum	2943403	1.2×10^{-4} (1)	Shamburger (1967) Bradley & Kalaswad (2003)
Winkler	Dockum	4616104	2.6×10^{-4} (1)	Garza & Wesselman (1959)
Winkler	Dockum	4616120	2.5×10^{-4} (1)	Garza & Wesselman (1959) Bradley & Kalaswad (2003)
Winkler	Dockum and Pecos Alluvium	4616130	2.7×10^{-4}	Garza & Wesselman (1959) Bradley & Kalaswad (2003)
Scurry	Triassic		2×10^{-3}	Myers (1969)
Scurry	Triassic		1×10^{-4}	Myers (1969)

(1) arithmetic average of two values reported in source(s)
(2) arithmetic average of three values reported in source



SC = specific capacity TCEQ = Texas Commission on Environmental Quality

Figure 4.6.1 Locations of hydraulic property data for the Dockum Aquifer.

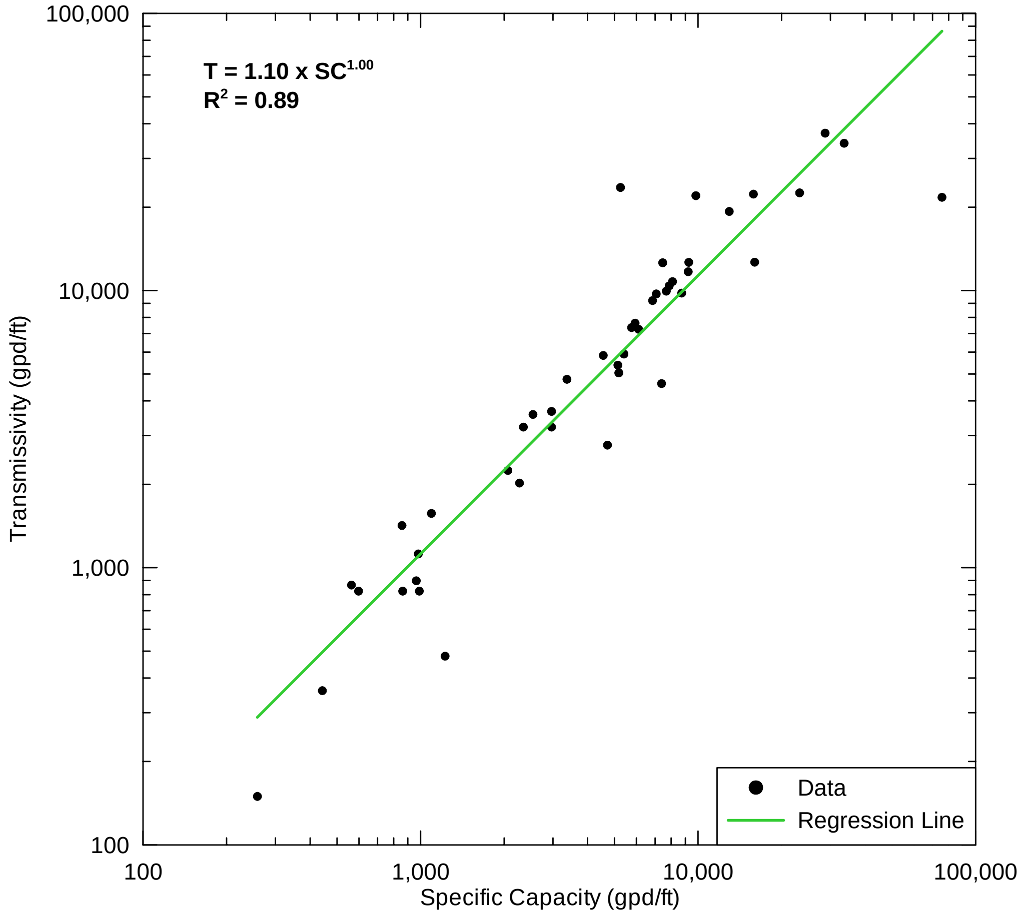
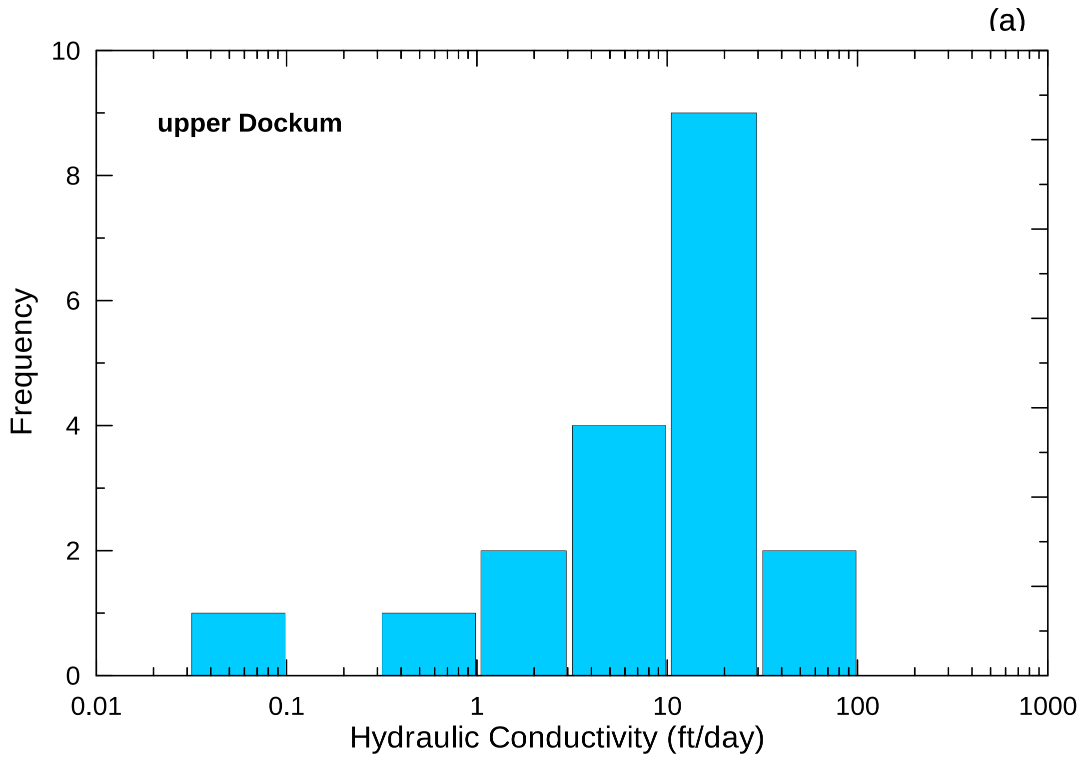


Figure 4.6.2 Empirical correlation between transmissivity (T) in gallons per day per foot and specific capacity (SC) in gallons per day per foot.



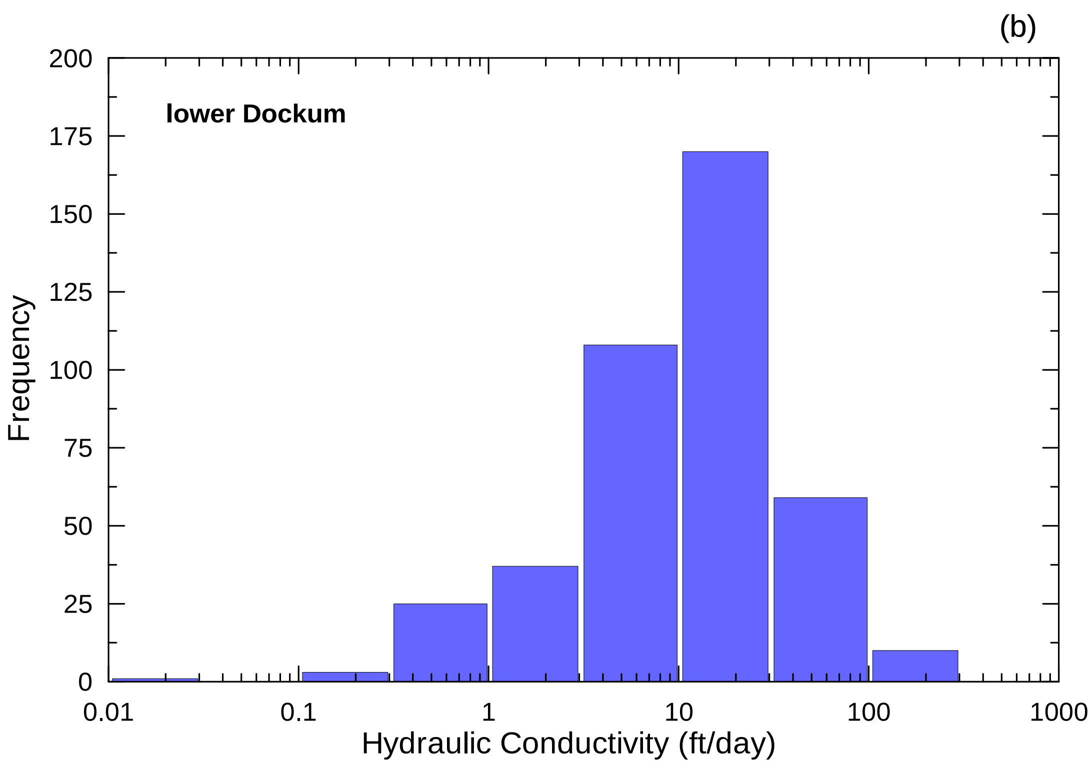


Figure 4.6.3 **Histogram of sand hydraulic conductivity data in feet per day for (a) the upper portion of the Dockum Aquifer and (b) the lower portion of the Dockum Aquifer.**

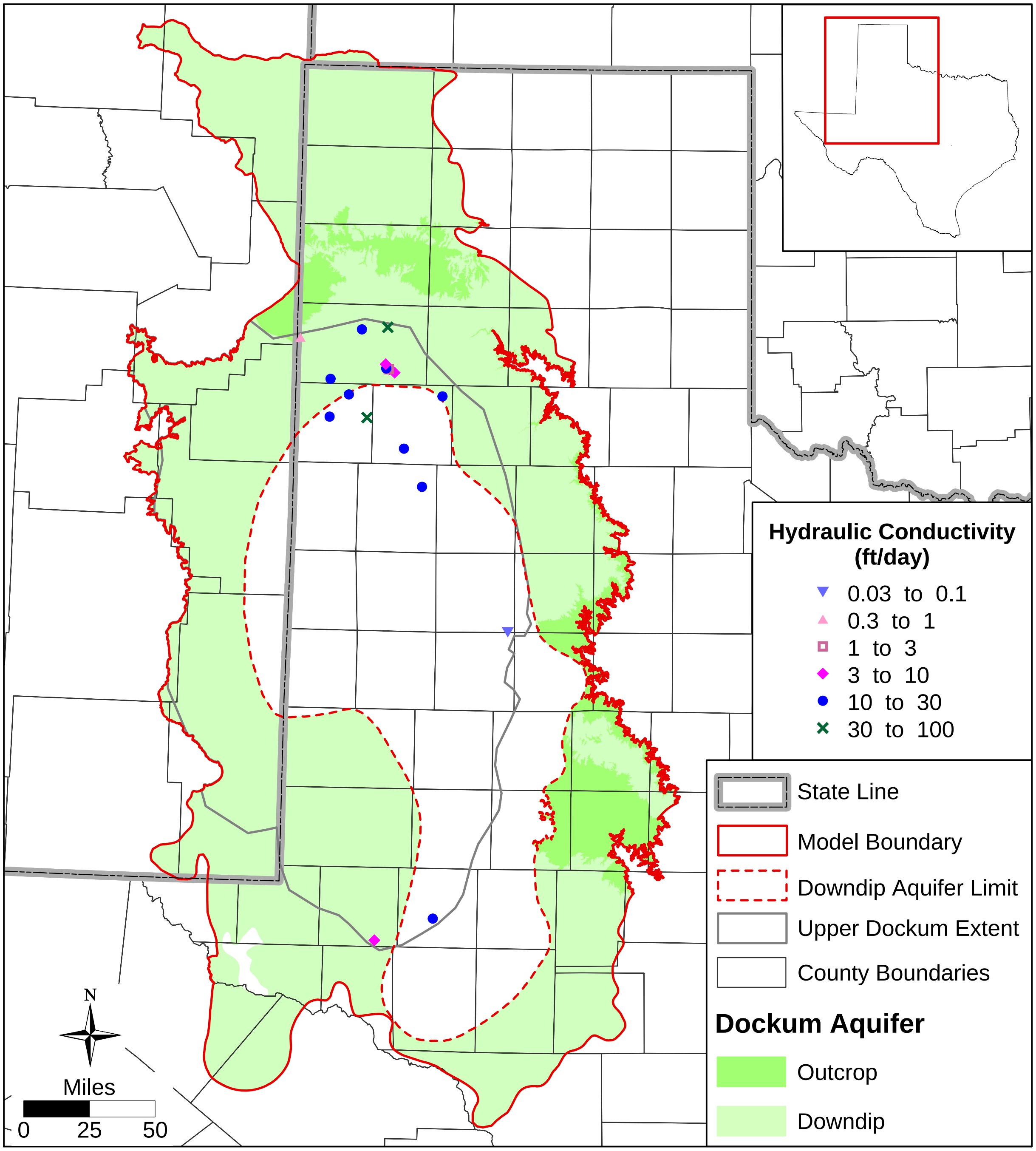


Figure 4.6.4 Sand hydraulic conductivities in feet per day for the upper portion of the Dockum Aquifer.

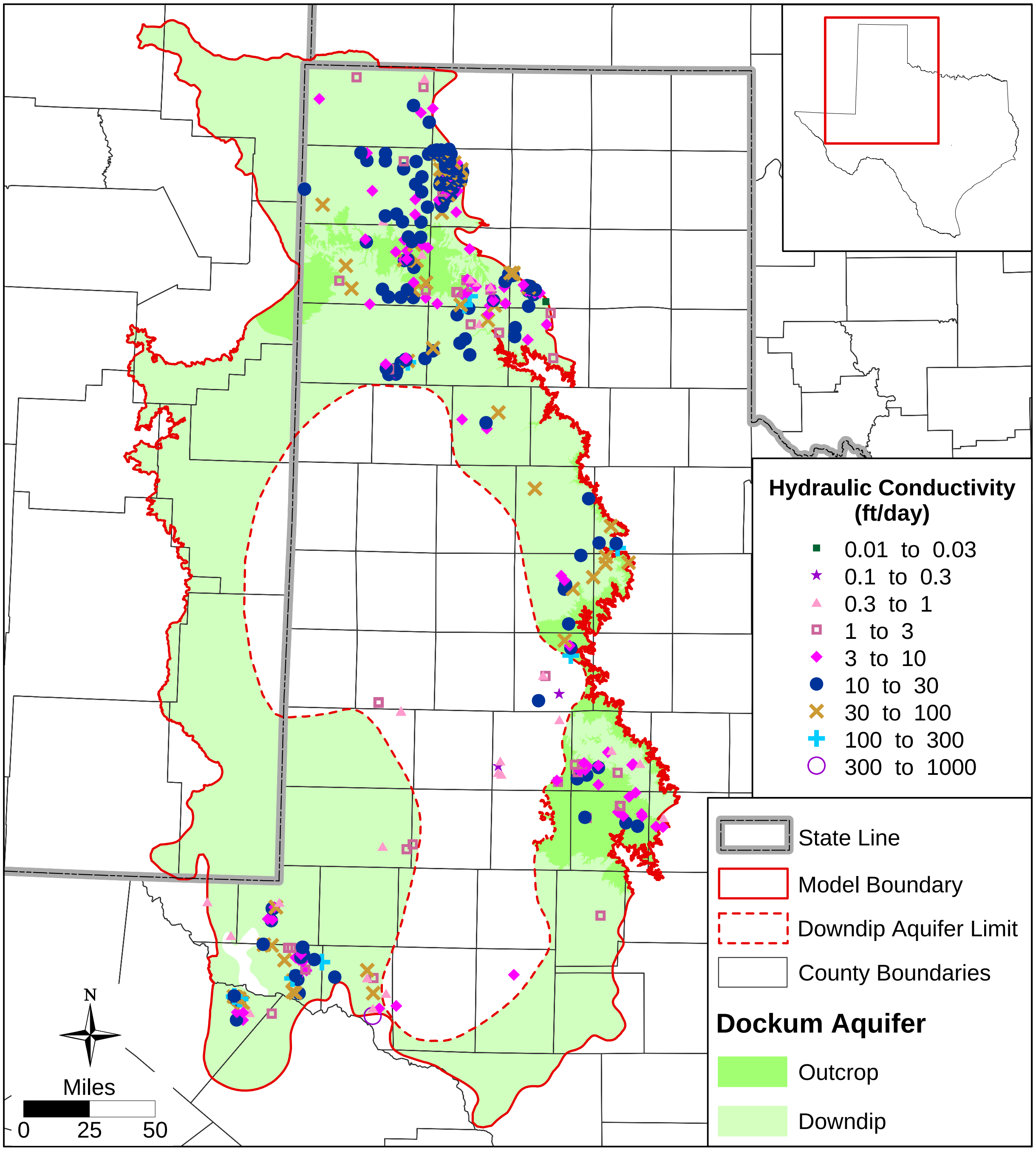


Figure 4.6.5 Sand hydraulic conductivities in feet per day for the lower portion of the Dockum Aquifer.

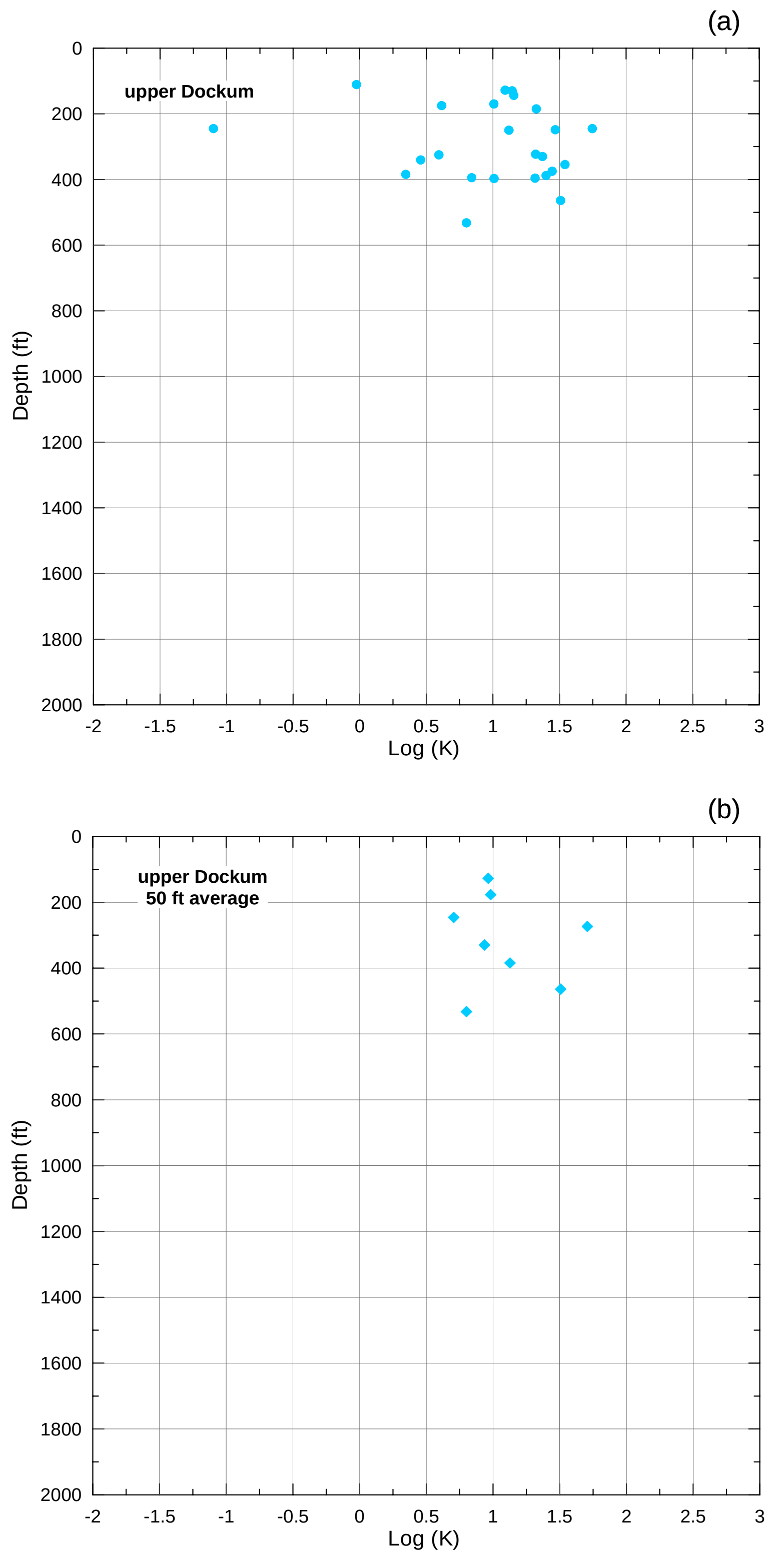


Figure 4.6.6 Log of sand hydraulic conductivity versus depth in feet for the upper portion of the Dockum Aquifer for (a) all data and (b) data averaged every 50 feet.

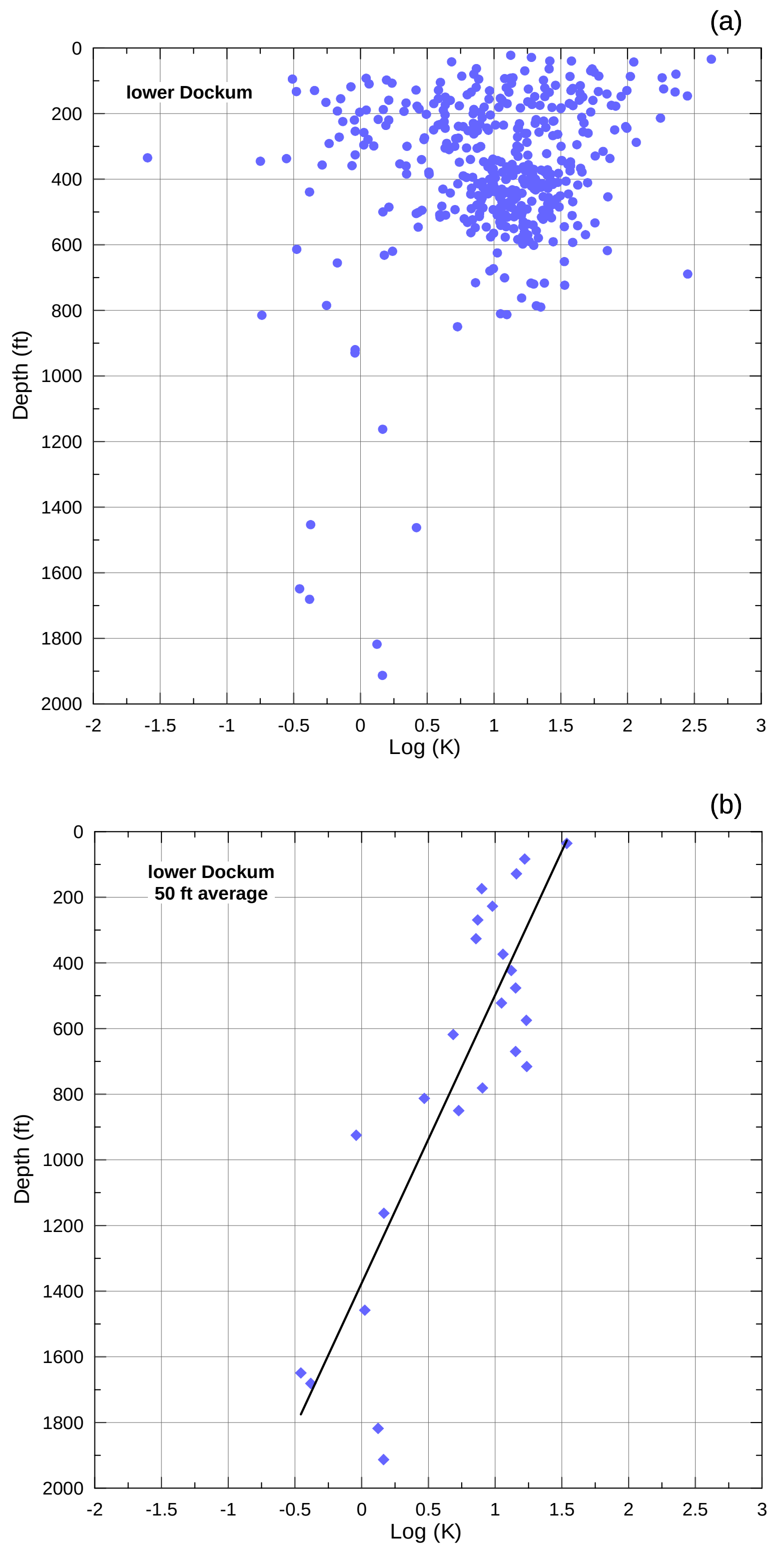
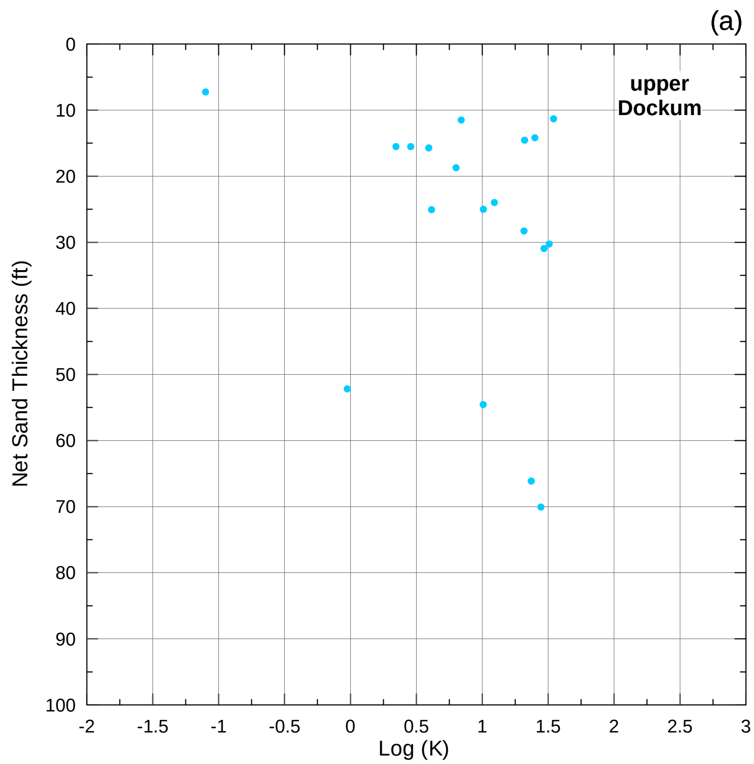


Figure 4.6.7 Log of sand hydraulic conductivity versus depth in feet for the lower portion of the Dockum Aquifer for (a) all data and (b) data averaged every 50 feet.



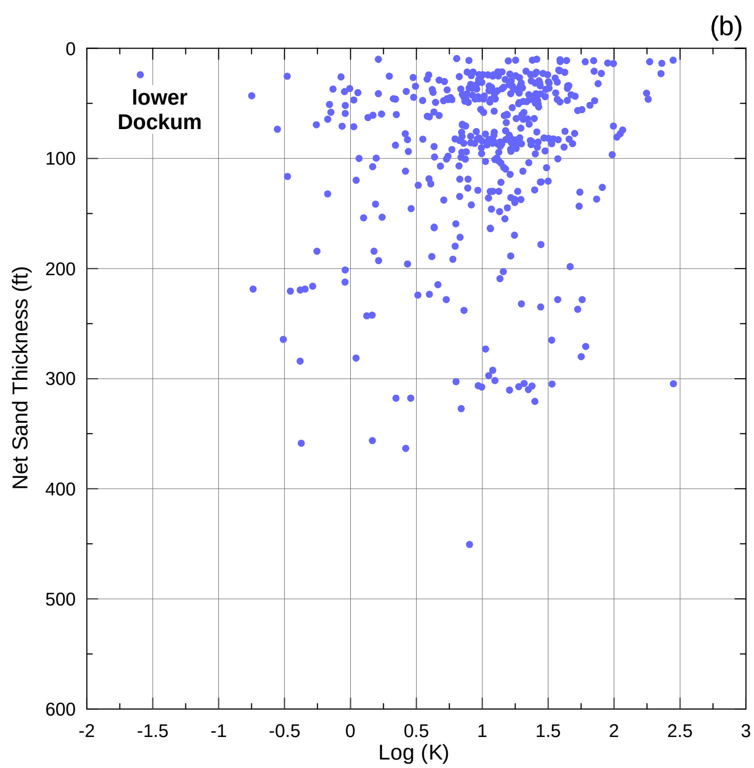
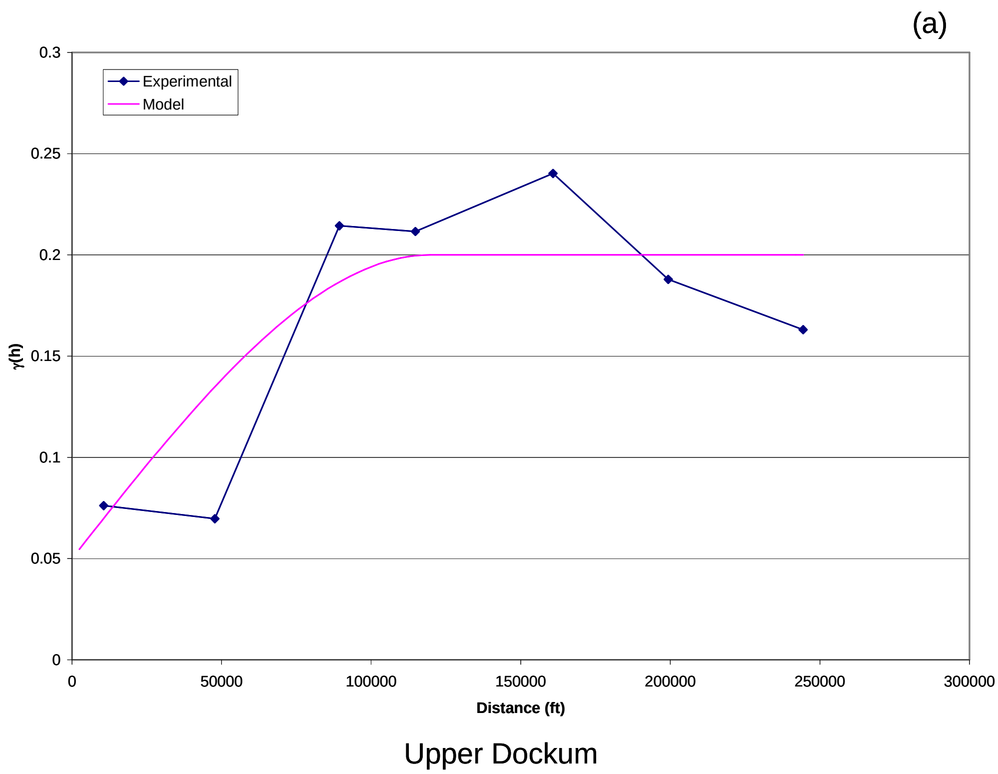


Figure 4.6.8 Log of sand hydraulic conductivity versus net sand thickness in feet for (a) the upper portion of the Dockum Aquifer and (b) the lower portion of the Dockum Aquifer.



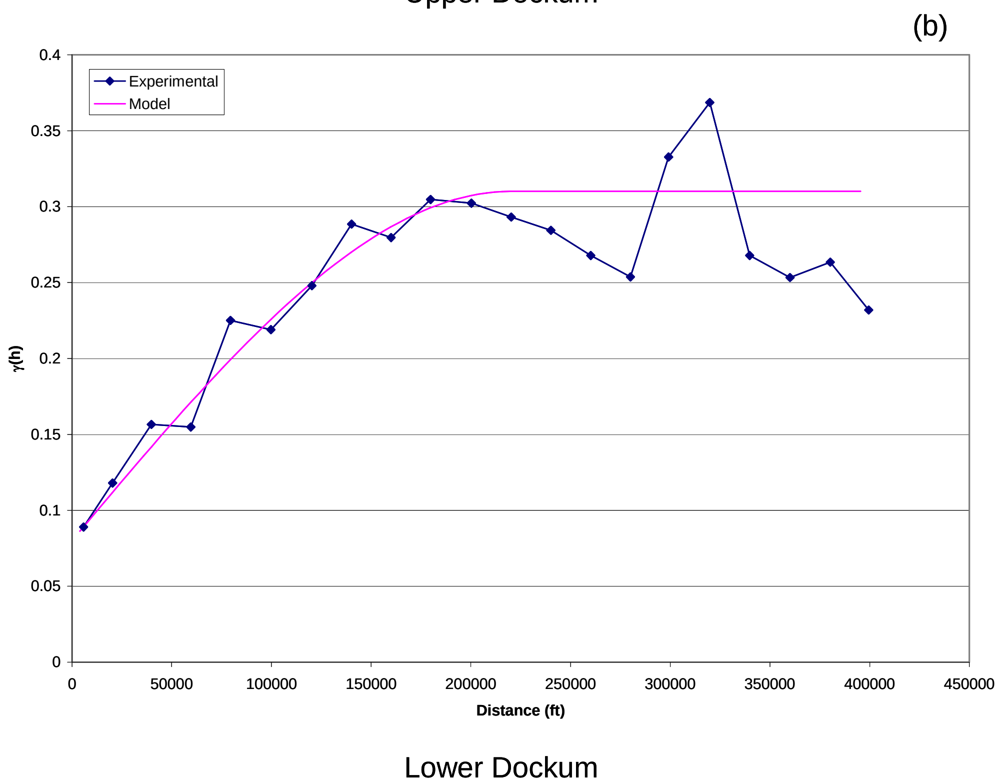


Figure 4.6.9 Experimental variogram of sand hydraulic conductivity for (a) the upper portion of the Dockum Aquifer and (b) the lower portion of the Dockum Aquifer.

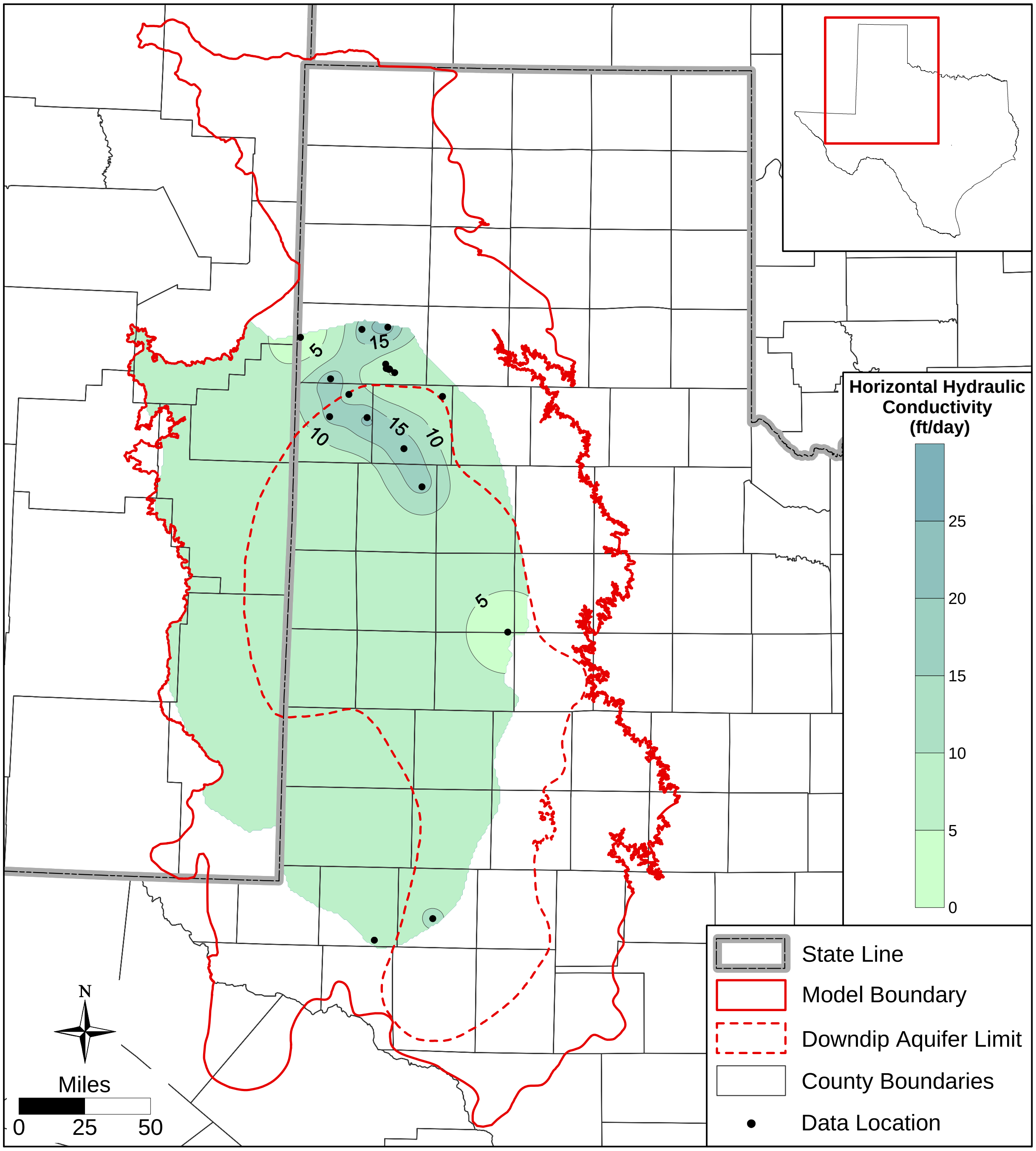


Figure 4.6.10 **Kriged map of sand hydraulic conductivity in feet per day for the upper portion of the Dockum Aquifer.**

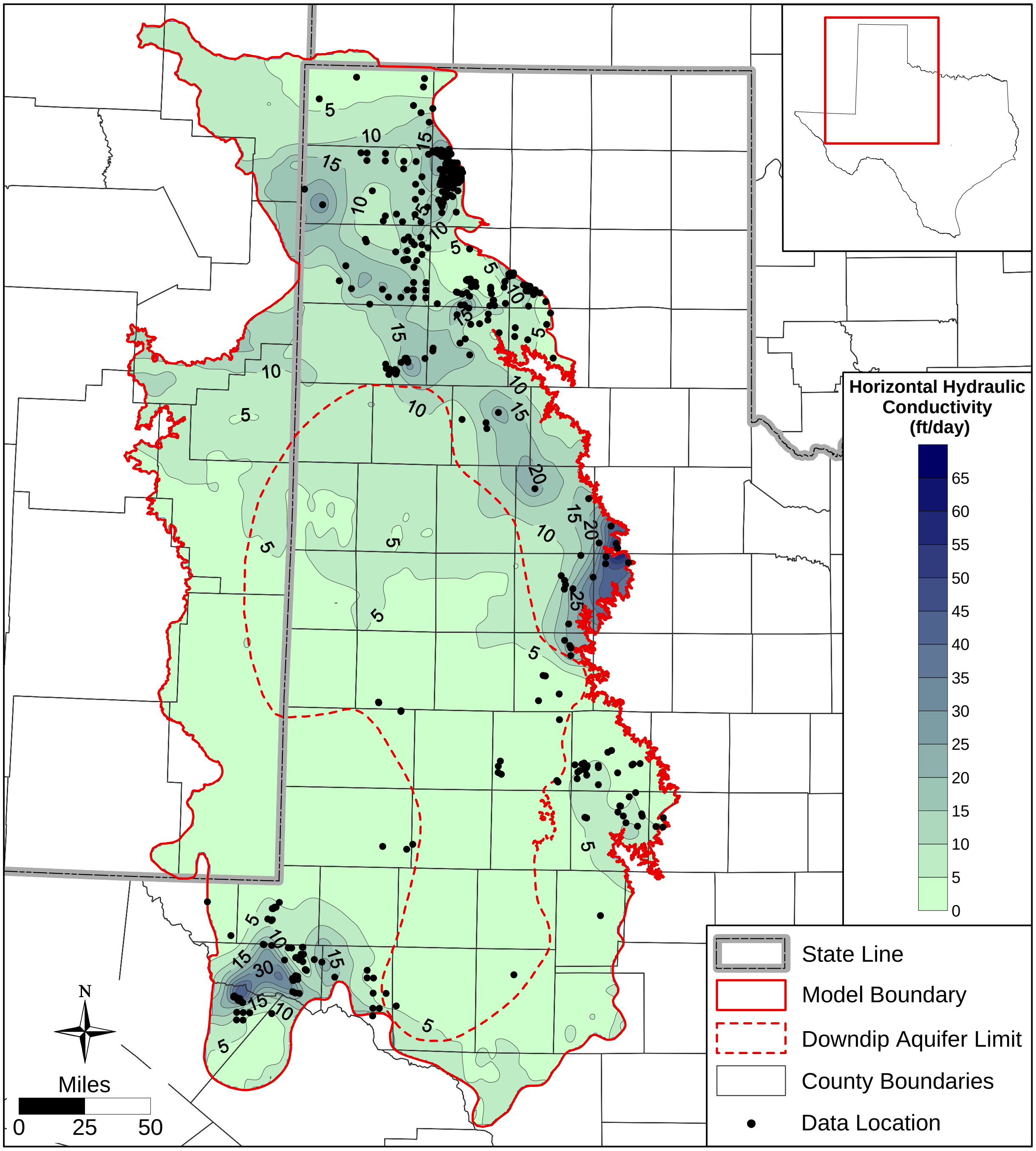


Figure 4.6.11 Kriged map of sand hydraulic conductivity in feet per day for the lower portion of the Dockum Aquifer.

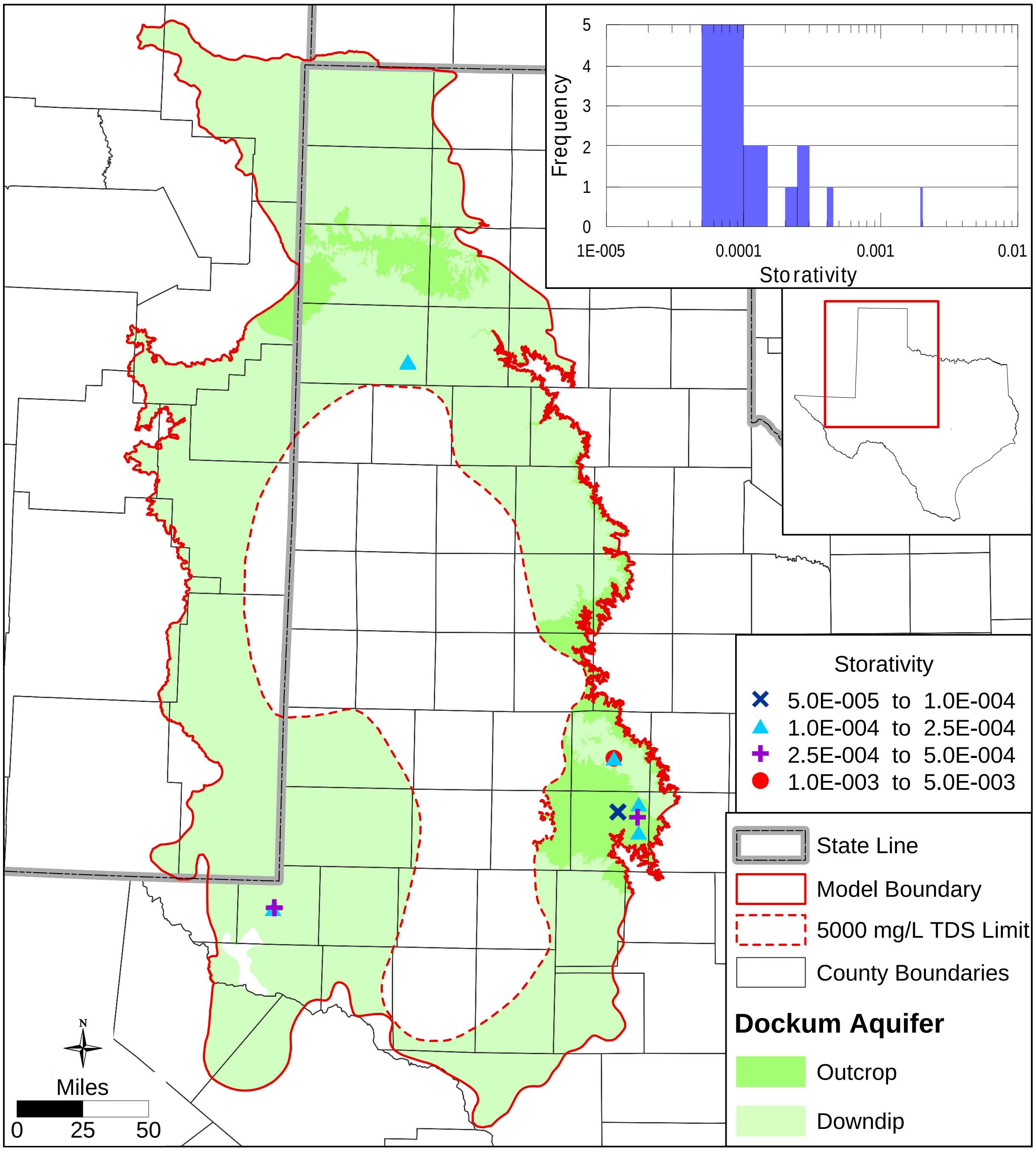


Figure 4.6.12 Storativity estimates in the Dockum Aquifer.

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4.7 Aquifer Discharge

Discharge from an aquifer can occur through either natural or man-made processes, both of which are discussed in the following sections.

4.7.1 Natural Discharge

Natural discharge from an aquifer can occur as cross-formational flow or discharge to rivers, streams, and springs. Discharge from the Dockum Aquifer via cross-formational flow is discussed in Section 4.3.5. This section discusses natural discharge to rivers, streams, and springs. Discharge to streams is limited to the outcrop area. For a complete description of streams and rivers in the study area see Section 4.5.1. One method for determining stream-aquifer interaction is through streamflow gain/loss studies. Section 4.5.1 summarizes the results of 11 gain/loss studies intersecting the Dockum Aquifer in the Colorado River outcrop area.

There are no gain/loss studies reported in the Canadian River outcrop area. Because the area of the watershed for the Canadian River is much larger than the area of the Dockum Aquifer outcrop along the river, it was felt that a baseflow separation study using the two gages along the river would not provide information relevant to the Dockum Aquifer. Comparison of two streamflow gages on the Canadian River shows consistent flow rates and fluctuations, thus, no apparent recharge to or discharge from the Dockum Aquifer occurs along the gaged reach of the river.

Springs flowing from the Dockum Aquifer are discussed in Section 4.5.2. About 90 springs or groups of springs issue from the Dockum Aquifer, the majority of which are located along the eastern escarpment. About 17 of the springs do, or at one time did, discharge at a rate greater than 100 gallons per minute. Throughout much of the state, including the active model area, spring flows have shown a general decline over time. Discharge of the Dockum Aquifer to springs is expected to be small relative to discharge through pumping.

4.7.2 Aquifer Discharge Through Pumping

Pumping discharge for each county in the active model area was developed for the transient calibration period (1980 through 1997). Pumping prior to 1980 was estimated from various sources.

4.7.2.1 Methodology

The methodologies used to estimate pumping in Texas and New Mexico counties located within the active model area are described in the following sections.

<u>Calibration Period Pumping</u>

Texas Counties

Estimates of groundwater pumping throughout Texas for the transient calibration period (1980 through 1997) are provided by the TWDB as master pumpage tables contained in a pumpage geodatabase. The six water use categories defined in the TWDB database are municipal, manufacturing, power generation, mining, livestock, and irrigation. Each water use record in the database carries an aquifer identifier that was used to select pumping records for the Dockum Aquifer. Pumping that was allocated to "OTHER AQUIFER" in the TWDB database was also reviewed to determine if it should be included with the Dockum Aquifer pumping. Rural domestic pumping, which consists primarily of unreported domestic water use, was estimated based on population density data provided by the TWDB.

The TWDB municipal, manufacturing, mining, and power pumping estimates are based on actual water use records reported by the water users. The pumpage geodatabase also includes historical annual pumping estimates for livestock and irrigation for each county-basin. A county-basin is a geographic unit created by the intersection of county and river basin boundaries. For example, Scurry County, which is intersected by both the Brazos River basin and the Colorado River basin, contains two county-basins.

Reported pumping for municipal, manufacturing, mining, and power water uses was matched to the specific wells from which it was pumped to identify the withdrawal location in the aquifer (latitude, longitude, and depth above mean sea level) based on the well's reported properties. The locations for these point sources of pumping are shown in Figure 4.7.1. The well properties were obtained primarily from the TWDB's state well database, with some additional information from the Texas Commission on Environmental Quality's Public Water System database, the United States Geological Survey's National Water Information System, or various other sources. When more than one well was associated with a given water user, groundwater withdrawals were divided evenly among those wells.

Livestock pumping totals within each county-basin were distributed uniformly over the rangeland within the county-basin, based on land use maps, using the categories “herbaceous” and “hay/pasture”.

Rural domestic pumping was distributed based on United States census block population density (Figure 4.7.2) in non-urban areas. The TWDB has provided a polygon feature class of census blocks, based on the 1990 United States census, and a table of factors for converting rural population density into annual groundwater use. Although these rural domestic use factors are uncertain, this uncertainty is not significant since rural domestic pumping accounts for less than 5 percent of total Dockum Aquifer pumping in Texas. Urban areas were excluded from rural population calculations and groundwater pumpage.

Rural domestic pumping within the areal extent of the Dockum Aquifer was allocated to the lower portion of the Dockum Aquifer. Although the TWDB database does not contain all wells in the state, it is assumed that the wells database provides a representative sample of domestic wells. All domestic wells within the outline of the Dockum Aquifer were plotted by aquifer code. Areas where the Dockum Aquifer provides water to domestic wells were identified (Figure 4.7.3). The identified areas include areas where domestic wells are almost entirely Dockum Aquifer wells, and locations where domestic wells tap the Dockum Aquifer combined with another aquifer (primarily the Ogallala Aquifer or the Pecos Valley Aquifer). It was estimated that, in areas where both the Dockum and Ogallala aquifers are sources for domestic wells, approximately 75 percent of the rural domestic use comes from the Dockum Aquifer. For areas where both the Dockum and Pecos Valley aquifers are sources for domestic wells, it was estimated that approximately 25 percent comes from the Dockum Aquifer.

Irrigation pumping within each county-basin was spatially distributed across the land use category “cropland”. The location of cropland in the active model area is shown in Figure 4.7.4.

New Mexico Counties

Groundwater pumping estimates for the part of the active model area in New Mexico were based on countywide pumping estimates from the New Mexico Office of the State Engineer (Sorensen, 1977; Sorensen, 1982; Wilson, 1992; Wilson and Lucero, 1997; Wilson and others, 2003) and the United States Geological Survey (United States Geological Survey, 2007), which covered the period from 1975 through 2000 in five year increments.

Wells from the United States Geological Survey Ground Water Site Inventory were used to help determine areas where the Dockum Aquifer (or equivalent) is used as a source of groundwater. County reports and Regional Water Plans were reviewed for information regarding Dockum Aquifer pumping. The location of other aquifers was also considered. In areas where the Dockum Aquifer is the only aquifer, the Dockum Aquifer was assumed to be the sole source of groundwater. Where the Ogallala or Pecos Valley aquifers overlie the Dockum Aquifer and the United States Geological Survey Ground Water Site Inventory suggests that the Dockum Aquifer is used, the Dockum Aquifer was assumed to be the source of 25 percent of the groundwater pumped from the area. Figure 4.7.3 shows areas where the Dockum Aquifer was identified as a source of groundwater in New Mexico.

The water-well database from the New Mexico Office of the State Engineer was used to determine the fraction of total pumping in a county that should be allocated to each area identified as an area of Dockum Aquifer pumping. Most of the well entries in the New Mexico Office of the State Engineer database indicate the primary use for the well. Wells were grouped into the eight data categories listed for water use by the New Mexico Office of the State Engineer and the United States Geological Survey: commercial, industrial, irrigation, mining, public supply, power generation, rural domestic, and livestock. The number of wells for each category was summed over the entire county and over each Dockum Aquifer pumping area within the county. For each category, the ratio of wells in a Dockum Aquifer pumping area to total wells in the county was determined. This ratio was used to calculate Dockum Aquifer pumping for all categories except rural domestic, assuming the ratio of wells is representative of pumping. As with Dockum Aquifer pumping in Texas, rural domestic allocation was based on population density. Following these calculations, commercial pumping and industrial pumping were combined for a category comparable to the manufacturing category of the TWDB pumpage geodatabase.

Manufacturing, mining, and public supply pumping were distributed in each county across wells that were defined as manufacturing, mining, and public supply, respectively. Irrigation pumping was spatially distributed in counties across the land use category “cropland” and stock pumping was spatially distributed across the land use categories “herbaceous” and “hay/pasture”. Rural domestic pumping was spatially distributed across counties based on population density.

Pre-1980 Pumping

Because detailed pumping data are not available prior to the calibration period, a somewhat synthetic pumping history was generated to account for the development that occurred during the period from 1950 to 1980. Development and implementation of this historical pumping is discussed in Section 6.3.5.

4.7.2.2 Pumping Plots and Tables

Pumping for the Dockum Aquifer has been summed by county and summed over the entire study area. Counties with less than one acre-foot of total pumping for each year between 1980 and 1997 were not included. Tables 4.7.1 and 4.7.2 list total groundwater withdrawals by county for Texas and New Mexico, respectively, for the years 1980, 1985, 1990, 1995, and 1997. Tables 4.7.3 through 4.7.9 list groundwater withdrawals from the Dockum Aquifer by category for all counties. If a county is not represented in any of the tables, it means that there was less than one acre-foot of groundwater withdrawal from the Dockum Aquifer for that category in that county in any of the years of interest.

Figure 4.7.5a provides a bar chart of total pumping by category for the Dockum Aquifer by year from 1980 through 1997 for the Texas portion of the active model region. Dockum Aquifer pumping in Texas shows a steady decline from about 41,500 acre-feet per year in 1980 to about 25,100 acre-feet per year in 1988. An increasing trend in pumping began in 1989 and peaked in 1993 at approximately 32,900 acre-feet per year. From 1993 to 1997, pumping was generally stable. Irrigation accounted for about 70 percent of total Dockum Aquifer pumping in Texas over the calibration period. Municipal pumping accounted for about 12 percent and mining and rural domestic about 5 percent each. Livestock pumping was about 4 percent of total pumping, and both manufacturing and power generation were less than 1 percent. Figure 4.7.6 shows the 1980 through 1997 average pumping demands by county for the Dockum Aquifer. This figure shows that the heaviest pumping in Texas occurred in Crosby, Deaf Smith, Moore, Scurry, and Winkler counties.

Figure 4.7.5b provides a bar chart of total pumping by category for the Dockum Aquifer by year from 1980 through 1997 for the New Mexico portion of the model region. It should be noted that New Mexico pumping estimates were developed from published data for 1980, 1985, 1990, 1995, and 2000. Pumping for intermediate years was interpolated from the available data. Dockum Aquifer pumping in New Mexico decreased from about 8,750 acre-feet per year in 1980 to about 6,500 acre-feet per year in 1985. An increasing trend in pumping began after 1985 and peaked in 1995 at approximately 9,100 acre-feet per year. Following 1995, pumping decreased. Irrigation and mining together accounted for over 87 percent of total Dockum Aquifer pumping in New Mexico over the calibration period. Municipal pumping was about 8 percent of total pumping. Rural domestic, livestock, and manufacturing together averaged about 5 percent of total pumping. No power generation pumping was identified in the Dockum Aquifer in New Mexico. The 1980 through 1997 average pumping demands by county for the Dockum Aquifer in New Mexico are shown in Figure 4.7.6.

Figures 4.7.7 through 4.7.53 show pumping for each county by category. Total pumping exceeded 1,000 acre-feet per year for at least one year during the calibration period in 15 Texas counties (Crosby, Dallam, Deaf Smith, Floyd, Hartley, Mitchell, Moore, Nolan, Oldham, Pecos, Randall, Reagan, Reeves, Scurry, and Winkler) and two New Mexico counties (Lea and Quay). Pumping was dominated by irrigation in 10 of these 15 Texas counties and Quay County, New Mexico. Municipal pumping was the predominant use in two Texas counties (Reeves and Winkler) and mining accounted for over 65 percent of total pumping in Lea County, New Mexico. Total pumping exceeded 5,000 acre-feet per year in Moore and Scurry counties, Texas and Quay County, New Mexico.

Table 4.7.1 Dockum Aquifer pumping in acre-feet per year in Texas by county for 1980, 1985, 1990, 1995, and 1997.

County	Year				
	1980	1985	1990	1995	1997
Andrews	8	8	38	11	10
Armstrong	103	58	95	82	80
Borden	65	58	58	56	56
Briscoe	17	12	13	8	6
Carson	348	163	279	172	121
Crane	42	54	52	459	41
Crockett	3	3	3	3	3
Crosby	3578	1280	2710	3445	3554
Dallam	1743	1536	1966	2343	2757
Dawson	1	1	2	1	2
Deaf Smith	3097	2637	2886	2836	2997
Dickens	22	19	15	11	13
Ector	98	92	61	26	528
Fisher	11	14	16	11	10
Floyd	1628	516	701	1285	1085
Garza	79	47	59	80	96
Hale	243	152	152	139	130
Hartley	1399	1648	1042	1531	1699
Hockley	559	761	922	504	571
Howard	27	43	57	33	61
Kent	3	3	3	3	2
Loving	21	4	8	8	7
Lubbock	2	2	3	5	3
Mitchell	3424	4643	1791	691	1235
Moore	4316	4057	5576	4845	5040
Motley	74	61	77	101	44
Nolan	820	881	796	690	721
Oldham	1192	751	509	588	1063
Pecos	955	816	636	825	777
Potter	717	564	463	656	770
Randall	1075	990	882	1009	954
Reagan	779	1009	1657	1904	2064
Reeves	1725	1470	1050	1172	1217
Scurry	8925	3094	1407	1124	1210
Sherman	562	439	442	487	485
Sterling	20	20	14	10	11
Swisher	219	151	143	197	162
Terry	<1	9	1	0	0
Upton	252	173	212	270	220
Ward	115	113	80	77	75
Winkler	3224	3535	2352	2369	2120
Texas Total	41490	31887	29229	30065	32000

Table 4.7.2 Dockum Aquifer pumping in acre-feet per year in New Mexico by county for 1980, 1985, 1990, 1995, and 1997.

County	Year				
	1980	**1985**	**1990**	**1995**	**1997**
Curry	500	387	653	524	508
DeBaca	24	12	17	18	18
Eddy	3	4	17	29	51
Lea	2902	2825	2363	2622	2975
Quay	5050	2927	3818	5685	3998
Roosevelt	265	327	353	245	245
New Mexico Total	8743	6482	7220	9124	7794

Table 4.7.3 Irrigation pumping in acre-feet per year by county for 1980, 1985, 1990, 1995, and 1997.

County	Year				
	1980	1985	1990	1995	1997
Armstrong, Texas	60	14	52	37	34
Briscoe, Texas	14	11	12	7	5
Carson, Texas	318	132	250	142	91
Crosby, Texas	3515	1265	2700	3434	3543
Dallam, Texas	1743	1536	1966	2343	2757
Deaf Smith, Texas	3088	2629	2878	2828	2989
Dickens, Texas	10	7	6	4	7
Floyd, Texas	1608	495	688	1261	1056
Garza, Texas	62	23	37	51	74
Hale, Texas	243	152	152	139	130
Hartley, Texas	734	668	607	710	840
Howard, Texas	17	32	46	20	46
Mitchell, Texas	3218	4414	1593	410	985
Moore, Texas	4315	4057	5576	4845	5040
Motley, Texas	64	52	70	93	37
Nolan, Texas	590	580	529	424	461
Oldham, Texas	294	201	130	174	559
Pecos, Texas	950	811	631	820	772
Potter, Texas	320	153	81	255	412
Randall, Texas	549	386	321	350	318
Reagan, Texas	765	992	1651	1896	2057
Reeves, Texas	100	54	33	190	180
Scurry, Texas	7979	2605	998	776	716
Sherman, Texas	562	439	442	487	485
Sterling, Texas	18	18	11	8	8
Swisher, Texas	219	151	143	197	162
Upton, Texas	181	108	146	206	162
Ward, Texas	39	41	7	11	11
Winkler, Texas	84	15	0	0	0
Curry, New Mexico	483	369	623	463	426
Lea, New Mexico	191	126	118	168	167
Quay, New Mexico	4961	2839	3672	5537	3839
Roosevelt, New Mexico	263	325	349	237	235
Total Irrigation	37554	25699	26518	28522	28604

Table 4.7.4 Manufacturing pumping in acre-feet per year by county for 1980, 1985, 1990, 1995, and 1997.

County	Year				
	1980	1985	1990	1995	1997
Ector, Texas	90	73	42	6	6
Scurry, Texas	22	2	1	<1	<1
Winkler, Texas	7	6	2	1	1
Eddy, New Mexico	0	2	14	26	45
Lea, New Mexico	52	77	195	175	217
Quay, New Mexico	0	0	3	4	4
Total Manufacturing	171	160	256	212	272

Table 4.7.5 Mining pumping in acre-feet per year by county for 1980, 1985, 1990, 1995, and 1997.

County	Year				
	1980	1985	1990	1995	1997
Crane, Texas	0	0	0	407	0
Ector, Texas	0	0	0	0	502
Hockley, Texas	559	761	922	504	571
Loving, Texas	14	1	2	0	0
Oldham, Texas	734	335	195	188	282
Scurry, Texas	723	330	239	160	197
Terry, Texas	<1	9	1	0	0
Winkler, Texas	300	390	452	326	174
Lea, New Mexico	2071	2062	1438	1518	1816
Total Mining	4401	3889	3249	3103	3543

Table 4.7.6 Municipal pumping in acre-feet per year by county for 1980, 1985, 1990, 1995, and 1997.

County	Year				
	1980	1985	1990	1995	1997
Mitchell, Texas	124	173	132	198	171
Nolan, Texas	183	269	238	232	233
Reeves, Texas	1568	1317	967	916	953
Winkler, Texas	2405	2919	1835	1973	1852
Lea, New Mexico	539	522	551	645	623
Quay, New Mexico	12	14	14	14	15
Total Municipal	4831	5215	3736	3978	3847

Table 4.7.7 Power generation pumping in acre-feet per year by county for 1980, 1985, 1990, 1995, and 1997.

County	Year				
	1980	1985	1990	1995	1997
Andrews, Texas	8	<1	32	1	<1
Scurry, Texas	8	2	0	0	0
Winkler, Texas	390	176	33	40	67
Total Power	406	179	66	41	67

Table 4.7.8 Rural Domestic pumping in acre-feet per year by county for 1980, 1985, 1990, 1995, and 1997.

County	Year				
	1980	1985	1990	1995	1997
Andrews, Texas	1	1	1	1	1
Armstrong, Texas	43	43	44	45	46
Borden, Texas	65	58	58	56	56
Briscoe, Texas	2	1	1	1	1
Carson, Texas	30	30	30	30	30
Crane, Texas	30	30	30	28	27
Crockett, Texas	3	3	3	3	3
Crosby, Texas	13	12	10	10	10
Dawson, Texas	1	1	2	1	2
Deaf Smith, Texas	5	4	4	4	4
Dickens, Texas	12	12	9	7	6
Ector, Texas	1	1	1	1	<1
Fisher, Texas	2	1	2	1	1
Floyd, Texas	4	1	1	2	2
Garza, Texas	9	17	14	19	13
Hartley, Texas	6	6	6	7	8
Howard, Texas	6	7	6	7	7
Kent, Texas	3	3	3	3	2
Loving, Texas	3	3	3	3	2
Lubbock, Texas	2	2	3	5	3
Mitchell, Texas	31	24	28	41	40
Motley, Texas	10	9	7	7	7
Nolan, Texas	13	14	15	10	5
Oldham, Texas	108	108	108	106	105
Pecos, Texas	5	5	5	5	5
Potter, Texas	379	389	353	375	332
Randall, Texas	408	455	450	473	438
Reeves, Texas	4	4	4	4	4
Scurry, Texas	116	126	141	146	259
Sterling, Texas	2	2	3	3	3
Upton, Texas	56	55	54	48	45
Ward, Texas	70	68	66	61	58
Winkler, Texas	20	19	17	16	15
Curry, New Mexico	3	1	2	1	1
DeBaca, New Mexico	12	2	1	1	1
Lea, New Mexico	11	9	10	16	16
Quay, New Mexico	14	8	7	6	6
Total Rural Domestic	1504	1535	1501	1552	1566

Table 4.7.9 Livestock pumping in acre-feet per year by county for 1980, 1985, 1990, 1995, and 1997.

County	Year				
	1980	1985	1990	1995	1997
Andrews, Texas	0	7	5	9	9
Crane, Texas	12	24	22	24	14
Crosby, Texas	50	2	1	1	1
Deaf Smith, Texas	6	4	4	4	4
Ector, Texas	7	19	19	19	20
Fisher, Texas	9	13	14	11	9
Floyd, Texas	16	20	12	22	26
Garza, Texas	8	6	8	10	9
Hartley, Texas	659	975	429	814	852
Howard, Texas	5	4	5	6	8
Loving, Texas	5	0	3	5	5
Mitchell, Texas	50	32	38	42	39
Nolan, Texas	34	18	14	24	22
Oldham, Texas	56	107	75	121	117
Potter, Texas	18	23	28	26	26
Randall, Texas	118	149	110	187	198
Reagan, Texas	14	17	6	8	7
Reeves, Texas	53	95	46	62	80
Scurry, Texas	77	29	28	41	38
Upton, Texas	15	10	13	16	13
Ward, Texas	5	4	7	5	5
Winkler, Texas	17	10	13	14	10
Curry, New Mexico	15	16	28	60	81
DeBaca, New Mexico	12	10	15	17	16
Eddy, New Mexico	3	2	3	3	6
Lea, New Mexico	38	29	51	100	136
Quay, New Mexico	63	65	122	123	133
Roosevelt, New Mexico	2	2	4	8	10
Total Livestock	1366	1692	1124	1782	1894

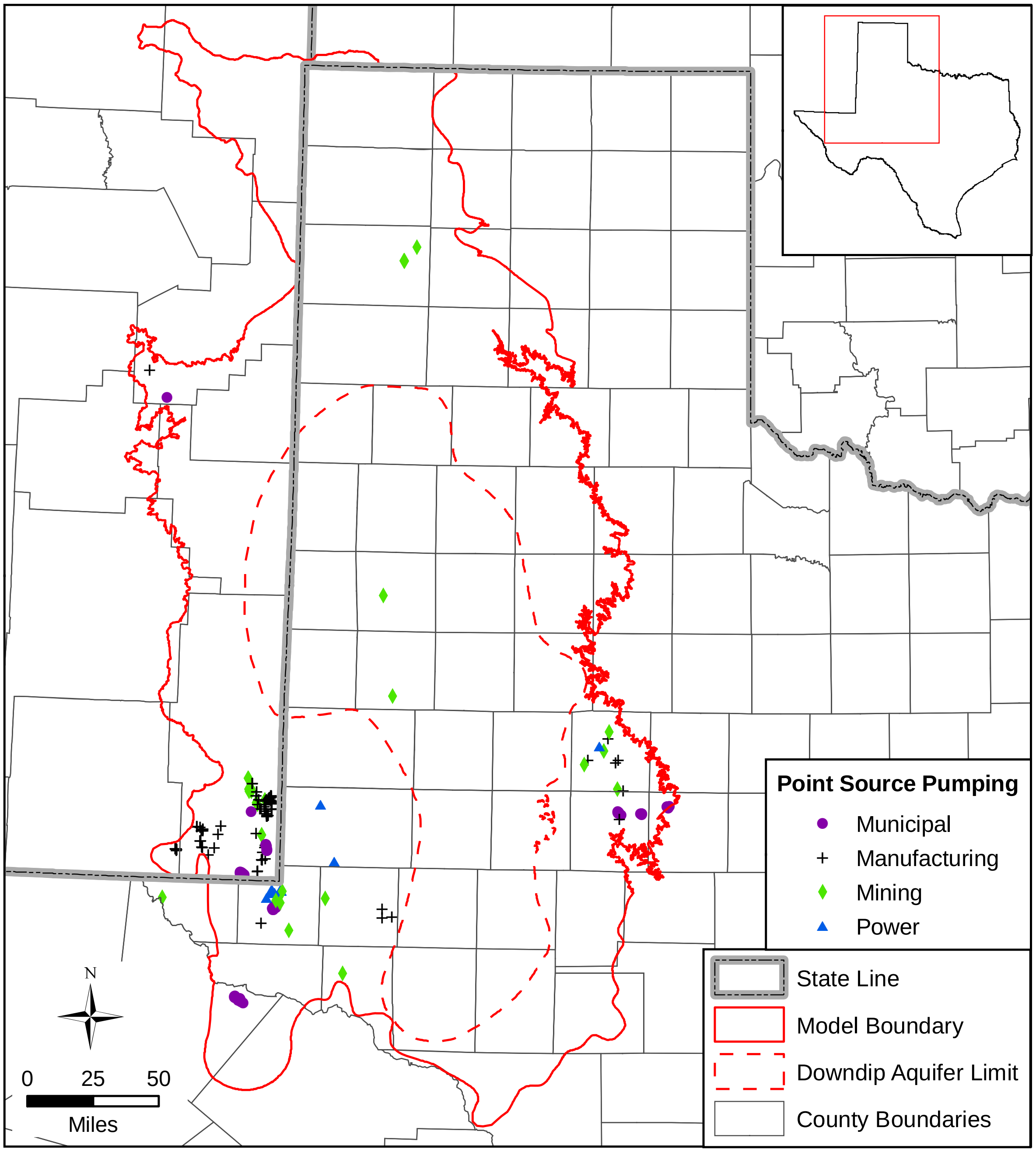
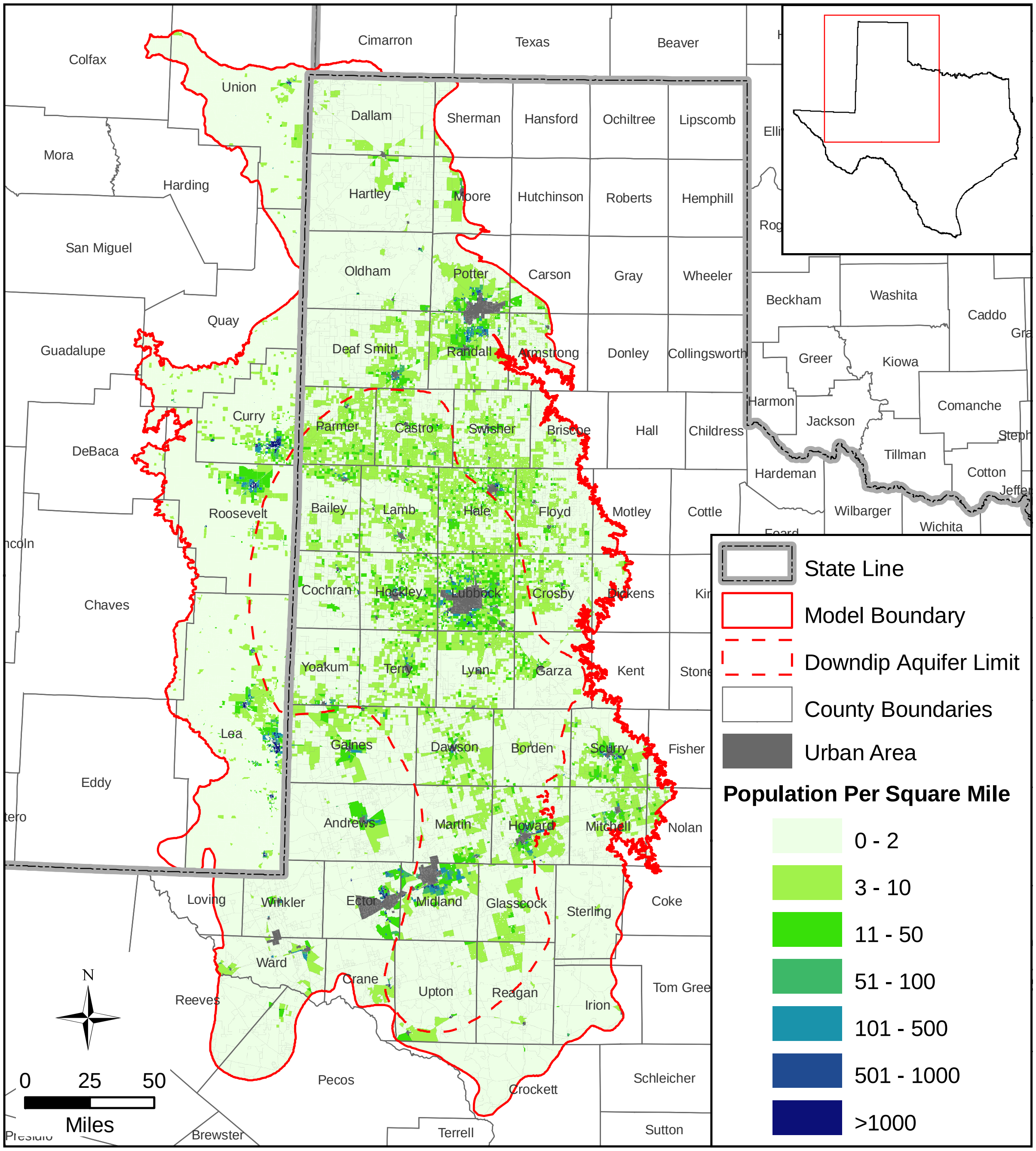


Figure 4.7.1 **Locations of pumping point sources in the active model area.**



Source: Online: Texas Water Development Board, Aug 2006/US Census Bureau American Fact Finder, 1990

Figure 4.7.2 Population density for the active model area.

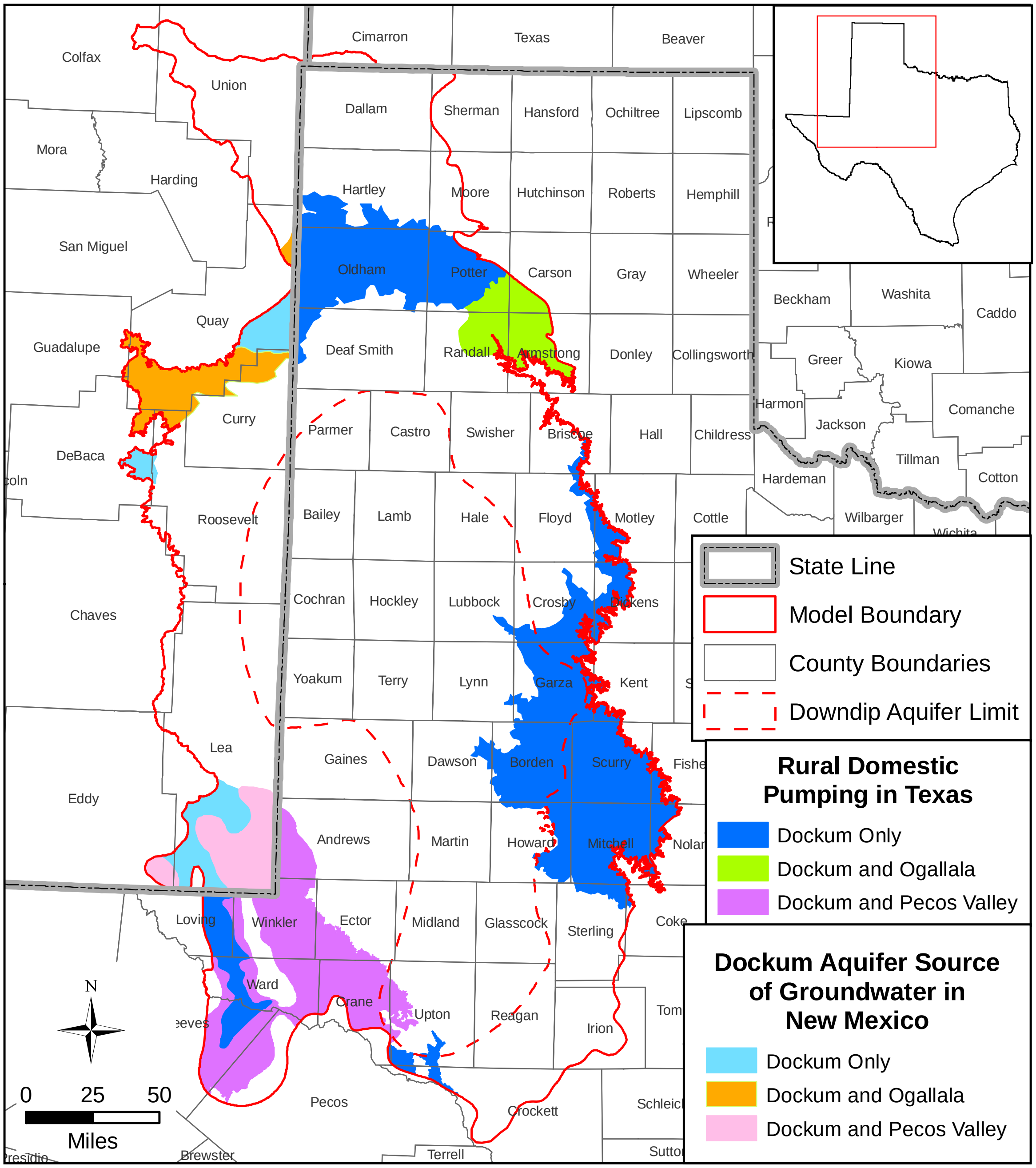


Figure 4.7.3 **In Texas, estimated locations where the Dockum Aquifer provides water to domestic wells and, in New Mexico, areas were the Dockum Aquifer was identified as a source of groundwater.**

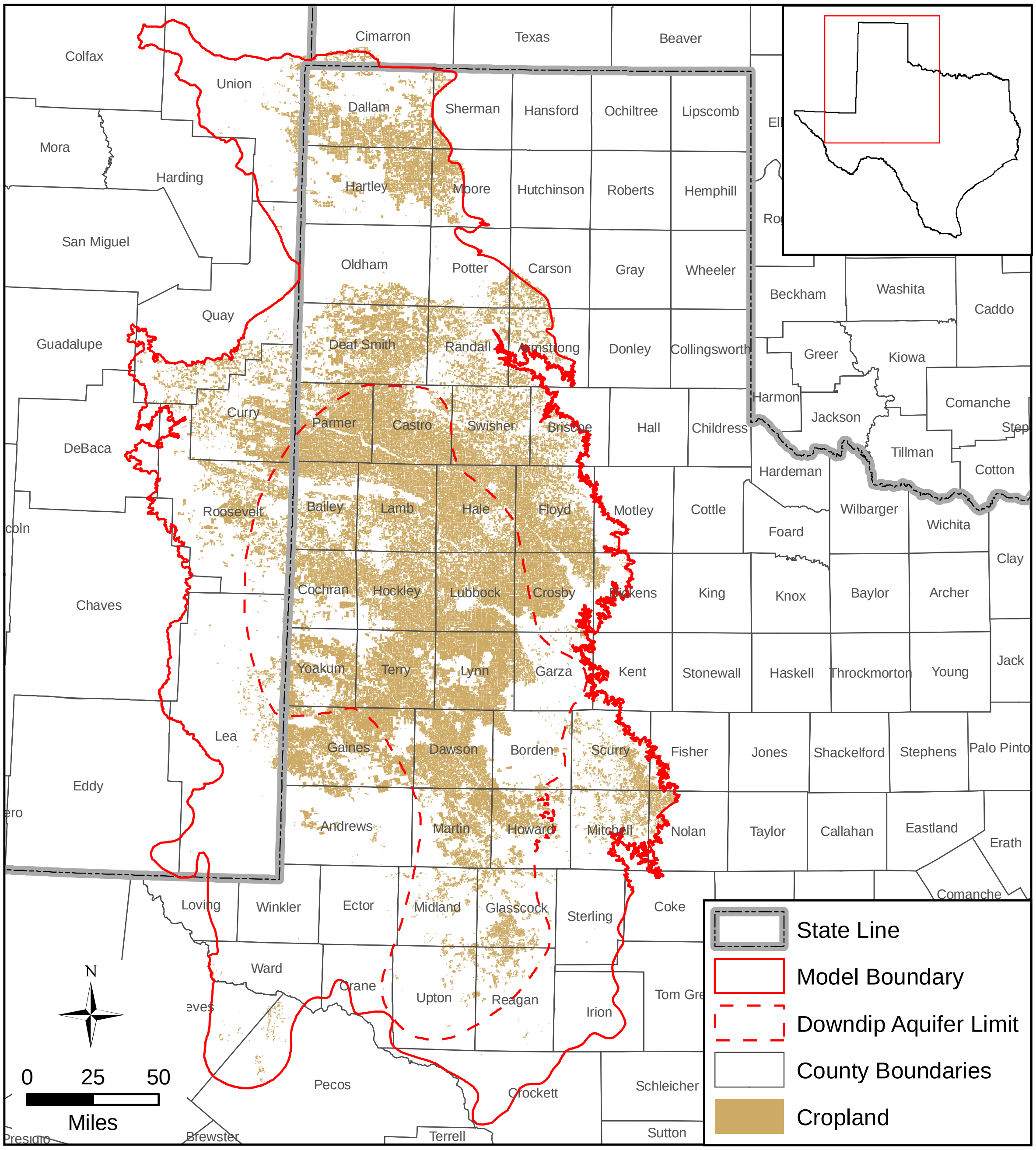
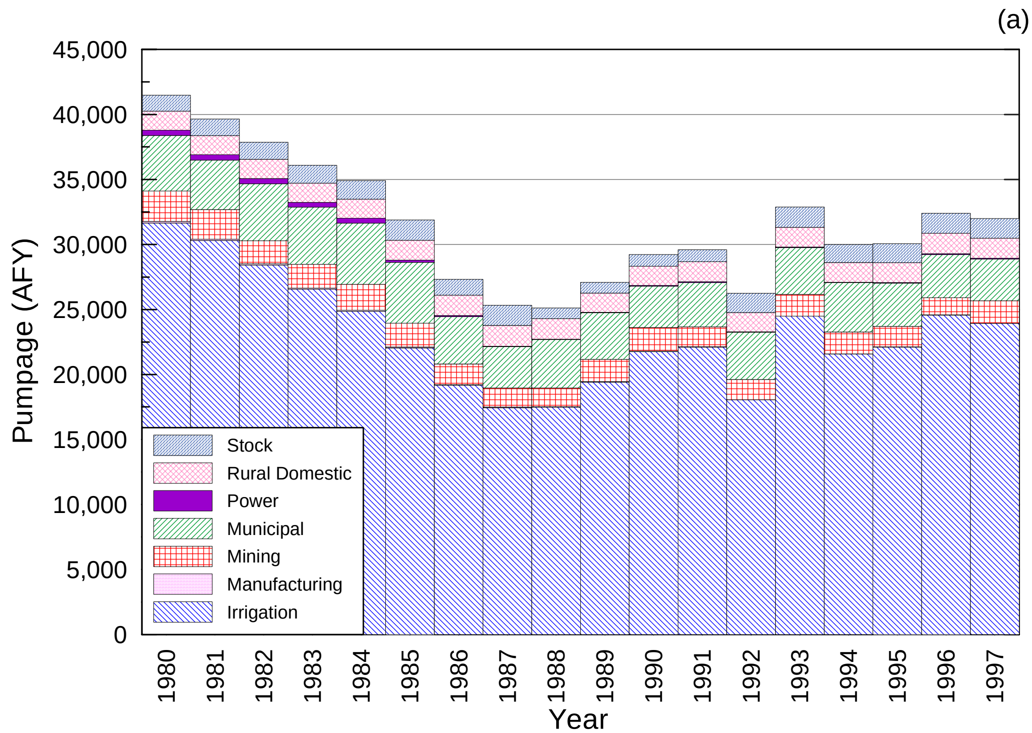


Figure 4.7.4 **Location of cropland in the active model area.**



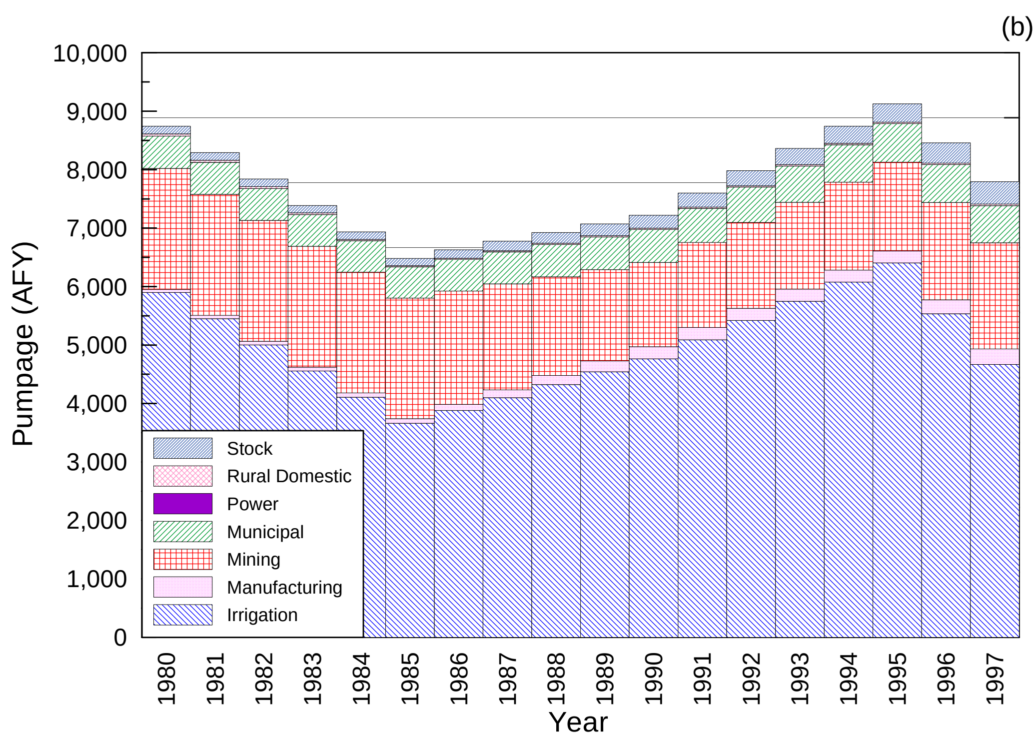


Figure 4.7.5 **Total groundwater withdrawals for the Dockum Aquifer in acre-feet per year in (a) Texas and (b) New Mexico by category.**

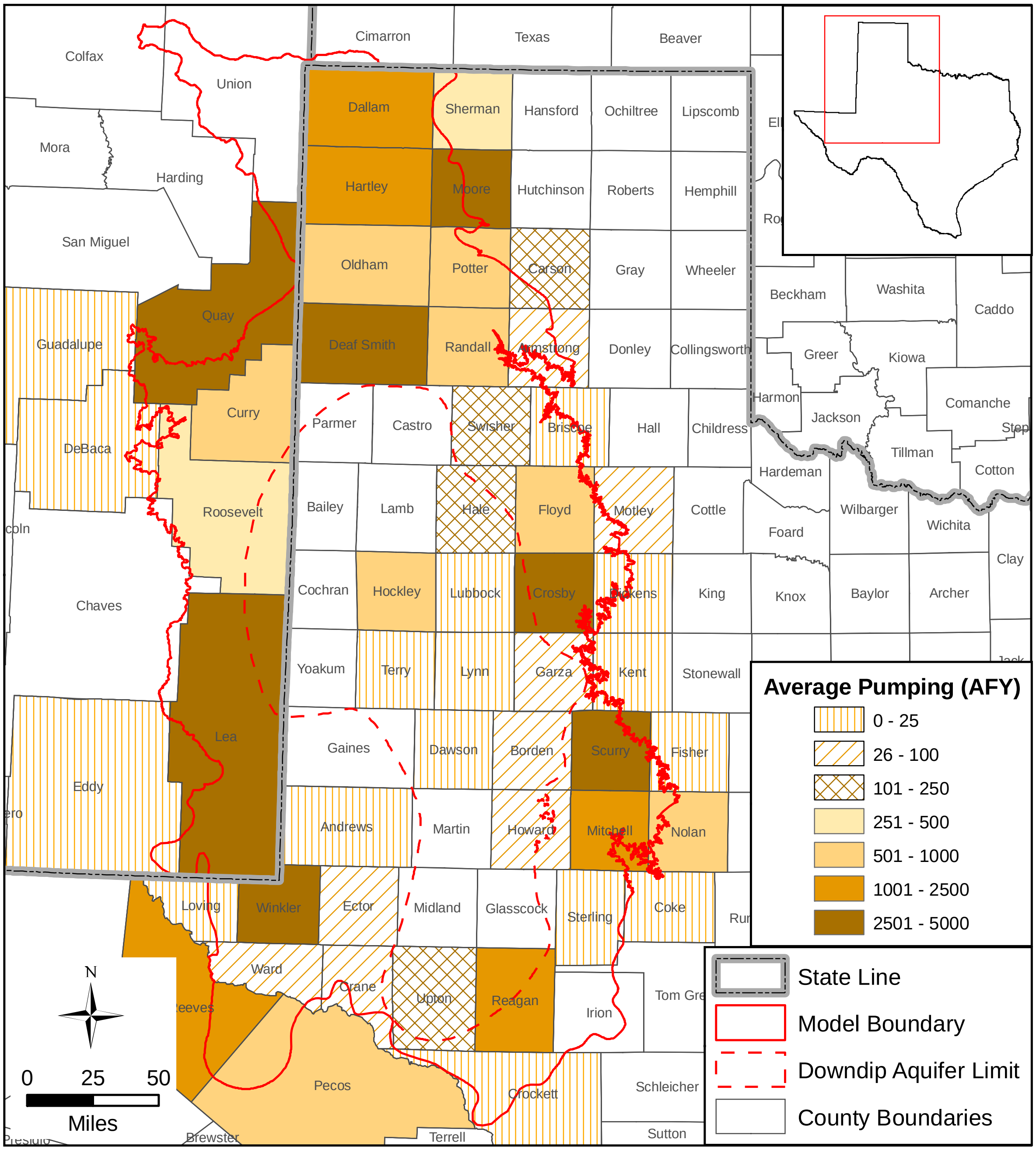


Figure 4.7.6 **1980 through 1997 yearly average pumping rate in acre-feet per year for the Dockum Aquifer.**

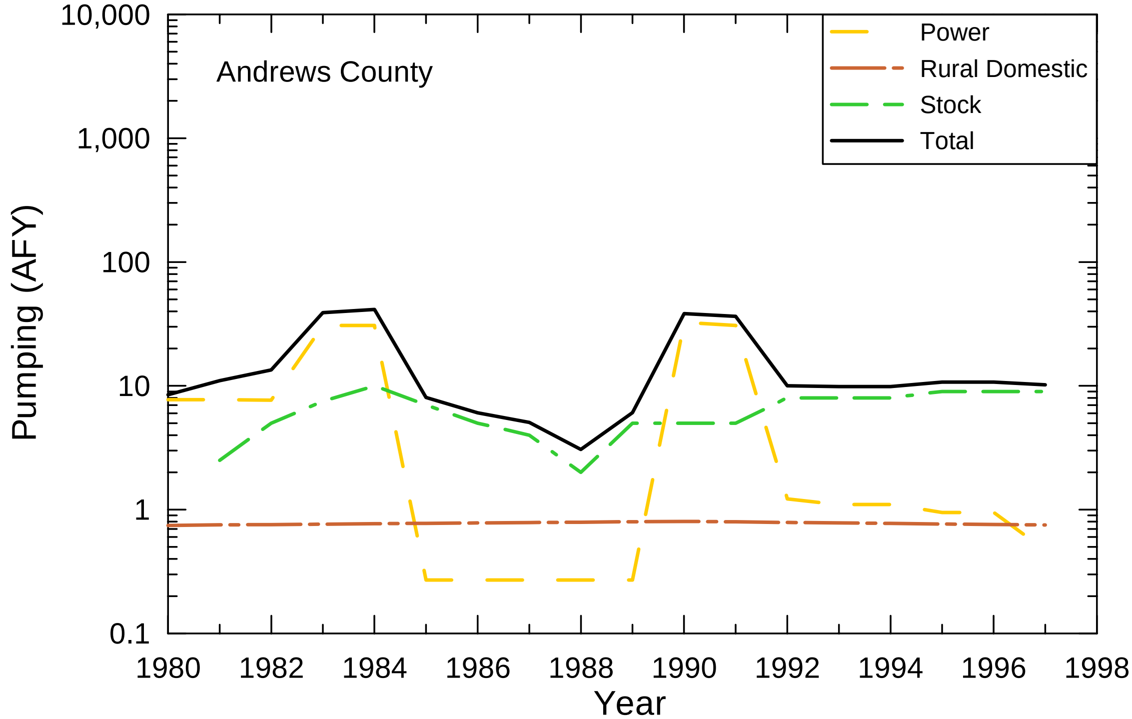


Figure 4.7.7 Groundwater withdrawals in acre-feet per year from the Dockum Aquifer for Andrews County, Texas.

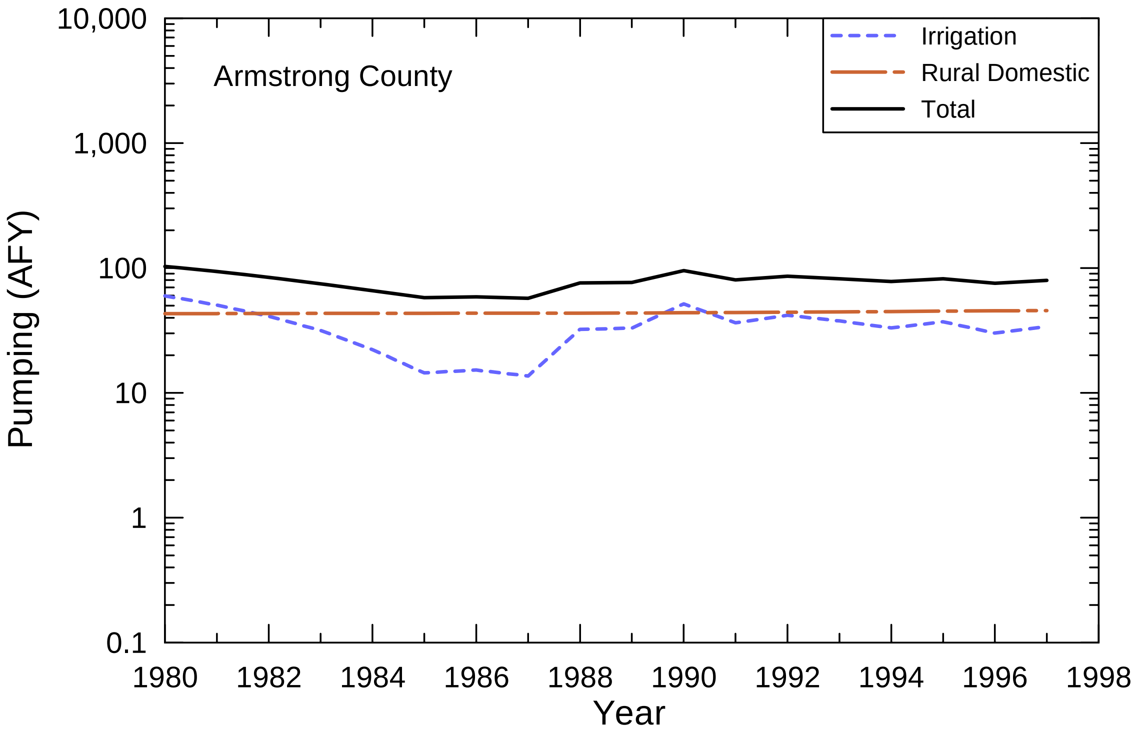


Figure 4.7.8 Groundwater withdrawals in acre-feet per year from the Dockum Aquifer for Armstrong County, Texas.

