Final Conceptual Model Report for the High Plains Aquifer System Groundwater Availability Model

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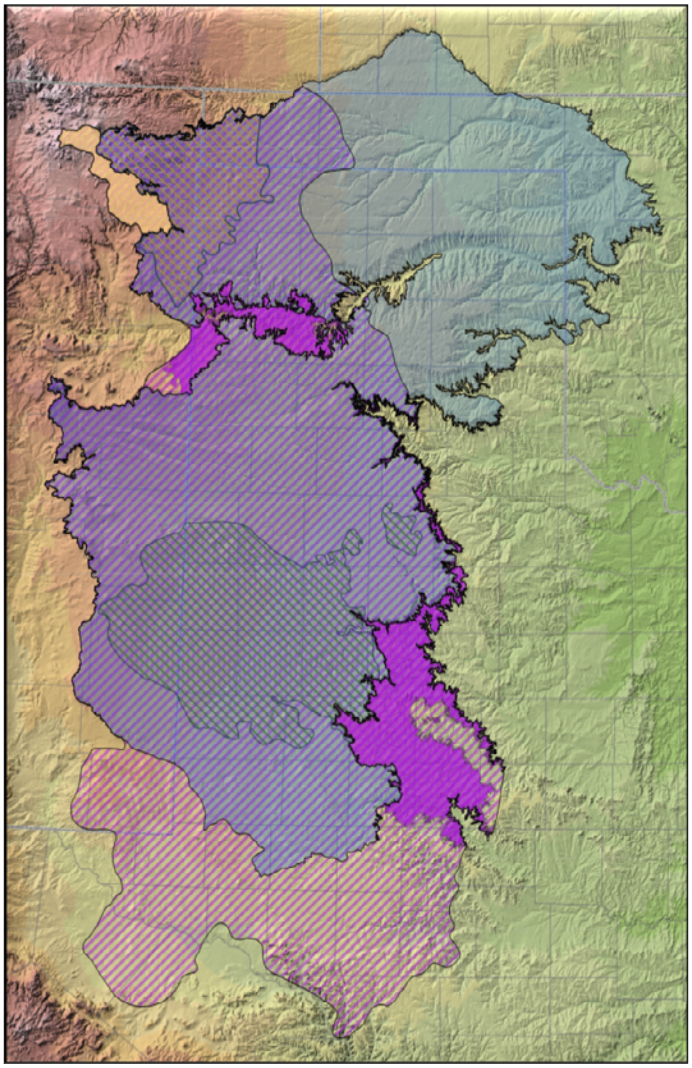

Prepared for:

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August 2015

Texas Water Development Board

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Geoscientist and Engineer Seals

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

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

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Executive Summary

This report documents the development of a conceptual model for the High Plains Aquifer System. The High Plains Aquifer System in Texas consists of the southern and northern portions of the major Ogallala Aquifer and the minor Rita Blanca, Edwards-Trinity (High Plains), and Dockum aquifers. The physiography and climate, geology, previous studies, hydrostratigraphy, hydrostratigraphic framework, water levels, recharge, surface water interaction, hydraulic properties, discharge, and water quality for the High Plains Aquifer System are documented in this report. For many of these aspects of the conceptual model, new work was completed to update or add to previous studies. This conceptual model provides the foundation for developing the numerical groundwater availability model for the High Plains Aquifer System, which is documented in a separate report.

The Tertiary Ogallala Aquifer forms the upper layer of the High Plains Aquifer System and is composed primarily of unconsolidated sand, gravel, and clay. This uppermost layer is entirely unconfined and overlies various other layers depending on location. The Ogallala Aquifer in Texas is separated into northern and southern parts by the Canadian River valley. In the northwest part of the High Plains Aquifer System, the Jurassic Rita Blanca Aquifer is exposed at the surface locally in northeast New Mexico and underlies the Ogallala Aquifer elsewhere. The Rita Blanca Aquifer is composed of complexly interbedded sandstones and shales and is in hydraulic communication with the overlying Ogallala Aquifer. The Cretaceous Edwards-Trinity (High Plains) Aquifer underlies the Ogallala Aquifer in the central portion of the High Plains Aquifer System and is generally composed of sandstone overlain by limestone overlain by clay/shale. However, there are some portions of the aquifer where either the limestone layer is absent (northwestern portion of the aquifer) or the clay/shale layer is absent (southern and far eastern portion of the aquifer). Where the shale layer is present, it generally serves as a confining unit for the lower layers of the aquifer. The hydrostratigraphy of the Dockum Group is quite complex, and a common approach divides it into upper and lower units. The upper Dockum Aquifer is entirely confined except for small surface exposures along the western margin of the High Plains Aquifer System. The lower Dockum Aquifer is mostly confined except for surface exposures in the Canadian River Valley and in the southeast. Both Dockum

Group layers are composed of complexly interbedded sandstone and shale, although in general, both are sandier in their lower parts.

Target water levels and hydrographs have been identified in each aquifer of the High Plains Aquifer System to be used in the calibration of the numerical model. In the Ogallala Aquifer, post-development irrigation pumping has significantly lowered the Ogallala Aquifer water table and locally affected groundwater flow direction. Pumping is now the largest discharge mechanism in the Ogallala Aquifer. Most of the pumping discharge is offset by a decrease in aquifer storage. The largest amount of pumping and corresponding drawdown occur where the initial saturated thickness was largest. Some of the pumping discharge is offset by capture, with decreased discharge to springs, streams, and other surface discharge features. Many springs have either experienced reduced flow or dried up completely. Streams and draws that were originally fed by springs or aquifer discharge also have reduced or no flow. Similar to the Ogallala Aquifer, the Rita Blanca Aquifer generally shows a decline in water levels due to increased pumping discharge, which is balanced by reduced groundwater storage and less cross-formational flow. The decline in the Edwards-Trinity (High Plains) Aquifer water levels is not as pronounced or as uniformly distributed as in the Ogallala or Rita Blanca aquifers. The increased discharge from pumping is balanced by less cross-formational flow and reduced groundwater storage.

The upper Dockum Aquifer does not show a change from pre-development conditions north of the Canadian River. Little development has occurred in the upper Dockum Aquifer due to its generally low productivity. In the southern portion of the aquifer, minor water-level declines are observed across the entire aquifer with higher declines concentrated in northeastern Deaf Smith County and south-central Swisher County. The lower Dockum Aquifer has shown a more consistently distributed decline in water level than in the upper Dockum Aquifer. The highest declines are seen in northwestern Pecos County and along the border of Curry and Roosevelt counties, New Mexico. In a few local areas, particularly in the Colorado River outcrop area, increased recharge due to irrigation return flow appears to offset this increased discharge through pumping. Elsewhere, discharge through pumping is offset by reduced natural discharge to springs and streams in outcrop areas and cross-formational flow.

Pre-development recharge to the northern portion of the Ogallala Aquifer was estimated based on chloride mass balance analyses and ranged from 0.2 to 0.6 inches per year. Pre-development recharge to the southern portion of the Ogallala Aquifer was distributed according to playa density and ranged from 0.007 to 0.2 inches per year. Pre-development recharge to the Dockum Aquifer was based on previous studies and averaged 0.15 inches per year.

Post-development recharge to the northern portion of the Ogallala Aquifer was assumed to be unchanged from pre-development recharge due to widespread low-permeability soils located under cultivated land. Post-development recharge to the southern portion of the Ogallala Aquifer was adjusted to reflect increased recharge under rainfed and irrigated cropland and ranged from 0.007 to 3 inches per year. Post-development recharge to the Dockum Aquifer was based on previous studies and averaged 0.19 inches per year. This estimate also took into account increased recharge under cultivated cropland.

The interactions between the aquifers of the High Plains Aquifer System and surface water bodies, including rivers, streams, reservoirs and saline lakes, have been evaluated. Existing gain/loss studies have been evaluated to describe the gains and losses between rivers, streams and the groundwater system at snap-shots in time. Particular attention was devoted to the decline in springflow and spring-fed streams in the study area over the period of increased groundwater development.

Initial distributions of hydraulic properties were developed for all aquifers in the High Plains Aquifer System. Horizontal hydraulic conductivity distributions were created using distributions from previous studies and, in the case of the Ogallala and Dockum aquifers, also incorporated recent aquifer pumping test data. Initial horizontal hydraulic conductivity values ranged from 1 to 527 feet per day in the Ogallala Aquifer, 0.1 to 11 feet per day in the Edwards-Trinity (High Plains) Aquifer, 0.01 to 6 feet per day in the upper Dockum Aquifer, and 0.09 to 22 feet per day in the lower Dockum Aquifer.

Groundwater production from the aquifers of the High Plains Aquifer System is used primarily for irrigation purposes, with smaller quantities used for rural domestic, livestock, municipal, mining, manufacturing and power purposes. Pumping estimates were based on the TWDB water use survey data, metered and voluntary production rates reported by groundwater conservation districts, and historical reports. The trends in the minor aquifers of the High Plains Aquifer

System suggest an increased use as availability in the Ogallala Aquifer declines. One of the goals of the High Plains Aquifer System groundwater availability model is to create a tool that can simulate the interaction between these aquifers as demands change through time.

Water quality in the High Plains Aquifer System varies widely between different aquifers. All aquifers were evaluated with respect to total dissolved solids, sulfate, chloride, fluoride, nitrate, arsenic, irrigation salinity hazard, and sodium hazard. North of the Canadian River, the Ogallala Aquifer typically produces fresh water with total dissolved solids concentrations lower than 400 milligrams per liter. However, the Ogallala Aquifer becomes slightly saline in much of the southern portion and can produce water with total dissolved solids concentrations greater than 1,000 milligrams per liter. According to the current analysis, the average total dissolved solids concentration of all Ogallala Aquifer wells was 701 milligrams per liter. The Rita Blanca Aquifer wells produced mostly fresh water with an average total dissolved solids concentration of 307 milligrams per liter. The Edwards-Trinity (High Plains) Aquifer wells were generally slightly saline with an average total dissolved solids concentration of 2,076 milligrams per liter. Groundwater in the Dockum Group is fresh in parts of the outcrop areas but can range from slightly saline to very saline in subcrop areas. The Dockum Aquifer is defined as the portion of the Dockum Group containing groundwater with a total dissolved solids concentration less than 5,000 milligrams per liter. The average total dissolved solids concentration in upper Dockum Aquifer wells was 879 milligrams per liter and was 2,508 milligrams per liter in lower Dockum Aquifer wells.

The purpose of this report is to provide a conceptual understanding, based on available data, of the hydrogeologic processes and properties governing groundwater flow in the High Plains Aquifer System. This conceptual model is prerequisite to constructing a numerical groundwater availability model for the aquifer. This report and associated geodatabase provides a documented, publicly-available, resource for use by state planners, regional water planning groups, groundwater conservation districts, groundwater management areas, and other interested stakeholders.

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. A general discussion of the major and minor aquifers is given in George and others (2011). 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.

The High Plains Aquifer System in Texas consists of the southern and northern portions of the major Ogallala Aquifer and the minor Rita Blanca, Edwards-Trinity (High Plains), and Dockum aquifers. In the south, the Dockum Aquifer is overlain by portions of the major Pecos Valley and Edwards-Trinity (Plateau) aquifers. The Pecos Valley and Edwards Trinity (Plateau) aquifers will not be explicitly modeled as part of the High Plains Aquifer System.

This report documents the development of a conceptual model for the High Plains Aquifer System groundwater availability model. The results of this analysis provide the foundation for developing the numerical groundwater availability model for the High Plains Aquifer System. The current report includes eight chapters containing the information used to develop the conceptual model of the High Plains Aquifer System, as well as an appendix addressing reviewer comments on the draft conceptual model report. Discussion of the development and calibration of the numerical model for the High Plains Aquifer System groundwater availability model is not included in this report but, rather, documented in a separate numerical model report (Deeds and Jigmond, 2015). The second numerical model report includes nine chapters and two appendices containing information on the development and calibration of the numerical model, as well as an appendix addressing reviewer comments on the draft numerical model report.

The combined Ogallala and Rita Blanca aquifers comprised approximately 48 percent of the available groundwater in the state in 2010 (TWDB, 2012a). The State Water Plan (TWDB, 2012a) projects that annual groundwater availability in the Ogallala and Rita Blanca aquifers will decrease by 46 percent from 2010 to 2060 (from 6,379,999 to 3,459,076 acre-feet per year), while availability in the Dockum Group will decrease 34 percent (from 382,188 to 252,570 acre-feet per year), and availability in the Edward-Trinity (High Plains) Aquifer will decrease

50 percent (from 4,160 to 2,065 acre-feet per year). The trends in the minor aquifers of the High Plains Aquifer System suggest an increased use as availability in the Ogallala Aquifer declines. One of the goals of the High Plains Aquifer System groundwater availability model is to create a tool that can simulate the interaction between these aquifers as demands change through time.

In the discussion below, salinity is noted using the United States Geological Survey (2012) terminology, which defines “fresh” as having a total dissolved solids concentration less than 1,000 milligrams per liter, “slightly saline” as 1,000 to 3,000 milligrams per liter, “moderately saline” as 3,000 to 10,000 milligrams per liter, and “very saline” as greater than 10,000 milligrams per liter. The Ogallala Aquifer (see Figure 1.0.1) is a highly productive, unconfined aquifer and, in the northern portion located north of the Canadian River, typically produces freshwater with total dissolved solids concentrations lower than 400 milligrams per liter. However, the Ogallala Aquifer becomes slightly saline in much of the southern portion and can produce water with total dissolved solids concentrations greater than 1,000 milligrams per liter (George and others, 2011). Production in the aquifer is greatest in paleovalleys, where transmissivity and predevelopment saturated thickness are greatest, but widespread production exists outside of these areas as well (Ashworth and Hopkins, 1995).

The Jurassic-age Rita Blanca Aquifer (see Figure 1.0.2) underlies the Ogallala Aquifer in the northwest corner of the Texas Panhandle, and produces moderate amounts of mostly freshwater (George and others, 2011). According to the well analysis conducted during the current study, wells producing from the Rita Blanca Aquifer are typically also completed in the overlying Ogallala Aquifer (see Section 4.3.1). In the central portion of the study area, the Ogallala Aquifer overlies the Cretaceous-age Edwards-Trinity (High Plains) Aquifer (see Figure 1.0.2), which generally yields slightly saline water with typical total dissolved solids concentrations between 1,000 and 2,000 milligrams per liter (George and others, 2011). Similar to the Rita Blanca Aquifer, wells producing from the Edwards-Trinity (High Plains) Aquifer are also often completed in the overlying Ogallala Aquifer (see Section 4.3.1). Groundwater in the Dockum Group is fresh in parts of the outcrop areas but can range from slightly saline to very saline in subcrop areas. The Dockum Aquifer (see Figure 1.0.2) is defined as the portion of the Dockum Group containing groundwater with a total dissolved solids concentration less than 5,000 milligrams per liter (Ashworth and Hopkins, 1995).

The High Plains Aquifer System numerical groundwater availability model will consist of an upper layer representing the Ogallala Aquifer, a second layer representing the Rita Blanca and Edwards-Trinity (High Plains) aquifers, where present, and third and fourth layers representing the upper and lower Dockum Group. While not explicitly modeled as part of the groundwater availability model, the Pecos Valley Aquifer will be represented by the uppermost layer and the Edwards Trinity (Plateau) Aquifer will be represented by the second layer, where present.

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 (Texas Water Code § 16.051). 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 an availability-based approach.

Groundwater models provide a tool to estimate the effects of various water use strategies and help 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 for performing complex analyses and making informed predictions and related decisions (Anderson and Woessner, 1992).

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 groundwater availability models also serve as an integral part of the process of determining modeled available groundwater based on desired future conditions, as required by House Bill 1763. The High Plains Aquifer System groundwater availability model will thus serve as a critical tool for groundwater planning in the state.

The High Plains Aquifer System groundwater availability model will be developed using a modeling protocol that is standard to the groundwater modeling industry (ASTM International, 2010). 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 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, which in this case is 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 (for example, water levels in wells) can be reproduced. The model will be calibrated to pre-development conditions representing, as closely as possible, conditions in the aquifer prior to significant development and to transient aquifer conditions from 1930 to 2012. Calibration will focus more on the later decades when more data are available. Sensitivity analyses will be performed on both the pre-development and transient models to offer insight on the uniqueness of the model and the impact of uncertainty in model parameter estimates.

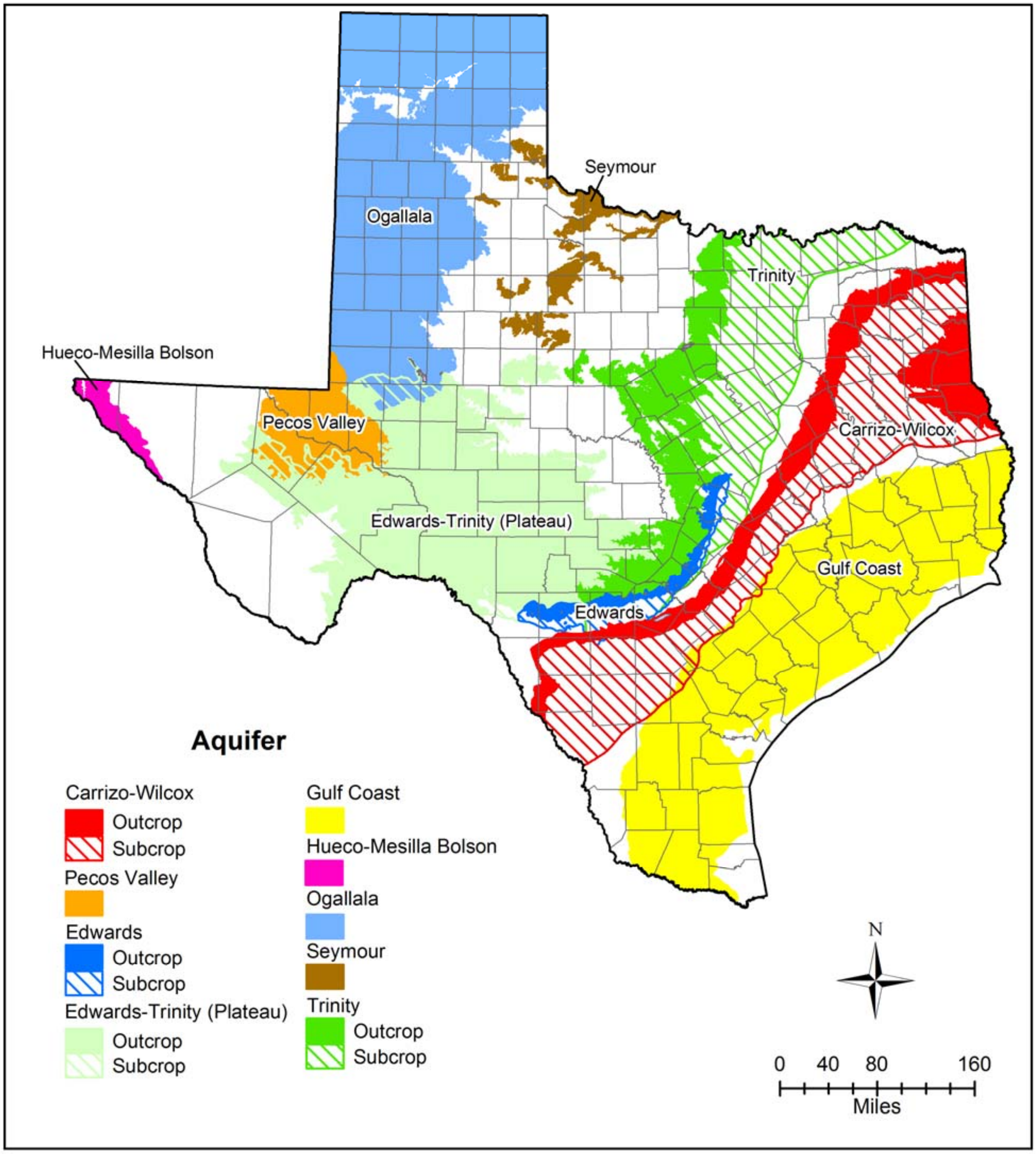


Figure 1.0.1 Locations of major aquifers in Texas (TWDB, 2006a).

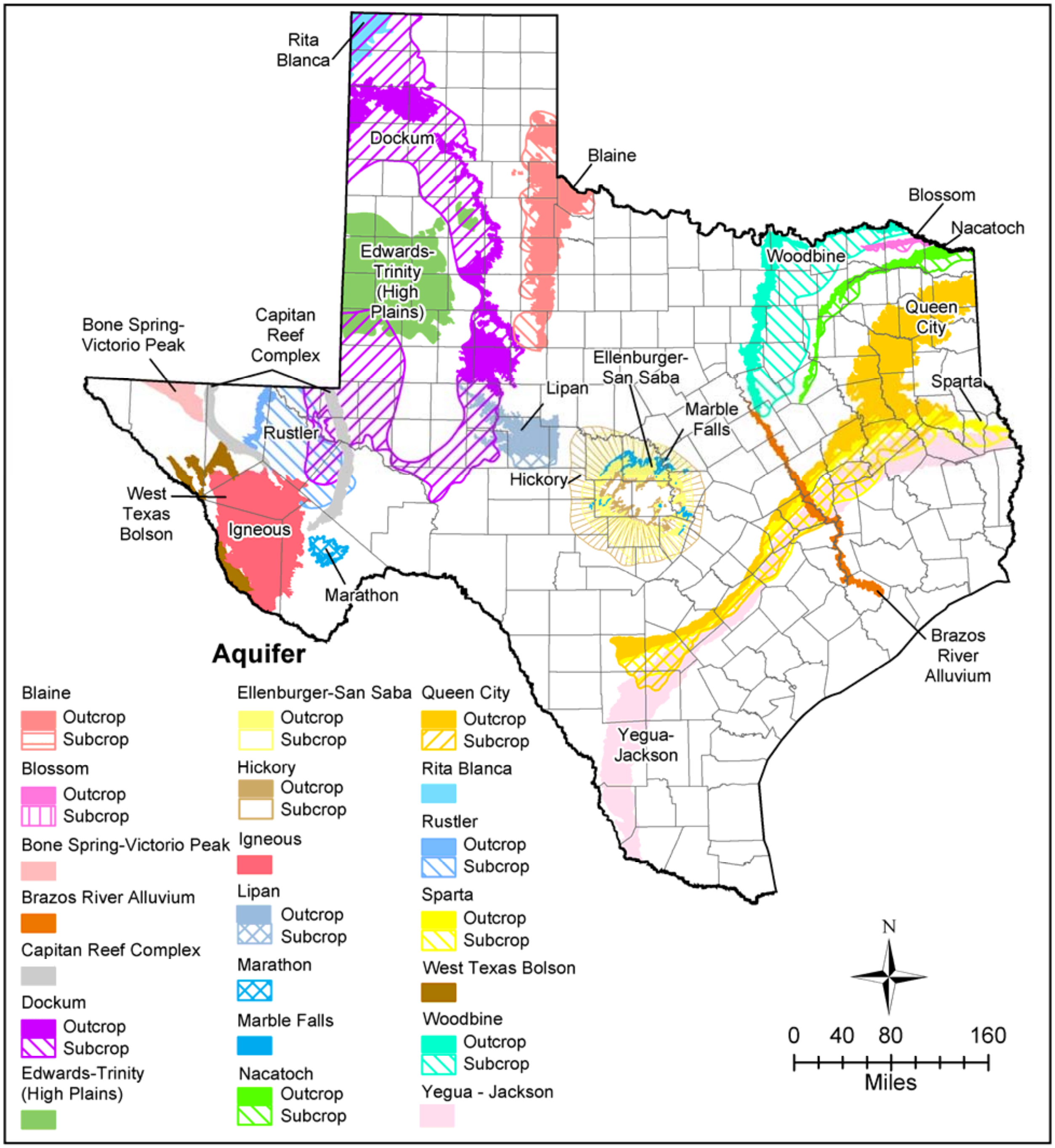


Figure 1.0.2 Locations of minor aquifers in Texas (TWDB, 2006b).

2.0 Study Area

The study area incorporates all of the aquifers that comprise the High Plains Aquifer System including the Ogallala, Edwards-Trinity (High Plains), Rita Blanca, and Dockum aquifers. Also included in the study area are the Pecos Valley Aquifer and a portion of the Edwards-Trinity (Plateau) Aquifer. The location of the active model area is shown in Figure 2.0.1 and the boundaries of the relevant aquifers are given in Figure 2.0.2.

The Tertiary-age Ogallala Aquifer is the largest aquifer in the United States and the most important water source in the study area (George and others, 2011). It is also referred to as part of the “High Plains Aquifer” in United States Geological Survey reports (for example, McGuire, 2014). Its non-renewable freshwater supply has been depleted by the demands of irrigation and much of the aquifer has experienced significant water-level decline since the 1940s (Ashworth and Hopkins, 1995). In the northwest portion of the study area, the Ogallala Aquifer overlies the Jurassic-age Rita Blanca Aquifer (see Figure 2.0.2). This small, but mostly fresh, minor aquifer serves as an irrigation and drinking water source for a few northwest Texas communities (George and others, 2011). In the central portion of the study area, the Ogallala Aquifer overlies the Cretaceous-age Edwards-Trinity (High Plains) Aquifer (see Figure 2.0.2), a slightly saline minor aquifer that serves mainly as an irrigation water source (George and others, 2011).

The majority of the study area is underlain by the Triassic-age Dockum Aquifer (see Figure 2.0.2), which is sometimes locally referred to as the “Santa Rosa Aquifer” (George and others, 2011). This aquifer, while extensive spatially, is considered only a minor aquifer due to its generally poor water quality. The Dockum Group only produces freshwater in outcrop areas (located at the northwestern and southeastern ends of the current study area), with salinity increasing downdip to over 20,000 milligrams per liter. The Dockum Aquifer is, therefore, officially defined by the TWDB as the portion of the Dockum Group containing groundwater with a total dissolved solids concentration less than 5,000 milligrams per liter (Ashworth and Hopkins, 1995). While this threshold excludes most of the central portion of the Dockum Group from the official aquifer boundary due to high total dissolved solids concentrations, this portion of the Dockum Group is included in the current model for hydraulic reasons. However, the numerical model will not simulate transport or variable density flow for this section. It should be noted that the higher salinity section of the Dockum Group is not completely uninteresting for water planners. Increasing water demand and the dwindling of other water sources (for example, the Ogallala Aquifer) have enhanced interest and research in brackish water development, which focuses on water sources with total dissolved solids concentrations greater than 1,000 milligrams per liter to less than 10,000 milligrams per liter (LBG-Guyton Associates, 2003).

In the southern portion of the study area, where the Ogallala Aquifer does not exist (see Figure 2.0.2), other aquifers serve as the major water sources for irrigation, municipal supply, and industrial use. In the southwestern portion, this role is filled by the Quaternary-age Pecos Valley Aquifer and in the southeast, by the outcropping Cretaceous-age Edwards-Trinity (Plateau) Aquifer (George and others, 2011).

Groundwater model boundaries are typically defined on the basis of surface or groundwater hydrologic boundaries. Because this model aims to provide a comprehensive view of the High Plains Aquifer System, the active model boundary was constructed by considering all of the boundaries of the aquifers in the High Plains Aquifer System. The northern boundary of the current model area is consistent with the boundaries of the northern Ogallala Aquifer groundwater availability models (Dutton and others, 2000, 2001a, 2001b; Dutton, 2004; INTERA and Dutton, 2010) with the exception of the northwestern area where the boundary was extended to include the extent of the Dockum Aquifer as defined by Ewing and others (2008). The northernmost extent of the model area is the Cimarron River (Figure 2.0.3). In the southern portion of the model area, boundaries were selected consistent with the boundary of the Dockum Aquifer groundwater availability model (Ewing and others, 2008) and the Pecos Valley Aquifer as defined by the TWDB. A slight modification to the boundary from that of the Dockum Aquifer was made in Nolan County where the Edwards-Trinity (Plateau) Aquifer overlaps the Dockum Group as indicated by HDR Engineering, Inc. (2009).

The locations of rivers, streams, lakes, and reservoirs in or near the study area are shown in Figure 2.0.3. Figure 2.0.4 shows the roadways, cities, and towns in and near the study area. All or part of 68 Texas counties, 11 New Mexico counties, nine Oklahoma counties, six Kansas counties and one Colorado county are included in the study area. The largest urban areas within the model boundary are the Midland-Odessa area, Lubbock, and Amarillo, all in Texas.

Figures 2.0.5 and 2.0.6 show the surface outcrop and subcrop of the major and minor aquifers, respectively, that intersect the study area. As discussed above, the major aquifers incorporated in the High Plains Aquifer System model are the Ogallala, Pecos Valley, and portions of the Edwards-Trinity (Plateau) aquifers and the minor aquifers are the Dockum, Edwards-Trinity (High Plains), and Rita Blanca aquifers. In addition to these, there are several additional minor aquifers in the study area that are not included in the High Plains Aquifer System model because they are expected to have little to no impact on the groundwater flow of the High Plains Aquifer System . The Lipan Aquifer is a very small alluvial aquifer and the Capitan Reef Complex and Rustler aquifers are much older than the aquifers of the High Plains Aquifer System and fall below the no-flow bottom boundary of the model.

Since water resources are largely governed by state, not federal, laws, different portions of the study area fall under different jurisdictions depending on the state in which they are located. Of the five states in the study area, Texas groundwater has the most complex administrative infrastructure for governing water and, therefore, this discussion of the administrative boundaries focuses on Texas distinctions and includes the equivalent entities from the other states, where applicable. In Texas, Regional Water Planning Groups are the divisions used to formulate the TWDB's State Water Plan, which is updated every 5 years and focuses on both surface and groundwater resources. The study area encompasses most of three Regional Water Planning Groups (Figure 2.0.7). They are the (1) Panhandle Regional Water Planning Group (Region A), (2) Llano Estacado Regional Water Planning Group (Region O), and (3) Region F Regional Water Planning Group (Region F). Small portions of the Region B, Brazos G (Region G), and Far West Texas (Region E) Regional Water Planning Groups located in or near the study area are also included. In New Mexico, the Office of the State Engineer State Water Plan is based on Water Planning Regions, similar to the Texas Regional Water Planning Group concept (New Mexico Office of the State Engineer, 2003). Most of the Northeast New Mexico and Lea County Water Planning Regions are represented in the study area, along with small portions of the Colfax, Mora/San Miguel/Guadalupe, and Lower Pecos Valley regions. The Oklahoma Comprehensive Water Plan by the Oklahoma Water Resources Board is based on divisions called Watershed Planning Regions (Oklahoma Water Resources Board, 2011). Most of the Panhandle Watershed Planning Region falls within the study area, as well as small portions of the Central, West Central, and Southwest regions. The Statewide Water Supply Initiative of the Colorado Water Conservation Board (2011) and the Kansas Water Plan (Kansas Water Office,

2009) use river basins to define planning regions, which are not included on Figure 2.0.7 but can be seen on the river basin map discussed below.

Groundwater Management Areas in Texas are geographic areas roughly corresponding to TWDB defined aquifer flow boundaries. The Groundwater Management Areas generally contain several Groundwater Conservation Districts, political entities that can enforce some limits on groundwater use. The study area intersects portions of Texas Groundwater Management Areas 1, 2, 3 and 7 and small portions of Groundwater Management Areas 4 and 6 (Figure 2.0.8). Within these Groundwater Management Areas, the study area also includes all or part of 25 Groundwater Conservation Districts in Texas as listed in Table 2.0.1 and shown on Figure 2.0.9. In New Mexico, the Office of the State Engineer created Declared Underground Water Basins, similar in concept to the Texas Groundwater Management Areas (New Mexico Office of the State Engineer, 1995). The Canadian River, Capitan, Carlsbad, Causey Lingo, Clayton, Curry County, Fort Sumner, Jal, Lea County, Portales, Roswell, and Tucumcari Declared Underground Water Basins intersect the study area (see Figure 2.0.8). In Colorado, the Ground Water Commission (2004) established Designated Ground Water Basins, similar to Texas Groundwater Management Areas, and created Ground Water Management Districts, entities similar to Groundwater Conservation Districts that can administer groundwater use within the basins. The Colorado Southern High Plains Designated Basin intersects the study area (see Figure 2.0.8) and the Southern High Plains Management District falls within that basin, but is located outside of the study area (see Figure 2.0.9). In Kansas, Groundwater Management Districts are local government entities, similar to Texas Groundwater Conservation Districts, which can administer groundwater use (Kansas Department of Agriculture, 2010). The Southwest Kansas Groundwater Management District #3 is the only Groundwater Management District that falls within the study area (see Figure 2.0.9).

In terms of surface water management, the study area intersects four Texas river authorities and one Kansas water office basin, which are given in Table 2.0.2 and shown on Figure 2.0.10. There are six major river basins and 21 sub-basins in and near the study area (Table 2.0.3 and Figure 2.0.11). Climate is the major control on flow in rivers and streams. The primary climatic factors are precipitation and evapotranspiration. In the south, the Pecos River is the only consistently perennial river and flows northwest to southeast across the study area. In general, flow in the southern rivers is episodic with extended periods of low flow, or no flow conditions and only becomes perennial towards the eastern edge of the study area. Some of these rivers tend to lose water to the underlying formations, as discussed in Section 4.5.1. In contrast, several rivers and streams in the northern portion of the study area are perennial (for example, the Canadian River) and tend to gain flow from the underlying saturated sediments and/or underlying aquifers. Table 2.0.3 provides a listing of the rivers in the study area and their associated river basins and sub-basins.

Table 2.0.1 Texas Groundwater Conservation Districts in or near the study area (TWDB, 2010).

Clear Fork GCD	Mesa UWCD
Coke County UWCD	Mesquite GCD
Crockett County GCD	Middle Pecos GCD
Garza County UWCD	North Plains GCD
Gateway GCD	Panhandle GCD
Glasscock GCD	Permian Basin UWCD
Hemphill County UWCD	Plateau UWC and Supply District
High Plains UWCD No. 1	Sandy Land UWCD
Irion County WCD	Santa Rita UWCD
Jeff Davis County UWCD	South Plains UWCD
Lipan-Kickapoo WCD	Sterling County UWCD
Llano Estacado UWCD	Wes-Tex GCD
Lone Wolf GCD	

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

Table 2.0.2 River Authorities in the study area (TWDB, 1999; Kansas Water Office, 2010).

Texas River Authorities
Brazos River Authority
Upper Colorado River Authority
Red River Authority
Palo Duro River Authority
Kansas Water Office Basin
Cimarron Water Basin

Table 2.0.3 **River basins in and near the study area (Natural Resources Conservation Service, 2012).**

Major River Basin[1]	River	Sub-basins within study area[2]
Rio Grande	Pecos River	Upper Pecos Lower Pecos Devils
Colorado	Colorado River	Upper Colorado Middle Colorado-Concho
Brazos	Brazos River	Brazos Headwaters Middle Brazos Clear Fork
Red	Red River	Prairie Dog Town Fork North Fork Salt Fork Red-Pease Red-Lake Texoma
	Washita River	Washita
Canadian	Canadian River	Upper Canadian Middle Canadian Lower Canadian Lower North Canadian
	Beaver River	Upper Beaver Lower Beaver
Arkansas	Cimarron River	Upper Cimarron Lower Cimarron

[1] Based on TWDB (2010) delineation, except Arkansas River (Natural Resources Conservation Service, 2012)

[2] From Natural Resources Conservation Service 6 digit Watershed Boundary Dataset (Natural Resources Conservation Service, 2012)

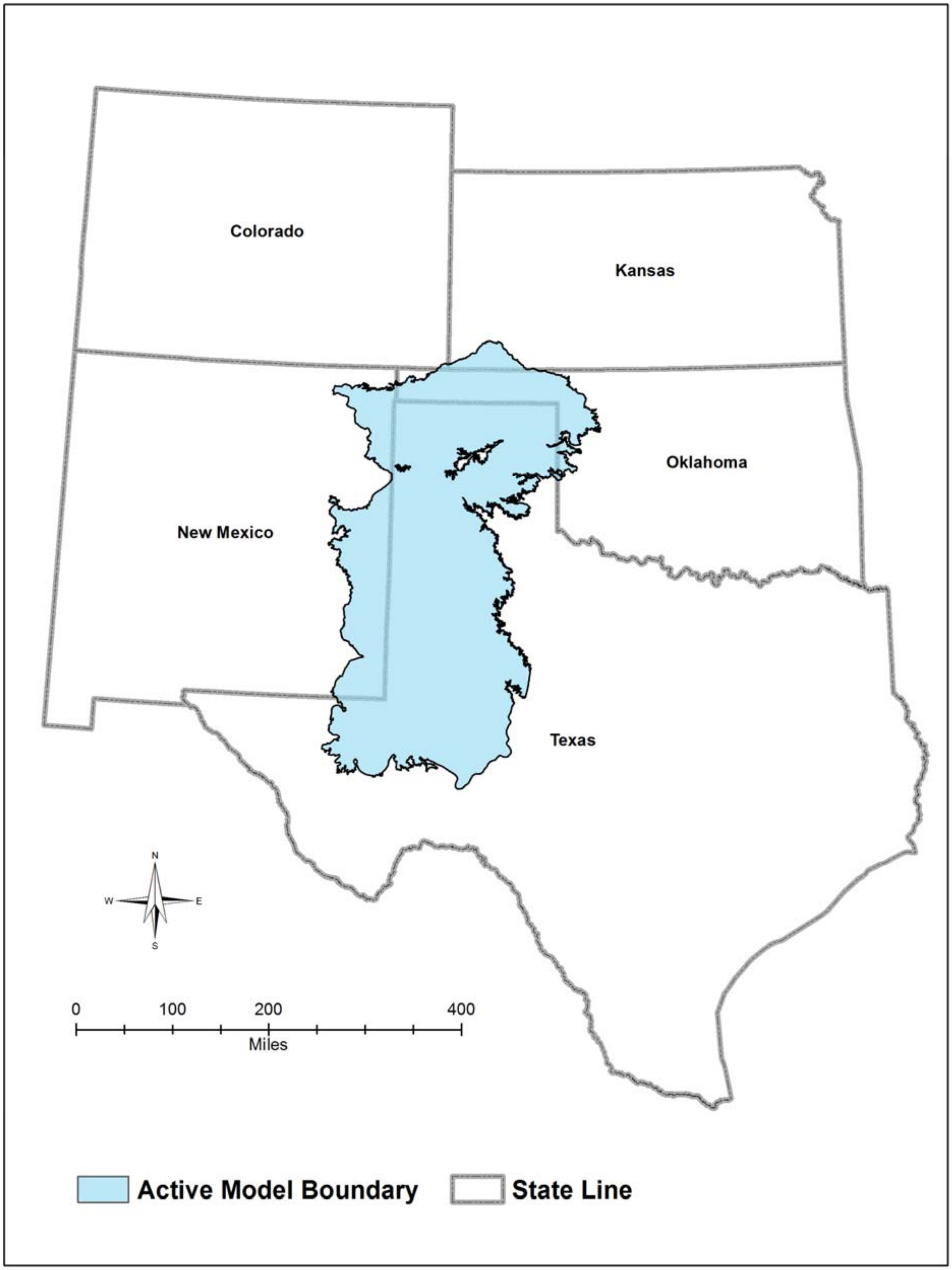


Figure 2.0.1 Study area for the High Plains Aquifer System groundwater availability model.

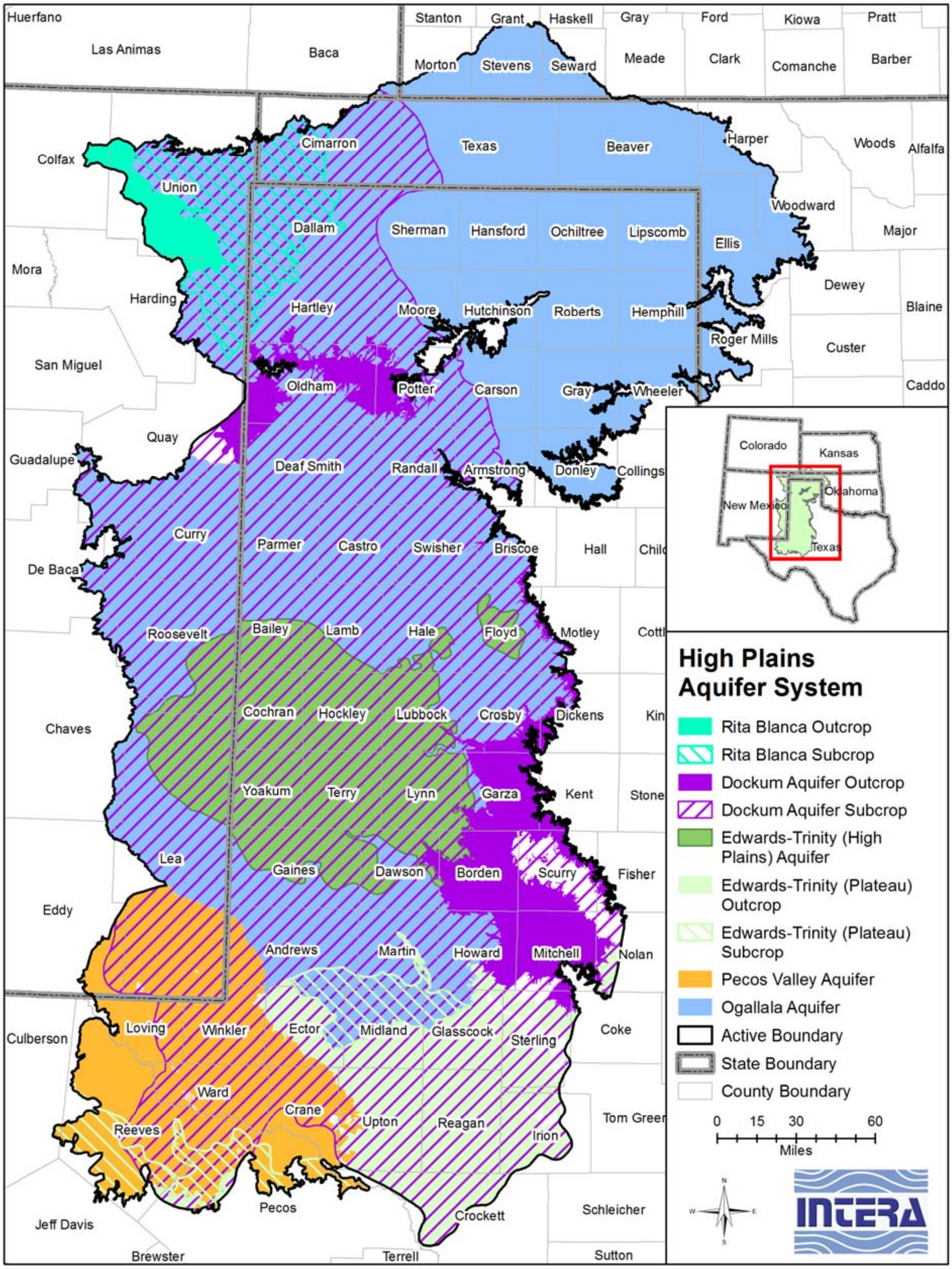


Figure 2.0.2 **Aquifers included in the High Plains Aquifer System groundwater availability model.**

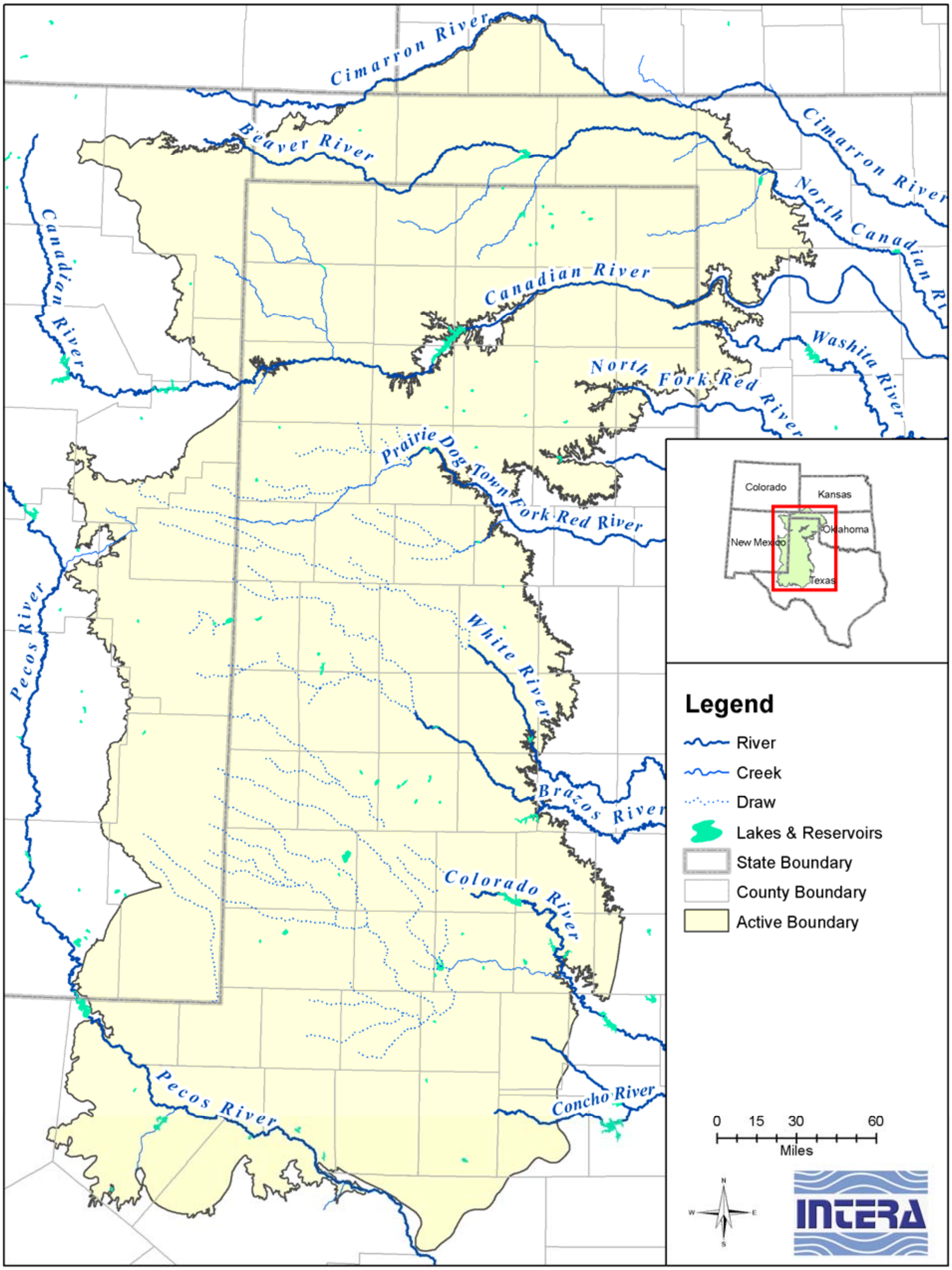


Figure 2.0.3 **Lakes and rivers in or near the study area.**

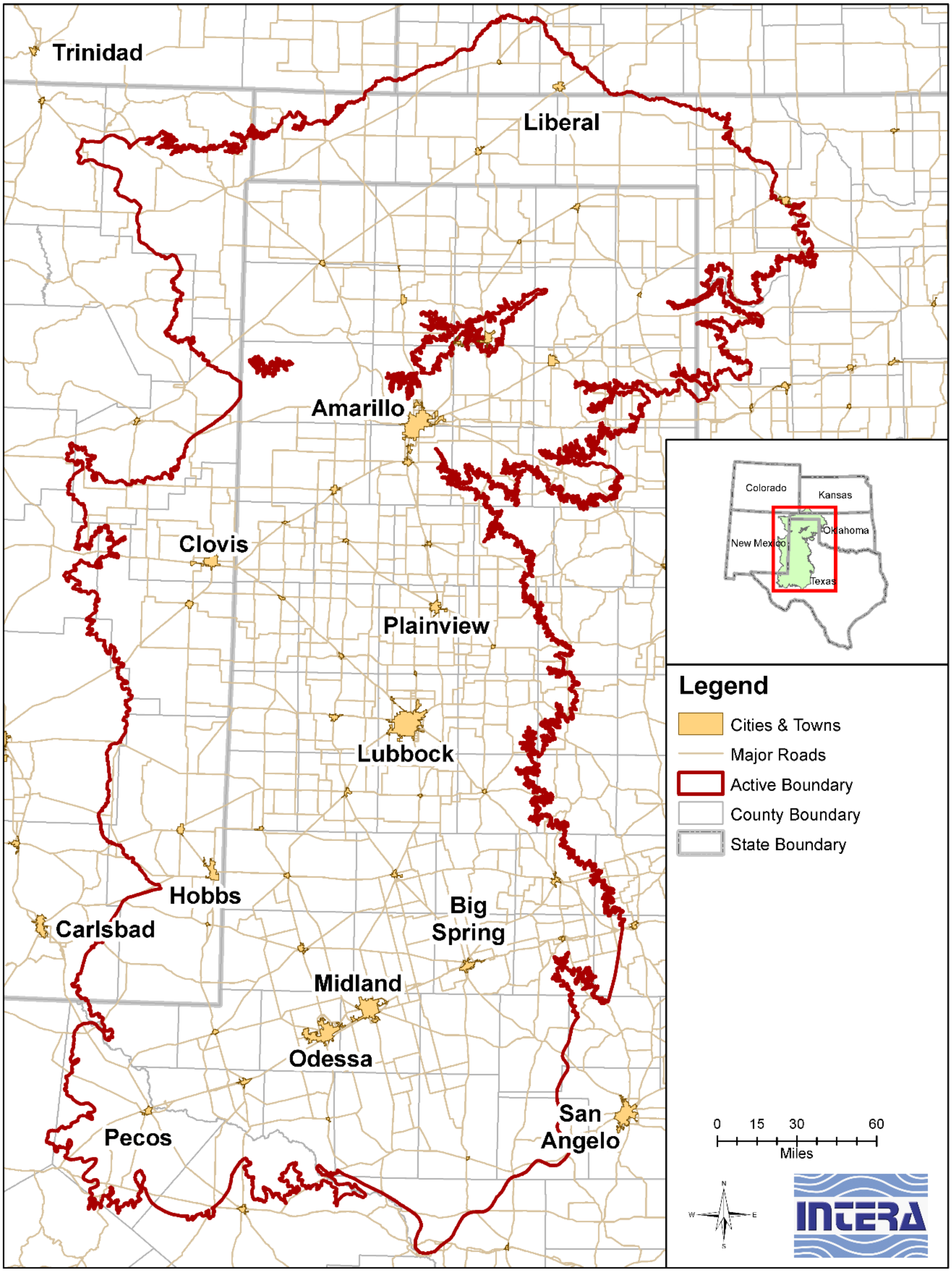


Figure 2.0.4 Cities and major roadways in or near the study area.

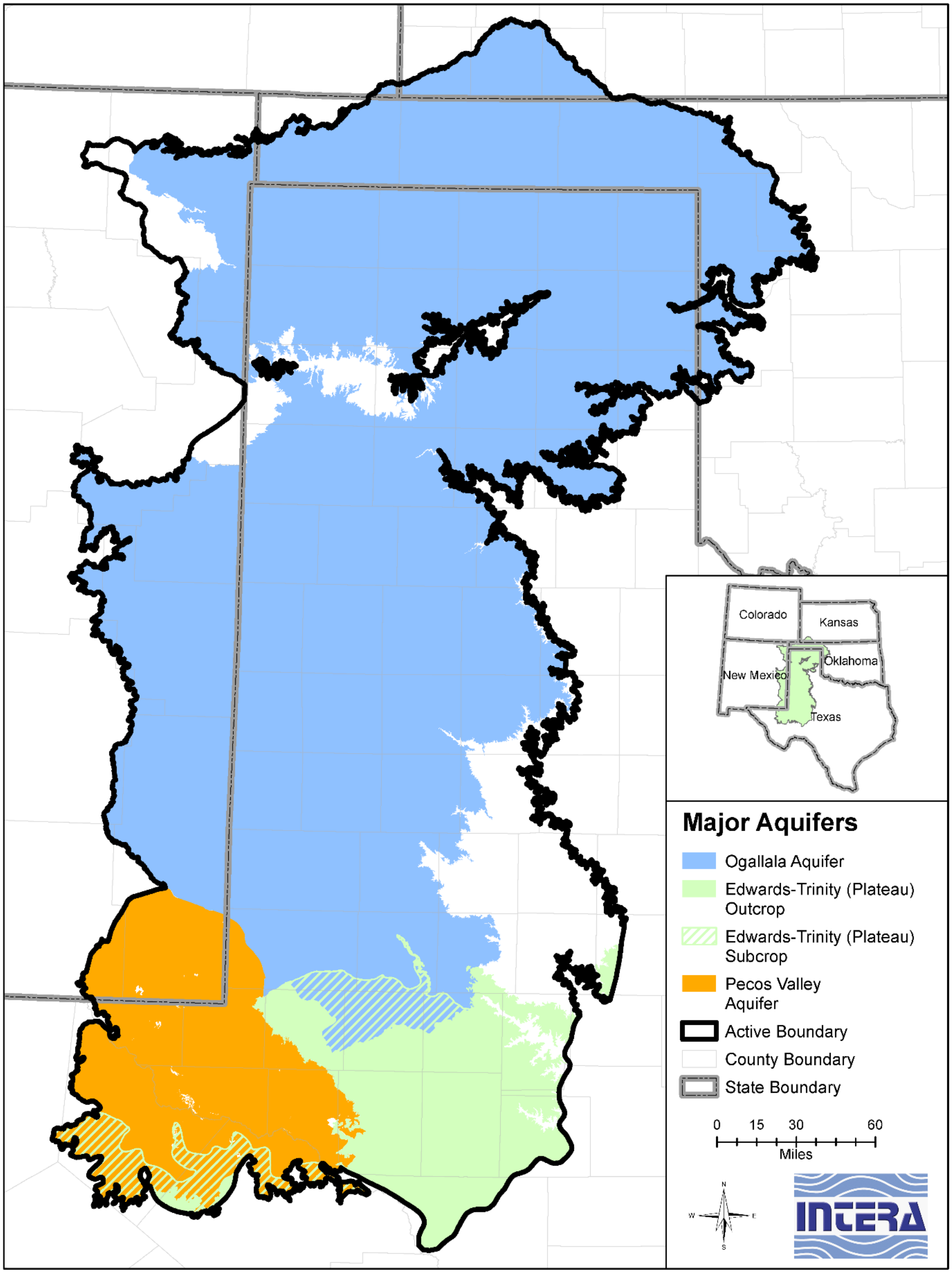


Figure 2.0.5 **Major aquifers intersecting the study area (TWDB, 2006a).**

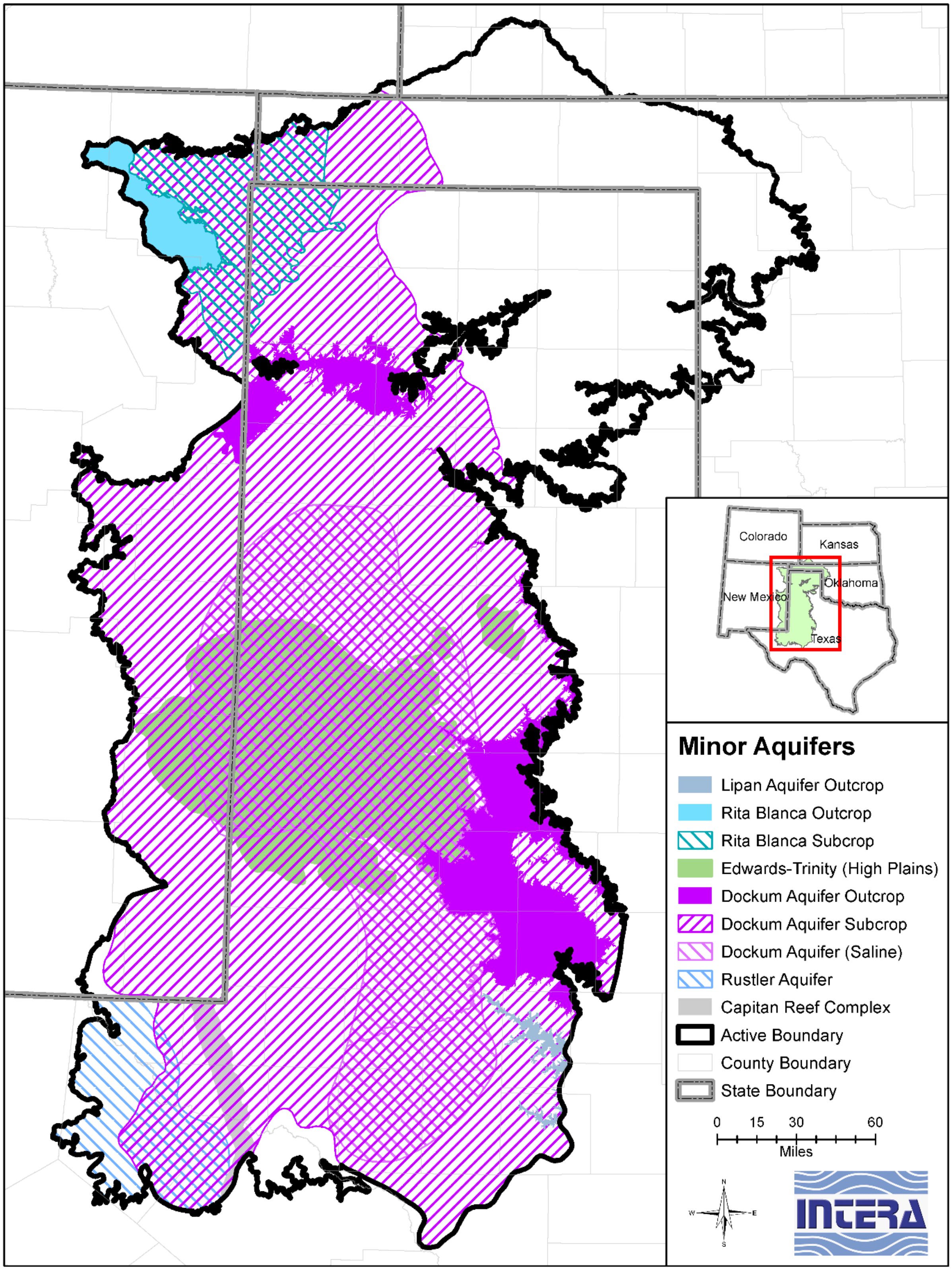


Figure 2.0.6 **Minor aquifers intersecting the study area (TWDB, 2006b).**

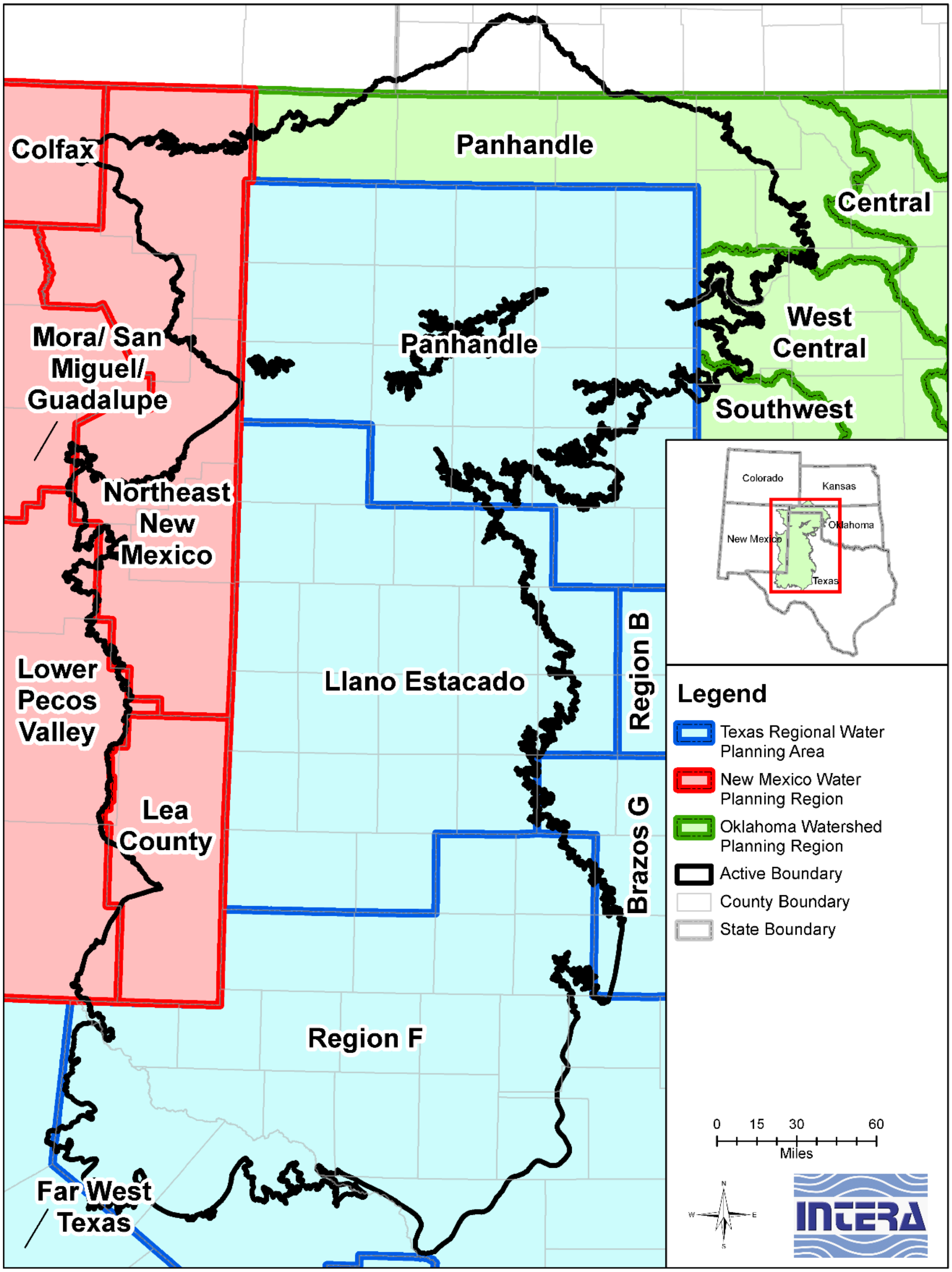


Figure 2.0.7 **Regional Water Planning Groups in the study area (TWDB, 2008; New Mexico Office of the State Engineer, 2003; Oklahoma Water Resources Board, 2011).**

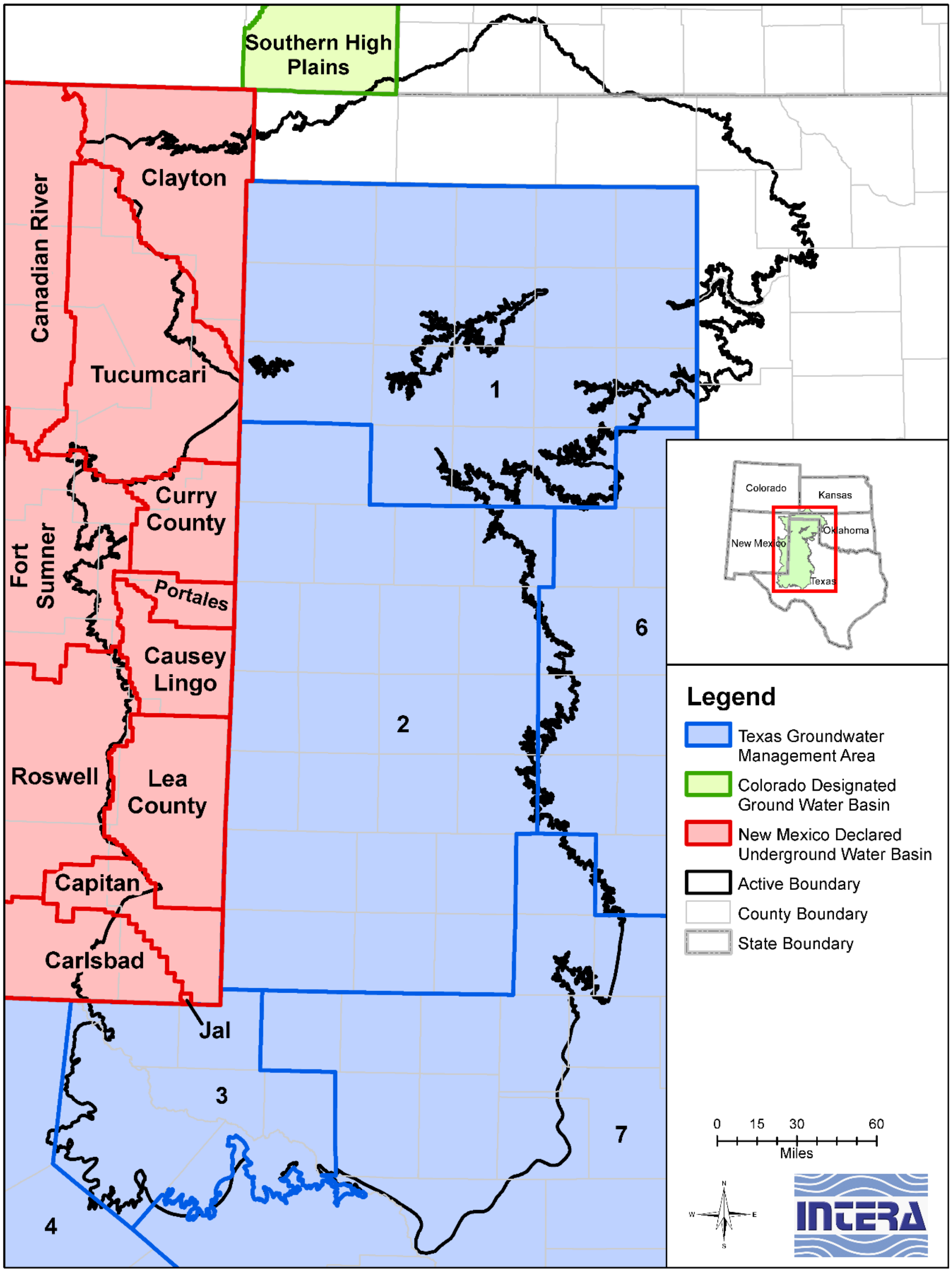


Figure 2.0.8 Groundwater Management Areas in the study area (TWDB, 2007; New Mexico Office of the State Engineer, 1995; Colorado Ground Water Commission, 2004).

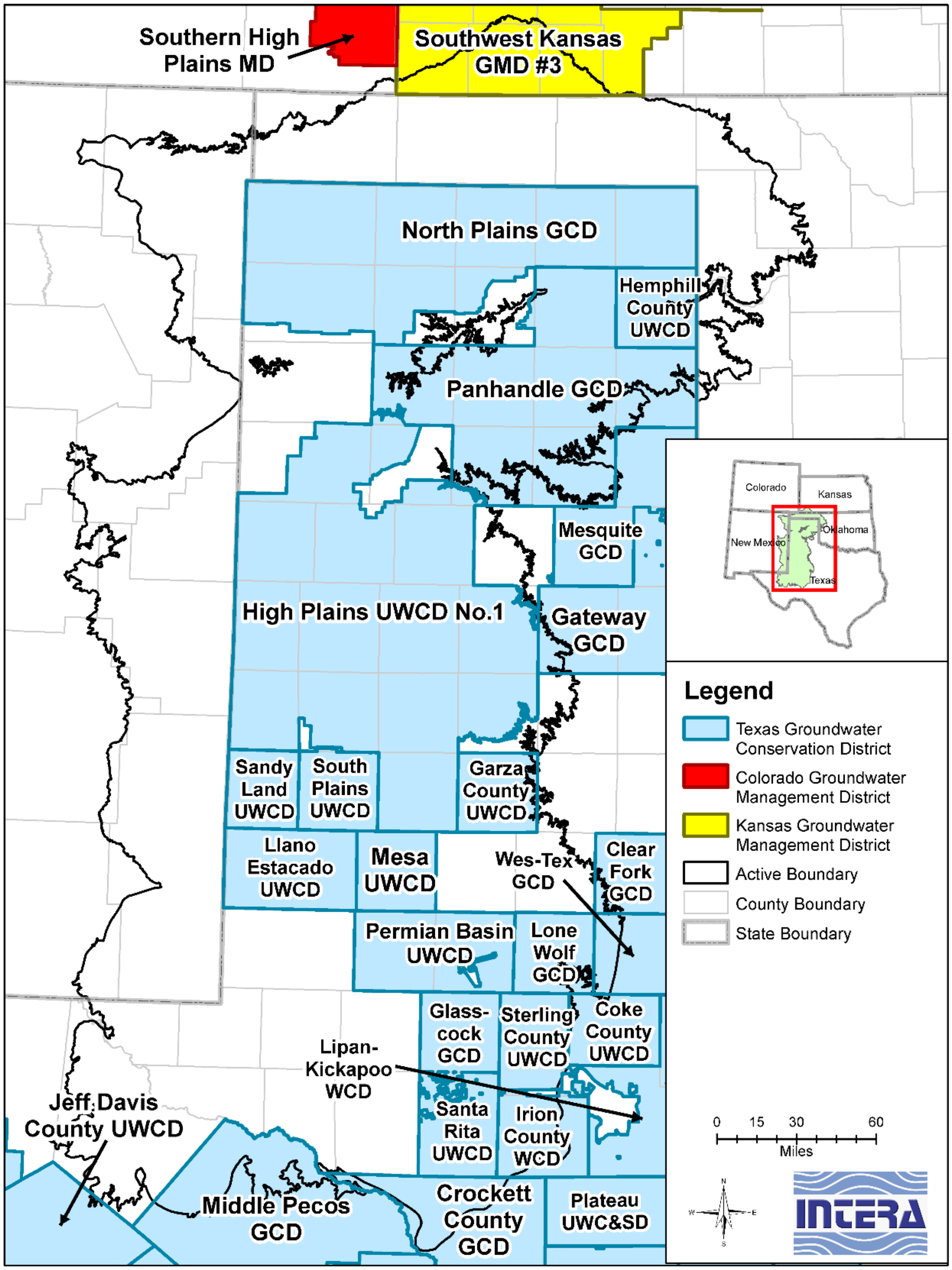


Figure 2.0.9 Groundwater Conservation Districts in or near the study area (TWDB, 2010; Colorado Ground Water Commission, 2004; Kansas Department of Agriculture, 2010). Abbreviation key: GCD = Groundwater Conservation District, UWCD = Underground Water Conservation District, UWC&SD = Underground Water Conservation & Supply District, MD = Management District, GMD = Groundwater Management District.

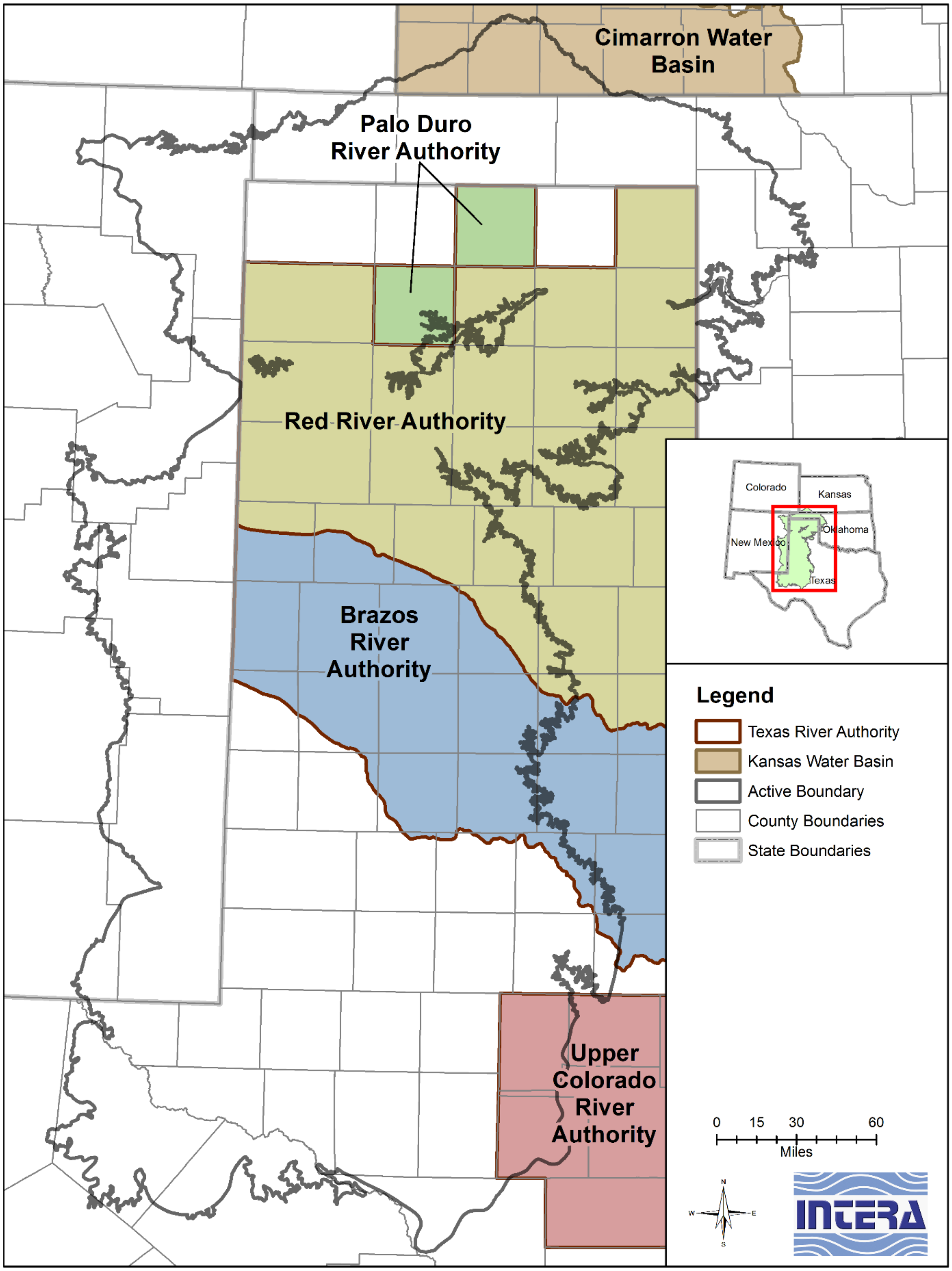


Figure 2.0.10 River Authorities in the study area (TWDB, 1999; Kansas Water Office, 2010).

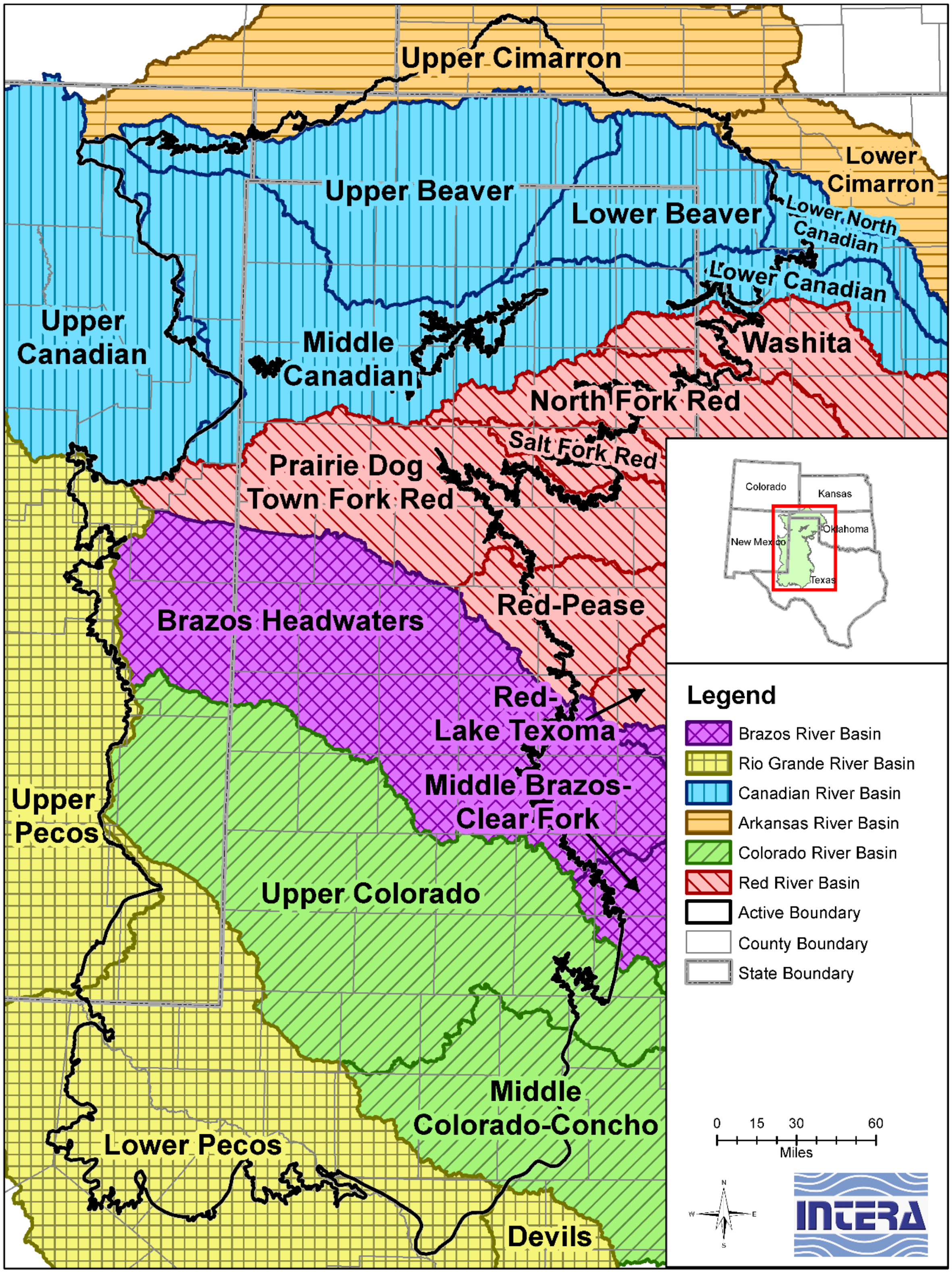


Figure 2.0.11 **Major river basins and sub-basins in the study area. (Natural Resources Conservation Service, 2012).**

2.1 Physiography and Climate

The study area for High Plains Aquifer System groundwater availability model falls within the Great Plains province of the Interior Plains physiographic region as defined by Fenneman and Johnson (1946). The majority of the study area is in the High Plains section, the remnant of a smooth alluvial plain that stretched from the Rocky Mountains to the central lowlands of Texas (Figure 2.1.1). The northwestern corner lies within the Raton section, an eroded zone characterized by volcanic features such as lava-capped plateaus and buttes. The northeastern corner is in the Plains Border section, an eroded zone marking the edge of the High Plains. The western and southwestern edges of the study area lie in the Pecos Valley section, a long trough separating the High Plains section from the western Basin and Range section. In the southeast corner, the High Plains transitions to the plain atop the Edwards Plateau section, a plateau formed by the massive south-dipping Edwards limestone. The eastern edge of the High Plains section is marked by the Osage Plains section of the Central Lowlands province and the highly eroded Central Texas section (descriptions from United States Department of Defense, 2001).

Figure 2.1.2 shows the Level III Ecological Regions in the study area as defined by the United States Environmental Protection Agency (2011). Ecological regions (also referred to as ecoregions) refer to areas exhibiting a distinct ecosystem type. The conterminous United States is divided into Level III Ecoregions based on factors such as vegetation, climate, hydrology, geology, and physiography. The majority of the study area falls within the High Plains Ecoregion, which consists predominately of cropland on smooth to slightly irregular plains. This ecoregion corresponds roughly to the High Plains physiographic section defined by Fenneman and Johnson (1946) as discussed above. The Southwestern Tablelands Ecoregion makes up a portion of the study area, cutting through the High Plains Ecoregion around the Canadian River Basin. This area is largely uncultivated, characterized by semiarid grassland and rangeland as well as canyons, mesas, and badlands. The study area is bounded in the northeast by the Central Great Plains Ecoregion. Like the High Plains Ecoregion, this region is largely under cultivation, but at lower elevations and with a wetter climate. The Edwards Plateau Ecoregion bounds the study area in the southeast and roughly corresponds with the Edwards Plateau physiographic region in Fenneman and Johnson (1946). It is characterized by karst topography and savanna vegetation and, is used mostly as grazing land. The study area is bounded to the southwest by the Chihuahuan Deserts Ecoregion, a basin and range terrain mostly covered with desert grassland and shrubland.

Figure 2.1.3 provides a topographic map of the study area (United States Geological Survey, 2012). Generally, the surface elevation decreases from northwest to southeast across the study area. The ground-surface elevation varies from over 7,400 feet above mean sea level in the northwest to less than 2,100 feet above mean sea level in the southeast along the Colorado River valley. The High Plains can be seen as a relatively uniform surface with a distinct escarpment at the eastern transition to the plains of central Texas. The drainage features of the major rivers can be seen in the topography in much of the study area, particularly the Canadian, Beaver, and Pecos rivers, which have created deeply incised valleys in some places.

The climate in the Texas portion of the study area is classified predominantly as Continental Steppe, as defined in Larkin and Bomar (1983) (Figure 2.1.4). This type of climate is typical of continental 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). The very eastern, southeastern, southern, and southwestern Texas portions of the study area are in the Modified Marine, or Subtropical, climatic division. Subdivisions of the Subtropical climatic division are created by changes in the moisture content of the onshore flow of air from the Gulf of Mexico. Air from the Gulf decreases in moisture content as it travels across the state. In addition, intrusion of continental air into the Gulf maritime air occurs seasonally and affects the moisture content of the air. Different portions of the study area fall under the subdivisions Subtropical Subhumid, Subtropical Steppe, and Subtropical Arid (see Figure 2.1.4), with Subtropical Subhumid having the highest moisture content and Subtropical Arid having the lowest (Larkin and Bomar, 1983).

The Parameter-elevation Regressions on Independent Slopes Model (PRISM) precipitation dataset developed and presented online by the Oregon Climate Service at Oregon State University provides a distribution of average annual precipitation and temperature across the active model area based on the period from 1981 to 2010 (Oregon Climate Service, 2013). In general, the average annual precipitation in the study area (Figure 2.1.5) increases from the west to the east and from a low of about 11 inches to a high of about 28 inches. The average annual temperature in the study area (Figure 2.1.6) ranges from a high of 67 degrees Fahrenheit in the south to a low of 44 degrees Fahrenheit in the northwest based on the period from 1981 to 2010 (Oregon Climate Service, 2013).

Precipitation data are available at over 100 Texas stations within the study area (Figure 2.1.7) from as early as 1931 through the present (National Climate Data Center, 2012). Measurement of precipitation at most gages began in the 1940s or 1950s. In general, measurements are not continuous on a month-by-month or year-by-year basis for the gages. Examples of historical variation in annual precipitation at selected gages in the study area are shown in Figure 2.1.8. On this figure, the blue lines represent annual precipitation and the red dashed lines correspond to the mean annual precipitation. A discontinuity in the blue line indicates a break in the availability of annual precipitation data. Figure 2.1.9 shows long-term average monthly variation in annual precipitation at selected gages. This figure illustrates the difference in precipitation patterns between the eastern and western portions of the study area. In the east, precipitation peaks in late spring to early summer and again in early fall. In the west, precipitation is lower and only peaks once during the summer.

Average annual lake evaporation in the study area ranges from a high of 72 inches per year in the south to a low of 59 inches per year in the north (TWDB, 2012b), as shown in Figure 2.1.10. Evaporation rates significantly exceed the average annual rainfall (see Figure 2.1.5) in all portions of the study area but especially in the south, where deficits (evaporation exceeds precipitation) are over 60 inches per year. 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 from January 1954 through December 2011. Figure 2.1.11 shows that average lake evaporation peaks in July.

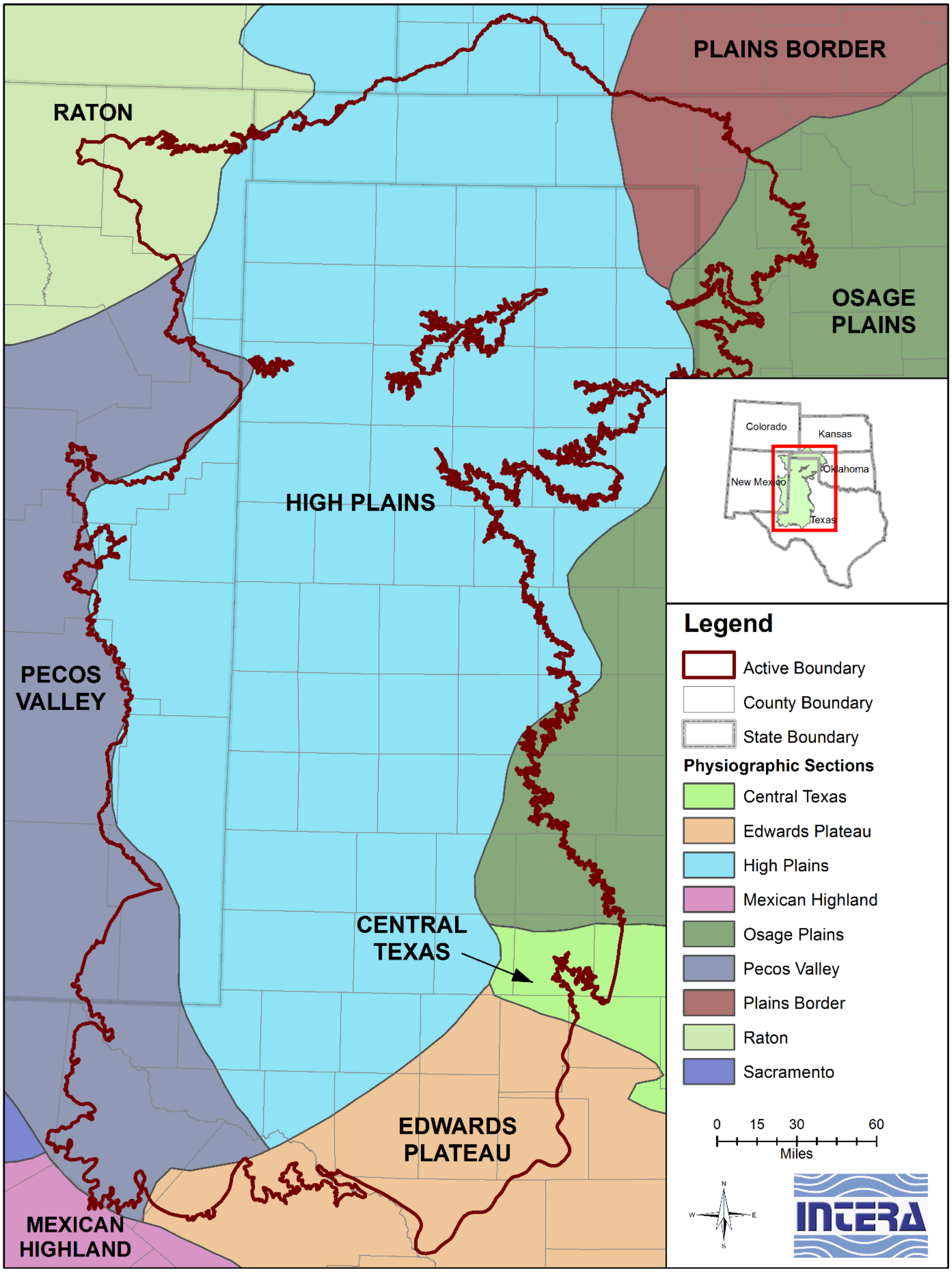


Figure 2.1.1 **Physiographic provinces in the study area (Fenneman and Johnson, 1946).**

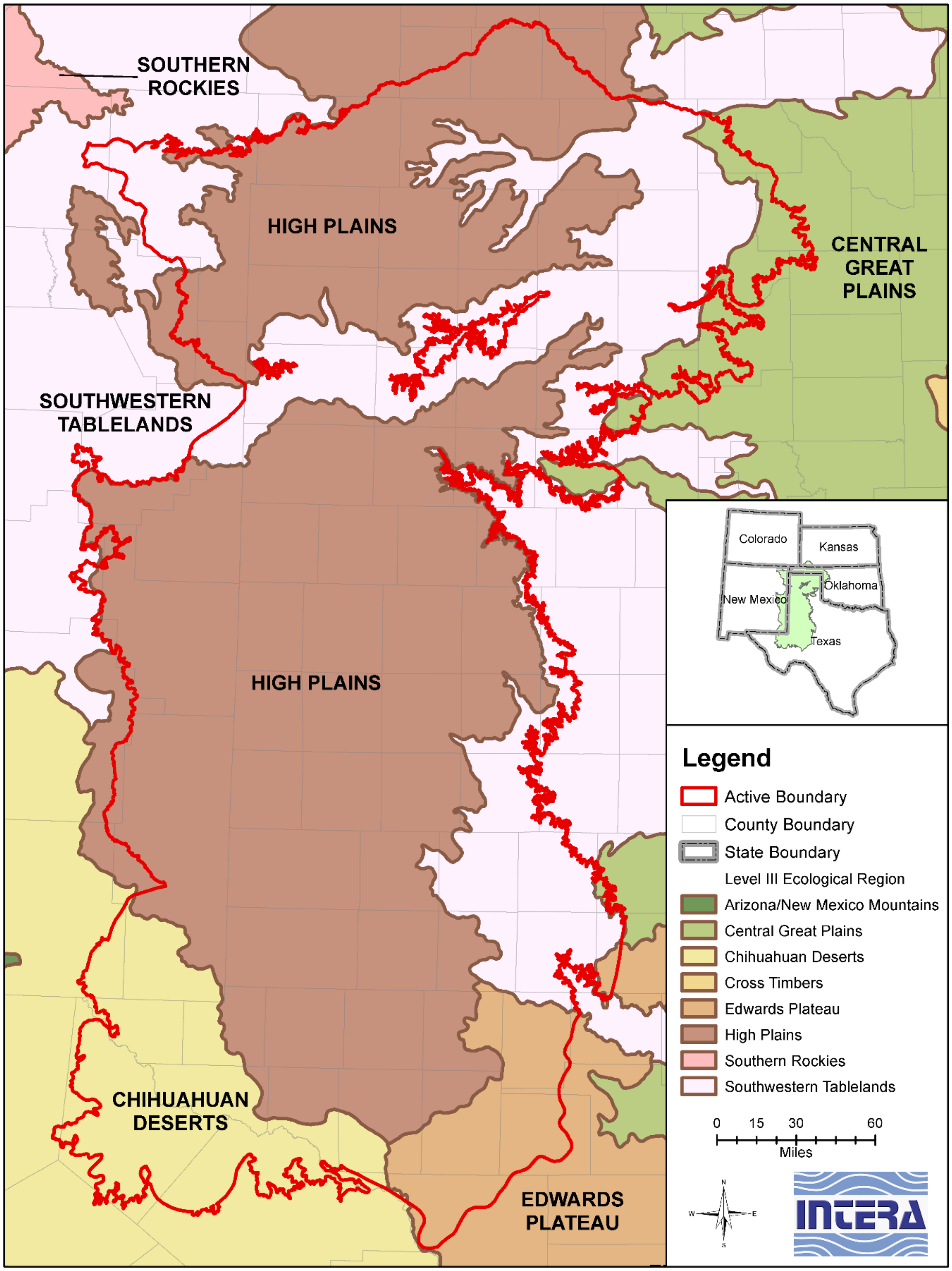


Figure 2.1.2 **Level III ecological regions in the study area (United States Environmental Protection Agency, 2011).**

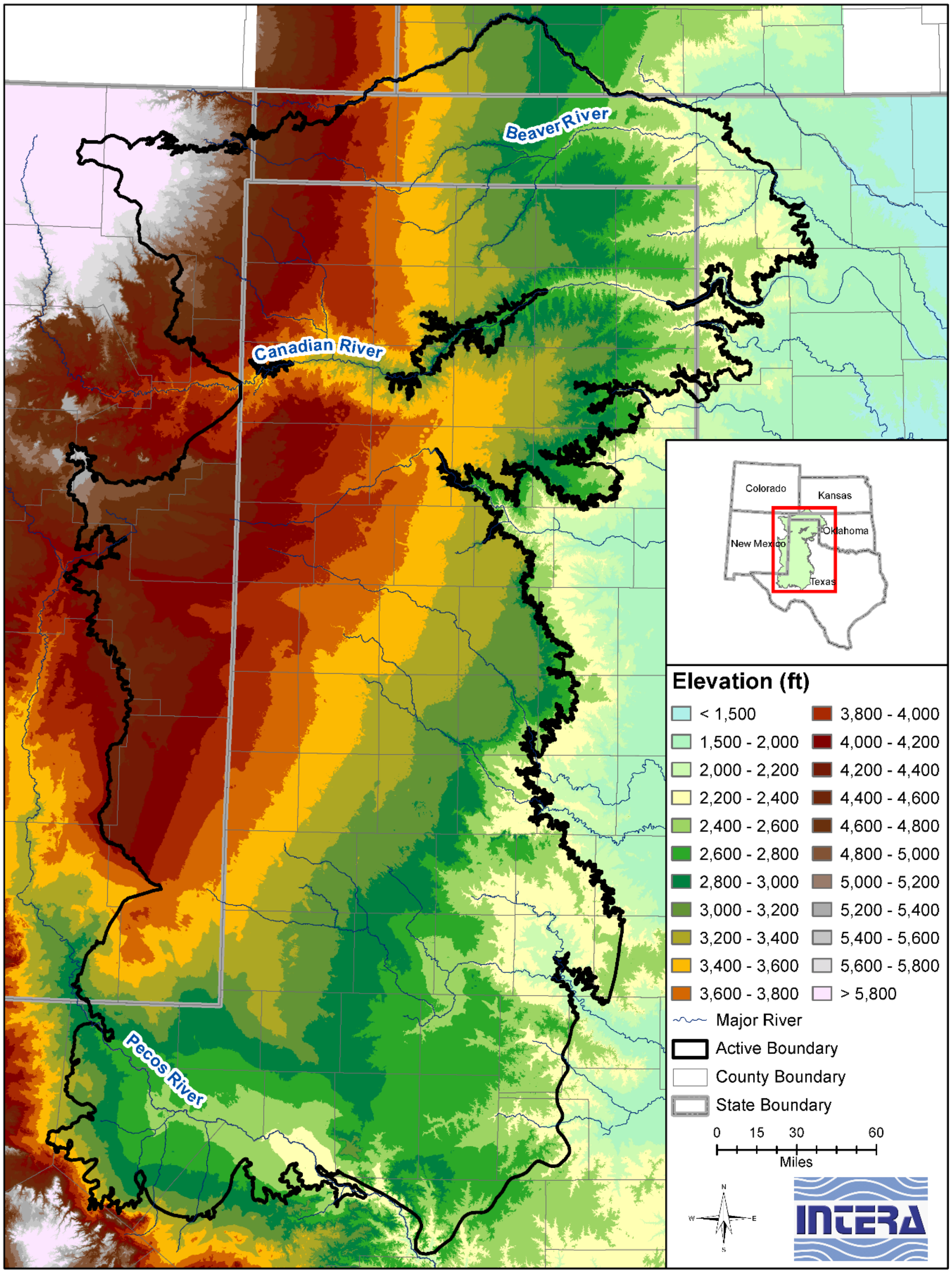


Figure 2.1.3 **Elevation (in feet above NAD 88 datum) for the study area (United States Geological Survey, 2012).**

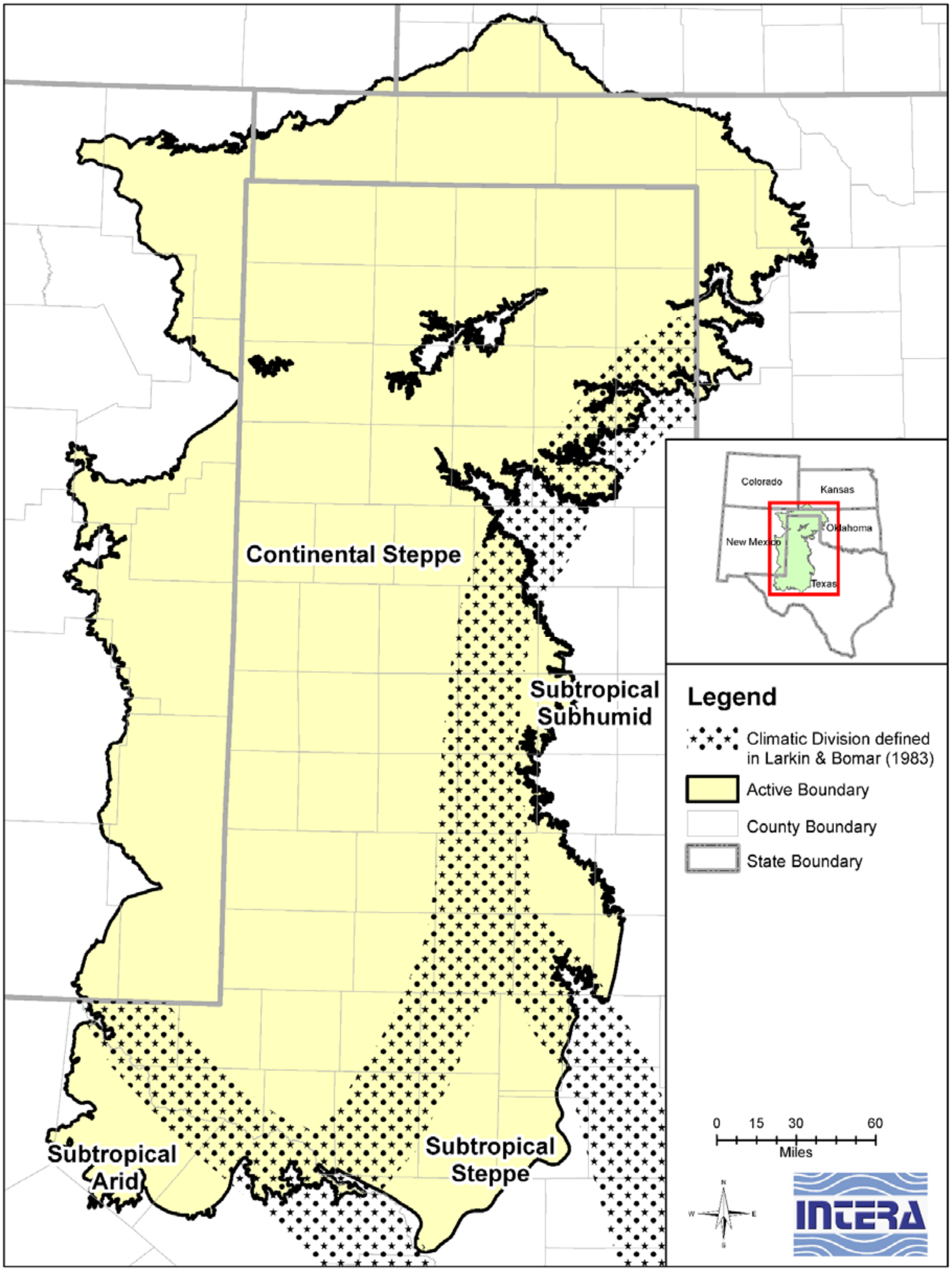


Figure 2.1.4 Climate divisions in the study area (Larkin and Bomar, 1983; National Climate Data Center, 1994).