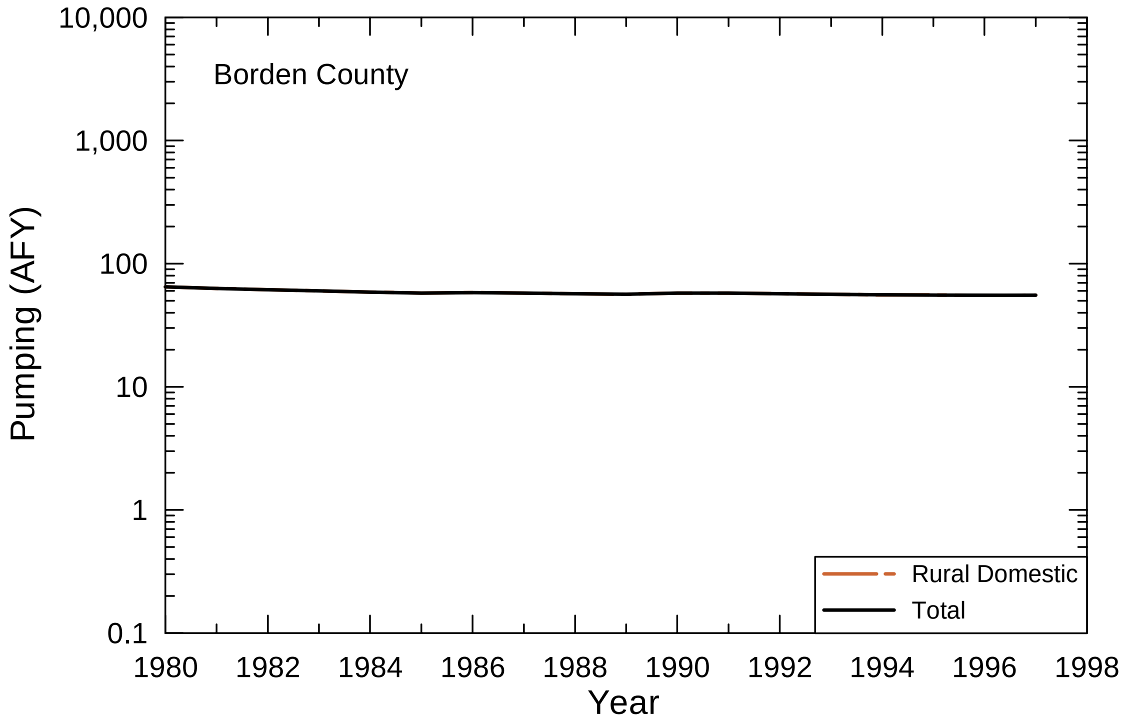


Figure 4.7.9 **Groundwater withdrawals in acre-feet per year from the Dockum Aquifer for Borden County, Texas.**

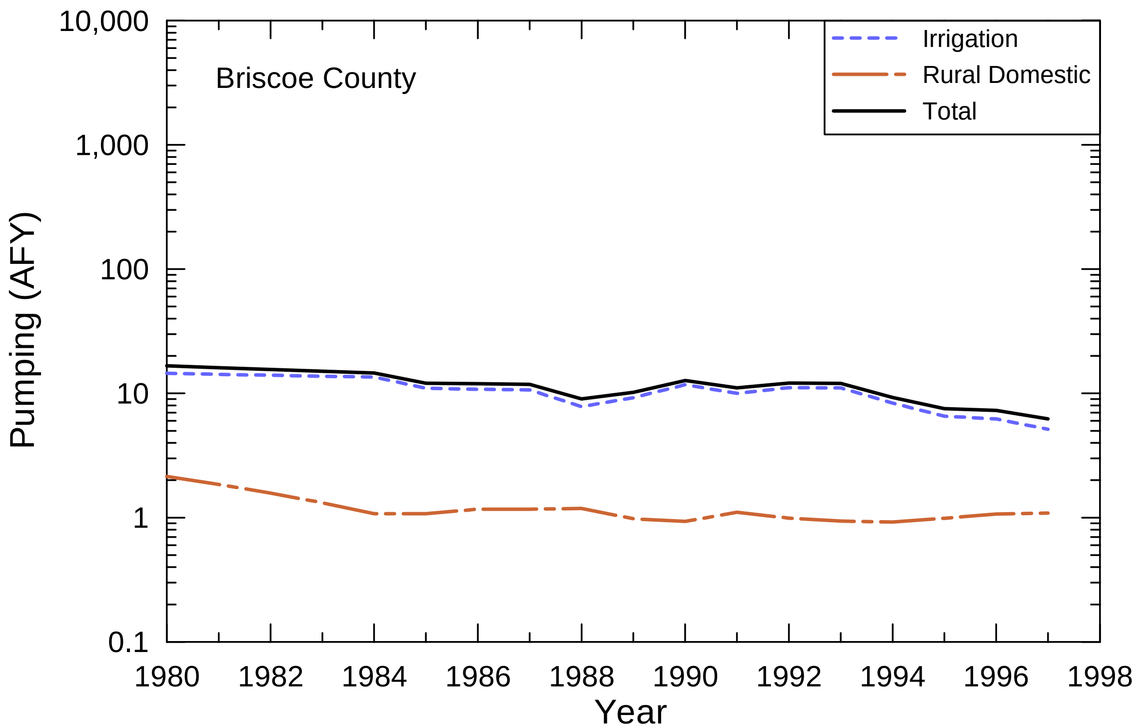


Figure 4.7.10 **Groundwater withdrawals in acre-feet per year from the Dockum Aquifer for Briscoe County, Texas.**

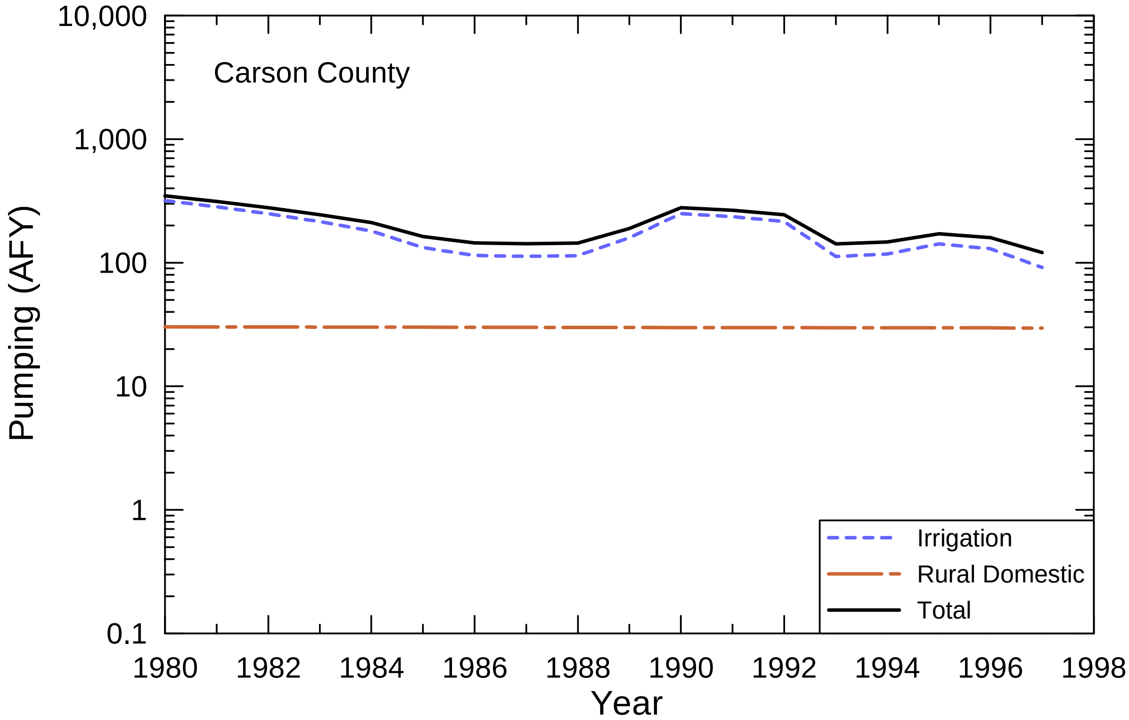


Figure 4.7.11 Groundwater withdrawals in acre-feet per year from the Dockum Aquifer for Carson County, Texas.

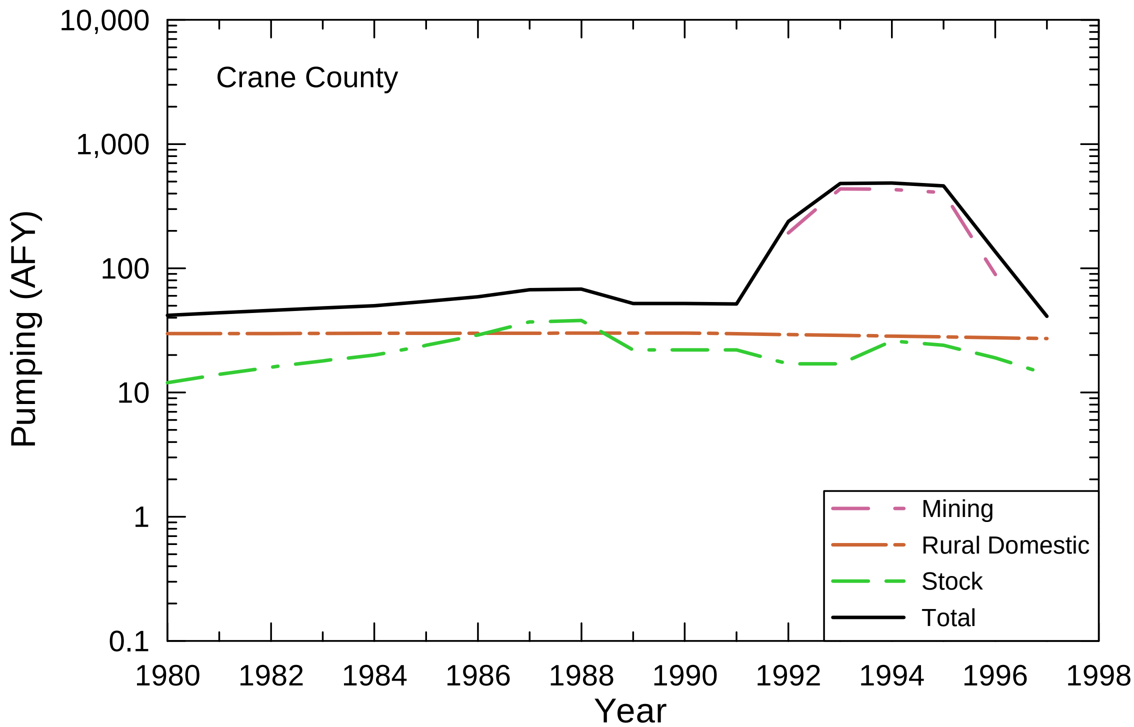


Figure 4.7.12 Groundwater withdrawals in acre-feet per year from the Dockum Aquifer for Crane County, Texas.

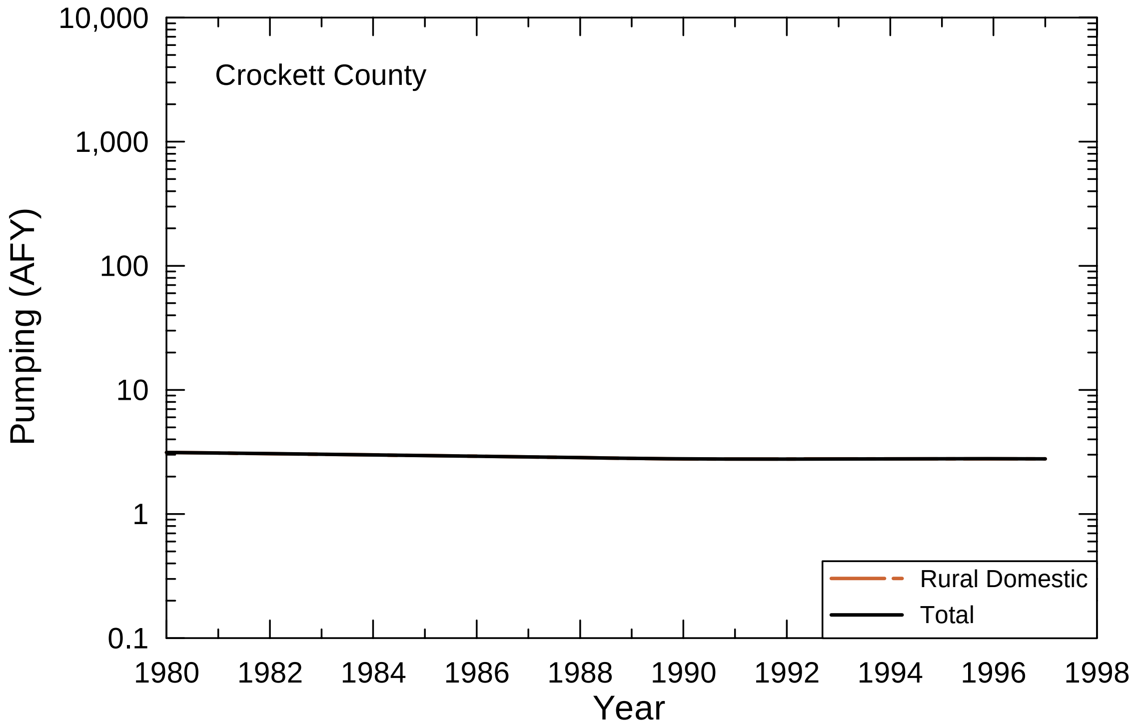


Figure 4.7.13 Groundwater withdrawals in acre-feet per year from the Dockum Aquifer for Crockett County, Texas

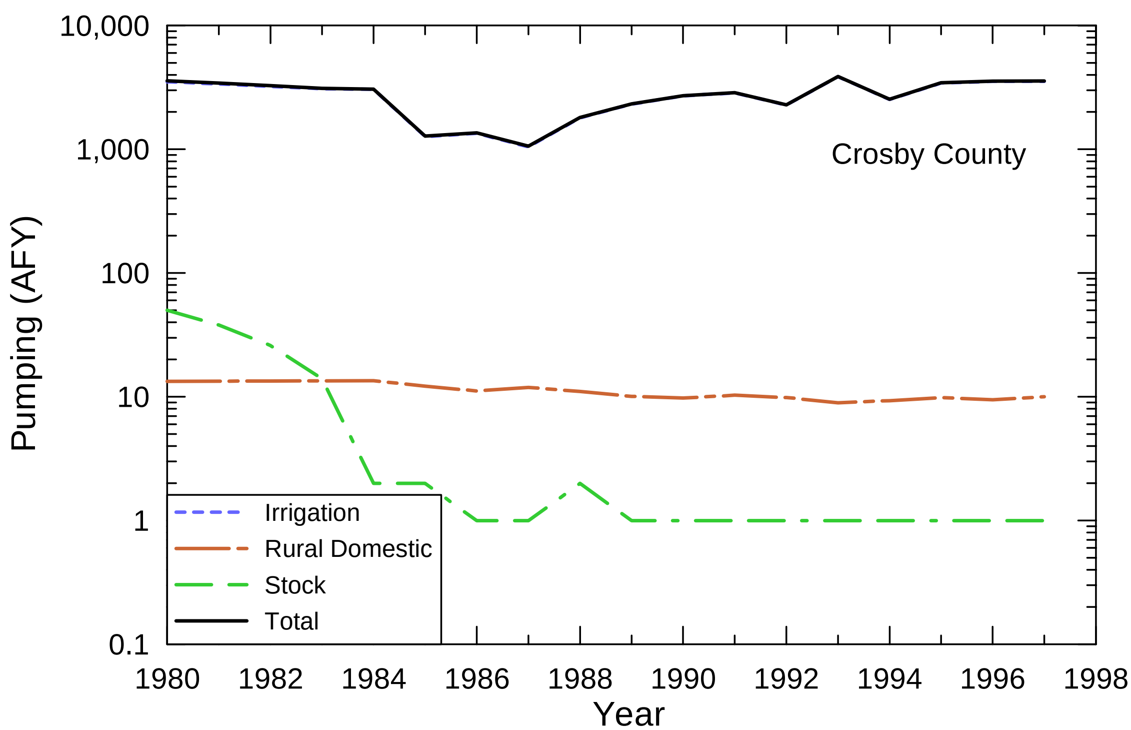


Figure 4.7.14 Groundwater withdrawals in acre-feet per year from the Dockum Aquifer for Crosby County, Texas.

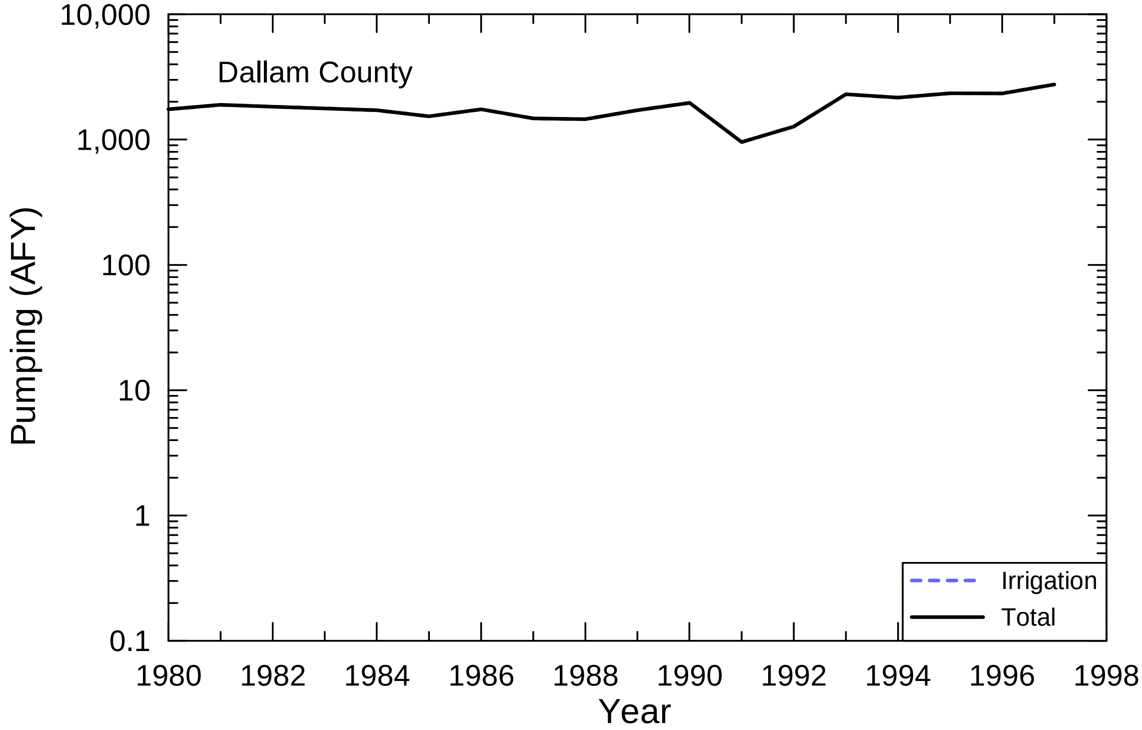


Figure 4.7.15 Groundwater withdrawals in acre-feet per year from the Dockum Aquifer for Dallam County, Texas.

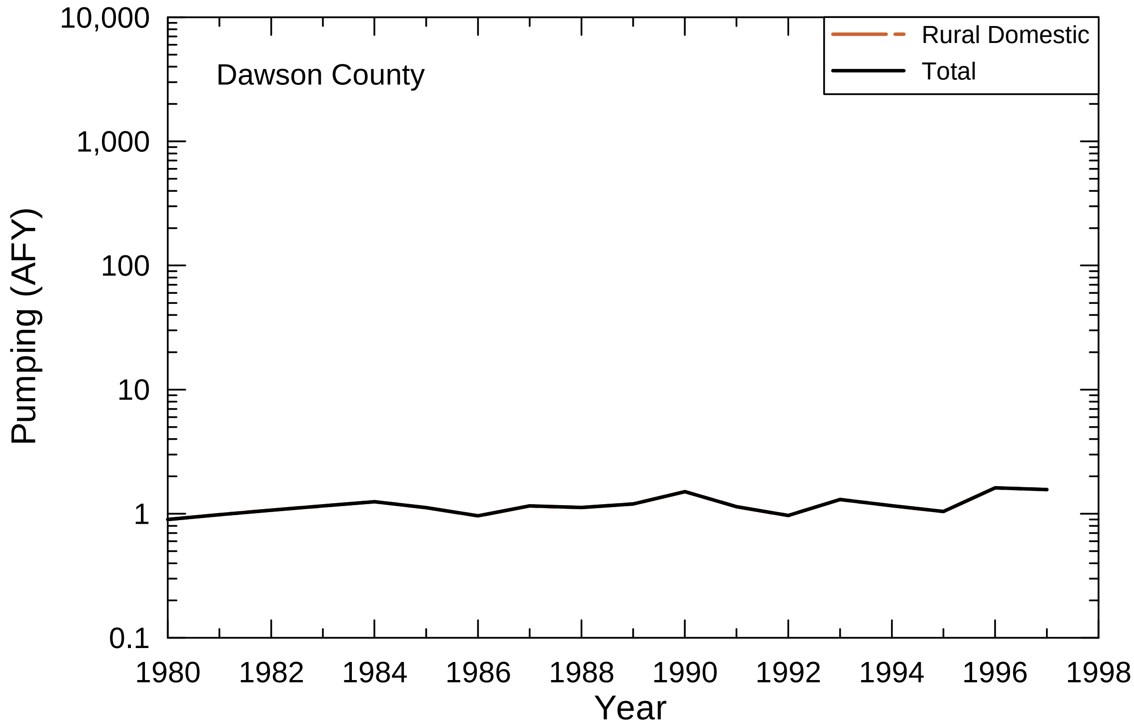


Figure 4.7.16 Groundwater withdrawals in acre-feet per year from the Dockum Aquifer for Dawson County, Texas.

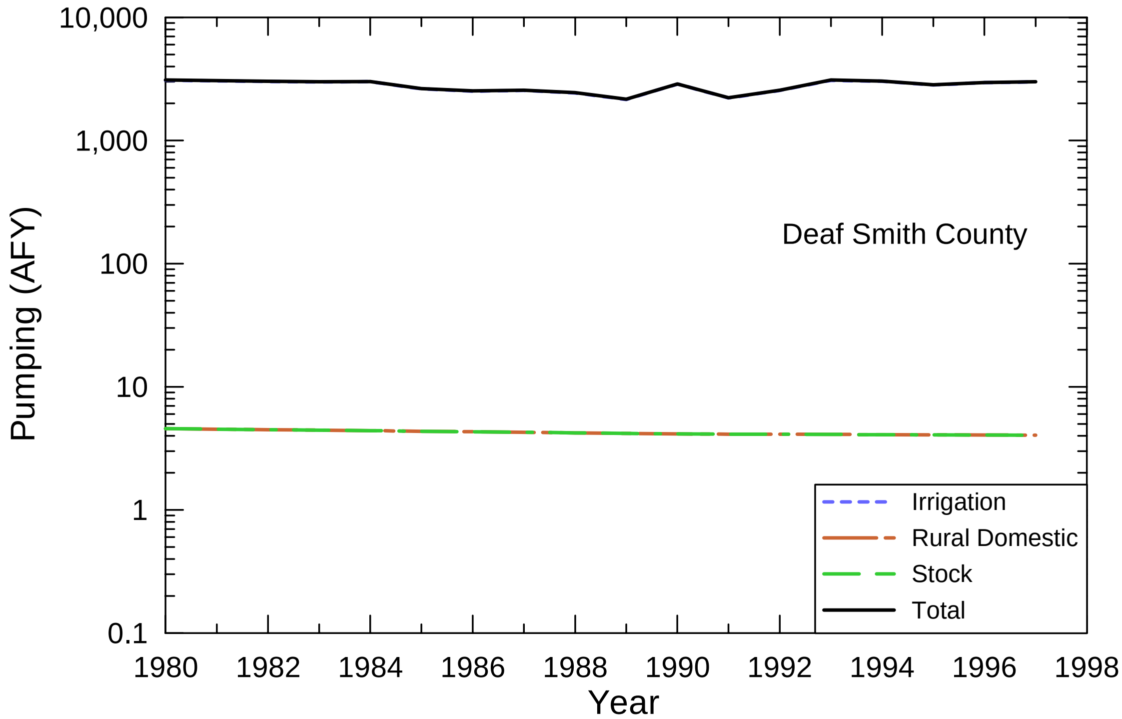


Figure 4.7.17 Groundwater withdrawals in acre-feet per year from the Dockum Aquifer for Deaf Smith County, Texas.

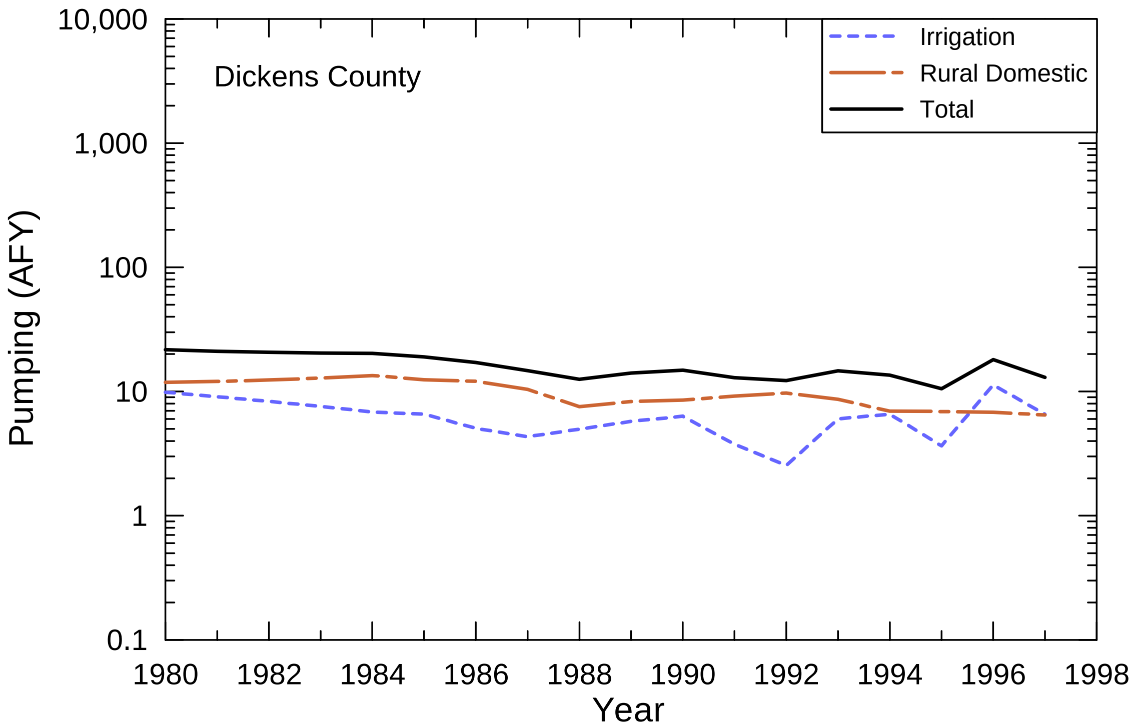


Figure 4.7.18 Groundwater withdrawals in acre-feet per year from the Dockum Aquifer for Dickens County, Texas.

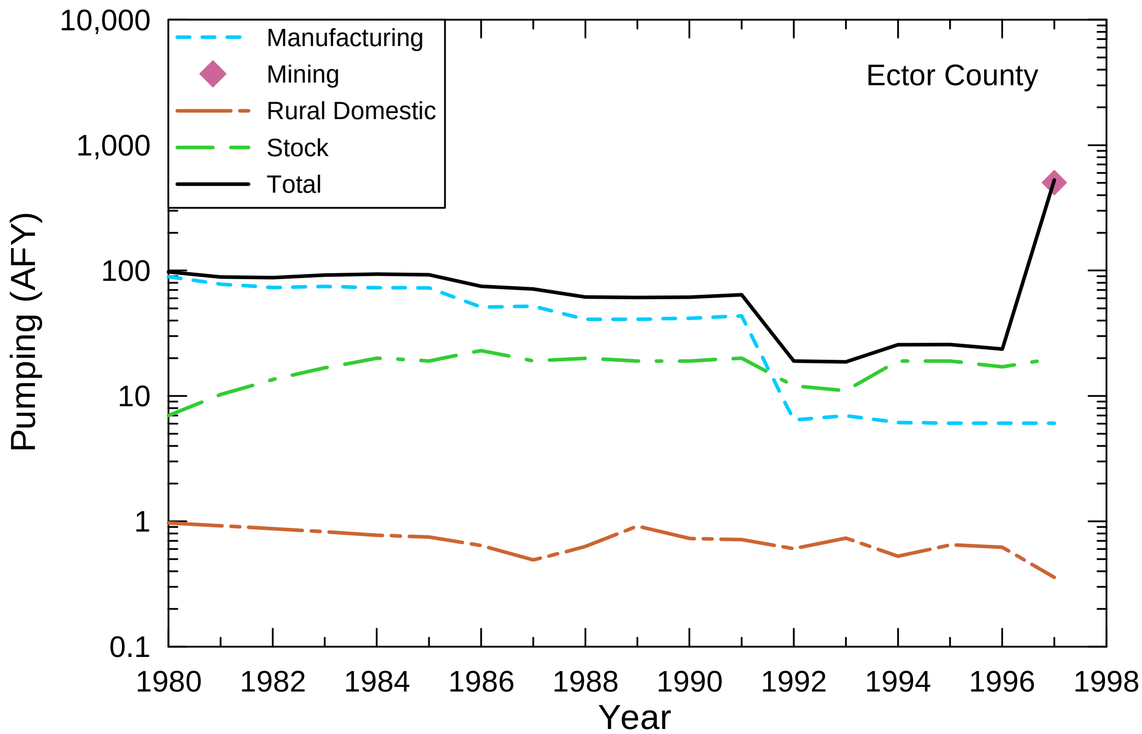


Figure 4.7.19 **Groundwater withdrawals in acre-feet per year from the Dockum Aquifer for Ector County, Texas.**

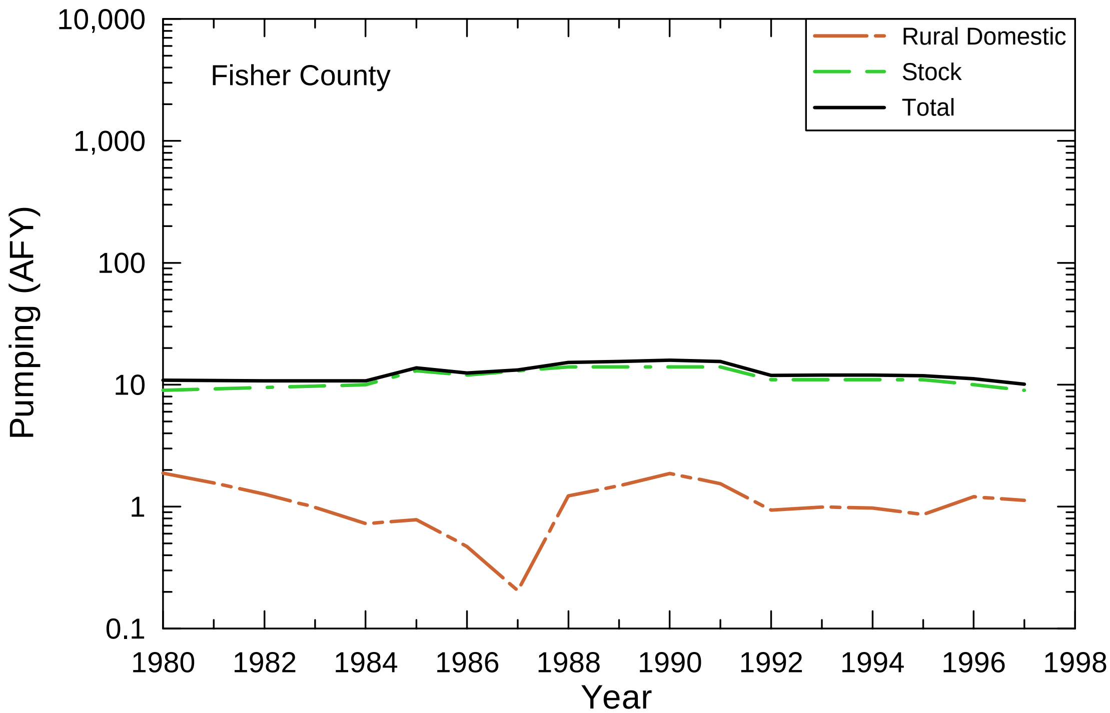


Figure 4.7.20 **Groundwater withdrawals in acre-feet per year from the Dockum Aquifer for Fisher County, Texas.**

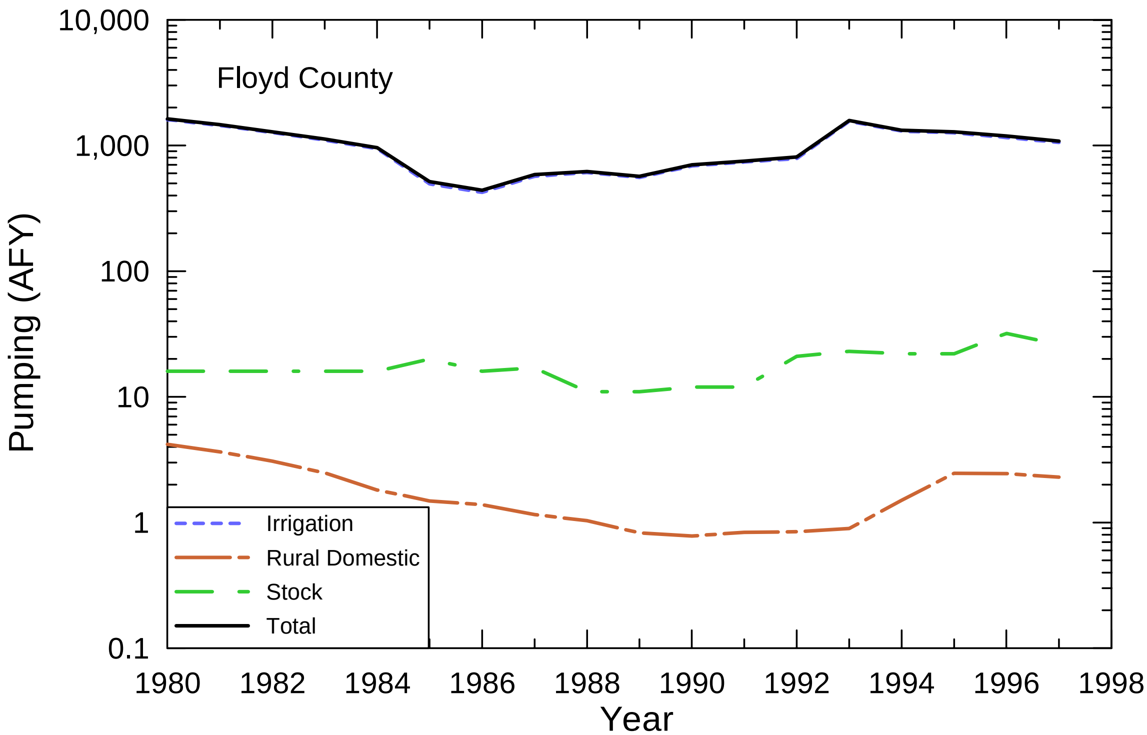


Figure 4.7.21 **Groundwater withdrawals in acre-feet per year from the Dockum Aquifer for Floyd County, Texas.**

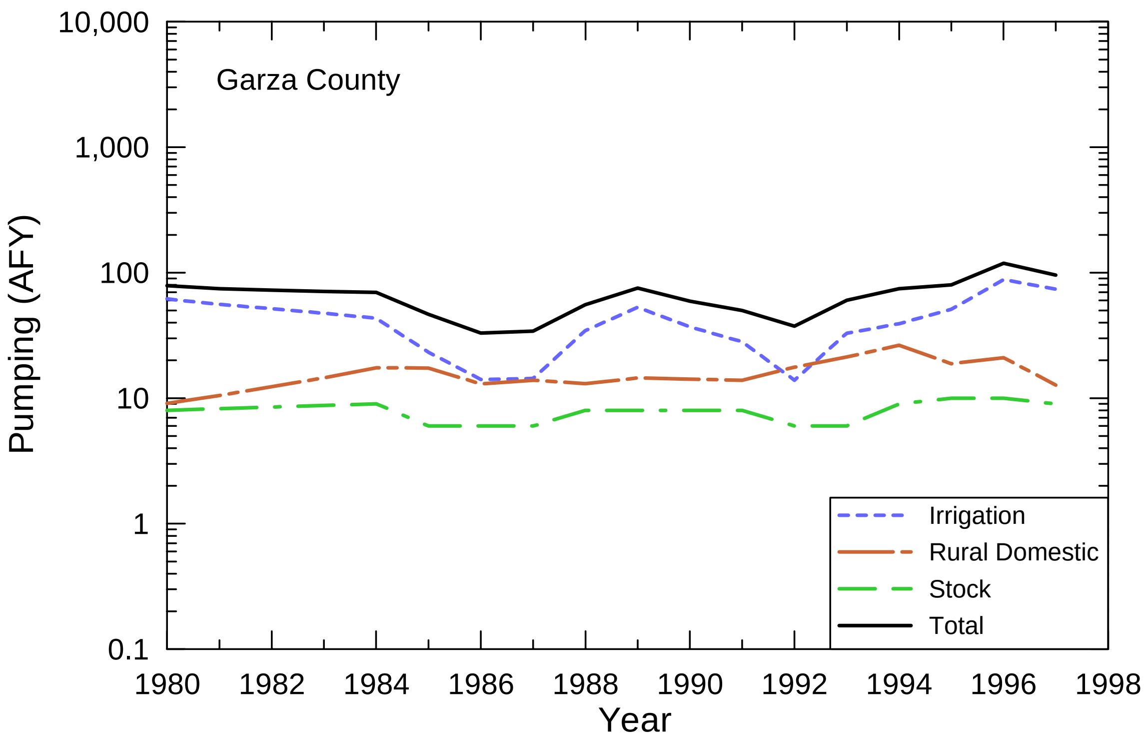


Figure 4.7.22 **Groundwater withdrawals in acre-feet per year from the Dockum Aquifer for Garza County, Texas.**

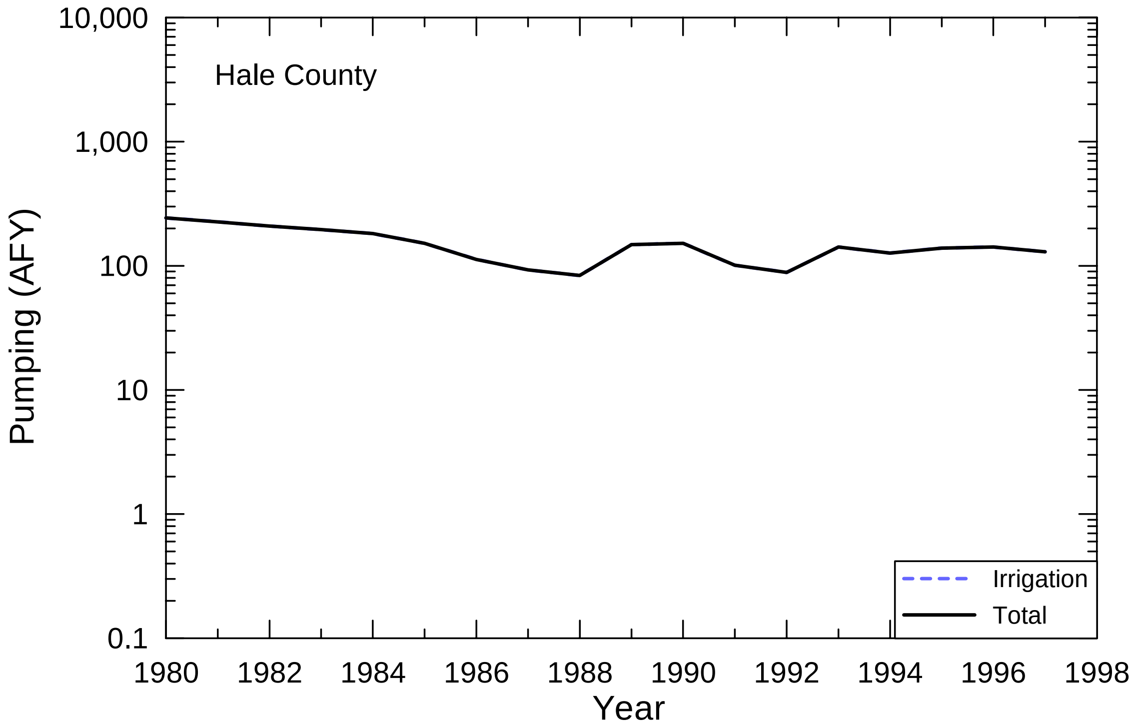


Figure 4.7.23 **Groundwater withdrawals in acre-feet per year from the Dockum Aquifer for Hale County, Texas.**

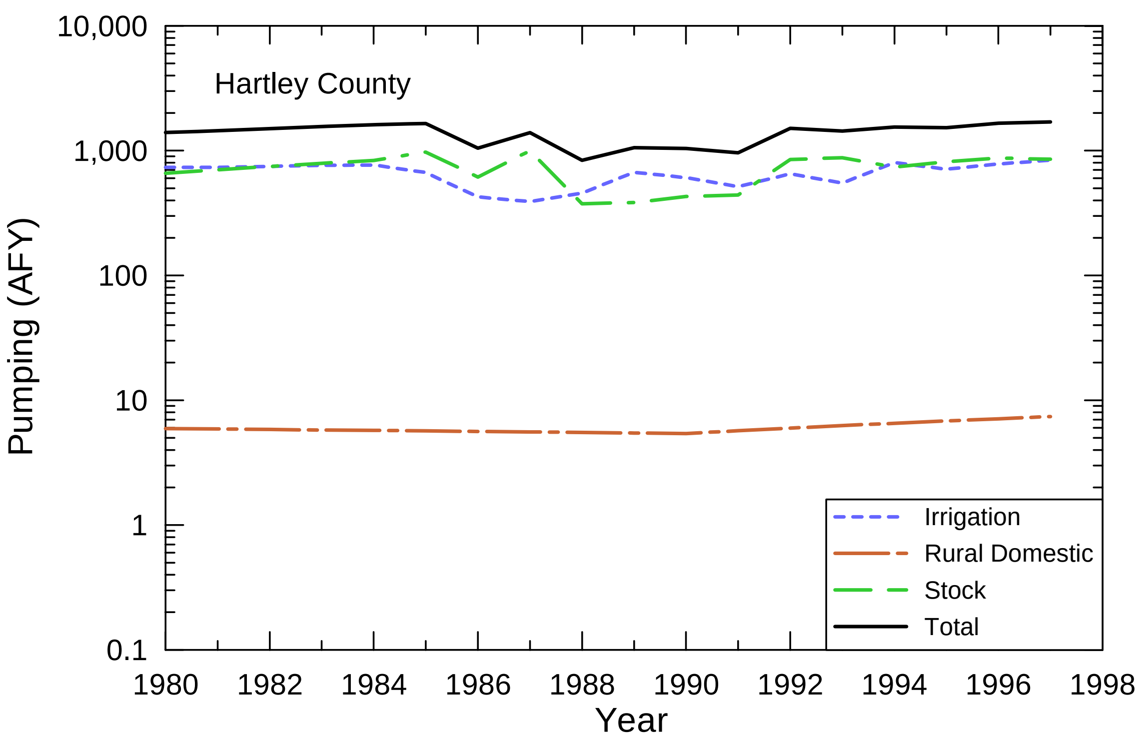


Figure 4.7.24 **Groundwater withdrawals in acre-feet per year from the Dockum Aquifer for Hartley County, Texas.**

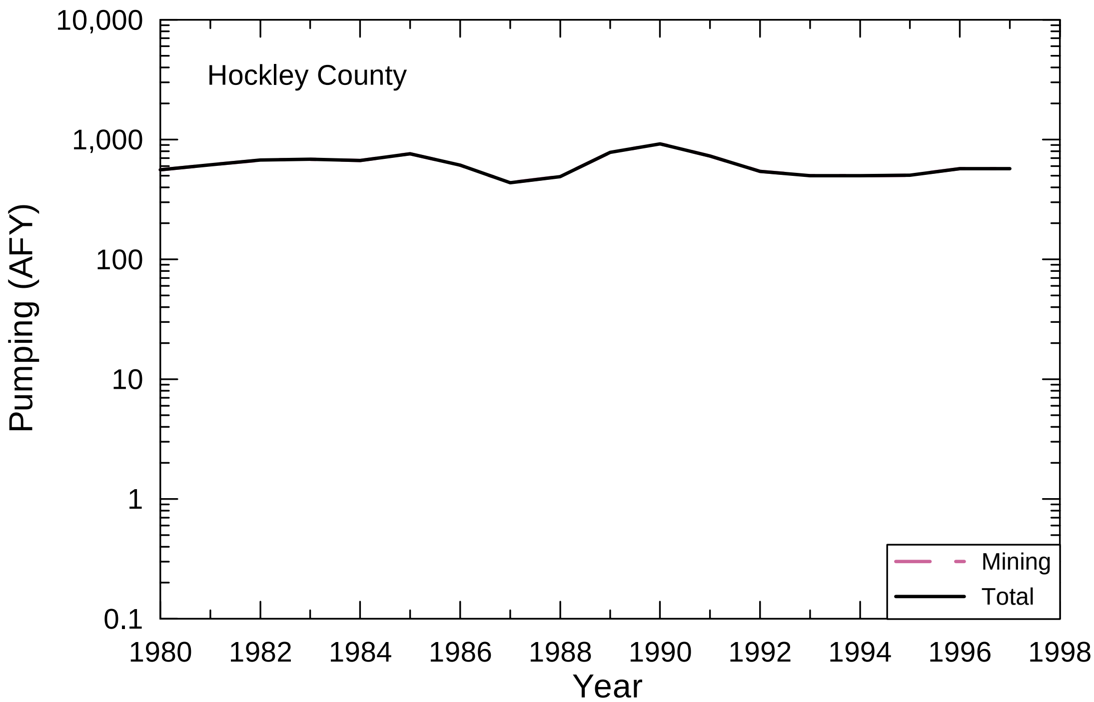


Figure 4.7.25 Groundwater withdrawals in acre-feet per year from the Dockum Aquifer for Hockley County, Texas.

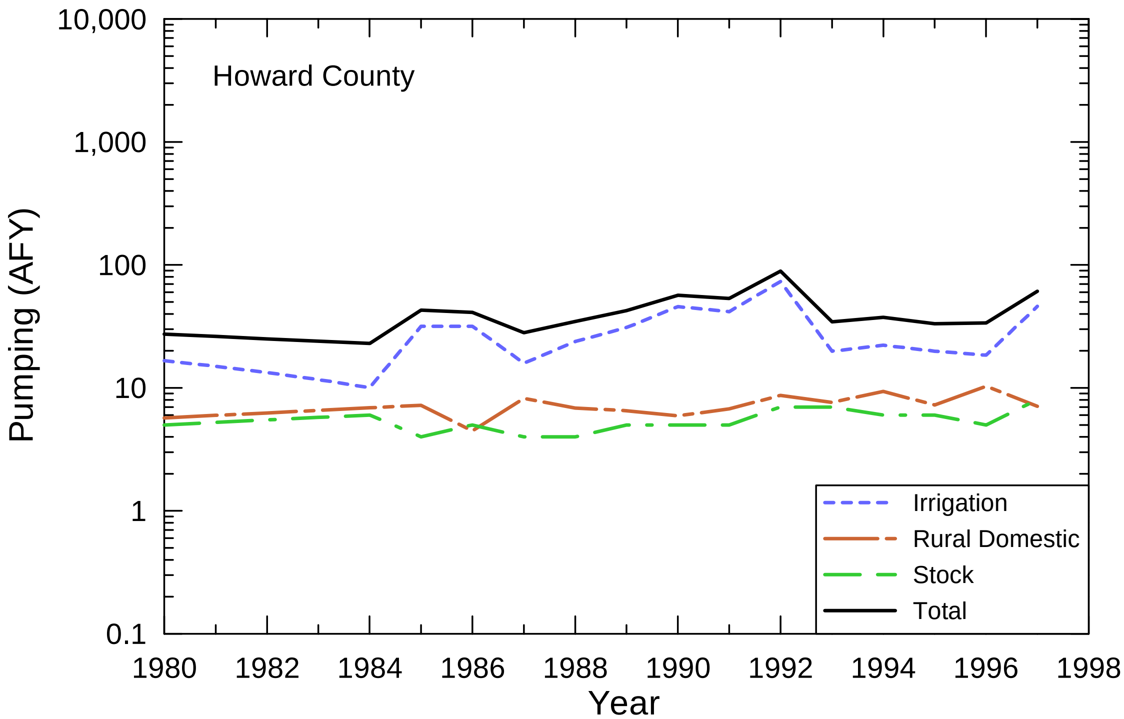


Figure 4.7.26 Groundwater withdrawals in acre-feet per year from the Dockum Aquifer for Howard County, Texas.

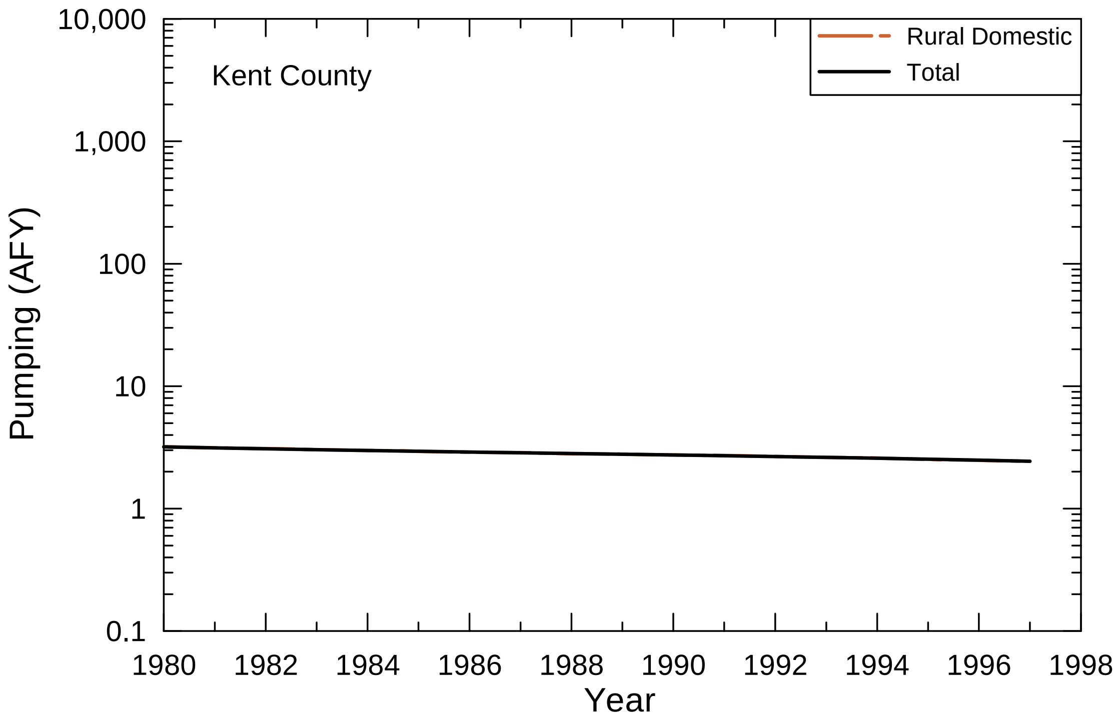


Figure 4.7.27 **Groundwater withdrawals in acre-feet per year from the Dockum Aquifer for Kent County, Texas.**

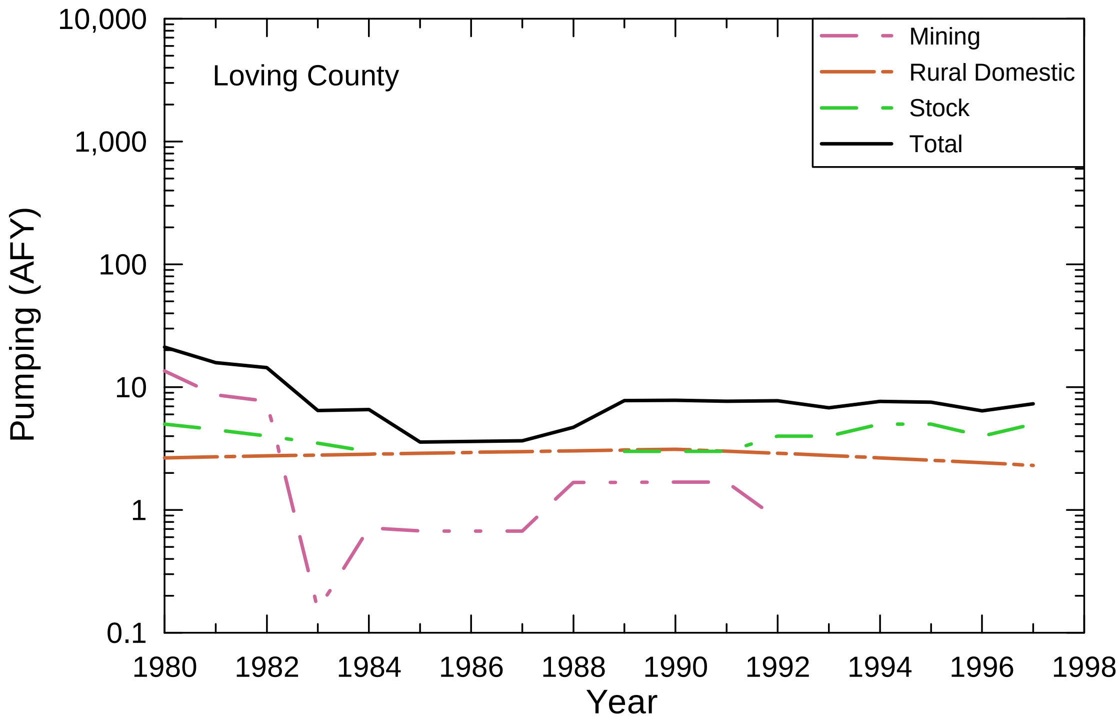


Figure 4.7.28 **Groundwater withdrawals in acre-feet per year from the Dockum Aquifer for Loving County, Texas.**

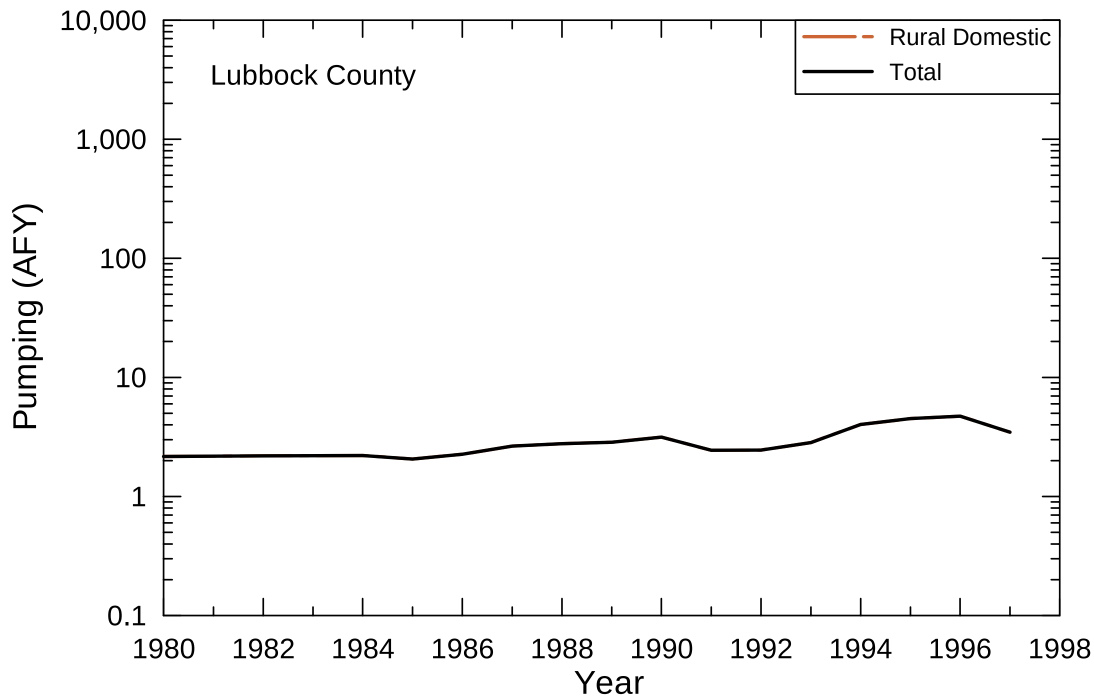


Figure 4.7.29 **Groundwater withdrawals in acre-feet per year from the Dockum Aquifer for Lubbock County, Texas.**

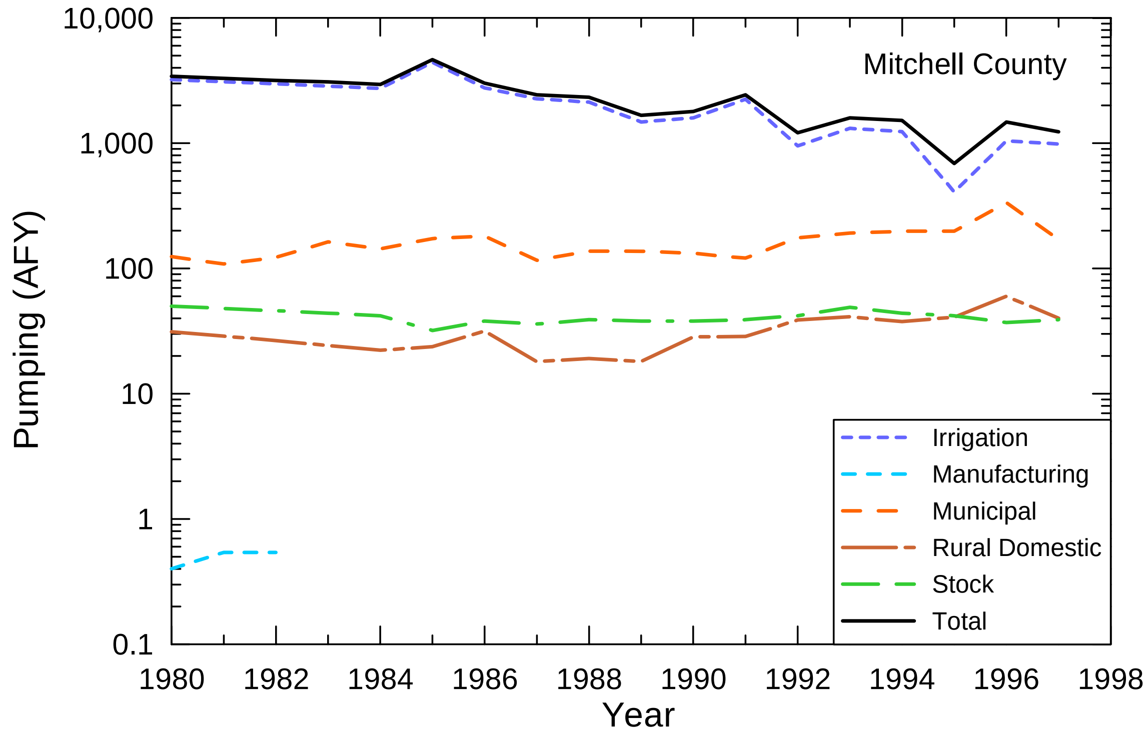


Figure 4.7.30 **Groundwater withdrawals in acre-feet per year from the Dockum Aquifer for Mitchell County, Texas.**

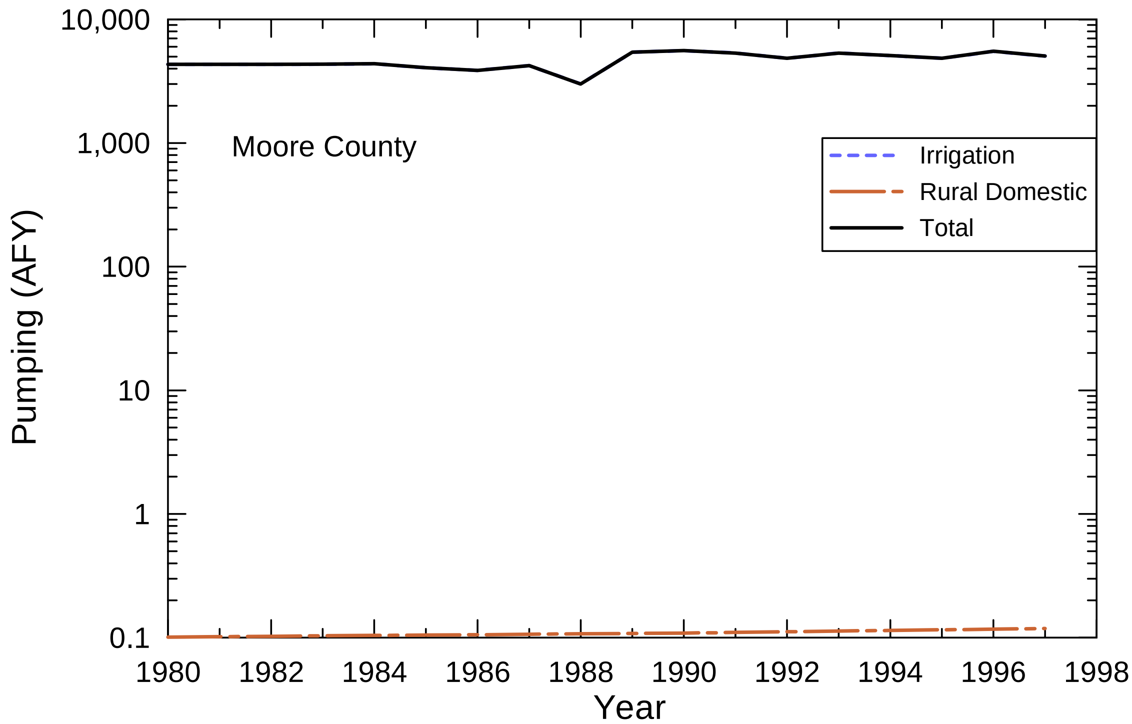


Figure 4.7.31 Groundwater withdrawals in acre-feet per year from the Dockum Aquifer for Moore County, Texas.

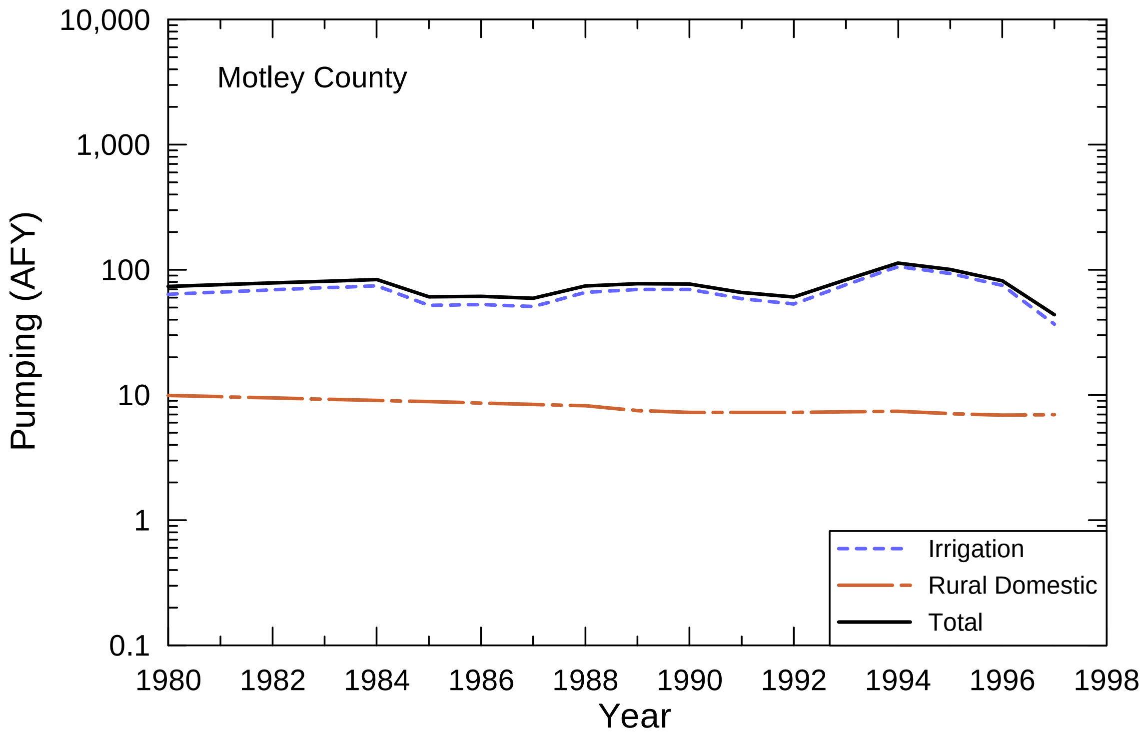


Figure 4.7.32 Groundwater withdrawals in acre-feet per year from the Dockum Aquifer for Motley County, Texas.

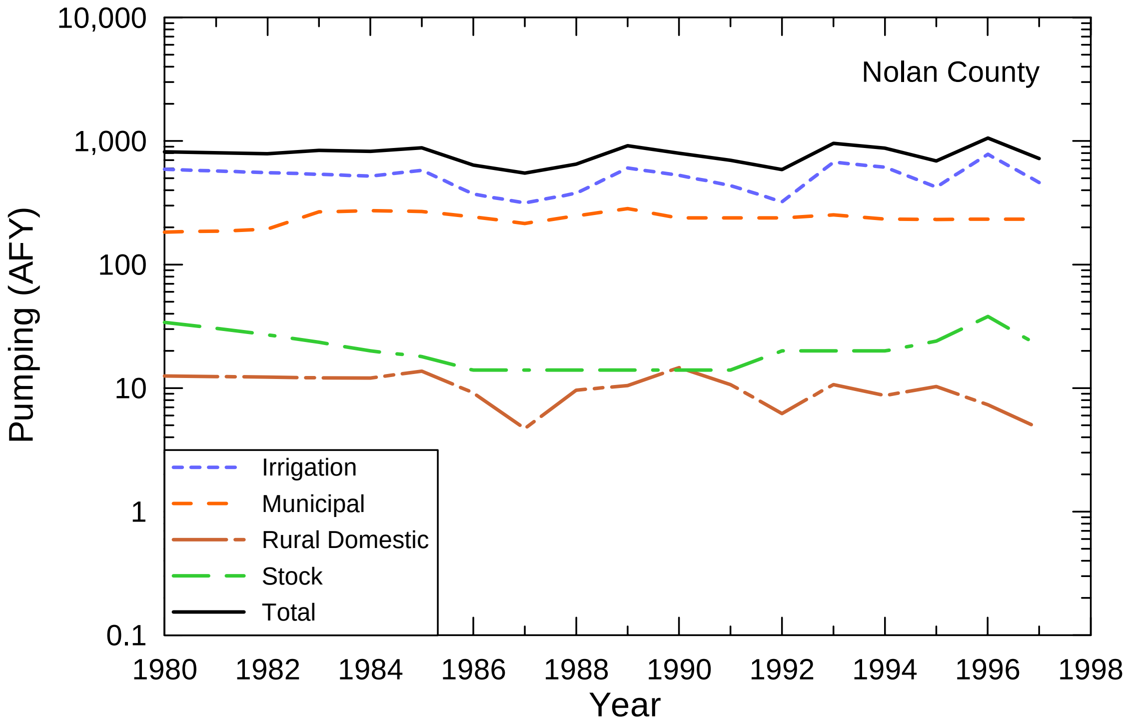


Figure 4.7.33 Groundwater withdrawals in acre-feet per year from the Dockum Aquifer for Nolan County, Texas.

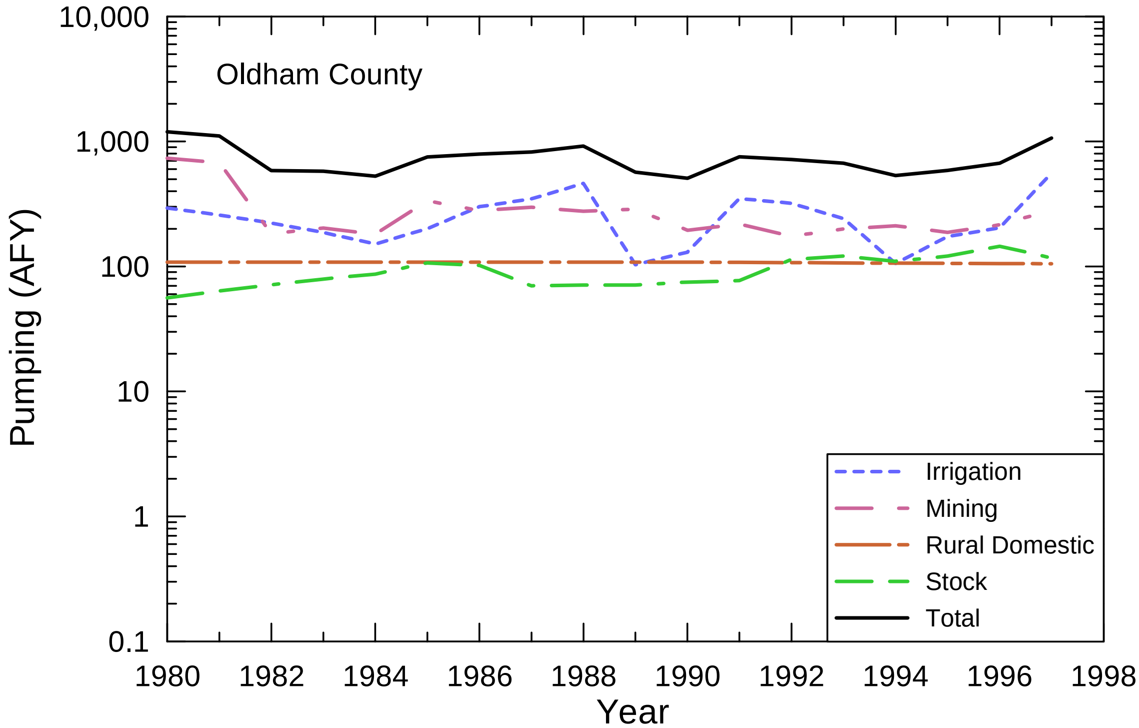


Figure 4.7.34 Groundwater withdrawals in acre-feet per year from the Dockum Aquifer for Oldham County, Texas.

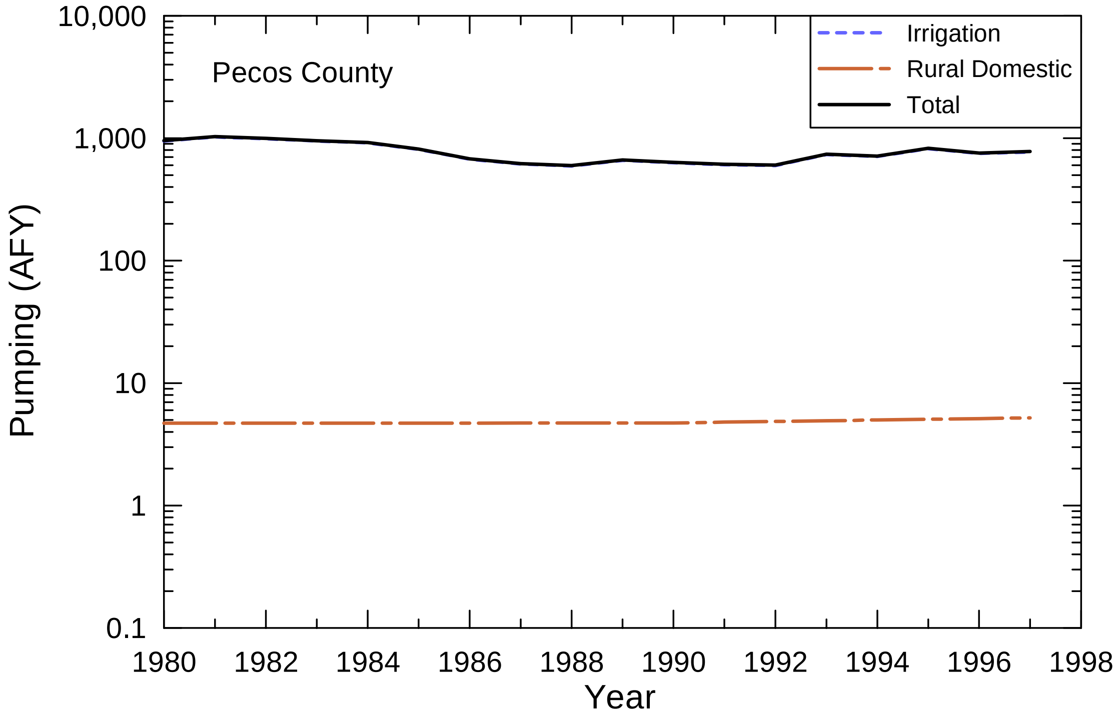


Figure 4.7.35 Groundwater withdrawals in acre-feet per year from the Dockum Aquifer for Pecos County, Texas.

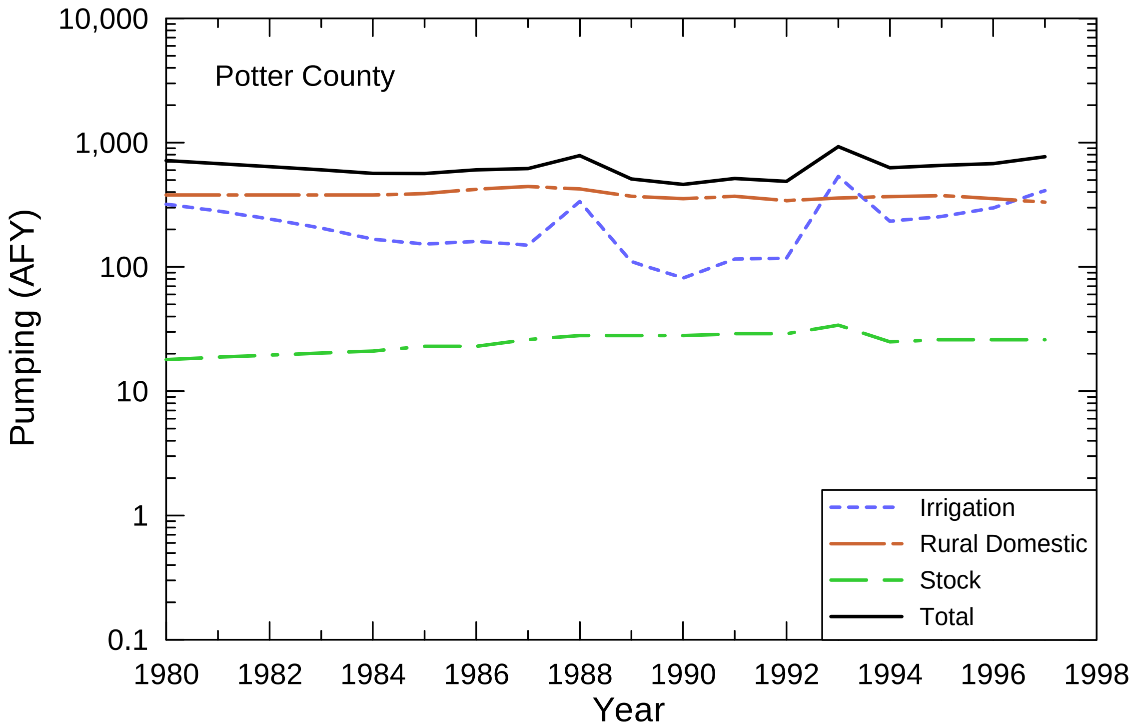


Figure 4.7.36 Groundwater withdrawals in acre-feet per year from the Dockum Aquifer for Potter County, Texas.

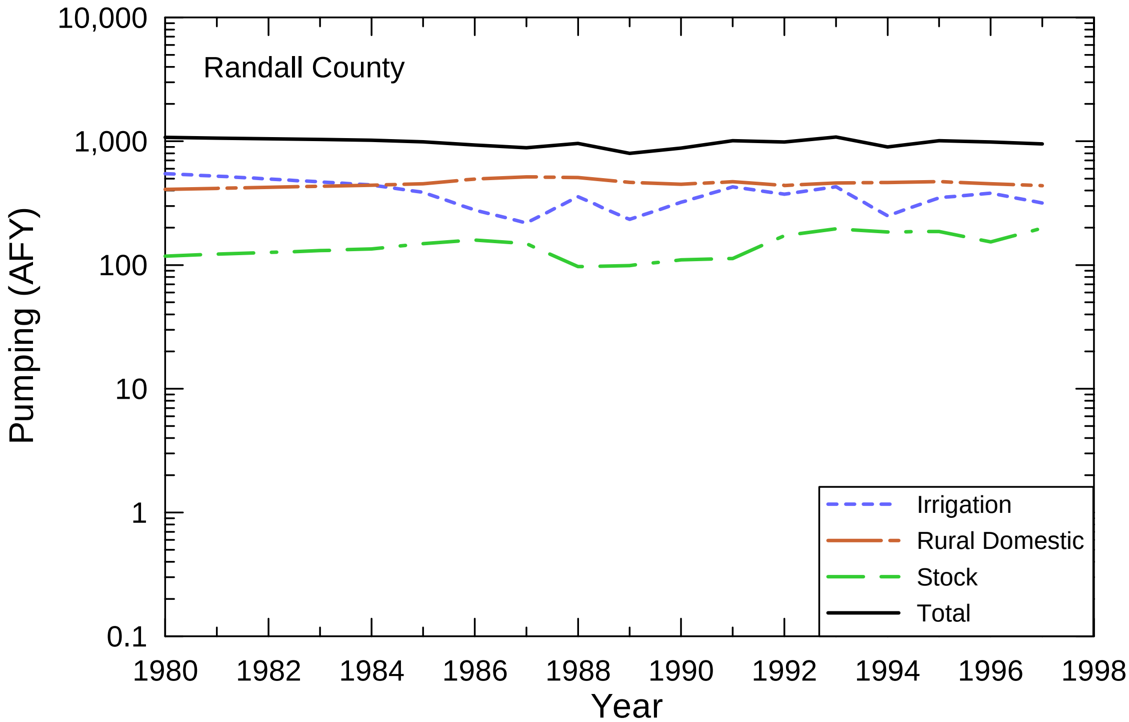


Figure 4.7.37 Groundwater withdrawals in acre-feet per year from the Dockum Aquifer for Randall County, Texas.

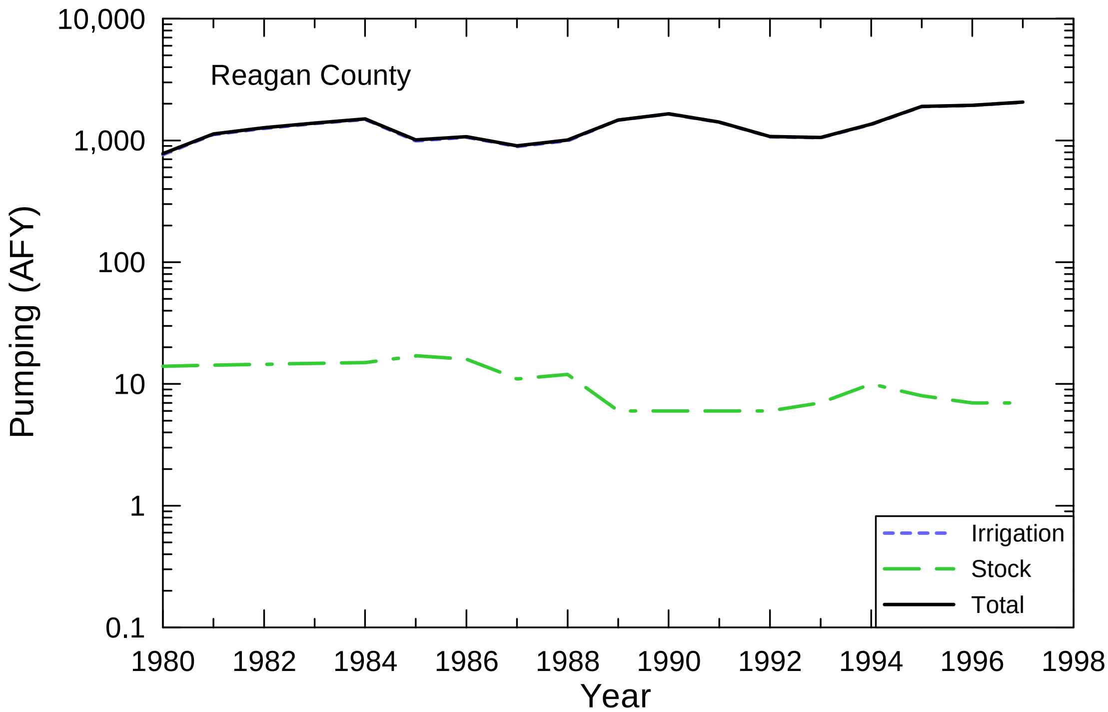


Figure 4.7.38 Groundwater withdrawals in acre-feet per year from the Dockum Aquifer for Reagan County, Texas.

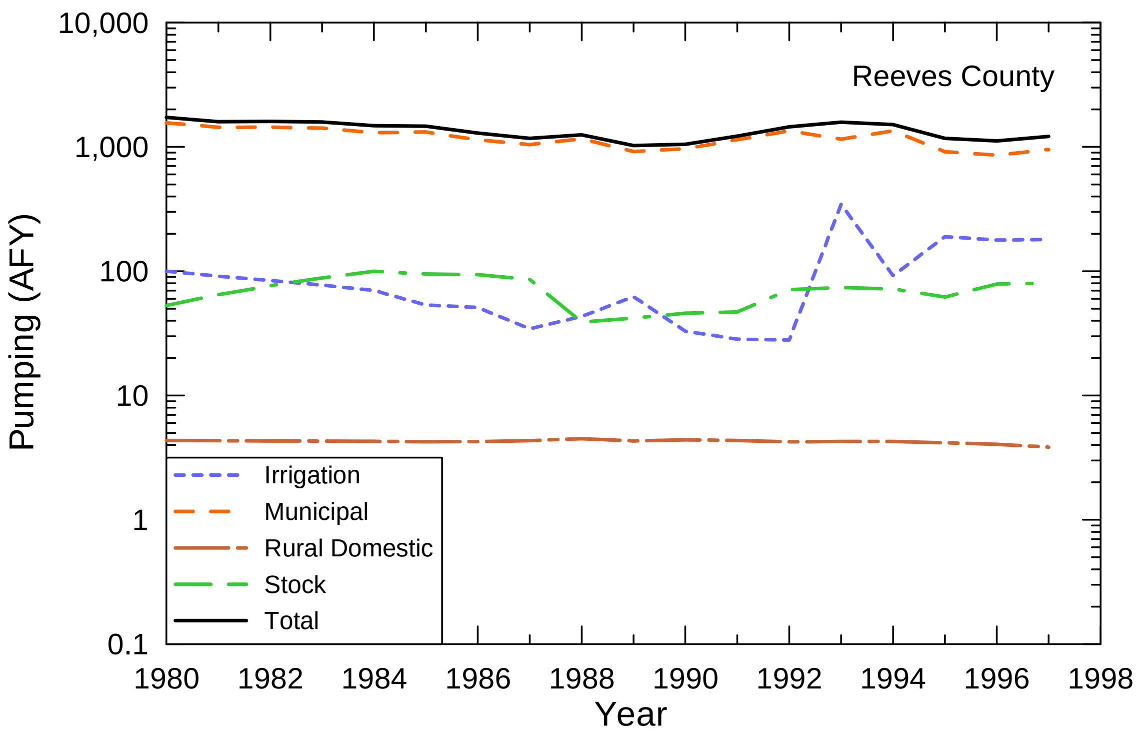


Figure 4.7.39 **Groundwater withdrawals in acre-feet per year from the Dockum Aquifer for Reeves County, Texas.**

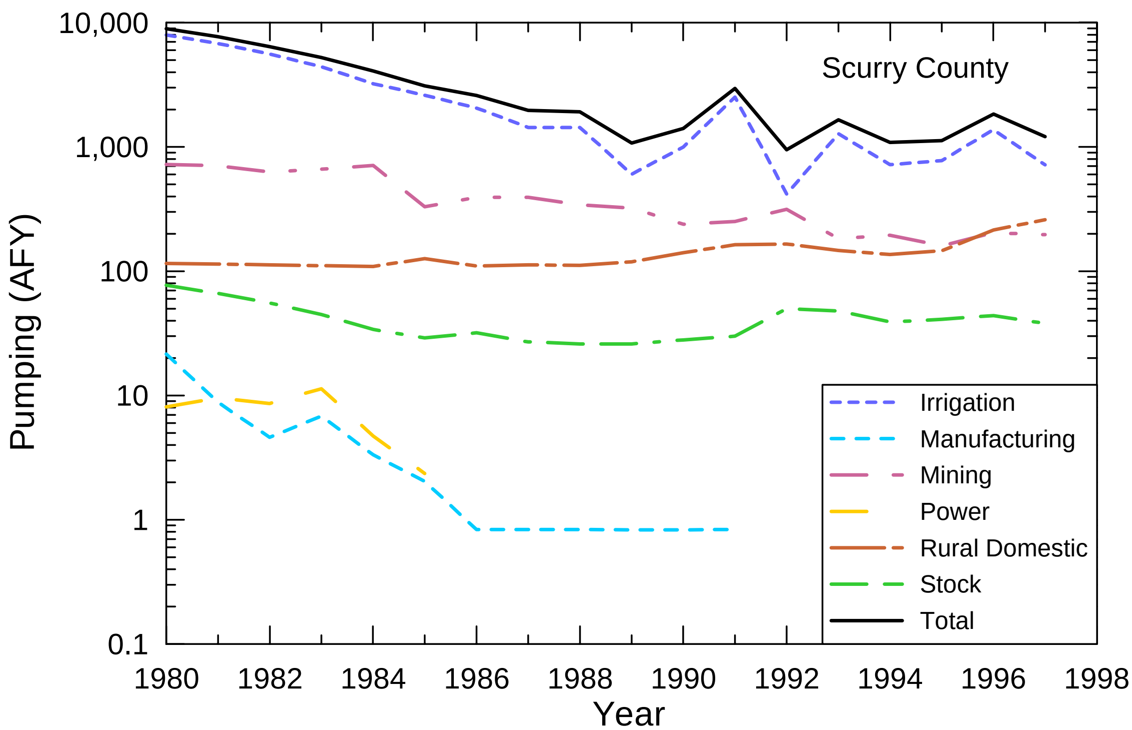


Figure 4.7.40 **Groundwater withdrawals in acre-feet per year from the Dockum Aquifer for Scurry County, Texas.**

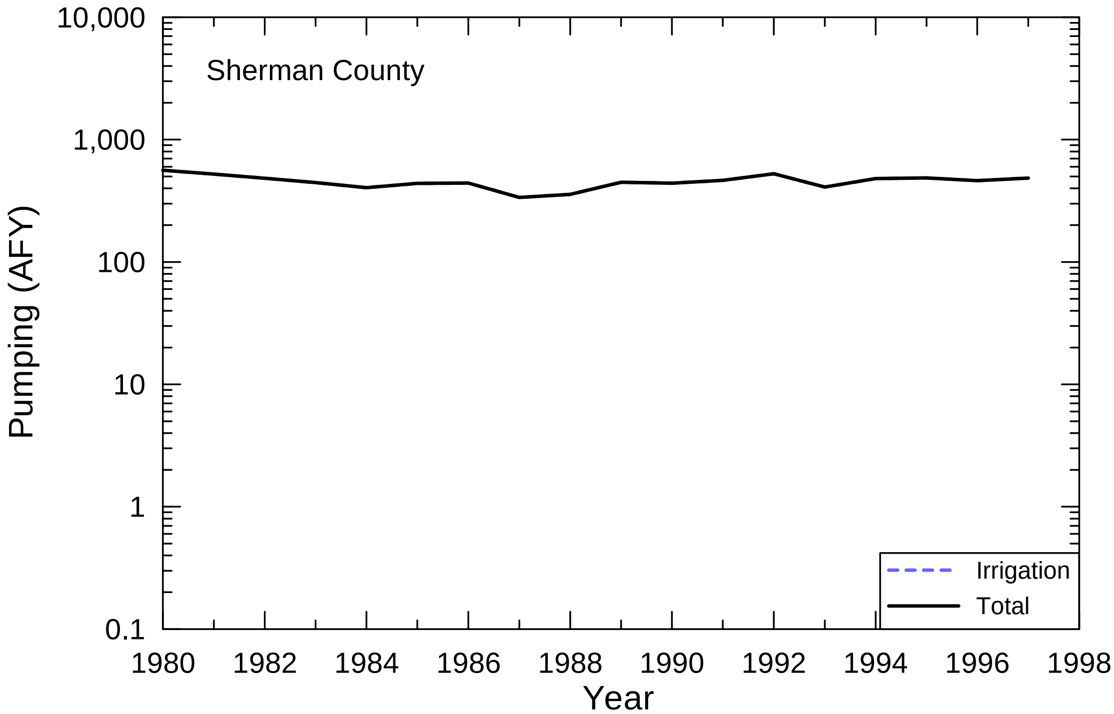


Figure 4.7.41 **Groundwater withdrawals in acre-feet per year from the Dockum Aquifer for Sherman County, Texas.**

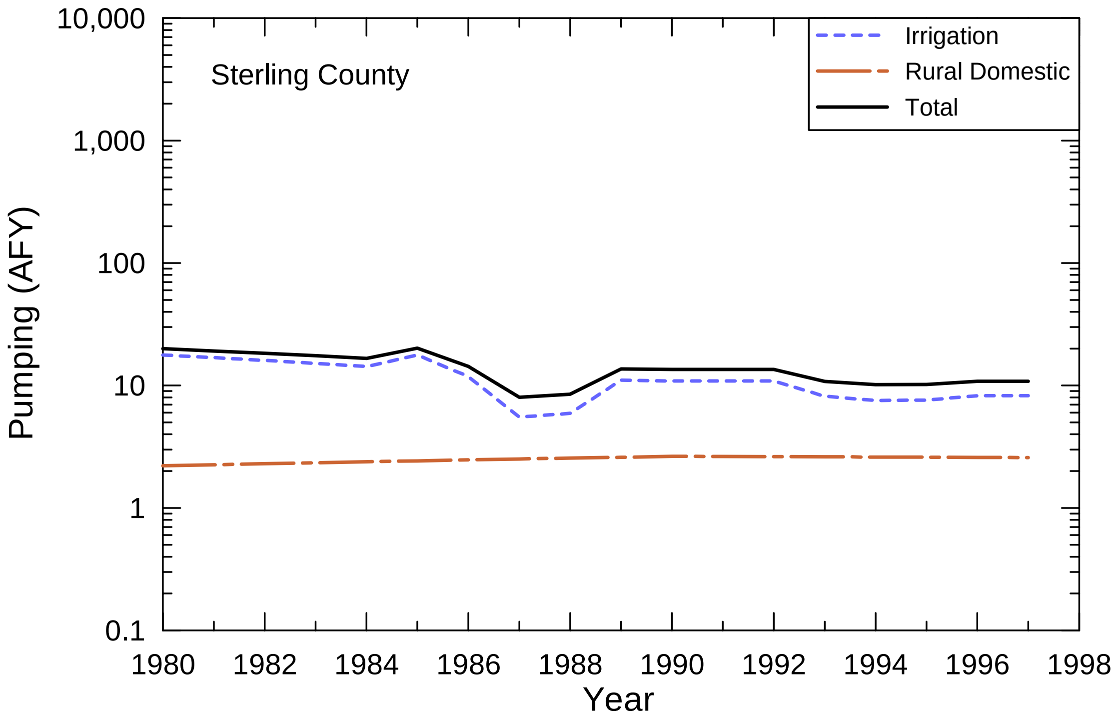


Figure 4.7.42 **Groundwater withdrawals in acre-feet per year from the Dockum Aquifer for Sterling County, Texas.**

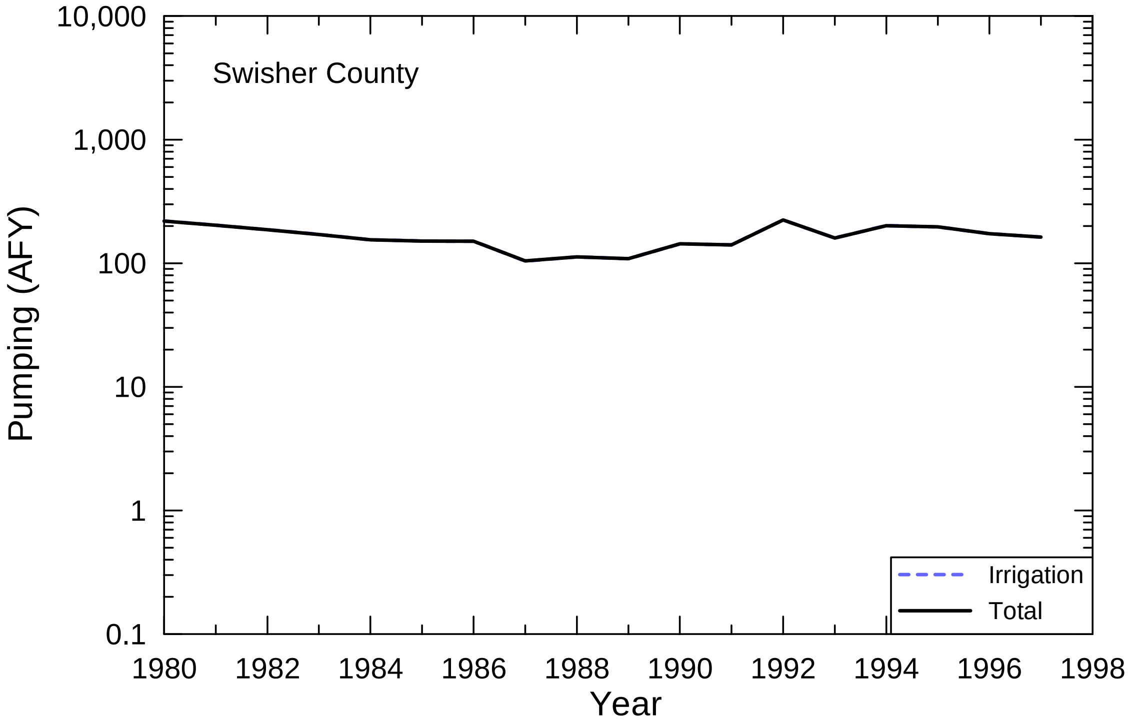


Figure 4.7.43 Groundwater withdrawals in acre-feet per year from the Dockum Aquifer for Swisher County, Texas.

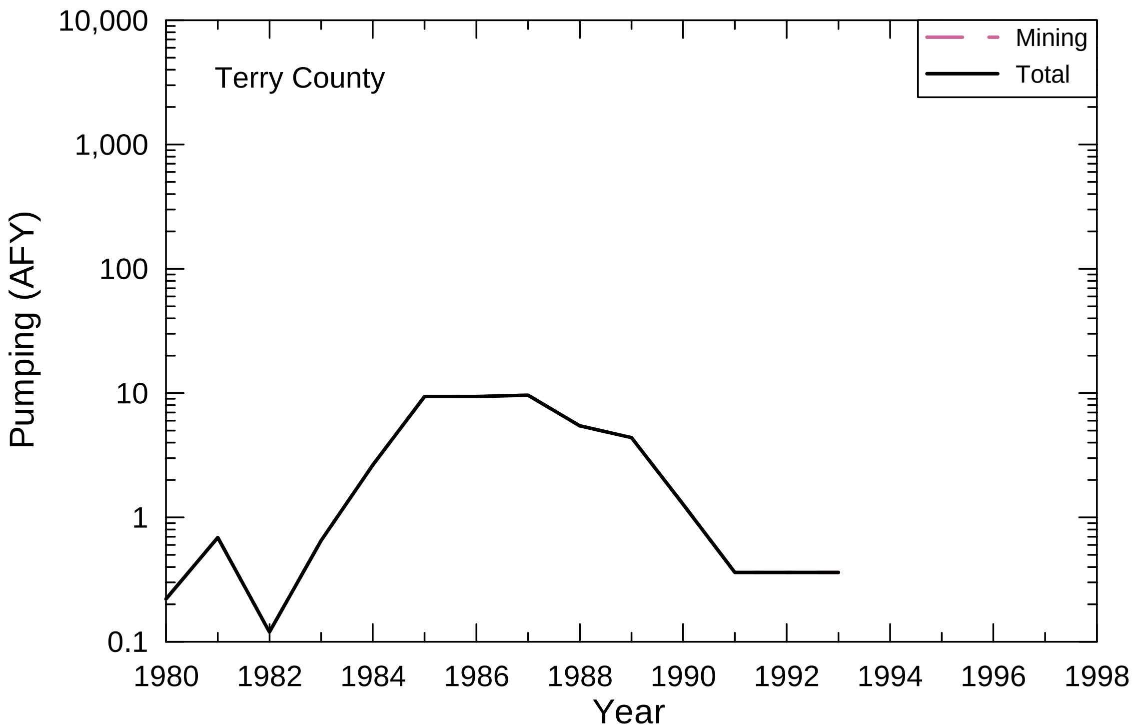


Figure 4.7.44 Groundwater withdrawals in acre-feet per year from the Dockum Aquifer for Terry County, Texas.

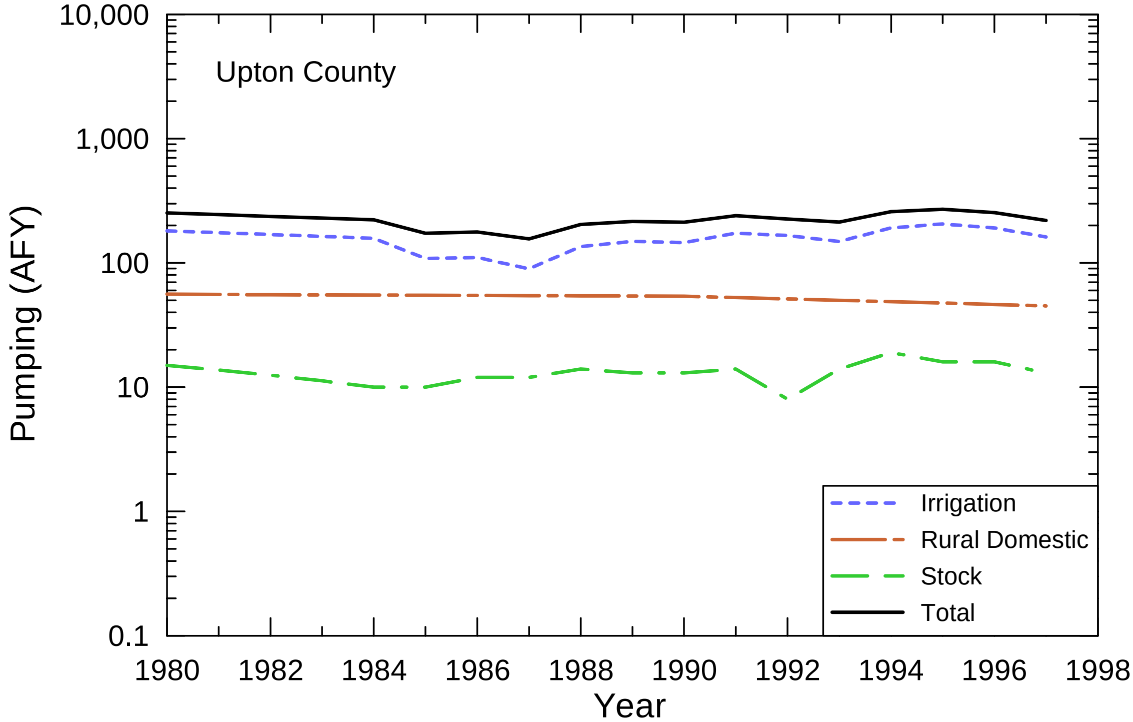


Figure 4.7.45 Groundwater withdrawals in acre-feet per year from the Dockum Aquifer for Upton County, Texas.

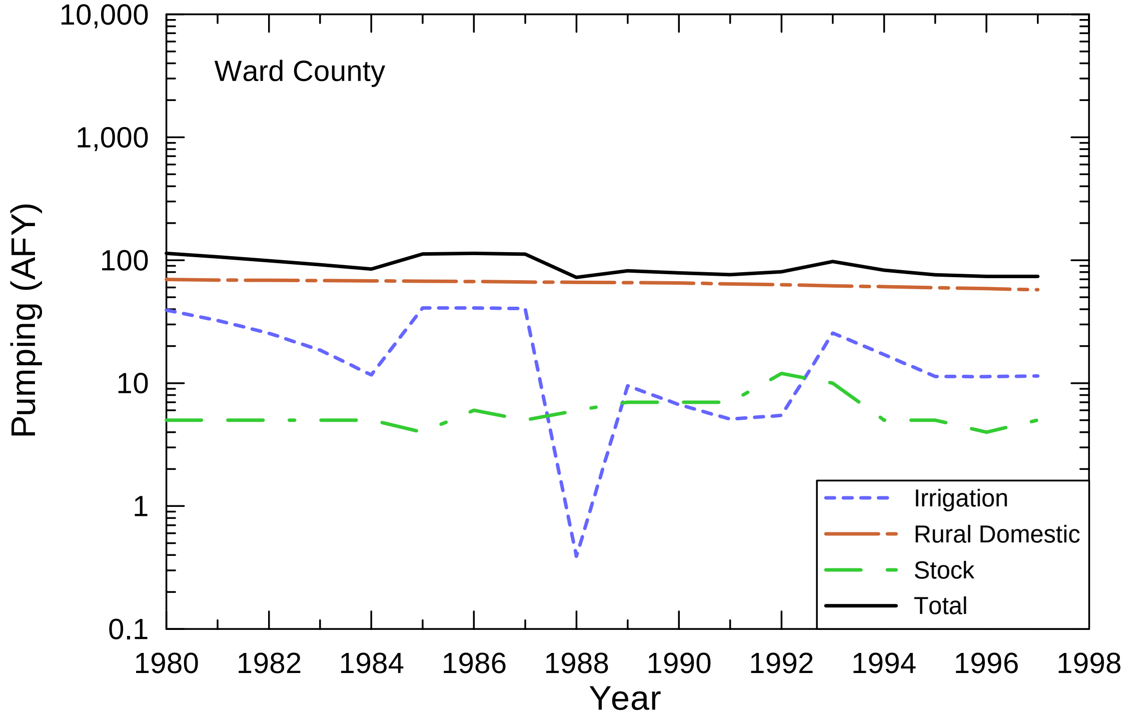


Figure 4.7.46 Groundwater withdrawals in acre-feet per year from the Dockum Aquifer for Ward County, Texas.

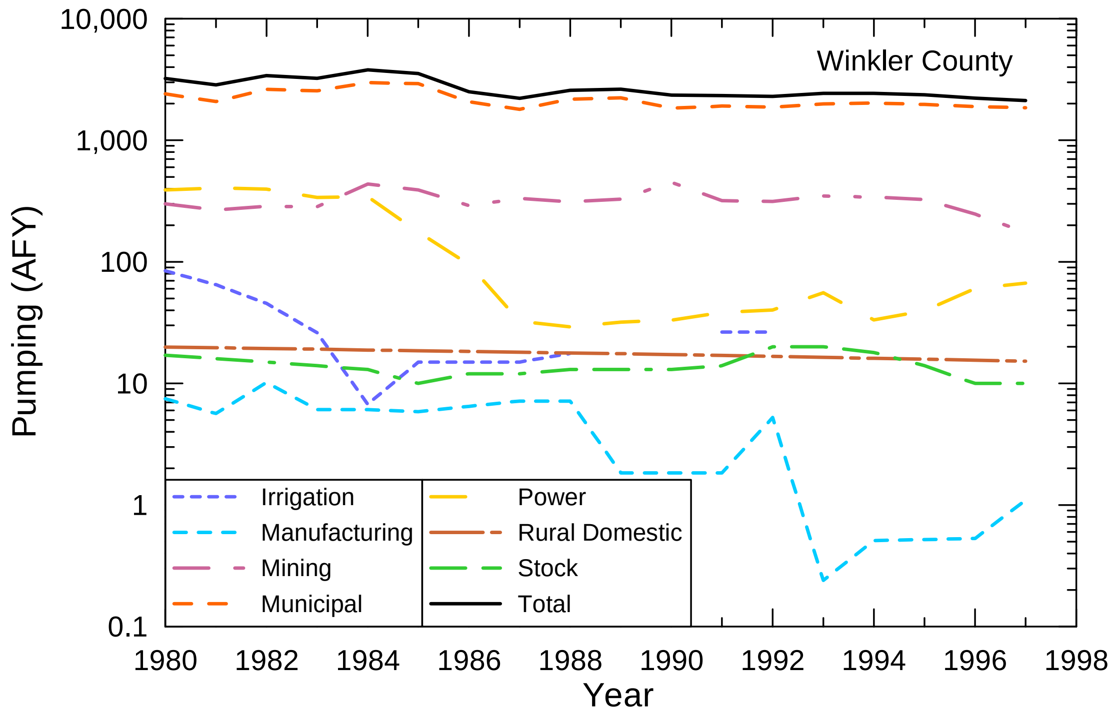


Figure 4.7.47 **Groundwater withdrawals in acre-feet per year from the Dockum Aquifer for Winkler County, Texas.**

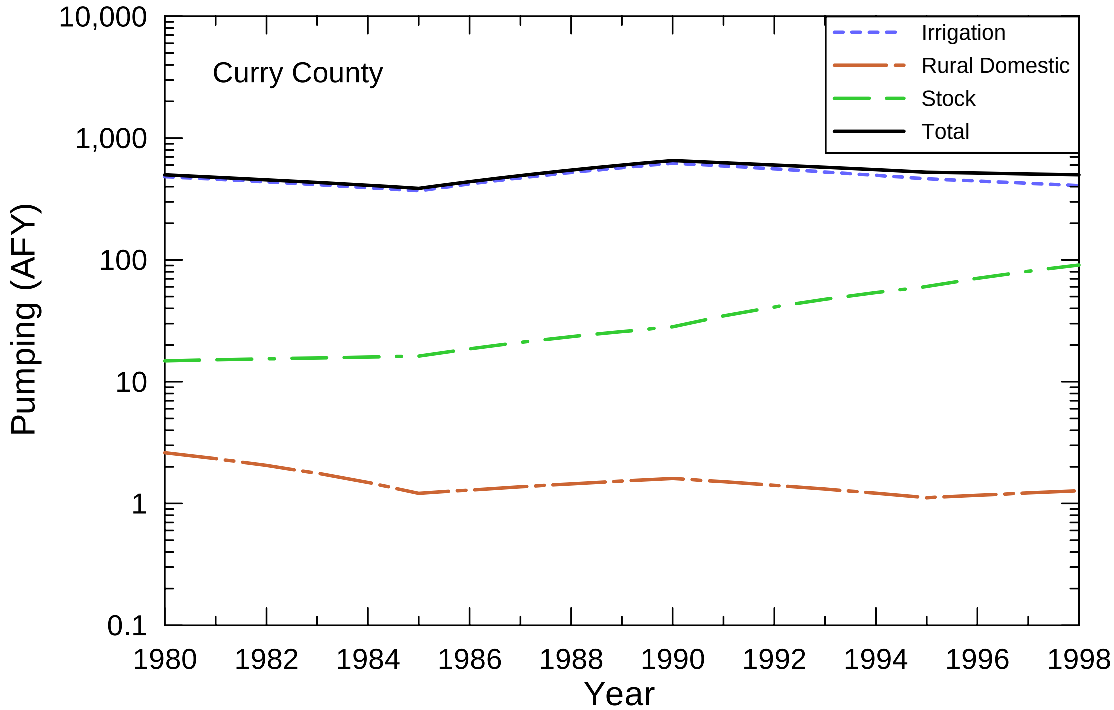


Figure 4.7.48 **Groundwater withdrawals in acre-feet per year from the Dockum Aquifer for Curry County, New Mexico.**

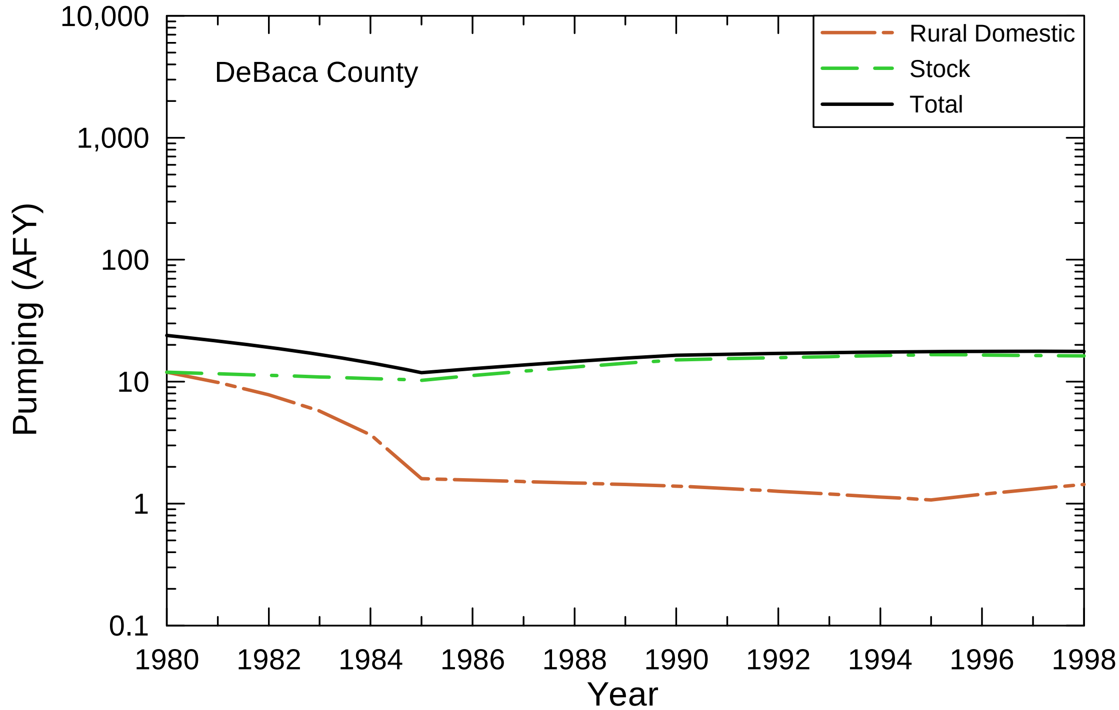


Figure 4.7.49 Groundwater withdrawals in acre-feet per year from the Dockum Aquifer for DeBaca County, New Mexico.

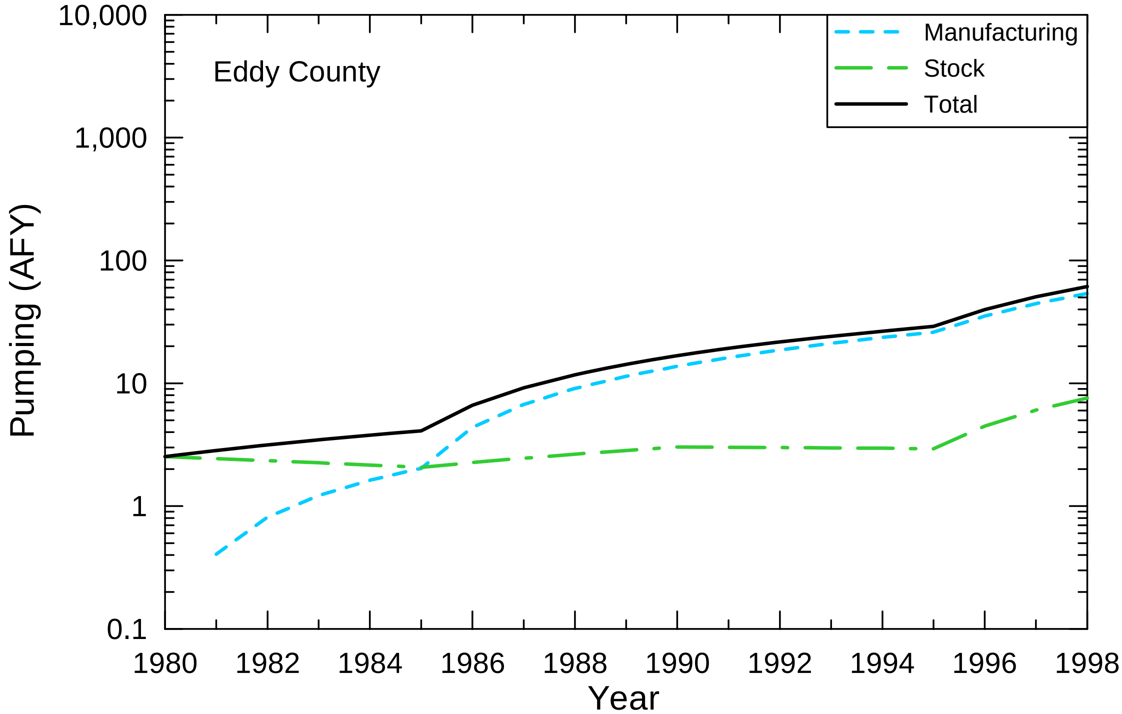


Figure 4.7.50 Groundwater withdrawals in acre-feet per year from the Dockum Aquifer for Eddy County, New Mexico.

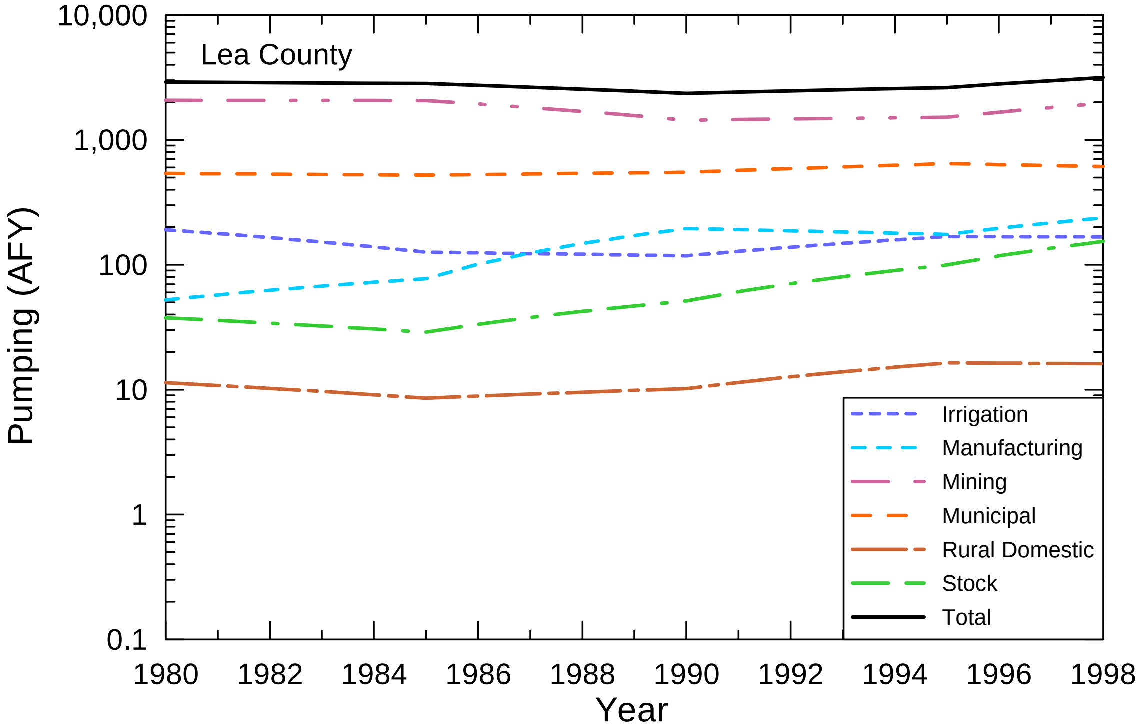


Figure 4.7.51 **Groundwater withdrawals in acre-feet per year from the Dockum Aquifer for Lea County, New Mexico.**

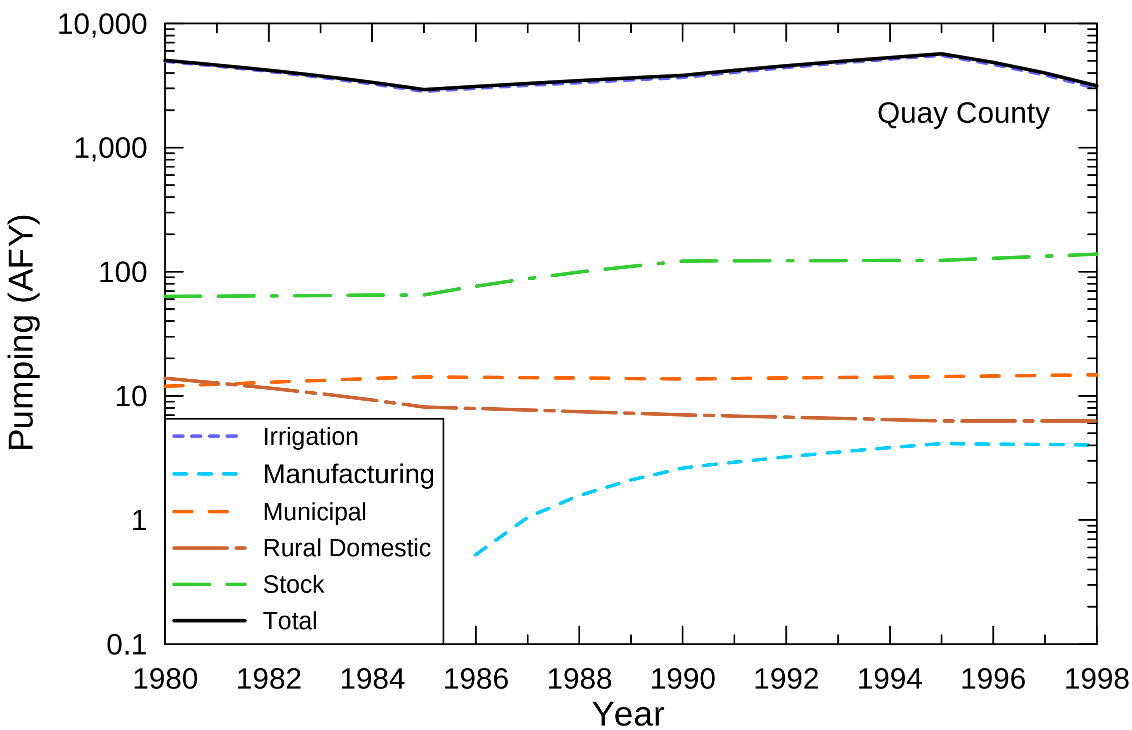


Figure 4.7.52 **Groundwater withdrawals in acre-feet per year from the Dockum Aquifer for Quay County, New Mexico.**

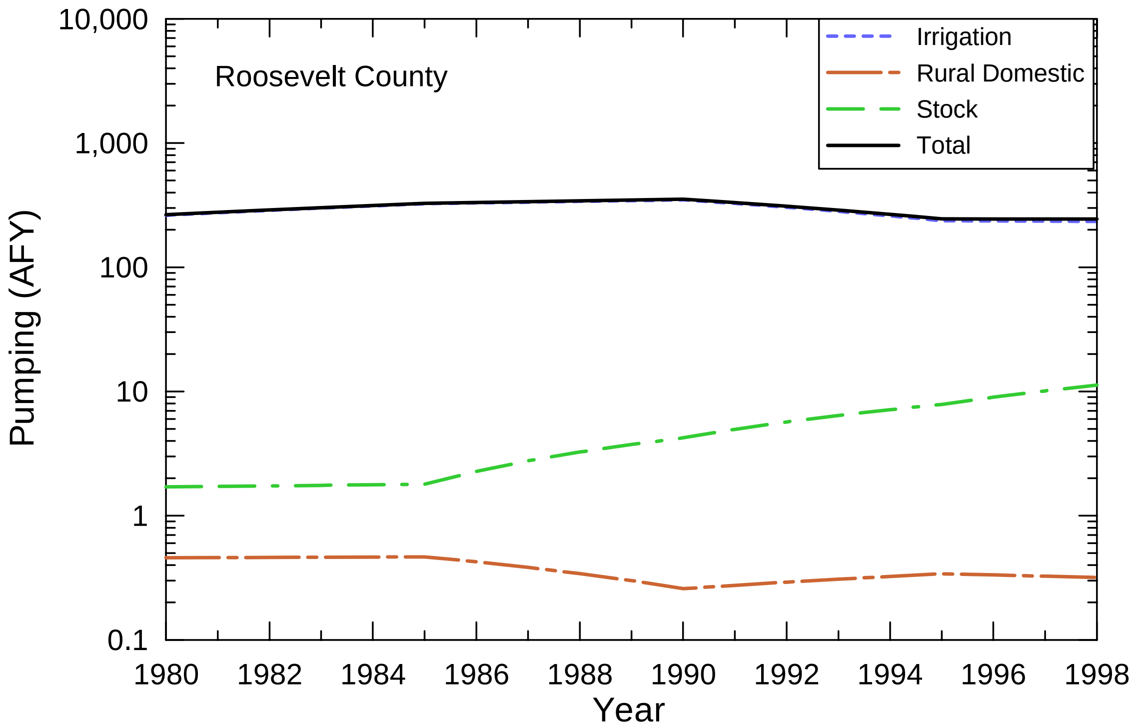


Figure 4.7.53 Groundwater withdrawals in acre-feet per year from the Dockum Aquifer for Roosevelt County, New Mexico.

4.8 Water Quality

The quality of groundwater in the Dockum Aquifer ranges from marginal to poor over a large part of its area with the best chemical quality occurring in shallow outcrop areas around the fringes of the aquifer's extent. Concentrations of total dissolved solids generally increase with depth, reaching over 50,000 milligrams per liter within the deepest part of the basin. Because of its primary uses for irrigation and human consumption, the quality of the groundwater in the Dockum Aquifer was evaluated with regard to drinking water standards and for its effect on soils and irrigated crops.

4.8.1 Previous Studies

The quality of groundwater in the Dockum Aquifer is discussed on a local basis in numerous county-level groundwater reports in Texas, New Mexico, and Oklahoma. However, on a regional basis, the quality of groundwater in the Dockum Aquifer is discussed primarily in two reports: Dutton and Simpkins (1986) and Bradley and Kalaswad (2003). McGowen and others (1977) investigated the radioactive nature of the Dockum Group. Nativ (1988) researched the vertical groundwater flow exchange between the Ogallala Aquifer and underlying Cretaceous and Triassic (Dockum) aquifers utilizing evaluation of hydrochemical facies.

In a Bureau of Economic Geology follow-up study to the McGowen and others (1977) project, Dutton and Simpkins (1986) provided the first regional assessment of the quality of groundwater in the Dockum Aquifer. Their report contains most of the water-quality data from previous local reports, including some data from New Mexico county reports. Dutton and Simpkins (1986) map the distribution of chemical facies in groundwater from the lower portion of the Dockum Aquifer and provide an explanation as to the mineral reactions that affect the chemical composition of each facies.

Bradley and Kalaswad (2003) conducted a similar assessment that included only the Texas portion of the aquifer and used additional groundwater sample analyses between 1981 and 1996. They provide tables in appendices of the range and mean values for total dissolved solids, sodium, potassium, calcium, magnesium, chloride, sulfate, bicarbonate, carbonate, percent sodium, sodium adsorption ratio, residual sodium carbonate, boron, and harness by county.

McGowen and others (1977) surveyed the Dockum Group for the occurrence of uranium. More than 400 rock samples from outcrop locations were analyzed for U_3O_8 to catalogue the occurrence of uranium with regard to facies type. The study also evaluated radioactive anomalies based on high gamma-ray values. McGowen and others (1977) concluded that "uranium occurrence and depositional facies are closely allied, but this association has been somewhat modified by a complex groundwater history." Radioactivity in groundwater in the Dockum Aquifer is further discussed in Section 4.8.3.3 below.

Nativ (1988) compared hydrochemical facies of groundwater from the Ogallala Aquifer with hydrochemical facies of groundwater from underlying, hydrologically connected Cretaceous, Triassic, and Permian aquifers. Based on those comparisons, Nativ (1988) identified areas where upward vertical flows from underlying aquifers occur to the Ogallala Aquifer.

Based on these previous studies, the predominant characteristics of the groundwater in the Dockum Aquifer include:

- salinity, in terms of total dissolved solids, generally increases with depth, ranging from less than 1,000 milligrams per liter in shallow outcrop areas around the periphery of the depositional basin to more than 50,000 milligrams per liter in the central, deeper portion of the aquifer,

- the chemical composition of groundwater in the Dockum Aquifer is derived largely from reactions of recharged groundwater with minerals,

- radiological constituents observed in groundwater in the Dockum Aquifer owe their origin to the occurrence of uranium within the aquifer, and

- hydrochemical facies that describe the dominant ion concentration of groundwater in the Dockum Aquifer change with increasing depth of the water-producing zones within the aquifer and spatially from north to south.

4.8.2 Data Sources and Methods of Analysis

The TWDB groundwater database is the primary source of water-quality data for groundwater in the Dockum Aquifer in Texas. Analyses of groundwater samples from 978 wells completed exclusively within the Dockum Aquifer are on record in the database. The Panhandle Groundwater Conservation District’s water-quality dataset consists of analyses from 37 wells completed into the Dockum Aquifer in Armstrong, Carson, and Potter counties, most of which are not in the TWDB database. Also, the Panhandle Groundwater Conservation District’s database contains 26 wells that the District classifies as Dockum Aquifer wells as opposed to the classification of Ogallala Aquifer wells in the TWDB database. Upon review, it appears that the Panhandle Groundwater Conservation District’s classification of these wells is correct (Ray Brady, personal communication). The North Plains Groundwater Conservation District's water-quality dataset contains water-chemistry data for five wells in Hartley and Moore counties; however, these data are duplicated in the TWDB database. The Texas Commission on Environmental Quality database was queried to identify municipal water suppliers producing from the Dockum Aquifer, as these locations are indicative of fresher water quality that meets safe drinking water standards.

In New Mexico, water-quality data for groundwater in the Dockum Aquifer is available in a United States Geological Survey electronic dataset containing analyses for samples of groundwater from 54 wells. These data include specific well locations. Additional water-quality data are available in New Mexico county groundwater reports (Berkstresser and Mourant, 1966; Cooper and Davis, 1967; Hendrickson and Jones, 1952; Mourant and Shomaker, 1970; Nicholson and Clebsch, 1961) and in a report on saline-water resources of New Mexico by Hood and Kister (1962). These reports provide locations as township, section, and range. Using this information, the well locations were estimated within one-half mile. Water-quality information for groundwater from the Dockum Aquifer in Oklahoma is limited to analyses from five “Triassic” wells given in Hart and others (1976). Locations of these wells were also estimated within one-half mile.

For the purpose of statistical evaluation and mapping, only the most recent sampling event for a given parameter was chosen from each well. The most recent data were used in order to assess the most current status of the quality of groundwater in the Dockum Aquifer. The datasets were also queried to evaluate samples with anomalous total dissolved solids values to insure that sampled wells are completed only into the Dockum Aquifer. Total dissolved solids data from samples with both balanced and unbalanced analyses were used because the total dissolved solids values for the unbalanced analyses were found to be within an acceptable range of total dissolved solids values for balanced analyses at locations in reasonable proximity.

Total dissolved solids data were posted and contoured using ArcView Spatial Analyst with the inverse-distance weighting method. In cases where estimated well locations were identical (mostly in New Mexico and Oklahoma), the highest total dissolved solids result was used for contouring. The gridded map was classified into five zones with nonuniform contour intervals between zero and greater than 20,000 milligrams per liter. Total dissolved solids data for the Dockum Aquifer are presented and discussed in Section 4.8.3.2.

The sodium hazard of groundwater in the Dockum Aquifer was computed to assess the potential chemical impact resulting from surface application on irrigated fields. A sodium hazard condition generally results when the sodium concentration in water is in excess of 60 percent of total cations, and is widely measured in terms of sodium adsorption ratio (United States Salinity Laboratory, 1954):

$$\text{Sodium Adsorption Ratio} = \frac{\text{Na}}{\sqrt{\frac{\text{Ca} + \text{Mg}}{2}}} \qquad (4.8.1)$$

where the sodium (Na), calcium (Ca), and magnesium (Mg) concentrations are expressed in milliequivalents per liter.

The hydrochemical nature of groundwater from the different parts of the Dockum Aquifer was evaluated using only balanced-ion water sample analyses. An acceptable charge balance was assumed to be plus or minus 10 percent. Hydrochemical facies are named for the ions that account for at least 50 percent of the total equivalent ionic concentrations. Mixed-cations and mixed-anions are analyses in which no one cation or anion is dominant.

4.8.3 Results

The following sections discuss the results of the water-quality data analysis conducted for groundwater in the Dockum Aquifer. A comparison of the chemistry of the groundwater in the Dockum Aquifer to drinking water standards is provided in the first section, a discussion of the total dissolved solids is provided in the second section, radiological constituents are discussed in the third section, the quality of groundwater in the Dockum Aquifer for irrigation purposes is discussed in the fourth section, and the hydrochemical facies of groundwater in the Dockum Aquifer are discussed in the last section.

4.8.3.1 Drinking Water Quality

Screening levels for drinking water supply are based on the maximum contaminant levels established in the Texas Administrative Code (Title 30 Chapter 290). Primary maximum contaminant levels are legally enforceable standards that apply to public water systems to protect human health from contaminants in drinking water. Secondary maximum contaminant levels are non-enforceable guidelines for drinking water contaminants that may cause aesthetic effects (taste, color, odor, and foaming), cosmetic effects (skin or tooth discoloration), and technical effects (corrosivity, expensive water treatment, plumbing fixture staining, scaling, and sediment).

Table 4.8.1 summarizes the occurrence and levels of some commonly measured groundwater quality constituents in the Dockum Aquifer. The percentage of samples exceeding the primary or secondary maximum contaminant level is greater than 10 percent for chloride, fluoride, iron, manganese, sulfate, total dissolved solids, and alpha activity.

Fluoride is a naturally-occurring element found in most rocks. At very low concentrations, fluoride is a beneficial nutrient. At a concentration of 1 milligram per liter, fluoride helps to prevent dental cavities. However, at concentrations above the secondary maximum contaminant level of 2 milligrams per liter, fluoride can stain children's teeth. Groundwater in approximately 30 percent of the sampled wells have exceeded this level. At concentrations above the primary maximum contaminant level of 4 milligrams per liter, fluoride can cause a type of bone disease. Groundwater in about 4 percent of the sampled wells exceed the primary maximum contaminant level for fluoride.

Elevated levels of iron and manganese adversely impact the quality of groundwater in approximately 27 and 16 percent, respectively, of the sampled wells. Water containing iron and manganese in excess of the secondary maximum contaminant level of 0.3 and 0.05 milligram per liter, respectively, may cause reddish-brown or blackish-gray stains on laundry, utensils, and plumbing fixtures, as well as color, taste, and odor problems.

4.8.3.2 Total Dissolved Solids

Total dissolved solids, a measure of water saltiness, is the sum of concentrations of all dissolved ions (such as sodium, calcium, magnesium, potassium, chloride, sulfate, carbonates) plus silica. Some dissolved solids, such as calcium, give water a pleasant taste, but most make water taste salty, bitter, or metallic. Dissolved solids can also increase the corrosiveness of water. The total dissolved solids level has exceeded the Texas secondary maximum contaminant level of 1,000 milligrams per liter in the groundwater in approximately 43 percent of the sampled wells (Figure 4.8.1). Concentrations of sulfate and chloride, major components of total dissolved solids, have exceeded the secondary maximum contaminant level in the groundwater in 41 and 30 percent, respectively, of the sampled wells.

Figure 4.8.1 shows that the total dissolved solids in groundwater in the Dockum Aquifer generally increases with depth toward the center of the depositional basin. Groundwater in the Dockum Aquifer that is sufficiently fresh (less than 1,000 milligrams per liter total dissolved solids) to meet safe-drinking water standards is limited to the shallower areas near and on the outcrop of the Dockum Aquifer. Table 4.8.2, which provides the range and average total dissolved solids concentration for groundwater in the Dockum Aquifer by county, shows that the minimum total dissolved solids concentration exceeds the secondary maximum contaminant level of 1,000 milligrams per liter in 20 of the 56 counties where total dissolved solids has been measured and the average total dissolved solids concentration exceeds the maximum contaminant level in 39 counties. Total dissolved solids concentrations over 20,000 milligrams per liter have been measured in seven counties in the central portion of the model region. The highest measured total dissolved solids concentrations for groundwater in the Dockum Aquifer are reported for Borden (69,170 milligrams per liter), Hockley (59,292 milligrams per liter), Garza (50,784 milligrams per liter), and Reagan (44,715 milligrams per liter) counties.

The location of the 5,000 milligrams per liter total dissolved solids limit published by the TWDB is very similar to the location determined from this analysis with a few minor exceptions. In small portions of Borden, Castro, Crane, Crosby, Glasscock, Hale, Howard, Martin, Midland, Parmer, Reagan, and Upton counties, the current analysis shows total dissolved solids concentrations in groundwater in the Dockum Aquifer lower than 5,000 milligrams per liter rather than higher as indicated by the aquifer limit given in Ashworth and Hopkins (1995). In small portions of Andrews, Crosby, Gaines, Irion, Martin, Reagan, and Swisher counties, the current analysis shows total dissolved solids concentrations in groundwater in the Dockum Aquifer higher than 5,000 milligrams per liter rather than lower as indicated by the aquifer limit given in Ashworth and Hopkins (1995).

4.8.3.3 Radiological Constituents

Bradley and Kalaswad (2003) state that the radiological constituents observed in groundwater in the Dockum Aquifer owe their origin to the occurrence of uranium within the aquifer and reference McGowen and others (1977) as the basis for this conclusion. McGowen and others (1977) found that uranium occurs in the Dockum Group in amounts ranging from a few parts per million to several hundred parts per million. They theorize that original sources of uranium are possibly granitic rocks of Oklahoma, Triassic volcanic rocks in Mexico and Texas, and volcanic ash contained in the Ogallala Formation. These original sources of uranium would have been oxidized, mobilized, transported by groundwater systems, and re-precipitated under reducing conditions in successively more basinward positions (McGowen and others, 1977). The study by McGowen and others (1977) suggests that the areal distribution of radioactive anomalies within the upper portion of the Dockum Group appears to be very uniform except around the margins, while the distribution of radioactive anomalies in the lower portion of the Dockum Group is not uniform. Alpha particles are one type of naturally occurring radionuclide that, at higher levels, are known to cause cancer. Figure 4.8.2 posts the alpha particle concentrations for groundwater in the Dockum Aquifer as determined by the current analysis as greater than the primary maximum contaminant level of 15 picoCuries per liter or as less than the primary maximum contaminant level. Table 4.8.1 shows that groundwater in 20 percent of the sampled wells had an alpha activity greater than the maximum contaminant level.

4.8.3.4 Irrigation Water Quality

The utility of groundwater from the Dockum Aquifer for crop irrigation was evaluated based on its salinity hazard, sodium hazard, and concentrations of boron and chloride. Saline irrigation waters limit the ability of plants to take up water from soils. Various crops differ in their tolerance of high salinity. Salinity is often measured by the total dissolved solids content or the electrical conductivity of the water. The salinity hazard classification system of the United States Salinity Laboratory (1954) indicates that waters with electrical conductivity over

750 micromhos present a high salinity hazard, and those with electrical conductivity over 2,250 micromhos present a very high salinity hazard. Of the wells in the Dockum Aquifer with chemical analyses, groundwater from 75 percent have exhibited a high salinity hazard and 33 percent have exhibited a very high salinity hazard (see Table 4.8.1).

Groundwater in the Dockum Aquifer commonly has a high percent sodium concentration, which results in a sodium hazard condition that is damaging to irrigated land in terms of soil cultivation and permeability. Dutton and Simpkins (1986) calculated sodium adsorption ratio for groundwater in the Dockum Aquifer and found the highest mean values (greater than 18) to occur in Borden, Deaf Smith, Ector, Garza, and Swisher counties in Texas and Lea, Quay, and Union counties in New Mexico. Bradley and Kalaswad (2003) found that sodium adsorption ratio values for groundwater samples from the central part of the Dockum Aquifer were generally higher than 18. The sodium hazard (sodium adsorption ratio) of groundwater in the Dockum Aquifer calculated by the current analysis is in good agreement with the above studies as shown in Figure 4.8.3. Table 4.8.3 summarizes the number and percentage of groundwater samples falling within the low, medium, high, and very high sodium adsorption ratio ranges as defined by the United States Salinity Laboratory (1954).

Other elements potentially toxic to crops at higher concentrations include boron and chloride. Boron may cause toxicity to many plants at levels above 2 milligrams per liter (Van der Leeden and others, 1990). Lemon and McFarland (2002) report lower peanut yields with boron concentrations above 0.75 milligrams per liter. Boron levels in groundwater in the Dockum Aquifer have exceeded 0.75 milligrams per liter in approximately 25 percent of the sampled wells and have exceeded 2 milligrams per liter in approximately 3 percent of the sampled wells (see Table 4.8.1). A post plot of boron concentration is provided in Figure 4.8.4.

Most crops cannot tolerate chloride levels above 1,000 milligrams per liter for an extended period of time (Tanji, 1990). Groundwater in about 15 percent of the sampled wells have a chloride concentration greater than 1,000 milligrams per liter (see Table 4.8.1). A post plot of chloride concentrations is provided in Figure 4.8.5. This figure shows locations where the chloride concentration in groundwater in the Dockum Aquifer is less than the secondary maximum contaminant level of 300 milligrams per liter, between the secondary maximum contaminant level and 1,000 milligrams per liter, and greater than 1,000 milligrams per liter.

4.8.3.5 Hydrochemical Facies

Groundwater in the Dockum Aquifer appears to be meteoric in origin and not isotopically (O/H and $^{18}O/^{16}O$ ratios) altered by exchange with rocks or by mixing with nonmeteoric water (Dutton and Simpkins, 1986). Based on differences in the chemistry of groundwater in the Ogallala and Dockum aquifers, Dutton and Simpkins (1986) suggest that groundwater in the Dockum Aquifer was recharged by precipitation during the Pleistocene at elevations of 6,000 feet to greater than 7,000 feet in Dockum Group sandstones along their original western extent. Because of this meteoric origin, reactions with minerals affect its chemical composition. Dutton and Simpkins (1986) state that the "chemical composition of Dockum Group groundwater is controlled by reactions with Dockum Group minerals, including calcite, chalcedony, dolomite, feldspar, kaolinite, opal, pyrite, and smectite."

The hydrochemical facies was determined for groundwater from 891 wells completed into the Dockum Aquifer. This analysis determined 14 different hydrochemical facies for groundwater in the Dockum Aquifer. Table 4.8.4 summarizes the percent of wells with groundwater of each hydrochemical facies.

The distribution of hydrochemical facies for groundwater in the Dockum Aquifer is shown in Figure 4.8.6. Note that only the eight hydrochemical facies found in groundwater in over 10 percent of the wells are shown separately in this figure. All other hydrochemical facies are plotted together under the distinction 'other'. The distribution shown in Figure 4.8.6 generally agrees, although with some divergence, with the facies analysis provided in Dutton and Simpkins (1986) and Bradley and Kalaswad (2003). Table 4.8.5 summarizes the distribution of hydrochemical facies in the Dockum Aquifer determined by the current analysis.

Table 4.8.1 Occurrence and levels of some commonly-measured groundwater quality constituents in the Dockum Aquifer.

Constituent	Type of Standard	Screening Level	Units	Number of Results	Number of Results Exceeding Screening Level	Percent of Results Exceeding Screening Level	Number of Results < Reporting Limit > Maximum Contaminant Level
Alpha Activity	Primary maximum contaminant level[1]	15	pCi/L	262	52	20%	6
Antimony	Primary maximum contaminant level[1]	6	µg/L	254	0	0%	11
Arsenic	Primary maximum contaminant level[1]	10	µg/L	305	13	4%	8
Barium	Primary maximum contaminant level[1]	2000	µg/L	308	1	0%	0
Beryllium	Primary maximum contaminant level[1]	4	µg/L	254	0	0%	16
Cadmium	Primary maximum contaminant level[1]	5	µg/L	307	0	0%	62
Chromium	Primary maximum contaminant level[1]	100	µg/L	303	0	0%	0
Fluoride	Primary maximum contaminant level[1]	4	mg/L	840	31	4%	0
Mercury	Primary maximum contaminant level[1]	2	µg/L	198	3	2%	0
Nitrate	Primary maximum contaminant level[1]	10	mg/L as N	896	92	10%	0
Nitrite	Primary maximum contaminant level[1]	1	mg/L as N	129	0	0%	0
Selenium	Primary maximum contaminant level[1]	50	µg/L	305	15	5%	3
Thallium	Primary maximum contaminant level[1]	2	µg/L	254	0	0%	20
Copper	Action Level[1]	1300	µg/L	305	1	0%	0
Lead	Action Level[1]	15	µg/L	304	0	0%	56
pH	Secondary maximum contaminant level[1] (lower bound)	7	-	882	75	9%	0
Aluminum	Secondary maximum contaminant level[1]	200	µg/L	320	3	1%	3
Chloride	Secondary maximum contaminant level[1]	300	mg/L	1,000	302	30%	0
Copper	Secondary maximum contaminant level[1]	1000	µg/L	305	1	0%	0
Fluoride	Secondary maximum contaminant level[1]	2	mg/L	840	249	30%	0

Table 4.8.1, continued

Constituent	Type of Standard	Screening Level	Units	Number of Results	Number of Results Exceeding Screening Level	Percent of Results Exceeding Screening Level	Number of Results < Reporting Limit > Maximum Contaminant Level
Iron	Secondary maximum contaminant level[1]	300	µg/L	337	92	27%	3
Manganese	Secondary maximum contaminant level[1]	50	µg/L	328	52	16%	0
Silver	Secondary maximum contaminant level[1]	100	µg/L	211	0	0%	0
Sulfate	Secondary maximum contaminant level[1]	300	mg/L	1,000	414	41%	0
total dissolved solids	Secondary maximum contaminant level[1]	1000	mg/L	959	411	43%	0
Zinc	Secondary maximum contaminant level[1]	5000	µg/L	326	0	0%	0
Specific Conductance	Irrig. Salinity Hazard - High[2]	750	µmhos/cm	848	632	75%	0
Specific Conductance	Irrig. Salinity Hazard - Very High[2]	2250	µmhos/cm	848	276	33%	0
Boron	Irrig. Peanut Hazard[3]	0.75	mg/L	400	100	25%	6
Boron	Irrig. General Hazard[4]	2	mg/L	400	13	3%	6
Chloride	Irrig. Hazard[5]	1000	mg/L	1,000	151	15%	0

[1] 30 Texas Administrative Code Chapter 290 Subchapter F
[2] United States Salinity Laboratory (1954)
[3] Lemon and McFarland (2002)
[4] Van der Leeden and others (1990)
[5] Tanji (1990)

pCi/L = picoCuries per liter
µg/L = micrograms per liter
mg/L = milligrams per liter
µmhos/cm = micromhos per centimeter

Table 4.8.2 Range and average total dissolved solids concentration of Dockum Aquifer groundwater.

County	Number of Analyses	Maximum Total Dissolved Solids (mg/L)	Minimum Total Dissolved Solids (mg/L)	Average Total Dissolved Solids (mg/L)
Andrews	30	24,346	1,554	3,656
Armstrong	11	1,649	280	485
Bailey	0			
Borden	20	69,170	518	8,720
Briscoe	11	2,397	387	759
Carson	0			
Castro	1	25,263	25,263	25,263
Chaves - New Mexico	3	38,400	3,840	18,747
Cimarron - Oklahoma	3	784	384	580
Cochran	1	19,457	19,457	19,457
Coke	0			
Colfax - New Mexico	0			
Crane	14	7,642	364	2,838
Crockett	3	2,315	1,152	1,840
Crosby	9	1,528	351	683
Curry - New Mexico	0			
Dallam	0			
Dawson	10	10,136	3,663	5,855
DeBaca - New Mexico	57	4,760	351	1,196
Deaf Smith	30	2,231	263	861
Dickens	18	1,200	284	560
Ector	8	5,665	1,676	2,624
Eddy - New Mexico	10	3,340	512	1,868
Fisher	9	2,622	393	1,222
Floyd	24	948	209	390
Gaines	12	11,962	2,241	6,962
Garza	20	50,784	321	22,239
Glasscock	4	11,392	8,812	10,349
Guadalupe - New Mexico	2	2,420	1,640	2,030
Hale	0			
Harding - New Mexico	3	3,060	367	1,357
Hartley	5	553	212	332
Hockley	2	59,292	33,920	46,606
Howard	44	5,704	377	2,610
Irion	2	1,536	420	978
Kent	4	2,363	885	1,589
Lamb	0			
Lea - New Mexico	6	1,950	426	1,090
Loving	19	5,291	290	1,572
Lubbock	0			
Lynn	0			
Martin	2	3,094	2,805	2,950
Midland	5	12,203	3,023	7,848
Mitchell	196	17,007	246	1,799

Table 4.8.2, continued

County	Number of Analyses	Maximum Total Dissolved Solids (mg/L)	Minimum Total Dissolved Solids (mg/L)	Average Total Dissolved Solids (mg/L)
Moore	2	671	305	488
Motley	28	1,142	221	448
Nolan	55	2,285	185	590
Oldham	40	3,802	209	851
Parmer	0			
Pecos	1	2,293	2,293	2,293
Potter	63	8,195	123	1,009
Quay - New Mexico	18	4,910	531	1,788
Randall	24	4,185	305	904
Reagan	4	44,715	1,532	12,585
Reeves	26	3,433	470	1,026
Roosevelt - New Mexico	2	8,260	6,560	7,410
San Miguel - New Mexico	4	2,220	1,100	1,460
Scurry	105	16,192	286	1,359
Sherman	0			
Sterling	9	1,351	195	424
Swisher	7	13,095	762	2,638
Terry	4	13,164	7,317	9,732
Texas - Oklahoma	2	387	375	381
Tom Green	0			
Union - New Mexico	2	2,670	1,070	1,870
Upton	20	14,996	792	4,245
Ward	21	4,819	285	1,184
Winkler	36	4,366	145	804
Yoakum	1	9,232	9,232	9,232

mg/L = milligrams per liter

Table 4.8.3 Sodium hazard (sodium adsorption ratio) for groundwater samples from the Dockum Aquifer.

Classification	Value Range	Number of Samples	Percentage of Samples
low	less than 10	661	71
medium	10 to 18	43	5
high	18 to 26	32	3
very high	greater than 26	193	21

Table 4.8.4 Hydrochemical facies for groundwater in the Dockum Aquifer.

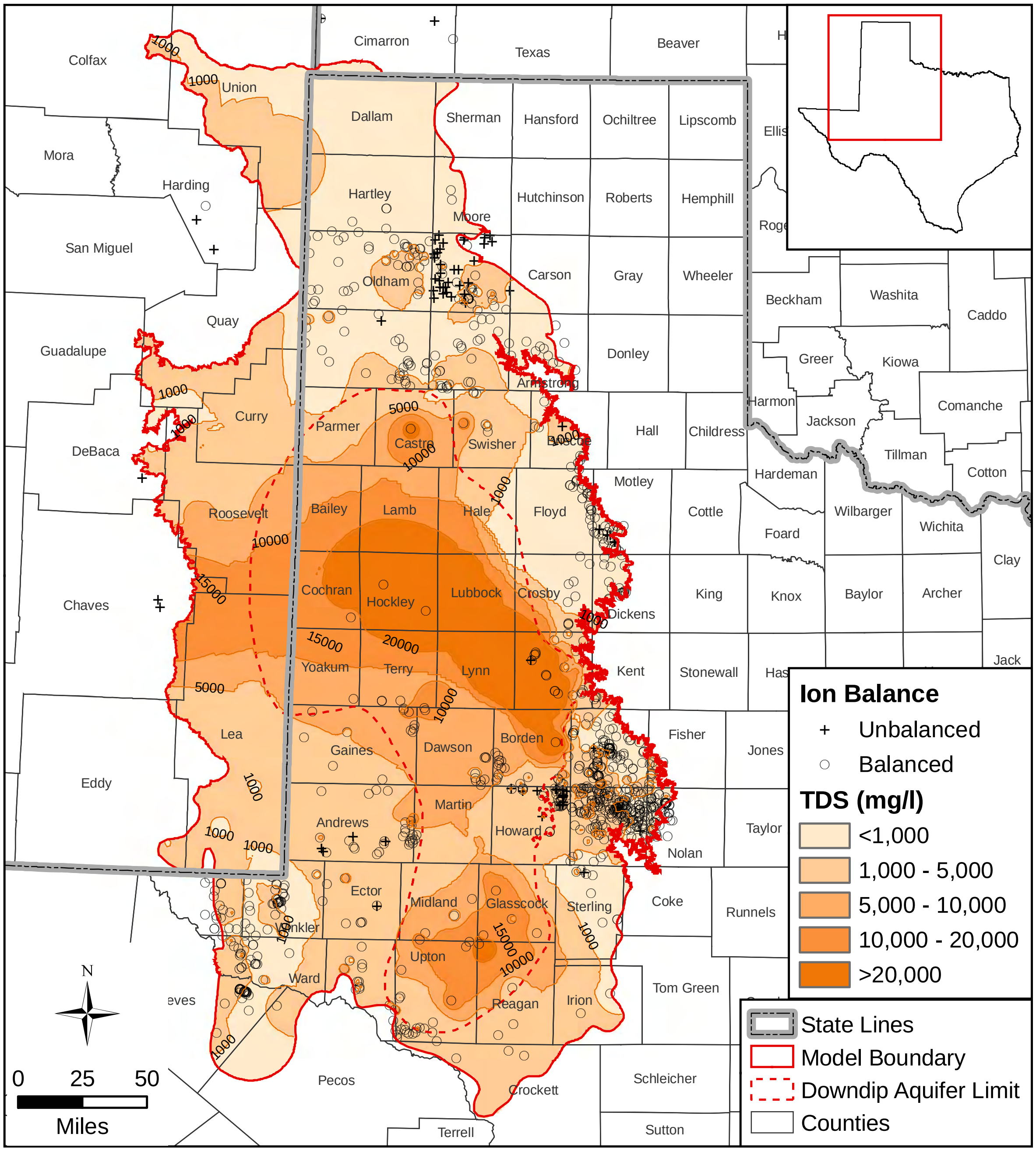
Hydrochemical Facies	Number of Wells	Percentage of Wells
Ca – Cl	17	1.9
Ca – HCO_3	78	8.8
Ca – Mixed anon	32	3.6
Ca – SO_4	23	2.6
Mg – HCO_3	6	0.7
Mg – Mixed anion	1	0.1
Mixed cation – Cl	23	2.6
Mixed cation – HCO_3	150	16.9
Mixed cation – Mixed anion	101	11.3
Mixed cation – SO_4	76	8.5
Na – Cl	104	11.7
Na – HCO_3	98	11.0
Na – Mixed anion	127	14.3
Na – SO_4	54	6.1

Ca = calcium Mg = magnesium SO_4 = sulfate HCO_3 = bicarbonate
Cl = chloride Na = sodium

Table 4.8.5 Geographical distribution of water types in the Dockum Aquifer.

Area	Water Quality	Predominant Hydrochemical Facies
Northern	Fresh to brackish	Mixed cation – HCO_3, Na – HCO_3, and Na – mixed anion
Eastern Escarpment	Fresh to brackish	Ca – HCO_3, Mixed cation – HCO_3, and Na – HCO_3
Colorado Outcrop	Fresh to brackish	Ca – HCO_3, Mixed cation – HCO_3, Mixed cation – Mixed anion, Na – Cl, Na – HCO_3, and Na – Mixed anion
Southeastern	Saline	Mixed cation – HCO_3, Mixed cation – SO_4, and Na – mixed anion
Downdip of Downdip Aquifer Limit and Gaines and Andrews counties	Saline	Na – Cl, Na – Mixed anion, and Na – SO_4
Southwestern	Fresh to brackish	Mixed cation – Mixed anion, Na –Mixed anion, and other

Ca = calcium Mg = magnesium SO_4 = sulfate HCO_3 = bicarbonate
Cl = chloride Na = sodium



Source: TWDB, Panhandle GCD; USGS/New Mexico; Hart and others (1976)

Figure 4.8.1 Total dissolved solids concentrations in milligrams per liter in groundwater in the Dockum Aquifer.

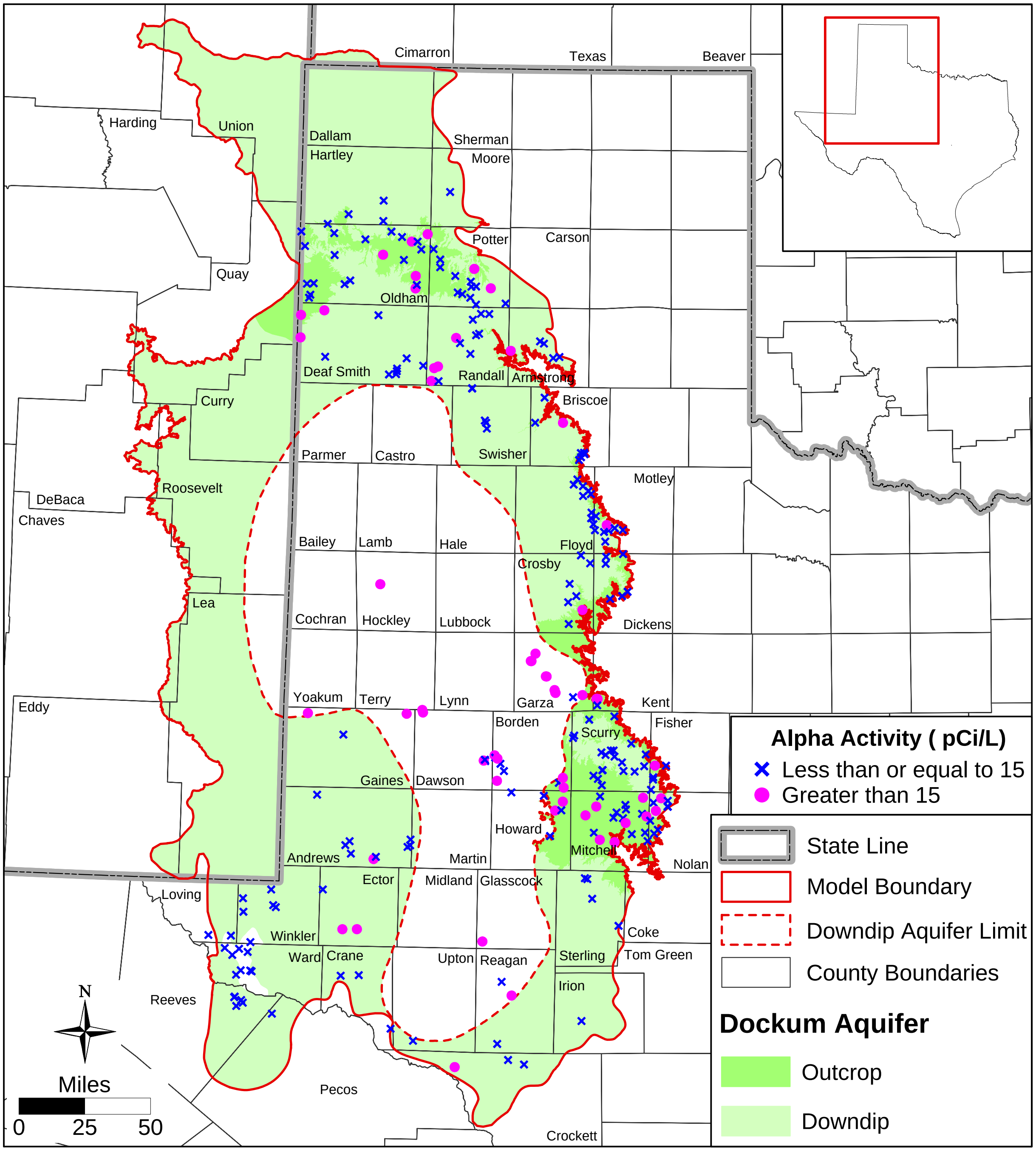


Figure 4.8.2 **Alpha activity in picoCuries per liter in groundwater in the Dockum Aquifer.**

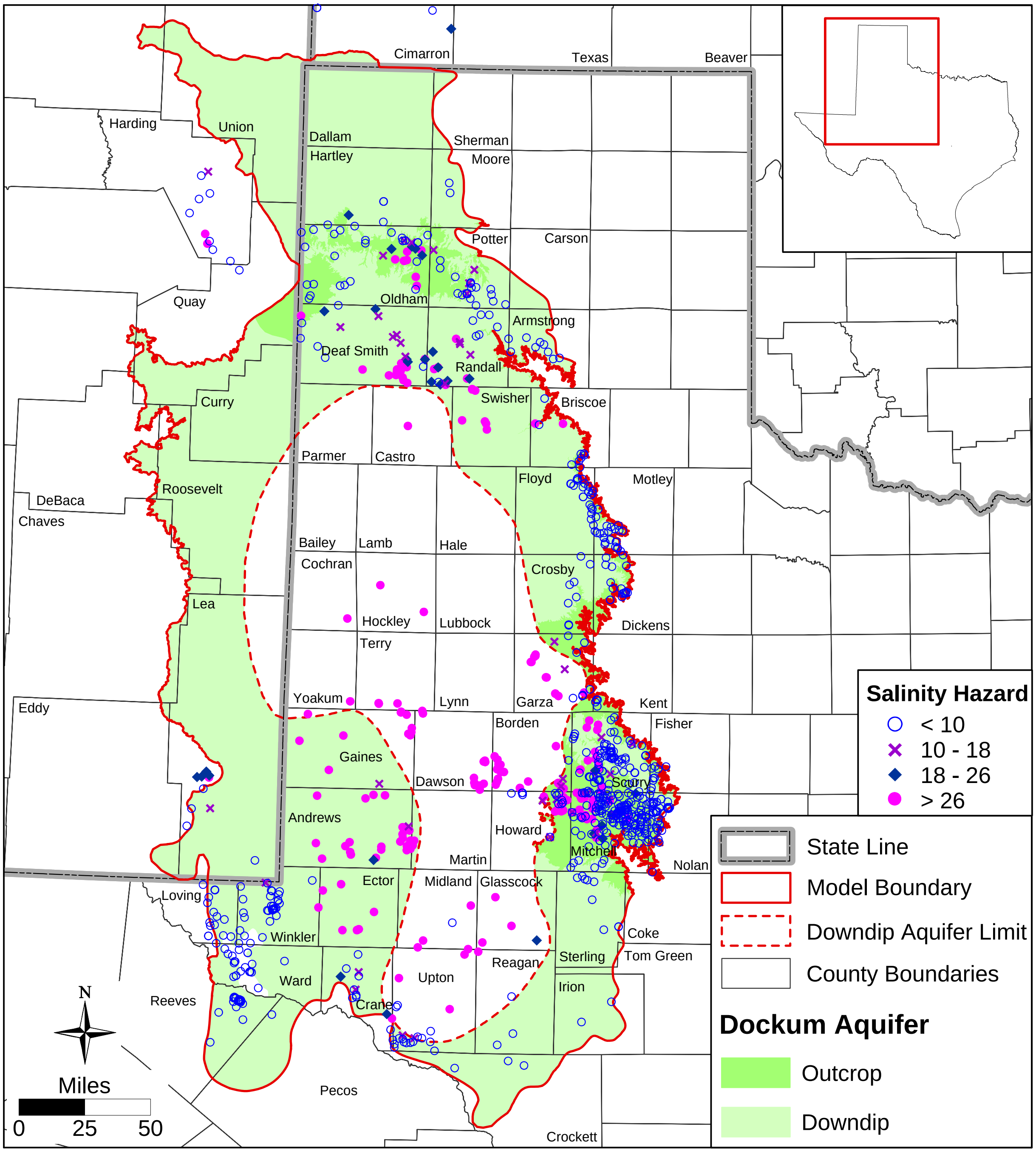


Figure 4.8.3 Salinity hazard (sodium adsorption ratio) in groundwater in the Dockum Aquifer.

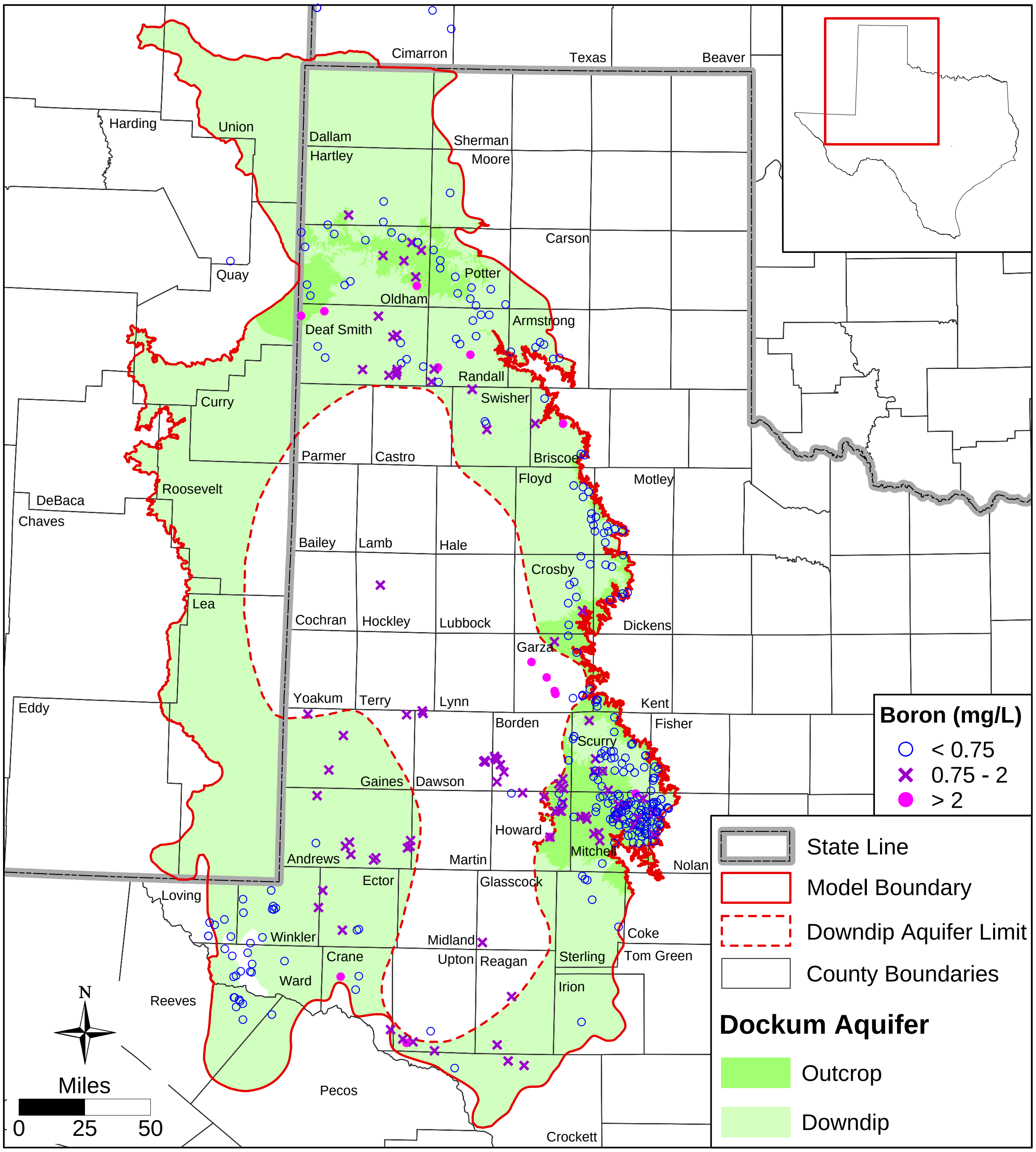


Figure 4.8.4 Boron concentrations in milligrams per liter in groundwater in the Dockum Aquifer.

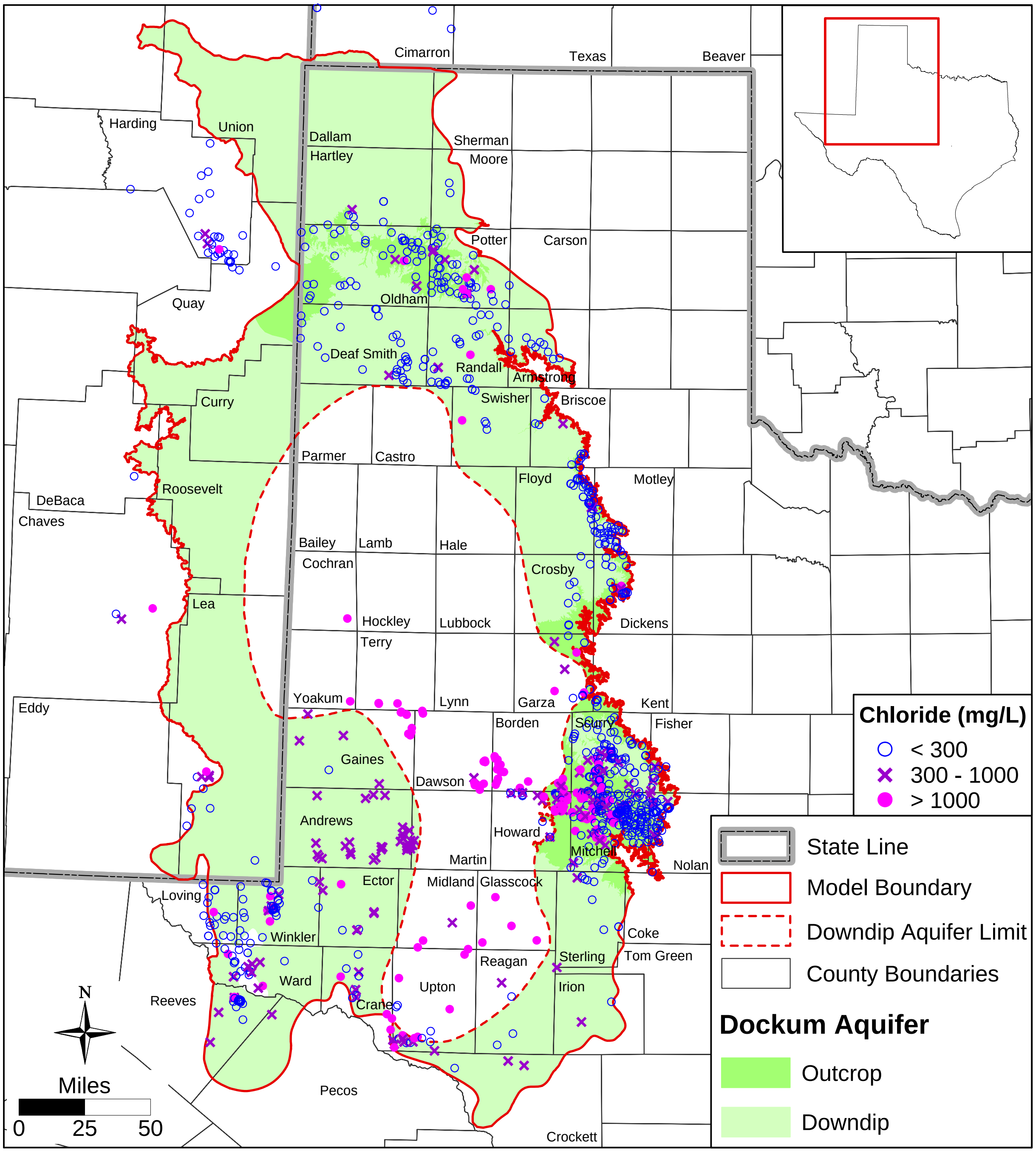


Figure 4.8.5 **Chloride concentrations in milligrams per liter in groundwater in the Dockum Aquifer.**

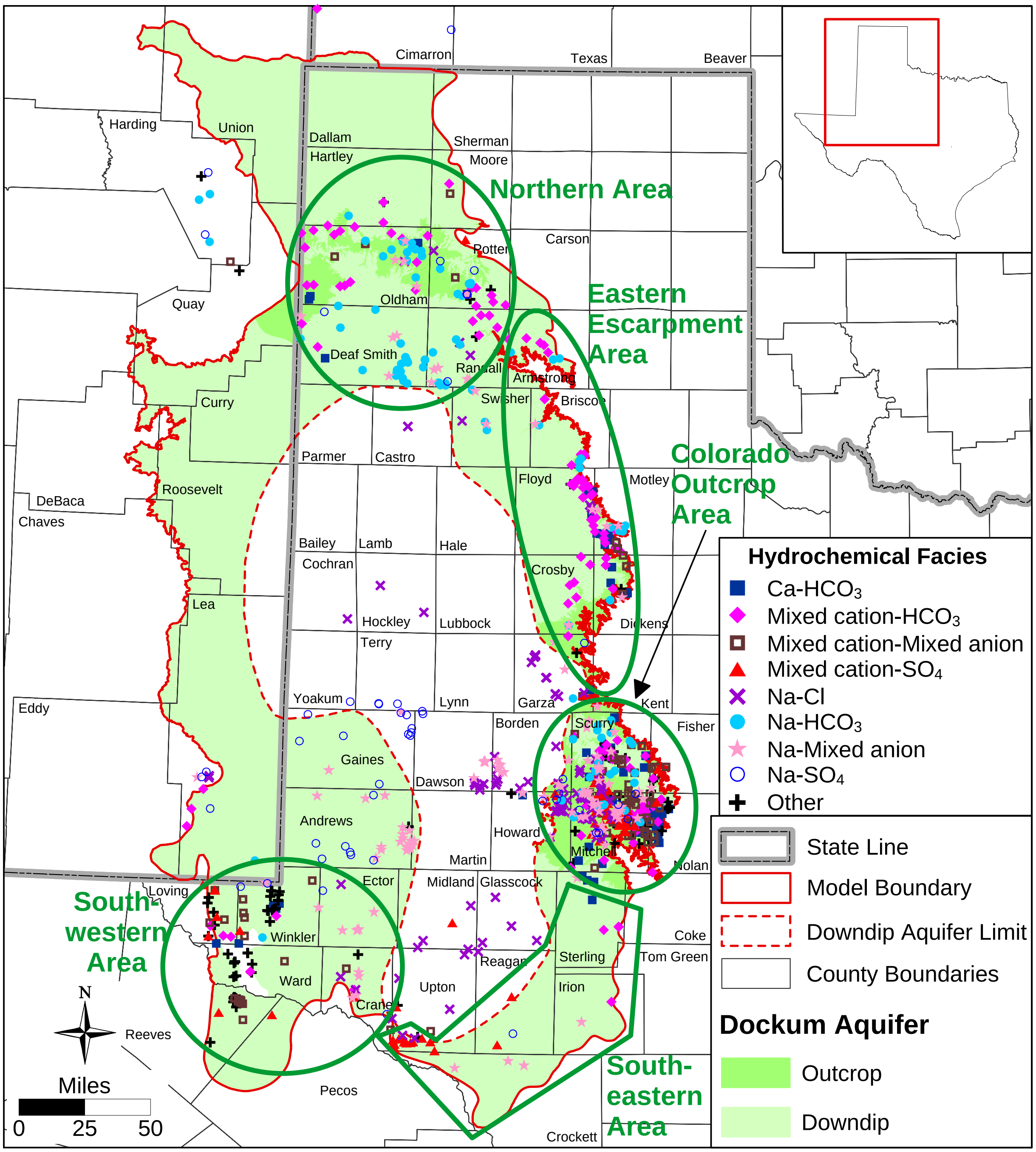


Figure 4.8.6 Hydrochemical facies of groundwater in the Dockum Aquifer.

5.0 Conceptual Model of Groundwater Flow for the Dockum Aquifer Groundwater Availability Model

The conceptual model for groundwater flow in the Dockum Aquifer is based on the hydrogeologic setting described in Section 4. The conceptual model is a simplified representation of the hydrogeological features that govern groundwater flow in the aquifer. These include the hydrostratigraphy, hydraulic properties, hydraulic boundaries, recharge and natural discharge, and anthropogenic stresses such as pumping. Each of the elements of the conceptual model are described below. The schematic diagram in Figure 5.0.1 for a northwest-to-southeast cross-section through the active model area depicts a simplified conceptualization of the hydrogeologic model describing groundwater flow in the Dockum Aquifer.

The conceptual model for the Dockum Aquifer groundwater availability model defines three layers: the younger units overlying the Dockum Aquifer, the upper portion of the Dockum Aquifer, and the lower portion of the Dockum Aquifer (Figure 5.0.1). Except in its outcrop area, the Dockum Aquifer is overlain by the Ogallala, Rita Blanca, Edwards-Trinity (High Plains), Pecos Valley, or Edwards-Trinity (Plateau) aquifers (Figure 4.1.1). Vertical flow between the Dockum Aquifer and overlying aquifers was established by defining general-head boundary conditions within the layer representing the Ogallala and younger units. In the outcrop areas, the Dockum Aquifer comprises the shallow water-table system, which was actively modeled. Interaction between the upper and lower portions of the Dockum Aquifer occurs via cross-formational flow. The Dockum Aquifer is underlain everywhere by Permian-age sediments. Vertical flow between the Dockum Aquifer and the underlying Permian was assumed to be negligible and a no-flow boundary was set at the base of the Dockum Aquifer.

The decision to use an additional model layer to account for the impacts of the overlying younger aquifers rather then using general-head boundary conditions within the model layers representing the Dockum Aquifer was made for several reasons. By including the uppermost layer, the simulated head in that layer is constrained by the physics governing groundwater flow. In contrast, heads specified using general-head boundaries within the Dockum Aquifer would be fixed and no small-scale redistribution would occur. This could potentially result in larger local flows between the general head boundary and the Dockum Aquifer than would occur using the additional model layer. Furthermore, an equivalent general-head boundary conductance is much less intuitive than vertical hydraulic conductivity values for each of the layers.

In addition to identifying the hydrostratigraphic layers of the aquifer, the conceptual model also defines the mechanisms of recharge and natural aquifer discharge, as well as groundwater flow through the aquifer. Precipitation recharge occurs in the outcrop areas. This is depicted by the recharge arrow on Figure 5.0.1. Additional water enters the aquifer by cross-formational flow from overlying aquifers, which is depicted by the cross-formational flow arrow on the figure. Cross-formational flow may redistribute groundwater between the model layers as a result of variations in hydraulic properties and hydraulic heads.

Recharge is a complex function of precipitation, soil type, geology, water level, soil moisture, topography, and evapotranspiration. Precipitation, evapotranspiration, water-table elevation, and soil moisture vary spatially and temporally, whereas soil type, geology, and topography vary spatially. In addition to natural phenomena, water levels are affected by pumpage, which in turn affects outflows. Diffuse recharge occurs throughout the outcrop areas. Focused recharge along streams can occur when the water table in the aquifer is below the stream-level elevation. If stream levels are lower than surrounding groundwater levels, groundwater discharges to the streams resulting in gaining streams. In this case, water levels in the valley are typically close to land surface and some of the shallow groundwater in this area can be lost to evapotranspiration. If stream levels are higher than the surrounding groundwater levels, groundwater is recharged by the streams resulting in losing streams.

Differences in average total dissolved solids concentrations in the Dockum Aquifer groundwater in the central part of the depositional basin versus the shallower areas near the aquifer perimeter have implications for the conceptual model of the movement of groundwater and recharge. The high total dissolved solids concentrations in the central part of the depositional basin are assumed to reflect no or insignificant displacement of connate water by meteoric water. Dutton and Simpkins (1986) suggest that the Dockum Aquifer was last recharged by precipitation in eastern New Mexico during Pleistocene time. They also suggest that the erosion of thick sandstones of the Dockum Aquifer in the valley of the Pecos River during the Pleistocene cut off recharge to the central part of the depositional basin from precipitation in eastern New Mexico after that time.

Groundwater in the central part of the basin, which is also the deepest part of the basin, has a higher fluid density than that around the perimeter. Density effects on groundwater flow were not incorporated in the model. Due to the relatively low hydraulic conductivity in the deep portions of the basin, the rising elevations of the lower portion of the Dockum Aquifer from the central to southeastern portion of the basin, and the higher fluid density in the deep part of the basin, very little groundwater movement in the deeper, central part of the basin is expected to occur.

Because of the configuration and location of the outcrop areas in the Dockum Aquifer, all precipitation recharge to the Dockum Aquifer is considered to be shallow recharge with none expected to reach the deeper and confined portions of the aquifer. Recharge in the Canadian River outcrop area discharges to the Canadian River and its tributaries, to springs and through evapotranspiration. Recharge along the eastern escarpment of the Dockum Aquifer within the Red River basin discharges to springs, evapotranspiration and to tributaries of the Red River. Within the Brazos River Valley, recharge to the outcrop discharges to the Brazos River and its tributaries, to springs, and through evapotranspiration. Recharge in the Colorado River outcrop area discharges to the Colorado River and its tributaries, to springs, and through evapotranspiration.

The Dockum Aquifer obtains water from the overlying Pecos Valley Aquifer and, in some areas, from the overlying Ogallala Aquifer through cross-formational flow. The locations where the Ogallala and Dockum aquifers have significant hydraulic communication are generally limited to areas where the upper portion of the Dockum Aquifer is missing and where the lower portion of the Dockum Aquifer is relatively shallow along the eastern edge of the aquifer. In areas where the upper portion of the Dockum Aquifer is present, low permeability mudstone in the upper portion of the Dockum Aquifer likely restricts downward flow from the overlying Ogallala as well as from the overlying Edwards-Trinity (High Plains). Some groundwater is expected to flow vertically from the overlying Edwards-Trinity (Plateau) Aquifer to the Dockum Aquifer but the volume of this flow is expected to be small relative to that coming from the overlying Ogallala and Pecos Valley aquifers.

The conceptual model defines very little movement of groundwater into or out of the Dockum Group in the deeper parts of the depositional basin, which is also the part of the aquifer where the upper portion of the Dockum Aquifer is present. This portion of the Dockum Aquifer generally corresponds to the portion that is not included as part of the Dockum Aquifer by the TWDB (total dissolved solids concentration greater than 5,000 milligrams per liter). In this area, the potential exists for groundwater to flow vertically downward from the overlying aquifers to the Dockum Aquifer. However, due to large differences in water-level elevation, the time period for this flow is conceptualized as being very long due to the confining nature of the mud-rich upper portion of the Dockum Aquifer. For the portion of the Dockum Group defined as the Dockum Aquifer, fresh water enters the aquifer via precipitation in the outcrop or vertically downward from overlying aquifers. The groundwater then flows a short distance and discharges to springs, streams, the underlying Permian-age sediments, or the overlying Ogallala Aquifer along the eastern escarpment.

In a natural aquifer system unaffected by anthropogenic activities, the aquifer system is in a long-term dynamic equilibrium condition generally referred to as a steady-state condition (or predevelopment). In this predevelopment state, aquifer recharge is balanced by aquifer discharge resulting in no net change in groundwater storage. Net recharge may include areal recharge from precipitation, cross-formational flow from adjacent formations, and, potentially, stream losses. Discharge includes stream base flow, spring flow, evapotranspiration, and cross-formational flow.

Human activities alter the dynamic equilibrium of the predevelopment flow system through pumping withdrawals, changes in recharge through development and irrigation return flow, and changes in vegetation. In the Dockum Aquifer, water-level rises due to anthropogenic land-use changes and water-level decline due to pumping have the most significant impact on aquifer hydraulics. The overall increase in water levels in areas with changes in land use is caused by increased recharge resulting from decreased evapotranspiration and runoff. The water removed by pumping is supplied through decreased groundwater storage, reduced groundwater discharge, and sometimes increased recharge. If pumping stays relatively constant, a new steady-state condition will be established. In this new equilibrium, the source of the pumped water will be drawn completely from either reduced discharge or increased recharge. Bredehoeft (2002) terms these two volumes as capture. The sources of discharge, which may ultimately be captured by pumping, include stream base flow, spring flow, evapotranspiration, and cross-formational flow.

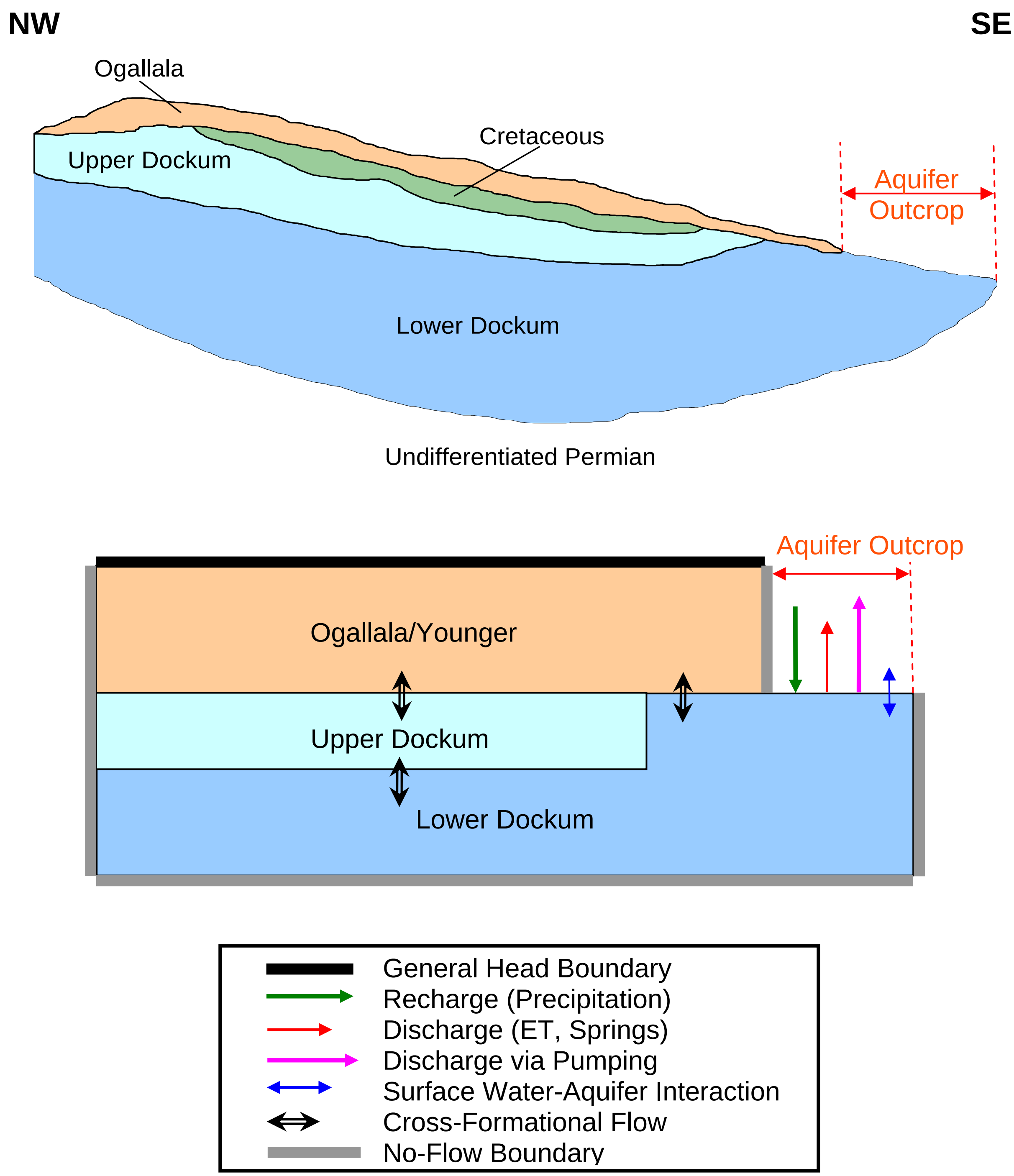


Figure 5.0.1 Conceptual groundwater flow model (cross-sectional view) for the Dockum Aquifer groundwater availability model.

6.0 Model Design

Model design represents the process of translating the conceptual model for groundwater flow in the aquifer (Section 5) into a numerical representation which is generally described as the model. The conceptual model for flow defines the required processes and attributes for the code to be used. In addition to selection of the appropriate code, model design includes definition of the model grid and layer structure, the model boundary conditions, and the model hydraulic parameters. Each of these elements of model design and their implementation are described in this section.

6.1 Code and Processor

The code selected for the groundwater availability models developed by or for the TWDB is MODFLOW-2000 (Harbaugh and others, 2000). MODFLOW is a three-dimensional finite-difference groundwater flow code which is supported by enhanced boundary condition packages to handle recharge, evapotranspiration, streams (Prudic, 1988), springs and reservoirs.

The benefits of using MODFLOW for the Dockum Aquifer groundwater availability model include: (1) MODFLOW incorporates the necessary physics represented in the conceptual model for flow described in Section 5 of this report, (2) MODFLOW is the most widely accepted groundwater flow code in use today, (3) MODFLOW was written and is supported by the United States Geological Survey and is public domain, (4) MODFLOW is well documented (McDonald and Harbaugh, 1988; Harbaugh and McDonald, 1996; Harbaugh and others, 2000), (5) MODFLOW has a large user group, and (6) there are a plethora of graphical user interface programs written for use with MODFLOW.

The MODFLOW datasets were developed to be compatible with Groundwater Vistas for Windows Version 4 (Rumbaugh and Rumbaugh, 2004). The model was executed on x86 compatible (i.e., Pentium or Athlon) computers equipped with the Windows XP operating system. MODFLOW is not typically a memory-intensive application in its executable form. However, if any preprocessor (such as Groundwater Vistas) is used for this size and complexity of model, at least 256MB of RAM is recommended.

6.2 Model Layers and Grid

MODFLOW requires a rectilinear grid. Typically, one axis of the model grid is aligned parallel to the primary direction of flow. As required in the Scope of Work, the Dockum Aquifer groundwater availability model grid was oriented to correspond directly to the grid of the overlying Southern Ogallala groundwater availability model. In this way, data and results can be efficiently translated between the two models. The grid cells are 1 mile by 1 mile squares throughout the model domain. The model grid origin is located at groundwater availability model coordinates 19,477,268 feet north and 3,663,110 feet east with the x-axis oriented east-west. The model has 212 columns and 422 rows for a total of 89,464 grid cells per layer. Not all of these grid cells are active in the model. Figure 6.2.1 shows the entire model grid and includes an inset with an enlargement of Scurry County to demonstrate the model grid at the county scale. After clipping the layers to their proper dimensions, layers 1, 2 and 3 have 47,919, 48,078, and 54,273 active grid cells, respectively. The total number of active grid cells in the model is 150,270.

The Dockum Aquifer groundwater availability model is divided into three model layers. The upper and lower portions of the Dockum Aquifer, the extents of which were discussed in Section 4.2.1, are represented by model layers 2 and 3, respectively. In addition to these two layers, an uppermost model layer was added to allow for simulation of cross-formational flow between the overlying Ogallala Aquifer and other younger formations and the underlying Dockum Aquifer. It should be noted, however, that the inclusion of this upper layer is intended only to provide a rudimentary representation of the overlying aquifers in order to avoid the condition of coincident general-head boundaries and pumping within the Dockum Aquifer layers. Layer 1 is not intended to explicitly simulate the Ogallala, Edwards-Trinity High Plains, Edwards-Trinity Plateau, Pecos Valley, and Rita Blanca aquifers. Specifically, all the recharge, pumping, and surface water interaction that occur within these younger formations are aggregated into the general-head boundary condition applied to all layer 1 cells.

The upper boundary of the model is defined by ground surface as calculated by the 30-meter digital elevation map averaged to the grid cells. This describes the top of the entirety of layer 1 and the outcrop portions of layers 2 and 3. The base of layer 1 is defined as the top of the Dockum Aquifer (Figure 4.2.1). Although the upper portion of the Dockum Aquifer is not present beneath all the active cells in layer 1, layer 2 cells located outside of the boundary delineating the upper portion of the Dockum Aquifer were made active to provide continuity between layer 1 and layer 3. The cell thickness for these connective layer 2 cells was set to 1 foot with the basal elevation of layer 1 increased by 1 foot, accordingly. The base of layer 2 is defined as the top of the lower portion of the Dockum Aquifer (Figure 4.2.4). The base of layer 3 (the base of the model) is defined by the base of the Dockum Aquifer (Figure 4.2.2). A minimum layer thickness of 25 feet was enforced whereby layer basal elevations were lowered if necessary.

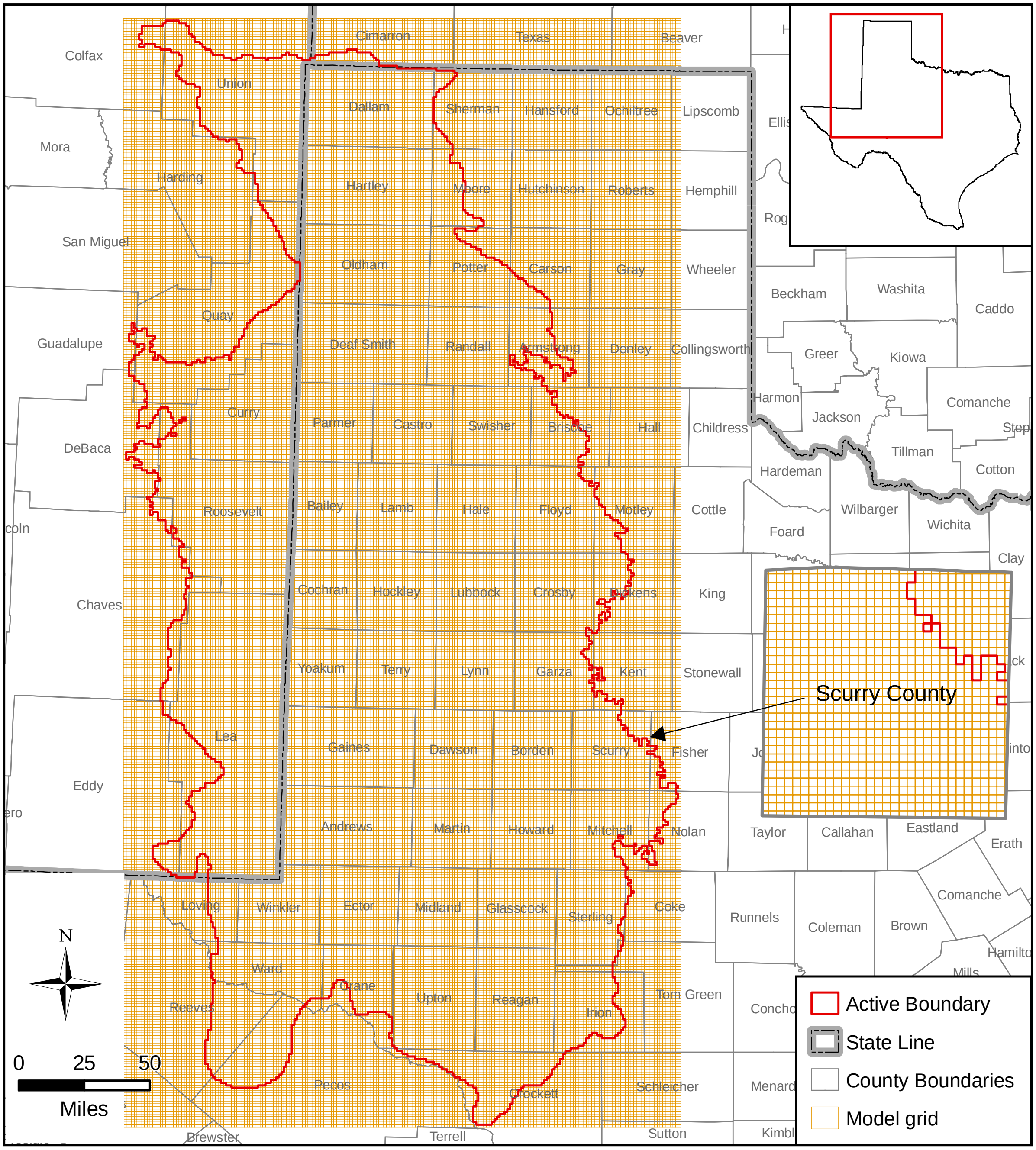


Figure 6.2.1 **Model grid for the Dockum Aquifer groundwater availability model.**

6.3 Boundary Condition Implementation

A boundary condition can be defined as a constraint put on the active model grid to characterize the interaction between the active simulation grid domain and the surrounding environment. There are generally three types of boundary conditions: specified head (First Type or Dirichlet), specified flow (Second Type or Neumann), and head-dependent flow (Third Type or Cauchy). The no-flow boundary condition is a special case of the specified flow boundary condition.

Boundaries can be either time independent or time dependent. An example of a time-dependent boundary is a pumping flow boundary (e.g., grid cell with a well) or a reservoir stage elevation. Because many boundaries require time-dependent (transient) specification, the stress periods used by MODFLOW must be specified. A stress period in MODFLOW defines the time period over which boundary and model stresses remain constant. Each stress period may have a number of computational time steps, which are some fraction of the stress period. For the transient model, the stress periods were set at 10 years for 1950 to 1970, 5 years for 1970 to 1975, and 1 year for 1975 to 1997. Therefore, transient boundaries in the model cannot change over a period of less than 10 years, 5 years or 1 year in the corresponding stress periods.

Boundaries requiring specification include: lateral and vertical boundaries for each layer, surface-water boundaries, recharge boundaries, and discharge boundaries, including evapotranspiration and pumping. Specified flow (no-flow, Second Type) boundary conditions were assigned to the lateral and lower boundaries and head-dependent flow (Third Type) was assigned to the top model layer. Surface-water boundaries, including streams, springs (drains) and evapotranspiration (drains), are head-dependent flow boundaries (Third Type). Recharge is a specified flow boundary (Second Type). Pumping discharge is a specified flow boundary (Second Type).

Figures 6.3.1 through 6.3.3 show the active and inactive grid cells along with the model boundary conditions for model layers 1, 2 and 3, respectively. Implementation of the boundary conditions for the Dockum Aquifer groundwater availability model is described below. Unless otherwise specified below, the boundary between the active and inactive cells is a no-flow boundary.

6.3.1 Lateral Model Boundaries

The lateral model boundaries have been defined by the extents of the Dockum Aquifer. Beyond the extents of the Dockum Aquifer outline, grid cells were set as inactive, creating a de facto no-flow boundary. For layer 1, a lateral, no-flow boundary was also set at the edge of the Dockum Aquifer outcrop so that layer 1 cells were inactive where the Dockum Aquifer outcrops. For layer 2, the lateral boundaries were identical to those of layer 1 with the exception of a few cells where the lateral boundary was extended to include the outcrop of the upper portion of the Dockum Aquifer. In addition, the dry portion of the Ogallala Formation (Ogallala "island") in Scurry, Borden, Fisher, Mitchell, and Nolan counties was inactive for layers 1 and 2. For layer 3, the lateral boundaries follow the entire extent of the Dockum Aquifer. Because MODFLOW is a finite-difference model where flow occurs only through grid cell faces, groups of a small number of would-be active grid blocks isolated laterally from other cell faces were also made inactive.

6.3.2 Vertical Boundaries

A no-flow boundary was used at the bottom of layer 3 (lower portion of the Dockum Aquifer). The model has a head-dependent flow boundary (Third Type) within layer 1 (Ogallala/younger aquifer). From the perspective of the Dockum Aquifer, this boundary represents the flow coming from the Ogallala or other younger formations. The general-head boundary package is able to simulate a head-dependent flow boundary condition, being provided with the head and hydraulic conductance. The conductance in the general-head boundary package, representing the connection between the heads in the boundary condition and the simulated heads, was set to 1000 square feet per day for both the steady-state and transient models. This relatively large value was chosen based on a conceptual model of the Ogallala vertical hydraulic conductivities being much greater than those of the Dockum Aquifer and the Dockum Aquifer conductivities being the primary limiter to flow into the Dockum Aquifer. In this way, the heads within layer 1 were very close to the heads prescribed in the general-head boundaries (based on Ogallala/younger aquifer head data) and the flows recharging/discharging the Dockum Aquifer were closely scrutinized to ensure compliance with respect to the conceptual model.

For the steady-state model period, water-level measurements were not available at a sufficiently small scale over many portions of the younger aquifers overlying the Dockum Aquifer.