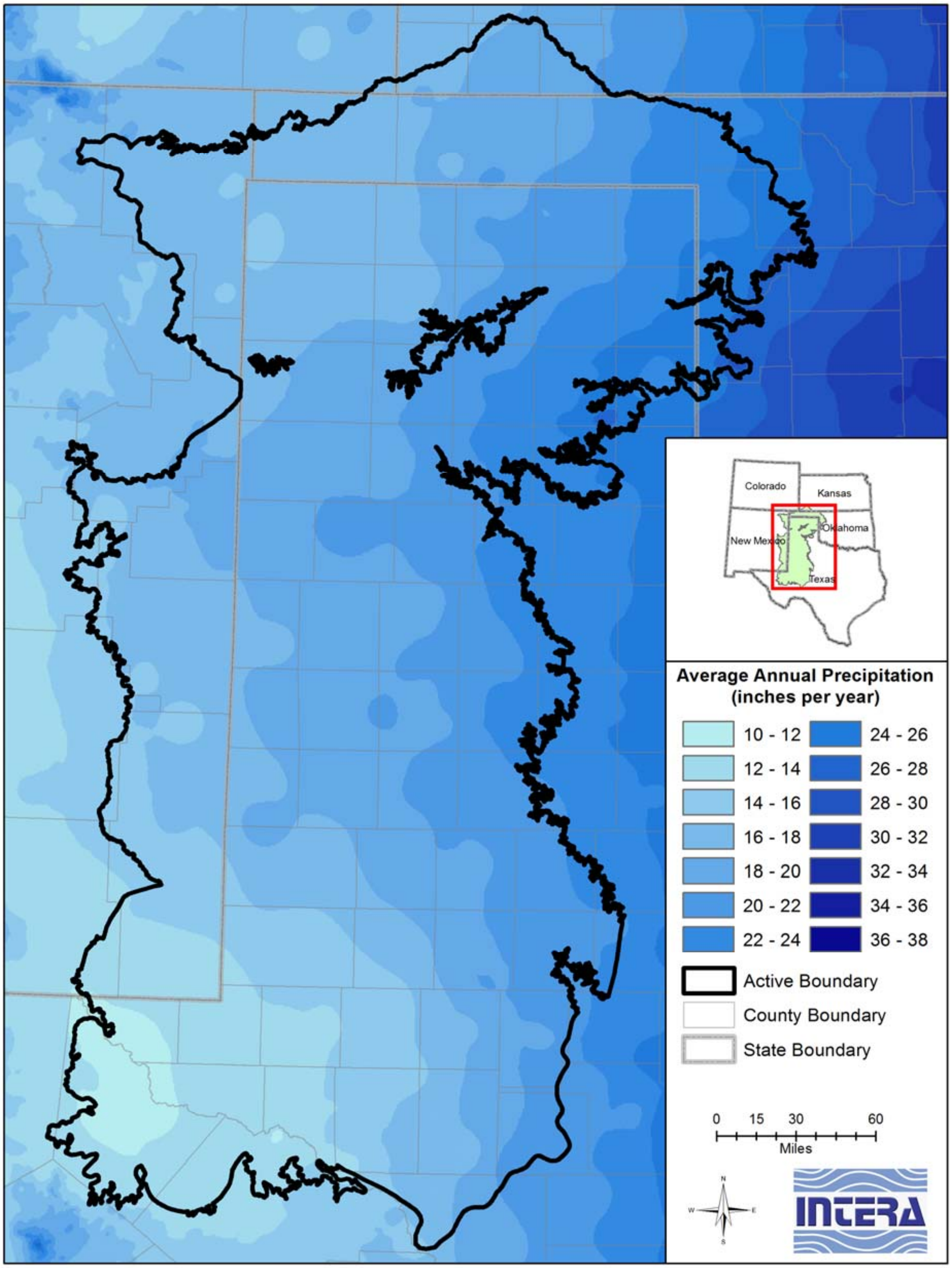


Figure 2.1.5 Average annual precipitation (in inches per year) over the study area for the time period 1981 to 2010 (Oregon Climate Service, 2013).

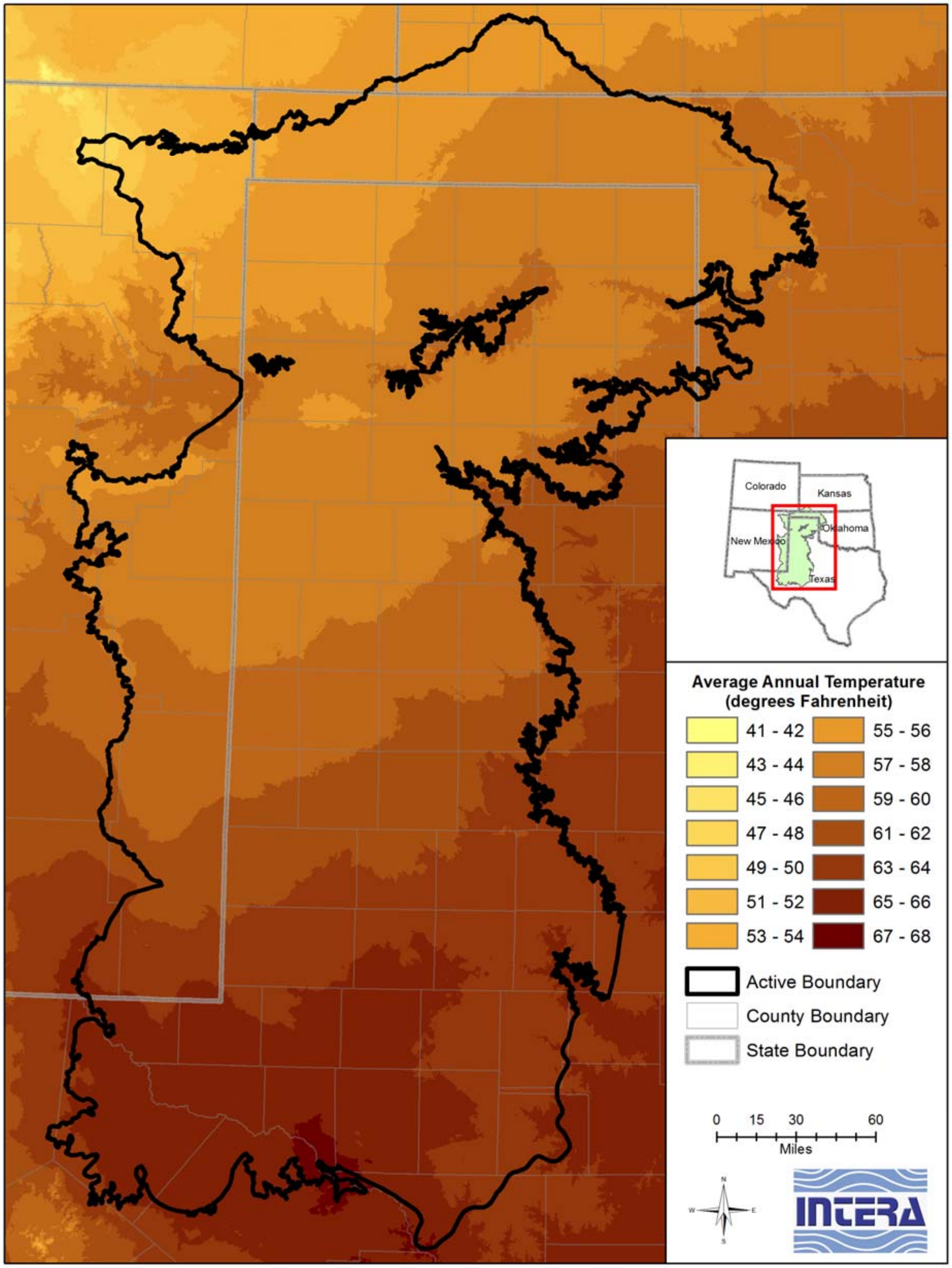


Figure 2.1.6 Average annual air temperature (in degrees Fahrenheit) of the study area for the time period 1981 to 2010 (Oregon Climate Service, 2013).

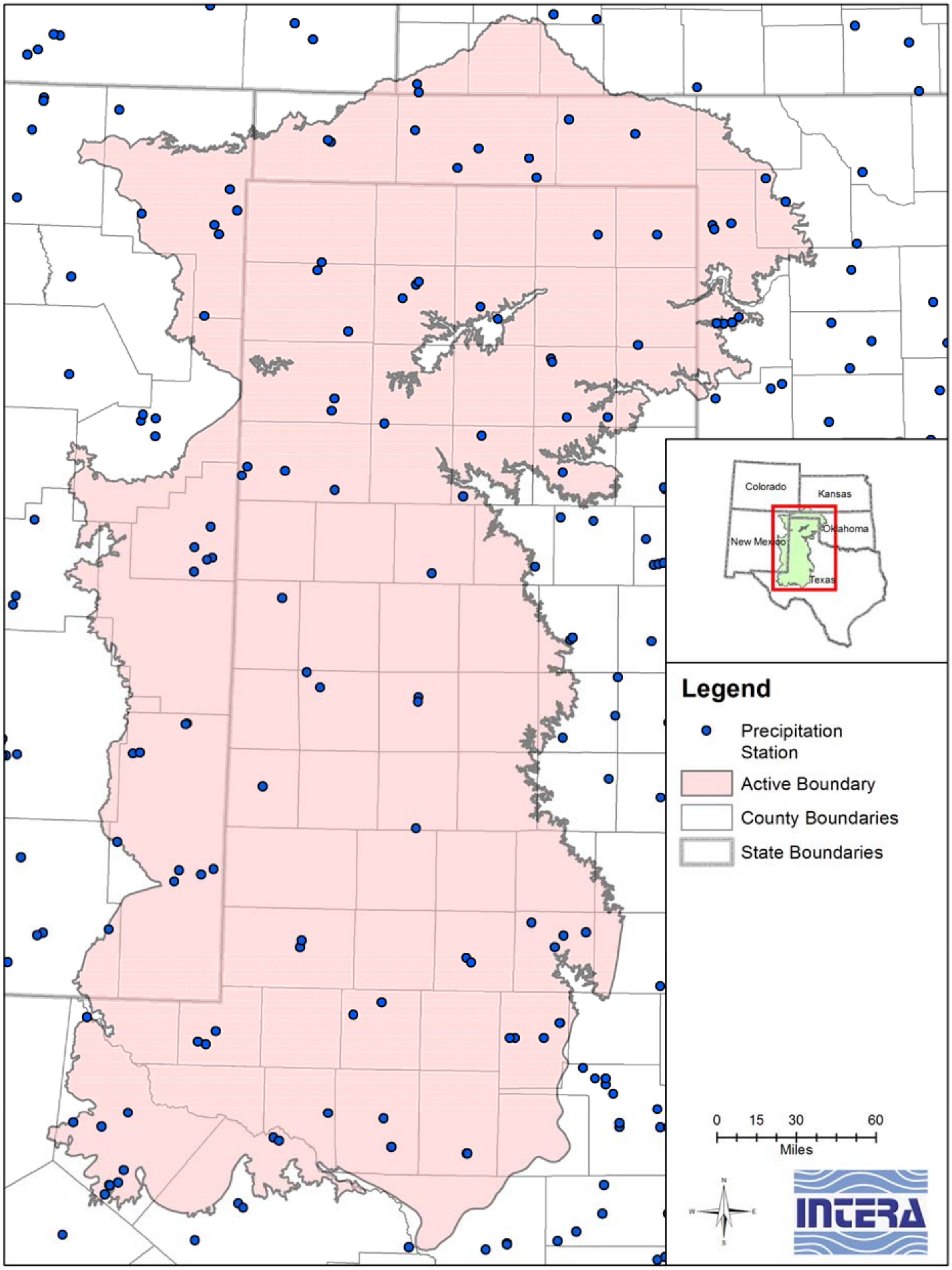


Figure 2.1.7 **Location of precipitation gages in the study area (National Climate Data Center, 2012).**

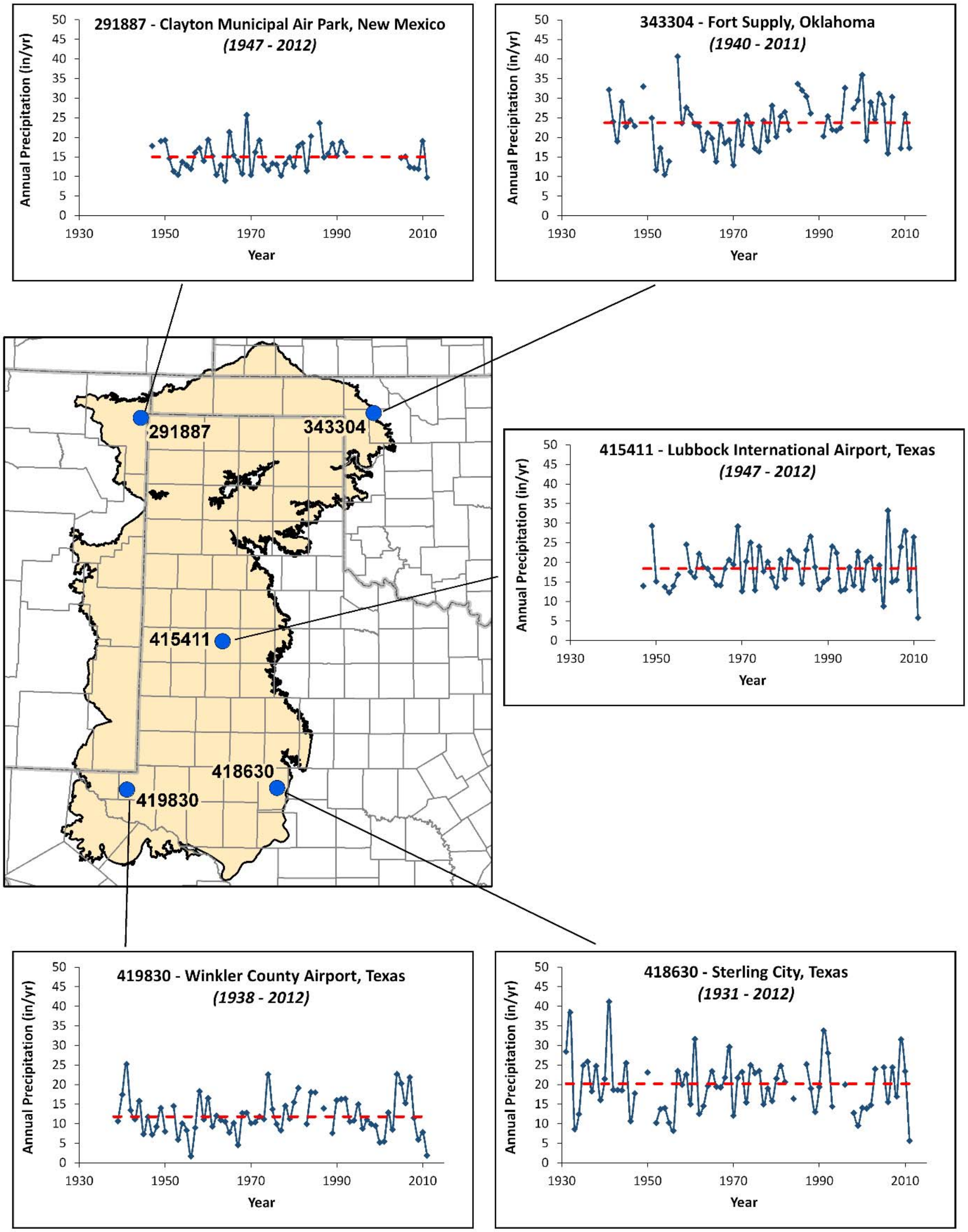


Figure 2.1.8 Select time series of annual precipitation (in inches per year) in the study area (National Climate Data Center, 2012). The red dashed lines indicate the mean annual precipitation over the period of record.

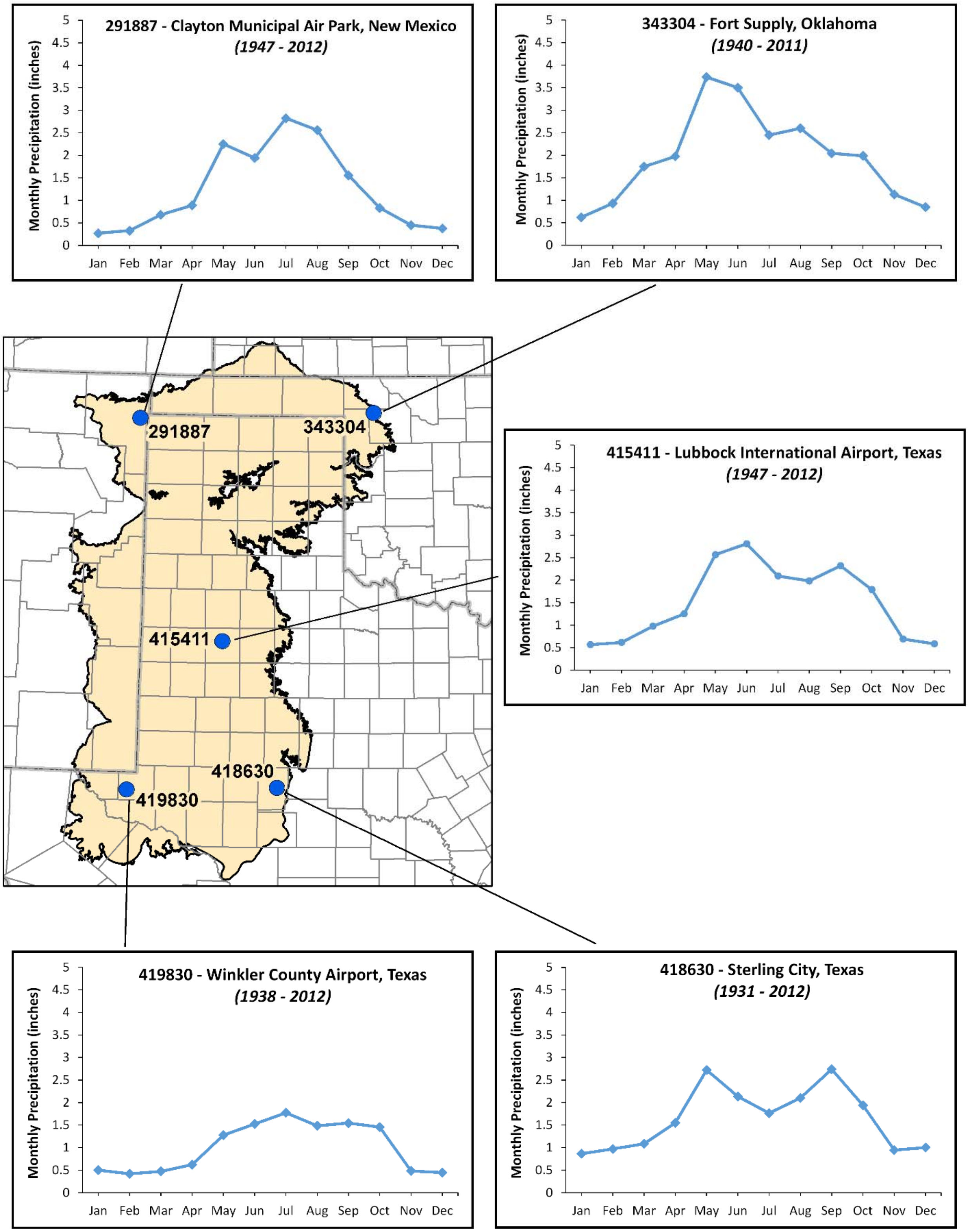


Figure 2.1.9 **Select time series of mean monthly precipitation (in inches per month) in the study area (National Climate Data Center, 2012)**

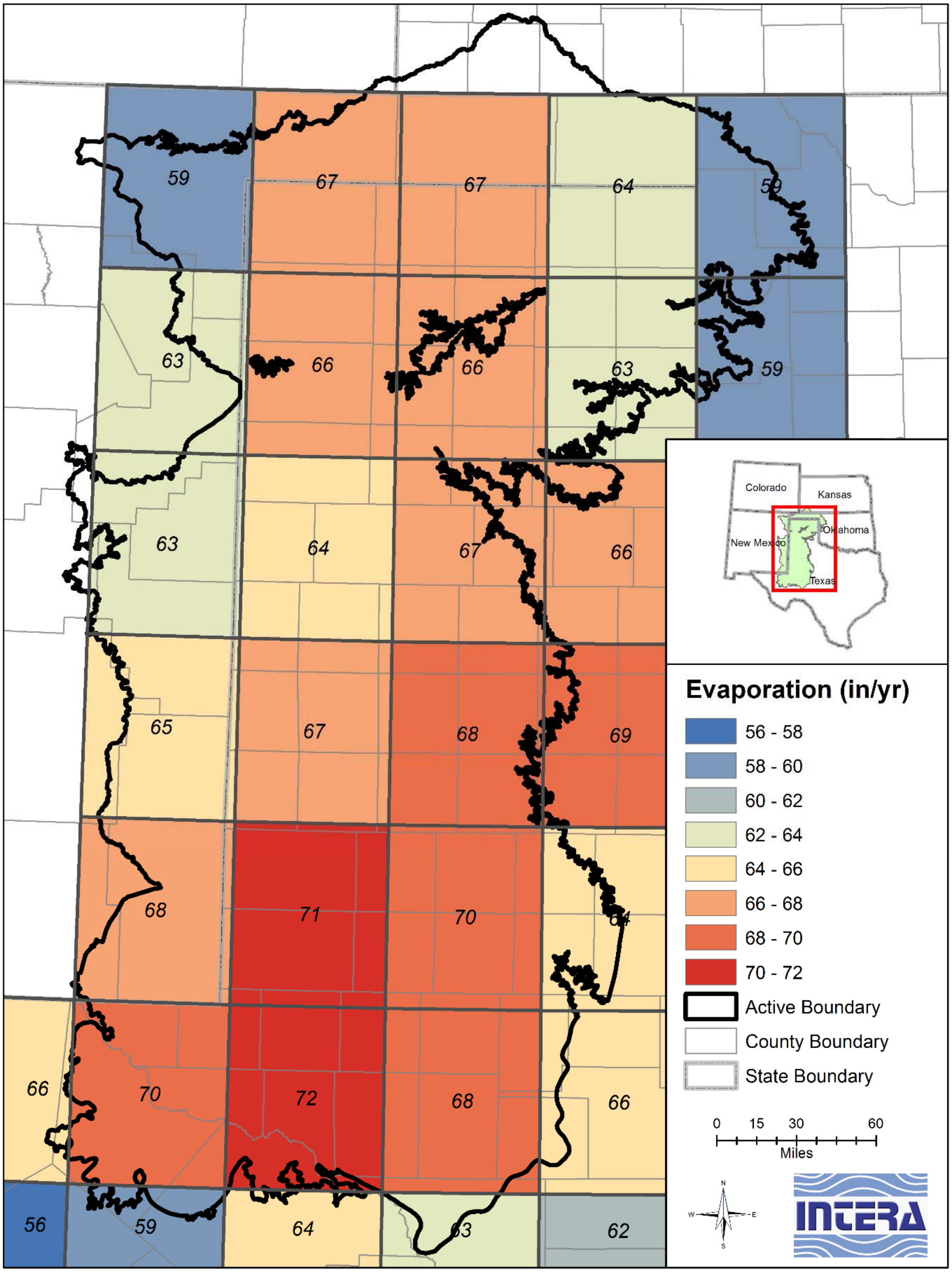


Figure 2.1.10 **Average annual lake evaporation rate (in inches per year) for the period 1954 through 2011 (TWDB, 2012b).**

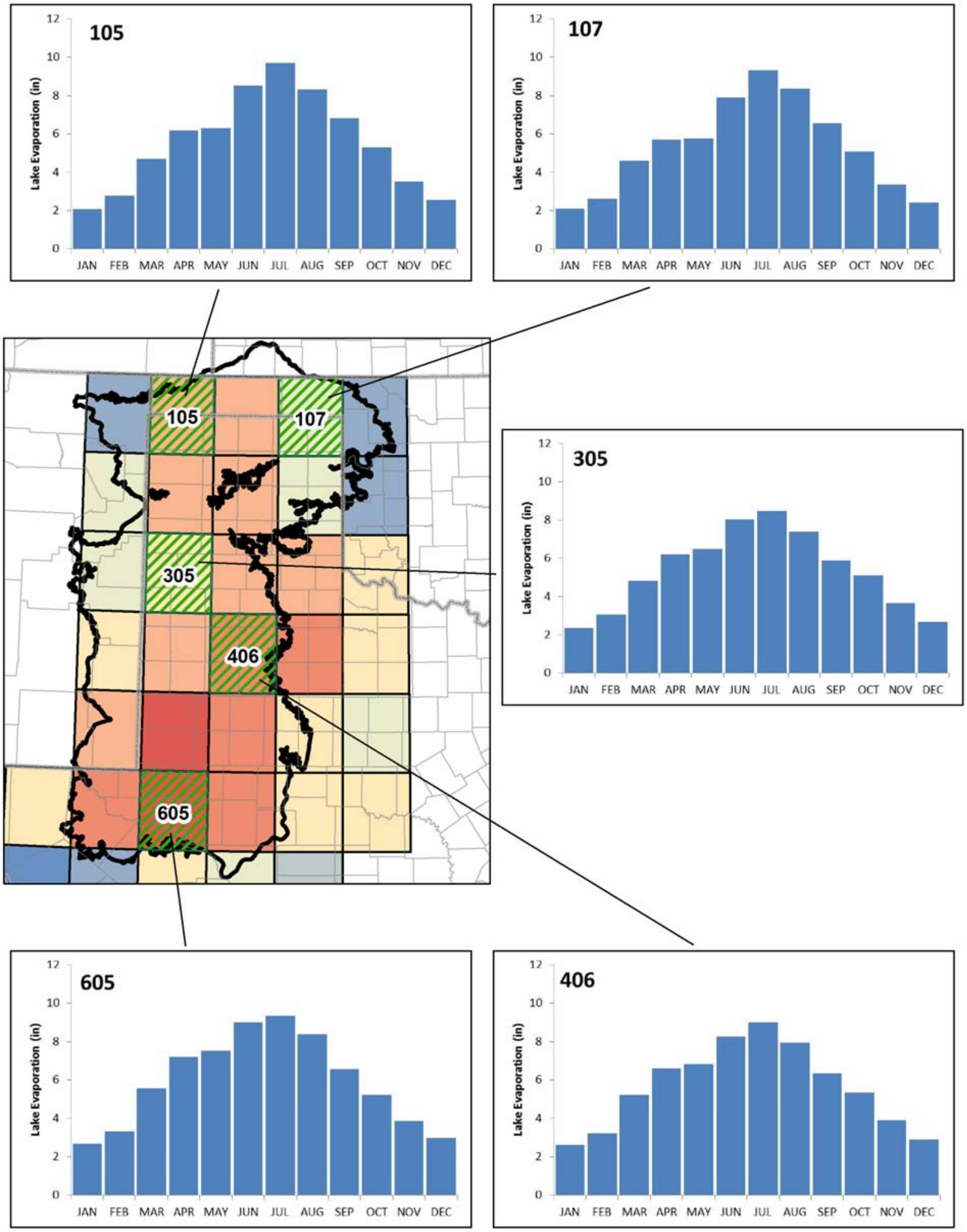


Figure 2.1.11 Average monthly lake evaporation rates (in inches) for the period 1954 through 2011 at select locations in the study area (TWDB, 2012b).

2.2 Geology

The geology of the High Plains Aquifer System includes up to 2,400 feet of rocks and sediments ranging in age from Triassic (245 million years) to Recent. Our conceptualization of this large and diverse rock volume integrates two components: (1) a synthesis of previous studies that cover various parts of the High Plains Aquifer System and (2) a comprehensive, geophysical-log-based study that was conducted for this project. The High Plains Aquifer System encompasses all or parts of six aquifers: the Triassic Dockum Aquifer, the Jurassic-Cretaceous Rita Blanca Aquifer, the Cretaceous Edwards-Trinity (Plateau) Aquifer, the Cretaceous Edwards-Trinity (High Plains) Aquifer, the Tertiary Ogallala Aquifer (along with surficial Quaternary deposits), and the Quaternary Pecos Valley Aquifer (Table 2.2.1). The Edwards-Trinity (Plateau) and Edwards-Trinity (High Plains) aquifers are composed of similar geologic formations but are geographically separated. In general, aquifers of the High Plains Aquifer System have distinct geographic locations and stratigraphic positions. Tertiary and Quaternary formations, which contain both the Ogallala and Pecos Valley aquifers, cover most of the land surface, whereas Cretaceous and Triassic formations crop out in the southeast and elsewhere in drainage valleys, canyons, and draws (Figure 2.2.1).

2.2.1 Tectonic History

The High Plains Aquifer System is everywhere underlain by low permeability Permian formations. The Permian Basin, a large subsided area across west Texas and eastern New Mexico, encompasses several structural subbasins and uplifted areas (Figure 2.2.2). The Triassic Dockum Group records the final filling of the Dalhart, Palo Duro, and Midland subbasins. The Dockum Group thickens into basinal areas and thins across uplifted areas. The change from Permian marine sedimentation to Triassic nonmarine sedimentation was a response to plate tectonic uplift related to the opening of the Gulf of Mexico (McGowen and others, 1979). Uplift closed the Permian seaway, resulting in the formation of a freshwater, inland basin during the time of the Dockum Group. The top of the Dockum Group surface records tectonic tilting eastward and multiple episodes of post-Dockum Group erosion.

Following the Triassic Period, the Jurassic and Cretaceous periods were characterized by long-term rising sea level and marine flooding of the continent. Crustal subsidence related to continued opening of the Gulf of Mexico caused reorientation of continental drainage during the

Jurassic Period (Fallin, 1989). River systems that during the Triassic had flowed into closed lacustrine basins began flowing southeastward toward the Gulf of Mexico. Early Cretaceous rivers eroded valleys into the underlying surface of the Dockum Group. Cretaceous rocks were once widespread, but post-Cretaceous uplift and erosion removed them from large areas. Isolated remnants of Cretaceous rocks form the Edwards-Trinity (High Plains) aquifer (Fallin, 1989). Another erosional remnant in the northwest composed of Jurassic and Cretaceous mixed nonmarine and marine rocks, forms the Rita Blanca Aquifer (Mankin, 1958). The Edwards-Trinity (Plateau) Aquifer is not an erosional remnant but instead is continuous to the east with Cretaceous formations in the Gulf of Mexico basin (Barker and Ardis, 1992, 1996). The northwestern edge of the Edwards-Trinity (Plateau) Aquifer, however, is erosionally truncated where it extends into the study area (see Figure 2.0.2).

Tertiary and Quaternary formations were deposited on a heavily eroded surface. Early Tertiary Laramide compressional tectonics resulted in formation of the Rocky Mountains along with uplift and eastward tilting in the study area. Eastward flowing fluvial systems eroded deep valleys into Cretaceous, Triassic, and Permian surfaces. Topographically elevated ridges were preserved between valleys. More irregular topography formed locally owing to dissolution of Permian evaporites (salt) by meteoric groundwater and collapse of the overlying surface (Gustavson and others, 1980; Seni, 1980). The Ogallala Formation was deposited on this eroded surface during the Miocene and Pliocene epochs (4.5 to 11 million years ago) of the Tertiary Period (Schultz, 1990). The upper surface of the Ogallala Formation is also an erosional remnant, having once extended from the Rocky Mountains to north-central Texas (Reeves, 1972). The caprock escarpment now forms a prominent erosional boundary on the east side of the study area, and the Pecos River valley truncates the Ogallala Formation in New Mexico. In Texas, Tertiary and Quaternary alluvial fill in the Pecos River valley forms a major aquifer in the southwest part of High Plains (see Figure 2.0.2) (Meyer and others, 2012).

2.2.2 Depositional Environments

The vertical succession of geologic formations in the High Plains Aquifer System records several major alternations between marine and nonmarine depositional environments. Upper Permian formations were deposited in shallow-water marine environments, which became increasingly more restricted northwards. More open marine circulation occurred in the south, whereas the north was occupied by closed hyper saline basins (Presley, 1981). Thus, limestones are more abundant in the south and evaporites (primarily gypsum and halite) are more abundant in the north. Eventually, Permian marine basins filled to sea level, and arid-region, fine-grained clastics (red beds) dominate uppermost Permian sediments (Nance, 1988). In the central parts of the basin, the Permian-Triassic boundary is apparently conformable and not easily identifiable. In those areas siltstone and mudstone red beds are present continuously across the boundary, suggesting that environmental change was not abrupt (Johns, 1989). In more peripheral areas, especially in outcrops, Permian and Triassic rocks are separated by an unconformity (McGowen and others, 1979; Lucas and Anderson, 1992).

Although environmental changes occurred gradually, the Triassic Dockum Group is significantly different from underlying upper Permian formations. Three major changes mark the transition into the Triassic: (1) shift from marine to nonmarine terrestrial environments, (2) climate change from arid to humid tropical, and (3) uplift of peripheral sediment source areas (McGowen and others, 1979; Johns, 1989). After the southern connection between the Permian Basin and world oceans was cut off, a large inland lacustrine basin formed, and major rivers flowed into this Dockum Basin from several directions (Figure 2.2.3). Sandstones were deposited in fluvial channels and lacustrine deltas, whereas mudstones were deposited in prodelta and offshore lacustrine environments. Climatic changes raised and lowered lake levels, causing cyclic shoreline progradation and transgression and resulting in sandstone/shale interbedding in the Dockum Group. In addition to this small-scale cyclicity, the Dockum Group is subdivided into upper and lower units based on regional upward fining trends (Granata, 1981). These large-scale trends probably record episodes of uplift in the source area and sand influx to the basin followed by gradual subsidence and decreasing sand influx. Thus, the lower and upper Dockum intervals are sandiest in their lower parts (Figure 2.2.4).

Depositional environments become more marine-influenced again in the Cretaceous. Jurassic formations in northeastern New Mexico and Dallam and Hartley counties, Texas, were deposited in nonmarine, arid-region, eolian, fluvial, and lacustrine environments, whereas overlying Cretaceous formations record several marine transgressions from east to west (Mankin, 1958). Thus, sandstones in the Rita Blanca Aquifer are mixed nonmarine and transgressive marine shoreline deposits. Formations in both the Edwards-Trinity (High Plains) and Edwards-Trinity (Plateau) aquifers were deposited in marine environments (Fallin, 1989; Barker and Ardis, 1992, 1996). Basal Antlers sandstones are marine shoreline deposits, whereas overlying Walnut and

Comanche Peak shales and shaly limestones are primarily lagoonal deposits. Massive Edwards limestones were deposited on a widespread carbonate platform. The overlying Kiamichi and Duck Creek formations are composed of thick shales with thin limestone and sandstone interbeds, which were deposited in lagoonal and open marine environments. The end of the Cretaceous Period marked a return to nonmarine conditions.

Tertiary formations of the High Plains were all deposited in nonmarine environments. Regionally, the Ogallala Formation forms a broad alluvial apron adjacent to the Rocky Mountains. Within this alluvial fan depositional system, the thickest and coarsest grained sediments are fluvial channel facies in alluvial fan lobes deposited in paleovalleys (Seni, 1980; Gustavson, 1996). Several overlapping alluvial fan lobes were deposited and then abandoned successively from north to south (Figure 2.2.5). This southward shift in depositional location was controlled primarily by elevation of the underlying surface. The lowest surface (Permian) had to be filled before higher surfaces (Dockum and Cretaceous) could accommodate sediment. Ogallala Formation alluvial fan deposits become finer grained with distance from the mountain front source areas. Most sediments in the preserved extent of the Ogallala Formation are sands and gravels that were deposited in braided stream channels (Seni, 1980). The upper part of the Ogallala Formation includes widespread eolian fine sand, silt, and clay. Calcic soil horizons are common in the upper part of the Ogallala Formation. The Caprock caliche is a 6-foot-thick bed of erosion-resistant white calcium carbonate-rich rock at the upper Ogallala Formation surface, which records a long period of landscape stability and soil formation (Gustavson, 1996). The Quaternary Blackwater Draw Formation is composed of eolian sands and soil horizons, which are similar to those in the upper part of the Ogallala. The Quaternary Pecos Valley Alluvium Formation consists of both alluvial and eolian deposits (Meyer and others, 2012). Most of the alluvium is in the form of alluvial fans entering the valley from Trans-Pecos uplands to the southwest. Surficial alluvial sediments are wind-reworked into large sand dunes.

2.2.3 Stratigraphy

This section presents an overview of the stratigraphy and lithology of the geologic formations that comprise the High Plains Aquifer System. More detailed stratigraphic descriptions that are based on our geophysical log study are presented in Section 4.2.5. High Plains aquifers are primarily in sands and sandstones, although gravel is common in the Ogallala Aquifer. The main sandy aquifer formations are the Santa Rosa and Trujillo formations in the Dockum Aquifer, the

Exeter Formation in the Rita Blanca Aquifer, the Antlers Formation in the Edwards-Trinity (High Plains) Aquifer, the Ogallala Formation of the Ogallala Aquifer, and the Pecos Valley Alluvium Formation of the Pecos Valley Aquifer (see Table 2.2.1). These sand-rich formations are separated vertically from each other by fine-grained formations, which are composed mainly of silt, clay, and/or argillaceous limestone. Exceptions to this vertical confinement are outcropping formations, primarily the Ogallala and Pecos Valley Alluvium formations and locally the Dockum Group (see Figure 2.2.1). The Cretaceous Edwards Formation is the only potential limestone aquifer.

Geologic formations vary geographically in thickness and lithology, and so formations defined in outcrop may not resemble those encountered miles away in the subsurface. For example, correlation of Dockum Group formations from outcrop to subsurface is uncertain (Johns, 1989). Nevertheless, a general vertical trend is present in the Dockum Group throughout the study area that coincides with outcrop descriptions. The Dockum Group is divisible into upper and lower intervals based on upward transitions of sandstone to shale (see Figure 2.2.4). The sand-rich part of the lower Dockum Group corresponds to the Santa Rosa Formation of outcrop, and the sand-rich part of the upper Dockum Group corresponds to the Trujillo Formation (see Table 2.2.1). The details of Dockum Group sandstone-shale interbedding, however, are more complicated and are described in Section 4.2.5.

Cretaceous formations, which were deposited primarily in marine environments, display more laterally persistent thickness and lithology trends than do nonmarine formations in the Dockum Group. Cretaceous marine environments were large. Quiet-water lagoons and wave-swept platforms individually covered 20 to 30 counties in central and west Texas (Fisher and Rodda, 1969). Partly because of this lateral continuity, Cretaceous formations are better defined and correlated in both outcrop and subsurface than are formations in the Dockum Group. In the study area, the Cretaceous interval consists of a sandstone lower part (Antlers Formation) and a limestone upper part (Edwards Formation) interbedded with several thin shale-dominated formations (see Table 2.2.1).

The Ogallala Formation is composed mainly of sand and gravel near the base and sand and clay in the upper part (Seni, 1980; Gustavson, 1996). Pebble- to boulder-size gravel lenses are common along the basal surface (Figure 2.2.6). Note that the location of the cross section in

Figure 2.2.6 is shown in Figure 2.2.7. Cross-stratified coarse sand and pebble-sized gravel typically overlie basal gravel deposits. These coarse-grained, lower Ogallala Formation sediments are mostly unconsolidated, although calcite cementation is present locally. Clay-dominated lenses are also present locally along the basal surface. The middle part of the Ogallala Formation contains less gravel and more sand and clay. Lenses of medium-grained sand are typically enclosed in large bodies of fine-grained sand and clay. The upper part of the Ogallala Formation is a heterogeneous mixture of sand, silt, clay, caliche, and soil horizons (see Figure 2.2.6).

Table 2.2.1 Generalized stratigraphic description of geologic formations in the High Plains Aquifer System. Descriptions are summarized from Fallin (1989), Granata (1981), Gustavson (1996), Johns (1989), Knowles and others (1984), Mankin (1958), Meyer and others (2012), and Seni (1980).

System	Group	Formation	General Description
Quaternary		Pecos Valley Alluvium	caliche, clay, silt, sand, and gravel
Tertiary		Ogallala	*sand:* fine- to coarse-grained quartz, silty in part, local caliche nodules, cemented locally by calcite and silica, locally cross-bedded, various shades of gray, brown, and red; *silt and clay:* caliche nodules, locally sandy, massive, white, gray, olive-green, brown, red and maroon; *gravel:* in lower part; *caliche horizons:* in upper part; overlain by veneer of Quaternary fine sand, silt, clay, caliche (Blackwater Draw Formation)
Cretaceous	Washita	Duck Creek	yellow sandy shale and thin gray to yellowish brown argillaceous limestone beds
	Fredericksburg	Kiamichi	gray to yellowish brown shale with thin interbeds of gray argillaceous limestone and yellow sandstone
		Edwards	light gray to yellowish gray, thick to massive bedded, fine- to coarse-grained limestone
		Comanche Peak	light gray to yellowish brown, irregularly bedded argillaceous limestone with thin interbeds of light gray shale
		Walnut	light gray to yellowish brown argillaceous sandstone; thin-bedded gray shale; light gray to grayish yellow argillaceous limestone
	Trinity	Antlers	white, gray, yellowish brown to purple, argillaceous, loosely cemented sand, sandstone, and conglomerate with interbeds of siltstone and clay
Jurassic		Morrison	sandy shale, thin sandstone, local thin-bedded limestone near top
		Exeter	sandstone
Triassic	Upper Dockum	Cooper Canyon	reddish-brown to orange siltstone and mudstone with lenses of sandstone and conglomerate
		Trujillo	gray, brown, greenish-gray, fine to coarse-grained sandstone and sandy conglomerate with thin gray and red shale interbeds
	Lower Dockum	Tecovas	variegated, sometimes sandy mudstone with interbedded fine to medium grained sandstone
		Santa Rosa	red to reddish-brown sandstone and conglomerate
Permian		various	red to reddish-brown shale and siltstone, gypsum and dolomite, upper part may be partly Triassic

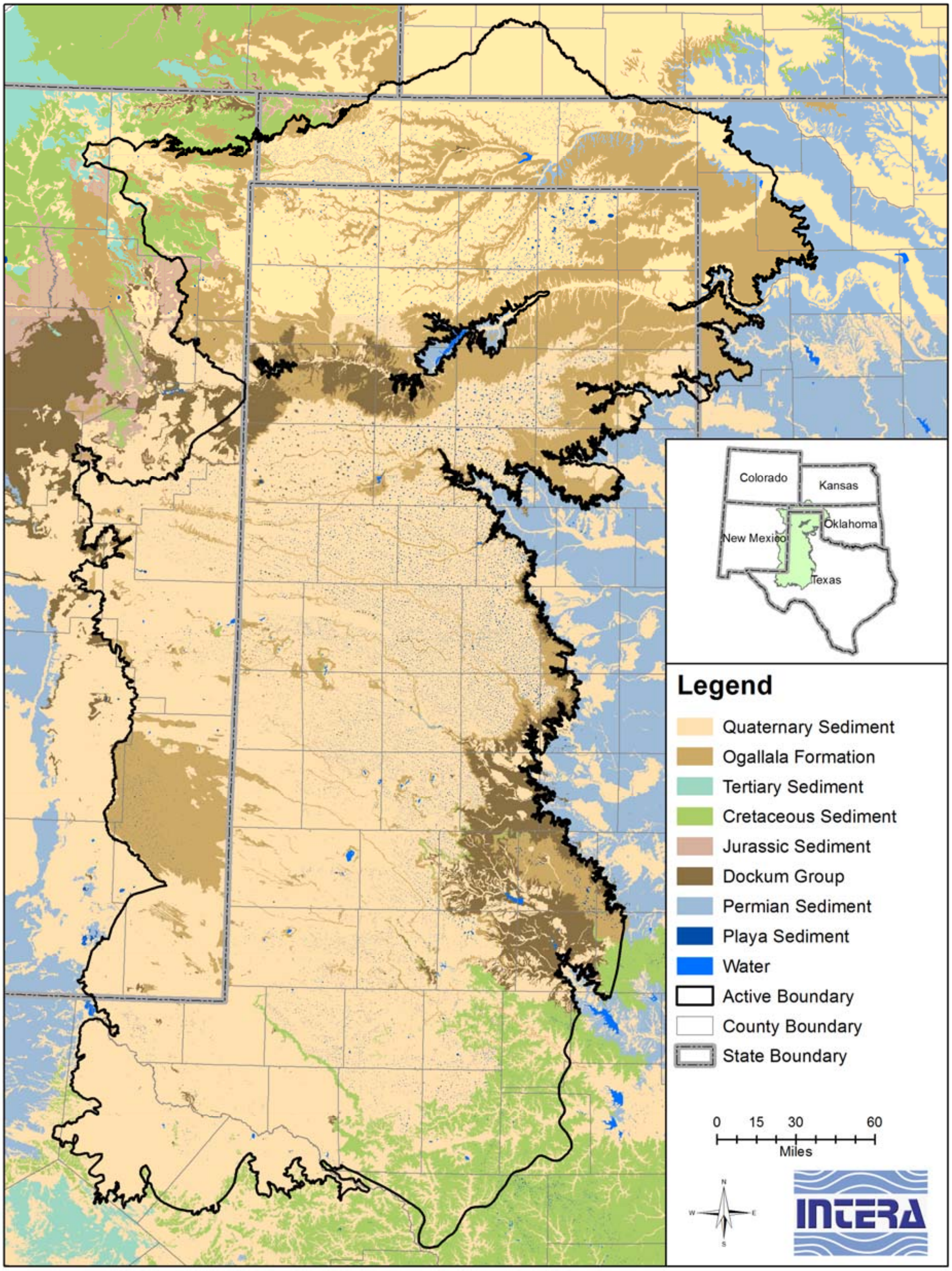


Figure 2.2.1 **Generalized surface geologic map in the study area (modified from Bureau of Economic Geology, 2007 and Stoeser and others, 2007).**

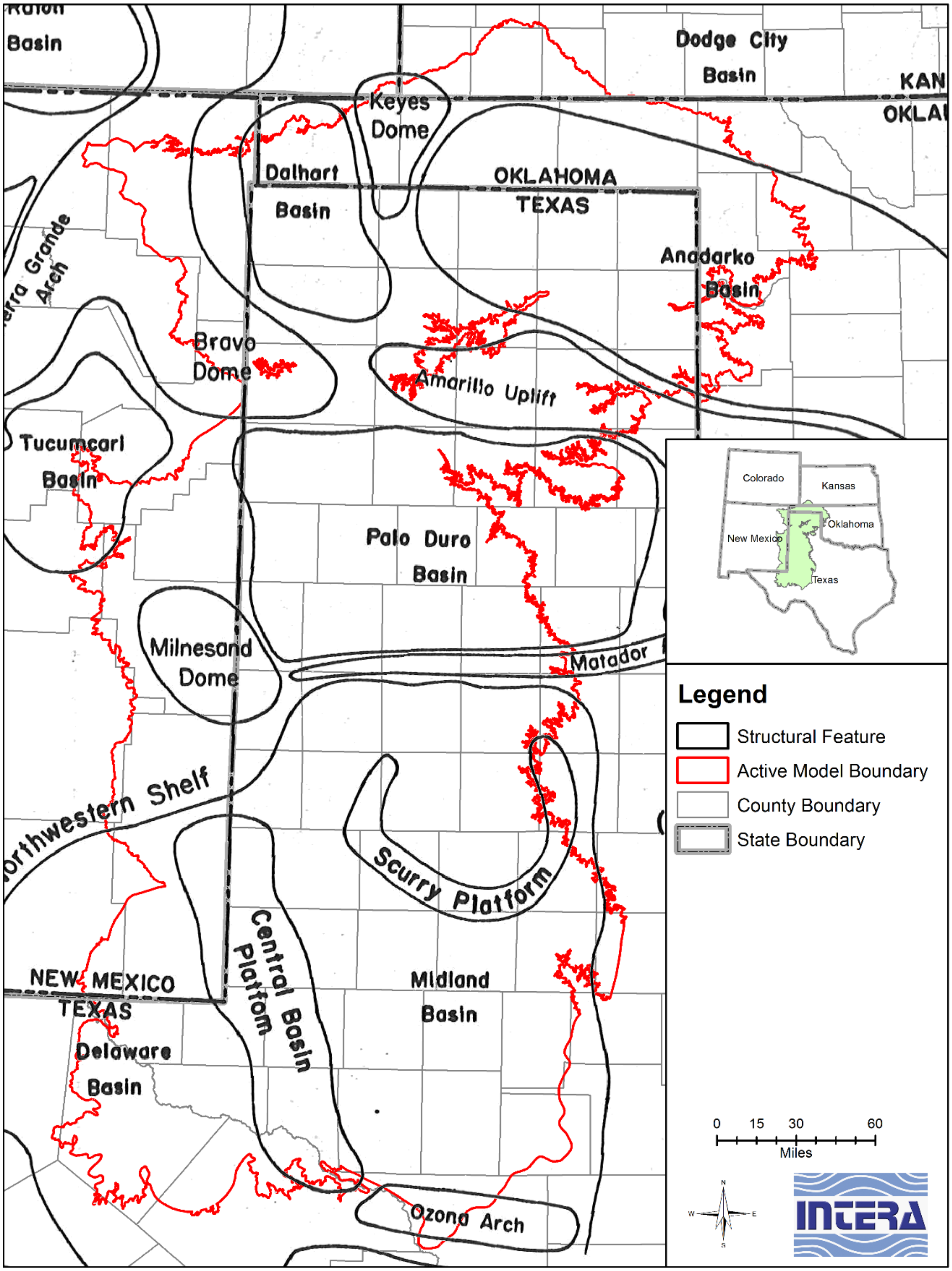


Figure 2.2.2 Generalized structure map for the study area (Ruppel, 1983).

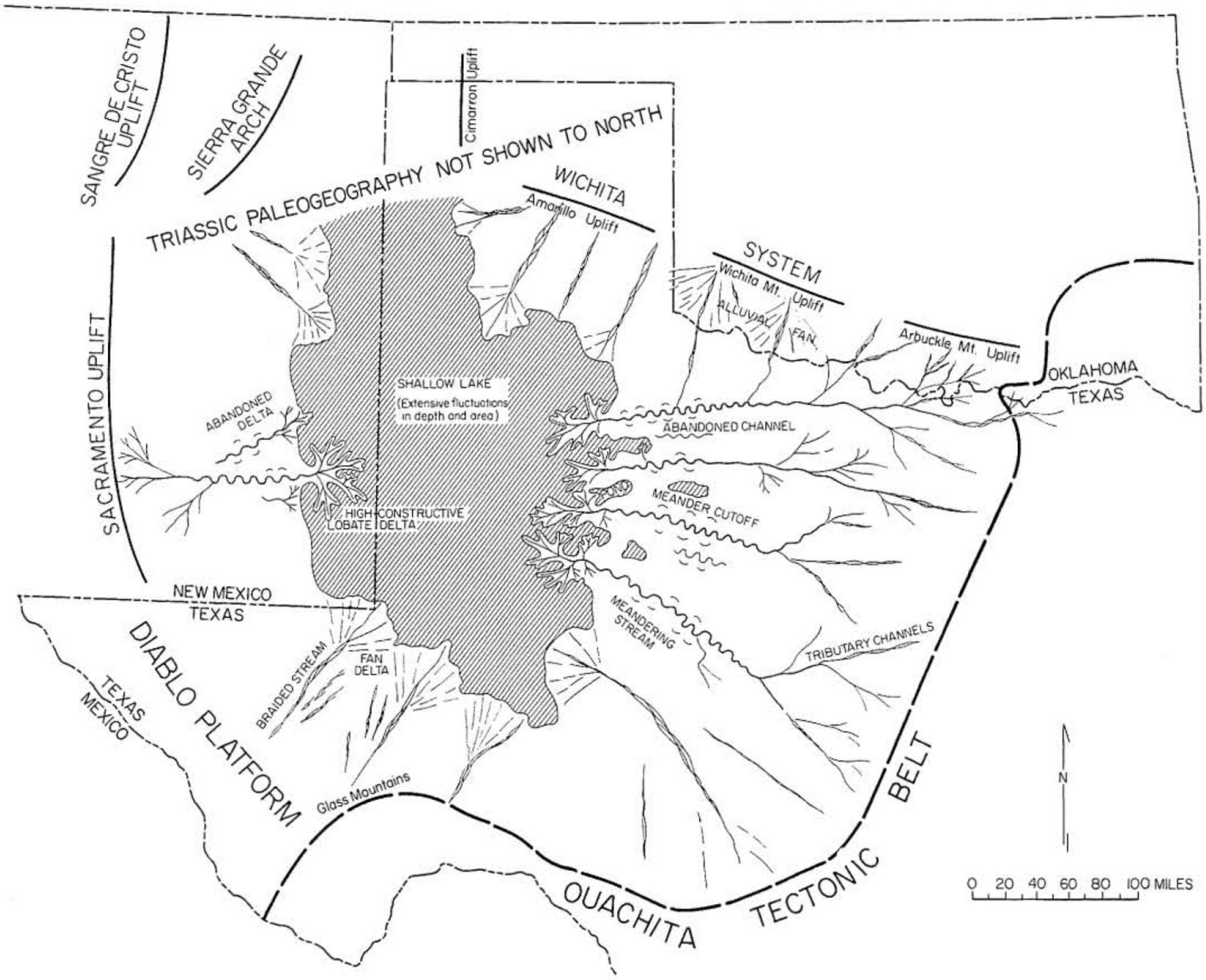


Figure 2.2.3 Inferred paleogeography during the initial stage of Dockum Group sedimentation in the area south of the Amarillo Uplift and Bravo Dome (from McGowen and others, 1979).

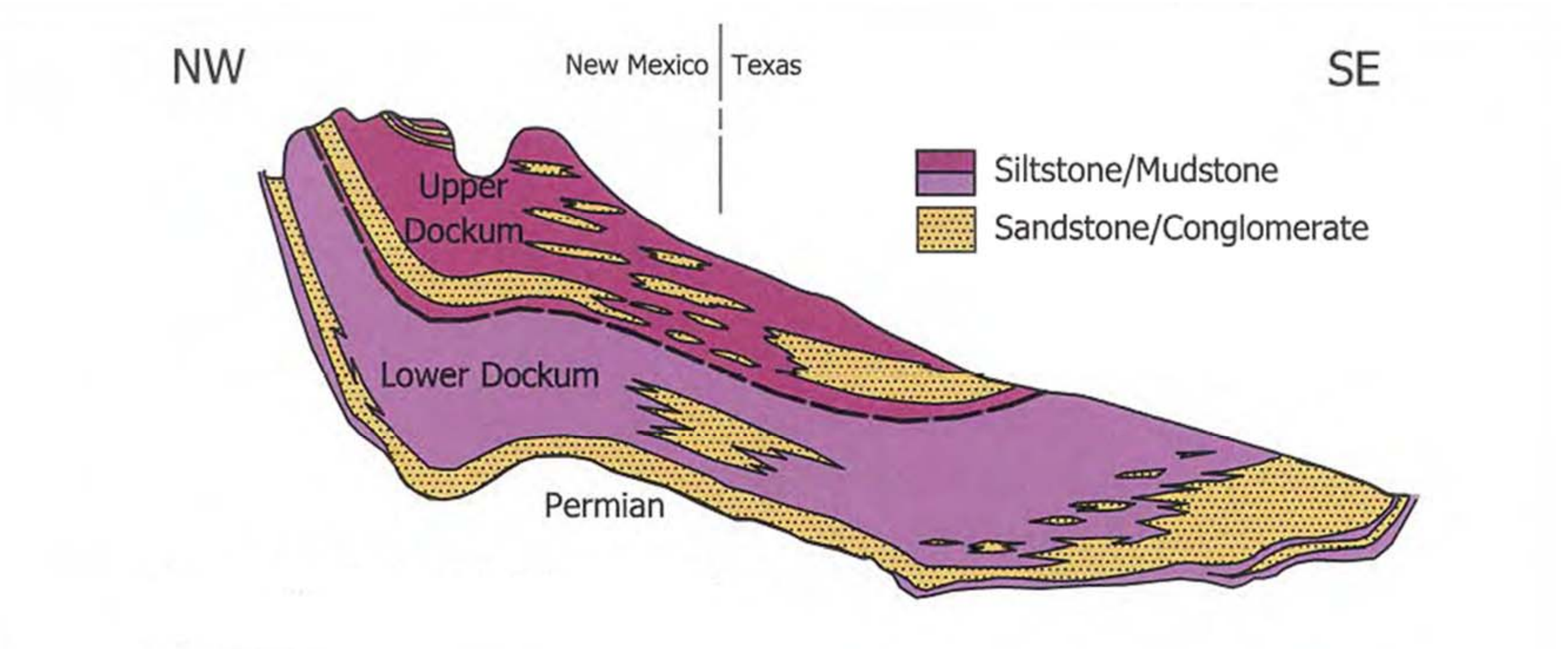


Figure 2.2.4 Schematic cross section of the Dockum Aquifer in New Mexico and Texas (modified from Ewing and others, 2008).

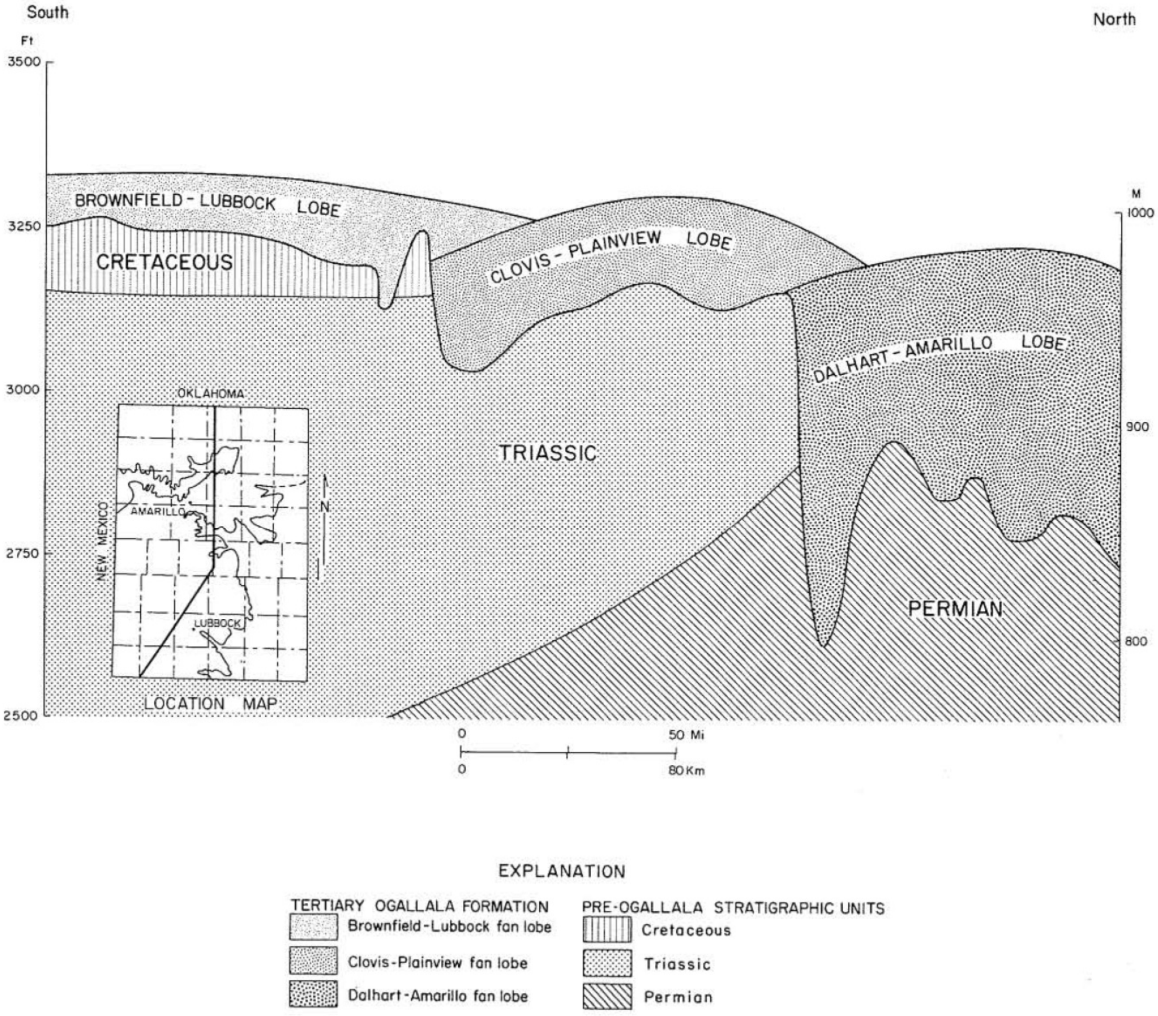


Figure 2.2.5 Schematic cross section showing overlapping alluvial fan lobes forming the Tertiary Ogallala Formation (from Seni, 1980).

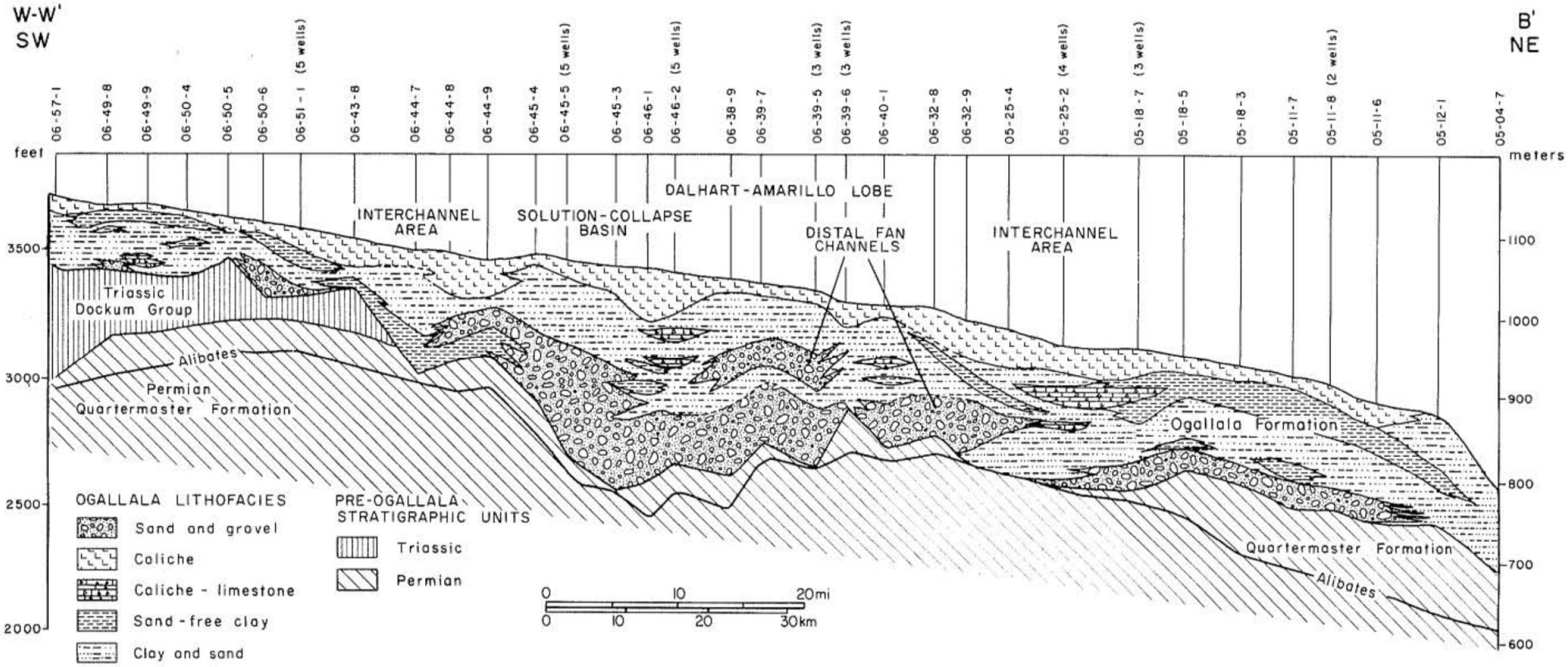


Figure 2.2.6 **Lithologic cross section showing the lithofacies in the Ogallala Formation (from Seni, 1980).**

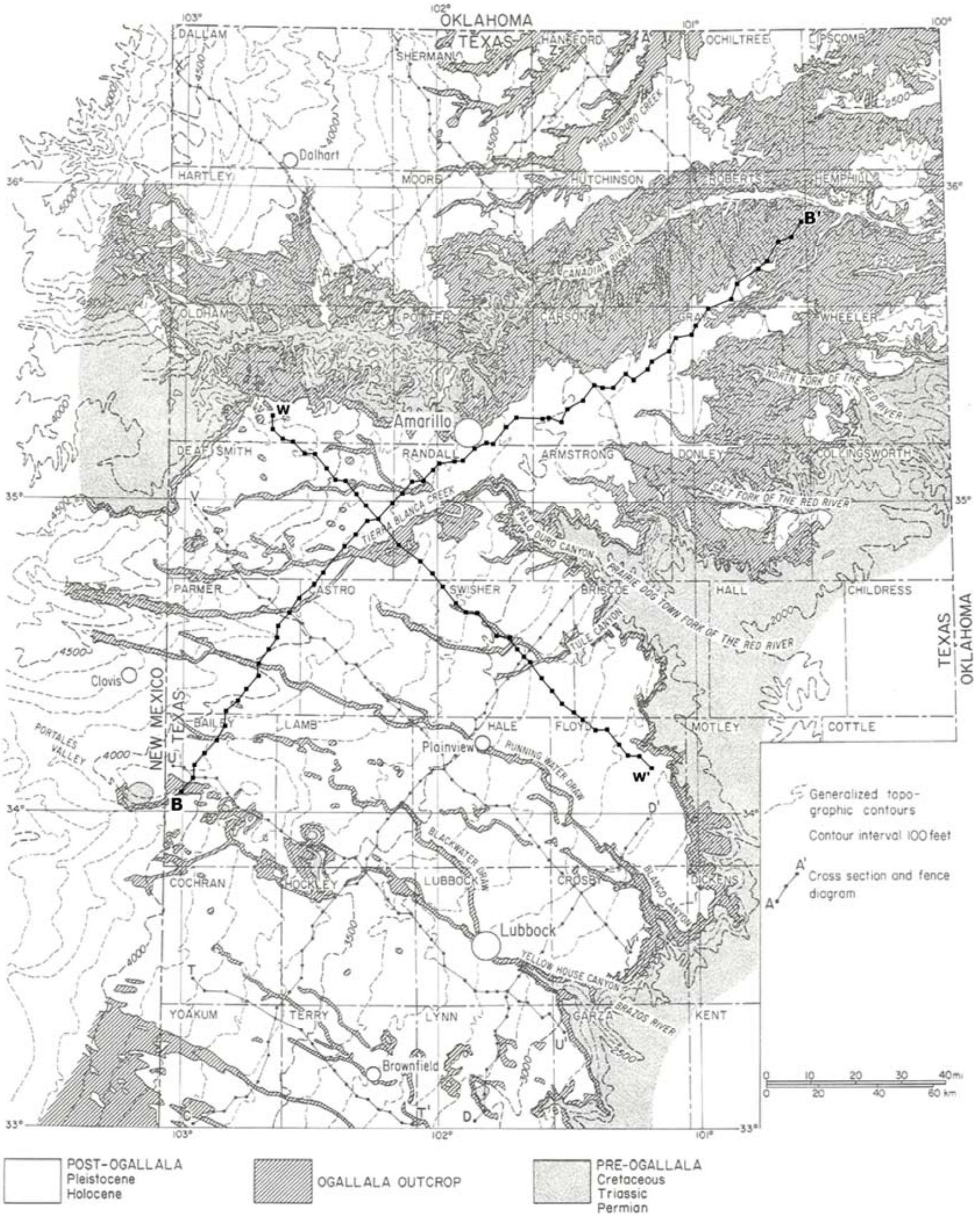


Figure 2.2.7 Location of the lithologic cross section shown in Figure 2.2.6 (from Seni, 1980 with relevant cross sections highlighted and re-labeled for clarity).

3.0 Previous Investigations

Numerous reports and papers documenting previous investigations of the formations composing the High Plains Aquifer System are available in the literature. A number of numerical models of the High Plains Aquifer System, or individual aquifers within the system, have been developed. The majority of the literature discusses the Ogallala Aquifer or the combined High Plains Aquifer System. This section provides a cursory review of the literature focusing on seminal works and/or relevant studies. The following discussion of previous investigations is divided into those related to geology and/or hydrogeology and those related to numerical modeling.

3.1 Previous Geologic and/or Hydrogeologic Investigations

Previous investigations related to the geology and hydrogeology of the High Plains Aquifer System are numerous. Several historical reports provide well-presented discussions of previous investigations. When available, those discussions are presented here. This section is divided into five subsections which discuss early investigations of the High Plains related predominantly to the portion in Texas and/or New Mexico, regional studies of the High Plains Aquifer System, studies specific to the Ogallala Aquifer, studies specific to the Edwards-Trinity (High Plains) Aquifer, and studies specific to the Dockum Aquifer. There are no previous investigations of the Rita Blanca Aquifer, however, the sediments composing this aquifer are discussed in several of the general High Plains investigations.

3.1.1 Early Investigations of the High Plains in Texas and/or New Mexico

In general, the early investigations of the High Plains provide an overview of geology and groundwater resources rather than detailed discussions of specific formations or aquifers. White and others (1940) provide a discussion of previous investigations conducted in the High Plains from 1900 to about 1939. The following is taken from their report.

> "*W.D. Johnson* [Johnson, 1901, 1902] *spent several years on the High Plains just prior to 1900 and published his findings in the 21st and 22nd Annual Reports of the U.S. Geological Survey. These relate in part to the ground-water resources. The geology and ground-water resources of the northern 20 counties of the Texas*

> *Panhandle were studied by C.N. Gould in 1904-05 and the results published in Water-Supply Papers 154 and 191 of the U.S. Geological Survey* [Gould, 1906, 1907]. *In 1909, O.E. Meinzer* [Meinzer, 1909] *made a brief study of ground-water on the High Plains in Portales Valley, New Mexico, and gave his conclusions in a manuscript report. C.L. Baker of the Texas Bureau of Economic Geology made a study of the geology and hydrology of a part of the region in 1914, and the following year published the results in Bulletin 57 of The University of Texas* [Baker, 1915]. *His report contains two chapters on ground water, and tables of water-well logs and water analyses, including information on the depth to water in a considerable number of wells, a part of which he determined by measurements.*
>
> *….A reconnaissance investigation of ground water in the High Plains of Texas and also of Kansas, Colorado, New Mexico, and Oklahoma was made by C.V. Theis, H.P. Burleigh, and H.A. Waite in 1933-34* [Theis and others, 1935]. *In this investigation a large amount of preliminary data was obtained, including well records and measurements of water levels in wells, of which several were located in Texas.*
>
> *During the last four years* [1936 to 1939] *inventories of water wells have been made in all or parts of … counties of the High Plains….The counties partly or fully covered by the inventories are Andrews, Armstrong, Bailey, Carson, Castro, Crosby, Dallam, Ector, Floyd, Glasscock, Hall, Hansford, Hartley, Hockley, Howard, Lamb, Lubbock, Martin, Midland, Ochiltree, Oldham, Parmer, Potter, Randall, and Roberts …. Dawson, Deaf Smith, and Swisher Counties and parts of Hale and Floyd Counties…Mimeographed bulletins giving tables of well records, well logs, and water analyses, together with a map showing the location of the wells, have been issued for all these counties."*

A series of progress reports on groundwater in the High Plains of Texas are provided in White and others (1940), Alexander and others (1943), Broadhurst (1944), Alexander (1945), White and others (1946), Broadhurst (1947), and Barnes and others (1949) (southern High Plains), and

Alexander (1961) (northern High Plains). These progress reports document investigations on the geology, source and extent of groundwater resources, use of groundwater for irrigation purposes, and changes in water levels.

A study of the geology and groundwater in the irrigated region of the southern High Plains in Texas was conducted by Barnes and others (1949). Their report provides brief discussions of the geology, recharge, natural discharge, water levels, water quantity, and water quality in the region. Also included in their report is a summary of the development of the groundwater resources in the irrigation region of the southern High Plains. Leggat (1951) provides a brief summary of the development of irrigation wells in the High Plains of Texas. He indicates that the use of wells for irrigation purposes began in 1911 and slowly increased to a total of 600 irrigation wells in 1936. The number of irrigation wells nearly doubled in 1937 and increased at a rate of 120 to 480 wells per year from 1938 through 1943. Over the period from 1943 through 1950, an additional 11,550 irrigation wells were drilled. Leggat (1951) states that the total number of irrigation wells in the Texas High Plains was 14,500 at the start of 1951. Of those wells, 14,000 were located in a 21-county region in the southern High Plains. He reports that the largest declines in water level have occurred in northwestern Floyd County and in Randall County southwest of the city of Amarillo. Additional discussions of water-level fluctuations and declines in this region are provided in Leggat (1954a, 1954b).

Numerous reports containing records of water-level measurements have been developed by the United States Geological Survey, the Texas Board of Water Engineers (TWDB predecessor), and the North Plains Ground Water Conservation District No. 2 (North Plains Ground Water Conservation District predecessor). In addition, reports documenting irrigation surveys for the High Plains of Texas in 1964 through 1977 by the Texas A&M Texas Agricultural Extension Service are available (New, 1964-1977).

Early reports documenting records of wells in many of the counties located in the study area were published by the Texas Board of Water Engineers. The references for those reports are provided in Table 3.1.1 by county. Several county-based investigations on water resources have also been published as documented in Table 3.1.1.

3.1.2 Regional Studies

A summary of the occurrence and development of groundwater in the southern High Plains of Texas is provided in Cronin (1961). He provides a summary of the geology and a brief discussion of water supply in the Dockum Group, Cretaceous Rocks, and Ogallala Formation. A more detailed discussion on the groundwater in the Ogallala Formation including hydraulic properties, groundwater movement, water level conditions, recharge, natural discharge, water in storage, and water quality is provided in Cronin (1961).

Knowles and others (1984) document the results of a regional groundwater study of the High Plains Aquifer system. This study was conducted by the Texas Department of Water Resources (TWDB predecessor) in cooperation with Texas Tech University and the water districts in the area. The purposes of the study were to "improve the data base describing the aquifer; to better describe the occurrence, operation, and use of the aquifer; and to develop a computer model of the aquifer." (Knowles and others, 1984). Their report describes the stratigraphy of the Ogallala Formation and associated water-bearing formations; describes the High Plains aquifer, including recharge, discharge, hydraulic characteristics, water quality, and water levels; describes the developed computer model; and presents the model results.

The High Plains Aquifer System was studied by the United States Geological Survey as part of their Regional Aquifer-System Analysis program. This study was one of the first conducted under this program. As a part of that study, the United States Geological Survey published a report on the geohydrology of the High Plains Aquifer provided in Gutentag and others (1984). That report provides a brief overview of development and production; a detailed discussion of the geology; a discussion of the groundwater hydrology; and a discussion of the quality of the groundwater.

3.1.3 Ogallala Aquifer

Nativ (1988) provides a discussion of the hydrogeology and hydrochemistry of the Ogallala Aquifer in the Texas panhandle and eastern New Mexico. She states that both of these aspects of the aquifer are primarily a function of the thickness, permeability, and mineralogy of the Ogallala Formation and the subjacent paleotopography. Nativ (1988) observed two hydrogeologic provinces in the Ogallala Aquifer; a thicker, more permeable section of the aquifer located in paleovalleys and a second thinner, less permeable section of the aquifer located between paleovalleys. She states that the hydrochemical composition of the groundwater in the first province is relatively constant. In the second province, the hydrochemical composition of the groundwater is variable due to cross formation flow from the underlying Cretaceous, Triassic, and Permian aquifers into the Ogallala Aquifer and the low permeability of the Ogallala Aquifer.

Based on high tritium values in the groundwater, Nativ (1988) suggests the possibility of rapid recharge to the Ogallala Aquifer in Hockley, Lamb, Lubbock, and Terry counties where the unsaturated zone is relatively thin. In the remaining portion of the aquifer, she found tritium values to be essentially zero and attributed these low values to the thicker unsaturated zone. Nativ (1988) indicates that recharge to the Ogallala Aquifer likely occurs from underlying aquifers where the hydraulic head in the underlying aquifer is higher than that in the Ogallala Aquifer and the two aquifers are in hydraulic connection. Natural discharge of water from the Ogallala Aquifer is reported by Nativ (1988) to be through springs, seeps, leakage to underlying formation, and possibly into adjacent formations east of the Eastern Caprock Escarpment.

Nativ (1988) used the chemical and isotopic composition of groundwater in the Ogallala Aquifer and underlying aquifers to trace cross-formation flow into and out of the Ogallala Aquifer. She identifies areas where the data indicate upward flow from the underlying Edwards-Trinity (High Plains) and Dockum aquifers and Permian-age formation into the Ogallala Aquifer. Nativ (1988) also compared the chemistry of groundwater in the Ogallala Aquifer to oil field brines to investigate contamination of the Ogallala Aquifer by oil field brines. She identified several places in Andrews, Howard, Gaines, and Hockley counties where contamination by oil field brines appears likely.

3.1.4 Edwards-Trinity (High Plains) Aquifer

Fallin (1989) conducted a study of the hydrogeology of the lower Cretaceous sediments under the southern High Plains of Texas and New Mexico. Provided in his report is a discussion of the geology, which includes the regional setting, tectonic history, and Cretaceous system stratigraphy and depositional history. He also presents a detailed discussion of the hydrogeology of the these sediments, which includes regional characteristics by water-bearing unit(s) (that is, Antlers Formation, combined Comanche Peak and Edwards formations, and combined Kiamichi and Duck Creek formations), regional recharge and discharge, and utilization and development. His discussions for each water-bearing unit include general features, pumping test data, water quality and chemistry, and regional storage.

An evaluation of the hydrogeology and hydrochemistry of the Cretaceous aquifers in the Texas panhandle and eastern New Mexico is provided in Nativ and Gutierrez (1988). They state that their study "is the first attempt to outline a hydrologic conceptual model of the Cretaceous aquifers beneath the Southern High Plains and to evaluate the role of these aquifers within the regional hydrologic system." Nativ and Gutierrez (1988) provide discussions of hydrologic setting, geologic framework, hydrogeology, and hydrochemistry. Their discussion of the geologic framework includes information on the lithologic characterization of the contact between the Cretaceous sediments and the sediments of the overlying and underlying Ogallala and Dockum aquifers, respectively, to identify locations where there may be continuous permeability across aquifers. Their section on hydrogeology includes a discussion of the potentiometric surfaces in the Cretaceous aquifers and the overlying Ogallala Aquifer and underlying Dockum Aquifer to identify the direction of potential flow between the aquifers. Discussions of recharge, discharge, and saturated thickness were also included in their hydrogeology section. Using groundwater chemistry and isotopic data, Nativ and Gutierrez (1988) created a hydrochemical facies map of the Cretaceous aquifer, evaluated the effects of vadose zone thickness on chemical composition, assessed recharge from precipitation, and evaluated the hydraulic communication between the Cretaceous aquifers and the overlying and underlying Ogallala and Dockum aquifers, respectively, and investigated areas of potential contamination.

3.1.5 Dockum Aquifer

A summary of previous investigations related to the Dockum Aquifer is available in Ewing and others (2008). The following is taken from that report.

> *"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 [of Ewing and others, 2008].

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. ….

…. 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).”*

Table 3.1.1 Summary of well records and water resources reports by county.

County	Records of Wells Report	Groundwater Resources Report
Andrews	George (1940a)	
Armstrong	George (1940b)	
Bailey	Turner (1937a)	
Borden	Ellis (1949)	
Briscoe		Popkin (1973b), Nordstrom and Fallin (1989)
Carson	Turner (1939a)	Gard (1958), Long (1961), McAdoo and others (1964)
Castro	George (1939a)	
Cochran		
Coke		Wilson (1973)
Collingsworth		
Crane		
Crockett		Iglehart (1967)
Crosby	George (1939b)	
Culberson		
Dallam	Turner (1937b)	Christian (1989)
Dawson		
Deaf Smith	Alexander (1946)	
Dickens		
Donley		Popkin (1973a)
Ector	Turner (1937c)	Knowles (1952)
Fisher		
Floyd	Follett and Dunte (1946)	Smith (1973)
Gaines	Cromack (1946)	Rettman and Leggat (1966)
Garza		
Glasscock	Turner (1937d)	
Gray		Long (1961), McAdoo and others (1964), Maderak (1973)
Hale	Merritt and Follett (1946)	Texas Board of Water Engineers (1960), Nordstrom and Fallin (1989)
Hall		Popkin (1973b)
Hansford	Turner (1936a)	
Hartley	Turner (1938a)	
Hemphill		
Hockley		
Howard		
Hutchinson		
Irion		

Table 3.1.1 continued

County	Records of Wells Report	Groundwater Resources Report
Jeff Davis		
Kent		
Lamb		
Lipscomb		
Loving		
Lubbock		
Lynn		Leggat (1952)
Martin	Turner (1936b)	
Midland	Turner (1938b)	Ashworth and Christian (1989)
Mitchell		Shamburger (1967)
Moore		
Motley		Smith (1973)
Nolan		Shamburger (1967)
Ochiltree	Turner (1939b)	
Oldham	White (1938)	
Parmer	Turner (1938c)	
Pecos		
Potter	Turner (1938d)	
Randall		
Reagan		Ashworth and Christian (1989)
Reeves		Ogilbee and others (1962)
Roberts	George (1940c)	
Scurry	Knowles (1946)	
Sherman		
Sterling	George and Dalgarn (1942)	
Swisher	Follett (1938)	Nordstrom and Fallin (1989)
Terry	Cromack (1944)	
Tom Green		
Upton		White (1968), Ashworth and Christian (1989)
Ward		White (1971)
Wheeler		Maderak (1973)
Winkler	George (1941)	Garza and Wesselman (1959)
Yoakum	Cromack (1945)	

3.2 Previous Numerical Models

This discussion of previous numerical models is divided into subsections discussing models of the High Plains Aquifer System and/or the Ogallala Aquifer, The Edwards-Trinity (High Plains) Aquifer, the Rita Blanca Aquifer, and the Dockum Aquifer. In addition, a final section summaries how the High Plains Aquifer System groundwater availability model will incorporate and improve upon previous models.

3.2.1 High Plains Aquifer System and Ogallala Aquifer Models

The primary aquifer in the High Plains Aquifer System is the Ogallala Aquifer. Dutton and others (2001a) provide a good discussion of previous models of the High Plains Aquifer System and the Ogallala Aquifer. The following was taken from that report.

> *"Few regional aquifers have been as extensively studied as the Ogallala aquifer (e.g., see regional hydrogeologic summaries by Gutentag and others, 1984; Knowles and others, 1984; Nativ and Smith, 1987). ... More than a dozen numerical groundwater flow models have been developed for different parts of the Ogallala aquifer in Texas (*[Figure 3.2.1]*). ... Each of the Ogallala models has had a specific purpose, and each has associated strengths and weaknesses (Mace and Dutton, 1998).*
>
> *... Nine of the models are regional in extent (*[Figure 3.2.1]*b-f) and were developed by State and Federal agencies, including the Texas Water Development Board (TWDB), U.S. Geological Survey (USGS), and Bureau of Economic Geology (Mullican and others [1997]). Since its initial development (Knowles, 1981), the TWDB model has been updated and converted from PLASM (Prickett and Lonnquist, 1971) to MODFLOW (McDonald and Harbaugh, 1988). Several of the models are local or subregional in scope; three address water-resource issues for one or a few counties (*[Figure 3.2.1]*a). The Ogallala aquifer was included in another model (3 in (*[Figure 3.2.1]*a) used in a study of a salt-dissolution zone.*
>
> *Claborn and others (1970) at Texas Tech University, in cooperation with the High Plains Underground Water Conservation District No. 1, developed the first Ogallala aquifer model in Texas as a management tool ((*[Figure 3.2.1]*a [1]). They used a polygonal finite-*

difference code developed by E. M. Weber of the California Department of Water Resources. They concluded that numerical models would be a valuable management tool for the aquifer but that high-quality data, especially accurate estimates of pumping, were lacking. Weaknesses of this model were its limited extent, limited calibration data, large block size, and artificial (nonhydrological) boundaries.

Knowles (1981, 1984) and Knowles and others (1982, 1984) developed northern and southern models of the Ogallala aquifer (([Figure 3.2.1]*b) for the TWDB using a modified PLASM code (Prickett and Lonnquist, 1971). The division into two models minimized the number of blocks in each model to reduce computation time, reflecting the constraint of computing power, which was markedly less in 1984 than now. Model results showed that the groundwater supply would be inadequate by the year 2030, given projected demand. After about 10 years, Peckham and Ashworth (1993) audited the model results and adjusted the recharge rates and updated pumping rates. Dorman (1996) and Harkins (1998) converted the models to run using MODFLOW, a widely used code that has a number of user-friendly pre- and postprocessors. Additional changes were made to internally calculate pumping rate adjustments on the basis of transmissivity and saturated thickness. The revised models showed a slight increase in water availability, perhaps related to boundary conditions or to changes in projected demand, but they still predicted an overall decline in water levels from 1990 to 2040. Harkins (1998) noted that even reducing irrigation pumping by half, 10 counties in the southern model area were at risk to severely deplete the aquifer.*

The strengths of the TWDB models include parameters based on hydrogeologic data and updated estimates of recharge and pumping rates. Weaknesses include continued limitations of input data, artificial western and northern boundaries, unrealistic relationships between surface and groundwater, and relatively coarse grids (block width of 4.66 km). Furthermore, the conversion between PLASM and MODFLOW versions of the models is questionable because of how the artificial boundary along the state lines is treated.