Therefore, a correlation between observed younger aquifer heads and a muted representation of topography (which is available over the entirety of the model domain) was developed. This is in accordance with the well recognized conceptualization that the water table within unconfined aquifers is a muted expression of topography (Freeze and Cherry, 1979; Domenico and Schwartz, 1998). Specifically, the heads used in the general-head boundary in layer 1 were estimated by regressing observed water-level data to a 5-mile average of land surface elevation as defined by the 30-meter digital elevation map. As a result of linear regression, the following equation was used to calculate the general-head boundary heads:

$$WL = 0.9961 \times DEM_{5mile\text{-}avg} - 91.784 \tag{6.3.1}$$

where WL is the fitted water level and $DEM_{5mile\text{-}avg}$ represents the 5-mile average elevation of the top of layer 1 digital elevation model. After applying Equation 6.3.1, the fitted water level was truncated by the elevations of the top and bottom of layer 1 to serve as the general-head boundary head in the model. The truncation was performed to ensure placement of the general-head boundary within layer 1.

In the transient model, the heads in the general-head boundary of layer 1 were adjusted to account for water-level changes within the Ogallala over time. First, the simulated drawdown of the Southern Ogallala groundwater availability model (yearly average 1939 through 2000) was selected at 881 control points. These drawdown values were interpolated at each grid block over the entire Dockum Aquifer domain using kriging. The drawdown values trended toward zero before reaching the extents of the Southern Ogallala groundwater availability model and the drawdown was assumed to be zero outside the extents of the Southern Ogallala. Finally, the interpolated drawdown values were added to the steady-state general-head boundary heads to determine general-head boundary heads for each stress period in the transient model.

6.3.3 Surface Water Implementation

Surface water acts as a head-dependent flow (Third Type) boundary condition for the top boundary of the active model grid cells in layer 3 (lower portion of the Dockum Aquifer) and a small portion of layer 2 (upper portion of the Dockum Aquifer). The stream package (Prudic, 1988) is a head-dependent flow boundary condition that offers a first-order approximation of surface water/groundwater interaction. The stream-routing package allows for stream-related discharge during gaining conditions and for stream-related recharge during losing conditions. When pumping affects water levels near stream/aquifer connections, streams may change from gaining to losing or become more strongly losing. Although several reservoirs are located within the model area, they were not included in the model because they do not likely interact with the Dockum Aquifer.

The stream-routing package requires designation of segments and reaches. A reach is the smallest division of the stream network and is comprised of an individual grid cell. A segment is a collection of reaches that are contiguous and do not have contributing or diverting tributaries. In MODFLOW, the hydraulic connection (conductance) between the stream and the aquifer must be defined.

INTERA developed a GIS-based method for creating the reach and segment data coverages for MODFLOW. Figures 6.3.2 and 6.3.3 show the grid cells that contain stream reaches in the model domain. Required physical properties of the reaches, including stream width, bed thickness, and roughness, were taken from the Enhanced River Reach File (Alexander and others,1999). The hydraulic conductivity used to define the hydraulic conductance between the aquifer and the stream was initially set to 1 foot per day.

The stream-routing package also requires specification of a stream flow rate at the starting reach of each headwater segment at each stress period. For steady-state conditions and the historical period, no representative stream gage data exist for the majority of the stream segments. For both the steady-state and transient simulations, mean flow rates from the Enhanced River Reach File were used to specify the flow rate entering each model headwater segment. The Enhanced River Reach File contains mean flow rates estimated along the entire stream and coinciding with all of the modeled stream segments.

After conducting several simulations, it became clear that the model was insensitive to stream flow. In the stream package, discharge to or from a stream cell is governed by the gradient (the difference between the stream stage and the water-level elevation in that cell) and the streambed conductance. In general, changes in the stream stage resulting from changes in the stream flow were very small compared to the gradient as a whole. It was, therefore, deemed reasonable to use the mean stream flow over the transient period.

Spring discharge records were reviewed for application in the Dockum Aquifer groundwater availability model as drain boundary conditions (Type 3). Table 4.5.2 summarizes the documented springs in the model domain. It is hypothesized in the conceptual model that the cumulative effect of the numerous spring and seeps, which discharge individually at smaller rates, may be a significant form of discharge for the aquifer. Therefore, an attempt to include all documented springs in the model domain was made. The lateral scale of the grid blocks resulted in many springs sharing a gridblock with another spring or coinciding with stream cells. Springs that were coincident with stream cells were not included in the model because streams provide a sufficiently similar type of boundary condition. For multiple springs occurring in one gridblock, the minimum elevation was used and only one drain boundary condition was applied to that cell. This resulted in a total of 71 spring drain boundary conditions being included in the model. Reported spring elevations were used to set the drain elevations. Where reported elevations were above the top of the model, the elevation of the drain was calculated by subtracting 20 feet from the 30-meter digital elevation model at the reported spring location.

6.3.4 Implementation of Recharge and Evapotranspiration

Because an evaluation of groundwater availability is largely dependent upon recharge (Freeze, 1971), it is an important model input parameter warranting careful examination and meaningful implementation. In typical model applications, recharge is either homogeneously defined as a percentage of the yearly average precipitation or calibrated as an unknown parameter. Unfortunately, recharge and hydraulic conductivity can be correlated parameters preventing independent estimation when using only head data constraints. Another compounding problem is that recharge is a complex function of precipitation rate and volume, soil type, water level and soil moisture, topography, and evapotranspiration (Freeze, 1969). Precipitation, evapotranspiration, water-table elevation, and soil moisture are areally and temporally variable. Soil type, geology, and topography are spatially variable. For the groundwater availability model, recharge requires specification for steady-state conditions and transient conditions from 1950 through 1997. Reliable tools for specification of recharge at the watershed scale, or the regional model scale (thousands of square miles for the groundwater availability models) do not currently exist.

The initial approach for estimating the steady-state recharge was to: (1) estimate recharge at limited points using chloride concentration, which was described in Section 4.4.1.2; (2) study the correlation between estimated recharge and saturated hydraulic conductivity, or between estimated recharge and land surface elevation; and (3) use one or both of the correlations to describe the recharge distribution over the Dockum Aquifer groundwater availability model domain. However, no obvious correlation was found in step (2).

Average recharge rates were calculated separately for the Canadian and Colorado river outcrops and, though they differ slightly, a significance analysis (t-test) indicated that it would not be warranted to separate the data for the two areas. Specifically, the variability of recharge values within a single outcrop area was large compared to the difference between the means for each. The average for all the recharge estimates based on chloride data was 0.15 inches per year.

A recharge elevation model was built using “local” topography which was calculated as the difference between the 1-mile (local) and 5-mile (sub-regional) average digital elevation models. Recharge rates were weighted as a power function of the local topography and normalized to conserve the total recharge volume equivalent to the average of 0.15 inches per year, if applied uniformly. The power function coefficient was adjusted until the maximum recharge rate was reasonable (approximately 0.5 inches per year). Figure 6.3.4 depicts the steady-state recharge distribution using this recharge elevation model. Recharge was set to zero in stream cells. This was done to avoid placing multiple surface water boundary conditions in a single cell and because the precipitation occurring in stream valleys is conceptualized to discharge to streams primarily through run-off or shallow interflow without interacting considerably with the regional groundwater system.

As discussed in Section 4.4.1, land-use changes have resulted in increased recharge within the Colorado River outcrop of the Dockum Aquifer. Stable water levels coupled with little cultivation within the Canadian River outcrop indicate that the recharge rate is likely unaltered from that during predevelopment. A linear increase in water levels in wells within the Colorado River outcrop indicates a median modern recharge rate within the cropland regions of approximately 1.6 inches per year (see Section 4.4.1.3). The average predevelopment recharge rate of 0.15 inches/year indicates that 1.45 inches per year of additional recharge occurs in modern times. Within the cropland portions of the Colorado River outcrop, this additional recharge of 1.45 inches per year was added uniformly to the predevelopment recharge distribution. Figure 6.3.5 depicts the modern (1950 to 1997) recharge distribution for the transient model.

For the simulation of evapotranspiration, initially the evapotranspiration package was used for riparian cells neighboring stream cells in the outcrop. Parameters needed in the evapotranspiration package include maximum evapotranspiration rate, extinction depth and elevation of evapotranspiration surface. Following Scanlon and others (2005), the maximum evapotranspiration rate can be estimated by the product of potential evapotranspiration and crop coefficient. The vegetation rooting depth was used as the extinction depth, and the elevation of the top of the model served as the elevation of the evapotranspiration surface. Both vegetation coefficient and rooting depth were adopted from the database in Scanlon and others (2005) according to the land type.

Using the evapotranspiration package, the model exhibited convergence problems. To investigate the underlying cause of the convergence problems, the evapotranspiration cells were replaced with drains at an elevation corresponding to the rooting depth and given a very large conductance value of 100,000 square feet per day. Even using this large conductance value, the maximum simulated discharge within any evapotranspiration cell (18 inches per year) was less than the calculated maximum evapotranspiration rate, which ranged from 32 to 52 inches per year. Furthermore, the evapotranspiration drain discharge rates were found to be insensitive to the drain conductance value. This indicates that discharge through evapotranspiration within the model is limited by the hydraulic parameters of the formation and the maximum evapotranspiration rates prescribed in the evapotranspiration package are not sustainable by the aquifer and result in high water table oscillations, drying cells, and, ultimately, solver oscillications. Therefore, the drain package was used to simulate evapotranspiration (requiring a total of 2,146 evapotranspiration drains). The drain package contains comments to clearly differentiate the evapotranspiration drains from the spring drains.

6.3.5 Implementation of Pumping Discharge

Pumping discharge is a primary stress on the transient model. Pumping discharge is a cell dependent specified flow boundary. The procedural techniques used in estimating and allocating pumping are provided in Section 4.7. Once the pumping was estimated for each of the seven user groups (municipal, manufacturing, power generation, mining, livestock, irrigation, and rural domestic), it was summed across all user groups for a given model cell (row, column, layer) and a given stress period. This process was repeated for each active cell and each stress period in the calibration period of the transient model.

Because detailed pumping was unavailable for the time period between 1950 and 1980, a somewhat synthetic pumping history was generated to account for the development that occurred during this period prior to the transient calibration period of 1980 through 1997. Total irrigation pumping numbers were available for the years 1958, 1964, 1969, 1974, 1979 and 1984. A curve was fit to these data to generate total irrigation pumping for each of the model stress periods from 1950 to 1980. The pumping history prior to 1950 was considered insignificant with respect to the storage history in the Dockum Aquifer. Ratios of the pumping for each user group to the total pumping from 1980 to 1997 ($FRAC_{user}$) were calculated. In addition, the ratios of pumping for a certain user group within each model grid cell to the total for that user group ($FRAC_{loc}$) were calculated. Based on the ratio of irrigation pumping to total pumping, a synthetic total pumping curve from 1950 to 1980 ($Q_{total,year}$) was generated. The pumping for each grid cell, for each stress period ($Q_{loc,year}$) was then calculated as the sum of the ratios multiplied by the total pumping in that stress period using:

$$Q_{loc,year} = \sum_{user=1}^{7} FRAC_{loc} \cdot FRAC_{user} \cdot Q_{total,year} \qquad (6.3.2)$$

For the transient model, the well-package dataset have a specified flow boundary condition for each stress period, for each active grid cell within which pumping occurs.

Figures 6.3.6 through 6.3.8 show the distribution of pumping in the lower portion of the Dockum Aquifer (layer 3) for the beginning of the transient period (1950), for the first year of model calibration (1980), and at the end of the calibration period (1997), respectively. Most of the pumpage from the Dockum Aquifer in Texas occurs in Scurry, Moore, Crosby, Mitchell, Deaf

Smith, and Winkler counties. Of the water pumped from the Dockum Aquifer, the largest volume is used for irrigation purposes. Overall, pumping from the Dockum Aquifer was substantially greater during the 1950s than during any other time period with pumping decreasing steadily until the 1980s after which time pumping rates remain relatively constant.

No pumping occurred within the upper portion of the Dockum Aquifer (layer 2). Although considerable development has occurred in the Ogallala Aquifer (layer 1), pumping in layer 1 was not explicitly simulated in the model. Instead, the change in Ogallala heads resulting from pumping was incorporated in the model by altering the head value for the general-head boundary condition assigned to all layer 1 cells. Specifically, the simulated drawdown within the Ogallala Aquifer from the Southern Ogallala groundwater availability model was used to account for the change in heads in the Ogallala due to development. The simulated drawdown from the Southern Ogallala groundwater availability model was kriged onto a grid with 5-mile centers to smooth out anomalies. Drawdown maps were produced for the years 1955, 1965 and 1972 to correspond to the midpoints of the early stress periods in the Dockum Aquifer model and annual drawdown maps were produced from 1975 to 1997 to correspond directly to the Dockum Aquifer model stress periods. For each model stress period, the corresponding drawdown map was then subtracted from the steady state general-head boundary head to generate the transient general-head boundary heads.

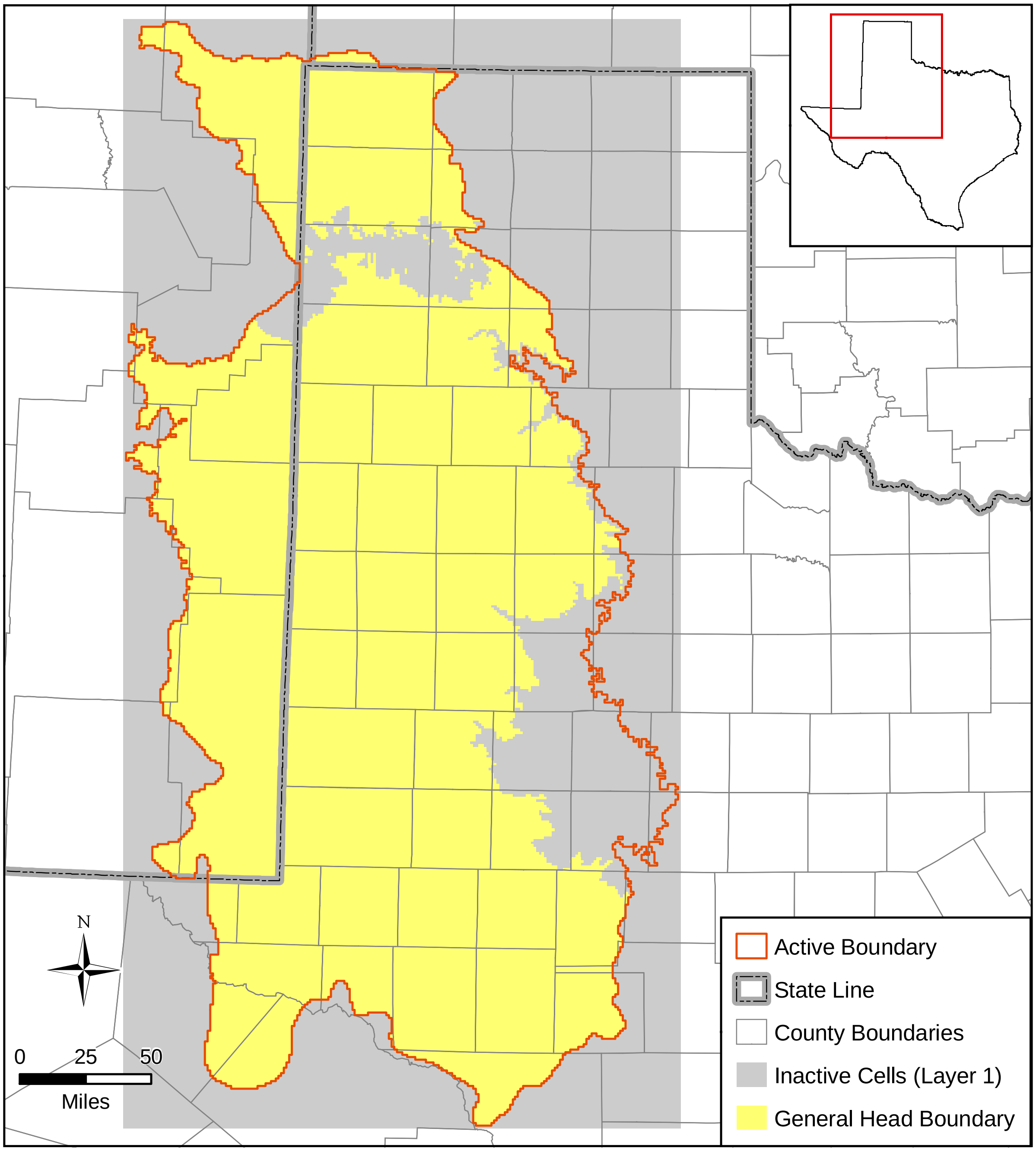


Figure 6.3.1 Layer 1 boundary conditions and active/inactive cells.

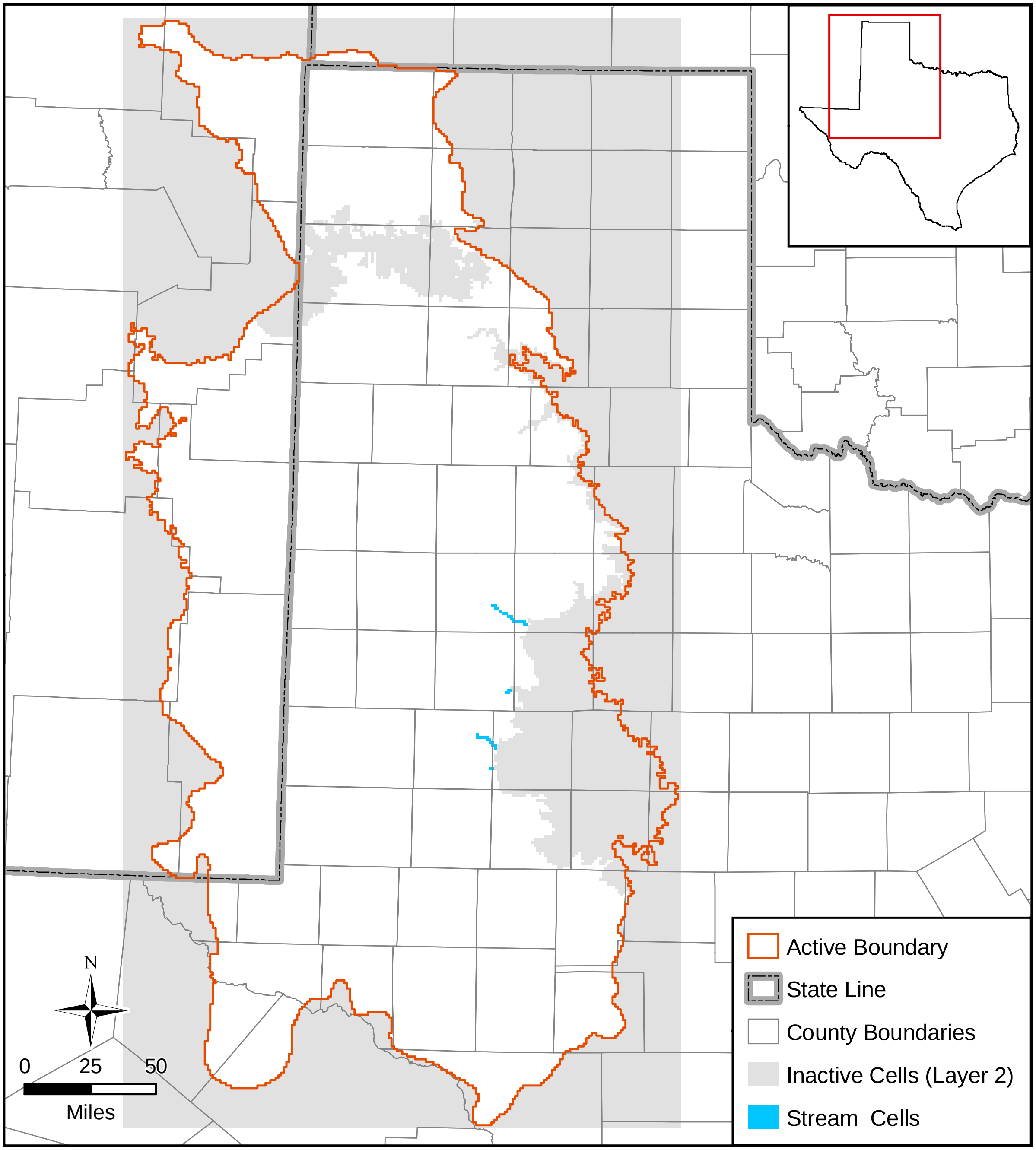


Figure 6.3.2 Layer 2 boundary conditions and active/inactive cells.

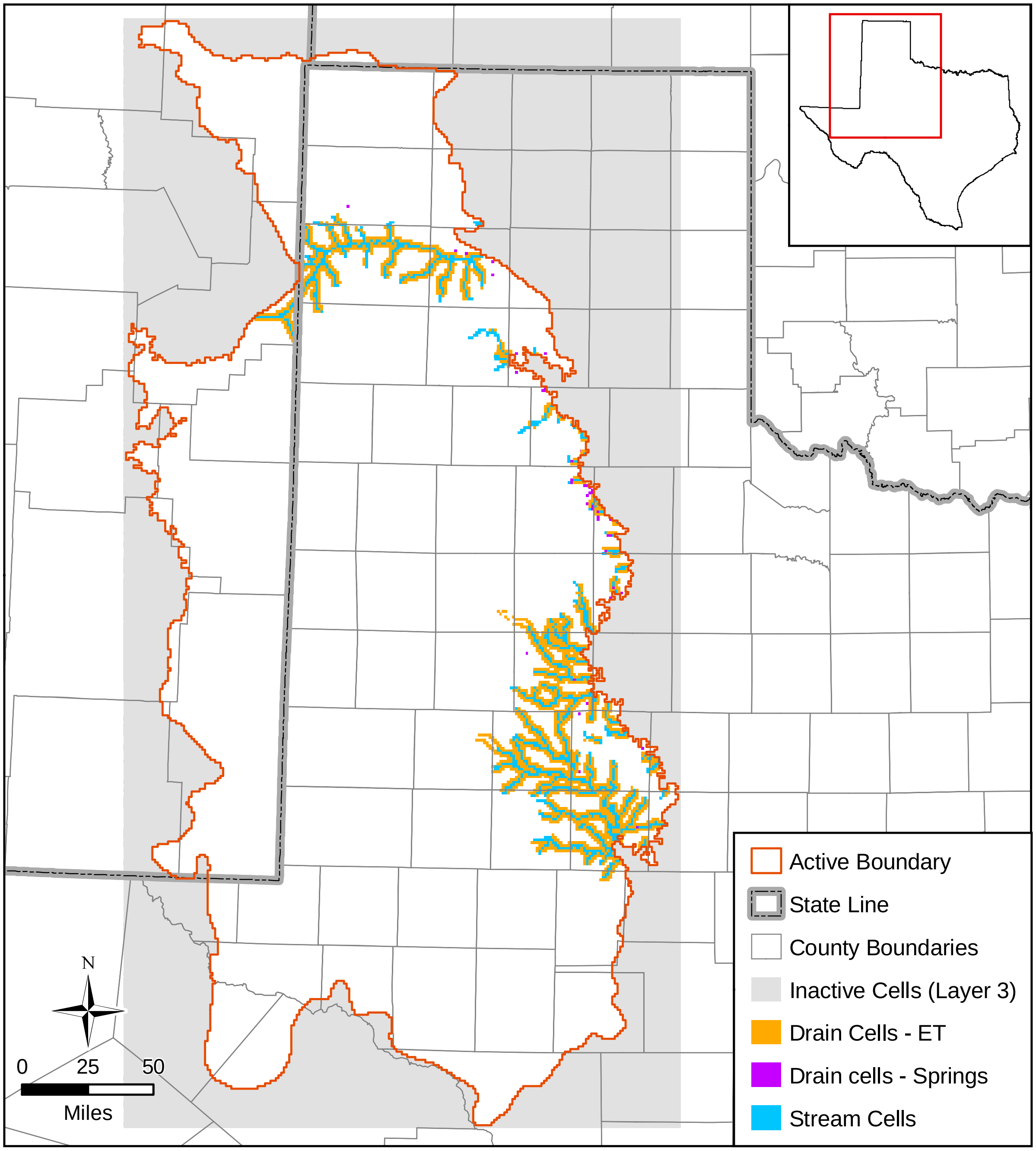


Figure 6.3.3 **Layer 3 boundary conditions and active/inactive cells.**

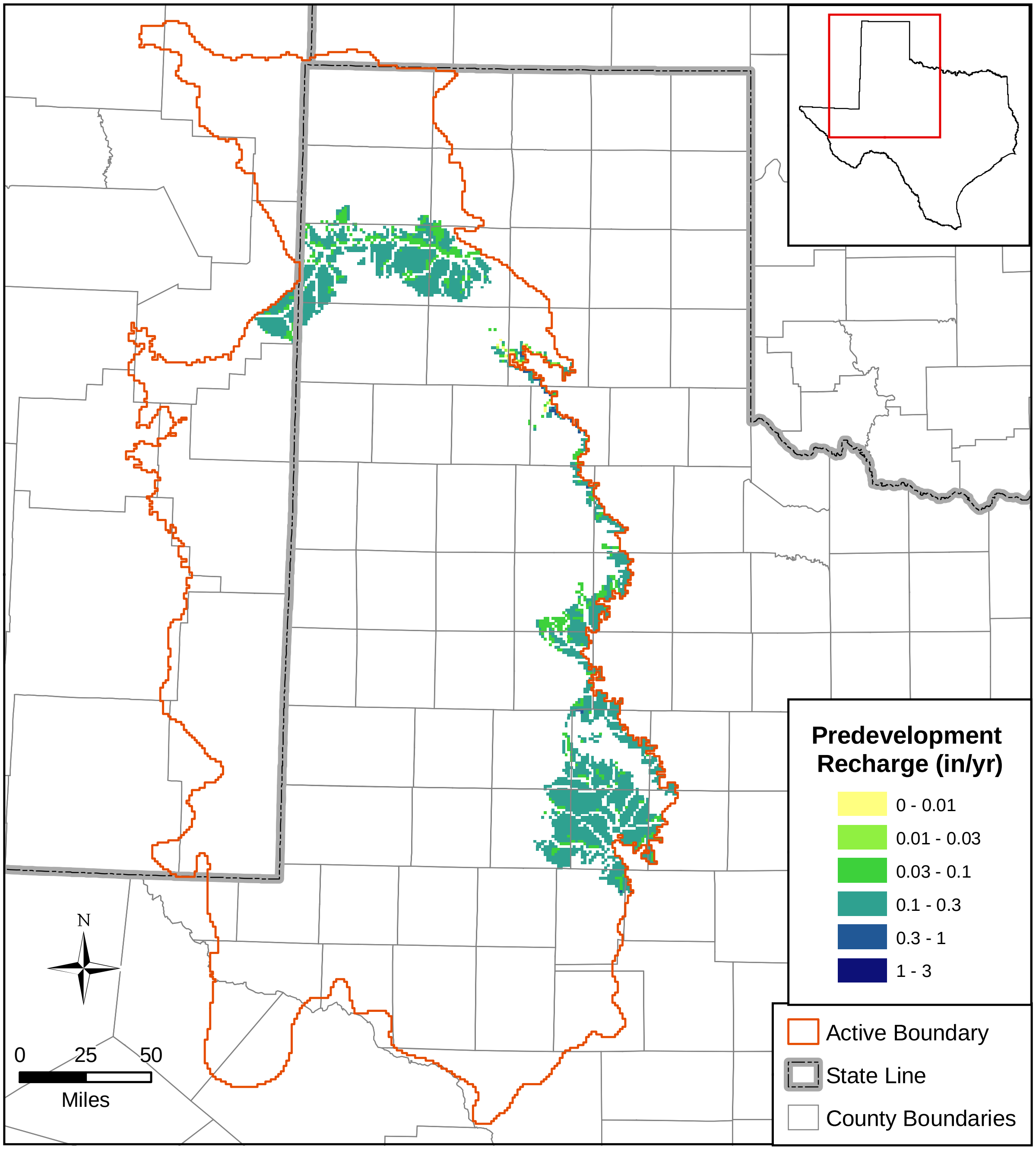


Figure 6.3.4 **Predevelopment recharge distribution in inches per year.**

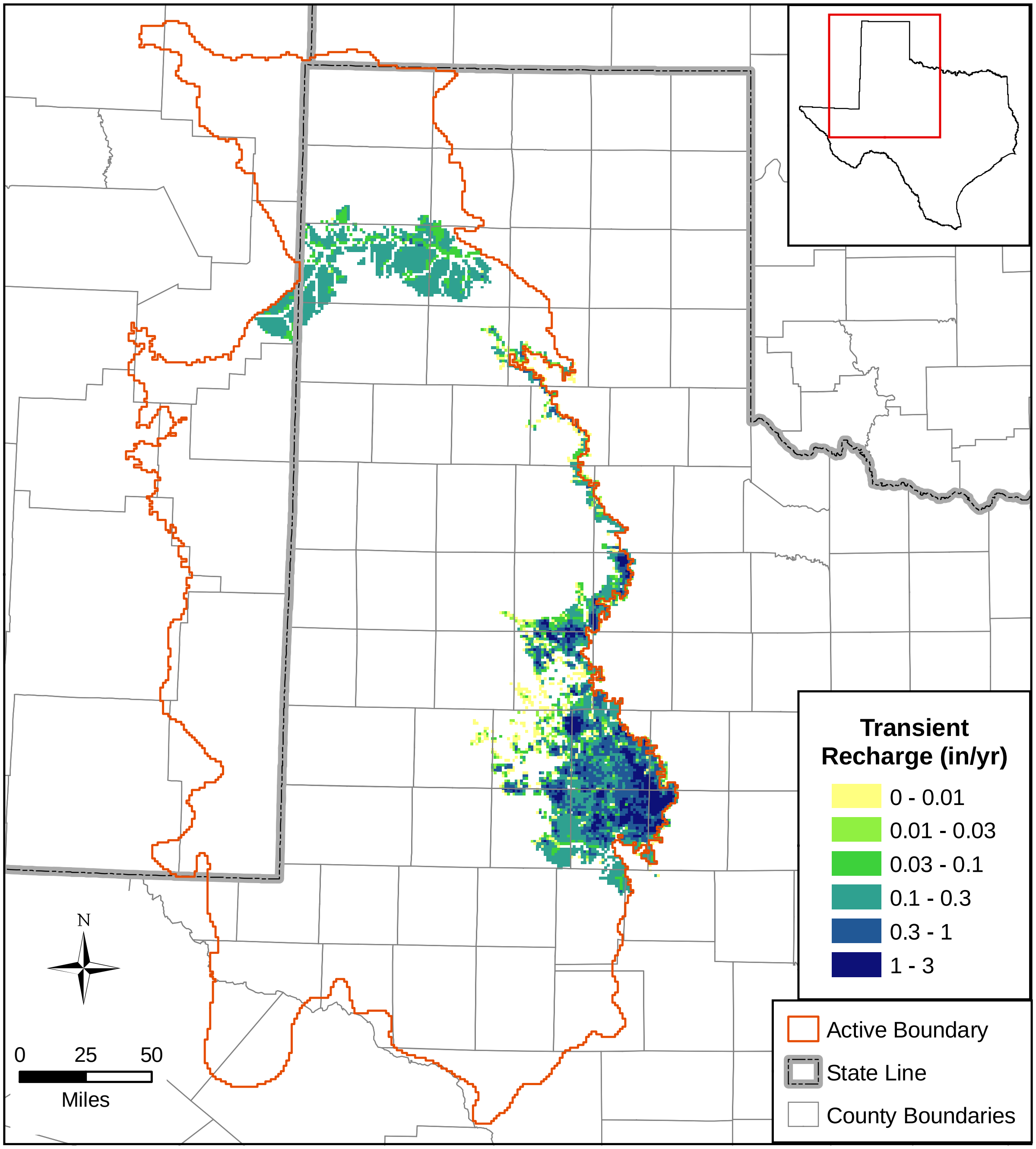


Figure 6.3.5 **Modern (1950 to 1997) recharge distribution in inches per year.**

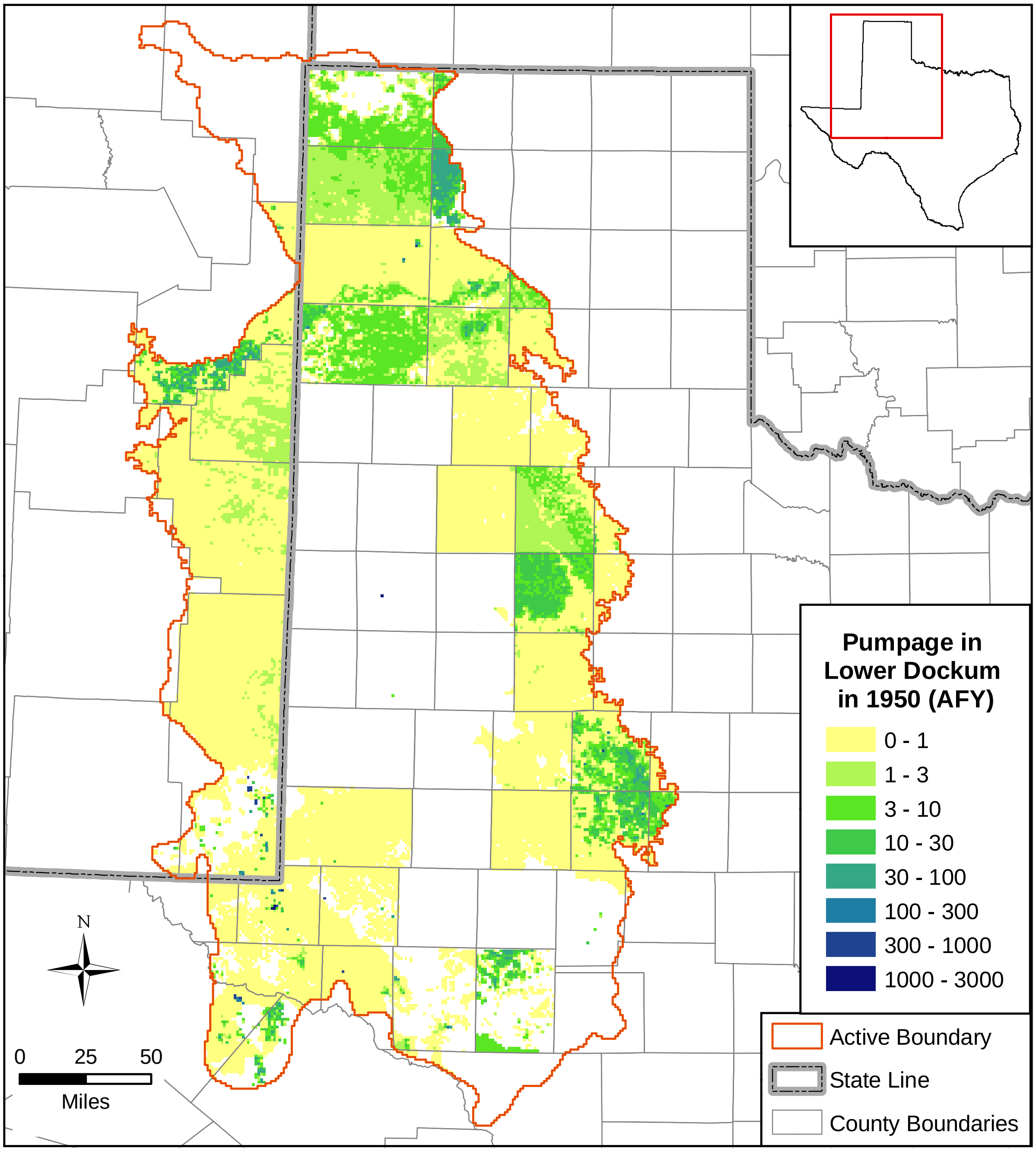


Figure 6.3.6 Pumping distribution in acre-feet per year for the lower portion of the Dockum Aquifer in 1950.

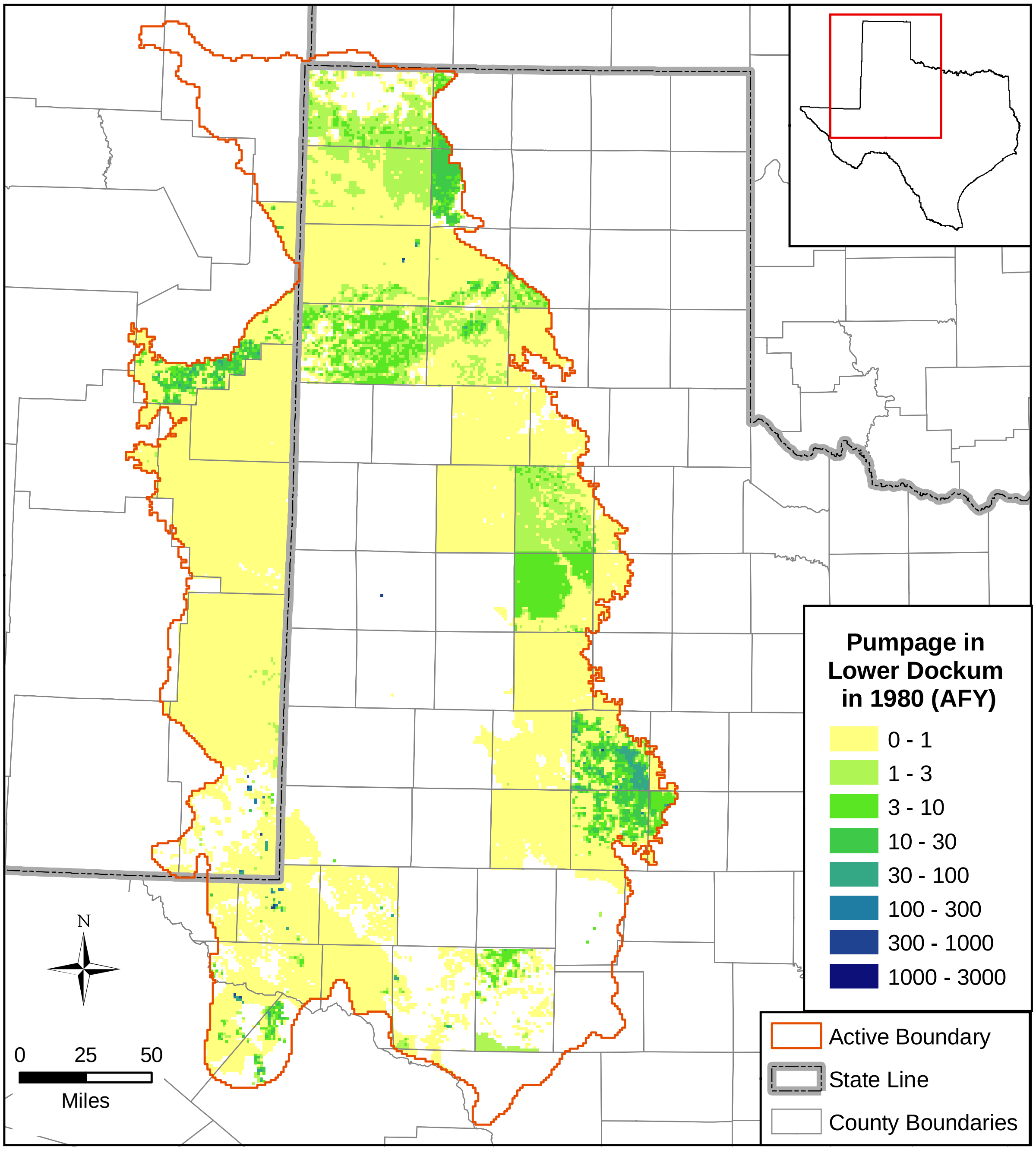


Figure 6.3.7 Pumping distribution in acre-feet per year for the lower portion of the Dockum Aquifer in 1980.

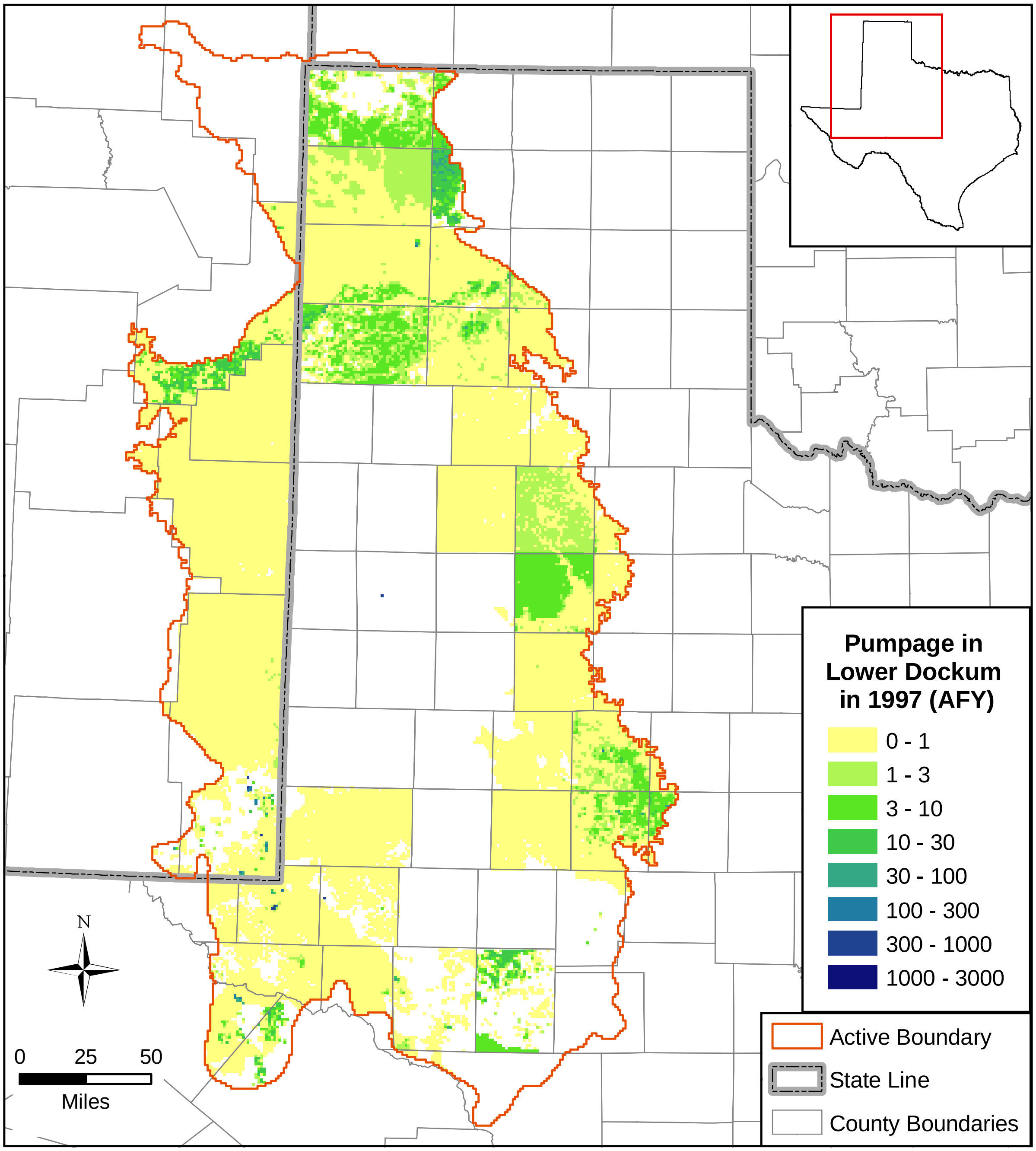


Figure 6.3.8 **Pumping distribution in acre-feet per year for the lower portion of the Dockum Aquifer in 1997.**

6.4 Model Hydraulic Parameters

For the steady-state model, the primary hydraulic parameter to be estimated and distributed across the model grid is hydraulic conductivity. For the transient model, the storage coefficient must also be included. The following sections describe the method used for distributing hydraulic conductivity and storage in the model domain.

6.4.1 Hydraulic Conductivity

In the groundwater availability model, model properties are constant within a given grid block. Each grid block is one square mile in area and varies in thickness from a minimum of 1 foot to a maximum of approximately 2,000 feet. One of the challenges in constructing a regional model is the development of an accurate "effective" hydraulic conductivity field that is representative of the different lithologies present in each grid cell. The effective hydraulic conductivity depends on the geometry, individual hydraulic conductivities, and the correlation scale relative to the grid and simulation scales of the various lithologies present in a grid cell (Freeze, 1975).

Many investigations exist regarding estimating average effective hydraulic conductivity given assumptions for flow dimension, layer geometry, and correlation scales (Warren and Price, 1961; Gutjahr and others, 1978). For one-dimensional flow in lithologies combined in parallel (i.e., layered), the appropriate effective hydraulic conductivity would be the weighted arithmetic mean. For one-dimensional flow in lithologies combined in series, the effective hydraulic conductivity is the harmonic mean. Hydraulic conductivity has been found to be a log-normally distributed parameter in many studies. In two-dimensional uniform flow, assuming that the hydraulic conductivity is log-normally distributed and randomly juxtaposed, the effective hydraulic conductivity is exactly the geometric mean (de Marsily, 1986).

For model layer 1 (Ogallala and younger aquifers), uniform properties were applied. The horizontal hydraulic conductivity was set to the geometric mean of the values used in the Southern Ogallala groundwater availability model (11 feet per day). The vertical hydraulic conductivity was given as 0.11 feet per day based on an anisotropy factor (ratio of horizontal hydraulic conductivity to vertical hydraulic conductivity) equal to 100. The properties of the Ogallala and other younger aquifers are generally much higher than those of the Dockum

Aquifer and, therefore, the Dockum Aquifer properties primarily govern vertical flow into the Dockum Aquifer. Because the only purpose of layer 1 is to simulate the impact of the Ogallala/younger aquifer heads on the Dockum Aquifer, this rudimentary description of layer 1 properties was deemed sufficient. Indeed, the model tends to be insensitive to layer 1 properties as is discussed in detail in Sections 8 and 9.

The horizontal hydraulic conductivity for layers 2 and 3 was calculated by multiplying the sand hydraulic conductivity and the sand fraction:

$$K_h \quad = \quad SF \cdot K_{sand} \tag{6.4.1}$$

where K_h is the horizontal hydraulic conductivity, SF is the sand fraction, and K_{sand} is the sand hydraulic conductivity. This is equivalent to a weighted arithmetic average only neglecting the contribution of the clay conductivity to the horizontal hydraulic conductivity. The sand fraction maps for layers 2 and 3 are shown in Figures 6.4.1 and 6.4.2, respectively. The effective horizontal hydraulic conductivity for layers 2 and 3, calculated using Equation 6.4.1, are depicted in Figures 6.4.3 and 6.4.4, respectively.

Vertical hydraulic conductivity is not measurable on a regional model scale and is, therefore, generally a parameter that is calibrated within predefined limits. The vertical hydraulic conductivity for layers 2 and 3 was estimated as the harmonic mean of the sand and clay conductivities using:

$$K_v \quad = \quad \frac{1}{\dfrac{SF}{K_{sand}} + \dfrac{1-SF}{K_{clay}}} \tag{6.4.2}$$

where K_v is vertical hydraulic conductivity and K_{clay} is the clay hydraulic conductivity. Typical vertical anisotropy ratios are on the order of 1 to 1,000 determined from model applications (Anderson and Woessner, 1992). Domenico and Schwartz (1998) list values of horizontal to vertical hydraulic conductivity ratios that range from 2 to 10 for materials similar to sediments in the study area. At the regional scale of the Dockum Aquifer groundwater availability model, much higher anisotropy ratios are expected. The aforementioned calculations of horizontal and vertical hydraulic conductivity result in median vertical anisotropies of 1.6 x 10^4 and 1.9 x 10^4

for the upper and lower portions of the Dockum Aquifer, respectively. The effective vertical hydraulic conductivity for layers 2 and 3 are depicted in Figures 6.4.5 and 6.4.6, respectively.

6.4.2 Storage Coefficient

For unconfined aquifer conditions, the specific yield was assumed to be homogeneous and was assigned a value equal to 0.15 for all layers. Grid cells that represented outcrop (land surface) were modeled as either confined or unconfined depending upon the elevation of the simulated water table in that grid cell. To account for conditions of ponding water in the outcrop cells, the storativity in the outcrop cells was assigned a value of 1.0. This was done because outcrop cells do not actually become confined but rather flooded when the water table is higher than land surface. An identical method of specifying storativity in outcrop cells was used in previous groundwater availability models (Deeds et al., 2002; Fryar et al., 2003; Ewing et al. 2004; Kelley et al., 2004).

For the confined portion of the Dockum Aquifer, there are a limited number (a total of 13) of available storativity measurements and estimates (see Section 4.6.8). Storativity estimates ranged in magnitude from 5 x 10^{-5} to 2 x 10^{-3}, with a geometric mean equal to 1.6 x 10^{-4}. Storativity measurements are too sparse to directly generate a spatial distribution by kriging or other mapping technique. Instead, specific storage was calculated based on the sand maps with clay having a higher specific storage than sand. Specific storage for layers 2 and 3 were calculated using:

$$Ss \quad = \quad SF \times Ss_{sand} + (1 - SF) \times Ss_{clay} \qquad (6.4.3)$$

where Ss is the specific storage, Ss_{sand} is the sand specific storage, and Ss_{clay} is the clay specific storage. Ss_{sand} and Ss_{clay} were initially set to the values used in the Queen-City Sparta groundwater availability model (Kelley and others, 2004) of 3 x 10^{-6} per foot and 7.5 x 10^{-6} per foot, respectively. Care was taken during calibration that the specific storage remain above a minimum of 1.3x10^{-6} per foot equal to the compressibility of water. Storativity was then calculated by multiplying the specific storage by the layer thickness within each cell. The resulting storativity values for the upper and lower portions of the Dockum Aquifer are shown in Figures 6.4.7 and 6.4.8, respectively.

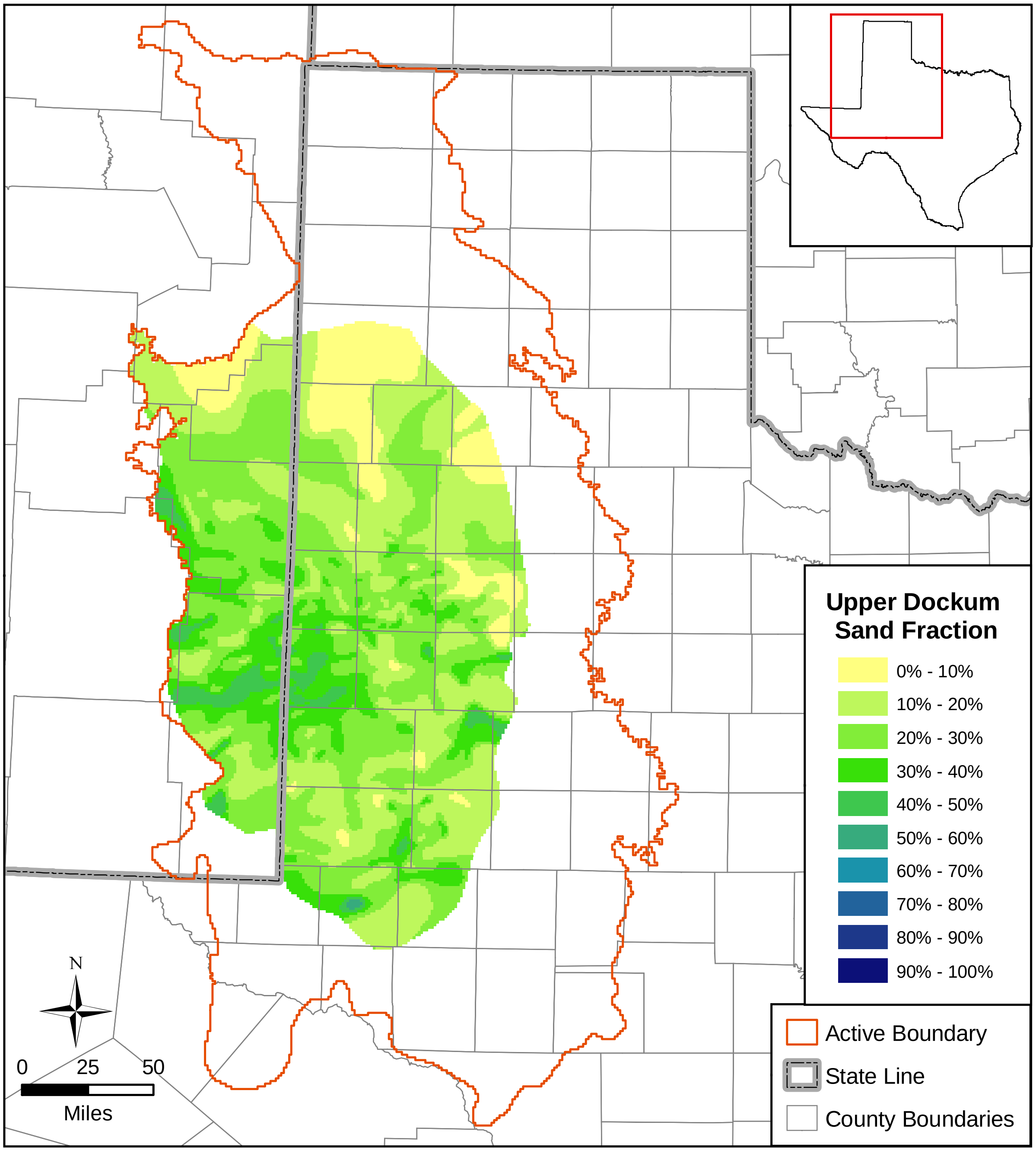


Figure 6.4.1 Layer 2 sand fraction.

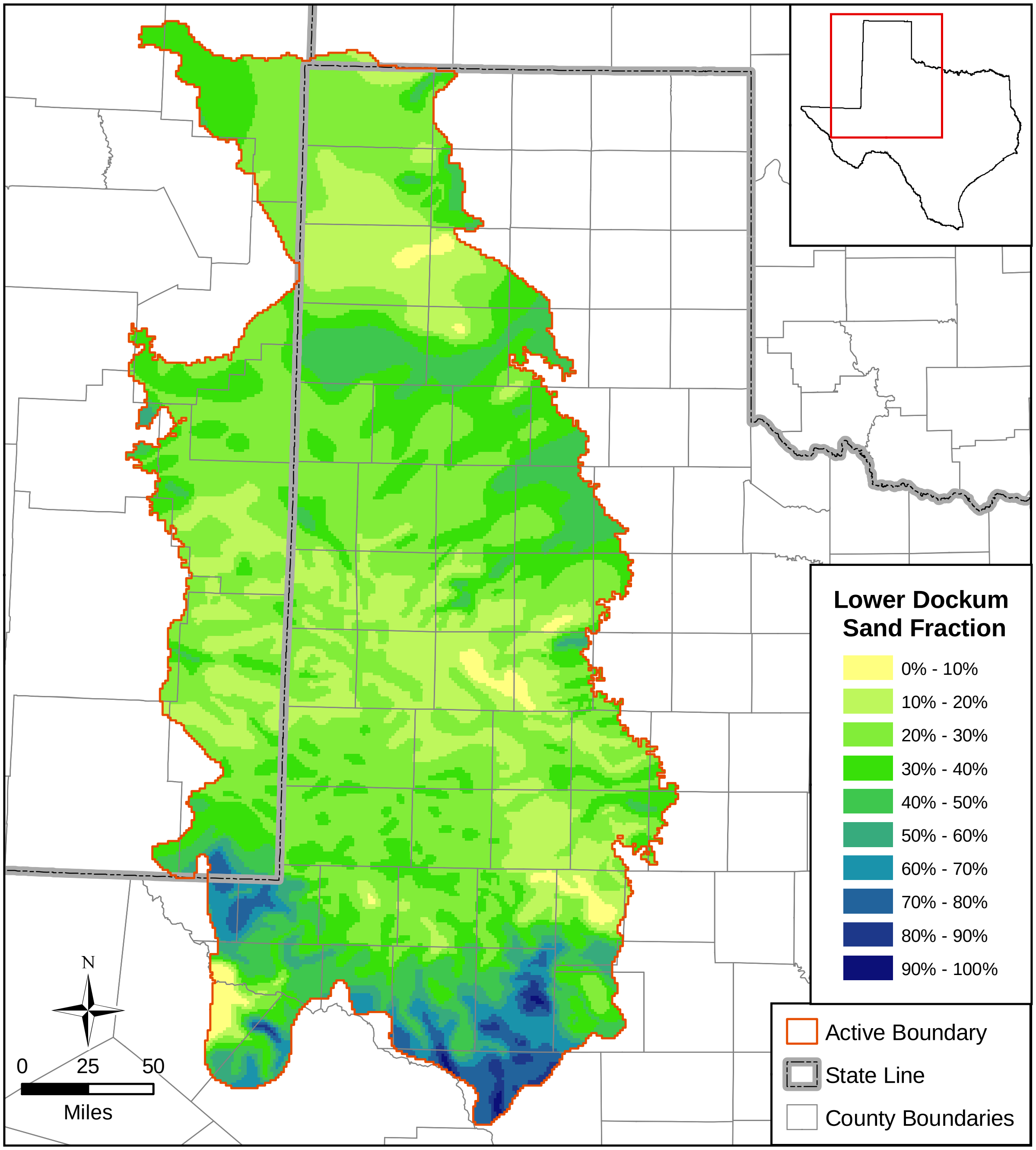


Figure 6.4.2 Layer 3 sand fraction.

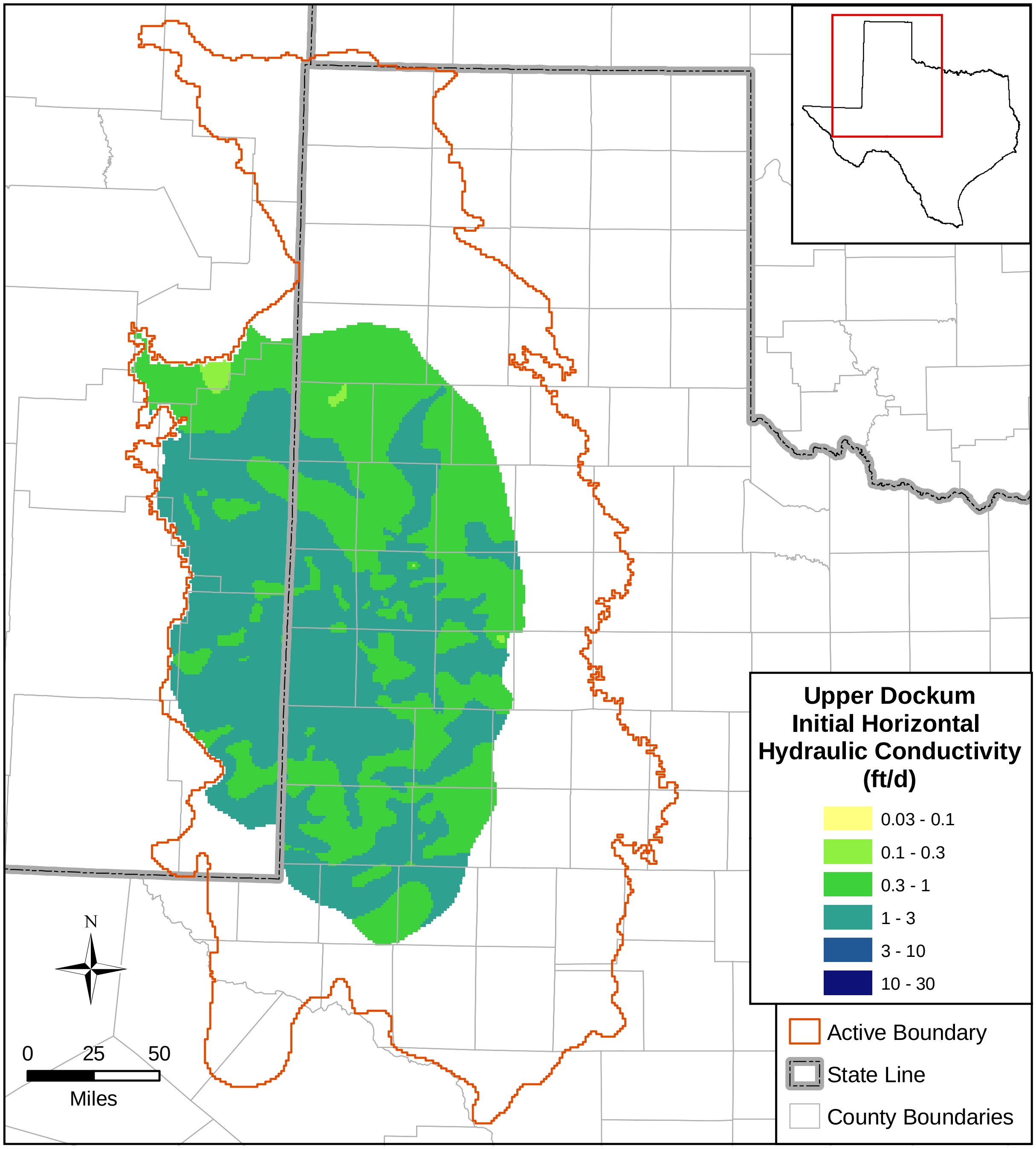


Figure 6.4.3 Layer 2 effective horizontal hydraulic conductivity in feet per day.

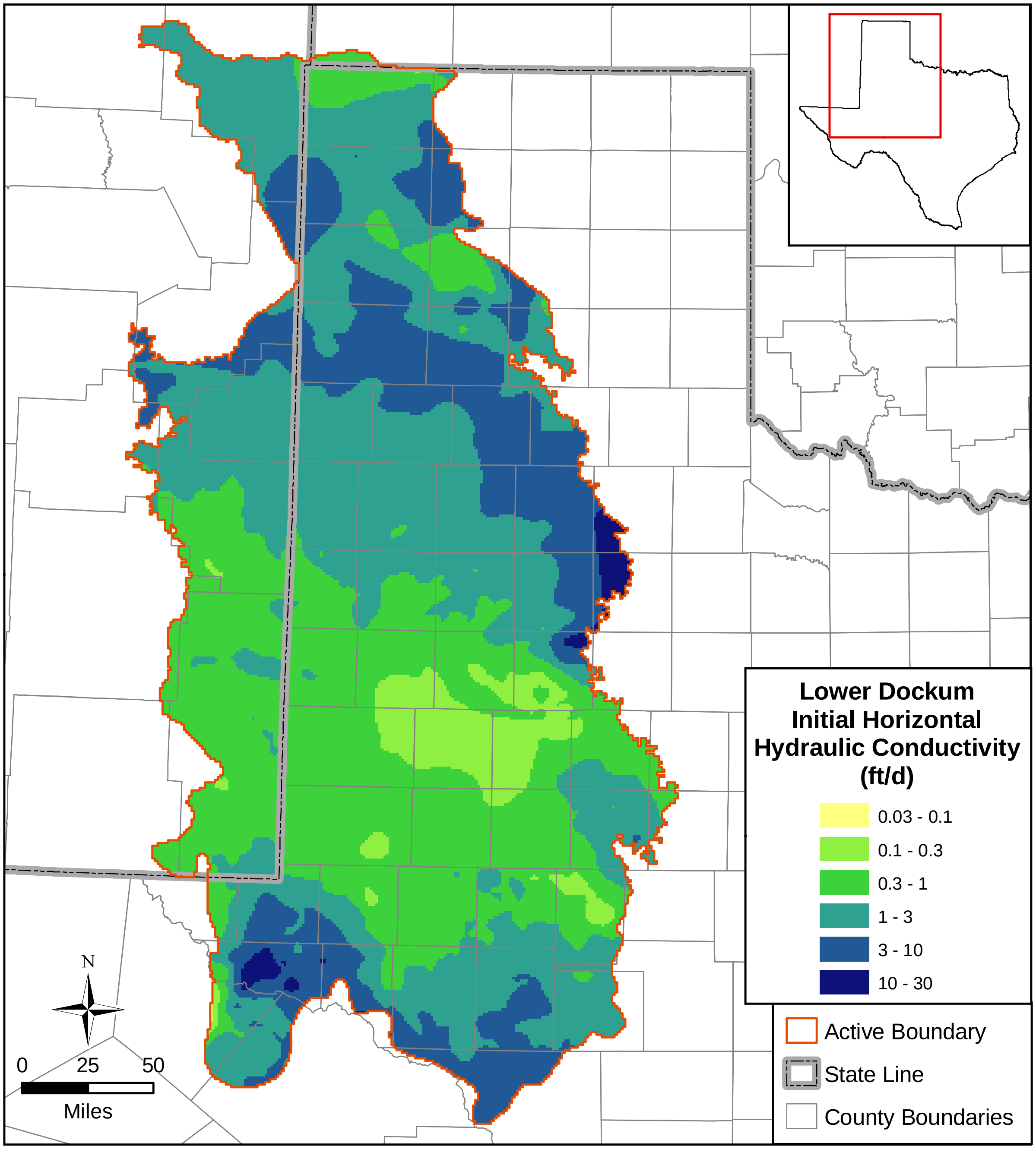


Figure 6.4.4 Layer 3 effective horizontal hydraulic conductivity in feet per day.

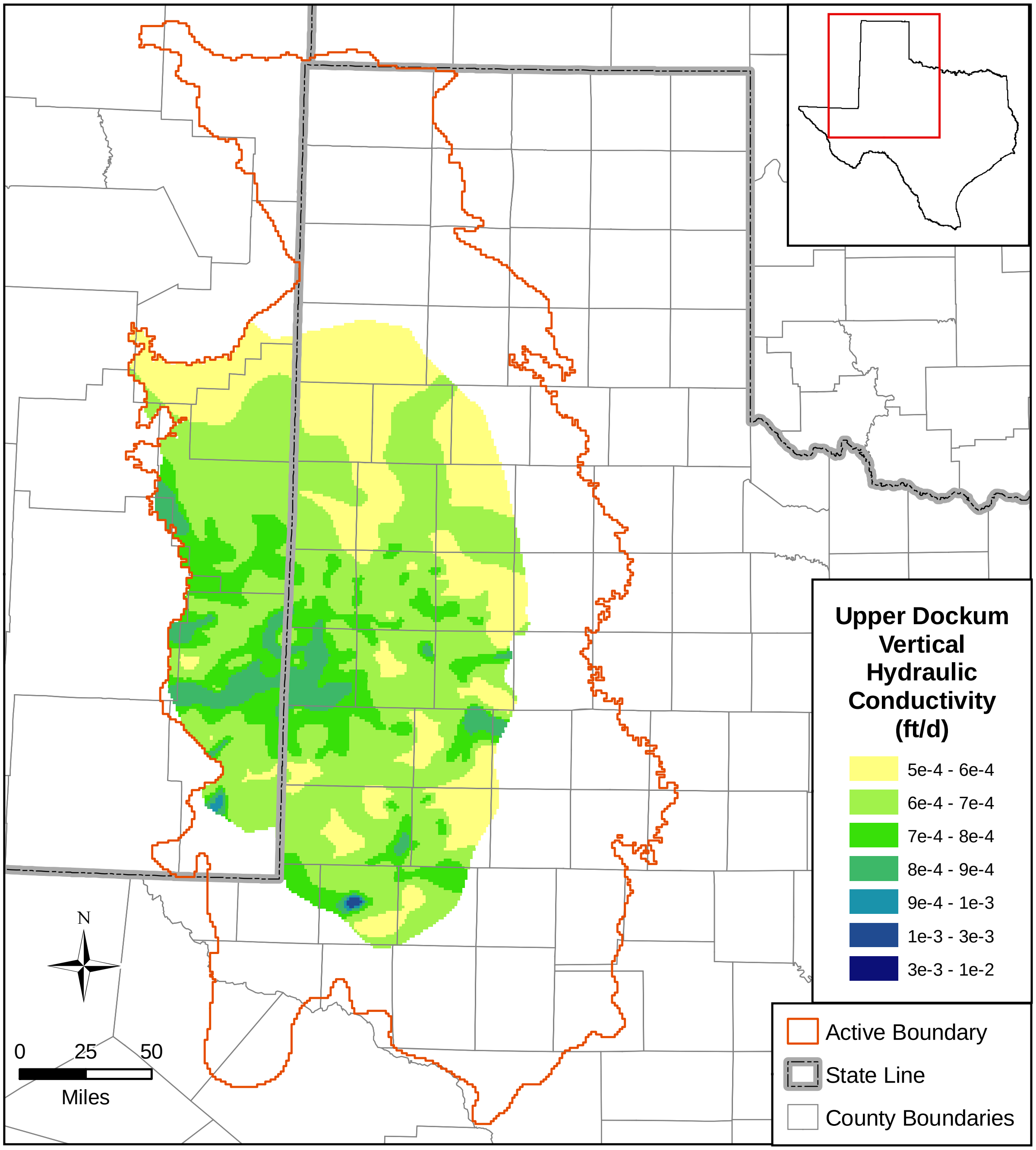


Figure 6.4.5 Layer 2 effective vertical hydraulic conductivity in feet per day.

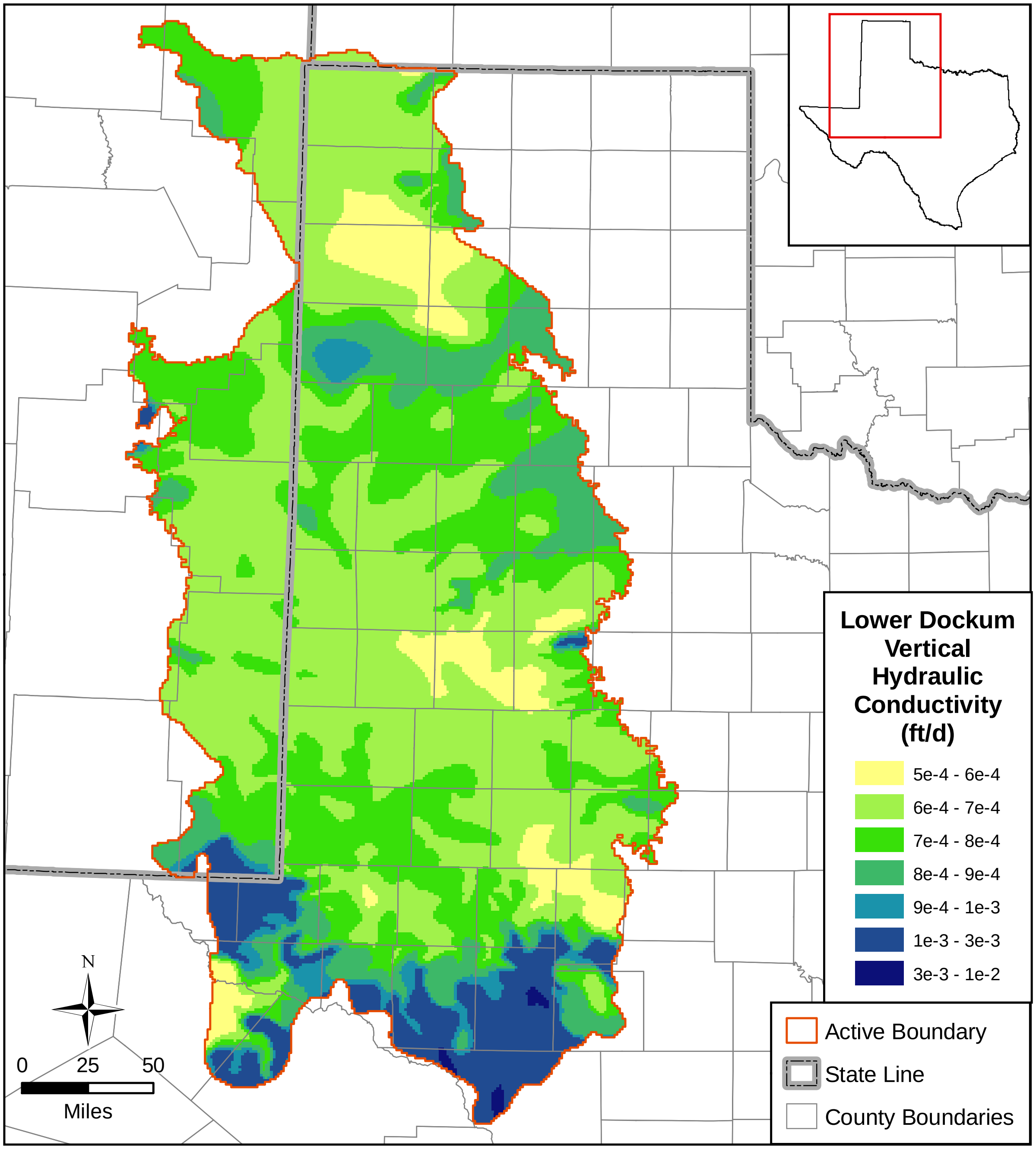


Figure 6.4.6 Layer 3 effective vertical hydraulic conductivity in feet per day.

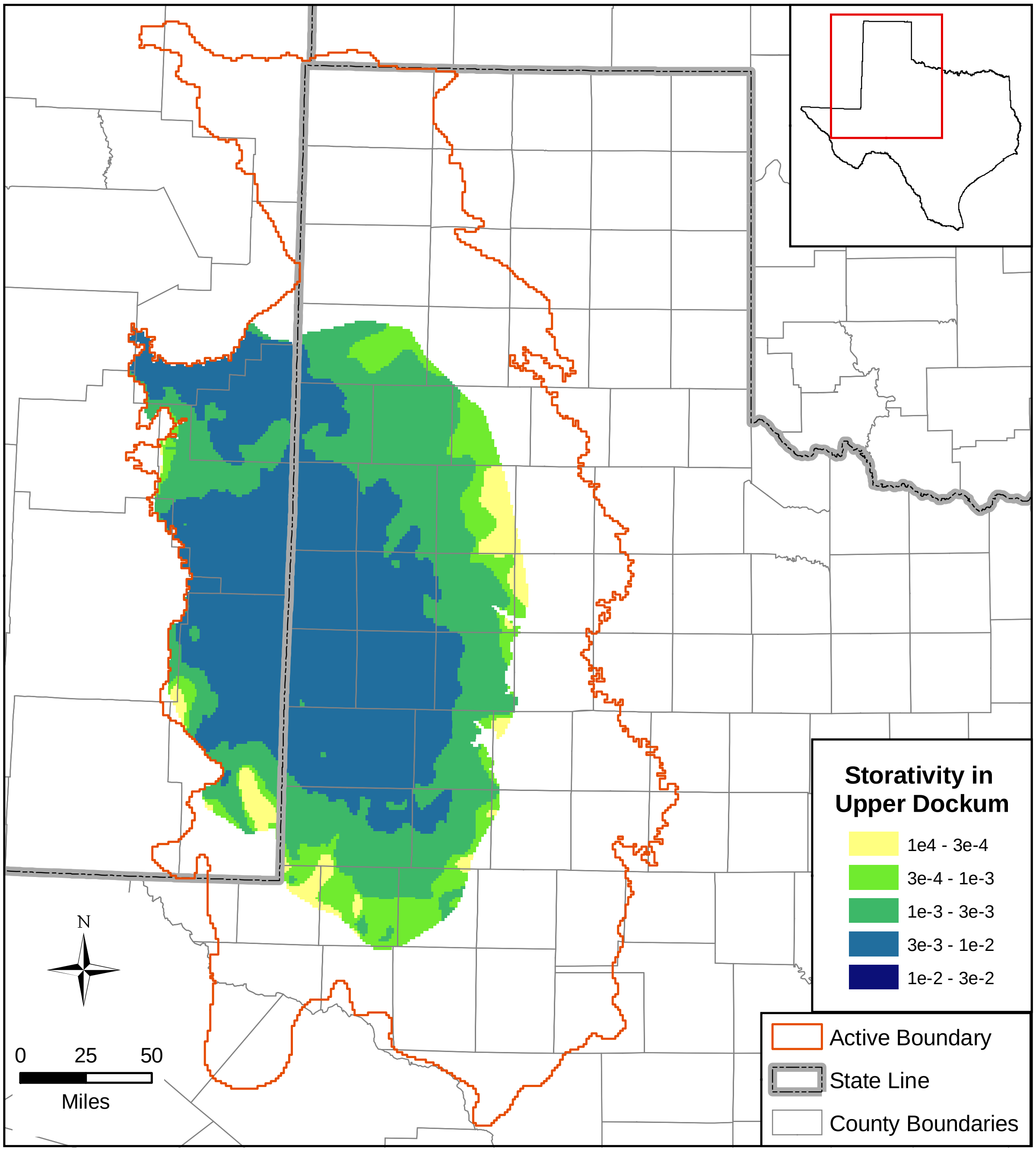


Figure 6.4.7 Layer 2 storativity.

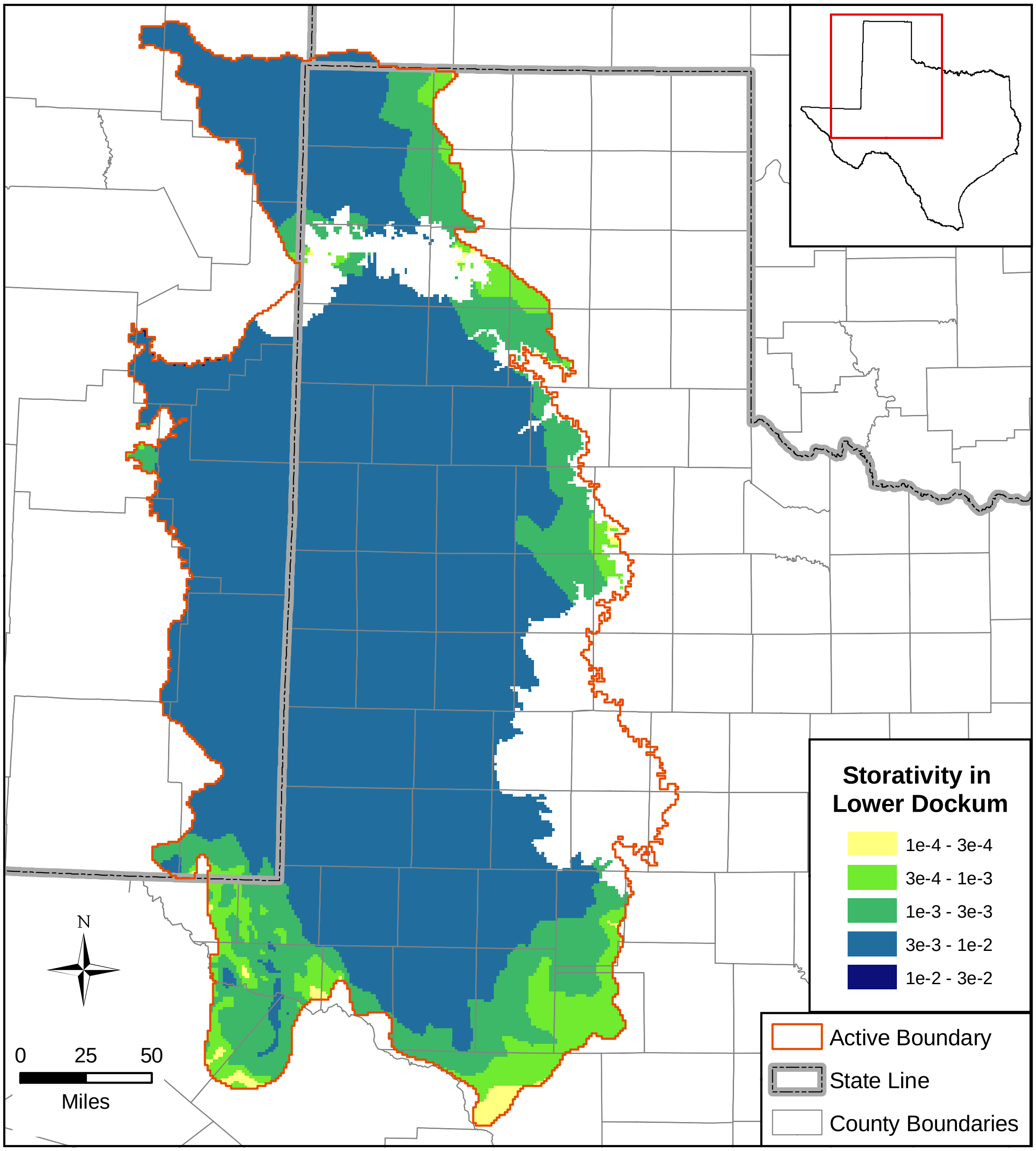


Figure 6.4.8 Layer 3 storativity.

7.0 Modeling Approach

The modeling approach included model calibration and model sensitivity analysis. In the context of groundwater modeling, model calibration can be defined as the process of producing an agreement between model simulated water levels and aquifer discharge, and field measured water levels and aquifer discharge through the adjustment of independent variables. Because the steady-state and transient models are combined within a single model, changes to the model made during calibration were propagated to both the steady-state and transient models. The generally accepted practice for groundwater calibration includes performance of a sensitivity analysis. A sensitivity analysis entails the systematic variation of the calibrated parameters and stresses with re-simulation of aquifer conditions. Those parameters which strongly change the simulated aquifer water levels and discharges are important parameters to the calibration. It is important to note that a standard "one-off" sensitivity analysis does not estimate parameter uncertainty, since limited parameter space is investigated and parameter correlation is not considered.

7.1 Calibration

Groundwater models are inherently non-unique, meaning that multiple combinations of hydraulic parameters and aquifer stresses can reproduce measured aquifer water levels. To reduce the impact of non-uniqueness, a calibration method described by Ritchey and Rumbaugh (1996) was employed. This method includes (1) calibrating the model using parameter values (i.e., hydraulic conductivity, storage coefficient, and recharge) that are consistent with measured values, (2) calibrating to multiple hydrologic conditions, and (3) using multiple calibration performance measures such as water levels and discharge rates to assess calibration. Each of these elements is discussed below.

Measured sand hydraulic conductivities for the Dockum Aquifer and literature values of clay hydraulic conductivity, specific yield, and sand and clay specific storage were used to initially estimate model parameters. The analysis of hydraulic parameters in Section 4.6 of this report indicates that adequate hydraulic conductivity data for the Dockum Aquifer are available for developing initial model values. However, minimal hydraulic conductivity measurements are available for the upper portion of the Dockum Aquifer and for the high total dissolved solids region of the lower portion of the Dockum Group. Vertical hydraulic conductivity is not measurable at the model scale and, thus, cannot be well constrained prior to calibration. Specific yield for the Dockum Aquifer was based on and was reasonably well constrained within literature values. Storativity for the Dockum Aquifer was developed based on sand maps and literature values for the specific storage of clay and sand. Storativity was reasonably well constrained by the literature values and several measurements. Although estimates of recharge are available in the study area, they serve primarily as reasonable bounds for average recharge and provide little information with respect to the spatial or temporal distribution of recharge. Adjustment of all model parameters were held to within plausible ranges based upon the available data and relevant literature. Adjustments to aquifer parameters from initial estimates were minimized, to the extent possible, to meet the calibration criteria. As a general rule, parameters with few measurements were adjusted preferentially as compared to properties with good supporting data.

The model was calibrated for two time periods, one representing steady-state conditions and the other representing transient conditions. The steady-state calibration considers a "predevelopment" time period prior to extensive aquifer development. The transient calibration period ran from 1980 through 1997 consistent with groundwater availability model requirements. 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 calibration period. Section 4.3 describes the aquifer water levels and how they were derived for use in the steady-state and transient calibration periods. Pumping estimates based upon historical records were applied on an annual time scale in the transient calibration period. Recharge and headwater stream flow remain constant throughout the transient period.

The model was calibrated through a wide range of hydrological conditions. The steady-state model represents a period of equilibrium where aquifer recharge and aquifer discharge are in balance. The transient calibration period (1980 through 1997) represents a time of transient aquifer behavior. The transient calibration period also helps to constrain the model parameterization because a wider range of hydrologic conditions are encountered and simulated.

The sensitivity of the transient model to certain parameters differs from that of the steady-state model.

Calibration requires development of calibration targets and specification of calibration measures. To address the issue of non-uniqueness, it is best to use as many types of calibration targets as possible. The primary type of calibration target is hydraulic head (water level). Stream leakages were also qualitatively used and the model was scrutinized with respect to the cross-formational flow with the aquifers overlying the Dockum Aquifer. Simulated water levels were compared to measured water levels at specific observation points through time (hydrographs) to ensure that model water levels are consistent with hydrogeologic interpretations.

Several stream gain/loss studies have been conducted on segments of the Colorado River and Beals Creek in the Colorado River outcrop. Simulated stream gains/losses were compared with values from these studies, however, the time scales of the studies (1 to 2 days) compared to the steady-state conditions of the predevelopment model and the annual stress-periods of the transient model limit the quantitative value of this comparison.

Springs constitute a small portion of the total discharge from the model domain. Because of the scale of the model grid cells, gross averaging of elevations and local hydraulic properties occur within the model cell. Some springs were coincident with stream cells and were removed. The spring with the largest discharge, Roaring Springs, lies outside the active model domain. These factors make direct comparison of simulated and observed flows in individual springs difficult. Instead, simulated spring flows were only evaluated in a qualitative manner to ensure that the total simulated spring flow approximated the total observed discharge through springs.

Traditional calibration measures (Anderson and Woessner, 1992), such as the mean error, the mean absolute error, and the root mean square error, quantify the average error in the calibration process. The mean error is the mean of the differences between simulated heads (h_s) and measured heads (h_m):

$$\text{mean error} = \frac{1}{n}\sum_{i=1}^{n}\left(h_s - h_m\right)_i \qquad (7.1.1)$$

where n is the number of calibration measurements. The mean absolute error is the mean of the absolute value of the differences between simulated heads (h_s) and measured heads (h_m):

$$\text{mean absolute error} = \frac{1}{n} \sum_{i=1}^{n} \left| (h_s - h_m)_i \right| \tag{7.1.2}$$

where n is the number of calibration measurements. The root mean square error is the average of the squared differences between simulated heads (h_s) and measured heads (h_m):

$$\text{root mean square error} = \left[\frac{1}{n} \sum_{i=1}^{n} (h_s - h_m)_i^2 \right]^{0.5} \tag{7.1.3}$$

where n is the number of calibration measurements. The difference between the measured hydraulic head and the simulated hydraulic head is termed a residual.

The mean absolute error was used as the basic calibration metric for heads. For the groundwater availability models, the required calibration criterion for heads is a mean absolute error that is equal to or less than 10 percent of the observed head range in the aquifer being simulated. To provide information on model performance with time, the mean absolute error was calculated for three periods (1980 through 1997, 1990, and 1997) within the calibration period. The mean absolute error is useful for describing model error on an average basis but, as a single measure, it does not provide insight into spatial trends in the distribution of the residuals.

An examination of the distribution of residuals is necessary to determine if they are randomly distributed over the model grid and not spatially biased. Post plots of head residuals for both Dockum Aquifer model layers were used to check for spatial bias. These plots indicate the magnitude and direction of the mis-match between the observed and simulated heads. Finally, plots of simulated versus observed water-level elevations and residual versus observed water levels were used to determine if the head residuals are biased based on the magnitude of the observed head surface.

7.2 Calibration Target Uncertainty

Calibration targets are uncertain. In order to not “over-calibrate” a model, which is a stated desire for the groundwater availability models, the calibration criteria should be defined consistently with the uncertainty in calibration targets. Uncertainty in head measurements can be the result of many factors including measurement errors, scale errors, and various types of averaging errors that are both spatial and temporal. The primary calibration criteria for head is a mean absolute error less than or equal to 10 percent of the observed head variation within the aquifer being modeled. Ranges in the observed water levels across the upper and lower portions of the Dockum Aquifer in the study area are on the order of 2,400 and 2,290 feet, respectively. This leads to an acceptable mean absolute error of 240 and 229 feet, for the upper and lower portions of the Dockum Aquifer, respectively. Comparison of this mean absolute error to an estimate of the head target errors indicates what level of calibration the underlying head targets can support.

Water-level measurement errors are typically on the order of tenths of feet and, at the groundwater availability model scale, can be considered insignificant. However, measuring-point elevation errors can be significant. The error (standard deviation) in averaging ground surface elevations available on a 30-meter grid to a one-mile grid averages 15 feet and exceeds 100 feet in hundreds of grid cells with higher topographic slopes (primarily along the edges of the Dockum Aquifer escarpment and in river valleys). Another error is caused by combining several sediment types into single one-square-mile grid blocks represented by one simulated head. Comparing coincident targets within a single grid block indicates errors averaging 36 feet and exceeding 100 feet in some areas. This error can be even greater near pumping centers. When these errors are added up, the average error in model heads could easily equal 30 to 40 feet. Calibrating to mean absolute error values significantly less than 40 feet would constitute over-calibration of the model and parameter adjustments to reach that mean absolute error are not supported by the hydraulic head uncertainty.

7.3 Sensitivity Analysis

A sensitivity analysis was performed on the steady-state and transient calibrated models to determine the impact of changes in a calibrated parameter on the predictions of the calibrated model. A standard “one-off” sensitivity analysis was performed. This means that hydraulic parameters or stresses were adjusted from their calibrated “base case” values one by one while all other hydraulic parameters remained unperturbed.

8.0 Steady-State Model

The steady-state model developed for the Dockum Aquifer represents a predevelopment period when water levels in the aquifer appeared to be constant. This section details calibration of the steady-state model and presents the steady-state model results. The sensitivity of the steady-state model to various hydrologic parameters is also described.

8.1 Calibration

This section describes the steady-state calibration targets and potential calibration parameters including horizontal and vertical hydraulic conductivity, recharge, evapotranspiration, general-head boundaries, and stream conductance.

8.1.1 Calibration Targets

Water-level measurements are needed as targets for steady-state calibration. Selection of water-level measurements representative of steady-state conditions was discussed in Section 4.3.2. Steady-state targets included water-level measurements from 29 well locations in the upper portion of the Dockum Aquifer and water-level measurements from 191 well locations in the lower portion of the Dockum Aquifer. Within the upper portion of the Dockum Aquifer, no grid blocks contained multiple steady-state targets. Within the lower portion of the Dockum Aquifer, three grid blocks contained multiple steady-state targets. The number of targets in these grid blocks ranges from 2 to 4 and the difference in water levels for the targets in these grid blocks ranges from 1.0 to 32.7 feet. The standard deviation (error) of the water levels for grid blocks containing two or more targets ranges from 0.7 to 17 feet and averages 8 feet for the lower portion of the Dockum Aquifer. For the grid blocks containing multiple steady-state water levels, the average water level was selected as the calibration target. To avoid introducing additional errors by using a surveyed ground-surface elevation at each well, the water-level elevation for the steady-state targets was calculated using the measured depth-to-water and the grid-block averaged ground-surface elevation from the model.

8.1.2 Horizontal and Vertical Hydraulic Conductivities

Section 6.4.1 described the determination of initial horizontal and vertical hydraulic conductivities for the model. Figures 8.1.1 and 8.1.2 depict the final calibrated horizontal hydraulic conductivity fields for the upper and lower portions of the Dockum Aquifer, respectively. The final calibrated horizontal hydraulic conductivity fields for both the upper and lower portions of the Dockum Aquifer were 20 percent of their initial estimates. During the conceptual model phase, it was postulated that the sand hydraulic conductivity measurements may be biased high based on wells being preferentially located in more conductive regions. This is consistent with the reduction in horizontal hydraulic conductivity required for calibration. Hydraulic conductivity and recharge can be correlated parameters preventing independent estimation when using only water-level data constraints. Accordingly, during calibration of the steady-state model, recharge was held constant and only the hydraulic conductivity was varied.

In the steady-state model, vertical leakance of groundwater from layer 1 to layers 2 and 3 is controlled primarily by the horizontal conductivity of layer 3 and the vertical conductivity of layer 2. The vertical hydraulic conductivity is primarily dictated by the value used for the hydraulic conductivity of clay. Literature values for clay hydraulic conductivity range from 2.8×10^{-6} to 1.3×10^{-3} feet per day (Domenico and Schwartz, 1998). This parameter was adjusted during calibration and a somewhat high – but well within the literature bounds – value of clay hydraulic conductivity equal to 5×10^{-4} feet per day was used for the calibrated steady-state model. Conceptually, smaller values would be applicable to smaller scales while larger values would be applicable to regional scales where clay layers would tend to be discontinuous over large distances. During calibration, the vertical hydraulic conductivity values for all three model layers were uniformly lowered to 50 percent of their initial estimates. The final, calibrated vertical hydraulic conductivities for the upper and lower portions of the Dockum Aquifer are shown in Figures 8.1.3 and 8.1.4, respectively.

8.1.3 Recharge and Groundwater Evapotranspiration

Recharge in the steady-state model was based on chloride measurements and its implementation is discussed in Section 6.3.4. Altering recharge and hydraulic conductivity concurrently leads to inherently non-unique calibrations (Castro and Goblet, 2003). Furthermore, using data to constrain recharge has been demonstrated to be more efficient at stabilizing the groundwater inverse problem than constraining conductivity values when calibrating primarily to hydraulic head data (Weiss and Smith, 1998). For these reasons, recharge was not altered during the calibration process.

As described in Section 6.3.4, investigatory simulations demonstrated that the evapotranspiration rates in the steady-state model are limited by the hydraulic properties of the Dockum Aquifer itself and not by the properties of the evapotranspiration boundary condition. The model was insensitive to the drain conductance of the evapotranspiration boundary condition and the drain elevations were set to the rooting depths, which were reasonably well constrained by data. Accordingly, the drain parameters controlling evapotranspiration rates were unaltered during the calibration process.

8.1.4 General-Head Boundaries

The heads in the general-head boundaries were estimated based on a regression between measured water levels and land surface elevation. The general-head boundary conductances were set at large values in consideration of the conceptual model of the Dockum Aquifer hydraulic properties generally being much lower in value to those of the overlying aquifers and, therefore, being the primary limiter of flow into the Dockum Aquifer. The model was insensitive to the general-head boundary conductances but sensitive to the general-head boundary heads. Because the general-head boundary heads were well constrained by numerous, spatially-distributed water-level measurements, they were unaltered during model calibration.

8.1.5 Stream Conductances

Because streams act as a major avenue of both recharge and discharge within the shallow, local flow system occurring in the outcrop portions of the Dockum Aquifer, simulated water levels in the outcrop of the lower portion of the Dockum Aquifer were sensitive to stream conductances. In addition, streams act as a discharge pathway for the regional flow system throughout the whole of the Dockum Aquifer. The stream conductance was lowered uniformly for all stream segments until the model would converge with sufficiently small head closure criteria (0.01 feet) and the total stream gain/loss was of approximately the same magnitude as the total areal recharge. This resulted in a uniform streambed hydraulic conductivity of 0.1 feet per day for all stream segments with individual streambed conductances ranging anywhere from 29 to

670,000 square feet per day depending on the Enhanced River Reach File stream width and the length of the stream within the gridblock.

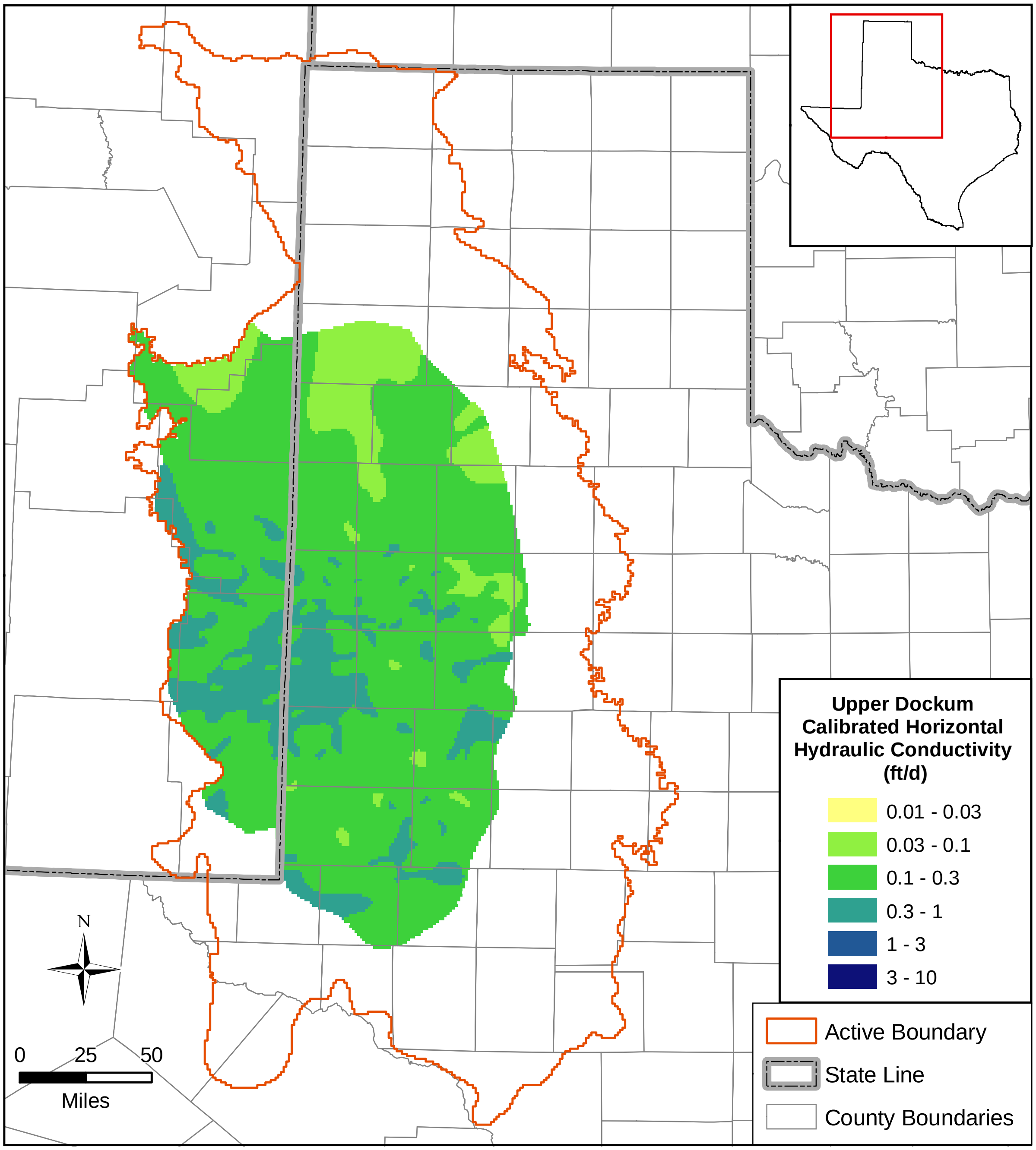


Figure 8.1.1 Calibrated horizontal hydraulic conductivity in feet per day for the upper portion of the Dockum Aquifer.

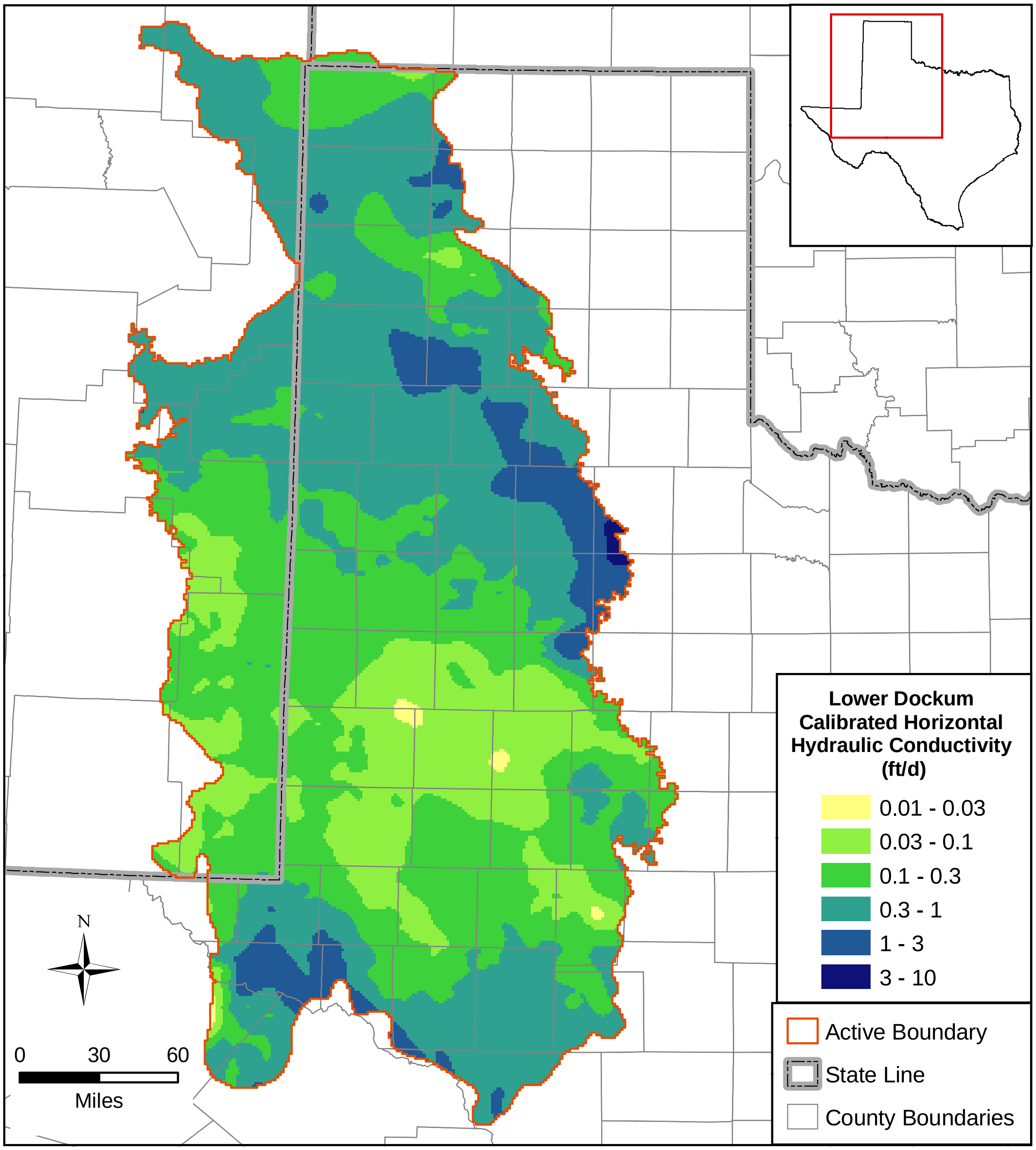


Figure 8.1.2 Calibrated horizontal hydraulic conductivity in feet per day for the lower portion of the Dockum Aquifer.

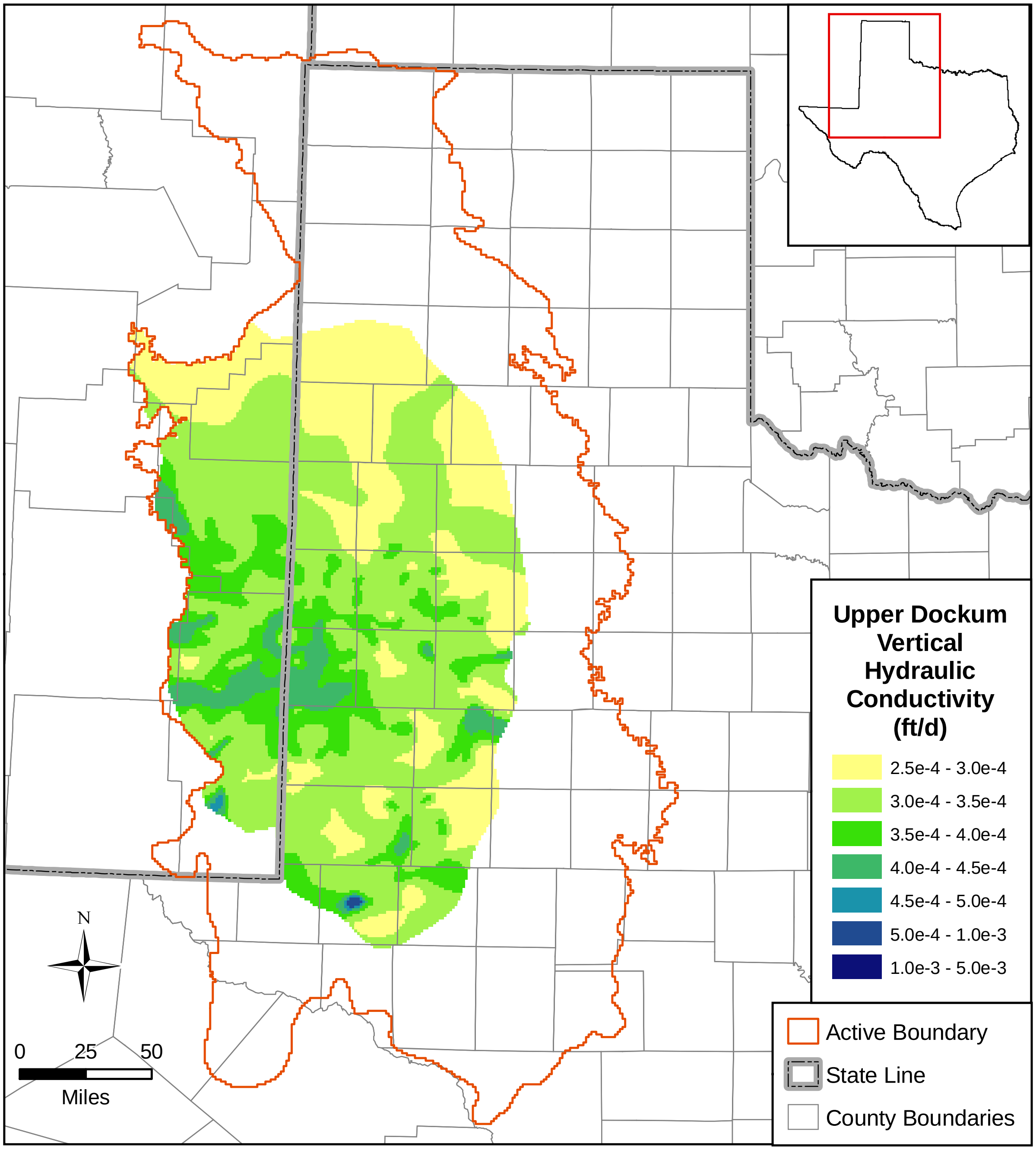


Figure 8.1.3 Calibrated vertical hydraulic conductivity in feet per day for the upper portion of the Dockum Aquifer.

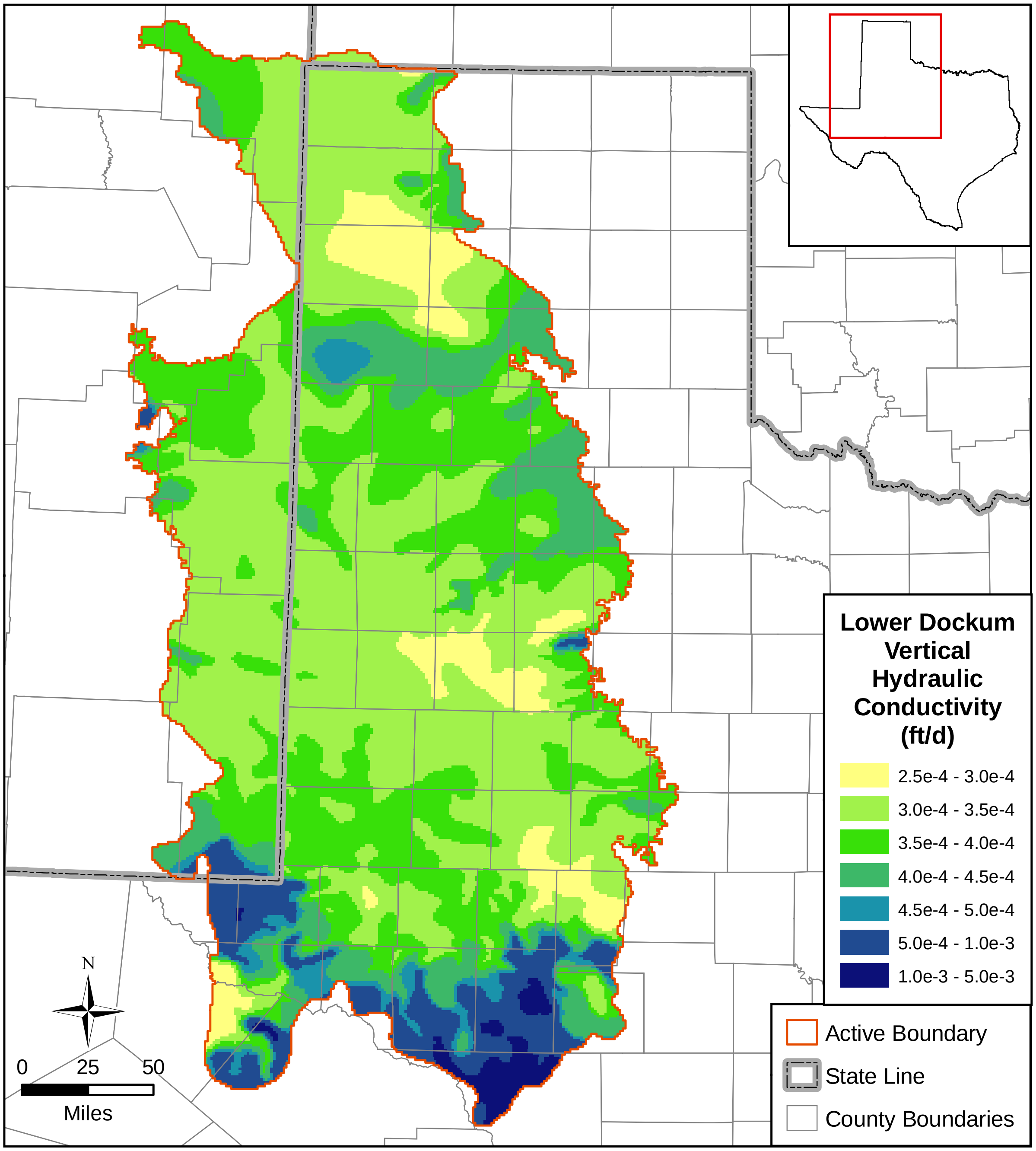


Figure 8.1.4 **Calibrated vertical hydraulic conductivity in feet per day for the lower portion of the Dockum Aquifer.**

8.2 Simulation Results

Calibration of the steady-state model is not unique. Calibrated results can be obtained by numerous combinations of recharge and vertical and horizontal hydraulic conductivities. Apart from the general-head boundary heads, which were not adjusted, the steady-state model is most sensitive to the horizontal hydraulic conductivity of the lower portion of the Dockum Aquifer and, in the case of the upper portion of the Dockum Aquifer, the vertical hydraulic conductivity of the upper portion of the Dockum Aquifer. This is to be expected, since the horizontal hydraulic conductivity in the lower portion of the Dockum Aquifer provides resistance across the major northwest to southeast flow path across the entire model and the vertical hydraulic conductivity of the upper portion of the Dockum Aquifer is the primary regulator of flow from the Ogallala into the upper portion of the Dockum Aquifer.

8.2.1 Water-Level Elevation

A comparison of simulated and observed water levels and residuals versus observed water levels are shown in Figure 8.2.1 for layer 2 and in Figure 8.2.2 for layer 3, where residuals are defined as:

$$\text{residual} = \text{head}_{\text{simulated}} - \text{head}_{\text{measured}} \qquad (8.2.1)$$

A positive residual indicates that the model has overpredicted the hydraulic head, while a negative residual indicates underprediction. Residuals in layer 2 range from –224 to 186 feet with 69 percent falling between –100 and 100 feet. The residuals for the upper portion of the Dockum Aquifer are equally split between underpredicting (52 percent) and overpredicting (48 percent) observed values, indicating very little overall bias in the simulations. Residuals in layer 3 range from –139 to 274 feet with 89 percent falling between –100 and 100 feet. The residuals for the lower portion of the Dockum Aquifer are relatively equally split between underpredicting (45 percent) and overpredicting (55 percent) observed values, indicating little overall bias in the simulations.

Figures 8.2.3 and 8.2.4 show the simulated water-level elevations for model layers 2 and 3, respectively. These figures show a general northwest to southeast groundwater gradient following the topographical gradient. Additionally, localized gradients are apparent toward river valleys within the outcrop of the lower portion of the Dockum Aquifer. Post plots of residuals are also included in Figures 8.2.3 and 8.2.4 for layers 2 and 3, respectively. In general, the model exhibits no obvious bias in the locations of the residuals.

The calibration statistics for both Dockum Aquifer layers are summarized in Table 8.2.1. The adjusted mean absolute error (i.e., mean absolute error divided by the range in observed water levels) is 3 percent for the upper portion of the Dockum Aquifer and 2 percent for the lower portion of the Dockum Aquifer. The adjusted mean absolute error is less than 1 percent of the range in observed heads for both the upper and lower portions of the Dockum Aquifer, indicating very little overall bias in the simulated heads.

Some grid cells exhibited dry conditions in the steady-state simulation. Out of 5,918 active outcrop cells, 12 were dry, or 0.2 percent. The majority (eight) of these dry cells were at the edges of the eastern escarpment of the Dockum Aquifer where the formation is thin. The remaining four dry cells were in the Canadian River outcrop in the areas where the Canadian River has incised through the Dockum Aquifer and actually lies on Permian sediments. These cells had been made active to provide continuity between active cells where the binary choice between an active and inactive cell is based on the somewhat arbitrary (in the context of one-mile grid cells) location of grid cell centers with respect to the Dockum Aquifer boundary. These dry cells may be indicative of actual subsurface conditions or limitations in the model caused by averaging structure and water level to one-mile grid blocks. Additionally, there were 33 dry cells in layer 1 and five dry cells in the 1-foot thick connective portions of layer 2. However, these are considered to be of little consequence as neither group constitutes part of the Dockum Aquifer. Furthermore, the dry cells are few enough in number that they do not impact the layer 1 boundary condition appreciably.

8.2.2 Streams, Springs, and Evapotranspiration

The simulated stream gain/loss distribution for the steady-state model is depicted in Figure 8.2.5. Stream gain/loss data are available only within a small portion the Colorado outcrop area of the model (see Section 4.5.1) and constitute studies conducted over only one or two days. In contrast, the model describes the steady-state gain/loss within the stream segment. The studies on both the Colorado River and on Beals Creek indicate that both gaining and losing conditions can be observed in both study areas. A comparison of the simulated and measured stream gains/losses is shown in Figure 8.2.6, where study A, B, C, and D refer to the first, second, third, and fourth studies, respectively, conducted on the reach. Note that the number of studies conducted on a given reach ranged from one to four. The model shows moderately gaining conditions of 7 acre-feet per year per mile on Beals Creek and a range from 14 to 23 acre-feet per year per mile on the slightly differing lengths of the same area on the Colorado River. Little quantitative information can be gained from this analysis as the time scale of the simulations is too dissimilar from those of the measurements.

The simulated spring flow for the steady-state model is shown in Figure 8.2.7. Some spring flow occurs in 54 out of a total of 71 springs, however, some of the larger measured flows could not be matched by the model. An analysis, whereby spring elevations were systematically lowered and spring conductances systematically increased, indicates that it is the properties of the Dockum Aquifer and the rates of cross-formational flow and recharge into the Dockum Aquifer, rather than the properties of the drain boundary conditions, that limit the spring discharge rate. The localized drainage system and geometry of individual springs are likely at a scale considerably smaller than that which the model can feasibly simulate. No further attempt to match individual spring flows was made during the calibration.

The simulated evapotranspiration discharge for the steady-state model is shown in Figure 8.2.8. Evaporation occurs in 565 of the 2,146 riparian cells with the maximum simulated rate equivalent to 18 inches per year. These evapotranspiration rates tend to be considerably less than the calculated maximum evapotranspiration rates, which range from 32 to 52 inches per year as discussed in Section 6.3.4. Because the drain elevations were set at the estimated root depths and the water level has reached the root depth when flow occurs, these positive but low flow rates indicate that either the Dockum Aquifer cannot supply water at a rate equal to the calculated maximum evapotranspiration rate or that the riparian areas are much smaller than the one-mile grid cells.

8.2.3 Cross-formational Flow from Younger Units

The simulated cross-formational flow from the Ogallala and younger aquifers to the Dockum Aquifer is depicted in Figure 8.2.9. This figure indicates that the majority of the cross-formational flow is downward, into the Dockum Aquifer. In agreement with the conceptual model, the cross-formational flow tends to be very small above the upper portion of the Dockum Aquifer and tends to be largest at the edges of the Dockum Aquifer along the eastern and southwestern escarpments. Cross-formational communication is also greater beneath the Pecos Valley Aquifer where the Dockum Aquifer is conceptualized to be in better hydraulic connection with the overlying units.

8.2.4 Water Budget

Tables 8.2.2 and 8.2.3 summarize the water budget for the steady-state model in terms of total volume and as a percentage of total inflow and outflow. The overall mass balance error for the steady-state simulation was 0.00 percent in the MODFLOW list output, well under the groundwater availability model requirement of one percent. The Dockum Aquifer is a minor aquifer underlying several major aquifers. Because the Ogallala (in particular) and other overlying aquifers tend to be much more conductive than the Dockum Aquifer, the water budgets for the overlying aquifers are much larger than that for the Dockum Aquifer. This means that the budget numbers in layer 1 tend to obfuscate the budget for the Dockum Aquifer, particularly when viewed in terms of percentages.

The predominant sources of inflow to the Dockum Aquifer are cross-formational flow from the overlying aquifers and recharge, followed by stream loss. Water discharges the Dockum Aquifer through streams and evapotranspiration and, to a much lesser extent, springs. To better illustrate the budget within the Dockum Aquifer, Table 8.2.4 shows the water budget for the Dockum Aquifer (layers 2 and 3) alone. Table 8.2.5 represents the equivalent budget expressed in terms of percentages of net inflow. Net cross-formational flow between the Ogallala/younger aquifers and the Dockum Aquifer is downward. Net cross-formational flow from the overlying units into the upper portion of the Dockum Aquifer accounts for 29 percent of the net inflow (areal recharge plus net cross-formational recharge) to the Dockum Aquifer as a whole. Net cross-formational flow from the overlying units to the lower portion of the Dockum Aquifer constitutes 35 percent of the net inflow to the Dockum Aquifer. Normalized to area, net recharge from cross-formational flow is equivalent to 0.015 inches per year into the upper portion of the Dockum Aquifer and 0.020 inches per year into the lower portion of the Dockum Aquifer. These values are approximately an order of magnitude less than the average areal recharge rate of

0.15 inches per year in the Dockum Aquifer outcrop. Evapotranspiration constitutes a discharge equal to 56 percent of the net inflow to the Dockum Aquifer. Streams in the model are generally gaining with a net gain equal to 42 percent of the net inflow to the Dockum Aquifer. Discharge to springs is relatively insignificant, comprising only 2 percent of the net Dockum Aquifer inflow. However, some portion of the actual spring discharge is incorporated into the stream discharge for the springs that coincide with stream cells. The steady-state water budgets for the Dockum Aquifer by county and by Groundwater Conservation District are summarized in Tables 8.2.6 and 8.2.7, respectively.

As discussed in Section 6.2, the upper portion of the Dockum Aquifer constitutes only a portion of layer 2 and, as discussed in Section 6.3.4, the drain package is used to represent both springs and evapotranspiration in the model. Because of these two aspects of the model, custom Perl scripts were used to differentiate flow within the upper portion of the Dockum Aquifer from other layer 2 flows and to differentiate spring flows from evapotranspiration flows in the reported water budgets. The scripts and associated documentation are included with the model files.

Table 8.2.1 Calibration statistics for the steady-state model.

Aquifer	Number	ME (feet)	MAE (feet)	RMS (feet)	Range (feet)	Adjusted MAE
Upper Dockum	29	16.1	76.3	99.8	2404	0.032
Lower Dockum	180	23.6	53.3	73.0	2289	0.023

ME = mean error MAE = mean absolute error RMS = root mean square

Table 8.2.2 Water budget for the steady-state model (all rates reported in acre-feet per year).

IN	Layer	Recharge	Streams		GHBs	Top	Bottom
	1	0	0		851,919	0	54,500
	2	127	83		0	90,508	45,366
	3	24,727	10,090		0	81,166	0
	sum	24,854	10,173		851,919	171,674	99,866
OUT	**Layer**	**ET**	**Streams**	**Springs**	**GHBs**	**Top**	**Bottom**
	1	0	0	0	-815,910	0	-90,508
	2	0	-420	0	0	-54,500	-81,166
	3	-26,083	-42,502	-2,030	0	-45,366	0
	sum	-26,083	-42,921	-2,030	-815,910	-99,866	-171,674

GHBs = general-head boundaries ET = evapotranspiration

Table 8.2.3 Water budget for the steady-state model with values expressed as a percentage of inflow or outflow.

IN	Layer	Recharge	Streams		GHBs
	1	0.00%	0.00%		96.05%
	2	0.01%	0.01%		0.00%
	3	2.79%	1.14%		0.00%
	sum	2.80%	1.15%		96.05%
OUT	**Layer**	**ET**	**Streams**	**Springs**	**GHBs**
	1	0.00%	0.00%	0.00%	91.99%
	2	0.00%	0.05%	0.00%	0.00%
	3	2.94%	4.79%	0.23%	0.00%
	sum	2.94%	4.84%	0.23%	91.99%

GHBs = general-head boundaries ET = evapotranspiration

Table 8.2.4 Water budget for the Dockum Aquifer portion of the steady-state model (all rates reported in acre-feet per year).

Layer	Recharge	Younger –Dockum Cross-Formational Flow	Streams	ET	Springs	Upper-Lower Cross-Formational Flow
Upper Dockum	127	17,048	-336	0	0	-16,915
Lower Dockum	24,727	18,884	-32,412	-26,083	-2,030	16,915
Sum	24,854	35,932	-32,748	-26,083	-2,030	0

ET = evapotranspiration
Note: positive values indicate net flow into the aquifer.

Table 8.2.5 Water budget for the Dockum Aquifer portion of the steady-state model expressed as percentage of net inflow.

Layer	Recharge	Younger –Dockum Cross-Formational Flow	Streams	ET	Springs
Upper Dockum	0.2%	28.0%	-0.6%	0.0%	0.0%
Lower Dockum	40.7%	31.1%	-53.3%	-42.9%	-3.3%
Sum	40.9%	59.1%	-53.9%	-42.9%	-3.3%

ET = evapotranspiration
Note: positive values indicate net flow into the aquifer.

Table 8.2.6 Steady-state water budget in the Dockum Aquifer by county (all rates reported in acre-feet per year).

County	State	Recharge	Younger–Dockum Cross-Formational Flow	Streams	ET	Springs
Andrews County	TX	0	1,732	0	0	0
Armstrong County	TX	650	-257	-189	-236	-164
Bailey County	TX	0	-1,138	0	0	0
Borden County	TX	412	503	-250	-816	0
Briscoe County	TX	692	5,334	-2,956	-2,164	-402
Carson County	TX	0	-15	0	0	0
Castro County	TX	0	1,747	0	0	0
Cochran County	TX	0	155	0	0	0
Coke County	TX	105	-235	0	0	0
Crane County	TX	0	-4,909	0	0	0
Crockett County	TX	0	-2,737	0	0	0
Crosby County	TX	870	10,399	-3,888	-2,825	-18
Dallam County	TX	0	-764	0	0	0
Dawson County	TX	0	1,515	-144	-625	0
Deaf Smith County	TX	594	8,645	-82	-3,059	0
Dickens County	TX	1,076	3,389	-359	-1,137	-143
Ector County	TX	0	5,229	0	0	0
Fisher County	TX	391	0	-213	-144	0
Floyd County	TX	367	5,476	-1,113	-164	-605
Gaines County	TX	0	-2,284	0	0	0
Garza County	TX	1,020	805	-1,821	-1,015	-42
Glasscock County	TX	0	360	0	0	0
Hale County	TX	0	575	0	0	0
Hartley County	TX	231	-869	-410	-567	0
Hockley County	TX	0	-948	0	0	0
Howard County	TX	1,521	370	-549	-551	0
Irion County	TX	0	-602	0	0	0
Kent County	TX	465	0	-217	-147	-15
Lamb County	TX	0	-1,156	0	0	0
Loving County	TX	0	364	0	0	0
Lubbock County	TX	0	1,906	-87	-1,551	0
Lynn County	TX	0	1,247	-43	0	0
Martin County	TX	0	-1,090	0	0	0
Midland County	TX	0	-410	0	0	0
Mitchell County	TX	3,949	387	-3,357	-1,871	-3
Moore County	TX	25	-653	-277	0	0
Motley County	TX	491	-17	-1,947	-1,012	-277
Nolan County	TX	366	0	-62	-54	0
Oldham County	TX	5,105	4,969	-7,761	-2,624	-63
Parmer County	TX	0	1,359	0	0	0

Table 8.2.6, continued

County	State	Recharge	Younger–Dockum Cross-Formational Flow	Streams	ET	Springs
Pecos County	TX	0	-445	0	0	0
Potter County	TX	2,266	-617	-761	-1,404	-123
Randall County	TX	116	4,780	-2,383	-819	-36
Reagan County	TX	0	321	0	0	0
Reeves County	TX	0	-237	0	0	0
Scurry County	TX	2,501	0	-1,007	-1,248	-137
Sherman County	TX	0	-516	0	0	0
Sterling County	TX	438	-95	-224	-27	0
Swisher County	TX	9	2,282	-307	0	0
Terry County	TX	0	-1,585	0	0	0
Tom Green County	TX	0	5	0	0	0
Upton County	TX	0	5,484	0	0	0
Ward County	TX	0	-3,189	0	0	0
Winkler County	TX	0	-291	0	0	0
Yoakum County	TX	0	74	0	0	0
Cimarron County	OK	0	154	0	0	0
Chaves County	NM	0	1,311	0	0	0
Colfax County	NM	0	1,740	0	0	0
Curry County	NM	10	9,118	0	0	0
DeBaca County	NM	0	-955	0	0	0
Eddy County	NM	0	-145	0	0	0
Guadalupe County	NM	0	152	0	0	0
Harding County	NM	0	537	0	0	0
Lea County	NM	0	3,223	0	0	0
Quay County	NM	1,183	5,836	-2,340	-2,022	0
Roosevelt County	NM	0	421	0	0	0
Union County	NM	0	6,273	0	0	0

ET = evapotranspiration TX = Texas NM = New Mexico

Table 8.2.7 Steady-state water budget in the Dockum Aquifer by Groundwater Conservation District (all rates reported in acre-feet per year).

Groundwater Conservation District	Recharge	Younger Recharge	Streams	ET	Springs
Clear Fork GCD	377	0	-213	-144	0
Coke County UWCD	105	-234	0	0	0
Crockett County GCD	0	-2,740	0	0	0
Garza County Underground And Fresh WCD	995	846	-1,895	-1,059	-42
Glasscock GCD	0	395	0	0	0
High Plains UWCD No.1	451	20,918	-2,243	-3,127	-179
Irion County WCD	0	-620	0	0	0
Llano Estacado UWCD	0	-2,280	0	0	0
Lone Wolf GCD	3,949	387	-3,357	-1,871	-3
Mesa UWCD	0	1,521	-163	-720	0
Middle Pecos GCD	0	-354	0	0	0
North Plains GCD	56	-2,743	0	0	0
Panhandle GCD	2,790	-625	-815	-1,640	-287
Permian Basin UWCD	1,521	-886	-549	-551	0
Salt Fork UWCD	535	0	-253	-147	-15
Sandy Land UWCD	0	67	0	0	0
Santa Rita UWCD	0	319	0	0	0
South Plains UWCD	0	-1,620	0	0	0
Sterling County UWCD	438	-129	-224	-27	0
Wes-Tex GCD	366	0	-62	-54	0

ET = evapotranspiration
GCD = Groundwater Conservation District
UWCD = Underground Water Conservation District
WCD = Water Conservation District

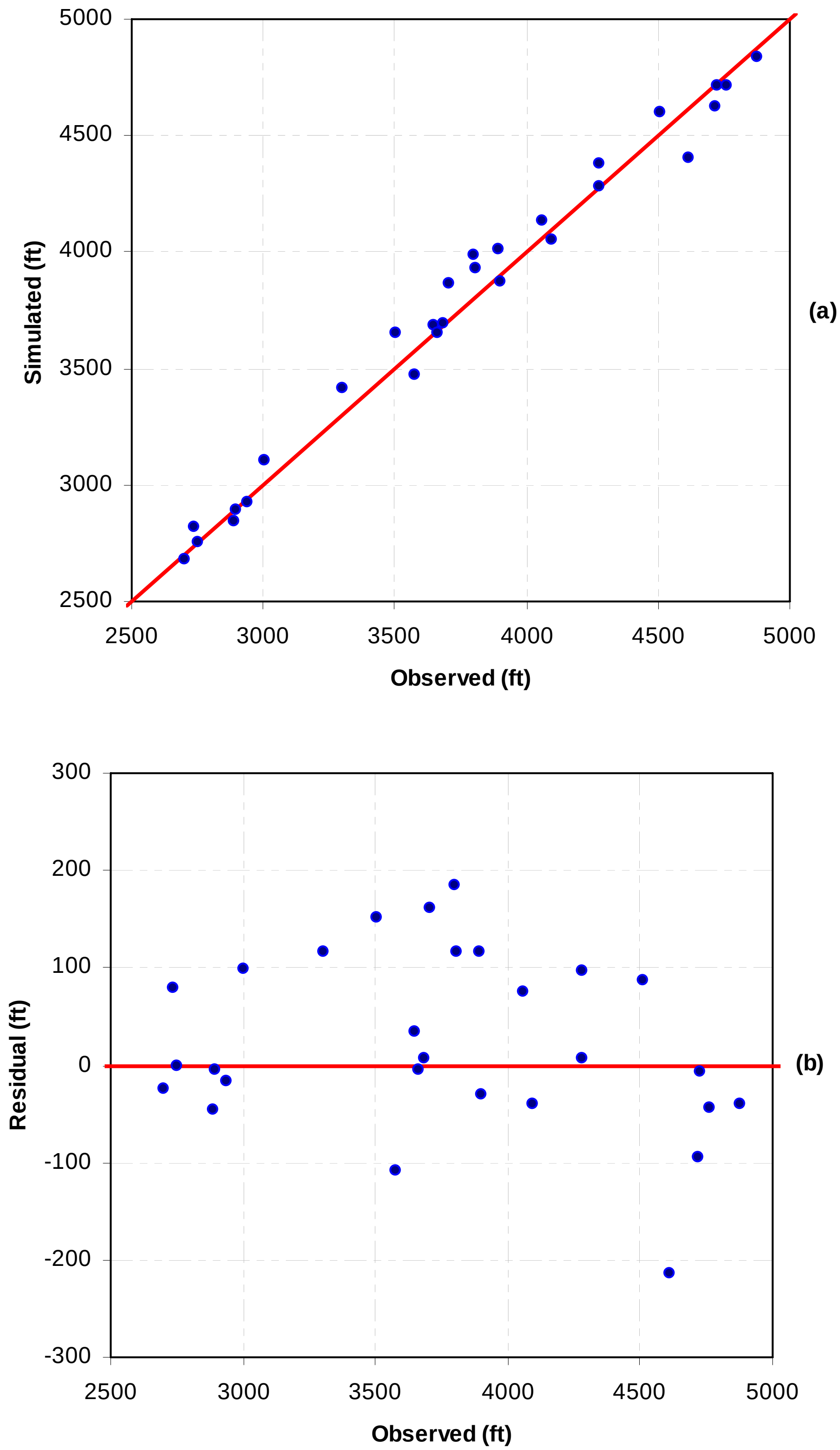
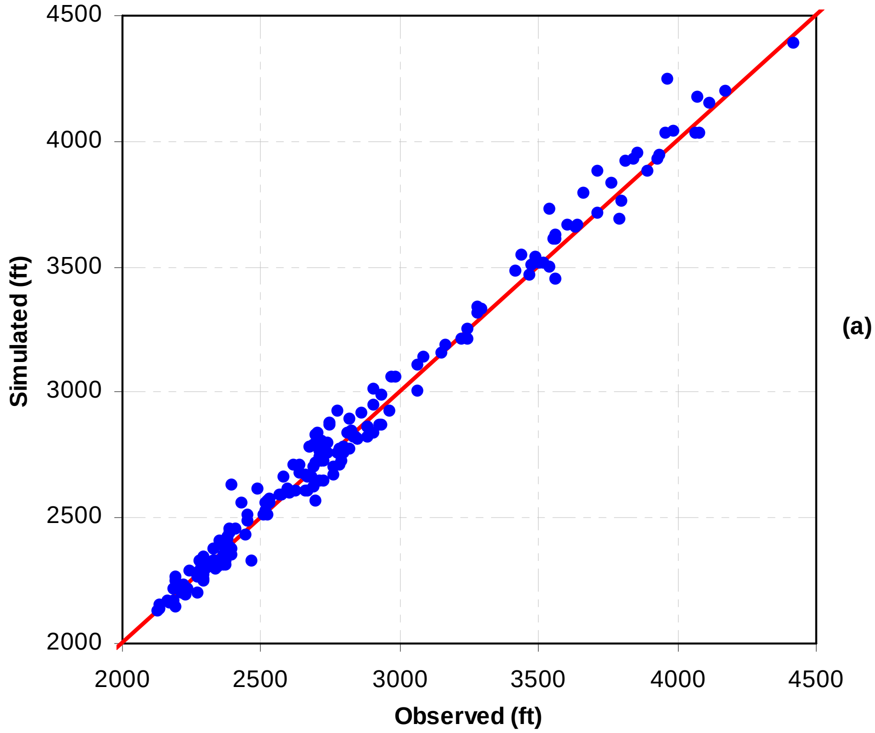


Figure 8.2.1 Plots of (a) simulated versus observed water-level elevations in feet and (b) residual versus observed water-level elevation in feet for the upper portion of the Dockum Aquifer in the steady-state model.



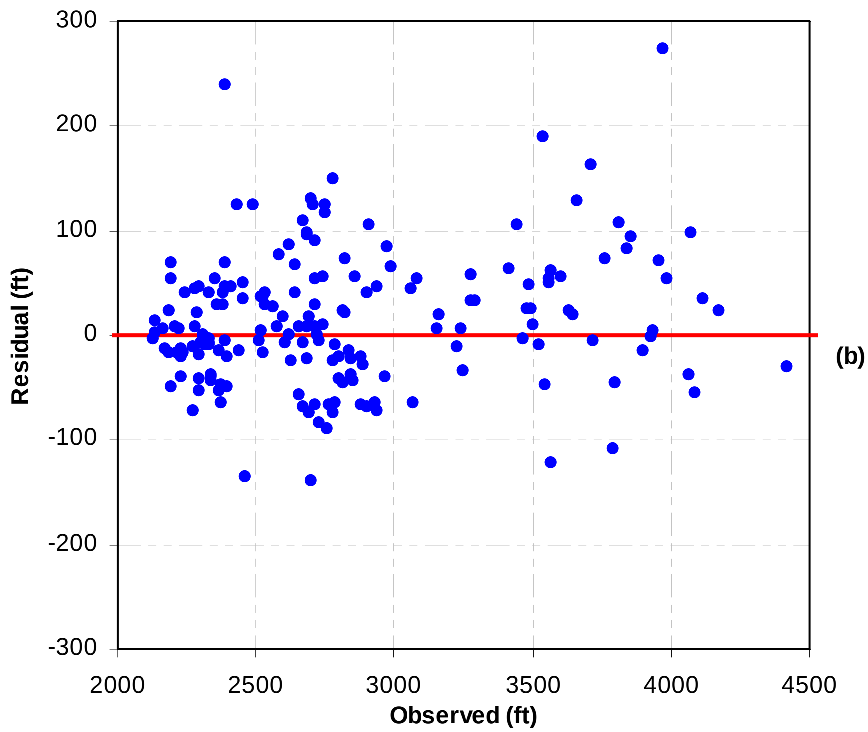


Figure 8.2.2 Plots of (a) simulated versus observed water-level elevations in feet and (b) residual versus observed water-level elevation in feet for the lower portion of the Dockum Aquifer in the steady-state model.

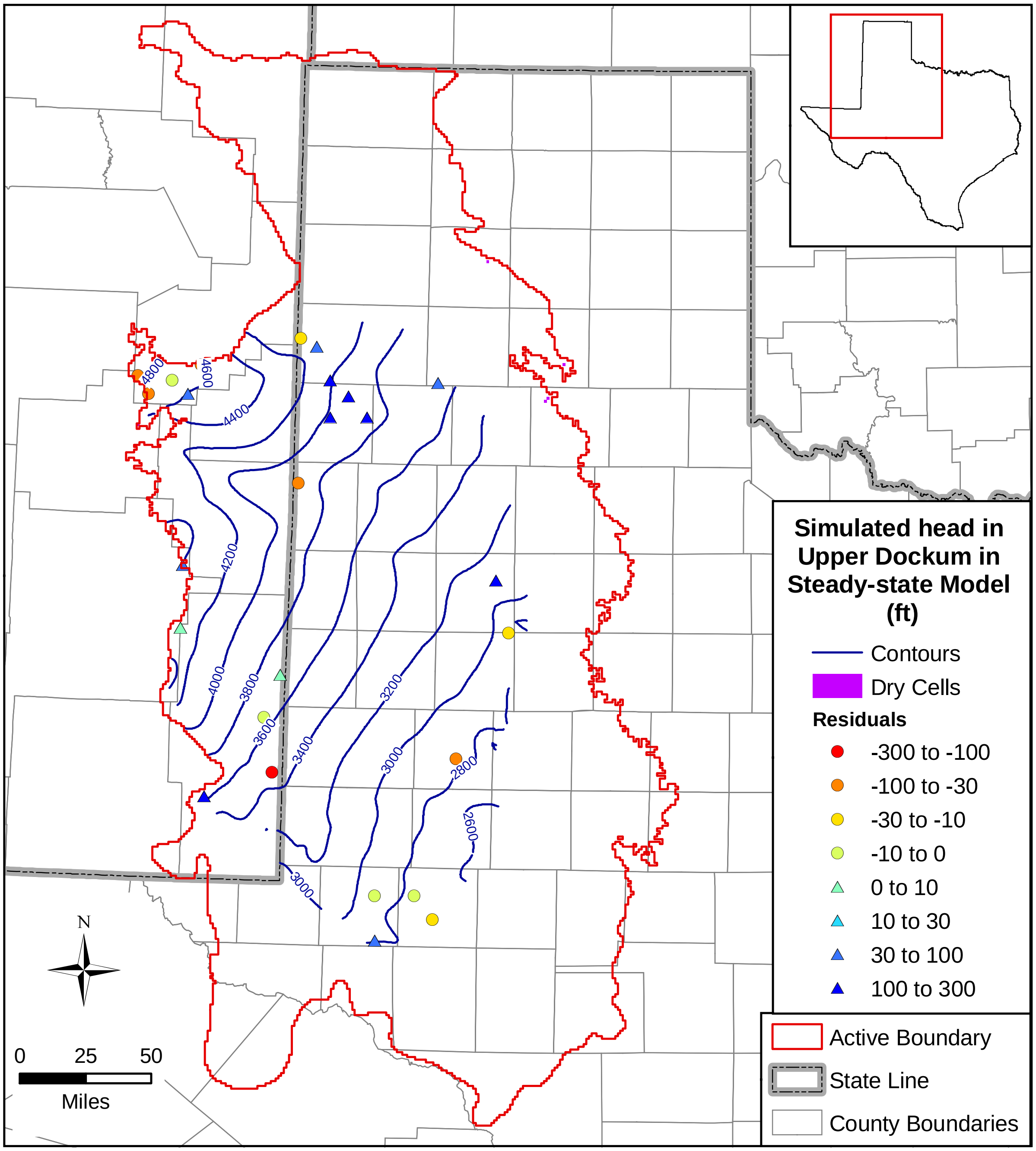


Figure 8.2.3 **Simulated steady-state water levels and residuals in feet for the upper portion of the Dockum Aquifer.**

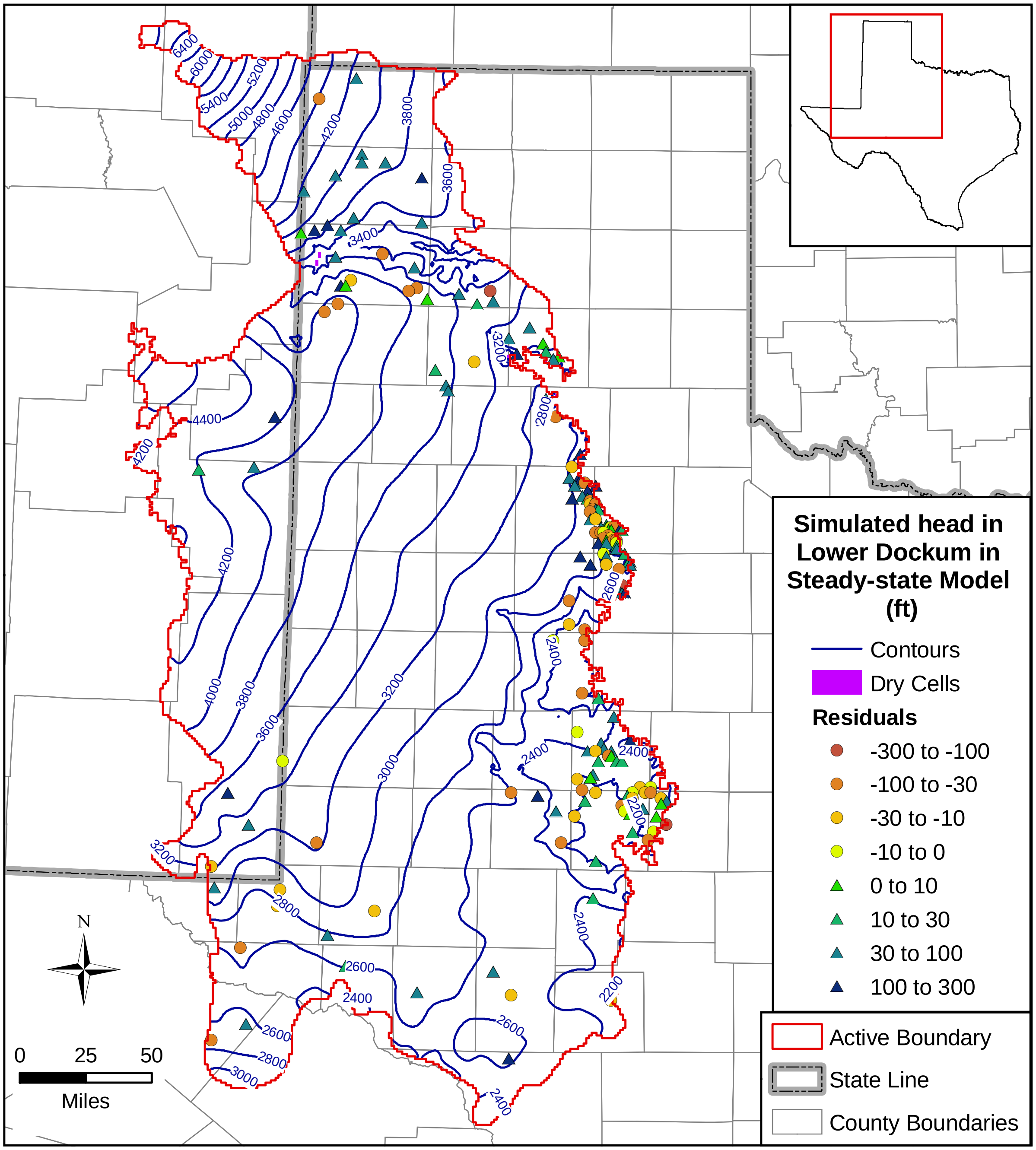


Figure 8.2.4 **Simulated steady-state water levels and residuals in feet for the lower portion of the Dockum Aquifer.**

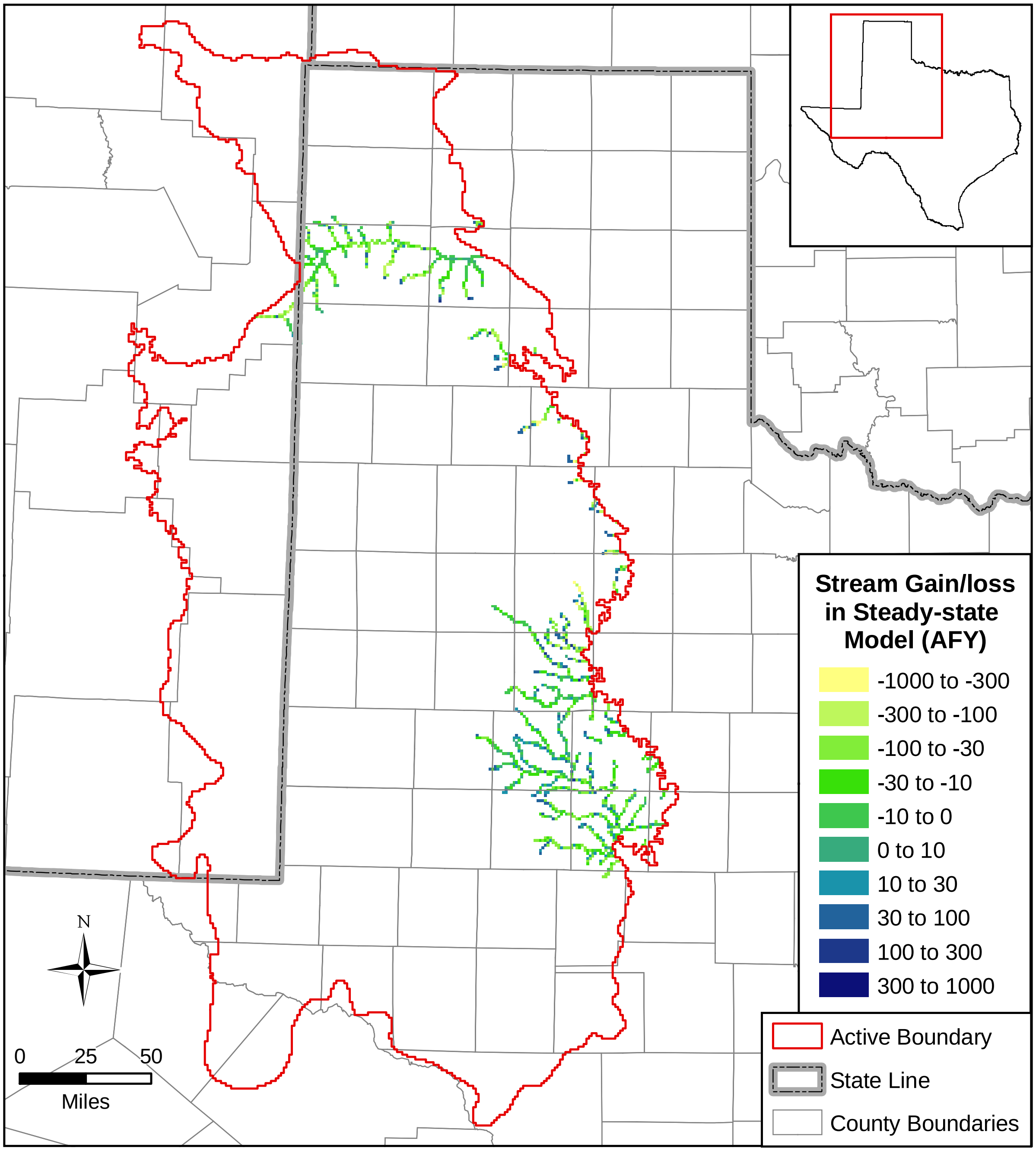


Figure 8.2.5 **Steady-state model stream gain/loss in acre-feet per year (negative values denote gaining streams).**

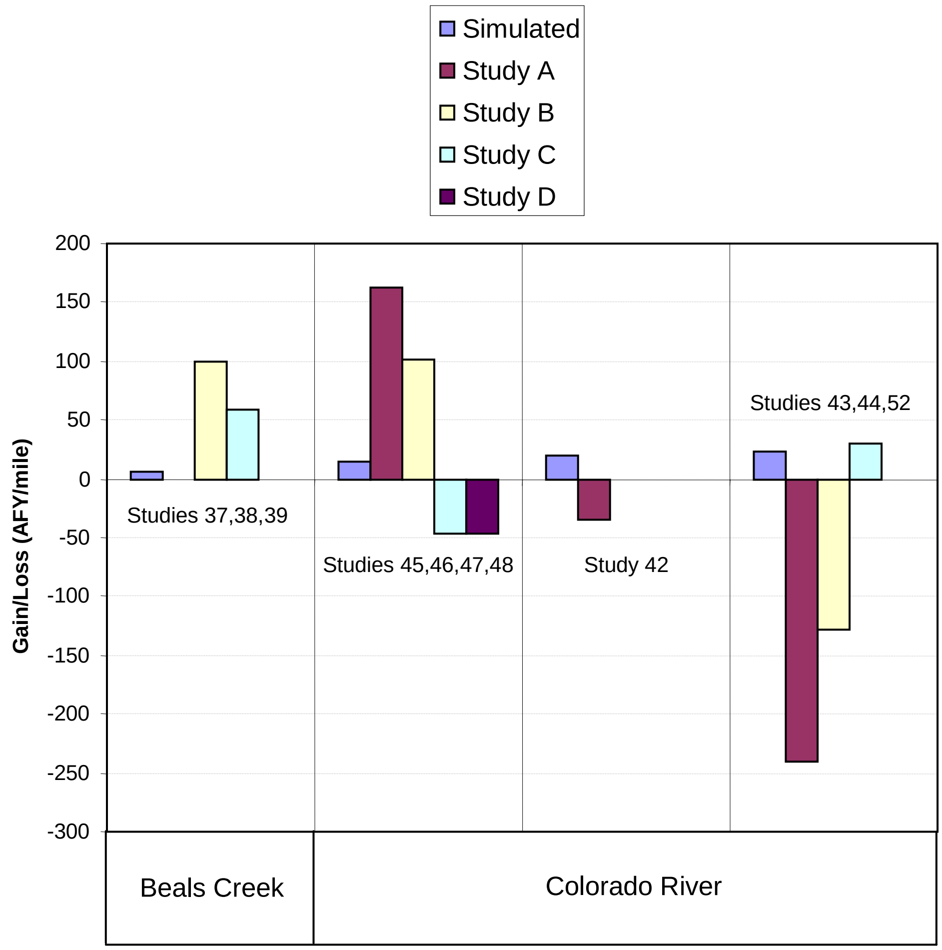


Figure 8.2.6 **Simulated stream gain/loss compared to measured values in acre-feet per year per mile. Studies (after Slade and others, 2002) are detailed in Table 4.5.1.**

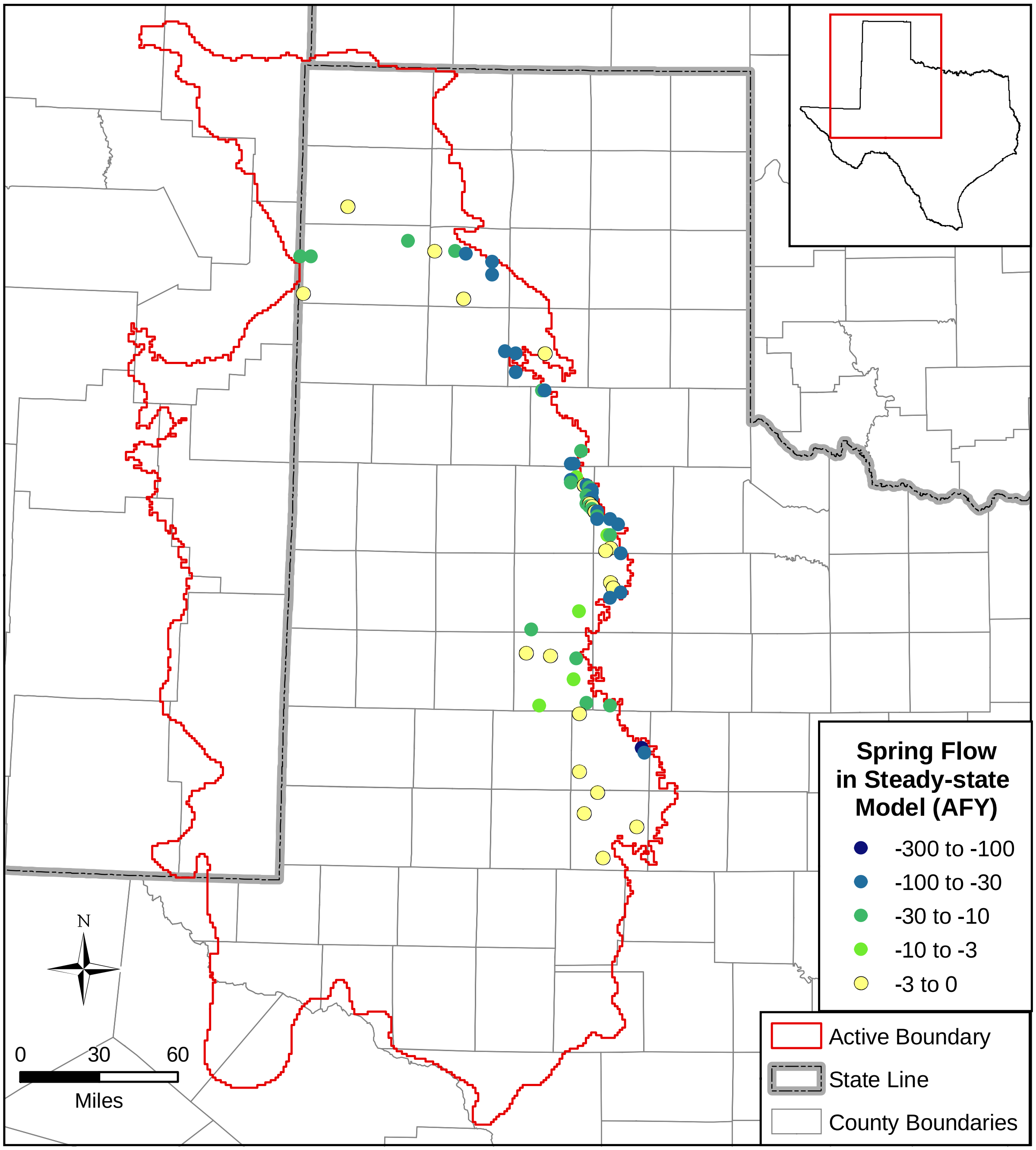


Figure 8.2.7 **Simulated spring flow in acre-feet per year in the steady-state model.**

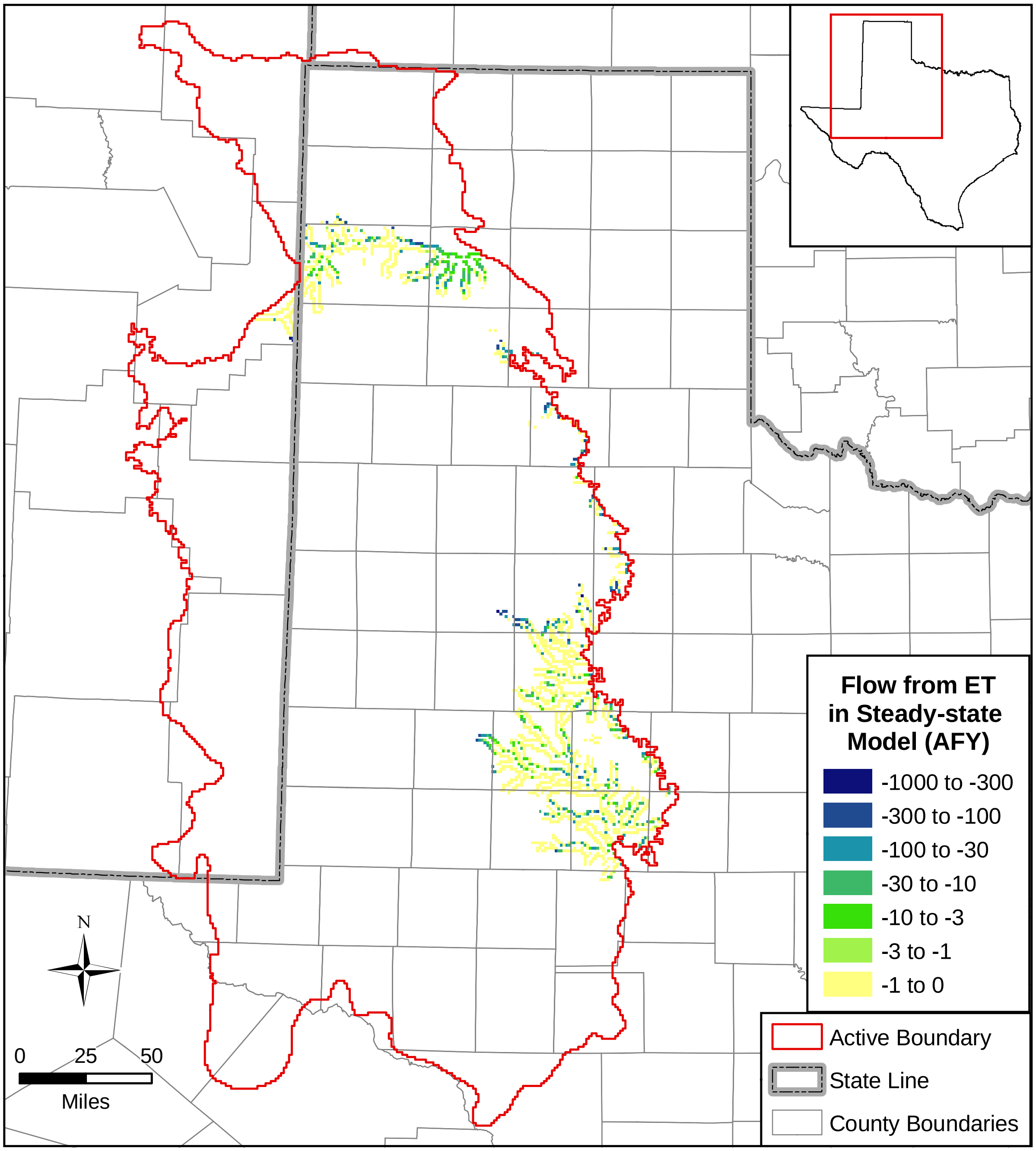


Figure 8.2.8 Simulated evapotranspiration discharge in acre-feet per year for the steady-state model.

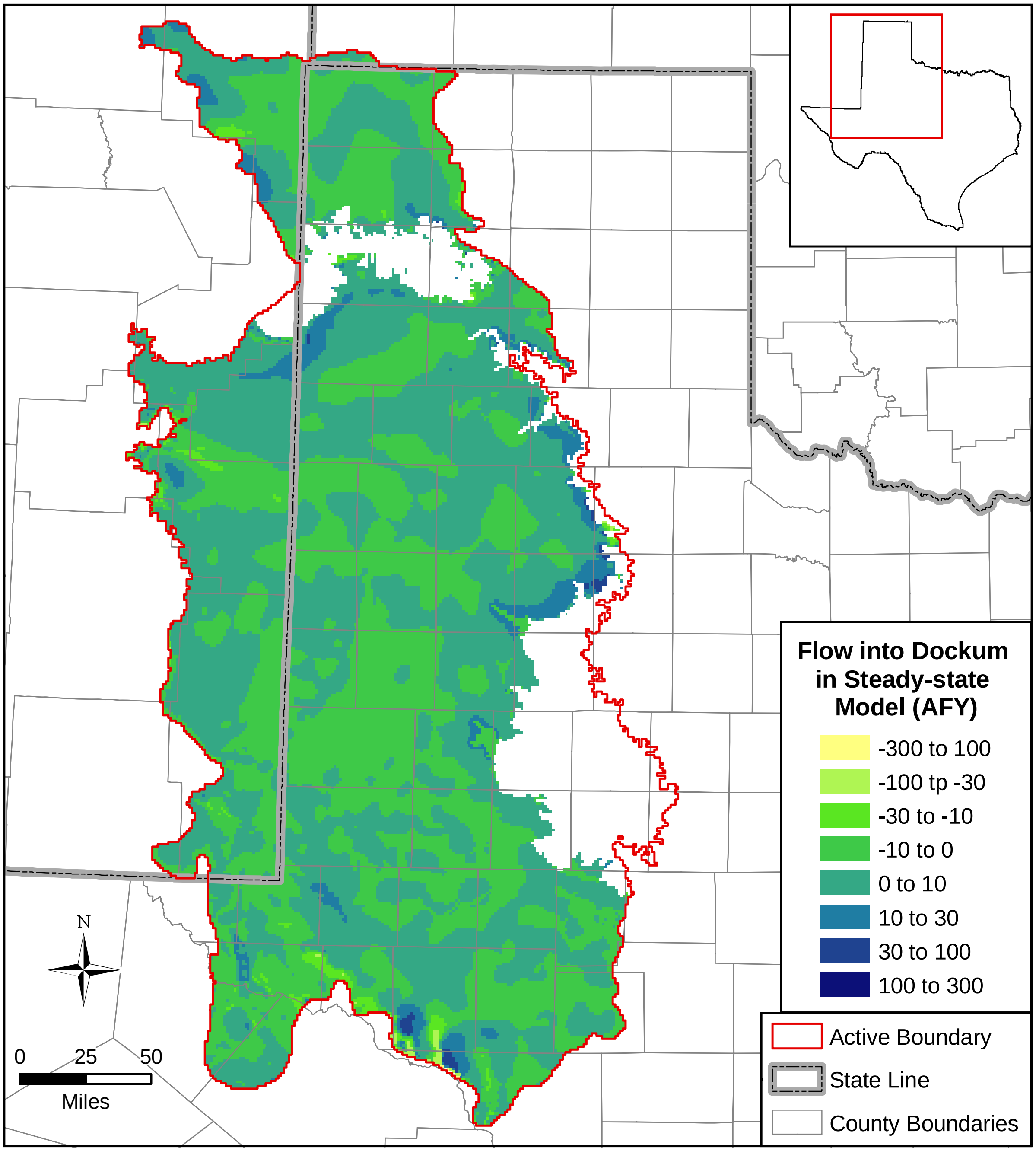


Figure 8.2.9 **Simulated cross-formational flow in acre-ft per year from overlying aquifers (positive denotes flow into the Dockum Aquifer).**

8.3 Sensitivity Analysis

A sensitivity analysis was performed on the calibrated steady-state model. A sensitivity analysis provides a means of formally describing the impact of varying specific parameters or groups of parameters on model outputs. In this sensitivity analysis, input parameters were systematically increased and decreased from their calibrated values while the change in water-level elevation was recorded. Four simulations were completed for each parameter sensitivity, where the input parameters were varied either according to:

$$\text{(new parameter)} = \text{(old parameter)} * \text{factor} \qquad (8.3.1)$$

or

$$\text{(new parameter)} = \text{(old parameter)} * 10^{\text{(factor - 1)}} \qquad (8.3.2)$$

or

$$\text{(new parameter)} = \text{(old parameter)} + \text{(factor * 40)} \qquad (8.3.3)$$

and the factors were 0.5, 0.9, 1.1, and 1.5. Parameters such as recharge were varied linearly using Equation 8.3.1. For parameters such as hydraulic conductivity, which are typically thought of as log-varying, Equation 8.3.2 was used. For parameters involving elevation changes in boundary conditions, Equation 8.3.3 was used. For the output variable, we calculated the mean difference (MD) between the base simulated head and the sensitivity simulated head:

$$MD = \frac{1}{n}\sum_{i=1}^{n}\left(h_{sens,i} - h_{cal,i}\right) \qquad (8.3.4)$$

where $h_{sens,i}$ is the sensitivity simulation head at active gridblock i, $h_{cal,i}$ is the calibrated simulation head at active gridblock i, and n is the number of active gridblocks.

Two approaches to applying Equation 8.3.4 to the sensitivity of output heads were considered. First, the heads in all active grid blocks between the sensitivity output and the calibrated output were compared. Second, the heads only at grid blocks where measured targets were available (i.e., n = number of targets in that layer) were compared. A comparison between these two methods can provide information about the bias in the target locations (i.e., a similar result indicates adequate target coverage).

For the steady-state sensitivity analysis, fifteen parameter sensitivities were investigated:

1. Horizontal hydraulic conductivity of layer 1 (Kh-Ogallala),
2. Horizontal hydraulic conductivity of layer 2 (Kh-Upper-Dockum),
3. Horizontal hydraulic conductivity of layer 3 (Kh-Lower-Dockum),
4. Vertical hydraulic conductivity in layer 1 (Kv-Ogallala),
5. Vertical hydraulic conductivity in layer 2 (Kv-Upper-Dockum),
6. Vertical hydraulic conductivity in layer 3 (Kv-Lower-Dockum),
7. Recharge, model-wide (Recharge),
8. Streambed conductance (K-Stream),
9. Stream elevation (z-Stream),
10. Spring conductance (K-Spring),
11. Spring elevation (z-Spring),
12. Evapotranspiration conductance (K-ET),
13. Evapotranspiration elevation (z-ET),
14. General-head boundary conductance (K-GHB), and
15. General-head boundary elevation (z-GHB).

Equation 8.3.1 was used for sensitivity 7, Equation 8.3.2 was used for sensitivities 1-6, 8, 10, 12, and 14, and Equation 8.3.3 was used for sensitivities 9, 11, 13, and 15.

Figures 8.3.1 and 8.3.2 show the results of the sensitivity analyses varying hydraulic parameters with mean differences calculated from just the grid blocks where targets were available. In comparison, Figures 8.3.3 and 8.3.4 show the corresponding sensitivity results with mean differences calculated from all active cells. Figures 8.3.5 and 8.3.6 show the results of the sensitivity analyses varying boundary condition conductances with mean differences calculated from just the grid blocks where targets were available. In comparison, Figures 8.3.7 and 8.3.8 show the corresponding sensitivity results with mean differences calculated from all active cells. Figures 8.3.9 and 8.3.10 show the results of the sensitivity analyses varying boundary condition elevations with mean differences calculated from just the grid blocks where targets were available. In comparison, Figures 8.3.11 and 8.3.12 show the corresponding sensitivity results with mean differences calculated from all active cells. It is important to note that the y-axis on the sensitivity plots can differ significantly.

Note that, in most cases, the corresponding figures for heads at targets and in all gridblocks indicate similar trends in sensitivities, indicating adequate target coverage. The notable exception is the sensitivity of the heads within the lower portion of the Dockum Aquifer to the general-head boundary conductance in the overlying aquifers. This is because the majority of the targets in the lower portion of the Dockum Aquifer occupy the Colorado River outcrop which is a major discharge avenue for the Dockum Aquifer as a whole. The Dockum Aquifer also discharges into the eastern edge of the Ogallala Aquifer abutting the Dockum Aquifer outcrop so, when the general-head boundary conductances are lowered, more flow enters the Dockum Aquifer outcrop, increasing water levels at the targets within the outcrop. For the majority of the lower portion of the Dockum Aquifer, however, the Ogallala and younger aquifers recharge the Dockum Aquifer and a decrease in the general-head boundary conductance results in a lowering of heads within the lower portion of the Dockum Aquifer.

The most sensitive parameter with respect to heads in both the upper and lower portions of the Dockum Aquifer is the elevation of the general-head boundary in layer 1, as illustrated by Figures 8.3.9 through 8.3.12. This parameter is based on data and it should be noted that, in the sensitivity analysis, the general-head boundary elevations were varied systematically (i.e., all at once and in the same direction). While there is uncertainty in the elevation of the general-head boundaries, the error is likely randomly distributed about the average of the measurements and there should be no systematic bias in the heads. The sensitivity analysis, therefore, greatly exaggerates the sensitivity of the simulated heads to the general-head boundary elevations in layer 1. For this reason, the general-head boundary elevations were not altered during calibration. Figures 8.3.1 and 8.3.3 indicate that the vertical hydraulic conductivity of the upper portion of the Dockum Aquifer and horizontal hydraulic conductivity of the lower portion of the Dockum Aquifer are the most sensitive calibrated parameters with respect to heads in the upper portion of the Dockum Aquifer. The horizontal hydraulic conductivity of the lower portion of the Dockum Aquifer is also the most sensitive parameter with respect to heads in the lower portion of the Dockum Aquifer as illustrated by Figures 8.3.2 and 8.3.4. Simply put, the horizontal hydraulic conductivity in the lower portion of the Dockum Aquifer provides resistance across the major northwest to southeast flow path across the entire model. Likewise, the vertical hydraulic conductivity of the upper portion of the Dockum Aquifer is the primary regulator of flow from the Ogallala into the Dockum Aquifer over much of the model domain. In particular, a decrease in the vertical hydraulic conductivity of the upper portion of the Dockum Aquifer will produce a larger head drop across the upper portion of the Dockum Aquifer and subsequently decrease the heads within it. Recharge rate is also a somewhat sensitive parameter with respect to heads within the lower portion of the Dockum Aquifer particularly at the target locations because the majority of the targets and all of the recharge occur in the outcrops.

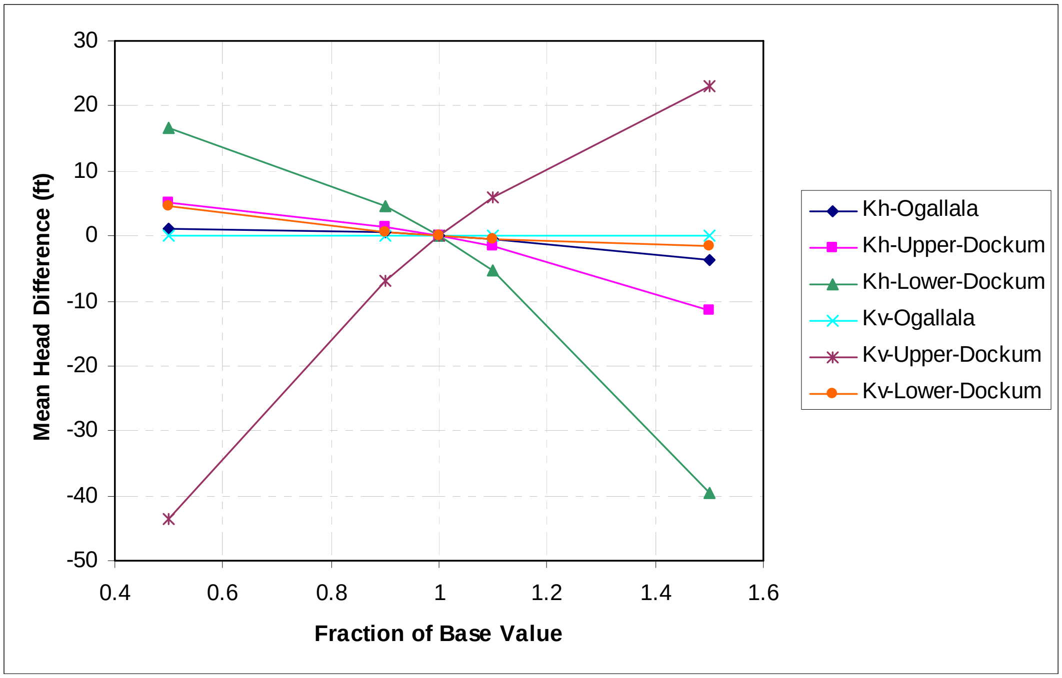


Figure 8.3.1 Steady-state sensitivity of hydraulic conductivity for layer 2 heads in feet using target locations.

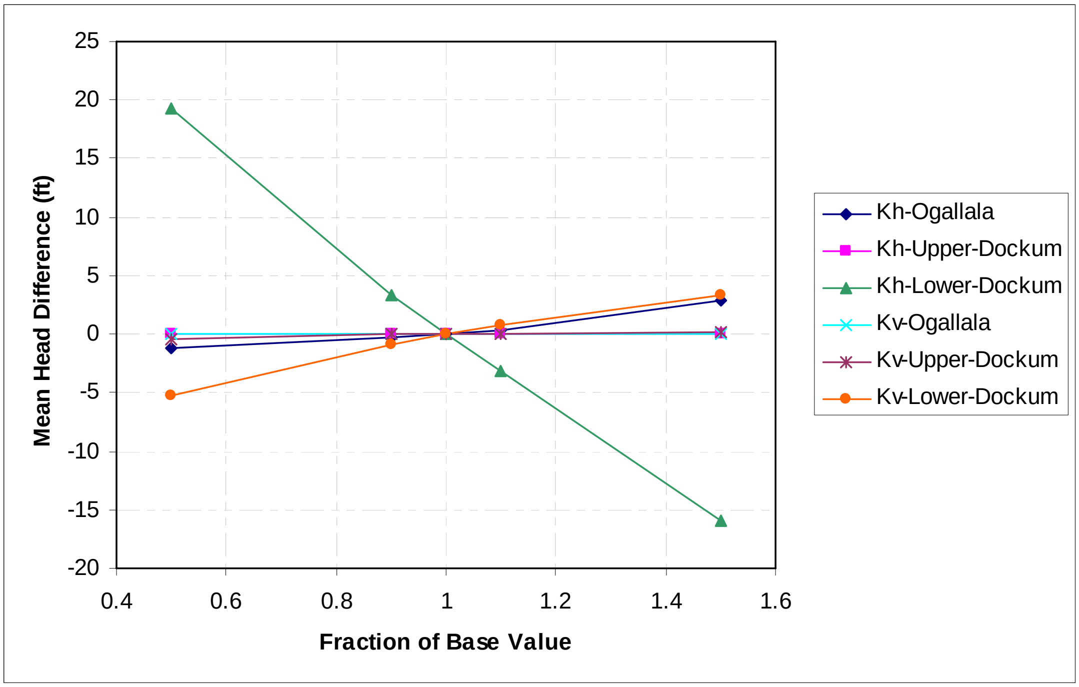


Figure 8.3.2 Steady-state sensitivity of hydraulic conductivity for layer 3 heads in feet using target locations.

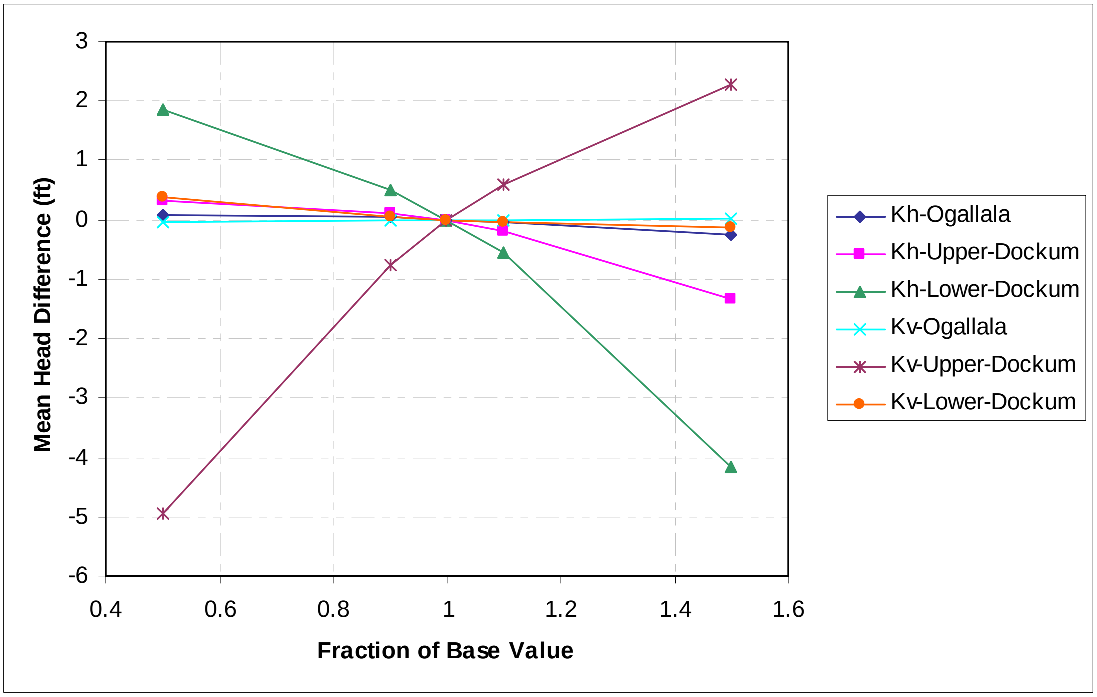


Figure 8.3.3 **Steady-state sensitivity of hydraulic conductivity for layer 2 heads in feet using all active gridblocks.**

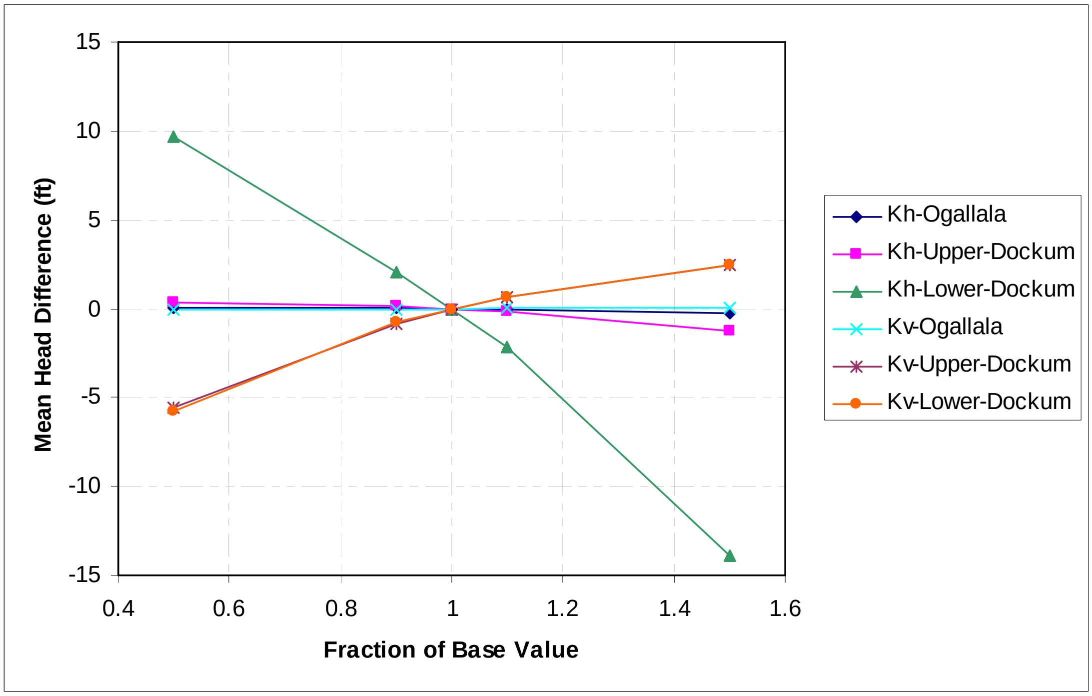


Figure 8.3.4 **Steady-state sensitivity of hydraulic conductivity for layer 3 heads in feet using all active gridblocks.**

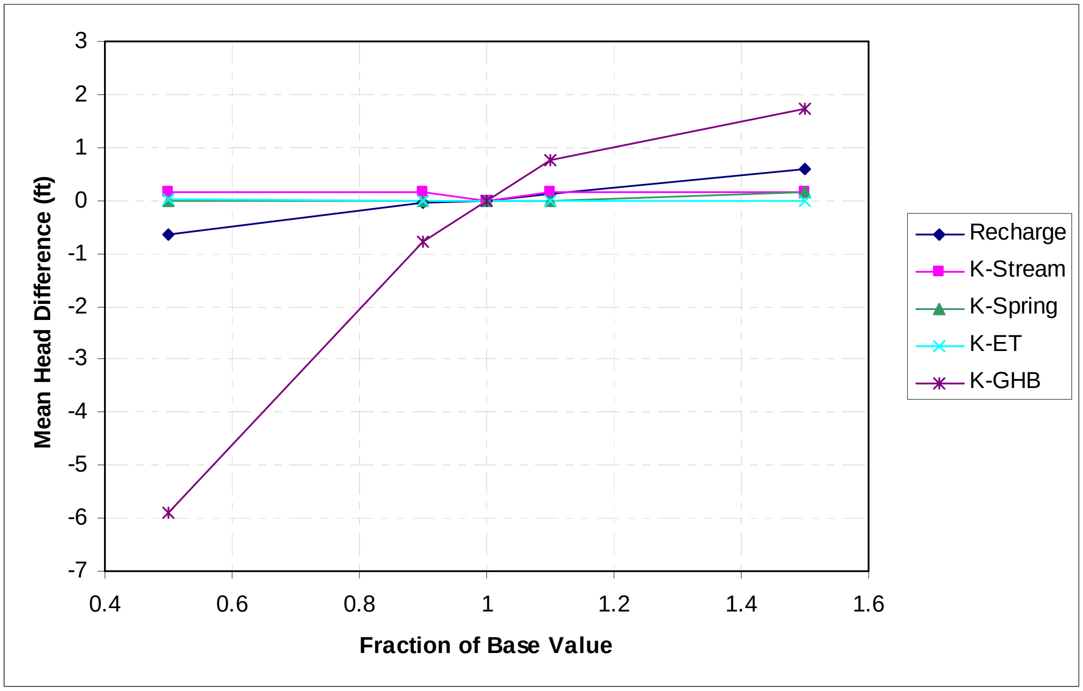


Figure 8.3.5 Steady-state sensitivity of boundary condition conductance for layer 2 heads in feet using target locations.

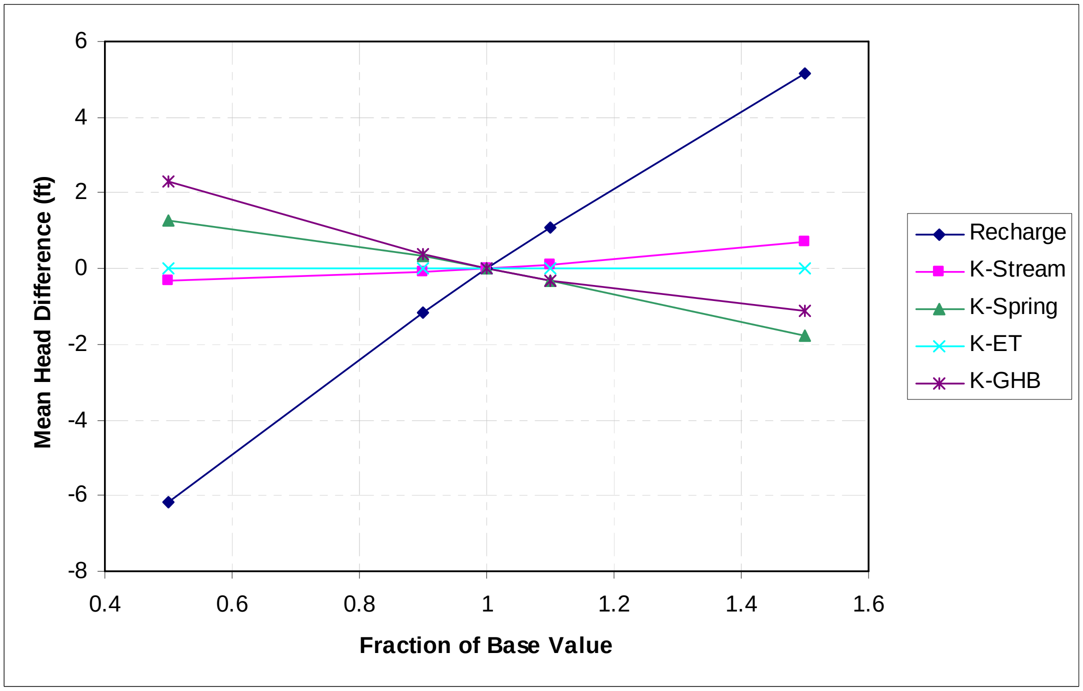


Figure 8.3.6 Steady-state sensitivity of boundary condition conductance for layer 3 heads in feet using target locations.

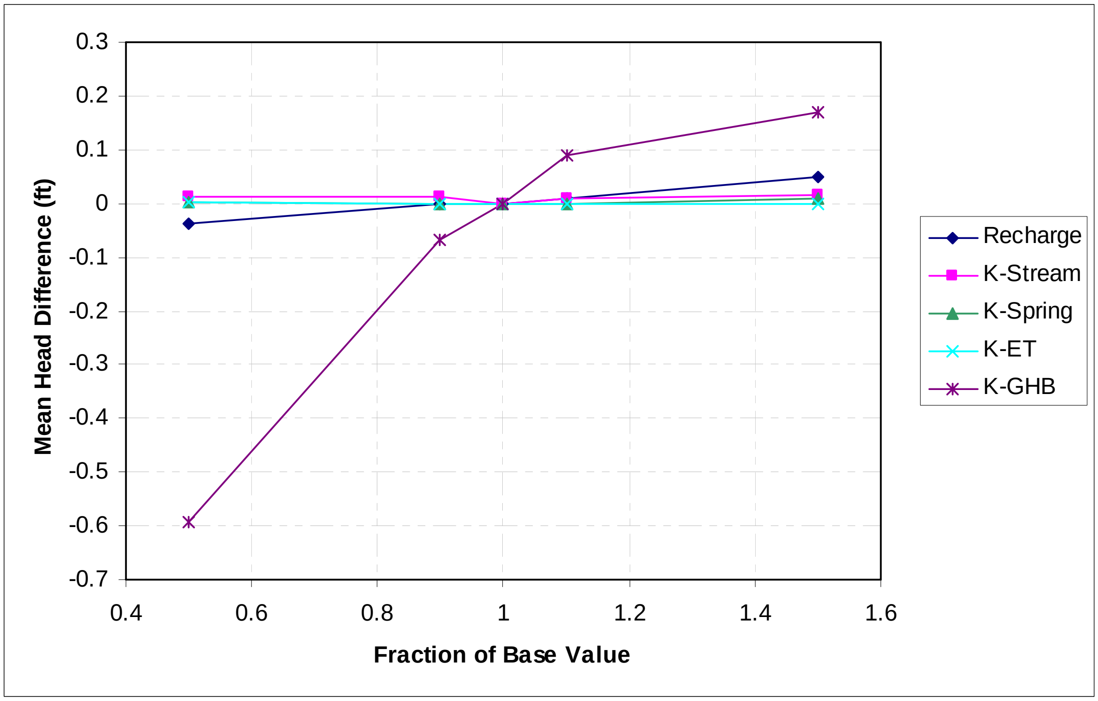


Figure 8.3.7 Steady-state sensitivity of boundary condition conductance for layer 2 heads in feet using all active gridblocks.

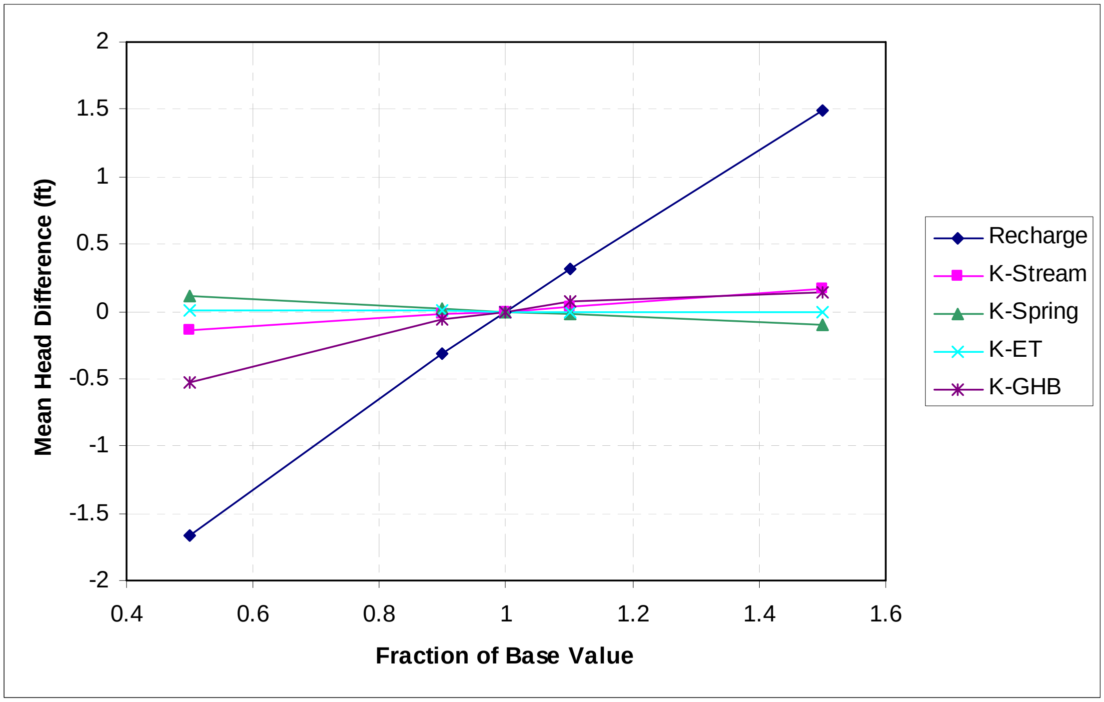


Figure 8.3.8 Steady-state sensitivity of boundary condition conductance for layer 3 heads in feet using all active gridblocks.

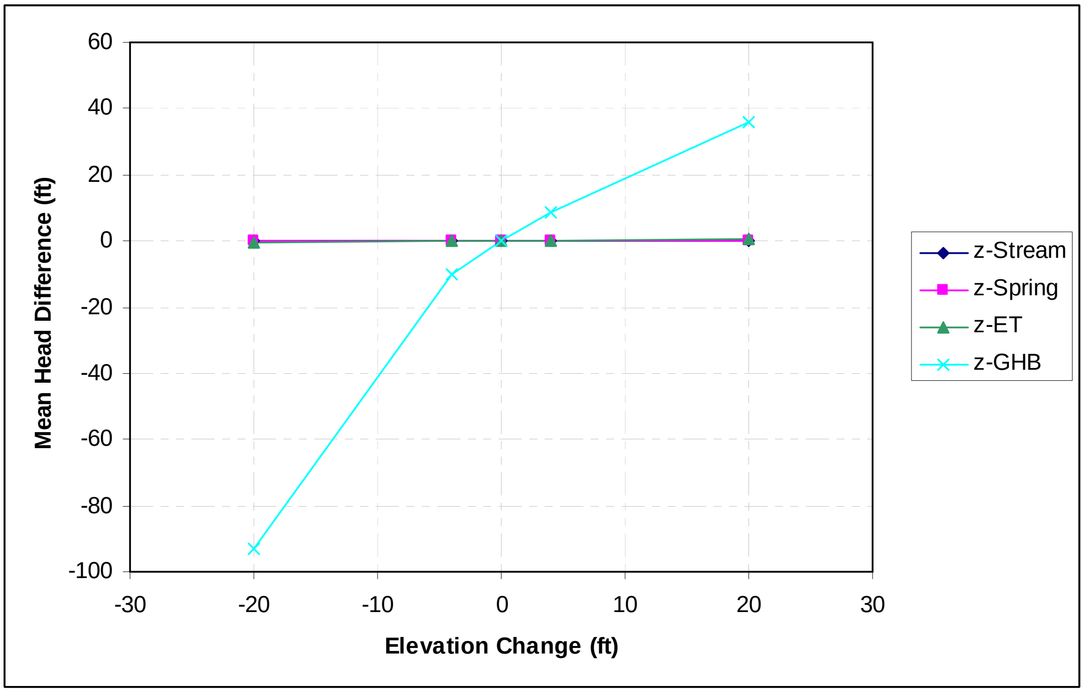


Figure 8.3.9 Steady-state sensitivity of boundary condition elevation in feet for layer 2 heads in feet using target locations.

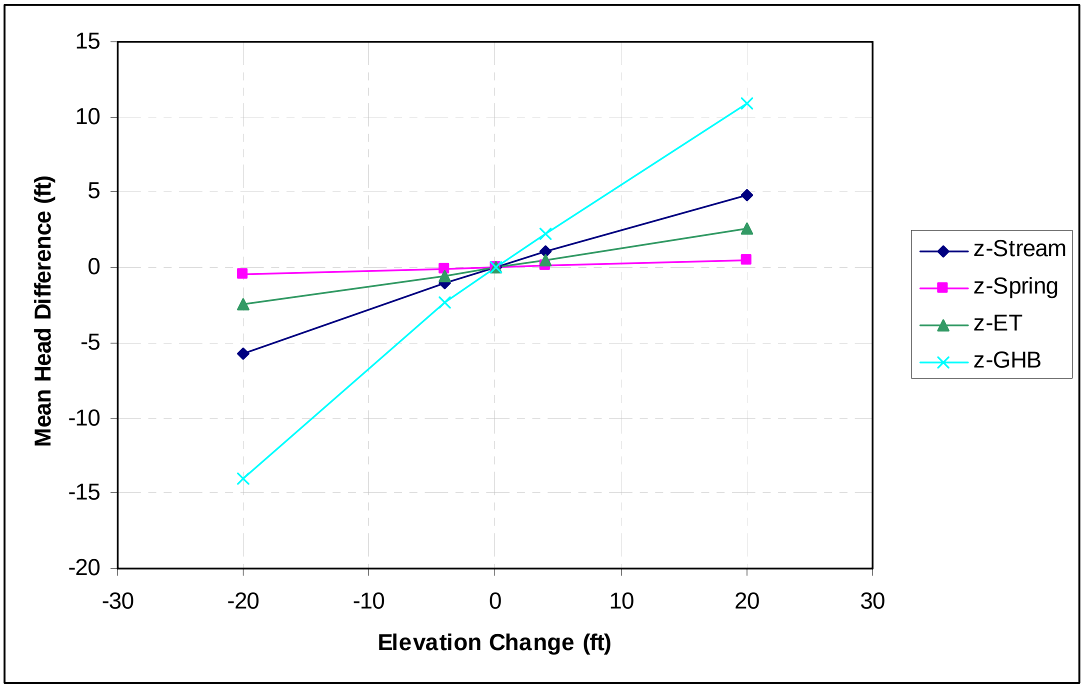


Figure 8.3.10 Steady-state sensitivity of boundary condition elevation in feet for layer 3 heads in feet using target locations.