Luckey (1984) and Luckey and others (1986) developed models of the Ogallala aquifer as part of the USGS Regional Aquifer-System Analysis (RASA) program. The model for the southern and central parts of the U.S. High Plains includes the Ogallala aquifer in Texas ([Figure 3.2.1]*c). The models use the code by Trescott and others (1976), modified by Larson (1978) and Luckey and others (1986), to improve control over iteration parameters and buffer change in transmissivity (i.e., saturated thickness) between iterations and to consider constant gradient boundary conditions for an unconfined aquifer. The models included estimated return flows from irrigation. Sensitivity analysis showed that estimates of recharge were highly dependent on assigned values of hydraulic conductivity. Drawdown of more than 100 ft (>30 m) between 1980 and 2020 was predicted. Luckey and Stephens (1987) revisited the southern model ((*[Figure 3.2.1]*d) to determine the effect of reducing block width from 10 to 5 mi (~16 to ~8 km). The smaller block size resulted in small differences in predicted water levels but the same general conclusions. The USGS models include data based on hydrogeologic studies, consider return flow, and have natural boundaries. Weaknesses include how surface and groundwater are related and a very coarse grid. Luckey and Becker (1999) covered part of the area included in the central RASA model (compared (*[Figure 3.2.1]*c and (*[Figure 3.2.1]*f). That model has 6,000-ft (~1.8-km) block widths and a single layer and was updated with hydrogeologic data collected during the 1980's.*

Mullican and others (1997) investigated both the role of playas in recharging the Ogallala aquifer and advective movement of solutes. Their model was bounded to the north by a major river (([Figure 3.2.1]*e). Block width was variable, ranging from 0.25 to 1 mi (~0.4 to ~1.6 km). The model was calibrated first for steady-state conditions and then for transient conditions through to 1990. Results showed that simulated water level was independent of spatial distribution of recharge in the model, whether focused at playas, distributed discretely through zones, or spread uniformly across the surface. The Mullican and others (1997) model includes a more realistic treatment of aquifer boundaries. Limitations of input data, especially transmissivity, are an inherent weakness of this model, as well as other models. Because the purpose of the model was to evaluate recharge scenarios and transport of contaminants, there are no predictions of water levels in response to future pumping. However, the Mullican and others (1997) model had to*

> *assign smaller pumping rates than those used by Knowles and others (1984), which caused excessive drawdown."*

Several numerical models of the Northern Ogallala Aquifer have been developed with MODFLOW for the purpose of assisting the Panhandle Regional Water Planning Area (RWPA) in assessing groundwater availability. They include the models of Dutton and others (2000, 2001a, 2001b), Dutton (2004), and INTERA and Dutton (2010) (Figure 3.2.1f). The first model of Dutton and others (2000, 2001b) and the recalibrated model of Dutton and others (2001a) were developed to replace a water-balance model previously used by the Panhandle Regional Water Planning Area. The numerical models provided a more accurate and precise method for estimating groundwater in each of the Region's counties based on predicted future pumping. Recalibration of the model occurred to improve the calibration in several counties within the Region. The TWDB adopted the Dutton and others (2001a) model as the groundwater availability model for the Northern Ogallala Aquifer.

The model of Dutton and others (2001a) was updated by Dutton (2004) using modified parameters including adjustments to the base of the Ogallala Aquifer, adjustments to the assignment of recharge rates, adjustments to the parameters defining the MODFLOW drains and general head boundaries, and minor modifications to hydraulic conductivity. The purpose of the 2004 update was to improve the model calibration. The model was again updated in 2010 by INTERA and Dutton (2010) for the Panhandle Regional Water Planning Area. The purpose of the 2010 update was to incorporate revised model parameters and pumping estimates in order to support planning activities in the 2011 planning cycle. The specific revisions included (1) addition of historical pumping data from 1999 through 2008 and revised future demand estimates through 2060, (2) incorporation of additional data on aquifer properties including hydraulic conductivity, elevation of the base of the Ogallala Aquifer, and specific yield, and (3) incorporation of research on recharge rates in the region that occurred after development of the Dutton (2004) model.

Three models designed to assess groundwater availability have been developed for the southern portion of the Ogallala Aquifer. The model by Stovall (2001) and Stovall and others (2001) was developed for the Llano Estacado Regional Water Planning Area to use as a management tool and assess groundwater resources in the 21 counties comprising that area (Figure 3.2.1d). The basis for that model was the model of Harkins and others (1998), but it included some significant changes to the model grid, domain, and boundary conditions; model parameters; and initial conditions. Blandford and others (2003) developed a groundwater availability model of the southern portion of the Ogallala Aquifer for the TWDB (Figure 3.2.2). Their model differs from previous models of the Southern Ogallala Aquifer in that it uses (1) a finer grid, (2) hydraulic conductivity data from interpretations of specific-capacity tests, (3) newly estimated detailed irrigation pumping for 1982 through 1997, and (4) refined inputs for the New Mexico portion of the model. The groundwater availability model of Blandford and others (2003) was updated in conjunction with development of the groundwater availability model of the Edwards-Trinity (High Plains) Aquifer by Blandford and others (2008). They included both aquifers in their model because they are hydraulically connected in some regions. Changes were made in the updated model to improve or maintain calibration for the Ogallala Aquifer. These changes included “selected adjustments to agricultural pumping, some updates to City of Lubbock historical pumping, and some updates to post-development recharge in the vicinity of Lubbock” (Blandford and others, 2008).

Two models of the High Plains Aquifer System have been developed which focus on portions of New Mexico (Musharrafieh and Chudnoff, 1999; Musharrafieh and Logan, 1999). The extents of these models, which were developed by the New Mexico Office of the State Engineer, are illustrated in Figure 3.2.1g. Both models use a single layer to represent the High Plains Aquifer System, which includes portions of the Dockum Aquifer that are hydraulically connected to the overlying Ogallala Aquifer. Senger and others (1987) developed a two-dimensional, cross-section model of the Palo Duro Basin (Figure 3.2.1g). 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.

3.2.2 Rita Blanca Aquifer Models

While portions of the Rita Blanca Aquifer hydraulically connected to the overlying Ogallala Aquifer have been included in previous regional models of the High Plains Aquifer System, it is not generally treated as a separate aquifer. For example, the groundwater availability model of the Northern Ogallala Aquifer developed by Dutton and others (2001a) incorporated all sediments from the surface to the top of the Dockum Group. Therefore, portions of the Rita Blanca Aquifer were included in that model by default. However, the Rita Blanca Aquifer was not analyzed as a unique aquifer but, rather, treated as part of the Ogallala Aquifer. An independent groundwater availability model of the Rita Blanca Aquifer has not been developed.

3.2.3 Edwards-Trinity (High Plains) Aquifer Models

Blandford and others (2008) state the following regarding modeling of the Edwards-Trinity (High Plains) Aquifer prior to their work.

> *"No previous comprehensive modeling studies have been completed for the Edwards-Trinity (High Plains) Aquifer. Previous modeling studies that encompass the aquifer (e.g., Luckey and others, 1986; Knowles and others, 1984; Peckham and Ashworth, 1993; Stovall and others, 2001; Blandford and others, 2003) focused primarily on the Ogallala Aquifer and have only considered the Edwards-Trinity (High Plains) Aquifer (1) where the uppermost permeable portions of the Edwards-Trinity (High Plains) Aquifer are in direct hydraulic communication with saturated Ogallala sediments (e.g. Gaines County) or (2) where Ogallala sediments are not saturated and the water table lies within permeable Cretaceous sediments that underlie the Ogallala Formation. This latter scenario is prevalent along the southern and southeastern margin of the Southern High Plains (Blandford and Blazer, 2004)."*

Therefore, the groundwater availability model of the Edwards-Trinity (High Plains) Aquifer developed by Blandford and others (2008) was the first model to focus on and simulate the entire aquifer.

3.2.4 Dockum Aquifer Models

Portions of the Dockum Aquifer hydraulically connected to the overlying Ogallala Aquifer were included in previous regional models of the High Plains Aquifer System. The Dockum Aquifer was also explicitly incorporated into the cross-section model of Senger and others (1987), but was not the focus of their model.

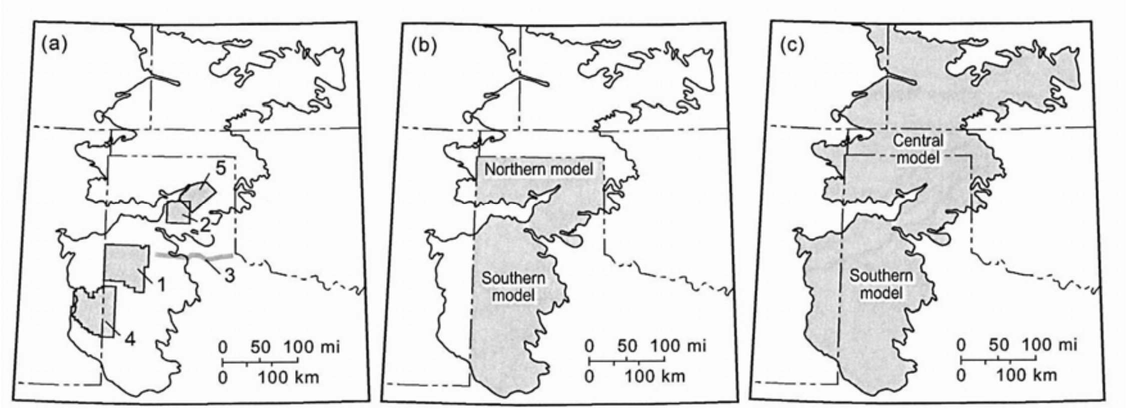
The first three-dimensional numerical model focused on only the Dockum Aquifer in Texas is the groundwater availability model of Ewing and others (2008), the boundary of which is shown in Figure 3.2.2. This model was developed using MODFLOW 2000 and consists of three layers. The upper layer rudimentarily 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 was calibrated for two time periods, one representing steady-state conditions and the other representing transient conditions. A sensitivity analysis was performed to determine which parameters have the most influence on model performance and calibration. A recalibration of this model by the TWDB is documented in Oliver and Hutchinson (2010).

A local-scale model of the Dockum and Edwards-Trinity (Plateau) aquifers was conducted by HDR Engineering (2009) for the Brazos G Water Planning Group in Mitchell and Nolan counties, Texas (see Figure 3.2.2). The purpose of that model was to develop “a tool to evaluate groundwater supplies in western Nolan and eastern Mitchell counties” and focuses on the city of Sweetwater’s Champion well field. The model was calibrated to steady-state and transient conditions. Verification of the model was conducted along with several predictive simulations for the time period 2008 to 2060.

3.2.5 Key Model Improvements

The groundwater availability model for the High Plains Aquifer System aims to both incorporate and improve upon the work done in previous models. To that purpose, it will integrate the most recent MODFLOW numerical groundwater availability models prepared for aquifers in the High Plains Aquifer System. These models include the INTERA and Dutton (2010) update of the Northern Ogallala Aquifer groundwater availability model, the Blandford and others (2008) groundwater availability model of the Edwards-Trinity (High Plains) and Southern Ogallala aquifers, and the Ewing and others (2008) groundwater availability model of the Dockum Aquifer. The purpose of combining these existing models into one consistent multi-aquifer groundwater availability model is to provide a resource for making water planning decisions based on the entire aquifer system rather than just isolated aquifers. For example, cross-formational flow is an important consideration in the process of deciding Desired Future Conditions. The High Plains Aquifer System groundwater availability model will provide a valuable framework for making those decisions that existing models cannot provide.

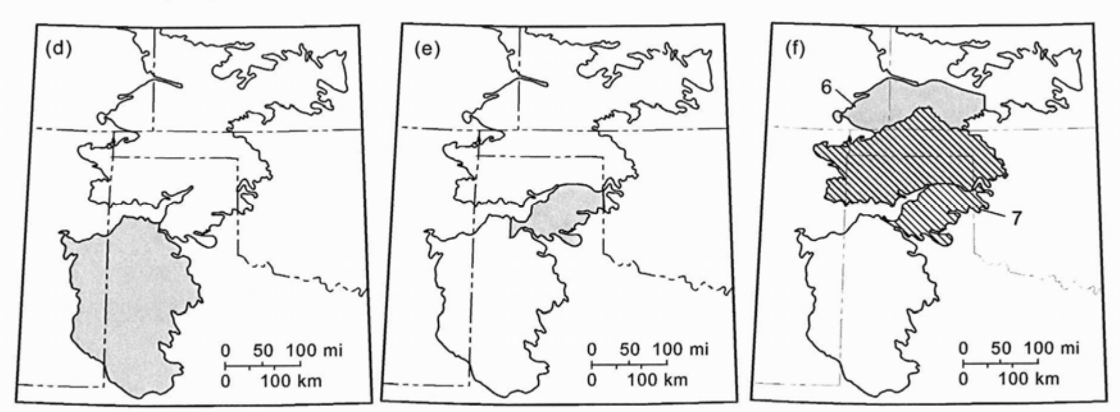
In addition to consolidating all available information from existing models, the current model also aims to improve upon existing datasets by adding new information where available. The current model develops an improved and more consistent hydrostratigraphic framework based on new structural picks from logs in the TWDB Brackish Resources Aquifer Characterization System database and provided by Groundwater Conservation Districts in the study area, including the High Plains Water District, the Panhandle Groundwater Conservation District, and the North Plains Groundwater Conservation District (see Section 4.2). The current model also seeks to improve on existing historical pumping estimates, since these are often an uncertain but vital element of groundwater availability models. For this reason, streamlined tools were created for estimating historical pumping estimates (see Section 4.7), incorporating new information from Groundwater Conservation Districts and utilizing more consistent methodology. The current model also attempts to improve the implementation of recharge in a way that more accurately reflects the local environmental differences apparent across the region. The current model considers a variety of factors, including soil characteristics, chloride mass balance information, and nitrate measurements to adjust recharge on a more localized level (see Section 4.4). This methodology also allows a more in-depth analysis of irrigation return flow, which has not been addressed in detail by previous regional groundwater availability models.



1. Claborn and others (1970)
2. Bell and Morrison (1979)
3. **Simpkins and Fogg (1982)**
4. McAda (1984)
5. Mullican (1995)

Knowles and others (1982, 1984)
Knowles (1984)
Peckham and Ashworth (1993)
Dorman (1996), Harkins (1998)
Harkins and others (1998)

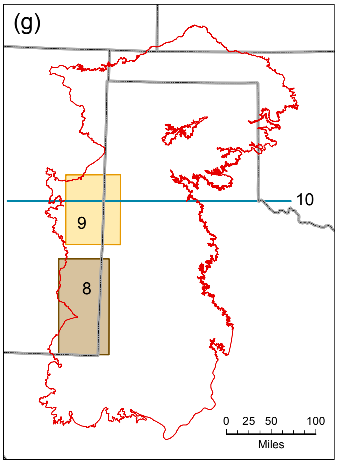
Luckey (1984)
Luckey and others (1986)



Luckey and Stephens (1987)
Stovall (2001)
Stovall and others (2001)

Mullican and others (1997)

6. **Luckey and Becker (1999)**
7. Dutton and others (2000, 2001a, 2001b), Dutton (2004), INTERA and Dutton (2010)



8. **Musharrafieh and Chudnoff (1999)**
9. **Musharrafieh and Logan (1999)**
10. **Senger and others (1987)**

Figure 3.2.1 Location and area of coverage of previous models of the High Plains Aquifer System (blue text) and the Ogallala Aquifer (black text) (after Dutton and others, 2001b).

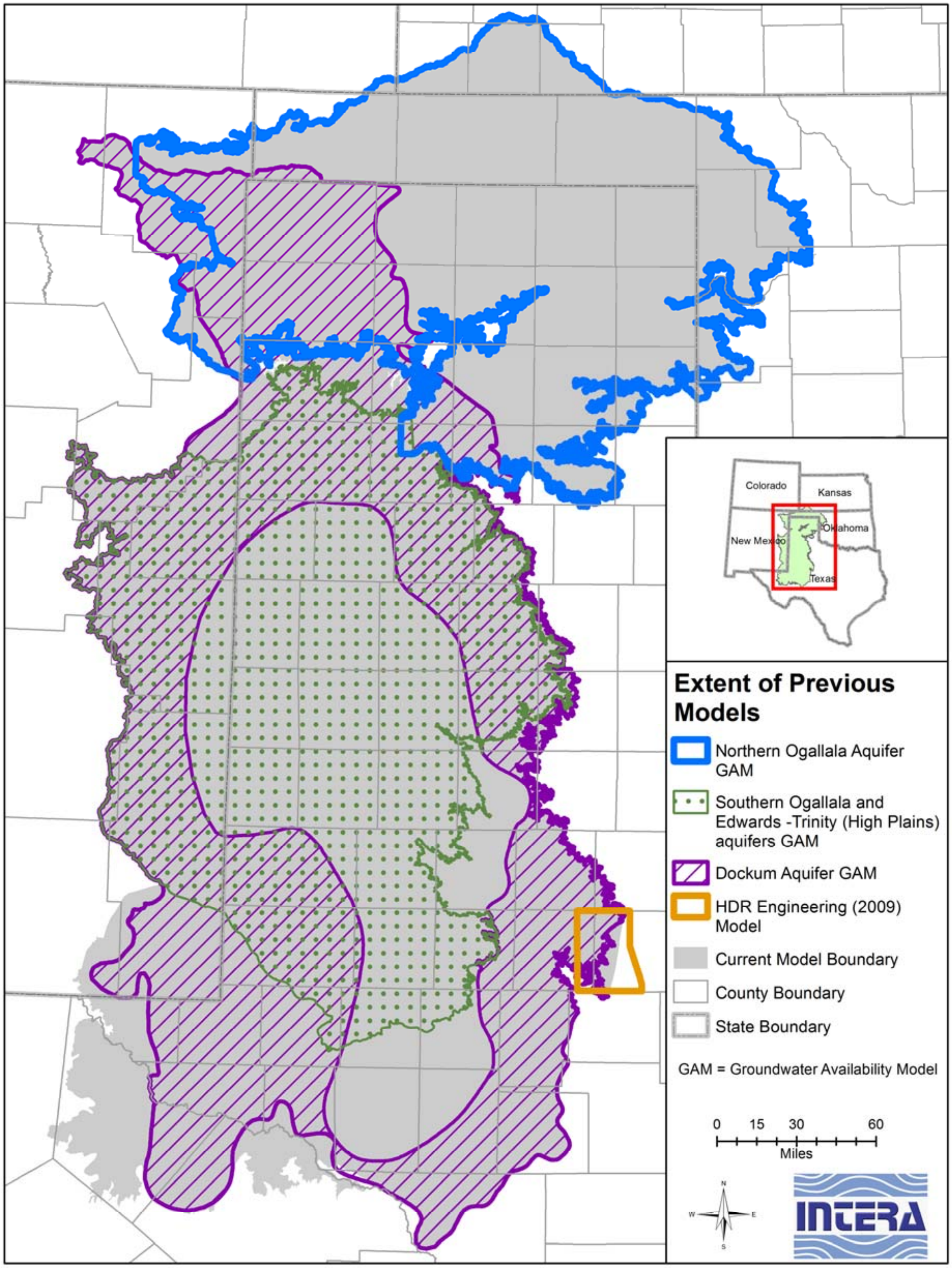


Figure 3.2.2 Boundaries of previous groundwater availability models for the Northern and Southern Ogallala Aquifers, the Edwards-Trinity (High Plains) Aquifer, and the Dockum Aquifer and for the HDR Engineering (2009) model.

4.0 Hydrologic Setting

4.1 Hydrostratigraphy

The geologic formations in the High Plains Aquifer System are grouped into four hydrostratigraphic units that define the model layers (Table 4.1.1). The aquifer system as a whole ranges from 0 to 3,105 feet in thickness and has an average thickness of 910 feet. The aquifer system is thickest in the south and thinnest in the Canadian River valley and along the eastern margin (Figure 4.1.1). Thickening and thinning are mostly related to subsidence and uplift, respectively, of the underlying Permian surface. Regional schematic cross sections, which are based on our geophysical log correlations, show thickness variations in the hydrostratigraphic layers of the High Plains Aquifer System. Figure 4.1.2 shows the location of the regional cross sections, which are shown in Figures 4.1.3 and 4.1.4.

While the hydrostratigraphy of the Dockum Group is quite complex, a common approach divides it into upper and lower units. The lower Dockum Group is more extensive than the upper Dockum Group (Figures 4.1.3 and 4.1.4). The upper Dockum Aquifer is entirely confined except for small surface exposures along the western margin of the High Plains Aquifer System. The lower Dockum Aquifer is mostly confined except for surface exposures in the Canadian River Valley and in the southeast (see Figure 2.2.1). Both Dockum Group layers are composed of complexly interbedded sandstone and shale, although in general, both are sandier in their lower parts (see Figure 2.2.4).

Cretaceous (and minor Jurassic) formations overlie the Dockum Group across large parts of the High Plains Aquifer System. In the northwest, the Rita Blanca Aquifer overlies the upper Dockum Aquifer and is overlain by the Ogallala Aquifer (Figure 4.1.3). The Rita Blanca Aquifer is composed of complexly interbedded sandstones and shales. The Rita Blanca Aquifer is exposed at the surface locally in northeast New Mexico and is in hydraulic communication with the overlying Ogallala Aquifer in Dallam County, Texas (Christian, 1989). The Rita Blanca, Edwards-Trinity (High Plains), and Edwards-Trinity (Plateau) aquifers are all at the same hydrostratigraphic level (Table 4.1.1), but are separated geographically from each other by many miles (see Figure 2.0.2) and are not in contact with each other (see Figure 4.1.3). The Edwards-Trinity (High Plains) aquifer is generally composed of sandstone overlain by limestone overlain by clay/shale. However, there are some portions of the aquifer where either the limestone layer is absent (northwestern portion of the aquifer) or the clay/shale layer is absent (southern and far eastern portion of the aquifer). Where the shale layer is present, it generally serves as a confining unit for the lower layers of the aquifer (Blandford and others, 2008). The Edwards-Trinity (Plateau) Aquifer overlies the Dockum Aquifer and generally comprises limestone underlain by sandstone. In areas where it is overlain by either the Pecos Valley or Ogallala aquifers, the Edwards-Trinity (Plateau) Aquifer is hydraulically connected to these aquifers (Anaya and Jones, 2009).

Tertiary and Quaternary formations form the upper layer of the High Plains Aquifer System (Table 4.1.1). The Ogallala and Pecos Valley aquifers, which are both composed primarily of unconsolidated sand, gravel, and clay, are at the same hydrostratigraphic level and contact each other (Meyer and others, 2012). This uppermost layer is entirely unconfined and overlies various other layers depending on location (see Figures 4.1.3 and 4.1.4). The Ogallala Aquifer layer is mostly separated into northern and southern parts by the Canadian River valley.

The Pecos Valley and Edwards-Trinity (Plateau) aquifers overlie the Dockum Aquifer in portions of the study area to the south, so structural tops and bottoms for these aquifers were determined where the Dockum Aquifer exists. However, because the Pecos Valley and Edwards-Trinity (Plateau) aquifers are not explicitly modeled in the High Plains Aquifer System groundwater availability model, lithology was not determined for these aquifers.

Table 4.1.1 Model layers defined by hydrostratigraphic units.

System	Formation		Aquifer	Model Layer		
				North	Central	South
Quaternary	Pecos Valley Alluvium		Pecos Valley			1
Tertiary	Ogallala		Ogallala	1	1	
Cretaceous	Duck Creek(1)	Boracho(2)	Edwards – Trinity		2(1)	2(2)
	Kiamichi(1)	Finlay(2)				
	Edwards(1)					
	Comanche Peak(1)					
	Walnut(1)					
	Antlers					
Jurassic	Morrison		Rita Blanca	2		
	Exeter					
Triassic	Cooper Canyon		Upper Dockum		3	3
	Trujillo					
	Tecovas		Lower Dockum	4	4	4
	Santa Rosa					
Permian	Dewey Lake			No Flow		
	Rustler		Rustler			

(1) Edwards-Trinity (High Plains) Aquifer represented by layer 2 in the central portion of the model domain.
(2) Edwards-Trinity (Plateau) Aquifer represented by layer 2 in the southern portion of the model domain.

Note: Gray-shaded areas indicate that the formation is not present in the corresponding portion (north, central, or south) of the model.

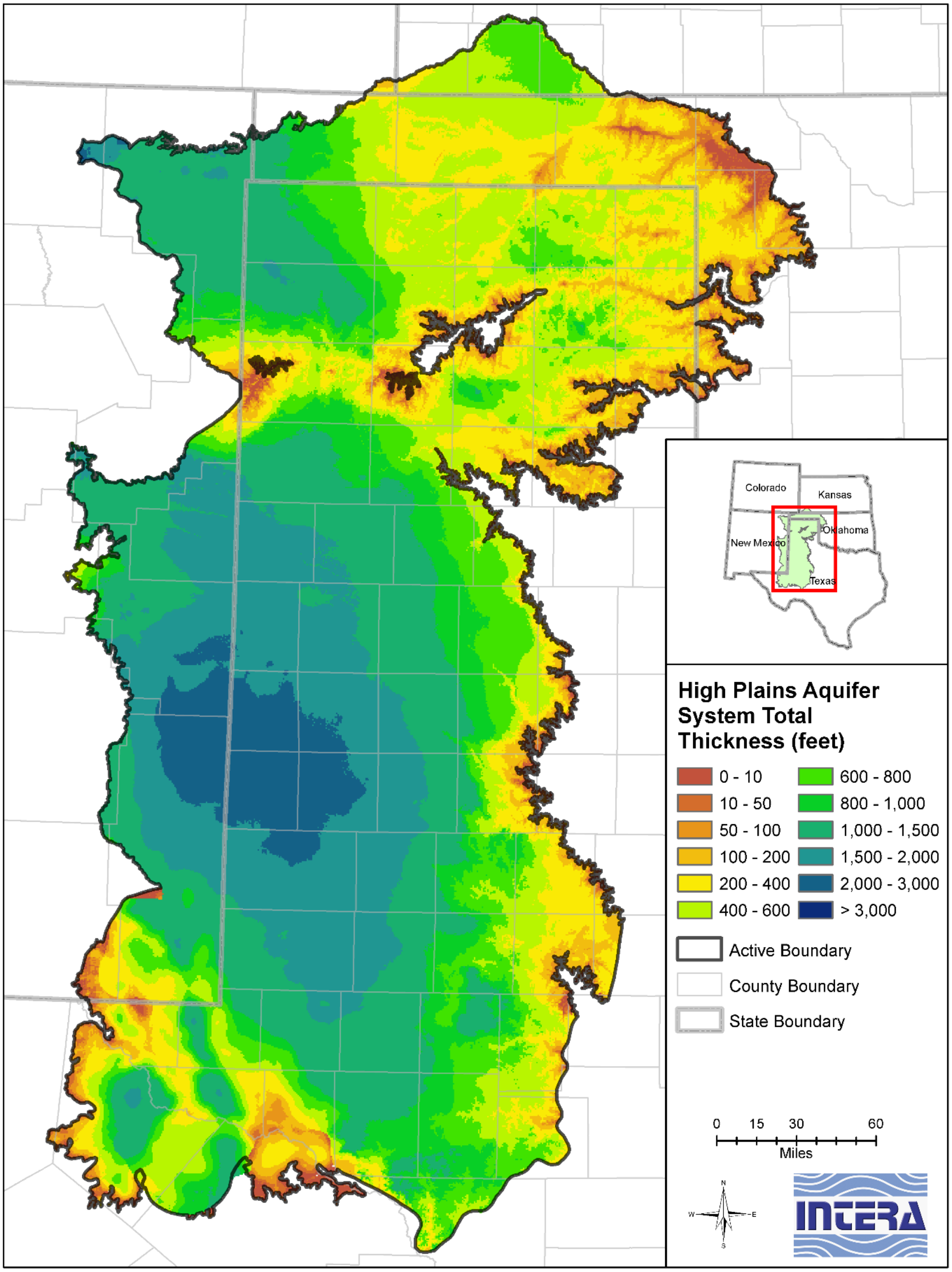


Figure 4.1.1 Depth to the top of Permian sediments, equivalent to the combined thickness of all formations comprising the High Plains Aquifer System.

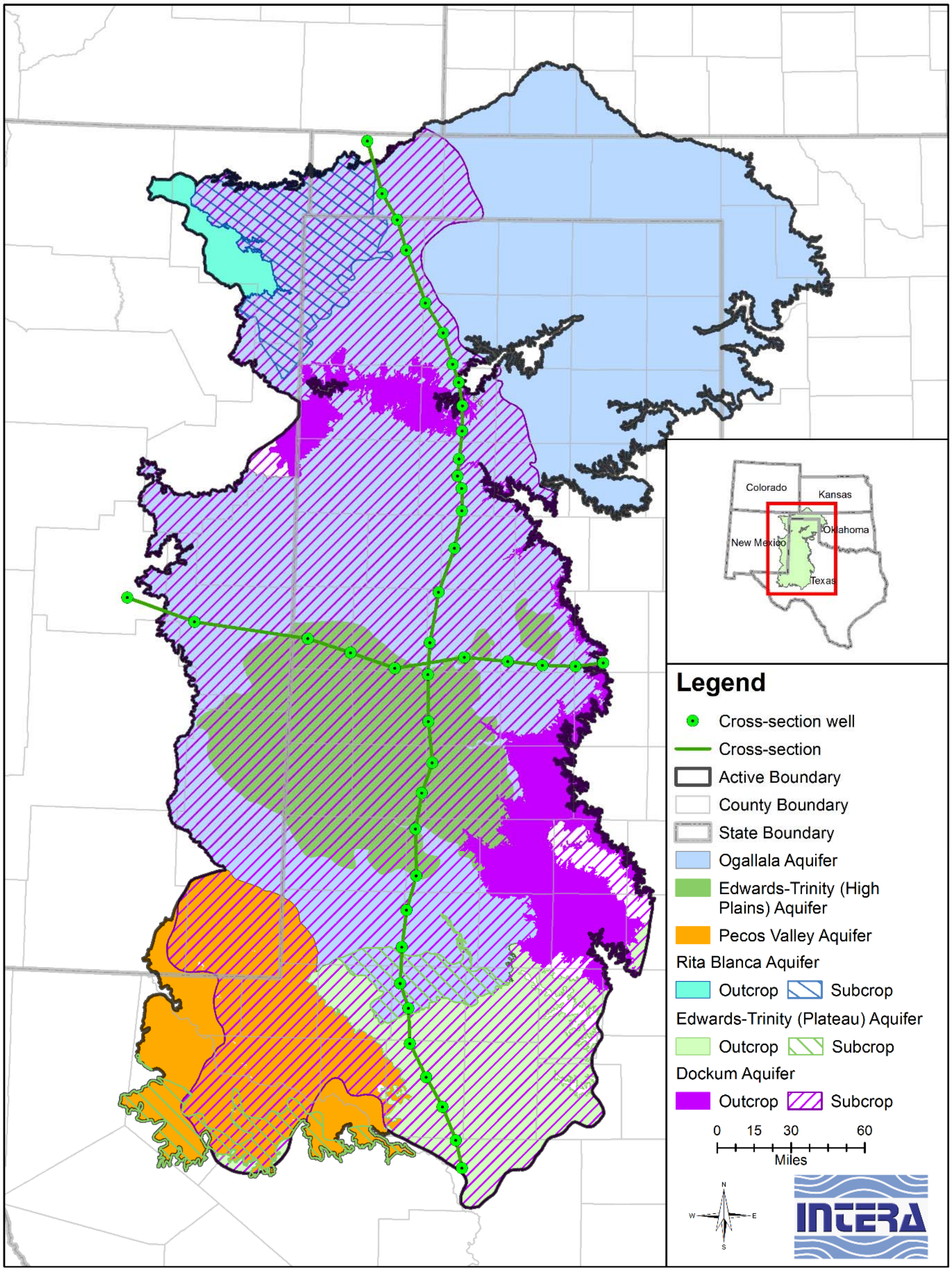


Figure 4.1.2 Location of regional cross sections shown in Figures 4.1.3 and 4.1.4.

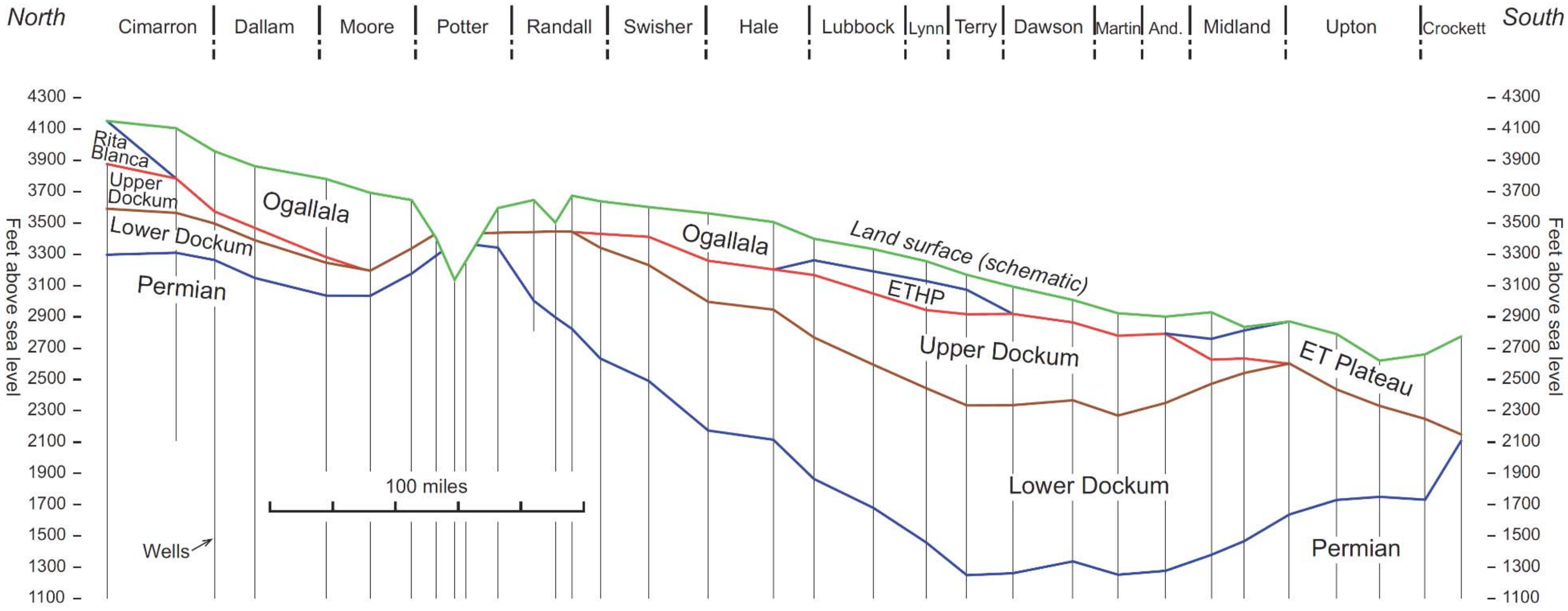


Figure 4.1.3 **North-south regional cross section for the High Plains Aquifer System. Abbreviation key: ETHP = Edwards-Trinity (High Plains) Aquifer, ET Plateau = Edwards-Trinity (Plateau) Aquifer.**

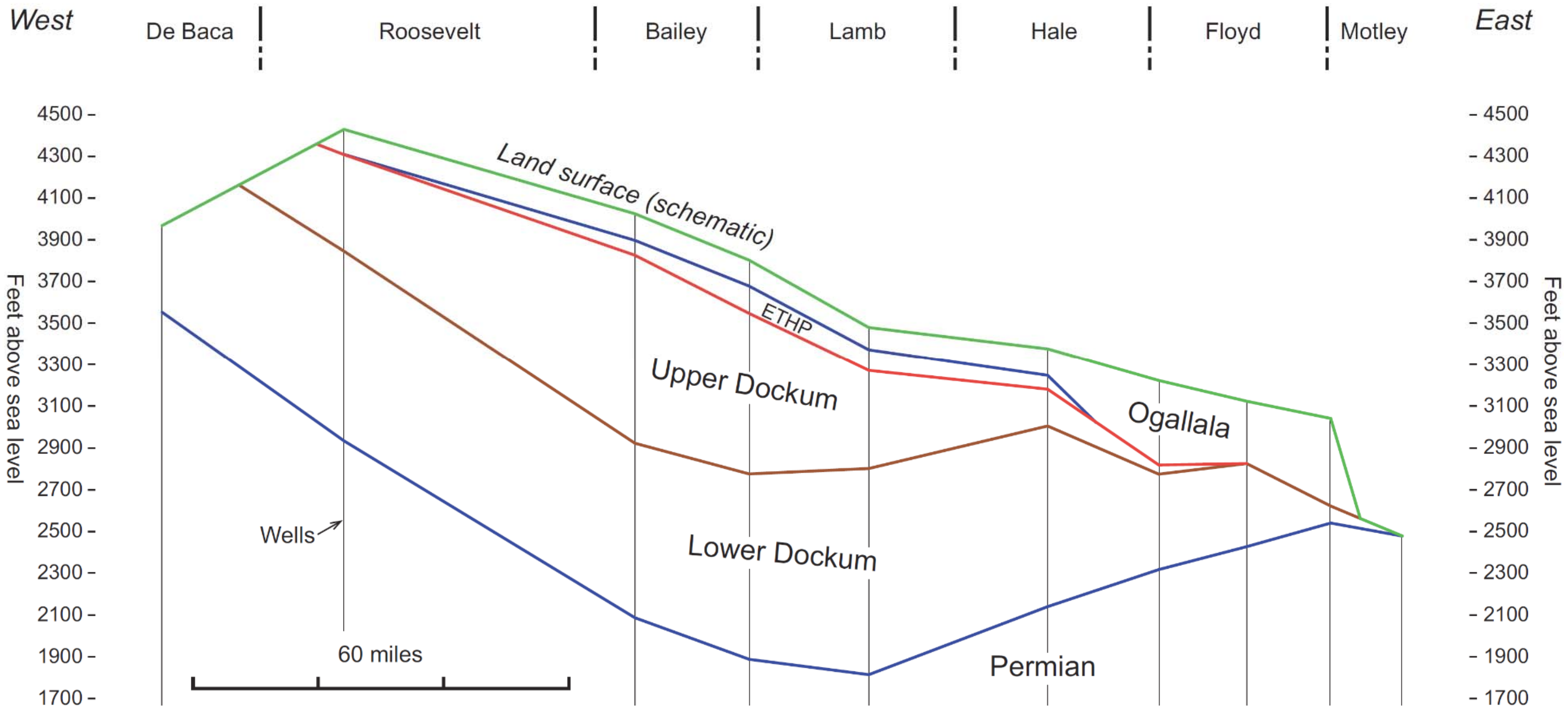


Figure 4.1.4 **East-west regional cross section for the High Plains Aquifer System. Abbreviation key: ETHP = Edwards-Trinity (High Plains) Aquifer.**

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4.2 Hydrostratigraphic Framework

The structure of the Permian surface forms a large subsidence basin, which is filled by the formations of the High Plains Aquifer System. Superimposed on this greater Permian Basin are smaller basins and uplifted areas (see Figures 2.2.2 and 4.1.1). High Plains Aquifer System layer thicknesses are clearly related to Permian structural features, filling subsidence basins and thinning over uplifted areas and, subsequently, during the Tertiary, the entire region was tilted eastward and southward (Figures 4.1.3 and 4.1.4). This section describes the structural surfaces and lithologies of each hydrostratigraphic layer as determined by geophysical log analysis.

4.2.1 Data Sources

Geophysical well logs were used to correlate formation boundaries and estimate lithology thicknesses. Large amounts of time and effort were spent up front searching for and evaluating the quality of well logs. Due to the variety of log sources and the large amount of older and low-image-quality logs, an extensive depth calibration process was undertaken to ensure vertical consistency between logs. Essentially, the depth calibration process assigned the geophysical log image to an actual x,y,z point in real space. The resulting depth-calibrated logs can subsequently be “hung” on cross-sections and correlated with each other. In addition to depth calibrating all of the logs, ones that appeared compressed or stretched vertically were resized to match the actual depth values written on the log file. The final database includes 2,050 well logs (Figure 4.2.1). Sources of well logs were the TWDB’s Brackish Resources Aquifer Characterization System database, the Bureau of Economic Geology Geophysical Log Facility, commercial suppliers, the Railroad Commission of Texas (recently drilled wells), the University of Texas Lands Office, the New Mexico Oil Conservation Division, the City of Amarillo, and the City of Canyon.

All of the geophysical logs have gamma-ray curves and most also have resistivity curves. Some logs have sonic or neutron curves instead of resistivity curves. Most logs were run in oil and gas wells, but 31 logs were run in water wells. The well log database is primarily composed of electronic image (TIFF) files. We prepared and interpreted logs and displayed results using commercially available Petra software (IHS, Inc.). Petra is a GIS-type program that specializes in spatial data from wells. Although the image files are just pictures of well logs, the depth-calibration process in Petra allows us to associate these images with actual elevation and depth values. Structural and lithologic interpretations were made directly on the corrected images and these elevation, depth, and thickness picks were automatically saved in the main Petra database. The geophysical log database also includes digital gamma-ray and resistivity curves for 108 wells. Digital logs are electronic files of quantified log responses recorded every half foot of depth. Information can be extracted wholesale from digital logs without painstaking visual examination. Most of the digital log locations are plotted on the cross sections in Figure 4.2.1.

4.2.2 Geophysical Log Analysis

To correlate formation boundaries between wells and to estimate lithology, we used all available log curves, although gamma-ray curves provided the most information. The gamma-ray curve graphs the amount of natural radiation at a given depth. Nuclear decay of uranium, thorium, and potassium are the major sources of natural gamma radiation in rocks and sediments. Potassium-bearing clay produces more gamma radiation than does quartz sand. Although other variables, such as uranium minerals and potassium feldspars, complicate the clay/sand control on gamma radiation, the gamma-ray curve is still the main geophysical log for estimating lithology in west Texas. Meyer and others (2012) present a good explanation of the use of gamma-ray logs, covering their strengths and weaknesses. The main drawbacks of gamma-ray logs are cased hole recordings, incomplete coverage of shallow intervals, and uncalibrated, nonstandardized results. Gamma radiation is attenuated when recorded through cement casing, and the casing itself may produce variable radiation, further obscuring real rock signals. Most wells are not logged completely to surface, although we were careful to include in our final database the shallowest logs available: 1,560 of our logs extend to within 50 feet of the surface, and 963 of those extend to the surface. Nonstandard gamma recording instruments used over 70 years makes it difficult to calibrate responses or to compare them between wells.

Resistivity logs respond mainly to compositional variations in pore fluids. Resistivity logs measure resistance to an induced electrical current. Resistivity is the inverse of conductivity, which is commonly measured in groundwater samples. Freshwater is more resistive than saline water, and oil is more resistive than water. However, lithology and porosity also influence resistivity response. Clay minerals are less resistive than quartz or calcite because of free electric charges on their surfaces. Permeable sandstone is less resistive than impermeable limestone. We attempted to use resistivity logs for water quality mapping but were unable to confidently interpret a sufficient coverage of logs for meaningful mapping. In general, Dockum Group sandstones display low resistivities and Ogallala Formation sandstones display high resistivities, but mappable patterns were not evident. The resistivity/water quality relationship has been used successfully in the Gulf Coast and east Texas (Collier, 1993). West Texas formations, however, have more complex lithologies, and west Texas well loggers employ different logging practices. Unlike gamma-ray logs, resistivity logs are not run in cased holes, which limits the available database. Only 732 resistivity logs were available for analysis.

4.2.3 Surface Correlation

We used standard well log correlation techniques to identify formation boundaries (surfaces) on every log. In the High Plains Aquifer System, model layers coincide with geologic formations (Table 4.1.1). Fortunately, the stratigraphy of these formations has been well defined by both surface (outcrop) and subsurface studies. Previous subsurface studies were based on either water well drillers' logs or geophysical logs. Drillers' logs are well sample descriptions. The main advantage of using drillers' log data is the high density of available logs. Seni (1980), for example, used over 15,000 drillers' logs to map the Ogallala Formation. The main disadvantage of drillers' logs is that they are not correlatable between wells in the same way that geophysical logs are. Geophysical logs are continuous records of vertical changes in multiple rock and fluid properties. Many of these vertical property changes reflect subtle horizontal layering, which is continuous laterally on scales of a few feet to many miles. This layering can be correlated between wells by matching similar patterns in log curves. In this study, gamma-ray curves and resistivity curves were most useful for correlation. Correlation allows us to trace formations from wells in which tops are known to wells in which they are not yet established.

The geophysical log correlation process starts with documenting tops on specific logs and confirming that these tops are generally agreed as correct. We used several published sets of cross sections in which log curves are shown (Granata, 1981; Bebout and Meador, 1985; McGookey and others, 1988) (Figure 4.2.2). Ashworth and Christian (1989) present additional reference logs for the southeast part of the study area. These reference geophysical logs cover all of the formations in the High Plains Aquifer System. We then correlated tops from reference logs through all of the logs in our database. The process was iterated until a best fit was established. We supplemented reference logs with additional studies in which formations are precisely defined. Broadhead (1984) and Holbrook and Dunbar (1992) define the Jurassic and Cretaceous formations of the Rita Blanca Aquifer. Cronin (1969), Seni (1980), and Knowles and others (1984) present excellent maps of Ogallala Formation surfaces, thicknesses, and lithologies. Cretaceous Edwards-Trinity formations are shown on maps and schematic cross sections in Walker (1979), Barker and Ardis (1992, 1996), and Blandford and others (2008). Meyer and others (2012) document Pecos Valley Alluvium stratigraphy, and we used their Brackish Resources Aquifer Characterization System database as the standard for this formation.

4.2.4 Lithology Estimation

For lithology estimation we calibrated gamma-ray logs using well sample descriptions. Johns (1989) described continuous drill cores through the Dockum Aquifer from four wells in the north (Figure 4.2.2). Seni (1980), Knowles and others (1984), and Blandford and others (2008) used well sample descriptions from drillers' logs to construct detailed lithology maps. Granata (1981) used the basic relationship between gamma radiation and lithology to map sandstone in the lower and upper Dockum Group. Based on these studies, we calibrated our gamma-ray logs in two ways. First, we made direct comparisons where both sample descriptions and corresponding gamma-ray logs are published (Johns, 1989). The second calibration process involved projecting interpolated sample data into our gamma-ray logs. Seni (1980), Knowles and others (1984), and Blandford and others (2008) used sample descriptions from thousands of water wells. We digitized contour maps from their publications of percent and net thickness of sandstone and limestone and made ArcGIS raster grids from the digital contours. We then used Petra to project values from the grids into each well location. This method provided lithology values that are based primarily on data from nearby drillers' logs. Separately, we estimated lithology directly from the gamma-ray logs using the methodology of Granata (1981) and Meyer and others (2012). We made final lithology estimations for each log based on comparisons of the two independent values within the context of surrounding values. We favored drillers' log data in shallow formations where gamma-ray logs are typically run through casing, but favored gamma-ray log data in deeper formations where gamma-ray logs are typically run in open holes.

Digital gamma-ray and resistivity curves facilitate the lithology calibration process and provide an excellent way to visualize results. Lithology from gamma-ray logs mainly involves setting a specific value (cut-off value) to separate sand-dominated intervals from clay-dominated intervals (Granata, 1981; Meyer and others, 2012). Because gamma-ray recordings are nonstandard between wells, the sand/clay cut-off value is usually determined individually for each log. Digital logs, however, can be normalized so that values are more comparable, and logs can be processed in batch. We normalized cased hole intervals separately from open hole intervals. First, we normalized gamma-ray values to a common mean value and then normalized to a common range of values. Resistivity logs, which were not used for lithology determination, were normalized to a common range of values. We used Petra to construct cross sections, showing log curves and color-coded lithologies. Petra determines vertical distribution of sandstones, shales, and limestones based strictly on foot-by-foot comparison of log value to cut-off value. We repeated the process using various cut-off values until the distribution of lithologies as visualized on cross sections agreed reasonably well with both drillers' log data and gamma radiation principles. Lessons learned from digital log calibration were applied to the image logs, which had to be analyzed individually. We constructed seven west-to-east digital log cross sections (Figure 4.2.1). These structural cross sections show the hydrostratigraphic layers of the High Plains Aquifer System relative to height in feet above mean sea level. Correlation log curves and lithologies are also shown. At each well location, gamma-ray curves are displayed on the left and resistivity curves, where available, are displayed on the right (Figures 4.2.3 through 4.2.9).

4.2.5 Spatial Interpolation of Geophysical Log Analyses

The results of the correlations described in the previous section provide estimates of the top and base of each aquifer at the geophysical log locations shown in Figure 4.2.1. These point values were interpolated to create regional surfaces for the active extent of each aquifer.

4.2.5.1 Workflow for Creating Surfaces

The interpolations were performed under the following rules:

1. The surfaces should match the values at control points as closely as possible, within the constraints of the interpolation method.
2. The surfaces should intersect land surface at outcrop edges, as previously defined by the surface geology. This is primarily achieved by adding control points along the boundary that were sampled to land surface based on the digital elevation model.
3. Aquifers with subsurface pinchouts (for example, the Edwards-Trinity (High Plains) and Rita Blanca aquifers) should smoothly thin to the edge of their defined active area. This was primarily achieved by adding control points along the aquifer boundary sampled to the bottom of the overlying aquifer.

4. The surfaces should not contain inversions (that is, points where an aquifer thickness is negative based on the top and bottom elevations). This might occur along edges or in thin areas where insufficient control is available.

The interpolations were completed using automated techniques (that is, no hand-contouring was required) and, thus, is completely reproducible. The end-to-end process used a series of Python scripts based on ArcGIS 10.1 libraries (including the Spatial Analyst extension).

4.2.5.2 Supplemental Data

The interpolations were first completed using only the results of the geophysical log analyses. After satisfactory surfaces were created, we then explored using additional data sources to refine the surface of the base of Ogallala Aquifer in areas between geophysical logs. These data sources were primarily from existing studies that had utilized driller's logs. While we consider the geophysical log analysis to be the "gold standard" for setting the regional structure, the additional drillers' log data could be used to increase resolution, as long as the supplemental data did not violate the character of the regional trends.

Seven supplemental data sources were considered:

1. Estimates of "redbed" from the Panhandle Groundwater Conservation District, provided as part of the District's database (Panhandle Groundwater Conservation District, 2013).
2. Estimates of "redbed" from North Plains Groundwater Conservation District, provided as part of the Northern Ogallala Aquifer groundwater availability model update (INTERA, Inc., and Dutton, 2010).
3. Estimates of the base of the Ogallala Aquifer from a five-county study performed for High Plains Water District (Daniel B. Stephens and Associates, 2012).
4. Estimates of "redbed" from Hemphill County UWCD (Hemphill County Underground Water Conservation District, 2013).
5. Estimates of the base of the Ogallala Aquifer from a study of Lipscomb County (Daniel B. Stephens and Associates, 2013).
6. Estimate of the base of the Ogallala Formation based on Seni (1980), primarily in Randall County and the surrounding area.

7. Estimate of the base of the Ogallala Aquifer from previous Southern Ogallala Aquifer groundwater availability model (Blandford and others, 2003) with minor modifications by High Plains Water District staff (High Plains Water District, 2013).

The location of these data sources are shown in Figure 4.2.10. In integrating this supplemental data, we performed a spatial query that excluded those data within 10,000 feet of an existing geophysical log, so that the surface would not be affected near the geophysical log. We then performed the interpolation with the supplemental data to produce a new surface. The new surface was compared to the original surface (based solely on the geophysical log data) to make sure that deviations (1) were equally distributed around the original surface (that is, no consistent bias was evident) and (2) the geophysical log values were still honored to the extent possible based on the interpolation method.

4.2.5.3 Interpolation Results

The interpolated base of the Ogallala and Pecos Valley aquifers is shown in Figure 4.2.11. A comparison of the elevation interpolated solely from geophysical logs (Figure 4.2.12a) and with adjustments from the supplemental data (Figure 4.2.12b) clearly shows increased resolution due to the supplemental data. The remaining basal surfaces are shown in Figure 4.2.13 through 4.2.15. Estimates of thickness were calculated for each aquifer based on subtraction of the elevation grids. Aquifer thickness maps are shown in Figures 4.2.16 through 4.2.19.

Regional cross sections were created by extracting elevation values from the final surfaces along the lines shown in Figure 4.1.2. These cross sections are shown in Figures 4.2.20 and 4.2.21, and are analogous to Figures 4.1.3 and 4.1.4. While the cross sections created from the interpolated surfaces are smoother between the control points (and show variations due to influence from other nearby control points) the character of the cross sections is very similar, confirming that the interpolated surfaces honor the geologic correlations.

Sand fraction maps were also created by interpolating the point estimates from the geophysical log analyses. The approach for this interpolation was much more straightforward, using a simple kriging approach and clipping the sand fraction rasters to the active boundary for each aquifer. The sand fraction maps are shown in Figures 4.2.22 through 4.2.25. Net sand thickness maps were calculated by multiplying the sand fraction maps by the aquifer thickness maps. The net sand thickness maps are shown in Figures 4.2.26 through 4.2.29. Using the same methodology, a limestone fraction map and net limestone thickness map were created for the Edwards-Trinity (High Plains) Aquifer (Figures 4.2.30 and 4.2.31).

4.2.6 Discussion

This section describes the results of the geophysical log study for each hydrostratigraphic layer. Permian fine-grained formations underlie aquifer and aquitard layers and form a no-flow lower boundary to the High Plains Aquifer System. Lower and upper Dockum Group layers are composed of interbedded sandstones and shales and display significant lateral variation in sandstone development. The Dockum Group layers form the thickest part of the aquifer system. The Ogallala Aquifer layer is thinner but sandier than either Dockum Group layer. Sandstone, although thin, is present consistently at the base of the Edwards-Trinity (High Plains) Aquifer layer. The Rita Blanca Aquifer layer is composed of thin sandstones and shales in Texas. Lithologies were not mapped for the Edwards-Trinity (Plateau) Aquifer layer or the Pecos Valley Aquifer layer.

The Permian layer is composed of red-bed shales (high gamma ray) and limestones, dolomites, and evaporites (low gamma ray). Some Permian formations include high-salinity aquifers, but these layers are deeper and are not in hydraulic communication with Dockum Group sandstones (Bebout and Meador, 1985; McGookey and others, 1988). We picked top of Permian (base of Dockum Group) operationally as the base of the lowest sandy interval in the Dockum Group (Santa Rosa Sandstone) (see Figures 4.2.3 through 4.2.9). Some of the redbeds below the Santa Rosa Sandstone may be Triassic in age, but they are not part of the High Plains Aquifer System.

The lower Dockum Aquifer layer is generally sandiest near the base. The Santa Rosa Sandstone appears as a low gamma-ray interval on most geophysical logs (see Figures 4.2.3 through 4.2.9). Other sandstones are scattered throughout the lower Dockum Group layer above the Santa Rosa Sandstone. The lower Dockum Group is thickest in a central area that defines the Dockum Basin (see Figure 4.2.19). Sandstones, however, are more concentrated around the margins of the Dockum Basin (see Figures 4.2.25 and 4.2.29). The lower Dockum Aquifer displays relatively low sandstone in and north of the Canadian River valley. High sandstone percentages are present in the lower Dockum Group under the Edwards-Trinity (Plateau) Aquifer layer and the Pecos Valley Aquifer layer in the south.

The upper Dockum Group layer is less consistently sandy at its base than is the lower Dockum Group. Basal sandstones in the upper Dockum Group are best developed in western areas and under the Edwards-Trinity (High Plains) Aquifer layer (see Figures 4.2.3 through 4.2.9). The upper Dockum Group is segmented by postdepositional erosion into two separate areas (Figure 4.2.18). Unlike the lower Dockum Group, the upper Dockum Group is sandiest in basin center areas (see Figures 4.2.24 and 4.2.28). Thick sandstones coincide generally with the thickest parts of the layer.

The Rita Blanca Aquifer layer is present only in the northwest corner of the study area. The Rita Blanca Aquifer thins from west to east and pinches out in Dallam and Hartley counties (see Figures 4.2.3 and 4.2.17). The Rita Blanca Aquifer is composed of interbedded sandstones and shales, which are distributed randomly and lack distinctive vertical trends. Minor limestone beds are also present. The net sandstone thickness reaches 250 feet in New Mexico but is generally less than 100 feet in Texas (Figure 4.2.27). Percent sandstone also decreases eastward into Texas before increasing again near the pinchout line (see Figure 4.2.23).

The Edwards-Trinity (High Plains) Aquifer layer is the only layer that includes thick limestone. The Edwards-Trinity (High Plains) Aquifer, which is an erosional remnant of more extensive Cretaceous formations to the southeast (Edwards-Trinity (Plateau) Aquifer), is thickest in its central part (Figure 4.2.17). Sandstones, however, are generally more abundant in peripheral areas (Figures 4.2.23 and 4.2.27). Sandstones in the Antlers and Walnut formations consistently form the base of this layer, and limestones (Comanche Peak and Edwards formations) directly overlie sandstones in many locations (Figures 4.2.6 and 4.2.7). Limestones are thickest in the east and thin to zero thickness near the Texas/New Mexico border (Figures 4.2.30 and 4.2.31). The upper part of the layer is mainly shale, which is overlain by Ogallala Aquifer sand and gravel.

The Ogallala Aquifer layer is the sandiest layer in the High Plains Aquifer System. Drillers' logs show that the Ogallala Aquifer includes abundant coarse sand and gravel and is unconsolidated (Seni, 1980). The Ogallala Aquifer is distinctly thicker in the north than in the south (see Figure 4.2.16). Three major paleovalleys are located in the north, and salt dissolution depressions are more common there. Thickest net sand is also concentrated in the north (Figure 4.2.26). High sand percent areas are present within the northern paleovalleys, in New

Mexico (closer to source areas), and along the south margin of the layer (Figure 4.2.22). The high sand area in the south is an erosional remnant of another paleovalley. The Ogallala Aquifer generally causes low gamma-ray and high resistivity responses on geophysical logs. The lower part of the Ogallala Aquifer is typically sandier than the upper part, although many logs show it to be sandy throughout (Figures 4.2.3 through 4.2.9). The Ogallala Aquifer interval is commonly cased with cement before running logs, and cased hole gamma-ray logs are not reliable indicators of lithology. Cross sections 1 through 4, however, include a number of open-hole logs through the Ogallala Aquifer, which accurately record lithology in those areas.

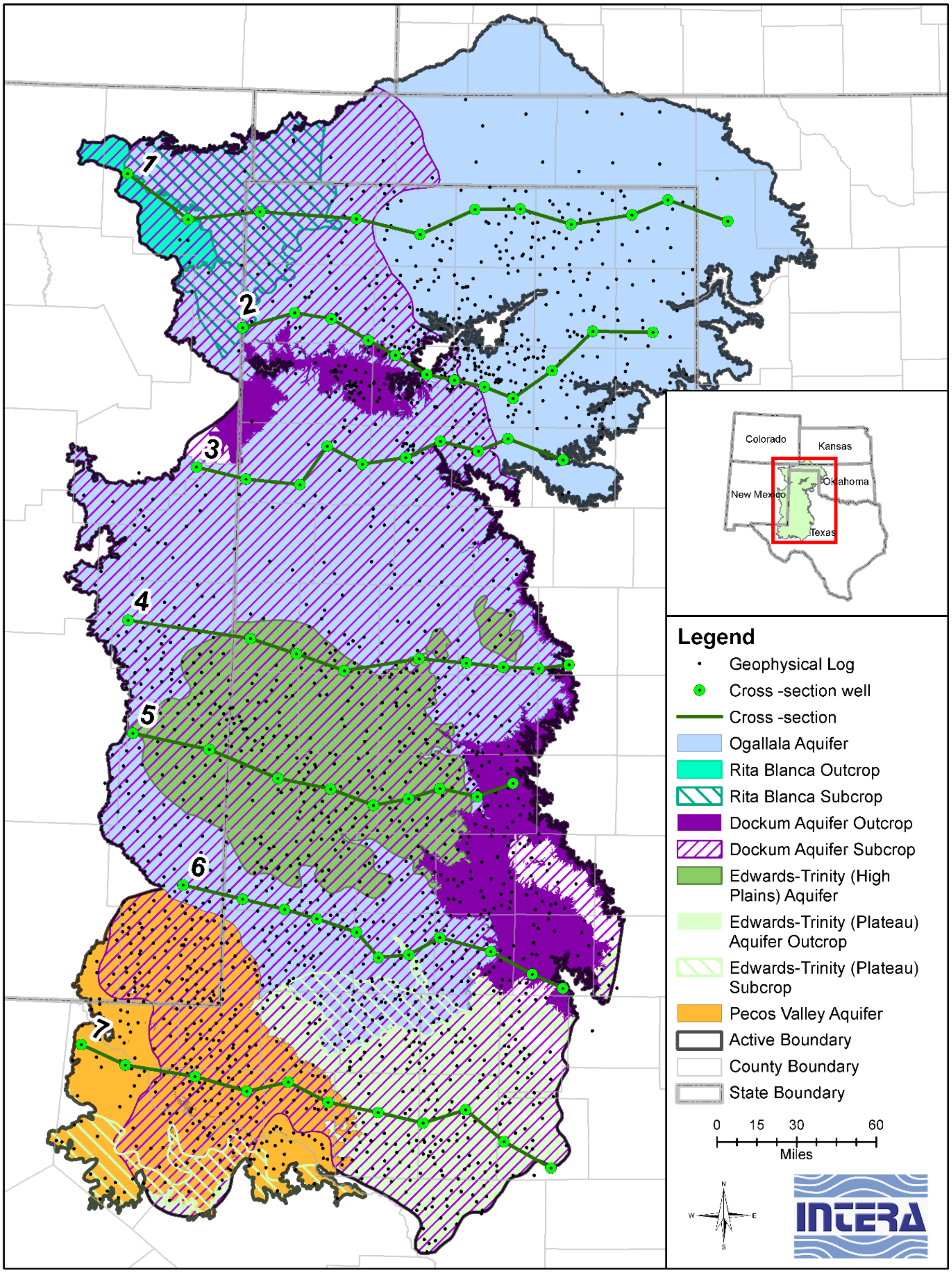

Figure 4.2.1 Location of geophysical logs used in the structure analysis and the seven cross sections shown in Figures 4.2.3 through 4.2.9.

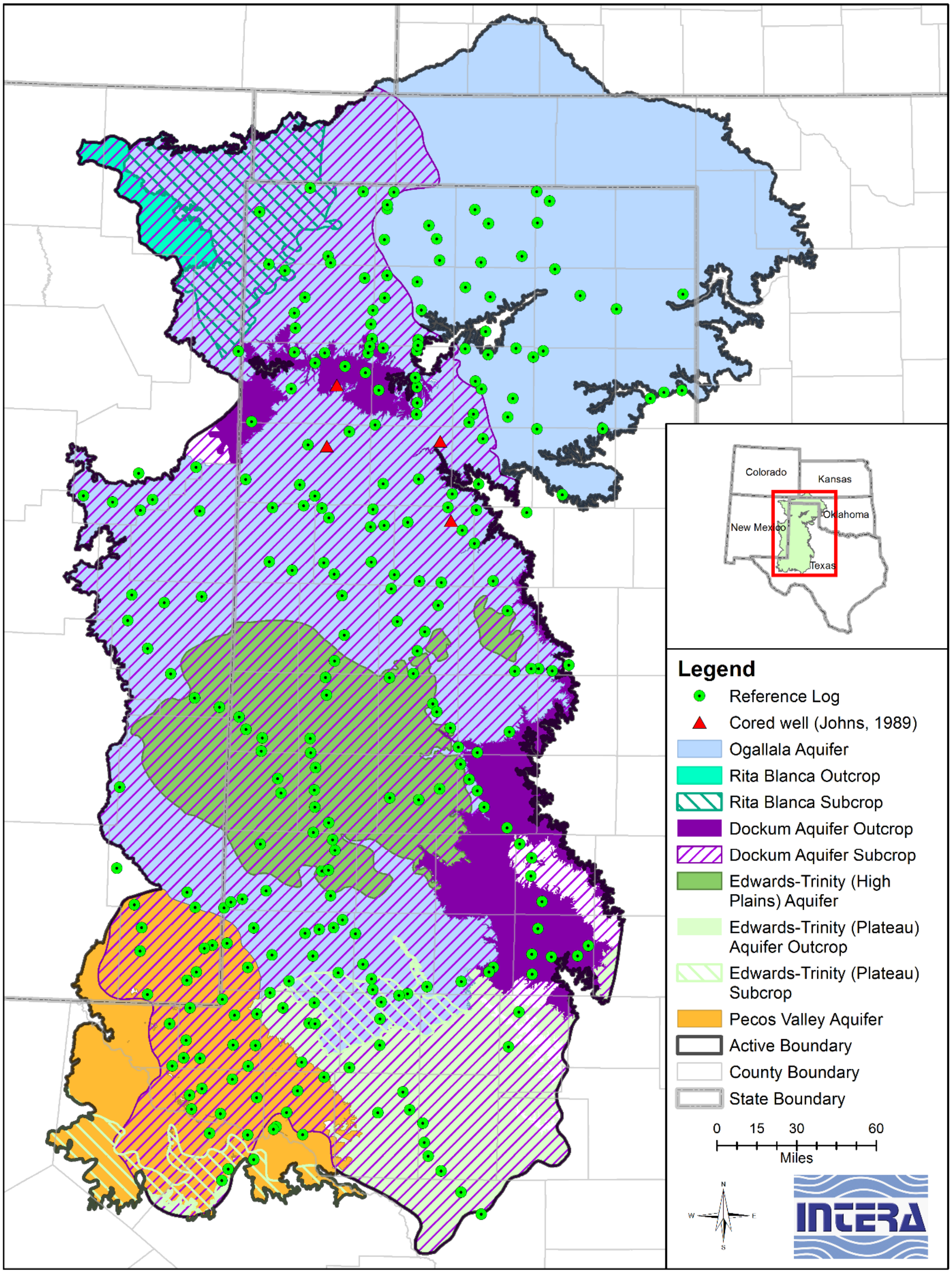

Figure 4.2.2 **Locations of reference geophysical logs.**

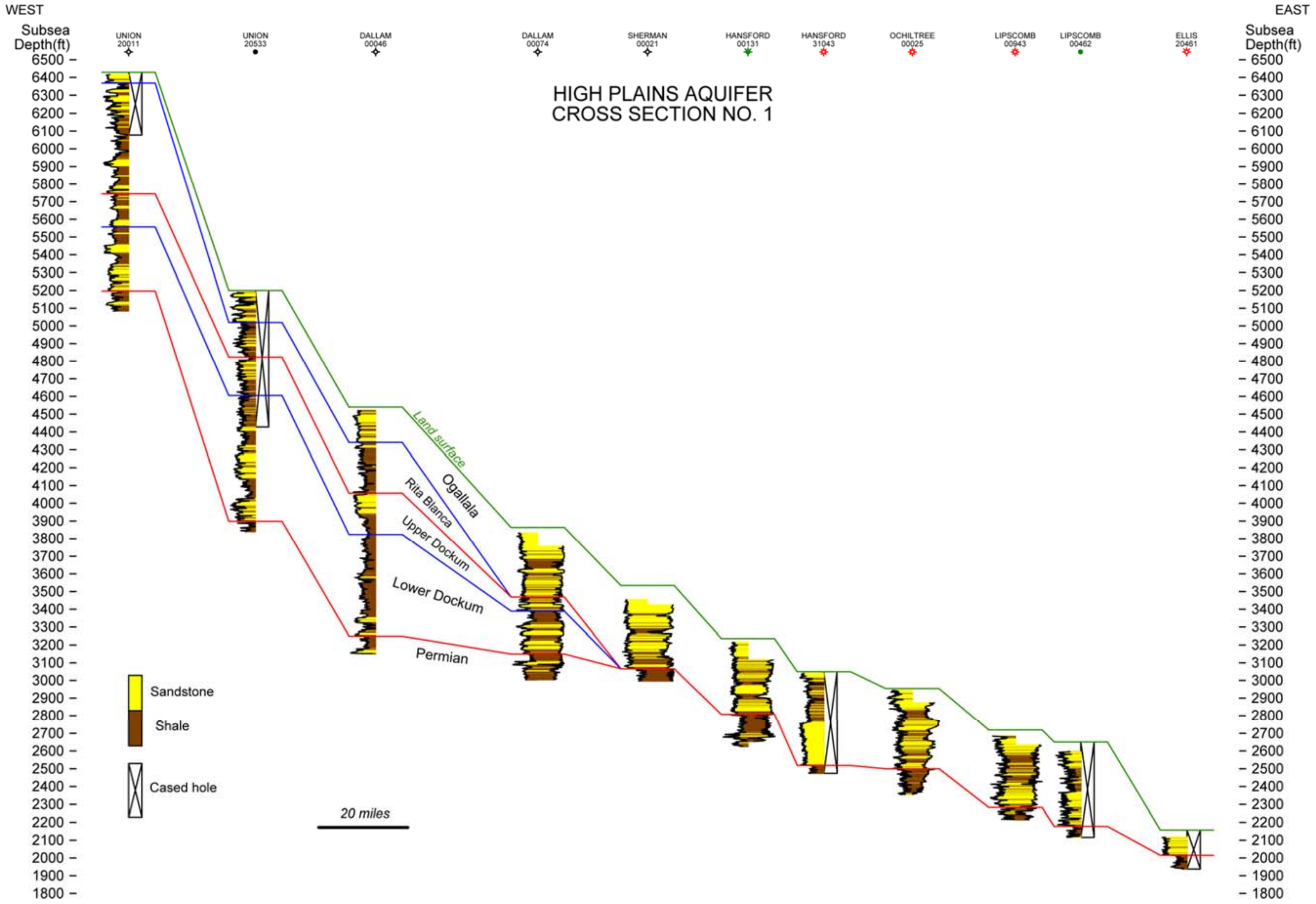

Figure 4.2.3 **Cross-section #1.**

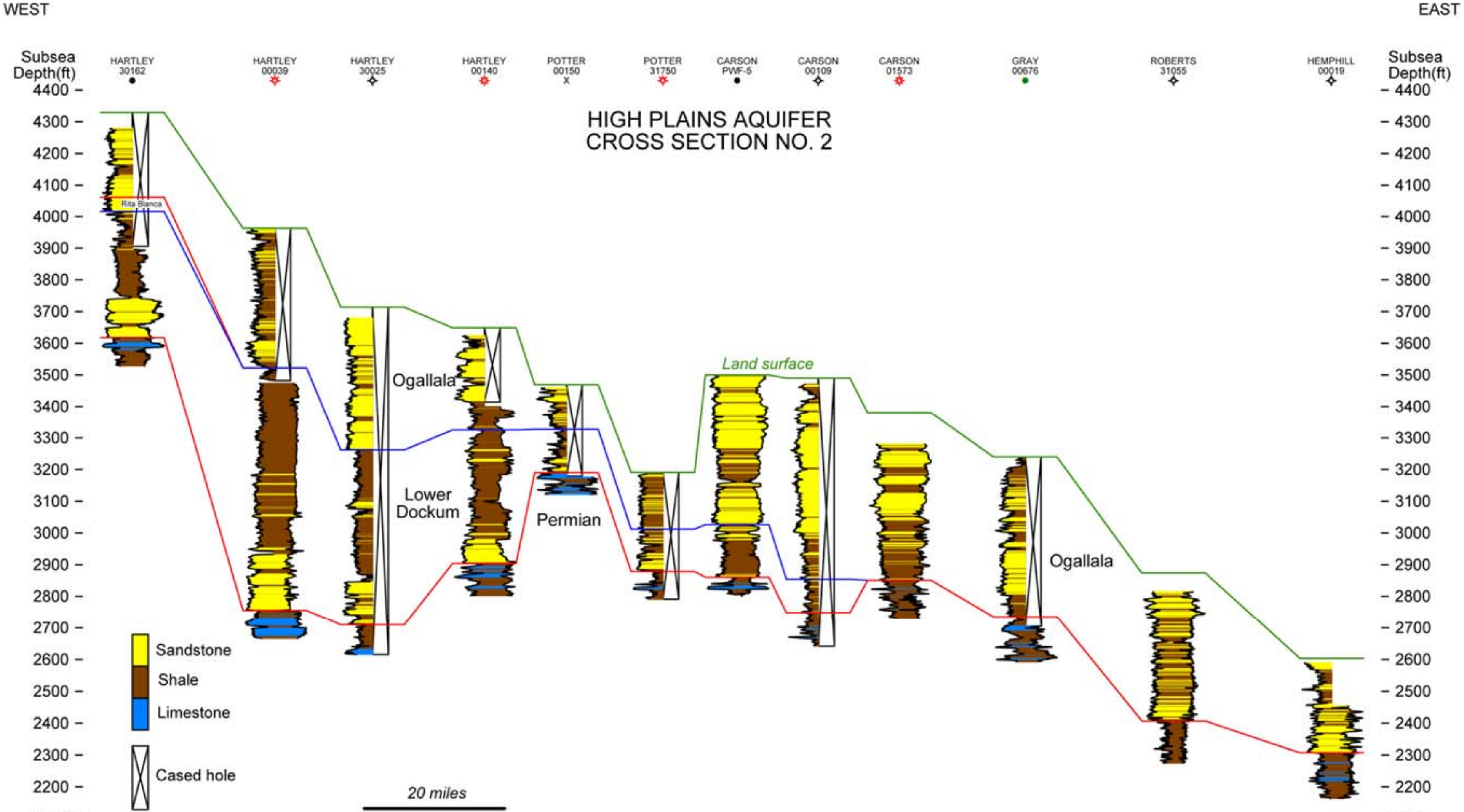

Figure 4.2.4 Cross-section #2.

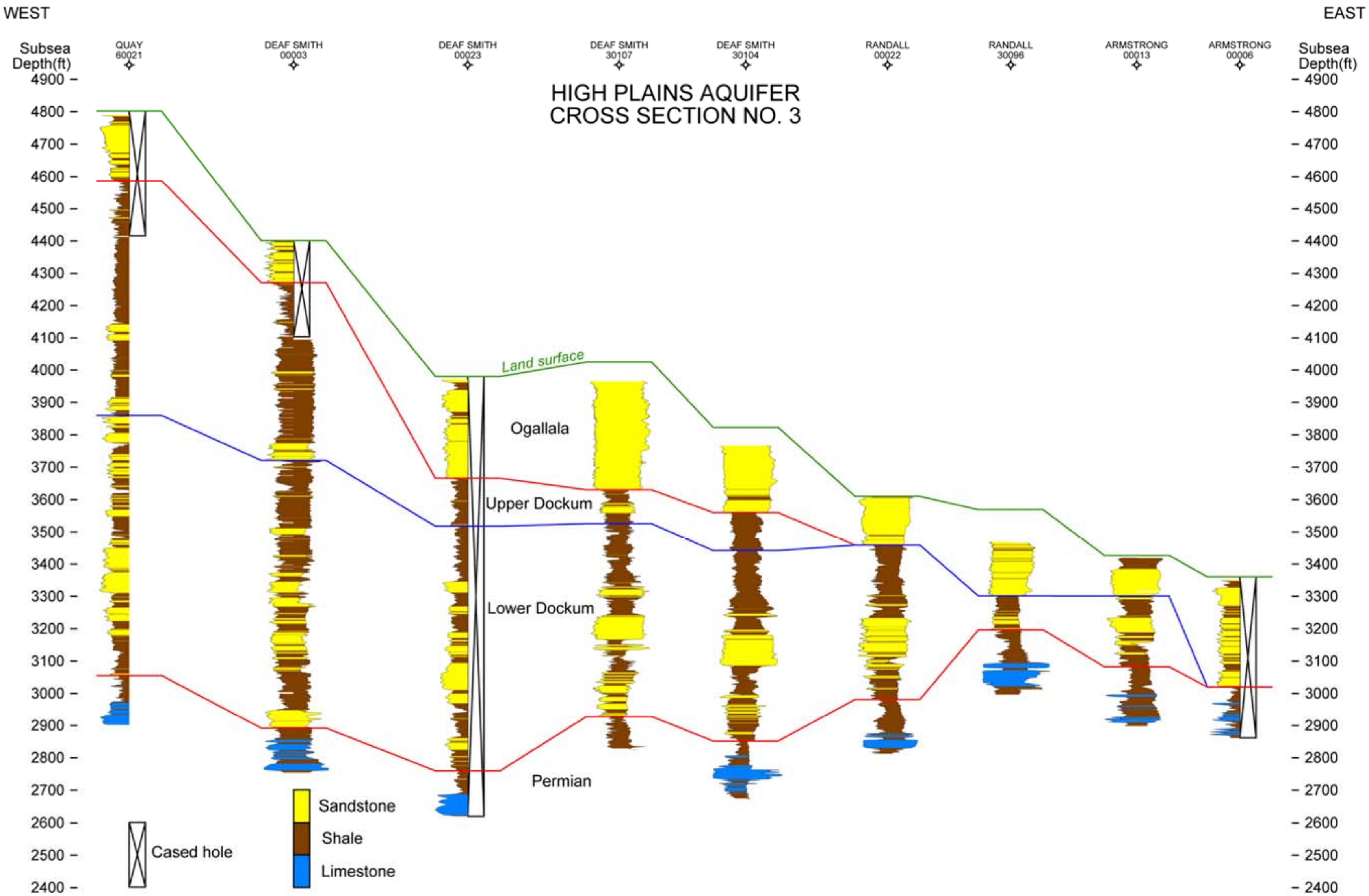

Figure 4.2.5 Cross-section #3.

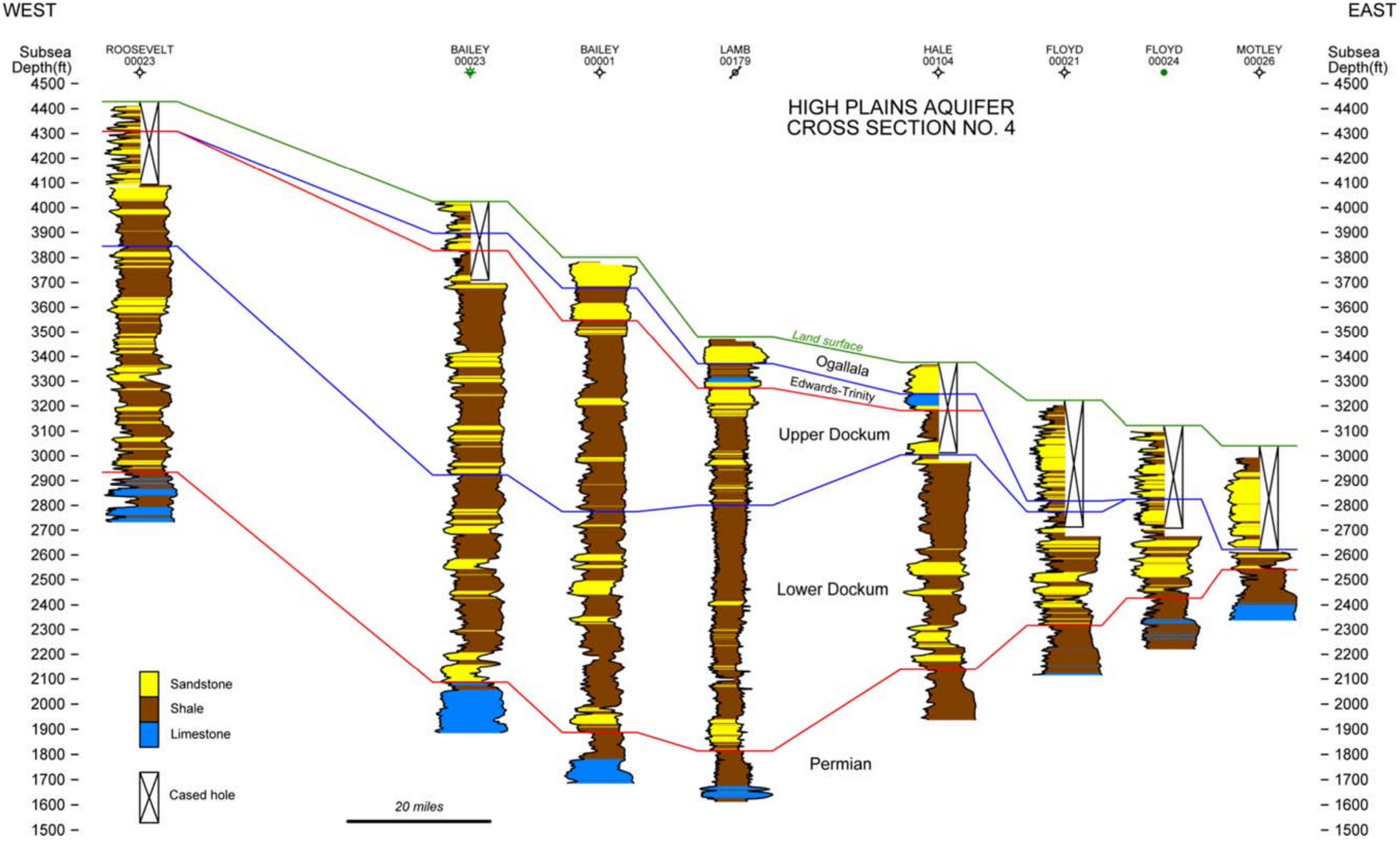

Figure 4.2.6 **Cross-section #4.**

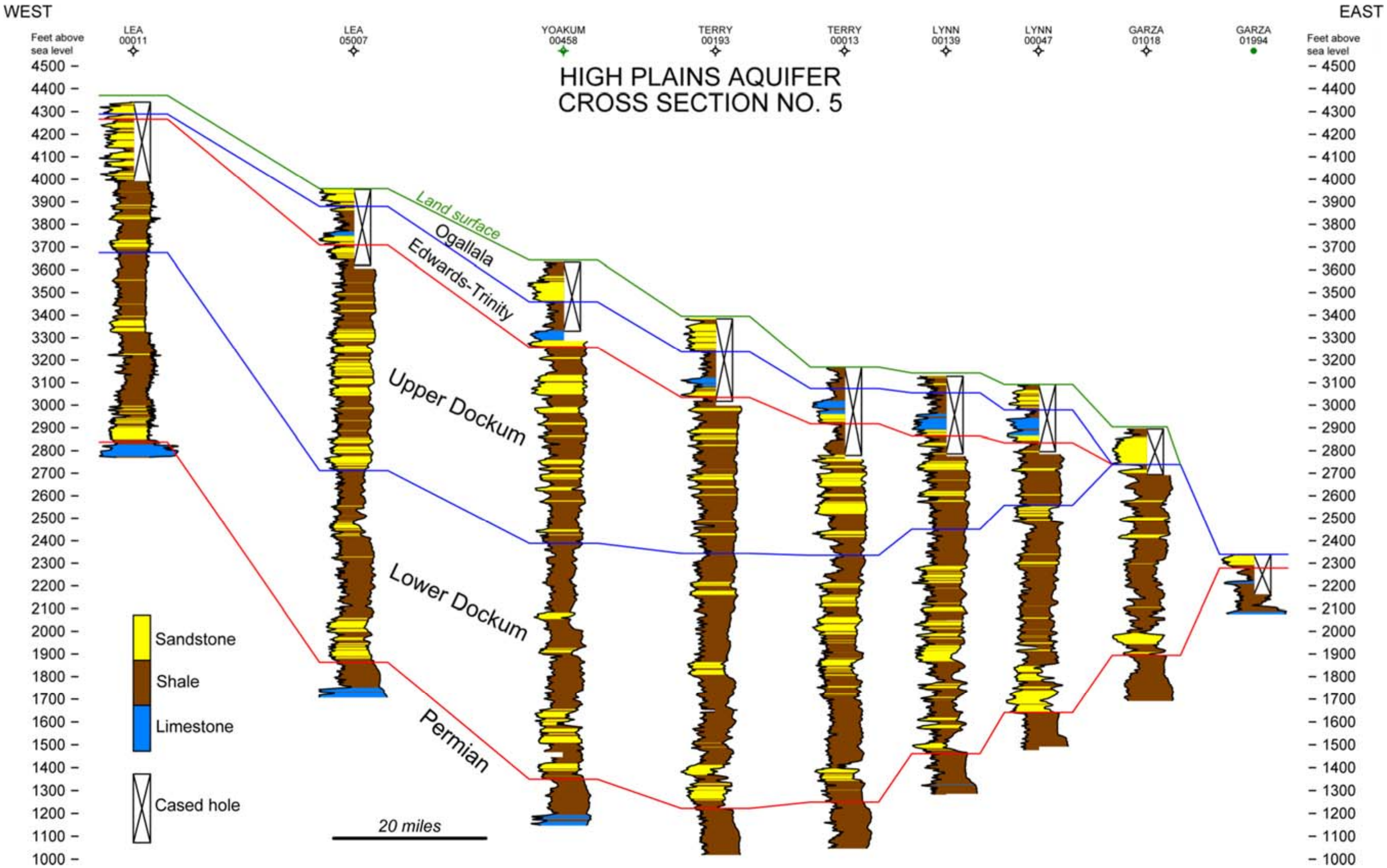

Figure 4.2.7 Cross-section #5.

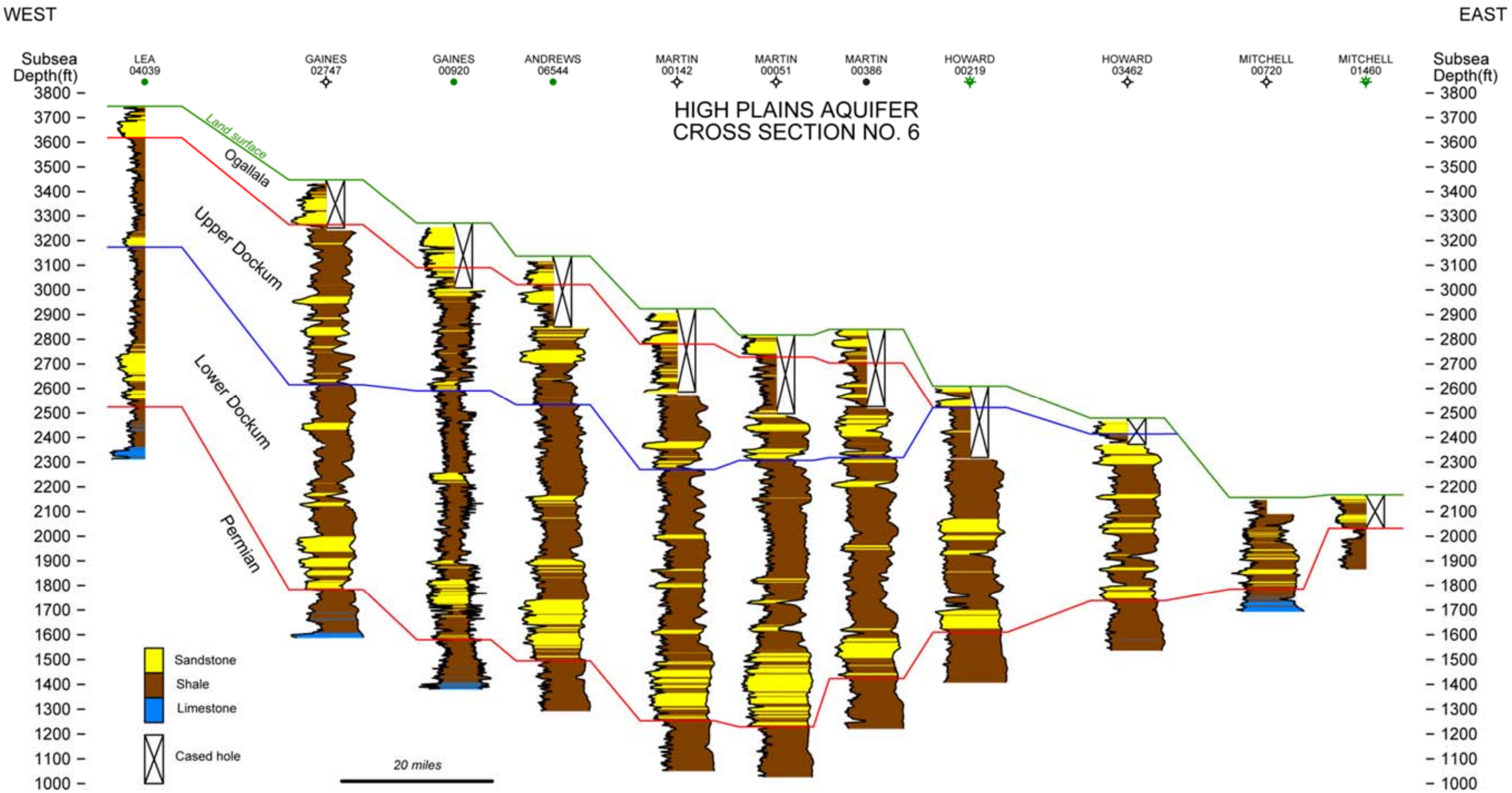

Figure 4.2.8 **Cross-section #6.**

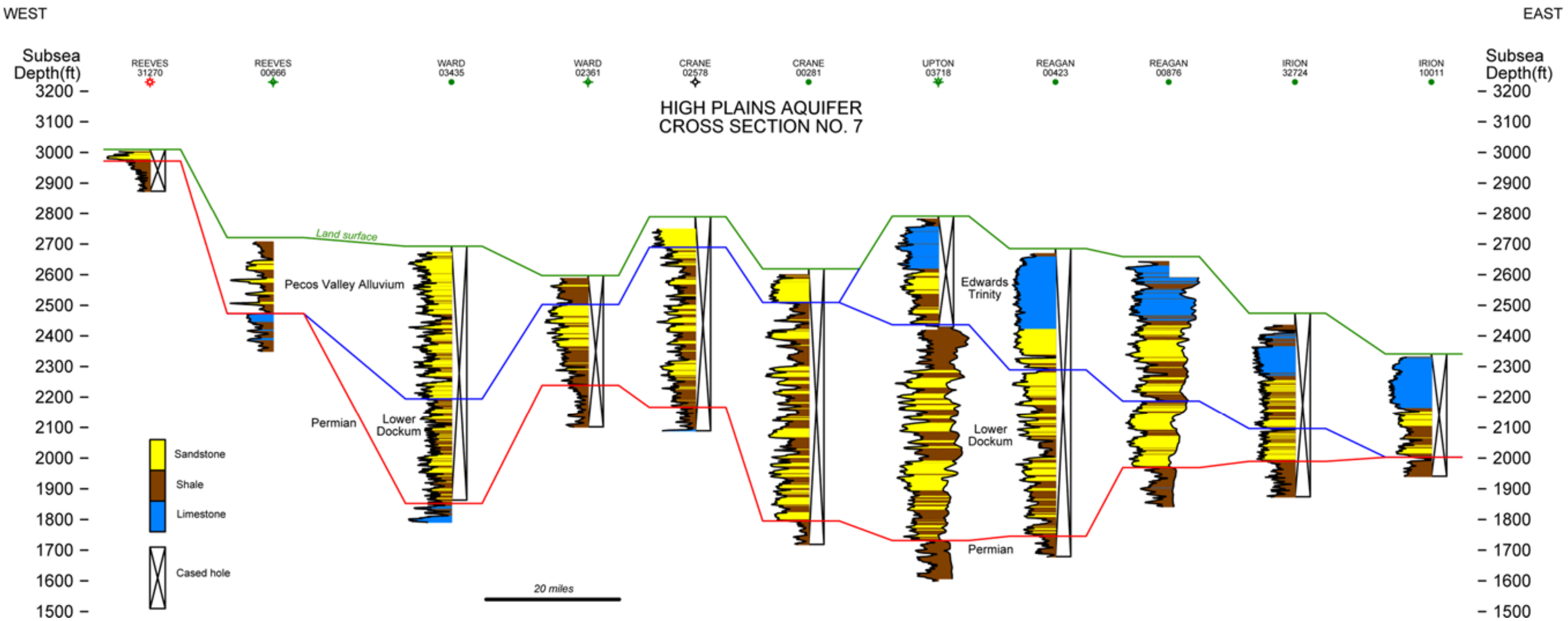

Figure 4.2.9 **Cross-section #7.**

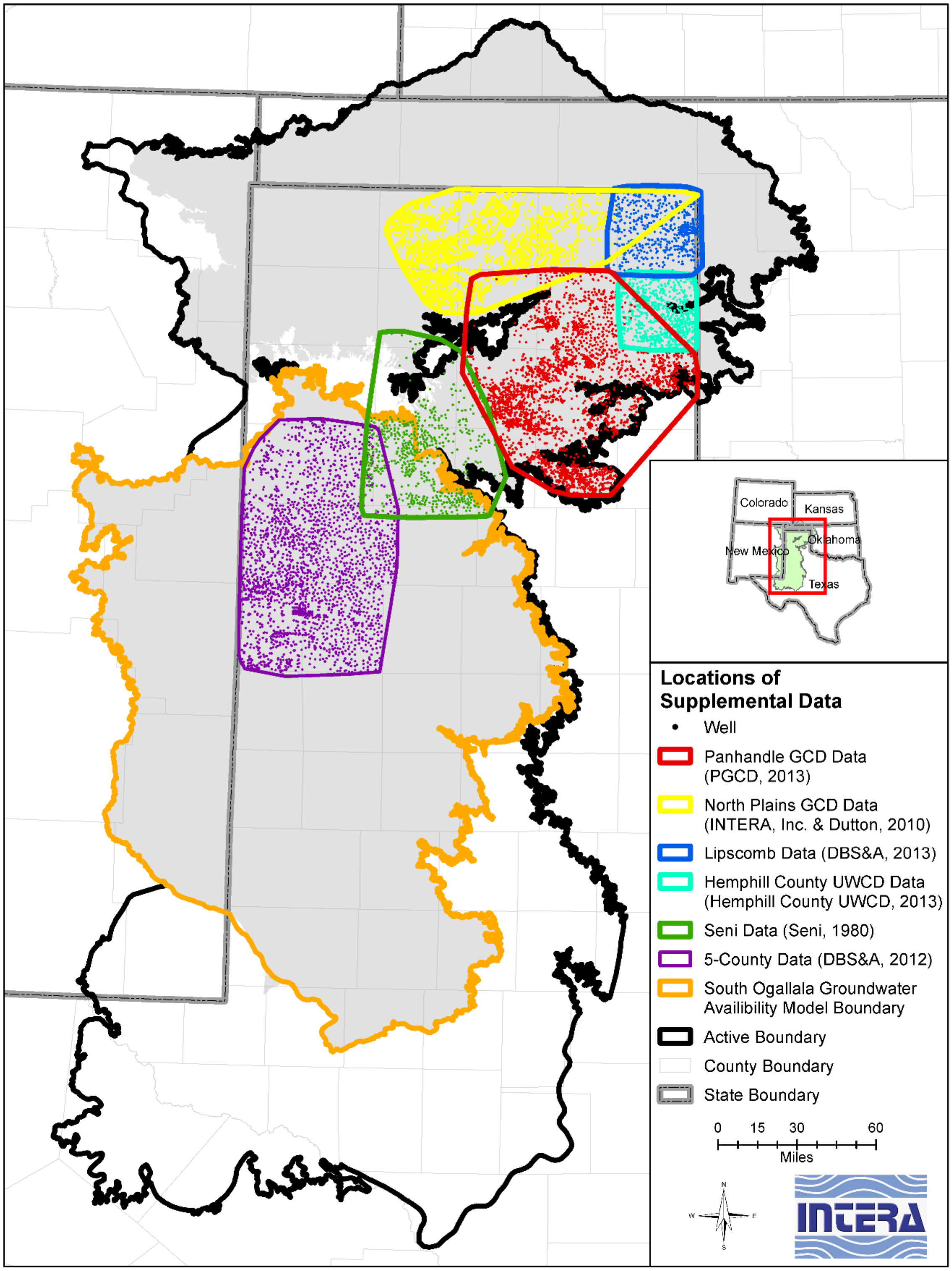

Figure 4.2.10 Location of potential sources of supplemental data for the base of the Ogallala Aquifer. Abbreviation key: GCD = Groundwater Conservation District; PGCD = Panhandle Groundwater Conservation District; DBS&A = Daniel B. Stephens and Associates; UWCD = Underground Water Conservation District.