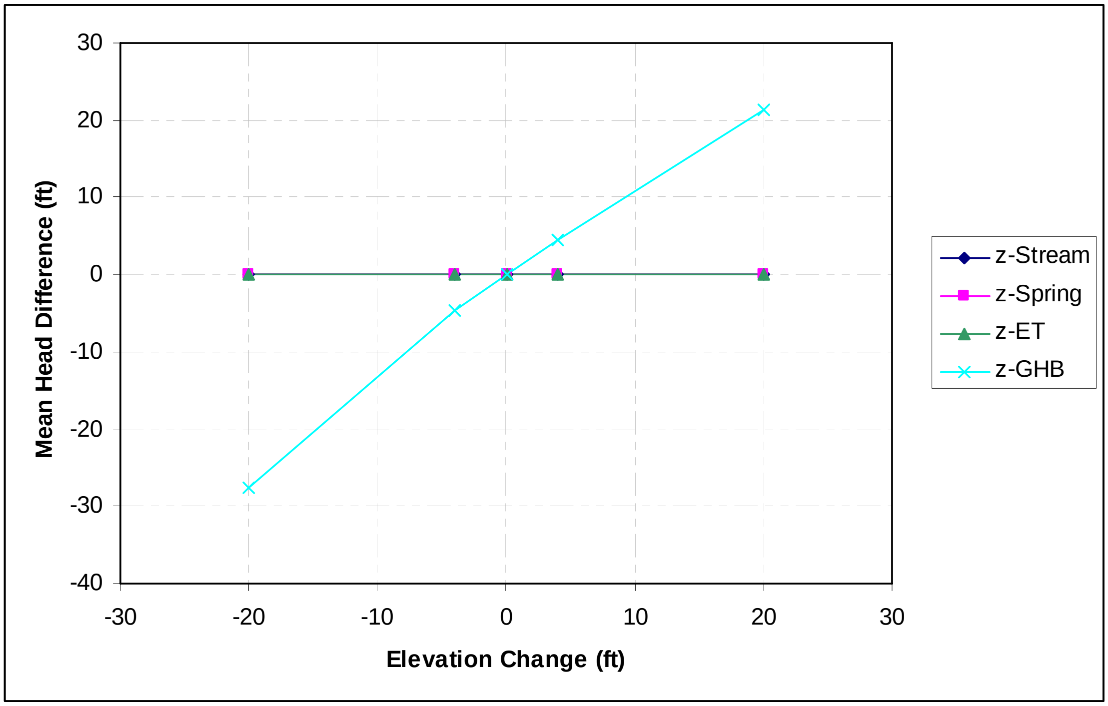


Figure 8.3.11 **Steady-state sensitivity of boundary condition elevation in feet for layer 2 heads in feet using all active gridblocks.**

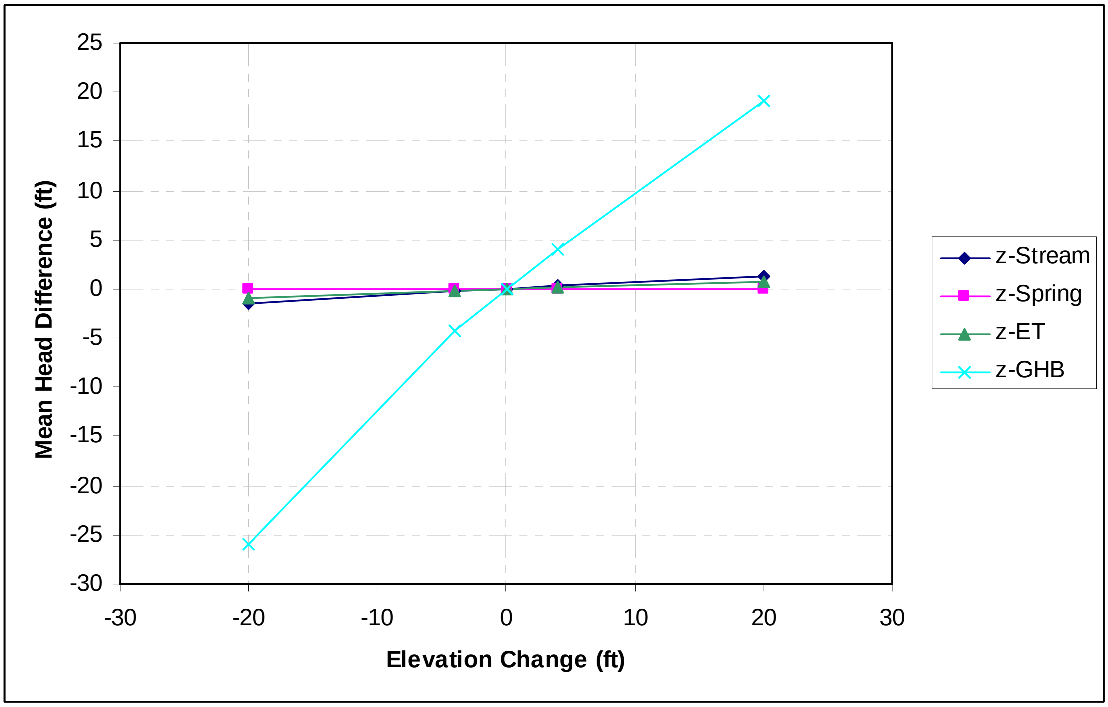


Figure 8.3.12 **Steady-state sensitivity of boundary condition elevation in feet for layer 3 heads in feet using all active gridblocks.**

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9.0 Transient Model

This section describes calibration of the transient model, presents the transient model results, and describes the sensitivity analysis for the transient model. The transient model included the steady-state model within the first stress period, a transient development period from 1950 to 1980, and a calibration period from 1980 through 1997. The time periods corresponding to the transient model stress periods are summarized in Table 9.0.1. Section 9.1 describes the model calibration. Section 9.2 presents model results for the calibration time period. Section 9.3 presents the sensitivity analysis results.

Table 9.0.1 Time periods corresponding to stress periods in the transient model.

Stress Period	Duration (years)	Time Period
1	n/a	Steady-state, pre-development
2	10	1950 through 1959
3	10	1960 through 1969
4	5	1970 through 1974
5	1	1975
6	1	1976
7	1	1977
8	1	1978
9	1	1979
10	1	1980
11	1	1981
12	1	1982
13	1	1983
14	1	1984
15	1	1985
16	1	1986
17	1	1987
18	1	1988
19	1	1989
20	1	1990
21	1	1991
22	1	1992
23	1	1993
24	1	1994
25	1	1995
26	1	1996
27	1	1997

9.1 Calibration

All properties or parameters common with the steady-state model were identical in the transient model. Section 8.1 contains the discussion of hydraulic properties in the steady-state and transient models. The calibrated hydraulic properties for the combined model are summarized in Table 9.1.1. Transient water-level measurements provide information about temporal trends in the aquifer and were compared with the simulated trends. A discussion of important inputs and new properties (such as storage estimates) follows.

9.1.1 Calibration Targets

Water-level measurements are needed as targets for transient calibration. Selection of water-level measurements over the transient calibration period was discussed in Section 4.3.2. Water-level targets were screened to omit wells being pumped, however, further screening was conducted to ensure that the measurements were applicable as targets in the transient model calibration. Wells dual-completed in overlying aquifers and the Dockum Aquifer were removed. Wells with water-level measurements beneath the base of the layer were removed. Additionally, confined wells with water levels beneath the top of the confining bed in areas without reported pumping were considered invalid targets and removed.

Transient targets included 25 water-level measurements from 5 well locations in the upper portion of the Dockum Aquifer and 1,293 water-level measurements from 352 locations in the lower portion of the Dockum Aquifer. No grid blocks within the upper portion of the Dockum Aquifer contained coincident wells. Within the lower portion of the Dockum Aquifer, 124 grid blocks contained multiple target wells. The number of coincident wells in these grid blocks ranged from 2 to 9 and the difference in water levels for the targets in the grid blocks ranges from 0 to 231 feet. The standard deviation (error) of the water levels for grid blocks containing two or more wells ranges from 0 to 133 feet and averages 20 feet for the lower portion of the Dockum Aquifer. The small sample sizes obviously limits the quantitative validity of these statistics, however, they are included in an attempt to illustrate the uncertainty in the targets in a model of this scale.

9.1.2 Storage Parameters

Storativity and specific yield are properties required in a transient model that are not needed in a steady-state model. The majority of the Dockum Aquifer is confined with only 0.6 percent of the upper portion of the Dockum Aquifer and 11 percent of the lower portion of the Dockum Aquifer outcropping. In the absence of any data, a uniform specific yield of 0.15 was used for all layers. Confined storage measurements exist but were of insufficient spatial extent to be used to populate the entire model domain. Instead, specific storage was calculated based on the maps of sand fraction and converted to storativity based on layer isopachs as detailed in Section 6.4.2. The model is somewhat sensitive to some storage parameters, however, storage was, at most, 5 to 10 times less sensitive than the horizontal hydraulic conductivity of the lower portion of the Dockum Aquifer and varying storage did little to improve the model calibration. Storage parameters were unaltered from their initial estimates following calibration.

Table 9.1.1 Hydraulic properties.

Parameter	Units	Layer	Minimum	Maximum	Median	Arithmetic Mean	Geometric Mean
Horizontal Hydraulic Conductivity	feet/day	1	uniform 11.0				
		2	0.0491	0.537	0.204	0.213	0.194
		3	0.0133	4.19	0.279	0.398	0.264
Vertical Hydraulic Conductivity	feet/day	1	uniform 0.055				
		2	0.000262	0.000540	0.000313	0.000321	0.000319
		3	0.000251	0.00334	0.000348	0.000383	0.000366
Storativity	--	1	not applicable				
		2	0.000128	0.00758	0.00306	0.00306	0.00240
		3	0.000120	0.0111	0.00527	0.00482	0.00407
Specific Yield	--	1	uniform 0.15				
		2	uniform 0.15				
		3	uniform 0.15				

9.2 Simulation Results

Results for the transient model are presented in this section. Simulated water-level elevations are compared to measured values, and stream and spring leakages and water budgets are discussed.

9.2.1 Water-Level Elevations

The transient modeling is divided into a pre-calibration development period (1950 through 1979) and a calibration period (1980 through 1997). Results for the calibration period are described in the following section. Table 9.2.1 provides the summary statistics of the transient model calibration for the upper and lower portions of the Dockum Aquifer. The adjusted mean absolute error for the upper portion of the Dockum Aquifer is 3 percent and the adjusted mean absolute error for the lower portion of the Dockum Aquifer is 3 percent for the transient calibration period. For both Dockum Aquifer layers, the adjusted mean absolute error is well below the groundwater availability model criteria of 10 percent. Tables 9.2.2 and 9.2.3 provide summary statistics for the early (1980 through 1989) and late (1990 through 1997) portions of the calibration period. These tables show that the calibration is not biased to either early or late time periods. In addition, summary statistics for 1990 and for 1997 are included in Tables 9.2.4 and 9.2.5, respectively. It should be noted that only one measurement exists for the upper portion of the Dockum Aquifer in either of these two years making the values statistically meaningless, however, the values are included as per groundwater availability specifications.

Comparisons of simulated versus observed water levels and residuals versus observed water levels at the target wells for the transient model calibration period from 1980 through 1997 are shown for the upper and lower portions of the Dockum Aquifer in Figures 9.2.1 and 9.2.2, respectively. The simulated versus observed water levels for the upper portion of the Dockum Aquifer are depicted in Figure 9.2.1a. Residuals in the upper portion of the Dockum Aquifer (Figure 9.2.1b) fall between -60.7 and 164 feet with 84 percent falling between –100 and 100 feet. It should be noted that multiple measurements exist at different times for a given well and that many of the measurements do not vary greatly over time. The measurements, therefore, often plot atop or nearly atop one another and may not appear as separate measurements in Figure 9.2.1. The residuals for the upper portion of the Dockum Aquifer are biased high with 76 percent overpredicting and 24 percent underpredicting. It should be noted that there are only

25 measurements at five wells in the upper portion of the Dockum Aquifer so this apparent bias is not statistically significant. The simulated versus observed water levels and residuals versus observed data for the lower portion of the Dockum Aquifer are shown in Figure 9.2.2a. Residuals in the lower portion of the Dockum Aquifer (Figure 9.2.2b) fall between -244 and 316 feet with 81 percent falling between –100 and 100 feet. The residuals for the lower portion of the Dockum Aquifer are biased high with 61 percent overpredicting and 39 percent underpredicting. However, the mean error for the lower portion of the Dockum Aquifer is 0.0 feet, indicating that, considering the magnitude of error, the model is unbiased.

Comparisons of simulated versus observed water levels in 1990 for both the upper and lower portions of the Dockum Aquifer are included in Figure 9.2.3. Similarly, simulated versus observed heads in 1997 are included in Figure 9.2.4. It should be noted, again, that only one measured value exists for the upper portion of the Dockum Aquifer in either of these two years, however, the figures are included as per groundwater availability specifications.

Posted average residuals between observed and simulated water levels for the calibration period from 1980 through 1997 are provided in Figure 9.2.5 for the upper portion of the Dockum Aquifer and Figure 9.2.6 for the lower portion of the Dockum Aquifer. A positive residual indicates that the model has overpredicted the water-level elevation, while a negative residual indicates underprediction. Figures 9.2.7 and 9.2.8 show the simulated water-level elevations and residuals in 1990 for the upper and lower portions of the Dockum Aquifer, respectively. The simulated water levels and residuals at the end of transient model calibration in 1997 are shown for the upper and lower portions of the Dockum Aquifer in Figures 9.2.9 and 9.2.10, respectively. Over the calibration period and for the individual years of 1990 and 1997, the model shows no significant indication of spatial bias in the residuals.

In the following discussion, selected hydrographs of simulated and observed water-level elevations are presented that describe the general model response and any temporal trends in the upper and lower portions of the Dockum Aquifer. Because of the varying magnitude of the mean error at any given well, hydrographs for the upper and lower portions of the Dockum Aquifer are shown at varying vertical scales applicable to the individual wells. All hydrographs for the transient model can be found in Appendix A. Figures 9.2.11 through 9.2.16 show selected hydrographs for wells located in the Dockum Aquifer. Hydrographs generally exhibit one of three trends: (1) stable water levels without any discernable long-term trend; (2) gently rising water levels resulting primarily from increased recharge due to land-use changes and, to a lesser extent, irrigation return flow and recovery from decreases in pumping from a maximum rate in the 1950s; and (3) decreasing trends as a result of pumping. Hydrographs with gently rising water levels occur primarily in the vicinity of the Colorado River outcrop where recharge has increased in modern times. Declining water levels tend to occur in the confined section of the lower portion of the Dockum Aquifer in the southwestern region of the model domain in areas with pumping. Stable hydrographs tend to characterize the remainder of the model domain.

9.2.2 Stream and Spring Leakance

The distribution of stream gain/loss at the end of the transient calibration period (1997) is shown in Figure 9.2.17. Stream gain/loss measurements are available for two streams in the Colorado River outcrop (see Section 4.5.1). Like the steady-state model, the annual stress periods of the transient model and the one-to-two day long tests for the gain/loss studies are too dissimilar in duration for a meaningful, quantitative comparison to be made. The measured and simulated stream gains/losses are shown in Figure 9.2.18a. On this figure, study A, B, C, and D refer to the first, second, third, and fourth gain/loss study, respectively, conducted on the river reach. Note that the number of studies on any given reach ranged from one to four. Apart from pumping, the transient stresses on the Dockum Aquifer were constant throughout the transient period. Therefore, seasonal changes were not accounted for in the simulation. Simulated flows were consistently gaining during the transient time period in the two streams for which gain/loss estimates were available. The simulated gains are steady over time in Beals Creek and increase slightly over time in the Colorado River, with an increase of approximately 20 percent between 1980 and 1997 (Figure 9.2.18b). Both gaining and losing conditions were observed over the short time period of the gain/loss studies. In addition, the studies did not provide information related to apparent long-term trends.

The spring flows at each spring at the end of the calibration period (1997) are shown in Figure 9.2.19. Spring flows did not vary significantly over time. Average spring flow for the calibration period amounted to 1,477 acre-feet per year model-wide. For the reasons discussed in Section 8.2.2, no attempt was made to calibrate the model to individual measured spring flows.

9.2.3 Water Budget

Table 9.2.6 shows the water budget for the transient model totaled for the years 1980, 1990, and 1997. The overall mass balance error for the transient simulation was 0.01 percent and the mass balance errors for individual stress periods never exceeded 0.03 percent, well under the groundwater availability model requirement of one percent. Like in the steady-state model, the considerably larger flows occurring in the overlying major aquifers tend to obscure the mass balance from the perspective of the Dockum Aquifer. For instance, the majority of the overall budget is water flowing from layer 1 storage out the layer 1 general-head boundaries. This is a consequence of the considerable development in the Ogallala, which is accounted for by a reduction in the elevation of the prescribed general-head boundary heads. Recall that no pumping is prescribed in layer 1 and Ogallala pumping manifests itself, in the context of this model, as general-head boundary outflow. It is out of the scope of the Dockum Aquifer groundwater availability model to explicitly simulate flow in the overlying aquifers. Rather, model layer 1 was included only to provide a mechanism for simulating flow between the overlying aquifers and the Dockum Aquifer.

Table 9.2.7 summarizes the water budgets for 1980, 1990 and 1997 within the Dockum Aquifer alone. The predominant sources of inflow to the Dockum Aquifer during the transient calibration period are recharge and cross-formational flow from the overlying aquifers. The most notable changes from predevelopment conditions are an increase in areal recharge, resulting primarily from land-use changes, and a decrease in cross-formational flow from the overlying aquifers, which decreases steadily over the transient calibration time period. The decrease in cross-formational flow from the overlying aquifers is the net result of two competing factors that are new to the transient model: (1) drawdown in the Ogallala causes the downward flow into the upper portion of the Dockum Aquifer that occurs in predevelopment to reverse direction; and (2) flow into the lower portion of the Dockum Aquifer from the overlying aquifers actually increases from predevelopment as a result of pumping in the lower portion of the Dockum Aquifer. Because the change in flow to the upper portion of the Dockum Aquifer is greater than that to the lower portion of the Dockum Aquifer (i.e., there is more pumping in the

Ogallala than in the lower portion of the Dockum Aquifer), the net change is a decrease in cross-formational flow from the overlying aquifers to the Dockum Aquifer. It is of particular interest that flow from the upper portion of the Dockum Aquifer to the Ogallala appears to steadily increase over time in the transient model. While the flow from the upper portion of the Dockum Aquifer into the Ogallala amounts to only 1.7 percent of the Ogallala pumping within the cone of depression in 1980 (which would not impact water quality in pumped Ogallala water), the increasing trend (it is 2.8 percent of Ogallala pumping in 1997) means that, at some point, the Ogallala water quality may be impacted by the saline water of the upper portion of the Dockum Aquifer. The major avenues of discharge from the Dockum Aquifer are pumping, evapotranspiration, and stream discharge, which are roughly of the same magnitude and change slightly over time (Table 9.2.7). Discharge through springs occurs but, like in the steady-state model, accounts for a small portion of the total Dockum Aquifer discharge. The water budgets for the Dockum Aquifer by county and by Groundwater Conservation District for 1990 are summarized in Tables 9.2.8 and 9.2.9, respectively. Analogous water budgets by county and Groundwater Conservation District for 1997 are summarized in Tables 9.2.10 and 9.2.11, respectively.

As discussed in Section 6.2, the upper portion of the Dockum Aquifer constitutes only a portion of layer 2 and, as discussed in Section 6.3.4, the drain package is used to represent both springs and evapotranspiration in the model. Because of these two aspects of the model, custom Perl scripts were used to differentiate flows within the upper portion of the Dockum Aquifer from other layer 2 flows and to differentiate spring flows from evapotranspiration flows in the reported water budgets. The scripts and associated documentation are included with the model files.

The temporal trends in the transient water budget for the Dockum Aquifer are illustrated in Figure 9.2.20. The mechanisms with obvious changes in rates over time are the pumping in the lower portion of the Dockum Aquifer, which decreases over time, the cross-formational flow from the upper portion of the Dockum Aquifer to the Ogallala, which increases over time, and the resulting flow from storage within the upper portion of the Dockum Aquifer to feed the Ogallala pumping.

Table 9.2.1 Calibration statistics for the transient calibration period (1980 through 1997).

Layer	Number of Targets	ME (feet)	MAE (feet)	RMS (feet)	Range (feet)	Adjusted MAE
Upper Dockum	25	56.6	65.0	82.2	2404	0.027
Lower Dockum	1293	6.2	69.6	98.2	2289	0.030

ME = mean error MAE = mean absolute error RMS = root mean square

Table 9.2.2 Calibration statistics for the early transient calibration period (1980 through 1989).

Layer	Number of Targets	ME (feet)	MAE (feet)	RMS (feet)	Range (feet)	Adjusted MAE
Upper Dockum	16	46.1	59.3	81.7	2404	0.025
Lower Dockum	835	5.0	77.8	107.8	2289	0.034

ME = mean error MAE = mean absolute error RMS = root mean square

Table 9.2.3 Calibration statistics for the late transient calibration period (1990 through 1997).

Layer	Number of Targets	ME (feet)	MAE (feet)	RMS (feet)	Range (feet)	Adjusted MAE
Upper Dockum	9	75.1	75.1	83.0	2404	0.031
Lower Dockum	458	8.2	54.7	77.5	2289	0.024

ME = mean error MAE = mean absolute error RMS = root mean square

Table 9.2.4 Calibration statistics for 1990.

Layer	Number of Targets	ME (feet)	MAE (feet)	RMS (feet)	Range (feet)	Adjusted MAE
Upper Dockum	1	87.3	87.3	87.3	2404	0.036
Lower Dockum	67	0.2	52.5	74.2	2289	0.023

ME = mean error MAE = mean absolute error RMS = root mean square

Table 9.2.5 Calibration statistics for 1997.

Layer	Number of Targets	ME (feet)	MAE (feet)	RMS (feet)	Range (feet)	Adjusted MAE
Upper Dockum	1	151.7	151.7	151.7	2404	0.063
Lower Dockum	44	10.1	60.3	83.7	2289	0.026

ME = mean error MAE = mean absolute error RMS = root mean square

Table 9.2.6 Water budget for the transient model (all rates reported in acre-feet per year).

Year	Layer	Recharge	Streams	ET	Springs	Pumping	GHBs	Storage	Top	Bottom
1980	1	31	0	0	0	0	-1,483,722	1,516,507	0	-32,652
	2	245	-389	0	0	0	0	14,759	32,652	-47,262
	3	86,909	-40,527	-32,106	-2,045	-50,522	0	-8,857	47,262	0
	sum	87,185	-40,916	-32,106	-2,045	-50,522	-1,483,722	1,522,408	79,915	-79,915
1990	1	31	0	0	0	0	-1,396,227	1,414,372	0	-17,894
	2	245	-393	0	0	0	0	15,206	17,894	-32,941
	3	86,909	-41,491	-33,385	-2,047	-36,806	0	-6,135	32,941	0
	sum	87,185	-41,884	-33,385	-2,047	-36,806	-1,396,227	1,423,444	50,835	-50,835
1997	1	31	0	0	0	0	-1,483,127	1,498,818	0	-15,440
	2	245	-395	0	0	0	0	15,939	15,440	-31,216
	3	86,909	-41,930	-33,919	-2,048	-40,669	0	437	31,216	0
	sum	87,185	-42,326	-33,919	-2,048	-40,669	-1,483,127	1,515,194	46,655	-46,655

ET = evapotranspiration GHBs = general-head boundaries

Table 9.2.7 Water budget for the Dockum Aquifer alone for the transient model (all rates reported in acre-feet per year).

Year	Layer	Recharge	Younger–Dockum Cross–Formational Flow	Streams	ET	Springs	Pumping	Storage	Upper–Lower Cross-Formational Flow
1980	Upper Dockum	245	-6,393	-389	0	0	0	14,759	-8,280
	Lower Dockum	86,909	38,982	-40,527	-32,106	-2,045	-50,522	-8,857	8,280
	sum	87,154	32,589	-40,916	-32,106	-2,045	-50,522	5,901	0
1990	Upper Dockum	245	-13,760	-393	0	0	0	15,206	-1,351
	Lower Dockum	86,909	31,590	-41,491	-33,385	-2,047	-36,806	-6,135	1,351
	sum	87,154	17,830	-41,884	-33,385	-2,047	-36,806	9,071	0
1997	Upper Dockum	245	-17,209	-395	0	0	0	15,939	1,368
	Lower Dockum	86,909	32,584	-41,930	-33,919	-2,048	-40,669	437	-1,368
	sum	87,154	15,375	-42,326	-33,919	-2,048	-40,669	16,376	0

ET = evapotranspiration

Table 9.2.8 Water budget in the Dockum Aquifer by county for 1990 (all rates reported in acre-feet per year).

County	State	Recharge	Younger–Dockum Cross-Formational Flow	Streams	ET	Springs	Pumping	Storage
Andrews County	TX	0	1,678	0	0	0	-38	98
Armstrong County	TX	658	83	-188	-236	-165	-95	-11
Bailey County	TX	0	-3,920	0	0	0	0	1,625
Borden County	TX	5,370	559	-1,483	-1,485	0	-56	-3,058
Briscoe County	TX	711	3,923	-2,910	-2,162	-400	-13	994
Carson County	TX	0	459	0	0	0	-279	25
Castro County	TX	0	-9,569	0	0	0	0	5,882
Cochran County	TX	0	-223	0	0	0	0	259
Coke County	TX	105	-235	0	0	0	0	0
Crane County	TX	0	-4,729	0	0	0	-53	-17
Crockett County	TX	0	-2,660	0	0	0	-3	1
Crosby County	TX	3,504	12,189	-4,342	-3,233	-18	-2,717	-364
Dallam County	TX	0	2,960	0	0	0	-1,960	-32
Dawson County	TX	14	3,334	-170	-629	0	-1	-888
Deaf Smith County	TX	596	5,291	-75	-2,955	0	-3,243	3,695
Dickens County	TX	4,254	3,014	-726	-1,498	-146	-22	-2,075
Ector County	TX	0	4,851	0	0	0	-61	209
Fisher County	TX	2,095	0	-319	-276	0	-18	-1,448
Floyd County	TX	387	3,658	-1,090	-164	-599	-695	1,636
Gaines County	TX	0	-3,478	0	0	0	0	646
Garza County	TX	6,556	830	-3,483	-1,655	-46	-59	-3,165
Glasscock County	TX	0	631	0	0	0	0	11
Hale County	TX	0	-13,322	0	0	0	-152	6,689
Hartley County	TX	232	2,829	-396	-554	0	-1,051	-320
Hockley County	TX	0	-3,647	0	0	0	-922	2,195
Howard County	TX	4,650	527	-1,006	-938	0	-57	-2,227
Irion County	TX	0	-601	0	0	0	0	0
Kent County	TX	995	0	-305	-274	-15	-2	-307
Lamb County	TX	0	-11,364	0	0	0	0	5,256
Loving County	TX	0	379	0	0	0	-8	0
Lubbock County	TX	8	-3,088	-84	-1,470	0	-3	2,576
Lynn County	TX	0	2,057	-45	0	0	0	-341
Martin County	TX	0	-1,296	0	0	0	0	69
Midland County	TX	0	-698	0	0	0	0	177
Mitchell County	TX	19,472	388	-6,580	-4,878	-9	-1,791	-7,513
Moore County	TX	25	7,990	-274	0	0	-5,569	639
Motley County	TX	619	51	-1,942	-1,096	-277	-70	-27
Nolan County	TX	7,135	0	-521	-543	0	-796	-5,040
Oldham County	TX	5,349	4,995	-7,632	-2,641	-63	-508	564
Parmer County	TX	0	-10,600	0	0	0	0	5,803

Table 9.2.8, continued

County	State	Recharge	Younger–Dockum Cross-Formational Flow	Streams	ET	Springs	Pumping	Storage
Pecos County	TX	0	893	0	0	0	-649	-94
Potter County	TX	2,312	-707	-712	-1,381	-123	-463	464
Randall County	TX	217	5,357	-2,275	-821	-36	-882	765
Reagan County	TX	0	2,654	0	0	0	-1,657	234
Reeves County	TX	0	1,139	0	0	0	-1,037	355
Scurry County	TX	20,249	0	-2,674	-2,479	-149	-1,405	-13,465
Sherman County	TX	0	437	0	0	0	-442	12
Sterling County	TX	439	-73	-224	-27	0	-14	0
Swisher County	TX	9	-6,347	-105	0	0	-143	3,912
Terry County	TX	0	-1,497	0	0	0	-1	0
Tom Green County	TX	0	5	0	0	0	0	0
Upton County	TX	0	6,029	0	0	0	-212	-11
Ward County	TX	0	-2,873	0	0	0	-79	-10
Winkler County	TX	0	5,722	0	0	0	-2,352	-648
Yoakum County	TX	0	400	0	0	0	0	-64
Cimarron County	OK	0	185	0	0	0	0	-2
Chaves County	NM	0	1,313	0	0	0	-1	4
Colfax County	NM	0	1,740	0	0	0	0	0
Curry County	NM	10	9,145	0	0	0	-652	1,286
DeBaca County	NM	0	-888	0	0	0	-17	66
Eddy County	NM	0	-125	0	0	0	-17	5
Guadalupe County	NM	0	163	0	0	0	0	14
Harding County	NM	0	537	0	0	0	0	0
Lea County	NM	0	5,174	0	0	0	-2,363	1,238
Quay County	NM	1,183	6,783	-2,322	-1,990	0	-3,818	2,460
Roosevelt County	NM	0	862	0	0	0	-355	315
Union County	NM	0	6,513	0	0	0	-2	18

ET = evapotranspiration TX = Texas NM = New Mexico

Table 9.2.9 Water budget in the Dockum Aquifer by Groundwater Conservation District for 1990 (all rates reported in acre-feet per year).

GCD/UWCD/WCD	Recharge	Younger Recharge	Streams	ET	Springs	Pumping	Storage
Clear Fork GCD	2,031	0	-319	-276	0	-16	-1,402
Coke County UWCD	105	-234	0	0	0	0	0
Crockett County GCD	0	-2,663	0	0	0	-3	1
Garza County Underground And Fresh WCD	6,509	867	-3,566	-1,701	-46	-59	-3,147
Glasscock GCD	0	1,428	0	0	0	-824	122
High Plains UWCD No.1	1,087	-41,102	-2,161	-3,179	-174	-7,014	35,669
Irion County WCD	0	-620	0	0	0	0	0
Llano Estacado UWCD	0	-3,469	0	0	0	0	645
Lone Wolf GCD	19,472	388	-6,580	-4,878	-9	-1,791	-7,513
Mesa UWCD	27	3,335	-197	-725	0	-2	-893
Middle Pecos GCD	0	943	0	0	0	-630	-87
North Plains GCD	56	13,143	0	0	0	-8,476	259
Panhandle GCD	2,843	460	-766	-1,617	-289	-791	329
Permian Basin UWCD	4,578	-937	-1,006	-938	0	-56	-2,069
Salt Fork UWCD	1,066	0	-341	-274	-15	-3	-312
Sandy Land UWCD	0	387	0	0	0	0	-62
Santa Rita UWCD	0	1,892	0	0	0	-832	121
South Plains UWCD	0	-1,536	0	0	0	-1	15
Sterling County UWCD	439	-106	-224	-27	0	-14	0
Wes-Tex GCD	7,135	0	-521	-543	0	-796	-5,040

ET = evapotranspiration
GCD = Groundwater Conservation District
UWCD = Underground Water Conservation District
WCD = Water Conservation District

Table 9.2.10 Water budget in the Dockum Aquifer by county for 1997 (all rates reported in acre-feet per year).

County	State	Recharge	Younger–Dockum Cross-Formational Flow	Streams	ET	Springs	Pumping	Storage
Andrews County	TX	0	1,577	0	0	0	-10	125
Armstrong County	TX	658	103	-188	-236	-166	-80	-25
Bailey County	TX	0	-4,051	0	0	0	0	1,744
Borden County	TX	5,370	576	-1,538	-1,534	0	-54	-2,974
Briscoe County	TX	711	3,751	-2,886	-2,158	-399	-6	1,140
Carson County	TX	0	252	0	0	0	-121	-10
Castro County	TX	0	-10,415	0	0	0	0	6,276
Cochran County	TX	0	-278	0	0	0	0	295
Coke County	TX	105	-235	0	0	0	0	0
Crane County	TX	0	-4,388	0	0	0	-42	-196
Crockett County	TX	0	-2,647	0	0	0	-3	1
Crosby County	TX	3,504	12,569	-4,356	-3,229	-18	-3,564	225
Dallam County	TX	0	3,246	0	0	0	-2,749	589
Dawson County	TX	14	3,509	-176	-630	0	-1	-954
Deaf Smith County	TX	596	4,605	-74	-2,889	0	-3,873	4,473
Dickens County	TX	4,254	2,995	-734	-1,512	-146	-17	-2,022
Ector County	TX	0	4,862	0	0	0	-528	651
Fisher County	TX	2,095	0	-322	-278	0	-12	-1,452
Floyd County	TX	387	3,984	-1,082	-164	-597	-1,076	1,813
Gaines County	TX	0	-4,937	0	0	0	0	1,345
Garza County	TX	6,556	889	-3,574	-1,693	-46	-95	-3,026
Glasscock County	TX	0	622	0	0	0	0	55
Hale County	TX	0	-14,129	0	0	0	-130	6,977
Hartley County	TX	232	2,991	-396	-551	0	-1,708	251
Hockley County	TX	0	-3,902	0	0	0	-571	1,953
Howard County	TX	4,650	507	-1,023	-984	0	-62	-2,139
Irion County	TX	0	-601	0	0	0	0	0
Kent County	TX	995	0	-305	-278	-15	-2	-303
Lamb County	TX	0	-12,132	0	0	0	0	5,685
Loving County	TX	0	379	0	0	0	-7	0
Lubbock County	TX	8	-4,050	-80	-1,448	0	-3	3,070
Lynn County	TX	0	2,029	-45	0	0	0	-302
Martin County	TX	0	-1,314	0	0	0	0	69
Midland County	TX	0	-715	0	0	0	0	178
Mitchell County	TX	19,472	388	-6,887	-5,275	-10	-1,235	-7,365
Moore County	TX	25	8,293	-274	0	0	-5,033	-39
Motley County	TX	619	30	-1,939	-1,098	-277	-40	-30
Nolan County	TX	7,135	0	-526	-586	0	-721	-5,067
Oldham County	TX	5,349	4,942	-7,585	-2,640	-63	-1,061	1,162
Parmer County	TX	0	-11,202	0	0	0	0	5,998

Table 9.2.10, continued

County	State	Recharge	Younger–Dockum Cross-Formational Flow	Streams	ET	Springs	Pumping	Storage
Pecos County	TX	0	977	0	0	0	-820	29
Potter County	TX	2,312	-471	-698	-1,382	-123	-770	629
Randall County	TX	217	5,451	-2,272	-820	-36	-954	889
Reagan County	TX	0	3,096	0	0	0	-2,064	359
Reeves County	TX	0	1,229	0	0	0	-1,174	458
Scurry County	TX	20,249	0	-2,782	-2,522	-151	-1,209	-13,510
Sherman County	TX	0	523	0	0	0	-485	7
Sterling County	TX	439	-77	-224	-27	0	-11	-1
Swisher County	TX	9	-6,527	-42	0	0	-162	3,885
Terry County	TX	0	-2,067	0	0	0	0	308
Tom Green County	TX	0	5	0	0	0	0	0
Upton County	TX	0	6,046	0	0	0	-219	2
Ward County	TX	0	-2,903	0	0	0	-74	-4
Winkler County	TX	0	5,437	0	0	0	-2,120	-712
Yoakum County	TX	0	146	0	0	0	0	84
Cimarron County	OK	0	183	0	0	0	0	0
Chaves County	NM	0	1,312	0	0	0	-1	7
Colfax County	NM	0	1,740	0	0	0	0	0
Curry County	NM	10	9,173	0	0	0	-508	1,227
DeBaca County	NM	0	-882	0	0	0	-18	66
Eddy County	NM	0	-87	0	0	0	-51	18
Guadalupe County	NM	0	164	0	0	0	0	14
Harding County	NM	0	537	0	0	0	0	0
Lea County	NM	0	5,392	0	0	0	-2,974	1,733
Quay County	NM	1,183	6,856	-2,319	-1,984	0	-4,000	2,506
Roosevelt County	NM	0	1,011	0	0	0	-246	177
Union County	NM	0	6,513	0	0	0	-2	34

ET = evapotranspiration TX = Texas NM = New Mexico

Table 9.2.11 Water budget in the Dockum Aquifer by Groundwater Conservation District for 1997 (all rates reported in acre-feet per year).

GCD/UWCD/WCD	Recharge	Younger Recharge	Streams	ET	Springs	Pumping	Storage
Clear Fork GCD	2,031	0	-322	-278	0	-10	-1,405
Coke County UWCD	105	-234	0	0	0	0	0
Crockett County GCD	0	-2,650	0	0	0	-3	1
Garza County Underground And Fresh WCD	6,509	927	-3,658	-1,739	-46	-96	-3,007
Glasscock GCD	0	1,562	0	0	0	-1,027	204
High Plains UWCD No.1	1,087	-45,529	-2,136	-3,145	-172	-8,068	38,427
Irion County WCD	0	-620	0	0	0	0	0
Llano Estacado UWCD	0	-4,923	0	0	0	0	1,342
Lone Wolf GCD	19,472	388	-6,887	-5,275	-10	-1,235	-7,365
Mesa UWCD	27	3,509	-203	-727	0	-2	-959
Middle Pecos GCD	0	1,018	0	0	0	-770	26
North Plains GCD	56	13,807	0	0	0	-9,168	603
Panhandle GCD	2,843	515	-752	-1,618	-289	-820	372
Permian Basin UWCD	4,578	-970	-1,023	-984	0	-61	-1,982
Salt Fork UWCD	1,066	0	-341	-278	-15	-3	-308
Sandy Land UWCD	0	133	0	0	0	0	87
Santa Rita UWCD	0	2,191	0	0	0	-1,037	209
South Plains UWCD	0	-2,120	0	0	0	0	330
Sterling County UWCD	439	-110	-224	-27	0	-11	-1
Wes-Tex GCD	7,135	0	-526	-586	0	-721	-5,067

ET = evapotranspiration
GCD = Groundwater Conservation District
UWCD = Underground Water Conservation District
WCD = Water Conservation District

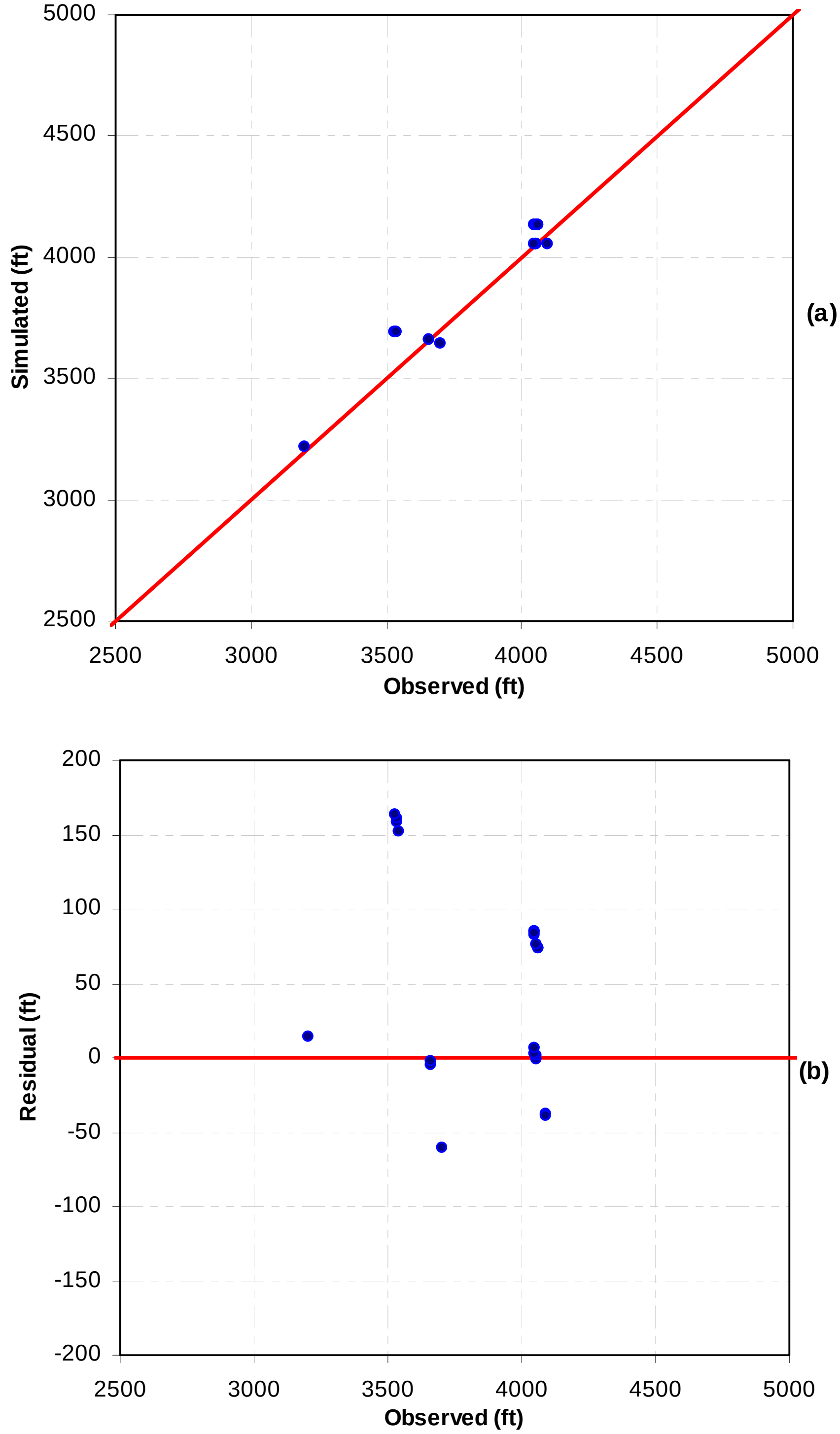

Figure 9.2.1 Plots of (a) simulated versus observed water-level elevations in feet and (b) residual versus observed water-level elevation in feet for the upper portion of the Dockum Aquifer for transient model calibration (1980 through 1997).

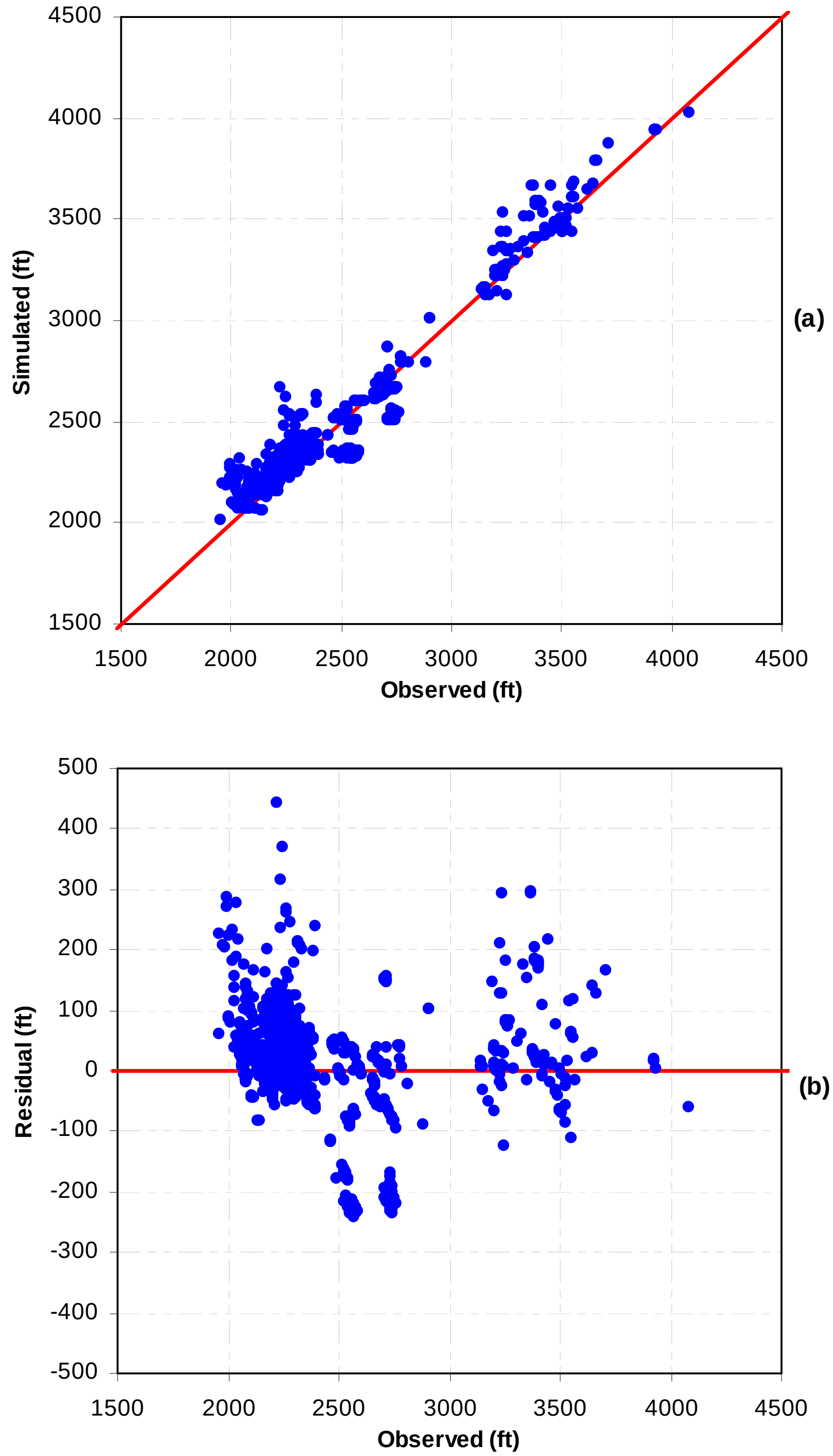

Figure 9.2.2 Plots of (a) simulated versus observed water-level elevations in feet and (b) residual versus observed water-level elevation in feet for the lower portion of the Dockum Aquifer for transient model calibration (1980 through 1997).

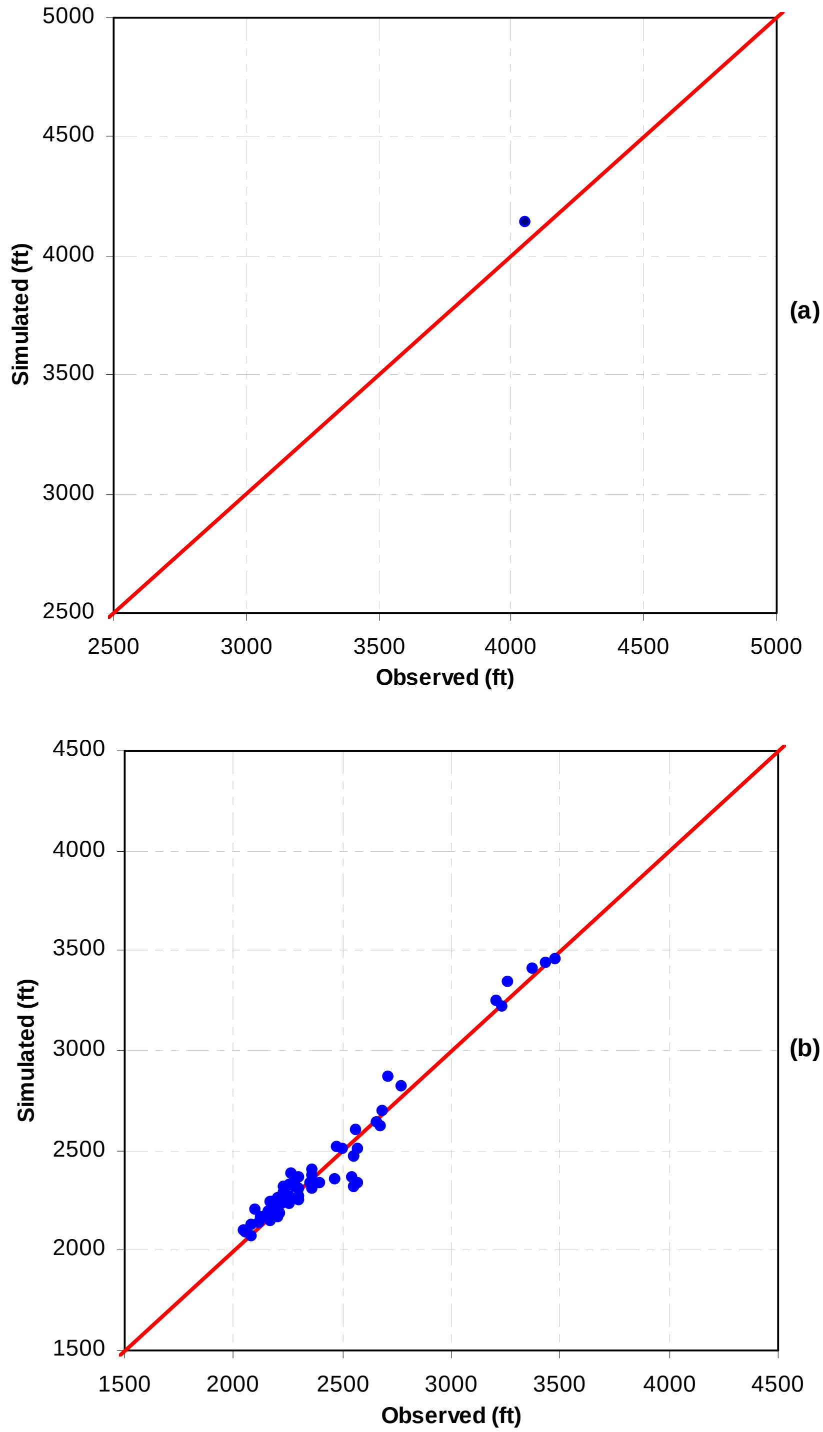

Figure 9.2.3 **Plots of simulated versus observed water-level elevations in feet for (a) the upper and (b) the lower portions of the Dockum Aquifer for 1990.**

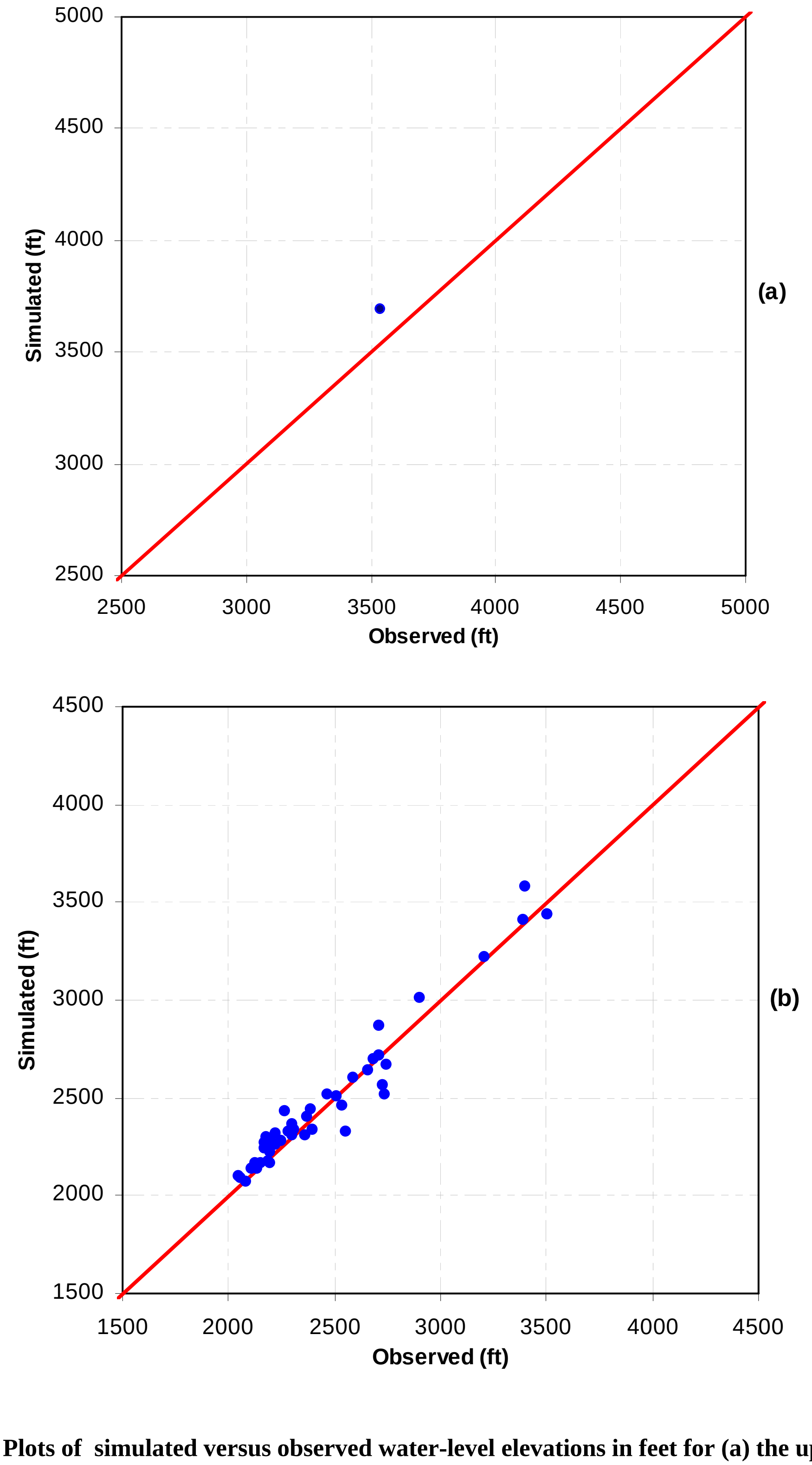

Figure 9.2.4 **Plots of simulated versus observed water-level elevations in feet for (a) the upper and (b) the lower portions of the Dockum Aquifer for 1997.**

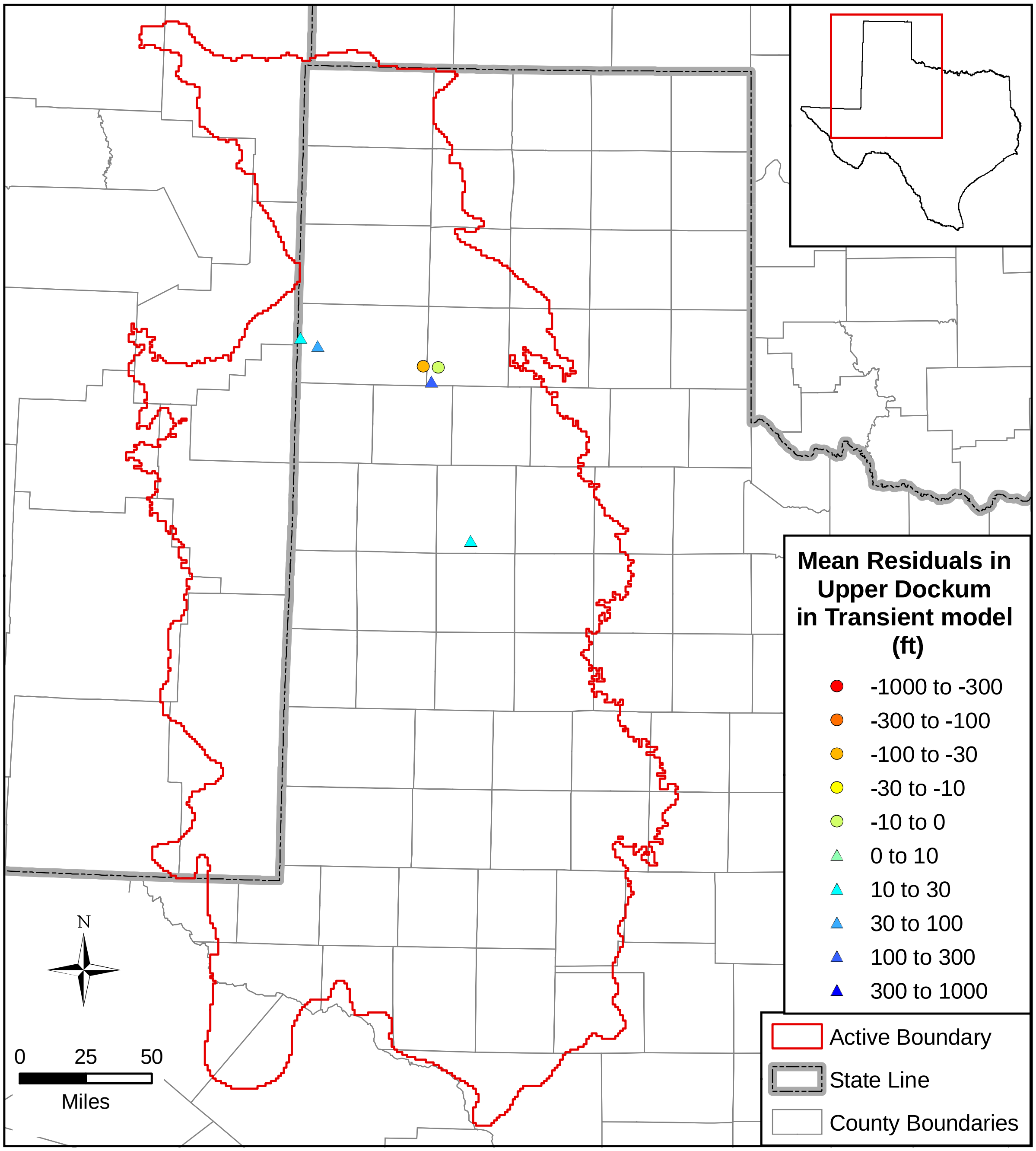

Figure 9.2.5 **Average residuals in feet at target wells for the upper portion of the Dockum Aquifer for the entire transient model calibration (1980 through 1997).**

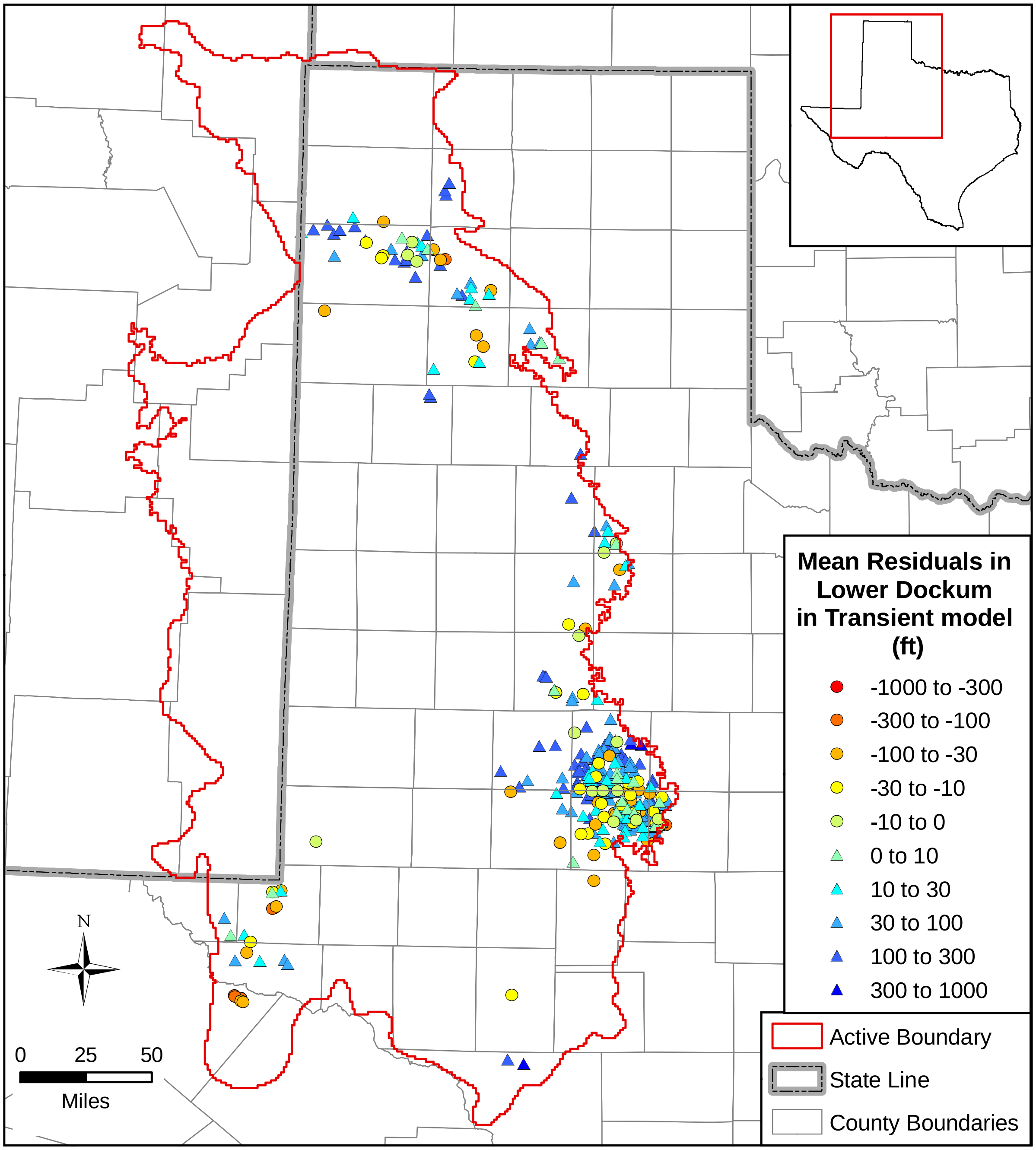

Figure 9.2.6 **Average residuals in feet at target wells for the lower portion of the Dockum Aquifer for the entire transient model calibration (1980 through 1997).**

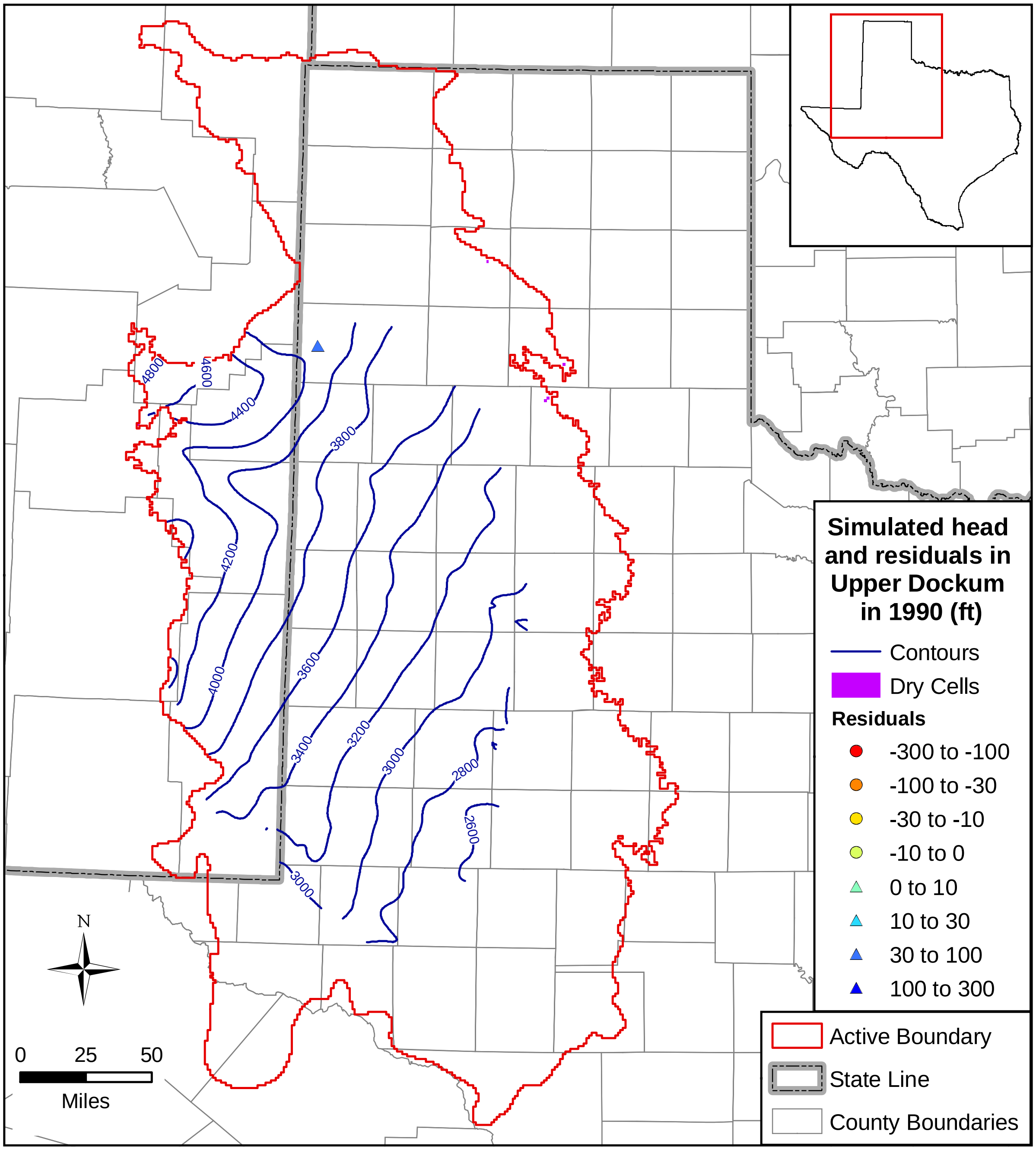

Figure 9.2.7 **Simulated water levels and residuals in feet at target wells for the upper portion of the Dockum Aquifer for 1990.**

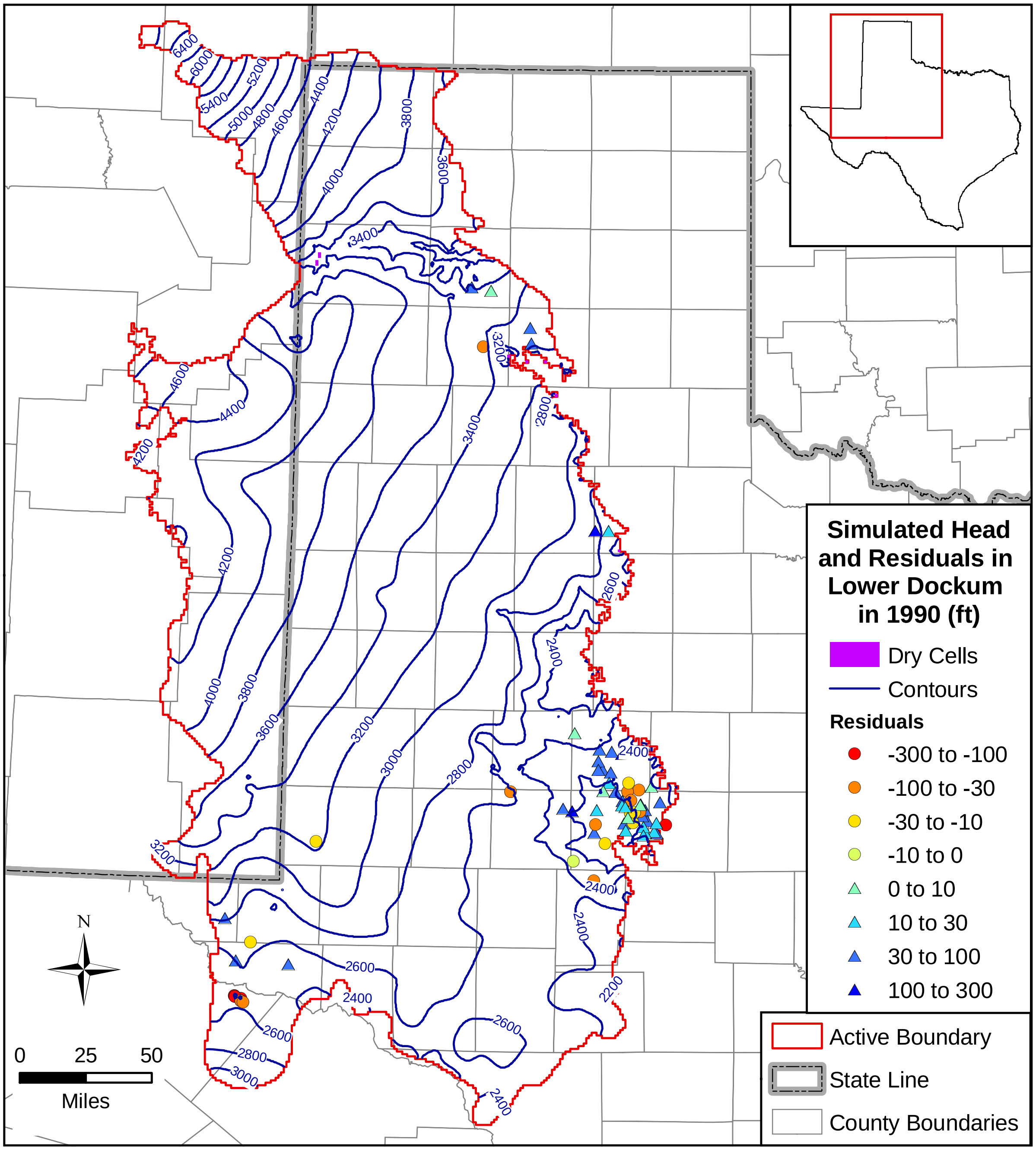

Figure 9.2.8 **Simulated water levels and residuals in feet at target wells for the lower portion of the Dockum Aquifer for 1990.**

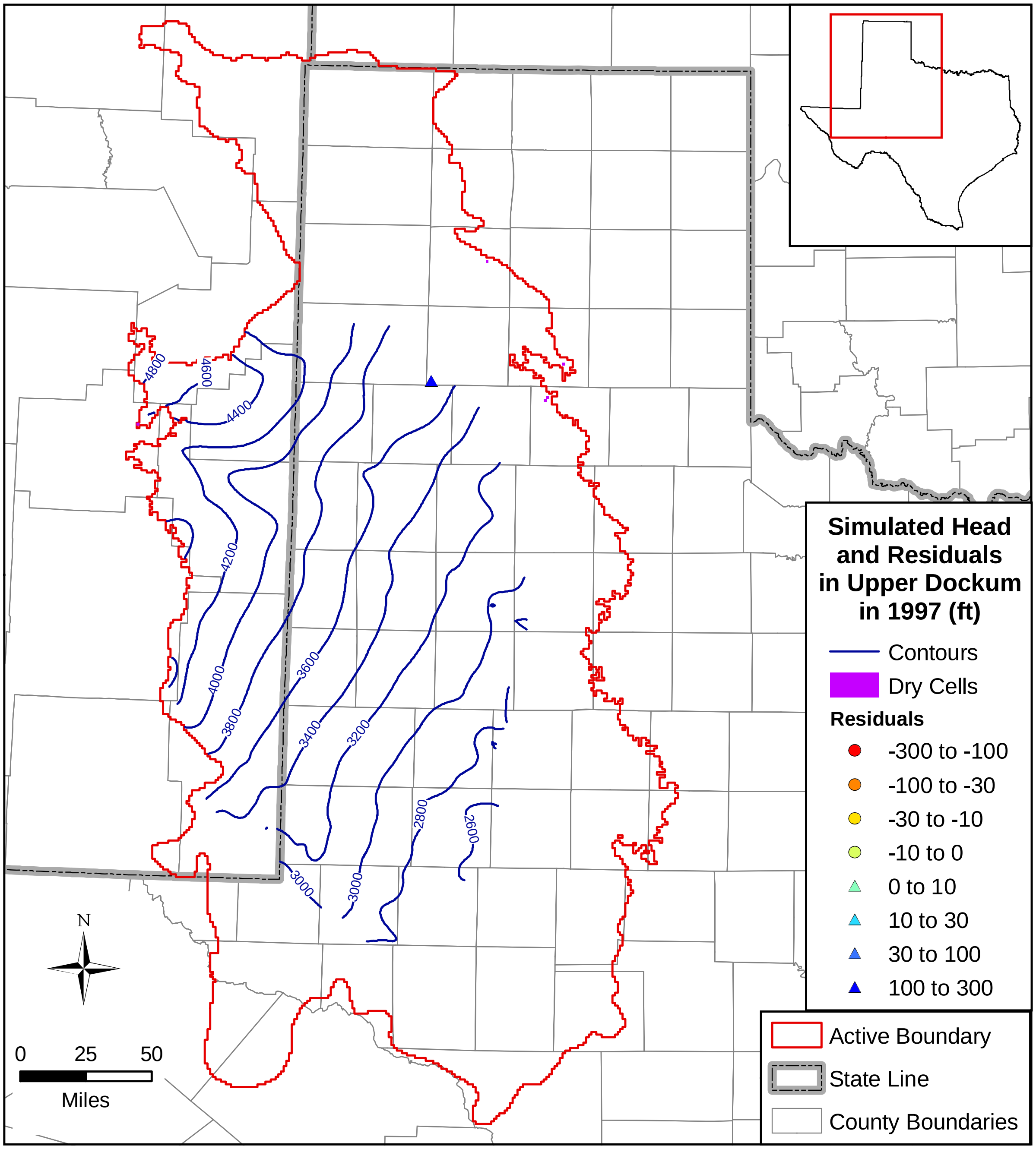

Figure 9.2.9 **Simulated water levels and residuals in feet at target wells for the upper portion of the Dockum Aquifer for 1997.**

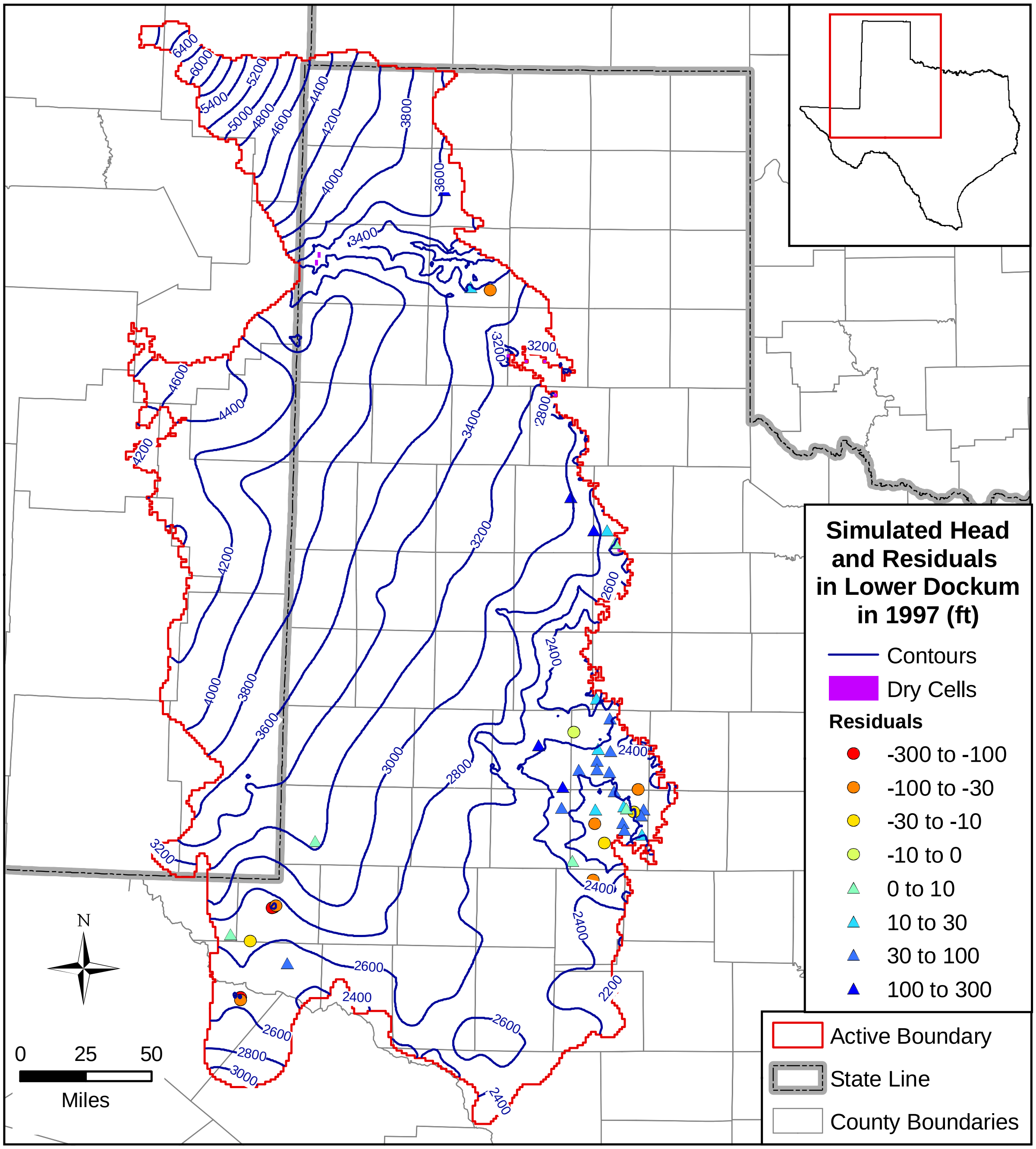

Figure 9.2.10 **Simulated water levels and residuals in feet at target wells for the lower portion of the Dockum Aquifer for 1997.**

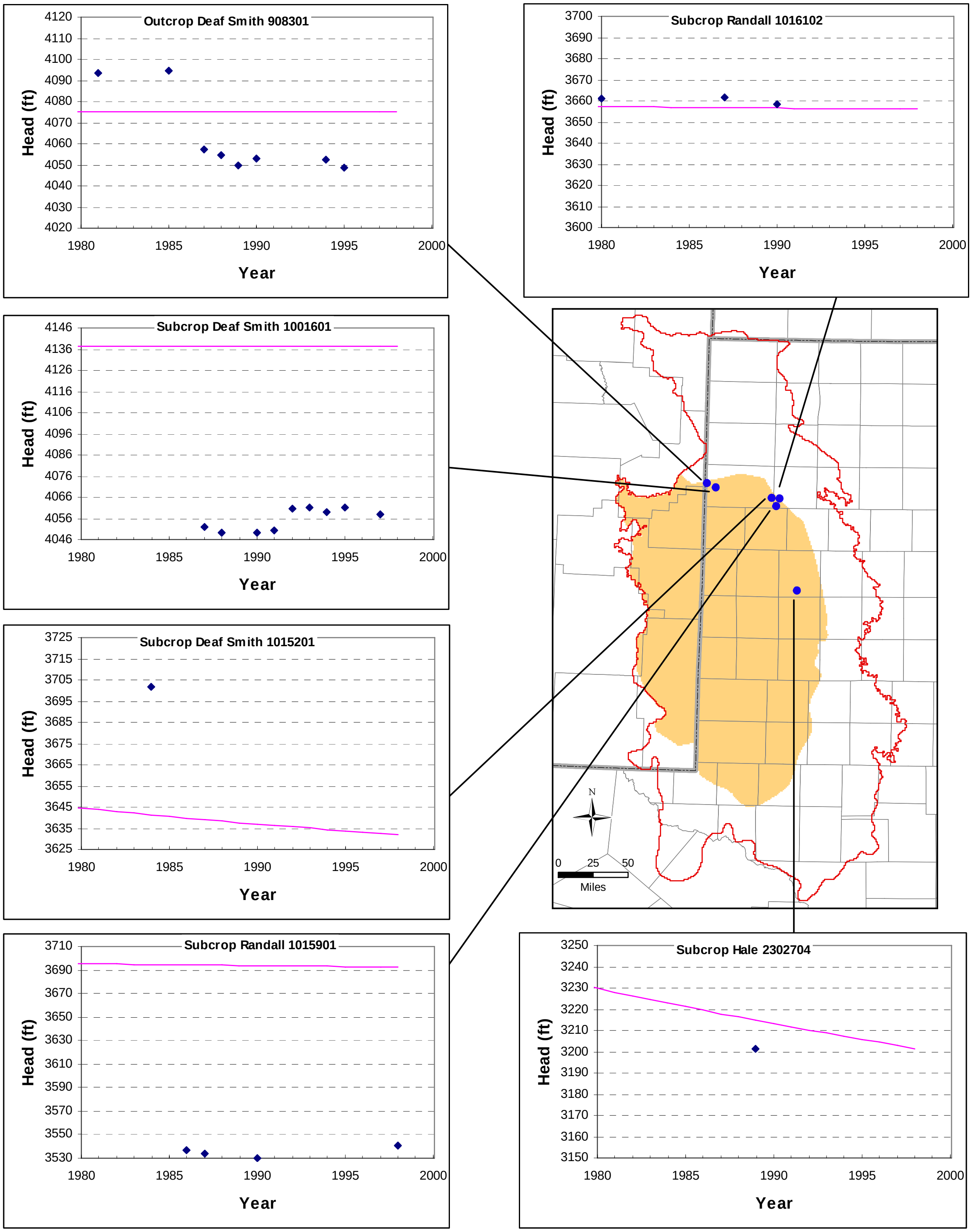

Figure 9.2.11 Hydrographs of simulated (lines) and measured (points) water-level elevations in feet in upper portion of the Dockum Aquifer.

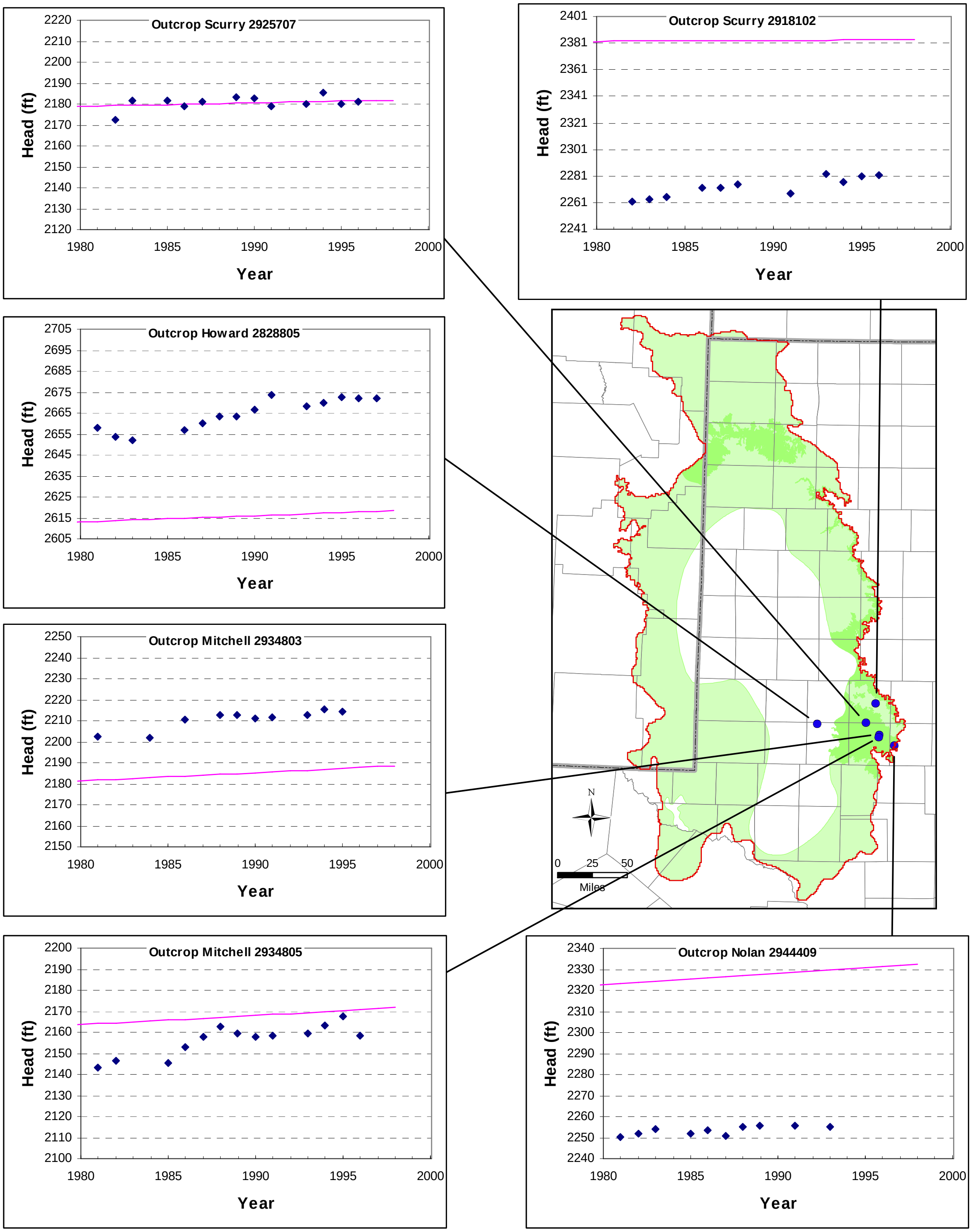

Figure 9.2.12 Selected hydrographs of simulated (lines) and measured (points) water-level elevations in feet with upward trends in the outcrop of the lower portion of the Dockum Aquifer.

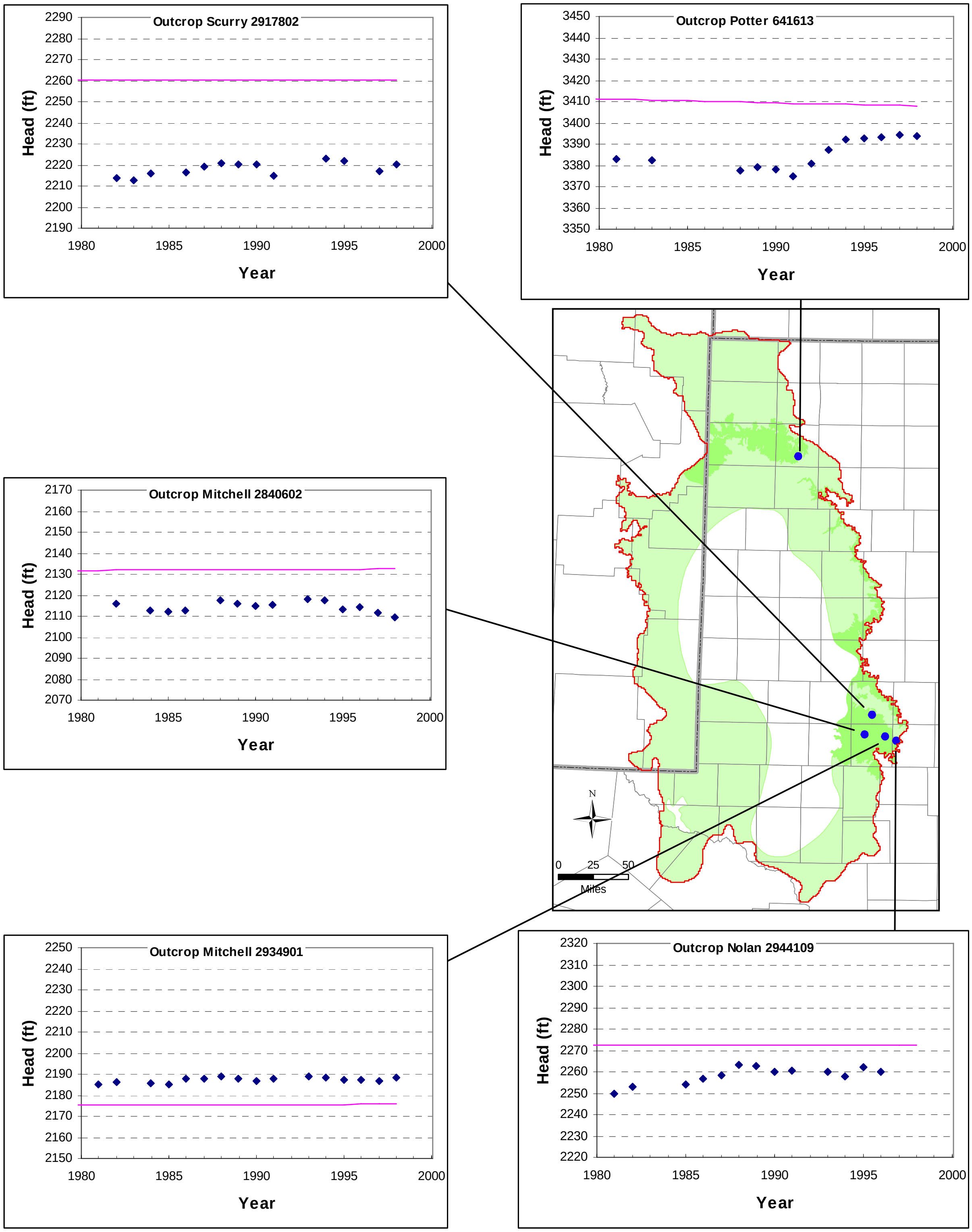

Figure 9.2.13 **Selected hydrographs of simulated (lines) and measured (points) water-level elevations in feet with stable trends in the outcrop of the lower portion of the Dockum Aquifer.**

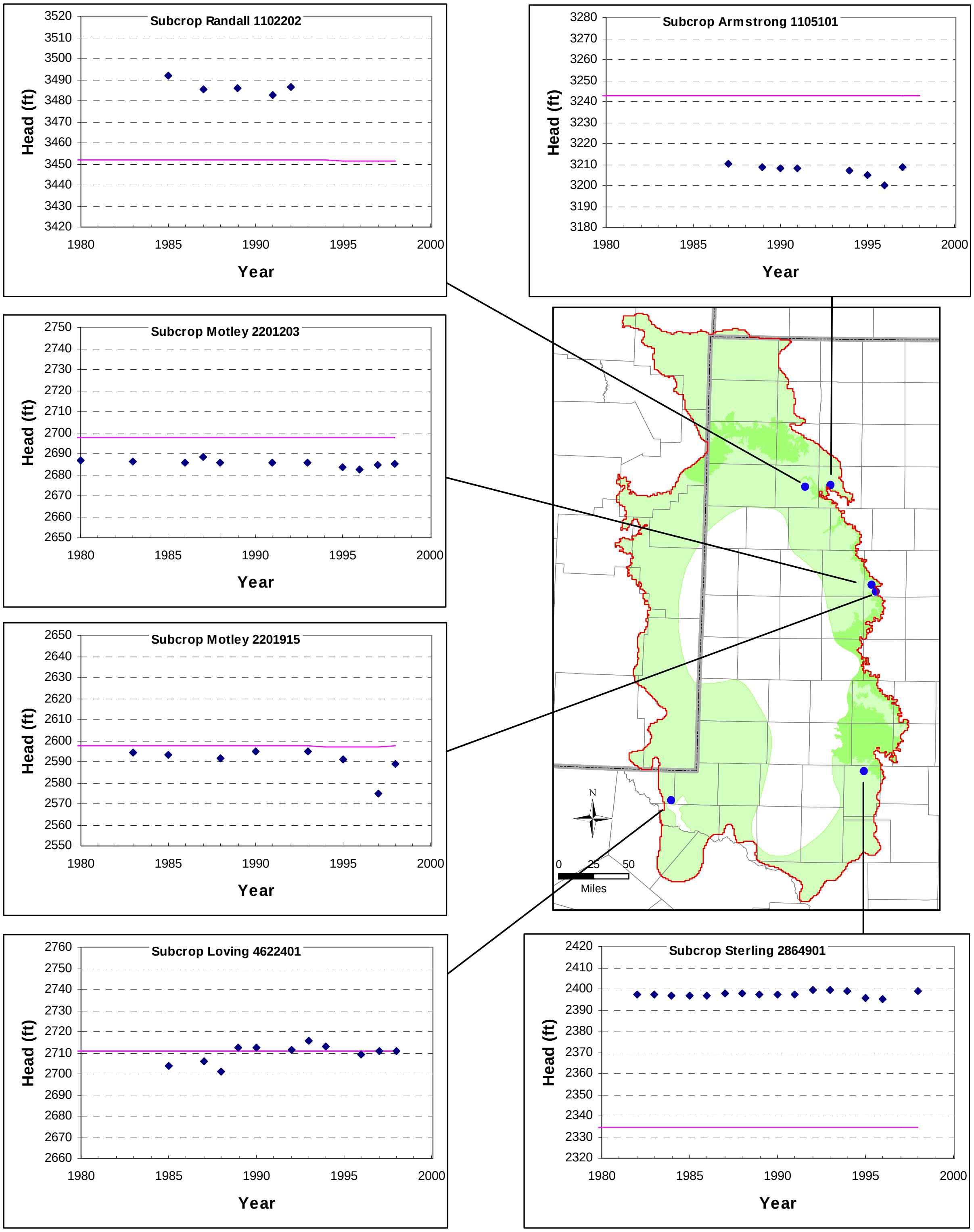

Figure 9.2.14 Selected hydrographs of simulated (lines) and measured (points) water-level elevations in feet with stable trends in the subcrop of the lower portion of the Dockum Aquifer.

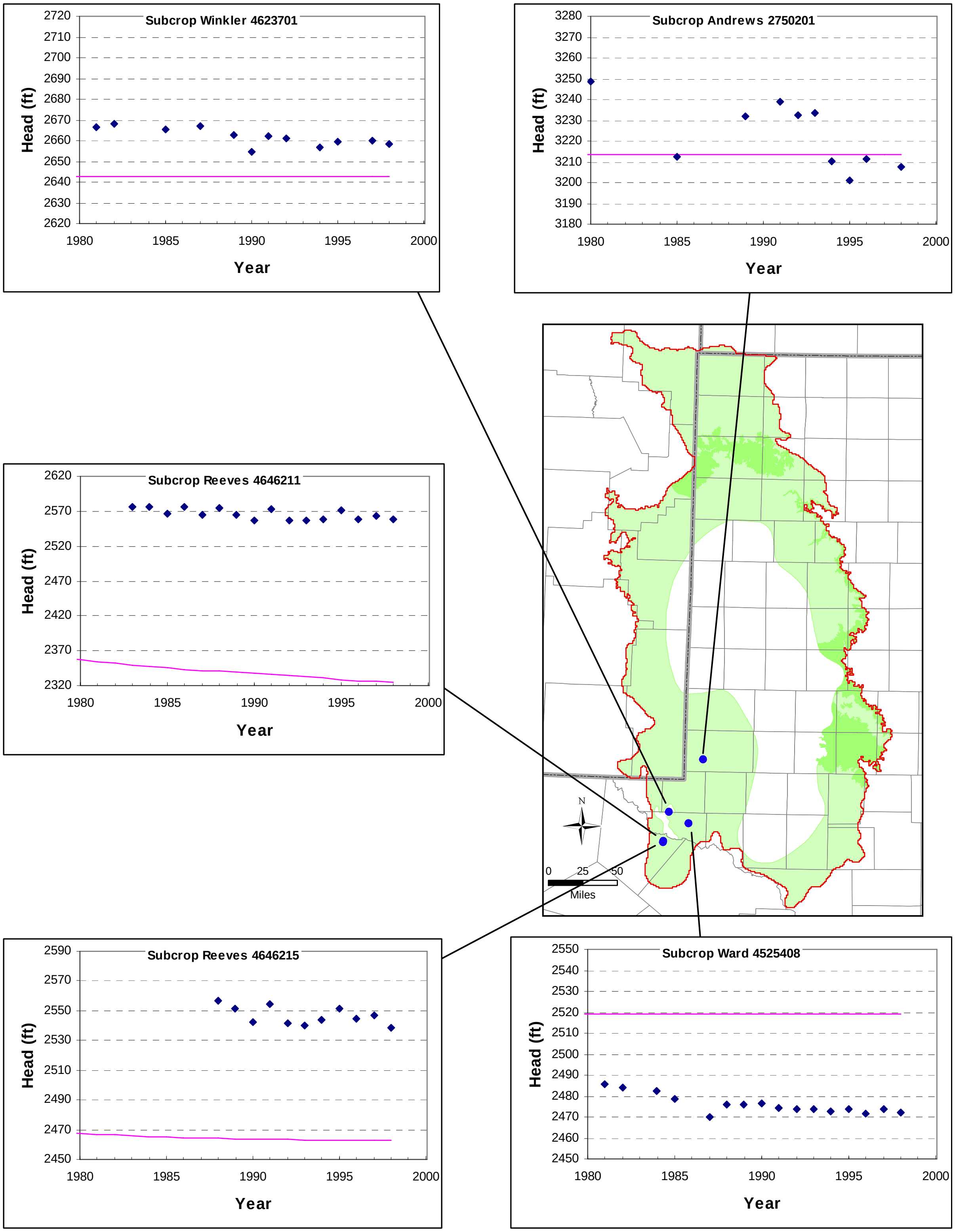

Figure 9.2.15 Selected hydrographs of simulated (lines) and measured (points) water-level elevations in feet with downward trends in the subcrop of the lower portion of the Dockum Aquifer.