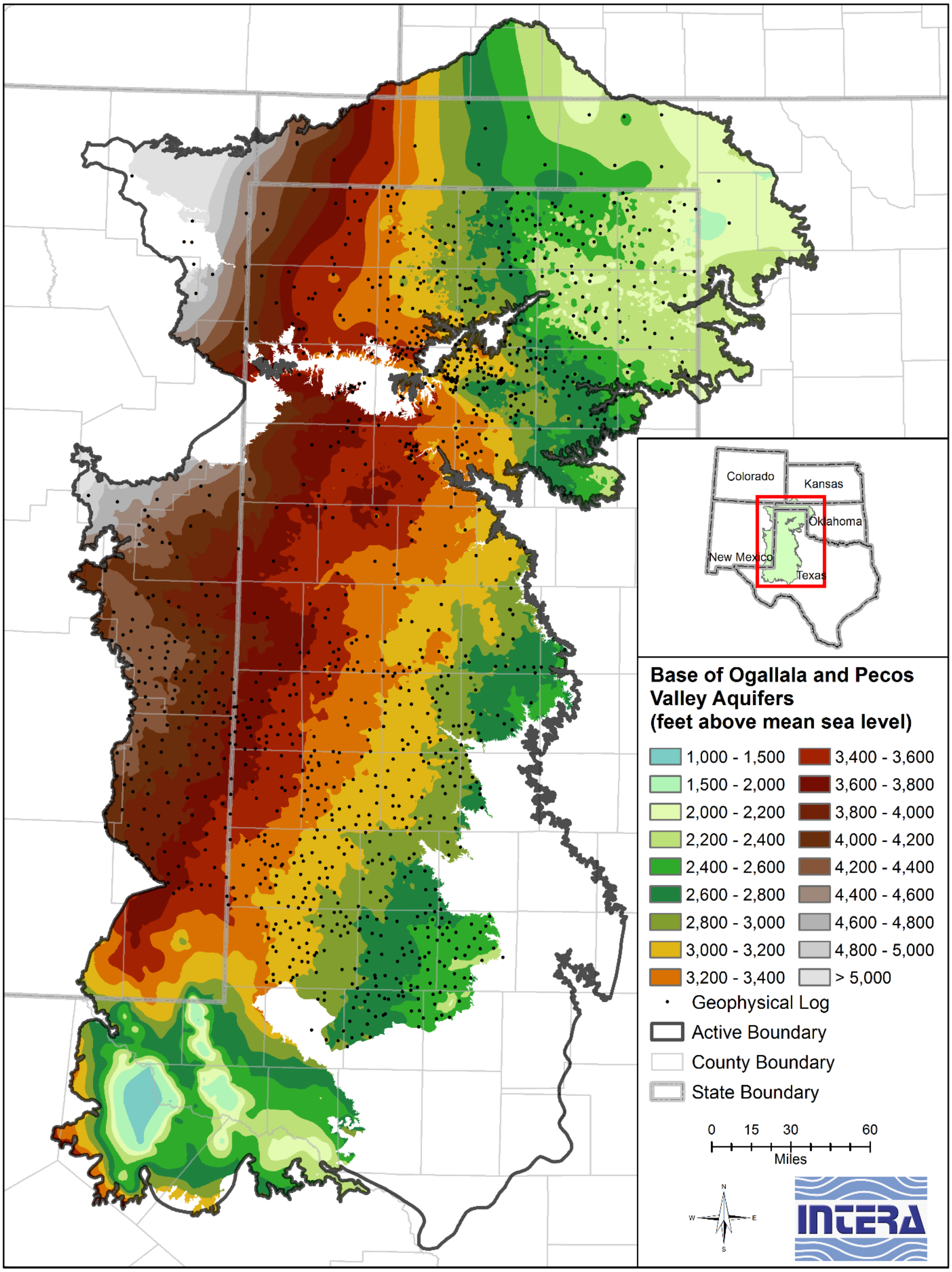

Figure 4.2.11 **Base of the Ogallala and Pecos Valley aquifers in feet above mean sea level.**

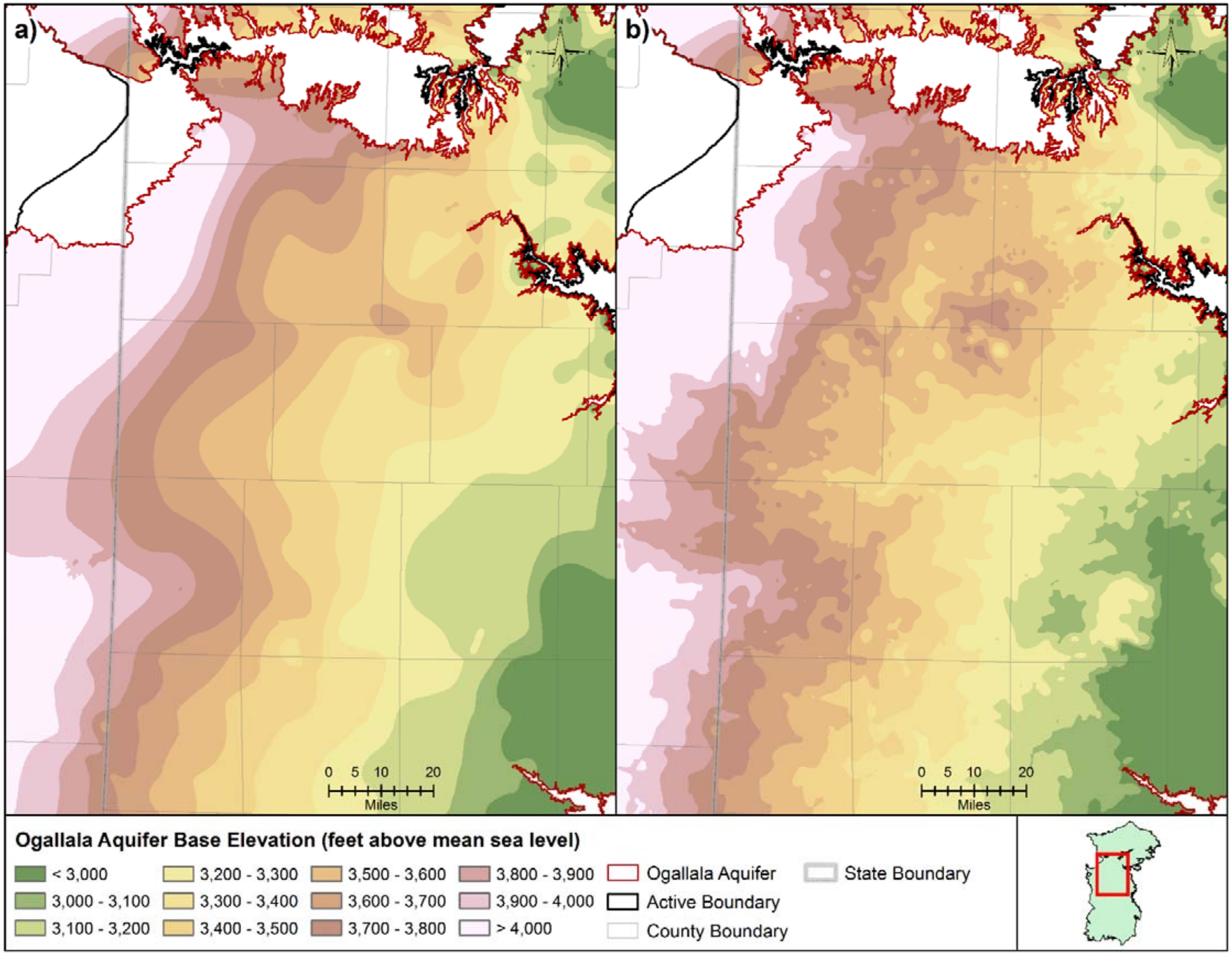

Figure 4.2.12 **Comparison of the base of Ogallala Aquifer interpolated (a) using geophysical logs only and (b) adding supplemental data.**

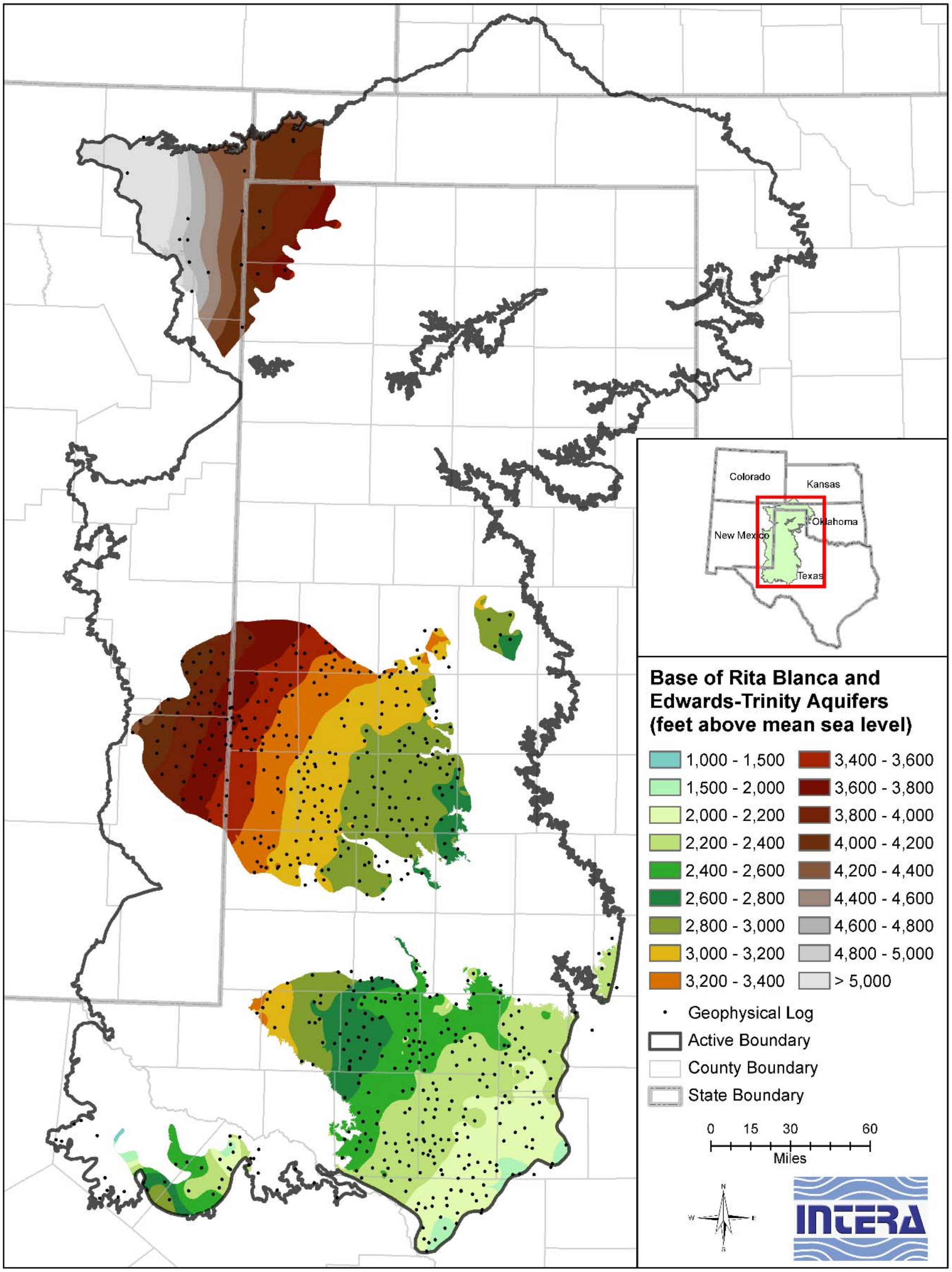

Figure 4.2.13 Base of the Rita Blanca, Edwards-Trinity (High Plains), and Edwards-Trinity (Plateau) aquifers.

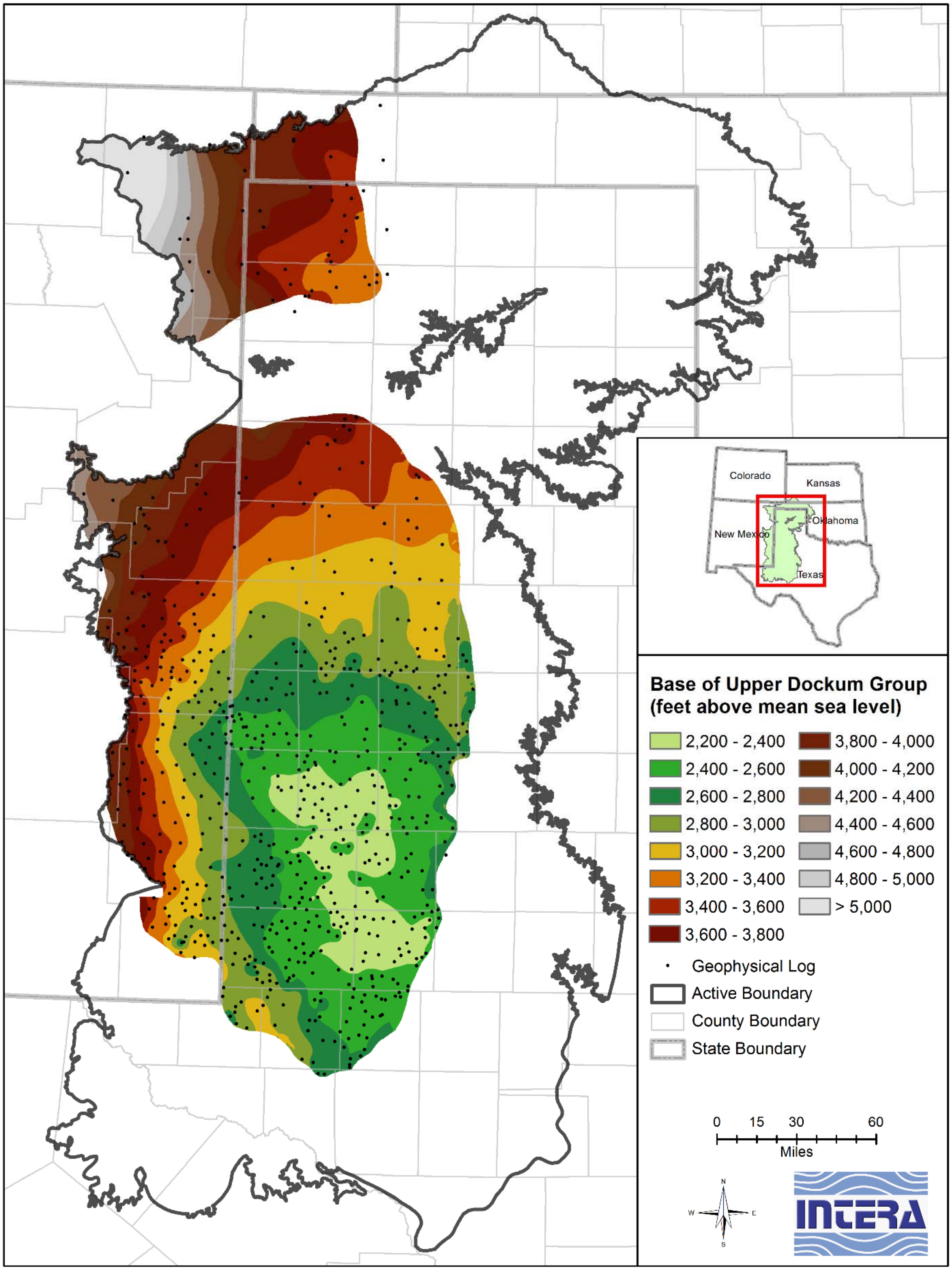

Figure 4.2.14 **Base of the upper Dockum Group.**

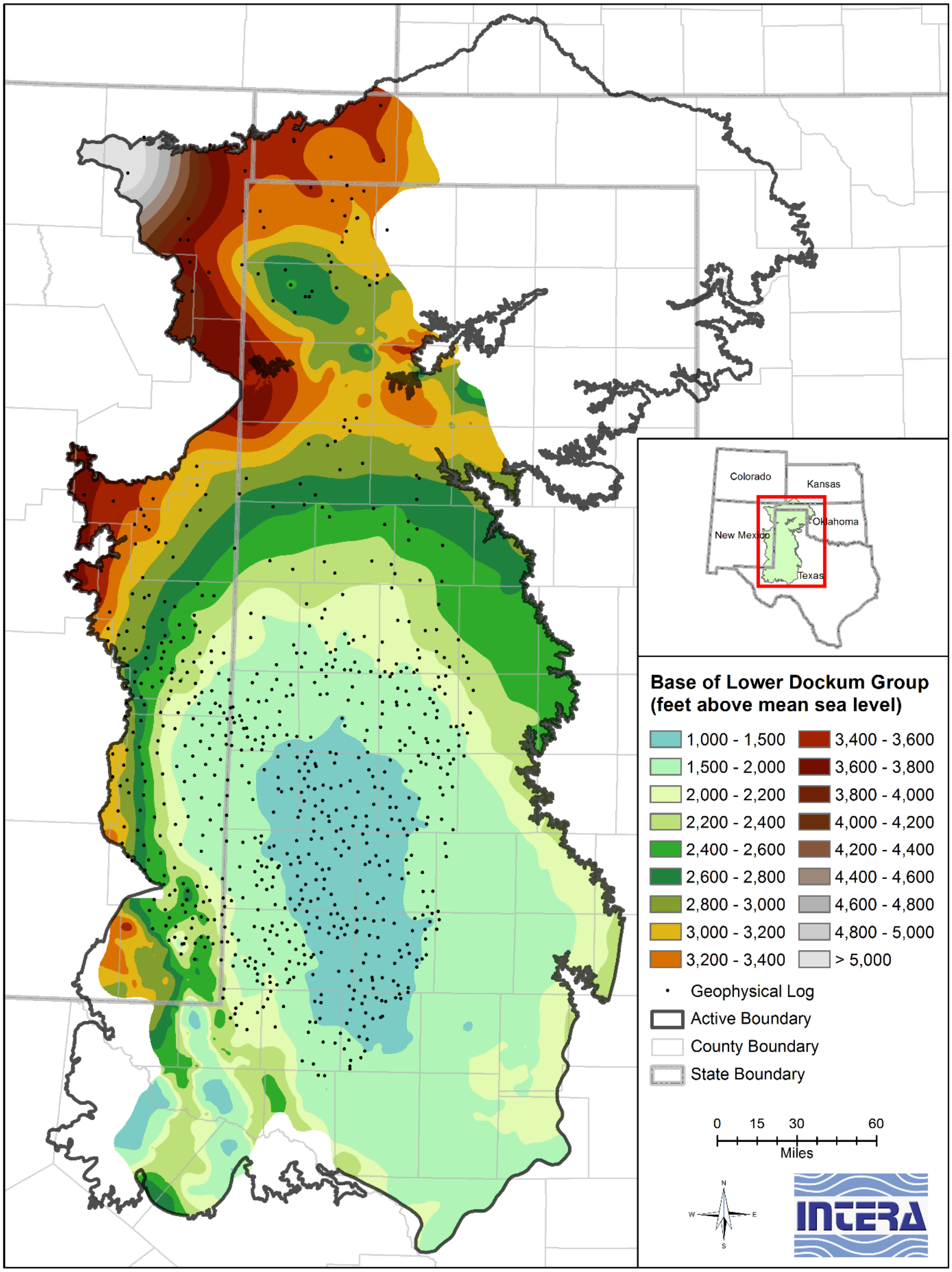

Figure 4.2.15 Base of the lower Dockum Group.

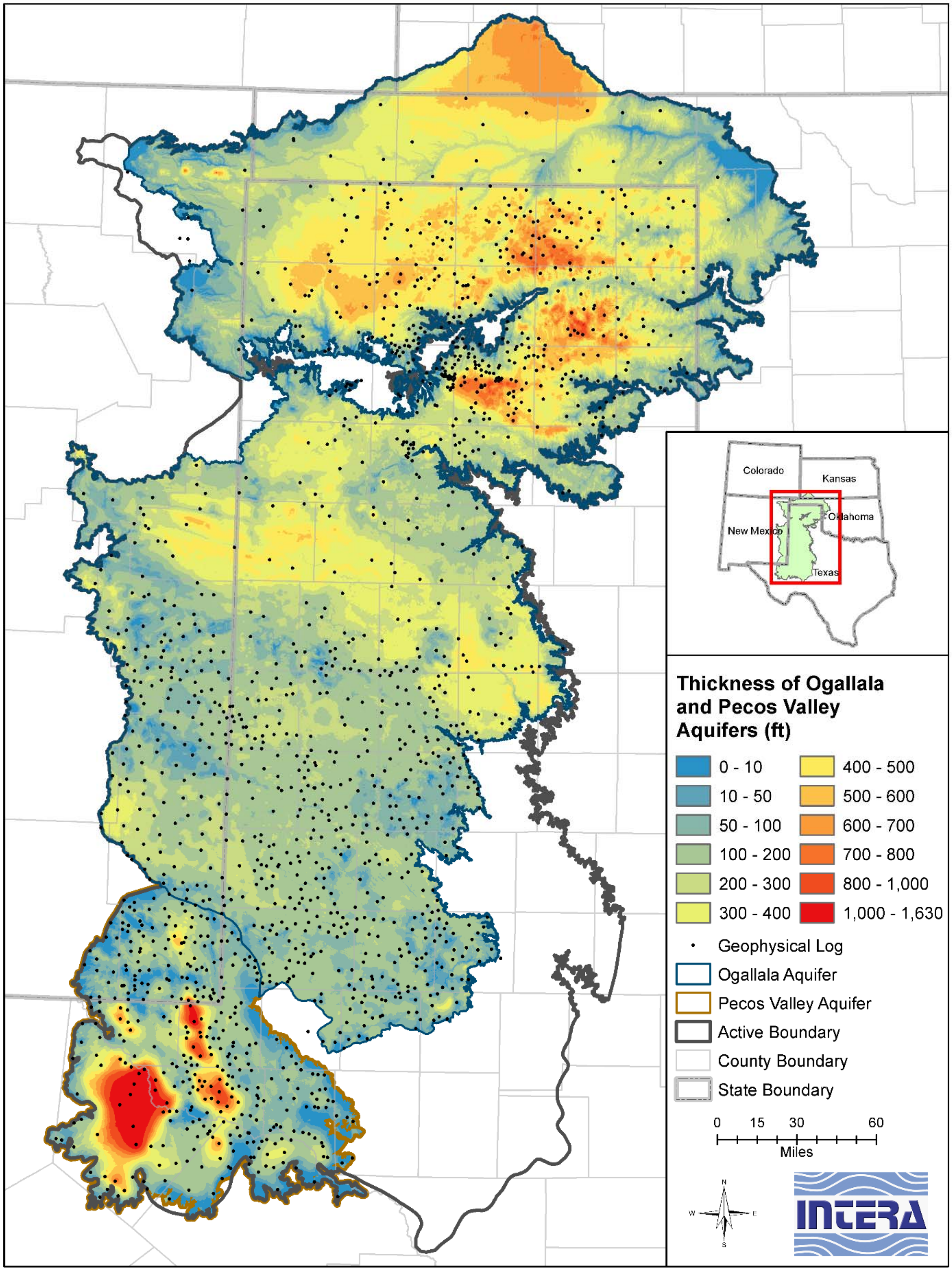

Figure 4.2.16 **Thickness of the Ogallala and Pecos Valley aquifers in feet.**

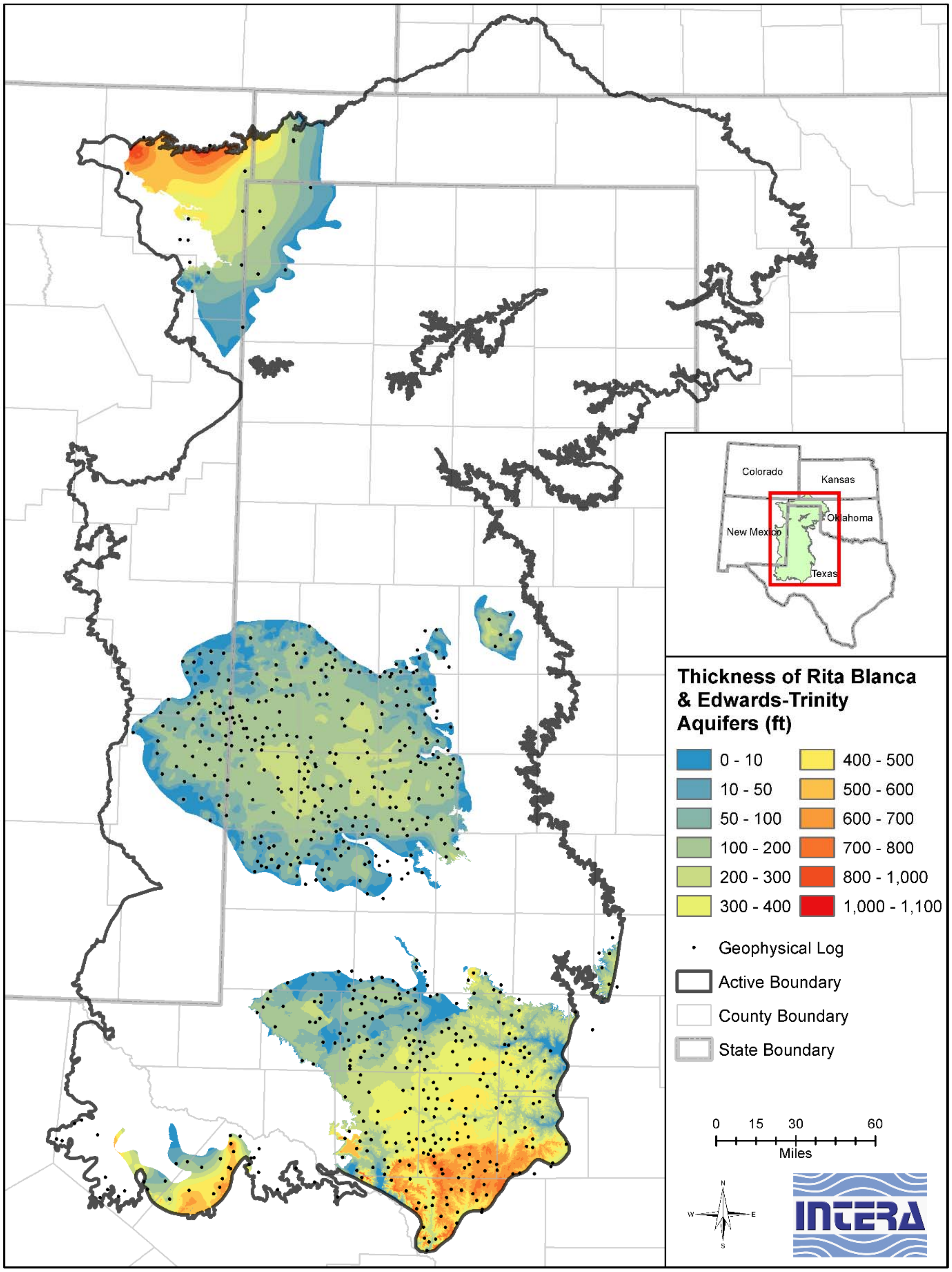

Figure 4.2.17 **Thickness of the Rita Blanca, Edwards-Trinity (High Plains), and Edwards-Trinity (Plateau) aquifers in feet.**

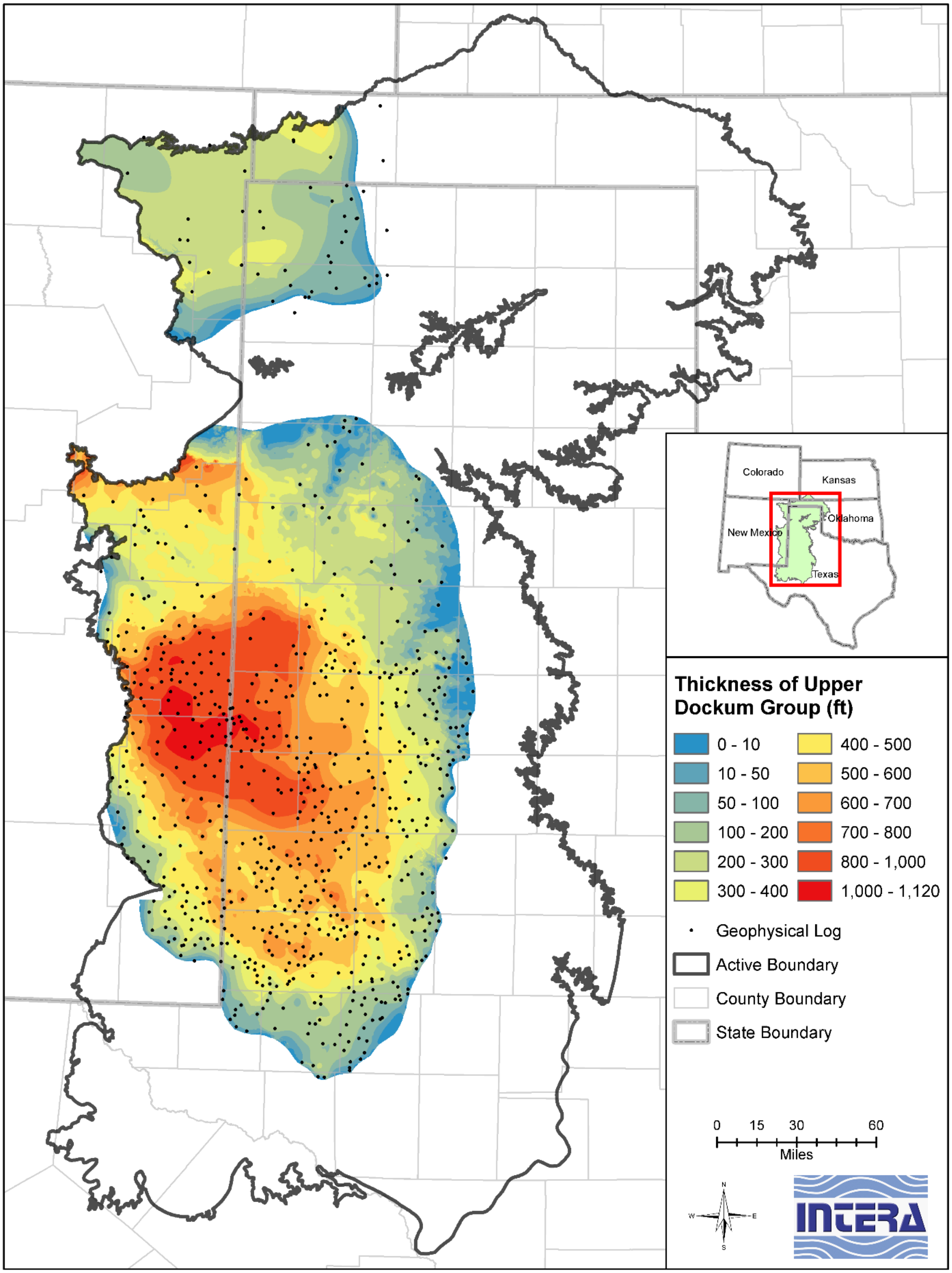

Figure 4.2.18 Thickness of the upper Dockum Group in feet.

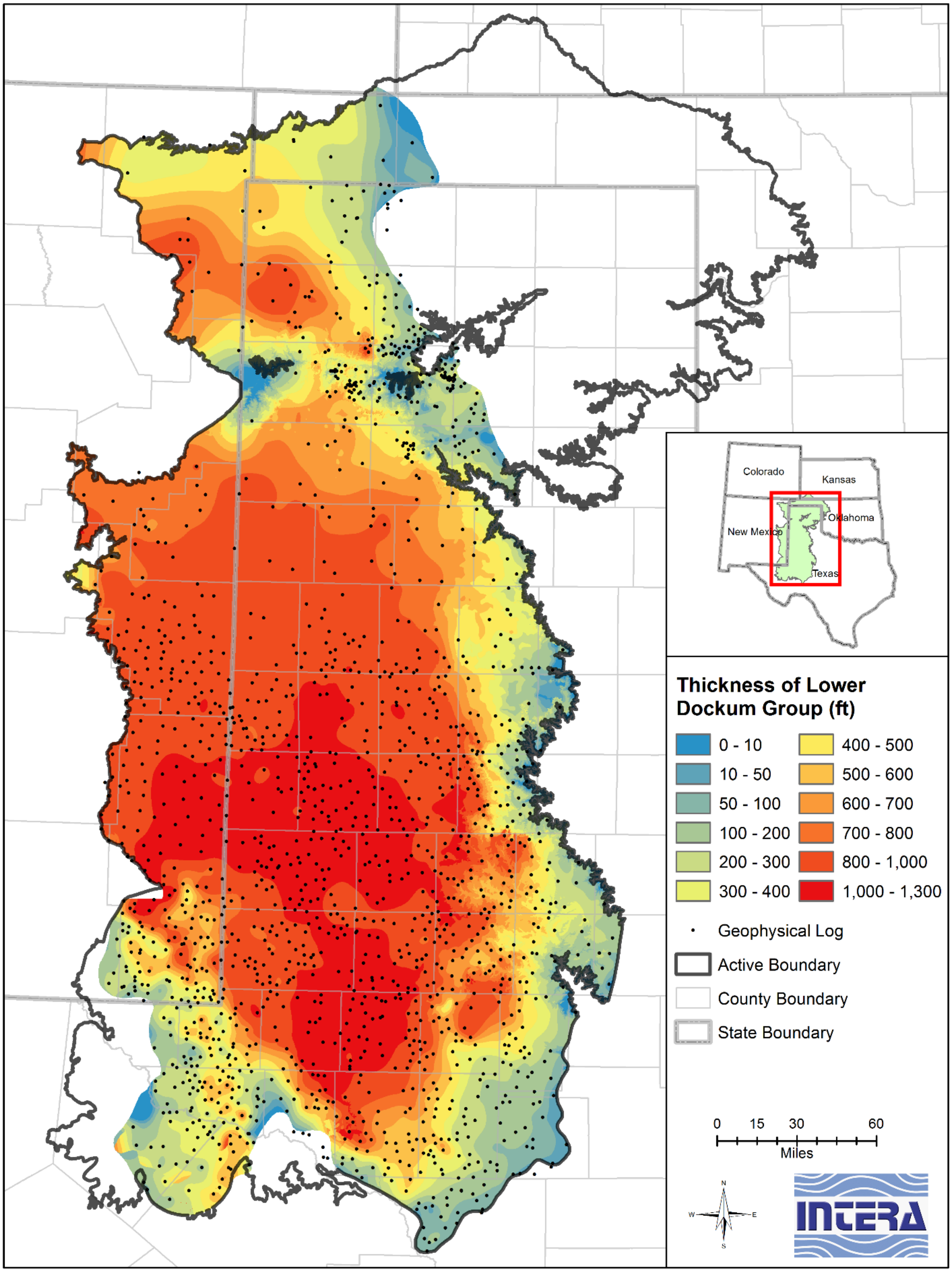

Figure 4.2.19 **Thickness of the lower Dockum Group in feet.**

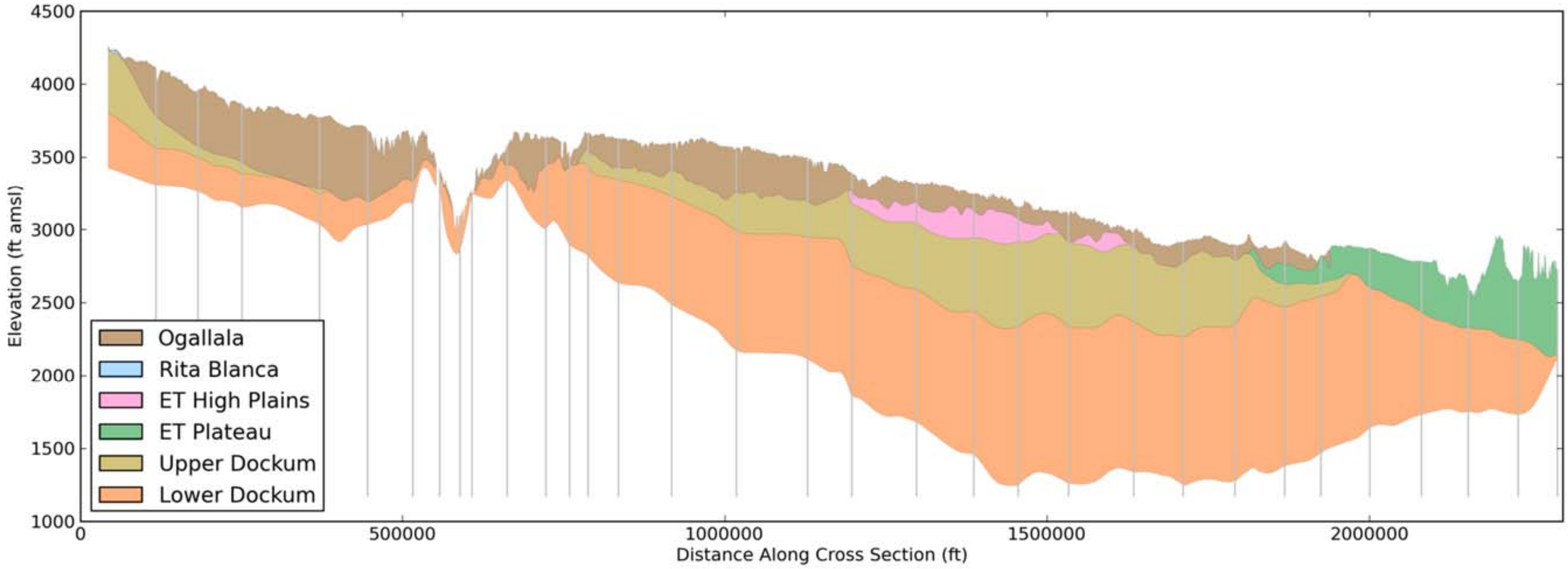

Figure 4.2.20 **Regional north-south cross section extracted from surface elevations. The location of the cross section line is shown in Figure 4.1.2. Abbreviation key: ET High Plains = Edwards-Trinity (High Plains) Aquifer, ET Plateau = Edwards-Trinity (Plateau) Aquifer.**

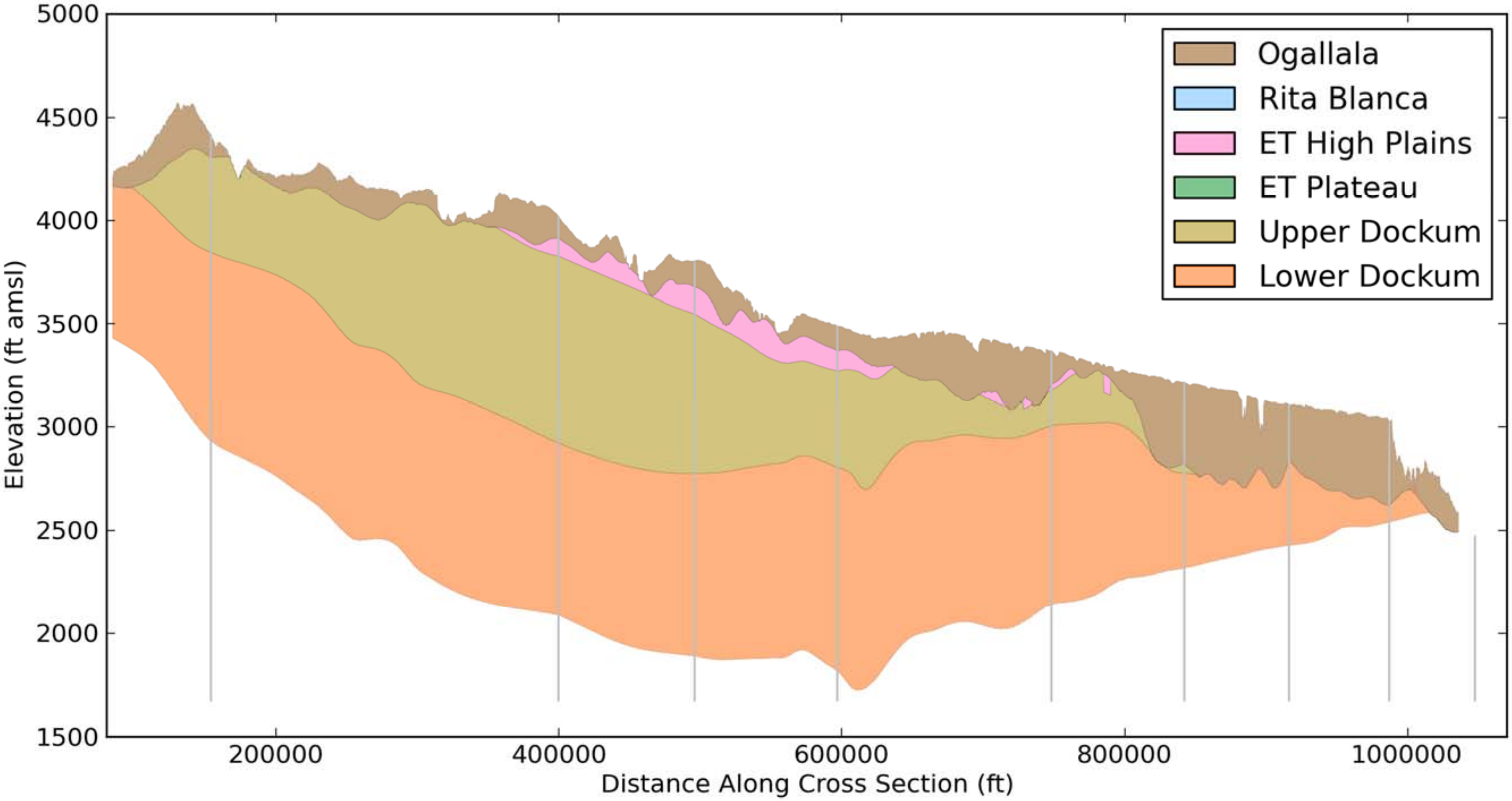

Figure 4.2.21 **Regional east-west cross section extracted from surface elevations. The location of the cross section line is shown in Figure 4.1.2. Abbreviation key: ET High Plains = Edwards-Trinity (High Plains) Aquifer, ET Plateau = Edwards-Trinity (Plateau) Aquifer.**

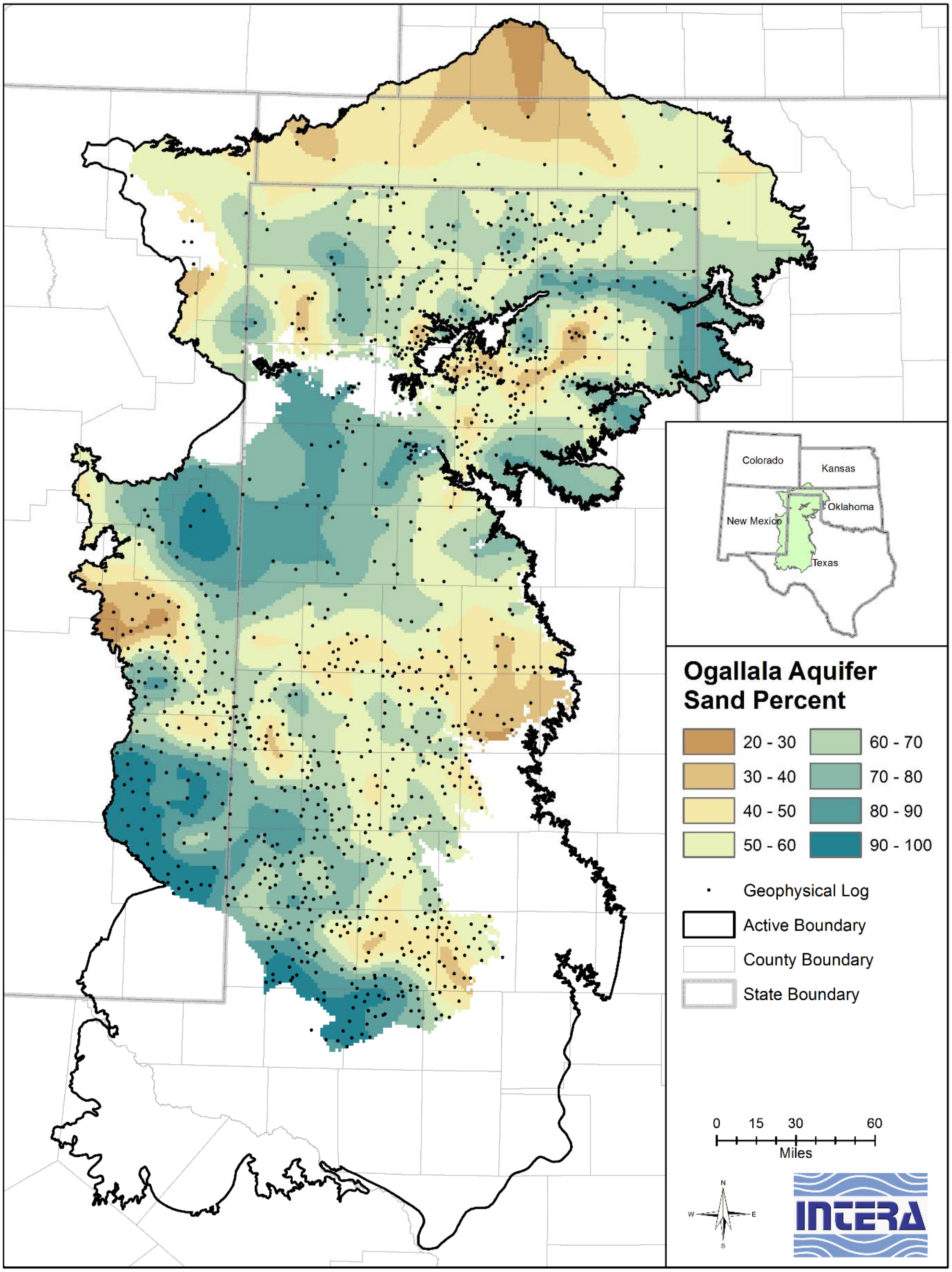

Figure 4.2.22 Sand percent of the Ogallala Aquifer.

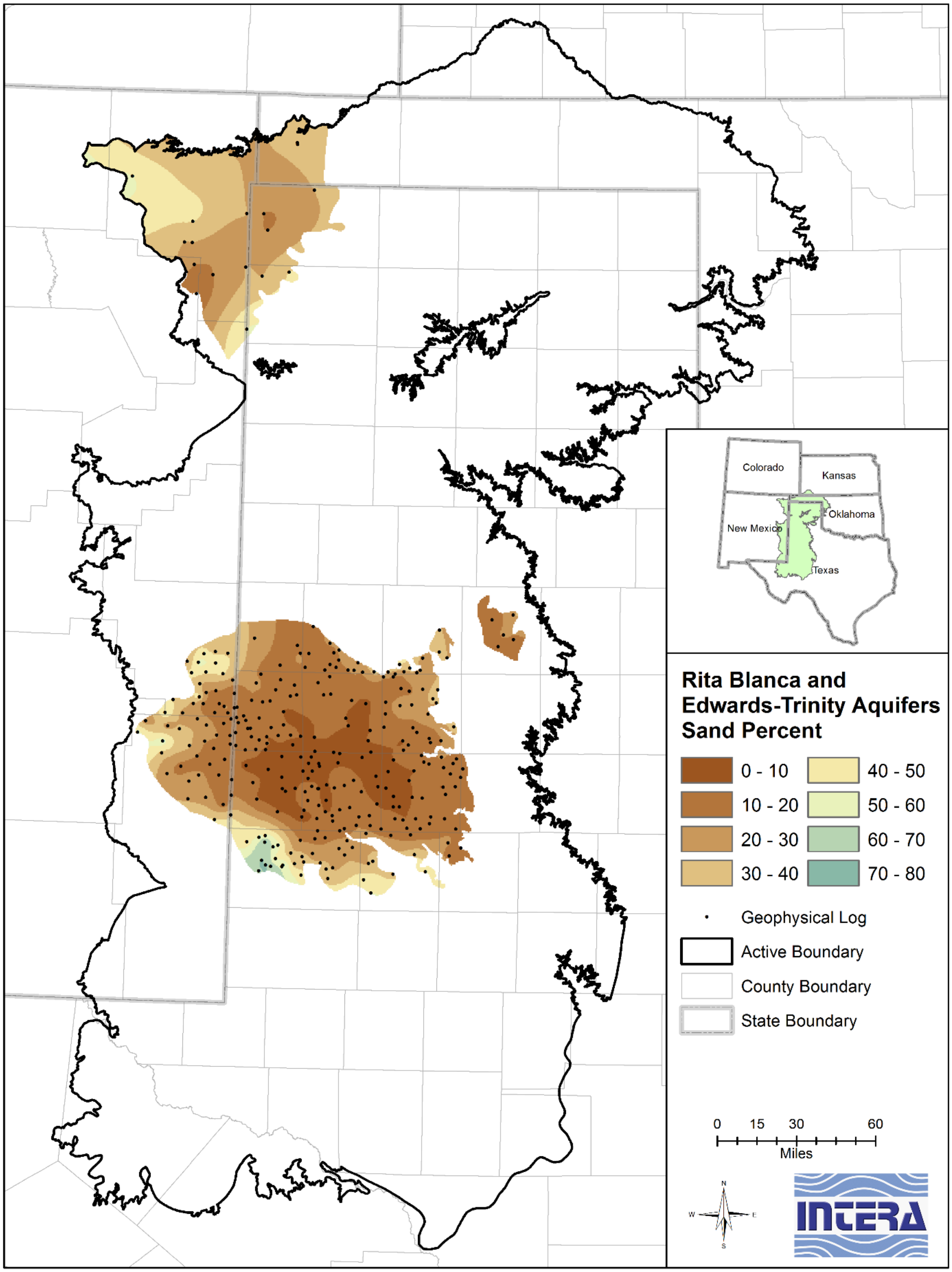

Figure 4.2.23 Sand percent of the Rita Blanca and Edwards-Trinity (High Plains) aquifers.

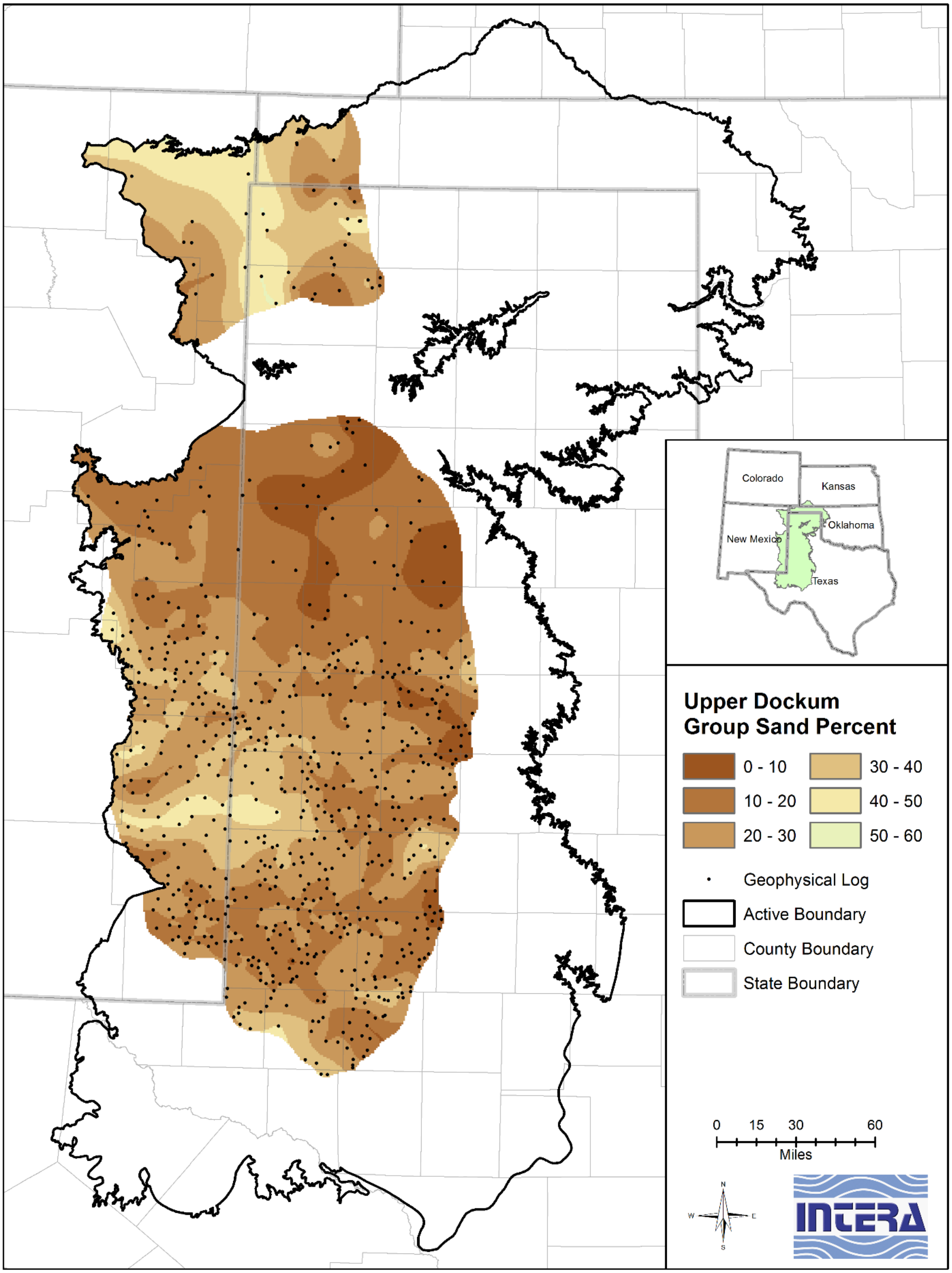

Figure 4.2.24 **Sand percent of the upper Dockum Group.**

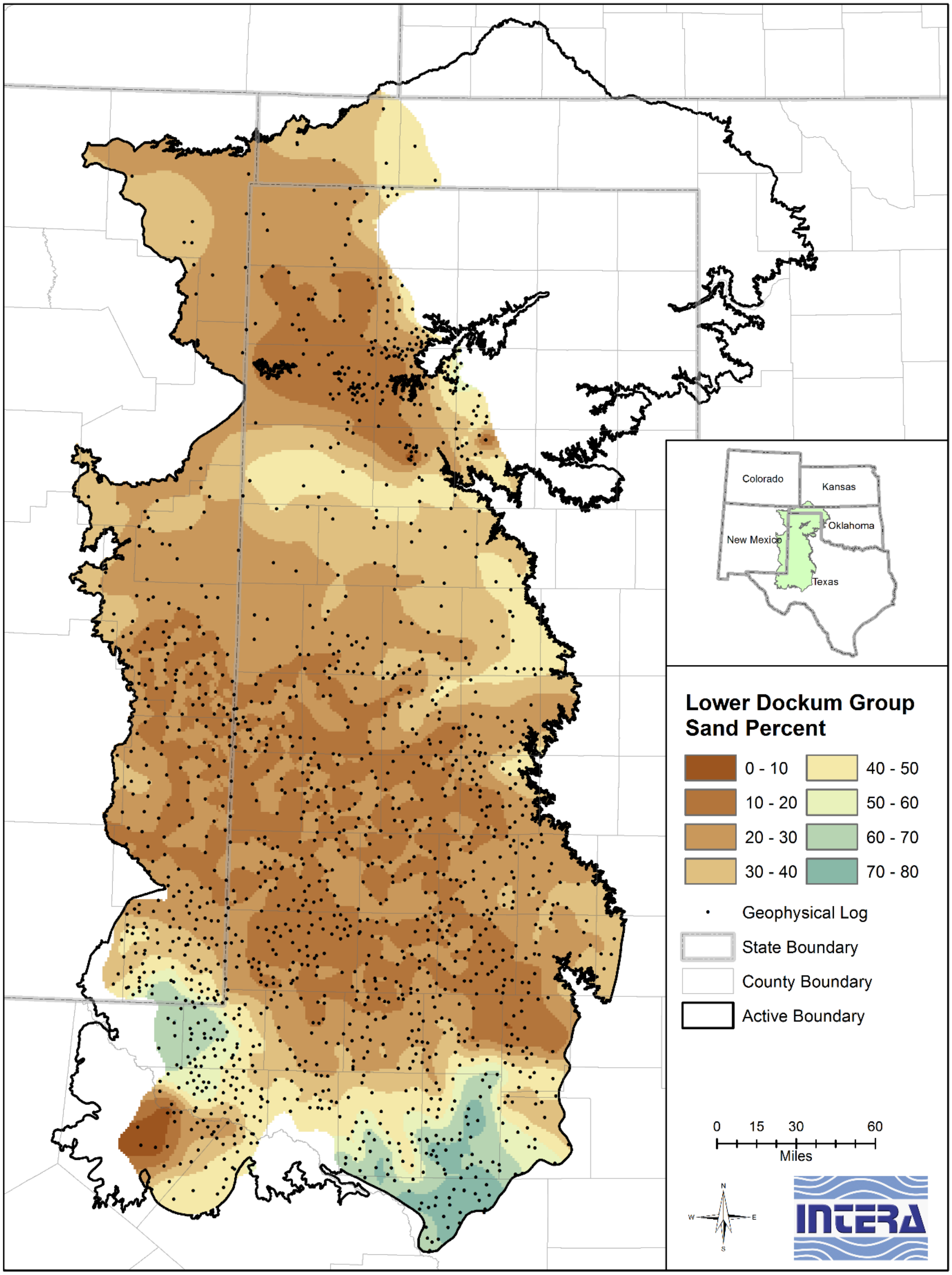

Figure 4.2.25 Sand percent of the lower Dockum Group.

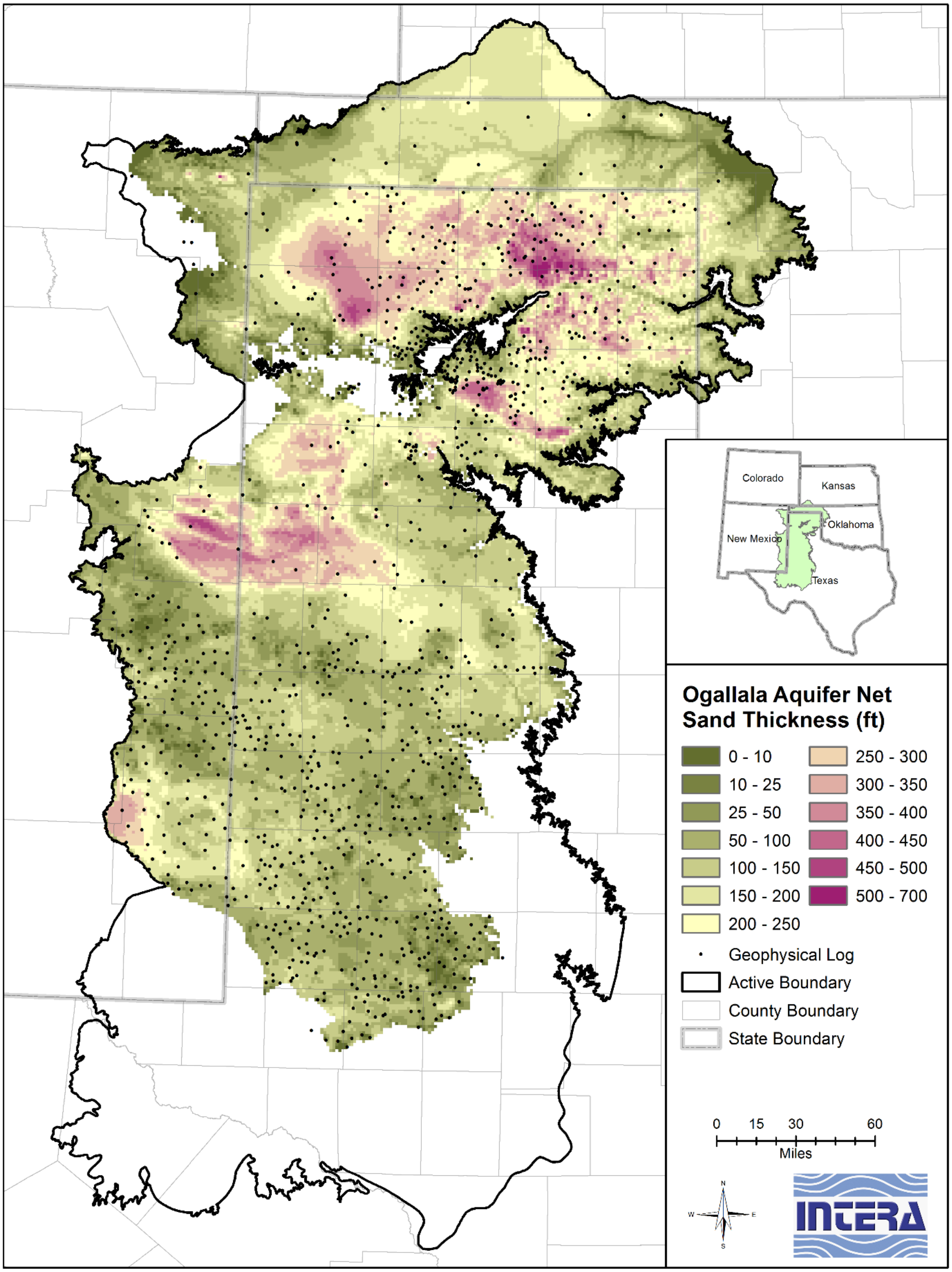

Figure 4.2.26 Net sand thickness of the Ogallala Aquifer in feet.

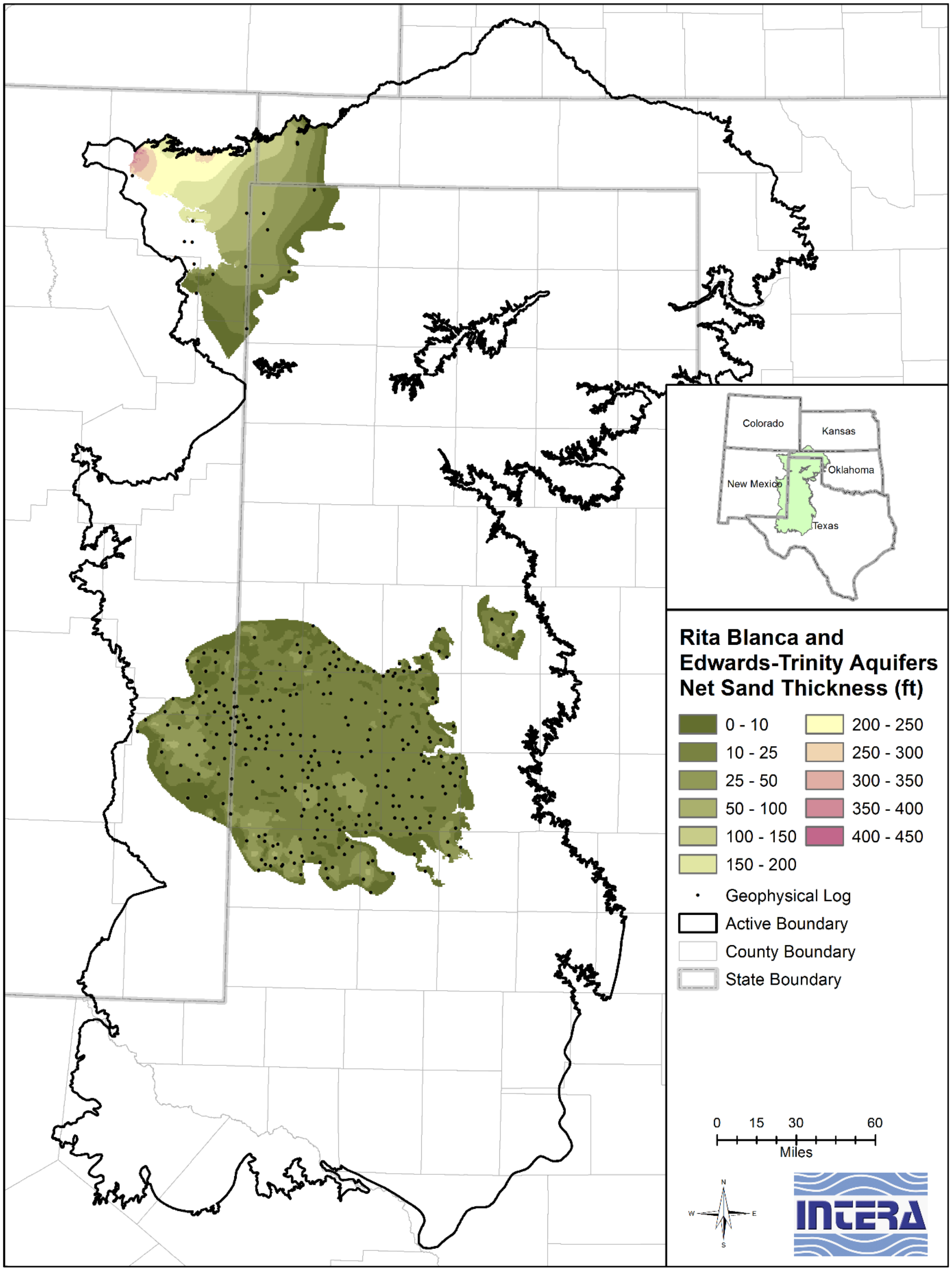

Figure 4.2.27 Net sand thickness of the Rita Blanca and Edwards-Trinity (High Plains) aquifers in feet.

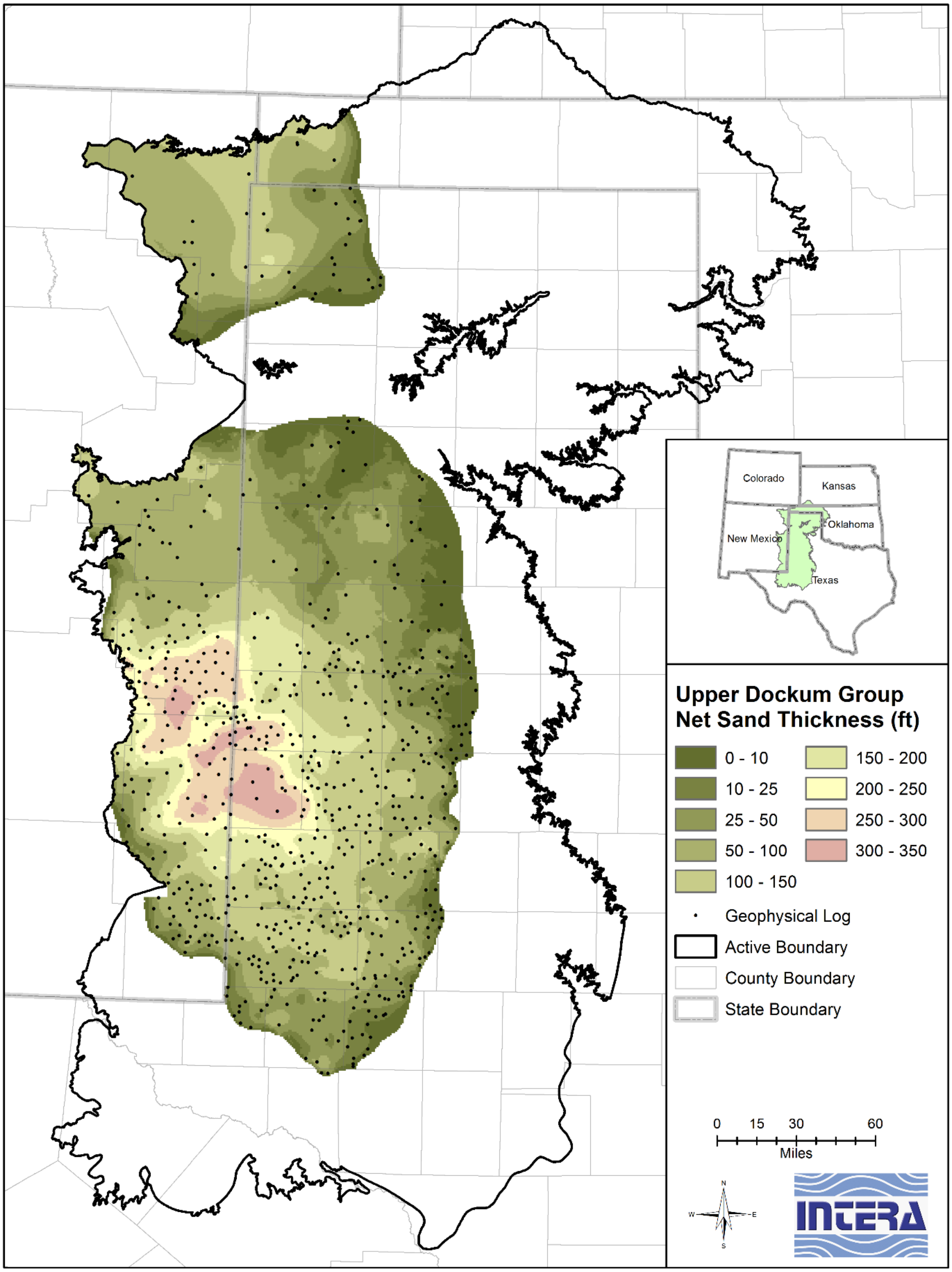

Figure 4.2.28 Net sand thickness of the upper Dockum Group in feet.

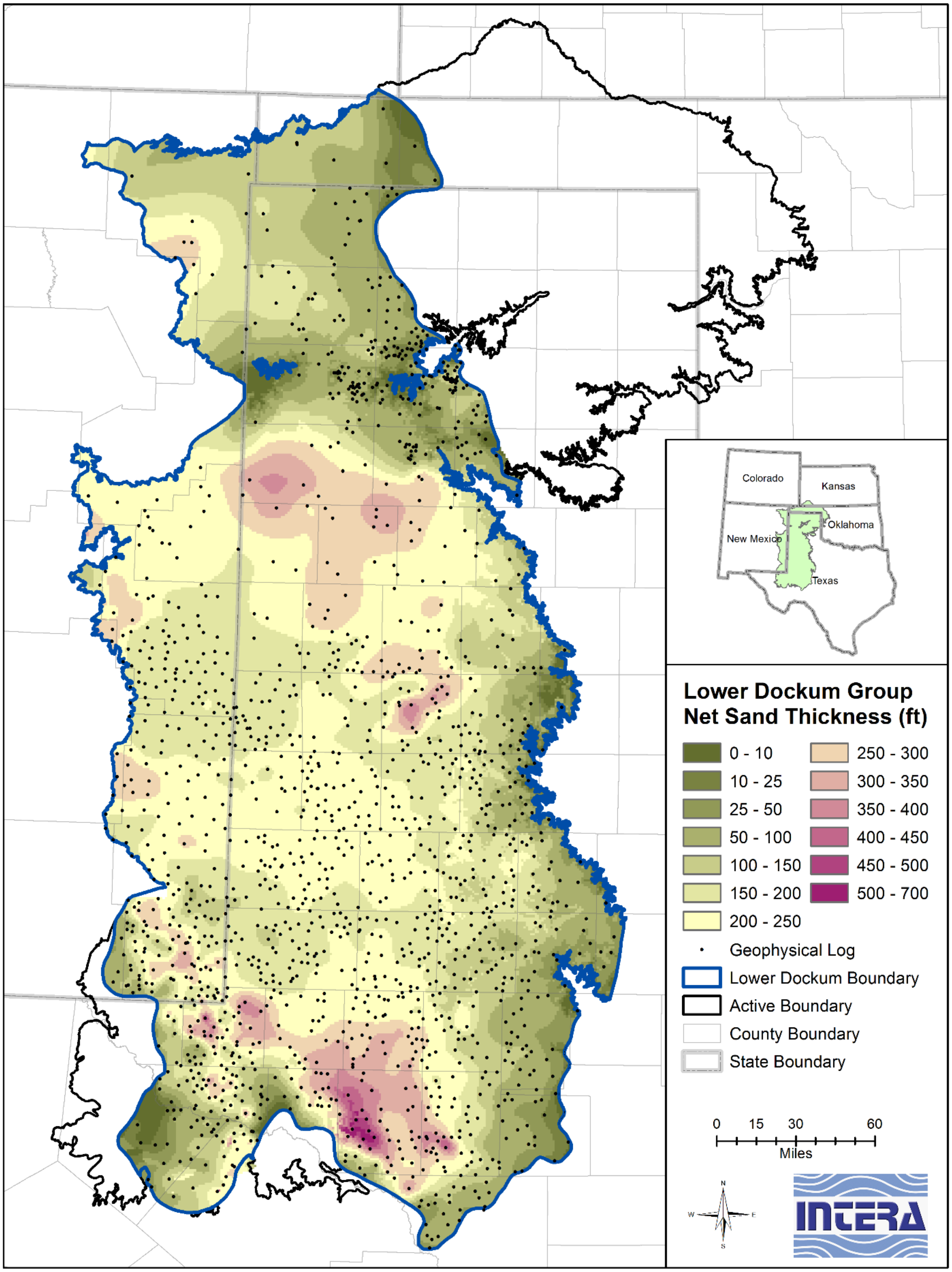

Figure 4.2.29 **Net sand thickness of the lower Dockum Group in feet.**

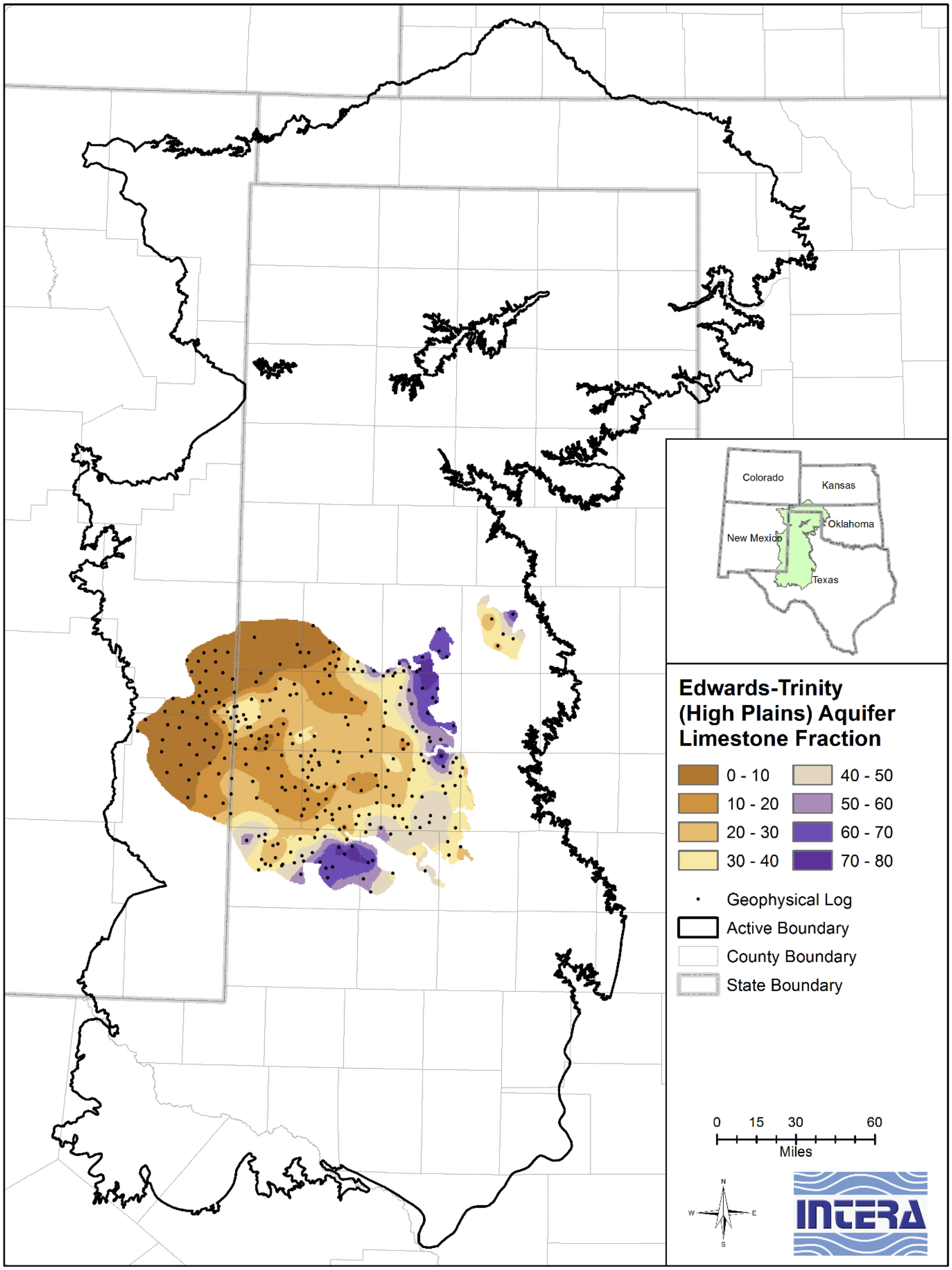

Figure 4.2.30 **Limestone fraction of the Edwards-Trinity (High Plains) Aquifer.**

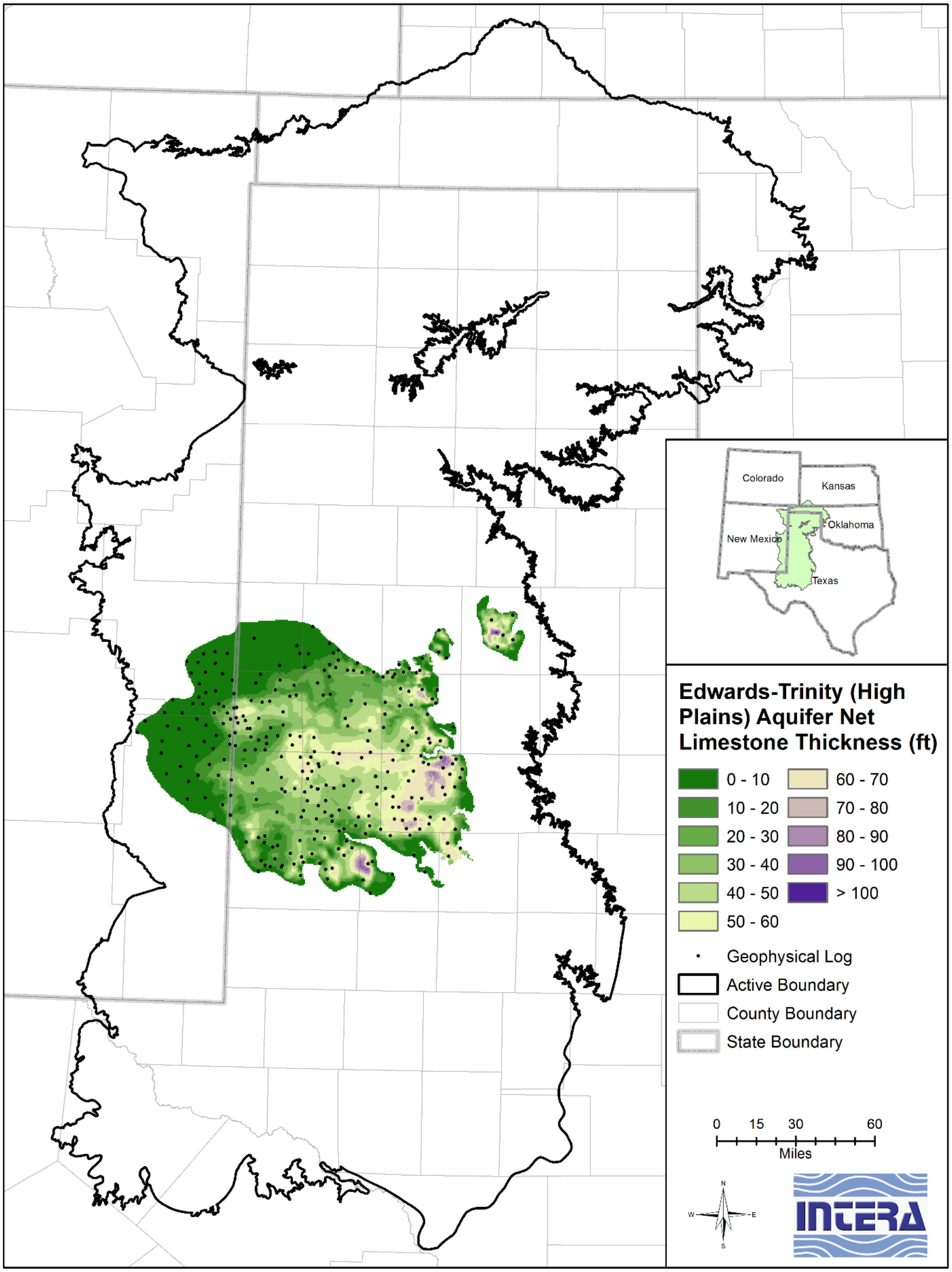

Figure 4.2.31 Net limestone thickness of the Edwards-Trinity (High Plains) Aquifer in feet.

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4.3 Water Levels and Groundwater Flow

Water-level data were collected for the High Plains Aquifer System groundwater availability model study area in order to estimate pre-development groundwater flow, estimate historical water-level surfaces and historical water-level declines, evaluate the transient behavior of water levels observed in wells, and identify water-level calibration targets for the model. The following subsections provide the sources used to collect water-level data in the active model area, discuss and present an estimate of pre-development water levels, discuss available transient water-level data and present an analysis of selected transient data throughout the active model area, present estimated water-level surfaces, and discuss water-level calibration targets. A summary of available literature data on cross-formational flow between the aquifers in the High Plains Aquifer System is provided in the last subsection.

4.3.1 Data Sources

Water-level data were obtained from the TWDB groundwater database (TWDB, 2013a), several Groundwater Conservation Districts within the active model area, and the United States Geological Survey online data (United States Geological Survey, 2013b). The TWDB groundwater database (TWDB, 2013a) was queried to obtain the available water-level data for the Texas counties in the active model area. All data identified as publishable and not affected by pumping were collected. Water-level data were obtained from the following Groundwater Conservation Districts:

- Hemphill County Underground Water District.
- Mesa Underground Water Conservation District.
- North Plains Groundwater Conservation District.
- Permian Basin Underground Water Conservation District.
- Panhandle Groundwater Conservation District.
- South Plains Underground Water Conservation District.

Care was taken to eliminate duplicate measurements in the data from the Groundwater Conservation Districts and the TWDB groundwater database. In addition, data from both sources for a well were integrated. All water-level data received from the Mesa Underground Water Conservation District, the North Plains Groundwater Conservation District, and the

Permian Basin Underground Water Conservation District were found to be duplicated in the TWDB groundwater database. Water-level data for New Mexico, Oklahoma, and Kansas were obtained from the United States Geological Survey groundwater data for the nation available online (United States Geological Survey, 2013b).

Historical groundwater data through the late 1990s were compiled from the previous groundwater availability models of the individual aquifers in the High Plains Aquifer System. However, the decision was made that those data would not be used and supplemented with data since the late 1990s to complete the groundwater data set used for the High Plains Aquifer System groundwater availability model. The reasons for making this decision included the following:

- Based on personal communication with TWDB staff responsible for maintaining the TWDB groundwater database, which is the primary source of water-level data, reconciliation of the database was conducted around early 2013 to try to eliminate inaccurate water levels or water levels with no confidence (Hopkins, 2013). Because of this reconciliation process and the removal of data from the database by TWDB staff, recompiling the water-level data from the TWDB groundwater database was considered to provide a more accurate data set than using the historically compiled data. In addition, the effort required to recompile the water-level data was considered to be less than the effort that would have been required to reconcile the historically compiled data with the revised content of the TWDB groundwater database.
- Likewise, recompiling water-level data from Groundwater Conservation Districts was considered to require less effort than determining which Groundwater Conservation District data were and were not included in the historically compiled data and enabled control in eliminating duplicate measurements with data in the TWDB groundwater database.

There are five water-bearing units of interest in the High Plains Aquifer System: the Ogallala Aquifer, the Rita Blanca Aquifer, the Edwards-Trinity (High Plains) Aquifer, the upper portion of the Dockum Aquifer, and the lower portion of the Dockum Aquifer. An accurate understanding of water levels in these aquifers requires knowledge of which water-level measurements are representative of which aquifer. Using available completion data for wells and the structural surfaces for the aquifers, the aquifer(s) across which the wells are completed was determined or estimated. The completion data consisted of screen top and bottom locations in 22 percent of the wells, total well depth only in 54 percent of the wells, and neither screen information nor total depth for 24 percent of the wells.

For the wells with screen information, it was possible to identify the aquifer(s) across which the well is completed. The completion interval identified for the wells is considered to be certain. For the wells with total depth only, the completion interval was estimated, when possible, based on the predominate aquifer(s) present shallower than that total depth and the aquifer code provided in the source data. The completion interval identified for these wells is considered to be somewhat uncertain. For wells with neither screen information nor total depth, the completion interval was estimated in some cases using the aquifer code provided in the source data and the predominate aquifer(s) present at the location of the well. The completion interval identified for these wells is considered to be highly uncertain. For many wells, no completion interval could be identified.

Using the estimated completion intervals, the wells were placed into “aquifer groups” for the purpose of distilling the multiple combinations of aquifer completions into a manageable list. The aquifer group identifies the principle aquifer across which the well is completed and, if applicable, whether the completion includes additional aquifers overlying and/or underlying the principle aquifer. The aquifer groups and the number of wells identified in each group are summarized in Table 4.3.1.

The spatial distribution of wells identified as completed into the Ogallala Aquifer or the Ogallala Aquifer and underlying aquifer(s) is provided in Figure 4.3.1. The location of wells identified as completed to the Rita Blanca or Edwards-Trinity (High Plains) aquifers, the Rita Blanca Aquifer and overlying and/or underlying aquifer(s), or the Edwards-Trinity (High Plains) Aquifer and overlying and/or underlying aquifer(s) are shown in Figure 4.3.2. The spatial distribution of wells identified as completed into the upper Dockum Group, both the upper and lower Dockum Group, or the upper Dockum Group and overlying aquifer(s) is shown in Figure 4.3.3. The spatial distribution of wells identified as completed into the lower Dockum Group, both the upper and lower Dockum Group, or the lower Dockum Group and overlying and/or underlying aquifer(s) is shown in Figure 4.3.4.

The location of wells for which a completion interval could not be determined or estimated and wells not used in the analysis of water levels are shown in Figure 4.3.5. The majority of the wells with an undetermined completion are located in the portion of the active model area where multiple aquifers are present. The unused wells are those for which the water-level data and completion information for the well are not consistent. That is, these wells have maximum depths to water that are deeper than the indicated total depth of the well. Due to the potential uncertainty in the well data, the limited number of these wells, and the availability of water-level data from numerous other wells in the areas of these wells, the impact of not using these wells in the analysis of water levels was considered to be negligible.

As shown in Figures 4.3.1 through 4.3.4, many wells were identified as being completed across more than one aquifer. For those wells, the measured water level represents a composite level and is not specific to any one aquifer. In order to provide the best estimate of water-level conditions within each aquifer in the High Plains Aquifer System, only water-level data for wells identified as completed into a single aquifer were used in the evaluation of water levels presented in the remainder of this section. A summary of the number of water-level measurements and wells by county for the Ogallala, Rita Blanca, Edwards-Trinity (High Plains), upper Dockum, and lower Dockum aquifers is provided in Table 4.3.2.

The temporal distribution of water-level measurements for wells identified as completed solely within the Ogallala, Rita Blanca, Edwards-Trinity (High Plains), upper Dockum, and lower Dockum aquifers are shown in Figures 4.3.6 through 4.3.10, respectively. These figures show that few to no water-level measurements are available for the aquifers prior to 1930. A significant number of water-level measurements are available during the 1940s for the Ogallala, upper Dockum, and lower Dockum aquifers but very few are available during the 1940s for the Rita Blanca and Edwards-Trinity (High Plains) aquifers. By far, the greatest number of water-level measurements is available for the Ogallala Aquifer. These figures also show that the available number of water-level measurements varies from year to year.

4.3.2 Pre-development Water-Level Surfaces

Pre-development conditions are defined as those existing in the aquifers before the natural flow of groundwater was disturbed by artificial discharge via pumping. Typically, pre-development conditions represent steady-state conditions in the aquifer; where aquifer recharge is balanced by natural aquifer discharge. The following discussion on pre-development conditions in the High Plains Aquifer System is presented by aquifer.

4.3.2.1 Ogallala Aquifer Pre-development Water-Level Surface

Gould (1906, 1907) provides insight into the pre-development conditions in the Ogallala Aquifer in the eastern and western portions of the Texas panhandle, respectively. These areas correspond to the northern portion of the Ogallala Aquifer in Texas. Although wells were common in this portion of the state during his investigation, they were predominantly domestic and/or stock wells and are assumed to have had little impact on the pre-development water-level surface. In his section on water conditions by county, Gould (1906, 1907) indicates that the source for many of the creeks and streams in the counties of the panhandle were springs issuing from Tertiary-age sediments, which are equivalent to the Ogallala Aquifer. In addition, he observed a large number of springs along creek and stream banks. The majority of the spring issued from sands and gravels in the Tertiary sediments or from the contact between the Tertiary-age sediments and underlying red beds of the Triassic-age sediments, which are equivalent to the Dockum Aquifer. This information from Gould (1906, 1907) indicates that, prior to development, groundwater in the northern portion of the Ogallala Aquifer flowed locally towards streams that incised the aquifer.

Several reports provide information on development of the Ogallala Aquifer for irrigation purposes. This information provides guidelines for evaluating the available water-level data with respect to which data are appropriate for use in estimating pre-development water levels. The following paragraphs provide a brief summary of the information provided in those reports.

White and others (1940) report that the use of groundwater for irrigation purposes in the High Plains of Texas began in 1911 with the drilling of the first successful irrigation well west of the town of Plainview in Hale County. Six to seven additional irrigation wells were drilled that same year. Development of groundwater for irrigation purposes on a large scale began in 1912 with the establishment of the Texas Land and Development Company on a large track of land near the town of Plainview. Between 1912 and 1913, that company began operation of 85 irrigation wells. The location of the early Plainview irrigation district is shown on Figure 4.3.11.