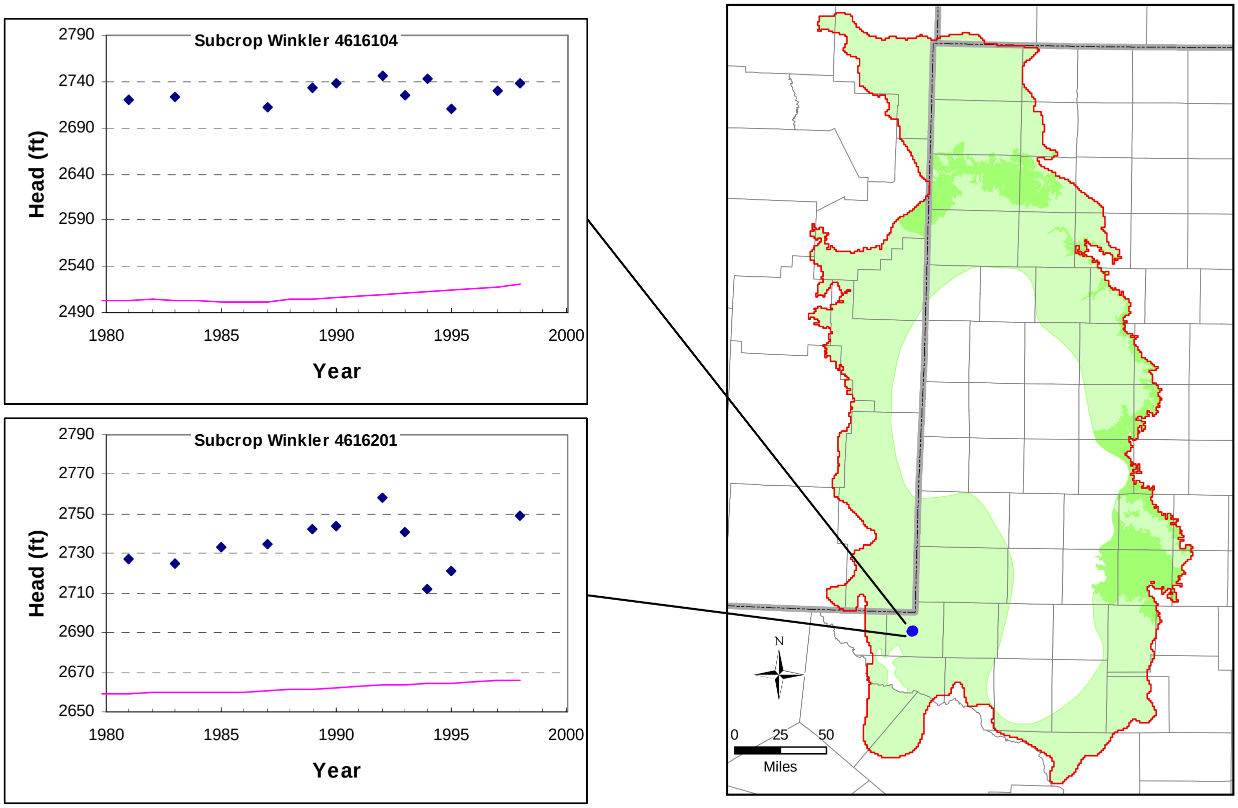

Figure 9.2.16 **Selected hydrograph of simulated (lines) and measured (points) water-level elevations in feet with upward trends in the subcrop of the lower portion of the Dockum Aquifer.**

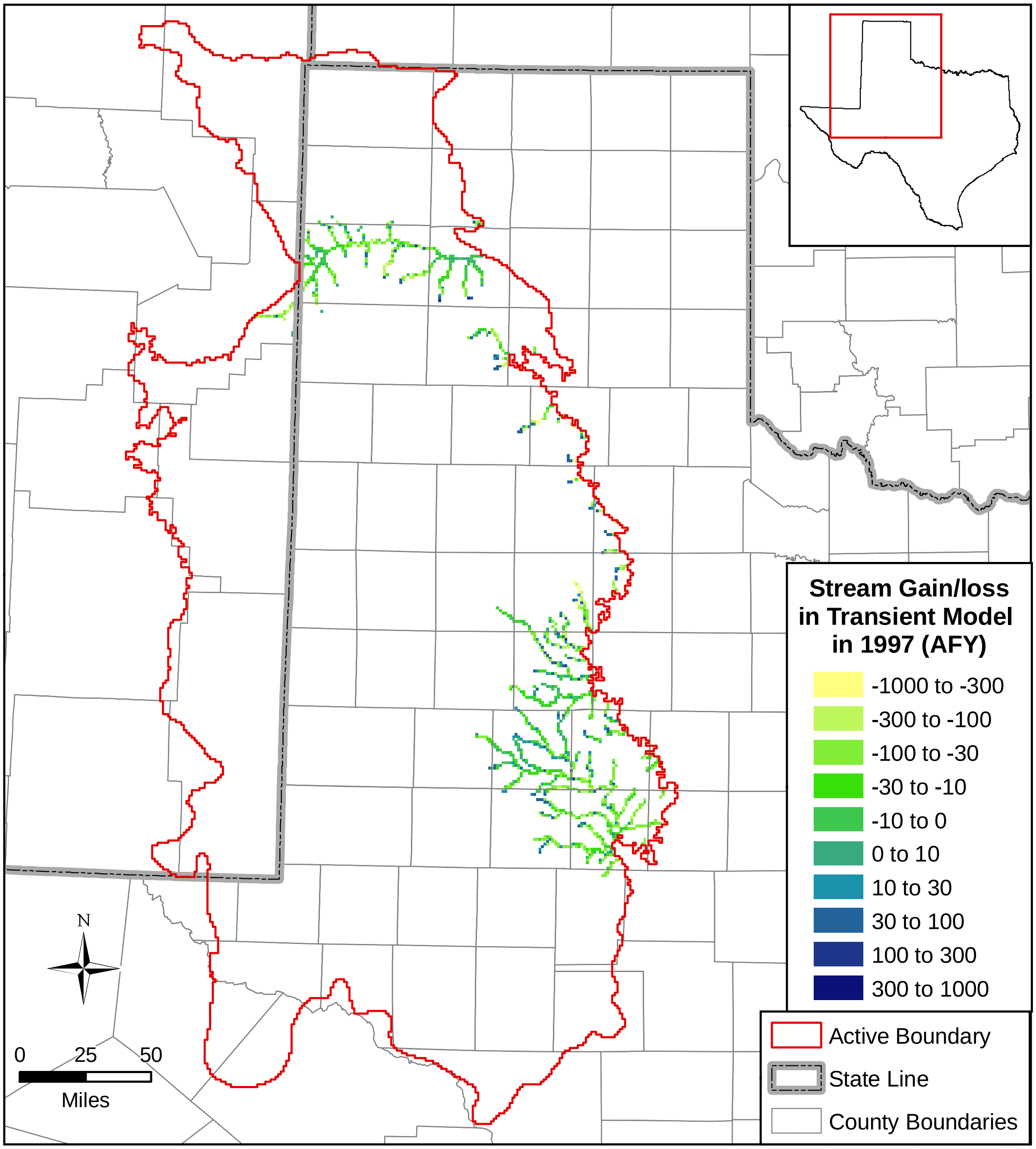

Figure 9.2.17 **Simulated stream gain/loss in acre-feet per year for 1997 (negative value indicates gaining stream cell).**

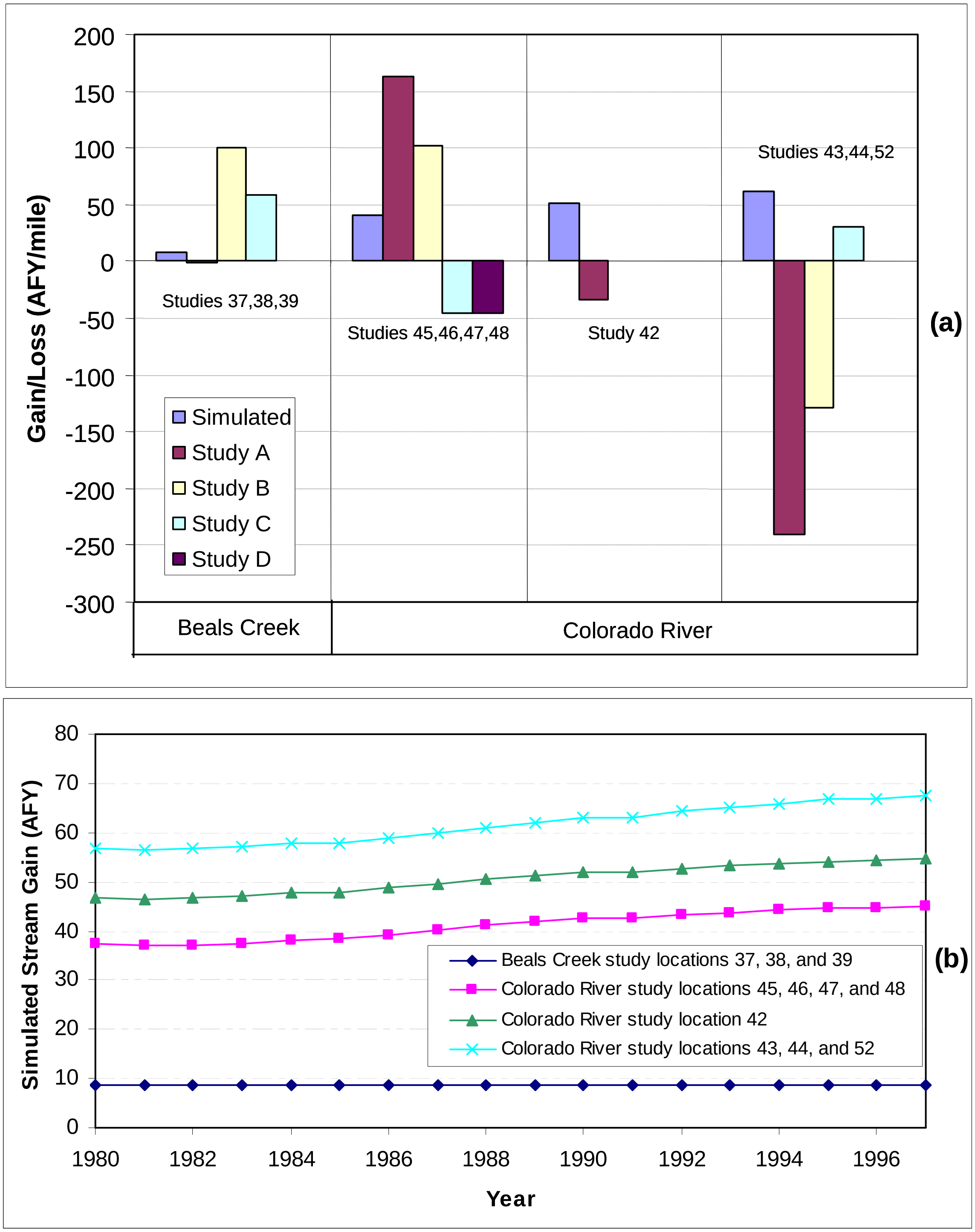

Figure 9.2.18 **(a) Comparison of simulated and measured stream gain/loss in acre-feet per year (positive value indicates gaining stream cell) and (b) temporal trend in simulated gains. Studies (after Slade and others, 2002) are detailed in Section 4.5.1.**

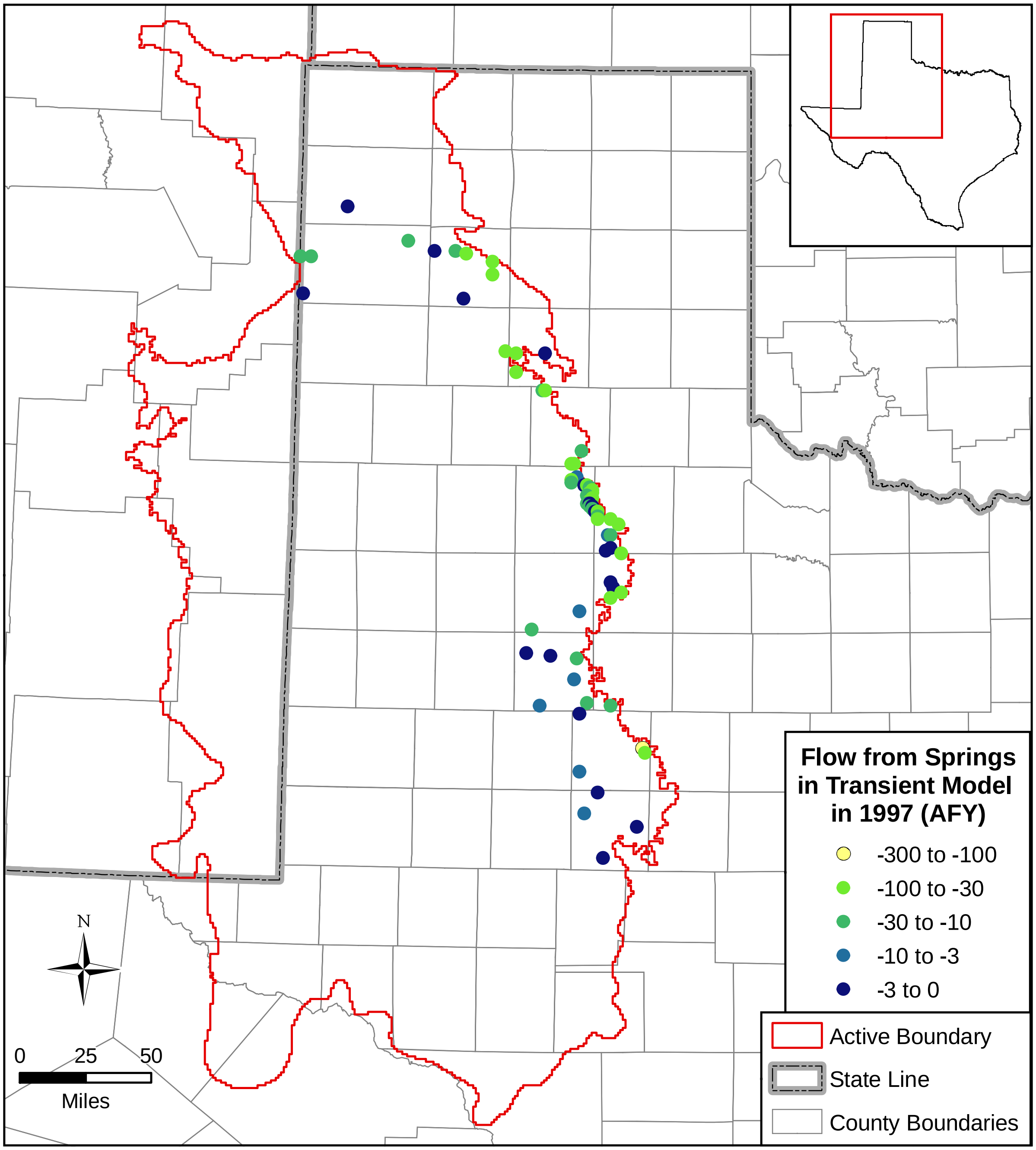

Figure 9.2.19 Simulated spring flow in acre-feet per year for the transient model in 1997.

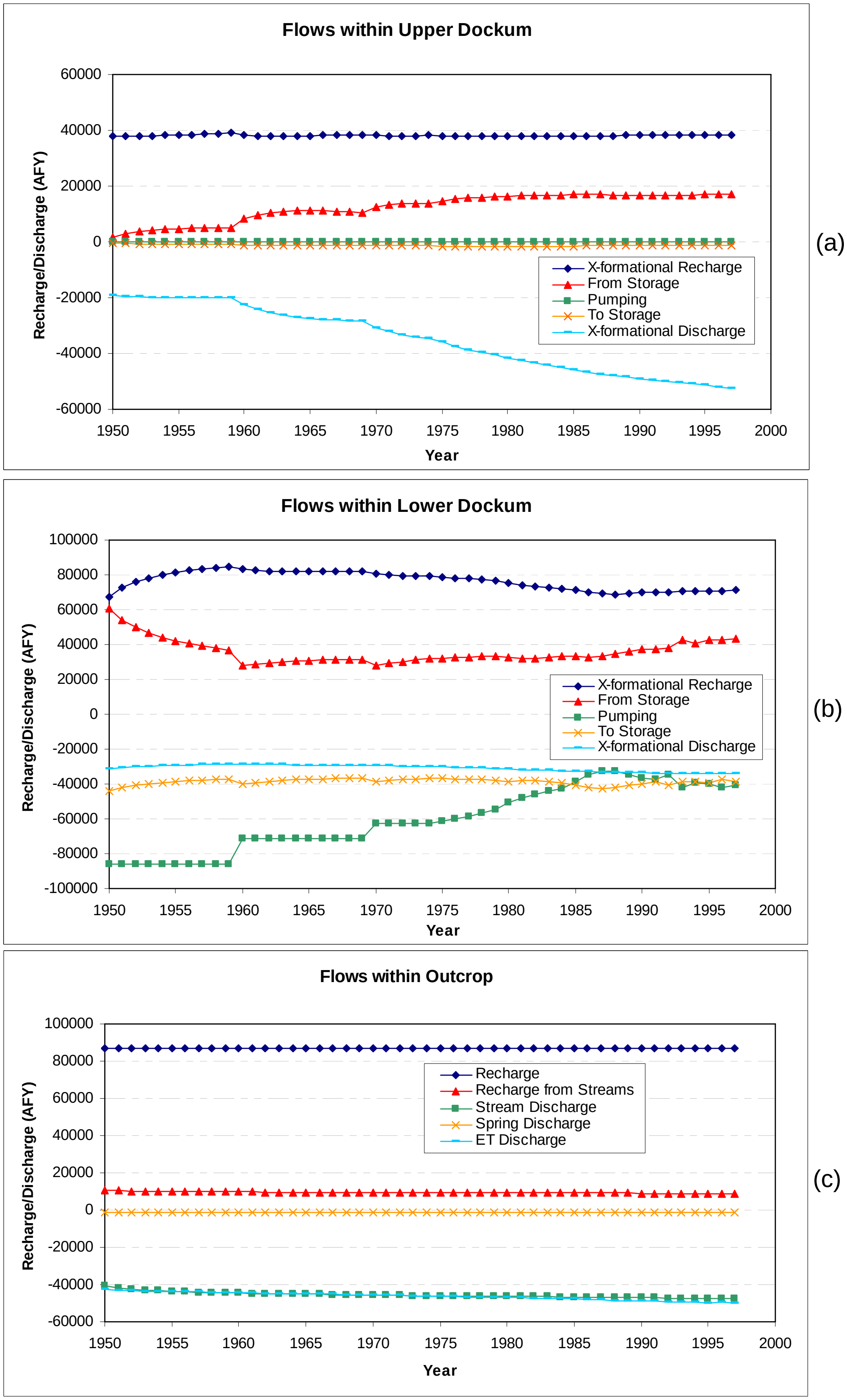

Figure 9.2.20 Time history of water budgets in acre-feet per year for (a) the upper portion of the Dockum Aquifer, (b) the lower portion of the Dockum Aquifer, and (c) the outcrop. Positive values denote recharge and negative values denote discharge.

9.3 Sensitivity Analysis

Section 8.3 discusses the approach for sensitivity analyses for the steady-state model. The analyses were similar for the transient model, with the addition of several sensitivities. For the transient sensitivity analysis, 21 parameter sensitivities were conducted:

1. Horizontal hydraulic conductivity in layer 1 (Kh-Ogallala),
2. Horizontal hydraulic conductivity in layer 2 (Kh-Upper-Dockum),
3. Horizontal hydraulic conductivity in layer 3 (Kh-Lower-Dockum),
4. Vertical hydraulic conductivity in layer 1 (Kv-Ogallala),
5. Vertical hydraulic conductivity in layer 2 (Kv-Upper-Dockum),
6. Vertical hydraulic conductivity in layer 3 (Kv-Lower-Dockum),
7. Storativity in layer 2 (S-Upper-Dockum),
8. Storativity in layer 3 (S-Lower-Dockum),
9. Specific yield in layer 1 (Sy-Ogallala),
10. Specific yield in layer 2 (Sy-Upper-Dockum),
11. Specific yield in layer 3 (Sy-Lower-Dockum),
12. Recharge, model-wide (Recharge),
13. Pumping, model-wide (Pumping),
14. Streambed conductance (K-Stream),
15. Stream elevation (z-Stream),
16. Spring conductance (K-Spring),
17. Spring elevation (z-Spring),
18. evapotranspiration conductance (K-ET),
19. evapotranspiration elevation (z-ET),
20. general-head boundary conductance (K-GHB), and
21. general-head boundary elevation (z-GHB).

Equation 8.3.1 (varying linearly) for parameter variation was used for sensitivities 9-13, Equation 8.3.2 was used for sensitivities 1-8, 14, 16, 18, and 20, and Equation 8.3.3 was used for sensitivities 15, 17, 19, and 21.

As with the steady-state model, the mean difference between the base simulated head and the sensitivity simulated head was calculated by applying Equation 8.3.4 at all grid blocks and also only at grid blocks where targets are present. Figures 9.3.1 and 9.3.2 show the transient sensitivity results for layers 2 and 3, respectively, varying hydraulic conductivities with mean differences calculated for the target grid blocks. In comparison, Figures 9.3.3 and 9.3.4 show the corresponding sensitivity results with mean differences calculated at all active grid blocks. Figures 9.3.5 and 9.3.6 show the transient sensitivity results for layers 2 and 3, respectively, varying storage with mean differences calculated for the target grid blocks. In comparison, Figures 9.3.7 and 9.3.8 show the corresponding sensitivity results with mean differences calculated at all active grid blocks. Figures 9.3.9 and 9.3.10 show the transient sensitivity results for layers 2 and 3, respectively, varying boundary condition conductance with mean differences calculated for the target grid blocks. In comparison, Figures 9.3.11 and 9.3.12 show the corresponding sensitivity results with mean differences calculated at all active grid blocks. Figures 9.3.13 and 9.3.14 show the transient sensitivity results for layers 2 and 3, respectively, varying boundary condition elevation with mean differences calculated for the target grid blocks. In comparison, Figures 9.3.15 and 9.3.16 show the corresponding sensitivity results with mean differences calculated at all active grid blocks.

Unlike in the steady-state model, the transient sensitivity analysis reveals several cases where sensitivity trends differ when considering heads at all active grid blocks versus considering only heads at the target locations. The elevations of the stream and evapotranspiration boundary conditions and the vertical hydraulic conductivity and specific yield of the lower portion of the Dockum Aquifer tend to be sensitive at the target locations but not sensitive over all active grid blocks. The storativity of the lower portion of the Dockum Aquifer and the general-head boundary conductance are sensitive over all active grid blocks but considerably less so at the target locations. This indicates that the spatial coverage of the targets is not adequate to constrain the entirety of the model domain. This is particularly true for the upper portion of the Dockum Aquifer where head targets are available at only five locations. The lower portion of the Dockum Aquifer has better target coverage but the majority of the targets are biased to the outcrops, the Colorado River outcrop in particular.

Like in the steady-state model, the most sensitive parameter for heads in both the upper and lower portion of the Dockum Aquifer is generally the elevation of the general-head boundary in layer 1, as illustrated by Figures 9.3.13 through 9.3.16, although, at the target locations within the lower portion of the Dockum Aquifer, the heads are more sensitive to elevations of streams and evapotranspiration boundary conditions. The general-head boundary elevation is based on data and it should be noted that, in the sensitivity analysis, the general-head boundary elevations were varied systematically (i.e., all at once and in the same direction). While there is uncertainty in the elevation of the general-head boundaries, the error is likely randomly distributed about the average of the measurements and there should be no systematic bias in the heads. The sensitivity analysis, therefore, greatly exaggerates the sensitivity of the simulated heads to the general-head boundary elevations. For this reason, the general-head boundary elevations were not altered during calibration. Of the calibrated parameters, the horizontal hydraulic conductivity of the lower portion of the Dockum Aquifer is the most consistently sensitive parameter as evidenced in Figures 9.3.1 through 9.3.4. Figures 9.3.1 and 9.3.2 indicate that the heads in the upper portion of the Dockum Aquifer are sensitive to the vertical hydraulic conductivity of the upper portion of the Dockum Aquifer. Heads are somewhat sensitive to recharge, particularly those at the layer 3 target locations as seen in Figure 9.3.11. Storage parameters of layers 1 and 3 are also somewhat sensitive (Figures 9.3.5 through 9.3.8), although approximately 5 to 10 times less sensitive than the hydraulic conductivity of the lower portion of the Dockum Aquifer.

Figure 9.3.17 through 9.3.21 show hydrographs illustrating the effects of independently varying the horizontal hydraulic conductivity of the lower portion of the Dockum Aquifer, recharge, the storativity of the lower portion of the Dockum Aquifer, the specific yield of the lower portion of the Dockum Aquifer, and pumping, respectively, on the simulated water levels for selected wells. Figure 9.3.17 indicates that most of the hydrographs are sensitive to changes in the horizontal hydraulic conductivity of the lower portion of the Dockum Aquifer. The figure also shows that decreasing the hydraulic conductivity in lower portion of the Dockum Aquifer tends to increase heads in the outcrop and decrease heads in the subcrop of the lower portion of the Dockum Aquifer. Figure 9.3.18 shows that increasing recharge increases heads in the outcrop but has little or no effect in the subcrop. All the selected hydrographs are insensitive to the storativity of the lower portion of the Dockum Aquifer as apparent in Figure 9.3.19.
Figure 9.3.20 shows that simulated water levels in the outcrop of the lower portion of the

Dockum Aquifer increase with a decrease in the specific yield of the lower portion of the Dockum Aquifer, presumably because recharge has more of an impact with a smaller specific yield. Conversely, the simulated water levels in the subcrop of the lower portion of the Dockum Aquifer in Reeves County decrease with a decrease in the specific yield of the lower portion of the Dockum Aquifer. This is an indication that the grid block cell in which that well lies has become unsaturated. Recall that this is in the area of the Monument Draw Trough where the Dockum Aquifer and the overlying Pecos Valley Aquifer are in good communication.

Figure 9.3.21 shows that pumping has the most impact in the subcrop of the lower portion of the Dockum Aquifer in Reeves County and an apparent but smaller impact in the outcrop in Mitchell County.

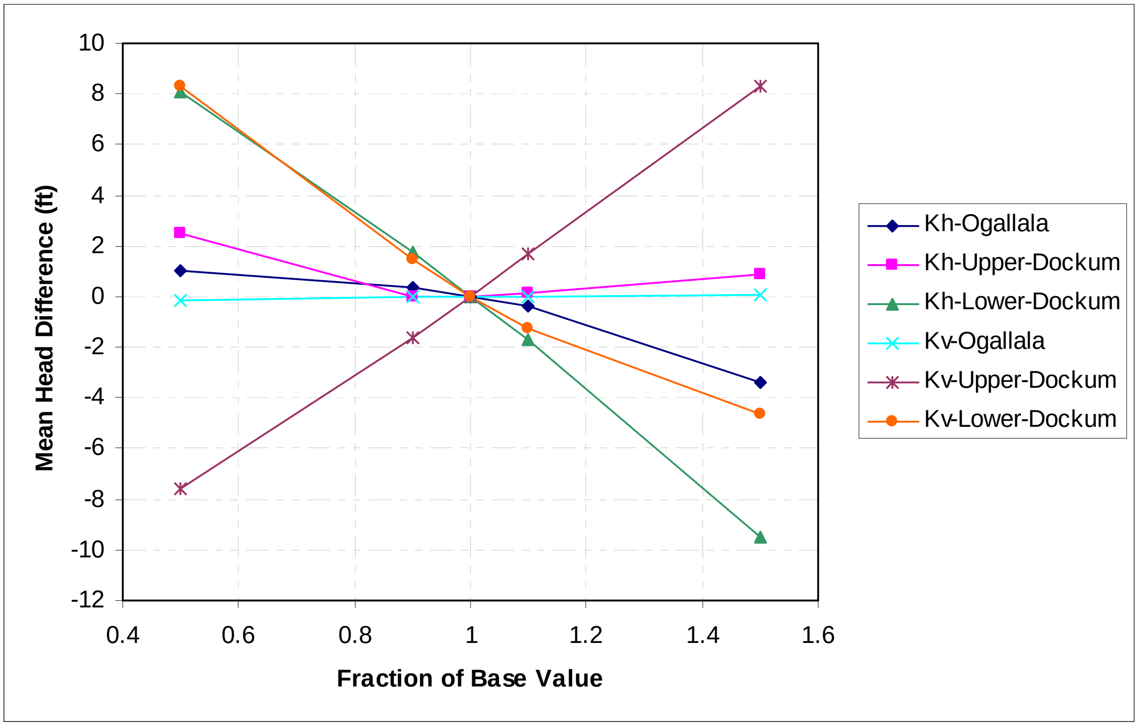

Figure 9.3.1 Transient sensitivity of hydraulic conductivity for the layer 2 heads in feet using target locations.

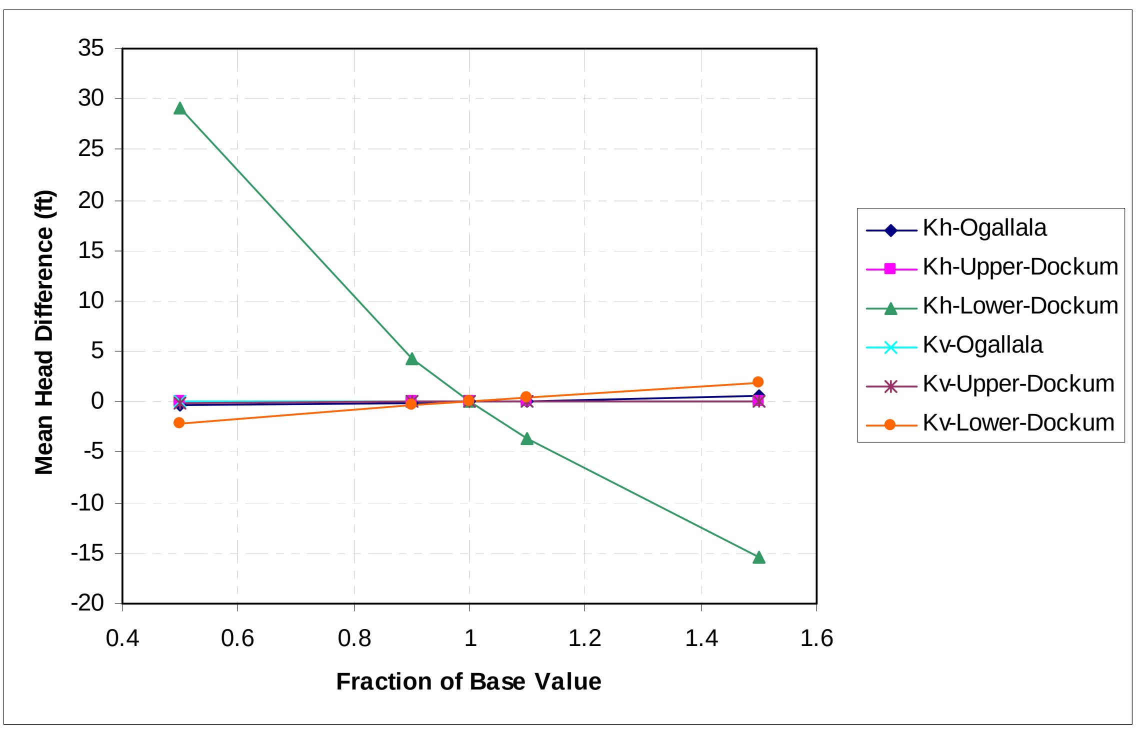

Figure 9.3.2 Transient sensitivity of hydraulic conductivity for the layer 3 heads in feet using target locations.

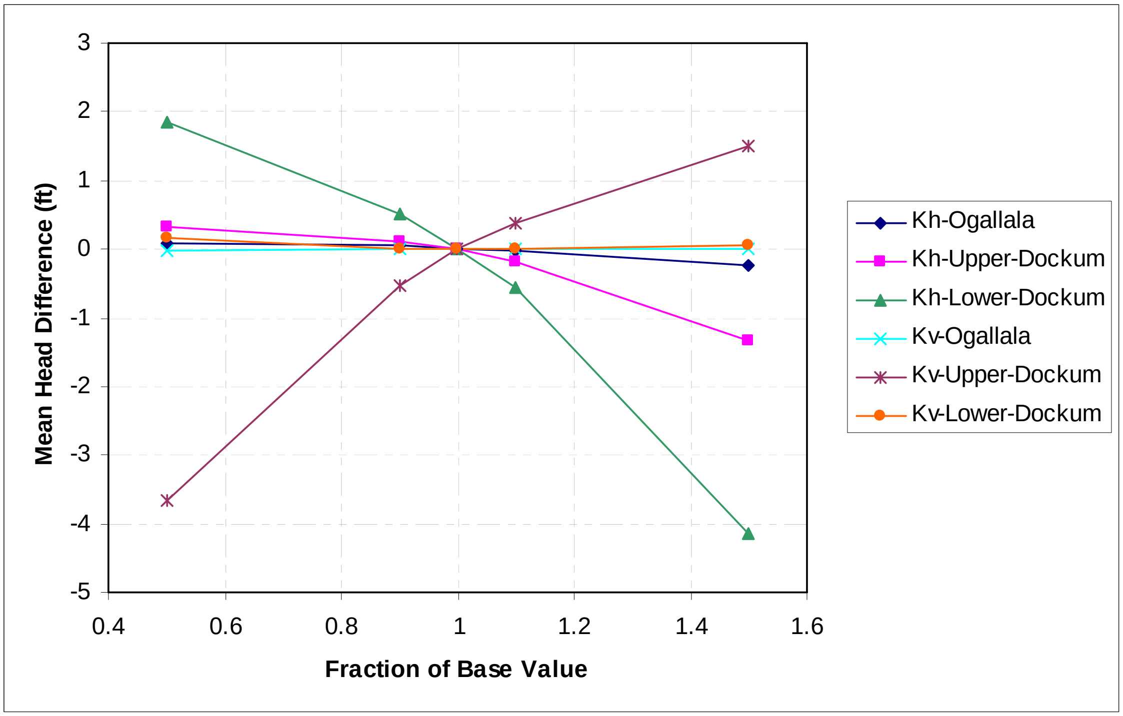

Figure 9.3.3 Transient sensitivity of hydraulic conductivity for the layer 2 heads in feet using all active grid blocks.

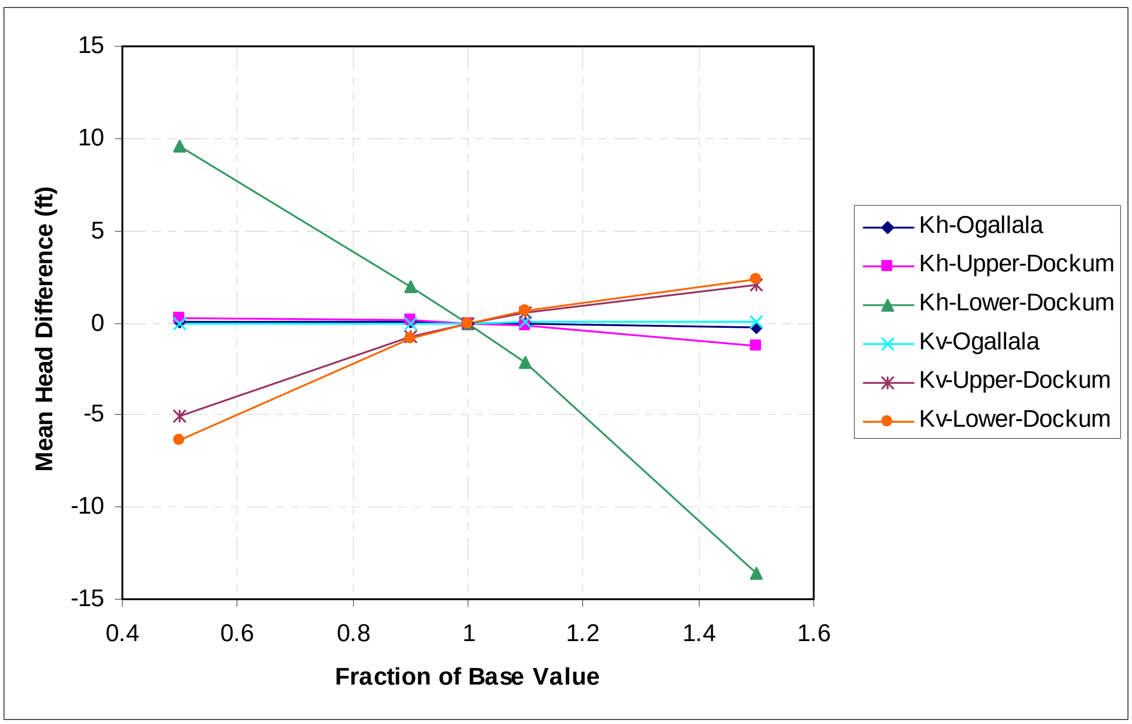

Figure 9.3.4 Transient sensitivity of hydraulic conductivity for the layer 3 heads in feet using all active grid blocks.

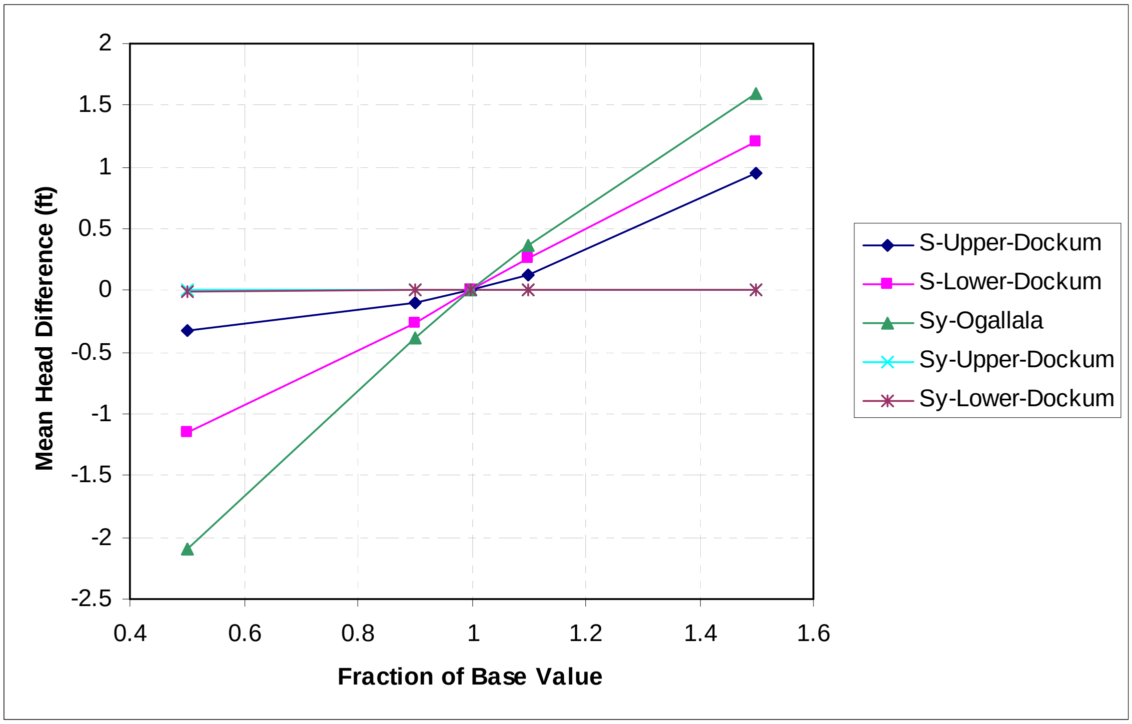

Figure 9.3.5 Transient sensitivity of storage for the layer 2 heads in feet using target locations.

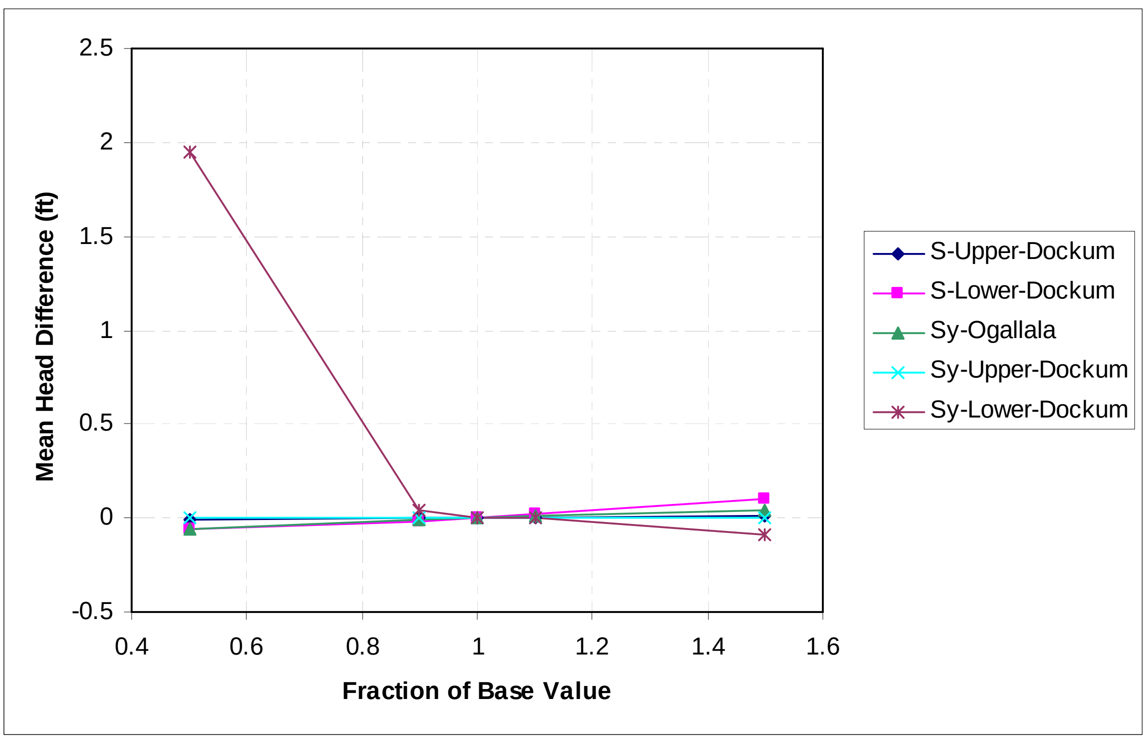

Figure 9.3.6 Transient sensitivity of storage for the layer 3 heads in feet using target locations.

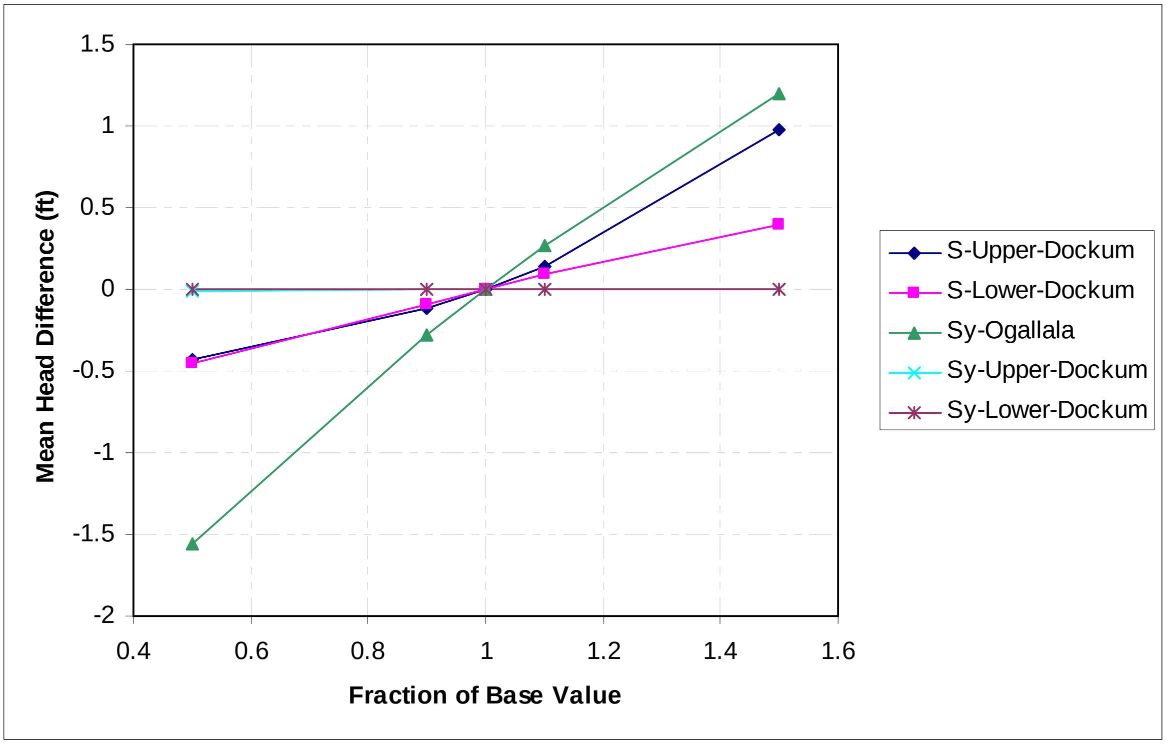

Figure 9.3.7 Transient sensitivity of storage for the layer 2 heads in feet using all active grid blocks.

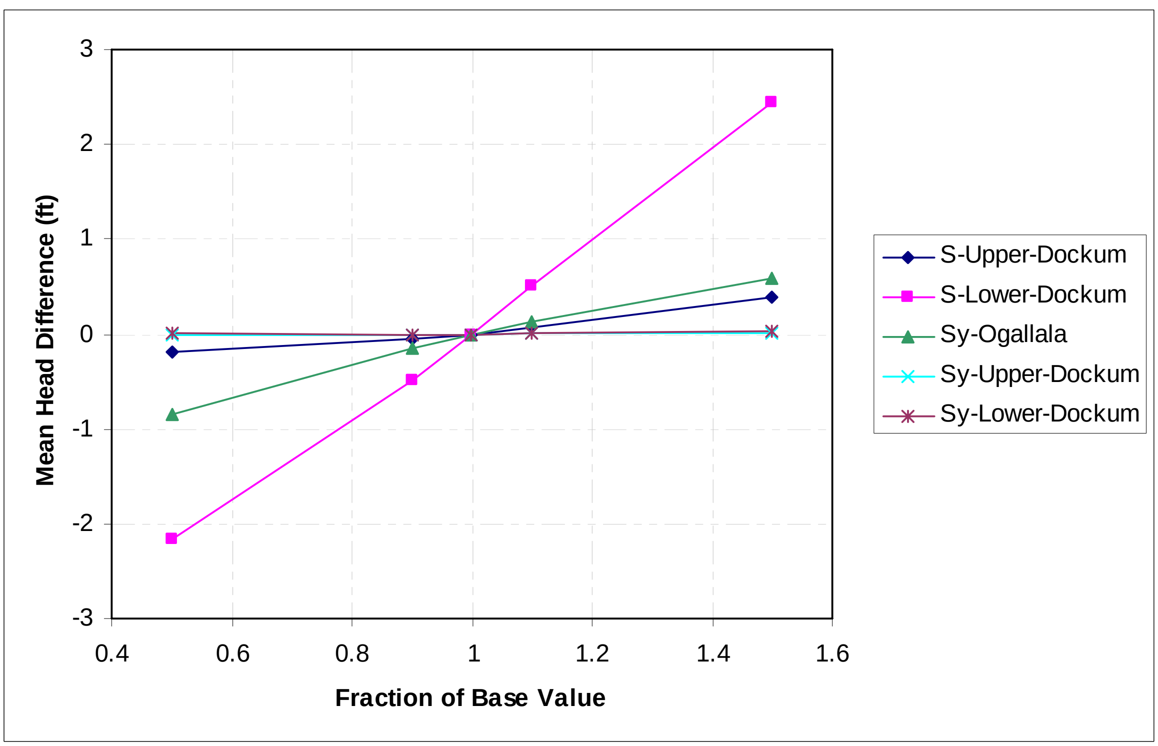

Figure 9.3.8 Transient sensitivity of storage for the layer 3 heads in feet using all active grid blocks.

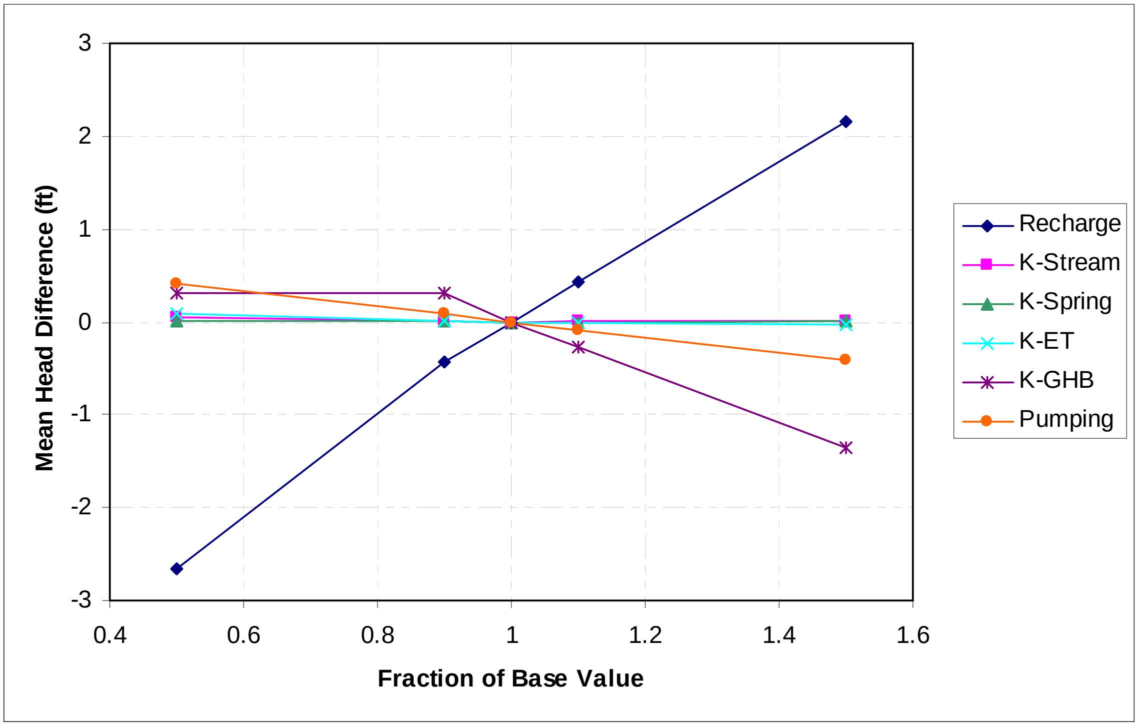

Figure 9.3.9 Transient sensitivity of boundary condition conductance for the layer 2 heads in feet using target locations.

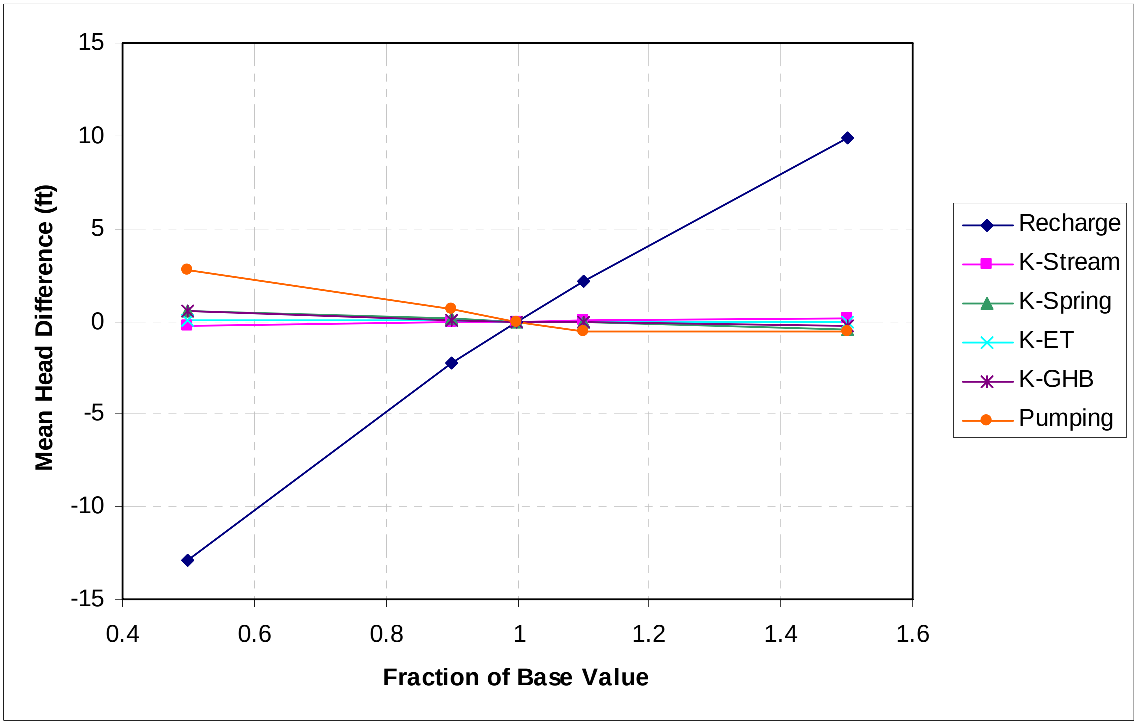

Figure 9.3.10 Transient sensitivity of boundary condition conductance for the layer 3 heads in feet using target locations.

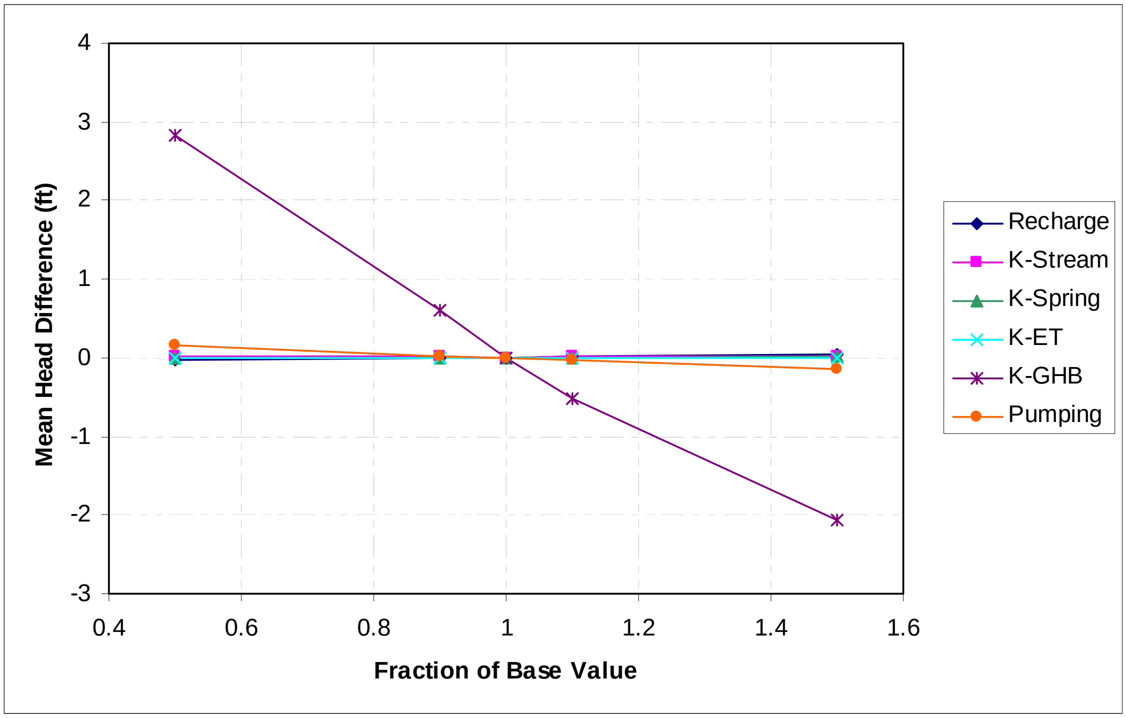

Figure 9.3.11 Transient sensitivity of boundary condition conductance for the layer 2 heads in feet using all active grid blocks.

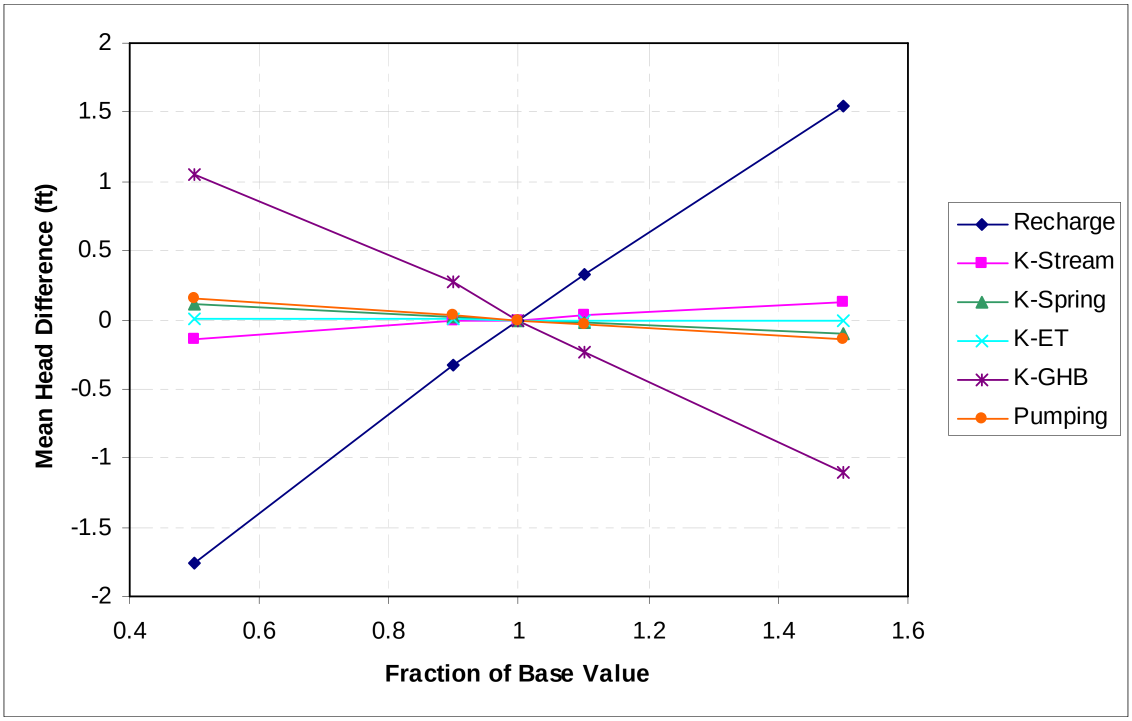

Figure 9.3.12 Transient sensitivity of boundary condition conductance for the layer 3 heads in feet using all active grid blocks.

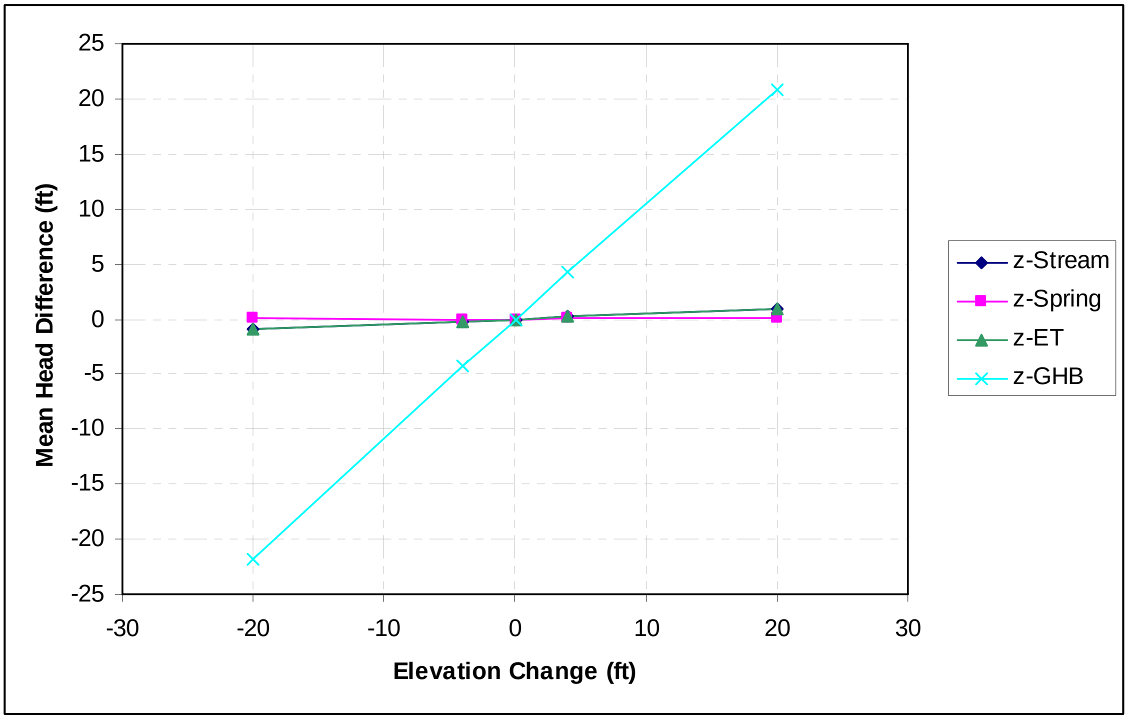

Figure 9.3.13 Transient sensitivity of boundary condition elevation in feet for the layer 2 heads in feet using target locations.

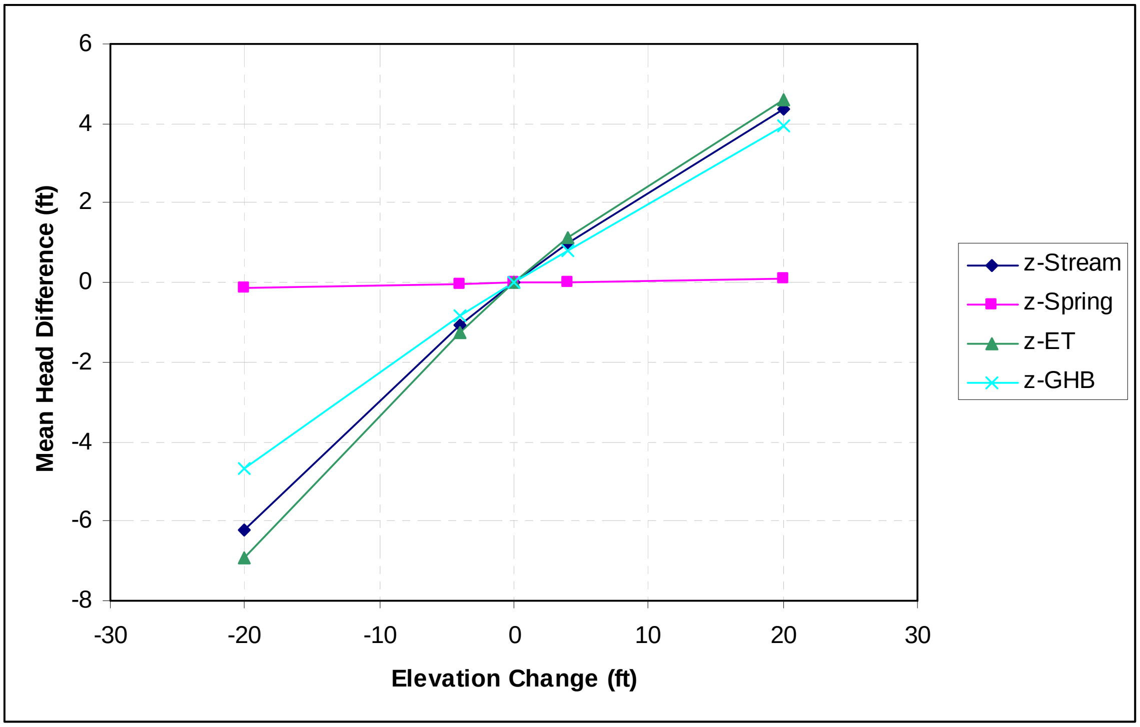

Figure 9.3.14 Transient sensitivity of boundary condition elevation in feet for the layer 3 heads in feet using target locations.

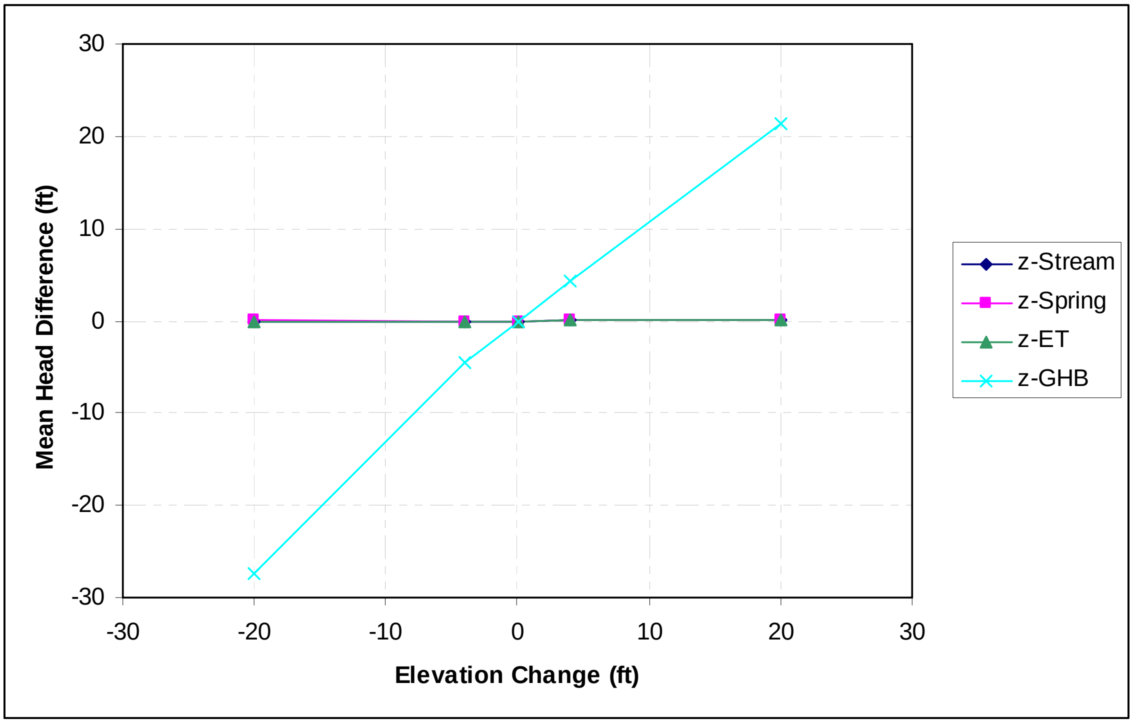

Figure 9.3.15 Transient sensitivity of boundary condition elevation in feet for the layer 2 heads in feet using all active grid blocks.

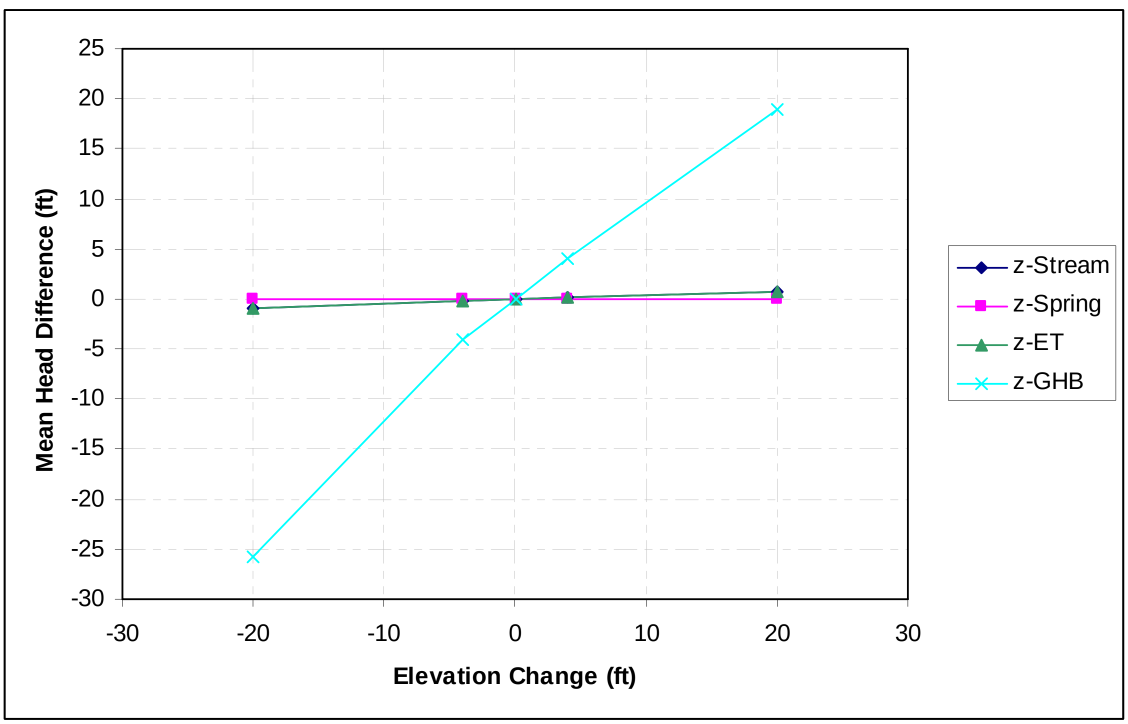

Figure 9.3.16 Transient sensitivity of boundary condition elevation in feet for the layer 3 heads in feet using all active grid blocks.

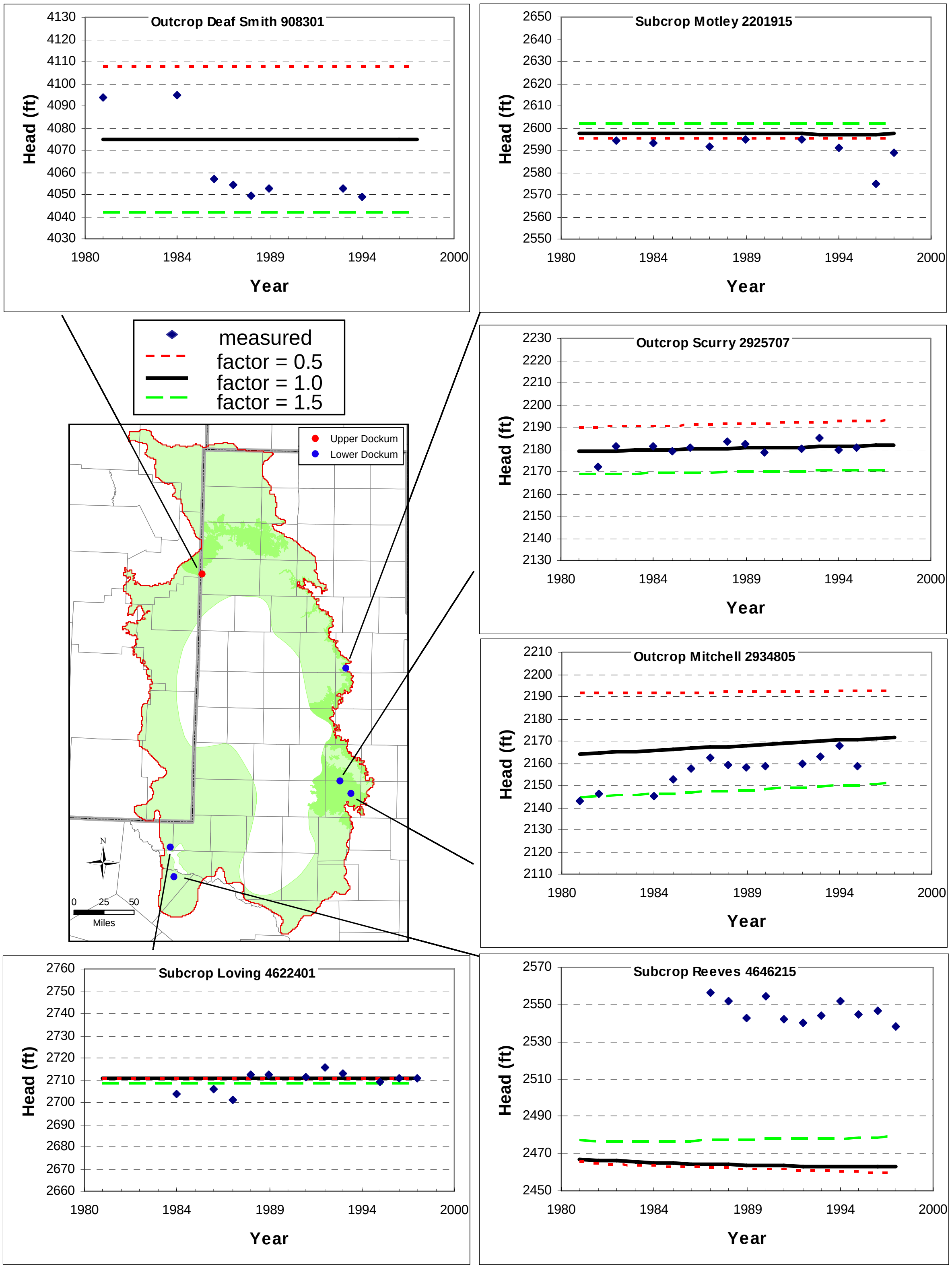

Figure 9.3.17 **Transient sensitivity hydrographs of head in feet where the horizontal hydraulic conductivity of the lower portion of the Dockum Aquifer is varied.**

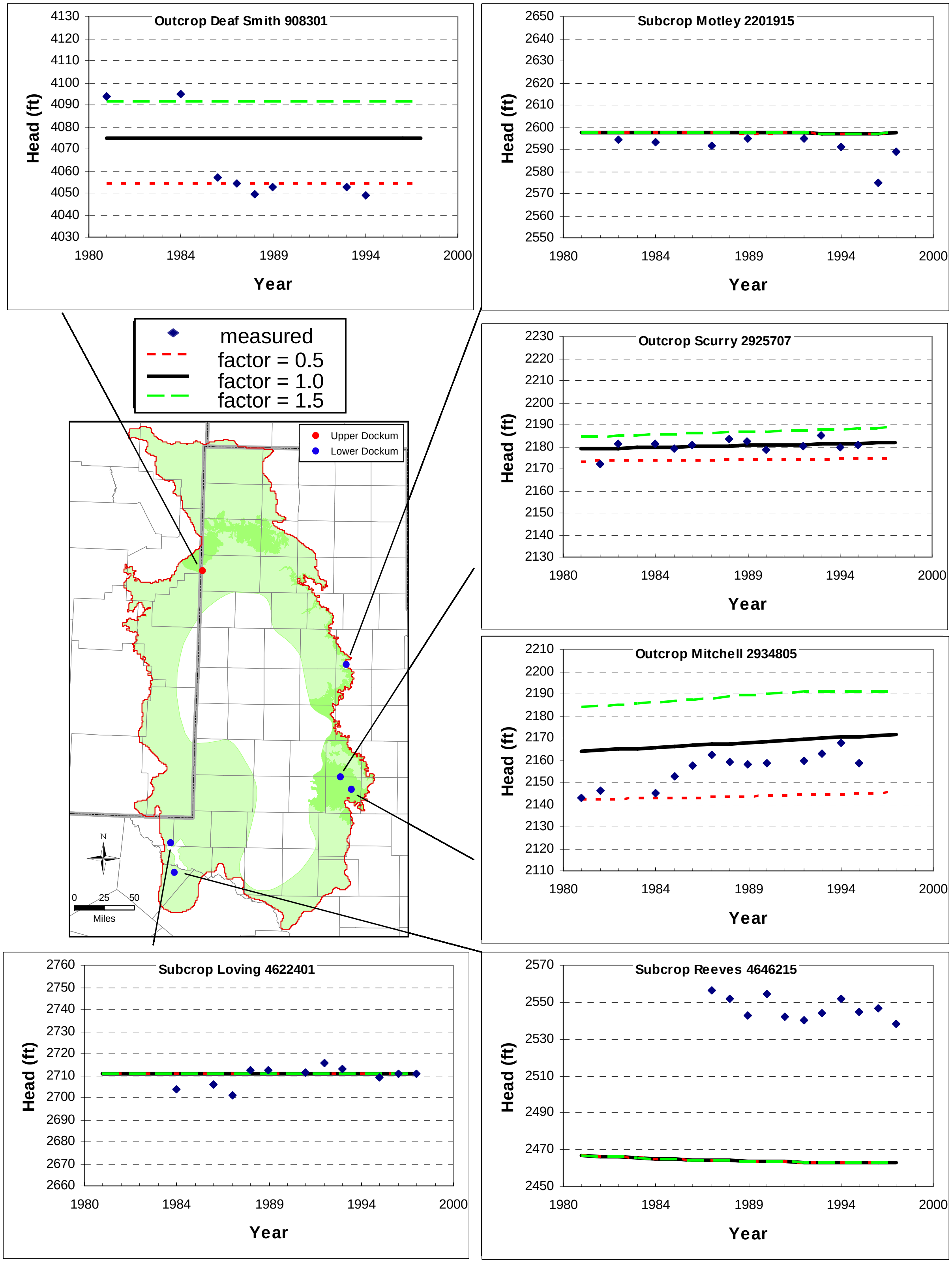

Figure 9.3.18 Transient sensitivity hydrographs of head in feet where recharge is varied.

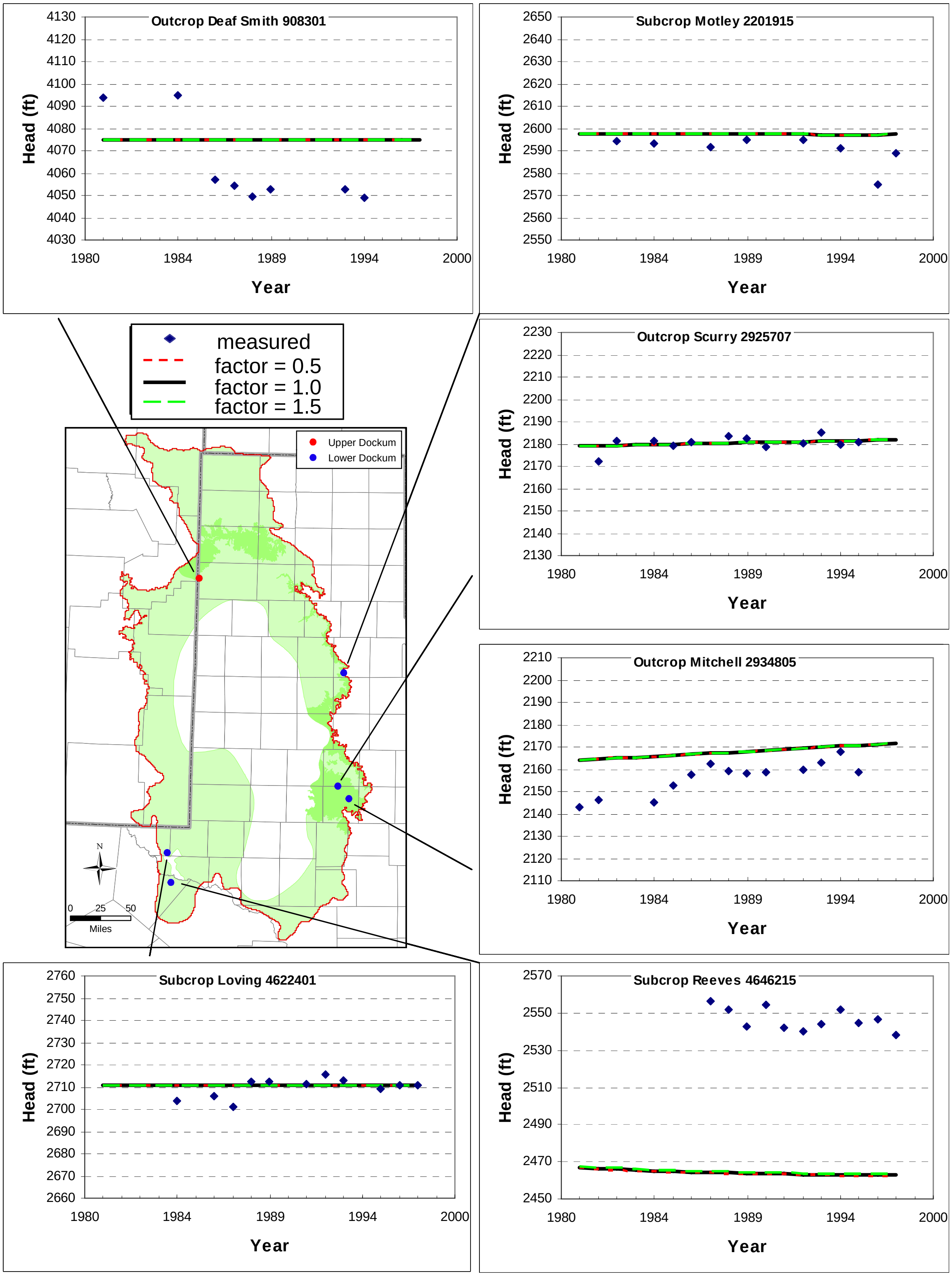

Figure 9.3.19 Transient sensitivity hydrographs of head in feet where the storativity of the lower portion of the Dockum Aquifer is varied.

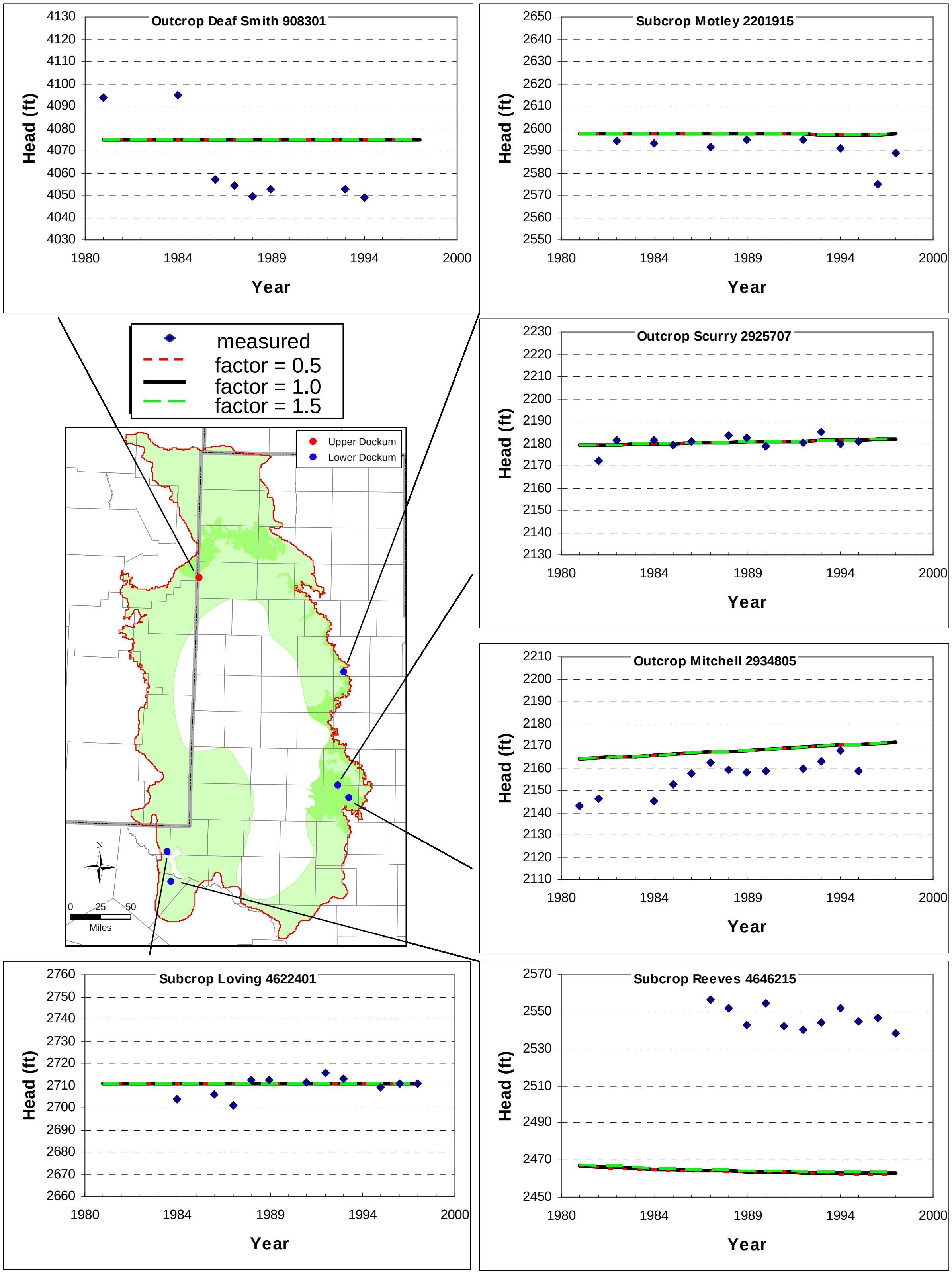

Figure 9.3.20 **Transient sensitivity hydrographs of head in feet where the specific yield of the lower portion of the Dockum Aquifer is varied.**

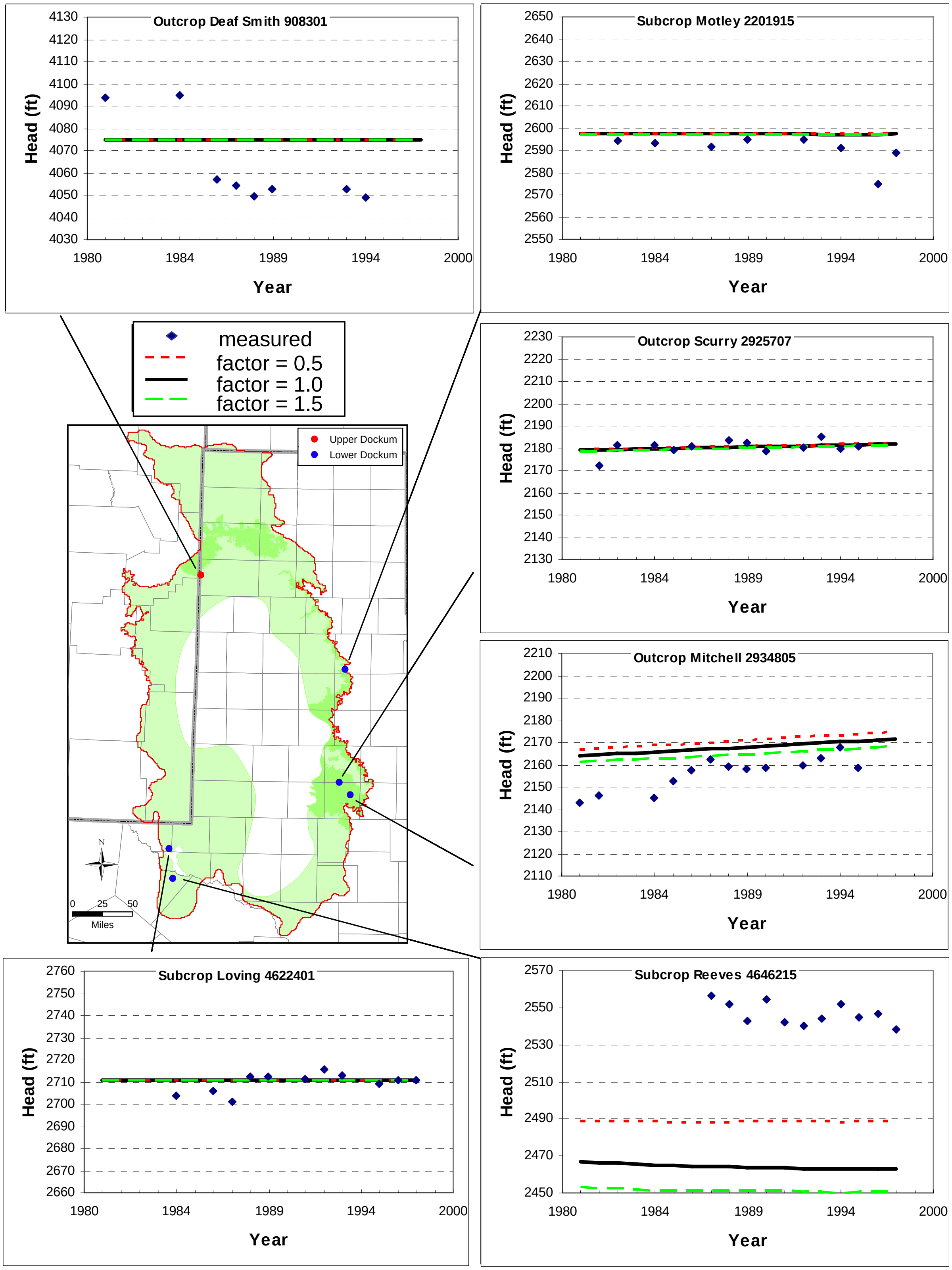

Figure 9.3.21 Transient sensitivity hydrographs of head in feet where pumping is varied.

10.0 Limitations of the Model

A model can be defined as a representation of reality that attempts to explain the behavior of some aspect of it, but is always less complex than the real system it represents (Domenico, 1972). As a result, limitations are intrinsic to models. Model limitations can be grouped into several categories including: (1) limitations in the data supporting a model, (2) limitations in the implementation of a model which may include assumptions inherent to the model application, and (3) limitations regarding model applicability. The limitations of this modeling study are discussed in the following paragraphs consistent with the groupings above.

10.1 Limitations of Supporting Data

Developing the supporting database for a regional model with a large number of grid cells is a challenge. The primary limitations of the supporting database for the Dockum Aquifer groundwater availability model are:

- Limited hydraulic head targets spatially and temporally,
- Limited frequency of water-level measurements to describe seasonal trends in the aquifer,
- Limited water-level measurements within the underlying Permian-age sediments,
- Few stream/aquifer gain/loss estimates with limited applicability,
- Limited hydraulic property data over portions of the model,
- Limited data quantifying cross-formational flow between the overlying aquifers and the Dockum Aquifer,
- Limitations to data defining pumping from the Dockum Aquifer,
- Many wells are dual-completions into the Dockum and other aquifers limiting the utility of associated water-level measurements as calibration targets, and
- Uncertain structural data in portions of the model.

Each of these database limitations is discussed below.

The primary type of calibration target used in most models, including this groundwater availability model, is hydraulic head. In the parts of the lower portion of the Dockum Aquifer located in the Colorado River outcrop in Mitchell and Scurry counties, sufficient head targets are available for both the steady-state and transient model calibrations. However, in most of the remainder of the Dockum Aquifer, there is a lack of available head data for both steady-state and transient conditions. Over all but the northernmost parts of the upper portion of the Dockum Aquifer and in the high total dissolved solids area of the lower portion of the Dockum Aquifer where the upper portion of the Dockum Aquifer is present, data were insufficient to assess the model's ability to match aquifer conditions. Both the steady-state and transient model calibrations could be improved with more head targets in these areas.

The temporal frequency of available water-level measurements was insufficient to identify any seasonal trends in Dockum Aquifer water levels. This lack of seasonal water-level data precludes calibrating the model to seasonal variations in hydrologic conditions.

Although the conceptual model indicates very little cross-formational flow between the Dockum Aquifer and the underlying Permian strata, the lack of water-level data for the Permian sediments limits the ability to include this mechanism in the model. It was decided that the uncertainty involved in adding an underlying layer with general-head boundary conditions would be more detrimental to the model than the assumption that cross-formational flow to underlying formations is insignificant to the overall Dockum Aquifer water balance.

There are stream gain/loss estimates for only two streams in the model area and the duration of the studies providing these estimates differs considerably from the stress period lengths in the model. The 1 to 2 day study periods, that yielded both gaining and losing results at different times for the same reach and did not provide information related to apparent long-term trends, are of limited comparative applicability to simulations based on annual stress periods or steady-state conditions. In addition, direct comparison to stream gages is problematic because the MODFLOW stream routing package does not model runoff.

Estimates of sand hydraulic conductivity were confined to localized areas of the model where development has occurred. Areas of development and, therefore, these sand conductivity estimates are likely biased to areas of higher hydraulic conductivity. In the absence of measurements over the majority of the model extent, horizontal hydraulic conductivity is based on global averages and maps of sand fraction. Vertical hydraulic conductivity is difficult to estimate at the lateral scale of the Dockum Aquifer based on measurements. Vertical conductivity was based on sand fraction maps and literature values of clay and sand conductivity. Clay conductivity was a calibrated parameter within literature bounds.

The Dockum Aquifer is a minor aquifer underlying several major aquifers. The Ogallala Aquifer, which overlies the majority of the Dockum Aquifer, has a water budget considerably larger than that of the Dockum Aquifer. Cross-formational flow from the Ogallala to the Dockum Aquifer is relatively inconsequential from the perspective of the Ogallala, however, from the perspective of the Dockum Aquifer, it can constitute a significant fraction of the Dockum Aquifer water budget. The percentage of the Dockum Aquifer that is confined makes cross-formational flow an important factor. The uncertainty in the cross-formational flow, therefore, is a significant limitation to the Dockum Aquifer groundwater availability model.

There are areas in the Dockum Aquifer where measured drawdown data indicate the occurrence of pumping but there is no reported pumping. For example, a cone of depression surrounds a well in Andrews County but there is no reported pumping for either the county or the well to support the observed drawdown. In Deaf Smith County, municipal wells supplying the City of Hereford and completed into the lower portion of the Dockum Aquifer have no reported pumping yet coincide with a region of observed drawdown within the aquifer. Limitations in reported pumping can have a large impact in the ability of the model to represent hydrologic conditions in these regions.

The aquifer or aquifers corresponding to the completion interval of many wells is ambiguous. Different data sources report different aquifers corresponding to the completion interval, often limiting the applicability of associated water-level measurements as calibration targets.

There are two limitations related to the uncertainty in the Dockum Aquifer structure. Both of which relate to the fact that the structure for the upper and lower portions of the Dockum Aquifer was developed based on the work presented in McGowen and others (1977). First, maps provided in their report were digitized and used to create the structure data for the Dockum Aquifer groundwater availability model. This digitization was complicated by the small size of their maps combined with the complexity of the structural contours for the elevation maps and the large contour interval for the isopach and sandstone percentage maps. The potential for the introduction of error was especially high with respect to the top and bottom elevation maps in the vicinity of Monument Draw Trough (Figure 2.2.3) in the southwestern portion of the model. Second, the extent of the upper portion of the Dockum Aquifer is reported inconsistently within McGowen and others (1977). The lateral extent of the upper portion of the Dockum Aquifer on their isopach and sandstone percent maps is greater than the extent indicated on their cross-sections. In developing the extent of the upper portion of the Dockum Aquifer for the model, it was assumed that the McGowen and others (1977) cross-sections provided the most accurate information. Since two extents for the upper portion of the Dockum Aquifer are presented in McGowen and others (1977) but only one could be selected for the model, there is uncertainty with respect to the extent of the upper portion of the Dockum Aquifer used in the Dockum Aquifer groundwater availability model.

10.2 Assessment of Assumptions

There are several assumptions that are key to the model regarding construction, calibration, and, although not included in this modeling effort, prediction. These assumptions are related to the following aspects of the Dockum Aquifer groundwater availability model:

- Use of general-head boundaries to simulate overlying aquifers, and
- Spatial variation and lack of temporal variation in recharge.

These are briefly discussed below along with the potential limitations of the assumption(s) used in developing the Dockum Aquifer model.

As discussed above, cross-formational flow is an important factor for the Dockum Aquifer because a large portion of the Dockum Aquifer underlies major aquifers. By simulating the overlying aquifers with a general-head boundary, it was assumed that flow into the Dockum Aquifer from the overlying aquifers is governed primarily by the hydraulic properties of the Dockum Aquifer and the heads in the overlying aquifers. The heads in the overlying aquifers are based on data and, in the case of the transient model, simulated drawdown from the Southern Ogallala groundwater availability model. There is uncertainty in the head data for the overlying aquifers as well as in the correlation of data to 5-mile averaged topography, which was used to populate the general-head boundary heads in the portions of the model domain lacking head data for the overlying aquifers. It was assumed that the localized uncertainty in the overlying aquifer heads is constrained by the averaged properties applied to layer 1 based on the property information provided in the Southern Ogallala groundwater availability model. Systematic error in the overlying heads should be minimized based on the large number of head measurements in the overlying aquifers. Any drawdown in the Ogallala north of the Dockum Aquifer's Canadian River outcrop is ignored. Lack of Dockum Aquifer head measurements coupled with this assumption mean that the simulated heads in the Dockum Aquifer are not well constrained in the region north of the Canadian River outcrop area.

While average recharge estimates from groundwater chloride measurements were available, the spatial distribution of recharge, while founded on fundamental principals of unconfined aquifer flow systems and literature, is uncertain. No correlation between either surficial hydraulic properties or elevation could be gleaned from the groundwater chloride data. Furthermore, while the modern recharge rate is based on measured water-level data and the distribution of that recharge is based on cropland maps, the temporal distribution is, for lack of data, assumed to be constant. A comparison of recharge rates estimated based on linear water-level rises in wells and pumping rates in the same areas indicates that the majority of the increase in modern recharge, compared to that of predevelopment, is due to land-use changes rather than irrigation return flow. Therefore, changes in irrigation practices do not greatly impact an assumed temporally constant modern recharge. However, lack of a method for correlating modern recharge to changes in precipitation results in the likely loss of some temporal trends in recharge.

10.3 Limits for Model Applicability

The purpose of the TWDB groundwater availability model program is the development of models to determine how regional water levels will respond to water resource development in an area smaller than a county and larger than a square mile. This is accomplished by developing regional models using a grid-block size of one square mile. These two design criteria limit the applicability of the Dockum Aquifer groundwater availability model. The accuracy of the model is likely representative at a scale of tens of miles. Because of the model grid scale of one square mile, the model is not capable of being used in its current state to predict aquifer responses at specific points such as a selected well at a particular municipality.

The lack of data for short time periods for use in describing model boundary conditions means that stress periods of less than one year were not warranted. Use of annual stress periods precludes the ability of the model to predict seasonal head or flow variability.

MODFLOW does not account for density dependant flow. Therefore, the higher density of the groundwater in the high total dissolved solids portion of the Dockum Aquifer and, to a lesser extent, the other portions of the aquifer which exhibit relatively high total dissolved solids concentrations are not accounted for in the governing flow equations of the model. Currently, little recharge and pumping occurs within this region of the aquifer and therefore, this shortcoming likely has little impact. However, potential future predictive simulations involving development of the high total dissolved solids portions of the Dockum Aquifer could be impacted by this limitation.

The groundwater availability model provides a first-order approach to coupling surface water to groundwater, which is adequate for the stated purposes of the model. However, the model does not provide a rigorous solution to surface-water modeling.

The groundwater availability model does not simulate transport of solutes and cannot explicitly address water quality issues. A preliminary assessment of water quality is given in this report in Section 4.8.

11.0 Future Improvements

To use models to predict future conditions requires a commitment to improve the model as new data become available or when modeling assumptions or implementation issues change. This groundwater availability model is no different. Through the modeling process, one generally learns what can be done to improve the model's performance or what data would help better constrain the model calibration. Future improvements to the model, beyond the scope of the current groundwater availability model, are discussed below.

11.1 Additional Supporting Data

Several types of data could be collected to better support future enhancement of the Dockum Aquifer groundwater availability model. These include additional water-level monitoring in areas of the Dockum Aquifer with sparse measurements, recharge studies, longer term surface-water/groundwater information, evaluation of pumping from the Dockum Aquifer, and additional study on the structure of the aquifer. Because of the character of the Dockum Aquifer, a minor aquifer underlying major aquifers, any additional estimates quantifying cross-formational flow would help constrain the Dockum Aquifer water budget. Additional data describing seasonal trends in water levels and boundary conditions might enable calibration of the transient model to stress periods smaller than one year.

Additional water-level monitoring in the upper portion of the Dockum Aquifer would be valuable in constraining the simulated heads in the upper portion of the Dockum Aquifer. Although pumping from these portions of the aquifer is small, it is still advantageous to monitor water levels in those areas to improve aquifer understanding and to incorporate those additional data into the model. Additional knowledge of heads in the upper portion of the Dockum Aquifer would also improve understanding of the cross-formational flow between the upper portion of the Dockum Aquifer and the overlying aquifers. It is also important to increase water-level monitoring in areas of the lower portion of the Dockum Aquifer with future development potential, even if they are not currently extensively developed. If monitoring begins prior to increased development, the model can be calibrated against the pre-development response to improve model predictive capability in those regions.

Recharge is the primary method by which water enters the outcrop of the Dockum Aquifer. Since much of the development in the Dockum Aquifer occurs in the Colorado River outcrop, recharge is important to the long-term sustainability of this pumping. Improving the understanding of the spatial and seasonal distribution of recharge within the outcrop will enhance future models of the aquifer. Studies should be continued into the nature of recharge in the Dockum Aquifer.

Much of the discharge within the Dockum Aquifer occurs in streams in the outcrops and data on stream/aquifer interaction is useful for understanding groundwater flow within the aquifer. Available gain/loss data for streams are at a much shorter time scale than the model stress periods. Hydrograph separation analyses may provide long-term information on baseflow to gaining streams. The model's ability to represent actual aquifer conditions will be greatly enhanced with long-term data regarding surface-water/groundwater interaction.

Although the rate of cross-formational flow between the Dockum Aquifer and the overlying aquifers is considered relatively small, the large percentage of the Dockum Aquifer that is confined means that a significant portion of the Dockum Aquifer water balance is derived from cross-formational flow. While considerable qualitative information exists, additional quantitative information regarding cross-formational flow would improve future models of the aquifer.

Further investigation of wells reportedly completed (depending on the data source) in either the Dockum Aquifer or the Dockum and overlying aquifers could be useful. Such an investigation could improve the Dockum Aquifer water-level targets either by removing ambiguous targets or by adding additional targets to locations within the aquifer that are currently poorly constrained by data.

In several counties, pumping for the Dockum Aquifer is inconsistent with well observations. For some counties, water-level data in wells indicate drawdown due to pumping, but no pumping is assigned to those counties. For other counties, very few wells are located within the county and the assigned pumping volume seems too high for the number of wells. In addition, point source pumping data are available for counties with no corresponding wells for that pumping. Fortunately, the areas with suspect pumping are also areas with little development of the

Dockum Aquifer, so any impacts are minimal. However, evaluation of future development in the untapped portions of the aquifer may be compromised if the model implemented pumping differs from actual pumping. Therefore, future models of the Dockum Aquifer could be improved by eliminating the apparent inconsistencies with the pumping.

The structure for the Dockum Aquifer was developed based on work conducted in the 1970s. The report presenting that work (McGowen and others, 1977) contained internal inconsistencies with respect to the lateral extent of the upper portion of the Dockum Aquifer. In addition, the maps constructed by that work are small with complex contouring or large contour intervals, which lead to uncertainty in the Dockum Aquifer structure that was developed through digitization of those maps. Therefore, future models of the Dockum Aquifer could benefit from a comprehensive review of additional structure data available for the aquifer.

11.2 Future Model Implementation Improvements

A large portion of the modeled Dockum Aquifer exhibits total dissolved solids concentrations in excess of 5,000 milligrams per liter. The greater density of this water is not accounted for in the governing equations of groundwater flow used in MODFLOW. If predictive simulations are going to include development of the aquifer within the high total dissolved solids region, use of a simulator with the capability of simulating density-dependant flow (e.g., SEAWAT) may be warranted.

The current Dockum Aquifer groundwater availability model assumes a no-flow condition at the base of the Dockum Aquifer. If water-level data become available to adequately describe hydrologic conditions in the Permian strata underlying the Dockum Aquifer, inclusion of a fourth, lower model layer containing general-head boundaries representative of water levels in the Permian might improve understanding of the Dockum Aquifer water balance.

As mentioned in Section 10.3, the Dockum Aquifer groundwater availability model is applicable for simulating water levels at a scale of tens of miles. If more refined simulations are desired in heavily developed areas such as the Colorado River outcrop, a refined model considering only a portion of the Dockum Aquifer could be considered. The existing Dockum Aquifer groundwater availability model could be used to constrain conditions at the boundaries of any refined models.

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12.0 Conclusions

This report documents a three-dimensional groundwater model developed for the Dockum Aquifer to the groundwater availability model standards defined by the TWDB. This regional-scale model was developed using MODFLOW with the stream-routing package to simulate stream/aquifer interaction. The Dockum Aquifer is modeled as two layers and the overlying younger aquifers are rudimentarily modeled with a third (uppermost) layer.

The purpose of this groundwater availability model is to provide a calibrated numerical model of the Dockum Aquifer 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. This groundwater availability model provides an integrated tool for the assessment of water management strategies to directly benefit state planners, Regional Water Planning Groups, Groundwater Conservation Districts, and Groundwater Management Areas.

This groundwater availability model was developed using a modeling protocol which is standard to the groundwater model industry. This protocol includes: (1) the development of a conceptual model for groundwater flow in the aquifer, (2) model design, (3) model calibration, (4) sensitivity analysis, and (5) reporting.

This model, like all models, has limitations and can be improved. The groundwater availability model reproduced the steady-state and transient conditions of the aquifer within the required calibration measures. More importantly, this calibrated groundwater availability model provides a documented, publicly-available tool for the assessment of future groundwater availability in the Dockum Aquifer.

The model was first calibrated to steady-state conditions. The steady-state model reproduces predevelopment water levels well and within the uncertainty of the head estimates. The average recharge rate estimated for the outcrop portions of the steady-state model area was 0.15 inches per year. 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. A sensitivity analysis was performed to determine which parameters had the most influence on aquifer performance and calibration. The most sensitive parameters for the steady-state model are the elevations of the general-head boundary heads in layer 1, the horizontal hydraulic conductivity of the lower portion of the Dockum Aquifer, and the vertical hydraulic conductivity of the upper portion of the Dockum Aquifer.

The model was also successfully calibrated to transient aquifer conditions from 1980 through 1997. The model satisfactorily reproduced aquifer heads during this time period. 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 on the transient model. Like for the steady-state model, the most sensitive parameters for the transient model are the elevations of the general-head boundary heads in layer 1, the horizontal hydraulic conductivity of the lower portion of the Dockum Aquifer, and the vertical hydraulic conductivity of the upper portion of the Dockum Aquifer.

Questions regarding local drawdown to a specific well should be based upon the analytical solution to the diffusion equation or a refined numerical model. This Dockum Aquifer model was built to determine how regional water levels will respond to water resource development in an area smaller than a county and larger than a square mile. In addition, the model is useful in estimating consistent boundary conditions and hydraulic properties on a regional scale that could be applied to any refined models of individual outcrops or sub-regions of the aquifer.

13.0 Acknowledgements

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The INTERA team was aided significantly in their efforts by stakeholders from the Panhandle and North Plains Groundwater Conservation Districts. The management of these two entities supplied well information, water-level data, and water-quality data. Local knowledge from the stakeholders proved especially valuable in development of the conceptual model.

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Appendix A

All Transient Hydrographs for the Dockum Aquifer for the Calibration Period (1980 through 1997)

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This appendix contains all hydrographs of simulated and observed water-level elevations for targets in the Dockum Aquifer for the transient calibration period (1980 through 1997). Hydrographs are only for wells having five or more water-level measurements during the calibration period. On the hydrographs, the model simulated response is shown by a line and the measured water-level elevations are shown as symbols. The hydrographs for the upper Dockum are shown first followed by those for the lower Dockum.

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Upper Dockum Hydrographs

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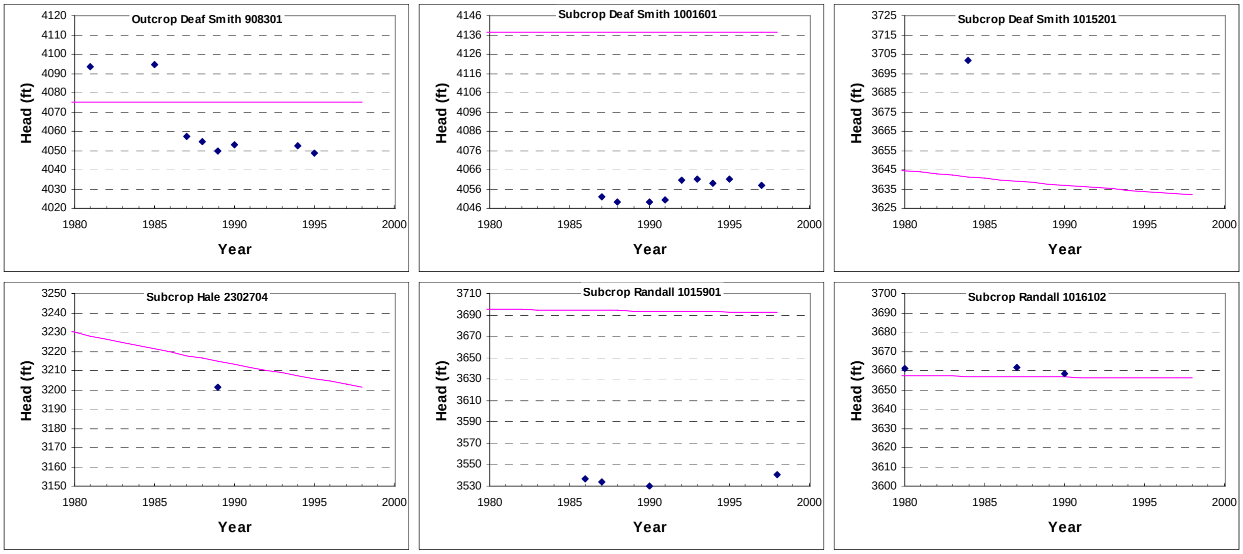

Symbols – measured water-level elevations
Line - model simulated response

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Lower Dockum Hydrographs

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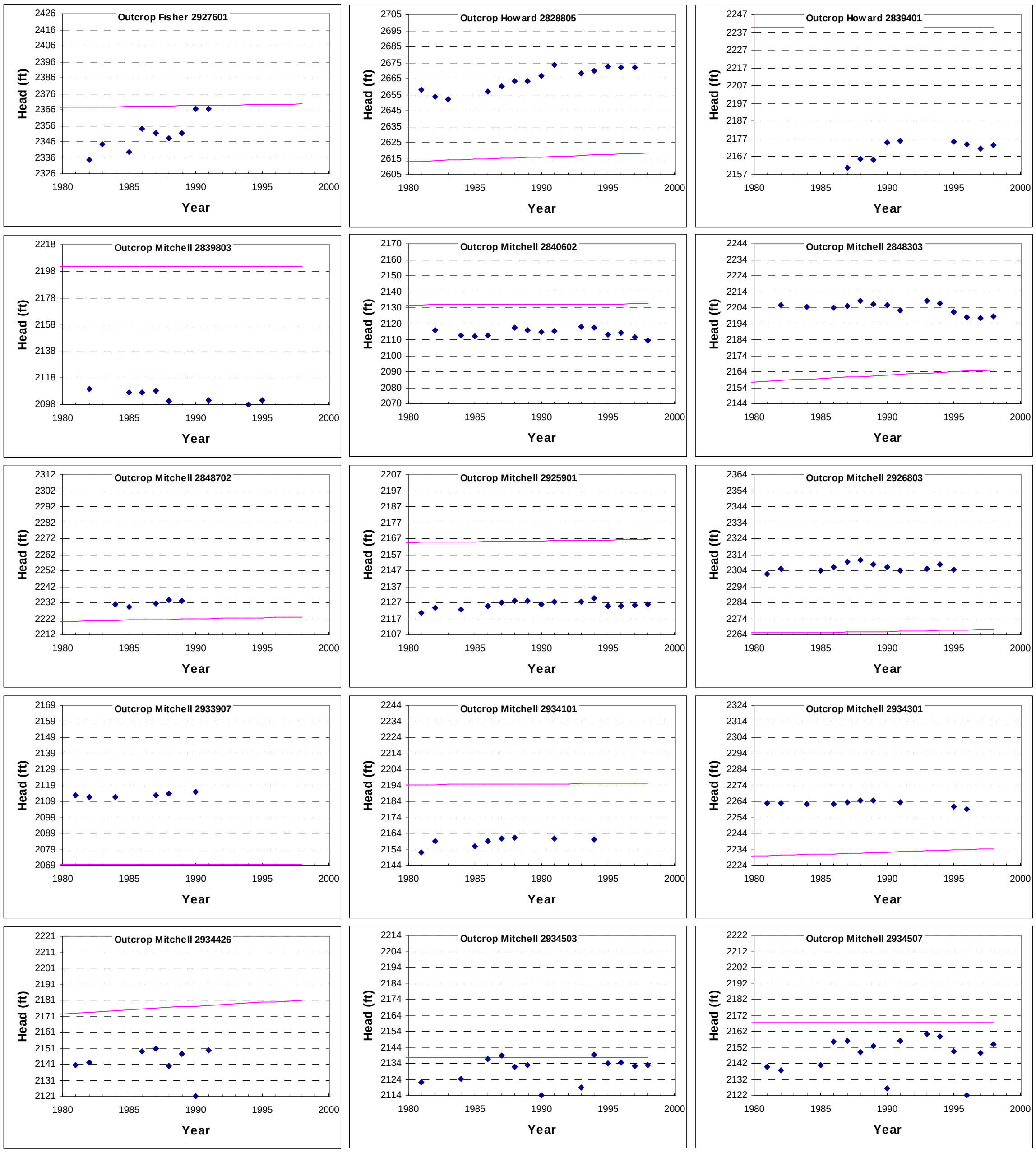
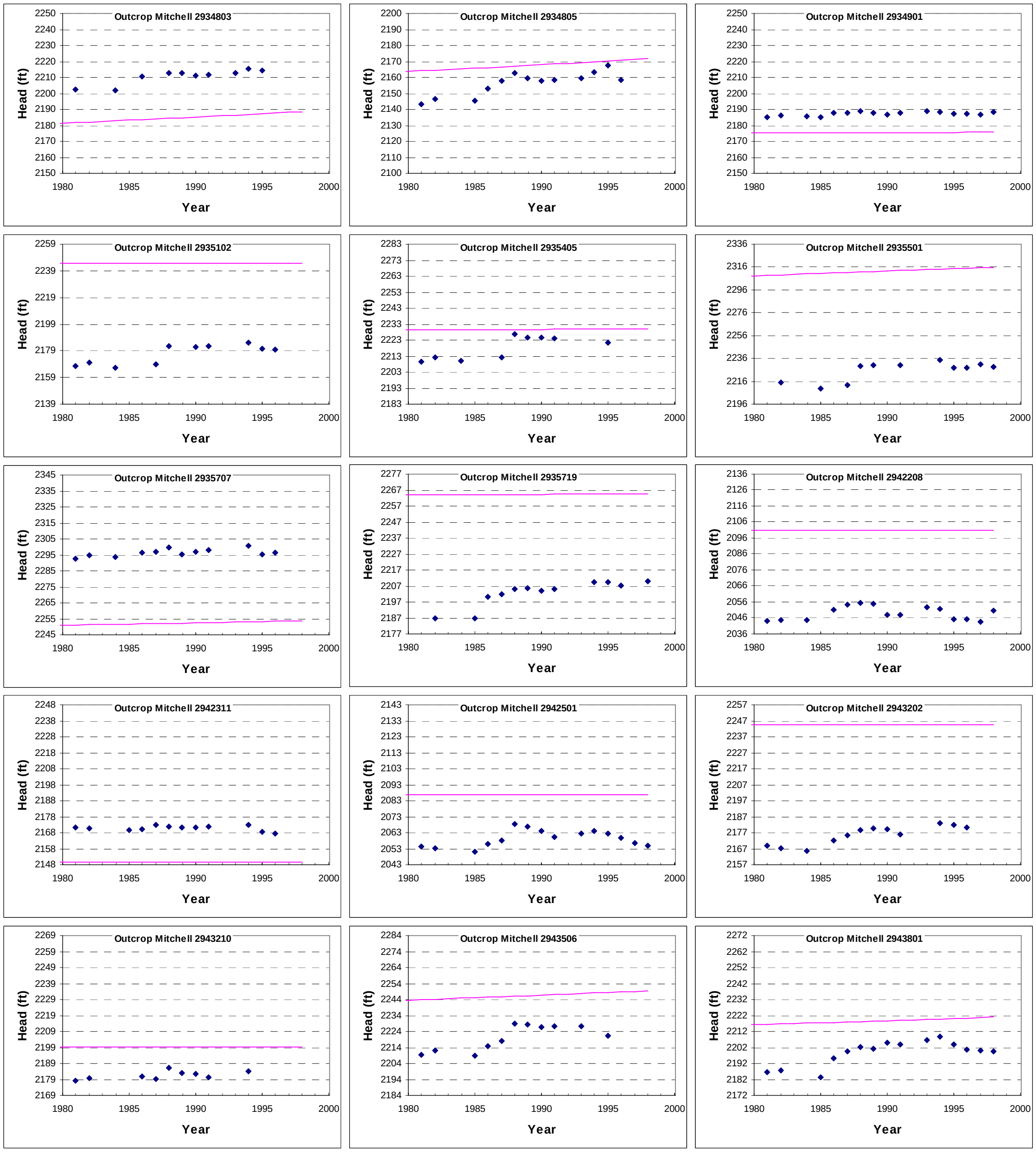
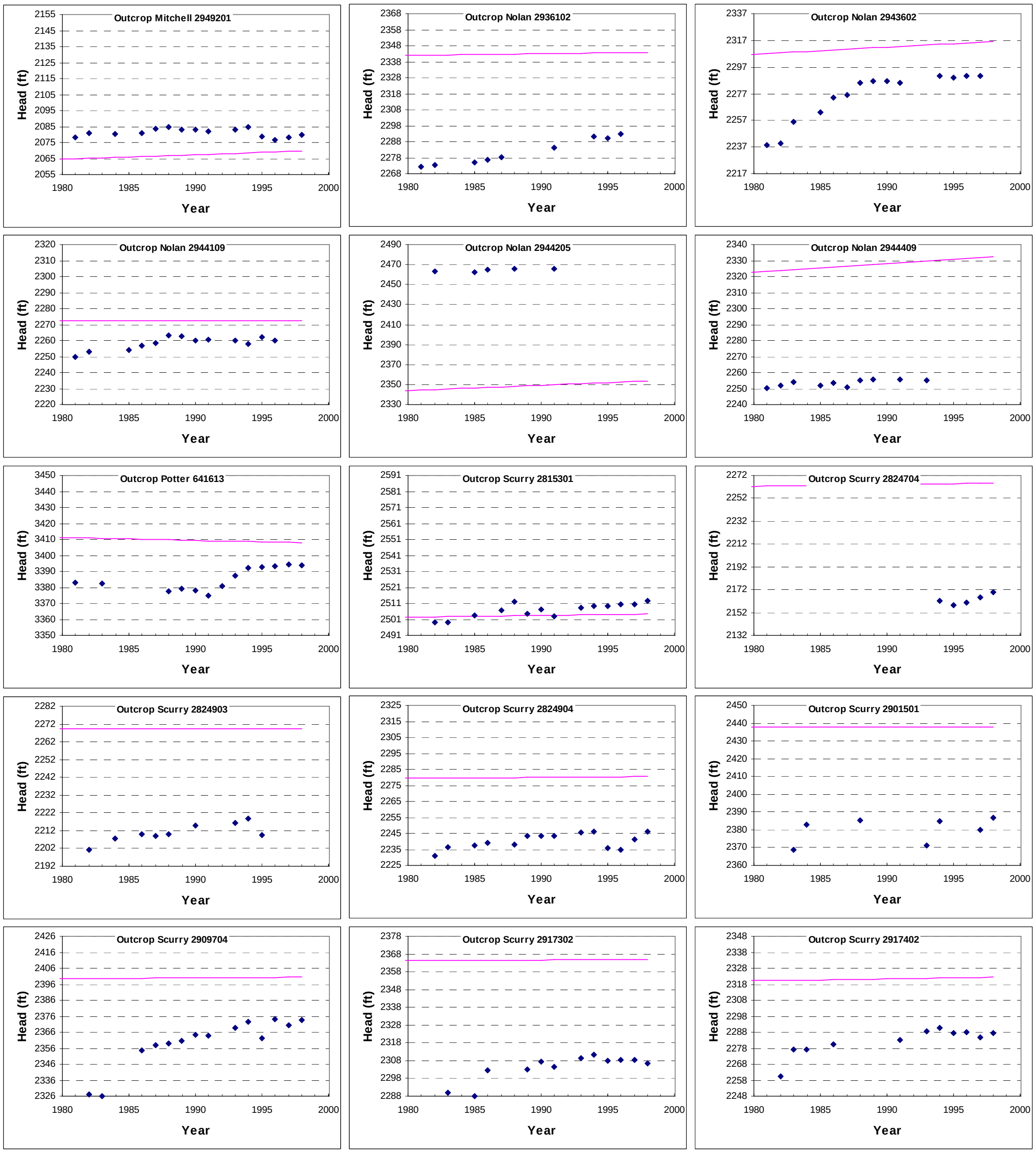


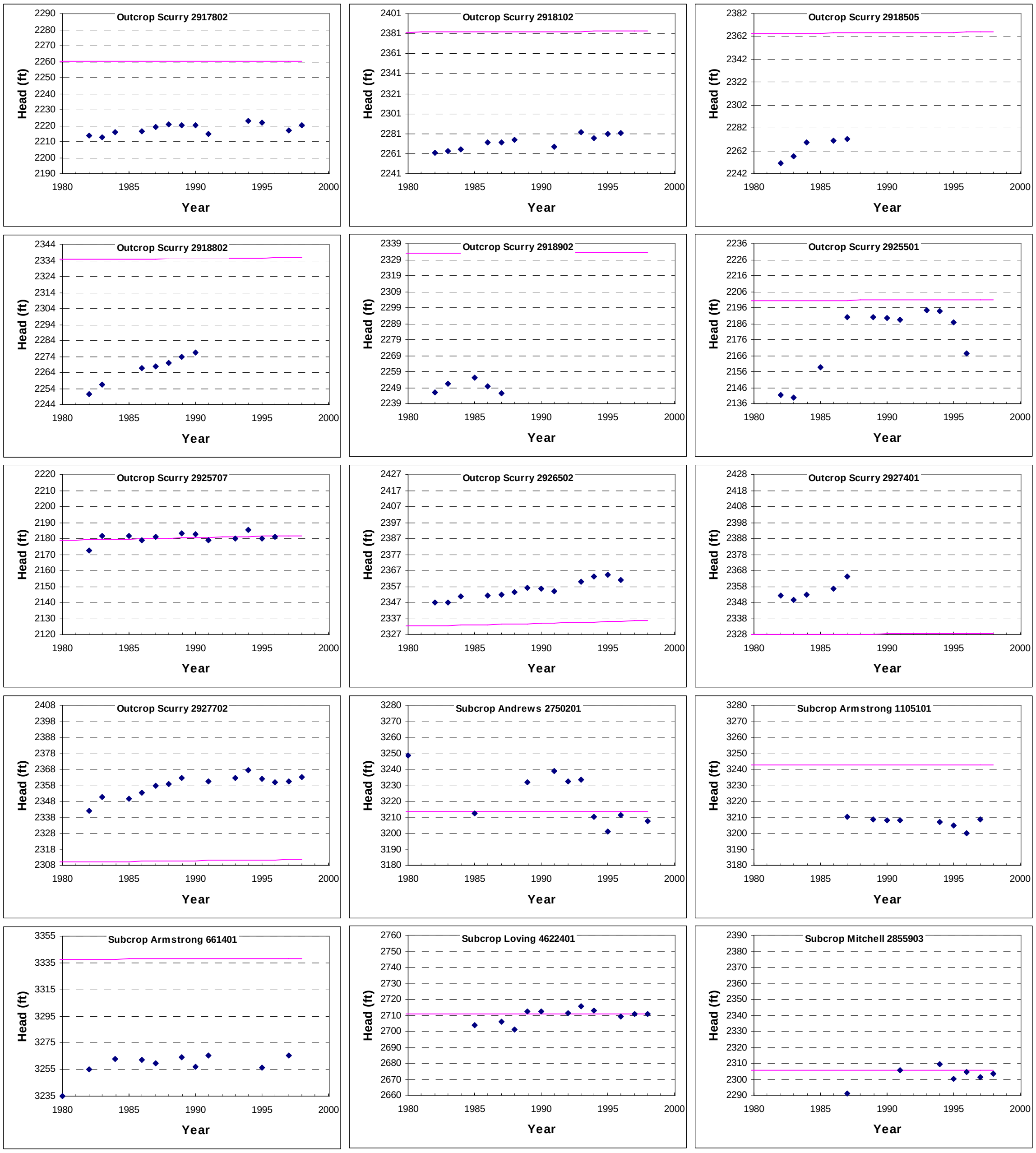
Symbols – measured water-level elevations
Line - model simulated response



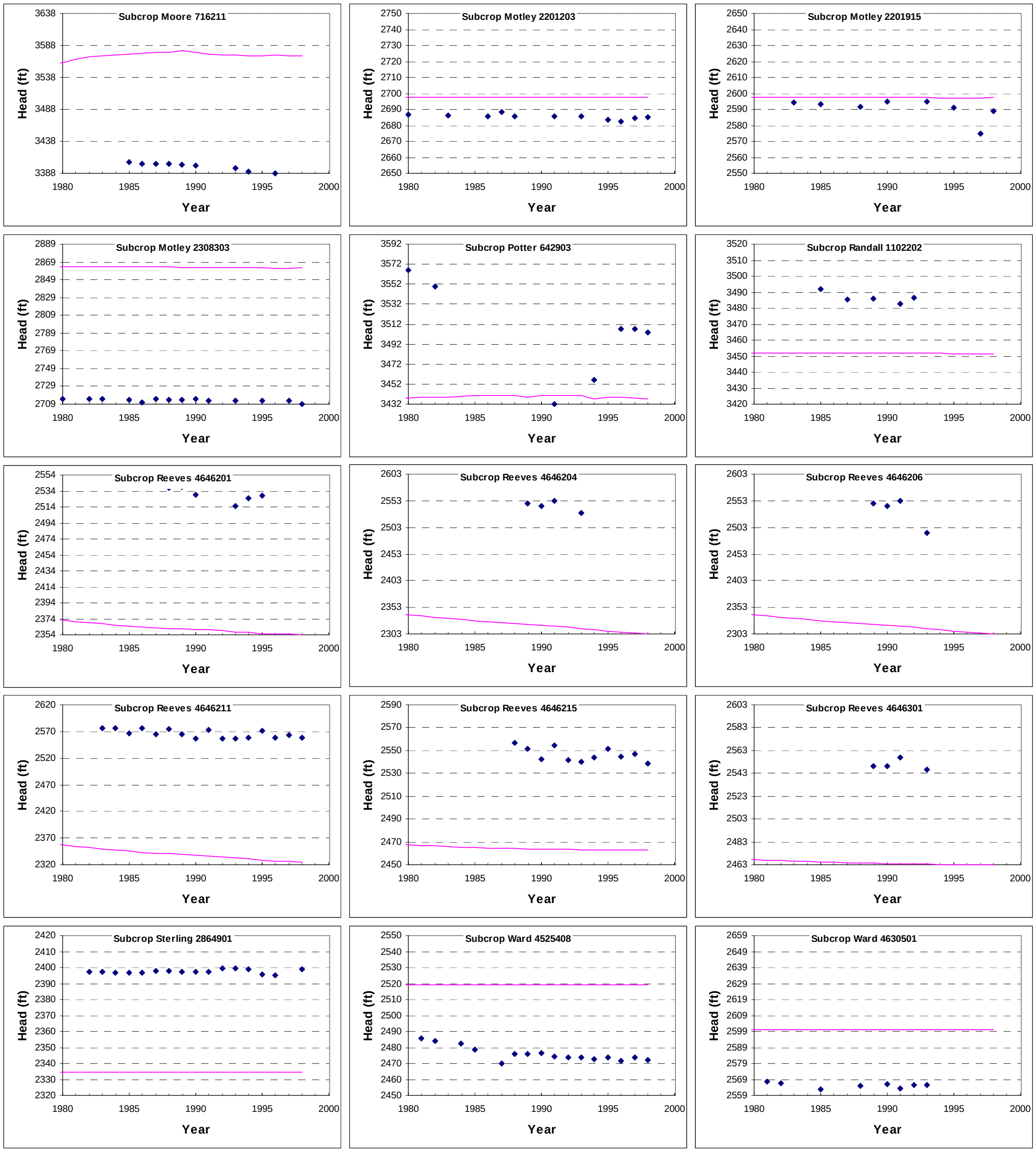
Symbols – measured water-level elevations
Line - model simulated response



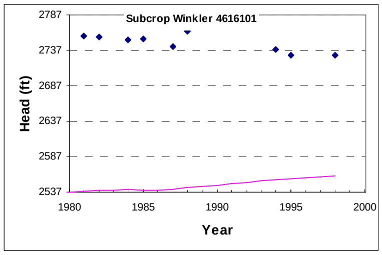
Symbols – measured water-level elevations
Line - model simulated response

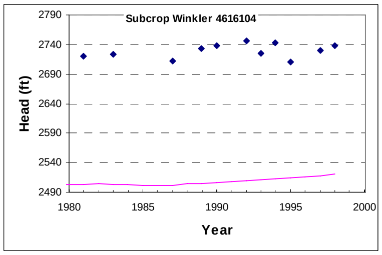


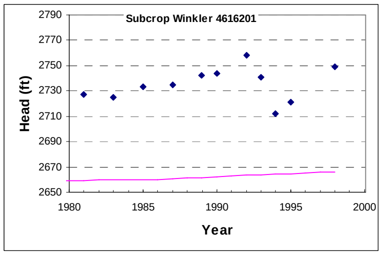
Symbols – measured water-level elevations
Line - model simulated response

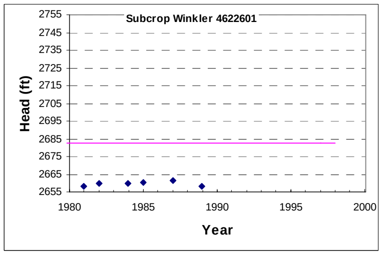


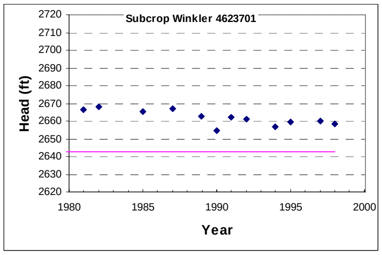
Symbols – measured water-level elevations
Line - model simulated response











Symbols – measured water-level elevations
Line - model simulated response

Appendix B

Draft Conceptual Model Report Comments and Responses

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Appendix B

Comments on May 2007 Draft Conceptual Model Report for the Dockum Aquifer Groundwater Availability Model

GENERAL COMMENTS

Please use "and others" instead of "et al." in text when citing more than two authors.

Completed.

Numbering of figures in section 2 is not consistent with numbering system used in section 4. Please use a consistent method of numbering figures and update report and text as needed.

Completed.

Several of the legends in the figures in section 4 listed values not depicted in the figures. Please update figure legends so they agree with the data shown. Some examples include figure 4.4.4 and 4.4.6.

Completed.

Per contract Exhibit B, Attachment 1, Section 3.1.7, any other information needed for the MODFLOW reservoir package and streamflow routing package shall be estimated and discussed. Please update section 4.5 with missing surface water information or cross-reference as needed.

Completed. See Section 4.5.

Per contract Exhibit B, Attachment 1, Section 3.3.1,Physiography and Climate, bullets: Section 2.1 should include descriptions and maps of spatial and temporal variability of precipitation, spatial and temporal variability of temperature, and spatial and temporal variability of evaporation. Please update section 2.1 with temporal variability (seasonal) of precipitation, temperature, and evaporation to assist with possible future enhancements to the model.

Completed. See Figures 2.1.5 through 2.1.11.

Please capitalize “Aquifer” wherever it appears after formation name.

Completed.

Based on our style guide, please spell out all acronyms except ‘TWDB’.

Completed.

SECTION 1: INTRODUCTION

Page 1-1, paragraph 3: Please change '…brackish to saline…' to '…brackish to brine…' and '…greater than 20,000 mg/L…' to '…greater than 1,000 mg/L…'. Capitalize the word 'panhandle'.

Completed. See Section 1.0, paragraph 3.

Page 1-1, paragraph 3: The use of '20,000 mg/l' to maximum dissolved solids in the aquifer is misleading because later the text mentions several examples of groundwater TDS over 50,000 mg/l. Please change statement to 'more than 50,000 mg/l'.

Completion of previous comment precludes completing this comment.

Page 1-2, paragraph 3: Please change 'dominate' to 'dominant'.

Completed. See Section 1.0, paragraph 6.

SECTION 2: STUDY AREA

Authors need to add a figure showing the river authorities in the study area.

Completed. See Figure 2.0.10.

Page 2-2, paragraph 1: Please change 'Captain' to 'Capitan'.

Completed. See Section 2.0, paragraph 5.

Page 2-2, paragraph 2: Please delete ', Underground Water Districts……in Texas'. UWCDs and WCDs are different names given to GCDs. Please delete 'UWCD' and 'WCD' where they appear throughout the text.

Completed. See Section 2.0, paragraph 6, Table 2.0.1, and Figure 2.0.8.

Figure 2-11: Need to extrapolate physiographic provinces into New Mexico. Please clarify if source was BEG (1996) instead of TPWD (2006) and update, if needed.

Detailed physiographic province data for Texas would be lost with extrapolation into New Mexico because a national coverage rather than a Texas specific coverage must be used. Therefore, the physiographic provinces were not extrapolated into the New Mexico. The source for the physiographic provinces data in Texas was changed. See Figure 2.1.1 (previously Figure 2.11).

Page 2-16, paragraph 2: Add a reference for the PRISM data.

Completed. See Section 2.1, paragraph 6.

Figure 2.16: please add stations located in New Mexico to this map.

Completed. See Figure 2.1.7 (previously Figure 2-16)

Page 2-26, paragraph 2: Please note that the Dockum Group crops out in the Pecos River Valley of <u>both</u> New Mexico and Texas.

Completed. See Section 2.2, paragraph 2.

Page 2-28, paragraph 3: Please change ‘gneisis’ to ‘gneiss’.

Completed. See Section 2.2.2, paragraph 5.

Page 2-28, paragraph 4: Please change ‘micacous’ to ‘micaceous’.

Completed. See Section 2.2.2, paragraph 6.

Page 2-29, paragraph 4: Please change ‘Trijillo’ to ‘Trujillo’.

Completed. See Section 2.2.3, paragraph 3.

Page 2-31, paragraph 1: Please change ‘…000 to 020 degrees’ to ‘…north-south to northeast-southwest’ and ‘…300 to 320 degrees’ to ‘…northwest-southeast’.

Completed. See Section 2.2.4, paragraph 5.

Figure 2.22: Please update Figure 2.22 with Monument Draw Trough as this is noted in Section 4.2 as a dominate structural feature for the Dockum Aquifer.

Completed. See Figure 2.2.3 (previously Figure 2.22).

Table 2.4: Please change ‘Trijillo’ and ‘Trecovas’ to ‘Trujillo’ and ‘Tecovas’, respectively.

Completed. See Table 2.2.2 (previously Table 2.4).

SECTION 3: PREVIOUS INVESTIGATIONS

Page 3-1, paragraph 1: Please explicitly cite Cummins (1890).

Completed. See Section 3.0, paragraph 1.

Page 3-1, paragraph 1: Please cite Cummins 1891 determination of the age of the Dockum Group.

Completed. See Section 3.0, paragraph 1.

Table 3.1.: Please change ‘Cummins, 1980’ to ‘Cummins, 1890’.

Completed. See Table 3.0.1 (previously Table 3.1).

Page 3-2, paragraph 4: Please add Dutton and Simpkin (1989) to the list of references.

The citation of Dutton and Simpkins (1989) should have been Dutton and Simpkins (1986). See Section 3.0, paragraph 7.

Page 3-2, paragraph 5: Please add figure showing grid extent of previous models, especially as pertains to the Dockum Aquifer.

Completed. See Figure 3.0.2.

Table 3.2: Please review citation of TWDB report 313 by Nordstrom and Fallin (1989) for information for Hall County. A word search for Hall County in this report does not return any citations of Hall County.

Completed. See Table 3.0.2 (previously Table 3.2).

SECTION 4: HYDROGEOLOGIC SETTING

Page 4-1, paragraph 3: This paragraph repeats information that appears earlier in the text, please delete.

Completed. See Section 4.1.

Table 4.1.1: Similar to Table 2.4, please delete and add information to Table 2.4, where necessary.

Completed. See Table 2.2.2 (previously Table 2.4).

Page 4-2, paragraph 2: Please delete the sentence ‘Bradley and Kalaswad…’, it is a repeat from earlier in the text.

Completed. See Section 4.1, paragraph 3.

Page 4-2, paragraph 4: Please move this paragraph to the Water Quality section.

This paragraph was removed from Section 4.1 but it was not added to the water-quality section because that section already contains similar information. See Section 4.1.

Figure 4.2.3: Thick zones in Deaf Smith, Randall, and Swisher counties seem to represent an edge effect associated with the margin of the Upper Dockum. Please consider revising this map to remove any edge effects.

The thick zones do represent edge effects, however, the edge effects can not be removed without deviating from the structure data given in McGowen and others (1977).

Figure 4.3.1: Please specify difference between open and solid symbols in figure. Please add an explanation in caption for multiple symbols and values as figures should stand independent of text.

Completed. See Figure 4.3.1.

Page 4-8, paragraph 2: Please clarify if minimum thickness of 50 feet was assigned in areas where the top surface was lower than the base surface using the base surface or top surface and then integrated with surrounding areas.

Completed. See Section 4.2.2, paragraph 6.

Page 4-10, paragraph 2: Please change the first sentence to say “Using the process outlined…”.

Completed. See Section 4.2.3, paragraph 2.

Page 4-19, paragraph 2: please discuss the data that falls outside of the active model area in Figure 4.3.1.

Completed. See Section 4.3, paragraph 2.

Page 4-20, paragraph 2: Please delete the last part of this paragraph, from ‘The first reported water-level…’. It does not contribute to our understanding of water levels in the aquifer.

Completed. See Section 4.3, paragraph 4.

Page 4-21, paragraph 2: Inferred water levels based on sparse data give the impression that groundwater flows to the east across the aquifer, however, the spatial distribution of groundwater salinity in the Dockum Aquifer indicates that this is not the case. It is quite likely that there is little to no groundwater flow in the center of the aquifer and that flow is limited to the aquifer margins. Please clearly point this out in the text.

Completed. See Section 4.3.1, paragraph 2.

Figures 4.3.5 through 4.3.12: Large swaths of the aquifer do not have any water-level data making the use of dashed contours meaningless. Please restrict contours to areas with data or as in Figure 4.3.11 show the data without contours.

Completed. See Figures 4.3.5 through 4.3.12.

Figure 4.3.6: Section 4.3.1 suggests predevelopment flow toward the Colorado River in Mitchell County; however, Figure 4.3.6 barely reflects this. Please clarify and adjust either text or figure.

Completed. See Section 4.3.2, paragraph 5 and Figure 4.3.6.

Page 4-22, paragraph 1: Please change ‘early 1990s’ to ‘early 1900s’.

Completed. See Section 4.3.2, paragraph 2.

Page 4-26, paragraph 3: Please update references from Figures 4.3.15 through 4.3.20 to Figures 4.3.17 and 4.3.18, as the captions for figures 4.3.17 and 4.3.18 indicate they represent hydrographs for wells only completed in the Dockum Aquifer.

Although Figures 4.3.15, 4.3.16, 4.3.19, and 4.3.20 show hydrographs for wells completed into the lower Dockum and another aquifer, they also show hydrographs for wells completed only into the Dockum Aquifer.

Page 4-29, paragraph 3: Please point out that the low TDS of groundwater in the Monument Draw Trough of the Pecos Valley Aquifer indicates that groundwater discharge rates from the Dockum Aquifer are very low.

Completed. See Section 4.3.5, paragraph 6.

Page 4-30, paragraph 3: Please add Walker (1979) to the list of references.

Completed. See Section 14.

Figure 4.3.8: This figure shows the 1990 data instead of 1980 data. Please revise to include the correct data.

Completed. See Figure 4.3.8.

Figure 4.3.12: Please revise this figure, the measurement points shown are 1990 data.

Completed. See Figure 4.3.12.

Page 4-67, paragraph 1: Please point out that the Freese and Nichols recharge estimate is probably only applicable to the portion of the Dockum within the Panhandle RWPA. This could explain why it is lower than the recharge estimate by Bradley and Kalaswad (2003) which applies to the entire aquifer.

The wording in the Freese and Nichols (2006) report suggests that the recharge number they report applies to the entire Dockum Aquifer. The difference between the recharge estimates from Freese and Nichols (2006) and Bradley and Kalaswad (2003) is most likely due to the fact that Bradley and Kalaswad (2003) include cross formation flow in their estimate and Freese and Nichols (2006) does not.

Page 4-67, paragraphs 2 & 3: Paragraph 3 lists recharge rates from different aquifers that have little similarity to the Dockum Aquifer. Please add a concluding statement about how this information relates to Dockum recharge or add recharge rates from aquifers of similar composition to Dockum Aquifer.

Completed. See Section 4.4.1.1, paragraph 3.

Page 4-68, paragraph 1: Comparison of chloride concentrations in precipitation and groundwater as a method of estimating recharge is not applicable to saline aquifers like the Dockum Aquifer where additional sources of chloride (connate water, halite dissolution in adjacent stratigraphic units, etc.). This method would grossly underestimate recharge. Please delete all text related to recharge estimation using this method.

Estimation of recharge using groundwater chloride data were modified to consider chloride data only for samples that also had a total dissolved solids concentration of less than 500 mg/l. See Section 4.4.1.2, first paragraph.

Figure 4.4.4: Please add chloride concentration data that appears in Figure 4.4.3 to this figure.

Restricting recharge estimates from chloride concentration in the groundwater to wells with a total dissolved solids concentration of less than 500 mg/L eliminated the need for this figure, which has been removed..

Page 4-70, paragraph 1: Please change the informal term ‘gip’ to ‘gyp’, and as a slang term should be in quotation marks.

Completed. See Section 4.4.1.3, first paragraph.

Page 4-70, paragraph 2: Please revise the text to state that the well responses shown in Figure 4.4.7 are random and thus do not indicate any regional trend. These responses are most likely responses to local changes in pumping. Please cite Figure 4.4.11 to support statements about overall water-level rise.

The discussion of water level rises in individual wells, and associated figures, were removed from the text.

Page 4-71, paragraph 5: The first sentence states that there is irrigation in the Canadian River outcrop, however, the previous paragraph states that there is no cropland the Canadian River outcrop. Please revise the text for consistency.

Completed. See Section 4.4.1.3, last paragraph.

Figure 4.4.13: Figure 4.4.13 does not appear to be cited or described in the text, please update as needed.

Figure 4.4.8 (previously Figure 4.4.13) is cited in Section 4.4.1.3, paragraph 3, last sentence.

Figure 4.4.14: Figure 4.4.14 does not appear to be cited or described in the text, please update as needed.

Figure 4.4.9 (previously Figure 4.4.14) is cited in Section 4.4.1.3, paragraph 4, second sentence.

Page 4-91, paragraph 2: Please revise the last sentence in this paragraph.

Completed. See Section 4.5.1, paragraph 1.

Page 4-93, paragraph 1: The last sentence is incorrect. The apparent matching of up- and downstream flow data in Figure 4.5.7 suggests that there is no interaction between the river and the Dockum Aquifer. Please revise the sentence to reflect this.

Completed. See Section 4.5.1, last paragraph.

Page 4-111, paragraph 1: This paragraph is largely a repeat from elsewhere in the text. Please delete.

Completed. See Section 4.6.

Page 4-115, paragraph 2: Please revise the ninth line to read ‘In general, the percentage of the wells…’.

Completed. See Section 4.6.3, paragraph 2.

Page 4-115, paragraph 2: Please revise line 11 to read ‘…the calculated sand hydraulic conductivities are biased….

Completed. See Section 4.6.3, paragraph 2.

Page 4-137, paragraph 1: Please revise the first sentence to remove grammatical errors.

Completed. See Section 4.7, first paragraph.

Figures 4.7.6 through Figure 4.7.51: Please revise the respective captions changing ‘withdraws’ to ‘withdrawals’.

Completed. See Figures 4.7.7 through 4.7.53 (previously Figures 4.7.6 through 4.7.51).

Page 4-118: Section 4.6.6 describes a methodology to generate the initial horizontal hydraulic conductivity fields for the model. Please update section with a figure showing the results of this analysis.

Completed. See Section 4.6.6, last paragraph.

Figure 4.6.2: Please change ‘regressoin’ to ‘regression’.

Completed. See Figure 4.6.2.

Page 4-137, paragraph 3: Please revise the last sentence in this paragraph to be consistent with comments for page 4-93, paragraph 1.

Completed. See Section 4.7.1, paragraph 2.

Page 4-137: Please add a brief discussion with regards to groundwater discharge through cross-formational flow to adjacent aquifers, for example, the Pecos Valley Aquifer. This will supplement Section 4.3.5.

Text was added to direct the reader to Section 4.3.5 for a discussion of cross-formational flow. See Section 4.7.1, first paragraph.

Figure 4.7.1: Please use light green for the 0-2 interval to distinguish it from areas outside of the study area.

Completed. See Figure 4.7.2 (previous Figure 4.7.1).

Figures 4.7.2 and 4.7.3: Please merge these two figures.

Changes to the text eliminated the need for Figure 4.7.3, which was removed.

Section 4.7: Please add figures showing cropland and locations of the municipal and different categories of industrial wells in the study area.

Completed. See Figures 4.7.1 (pumping point sources) and 4.7.4 (cropland).

Figure 4.7.5: Please add data for New Mexico.

Completed. See Figure 4.7.6 (previously Figure 4.7.5).

Page 4-141, paragraph 5: Please cite New Mexico State Engineer Office reports as they appear in the list of references (Sorensen, 1977; 1982; Wilson, 1971; Wilson and Lucero, 1997; Wilson et al., 2003).

Completed. See Section 7.4.2.1, New Mexico Counties, first paragraph.

Page 4-179, paragraph 1: '20,000 mg/l' is misleading because later in text mentions several examples of groundwater TDS over 50,000 mg/l. Please change statement to 'more than 50,000 mg/l'.

Completed. See Section 4.8, first paragraph.

Page 4-180, paragraph 4: '20,000 mg/l' is misleading because later in text mentions several examples of groundwater TDS over 50,000 mg/l. Please change statement to 'more than 50,000 mg/l'.

Completed. See Section 4.8.1, last paragraph.

Page 4-181, paragraph 2: The Hood and Kister publication date is 1961 in the text and 1962 in the list of references. Please revise as appropriate.

Completed. See Section 4.8.2, paragraph 2.

Page 4-181, paragraph 3: Please discuss whether water quality may be changing over time.

Discussion of water quality changes over time is beyond the scope of this work.

Page 4-181, paragraph 4: Please cite Figure 4.8.1.

This section discusses data sources and methods of analysis and does not discuss the data itself. A sentence was added to indicate that the total dissolved solids data are presented and discussed in Section 4.8.3.2. See Section 4.8.2, paragraph 4.

Figure 4.8.1: The interpolation in some counties, such as Floyd, Hale, and Lubbock counties, is not consistent with the data shown. Please revise this figure.

A review of the data in the figure does not show an inconsistency between the data and the contours. Reinterpolation of the data using a different scheme yield results almost identical to those shown in the figure suggesting no inconstancy.

Page 4-184, paragraph 2: Please delete the first two sentences, they are unnecessary repetition from earlier in the text.

Completed. See Section 4.8.3.2, last paragraph.

Page 4-185, paragraph 3: The sentence ‘Bradley and Kalaswad (2003)…’ does not make sense, please revise.

Completed. See Section 4.8.3.4, paragraph 2.

Page 4-186, paragraph 3: Please specify which isotope(s) the first sentence refers to.

Completed. See Section 4.8.3.5, first paragraph.

Page 4-186, paragraph 3: Please cite a reference for the minerals listed in the last sentence, ensure that all of these minerals actually occur within the Dockum Aquifer.

Completed. See Section 4.8.3.5, first paragraph.

Page 4-186, paragraph 4: Please change ‘water quality types’ to ‘hydrochemical facies’. Also, please define the ‘Other’ hydrochemical facies.

Completed. See Section 4.8.3.5, paragraphs 2 and 3 and new Table 4.8.4.

Figure 4-4.8.6: Please make absolutely certain that the Ca-HCO_3 hydrochemical facies is in fact Dockum Aquifer groundwater and not Ogallala groundwater, and revise the figure and text accordingly.

Completed. All Ca-HCO3 hydrochemical facies are Dockum Aquifer groundwater based on the well aquifer codes in the TWDB database.

Figure 4-4.8.6: Please add the areas mentioned in Table 4.8.4.

Completed. See Figure 4.8.6.

Table 4.8.4: Based on Figure 4-4.8.6, please: (1) add 'Other' and Na-Mixed anion' to the northern area, (2) add '$Na\text{-}HCO_3$' and 'Other' to the central and southeastern area, and (3) delete '$Ca\text{-}HCO_3$' from and add 'Na-Mixed anion' to the southwestern area.

Table has been completely revised. See Table 4.8.5 (previously Table 4.8.4) and Figure 4.8.6.

SECTION 5: CONCEPTUAL MODEL

Page 5-1, paragraph 2: As drawn, the figure implies that the Lower Dockum occurs in both layers which is incorrect. Please revised this figure to reflect this.

Completed. See Figure 5.1.

SECTION 6: REFERENCES

Please revise the reference for Anaya and Jones (2004) to reflect that it is an <u>unpublished</u> TWDB report.

Completed. See Section 14.

Please specify that Brune (2002) is the 2nd edition.

Completed. See Section 14.

GEODATABASE

Please clip nationwide and statewide feature classes to the study area.

Completed.

Please merge Texas and New Mexico city feature classes.

Completed. See Boundary Feature Dataset

The grids were not correctly imported into the geodatabase, please correct this.

Completed. See Raster Catalogs

Please define the ‘Regions’ field in the natural regions feature class.

Completed. See Conservation Feature Dataset

Please rename the ‘faciestype’ feature class ‘hydrochemicalfacies’. Metadata text should refer to hydrochemical facies. As written the text could be referring to rock facies.

Completed. See Geology Feature Dataset

The metadata for the ‘netsand_lower’ and ‘netsand_upper’ feature classes does not indicate units, please revise.

Completed. See Geology Feature Dataset

Please delete the feature class ‘tds_contours’. This is not used in the conceptual model report and is poor quality contouring.

Completed.

The metadata for feature classes ‘thickness_upper’ and ‘thickness_lower’ do not explicitly state the units, please revise.

Completed. See Geology Feature Dataset

The metadata for feature classes ‘avg_wl_1980_l2’, ‘avg_wl_1990_l2’, and ‘avg_wl_1997_l2’ incorrectly state that they contain water-level data for the upper Dockum when it is really the lower Dockum, please revise.

Completed. See SubSurfaceHydro Feature Dataset

Feature class ‘specific_capacity_data’ metadata attributes list three field twice, please revise.

Completed. See SubSurfaceHydro Feature Dataset

Add a source field to feature classes ‘calculated_K_data_layer1’ and ‘calculated_K_data_layer2’.

Completed. See SubSurfaceHydro Feature Dataset

Please clip and merge feature classes ‘EPA_RF1_Riverreach’ and ‘Streams_NM’.

Completed. See SurfaceHydro Feature Dataset

Please clip and merge feature classes ‘Roads_NM’ and ‘TxDOT_Routes’.

Completed. See Transportation Feature Dataset

Please add more details to the metadata for feature class 'CLIM_NCDC_Precipitation', such as station names.

Completed. See Climate Feature Dataset.

Please add metadata to grid '1971_2000prcp'.

Completed. See Climate Raster Catalog

Please add source data for the topographic map to the geodatabase.

Completed. See GeomorphologyDEM Raster Catalog

Please revise the feature class 'WL_Elevations_Layer1_1997', it is missing the point in New Mexico.

Completed. See SubSurfaceHydro Feature Dataset

Feature classes 'WL_Elevations_Layer2_1980' and 'avg_wl_1980_l2' do not match Figure 4.3.8, please revise.

Completed. See SubSurfaceHydro Feature Dataset

Please add the transient water-level data that appear in Figures 4.3.14 to the geodatabase.

All transient water-level data, including those shown in Figure 4.3.14, can be found in SUBHYD_waterleveldata Feature Class.

Please add the soil data in Figure 4.4.4 to the geodatabase.

Completed. See Soil Feature Database

Please add the playas in Figure 4.4.5 to the geodatabase.

Completed. See Geology Feature Database

Please add the water-level rise data in Figure 4.4.13 to the geodatabase.

Completed. See SubSurfaceHydro Feature Datase

Please add the hydraulic property data in Figure 4.6.1 to the geodatabase.

Completed. See Hydraulic_Property_Data Feature Class in SubSurfaceHydro Feature Dataset

Please add the pumping data in Tables 4.7.1 through 9 to the geodatabase.

Completed. See SubHyd Tables

The SAR data in feature class ‘SAR’ does not match the data in Figure 4.8.3, please revise.

Completed. See Geology Feature Dataset

Note: We were unable to review the pumpage data because the pumpage geodatabase was not submitted.

Appendix C
Draft Report Comments and Responses

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Appendix C

Comments on June 2008 Draft Report for the Dockum Aquifer Groundwater Availability Model

The following comments are 1) reported as those that apply to the contract or previous comments from the Conceptual Model review which must be addressed and then 2) editorial suggestions related to grammatical errors or for readability.

GENERAL COMMENTS

1. Reminder, per contract 0604830593, Exhibit B, Attachment 1, Section 4.4.3: Please submit report in Microsoft Word format and electronic files containing the individual figures in the report per the contract so this report may be considered for a TWDB publication.

   The Microsoft Word and electronic figure files are included.

2. Per contract 0604830593, Exhibit B, Attachment 3, Section 2.2, first paragraph: Please review and revise figures, as appropriate, to meet contract requirements, for example, all figures should be decipherable in grayscale.

   Completed.

3. Per contract 0604830593, Exhibit B, Attachment 3, Section 4.2: Please move footnotes to the list of references per the formatting outlined in the contract.

   Completed.

4. Numbering of figures in sections 1 and 5 are not consistent with the numbering system in the rest of the report for example figures 1.1, 1.2, and 5.1 for consistency should be referenced as 1.0.1, 1.0.2, and 5.0.1. Please use a consistent method of numbering figures and update the text as needed.

   Completed.

5. Several figures include vertical captions referring to ArcMap map documents. Please remove such captions from applicable figures.

   Completed.

6. Do not use the term “Dockum”. Please specify either use “Dockum Group” if referring to the geological unit or “Dockum Aquifer” if referring to the aquifer.

   Completed.

7. For consideration for Board publication, please spell out units of measurement, for example acre-feet per year instead of ac-ft/yr.

    Completed.

ABSTRACT

8. Page xxi, paragraph 2: Please specify the steady-state simulation time period.

    Completed.

9. Page xxii, line 4: Please revise numbers because net aquifer inflow amounts to 101 percent.

    This is an artifact of summing multiple rounded numbers. It would be mathematically incorrect to change any of the individual numbers so that the sum happens to round to 100%. We stand by the current presentation of the numbers.

SECTION 1: INTRODUCTION

SECTION 2: STUDY AREA

10. Page 2-1, paragraph 4: Mentions 54 counties in the active model area, however on page 1-1 the report states the Dockum is present in all or parts of 46 counties. Please clarify if the eight other counties in the study area overlie the Dockum Group but do not contain the fresher portion of the Dockum Aquifer.

    Completed. See Section 2.0, paragraph 4.

11. Page 2-1, paragraph 2: Please explicitly state that the model includes the high salinity parts of the Dockum Group that are excluded from the aquifer as defined by Ashworth and Hopkins.

    Completed. See Section 2.0, paragraph 2.

12. Page 2-15, paragraph 1: Please add brief description of “caprock”.

    Completed. See Section 2.1, first paragraph.

13. Page 2-15, paragraph 1: Please revise the description of the Edwards Plateau Province to be applicable to the study area.

    Completed. See Section 2.1, first paragraph.

14. Figures 2.0.2: Please shade in area beyond down-dip aquifer limit because it is included in model.

The figure was not changed since the area inside the downdip aquifer limit lies within the red line of the model boundary.

15. Figures 2.0.2 through 2.2.7: Maps either show or do not show the border between New Mexico and Oklahoma. Please revise for consistency.

    Completed. See Figures 2.0.2 through 2.2.7.

16. Figure 2.0.7: Please either change RWP's to RWPG's and add (RWPG) after Regional Water Planning Group in the caption so it is clear what the acronym in the legend means or please spell out Regional Water Planning Group in the legend.

    Completed. See Figure 2.0.7.

17. Figure 2.0.8: Please spell out GCD and remove UWCD and WCD from the legend as per Conceptual Model comments.

    Completed. See Figure 2.0.8.

18. Figure 2.1.1: Please update 'Southern High Plain' to 'Southern High Plains'.

    Completed. See Figure 2.1.1.

19. Figure 2.1.6: Please indicate source of data in caption.

    Completed. See Figure 2.1.6.

20. Figure 2.1.6: Please fix Upton County graph or indicate why March is incomplete, use a common border line for all graphs, remove the blue L-shaped (backwards) border line that encompasses field of graphs, correct the spelling of Floyd County , and add Nolan County station (currently missing) to the 'NCDCdata' feature class in the source geodatabase.

    Completed. See Figure 2.1.6 and the 'NCDCdata' feature class in the source geodatabase.

21. Figure 2.1.8: Please use heavier lines or note if discontinuous lines indicate a break in the recording history, and indicate the significance of the red line (average precipitation), and correct the spelling of Upton County.

    Completed. See Figure 2.1.8.

22. Figure 2.1.11: Section 2.1 last paragraph mentions 6 locations, while the figure shows five. Please revise text or figure and add location information to each graph, such as identification reference or name of station.

    Completed. See Section 2.1, last paragraph.

23. Figure 2.2.3: Please add structural contours and shading in Figure 4.2.2. for each of the structural features to clarify what the labels represent.

    The structural contours in Figure 4.2.2 show only the structure for the base of the Dockum Group and do not show all of the structural features found in the active model area. Therefore, the structural contours in Figure 4.2.2 were not added to Figure 2.2.3. However, approximate outlines for the structure features were added to Figure 2.2.3.

SECTION 3: PREVIOUS INVESTIGATIONS

SECTION 4: HYDROGEOLOGIC SETTING

24. Page 4-7, paragraph 3, last sentence: Please clarify which quarter-mile grid you are referring to and include it in the geodatabase.

    Completed. See Section 4.2.2, paragraph 4.

25. Page 4-25, last paragraph and Table 4.3.3: Total percentage of wells in the Lower Dockum and Ogallala amounts to 101 percent. Please revise to total 100 percent.

    This is an artifact of summing rounded numbers. It would be mathematically incorrect to change any of the individual numbers so that the sum happens to round to 100%. We stand by the current presentation of the numbers.

26. Page 4-29, paragraph 1: Please revise the text to state that the much lower total dissolved solids (TDS) of Pecos Valley Aquifer groundwater in Monument Draw is indicative of very low flow rates from the Dockum Aquifer. Also see paper by Jones in TWDB Report 360. Please revise the last sentence in this paragraph to clarify it.

    A review of the TWDB Report 360 indicates that the total dissolved solids concentration in the Pecos Valley Aquifer is higher than 3,000 milligrams per liter at some locations along the Monument Draw Trough. Figure 4.8.1 of this report indicates that the total dissolved solids concentration of the Dockum Aquifer in this same area is less than 5,000 milligrams per liter. This does not indicate that the total dissolved concentration in the Pecos Valley Aquifer is much lower than that in the Dockum Aquifer. No change was made to the text.

27. Page 4-69, paragraph 1: Please point out that the Freese and Nichols recharge estimate only applies to the portion of the Dockum Aquifer within the Panhandle Regional Water Planning Area. This could explain why it is lower than the recharge estimate by Bradley and Kalaswad (2003) which applies to the entire aquifer.

    Completed. The wording in the Freese and Nichols (2006) report suggests that the recharge number they report applies to the entire Dockum Aquifer. Text was added stating that if their number does not

apply to the entire aquifer, the calculated recharge rate would be higher than the presented number. In addition, text was added stating that the difference between the recharge in Freese and Nichols (2006) and Bradley and Kalaswad (2003) may be due to the fact that Bradley and Kalaswad (2003) include cross-formational flow in their recharge estimate and Freese and Nichols (2006) do not. See Section 4.4.1.1, first paragraph.

28. Page 4-179, paragraph 3: Please justify the use of only the most recent sampling data.

    Completed. See Section 4.8.2, paragraph 3.

29. Table 4.5.2: Please provide the table and corresponding metadata in the source geodatabase.

    Completed. See table 'SURHYD_spring_flows' in the source geodatabase.

30. Table 4.6.3: Please use consistent format for citations.

    Completed. See Table 4.6.3.

31. Figure 4.1.1: Please specify Outcrop for Dockum Aquifer and remove trailing comma.

    Completed. See Figure 4.1.1.

32. Figures 4.2.1 to 4.2.7 and section 4.2.1: The ‘McGowen_Control_Points’ feature class attribute table has limited usable attributes. Please include all attributes used to derive the above mentioned figures and text. The source geodatabase should include all relevant information so that Figures 4.2.1 to 4.2.7 could be independently reproduced with the same results.

    The McGowen control points shown on the structure figures do not contain any data used to construct the structure used for the Dockum Aquifer groundwater availability model. These points are included on the figures only to show the locations of the gamma-ray logs used by McGowen and Others (1977) to develop their structure. A sentence was added to the text to clarify this fact. See Section 4.2.2, paragraph 7.

33. Figure 4.2.3: Please discuss the edge effects in Deaf Smith, Randall, and Swisher counties in Section 4.2.2 of the text.

    Completed. See Section 4.2.2, paragraph 8.

34. Figures 4.3.13 through 4.3.18: Please revise the shading in the location maps in these figures to be consistent with other similar figures in this section, for example Figures 4.3.19 to 4.3.27.

Completed. See Figures 4.3.13 through 4.3.18.

35. Please fix the border on Figure 4.4.3. Left and top portions have dotted red/black lines implying the downdip limit.

    Completed. See Figure 4.4.3.

36. Figures 4.5.4-5, 4.5.7, 4.5.9-10: Please provide the data for the stream and spring discharge hydrographs, as well as data for lake levels; attribute tables for feature classes ‘StreamGageLocations’, ‘Dockum_Spring_Locations’ and ‘TX_Reservoirs’ do not contain any discharge or lake level data.

    The spring discharge hydrograph data can be found in the 'SURHYD_SpringData' table in the source geodatabase. Note that for Chicken Springs, this table gives discharge rates in liters per second rather than gallons per minute because those are the units in Brune (2002), which is the source for the data. The streamflow hydrograph data can be found in the 'SURHYD_MonthlyStramflow' table in the source geodatabase. The reservoir hydrograph data can be found in the 'SURHYD_ReservoirElevations' table found in the source geodatabase.

37. The nugget in Figure 4.6.9(a) does not reflect the text (page 4-116). Please revise.

    Completed. See Section 4.6.5, paragraph 4.

38. Figure 4.7.3: Please add New Mexico data that appeared in Figure 4.7.3 of the draft conceptual model report to this figure.

    Completed. See Figure 4.7.3.

SECTION 5: CONCEPTUAL MODEL

39. Page 5-1, paragraph 2: Please explain why aquifers that overlie the Dockum Aquifer are simulated using both a model layer and overlying general-head boundary versus a general-head boundary directly over the Dockum Aquifer.

    Completed.

40. Page 5-2, paragraph 4: Please revise the last sentence to clarify the different recharge and discharge zones.

    Completed.

41. Figure 5.1: Please update legend to read “Discharge via Pumpage”.

    Completed.

SECTION 6: MODEL DESIGN

42. Page 6-10, paragraph 2: Please discuss the reasoning for not including recharge in cells that coincide with streams.

    Completed.

43. Per Contract, Exhibit B, Attachment 1, Section 4.4.1.: Please discuss storativity in terms of specific yield and specific storage on page 6-24, section 6.4.2.

    We discuss specific storage, storativity, and specific yield on page 6-24. We have retitled Section 6.4.2 "Storage Coefficient" since it refers to both confined storage (storativity) and unconfined storage (specific yield). We have also reworded mention of storage coefficients in order to avoid confusion.

44. Page 6-24, paragraph 2: Please add more detailed justification, including references, for using a 'confined storativity' value of 1 in outcrop cells. Please update or clarify why these values do not seem to appear in Figure 6.4.8.

    Additional clarification was added. This concept was also used in previous GAMs (Deeds et al., 2002; Fryar et al., 2003; Ewing et al. 2004; Kelley et al., 2004).

45. Figures 6.3.1 through 6.3.3: Please move these figures to section 6.2 and renumber.

    The discussion of active/inactive cells that had been in Section 6.2 was moved to Section 6.3.1 as it pertains to the lateral model boundaries. Since these figures concern the lateral and vertical boundary conditions which are discussed in Section 6.3, it is no longer necessary to move them.

46. Figures 6.4.7 and 6.4.8: Please change "storativity" to "specific storage"

    Storativity is equal to specific storage multiplied by the aquifer thickness. The figures represent storativity, not specific storage and were not altered.

SECTION 7: MODELING APPROACH

47. Per Contract, Exhibit B, Attachment 1, Section 4.4.1. Please specify whether the term "storativity" refers to "specific storage" or "specific yield" on page 7-2, paragraph 1.

    Storativity is the confined storage coefficient and is neither specific storage nor specific yield. It is equal to specific storage multiplied by aquifer thickness. The text was reworded slightly in attempts to clarify.

48. Page 7-4, paragraph 2: In the contract (Exhibit B, Attachment 1, Section 3.3), the GAM requirement is *"The mean absolute error between measured hydraulic-head and simulated hydraulic head shall be less than 10 percent of the measured*

hydraulic-head drop across the model area and better if possible." Please revise this paragraph to reflect this.

Completed.

49. Page 7-5, paragraph 1: Please revise this paragraph to reflect the use of mean absolute error instead of root mean square error per Contract, Exhibit B, Attachment 1, Section 3.3.

    Completed.

SECTION 8: STEADY-STATE MODEL

50. Page 8-2, paragraph 2: The model seems to utilize vertical leakance input data rather than vertical conductance. Please mention this in the text and discuss what vertical leakance is and how it is calculated.

    Vertical leakance (VCONT) is the required input for the MODFLOW-2000 BCF package. Its use is documented thoroughly in the MODFLOW-2000 User Guide as well as the Groundwater Vistas v4.0 User's Manual.

51. Page 8-9, paragraph 1: Please revise this paragraph to reflect use of mean absolute error as the main calibration measure per Contract, Exhibit B, Attachment 1, Section 3.3.

    Completed.

52. Page 8-9, paragraph 2: Please show the dry cells in Figures 8.2.1 and 8.2.2.

    These figures have been revised as per comment 57 and dry cells are shown in the legend and on the map.

53. Page 8-10, paragraph 3: Please cross reference discussion on evapotranspiration with Section 6.3.4. Please clarify if the water levels not reaching root depth (or drain elevation) may be another reason evapotranspiration rates are so low.

    Completed.

54. Table 8.2.1: Please change "Adjusted RMS" to "Adjusted MAE" per Contract, Exhibit B, Attachment 1, Section 4.4.2.

    Completed.

55. Tables 8.2.4 and 8.2.5: Please note that positive values indicate net flow into the aquifer.

    Completed.

56. Figures 8.1.1 and 8.1.2: Please revise, differs slightly from model data.

Completed.

57. Figures 8.2.1 and 8.2.2: Please combine these figures with Figures 8.2.5 and 8.2.6, respectively.

    Completed.

58. Figures 8.2.5- to 8.2.7 and 8.2.9 to 8.2.11: The feature classes used to create these figures are either empty or missing from the 'ModelResultsSS' feature dataset. Please update 'ModelResultsSS' feature dataset to include model results data.

    Completed.

59. Figure 8.2.8: Please include references for the different studies indicated in the figure (…Studies 37, 38, 39, …).

    Completed.

60. Figures 8.3.1 through 8.3.12: Please renumber these figures in the order in which they are cited in the text.

    Completed.

SECTION 9: TRANSIENT MODEL

61. In Sect. 9.1: Please add a table of the range and mean of horizontal and vertical hydraulic conductivity and storativity (per Exhibit B, Attachment 1, Section 4.4.2).

    Completed.

62. In Sect. 9.1: Please add a table listing mean absolute error and mean error for the transient calibration per layer for 1990 and 1997 (per Exhibit B, Attachment 1, Section 4.4.2).

    Completed.

63. In Sect. 9.1: Please add a scatter/cross plot of simulated vs. measured hydraulic head for 1990 and 1997 for each layer in the model (per Exhibit B, Attachment 1, Section 4.4.2).

    Completed.

64. In Sect. 9.1: Please add a water budget for 1990 by Groundwater Conservation District and county similar to that reported for 1997 (per Exhibit B, Attachment 1, Section 4.4.2).

    Sentence 2 of the final paragraph on page 11 of Exhibit B, Attachment 1, Section 3.3 of the contract states "The contractors shall also extract the water budget per county and per groundwater conservation district for

1997, the end of the calibration period." No mention is made of 1990 nor is any mention made in Exhibit B, Attachment 1, Section 4.4.2 of county or groundwater conservation district budgets. This was included, however, in hopes that it is of some utility to readers of the report.

65. In Sect. 9.1: Please add a table showing stress periods and their corresponding time periods for the transient model (per Exhibit B, Attachment 1, Section 4.4.2).

    Completed.

66. Page 9-2, paragraph 2: Please remove all references to "Primary" and "Secondary" storage and instead use the terms specific storage and specific yield.

    Replaced "primary storage" with "storativity" and "secondary storage" with "specific yield" in the one place the terms occur. It would be incorrect to use the term specific storage here.

67. Page 9-5, Sect. 9.2.3: Please add a description of specifically how the water budgets were calculated. If a water budget calculation program outside of Groundwater Vistas, PMWIN, or ZONEBUDGET is used, please document how this program operates (especially in how it is different from above programs) and why it was preferred over the prepackaged programs. The goal here is to present enough information for someone to be able to closely replicate (either by writing a script or using a prepackaged water budget program) the water budget results in the report.

    The reason custom scripts were necessary and the location of the scripts and documentation were added to Sections 8.2 and 9.2.

68. Page 9-6, paragraph 1: Please specify when flow from the upper Dockum Aquifer to the Ogallala Aquifer is 1.7 percent. Cite Table 9.2.5 at the end of the sentence "The major avenues…".

    Completed.

69. Tables 9.2.1 through 9.2.3: Please add units to column headings consistent with Table 8.2.1.

    Completed.

70. Figure 9.2.3 is missing data available in the 'tr_residuals_l2' feature class. Please revise.

    The figure has been fixed.

71. Figure 9.2.9: The number of observed measurements seems to be far fewer than in the model. Please clarify and if necessary revise this figure.

Multiple measurements exist at different times at a given location. Therefore, there are more observed measurements than measurement locations. Many of the measurements at a given location do not vary greatly over time and are therefore plotted atop one another. Clarification has been added to the text, however, the figure is correct.

72. Figure 9.2.18: Please cite the studies and data sources for the graphs.

    Completed.

73. Figures 9.3.17 through 9.3.21: It is difficult distinguish factor=0.5 from factor=1.0, please different colors.

    Completed.

SECTION 10: LIMITATIONS OF THE MODEL

74. Page 10-3, paragraph 5: Please cite figure indicating the location of the Monument Draw Trough in the sentence “The potential for introduction…”.

    Completed.

75. Page 10-6, paragraph 2: Please change the second sentence to reflect the fact that groundwater salinity and associated density issues occur throughout the aquifer to varying degrees and are not accounted for in the model.

    Completed.

SECTION 11: FUTURE IMPROVEMENTS

76. Page 11-3, paragraph 2: Please mention the likelihood of incorporating additional data collected since the 1970s.

    Completed.

SECTION 12: CONCLUSIONS

77. Page 12-1, paragraph 1: Please capitalize ‘Aquifer’.

    Completed.

78. Page 12-2: Please adjust net aquifer inflow to amount to no more than 100 percent.

    This is an artifact of summing multiple rounded numbers. It would be mathematically incorrect to change any of the individual numbers so that the sum happens to round to 100%. We emphatically hold to the current presentation of the numbers.

SECTION 13: ACKNOWLEDGEMENTS

SECTION 14: REFERENCES

79. Page 14-13: Please check spelling of “Wiroganagud”.

    Completed.

APPENDIX

80. Appendix or Section 8.2: Please add model results per county and Groundwater Conservation District for the steady-state model run. If added to appendix, please move results per county and Groundwater Conservation District for the end of the transient model from Sect. 9.2 to the appendix as well and cross reference.

    The two tables were added to Section 8.2.

81. Page 13-1, paragraph 3: Please capitalize “groundwater availability model” and add “Section”. Change “exercise” to “project” and “Ian Jones” to “Dr. Ian Jones”.

    Completed.

82. Page 13-1, paragraph 4: Please change “Dr. David Johns” to “David Johns”.

    Completed.

DATA GEODATABASE

83. Please clip the following feature classes to the study area: ‘State_NM’, ‘County’, ‘tx_state’, and ‘Triassic_Age_Sediments_US’.

    All the features of each of these shape files were used in plotting figures in the report. Clipping them will make certain figures incomplete. No change was made.

84. The ‘GeomorphologyDEM’ raster covers only 75 percent of the study area. Please revise.

    Figure 2.0.1 depicting the study area has been revised to encompass only the region in the near vicinity of the Dockum Aquifer. The ‘GeomorphologyDEM’ raster now covers the entire study area.

85. Please merge feature classes ‘WaterBodiesNM’ and ‘TX_Reservoirs’.

    Completed.

86. Several features in the ‘Cities’ feature class are missing names. Please revise.

    Completed. See Boundary Feature Dataset.

87. The following feature classes: ‘SS_flows’, ‘SS_heads’, ‘Flow_ss_springs’, ‘ss_residuals_l2’, ‘ss_residuals_l3’ are empty (meaning the there are no features). Please revise.

    Completed.

88. The ‘McGowen_Control_Points’ feature class has no usable attributes. Please populate the table with data described in the abstract.

    The ‘McGowen_Control_Points’ feature class shows the locations of the control points used by McGowen and others (1977) to develop their structure. No data for these control points were used for the Dockum Aquifer groundwater availability model.

89. There are now two feature classes called ‘Hydrochemical_Facies’ and ‘hydrochemicalfacies’ (possibly duplicates, although the tables are slightly different). Please revise.

    Completed. ‘hydrochemicalfacies’ feature class was deleted. See Geology Feature Dataset.

90. ‘Specific_Capacity_Data’ feature class metadata still contains duplicate fields. Please revise.

    Completed. See SubSurfaceHydro Feature Dataset.

91. ‘calculated_K_data_layer1’ and ‘calculated_K_data_layer2’ needed to have a source field. Both feature classes are missing. I suspect they have been renamed; however, we need written clarification. Please revise.

    Completed. ‘calculated_K_data_layer1’ and ‘calculated_K_data_layer2’ were renamed as ‘Calculated_K_Data_Upper_Dockum’ and ‘Calculated_K_Data_Lower_Dockum’. These new feature classes have source fields. See SubSurfaceHydro Feature Dataset.

92. ‘CLIM_NCDC_Precipitation’ feature class does not have station names. Please revise.

    The station names are contained as the headings for columns C through H.

93. ‘1971_2000prcp’ raster dataset metadata is largely incomplete. “Abstract” is the only section completed and makes no reference to which climate parameter is being modeled with unit of measurement. Please revise.

    ‘1971_2000prcp’ raster metadata does contain detailed information, including abstract, purpose and supplementary information etc. A brief

description of this raster was added to 'ClimatePRISM' raster catalog metadata.

94. Figure 4.3.14 cannot be reproduced because the 'SUBHYD_waterleveldata' feature class (as you called it in the answer to the original comment) is missing. Please revise.

    Completed. SUBHYD_waterleveldata feature class has been updated.

95. 'soil_data' feature class doesn't have metadata. Please revise.

    The 'soil_data' feature class was deleted from the geodatabase because it was not used in the model or the report.

96. 'playas' feature class metadata describes how playas were mapped in several states other than Texas and New Mexico. Please revise to reflect the study area.

    Completed. The metadata for the 'playas' feature class now only contains information for playas in Texas and New Mexico. See Geology Feature Dataset.

97. 'water_rise_data' feature class doesn't have metadata. Please revise.

    This feature class, which should have been removed from the geodatabase in response to previous comments on the conceptual model report, has been removed.

98. Data from the following tables: 4.7.1, 4.7.3, 4.7.4, 4.7.5, 4.7.6, 4.7.7, 4.7.8, and 4.7.9 are inconsistent with data found in the geodatabase tables: 'SUBHYD_pumping_in_Texas_by_county', 'SUBHYD_irrigation_pumping_by_county', 'SUBHYD_manufacturing_pumping_by_county', 'SUBHYD_mining_pumping_by_county', 'SUBHYD_municipal_pumping_by_county', 'SUBHYD_power_generation_pumping_by_county', 'SUBHYD_rural_domestic_pumping_by_county', and 'SUBHYD_livestock_pumping_by_county'. Also, Table 4.7.2 totals are wrong. Please revise to make sure numbers add up and they match data from the geodatabase.

    Completed. These tables are updated while the names remain the same. The updated tables are consistent with tables in the report.

99. 'SAR' feature class did not match Figure 4.8.3. There are now two SAR feature classes: 'SAR' and 'SAR_1'. The tables show a different number of records. Please clarify as to which was used for the figure, and delete the one containing the wrong data.

Completed. 'SAR' was deleted and 'SAR_1' was renamed as 'SAR'. See Geology Feature Class Dataset.

100. 'netsand_lower' feature class metadata refers to the lower Dockum as layer 2 instead of 3. Please revise.

Completed. See Geology Feature Dataset.

101. Please include a brief description of each raster dataset in the 'GeologyGrids' raster catalog along with measurement units.

Completed. Each raster in 'GeologyGrids' raster catalog has already had detailed metadata. A brief description was added into 'GeologyGrids' raster catalog metadata.

102. Please include units in metadata for DEM raster in the 'GeomorphologyDEM' raster catalog.

Completed. See GeomorphologyDEM raster catalog.

103. 'streams' feature class metadata is missing units for hydraulic conductance (CONDUCT field). Please revise.

Completed. See ModelBoundary Feature Dataset.

104. 'sand_fraction' feature class metadata is inconsistent. Description mentions layers 1 and 2, while Attributes mentions layers 2 and 3.

Completed. See ModelHydraulicProperties Feature Dataset.

105. 'Storativity' feature class metadata is inconsistent. Description mentions layers 1 and 2, while Attributes mentions layers 2 and 3.

Completed. See ModelHydraulicProperties Feature Dataset.

106. Please define CBB in metadata where used (e.g. ModelResultTR feature dataset).

Completed.

107. The average water levels feature classes in the 'SubSurfaceHydro' feature dataset have inconsistent data and metadata. Depth from surface in some feature classes is either positive or negative. In your metadata you claim negative values represent water levels below land surface. Should we assume a positive means water level above land surface? Please decide on whether to use either positive or negative but not both (except maybe artesian wells?) values for depth from land surface. Also adjust water levels if necessary and the metadata accordingly. The 'SUBHYD_waterleveldata' table suffers from the same positive/negative data inconsistencies. Please revise.

Completed. The average water level feature classes in SubSurfaceHydro feature datasets have been revised. Negative values indicate water levels below land surface; positive values (only a few of them) represent water levels above land surface (artesian wells).

108. Please include a description in the metadata of each raster in the 'SubSurfaceHydroHydraulics' and 'SubSurfaceHydroWaterLevels' raster catalogs and include measurement units.

Detailed metadata, including unit, was added into SubSurfaceHydroHydraulics raster catalog. SubSurfaceHydroWaterLevels raster catalog has been deleted because it is not used in the model or the report.

109. In table 'SURHYD_SpringsData', please redefine the state_well_no field to represent a spring number.

Completed. The state_well_no field name has been changed to STATE_SPRG.

110. Please include an up-to-date GCD layer in your maps and geodatabase and specify a validity date.

Completed. Figure 2.0.8 has been updated using the up-to-date GCD shapefile (August 2008) which has been imported to Conservation Feature Dataset in the geodatabase.

111. Please submit the shapefile of the extent of the upper Dockum Aquifer.

Completed. A shapefile with metadata was added into the geodatabase. See Boundary Feature Dataset.

PUMPAGE GEODATABASE

112. The 'PumpageTools' toolbox contains duplicate tools as follows:

- 'Assign_MFG' and 'Assign_MFG (2)' (the latter is broken)
- 'Assign_MIN' and 'Assign_MIN (2)' (the latter is broken)
- 'Assign_MUN' and 'Assign_MUN (3)'
- 'Assign_PWR' and 'Assign_PWR (2)'

Please clean up tools that don't belong in the toolbox or are broken. You can choose to import the toolbox from the original GAM_PUMPAGE_v3.mdb geodatabase we provided (this would be the preferred way because the 9.1 version of the tools works in ArcGIS 9.1).

Completed. The duplicated tools were deleted.

113. The 'tbl_MFG_WellPump' table lists pumpage assignments to cells that do not have wells according to the wells layer; e.g.:

- After running the ‘Assign_MFG’ tool our ‘tbl_MFG_WellPump’ table contains 71 records while your table contains 107 records
- There are no wells with alphanum = 813400 in the wells layer, yet this alphanum appears in the final ‘tbl_MFG_WellPump’ table. This shouldn’t happen because the ‘Assign_MFG’ tool selects only records with matching alphanum’s. Please revise the wells layer and re-run the ‘Assign_MFG’ tool and verify through the QA process.
- The AFY_cell fields in the two tables (TWDB run and INTERA run) do not match for records with more than one well per cell. This issue also appears in the ‘tbl_MIN_WellPump’ and ‘tbl_MUN_WellPump’ tables and will be mentioned below.

Completed. The data was corrected and the tools were rerun.

114. ‘tbl_MIN_WellPump’ table. The AFY_cell fields in the two tables (TWDB run and INTERA run) do not match for records with more than one well per cell. Please re-run the ‘Assign_MIN’ tool and verify through the QA process.

Completed. The data was corrected and the tools were rerun.

115. ‘tbl_MUN_WellPump’ table. The AFY_cell fields in the two tables (TWDB run and INTERA run) do not match for records with more than one well per cell. Please re-run the ‘Assign_MUN’ tool and verify through the QA process.

Completed. The data was corrected and the tools were rerun.

MODEL

116. The drain cells in the model do not match the drain cells in the text. Please revise text or model for consistency.

Completed. There was an error in the model drain package which has been fixed. This had only minor impacts on the model results, however, the model output figures, tables, and text have been updated. Text in Section 6.3.4 has been corrected.

117. The water budgets in the MODFLOW version of the model does not match the water budget of the Groundwater Vistas version. Please revise the Groundwater Vistas version for consistent results.

Completed. The two versions of the model now match identically with respect to the simulated water budget.

118. Please include documentation of the script(s) used to calculate the county water budgets.

Completed.

<u>SUGGESTIONS:</u>

GENERAL COMMENTS

1. Please change “gridblocks” or “grid blocks” to “grid cells”.

   The terms are used correctly and were not altered.

2. Please change “hydraulic head” to “water level”.

   The terms are used correctly and were not altered.

3. Please move data source information placed at the bottom of figures to the caption.

   Including this information in the caption makes many of the captions excessively long which adversely impacts the readability of the table of contents. The source information was not moved.

ABSTRACT

4. Pg. xxi, paragraph 2: Please remove the unnecessary “and” in the last sentence.

   This would change the meaning of the sentence from that intended. The sentence was not altered.

5. Page xxi, paragraph 3: Please delete this paragraph.

   The paragraph provides a summary of the important aspects of the groundwater availability model, is considered appropriate in the abstract, and was kept.

6. Page xxi, paragraph 3: Please add a brief explanation of why average pre-development and transient recharges are different or cite where this is discussed.

   Completed.

7. Page xxii, paragraph 3: Please move this paragraph. This should be the second paragraph in the abstract.

   We prefer the current narrative order of the abstract and the paragraph was not moved.

8. Page xxii, paragraph 3: Please delete “(e.g., an area … square mile)”.

   The scale of the model applicability is considered important knowledge for any user of the model. The sentence was kept.

9. Page xxii, paragraph 3: Please delete “This model is well suited…resource questions.”.

   Completed.

10. Page xxii, paragraph 3: The last sentence in this paragraph should be the second sentence in this paragraph

    We prefer the current narrative order of the paragraph and the sentence was not moved.

SECTION 1: INTRODUCTION

11. Page 1-1, paragraph 3: Please change “…fresh in part…” to “…fresh in parts…”.

    Completed. See Section 1.0, paragraph 3.

12. Page 1-1, paragraph 3: Please change “…make up the Dockum Aquifer (Ashworth and Hopkins, 1995)” to “…make up the Dockum Aquifer as defined by Ashworth and Hopkins (1995)”.

    Completed. See Section 1.0, paragraph 3.

13. Page 1-1, paragraph 3: Please delete “Panhandle and western” and mention that the aquifer extends into New Mexico, Oklahoma, Kansas, and Colorado.

    Since the focus of this report is the Dockum Aquifer in Texas, this change was not made.

14. Page 1-1, paragraph 3: Please change “…industrial use…” to “…industrial uses…”.

    Completed. See Section 1.0, paragraph 3.

15. Page 1-2, paragraph 1: Please change “…layers will be defined…” to “…layers are defined…”.

    Complete. See Section 1.0, paragraph 4. Note: "will be" was changed to "were" rather than "are".

16. Page 1-3, last paragraph, first line: Should it be “…model [was] developed…” instead of “…model is being developed…”?

    Completed. See Section 1.0, last paragraph.

SECTION 2: STUDY AREA

17. Page 2-2, paragraph 3: Delete last sentence. Table has little relevance to the study area.

    Although the table has little relevance to the study area, it was not removed.

18. Page 2-3, Table 2.0.2: Delete table or revise to apply to the study area.

    Although the table has little relevance to the study area, it was not removed.

19. Page 2-15, paragraph 1: Please either delete “The west-facing escarpment…” or include New Mexico portion of the Southern High Plains to Figure 2.1.1.

    Completed. See Section 2.1, first paragraph.

20. Page 2-15, paragraph 1: Please revise the description of the Edwards Plateau Province to be applicable to the study area.

    Completed, See Section2.1, t paragraph.

21. Figure 2.1.4: Please revise this figure to include delineations between climate zones. It’s not clear if the green is mountain climate everywhere on the map.

    Completed. See Figure 2.1.4.

22. Figure 2.1.6: Please remove the white box covering a portion of the figure for Upton County temperatures.

    Completed. See Figure 2.1.6.

23. Figure 2.2.1: Please change “et al.” to “and others”.

    Completed. See Figure 2.2.1.

SECTION 4: HYDROGEOLOGIC SETTING

24. Page 4-2, paragraph 4: Please change “In the remaining areas,…” to “In the remaining area,…”.

    Rather than making the suggested change, "makes" was changed to "make" later in the sentence. See Section 4.1, paragraph 6.

25. Page 4-8, paragraph 2: Please cite figure(s).

    No change made. The figures are cited in the first sentence of the following paragraph.

26. Page 4-8, paragraph 4: Please remove the word “force” after the word “help.”

No change made. The point of the sentence is that the additional data were added to force the interpolation routine to reproduce the original contours.

27. Page 4-9, section 4:2:3, paragraph 1 – Please change the word “thickness” to “thicknesses.

    Completed. See Section 4.2.3, first paragraph.

28. Page 4-29, paragraph 1: Please change “…Dockum discharges to …” to “…Dockum Aquifer would discharge to…”.

    No change made.

29. Page 4-138, paragraph 1: ‘overly’ is not a verb. Please replace with overlie.

    Completed. See Section 4.7.2.1, paragraph 10.

30. Page 4-184, paragraph 4: Please delete “(O/H and $^{18}O/^{16}O$)” and briefly explain the basis for conclusions outlined in the first sentence. Delete the quotation marks in the last sentence.

    No change made. The isotopes are included in the sentence in response to a comment on the Draft Conceptual Model report. No text was added because the basis for the conclusion outlined in the first sentence can be found in the reference cited at the end of the sentence. The quotations were not deleted from the last sentence because that portion of the sentence is a direct quote from the reference cited at the beginning of the sentence.

31. Page 4-185, paragraph 1: Please delete “type”.

    Completed. See Section 4.8.3.5, paragraph 2.

32. Page 4-185, paragraph 2: Please change “…groundwater at over…” to “…groundwater in over…”.

    Completed. See Section 4.8.3.5, last paragraph.

33. Figures 4.2.1 through 4.2.7: Please change “et al.” to “and others”.\

    Completed. See Figures 4.2.1 through 4.2.7.

34. Figure 4.8.1: Please change “et al.” to “and others” and please adjust circle symbols bolder and therefore easier to see.

    On Figure 4.8.1, "et al." was changed to "and others". No change was made to the circle symbols. See Figure 4.8.1.

SECTION 5: CONCEPTUAL MODEL

35. Page 5-1, paragraph 2: Please change "see Figure…" to "Figure…" where ever it appears in the paragraph.

    Completed.

36. Page 5-4, paragraph 2: Please change "…groundwater withdrawals..." to "…water-level decline…". Please change "…supplied by increased..." to "…caused by increased…".

    Completed.

37. Figure 5.1: Please change the legend of figure from "Discharge vie Pumping" to "Discharge via Pumping.

    Completed.

SECTION 6: MODEL DESIGN

38. Page 6-1, paragraph 2: Please remove the hyphen from "ground-water'.

    Completed.

39. Page 6-2, paragraph 2: Suggestion: please replace center with centroid.

    Completed.

40. Page 6-2, paragraph 2: Please cite Figures 6.3.1 through 6.3.3.

    The portions of this paragraph pertaining to active/inactive cells were moved to Section 6.3 and the figures are referenced accordingly there.

41. Page 6-3, paragraph 2: Please move this paragraph to the beginning of section 6.2.

    Completed.

42. Page 6-5, paragraph 1: Please delete "(First Type or Dirichlet)", "(Second Type or Neumann)", and "(Third Type or Cauchy)".

    These are the fundamental terms common to numerical modeling and are included to provide clarification of MODFLOW specific terminology. They have been left in.

43. Page 6-5, paragraph 3: Please delete "Second Type" and "Third Type" wherever they appear in the paragraph.

    See response to suggestion 42.

44. Page 6-5, paragraph 4: Please delete the first sentence.

    As per response to suggestion 40, the portions of Section 6.2 that previously pertained to active/inactive cells have been moved to Section 6.3 and this sentence is now the first and only reference to Figures 6.3.1 through 6.3.3 so it was left in.

45. Page 6-6, paragraph 2: Please delete “Third Type” wherever it appears in the paragraph. Change “…(or other younger) Formation.” To “…or other younger formations. Change “…flow boundary condition,…” to “…flow boundary conditions,…”.

    See response to suggestion 42 regarding “Third Type”. Second suggestion completed. The singular tense of “condition” was unaltered as it would be grammatically incorrect to alter to plural tense.

46. Page 6-7, paragraph 3: Please delete “Third Type” wherever it appears in the paragraph. Change “The stream package…” to “The stream-routing package…”.

    See response to suggestion 42.

47. Page 6-8, paragraph 5: Please delete “Type 3” wherever they appear in the paragraph.

    See response to suggestion 42.

48. Page 6-10, paragraph 2: Please add comma after “0.15 in/yr”.

    Completed.

49. Page 6-10, paragraph 3: Second sentence is unclear, please amend and please change “…in/yr leaves 1.45…”to “…in/yr indicates 1.45…”.

    Completed.

50. Page 6-11, paragraph 3: Please delete the sentence “For procedural details…”.

    Completed.

51. Page 6-12, paragraph 3: Please state which years of the southern Ogallala GAM were used to provide the general-head boundary condition assigned to layer 1 or if the drawdowns for each year in the southern Ogallala GAM were correlated with the Dockum GAM.

    Completed.

52. Page 6-22, paragraph 3: Please delete this paragraph, it contributes very little to the section. Please check the spelling of “Gutjahhr”.

The spelling of "Gutjahr" has been corrected. However, we feel that this paragraph provides important theory and rationale that are the basis for our parameterization of horizontal and vertical hydraulic conductivity. The paragraph has been unaltered.

53. Page 6-24, paragraph 3: Please remove the hyphen from "specific-storage".

    Completed.

SECTION 7: MODELING APPROACH

54. Sect. 7.0: Please clarify that changes made to the model, if any, during transient calibration are propagated into the steady-state model.

    Completed.

55. Page 7-1, paragraph 1: Please revise the sentence "A sensitivity analysis entails…", it does not make sense.

    Meaning is correct. Sentence was left unaltered.

56. Page 7-1, paragraph 3: In the sentence "Minimal hydraulic conductivity…", please move the word "however" to the beginning of the sentence.

    Completed.

57. Page 7-3, paragraph 2: Please change "…were conducted…" to "…have been conducted…". Please change "…this comparison." to "…these comparisons.".

    Completed.

58. Page 7-3, paragraph 3: Please change "…lay outside…" to "…lies outside…". Change "…make a direct comparison…" to "…make direct comparison…".

    Completed.

59. Page 7-3, paragraph 4: There is no need to repeat the definitions of the parameters in Equations 7.1.2 and 7.1.3, that are defined for Equation 7.1.1, please delete.

    As the definitions are not verbose and make the individual equations complete unto themselves, we prefer the current convention.

60. Page 7-4, paragraph 4: Please delete the sentence "The primary target…", this statement is made earlier in the chapter.

    Completed.

61. Page 7-5, paragraph 2: Please change "Measurement errors…" to "Water-level measurement errors…". Change "…root mean square…" to "…mean absolute

error…" where it appears in the paragraph. Change "…over calibration…" to "…over-calibration…".

Completed.

SECTION 8: STEADY-STATE MODEL

62. Page 8-8, paragraph 1: Please delete this paragraph, it repeats information found elsewhere in the text.

    As the introductory paragraph to this section, it summarizes concepts discussed elsewhere but in the context of the model results. We feel removal of the paragraph would be a detriment to the report.

63. Page 8-10, paragraph 2: Please change "…that limits the spring…" to "…that limit the spring…".

    Completed.

64. Page 8-11, paragraph 2: In the sentence "Water discharges…", please arrange flow terms in decreasing order. In sentence "Cross-formational flow…" change "Cross-formational" to "Net cross-formational" and delete "primarily".

    Completed.

65. Page 8-11, paragraph 2: In the last sentence of this paragraph, please remove the word "are".

    Completed.

66. Figure 8.2.11: This figure would be even more useful if it incorporated all net inflows and outflows in the aquifer, such as ET, streams, and outcrop recharge.

    The purpose of the figure is to show the net cross-formational flow from overlying aquifers. The addition of other recharge/discharge mechanisms would render it impossible to discern which mechanism is occurring where.

SECTION 9: TRANSIENT MODEL

67. Page 9-2, paragraph 2: Please remove all references to "Primary" and "Secondary" storage and instead use the terms specific storage and specific yield.

    Replaced "primary storage" with "storativity" and "secondary storage" with "specific yield" in the one place the terms occur. It would be incorrect to use the term specific storage here.

68. Page 9-6, paragraph 1: Cite Table 9.2.5 at the end of the sentence "The major avenues…".

Completed.

69. Figure 9.2.20: Please change “Recharge” to “Recharge from Precipitation”. This figure is a bit counterintuitive, recommend only using positive values.

    Completed. “Recharge” changed to “Recharge from Precipitation”. Clarification added to caption that positive values denote recharge and negative values denote discharge.

SECTION 10: LIMITATIONS OF THE MODEL

70. Page 10-5, paragraph 4: Please delete the last sentence in this paragraph.

    Completed.

SECTION 11: FUTURE IMPROVEMENTS

71. Page 11.1, paragraph 3: Please change “improve<u>d</u>” to “improve” in the third sentence.

    Completed.

72. Page 11-3, paragraph 3: Please change “…a simulator with…” to “…use of a simulator with…”.

    Completed.

73. Page 11-3, paragraph 5: Please change “…should be considered.” to “…could be considered”.

    Completed.

SECTION 12: CONCLUSIONS

74. Page 12-1, paragraph 4: Please change “…steady-state aquifer heads…” to “…predevelopment water levels…”.

    Completed.

75. Page 12-2, paragraph 3: Please move this paragraph to follow paragraph 3 on page 12-1.

    Completed.

SECTION 13: ACKNOWLEDGEMENTS

76. Page 13-1, paragraph 1: Please change “…participants in the Dockum groundwater availability…” to “…participants in the Dockum Aquifer groundwater availability…”. Change “…Forum meetings…” to “…Forums…” where it occurs in the paragraph. Change “…July 2007.” to “…June 2007.”.

Completed.

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