A survey of irrigation wells by Baker (1915) indicates that in 1914 there were 100 irrigation wells in the general vicinity of the town of Plainview (eastern Hale, western Floyd, and southern

Swisher counties), 27 near the town of Hereford (southeastern Deaf Smith County), and 12 near the town of Muleshoe (northeastern Bailey and northwestern Lamb counties). These three areas were termed the Plainview, Hereford, and Muleshoe irrigation districts (see Figure 4.3.11). The number of irrigation wells in the Plainview district was reported at 160 in 1918 by the Texas Land and Development Company. Use of groundwater for irrigation purposes declined during World War I and, due to above-average rainfall, little irrigation was practiced from 1919 to 1926. Subsequent years of reduced rainfall resulted in increased development of the groundwater for irrigation purposes. By 1934, the number of irrigation wells in the Texas High Plains was 296 with 180 in the Plainview district, 46 in the Hereford district, and 27 in the Muleshoe district. A rapid increase in the number of irrigation wells occurred from 1934 to 1937, a slower increase occurred in 1938 and 1939, and the rate of increase in irrigation wells again increased in 1940. The majority of the irrigation wells were located in the Plainview, Hereford, or Muleshoe district prior to 1935. From 1935 to 1939, some of the new irrigation wells were drilled in these districts but many were drilled in new areas, including the Lubbock-Littlefield and Spring Lake irrigation districts (see Figure 4.3.11).

Development of the Ogallala Aquifer in the northern High Plains began after that in the southern High Plains. Alexander (1961) reports that use of wells for irrigation began in the northern High Plains in the early 1930s with the drilling of about 16 wells. The majority of these early wells were located in Dallam County near the town of Texline (Texline irrigation district) (see Figure 4.3.11) and in Hansford County. Development of the aquifer for irrigation purposes accelerated in the 1950s due to the record drought that occurred during that decade. The number of irrigation wells in the northern High Plains was 150 in 1950 and increased to 1,206 in 1959. The greatest density of early irrigation wells was located in northwestern Dallam County near the town of Texline. Concentrated development also occurred in a large area in northern Moore, southern Sherman, and northwestern Hutchinson counties.

A review of available transient water-level data from the early part of the 1900s also provided useful information for constructing the pre-development water levels for the Ogallala Aquifer. A review of these data indicated that water levels for wells located in the Texas portion of the Southern Ogallala Aquifer showed evidence of drawdown in the 1930s while water levels for some wells in the northern Ogallala Aquifer showed stable or slightly rising water levels during the 1930s to 1950s time period.

Based on the information in Gould (1906, 1907) regarding the Ogallala Aquifer as the source of water for many streams and springs in the northern portion of the aquifer; the early history of irrigation development provided in White and others (1940), Baker (1915), and Alexander (1961); and a review of early transient water-level data, the pre-development water-level surface for the Ogallala Aquifer was initially developed using:

- The ground surface elevation at the location of springs issuing from the Ogallala Aquifer (see Section 4.5 for a discussion of springs). The ground surface elevation was taken as the digital elevation model value at the spring location using ArcGIS.
- The ground surface elevation at select locations along valleys where the Ogallala Aquifer is incised by streams. The ground surface elevation was taken as the digital elevation model value at locations where the base of the Ogallala Aquifer is exposed in valleys using ArcGIS.
- Water-level measurements prior to 1930 in the Ogallala Aquifer.
- Water-level measurements during the 1930s for wells located in the Northern Ogallala Aquifer having stable or slightly increasing water levels. These water levels were used because of a lack of pre-1930 data for this portion of the aquifer.

The water-level control points used to construct the pre-development water-level surface for the Ogallala Aquifer are general coincident with those provided by United States Geological Survey (2013). Where not identical to the United States Geological Survey (2013) data, they are very similar in value.

Using the above data, the initial pre-development water-level surface for the Ogallala Aquifer was above ground surface in many areas with local topographic lows. To force the pre-development water levels below ground surface, artificial control points were created. The water-level elevation for these control points was calculated as the ground surface elevation at those points (as determined in ArcGIS from the digital elevation model) minus an estimated depth to water. The estimated depth to water ranged from 10 to 50 feet and was based on observed depths to water for water-level measurements prior to 1930.

In addition, the initial pre-development water-level surface for the Ogallala Aquifer was lower than water levels measured in the 1950s in central Lea County, New Mexico. Therefore, 1950s water-level measurements from this area of the aquifer were used in constructing the pre-development surface.

The estimated pre-development water-level surface for the Ogallala Aquifer is shown in Figure 4.3.12. This figure also shows the control points used to create the surface and indicates the type for the control point. The type indicated as 'modified DEM' corresponds to the control points used to constrain the pre-development water levels below ground surface. The water-level control points in Texas will be used as calibration targets for the steady-state model. The water-level control points in New Mexico, Oklahoma, and Kansas will be used to guide calibration of the steady-state model but will not specifically be used as calibration targets. The calibration targets in the Ogallala Aquifer for the steady-state model are summarized in Table 4.3.3.

Figure 4.3.12 shows pre-development groundwater flow predominately from the northwest to southeast with local diversions, which correspond to local topographic lows, in the Southern Ogallala Aquifer. Refer to Figure 2.1.3 for the location of topographic lows. Flow in the Northern Ogallala Aquifer is generally from west to east, again with local diversions to topographic lows. Flow between the southern and northern portions of the aquifer is to the northeast from about the northeastern corner of Randall County, Texas through Hemphill County, Texas.

The pre-development water-level surface and resultant flow directions are consistent with those given in the United States Geological Survey Regional Aquifer-System Analysis reports for the Ogallala Aquifer (Gutentag and others, 1984; Luckey and others, 1986), the Southern Ogallala Aquifer groundwater availability model (Blandford and others, 2003, 2008), and the Northern Ogallala Aquifer groundwater availability model (Dutton and others, 2001a, Dutton 2004, INTERA, Inc. and Dutton, 2010).

4.3.2.2 Rita Blanca Aquifer Pre-development Water-Level Surface

The earliest water levels available for wells completed into the Rita Blanca Aquifer were measured in the late 1930s, all in Cimarron County, Oklahoma. The earliest measurements in Texas and New Mexico were taken in the late 1940s and mid-1950s, respectively. Since few early water-level data are available for the Rita Blanca Aquifer, the pre-development surface was constructed using maximum water levels measured in wells regardless of time. In a few instances, the maximum water level for a well was not used in developing the pre-development surface because that value was inconsistent with maximum water-level values for nearby wells. The ground surface elevations at springs issuing from the Rita Blanca Aquifer (see Section 4.5) were also used in constructing the pre-development surface.

The estimated pre-development water-level surface for the Rita Blanca Aquifer is shown in Figure 4.3.13. This figure also shows the control points used to create the surface and indicates the type for the control points. The water-level control points in Texas will be used as calibration targets for the steady-state model. The water-level control points in New Mexico and Oklahoma will be used to guide calibration of the steady-state model but will not specifically be used as calibration targets. The calibration targets in the Rita Blanca Aquifer for the steady-state model are summarized in Table 4.3.3. Figure 4.3.13 shows that groundwater flow in the aquifer is to the southeast. Generally, the estimated pre-development water levels in the Rita Blanca Aquifer are about 50 to 100 feet lower than the estimated pre-development water levels in the Ogallala Aquifer.

4.3.2.3 Edwards-Trinity (High Plains) Aquifer Pre-development Water-Level Surface

The pre-development water-level surface for the Edwards-Trinity (High Plains) Aquifer was developed using the maximum water levels measured in wells regardless of time. The maximum water level for a well was not used in instances where that value was inconsistent with maximum water-level values for nearby wells. In addition, values for select wells were used in areas having numerous wells.

The estimated pre-development water-level surface for the Edwards-Trinity (High Plains) Aquifer is shown in Figure 4.3.13. This figure also shows the control points used to create the surface. The control points in Texas will be used as calibration targets for the steady-state model. The water-level control points in New Mexico will be used to guide calibration of the steady-state model but will not specifically be used as calibration targets. The calibration targets in the Edwards-Trinity (High Plains) Aquifer for the steady-state model are summarized in Table 4.3.3.

Figure 4.3.13 shows that groundwater flow in the aquifer is to the southeast. A comparison of this figure to the pre-development water levels in the Edwards-Trinity (High Plains) Aquifer groundwater availability model (Blandford and others, 2008) shows good consistency. Generally, the estimated pre-development water levels in the Edwards-Trinity (High Plains)

Aquifer are about 50 to 100 feet lower than the estimated pre-development water levels in the Ogallala Aquifer.

4.3.2.4 Upper Dockum Group Pre-development Water-Level Surface

The earliest water-level data for the upper Dockum Group consist of one value each in two wells measured in the late 1930s. Since these data are insufficient to create an estimate of pre-development conditions across the entire aquifer, additional control points were taken as the maximum water level measured in a well regardless of time. For the two wells with the early measurement, that measurement rather than the maximum water level measured in the well was used. The maximum water level for a well was not used in instances where that value was inconsistent with maximum water-level values for nearby wells. In addition, values for select wells were used in areas having numerous wells.

The estimated pre-development water-level surface for the upper Dockum Group is shown in Figure 4.3.14. This figure also shows the control points used to create the surface and indicates the type for the control point. The control points in Texas will be used as calibration targets for the steady-state model. The water-level control points in New Mexico and Oklahoma will be used to guide calibration of the steady-state model but will not specifically be used as calibration targets. The calibration targets in the upper Dockum Group for the steady-state model are summarized in Table 4.3.3.

Figure 4.3.14 shows that groundwater flow is to the southeast in the southern portion of the aquifer and predominately to the east in the northern portion of the aquifer, with some diversion around topographic lows. A comparison of this figure to the pre-development water levels for the upper Dockum Group in the Dockum Aquifer groundwater availability model (Ewing and others, 2008) shows that the pre-development water levels constructed for the current model are generally about 100 to 200 feet lower than those given in Ewing and others (2008). As discussed in Section 4.2, this current model includes a detailed investigation conducted to determine the structural surfaces for the aquifers of the High Plains Aquifer System. Those structures were then used to determined or estimate well completions. As a result, there is a difference in the wells identified as completed into the upper Dockum Group between the two studies. The identification of wells completed into the upper Dockum Group is considered to be more certain for this current study than for the study by Ewing and others (2008). This results in a significant difference in the estimated pre-development water-level surface for the upper Dockum Group between the two studies. Although the magnitude of the water levels is different for the two studies, both show that flow in the southern portion of the upper Dockum Group is predominately to the southeast.

In the southern portion of the upper Dockum Group, pre-development water levels in the aquifer are about 25 to 100 feet lower than those in the overlying Ogallala Aquifer. In the northern portion of the upper Dockum Group, pre-development water levels in the aquifer are about 100 to 200 feet lower than those in the overlying Ogallala Aquifer. The estimated pre-development water levels in the southern portion of the upper Dockum Group are very similar to those in the Edwards-Trinity (High Plains) Aquifer.

4.3.2.5 Lower Dockum Group Pre-development Water-Level Surface

Several water-level measurements are available for the lower Dockum Group prior to 1940, primarily located in the outcrop, southwest, and extreme northern portions of the aquifer. These measurements were assumed to be representative of pre-development conditions. The spatial distribution of these data is insufficient to create an estimate of pre-development water levels across the entire aquifer. Therefore, two additional types of control points were used to construct the pre-development water-level surface for the aquifer. The first was the ground surface elevation at the locations of springs issuing from the Dockum Aquifer. The ground surface elevation was taken as the digital elevation model value at the location of the springs as determined using ArcGIS. See Section 4.5 for a discussion of Dockum Aquifer springs. The second additional control consisted of the maximum water level measured in a well regardless of time. For the wells with water-level measurements prior to 1940, those measurements rather than the maximum water level measured in the wells were used. The maximum water level for a well was not used in instances where that value was inconsistent with maximum water-level values for nearby wells. In addition, values for select wells were used in areas having numerous wells. In a few instances, the maximum water level reported for a well appeared anomalous relative to other measurements in the well. In those instances, the highest value most consistent with the other values was used rather than the maximum reported value.

The estimated pre-development water-level surface for the lower Dockum Group is shown in Figure 4.3.15. This figure also shows the control points used to create the surface and indicates the type for the control point. The water-level control points in Texas will be used as calibration targets for the steady-state model. The water-level control points in New Mexico and Oklahoma will be used to guide calibration of the steady-state model but will not specifically be used as calibration targets. The calibration targets in the lower Dockum Group for the steady-state model are summarized in Table 4.3.3.

Figure 4.3.15 shows that groundwater flow is generally to the southeast in the southern portion of the aquifer and to the east-southeast in the northern portion of the aquifer. Locally, groundwater is diverted from this general direction towards springs and the Canadian, Brazos, and Colorado rivers (refer to Figure 2.0.4 for the river locations) and in the vicinity of topographic lows (refer to Figure 2.1.3 for the location of topographic lows).

A comparison of Figure 4.3.15 to the pre-development water levels for the lower Dockum Group in the Dockum Aquifer groundwater availability model (Ewing and others, 2008) was made. South of the Canadian River, that comparison shows that the surfaces are relatively similar in the southeast but differ by 100 to 200 feet to the northeast, with the current surface higher than that in Ewing and others (2008). For both studies, the overall direction of groundwater flow is similar. North of the Canadian River, the surface in Ewing and others (2008) indicates flow towards the southeast while the current surface indicates predominately eastward flow. The difference between the two surfaces is attributed to the difference in wells identified as completed into the lower Dockum Group between the two studies.

In the southern portion of the lower Dockum Group, pre-development water levels in the aquifer are similar to those in the overlying Ogallala Aquifer over much of the area and are about 25 to 100 feet higher than those in the Ogallala Aquifer in places near the southern boundary of the Ogallala Aquifer. In the northern portion of the lower Dockum Group, pre-development water levels in the aquifer are about 100 to 200 feet lower than those in the overlying Ogallala Aquifer.

The estimated pre-development water levels in the southern portion of the lower Dockum Group are, in general, about 100 to 200 feet higher than those in the Edwards-Trinity (High Plains) Aquifer. In general, the pre-development water levels in the lower Dockum Group are about 100 to 200 feet higher than those in the upper Dockum Group south of the Canadian River and about 25 to 200 feet lower than those in the upper Dockum Group north of the Canadian River.

4.3.3 Transient Water-Level Data (Hydrographs)

An evaluation of the transient behavior of water levels in the aquifers was conducted using transient water-level data in wells. In general, transient data were considered to consist of more than five water-level measurements. Due to the large volume of data for the Ogallala Aquifer, transient data were considered to consist of 10 or more water-level measurements over a period of five or more years. The location of wells with transient water-level data is shown in Figure 4.3.16 for wells completed into the Ogallala Aquifer, in Figure 4.3.17 for wells completed into the Rita Blanca and Edwards-Trinity (High Plains) aquifers, and in Figure 4.3.18 for wells completed into the upper and lower Dockum aquifers.

Due to the large volume of transient data available for wells in the active model area, all hydrographs could not be presented and discussed in the report. The hydrographs discussed here were selected based on several criteria. First, a review of all hydrographs for an aquifer was conducted in order to select those with a long-term record. Second, hydrographs were selected based on spatial location in an effort to show transient conditions across as much of the aquifer as possible. Third, an effort was made to select hydrographs with sufficient data to define a water-level trend and with data that appear to be free of measurements potentially impacted by drilling and/or pumping activities.

Since all hydrographs could not be presented, a brief summary of the trends observed in the available data is provided in Table 4.3.4 for wells located in Texas. This table is organized by aquifer and county. The county order is from north to south and east to west. The purpose of this table is to provide a general overview of the observed trends in water levels based on a review of all of the transient data.

The remainder of this section first discusses overall trends observed in the transient water-level data and presents example hydrographs for select wells by aquifers. The scale for years on the x-axis is from 1900 to 2013 for all hydrographs. The scale for the water-level elevation on the y-axis is variable from hydrograph to hydrograph depending on the range of the observed data; however, the division of the y-axis is consistent at 25 feet. At the end of this section, select hydrographs for the aquifers showing seasonal trends are presented and discussed.

4.3.3.1 Ogallala Aquifer Transient Water-Level Data

This discussion provides a summary of the trends in water-level data observed in the Ogallala Aquifer and compiled in Table 4.3.4. Also included are example hydrographs for select wells identified as completed into the Ogallala Aquifer and located in the northern portion of the aquifer (Figure 4.3.19) and in the northern and southern counties in the southern portion of the aquifer (Figures 4.3.20 and 4.3.21, respectively). In some instances, a trend is discussed for a county but an example hydrograph for that county is not included in the figures. For these counties, refer to Table 4.3.4 for a description of the trends observed in the water-level data for wells located in that county.

Counties in the Northern Portion of the Ogallala Aquifer

Overall declining trends are observed in all or most wells in Dallam, Sherman, Hansford, Ochiltree, Hartley, Moore, Hutchinson, Roberts, Potter, and Carson counties, with the largest declines (up to 150 to 200 feet) occurring in Sherman, Hansford, Ochiltree, Hartley, Moore, and Carson counties. The hydrographs for wells 261703, 264901, and 356501 located in Hartley, Moore, and Ochiltree counties, respectively, shown on Figure 4.3.19 provide examples of these large declines. The smallest declines (50 to 75 feet) have been observed for wells in Roberts and Potter counties. The rate of decline in water level has been fairly stable in most wells, but decreased in around 1970 to 1980 for many wells. A few wells show a substantial increase in the rate of decline since the late 1990s. The hydrograph for well 264901 in Moore County provides an example of a fairly constant rate of decline and the hydrographs for well 247603 in Sherman County and well 356501 in Ochiltree County provide examples of the decline rate decreasing in about 1970 to 1980 and increasing again in the late 1990s (see Figure 4.3.19).

Overall stable or slightly increasing or decreasing water-level trends are observed for the majority of the wells in Lipscomb, Hemphill, Gray, Wheeler, Armstrong, and Donley counties. In general, these rises and declines are on the order of less than 25 feet. The hydrographs for well 505901 in Hemphill County and well 529201 in Wheeler County show examples of stable water levels since the mid-1950s, and the hydrograph for well 1201617 in Donley County shows an example of rising water levels since about 1980 (see Figure 4.3.19). A few of the wells in Lipscomb County show a recent 50 to 75-foot decline in water level as shown by the hydrograph for well 439603 (see Figure 4.3.19). The water-level trend in several wells in Gray County show periods of recovery imposed on overall declining levels. One such example is shown for well 525904 (see Figure 4.3.19).

Although many wells in Dallam and Carson counties show declining water-level trends, several wells in these counties show overall stable or slightly increasing trends. The hydrograph for well 239101 in Dallam County provides an example of a slightly rising overall trend (see Figure 4.3.19).

Northern Counties in the Southern Portion of the Ogallala Aquifer

In many of the northern counties of the southern portion of the Ogallala Aquifer, the overall long-term trend in water levels has not been consistent across the entire county. Good examples are observed in wells 1051703 and 2410201 in Bailey County and wells 2325904 and 2312803 in Lubbock County (see Figure 4.3.20). In Bailey County, well 1051703 shows an overall decline in water level of about 75 feet since 1950 and well 2410201 shows water levels that have fluctuated throughout the years but overall remained fairly stable. In Lubbock County, the water level in well 2325904 rose about 50 feet between about 1980 and 2000 and then remained constant while the water level in well 2312803 has continually declined by about 100 feet since the late 1950s (see Figure 4.3.20).

In Parmer, Lamb, Hale, and Floyd counties, water levels throughout the county have predominately declined. The range in declines has been about 25 to 225 feet. A couple of wells in Hale County with long-term water-level data that includes early measurements show stable water levels from about 1915 to 1940 and declining water levels beginning in the early to late 1940s. An example of this trend is shown for well 1152703 (see Figure 4.3.20). Overall declining water levels in most wells and stable or rising water levels in a few wells are observed in Deaf Smith, Randall, Castro, Swisher, Briscoe, Bailey, and Crosby counties. Declines up to 200 feet have been observed in Swisher and Crosby counties and up to about 100 to 150 feet in in Deaf Smith, Castro, Briscoe, and Bailey counties. The rate of decline has been fairly constant for many of the wells with an overall declining trend. For example, well 1033802 in Parmer County and well 1152703 in Hale County (see Figure 4.3.20). For many wells with an overall declining trend in water level, the rate of decline decreased, temporarily stopped or became very small, or water levels began to recover starting in about1970 to 1980. Wells 1032703 and 2304603 in Castro and Floyd counties, respectively, show examples of the decreasing rate of decline (see Figure 4.3.20). An example of the decline temporarily stopping and some recovery in the water level is provided in the hydrograph for wells 2419801 and 2421905 in Cochran and Hockley counties, respectively (see Figure 4.3.20). An example of the rate of decline becoming very small is provided in the hydrograph for well 1119401 in Swisher County, and the hydrograph for well 1007701 in Deaf Smith County shows an example of the decline stopping in about 1970 with some water-level recovery through current day (see Figure 4.3.20). In a few wells, the rate of water-level decline has increased since about 2005. For example, see the hydrograph for well 1044711 in Lamb County in Figure 4.3.20.

Southern Counties in the Southern Portion of the Ogallala Aquifer

Overall, declines in water levels have been less and occurred over a smaller area in the southern counties of the southern portion of the aquifer than in the counties in the northern portion of the Southern Ogallala Aquifer. Overall stable water levels are observed in Dickens and Midland counties. For example, see the hydrograph for well 2858601 in Midland County in Figure 4.3.21. Predominately rising trends in water level of less than 25 feet have been observed in Howard and Glasscock counties. Various trends in the water level are observed throughout Cochran, Hockley, Yoakum, and Ector counties. These trends include overall stable, rising, and declining water levels, as well as trends showing periods of both rising and declining water levels. The hydrograph for well 2439904 in Terry County shows an overall rising trend since the mid-1950s, and the hydrographs for well 2458101 in Yoakum County and well 4505916 in Ector County show periods of both rising and declining water levels (see Figure 4.3.21). The water level in several wells in Terry, Lynn, Gaines, Dawson, Andrews, Martin, Howard, and Midland counties show local highs centered on about 1990. Examples of these highs are provided in the hydrographs for wells 2707401 and 2342801 located in Gaines and Lynn counties, respectively (see Figure 4.3.21). Recent rises in water levels of about 25 to 50 feet are observed in a few wells each in Yoakum, Terry, Lynn, Gaines, Dawson, Martin, and Ector counties. One such example is provided by the hydrograph for well 2724202 in Dawson County (see Figure 4.3.21).

4.3.3.2 Rita Blanca Aquifer Transient Water-Level Data

A summary of the trends in water-level data observed in the Rita Blanca Aquifer is provided in Table 4.3.4. Select hydrographs for wells identified as completed into the aquifer are shown in Figure 4.3.22. In Dallam County, Texas, the majority of the hydrographs show an overall decline in water level. Declines up to 150 feet have been observed in some wells. The rate of decline has generally been fairly constant in most wells. For example, see the hydrograph for well 249704 in Figure 4.3.22. In a few wells, a decrease in the rate of decline or a temporary stop in decline is observed for a period of time. The time period during which decline slowed or stopped varied between wells. Well 148902 shows a stop in decline between about 1985 and 2000, and the water level in well 242903 shows a slow rate of decline from about 1960 through 2010 and then a rapid rate of decline since that time (see Figure 4.3.22).

In general, the water levels in wells in Cimarron County, Oklahoma have remained fairly constant or slightly declined over their period of record. Figure 4.3.22 includes the hydrograph for well 364241102591501, which shows an overall slightly declining trend, located in Cimarron County. In Union County, New Mexico, both relatively constant water levels and declining trends are observed in wells completed into the Rita Blanca Aquifer. The hydrograph for well 361847103064701 shows a fairly constant rate of decline over the period of record and the hydrograph for well 36131410318301 shows a fairly stable trend over the period of record (see Figure 4.3.22). Although the overall trend in water level in well 363041103054601 is declining, periods of both reduced decline and water-level recovery are observed in the water level for this well (see Figure 4.3.22).

4.3.3.3 Edwards-Trinity (High Plains) Aquifer Transient Water-Level Data

A summary of the trends in water-level data observed in the Edwards-Trinity (High Plains) Aquifer is provided in Table 4.3.4. Select hydrographs for wells identified as completed into the aquifer are shown in Figure 4.3.22. Transient water-level data are available for only a few wells in Texas identified as completed into the Edwards-Trinity (High Plains) Aquifer. The trend in water level is variable for these wells. An overall declining trend is observed in well 2441402 in Yoakum County, and a relatively stable trend is observed in well 2309903 in Lubbock County. Periods of both rising and declining water level are observed in wells 2410303 and 2461401 in Bailey and Terry counties, respectively. In both of these wells, the water level rose from about 1970 to 1989, remained stable from about 1989 to 1995, and then declined. The rate of decline was greater in well 2410303 in Bailey County than in well 2461401 in Terry County.

In general, the water level in wells identified as completed into the Edwards-Trinity (High Plains) Aquifer and located in New Mexico has remained fairly stable or slightly declined as shown for well 332501103270301 in Lea County and well 334700103030601 in Roosevelt County.

4.3.3.4 Upper Dockum Group Transient Water-Level Data

A summary of the trends in water-level data observed in the upper Dockum Group is provided in Table 4.3.4. Select hydrographs for wells identified as completed into the aquifer are shown in Figure 4.3.23. Various trends in water level are observed in the aquifer. These trends include overall declining, overall rising, overall stable, and periods of both rising and declining water levels. Example declining water levels are provided by the hydrographs for well 755701 in Deaf Smith County and well 1134907 in Swisher County. Example rising water levels are shown for well 2759903 in Ector County and well 2335301 in Lubbock County. Example stable water levels are shown for wells 1010701 and 4501901 in Deaf Smith and Winkler counties, respectively. Transient records showing periods of both rising and declining water levels are provided by the hydrographs for wells 2849402 and 4521304 in Martin and Ector counties, respectively.

4.3.3.5 Lower Dockum Group Transient Water-Level Data

A summary of the trends in water-level data observed in the lower Dockum Group is provided in Table 4.3.4. Select hydrographs for wells identified as completed into the aquifer are shown in Figure 4.3.24. In general, stable trends in the water level until between about 1995 and 2000 and then declining trends are observed for wells located in the northern portion of the aquifer. Example hydrographs showing these trends are given for well 717201 and 724403 in Hartley and Moore counties, respectively (see Figure 4.3.24).

The overall trend in water level is either stable, rising, or declining for most wells located in the central portion of the aquifer. In general, the changes in water level are typically less than 50 feet. The hydrograph for well 743401 located in Oldham County shows an example of a slightly rising trend (see Figure 4.3.24). While not all counties are represented by hydrographs in Figure 4.3.24, the overall county trends and notable hydrographs are included in the county descriptions in Table 4.3.4. For example, a 125-foot decline from 1965 to 1990 is observed in one well located in Deaf Smith County. For wells located in Swisher County, periods of both rising and declining water levels are observed with the changes ranging from less than 25 feet to about 75 feet. Stable or slightly declining water levels (less than 10 feet) are observed in Crosby and Motley counties. An overall decline of about 75 feet from 1940 to 1970 is observed in one well located in Floyd County (Table 4.3.4). The hydrograph for well 661401 located in Armstrong County shows an initial steady decline followed by fairly stable water levels (see Figure 4.3.24).

In the southern counties of the aquifer, the following observations are made based on review of the transient water-level data. Overall stable trends are observed for wells located in Crane, Sterling, and Upton counties (Table 4.3.4). An example hydrograph is given in Figure 4.3.24 for well 4554501 in Crane County. Overall slightly declining trends (less than 25 feet) are observed in Loving and Martin counties, moderate declines of 25 to 50 feet are observed in Reeves County, and some large declines (greater than 50 feet) are observed in Pecos County. Periods of both increasing and declining water levels are observed for wells in Glasscock County. Both stable and large declining trends are observed in wells in Ector, Ward, and Winkler counties (Table 4.3.4). An example declining trend in Ward County is given for well 4525713 in Figure 4.3.24. Periods of rising and declining water levels are also observed in several wells in Ward and Winkler counties (Table 4.3.4). One example is provided in Figure 4.3.24 for well 4616201 in Winkler County.

The majority of the available transient water-level data for the lower Dockum Aquifer are for wells located in the outcrop area. Three types of trends are observed for these wells: overall rising water levels, overall declining water levels, and periods of rising and declining water levels. Generally, the rises and declines are less than 25 feet. However, periods of increases greater than 50 feet are observed in some wells (Table 4.3.4). Figure 4.3.24 shows several examples of hydrographs for wells located in the outcrop area of the aquifer. The hydrographs for wells 2925901 and 2943801 in Mitchell County and wells 2824904 and 2927702 in Scurry County show increasing water levels from about 1955 or 1965 to about 1990 and either stable or slightly declining water levels after that time. The hydrograph for well 2344608 in Garza County shows two cycles of rising and declining water levels with lows in about 1975 and 1998 and highs in about 1993 and 2008.

4.3.3.6 Seasonal Transient Water-Level Data

The majority of the wells completed into the Ogallala Aquifer are used for irrigation purposes. Therefore, they are typically pumped for only a portion of the year during crop growing season.

Examples of seasonal changes in water levels are shown by the hydrographs for four wells in Figure 4.3.25. The hydrographs show, in general, declining water levels during the spring and summer and rising water levels from fall through winter of the next year. This trend is best observed in the hydrograph for well 712401 in Hartley County. For three of the hydrographs, this seasonal trend is imposed on an overall declining trend in water level. For well 2330103 in Crosby County, the seasonal trend is imposed on long-term declining and rising trends.

Transient data at a sufficient frequency to show seasonal variations in water levels were found for one well each completed into the Rita Blanca, Edwards-Trinity (High Plains), and lower Dockum aquifers (Figure 4.3.26). The transient data for wells completed into the upper Dockum Group were not sufficient at any well to show seasonal variations. The seasonal data for well 249704 completed into the Rita Blanca Aquifer in Dallam County are for the early 1950s and show only about two seasonal cycles; one in 1952 and one in 1953. These data show highest water levels in the winter months, declining water levels in the spring to summer months, and rising water levels in the fall months. Seasonal data for well 2310401 completed into the Edwards-Trinity (High Plains) Aquifer in Hale County generally show rising water levels in the fall and winter months and declining water levels in the spring and summer months. Seasonal data for well 5206604 completed into the lower Dockum Group in Pecos County generally show rising water levels in the late summer to winter months and declining water levels in the spring and early summer months. These trends are consistent with seasonal pumping for crop irrigation.

4.3.4 Historical Water-Level Surfaces and Water-Level Declines

Estimated historical water-level surfaces in the Ogallala, Rita Blanca, Edwards-Trinity (High Plains), lower Dockum, and upper Dockum aquifers were estimated for the years 1950, 1980, and 2010. In addition, the decline in water level from pre-development to 2010 was estimated. Only wells known to be completed into the aquifers were used to estimate their water-level surfaces. This was done so that the developed surfaces represent conditions within the aquifers themselves and are not influenced by composite water levels from wells completed into multiple aquifers.

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 sparse. Since the amount of water-level data available are typically not sufficient for a particular year of interest, the historical water-level surfaces were generally developed based on data from a few years before and after the year of interest. Generally, data from the year of interest and two years prior to and two years after the year of interest were used. On occasion, the range was expanded if there were insufficient data and narrowed if there were sufficient data. The ranges of years used to develop the historical surfaces are summarized in Table 4.3.5. For all aquifers, the average water level for a well was used if the well had several water-level measurements during the date range.

4.3.4.1 Water-Level Surfaces and Decline for the Ogallala Aquifer

The estimated water-level surface for the Ogallala Aquifer in 1950 is shown in Figure 4.3.27. In order to constrain this surface below ground surface, several types of control points in addition to the 1950 water-level data were used to develop the surface. These control points were based on the assumptions that (1) springs issuing from the Ogallala Aquifer where still flowing in 1950 and (2) seepage from the aquifer where it is incised by the Canadian River was still occurring in 1950. Two pre-development water-level elevations in Lea County, New Mexico were used to ensure that the 1950 surface was below ground surface in that area of the aquifer. In addition, several of the modified digital elevation model control points developed for construction of the pre-development surface were also used to construct the 1950 surface. These points were used to insure that the 1950 surface was below ground surface in areas of topographic lows with no water-level control. The location and types of control points used to construct the 1950 water-level surface for the Ogallala Aquifer are also shown on Figure 4.3.27.

The estimated water-level surfaces for the Ogallala Aquifer in 1980 and 2010 are shown in Figures 4.3.28 and 4.3.29, respectively. These surfaces were constructed using only water-level data for control. These surfaces do not show cones of depression centered on specific areas of high pumping. Rather, they show regional changes in water-level contours due to widespread pumping. This is best seen where the 3,400 and 3,600-foot contours shift to the west in Moore and Hartley counties in the Northern Ogallala Aquifer and shift to the northwest in Swisher and Castro counties in the Southern Ogallala Aquifer.

The decline in water level in the Ogallala Aquifer from pre-development to 2010 was estimated using the changes in water levels observed in wells. The water-level change was calculated as the difference between the initial water level measured in a well and the last water level measured in a well. The most appropriate date for the first water-level measurement is prior to 1930 for that measurement to be representative of pre-development conditions. Ideally, the most appropriate last water level would be one measured after 2009. However, water-level measurements prior to 1930 and after 2009 were not available for any wells completed into the Ogallala Aquifer. However, a water-level measurement prior to 1930 and after 2005 was available for four wells. Since pre-1930 water-level data are available for few wells, the date for the first water-level measurement was increased to prior to 1960. For wells with a later date for the first water-level measurement, last measurements after 2009 were available. Based on the available data, four classes of control points were used to develop the pre-development to 2010 decline estimates. These are:

- Initial measurement prior to 1930 and last measurement after 2005 (four wells)
- Initial measurement during the 1930s and last measurement after 2009 (21 wells)
- Initial measurement during the 1940s and last measurement after 2009 (58 wells)
- Initial measurement during the 1950s and last measurement after 2009 (262 wells)

The decline in water level in the Ogallala Aquifer estimated using these control points is shown in Figure 4.3.30. The control point type is also provided in this figure. Because some of the declines used to create this surface were calculated using later water-level measurements taken after development of the aquifer began, the actual decline in the aquifer is likely greater than shown on the figure. The largest water-level declines of over 200 feet are observed in the Southern Ogallala Aquifer in portions of Floyd and Hale counties and in small areas in Castro and Parmer counties. Declines of more than 150 feet have been experienced in large areas including portions of Parmer, Castro, Swisher, Lamb, Hale, Floyd, and Crosby counties in the Southern Ogallala Aquifer and in smaller areas including portions of Sherman, Moore, and Ochiltree counties in the Northern Ogallala Aquifer. The water-level declines shown in Figure 4.3.30 are very similar to the pre-development to 2011 declines given in McGuire (2012) for the High Plains Aquifer.

4.3.4.2 Water-Level Surfaces and Decline for the Rita Blanca Aquifer

Water-level measurement data for the Rita Blanca Aquifer are insufficient to construct contours of the water-level surface in the aquifer in 1950. Therefore, the available data are posted in

Figure 4.3.31. The estimated water-level surface for the Rita Blanca Aquifer in 1980 and 2010 are shown in Figures 4.3.32 and 4.3.33, respectively.

The decline in water level from pre-development to 2010 in the Rita Blanca Aquifer is shown in Figure 4.3.34. These declines were constructed using the calculated water-level decline in wells with water-level measurements in both pre-development and 2010. The maximum decline of about 150 feet is observed in southwestern Dallam County.

4.3.4.3 Water-Level Surfaces and Decline for the Edwards-Trinity (High Plains) Aquifer

Water-level measurement data for the Edwards-Trinity (High Plains) Aquifer are insufficient to construct contours of the water-level surface in the aquifer in 1950. Therefore, the available data are posted in Figure 4.3.31. The estimated water-level surface for the Edwards-Trinity (High Plains) Aquifer in 1980 is shown in Figure 4.3.32. Water-level measurement data for the Edwards-Trinity (High Plains) Aquifer are also insufficient to construct contours of the water-level surface in the aquifer in 2010. Therefore, the available data are posted in Figure 4.3.33.

The decline in water level in the Edwards-Trinity (High Plains) Aquifer was estimated using the calculated water-level decline in wells with water-level measurements in both pre-development and 2010. These data are insufficient to construct contours, so the data are posted in Figure 4.3.34. The declines range from a high of more than 30 feet in Cochran and Yoakum counties to a low of 4 feet in Lubbock County. Note that the amount of the water-level decline varies significantly over short distances in some areas.

4.3.4.4 Water-Level Surfaces and Decline for the Upper Dockum Group

The estimated water-level surfaces for the upper Dockum Group in 1950, 1980, and 2010 are shown in Figures 4.3.35 through 4.3.37, respectively. The 1950 surface is shown only in the southern portion of the aquifer because no data were available for the northern portion of the aquifer. For the 1980 surface, water-level elevations were not contoured for the northern portion of the upper Dockum Group because the spatial distribution of the data is insufficient to construct meaningful contours.

The decline in water level from pre-development to 2010 in the upper Dockum Group is shown in Figure 4.3.38. The decline in water level in the aquifer was estimated using the calculated water-level decline in wells with water-level measurements in both pre-development and 2010. The decline surface is contoured only for the southern portion of the aquifer because the spatial distribution of the data in the northern portion of the aquifer is insufficient to construct meaningful contours. The largest declines are about 50 to 70 feet and occur in northeastern Deaf Smith County and south-central Swisher County. In general, declines of less than 10 feet are observed in the southern portion of the aquifer. The declines in the northern portion of the aquifer range from 1 to 24 feet and are greatest in southwestern Dallam County (see Figure 4.3.38).

4.3.4.5 Water-Level Surfaces and Decline for the Lower Dockum Group

The estimated water-level surfaces for the lower Dockum Group in 1950, 1980, and 2010 are shown in Figures 4.3.39 through 4.3.41, respectively. Construction of the 1950 surface assumed that springs issuing from the aquifer were still flowing in 1950. As such, the digital elevation model values for the ground surface elevation at spring locations were used as control points along with the available 1950 water-level data. The decline in water level from pre-development to 2010 in the lower Dockum Group is shown in Figure 4.3.42. The decline in water level in the aquifer was estimated using the calculated water-level decline in wells with water-level measurements in both pre-development and 2010. The maximum decline of about 95 feet is observed in northwestern Pecos County. The decline in this portion of the aquifer appears to be confined to a small area. A local region of decline on the order of about 35 feet is observed in southwestern Andrews County and north-central Winkler County. A larger region of decline is observed around an area of about a 60-foot decline located in New Mexico along the border between Curry and Roosevelt counties. A small local decline of about 45 feet is observed in southwestern Hartley County and of about 20 feet is observed along the boundary between Hartley and Moore counties.

4.3.5 Transient Water-Level Calibration Targets

Water-level calibration targets for the transient model will include all water-level measurements for wells in Texas identified as completed into the Ogallala, Rita Blanca, Edwards-Trinity (High Plains), upper Dockum, or lower Dockum aquifers. Refer to Figures 4.3.1 through 4.3.4 for the location of wells completed to these aquifers. Although water levels measured in wells located in New Mexico, Oklahoma, and Kansas will be used to guide calibration of the transient model, those measurements will not specifically be used as calibration targets. Water-level data for wells where the completion interval could not be determined will not initially be used as calibration targets. This is because the aquifer associated with water levels in these wells is uncertain. However, if a well with an undetermined completion and transient water-level data is located in an area of the model with few calibration targets, an investigation may be conducted to estimate the most likely completion interval for the well. This investigation would compare the total depth of the well and the measured water levels to the total depths and water levels in nearby wells with known completion intervals to see if they are similar. If so, the assumption may be made that the completion interval for the well is the same as that of the nearby well with approximately the same total depth and water levels. The number of calibration targets for the transient model by aquifer, county, and decade is shown in Table 4.3.6.

4.3.6 Cross Formational Flow

Several studies of the hydrogeology and/or hydrochemistry between the aquifers in the High Plains Aquifer System have been published. This section provides a brief summary of the results related to cross-formational flow in those studies. Nativ and Gutierrez (1988) evaluated the lithology between the Edwards-Trinity (High Plains) Aquifer and the overlying Ogallala Aquifer and underlying Dockum Group. They also compared potentiometric surfaces in the 1978 through 1987 time frame and hydrochemistry between the aquifers to assess locations with potential cross-formational flow. This evaluation identified locations where the water level in Edwards-Trinity (High Plains) Aquifer was higher than that in the Ogallala Aquifer and a permeable or semi-permeable contact exists between the two aquifers, indicating the potential for upward flow, in central Bailey, northwest Lubbock, northeast Gaines, and Dawson counties, Texas and central Lea and southwestern Roosevelt counties, New Mexico. A comparison of water chemistry in the two aquifers in these areas is consistent with cross-formational flow from the Edwards-Trinity (High Plains) Aquifer to the Ogallala Aquifer. Citing Nativ and Smith (1985), they indicate the probability of cross-formational flow from the Edwards-Trinity (High Plains) Aquifer to the overlying Ogallala Aquifer where the Ogallala Aquifer is thin and where it has a small saturated thickness based on groundwater chemistry and isotopic data. They do not, however, identify the areas where this likely occurs.

Nativ and Gutierrez (1988) found that the water level in the Edwards-Trinity (High Plains) Aquifer was higher than that in the Dockum Group throughout most of the extent of the Edwards-Trinity (High Plains) Aquifer. In areas of Cochran, Hockley, Yoakum, Terry, Lynn, and Gaines counties, a permeable contact also exists between the two aquifers, indicating potential areas for downward flow from the Edwards-Trinity (High Plains) Aquifer to the

Dockum Group. They could not, however, confirm this downward flow with chemical data due to a lack of available wells in the Dockum Group. In addition, they suggest likely upward flow from the Dockum Group to the Edwards-Trinity (High Plains) Aquifer in Lea and Roosevelt counties, New Mexico based on lithology and water level and water chemistry data.

Additional information related to the potential for cross-formational flow between the Ogallala, Edwards-Trinity (High Plains), and Dockum aquifers is available in Nativ (1988). Her analysis considered water-level surface maps for the Ogallala Aquifer in 1978. The dates for the water-level maps she used for the Edwards-Trinity (High Plains) and Dockum aquifers are not provided. The chemical and isotopic composition of the groundwater in the aquifers was compared and the lithology of the sediments at aquifer contacts was investigated. Based on her study, Nativ (1988) states that the data suggests that flow occurs from the Edwards-Trinity (High Plains) Aquifer to the Ogallala Aquifer in the Midland Region (in parts of Bailey, Lamb, Hale, Cochran, Hockley, Lubbock, Yoakum, Terry, Lynn, Gains, Dawson, Ector, Martin, and Glasscock counties, Texas and Lea County, New Mexico). In areas where the water level in the Ogallala Aquifer is higher than that in the Dockum Group and lithologic evidence indicates the potential for hydraulic connection between the two aquifers, the chemical and isotopic composition of the aquifers is not similar, indicating a lack of downward flow from the Ogallala Aquifer to the Dockum Group. Along the Eastern Caprock Escarpment and a few areas to the west, the water level in the Dockum Group is higher than that in the Ogallala Aquifer. In these areas, which include Crosby, northwestern Deaf Smith, Dickens, Garza, Howard, and Parmer counties, Texas and Curry County, New Mexico, chemical and isotopic data support upward flow from the Dockum Group to the Ogallala Aquifer. Upward flow from the Dockum Group into the Ogallala Aquifer is also suggested by chemical and isotopic data in areas where the water level is higher in the Dockum Group than in the Ogallala Aquifer and the saturated thickness of the Ogallala Aquifer is small. Such an area occurs in southeastern Deaf Smith County near Tierra Blanca Creek. Nativ (1988) indicates the possibility of some localized flow from the Permian-age formations upward to the Ogallala Formation along the Eastern Caprock Escarpment based on chemical and isotopic data. One such occurrence is indicated in Donley County.

Information regarding the potential for cross-formational flow is also available in Scanlon and others (2005b) based on measured arsenic concentrations in the Ogallala, Edwards-Trinity (High

Plains), and Edwards-Trinity (Plateau) aquifers. In general, arsenic concentrations in the Ogallala Aquifer are high in the south and decline to the north. The northern portion of the Edwards-Trinity (High Plains) Aquifer underlying the area of the Ogallala Aquifer with lower arsenic concentrations also has low arsenic concentrations. However, the southern portion of the Edwards-Trinity (High Plains) Aquifer underlying the area of the Ogallala Aquifer with higher arsenic concentrations also has elevated arsenic concentrations. These results suggest the likelihood that arsenic is not naturally occurring in the Edwards-Trinity (High Plains) Aquifer but, rather, is a result of cross-formational flow from the Ogallala Aquifer to the Edwards-Trinity (High Plains) Aquifer. In addition, arsenic concentrations in the Edwards-Trinity (Plateau) Aquifer are elevated only where it overlies the very southern portion of the Ogallala Aquifer, which has elevated arsenic concentrations. In the remainder of the Edwards-Trinity (Plateau) Aquifer, arsenic concentrations are very low, indicating that it is unlikely that arsenic is originating from the formations comprising the Edwards-Trinity (Plateau) Aquifer. Rather, the trend in arsenic concentrations suggest the likelihood of downward flow from the Ogallala Aquifer to the Edwards-Trinity (Plateau) Aquifer.

Table 4.3.1 Summary of wells by aquifer group.

Aquifer Group	Number of Wells
Ogallala Aquifer	13,931
Ogallala Aquifer and underlying aquifer(s)	3,223
Rita Blanca Aquifer	158
Rita Blanca Aquifer and overlying aquifer	8
Rita Blanca Aquifer and underlying aquifer(s)	28
Rita Blanca Aquifer and overlying & underlying aquifers	9
Edwards-Trinity (High Plains) Aquifer	297
Edwards-Trinity (High Plains) Aquifer and overlying aquifer	42
Edwards-Trinity (High Plains) Aquifer and underlying aquifer(s)	68
Edwards-Trinity (High Plains) Aquifer and overlying & underlying aquifers	22
upper Dockum Group	156
lower Dockum Group	1,677
upper Dockum Group and overlying aquifer(s)	65
lower Dockum Group and overlying aquifer(s)	42
lower Dockum Group and underlying aquifer(s)	267
upper & lower Dockum Groups	15
upper & lower Dockum Groups and underlying aquifer(s)	1
undetermined	1,632

Table 4.3.2 Number of water-level measurements and wells per aquifer by state and county.

County	Number of Water-Level Measurements / Wells				
	Ogallala Aquifer	Rita Blanca Aquifer	Edwards-Trinity (High Plains) Aquifer	Upper Dockum Group	Lower Dockum Group
Texas					
Andrews	727 / 74			8 / 3	73 / 7
Armstrong	1,693 / 100				334 / 26
Bailey	5,721 / 315		102 / 5	116 / 4	
Borden	112 / 8				42 / 12
Briscoe	1,433 / 86				62 / 14
Carson	5,909 / 282				76 / 5
Castro	4,314 / 183			14 / 2	35 / 4
Cochran	1,828 / 48		116 / 7		
Coke					1 / 1
Collingsworth	6 / 4				

Table 4.3.2, continued

County	Number of Water-Level Measurements / Wells				
	Ogallala Aquifer	Rita Blanca Aquifer	Edwards-Trinity (High Plains) Aquifer	Upper Dockum Group	Lower Dockum Group
Crane					61 / 10
Crockett					16 / 15
Crosby	4,092 / 176				26 / 3
Dallam	2,483 / 163	551 / 21		52 / 5	31 / 2
Dawson	3,761 / 313			8 / 4	56 / 5
Deaf Smith	6,383 / 291			482 / 10	45 / 11
Dickens	172 / 17				26 / 10
Donley	2,628 / 425				
Ector	321 / 90			212 / 39	60 / 18
Fisher					31 / 4
Floyd	6,381 / 244		1 / 1		37 / 17
Gaines	3,270 / 550		55 / 10		16 / 4
Garza	147 / 10				94 / 11
Glasscock	182 / 48				77 / 30
Gray	3,165 / 250				
Hale	8,356 / 432		826 / 12	29 / 5	81 / 4
Hansford	5,501 / 204				
Hartley	2,214 / 76	2 / 1		20 / 2	216 / 21
Hemphill	2,066 / 291				
Hockley	2,508 / 101		6 / 5		
Howard	743 / 234				339 / 154
Hutchinson	2,204 / 138				
Irion					3 / 3
Kent					52 / 4
Lamb	5,781 / 299		38 / 4	62 / 5	
Lipscomb	1,564 / 82				
Loving					31 / 2
Lubbock	6,563 / 409		262 / 7	98 / 4	17 / 1
Lynn	1,564 / 104		106 / 7		
Martin	3,153 / 170			74 / 6	59 / 4
Midland	915 / 154				2 / 1
Mitchell					1,454 / 405
Moore	4,351 / 243				40 / 3
Motley	102 / 34				65 / 16
Nolan					416 / 121

Table 4.3.2, continued

County	Number of Water-Level Measurements / Wells				
	Ogallala Aquifer	Rita Blanca Aquifer	Edwards-Trinity (High Plains) Aquifer	Upper Dockum Group	Lower Dockum Group
Ochiltree	2,830 / 132				
Oldham	506 / 32			18 / 1	197 / 42
Parmer	3,625 / 171				5 / 1
Pecos					320 / 10
Potter	446 / 37				787 / 78
Randall	2,986 / 203			62 / 7	89 / 22
Reagan					1 / 1
Reeves					248 / 22
Roberts	6,094 / 233				
Scurry					843 / 152
Sherman	4,190 / 227				
Sterling					278 / 62
Swisher	4,303 / 214			56 / 1	55 / 10
Terry	1,833 / 134		154 / 4	6 / 1	2 / 2
Upton					114 / 50
Ward					172 / 57
Wheeler	2,203 / 333				
Winkler				98 / 2	333 / 53
Yoakum	1,170 / 34		88 / 6	22 / 2	
New Mexico					
Curry	6,579 / 1,029			16 / 2	283 / 72
Lea	16,277 / 1,457		229 / 55	133 / 20	85 / 18
Quay	172 / 23			4 / 1	243 / 35
Roosevelt	1,063 / 236		1,095 / 174	166 / 26	82 / 29
Union	172 / 22	789 / 118		4 / 2	49 / 7
Oklahoma					
Beaver	2,995 / 884				
Cimarron	1,839 / 329	59 / 18		40 / 2	7 / 6
Ellis	2,321 / 124				
Harper	149 / 25				
Roger Mills	243 / 55				
Texas	6,924 / 1,287				
Woodward	375 / 35				

Table 4.3.2, continued

County	Number of Water-Level Measurements / Wells				
	Ogallala Aquifer	**Rita Blanca Aquifer**	**Edwards-Trinity (High Plains) Aquifer**	**Upper Dockum Group**	**Lower Dockum Group**
Kansas					
Morton	100 / 14				
Seward	143 / 3				
Stevens	207 / 10				

Table 4.3.3 Steady-state calibration targets by aquifer.

State Well Number/Site Number	County	Pre-Development Water-Level Elevation (feet)	Water-Level Description	Water-Level Source
Ogallala Aquifer				
1043907	Bailey	3752.0	pre1930 value	TWDB gw db
1043908	Bailey	3751.0	pre1930 value	TWDB gw db
1044708	Bailey	3745.0	pre1930 value	TWDB gw db
1051301	Bailey	3750.5	pre1930 value	TWDB gw db
1051302	Bailey	3746.0	pre1930 value	TWDB gw db
640405	Carson	2964.1	1930s value	TWDB gw db
156901	Dallam	4380.7	1950s value	TWDB gw db
233603	Dallam	4462.4	1950s value	TWDB gw db
233803	Dallam	4442.5	1950s value	TWDB gw db
233807	Dallam	4469.0	1950s value	TWDB gw db
233901	Dallam	4446.1	1950s value	TWDB gw db
233913	Dallam	4379.0	1950s value	TWDB gw db
234702	Dallam	4369.5	1950s value	TWDB gw db
234703	Dallam	4370.0	1950s value	TWDB gw db
234708	Dallam	4379.5	1950s value	TWDB gw db
234805	Dallam	4352.2	1950s value	TWDB gw db
235401	Dallam	4210.4	1950s value	TWDB gw db
235603	Dallam	4141.8	1950s value	TWDB gw db
236101	Dallam	4112.6	1950s value	TWDB gw db
236301	Dallam	4029.6	1950s value	TWDB gw db
236302	Dallam	4027.0	1950s value	TWDB gw db
236401	Dallam	4105.2	1950s value	TWDB gw db
242101	Dallam	4373.4	1950s value	TWDB gw db
1013303	Deaf Smith	3786.5	pre1930 value	TWDB gw db
1201607	Donley	2665.0	pre1930 value	TWDB gw db
1202913	Donley	2559.0	pre1930 value	TWDB gw db
1203712	Donley	2488.4	pre1930 value	TWDB gw db
1203713	Donley	2500.1	pre1930 value	TWDB gw db
1211201	Donley	2545.0	pre1930 value	TWDB gw db
1152603	Floyd	3260.5	pre1930 value	TWDB gw db
1152604	Floyd	3259.5	pre1930 value	TWDB gw db
1152606	Floyd	3262.0	pre1930 value	TWDB gw db
1152801	Floyd	3261.0	pre1930 value	TWDB gw db
1152901	Floyd	3245.0	pre1930 value	TWDB gw db
1152901	Floyd	3250.8	pre1930 value	TWDB gw db

Table 4.3.3, continued

State Well Number/Site Number	County	Pre-Development Water-Level Elevation (feet)	Water-Level Description	Water-Level Source
1152902	Floyd	3257.0	pre1930 value	TWDB gw db
1152903	Floyd	3252.0	pre1930 value	TWDB gw db
1152904	Floyd	3248.5	pre1930 value	TWDB gw db
1152904	Floyd	3248.5	pre1930 value	TWDB gw db
1152905	Floyd	3249.8	pre1930 value	TWDB gw db
1152905	Floyd	3249.8	pre1930 value	TWDB gw db
1152909	Floyd	3258.8	pre1930 value	TWDB gw db
1152910	Floyd	3242.0	pre1930 value	TWDB gw db
1152910	Floyd	3242.0	pre1930 value	TWDB gw db
1153702	Floyd	3234.5	pre1930 value	TWDB gw db
1153703	Floyd	3230.0	pre1930 value	TWDB gw db
1160304	Floyd	3250.8	pre1930 value	TWDB gw db
1160606	Floyd	3229.0	pre1930 value	TWDB gw db
1161107	Floyd	3234.8	pre1930 value	TWDB gw db
1161109	Floyd	3232.3	pre1930 value	TWDB gw db
525810	Gray	2878.0	pre1930 value	TWDB gw db
527601	Gray	2728.0	pre1930 value	TWDB gw db
1142602	Hale	3403.0	pre1930 value	TWDB gw db
1142902	Hale	3382.0	pre1930 value	TWDB gw db
1142903	Hale	3384.5	pre1930 value	TWDB gw db
1142904	Hale	3388.0	pre1930 value	TWDB gw db
1143405	Hale	3375.5	pre1930 value	TWDB gw db
1143412	Hale	3390.0	pre1930 value	TWDB gw db
1143413	Hale	3378.3	pre1930 value	TWDB gw db
1143503	Hale	3347.0	pre1930 value	TWDB gw db
1143506	Hale	3335.0	pre1930 value	TWDB gw db
1143903	Hale	3331.0	pre1930 value	TWDB gw db
1149303	Hale	3423.5	pre1930 value	TWDB gw db
1150305	Hale	3376.9	pre1930 value	TWDB gw db
1150504	Hale	3392.3	pre1930 value	TWDB gw db
1150603	Hale	3390.0	pre1930 value	TWDB gw db
1150603	Hale	3390.0	pre1930 value	TWDB gw db
1150803	Hale	3382.0	pre1930 value	TWDB gw db
1151302	Hale	3326.0	pre1930 value	TWDB gw db
1151408	Hale	3355.8	pre1930 value	TWDB gw db
1152201	Hale	3291.0	pre1930 value	TWDB gw db

Table 4.3.3, continued

State Well Number/Site Number	County	Pre-Development Water-Level Elevation (feet)	Water-Level Description	Water-Level Source
1152501	Hale	3275.0	pre1930 value	TWDB gw db
1152703	Hale	3281.0	pre1930 value	TWDB gw db
1152704	Hale	3284.0	pre1930 value	TWDB gw db
1152705	Hale	3305.0	pre1930 value	TWDB gw db
1159102	Hale	3326.5	pre1930 value	TWDB gw db
1160201	Hale	3262.4	pre1930 value	TWDB gw db
1160202	Hale	3260.0	pre1930 value	TWDB gw db
1160203	Hale	3250.0	pre1930 value	TWDB gw db
1160204	Hale	3258.0	pre1930 value	TWDB gw db
344702	Hansford	3181.4	1930s value	TWDB gw db
345901	Hansford	3022.9	1930s value	TWDB gw db
346901	Hansford	2889.1	1930s value	TWDB gw db
353306	Hansford	3008.5	1930s value	TWDB gw db
353601	Hansford	3001.7	1930s value	TWDB gw db
353603	Hansford	2995.1	1930s value	TWDB gw db
353604	Hansford	3028.4	1930s value	TWDB gw db
354203	Hansford	2925.9	1930s value	TWDB gw db
354302	Hansford	2896.5	1930s value	TWDB gw db
354303	Hansford	2910.6	1930s value	TWDB gw db
361703	Hutchinson	3104.4	1950s value	TWDB gw db
2326106	Lubbock	3170.0	pre1930 value	TWDB gw db
2335625	Lubbock	3008.0	pre1930 value	TWDB gw db
519802	Roberts	2808.2	1930s value	TWDB gw db
520202	Roberts	2609.6	1930s value	TWDB gw db
342601	Sherman	3292.2	1930s value	TWDB gw db
343402	Sherman	3375.2	1930s value	TWDB gw db
1135201	Swisher	2586.0	pre1930 value	TWDB gw db
530302	Wheeler	2497.0	pre1930 value	TWDB gw db
539701	Wheeler	2497.0	pre1930 value	TWDB gw db
539702	Wheeler	2490.0	pre1930 value	TWDB gw db
539703	Wheeler	2491.0	pre1930 value	TWDB gw db
539704	Wheeler	2504.2	pre1930 value	TWDB gw db
539705	Wheeler	3375.2	pre1930 value	TWDB gw db
Rita Blanca Aquifer				
140601	Dallam	4510.4	max value	TWDB gw db
140907	Dallam	4533.0	max value	TWDB gw db

Table 4.3.3, continued

State Well Number/Site Number	County	Pre-Development Water-Level Elevation (feet)	Water-Level Description	Water-Level Source
148303	Dallam	4513.9	max value	TWDB gw db
148901	Dallam	4471.9	max value	TWDB gw db
148902	Dallam	4430.4	max value	TWDB gw db
156301	Dallam	4433.0	max value	TWDB gw db
156602	Dallam	4398.4	max value	TWDB gw db
156902	Dallam	4371.2	max value	TWDB gw db
164301	Dallam	4341.0	max value	TWDB gw db
241801	Dallam	4379.0	max value	TWDB gw db
242103	Dallam	4336.2	max value	TWDB gw db
242701	Dallam	4244.1	max value	TWDB gw db
242903	Dallam	4026.5	max value	TWDB gw db
249201	Dallam	4364.0	max value	TWDB gw db
249401	Dallam	4342.8	max value	TWDB gw db
249503	Dallam	4259.2	max value	TWDB gw db
249704	Dallam	4331.9	max value	TWDB gw db
249801	Dallam	4285.7	max value	TWDB gw db
249901	Dallam	4229.9	max value	TWDB gw db
250701	Dallam	4123.0	max value	TWDB gw db
Edwards-Trinity (High Plains) Aquifer				
1057901	Bailey	3849.8	max value	TWDB gw db
2401202	Bailey	3900.0	max value	TWDB gw db
2402201	Bailey	3809.8	max value	TWDB gw db
2410303	Bailey	3677.8	max value	TWDB gw db
2411803	Cochran	3584.0	max value	TWDB gw db
2417701	Cochran	3682.9	max value	TWDB gw db
2418306	Cochran	3633.7	max value	TWDB gw db
2418313	Cochran	3603.5	max value	TWDB gw db
2425401	Cochran	3730.2	max value	TWDB gw db
2435501	Cochran	3513.3	max value	TWDB gw db
2532801	Cochran	3781.4	max value	TWDB gw db
1162501	Floyd	3070.3	max value	TWDB gw db
2701619	Gaines	3451.0	max value	TWDB gw db
2709903	Gaines	3413.8	max value	TWDB gw db
2713901	Gaines	3091.2	max value	TWDB gw db
2714302	Gaines	3025.5	max value	TWDB gw db
2714802	Gaines	3085.3	max value	TWDB gw db

Table 4.3.3, continued

State Well Number/Site Number	County	Pre-Development Water-Level Elevation (feet)	Water-Level Description	Water-Level Source
2721603	Gaines	3084.9	max value	TWDB gw db
2722102	Gaines	3034.2	max value	TWDB gw db
2722401	Gaines	3025.1	max value	TWDB gw db
2722403	Gaines	3065.0	max value	TWDB gw db
2722404	Gaines	3066.0	max value	TWDB gw db
1159801	Hale	3284.0	max value	TWDB gw db
1159804	Hale	3226.1	max value	TWDB gw db
1159806	Hale	3209.7	max value	TWDB gw db
2303101	Hale	3273.2	max value	TWDB gw db
2303202	Hale	3248.2	max value	TWDB gw db
2303403	Hale	3212.6	max value	TWDB gw db
2303502	Hale	3215.9	max value	TWDB gw db
2303509	Hale	3180.4	max value	TWDB gw db
2310111	Hale	3158.3	max value	TWDB gw db
2310401	Hale	3169.5	max value	TWDB gw db
2310407	Hale	3179.6	max value	TWDB gw db
2415612	Hockley	3279.2	max value	TWDB gw db
2415617	Hockley	3275.4	max value	TWDB gw db
2415620	Hockley	3275.3	max value	TWDB gw db
2415621	Hockley	3288.4	max value	TWDB gw db
2415622	Hockley	3276.3	max value	TWDB gw db
2404102	Lamb	3646.0	max value	TWDB gw db
2404401	Lamb	3619.9	max value	TWDB gw db
2405702	Lamb	3541.1	max value	TWDB gw db
2309501	Lubbock	3246.5	max value	TWDB gw db
2309901	Lubbock	3229.4	max value	TWDB gw db
2309903	Lubbock	3165.4	max value	TWDB gw db
2317301	Lubbock	3143.7	max value	TWDB gw db
2416601	Lubbock	3288.5	max value	TWDB gw db
2416902	Lubbock	3228.9	max value	TWDB gw db
2344101	Lynn	3020.9	max value	TWDB gw db
2344103	Lynn	2979.3	max value	TWDB gw db
2344701	Lynn	2999.7	max value	TWDB gw db
2352801	Lynn	2885.8	max value	TWDB gw db
2357301	Lynn	3055.5	max value	TWDB gw db
2358501	Lynn	2998.9	max value	TWDB gw db

Table 4.3.3, continued

State Well Number/Site Number	County	Pre-Development Water-Level Elevation (feet)	Water-Level Description	Water-Level Source
2801101	Lynn	2911.0	max value	TWDB gw db
2445201	Terry	3337.4	max value	TWDB gw db
2445301	Terry	3315.8	max value	TWDB gw db
2461401	Terry	3322.0	max value	TWDB gw db
2707301	Terry	3105.6	max value	TWDB gw db
2441401	Yoakum	3712.3	max value	TWDB gw db
2441402	Yoakum	3707.3	max value	TWDB gw db
2444401	Yoakum	3415.0	max value	TWDB gw db
2458601	Yoakum	3498.9	max value	TWDB gw db
2556502	Yoakum	3691.8	max value	TWDB gw db
2608317	Yoakum	3537.5	max value	TWDB gw db
Upper Dockum Group				
2736211	Andrews	3056.1	max value	TWDB gw db
2403103	Bailey	3720.4	max value	TWDB gw db
233604	Dallam	4379.4	max value	TWDB gw db
241305	Dallam	4206.7	max value	TWDB gw db
244301	Dallam	3766.4	max value	TWDB gw db
257307	Dallam	4051.7	max value	TWDB gw db
257501	Dallam	4223.4	max value	TWDB gw db
2731803	Dawson	2851.7	max value	TWDB gw db
2802803	Dawson	2856.6	pre 1940 value	TWDB gw db
2810101	Dawson	2958.2	max value	TWDB gw db
2827411	Dawson	2740.0	max value	TWDB gw db
755701	Deaf Smith	3703.0	max value	TWDB gw db
916901	Deaf Smith	4147.5	max value	TWDB gw db
1001601	Deaf Smith	4059.7	max value	TWDB gw db
1001701	Deaf Smith	4190.1	max value	TWDB gw db
1001702	Deaf Smith	4199.1	max value	TWDB gw db
1009701	Deaf Smith	4161.6	max value	TWDB gw db
1009801	Deaf Smith	4154.5	max value	TWDB gw db
1010501	Deaf Smith	3999.1	max value	TWDB gw db
2302704	Hale	3201.3	max value	TWDB gw db
2303904	Hale	3022.6	max value	TWDB gw db
2310205	Hale	3170.0	max value	TWDB gw db
2416207	Hale	3291.6	max value	TWDB gw db
701302	Hartley	4039.2	max value	TWDB gw db

Table 4.3.3, continued

State Well Number/Site Number	County	Pre-Development Water-Level Elevation (feet)	Water-Level Description	Water-Level Source
808602	Hartley	4210.8	max value	TWDB gw db
2405301	Lamb	3562.5	pre 1940 value	TWDB gw db
2327703	Lubbock	3037.1	max value	TWDB gw db
2327719	Lubbock	3036.3	max value	TWDB gw db
2327902	Lubbock	2990.9	max value	TWDB gw db
2335301	Lubbock	2990.0	max value	TWDB gw db
2849402	Martin	2673.5	max value	TWDB gw db
2849807	Martin	2642.0	max value	TWDB gw db
2849808	Martin	2680.5	max value	TWDB gw db
2849907	Martin	2627.8	max value	TWDB gw db
2849908	Martin	2673.0	max value	TWDB gw db
2849909	Martin	2633.0	max value	TWDB gw db
754202	Oldham	3779.4	max value	TWDB gw db
1008135	Randall	3636.0	max value	TWDB gw db
1008402	Randall	3627.0	max value	TWDB gw db
1008406	Randall	3682.0	max value	TWDB gw db
1016702	Randall	3654.8	max value	TWDB gw db
1102701	Randall	3514.6	max value	TWDB gw db
1102801	Randall	3479.0	max value	TWDB gw db
1134907	Swisher	3321.6	max value	TWDB gw db
2704311	Terry	3214.2	max value	TWDB gw db
4501501	Winkler	3032.1	max value	TWDB gw db
4501901	Winkler	2992.9	max value	TWDB gw db
2444701	Yoakum	3401.1	max value	TWDB gw db
2458902	Yoakum	3501.9	max value	TWDB gw db
Lower Dockum Group				
2640201	Andrews	3410.6	max value	TWDB gw db
2750501	Andrews	3246.1	max value	TWDB gw db
660902	Armstrong	3253.6	max value	TWDB gw db
661608	Armstrong	3244.1	max value	TWDB gw db
1105101	Armstrong	3232.6	max value	TWDB gw db
1105102	Armstrong	3205.5	max value	TWDB gw db
1105301	Armstrong	3231.6	max value	TWDB gw db
1105602	Armstrong	3204.1	max value	TWDB gw db
1106101	Armstrong	3226.7	max value	TWDB gw db
1106501	Armstrong	3179.3	max value	TWDB gw db

Table 4.3.3, continued

State Well Number/Site Number	County	Pre-Development Water-Level Elevation (feet)	Water-Level Description	Water-Level Source
1106804	Armstrong	3151.7	max value	PGCD
2831401	Borden	2158.5	max value	TWDB gw db
628701	Carson	3157.9	max value	TWDB gw db
636101	Carson	3170.0	max value	TWDB gw db
1023702	Castro	3675.9	max value	TWDB gw db
4536802	Crane	2432.1	max value	TWDB gw db
4554501	Crane	2313.6	max value	TWDB gw db
4564603	Crockett	2244.7	max value	TWDB gw db
2339501	Crosby	2454.1	max value	TWDB gw db
245101	Dallam	3681.2	max value	TWDB gw db
2810703	Dawson	2820.2	max value	TWDB gw db
750901	Deaf Smith	4036.5	max value	TWDB gw db
4512104	Ector	2962.2	max value	TWDB gw db
4512107	Ector	2967.6	pre 1940 value	TWDB gw db
4513808	Ector	2849.0	pre 1940 value	TWDB gw db
4519101	Ector	2714.0	max value	TWDB gw db
4522701	Ector	2788.3	pre 1940 value	TWDB gw db
1154301	Floyd	3006.0	max value	TWDB gw db
1156805	Floyd	2835.5	pre 1940 value	TWDB gw db
1164209	Floyd	2788.0	pre 1940 value	TWDB gw db
2344208	Garza	2914.5	max value	TWDB gw db
2344608	Garza	2862.2	max value	TWDB gw db
2353402	Garza	2846.9	max value	TWDB gw db
2860901	Glasscock	2486.0	pre 1940 value	TWDB gw db
2860905	Glasscock	2472.3	pre 1940 value	TWDB gw db
2862418	Glasscock	2463.5	max value	TWDB gw db
709301	Hartley	3986.7	max value	TWDB gw db
709403	Hartley	4033.0	max value	TWDB gw db
709902	Hartley	3947.2	max value	TWDB gw db
717201	Hartley	3964.0	max value	TWDB gw db
717304	Hartley	3915.8	max value	TWDB gw db
717901	Hartley	3919.8	max value	TWDB gw db
718101	Hartley	3920.8	max value	TWDB gw db
720801	Hartley	3446.1	max value	TWDB gw db
721402	Hartley	3413.6	max value	TWDB gw db
816602	Hartley	4051.0	max value	TWDB gw db

Table 4.3.3, continued

State Well Number/Site Number	County	Pre-Development Water-Level Elevation (feet)	Water-Level Description	Water-Level Source
2828808	Howard	2590.0	pre 1940 value	TWDB gw db
2829704	Howard	2556.8	pre 1940 value	TWDB gw db
2837202	Howard	2451.4	pre 1940 value	TWDB gw db
2838101	Howard	2387.4	pre 1940 value	TWDB gw db
2845913	Howard	2365.8	pre 1940 value	TWDB gw db
2846608	Howard	2348.5	pre 1940 value	TWDB gw db
2851201	Howard	2457.5	pre 1940 value	TWDB gw db
4333803	Irion	2156.6	max value	TWDB gw db
2257701	Kent	2298.6	max value	TWDB gw db
2364901	Kent	2301.9	max value	TWDB gw db
4622401	Loving	2708.7	max value	TWDB gw db
2850601	Martin	2603.5	max value	TWDB gw db
2839802	Mitchell	2169.2	max value	TWDB gw db
2839803	Mitchell	2148.1	max value	TWDB gw db
2840602	Mitchell	2140.9	max value	TWDB gw db
2848303	Mitchell	2180.9	max value	TWDB gw db
2848702	Mitchell	2291.4	max value	TWDB gw db
2856601	Mitchell	2100.4	max value	TWDB gw db
2864302	Mitchell	2230.8	max value	TWDB gw db
2925901	Mitchell	2165.3	max value	TWDB gw db
2933202	Mitchell	2113.6	max value	TWDB gw db
2934101	Mitchell	2164.8	max value	TWDB gw db
2934301	Mitchell	2205.5	max value	TWDB gw db
2934426	Mitchell	2129.7	max value	TWDB gw db
2934502	Mitchell	2168.9	max value	TWDB gw db
2934503	Mitchell	2136.9	max value	TWDB gw db
2934507	Mitchell	2148.7	max value	TWDB gw db
2934803	Mitchell	2182.2	max value	TWDB gw db
2934805	Mitchell	2171.8	max value	TWDB gw db
2934807	Mitchell	2155.2	max value	TWDB gw db
2934808	Mitchell	2140.5	max value	TWDB gw db
2934901	Mitchell	2190.2	max value	TWDB gw db
2935102	Mitchell	2224.6	max value	TWDB gw db
2935707	Mitchell	2223.3	max value	TWDB gw db
2941401	Mitchell	2140.9	max value	TWDB gw db
2942208	Mitchell	2117.1	max value	TWDB gw db

Table 4.3.3, continued

State Well Number/Site Number	County	Pre-Development Water-Level Elevation (feet)	Water-Level Description	Water-Level Source
2942303	Mitchell	2120.3	max value	TWDB gw db
2942311	Mitchell	2120.3	max value	TWDB gw db
2942603	Mitchell	2139.9	max value	TWDB gw db
2942802	Mitchell	2133.2	max value	TWDB gw db
2942804	Mitchell	2141.8	max value	TWDB gw db
2943111	Mitchell	2178.1	max value	TWDB gw db
2943801	Mitchell	2205.6	max value	TWDB gw db
2949201	Mitchell	2095.7	max value	TWDB gw db
618401	Moore	3353.3	max value	TWDB gw db
724403	Moore	3410.0	max value	TWDB gw db
2201203	Motley	2715.8	max value	TWDB gw db
2308303	Motley	2794.9	max value	TWDB gw db
2936109	Nolan	2298.1	max value	TWDB gw db
2936615	Nolan	2262.0	pre 1940 value	TWDB gw db
2936814	Nolan	2340.3	max value	TWDB gw db
2936901	Nolan	2325.6	pre 1940 value	TWDB gw db
2936902	Nolan	2324.7	pre 1940 value	TWDB gw db
2936917	Nolan	2334.8	max value	TWDB gw db
2943602	Nolan	2331.1	max value	TWDB gw db
2944106	Nolan	2277.2	max value	TWDB gw db
2944205	Nolan	2362.5	max value	TWDB gw db
2944306	Nolan	2385.6	max value	TWDB gw db
2944409	Nolan	2288.9	max value	TWDB gw db
2944418	Nolan	2292.4	max value	TWDB gw db
734801	Oldham	3645.0	max value	TWDB gw db
743401	Oldham	3912.2	max value	TWDB gw db
744701	Oldham	3987.7	max value	TWDB gw db
746705	Oldham	3773.0	max value	TWDB gw db
832601	Oldham	3906.6	max value	TWDB gw db
4656306	Pecos	2372.9	max value	TWDB gw db
4656703	Pecos	2518.1	max value	TWDB gw db
4663302	Pecos	2594.6	max value	TWDB gw db
5206603	Pecos	2765.0	max value	TWDB gw db
5206604	Pecos	2829.7	max value	TWDB gw db
5206605	Pecos	2765.0	max value	TWDB gw db
5206606	Pecos	2763.0	max value	TWDB gw db

Table 4.3.3, continued

State Well Number/Site Number	County	Pre-Development Water-Level Elevation (feet)	Water-Level Description	Water-Level Source
5206607	Pecos	2753.0	max value	TWDB gw db
625801	Potter	3346.5	max value	TWDB gw db
635206	Potter	3147.3	max value	TWDB gw db
635301	Potter	3152.0	max value	PGCD
635501	Potter	3155.9	max value	PGCD
635623	Potter	3132.6	max value	TWDB gw db
635624	Potter	3131.1	max value	TWDB gw db
649305	Potter	3475.6	max value	TWDB gw db
650209	Potter	3448.8	max value	TWDB gw db
732302	Potter	3488.3	max value	PGCD
739301	Potter	3126.4	max value	TWDB gw db
658902	Randall	3262.4	max value	TWDB gw db
659504	Randall	3272.1	max value	TWDB gw db
4427804	Reagan	2528.5	max value	TWDB gw db
4646103	Reeves	2561.5	pre 1940 value	TWDB gw db
4646201	Reeves	2523.0	max value	TWDB gw db
4646203	Reeves	2542.0	max value	TWDB gw db
4646204	Reeves	2536.0	max value	TWDB gw db
4646206	Reeves	2536.0	max value	TWDB gw db
4646207	Reeves	2513.0	pre 1940 value	TWDB gw db
4646208	Reeves	2589.2	max value	TWDB gw db
4646209	Reeves	2583.0	max value	TWDB gw db
4646211	Reeves	2556.0	max value	TWDB gw db
4646215	Reeves	2555.0	max value	TWDB gw db
4646301	Reeves	2548.0	max value	TWDB gw db
2807903	Scurry	2591.5	max value	TWDB gw db
2815301	Scurry	2558.0	max value	TWDB gw db
2824704	Scurry	2189.8	max value	TWDB gw db
2824903	Scurry	2258.4	max value	TWDB gw db
2824904	Scurry	2260.2	max value	TWDB gw db
2832601	Scurry	2261.4	max value	TWDB gw db
2909501	Scurry	2335.1	max value	TWDB gw db
2909502	Scurry	2330.4	max value	TWDB gw db
2909704	Scurry	2359.2	max value	TWDB gw db
2909805	Scurry	2316.7	max value	TWDB gw db
2917302	Scurry	2324.8	max value	TWDB gw db

Table 4.3.3, continued

State Well Number/Site Number	County	Pre-Development Water-Level Elevation (feet)	Water-Level Description	Water-Level Source
2917702	Scurry	2254.0	max value	TWDB gw db
2918505	Scurry	2297.5	max value	TWDB gw db
2918506	Scurry	2279.4	max value	TWDB gw db
2918902	Scurry	2280.7	max value	TWDB gw db
2925707	Scurry	2199.8	max value	TWDB gw db
2864601	Sterling	2346.4	max value	TWDB gw db
2864901	Sterling	2384.8	max value	TWDB gw db
4414601	Sterling	2456.5	max value	TWDB gw db
4416315	Sterling	2264.6	max value	TWDB gw db
4555601	Upton	2496.6	max value	TWDB gw db
4555702	Upton	2382.7	max value	TWDB gw db
4555801	Upton	2394.4	max value	TWDB gw db
4525202	Ward	2586.0	pre 1940 value	TWDB gw db
4525318	Ward	2570.0	pre 1940 value	TWDB gw db
4525321	Ward	2591.0	max value	TWDB gw db
4525713	Ward	2527.7	max value	TWDB gw db
4526701	Ward	2516.9	max value	TWDB gw db
4630501	Ward	2573.3	max value	TWDB gw db
4630802	Ward	2586.3	pre 1940 value	TWDB gw db
4608501	Winkler	2875.3	max value	TWDB gw db
4616101	Winkler	2774.6	max value	TWDB gw db
4616102	Winkler	2782.9	max value	TWDB gw db
4616103	Winkler	2784.8	max value	TWDB gw db
4616201	Winkler	2764.8	max value	TWDB gw db
4623701	Winkler	2660.0	max value	TWDB gw db

max = maximum
gw db = groundwater database
PGCD = Panhandle Groundwater Conservation District

Table 4.3.4 Summary of hydrograph trends by aquifer and county.

Texas County	Number of Hydrographs	Hydrograph Trends
Northern Ogallala Aquifer		
Dallam	75	Most hydrographs show an overall declining trend. Declines range from less than 25 feet to about 125 feet. Hydrographs for some wells show an overall stable or only slightly declining (less than 25 feet) trend. A few hydrographs show a slightly rising (less than 25 feet) trend.
Sherman	118	All hydrographs show an overall decline in water level. The declines range from about 25 to 175 feet. The typical decline for wells with a long period of record is about 100 feet. For many of the wells, the rate of decline decreased in about 1980. Some wells show a period of slight water-level recovery from about 1980 to 1995. For many wells, the rate of decline remained fairly constant.
Hansford	137	Most hydrographs show an overall decline in water level. The declines range from less than 25 feet to about 175 feet. Most of the hydrographs show a fairly constant rate of decline. Some hydrographs show an increasing rate of decline in recent years. A few show periods of recovery followed by declining levels. A few hydrographs show overall stable water levels.
Ochiltree	88	All hydrographs show an overall decline in water level. The declines range from about 25 to 200 feet. The typical decline appears to be about 75 feet. For many wells, the rate of decline decreased in about 1980. In a few wells, the rate of decline significantly increased in about 2000. Some wells show temporary periods of water-level recovery imposed on the overall declining trend. In a couple of wells, the water level has recovered about 50 feet in recent years resulting in recent water levels that are at or only slightly less than the level originally observed in the wells.
Lipscomb	39	Many show overall declining trends of less than 25 feet. Some show relatively stable water levels throughout the period of record. A few show recent declines of 25 to 75 feet. One shows a recent increase of about 50 feet.
Hartley	47	All show overall declining water levels. Declines range from less than 25 feet to about 150 feet.
Moore	123	All show a declining trend. Declines range from 25 to 200 feet. The rate of decline has been fairly constant in most wells. In some wells, the rate of decline decrease in about 1980. In a few wells, the rate of water-level decline significantly increased in about 2000.
Hutchinson	65	All show overall declining water levels. Declines range from less than 25 feet to about 125 feet. Most have large declines, only a couple have a less than 25-foot decline. For most, the rate of decline has been fairly stable but, for some, the rate of decline significantly decreased in about 1980.
Roberts	86	Many of the wells show slightly declining (less than 25 feet) water levels. A few show larger declines of about 50 to 75 feet. The water level in a few wells has declined over 100 feet since about 2000. Periods of water-level recovery are observed in a few wells
Hemphill	50	All hydrographs show relatively constant trends that are either stable or slightly (less than 25 feet) declining or rising. A couple of wells show rising water levels of about 50 feet from the mid-1970s to about 1980 followed by relatively stable levels.
Potter	10	Most hydrographs show overall declining water levels with declines ranging from about 25 to about 75 feet. Recent rising water levels of less than 25 feet are observed in several wells whose period of record begins in the mid to late 1990s.

Table 4.3.4, continued

Texas County	Number of Hydrographs	Hydrograph Trends
Carson	154	Most of the hydrographs show an overall large decline in water level since the mid-1950s (declines up to 150 to 200 feet). Some of the hydrographs show stable or slightly declining (less than 25 feet) trends. A couple of the hydrographs show large declines until about 1980 and then a slower rate of decline. A couple of hydrographs show declining water levels until about 1980 and then rising water levels.
Gray	82	Most hydrographs show an overall stable or slightly increasing or decreasing water level. The largest overall decrease is about 25 feet. A few hydrographs show periods of both rising and declining water levels with changes of about 25 feet.
Wheeler	57	Most of the hydrographs show overall stable or slightly rising or declining (less than 25 feet) water levels.
Randall	66	Hydrographs showing stable, increasing, and decreasing water -level trends are observed. The declines range from less than 10 feet to about 100 feet. For most wells, the rate of decline significantly decreased in about 1970 to 1980. Many of the wells show stable water levels since about 1980.
Armstrong	38	Some hydrographs show declining water levels until 1970 to 1980 and then rising or stable water levels with the overall amount of rise less than the amount of decline. Many hydrographs show overall stable or slightly rising water levels. Many hydrographs show overall declines since 1970, general on the order of about 50 feet.
Donley	53	Most hydrographs show stable or slightly declining (less than 25 feet) trends. A few hydrographs show slightly increasing (less than 25 feet) trends. The largest observed overall decline is less than 50 feet.
Southern Ogallala Aquifer		
Oldham	20	Most hydrographs show stable or slightly increasing or decreasing (less than 25 feet) trends. Two hydrographs show decreases until about 1970 and then stable/slightly decreasing water levels after that time.
Deaf Smith	162	Many hydrographs show declining water levels. The declines range from less than 25 feet to about 100 feet. Most of the hydrographs with a long-term record that show a declining trend have declines ranging from about 75 to 100 feet. In many of these wells, the rate of decline decreases in about 1980. In a few wells, water levels temporarily recovered from about 1965 to 1980 or from 1980 to 1990. Several of the wells show an overall rising trend.
Parmer	111	Almost all hydrographs show an overall declining trend. Declines range from 25 to about 200 feet. Typical declines are greater than 100 feet. The rate of decline decreased in many wells in 1975 to 1980. The water level began to recovery in many of those wells, but not to pre-decline levels. The rate of decline was constant for many of the wells.
Castro	102	Most hydrographs show an overall decline in water level but a few show an overall rise in water level. The declines range from less than 25 feet to 150 feet. The typical decline is 75 to 100 feet. The rate of decline was constant in many wells but decreased in about 1980 for many wells. The overall rise observed in a few wells is as large as about 25 feet.
Swisher	93	Most hydrographs show overall declining water levels. The declines range from less than 25 feet to about 200 feet. Many wells show a decrease in the rate of decline in about 1980. In some cases, the water levels recovered slightly and/or remained stable after that time. In a few wells, the water level remained stable over the period of record from about 1980 to present.

Table 4.3.4, continued

Texas County	Number of Hydrographs	Hydrograph Trends
Briscoe	40	Most hydrographs show declining water levels. The declines range from less than 25 feet to 125 feet. Hydrographs showing stable water levels are observed for two wells and hydrographs showing a water-level rise of 25 to 40 feet are observed for two wells.
Bailey	127	Most hydrographs show declining water levels. The declines range from less than 25 feet to about 125 feet. For several wells, the hydrographs show an overall slightly rising trends, with rises less than or equal to about 25 feet.
Lamb	125	Almost all hydrographs show an overall declining trend. The declines range from 25 to about 200 feet. Most of the hydrographs show a fairly constant rate of decline. Recent stable water levels are observed in one well and a rise of about 25 feet since 1970 is observed in another well.
Hale	142	All hydrographs show an overall declining trend in water levels. The declines range from about 40 to about 225 feet. Most of the hydrographs with a long-term record show a decline of 100 feet or greater. A couple of hydrographs with early measurements show stable water levels from about 1915 to 1940 and declines beginning in the early to late 1940s. The hydrographs for most of the wells show a constant rate of decline.
Floyd	140	Hydrographs show overall declining trends in all but five wells. The declines range from less than 25 feet to about 175 feet. The rate of decline decreased in 1980 for some wells. Recent increasing or stable water levels are observed in five wells. The maximum observed increase is about 10 feet.
Motley	2	Both hydrographs show slightly declining (less than 25 feet) water levels.
Cochran	32	Hydrographs showing overall declining, rising, and stable water levels are observed. The declines range from less than 25 feet to about 75 feet. The rises are all less than 25 feet. Some wells with an overall declining trend show a stop in the decline and some recovery from about 1970 to 1990 before declining again.
Hockley	61	Some hydrographs show declines ranging from less than 25 feet to about 100 feet. Some hydrographs show rising water levels on the order of less than 25 feet. In some wells with an overall declining trend, temporary recover is observed between the mid-1980s and mid-1990s. Decline in the water level slowed or stopped in some wells from about 1970 to 1980.
Lubbock	144	Hydrographs for many wells show an overall decline ranging from less than 25 feet to about 150 feet. Hydrographs for most wells with an overall declining trend show a stop in decline, a reduced rate of decline, or recovery starting between 1960 to 1980. Hydrographs for a few wells show recent water-level rises of about 50 feet.
Crosby	51	Most hydrographs show an overall declining trend. A couple of hydrographs show a recent overall increasing trend. The range in declines is less than 25 feet to about 200 feet. The hydrographs for many wells with an overall declining trend show a stop in the decline from about 1980 to 1990 before water levels again declined.
Dickens	6	Most hydrographs show stable water levels.
Yoakum	21	Several hydrographs show an overall decline of 25 to 100 feet. Two hydrographs show a recent rise of about 25 feet. One hydrographs shows recent stable water levels. A couple of hydrographs show initially rising and then declining water levels.

Table 4.3.4, continued

Texas County	Number of Hydrographs	Hydrograph Trends
Terry	42	Most hydrographs show periods of both declining and rising water levels. A local high in the water level centered on 1990 is typically observed. A local low water level during the 1960s is observed in some wells. One well shows an overall rise of over 25 feet since the mid-1950s
Lynn	47	Some hydrographs show periods of rising and declining water levels. Most hydrographs show overall stable water levels. A few hydrographs show overall declining water levels of less than 25 feet to about 75 feet. A few hydrographs show overall rising water levels of up to 25 feet.
Garza	5	All show an overall rising trend. Rises range from about 10 to 25 feet.
Gaines	62	Some hydrographs show overall declines of less than 25 feet to about 125 feet. Some hydrographs show overall rises of less than 25 feet to about 50 feet. Some hydrographs show periods of declining and rising water levels with no overall change in water level.
Dawson	84	Several hydrographs show periods of both rising and declining water levels. For many of these, a local water-level high centered on about 1990 to 1995 is observed. Some hydrographs show an overall decline of about 25 to 50 feet and some show an overall rise of less than 25 feet to about 75 feet.
Borden	4	The two hydrographs with the longest period of record (1960 to present) show a rising trend of about 25 feet from about 1970 to 1985, a declining trend of about 15 feet from 1985 to 2004, and a rising trend of about 15 feet from 2004 to present. Two hydrographs show an overall rising trends over short periods of record from 1960 to 1982 for one well and 1960 to 1990 for the other well. The rise was about 30 feet in one well and about 10 feet in the other well.
Andrews	17	Most hydrographs show stable or slightly declining (less than 25 feet) water levels. A few hydrographs show a local high in water level centered on about 1990 to 2000.
Martin	57	Most hydrographs show overall stable, declining, or rising trends. Overall declines range from less than 25 feet to about 100 feet. The rate of decline varied in the wells with overall declining trends and in some cases decline temporarily stopped and or temporary recovery occurred. Overall rises range from less than 25 feet to about 50 feet. Some wells show periods of declining and rising water levels. Typically, a local low occurs around 1980 and a local high in water level occurred around 2000.
Howard	19	Most hydrographs show an increasing trend of less than 25 feet. One hydrographs shows rising water levels from about 1970 to about 1990 and then declining water levels to 2013.
Ector	7	Most hydrographs show a water-level decline of about 25 feet. One hydrograph shows a rise of about 25 feet. One hydrograph shows a decline until about 1970 and then an overall rise.
Midland	23	Most hydrographs show overall fairly constant water levels. One hydrograph shows about 25 feet fluctuations centered on 1970 and 1992, but overall stable water levels.
Glasscock	5	Most hydrographs show rising of less than 25 feet. One hydrograph shows a decline from 1960 to 1965, rise from 1965 to 1992, decline from 1992 to 2005 then rise.

Table 4.3.4, continued

Texas County	Number of Hydrographs	Hydrograph Trends
Rita Blanca Aquifer		
Dallam	19	All hydrographs show an overall declining trend in water level. The rate of decline was constant for some wells and temporarily decreased during some portion of the 1970 to 1990 period in some wells. Two wells with early water-level measurements show slight declines of about 5 to 10 feet from about 1950 to 1970 followed by a significant increase in the rate of decline. One well shows slightly declining levels of about 10 feet from about 1963 to 2010 followed by a significant increase in the rate of decline. A few wells show temporary water-level recovery in the period from about 1985 to 1990 or 1995 imposed on the overall declining trend.
Edwards-Trinity (High Plains) Aquifer		
Bailey	1	The hydrograph shows a rising trend of about 30 feet from 1980 to 1990, stable levels from 1990 to 1995, declining levels of about 25 feet from 1995 to 2003, and then stable levels to present.
Hale	2	Both hydrographs show overall stable trends over the period of record.
Cochran	2	The hydrograph for one wells shows a 25-foot decline from about 1980 to 1992 and then about a 30-foot rise until the end of the record in 2001. The hydrograph for the other well shows an overall declining trend of about 10 feet from 1980 to present.
Lubbock	2	Both hydrographs show slightly declining trends of about 10 feet over the period of record from about 1980 to present.
Yoakum	1	The hydrograph shows an overall declining trend of about 30 feet from 1992 to present.
Terry	1	The hydrograph shows a declining trend of about 50 feet from 1957 to 1965, an overall rising trend of about 50 feet from 1965 to 1993, and an overall declining trend of about 20 feet from 1993 to present.
Lynn	1	The hydrograph shows an overall rising trend of about 20 feet over the short period of record from about 1971 to 1977.
Upper Dockum Group		
Dallam	3	Two hydrographs show an overall declining trend of about 50 feet over their short period of record from about 1998 to present. One hydrographs shows an overall decline of about 20 feet over its short period of record from about 1975 to 1990.
Hartley	1	The hydrograph shows an overall declining trend of about 25 feet over its short period of record from about 1998 to present.
Oldham	1	The hydrograph shows a stable trend over the period of record from about 1974 to 1993.
Deaf Smith	7	A stable or slightly rising or declining trend of less than 10 feet is observed in five wells. A decline of about 75 feet is observed in one well over its period of record from about 1960 to present. The rate of decline in this well decreased in the period from about 1980 to 2007 and then increased. A decline of about 20 feet is observed in one well over its period of record from about 19776 to present.
Randall	3	All of the hydrographs show an overall stable trend.
Swisher	1	The hydrograph shows an overall declining trend of about 60 feet from about 1974 to 2010.
Bailey	1	The hydrographs shows an overall declining trend of about 10 feet over period of record from 1980 to present.

Table 4.3.4, continued

Texas County	Number of Hydrographs	Hydrograph Trends
Lamb	1	The period of record for the hydrograph is from about 1935 to 1960. Water levels declined about 10 feet from 1935 to 1940, increased about 10 feet from 1940 to 1948, and declined about 25 feet from 1948 to 1960.
Lubbock	1	The hydrograph shows an overall rising trend of about 15 feet over its period of record from the late 1960s to present.
Yoakum	1	The hydrograph shows an overall declining trend of about 80 feet from 1960 to 1990.
Martin	1	The hydrograph shows a slightly declining trend of about 5 feet from 1958 to 1981, increasing trend of about 50 feet from 1981 to 1988, stable trend from 1988 to 1992, and declining trend of about 25 feet from 1992 to present.
Winkler	1	The hydrograph shows an overall stable trend over period of record from about 1955 to present.
Ector	4	An overall stable trend is observed in three wells and a recent overall rising trend of about 25 feet is observed in another well.
Lower Dockum Group		
Carson	2	Both hydrographs show an overall declining trends, with declines of about 25 feet
Deaf Smith	2	Overall declining trend of about 125 feet in one well and overall rising trend of about 15 feet in the other well.
Oldham	5	Overall stable trends in four wells and an overall declining trend of about 15 feet in one well.
Randall	3	Overall stable trend in one well, overall increasing trend of about 15 feet in one well, and overall decreasing trend of about 15 feet in one well.
Swisher	2	Periods of rising and declining water levels with changes up to 75 feet in both wells. The timing of low and high water levels is not consistent between the wells.
Crosby	1	The hydrograph shows a stable trend during the period of record from the mid-1970s to 2000.
Floyd	1	The hydrograph shows a declining trend during the period of record from 1950 to the early 1970s.
Motely	2	Both hydrographs show overall slightly declining trends of about 10 feet.
Armstrong	12	All hydrographs show stable or slightly rising trends (less than 25 feet) after 1970. The one hydrograph with data prior to 1970 shows declining water levels until 1970 and then stable water levels.
Dallam	1	The hydrograph shows fairly stable water-levels from the mid-1970s to 2000, then a decline of about 25 feet.
Hartley	11	All hydrographs show stable trends prior to about 1990 or 2000 and then declining trends with declines up to about 75 feet
Moore	1	The hydrograph shows a declining trend since mid-1990s
Potter	7	Most hydrographs show stable trends throughout the period of record. An overall rising trend of about 50 feet from about 1975 to present is observed in one well and an overall declining trend of about 15 feet from 1995 to present is observed in another well.
Borden	2	One hydrographs shows a slightly rising recent trend of about 10 feet and the other shows a decreasing recent trend of about 25 feet.

Table 4.3.4, continued

Texas County	Number of Hydrographs	Hydrograph Trends
Fisher	2	One hydrograph shows a stable trend over its period of record from about 1995 to 2009 and the other shows an overall rising trend of about 50 feet over its period of record from about 1970 to 1990.
Garza	3	Periods of increasing and decreasing water levels with changes less than 50 feet are observed in two wells from about 1970 to present. An overall rising trend of about 15 feet is observed in the other well over its period of record from about 1969 to 1992.
Howard	7	Most hydrographs show a stable trend over the period of record, including one well whose record extends from about 1935 to present. An overall rising trend of about 20 feet is observed in two wells and an overall declining trend of about 20 feet is observed in another well.
Kent	2	One hydrograph shows a slightly declining trend of about 5 feet from about 1995 to present and the other shows a slightly rising overall trend of about 15 feet from about 1972 to present.
Mitchell	34	Water levels in most wells show periods of both increasing and decreasing water levels with changes typically less than 25 feet. A few show a greater than 50-foot water-level rise from the early 1960s to 1990.
Nolan	9	Water levels in most wells show periods of both increasing and decreasing water levels with changes typically less than 25 feet. A few show a greater than 50-foot water-level rise from the early 1960s to 1990.
Scurry	17	Water levels in most wells show periods of both increasing and decreasing water levels with changes typically less than 25 feet. Periods with a rise of about 50 feet are observed in some wells.
Crane	2	Both hydrographs show stable trends throughout their period of record.
Ector	2	One hydrograph shows a declining trend from the mid-1960s to 1990 and the other shows an overall stable trend over the period of record from the early 1970s to present
Glasscock	2	Water levels in one well show about a 100-foot decline from the early 1960s to mid-1970s then a 75-foot rise from 1980 to about 2005. Water levels in the other well show a 25-foot rise from the late 1980s to mid-1990s and 25-foot decline from the mid-1990s to about 2005.
Loving	1	The hydrographs shows an overall slightly declining trend of about 5 feet over the period of record from about 1974 to present.
Martin	1	The hydrograph shows an overall slightly declining trend of about 25 feet over the period of record from about 1979 to present.
Pecos	6	The water level in some wells fluctuates widely with no obvious trend. Water levels in several wells show a large decline of about 100 to 150 feet in the period from the late 1950s to the early 1970s followed by relatively stable water levels.
Reeves	9	Generally declining trends observed in all hydrographs with declines ranging from about 25 to 75 feet.
Sterling	4	Overall stable water levels since 1960 in two wells. A decline of about 25 feet from 1940 to 1960 and then stable water levels to present is observed in one well. Stable water level from about 1960 to 1995 and then rising level of about 10 feet is observed in one well.

Table 4.3.4, continued

Texas County	Number of Hydrographs	Hydrograph Trends
Upton	3	An overall stable trend is observed in all wells.
Ward	3	Overall declining trend of 10 feet in one well and about 50 feet in another well. Overall rising trend of about 50 feet in one well.
Winkler	6	Overall stable trends in two wells. Overall declining trend of about 25 feet in one well and 50 feet in another well. Periods of both rising and declining water levels in one well. Slightly rising trend of about 15 feet from 1955 to 2000 and then decline of about 30 feet in one year followed by stable water level in another well.

Table 4.3.5 Summary of years averaged to obtain data for constructing estimated historical water-level surfaces.

Aquifer	Year Range Used to Obtain Data for Historical Water-Level Surfaces		
	1950 surface	1980 surface	2010 surface
Ogallala Aquifer	1950	1980	2010
Rita Blanca Aquifer	1945-1954	1978-1982	2008-2012
Edwards-Trinity (High Plains) Aquifer	1945-1954	1978-1982	2008-2012
Upper Dockum Group	1945-1954	1978-1982	2008-2012
Lower Dockum Group	1948-1952	1978-1982	2008-2012

Table 4.3.6 Number of water-level targets for the transient model by decade by aquifer and county.

Aquifer and County	Decade											
	1900s	1910s	1920s	1930s	1940s	1950s	1960s	1970s	1980s	1990s	2000s	2010s
Ogallala Aquifer												
Andrews				17	7	8	66	104	125	210	140	50
Armstrong						28	142	260	218	322	459	264
Bailey		5		411	504	312	463	607	945	1,013	1,192	269
Borden							8	33	21	25	19	6
Briscoe				1	112	132	171	298	256	234	189	40
Carson				4	5	245	948	971	951	906	1,356	523
Castro				195	297	278	476	582	672	699	910	205
Cochran				6	9	72	218	286	306	540	349	42
Collingsworth				2			4					
Crosby				90	120	175	409	618	628	880	858	314
Dallam			1	279	192	311	230	396	373	367	259	75
Dawson				181	71	126	169	158	272	751	1,580	453
Deaf Smith		1		573	738	486	717	868	1,079	883	819	219
Dickens						4	30	43	36	39	15	5
Donley		2	3		176	13	195	150	188	377	814	710
Ector				38	63		46	43	35	55	33	8
Floyd		21		650	714	660	788	900	874	867	664	243
Gaines				37	36	249	741	354	275	408	901	269
Garza						1	8	48	35	30	17	8
Glasscock				12			48	15	34	32	36	5
Gray			2	1	10	64	358	339	548	629	854	360
Hale		28		1,521	1,255	1,009	782	701	639	890	1,170	361
Hansford				116	26	242	895	1,094	1,046	983	842	257

Table 4.3.6, continued

Aquifer and County	Decade											
	1900s	1910s	1920s	1930s	1940s	1950s	1960s	1970s	1980s	1990s	2000s	2010s
Hartley				4	1	65	320	401	436	410	424	153
Hemphill						12	49	398	384	294	639	290
Hockley				138	156	166	315	415	456	394	339	129
Howard				170			41	88	99	115	151	79
Hutchinson						91	412	489	421	321	359	111
Lamb				277	436	607	652	711	1,001	841	883	373
Lipscomb					1	11	41	421	373	336	260	121
Lubbock			2	537	683	761	766	919	1,047	890	710	248
Lynn				56	65	79	158	210	290	337	299	70
Martin				175	68	218	345	353	446	567	685	296
Midland				59	21	8	257	191	122	139	88	30
Moore					1	327	941	957	916	662	404	143
Motley				6		8	36	16	17	8	9	2
Ochiltree				17	9	131	505	669	563	440	340	156
Oldham						5	18	82	139	148	94	20
Parmer				75	35	234	459	567	679	686	712	178
Potter						1	31	42	60	77	194	41
Randall				93	195	217	329	533	531	491	467	130
Roberts				10	16	41	36	211	260	522	3,496	1,502
Sherman				14	4	232	969	835	886	668	430	152
Swisher		1		419	453	499	400	505	407	827	574	218
Terry				24	33	70	143	229	250	281	389	414
Wheeler			6		8	111	385	157	242	225	756	313
Yoakum						35	224	278	251	205	137	40
Total		**58**	**14**	**6,208**	**6,518**	**8,344**	**15,744**	**18,545**	**19,832**	**21,023**	**26,315**	**9,895**

Table 4.3.6, continued

Aquifer and County	Decade											
	1900s	1910s	1920s	1930s	1940s	1950s	1960s	1970s	1980s	1990s	2000s	2010s
Rita Blanca Aquifer												
Dallam					2	46	23	92	111	111	113	53
Hartley										2		
Total					**2**	**46**	**23**	**92**	**111**	**113**	**113**	**53**
Edwards-Trinity (High Plains) Aquifer												
Bailey					1	4		9	22	26	30	10
Cochran									29	39	39	9
Floyd									1			
Gaines				4			10	2	4	6	21	8
Hale				41	32	21	24	20	15	373	210	90
Hockley									6			
Lamb				1		1	8	1	7	11	8	1
Lubbock					2	21	50	54	40	40	39	16
Lynn				1	2	11	19	33	16	10	11	3
Terry						2	15	30	17	34	40	16
Yoakum							2	11	8	19	40	8
Total				**2**	**4**	**35**	**94**	**129**	**94**	**114**	**138**	**44**
Upper Dockum Group												
Andrews									2		2	
Bailey						5	22	21	8	17	18	5
Castro							1	1			2	3
Dallam								2	6		4	14
Dawson				1							3	
Deaf Smith						1	8	33	60	61	59	19
Ector				9		5	23	11	10	23	21	4

Table 4.3.6, continued

Aquifer and County	Decade											
	1900s	1910s	1920s	1930s	1940s	1950s	1960s	1970s	1980s	1990s	2000s	2010s
Hale					3	11	7		3		1	
Hartley											2	8
Lamb				3	9	10	2		3		1	3
Lubbock							2	10	11	12	10	4
Martin						4			11	9	9	4
Oldham								3	4	2		
Randall						1	3	5	6	2	12	2
Swisher								5	7	9	7	
Terry												3
Winkler						2	10	8	6	10	10	3
Yoakum						1		4	6			
Total				**13**	**12**	**40**	**78**	**103**	**143**	**145**	**161**	**72**
Lower Dockum Group												
Andrews							1	7	14	23	24	4
Armstrong						3	12	46	50	88	99	36
Borden								1	5	10	18	8
Briscoe					4		1	5	12	17	20	3
Carson						1	1	5	14	20	23	12
Castro								4	9	10	9	3
Crane						8	15	13	8	5	10	2
Crockett							15	1				
Crosby								3	4	4	12	3
Dallam								5	5	6	7	8
Dawson								5		21	30	
Deaf Smith						1	7	6	16	15		

Table 4.3.6, continued

Aquifer and County	Decade											
	1900s	1910s	1920s	1930s	1940s	1950s	1960s	1970s	1980s	1990s	2000s	2010s
Dickens					1		6	5	13	1		
Ector				3	1	2	16	15	9	5	6	3
Fisher								10	9	7	5	
Floyd				3	3	9	20	1	1			
Gaines							2			2	10	2
Garza							4	27	21	20	15	7
Glasscock				5			30	4	8	17	12	1
Hale						44				4	22	11
Hartley						16	6	5	50	46	58	35
Howard				90		3	37	10	44	29	83	43
Irion							2				1	
Kent							1	8	4	15	20	4
Loving							1	4	5	8	9	4
Lubbock						4	9	4				
Martin						8	10	10	9	9	9	4
Midland						2						
Mitchell					45	110	593	247	207	139	81	32
Moore							1	3	16	8	8	4
Motley						1	14	7	12	18	10	3
Nolan			2	1	4	7	172	65	82	44	30	9
Oldham						5	12	28	73	48	24	7
Parmer							4	1				
Pecos						6	15	18	6	91	105	79
Potter							7	13	32	35	472	181
Randall					3	1		12	23	23	22	5

Table 4.3.6, continued

Aquifer and County	Decade											
	1900s	1910s	1920s	1930s	1940s	1950s	1960s	1970s	1980s	1990s	2000s	2010s
Reagan							1					
Reeves				4	5	68	6	7	106	33	16	3
Scurry					3	55	162	238	171	110	72	32
Sterling					11		61	10	24	36	115	21
Swisher							1	11	17	16	6	4
Terry									2			
Upton							57	16	16	9	12	4
Ward				3	6	11	47	27	21	24	24	9
Winkler					3	31	95	48	42	47	47	20
Total			**2**	**109**	**89**	**396**	**1,444**	**955**	**1,160**	**1,063**	**1,546**	**606**

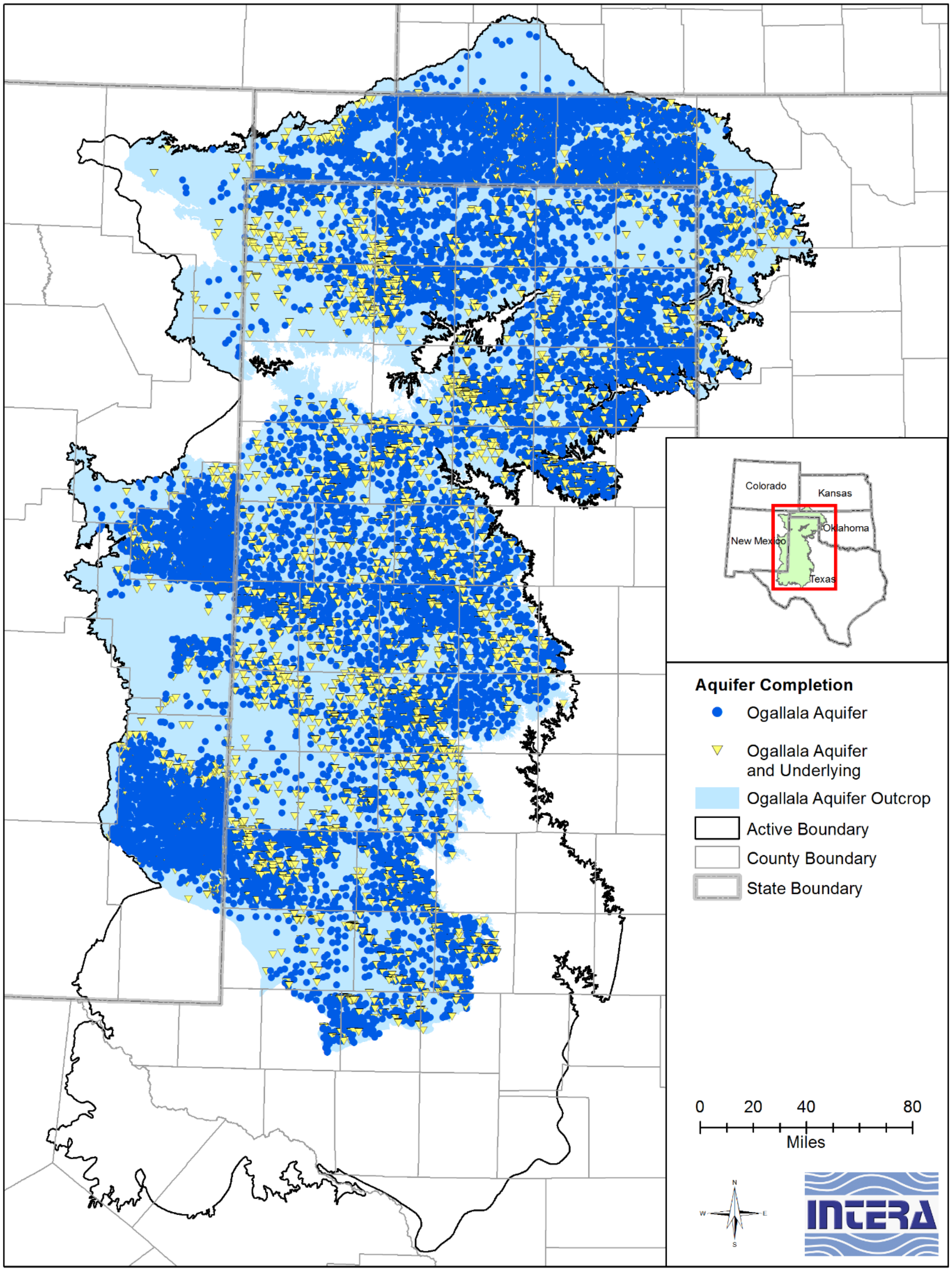
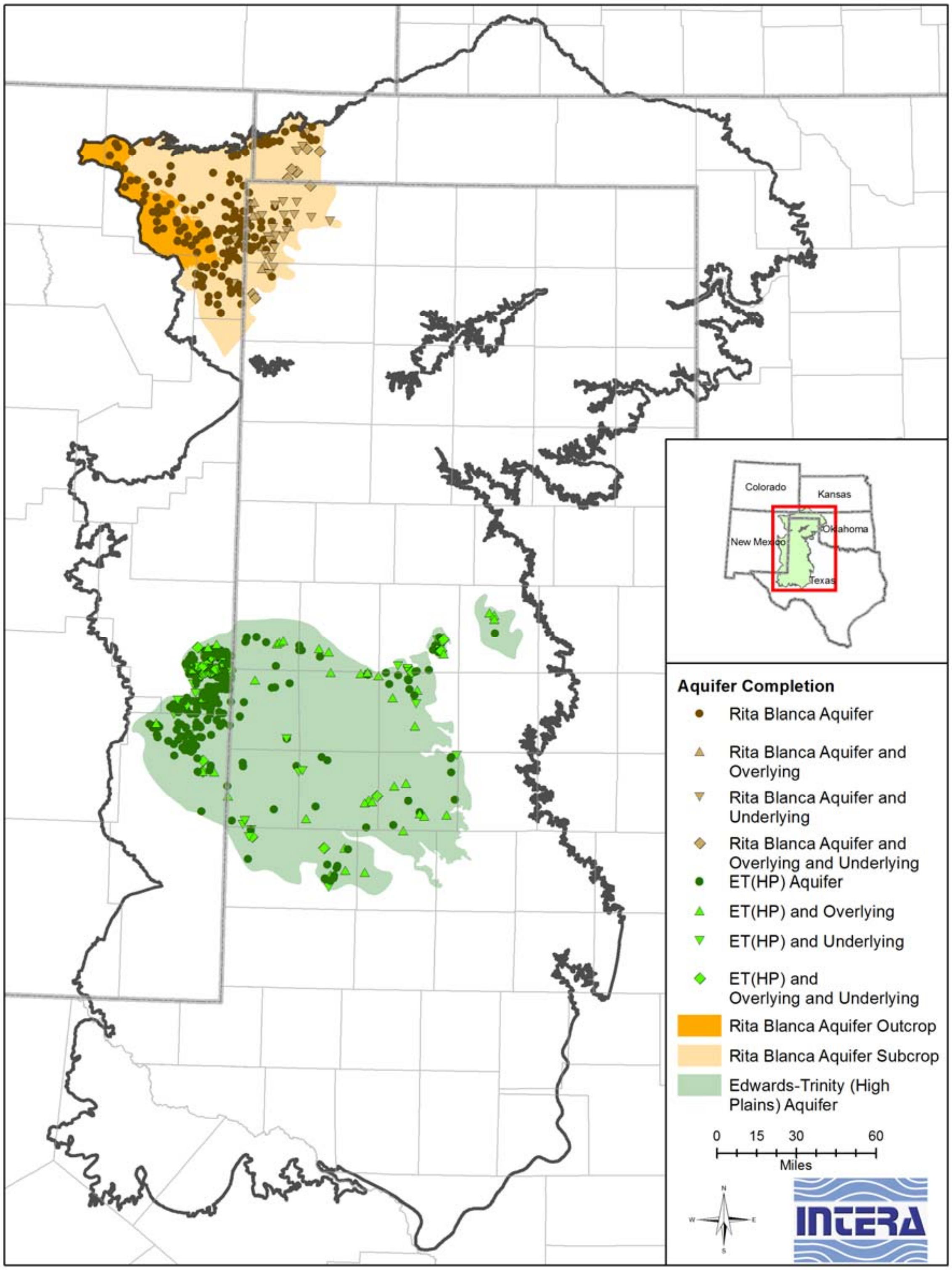


Figure 4.3.1 Location of wells identified as completed into the Ogallala Aquifer or the Ogallala Aquifer and underlying aquifer(s).



ET(HP) = Edwards-Trinity (High Plains) Aquifer

Figure 4.3.2 Location of wells identified as completed into the Rita Blanca or Edwards-Trinity (High Plains) aquifers, the Rita Blanca Aquifer and overlying and/or underlying aquifer(s), or the Edwards-Trinity (High Plains) Aquifer and overlying and/or underlying aquifer(s).

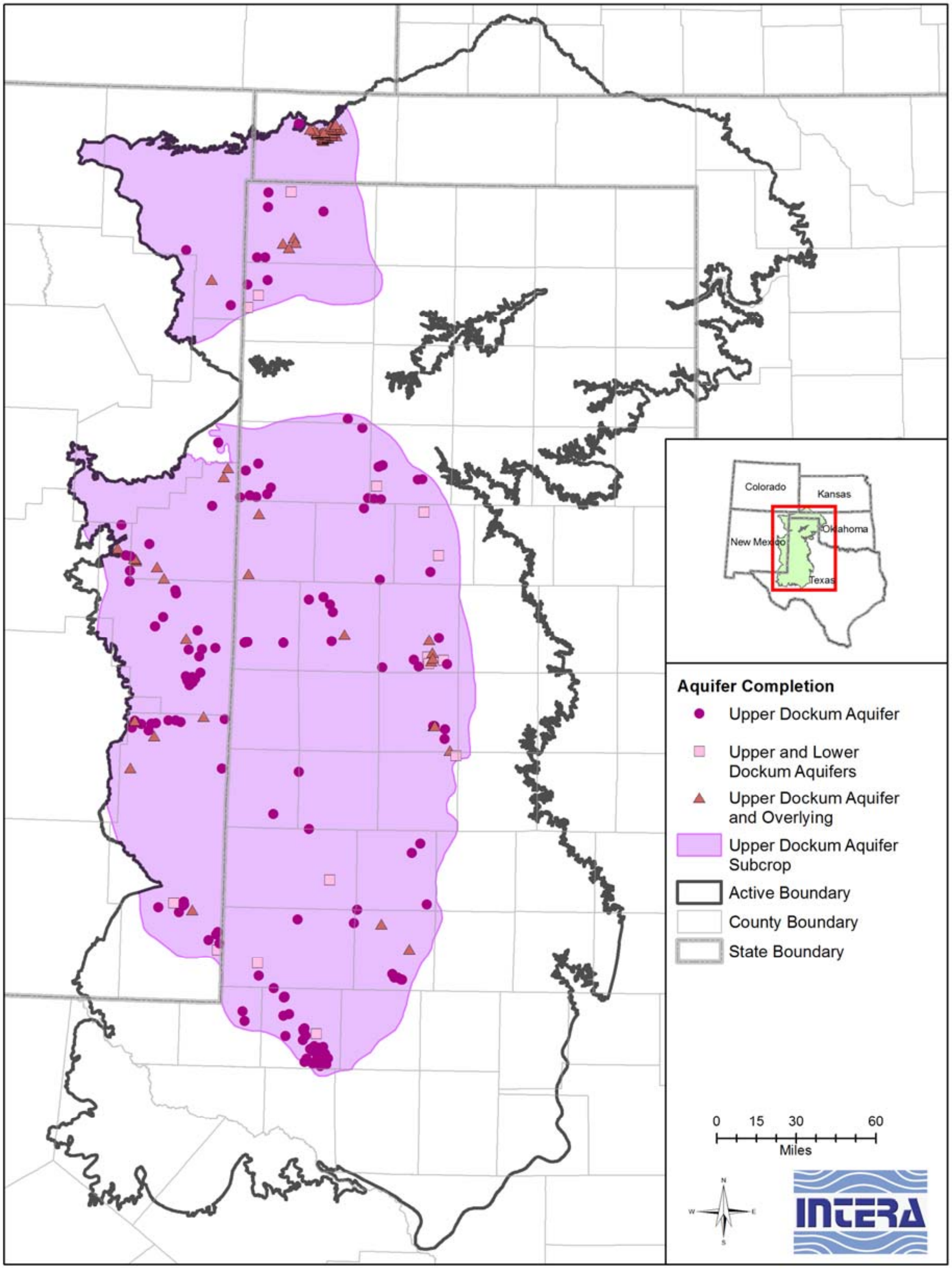


Figure 4.3.3 **Location of wells identified as completed into the upper Dockum Group, both the upper and lower Dockum Group, or the upper Dockum Group and overlying aquifer(s).**

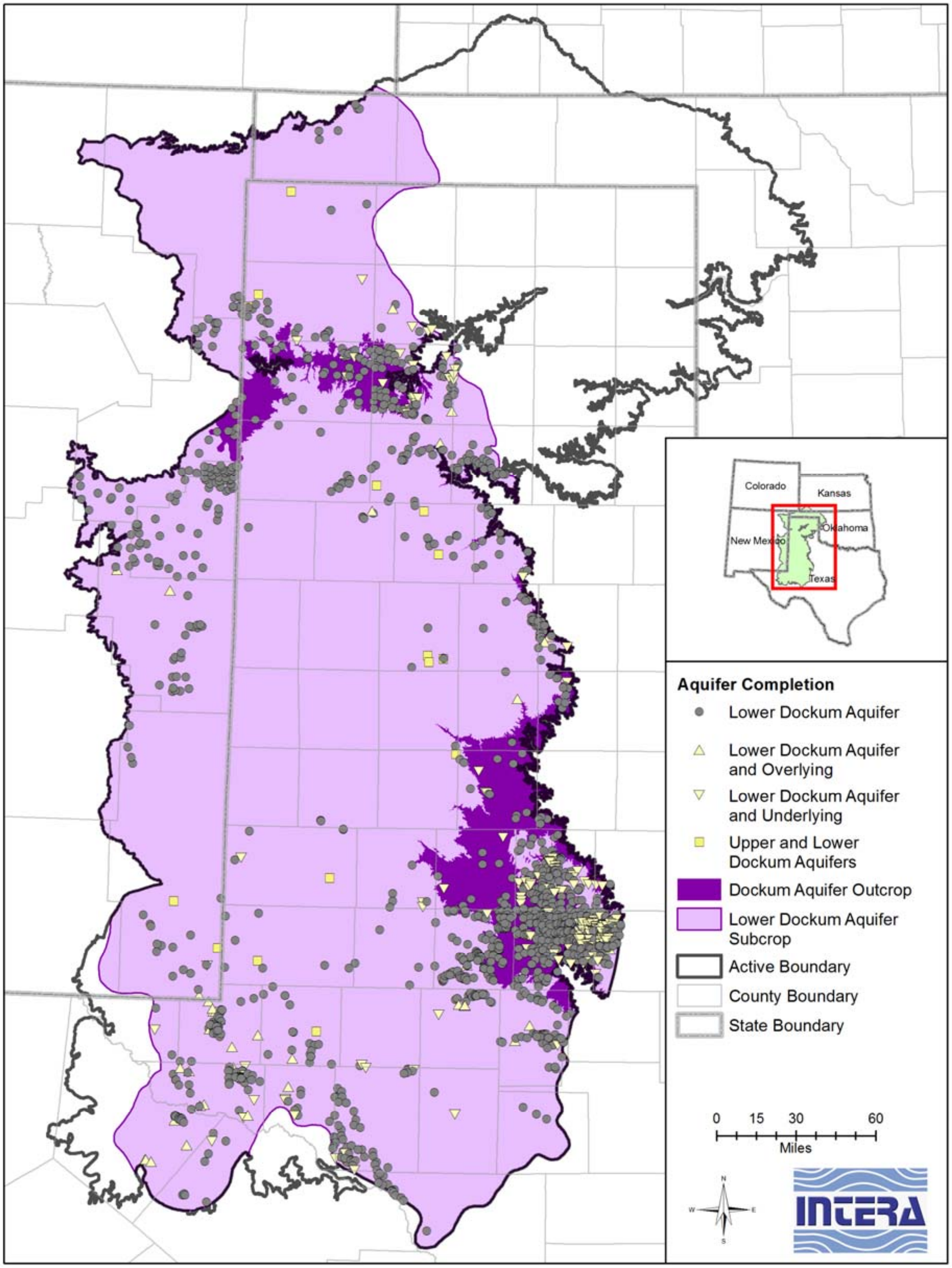


Figure 4.3.4 Location of wells identified as completed into the lower Dockum Group, both the upper and lower Dockum Group, or the lower Dockum Group and overlying and/or underlying aquifer(s).

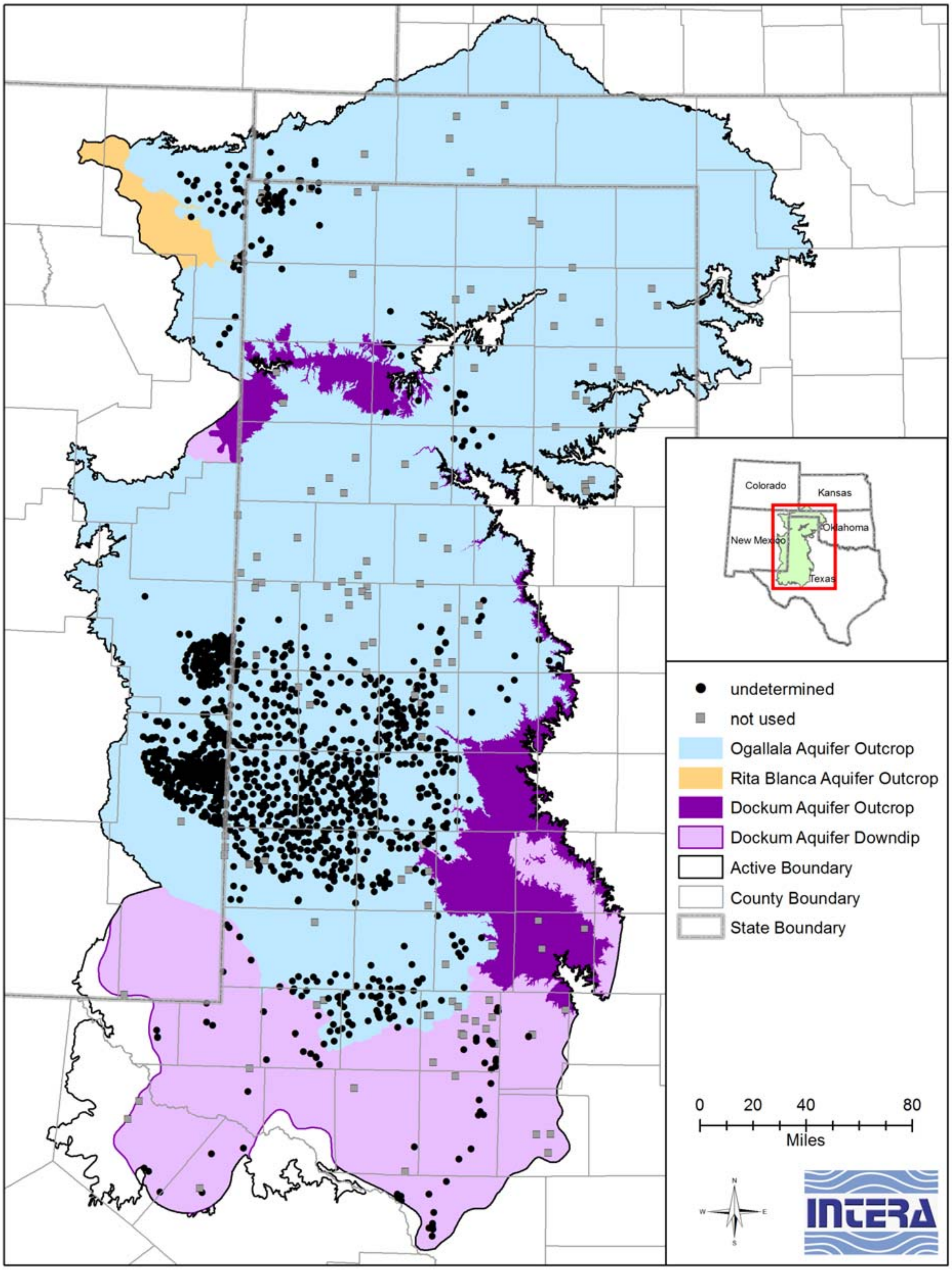


Figure 4.3.5 **Location of wells for which a completion interval could not be determined or estimated.**

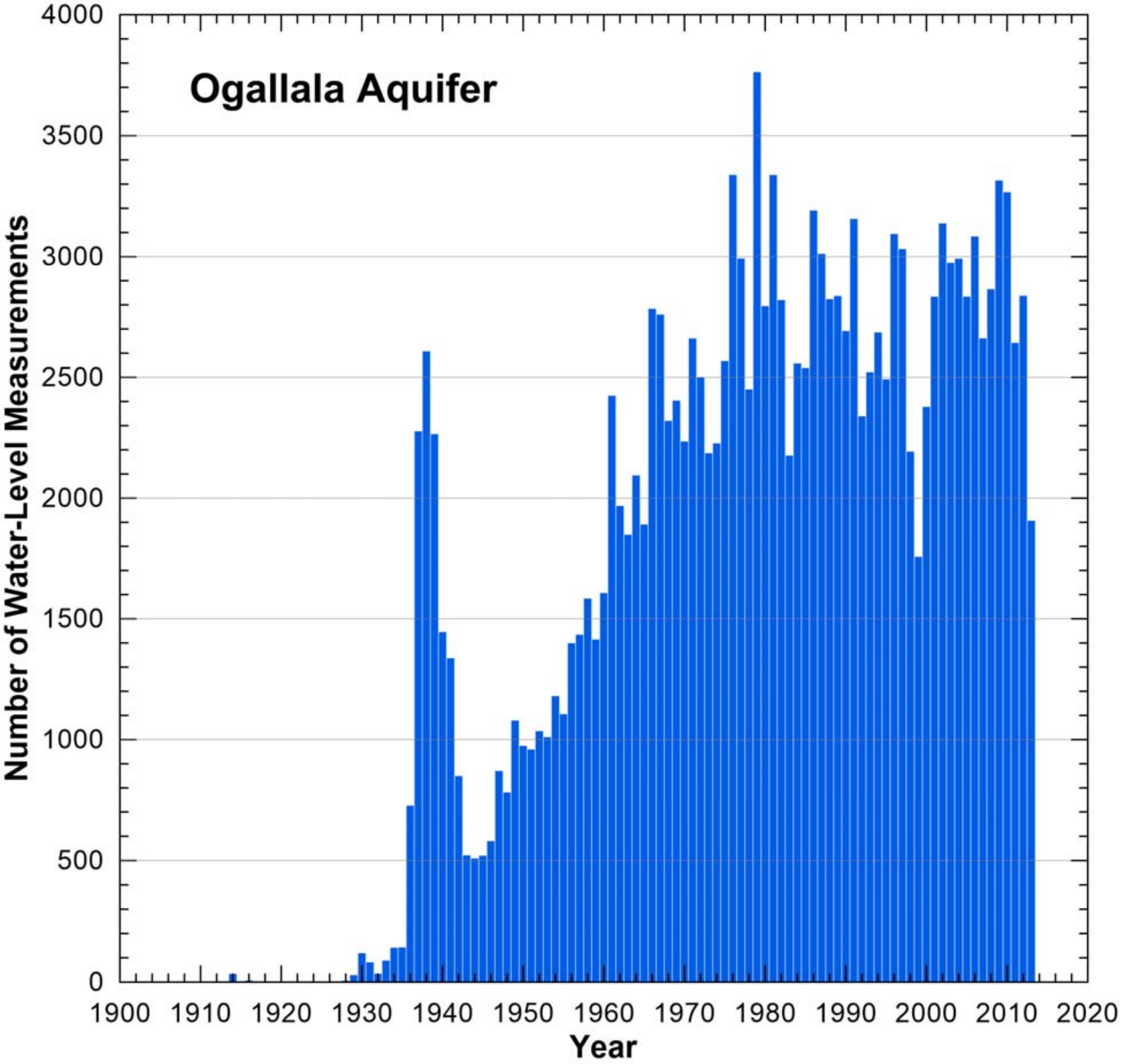


Figure 4.3.6 Temporal distribution of water-level measurements in the Ogallala Aquifer.

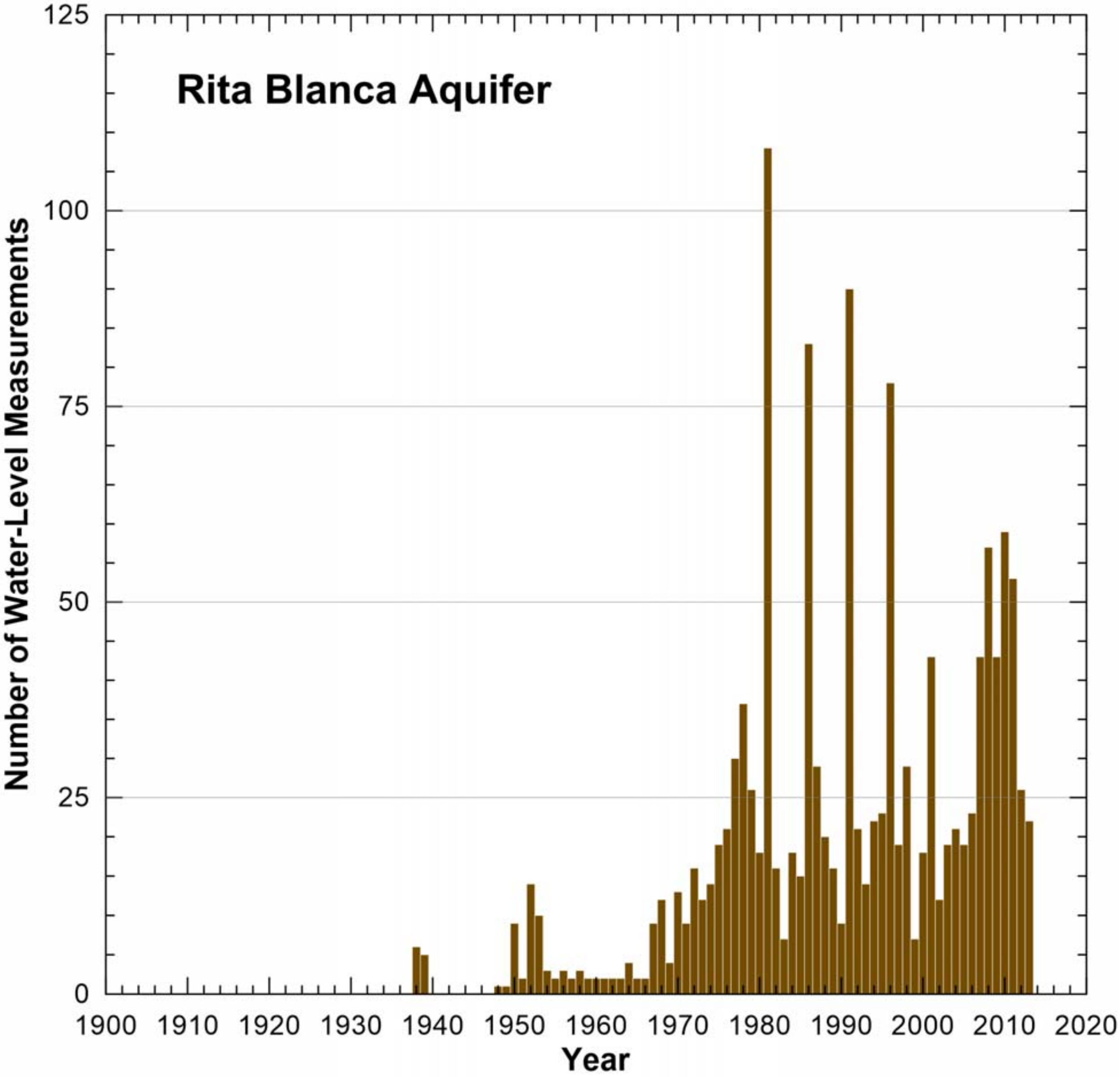


Figure 4.3.7 Temporal distribution of water-level measurements in the Rita Blanca Aquifer.

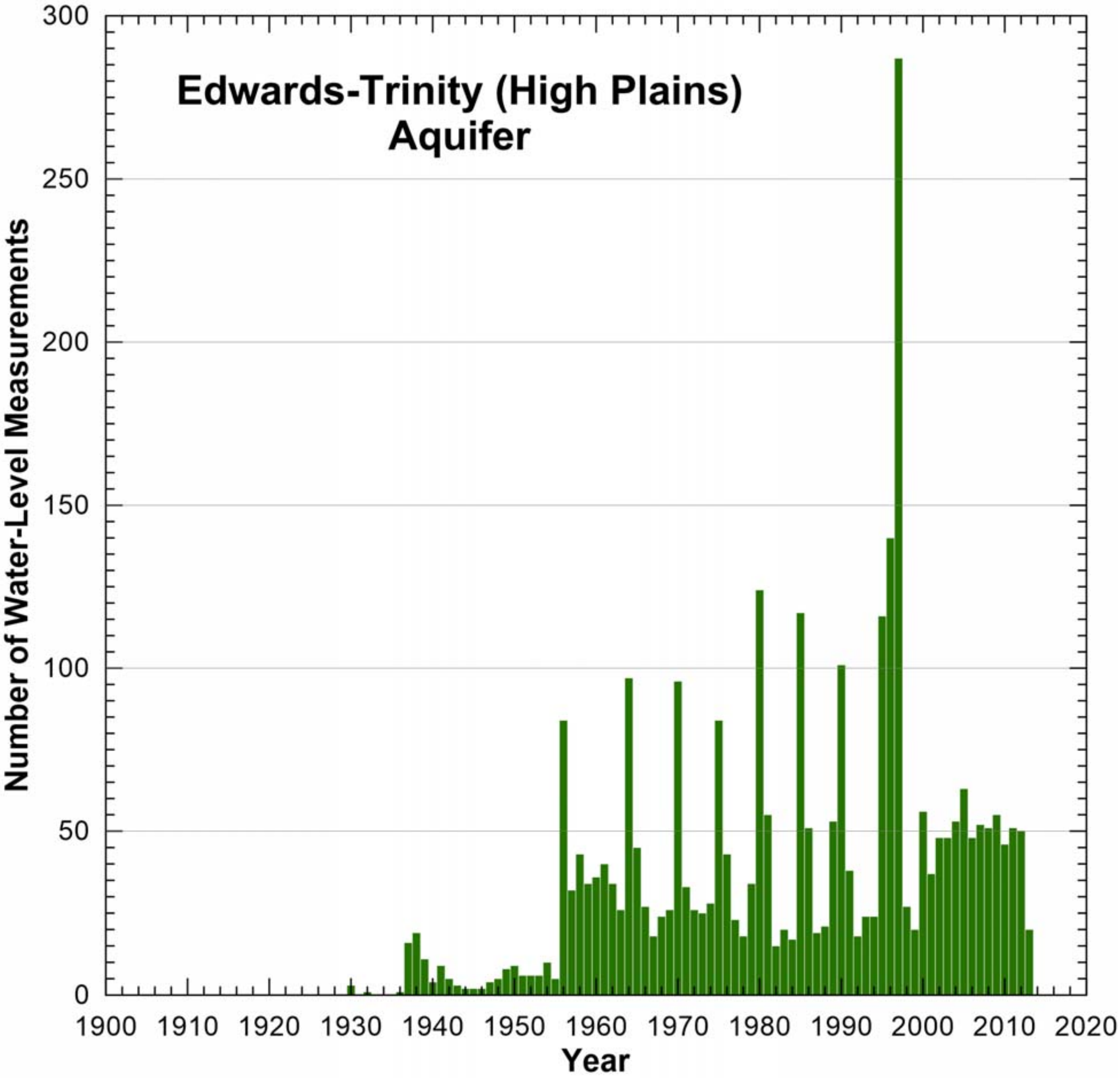


Figure 4.3.8 Temporal distribution of water-level measurements in the Edwards-Trinity (High Plains) Aquifer.

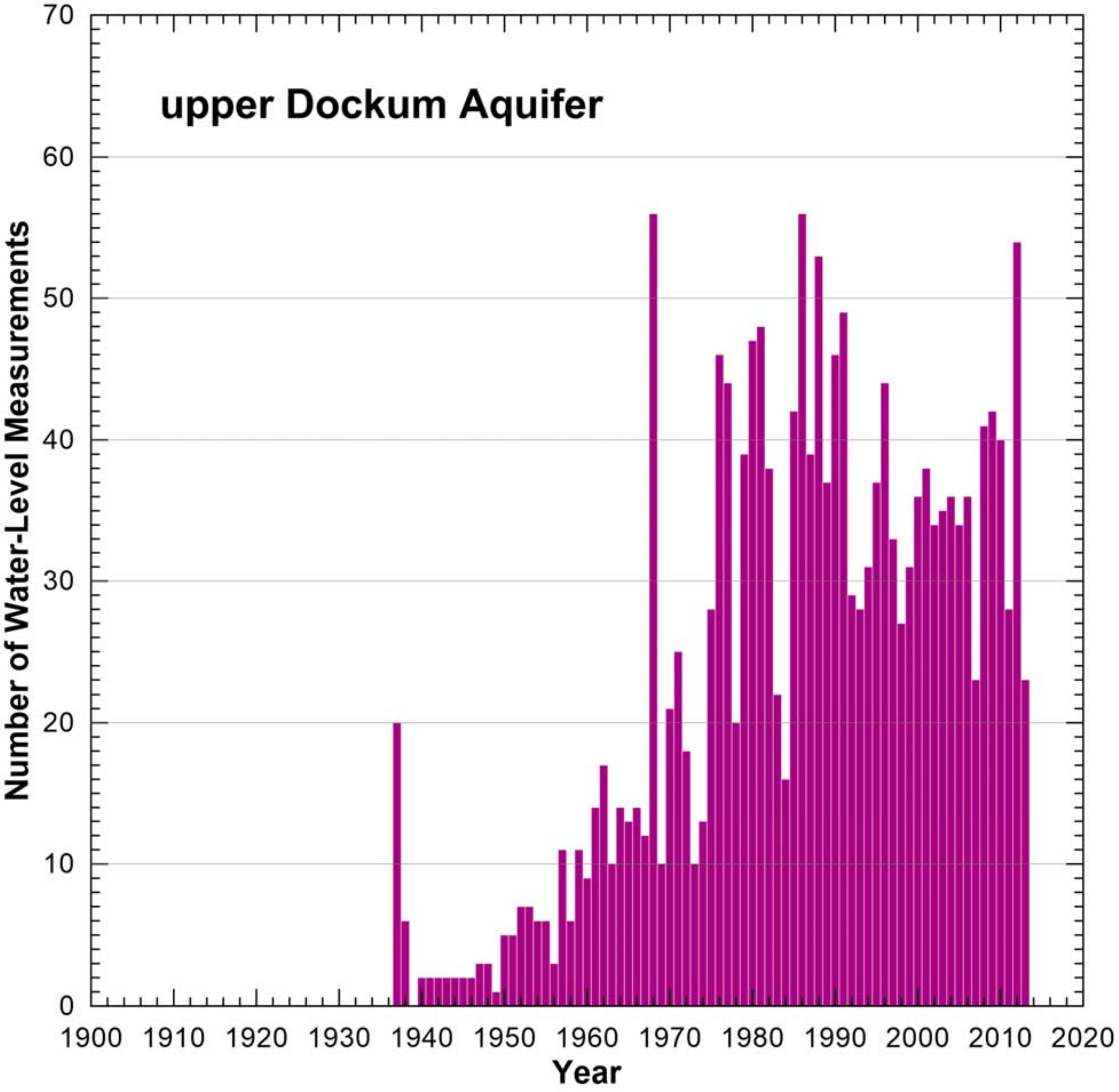


Figure 4.3.9 Temporal distribution of water-level measurements in the upper Dockum Group.

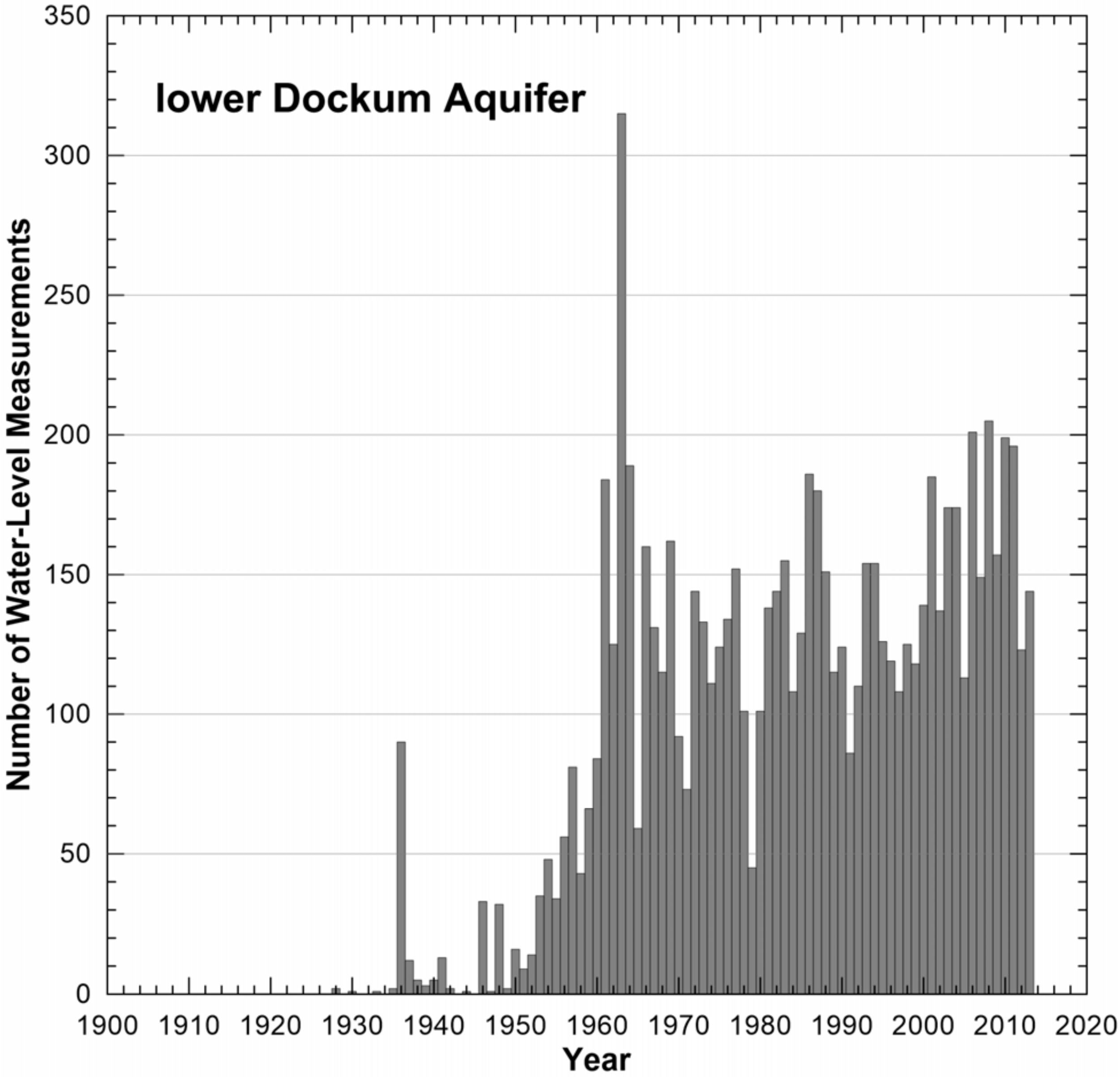


Figure 4.3.10 Temporal distribution of water-level measurements in the lower Dockum Group.

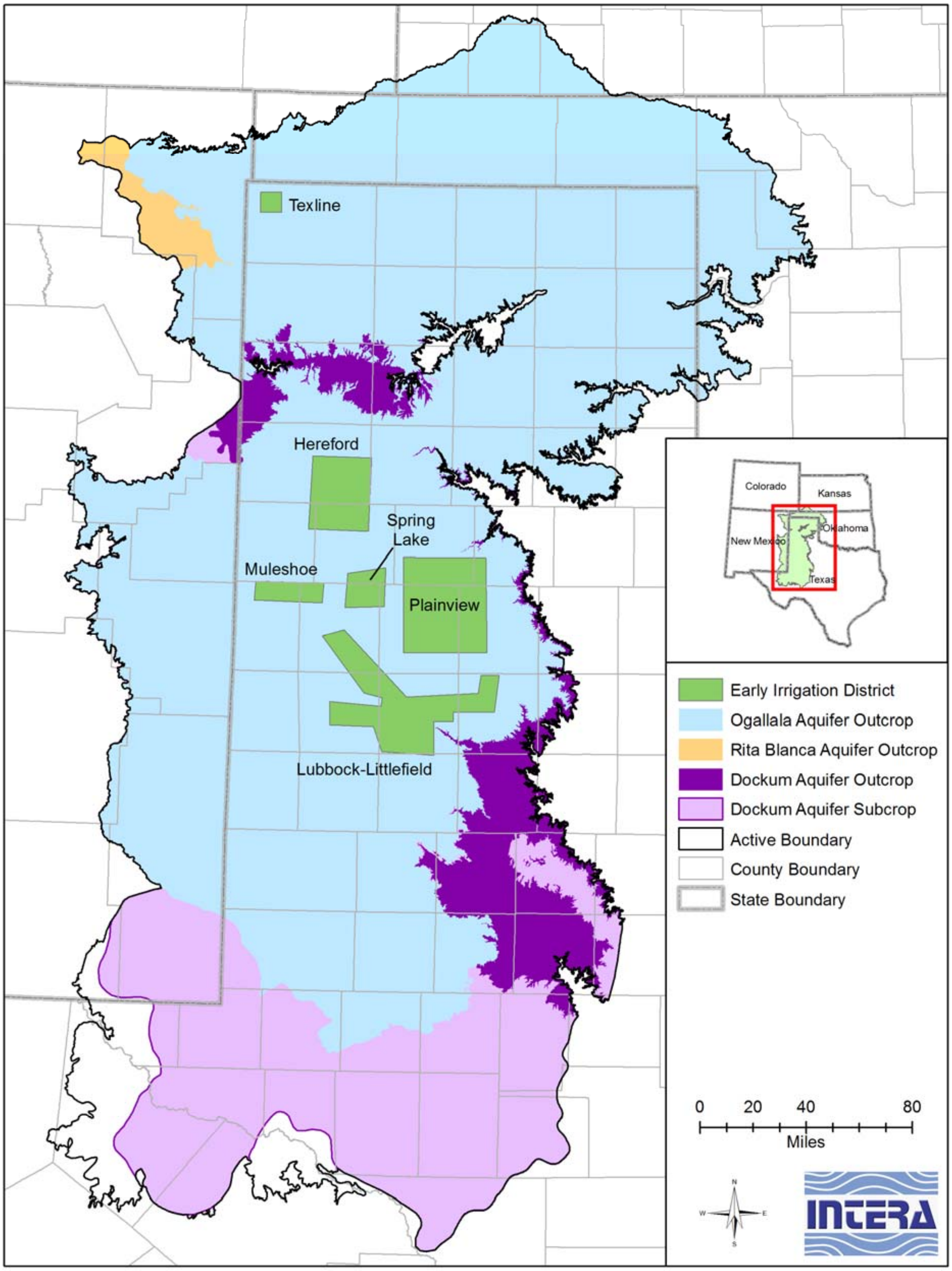
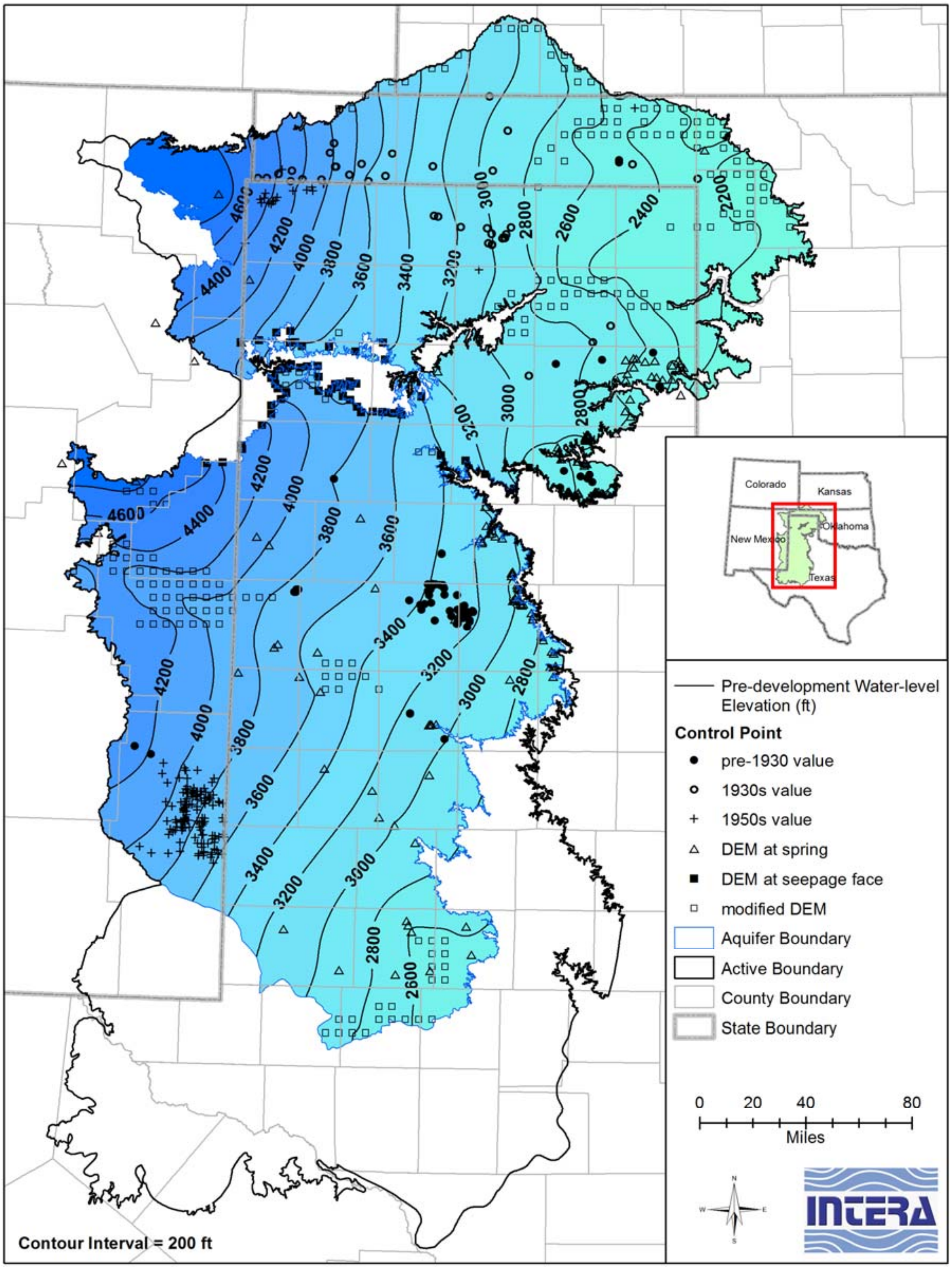
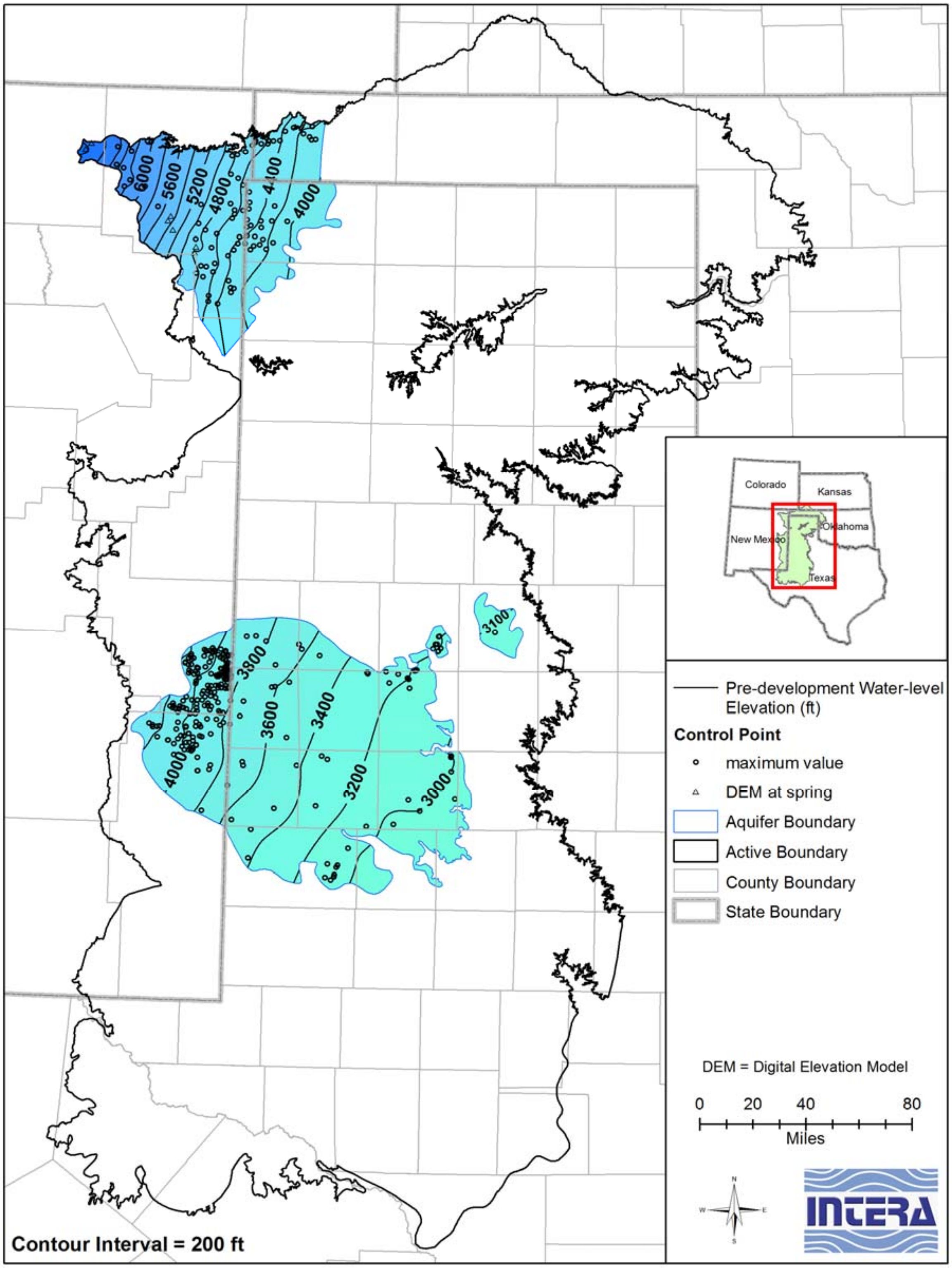


Figure 4.3.11 Location of early irrigation districts.



DEM = Digital Elevation Model

Figure 4.3.12 Estimated pre-development water-level elevation contours in feet for the Ogallala Aquifer.



DEM = Digital Elevation Model

Figure 4.3.13 Estimated pre-development water-level elevation contours in feet for the Rita Blanca and Edwards-Trinity (High Plains) aquifers.

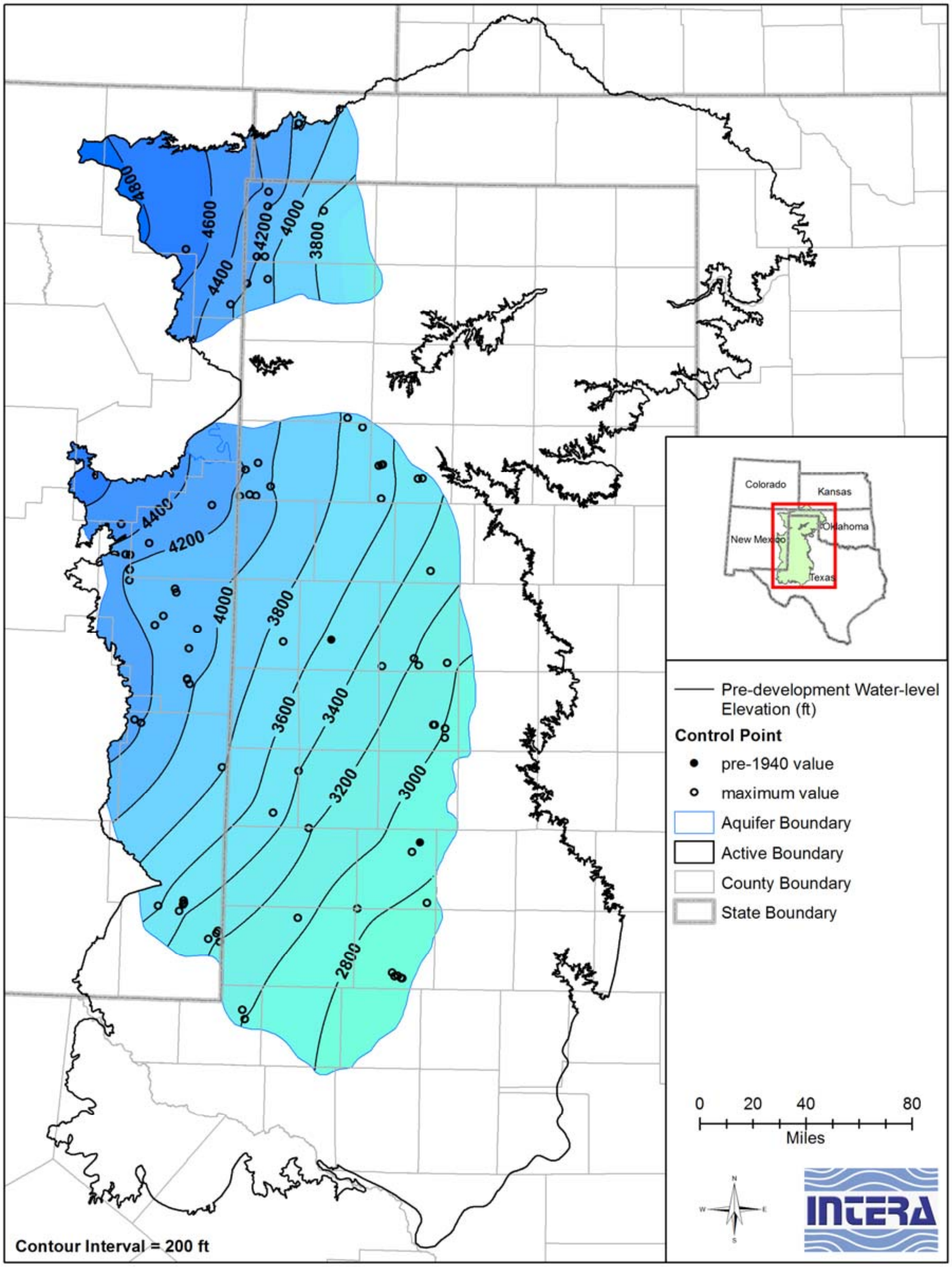
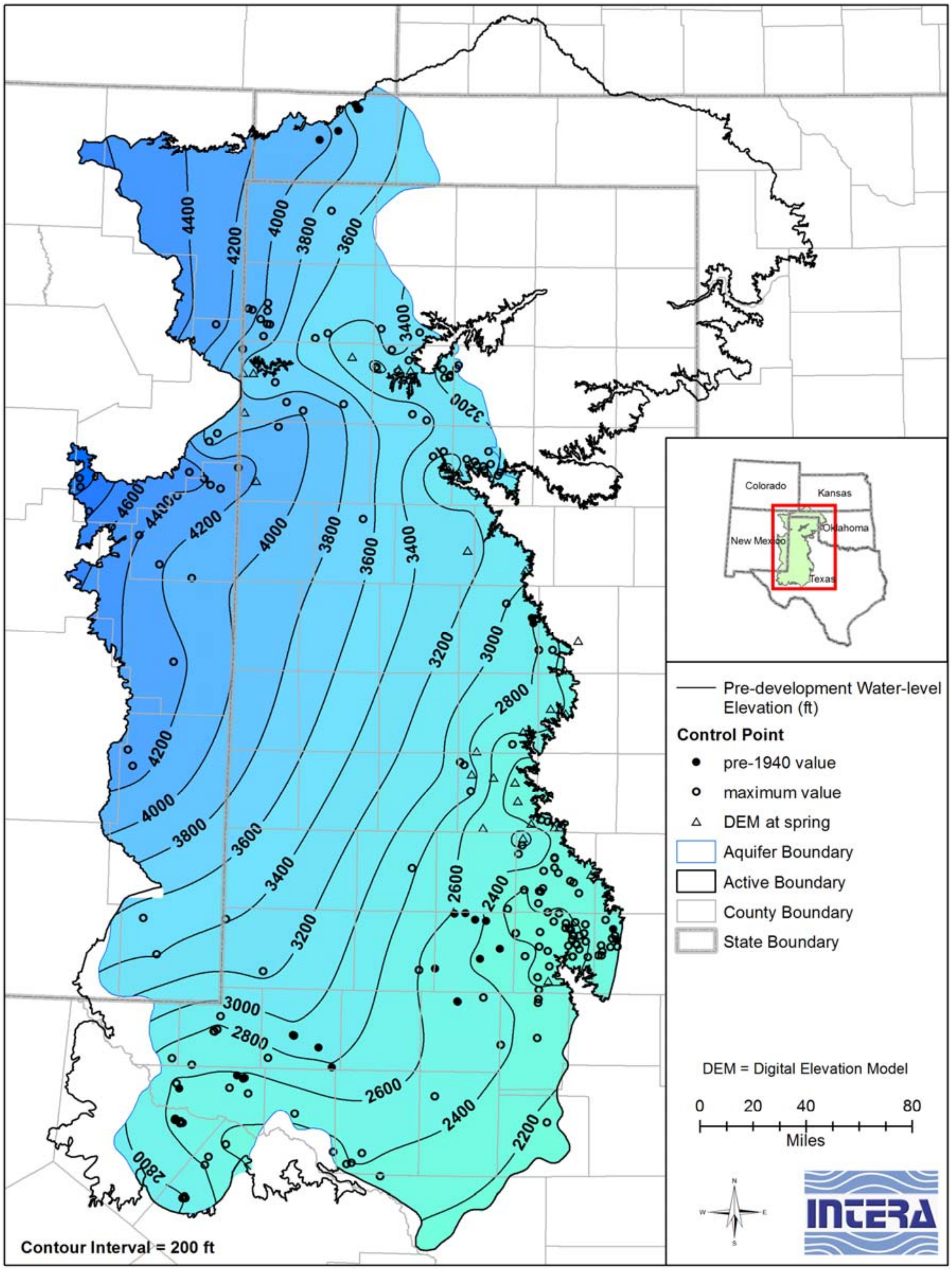


Figure 4.3.14 Estimated pre-development water-level elevation contours in feet for the upper Dockum Group.



DEM = Digital Elevation Model

Figure 4.3.15 Estimated pre-development water-level elevation contours in feet for the lower Dockum Group.

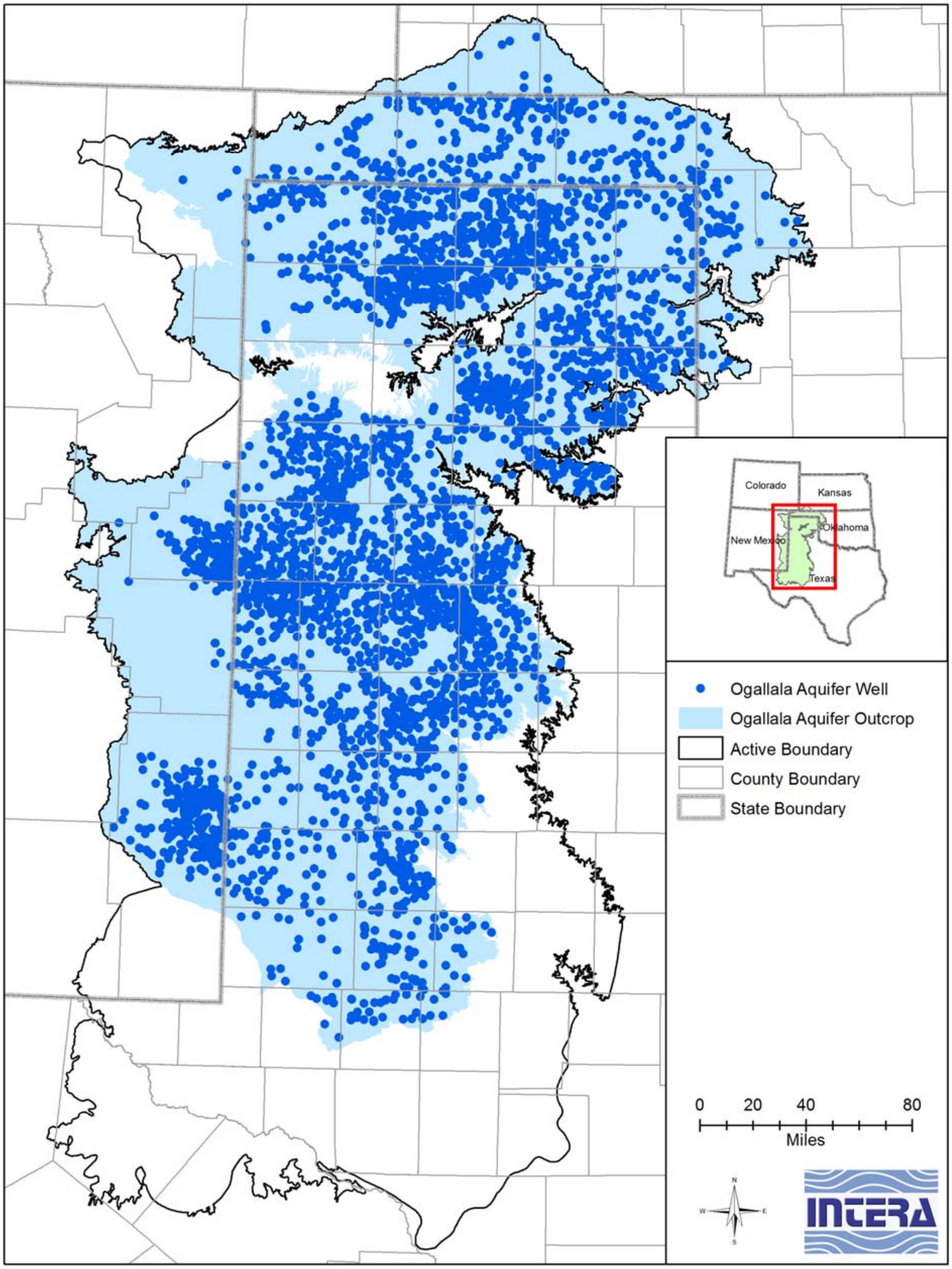


Figure 4.3.16 Locations of wells completed into the Ogallala Aquifer with transient water-level data.

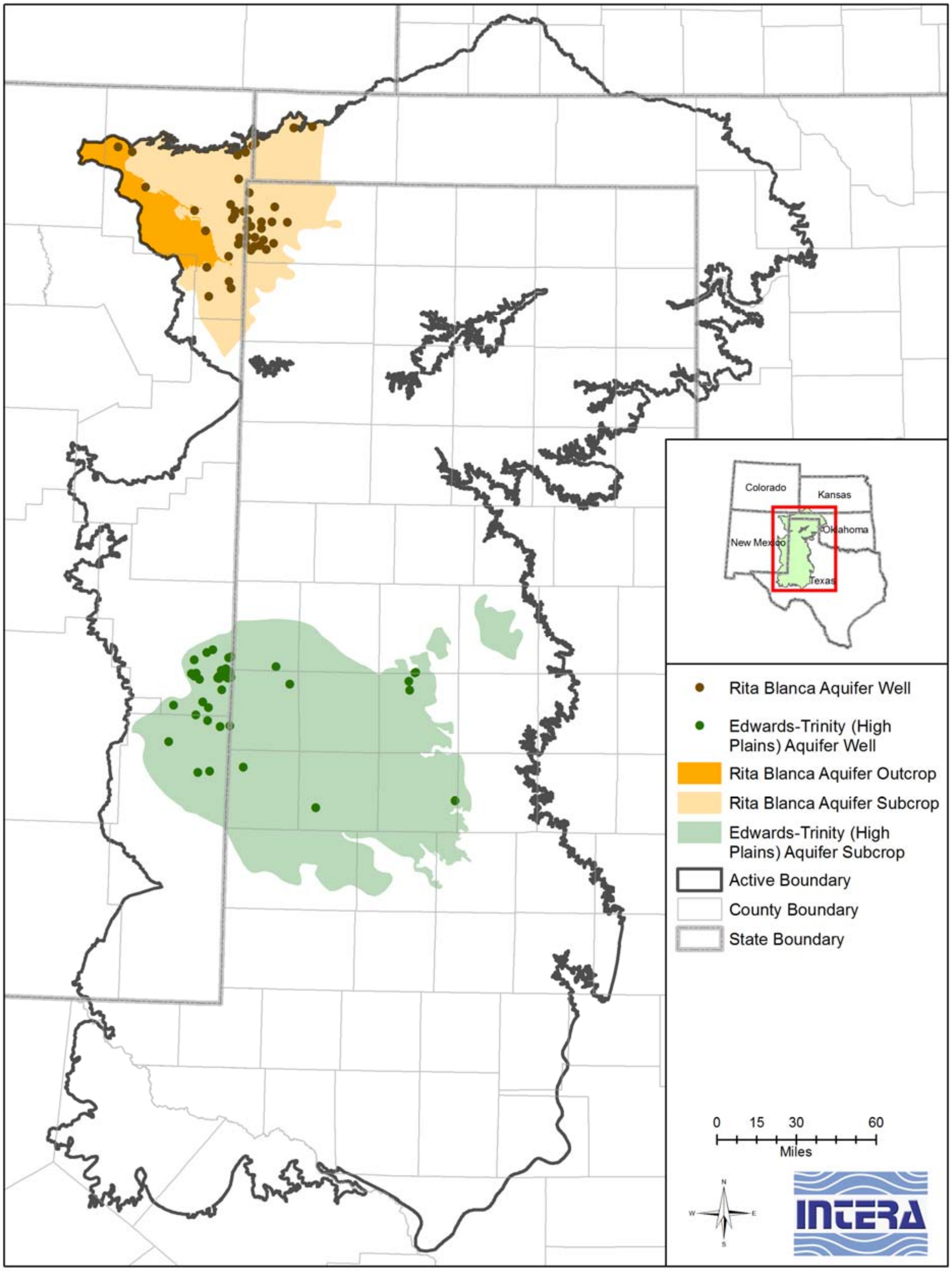


Figure 4.3.17 Location of wells completed into the Rita Blanca or Edwards-Trinity (High Plains) aquifers with transient water-level data.

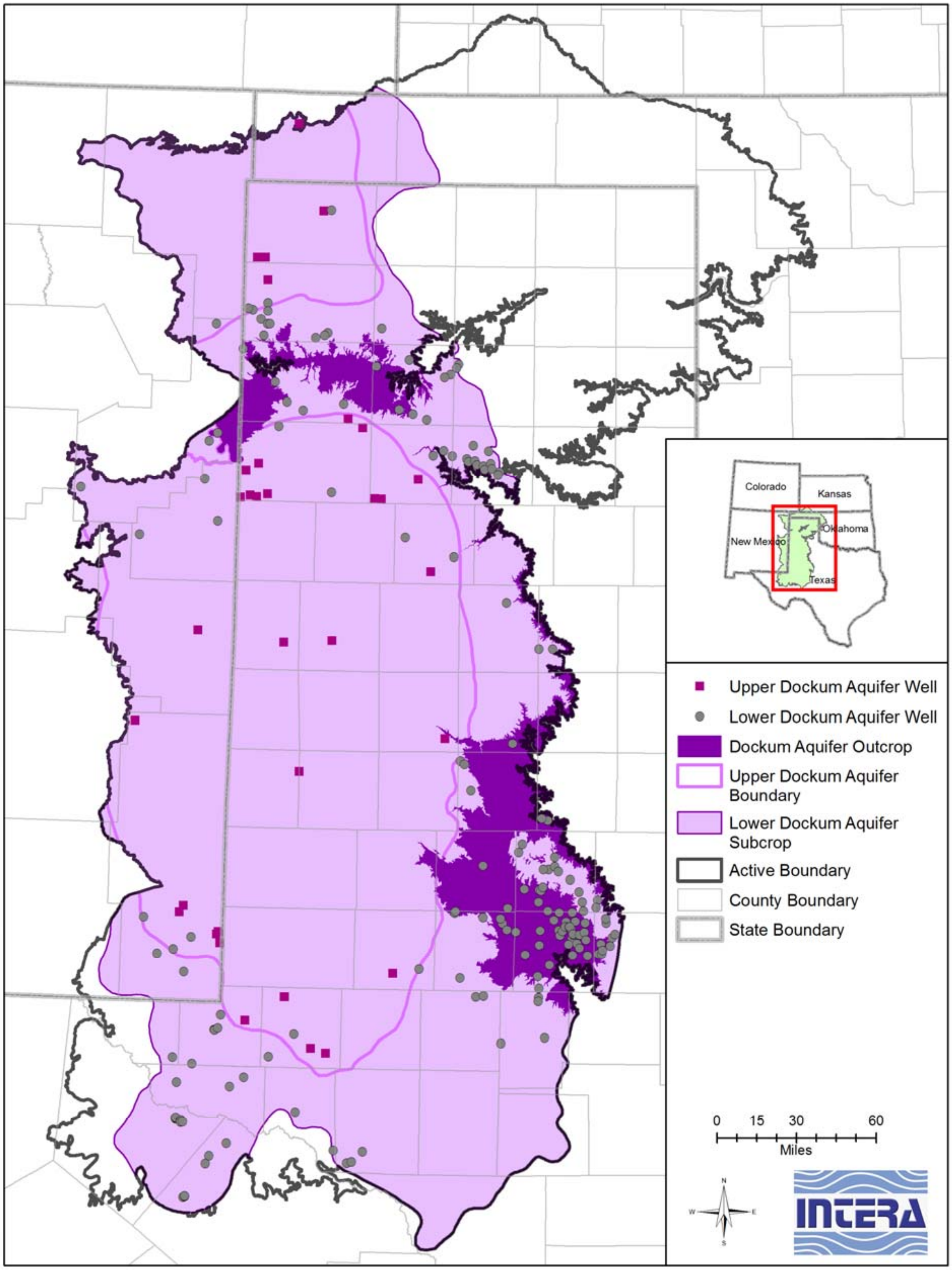


Figure 4.3.18 **Location of wells completed into the upper or lower Dockum Group with transient water-level data.**

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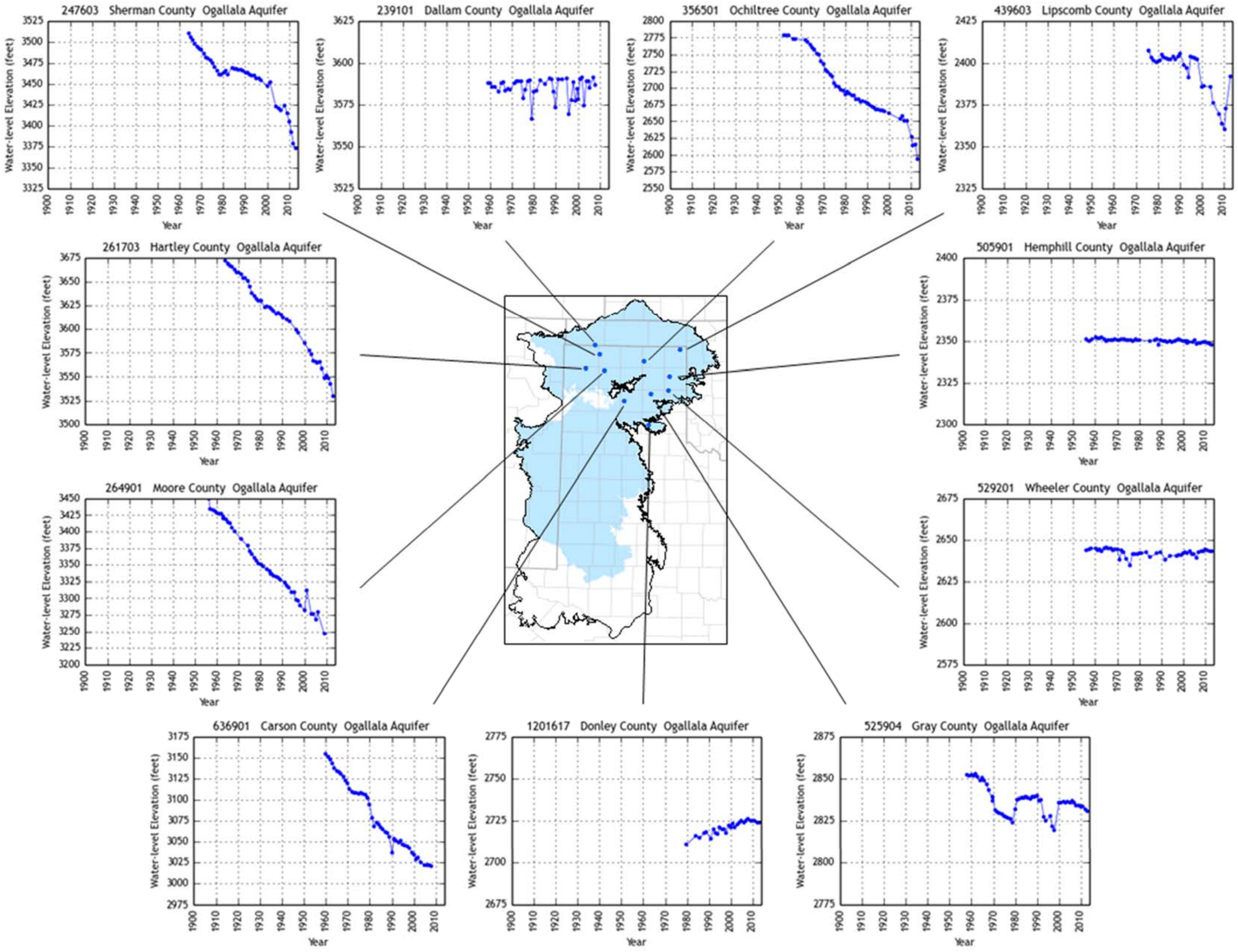


Figure 4.3.19 Select hydrographs for wells completed into the Ogallala Aquifer and located in the northern portion of the aquifer.

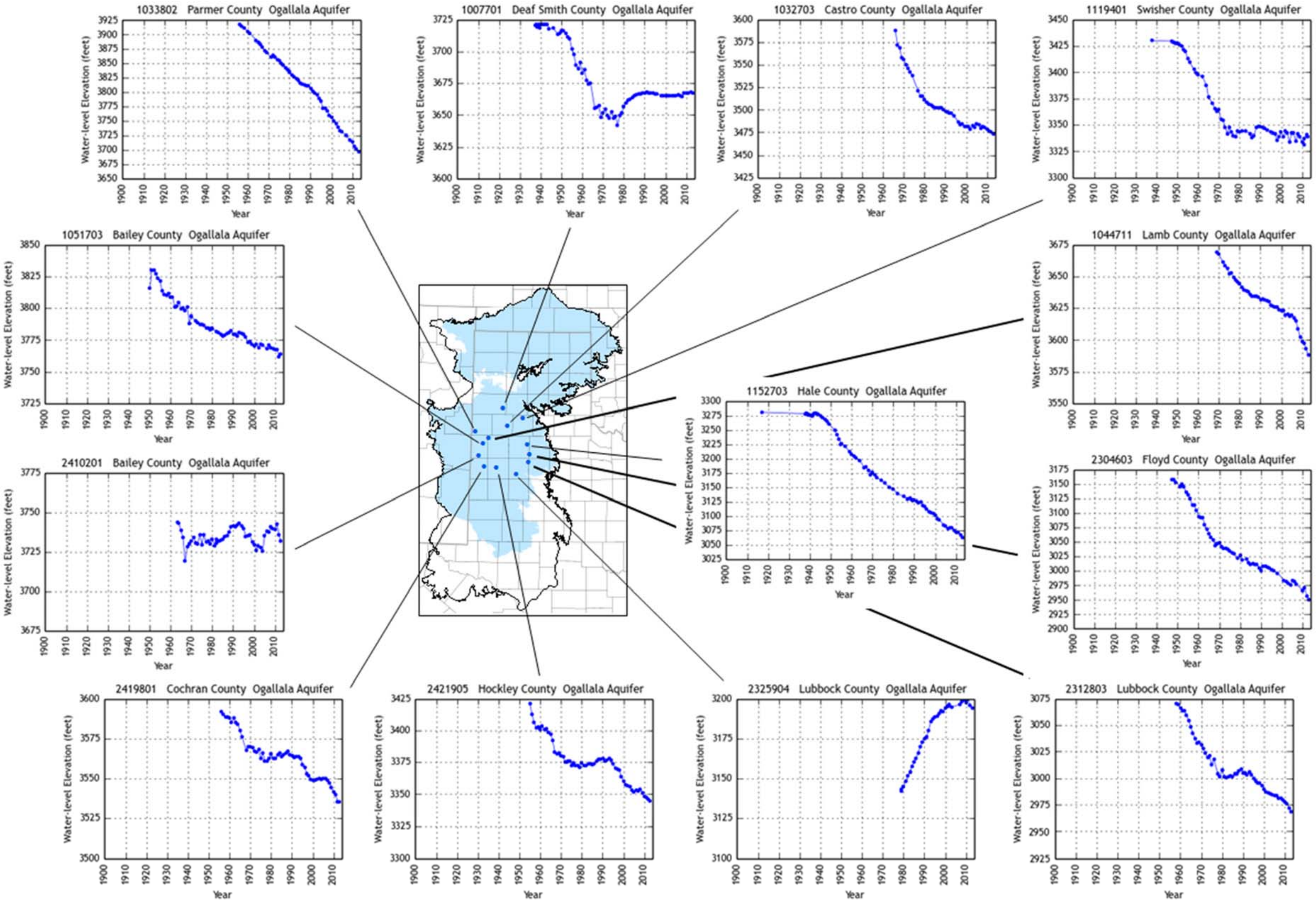


Figure 4.3.20 Select hydrographs for wells completed into the Ogallala Aquifer and located in the northern counties of the southern portion of the aquifer.

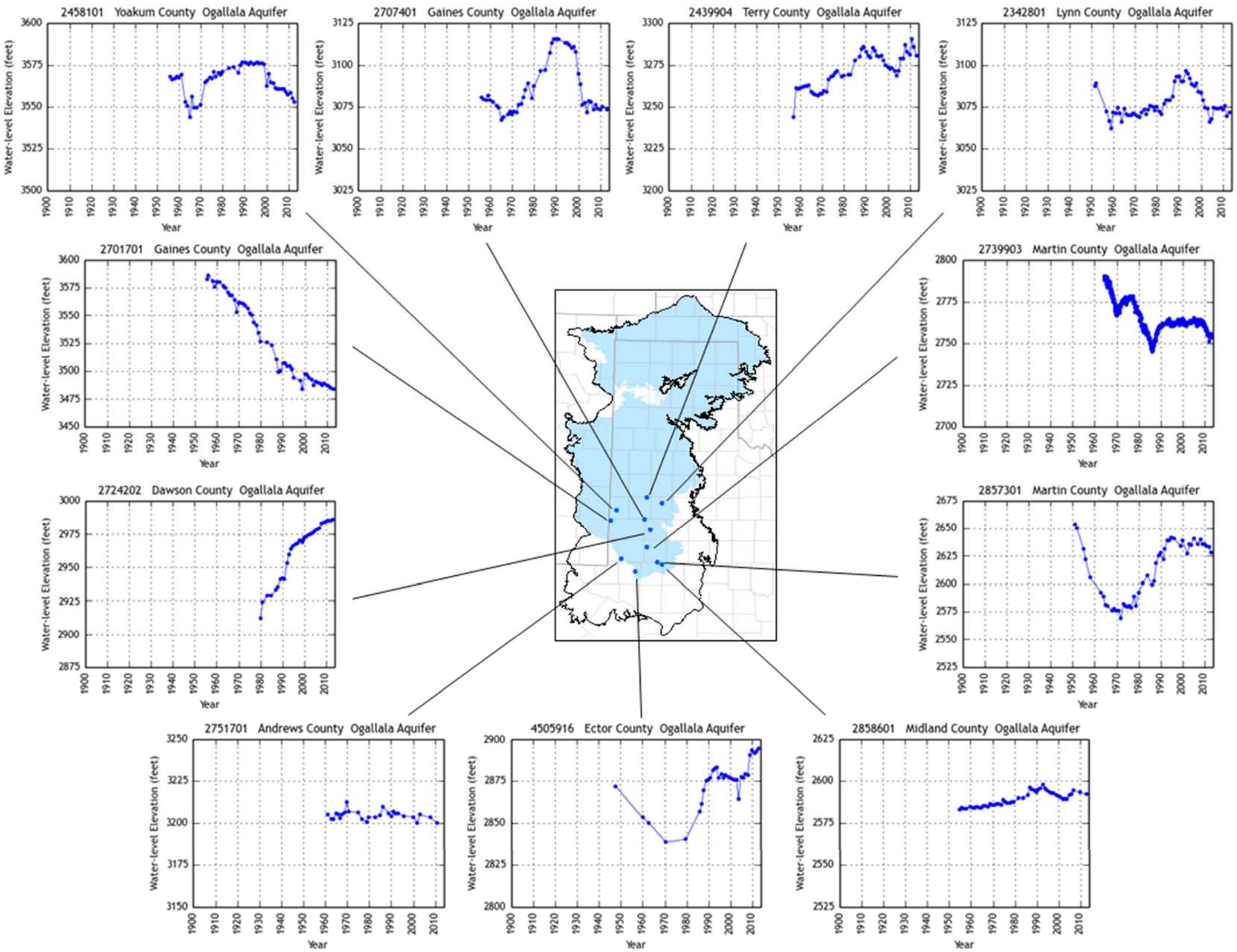


Figure 4.3.21 **Select hydrographs for wells completed into the Ogallala Aquifer and located in the southern counties of the southern portion of the aquifer.**

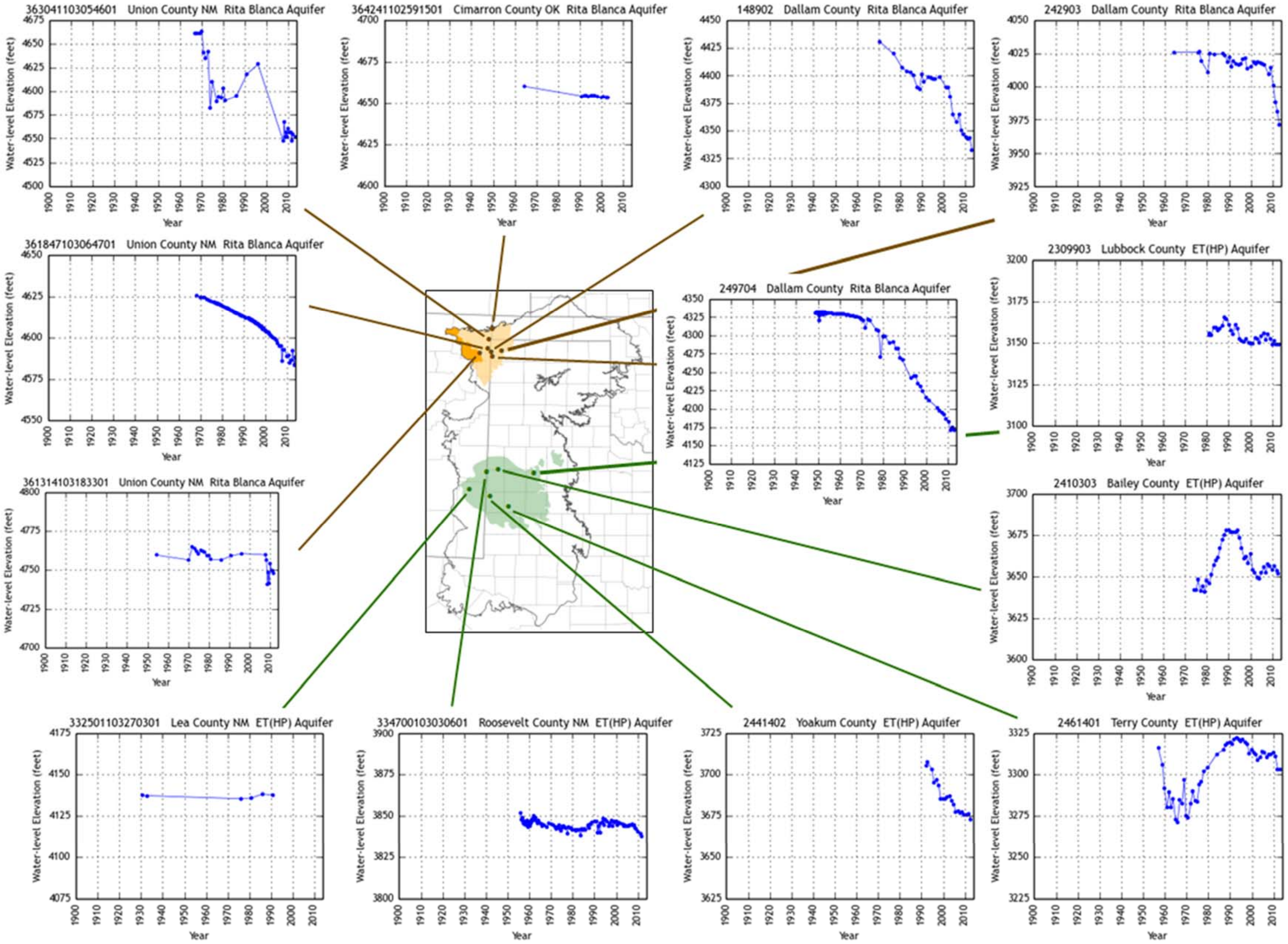


Figure 4.3.22 Select hydrographs for wells completed into the Rita Blanca or Edwards-Trinity (High Plains) aquifers. Abbreviation key: ET(HP) = Edwards – Trinity (High Plains) Aquifer.

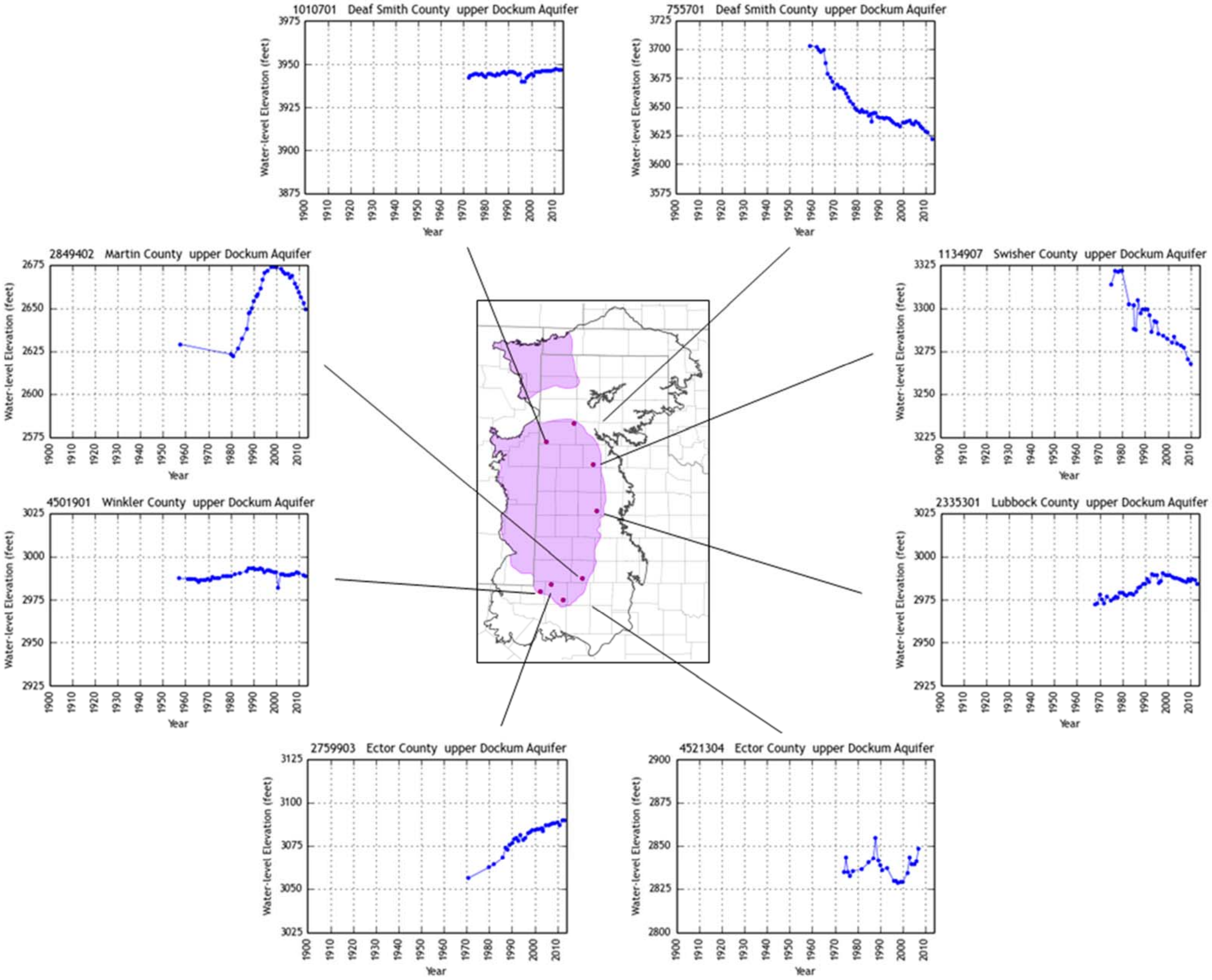


Figure 4.3.23 Select hydrographs for wells completed into the upper Dockum Aquifer.

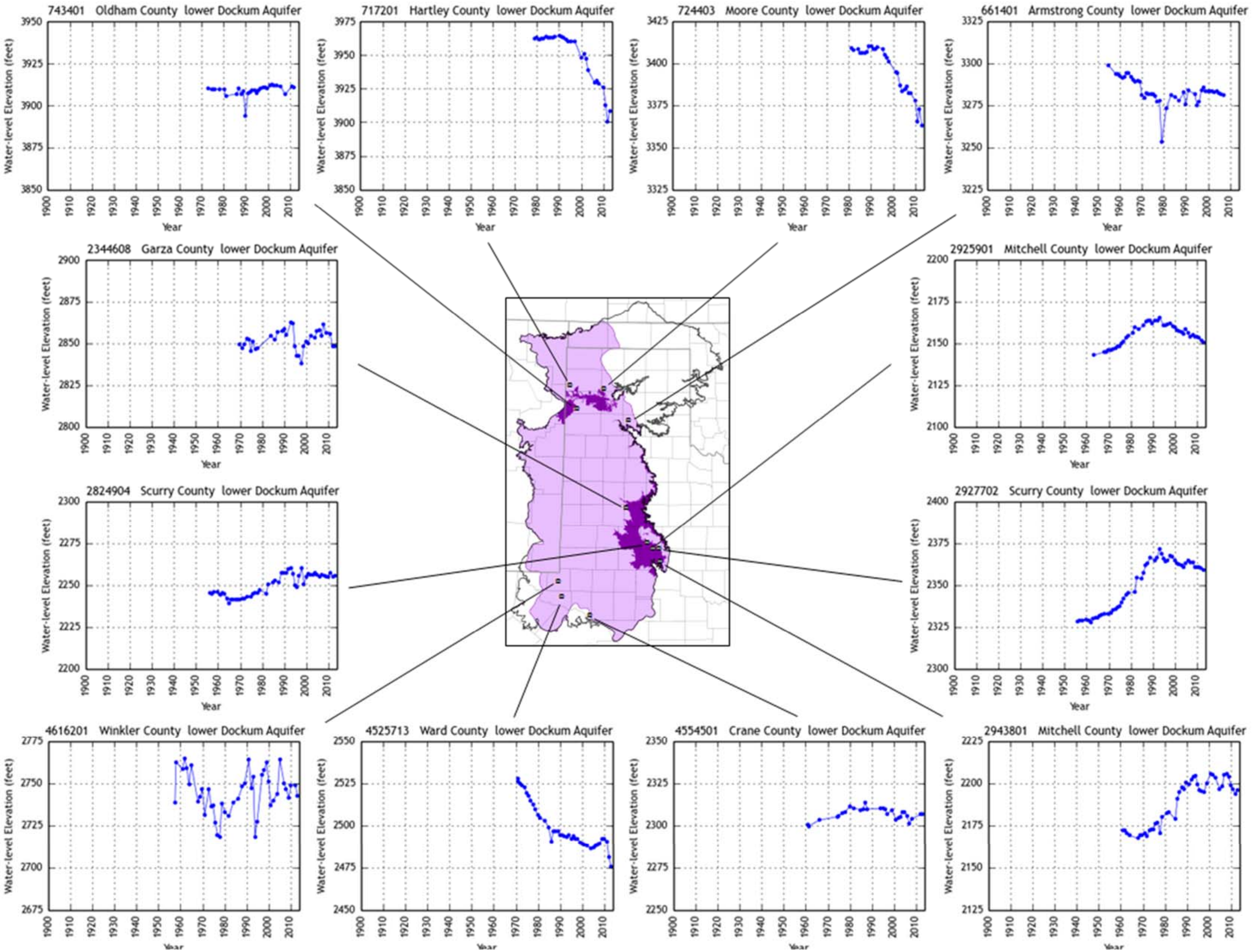


Figure 4.3.24 Select hydrographs for wells completed into the lower Dockum Aquifer.

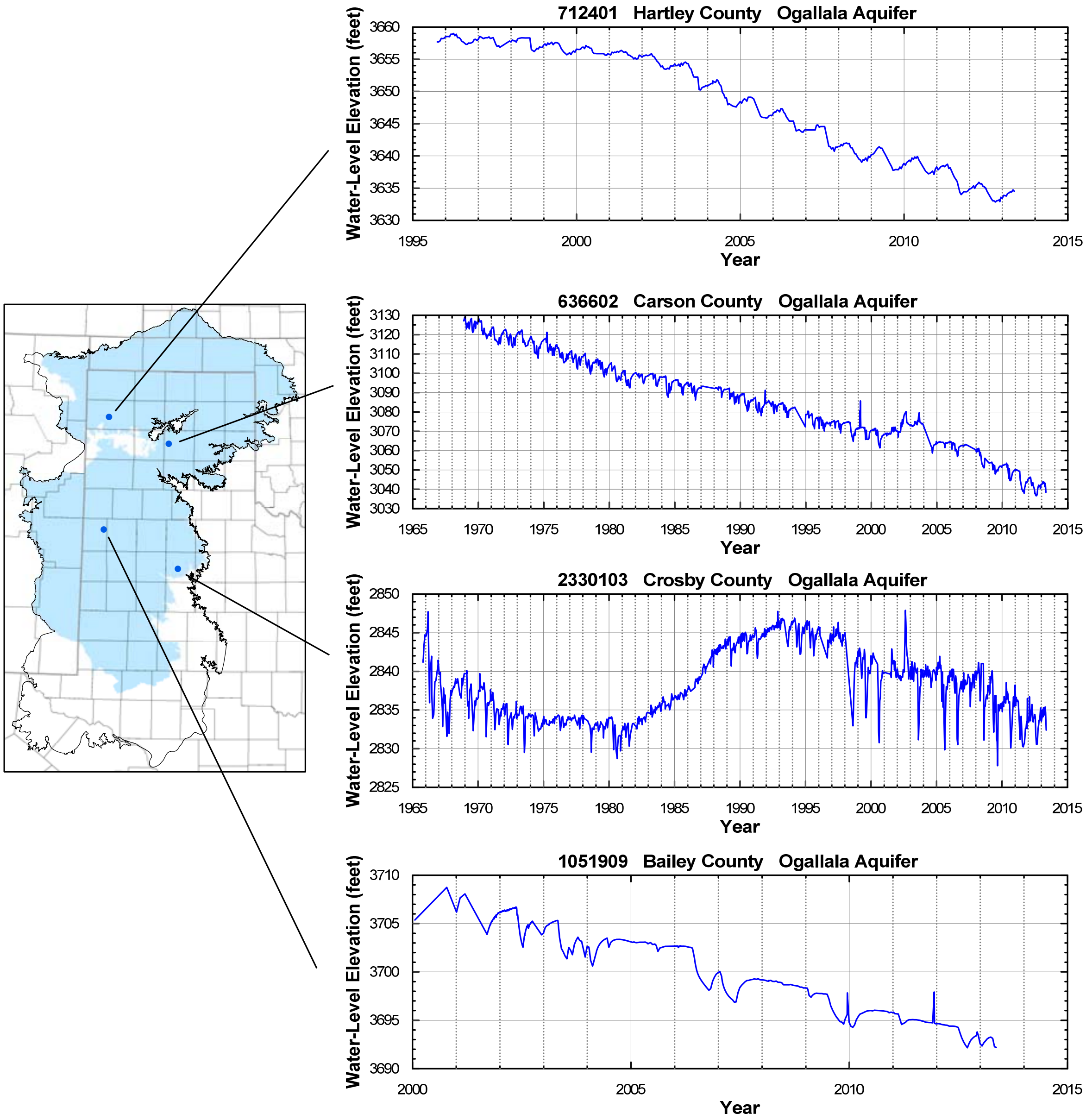


Figure 4.3.25 **Select hydrographs showing seasonal water-level changes for wells completed into the Ogallala Aquifer.**

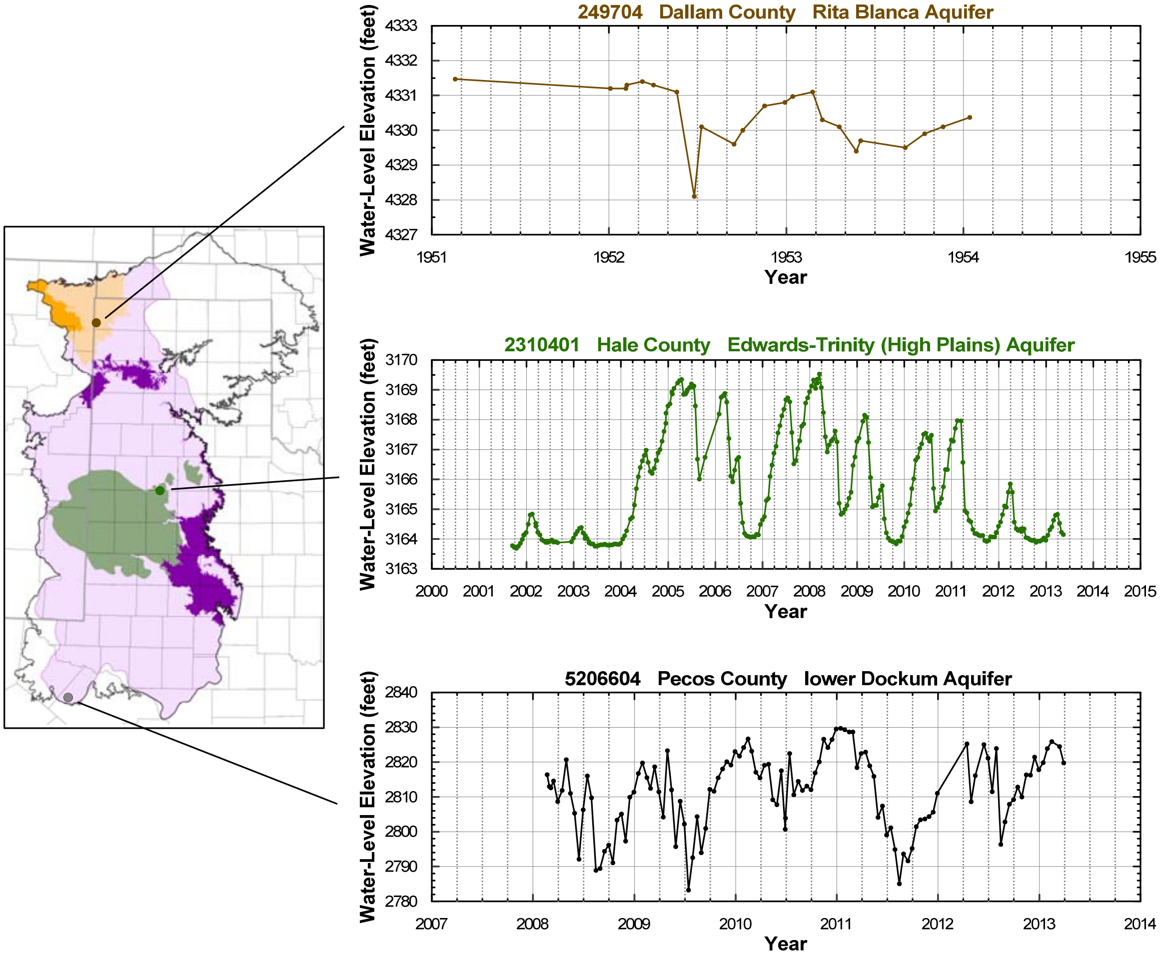
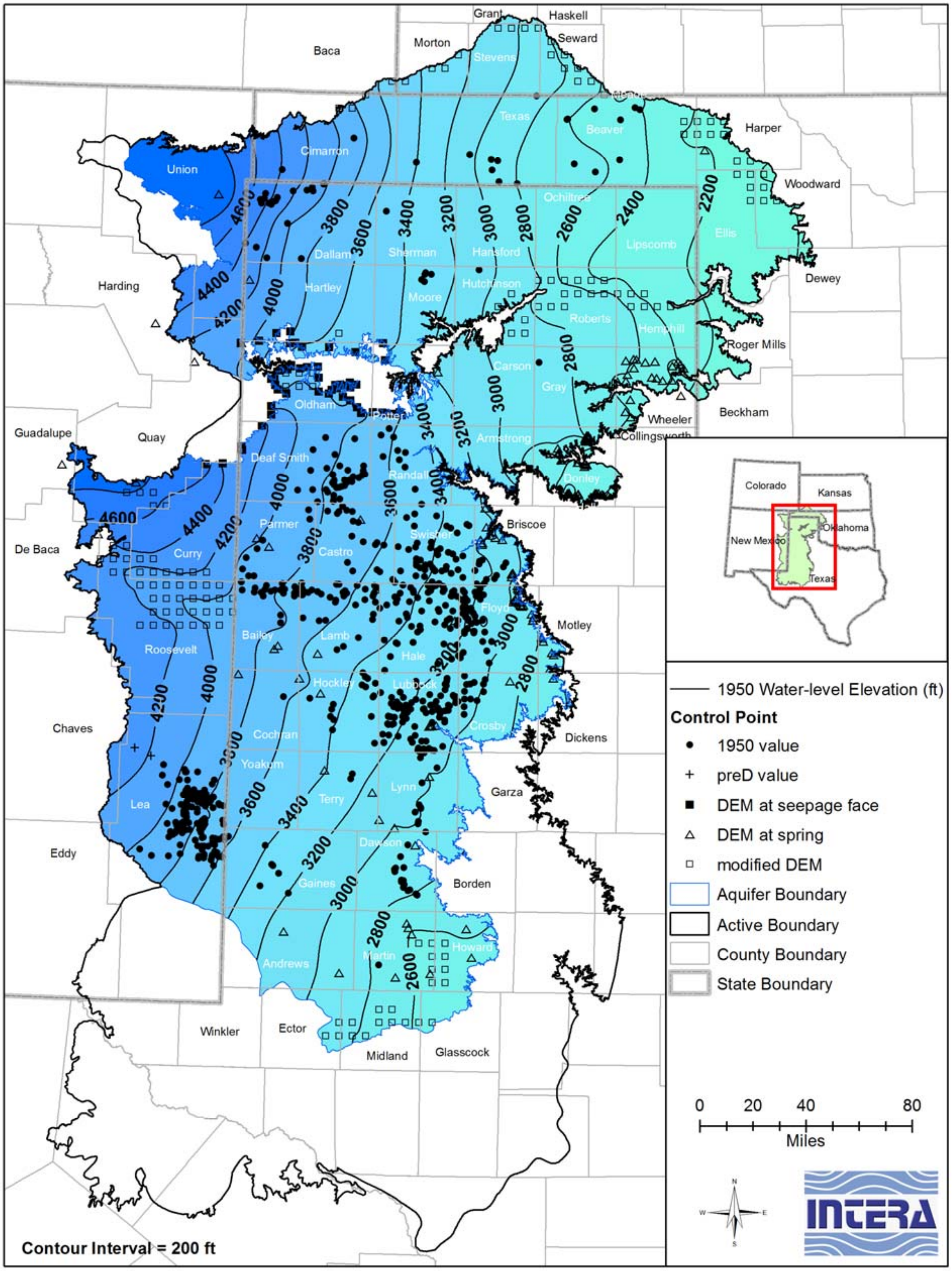


Figure 4.3.26 Select hydrographs showing seasonal water-level changes for one well each completed into the Rita Blanca, Edwards-Trinity (High Plains), and lower Dockum aquifers.



DEM = Digital Elevation Model preD = pre-development

Figure 4.3.27 Estimated water-level elevation contours in feet for the Ogallala Aquifer in 1950.

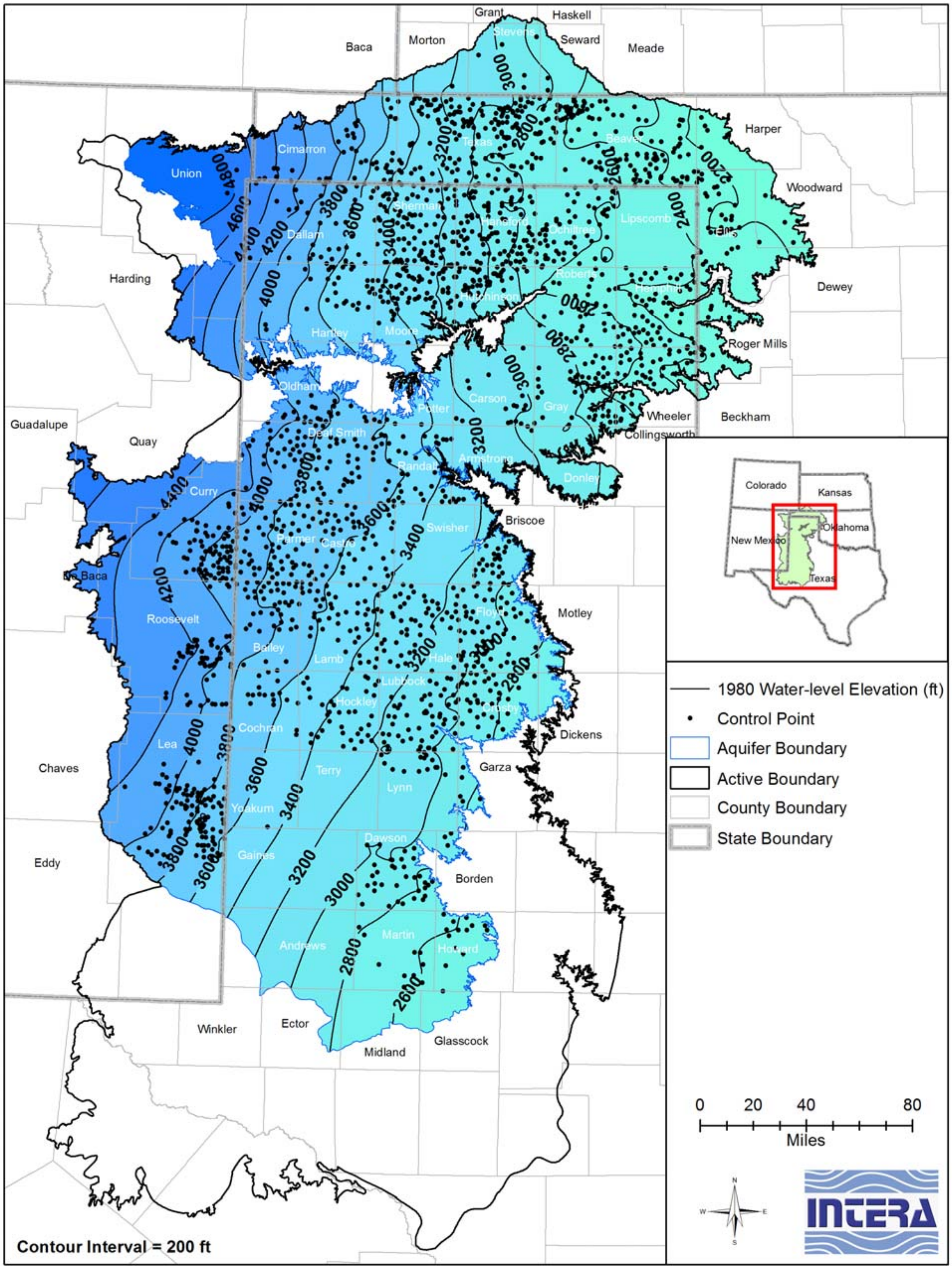


Figure 4.3.28 Estimated water-level elevation contours in feet for the Ogallala Aquifer in 1980.

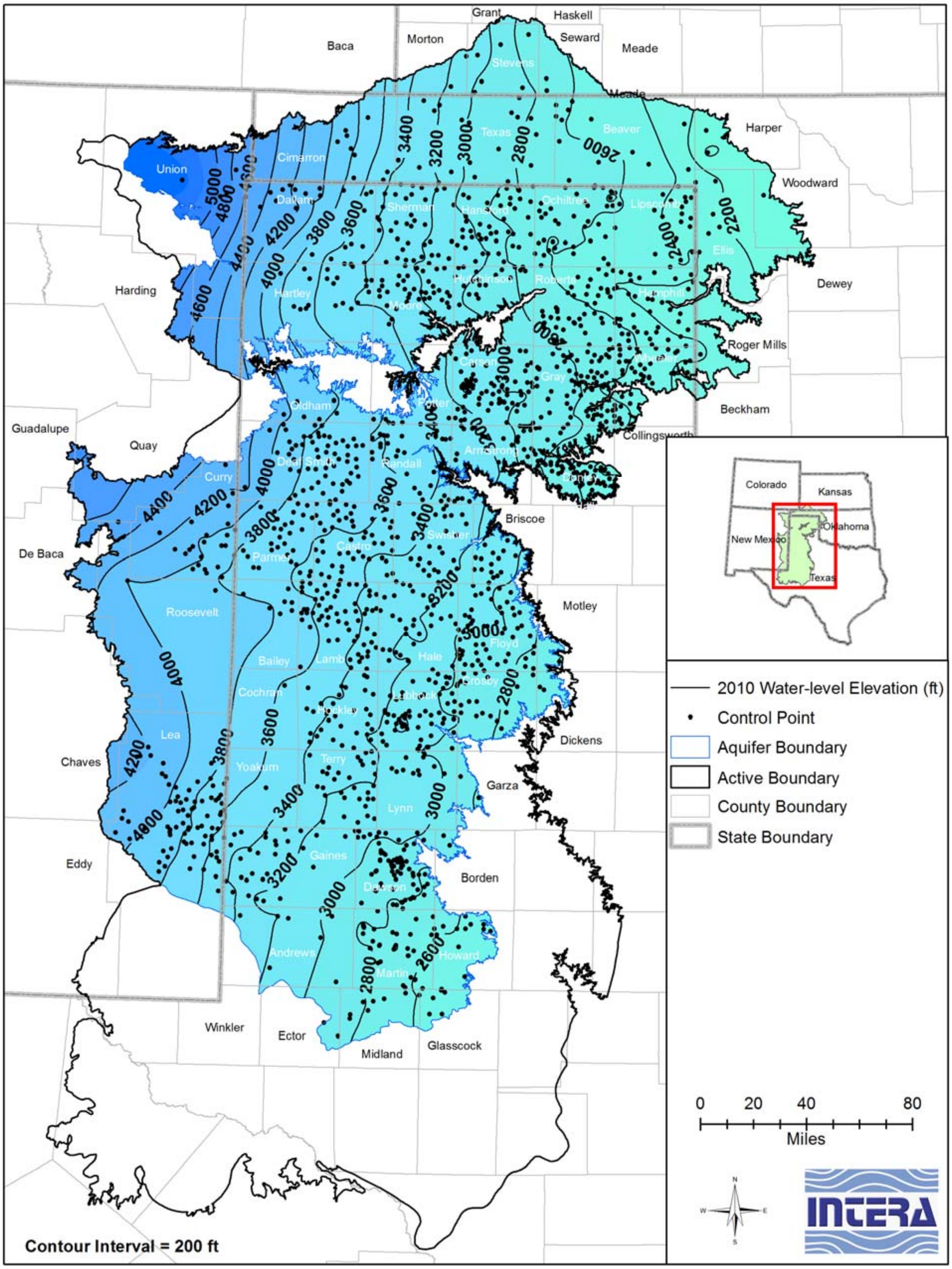


Figure 4.3.29 Estimated water-level elevation contours in feet for the Ogallala Aquifer in 2010.

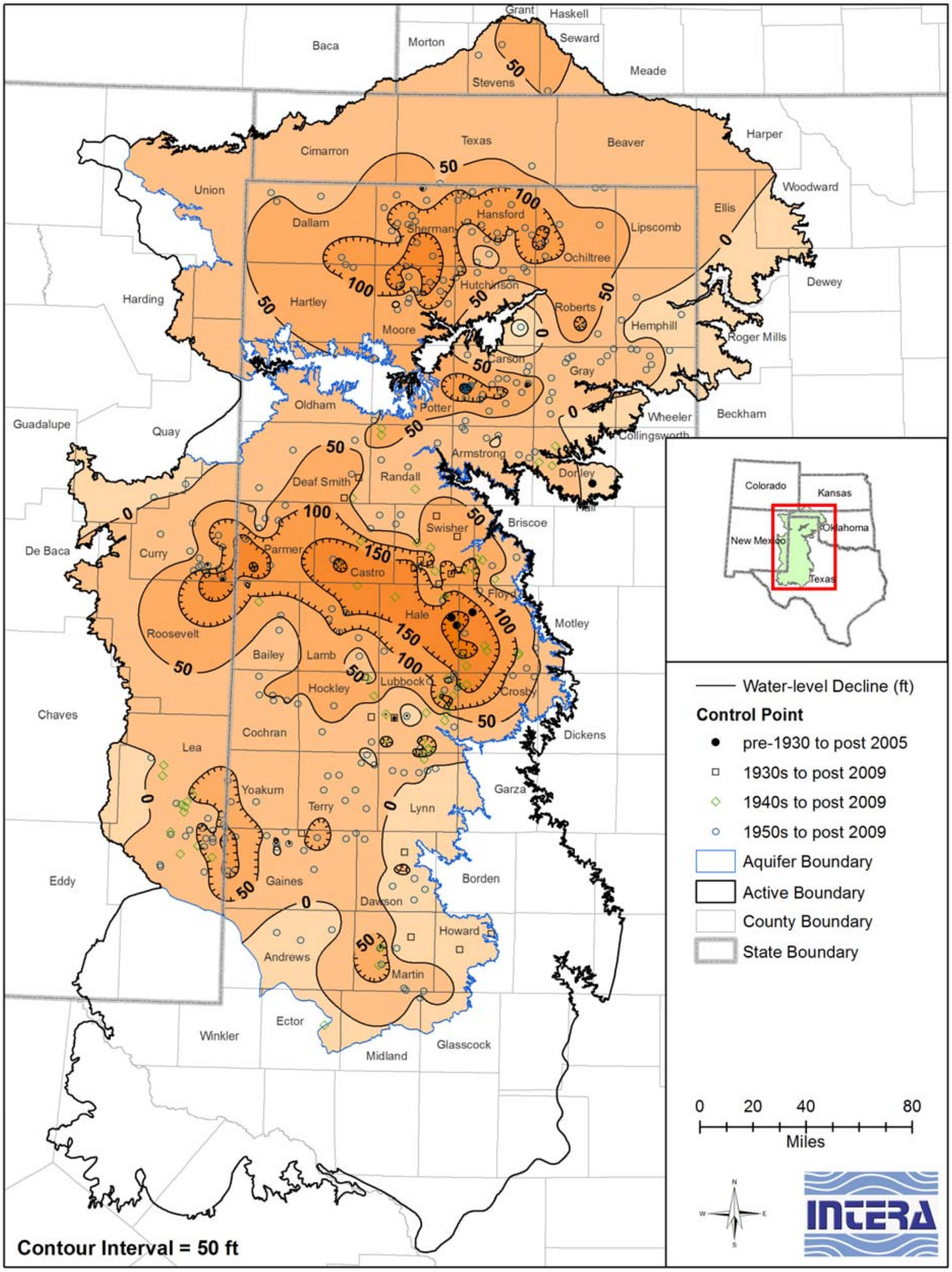


Figure 4.3.30 Estimated water-level decline in feet in the Ogallala Aquifer from pre-development to 2010.

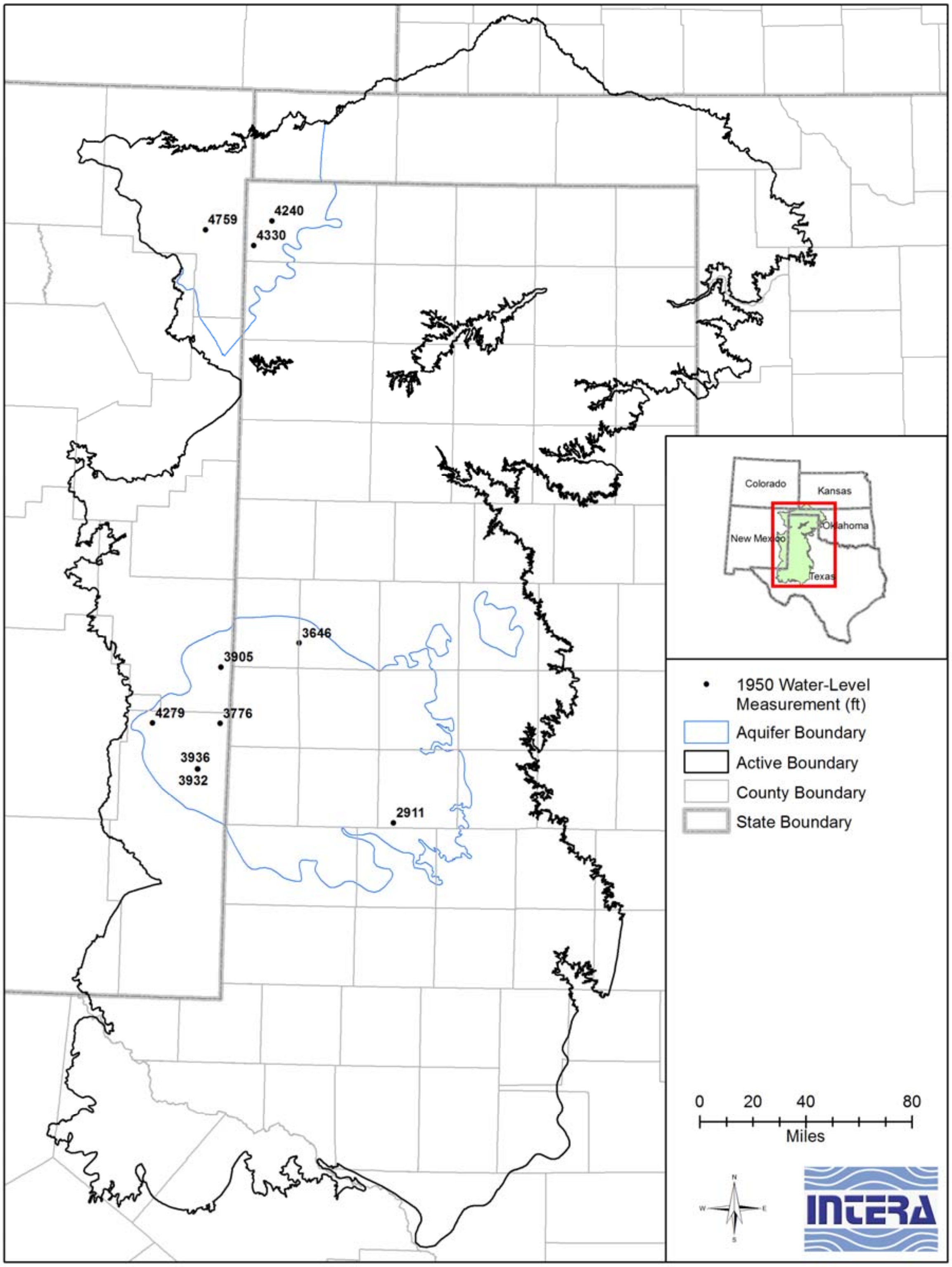


Figure 4.3.31 **Estimated water-level elevations in feet in the Rita Blanca and Edwards-Trinity (High Plains) aquifers in 1950.**

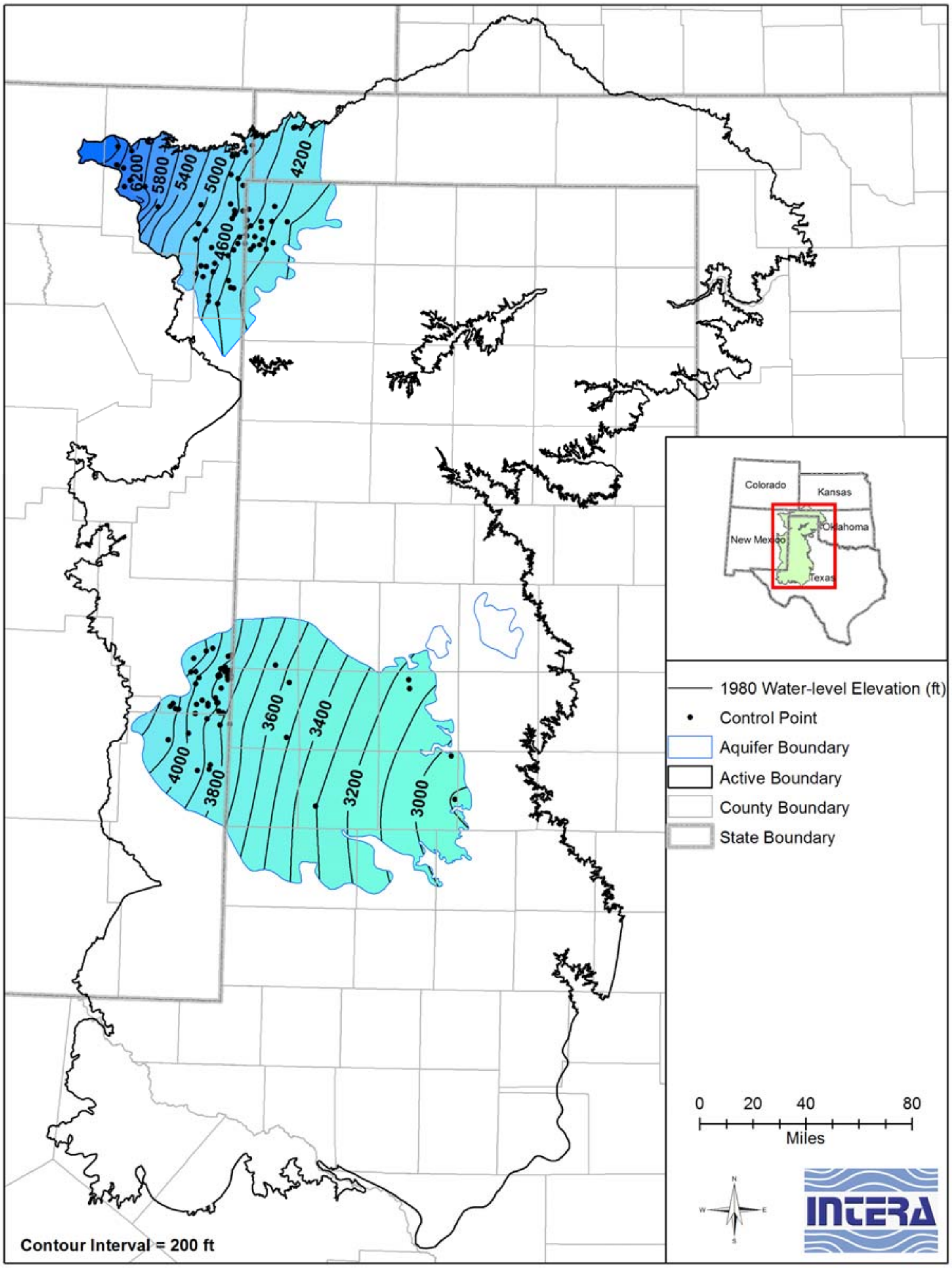


Figure 4.3.32 Estimated water-level elevation contours in feet for the Rita Blanca and Edwards-Trinity (High Plains) aquifers in 1980.

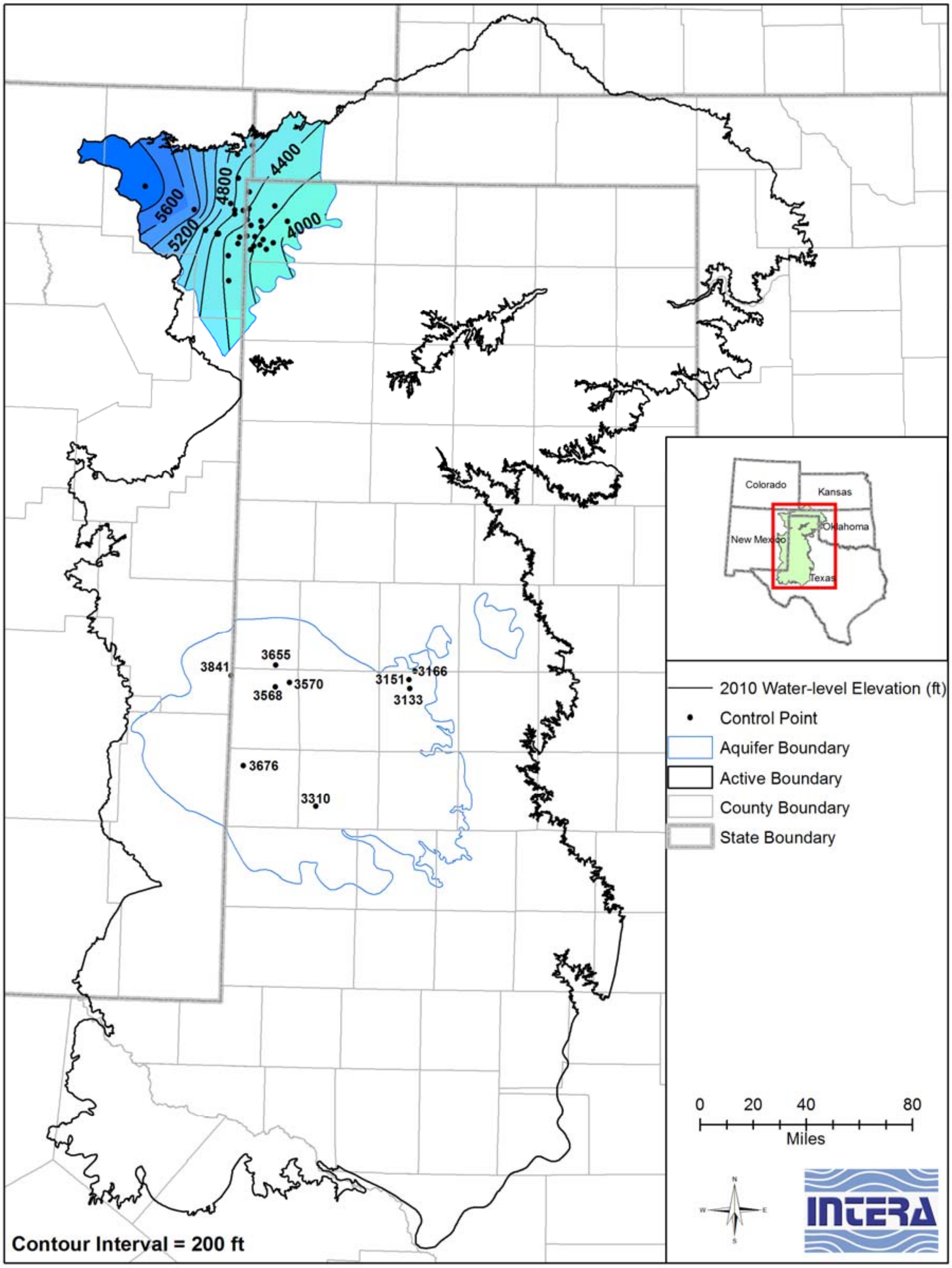


Figure 4.3.33 **Estimated water-level elevation contours in feet for the Rita Blanca Aquifer and estimated water-level elevations in feet for the Edwards-Trinity (High Plains) Aquifer in 2010.**

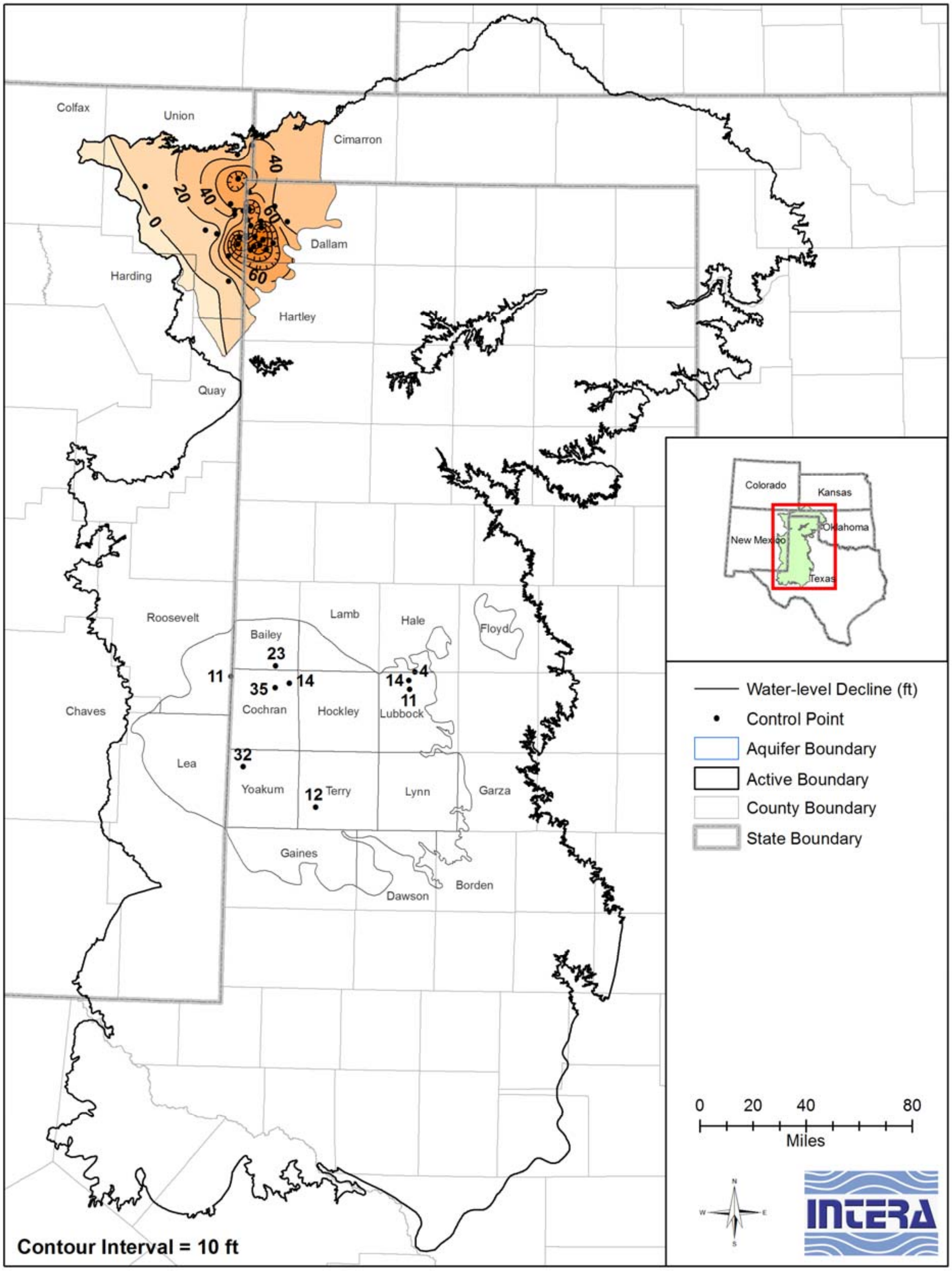


Figure 4.3.34 **Estimated water-level decline in feet in the Rita Blanca and Edwards-Trinity (High Plains) aquifers from pre-development to 2010.**

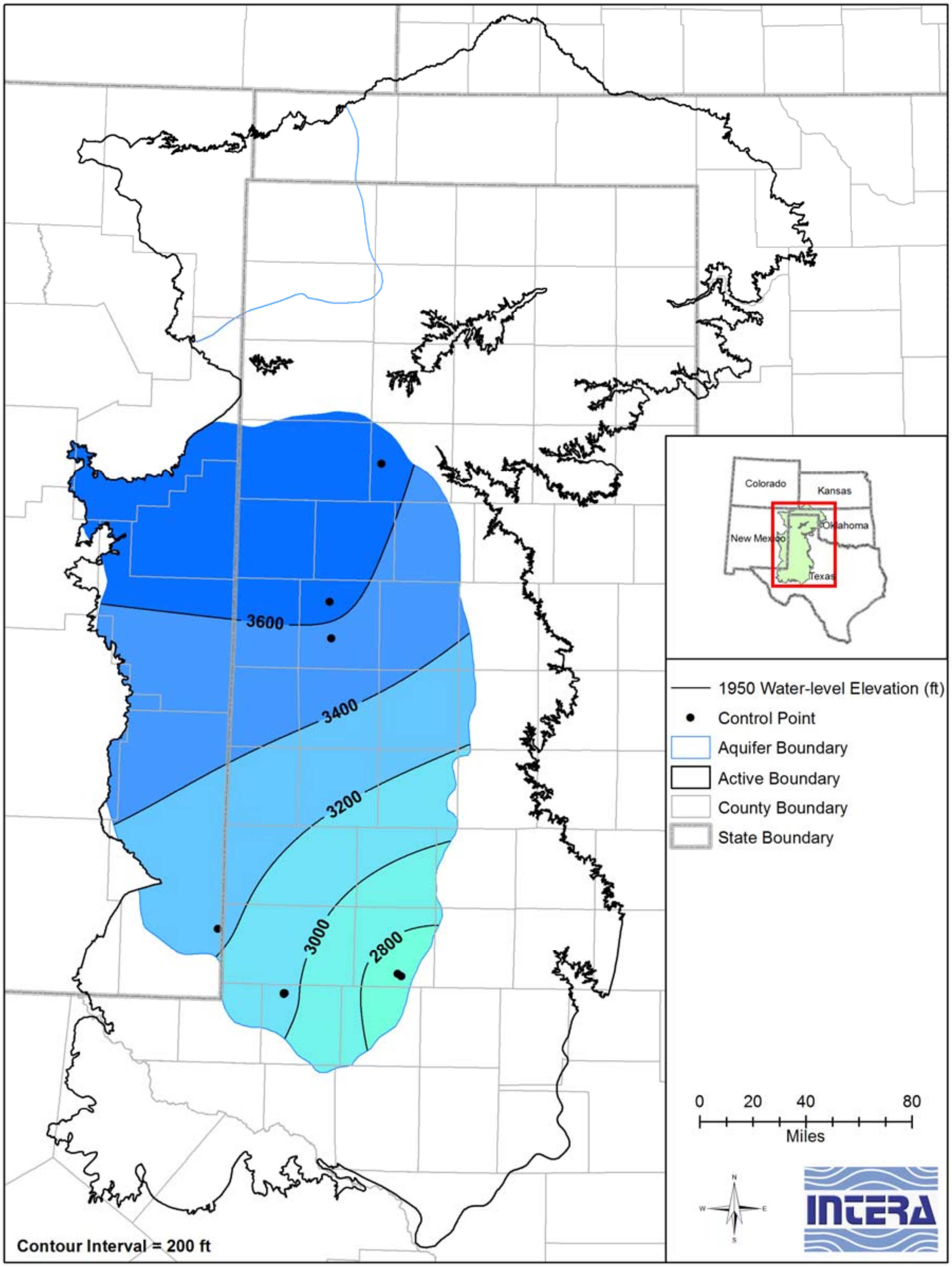


Figure 4.3.35 Estimated water-level elevation contours in feet for the upper Dockum Group in 1950.

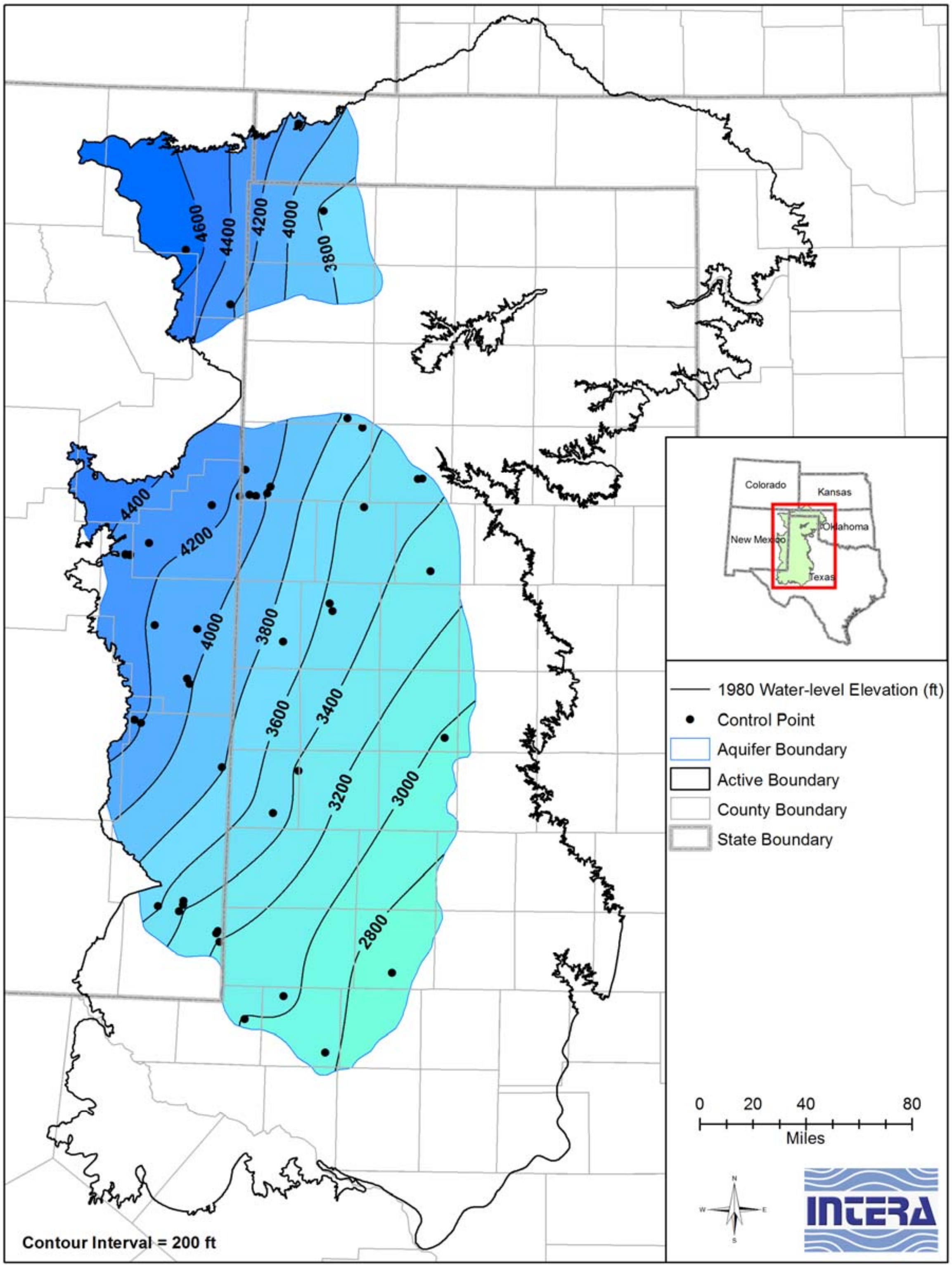


Figure 4.3.36 Estimated water-level elevation contours in feet for the upper Dockum Group in 1980.

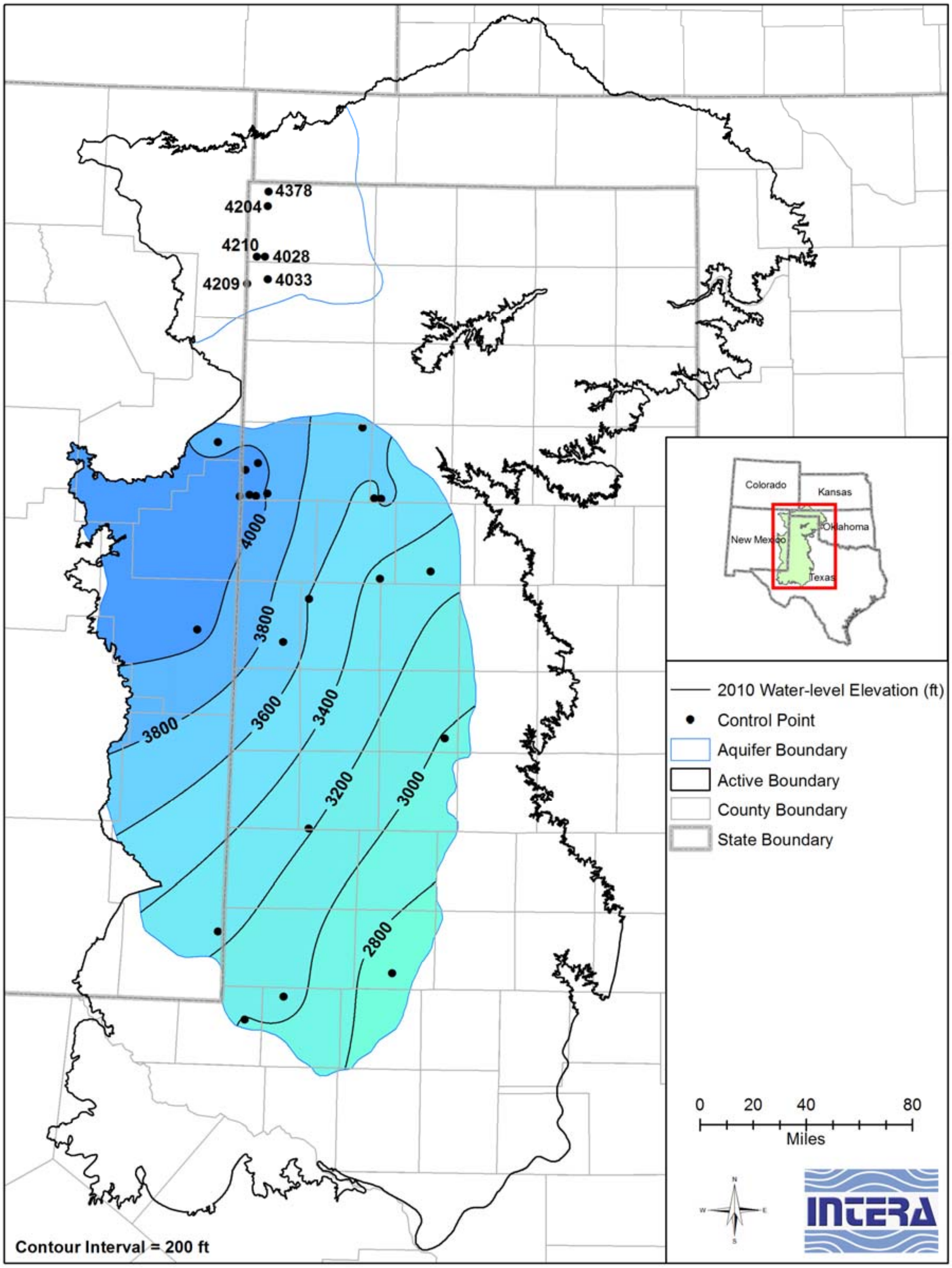


Figure 4.3.37 Estimated water-level elevation contours in feet for the upper Dockum Group in 2010.

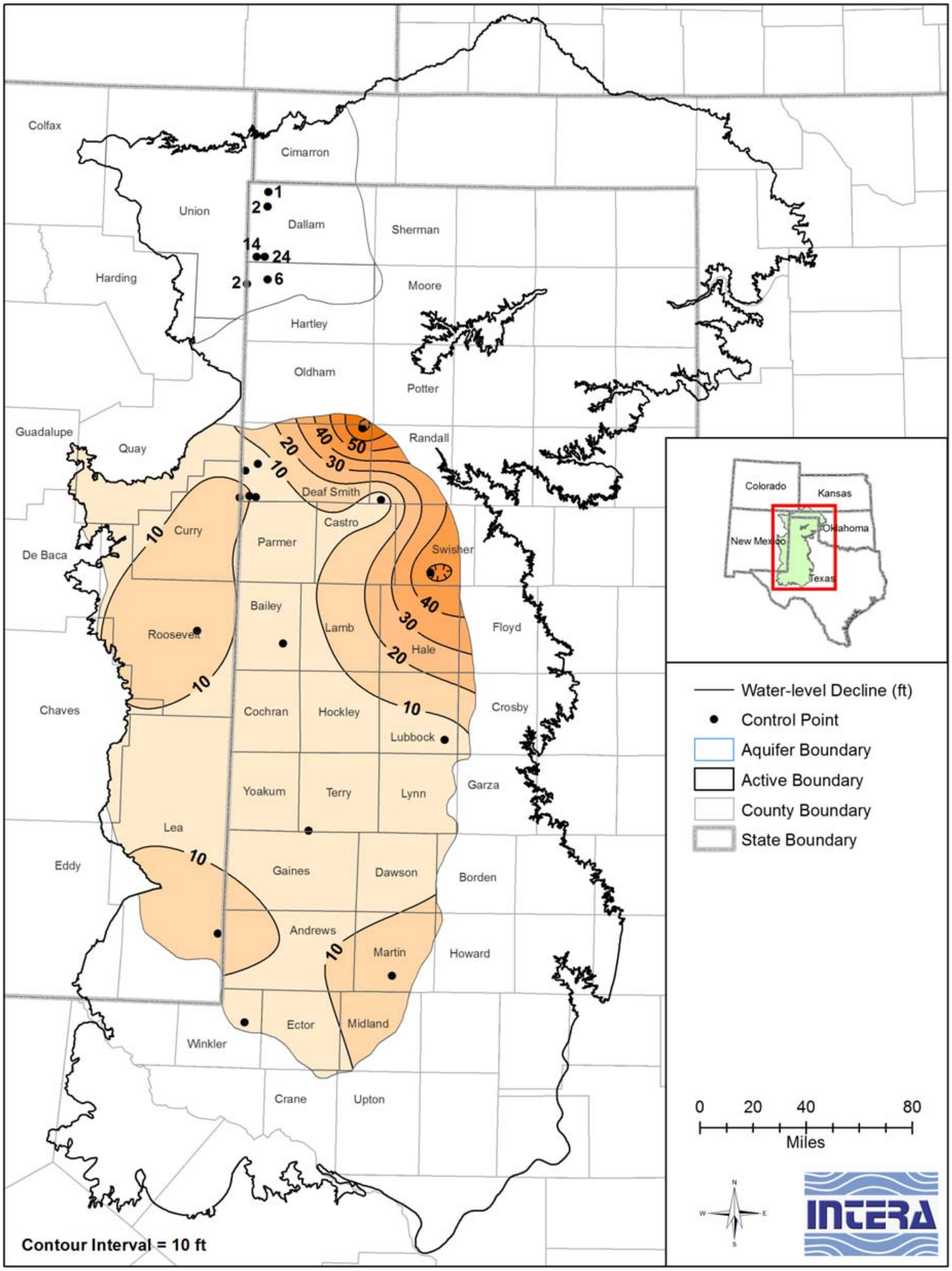


Figure 4.3.38 Estimated water-level decline in feet in the upper Dockum Group from pre-development to 2010.

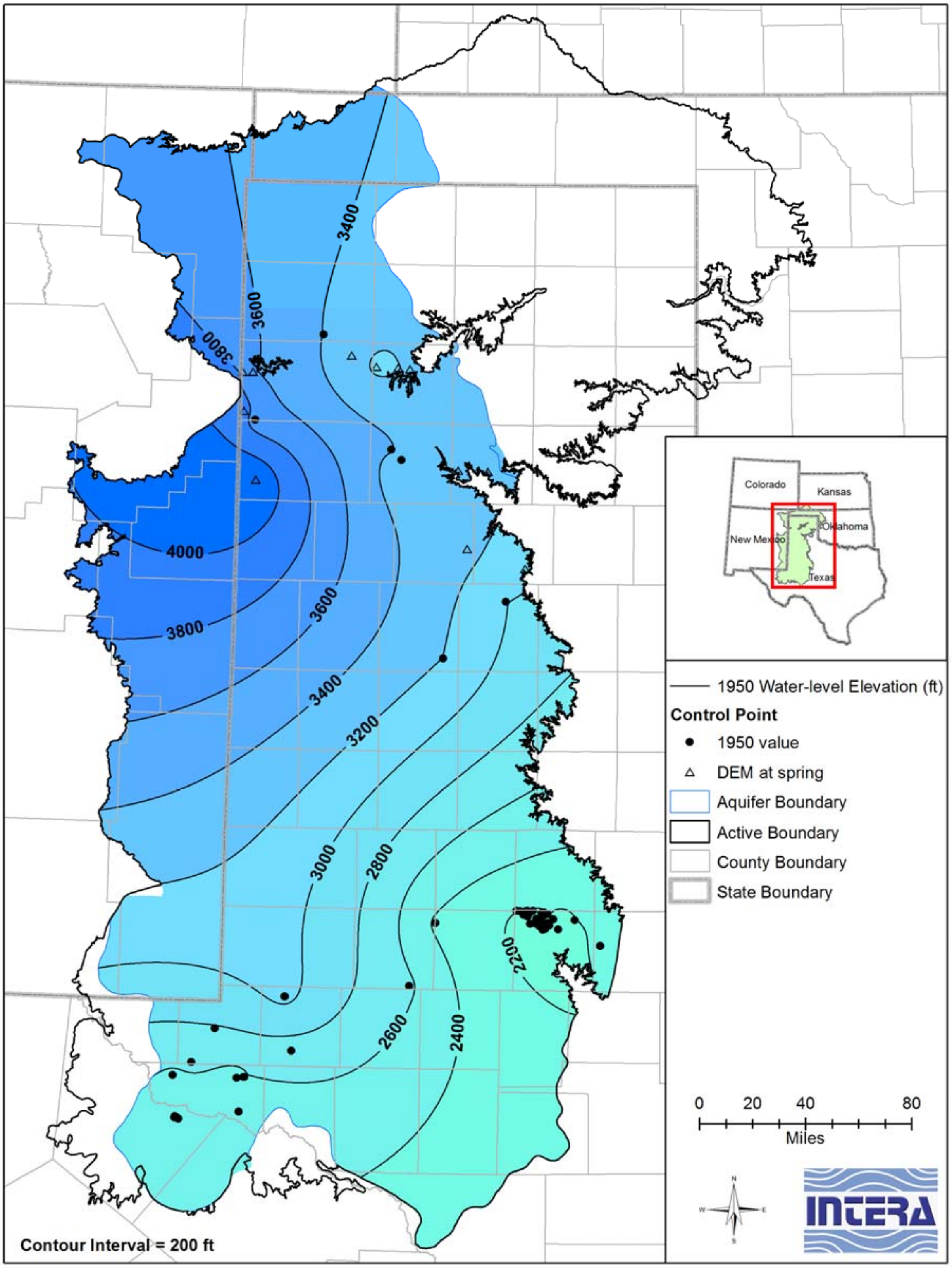


Figure 4.3.39 **Estimated water-level elevation contours in feet for the lower Dockum Group in 1950.**

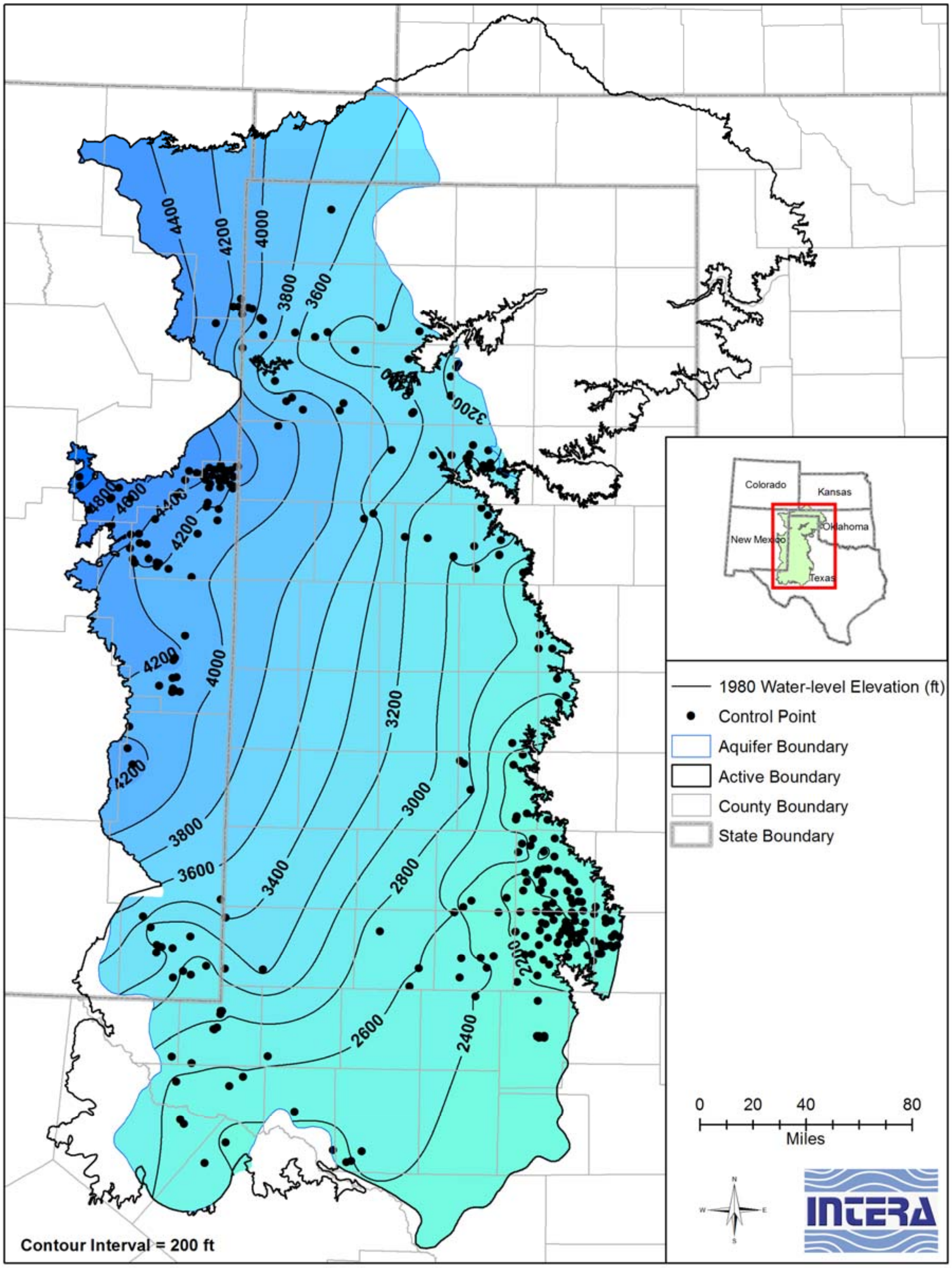


Figure 4.3.40 Estimated water-level elevation contours in feet for the lower Dockum Group in 1980.

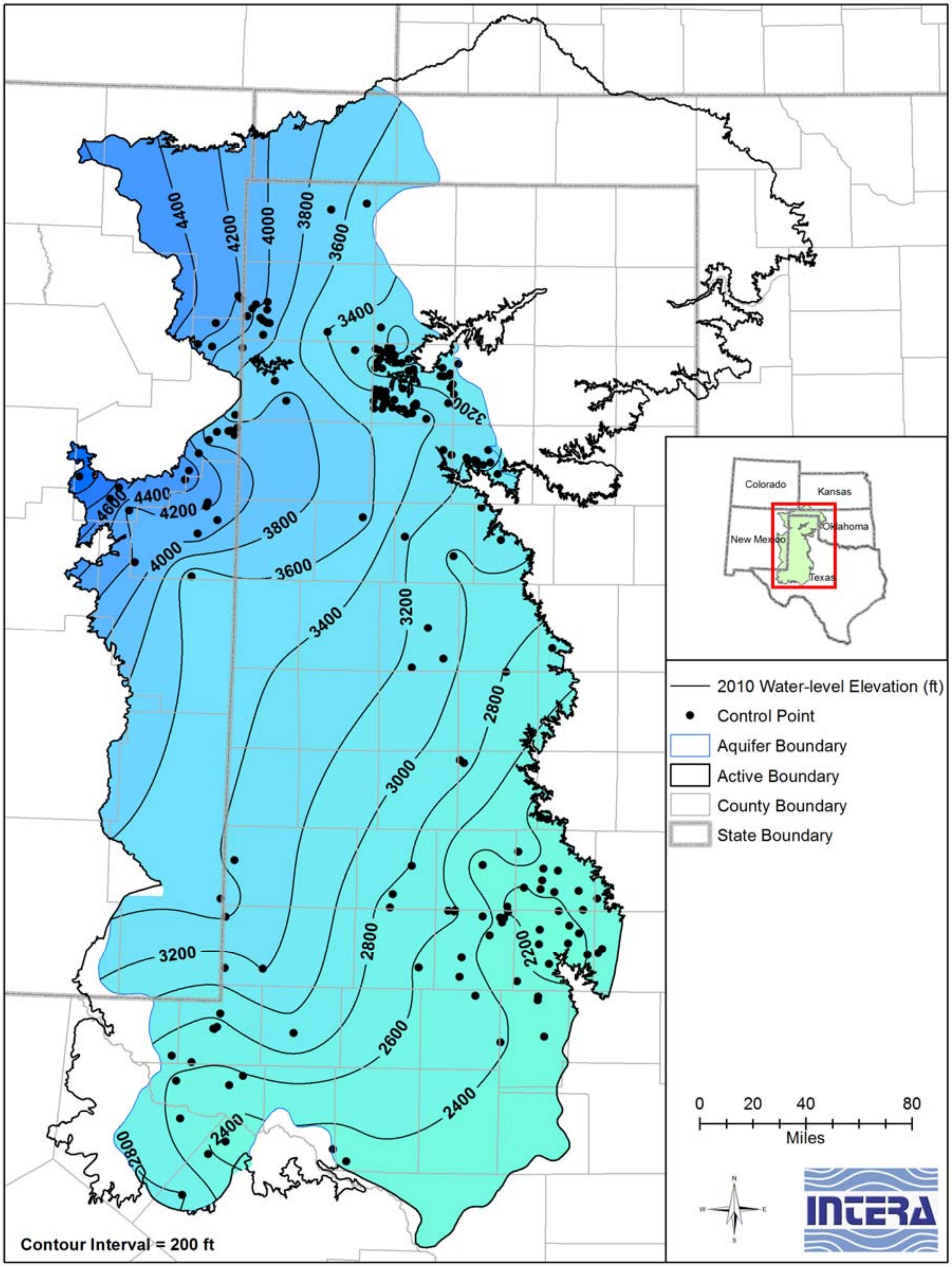


Figure 4.3.41 Estimated water-level elevation contours in feet for the lower Dockum Group in 2010.

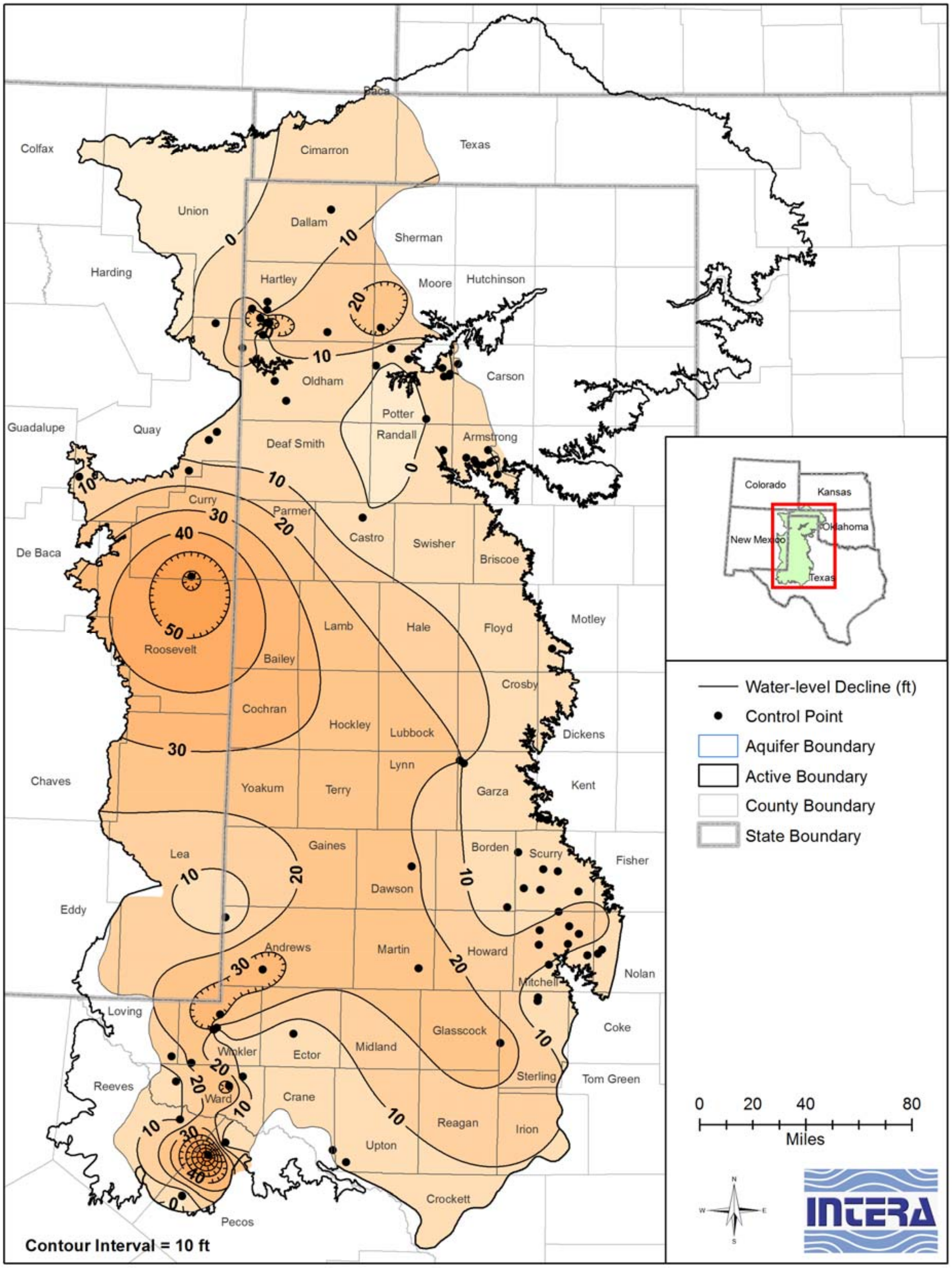


Figure 4.3.42 Estimated water-level decline in feet in the lower Dockum Group from pre-development to 2010.

4.4 Recharge

This section discusses the conceptual approach for estimating average recharge and for distributing recharge spatially and temporally in the High Plains Aquifer System.

4.4.1 Introduction

Recharge can be defined as water that enters the saturated zone at the water table (Freeze, 1969). Recharge is a complex function of the rate and volume of precipitation, soil type, water level, soil moisture, topography, and evapotranspiration (Freeze, 1969). In the High Plains Aquifer System, potential sources for recharge include precipitation, irrigation subsurface return flow, and leakage from playa lakes, streams and reservoirs. 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. Playa lakes, a distinct feature of the High Plains, are technically point sources of recharge. However, the playa density in many areas is sufficiently high to result in what is effectively an areally-distributed source of recharge (Mullican and others, 1997).

In the model area, recharge primarily occurs in the Ogallala Aquifer and Dockum Aquifer outcrops. Although not explicitly included in this analysis, the Rita Blanca Aquifer outcrop is assumed to have similar recharge behavior to the Ogallala Aquifer outcrop. The Edwards Trinity (High Plains) Aquifer has minimal outcrop exposure and so is not included in this analysis. Within the model area, there are some alluvial areas, including one near the southeastern section of the Dockum Aquifer near the Colorado River, that may have some infiltration.

The Ogallala Aquifer outcrop consists of a distinct northern and southern region, divided approximately at the Canadian River incision in the west (Figure 4.4.1). Since these two regions have different recharge characteristics, they are treated separately in this recharge analysis. For clarification, in this report, the area described as the "Southern Ogallala Aquifer" is consistent with the region described as the "Southern High Plains Aquifer" in United States Geological Survey reports (for example, Fahlquist, 2003) and the "Southern Ogallala Aquifer" in TWDB reports (Blandford and others, 2003; Blandford and others, 2008). The area described as the "Northern Ogallala Aquifer" in this report corresponds to the portion of the region described as the "Central High Plains Aquifer" in United States Geological Survey reports (for example, Bruce and others, 2003) that falls below the Cimarron River. It is also consistent with the extent of the "Northern Ogallala Aquifer" as described in TWDB reports (Dutton and others, 2001a). The Southern Ogallala Aquifer comprises a larger portion (approximately 29,600 square miles) of the current model area than the Northern Ogallala Aquifer (approximately 25,500 square miles).

The Dockum Aquifer outcrop is separated into three regions, although this is due to geography, not necessarily due to recharge differences. The largest section of the Dockum Aquifer outcrop (3,447 square miles) is located southeast of the Southern Ogallala Aquifer, near the headwaters of the Colorado River (Figure 4.4.1). Another outcrop area (1,338 square miles) falls between the Southern and Northern Ogallala aquifers along the Canadian River, and the smallest outcrop area (213 square miles) comprises a thin strip along the eastern escarpment of the Southern Ogallala Aquifer.

4.4.2 Previous Regional Recharge Studies

Many previous studies have estimated groundwater recharge in the Texas High Plains based on regional groundwater flow modeling and groundwater tracer data (Table 4.4.1). One of the earliest groundwater models of the Texas High Plains used recharge estimates of 0.06 – 0.83 inches per year based on unsaturated zone water content data in irrigated and nonirrigated areas of each county (Klemt, 1981; Knowles and others, 1984). Regional groundwater flow modeling by Luckey and others (1986) in the Southern Ogallala Aquifer used a mean pre-development recharge rate of 0.13 and 0.14 inches per year in the Northern Ogallala Aquifer. They assumed recharge under rainfed and irrigated land in the Southern Ogallala Aquifer increased by 2 inches per year during the development period of 1960 to 1980, which provided the equivalent of 0.6 inches per year additional recharge spread over the whole Southern Ogallala Aquifer area. Automated inverse modeling in the regional flow model by Stovall (2001) produced a mean recharge rate of 2.75 inches per year in the Southern Ogallala Aquifer.

Luckey and Becker (1999) simulated regional groundwater flow in the Northern Ogallala Aquifer. Pre-development recharge was determined according to soil type, ranging from 0.4 percent of precipitation in most of the region to 4 percent of precipitation in very sandy areas. Post-development recharge rates were adapted to account for the effects of cultivation. Recharge was assumed to be 3.9 percent of precipitation in areas under dryland cultivation due to the increased infiltration during land fallowing. In irrigated agricultural areas, they assumed that irrigation return flow was 24 percent of pumpage during the 1940s and 1950s and decreased to 2 percent by the 1990's due to increases in irrigation efficiency.

Dutton and others (2001a) varied recharge rates with precipitation and soil texture in the regional groundwater flow model of the Northern Ogallala Aquifer, with recharge rates varying from less than 1 to 6 percent of precipitation. These recharge rates were weighted according to soil texture by a factor of 1.2 in loamy surface and subsurface soils, a factor of 0.4 in loamy surface soils underlain by clayey subsurface soils, and a factor of 2.0 in windblown sands. As in Luckey and Becker (1999), Dutton and others (2001a) conceptualized that percolation from irrigation return flow was decreased from 24 percent of irrigation in the 1950s to 2 percent after the 1990s, reflecting increasing efficiency of irrigation technologies. However, they eventually concluded that the percolation from irrigation return flow has not reached the water table and, therefore recharge was not affected.

Blandford and others (2003) applied recharge rates of 0.007 to 0.085 inches per year for the pre-development period in the Southern Ogallala Aquifer. Higher recharge rates were applied in the northern region of the model, in areas of low permeability soils but high playa density. Recharge representative of the development period averaged 0.65 inches per year in the Southern Ogallala Aquifer overall but 1 inches per year in the northern portion.

Wood and Sanford (1995a) and Scanlon and others (2010b) used the chloride mass balance approach to estimate regional recharge rates in the central and northern sections of the Southern Ogallala Aquifer. Wood and Sanford (1995a) estimated that regional recharge in the northern part of the Southern Ogallala Aquifer was 0.43 inches per year. Scanlon and others (2010b) estimated regional recharge rates ranging from 0.16 to 0.91 inches per year in the western half of the Northern Ogallala Aquifer where groundwater is not affected by upward flow of deep brines. High recharge rates (0.55 to 1.61 inches per year) along the eastern escarpment are attributed to very sandy soils (clay content 5 to 12 percent). Scanlon and others (2010b) also estimated recharge rates using groundwater level hydrographs in the sandy zones in the southeastern section of the Northern Ogallala Aquifer where total groundwater level rise was 3.3 to 18.7 feet over time periods of 9 to 53 years (median 30 years). This resulted in an estimated recharge rate of 0.17 to 2.68 inches per year (median 0.55 inches per year) for this region.

4.4.3 Factors Affecting Recharge

4.4.3.1 Precipitation

All natural (that is., not irrigation return flow) recharge originates as precipitation. Even when other factors, such as soil texture, are used to determine recharge distribution, the amount of recharge is still often described as a percentage of total precipitation. Therefore, regardless of other controlling factors, recharge is expected to scale with precipitation. As shown in Figure 2.1.6, mean annual precipitation in the model area increases from southwest to northeast. Mean annual precipitation is slightly higher in the Northern Ogallala Aquifer outcrop (20.3 inches) relative to the Southern Ogallala Aquifer outcrop (18.3 inches). The southeastern Dockum Aquifer outcrops along the Colorado River and the eastern escarpment also have slightly higher mean annual precipitation (21.1 and 22.1 inches, respectively) compared to the northwestern outcrop along the Canadian River (18.4 inches). Therefore, potential recharge is slightly higher in the Northern Ogallala Aquifer outcrop and the eastern Dockum Aquifer outcrops.

4.4.3.2 Soils

Soil properties can have a significant influence on recharge because of their impact on runoff, infiltration, and even evapotranspiration. In general, sandy soils will typically accept more infiltration for a given precipitation event than will clayey soils. Clay soils will tend to retain water, allowing more time for evapotranspiration by vegetation.

Soils were evaluated based on data from the STATSGO database (United States Department of Agriculture, 1994), which includes data on soils to a depth up to about 6 to 7 feet below the surface. Soils in the model area are highly variable, ranging from clay loam to sand with clay content values ranging from near zero to 68 percent. Soils in the region can be categorized broadly into four categories based solely on soil texture including (1) clay loams, with clay contents greater than 35 percent, (2) loams, with clay contents ranging from 25 to 35 percent, (3) sandy loams, with clay contents ranging from 14 to 25 percent and (4) sands, with clay contents less than 14 percent (Figure 4.4.2).

Clay loams generally correspond to lower recharge rates, since the high clay content (greater than 35 percent) means they can swell and restrict the flow of water from the surface to the water table. Clay loams are located primarily in the central regions of the Northern Ogallala Aquifer and the northern part of the Southern Ogallala Aquifer. They appear as Sherm series soils north of the Canadian River and as Pullman series soils south of the Canadian River. Clay loam occupies approximately 20 percent of both the Northern and Southern Ogallala Aquifer regions. Clay loam is also present in the Dockum Aquifer Colorado River outcrop area as Vernon, Stamford, Sagerton, and Rowena series soils, representing approximately50 percent of that outcrop area (Figure 4.4.2)

Loams are less restrictive for recharge than clay loams, but the greatest recharge is expected under sandy soils. As well as having a higher clay content, loams are generally finer-grained, allowing for water retention, whereas sands are coarser-grained, leading to less water retention and more direct flow from the surface to the water table. Loams make up 51 percent of the Northern Ogallala Aquifer area, primarily falling west of the Sherm clay loam. Sands are more prevalent along the Canadian River and the eastern margin, representing approximately15 percent of the Northern Ogallala Aquifer area. South of the restrictive Pullman clay loam, soils in the Southern Ogallala Aquifer transition from finer grained loamy soils (25 to 28 percent clay) in the northern and eastern regions to sandier loamy soils (11 to 24 percent clay) in the south and west. Loams make up 75 percent of the Southern Ogallala Aquifer and consist mostly of Amarillo, Patricia, Olton, and Portales series soils. Sandy soils represent only ~3 percent of the Southern Ogallala Aquifer area and consist mostly of Wickett, Triomas, Penwell, Stegal, and Jalmar series soils.

The Dockum Aquifer outcrop area in the Colorado River region has small regions of loam consisting of Miles, Cobb, and Mansker series soils (24 to 25 percent clay) and only isolated areas of sandy soils consisting mainly of Springer and Tivoli series soils (11 to 16 percent clay). The Dockum Aquifer outcrop area in the Canadian River region is dominated by loam consisting of Quay, Montoya, and Glenrio series soils (average approximately 33 percent clay). Some sandy soil occurs adjacent to the Canadian River, consisting of Yahola and Lincoln series soils (average 12 percent clay).

4.4.3.3 Topography

Topography affects the distribution of recharge, concentrating recharge in highlands and discharge in lowlands (Meyboom, 1966; Toth, 1963). Modeling studies in Freeze (1971) concluded that when the saturated zone is under higher gradients, for instance in a topographically elevated area, the unsaturated zone delivers greater flow rate, thus, increasing recharge. However, while the effects of topography are important in our study area, they cannot be separated from the effects of soil texture described in the previous section. A previous study of the Northern Ogallala Aquifer in Texas showed that recharge was regionally related to not just topography or soil texture individually but a combination of the two properties (Scanlon and others, 2010b). As long as an area has a low slope (less than 5 percent), soil texture has the greatest effect on recharge. However, regions that have a slope greater than 5 percent exhibit similar recharge behavior regardless of soil texture. Therefore, in addition to the four soil categories listed earlier, a fifth category is necessary to differentiate high slope areas of any soil texture.

For this analysis, mean slopes were derived from a 30-meter digital elevation model (United States Geological Survey, 2012) of the region (Figure 4.4.3). These data were used to calculate the average slope value for each STATSGO soil map unit. If the average slope is greater than 5 percent, that soil map unit is designated as "high slope" in Figure 4.4.2. Topography in the Ogallala Aquifer region is variable but mostly flat (slope less than 5 percent) in the Southern Ogallala Aquifer and in much of the Northern Ogallala Aquifer (Figure 4.4.3). This results in a largely internal drainage system for the region, in which runoff generally concentrates in playa lakes. The effects of these playa lakes on recharge are discussed in Section 4.4.3.5. Steeper topography is limited to the margins of the eastern escarpment and along a few incised river valleys located in the northern part of the study area, including the Canadian River, the drainage network of small tributaries to the Beaver River, and Wolf Creek. Thus, areas with higher median slope (greater than 5 percent) are primarily located in the Northern Ogallala Aquifer region in areas with marginal to clay loam and in areas near the Canadian River. These sections have a mean slope of 6.5 percent and represent approximately 14 percent of the Northern Ogallala Aquifer area. The average clay content is approximately 22 percent and generally consists of soils with a sandy loam soil texture.

Topography in the Dockum Aquifer outcrop areas is generally steeper and more variable than in the Ogallala Aquifer areas, ranging from an average slope of 3.1 percent in the Colorado River area to 4.4 percent in the Canadian River area to 18 percent in the narrow eastern escarpment area. Areas with steeper slopes tend to have enhanced runoff and are, thus, less likely to be areas where significant recharge occurs. In these regions, recharge is generally restricted to areas where runoff is focused, such as in stream beds, or areas with very coarse textured soils, such as sand dunes.

4.4.3.4 Land Use/Vegetation Type

When infiltrating water evaporates from the shallow subsurface or is transpired by plants, it is no longer available to reach the water table and become recharge. Therefore, land use and vegetation type, which generally control the amount of evapotranspiration occurring, can have a significant impact on recharge. For instance, if rangeland is developed and given an impervious surface, infiltration and, thus, recharge are severely reduced. If a field of deep-rooted grass is replaced with shallow-rooted crops, it becomes easier for precipitation to infiltrate below the shallower rooting zone, resulting in greater recharge. The natural vegetation prior to agricultural development primarily consisted of short-grass prairie grazed by bison (Fahlquist, 2003). Agricultural development began in the late 1800s and early 1900s. In counties where the majority of land falls within either the Ogallala Aquifer or Dockum Aquifer outcrops, farm acreage peaked in the 1950s (United States Department of Agriculture, 1935, 1954, 1974, 2007). However, after a small decline, the amount of agricultural land has remained relatively stable to the present day (Figure 4.4.4). Current land use in the Ogallala Aquifer region of the model area is dominated by rangeland (62 percent of the area) and cropland (32 percent of area) (Fry and others, 2011) (Figure 4.4.5, Table 4.4.2). The outcrop areas of the Dockum Aquifer consist mostly of rangeland (90 percent) and crops (7 percent) in the Colorado River region and almost exclusively rangeland (99 percent) in the Canadian River and eastern escarpment outcrop areas.

4.4.3.4.1 Rangeland

Rangeland, which includes grassland and shrubland, covers 62 percent of the Ogallala Aquifer in the model area. Scanlon and others (2010a,b) estimated recharge rates in the Ogallala Aquifer based on nitrate and chloride profiles in boreholes drilled into the unsaturated zone (Figure 4.4.5). In the Northern Ogallala Aquifer, the average recharge rate in rangeland vegetation was negligible (0.058 inches per year). In the Southern Ogallala Aquifer, none of the boreholes showed evidence of any recharge.

The general lack of recharge in rangeland areas is attributed to perennial growth and deep roots of primarily native grasses and shrubs that opportunistically remove all infiltrated water.

However, this process apparently does not completely intercept all infiltrating water in areas of extremely coarse grained soils in the Northern Ogallala Aquifer (Scanlon and others, 2010b).

In the Dockum Aquifer outcrop areas, rangeland vegetation dominates all three regions, comprising 99 percent of both the Canadian River and eastern escarpment regions and 90 percent of the Colorado River region. Shrubland is the dominant land cover in all three regions (53 to 62 percent), followed by grassland (16 to 40 percent). Forest comprises 21 percent of the eastern escarpment region and crops cover 7 percent of the Colorado River outcrop region.

4.4.3.4.2 Cropland

Total cultivated agriculture covers 17,835 square miles (32 percent) of the land area in the entire Ogallala Aquifer (Fry, and others, 2011). Of that, the Southern Ogallala Aquifer has approximately twice as much cultivated area (11,823 square miles) relative to the Northern Ogallala Aquifer (6,011 square miles) because soil types and surface slopes more conducive to farming are more widespread in the south. Dominant crops include wheat (63 percent of cropland), corn (27 percent), and sorghum (10 percent), according to the Agricultural Census for 2007 from the National Agricultural Statistics Service (United States Department of Agriculture, 2007).

Land under rainfed agriculture has very different recharge characteristics from land under irrigated agriculture. However, since the Fry and others (2011) land use/land cover map shown in Figure 4.4.5 does not distinguish between irrigated and rainfed agriculture, these distinctions had to be determined by other methods. Two studies produced estimates of the percentage of irrigated land surface in the model area based on analysis of satellite imagery. Ozdogan and Gutman (2008) estimated that irrigated land made up 8 percent of the total Ogallala Aquifer model area in 2001, while Qi and others (2002) estimated it made up 12 percent in 1992. Assuming the rest of the cultivated area is under rainfed agriculture, approximately 62 to 75 percent (approximately two thirds) of the total cultivated area in the Ogallala Aquifer is rainfed agriculture. These estimates agree well with recent Census of Agriculture data (United States Department of Agriculture, 1997, 2007) which place irrigated acreage at about 8 percent of the total area of counties in the Northern Ogallala Aquifer and 14 percent in the Southern Ogallala Aquifer. The irrigated acreage in the Southern Ogallala Aquifer has remained relatively constant since the 1950s, except for a peak in the 1970s when irrigated acreage was 20 percent of total area. The irrigated acreage in the Northern Ogallala Aquifer has been constant since the 1970s. Prior to that, however, the reported irrigated acreage was much lower: less than 1 percent of total area in the 1950s. The irrigated acreage in the Dockum Aquifer has been consistently low since the 1950s, hovering at approximately 1 percent of the total area of the counties in both the Canadian and Colorado River outcrops (United States Department of Agriculture, 1954, 1974, 1997, 2007).

4.4.3.4.2.1 Rainfed Agriculture

Rainfed agriculture is more widespread in the Southern Ogallala Aquifer, constituting 67 to 77 percent of the total cultivated area. In the Northern Ogallala Aquifer, it constitutes 58 percent to 75 percent of the total cultivated area. Recharge from land under rainfed cultivation depends heavily on the amount of precipitation and the crop being cultivated. As the amount of water a particular crop can consume is fixed, the total amount of precipitation determines whether there is any excess water to recharge the aquifer. Scanlon and others (2010b) found that most of the rainfed agriculture land in the Northern Ogallala Aquifer showed little or no recharge with the exception of an area of medium to coarse soil north of the Canadian River. The average recharge rate in the Northern Ogallala Aquifer was 0.42 inches per year with a maximum of 1.41 inches per year located in the coarser sand.

In the Southern Ogallala Aquifer, the average recharge rate for rainfed agriculture was 0.94 inches per year. However, the region of Pullman clay loam in Potter County showed no evidence of current recharge at all (Scanlon and others, 2010b).

Although unsaturated zone profiles have not been drilled in the Dockum Aquifer outcrop zones, rising water levels over past decades in the Colorado River outcrop of the Dockum Aquifer is assumed to be related to increased recharge under cultivated agricultural land (Ewing and others, 2008). Therefore, it is reasonable to assume that the impact of rainfed agriculture on Dockum Aquifer recharge is similar that in the Ogallala Aquifer.

4.4.3.4.2.2 Irrigated Agriculture

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 good agricultural management practices for most crops include balancing irrigation application with plant evapotranspiration requirements (for example, Allen and others, 1998), so that the amount of water that moves beyond the root zone to the water table below is minimized. Thus, a large amount of irrigation would be required to yield significant potential return flow.

Irrigated cultivation makes up about 12 percent (Qi and others, 2002) to about 9 percent (Ozdogan and Gutman, 2008) of the total cultivated area of the Ogallala Aquifer. Irrigation is currently predominantly applied by center pivot systems. Irrigated boreholes have an average percolation rate of 1.6 inches per year in the Northern Ogallala Aquifer (Scanlon and others, 2010b). However, the presence of chloride bulges in these profiles indicates that the increased percolation from irrigation has not recharged the aquifer. The average percolation rate for irrigated boreholes was 1.9 inches per year in the Southern Ogallala Aquifer (Scanlon and others, 2010a). Enhanced percolation due to cultivation is evident in the southern portion of the Southern Ogallala Aquifer, below the 500 milligrams per liter contour for total dissolved solids, and increased nitrate levels are suggestive of an impact from irrigation return flow.

There is limited irrigation in the outcrop zones of the Dockum Aquifer and as mentioned before, unsaturated borehole profiles were not drilled in this region. The recharge response to irrigation in the Dockum Aquifer outcrop is, therefore, assumed to be similar to that in nearby Ogallala Aquifer regions.

4.4.3.4.3 Urban Areas

Approximately 4 percent of the Ogallala Aquifer area is developed land. The main urban centers in the region include Amarillo (population 190,695), Lubbock (population 229,573), and Midland-Odessa (population 211,087) (United States Census Bureau, 2010). Generally, urban areas are assumed to produce little recharge due to the abundance of paved and other impervious surfaces that prevent infiltration. However, in the Ogallala Aquifer, urban areas can actually indirectly lead to higher recharge. For instance, runoff from paved and other impervious areas of the City of Lubbock is directed to several local playas, which has resulted locally in enhanced recharge and increased groundwater levels (Kier and others, 1984; West, 1998). The effect of playas on recharge is discussed in the following section.

4.4.3.5 Focused Recharge from Surface Water Features

Surface water in the Texas High Plains is dominated by playas, or ephemeral lakes. There are 30,625 playas greater than 1 acre in size that have been mapped within the model boundary area (Figure 4.4.6). Of these, 29,674 (97 percent) are located within the Ogallala Aquifer model boundary area and range from 1 to 580 acres (median 7.3 acres, mean 13.3 acres). Playa floors cover a total area of 396,000 acres in the Ogallala Aquifer model area, representing approximately 1 percent of the surface area. In many areas of the Southern Ogallala Aquifer, playas are arranged along sub-parallel, *en echelon* lineaments generally trending northwest-southeast.

Playas were considered evaporation ponds until the 1960s. However, unsaturated zone studies conducted beneath individual playas in the 1990s showed that playas are actually important sources of recharge to the aquifer (Wood and Sandford, 1995a; Scanlon and Goldsmith, 1997). Tracking bomb pulse tritium under selected playas suggested recharge rates ranging from 3 to 4.7 inches per year (Scanlon and Goldsmith, 1997; Wood and others, 1997). Playa recharge becomes additionally important because the playas of the High Plains are largely located in areas that have otherwise very low recharge rates, such as restrictive clay loams or loams with > 25 percent clay content (see Figure 4.4.6).

Mullican and others (1997) showed that the localized recharge under individual playas results in increased regional recharge at the water table. Using the chloride mass balance rate approach, they estimated that playas contributed 0.4 inches per year to the regional groundwater recharge in the northern portion of the Southern Ogallala Aquifer. Model simulations by Mullican and others (1997) showed that implementing playas as point sources of recharge versus an areally-distributed source of recharge had little effect on the final recharge rate at the water table. Therefore, for the purposes of this study, playa recharge is considered to be a diffuse source of recharge, dependent on playa density.

Playa density, calculated as the percentage of playa area (based on the playa coverage shown in Figure 4.4.6) within a 1-mile radius, is zero for about 60 percent of the Ogallala Aquifer surface area (Figure 4.4.7). In areas where playas are found, playa density ranges up to a maximum of 47 percent, though 90 percent of these areas have values ranging from 0.1 to 6 percent. The highest playa densities fall in areas of restrictive Pullman clay loam northeast of Amarillo and along the eastern escarpment north of Lubbock in the Southern Ogallala Aquifer. The Northern Ogallala Aquifer has high playa density in the eastern lobes of restrictive Pullman and Sherm clay loam soils. Playas do occur in limited areas of the eastern Colorado River outcrop of the Dockum Aquifer but are not as widespread as in the Ogallala Aquifer (see Figure 4.4.7).

4.4.3.6 Depth to Water

The depth of the water table can significantly influence recharge because infiltrating water can more readily reach a shallow water table than a deeper one. If pumping draws down the water table, this can increase the travel time from the surface to the water table, decreasing the amount of recharge. Estimated pre-development water table depths are shown in Figure 4.4.8. Depth to water was calculated by subtracting the pre-development water level elevation (see Figure 4.3.12) from the 10- meter digital elevation model (see Figure 2.1.3). In the Ogallala Aquifer, the shallowest water tables occur in the few drainage networks and along the eastern and southern margins of the Northern Ogallala Aquifer. These generally correspond to areas of coarser-grained soil, which also makes them conducive to recharge.

4.4.4 Estimating Recharge

4.4.4.1 Natural Discharge

In regions where the streams are gaining, the base flow component of stream flow (that is, stream flow that originates from groundwater) can provide a lower-bound estimate for recharge. However, as discussed in Section 4.5, the majority of streams in the study area are not gaining. Those that are gaining are generally highly regulated, resulting in estimates of base flow that do not reflect the natural recharge conditions of that area. Springflow can also provide an estimate of recharge when it is thought to be sourced from shallow formations. This is likely the case for many of the western springs in the Southern Ogallala Aquifer described in Section 4.5. However, many of these springs have since stopped flowing and few have measurements of springflow. There is not sufficient data to estimate recharge based on natural discharge values for the model area.

4.4.4.2 Chloride Mass Balance

A mass balance method based on chloride (also called chloride mass balance can be used to estimate the unsaturated zone percolation or recharge rate (Allison and Hughes, 1983). According to the chloride mass balance method, chloride input from precipitation (*P*) and irrigation (*I*) balances chloride output in percolation (Pe_{CMB}) or recharge (R_{CMB}):

$$Pe_{CMB} = R_{CMB} = \frac{(P \times Cl_P) + (I \times Cl_I)}{Cl_{UZ}} \tag{4.4.1}$$

where Cl_P, Cl_I, and Cl_{UZ} are the chloride concentrations of precipitation, irrigation water, and unsaturated zone pore water, respectively. Similarly, the CMB method can be used to estimate the groundwater recharge rate (R_{GW}) for the saturated zone:

$$R_{GW} = \frac{P \times Cl_P}{Cl_{GW}} \tag{4.4.2}$$

where Cl_{GW} is the chloride concentration in groundwater. The distribution of chloride concentrations in precipitation were estimated spatially based on sample information from the National Atmospheric Deposition Program (2013) for a national network of monitoring stations. Monitoring at different stations began in the late 1970s to the early 1980s. The National Atmospheric Deposition Program concentrations were doubled to account for dry fallout, which is consistent with total chloride fallout according to pre-bomb ^{36}Cl/Cl ratios in Amarillo, Texas (Scanlon and Goldsmith, 1997).

Recharge rates derived from chloride mass balance in clay-rich areas of the Southern Ogallala Aquifer are generally about 0.3 inches per year. In clay-rich areas of the Northern Ogallala Aquifer, chloride mass balance recharge rates range from about 0.4 inches per year south of the Canadian River to about 0.5 inches per year north of the Canadian River (Scanlon and others, 2010b). In less clay-rich regions of the Northern Ogallala Aquifer, recharge is about 0.3 inches per year in the northwest and 0.3 to 0.4 inches per year in loamy regions to the east. Recharge can be up to 0.65 inches per year in sandy areas located in the Canadian River area and along the smaller drainage networks in the eastern and northern parts of the region.

High natural groundwater chloride concentrations are present in the Southern Ogallala Aquifer due to mixing with more saline water from underlying formations. As a result, the chloride mass balance method cannot be used on groundwater chloride concentrations, as it does not provide valid estimates of groundwater recharge in this region. However, it can be applied to unsaturated zone profiles, as these are unaffected by cross-formational flow. Median recharge rates derived from unsaturated zone profiles range from 0.94 inches per year under rainfed agricultural areas (Scanlon and others, 2007) to 1.9 inches per year under irrigated agricultural areas (Scanlon and others, 2010a).

4.4.4.3 Hydrograph Analysis

Water table fluctuations can be used as a measure of recharge, particularly in areas that are not unduly influenced by large-scale pumping (Healy and Cook, 2002). Under appropriate conditions, water level increases can be used to estimate recharge rates based on the equation:

$$R = S_y \frac{\Delta h}{\Delta t} \tag{4.4.3}$$

where *R* is the recharge rate, S_y is aquifer specific yield, Δh is water table elevation change, and Δt is the time over which the water table elevation change occurred. A uniform estimated specific yield value of 0.15 is assumed for this study.

In the Northern Ogallala Aquifer and the northern portion of the Southern Ogallala Aquifer , hydrographs for wells located in agricultural areas with finer grained soils generally showed long-term groundwater level declines attributed to irrigation pumping (Scanlon and others, 2010a, b). This indicates that recharge in these areas is insufficient to replace water lost to pumping. However, in coarse textured soils along the southeast margins of the Northern Ogallala Aquifer and in the southern portion of the Southern Ogallala Aquifer, persistent periods of rising water levels indicated the occurrence of significant aquifer recharge. Based on the hydrographs, recharge rates range from 0.17 to 2.66 inches per year (median 0.55 inches per year) in the Northern Ogallala Aquifer (Scanlon and others, 2010b) and 0.4 to 4.8 inches per year (median 2.2 inches per year) in the Southern Ogallala Aquifer (Scanlon and others, 2005c).

4.4.4.4 Groundwater Nitrate Concentrations

Concentrations of nitrate in groundwater can be used to detect and estimate the occurrence of aquifer recharge. Following initial cultivation, soil moisture content increases, resulting in enhanced bacterial growth and conversion of soil organic nitrogen to nitrate, which generally occurs in the shallowest 0.3 m of the soil horizon (Scanlon and others, 2008). Assuming that soil texture does not inhibit percolation, increasing water percolation will mobilize that nitrate and other soluble ions to depths below the root zone and eventually the water table. This behavior was observed in the High Plains as peaks of nitrate and chloride displaced lower than expected compared to natural setting profiles (Scanlon and others, 2008). If this downward mobilization process continues for a sufficient period to allow for flushing of nitrate through the unsaturated zone, nitrate reaches the groundwater. Under natural conditions, the maximum natural groundwater concentration of nitrate is expected to be 4 milligrams per liter (Gurdak and Qi, 2006). Thus, the presence of nitrate concentrations greater than 4 milligrams per liter can be used as an indicator of recharge.

Figure 4.4.9 shows the probability of groundwater nitrate concentrations exceeding 4 milligrams per liter in the Ogallala Aquifer. Nitrate concentrations are available for 2,032 groundwater wells completed in the Ogallala Aquifer in Texas. For each well, only the most recent sample was used in order to represent current conditions. Only samples after 1988 were used, with an average sample date of 2000. Indicator kriging was used to estimate the spatial distribution of nitrate. Rather than attempt to estimate actual concentrations as is performed with either the simple or ordinary methods of kriging, the indicator method generates estimates of the *probability of exceeding* a stated threshold value, in this case, a threshold of 4 milligrams per liter nitrate consistent with Gurdak and Qi (2006). The method assigns a value of 0 (zero) to points that are at or below the threshold and a value of 1 to “indicate” points that exceed the threshold. As with other forms of kriging, a variogram is used to describe any spatial correlation in the dataset. Indicator kriging has an advantage over other forms of kriging in that no assumptions are required regarding the normality of the data distribution. Additionally, non-detects or “less-than” analytical results can be used directly where the analytical method detection limit is less than the threshold value. Since very few non-Texas data points were available from the United States Geological Survey National Water Information System database (United States Geological Survey, 2013b), results of the indicator kriging are limited to the area covered by the TWDB database (TWDB, 2013).

The results indicate that much of the southern half of the Southern Ogallala Aquifer region has an elevated probability (greater than 50 percent) of groundwater nitrate exceeding 4 milligrams per liter (Figure 4.4.9). Comparison of the nitrate probability map with the land use map (see Figure 4.4.5) indicates that the regions of elevated probability in the Southern Ogallala Aquifer region are closely and almost exclusively associated with areas of agricultural land use. Of the remaining regions in Texas, only the southeastern and eastern Northern Ogallala Aquifer margins show elevated probabilities. These regions are generally consistent with areas that are both cultivated and have coarser textured soils (see Figure 4.4.2). In the majority of the Northern Ogallala Aquifer and the northern portion of the Southern Ogallala Aquifer, where agricultural areas are associated with finer textured soils, elevated groundwater nitrate concentrations are less common and only occur locally. It is possible that the lower nitrate concentrations in the north are due to the widespread lowering of the water table due to large-scale irrigation. If this process significantly increased the thickness of the unsaturated zone, it would prolong the time required for nitrate to reach the water table, leading to the lower observed nitrate concentrations. However, this impact is only likely to occur in very limited agricultural areas with less clay-rich soils.

The observed nitrate distributions indicate that recharge in the High Plains is controlled by both land use and soil texture. Recharge is more dependent on land use in the Southern Ogallala Aquifer region, where nitrate concentrations are elevated in areas associated with agriculture and low in areas dominated by rangeland. However, in the Northern Ogallala Aquifer region, recharge is relatively unaffected by land use but dependent on soil texture. Elevated nitrate concentrations are generally associated with areas of coarser textured soils and low nitrate concentrations occur in areas of finer grained soil even when that land is under cultivation. This is likely because agriculture in the Northern Ogallala Aquifer is predominantly located on clay rich soils, which limit recharge. Thus, conversion to agriculture has little effect on recharge.

4.4.4.5 Timing of Recharge Events

Since elevated nitrate concentrations indicate the occurrence of recharge, time series of nitrate in groundwater, when available, can be used to constrain travel time of recharge from the surface to the water table. Figures 4.4.10 through 4.4.13 show multi-decadal time series of total dissolved solids and nitrate concentrations in the Southern Ogallala Aquifer in all or part of 19 Texas counties. The data used for this analysis was sourced from the TWDB groundwater database (TWDB, 2013). There were 4,828 total dissolved solids analyses and 4,510 nitrate analyses with dates ranging from the 1930s to the present. For this analysis, samples were first grouped spatially by county area. Sixteen of the counties have an average of 331 samples though time, ranging from 183 samples (Yoakum County) to 1,014 samples (Gaines County). Five counties (Borden, Crosby, Ector, Garza, and Glasscock counties) have relatively small areas in the region and too few water samples (17 to 68) for independent analysis and were, therefore, grouped with adjacent counties.

Within each county or multi-county area, samples were then grouped by sequential decadal periods until there were generally a minimum of approximately 70 wells in each subpopulation to provide both statistical reliability and assumed spatial coverage within each area. This resulted in 3 to 4 time periods for each area. Concentration for the 50th, 75th, and 90th percentiles were plotted against time for both total dissolved solids and nitrate concentration (see Figures 4.4.10 through 4.4.13). These "upper end" percentile distributions were then used to estimate the general timing of widespread water quality impacts due to land use change.

Results indicate that nitrate concentrations in agricultural areas became elevated above background early in Dawson and Borden counties (prior to 1940) and also in Lynn and Garza counties (prior to 1960). None of the remaining agricultural counties showed widespread impacts from nitrate prior to 1970 (Bailey, Cochran, Gaines, Hockley, Howard, Lamb, Lubbock, and Crosby counties) or 1980 (Lamb, Martin, Terry, and Yoakum counties) representing the earliest sample periods in those areas. Widespread impacts from nitrate in most areas outside of the Lynn and Dawson counties area generally began in the 1970s and 1980s, though impacts may have begun as late as the 1990s in Gaines, Lamb, Lubbock, Terry, and Yoakum counties. Cochran and Hockley counties appear to have had little impact from nitrate to date.

In rangeland areas and areas with large urban/suburban areas (Lubbock, Andrews, Midland, Glasscock, and Ector counties), nitrate contributions due to agricultural recharge are expected to be minimal. Therefore, the elevated nitrate concentrations in these areas are not interpreted as evidence of agricultural recharge but, rather, as evidence of septic contamination. The fact that total dissolved solids concentrations do not increase simultaneously with nitrate, but remain relatively stable, supports this assumption.

The rate at which nitrate and other soluble ions reach the water table is controlled by water inputs, including precipitation rates and irrigation rates, and by the unsaturated zone profile characteristics, including texture, layering, pre-existing moisture content, and overall thickness (that is, depth to the saturated zone). Figure 4.4.14 shows no evidence of correlation between soil type and the timing of recharge from land use change. Some areas with sandy soil, where recharge is expected to occur more rapidly, have some of the latest recharge dates. Other areas that share the same type of soil have vastly different recharge times. Land use, on the other hand, does have a clear influence on recharge travel time, with early recharge occurring under cropland and late recharge occurring under areas with less irrigated land. For instance, Cochran and Hockley counties, which have no evidence of recharge, contain primarily rangeland (Figure 4.4.15). Depth to water may also be a controlling factor for timing of recharge, as

Cochran and Hockley counties are in areas where the water table is very deep (Figure 4.4.16). When recharge must travel a larger vertical distance, travel time to the water table increases. As shown by the inset graph in Figure 4.4.16, the timing of recharge becomes progressively later as the water table get deeper. While the correlation is not 1:1, an upward trend can be seen in the plot.

4.4.5 Pre-development Recharge Distribution (pre-1930)

Prior to the agricultural development of the late 19th and early 20th centuries, recharge to the Ogallala Aquifer was generally restricted to focused flow beneath playas. Otherwise, in areas with no playas, the native vegetation intercepted most precipitation and prevented any significant recharge from occurring. In the Northern Ogallala Aquifer, however, some interplaya recharge may have occurred in regions dominated by coarse textured soils, like those along drainages and along the eastern and southern margins of the Northern Ogallala Aquifer. These areas of coarse-textured soil tend to correspond with areas where the upper sections of the Ogallala Formation have been removed by erosion and the coarser lower sections are exposed at the surface, enhancing recharge potential. Recharge to the northern section of the Southern Ogallala Aquifer appears to be similarly influenced by soil type. However, the same is not true of the southern portion of the Southern Ogallala Aquifer, where soil type does not appear to affect recharge. There, coarse-textured soils, like those in the southwest margins of the Southern Ogallala Aquifer, represent surficial eolian deposits that are underlain by less permeable layers, limiting recharge potential. Unsaturated zone profiles in this area support the assumption that no recharge has occurred in these interplaya areas since the Pleistocene. To account for these differences, the Southern Ogallala Aquifer was split into two distinct sections for the current recharge analysis. The delineation of these two areas is based on Scanlon and others (2010a), which splits the Southern Ogallala Aquifer using salinity, with the 500 milligrams per liter total dissolved solids contour (Figure 4.4.17) marking the boundary between the higher salinity southern portion and the fresher northern portion. This delineation also coincides with other physical transitions that affect how recharge occurs on either side of the boundary. The northern portion is a paleovalley with high saturated thicknesses and a deep water table while the southern portion is a paleoupland with low saturated thicknesses and a shallow water table (Scanlon and others, 2010a).

Because of these differences, the initial pre-development recharge distribution groups together the Northern Ogallala Aquifer and the northern portion of the Southern Ogallala Aquifer and applies recharge in these areas differently than in the southern portion of the Southern Ogallala Aquifer. Due to the larger number of samples in the north, it was possible to use the chloride mass balance method to determine pre-development recharge rates and then extrapolate these point values to the whole grid according to soil type. Based on the groundwater chloride mass balance method, pre-development recharge rates ranged from 0.3 to 0.6 inches per year in the Northern Ogallala Aquifer and from to 0.2 to 0.4 inches per year in the northern part of the Southern Ogallala Aquifer (Figure 4.4.17).

In the south, there were not enough chloride mass balance data points to create a recharge distribution. However, there is a decreasing regional trend in recharge rates as you move south. Extending that trend based on northern values, predevelopment recharge rates in the southern region are estimated to be about 0.1 to 0.2 inches per year, but this recharge is restricted to areas with playas. To account for the control that playas have on recharge in this region, recharge was distributed according to the playa density shown in Figure 4.4.7. Areas with 0 percent playa density were assigned a minimal value of 0.007 inches per year, based on the calibrated value from Blandford and others (2008). Although there is no measured evidence of recharge happening in these non-playa areas, the record of some springs in the western portion of the Ogallala Aquifer indicates a non-zero amount of recharge. Where playas are present, a recharge value of 0.1 inches per year was assigned to areas with less than 5 percent playa density, 0.15 inches per year to areas with 5 to 20 percent playa density, and 0.2 inches per year to areas with playa density greater than 20 percent (Figure 4.4.17).

For the Dockum Aquifer, the current study uses the same pre-development recharge distribution as Ewing and others (2008). This conceptualization assumes no deep recharge to the confined portion of the aquifer. Instead, all recharge is shallow and eventually discharged to local drainages. Recharge rates were distributed according to local topography and average 0.15 inches per year (Figure 4.4.18). In the western portion of the Colorado River outcrop (Borden, Dawson, and Garza counties), the total dissolved solids concentration is greater than 5,000 milligrams per liter. This high salinity value and the high clay content of the soil suggest negligible recharge in this portion of the outcrop. A small area of Ogallala Formation sediments intersects the Dockum Aquifer in the Colorado River outcrop. It is hydraulically isolated from the Ogallala Aquifer and acts as a source of recharge for the Dockum Aquifer. This is assigned a recharge value of 0.04 inches per year according to estimates in Ewing and others (2008).

4.4.6 Post-Development Recharge Distribution (1930 to present)

In the Northern Ogallala Aquifer and the northern section of the Southern Ogallala Aquifer, unsaturated zone borehole profiles indicate that the conversion to cultivated agricultural land has had little to no impact on recharge. This is likely due to the clustering of cultivated lands in areas dominated by clay loam soils. These relatively impermeable soils restrict the effects of agricultural activity to the shallowest 10 to 20 feet of the unsaturated zone and preclude any significant deep recharge. Some of the borehole profiles from Scanlon and others (2010b) indicate that enhanced percolation occurs under irrigated agriculture, but this percolation has not occurred at a rate sufficient to have reached the water table. The lack of elevated nitrate concentrations in the groundwater in this region supports this conclusion (Figure 4.4.9). So agricultural activity, including irrigation, has not led to enhanced recharge in the Northern Ogallala Aquifer and the northern section of the Southern Ogallala Aquifer. These regions have recharge that is effectively unchanged since pre-development. The post-development recharge distribution used in the Northern Ogallala Aquifer and the northern portion of the Southern Ogallala Aquifer region in this study are, thus, the same as the pre-development distribution (Figure 4.4.19).

By contrast, recharge in the southern portion of the Southern Ogallala Aquifer has been impacted by conversion to cultivated agriculture. Whereas pre-development recharge was limited to playa areas, post-development recharge occurs under rainfed and irrigated agricultural lands. Local areas of increasing water levels under cultivated lands are indicators of this effect. Irrigation return flow can be delayed by years to decades due to physical factors influencing recharge travel time, most notably depth to water table. For this reason, recharge might occur much later than the actual application of irrigation at the surface. Chloride mass balance recharge values for unsaturated zone borehole profiles in cultivated agricultural land range from 0.2 to 4.4 inches per year, with a median of 0.94 inches per year for rainfed and 1.9 inches per year for irrigated profiles. Therefore, in the southern portion of the Southern Ogallala Aquifer, post-development recharge is distributed based on the land use distribution shown in Figure 4.4.5. In areas where there has been no agricultural development, the recharge is assumed to be unchanged from pre-development recharge (Figure 4.4.19).

During the development of the numerical model, we will look at the sensitivity of heads to delaying the effect of irrigation return flow to when evidence of nitrate breakthrough occurred. That is, in the year when nitrate breakthrough occurred in a given county, we can increase the recharge rate from a rainfed value to an irrigated value. For example, because of the early evidence of breakthrough in Dawson County, elevated recharge will be applied near the beginning of the historical simulation, which will help to match the steady or increasing water levels in that area.

The recharge distribution shown in Figure 4.4.19 does not show the impact of runoff from impervious cover in the City of Lubbock to nearby playas. We recognize that in calibration, additional focused recharge that represents a few individual playas may be required to match local hydrographs, similar to Blandford and others (2008).

The current study uses the same post-development recharge distribution for the Dockum Aquifer as adopted by Ewing and others (2008). Their conceptualization attributes increases in water levels in the Colorado River outcrop to agricultural land use change and assumes an additional 1.45 inches of recharge in cropland areas. They implemented this increased recharge in the model grid by adding additional recharge, up to 1.45 inches, to the pre-development recharge rates of grid cells, weighted by the amount of cropland falling in that grid cell (Figure 4.4.20). No distinction between rainfed and irrigated cropland was made. The recharge distribution in the Canadian River outcrop remains unchanged from pre-development conditions. In this region, little cultivation has occurred and stable water levels indicate little to no effect on recharge due to land use change (Ewing and others, 2008). Cropland areas in the area of isolated Ogallala Formation sediments are assigned a recharge value of 0.94 inches per year, the same as rainfed agriculture in the Ogallala Aquifer.

Table 4.4.1 Recharge rates from the literature (summary of Section 4.4.2)

Rate (inches per year)	Range (inches per year)	Percent of Precipitation	Method (study area[1])	Reference
	0.06 - 0.83		Unsaturated zone water content measurements (Ogallala Aquifer)	Klemt (1981); Knowles and others (1984)
0.13[2]/0.73[3]			Regional Groundwater Model (Southern Ogallala Aquifer)	Luckey and others (1986)
0.14[2]			Regional Groundwater Model (Northern Ogallala Aquifer)	Luckey and others (1986)
2.75			Inverse modeling (Southern Ogallala Aquifer)	Stovall (2001)
		0.4 – 4[2]	Regional Groundwater Model (Northern Ogallala Aquifer)	Luckey and Becker (1999)
		1 – 6	Regional Groundwater Model (Northern Ogallala Aquifer)	Dutton and others (2001a)
	0.007 – 0.085[2]		Regional Groundwater Model (Southern Ogallala Aquifer)	Blandford and others (2003)
	0.65 – 1[3]		Regional Groundwater Model (Southern Ogallala Aquifer)	Blandford and others (2003)
0.43			Chloride Mass Balance (Southern Ogallala Aquifer)	Wood and Sanford (1995a)

[1] "Study area" refers to the approximate aquifer or sub area (see Figure 4.4.1) where the recharge estimate applies. The original study areas in the literature may have been larger or smaller than the areas shown in Figure 4.4.1.

[2] Pre-development estimate

[3] Post-development estimate

Table 4.4.2 Land use/land cover in the model area and selected sub areas. Sub areas are delineated in Figure 4.4.1.

Region	Area (mi^2)	Area (% of model)	Grassland (%)	Shrubland (%)	Crops (%)	Developed (%)	Other[1] (%)
Model Area	77,049	100.0	37.7	33.4	24.1	3.8	1.1
Ogallala Aquifer (all)	55,059	71.5	46.5	15.8	32.4	4.5	0.8
Northern Ogallala Aquifer	25,497	33.1	58.6	13.6	23.6	3.5	0.7
Southern Ogallala Aquifer	29,562	38.4	36.0	17.8	40.0	5.3	0.9
Dockum Aquifer Outcrop (all)	4,997	6.5	35.8	55.0	4.6	2.1	2.4
Canadian River Outcrop (Dockum Aquifer)	1,338	1.7	39.8	58.8	0.3	0.7	0.4
Eastern Escarpment Outcrop (Dockum Aquifer)	213	0.3	16.4	61.7	0.0	0.6	21.3[2]
Colorado River Outcrop (Dockum Aquifer)	3,447	4.5	35.5	53.1	6.6	2.8	2.0

[1] Includes water, wetland, barren, and pasture areas.

[2] Includes 21.0 percent forest.

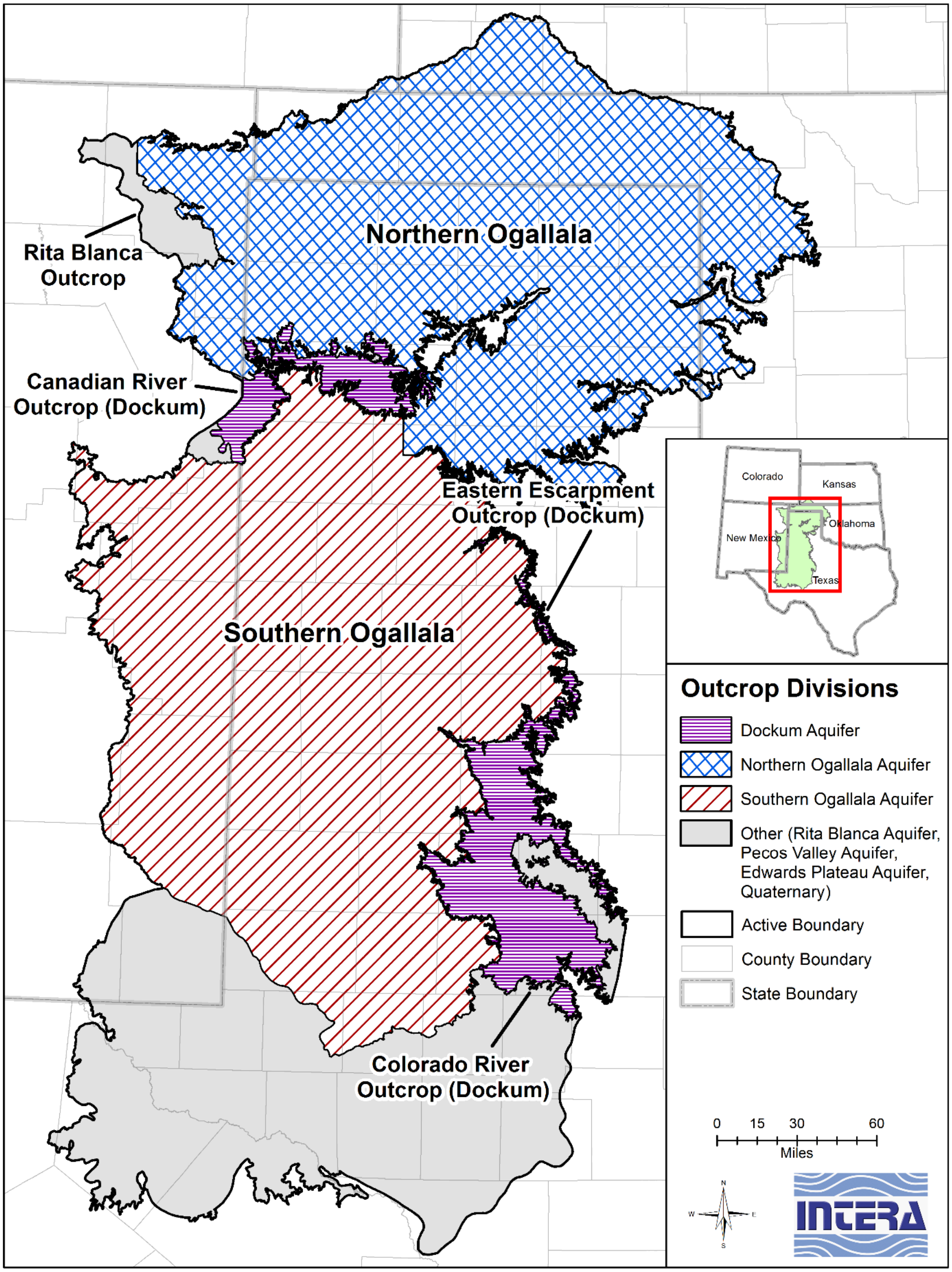


Figure 4.4.1 **Outcrop divisions used in the current recharge analysis.**

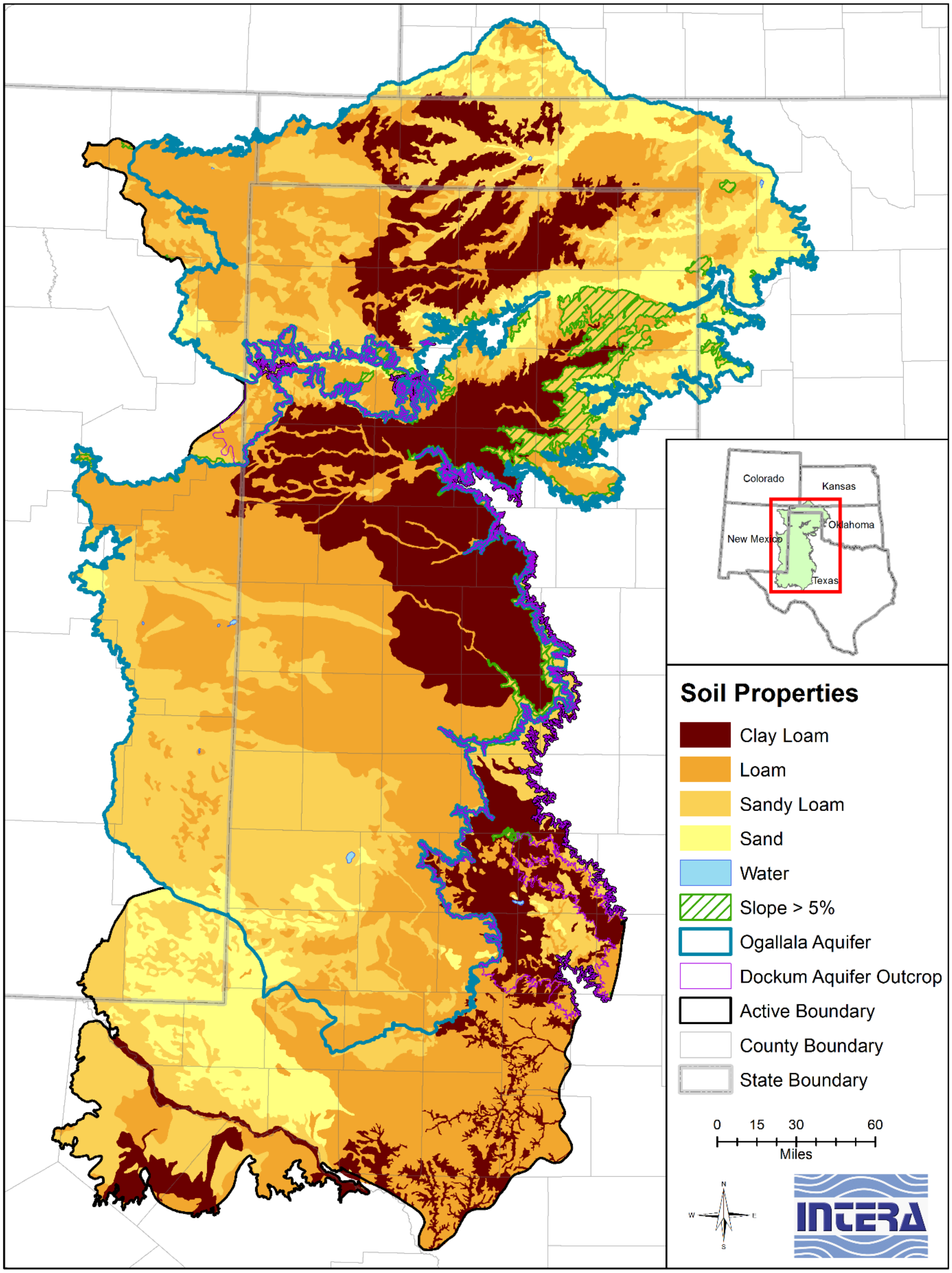


Figure 4.4.2 Generalized soils map based on STATSGO (United States Department of Agriculture, 1994).

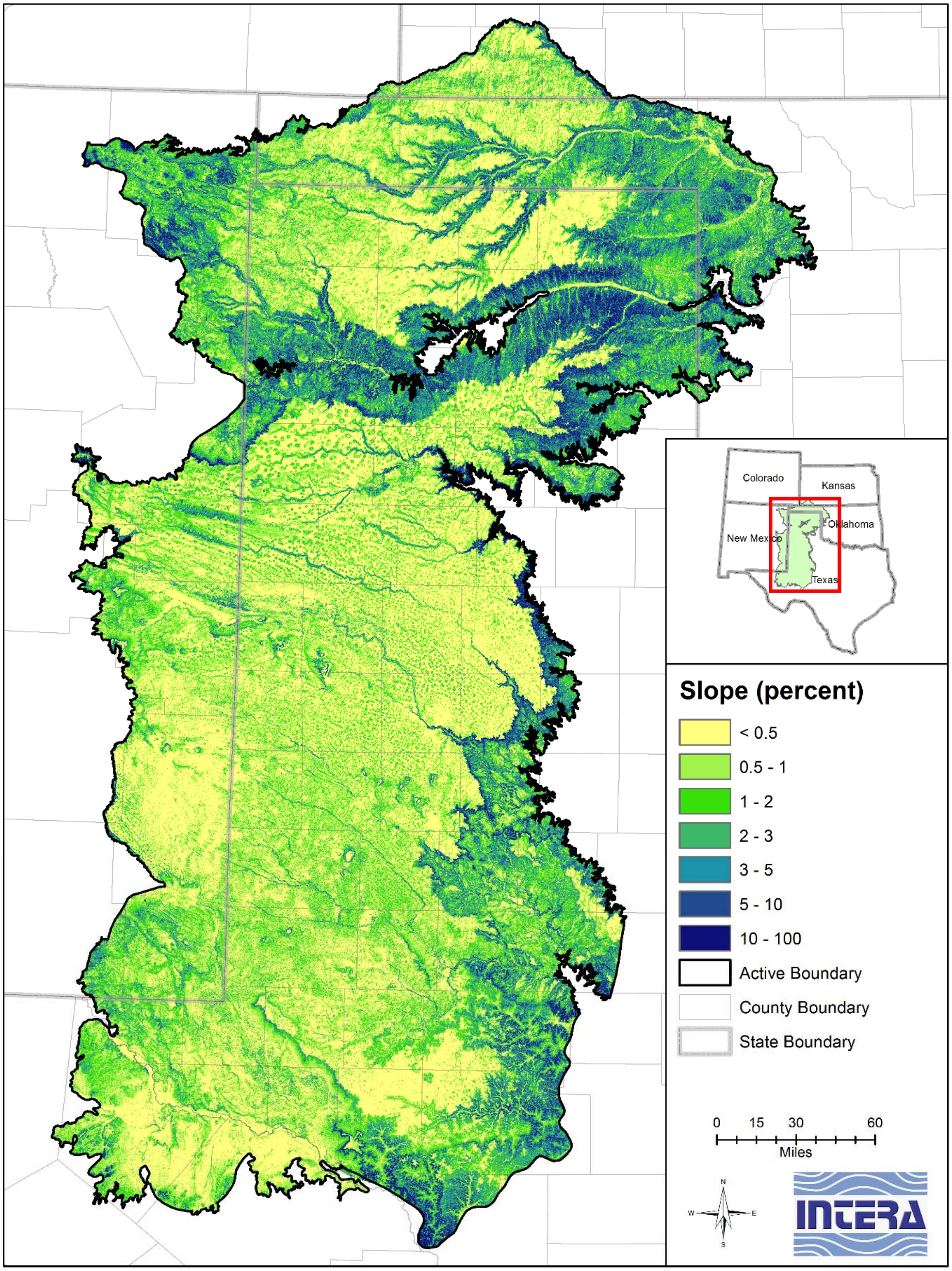


Figure 4.4.3 Average ground surface slope based on the 30-meter digital elevation model (United States Geological Survey, 2012).

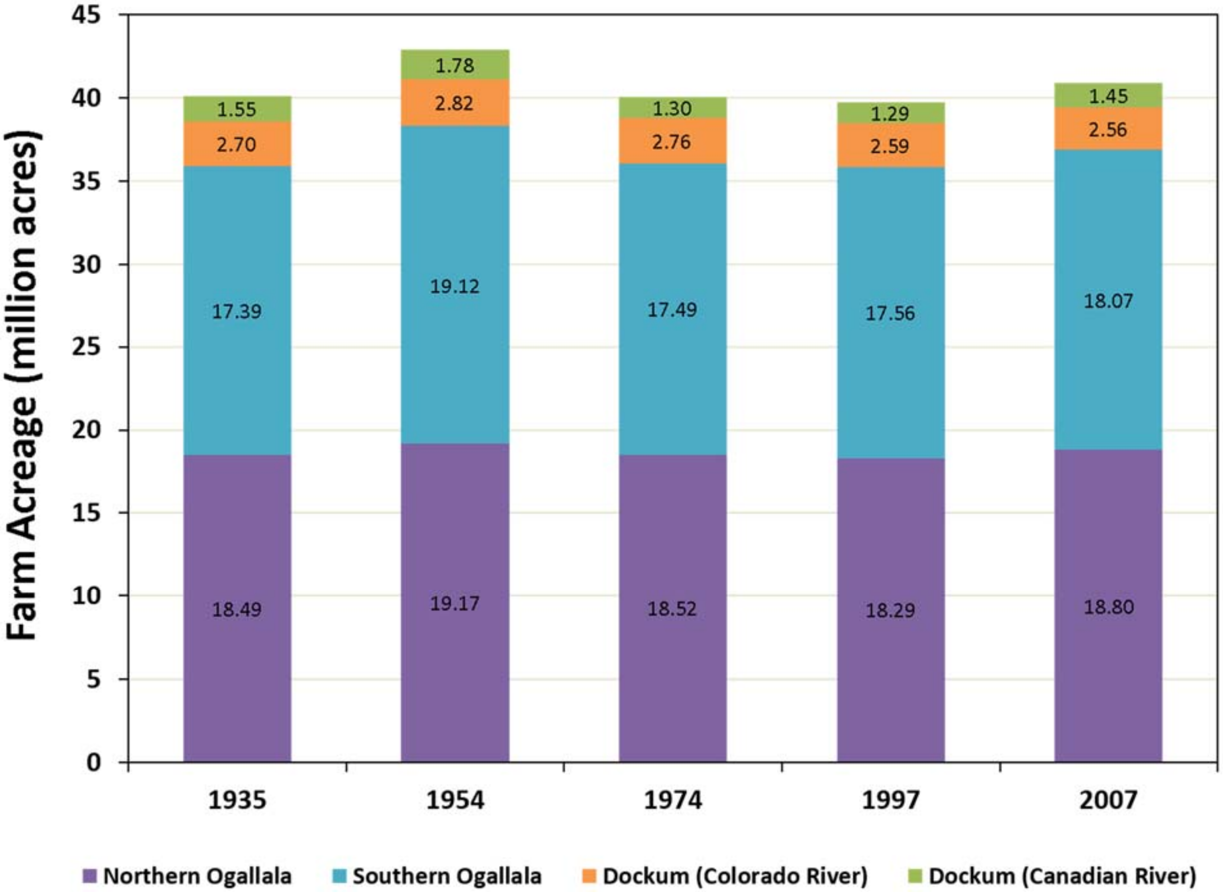


Figure 4.4.4 Farm acreage of counties falling mostly within the Ogallala Aquifer or Dockum Aquifer outcrops (United States Department of Agriculture, 1935, 1954, 1974, 1997, 2007).

Dockum (Canadian River) Counties: Oldham, Potter (TX)
Dockum (Colorado River) Counties: Garza, Scurry, Borden, Howard, Mitchell (TX)
Northern Ogallala Counties: Lipscomb, Sherman, Dallam, Hansford, Ochiltree, Roberts, Hemphill, Hutchinson, Hartley, Moore, Carson, Gray, Wheeler, Armstrong, Donley (TX), Cimarron, Beaver, Texas, Harper, Woodward, Ellis, Roger Mills (OK), Union (NM), Stevens, Morton, Seward (KS)
Southern Ogallala Counties: Randall, Deaf Smith, Parmer, Castro, Swisher, Briscoe, Floyd, Hale, Lamb, Bailey, Crosby, Lubbock, Hockley, Cochran, Lynn, Terry, Yoakum, Dawson, Gaines, Howard, Martin, Andrews, Midland (TX), Curry, Roosevelt, Lea (NM)

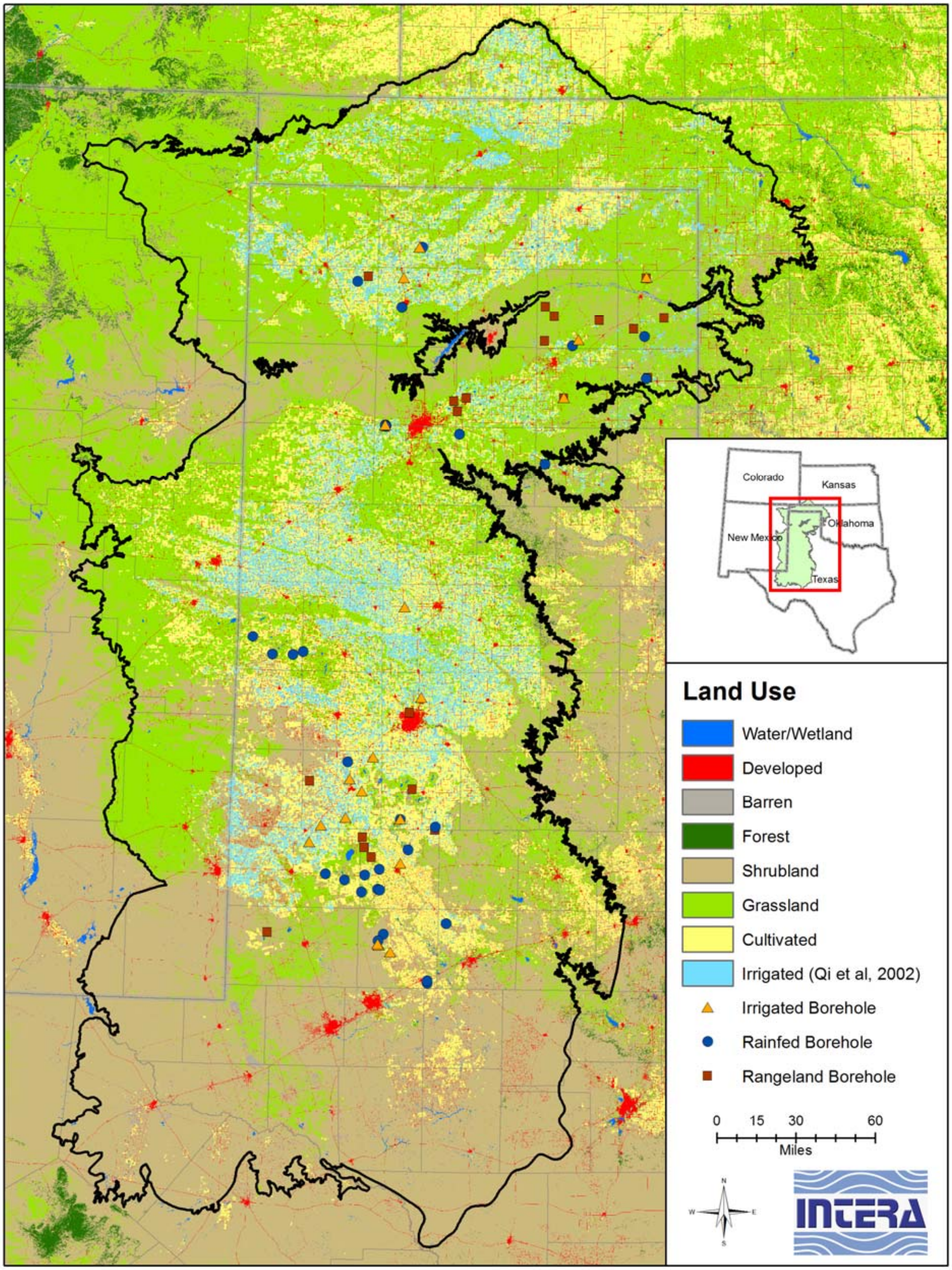


Figure 4.4.5 Land use in the model area (Fry and others, 2011; Qi and others, 2002).

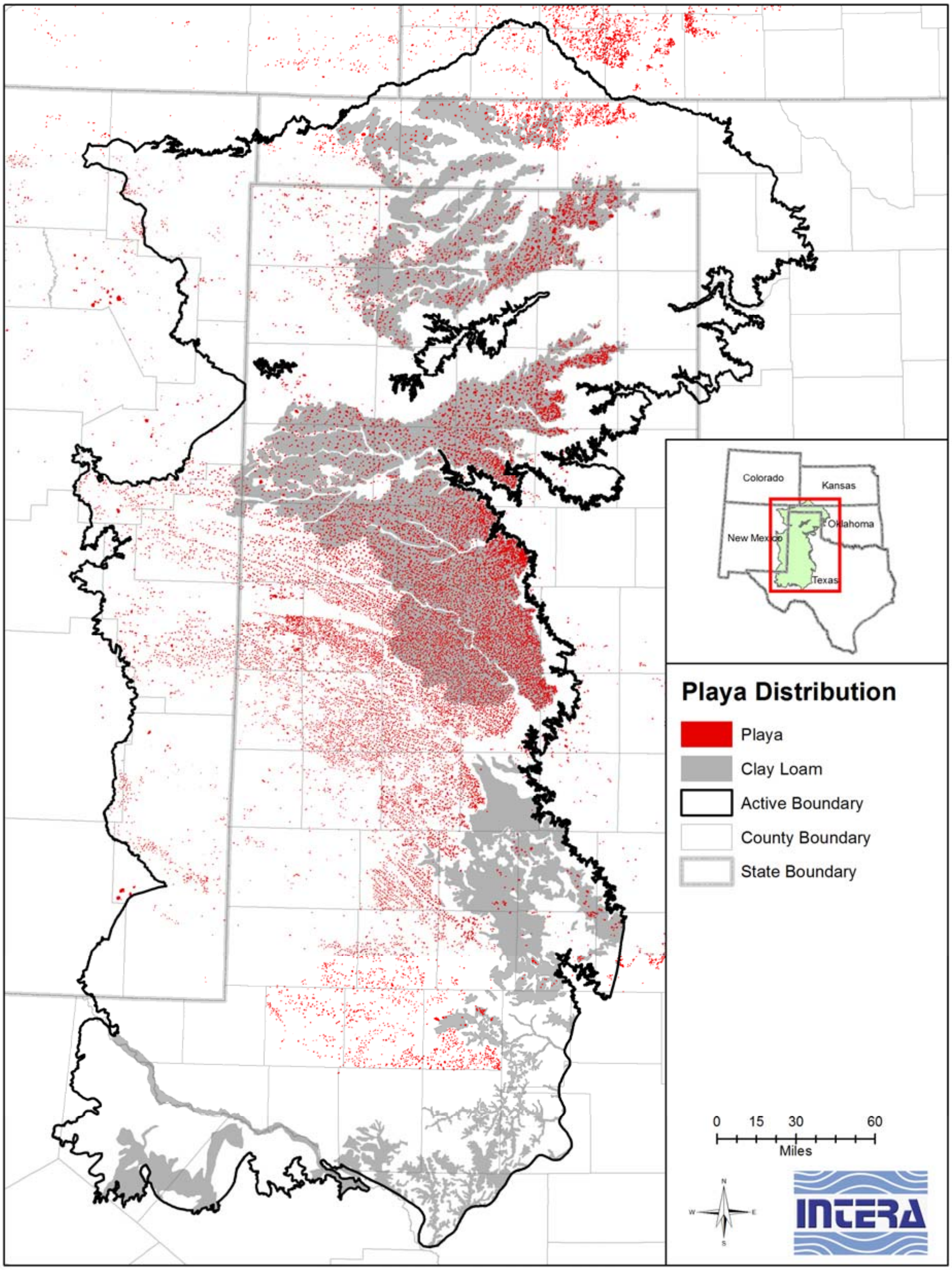


Figure 4.4.6 Playa locations in the model area (Playa Lake Joint Venture, 2013).

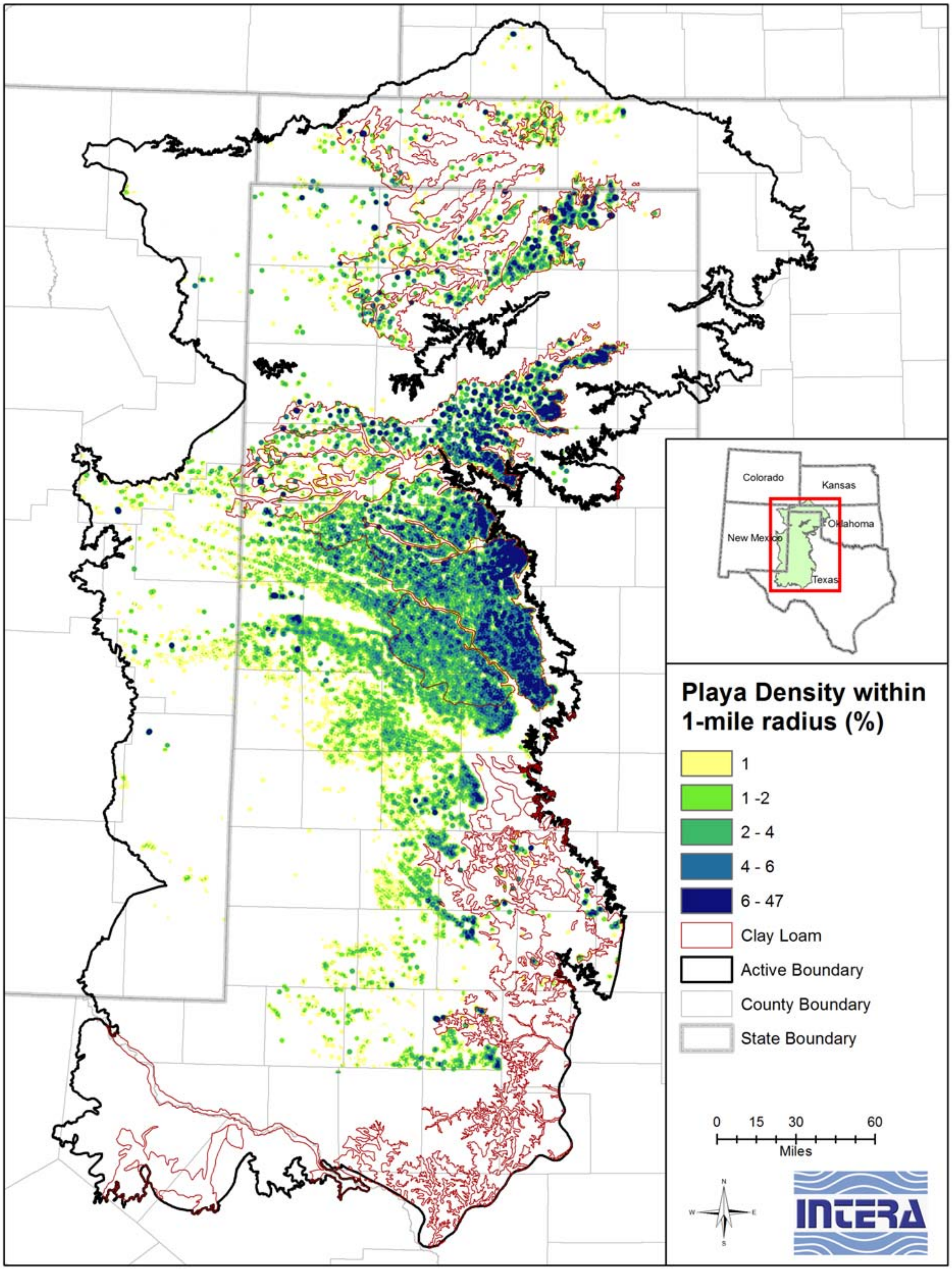


Figure 4.4.7 **Playa density in percent in the model area (based on Playa Lake Joint Venture, 2013).**

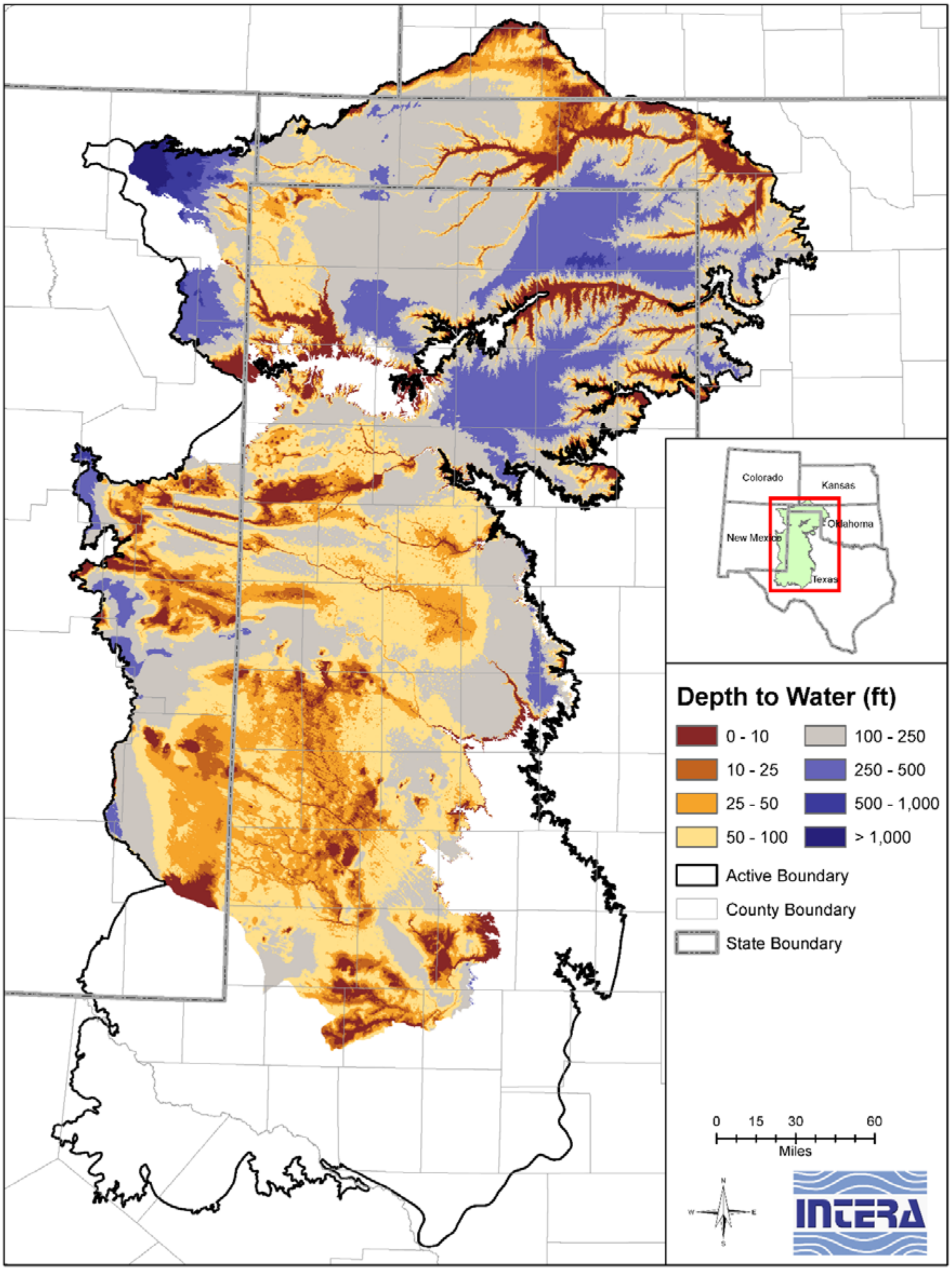


Figure 4.4.8 Estimated pre-development depth to water in feet in the model area, calculated from the 10-meter digital elevation model (United States Geological Survey, 2012).

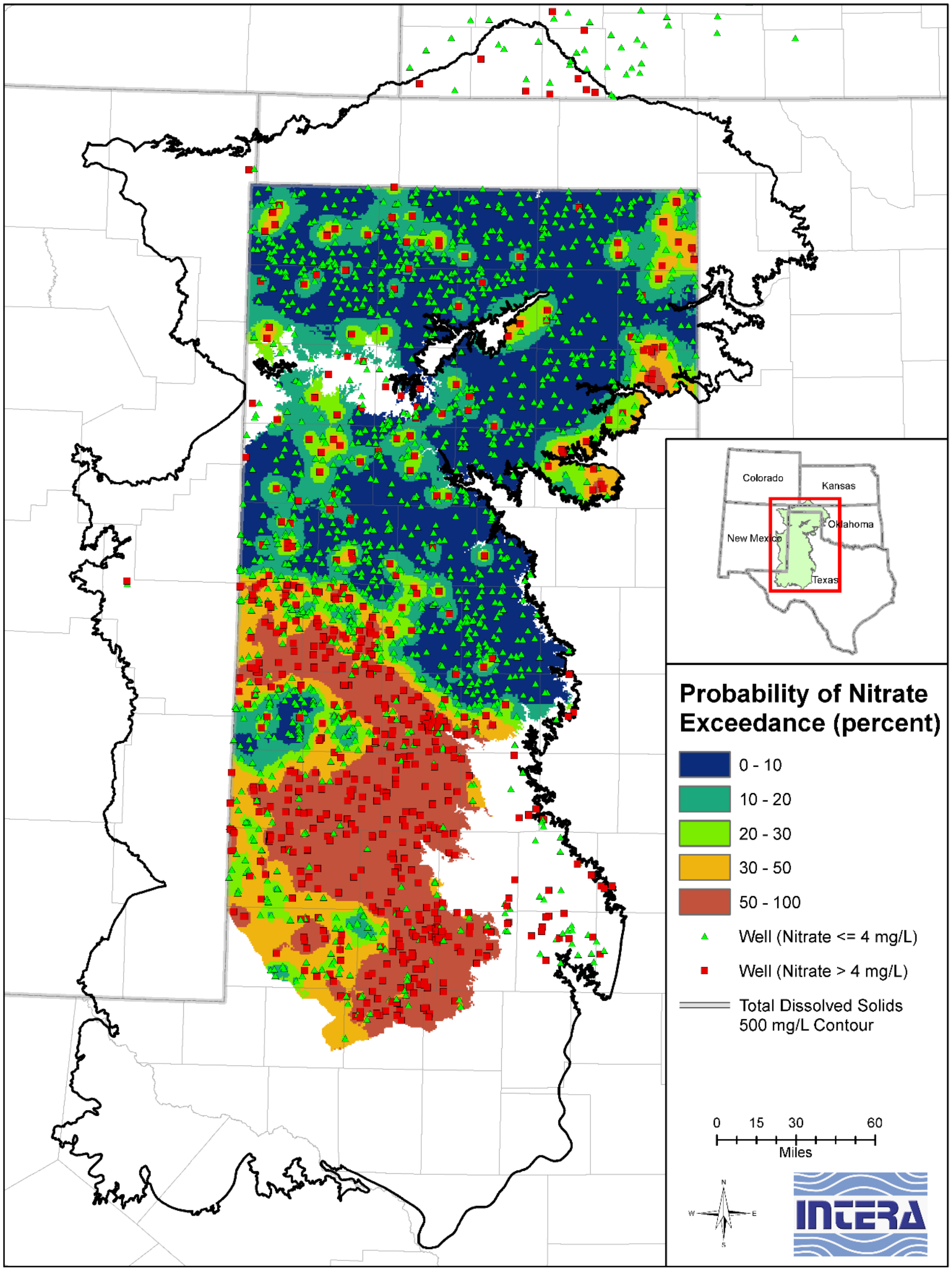


Figure 4.4.9 The probability distribution of groundwater nitrate concentrations exceeding 4 milligrams per liter (TWDB, 2013a).

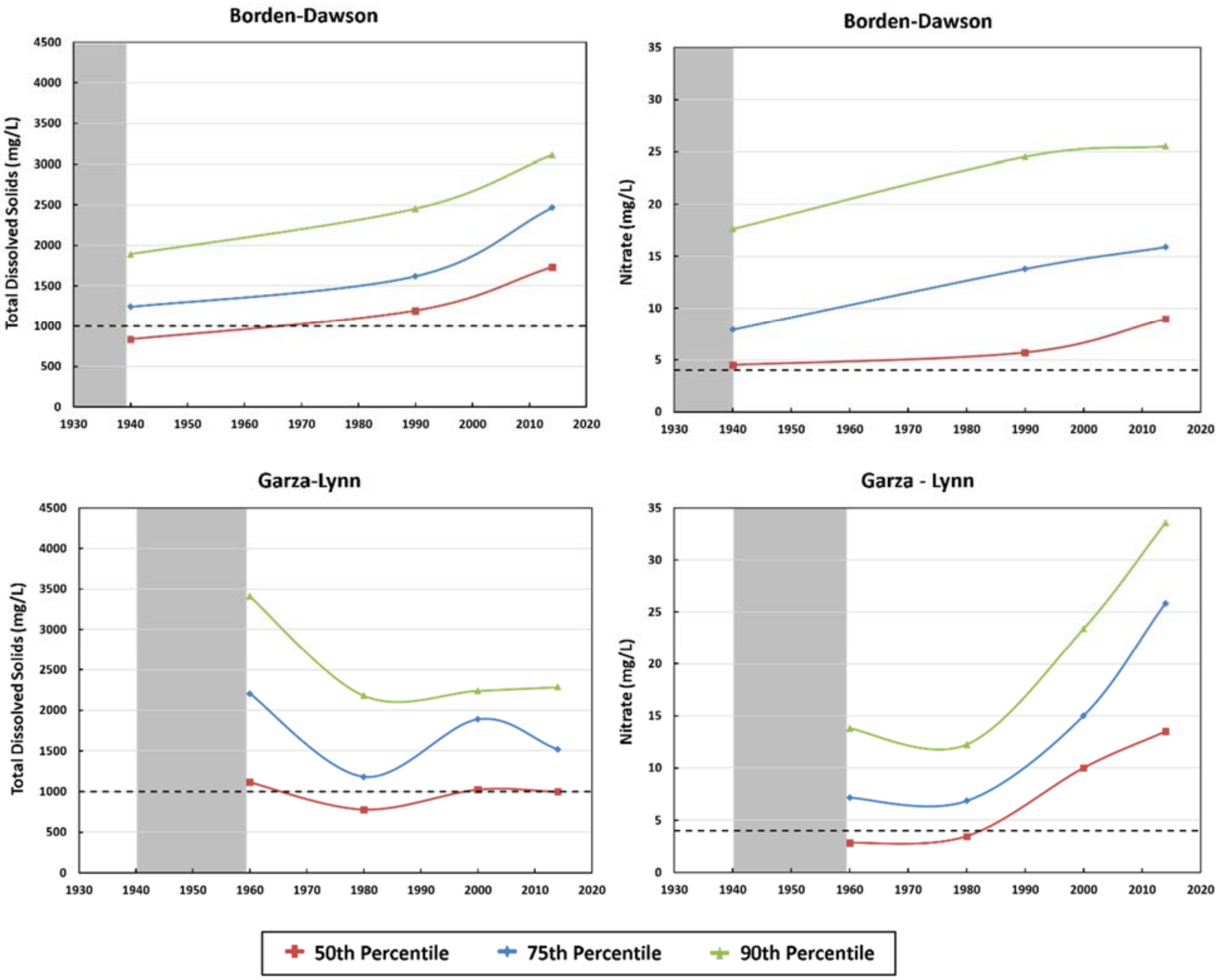


Figure 4.4.10 **Counties where recharge due to agriculture occurred very early. (Gray indicates time at which surface recharge first reached water table.)**

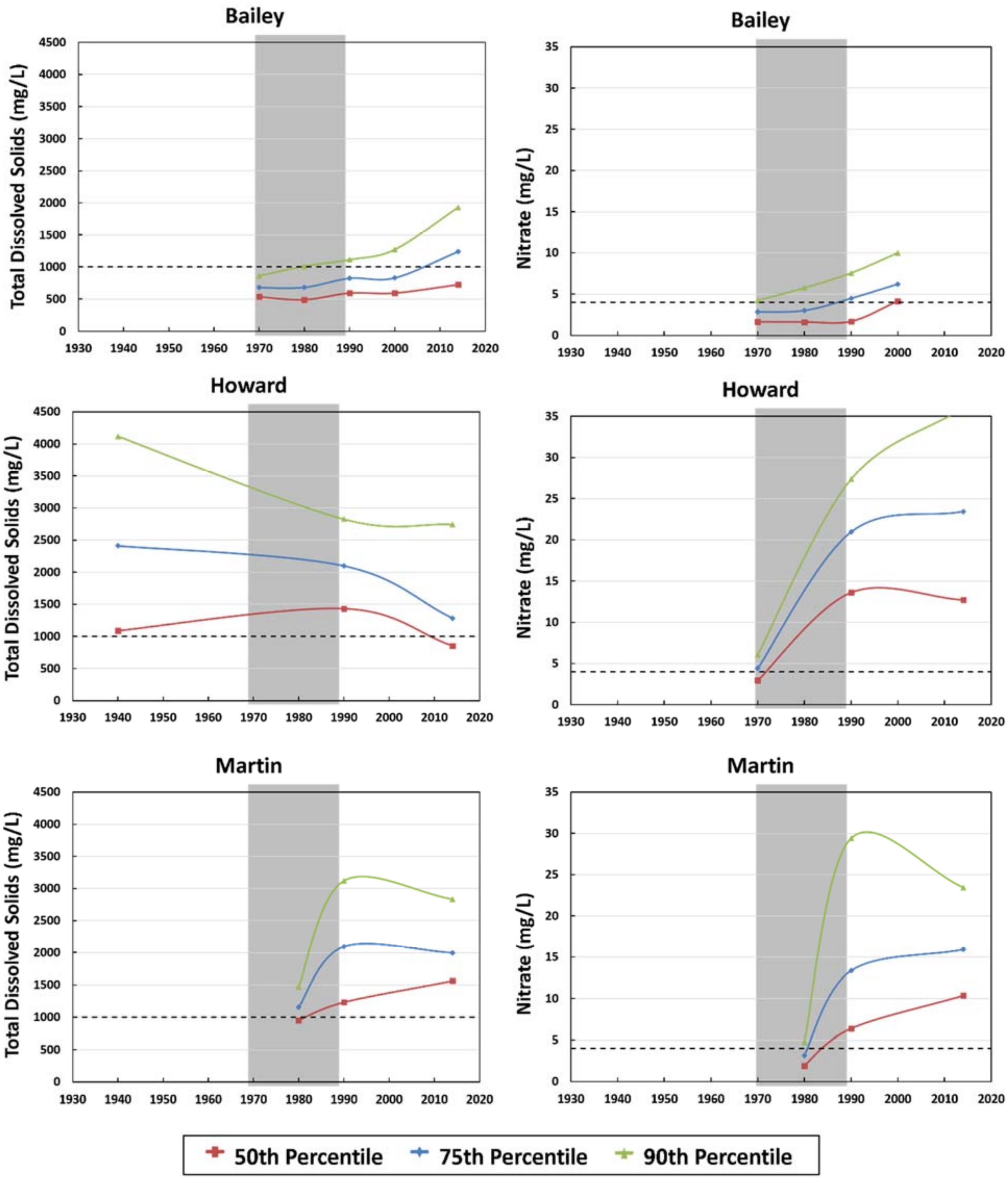


Figure 4.4.11 Counties where recharge due to agriculture occurred during the 1970s-1980s. (Gray indicates time at which surface recharge first reached water table.)

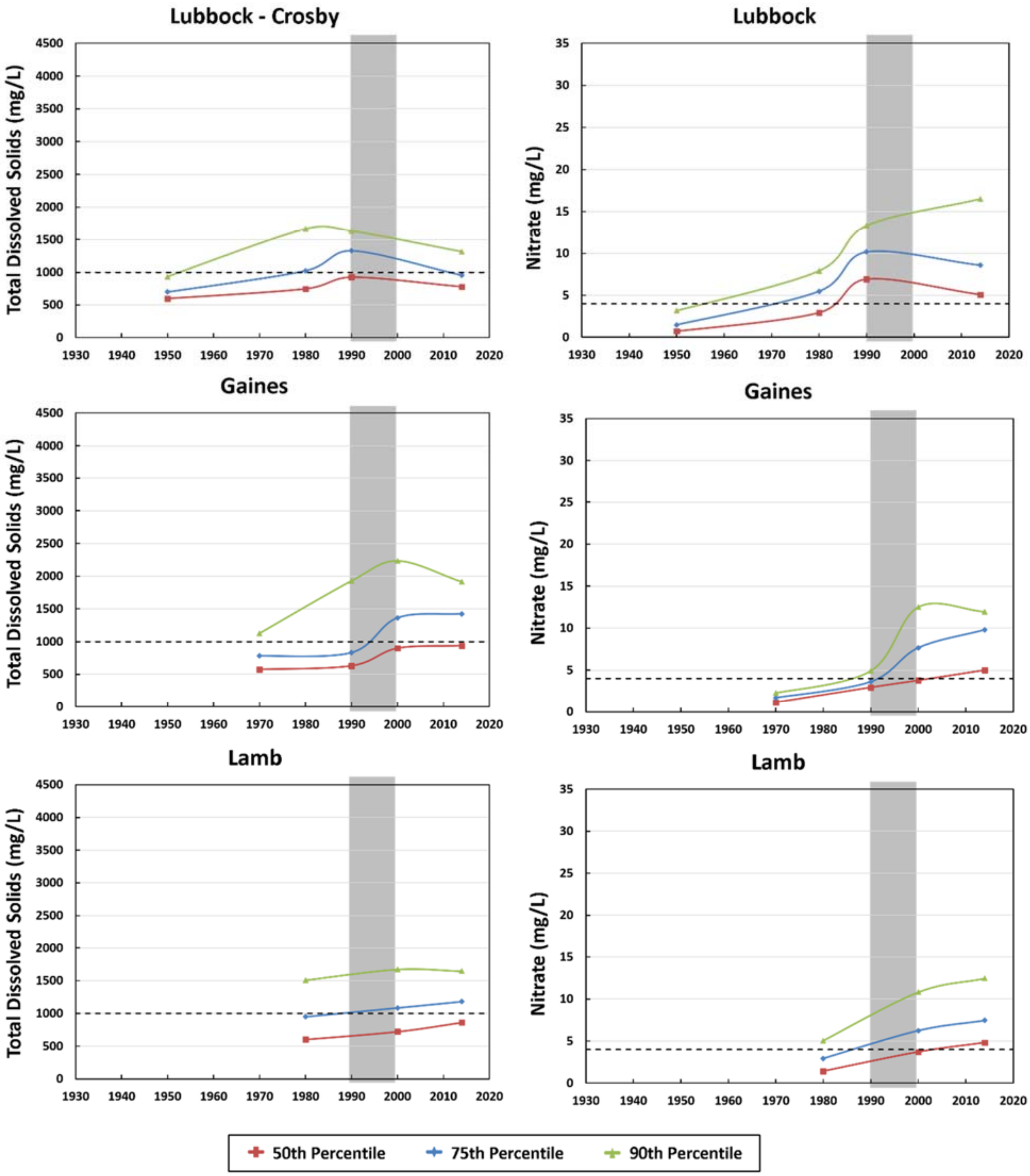


Figure 4.4.12a Counties where recharge due to agriculture occurred during the 1990s. (Gray indicates time at which surface recharge first reached water table.)

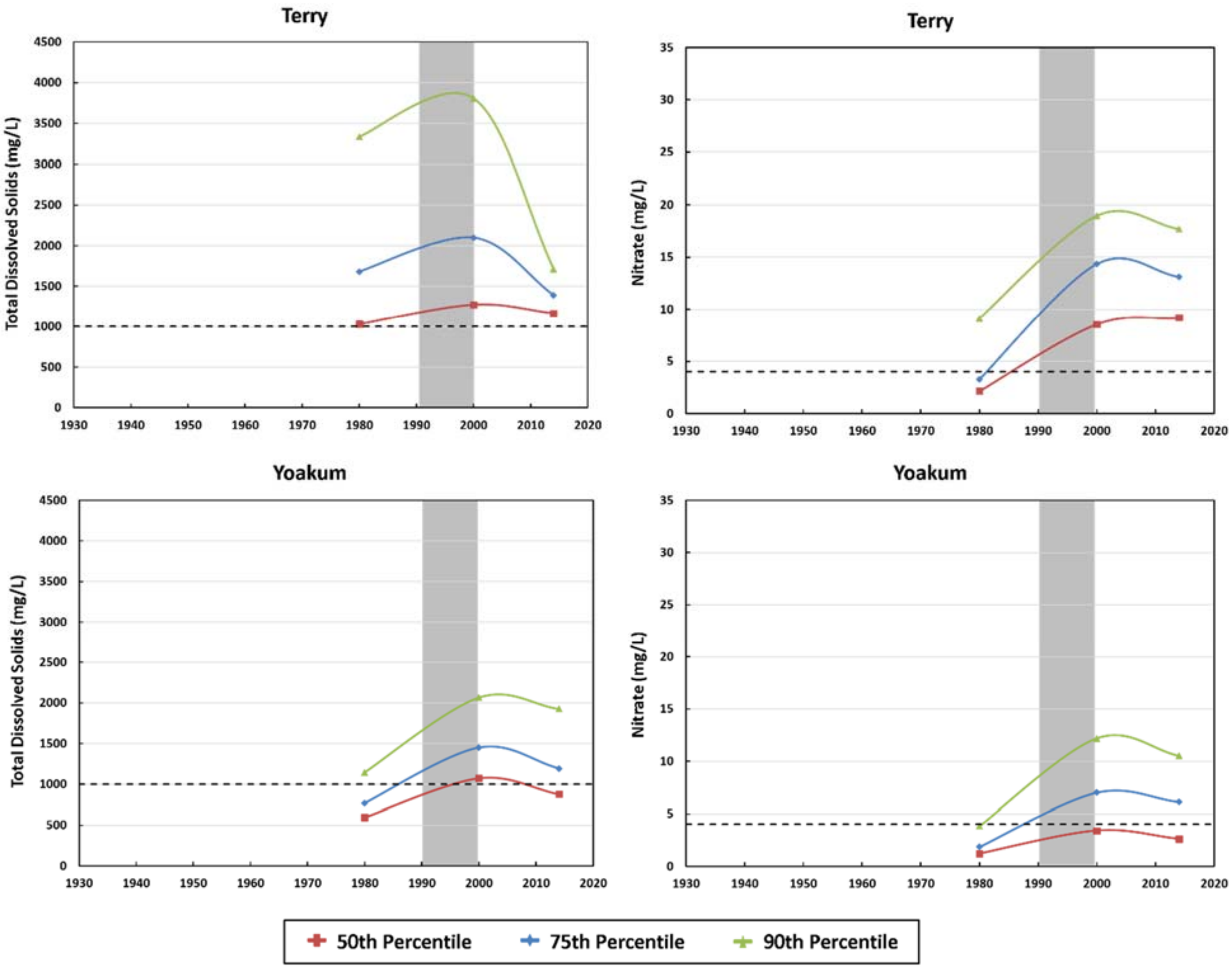


Figure 4.4.12b Additional counties where recharge due to agriculture occurred during the 1990s. (Gray indicates time at which surface recharge first reached water table.)

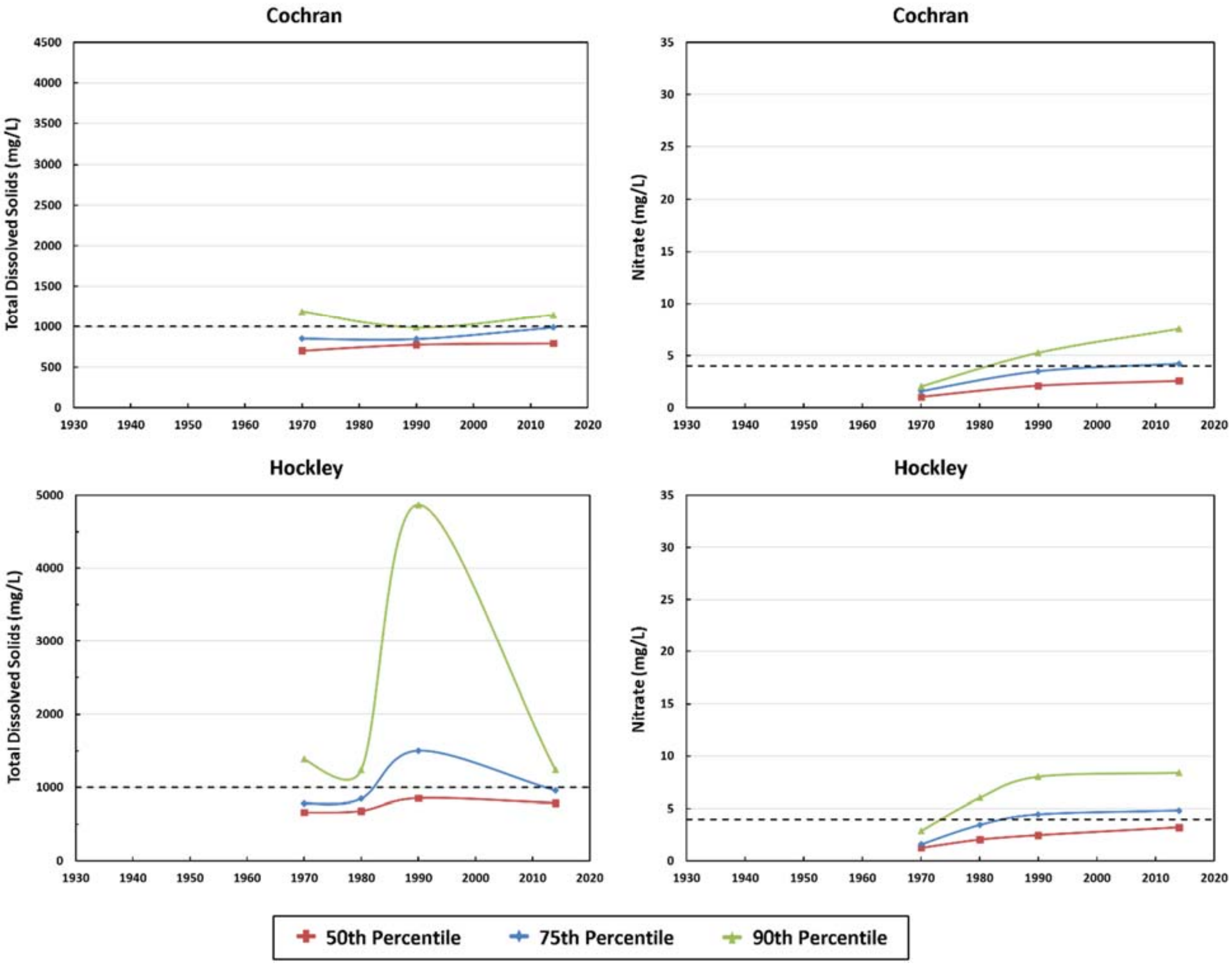


Figure 4.4.13 Counties with little to no evidence of recharge due to agriculture.

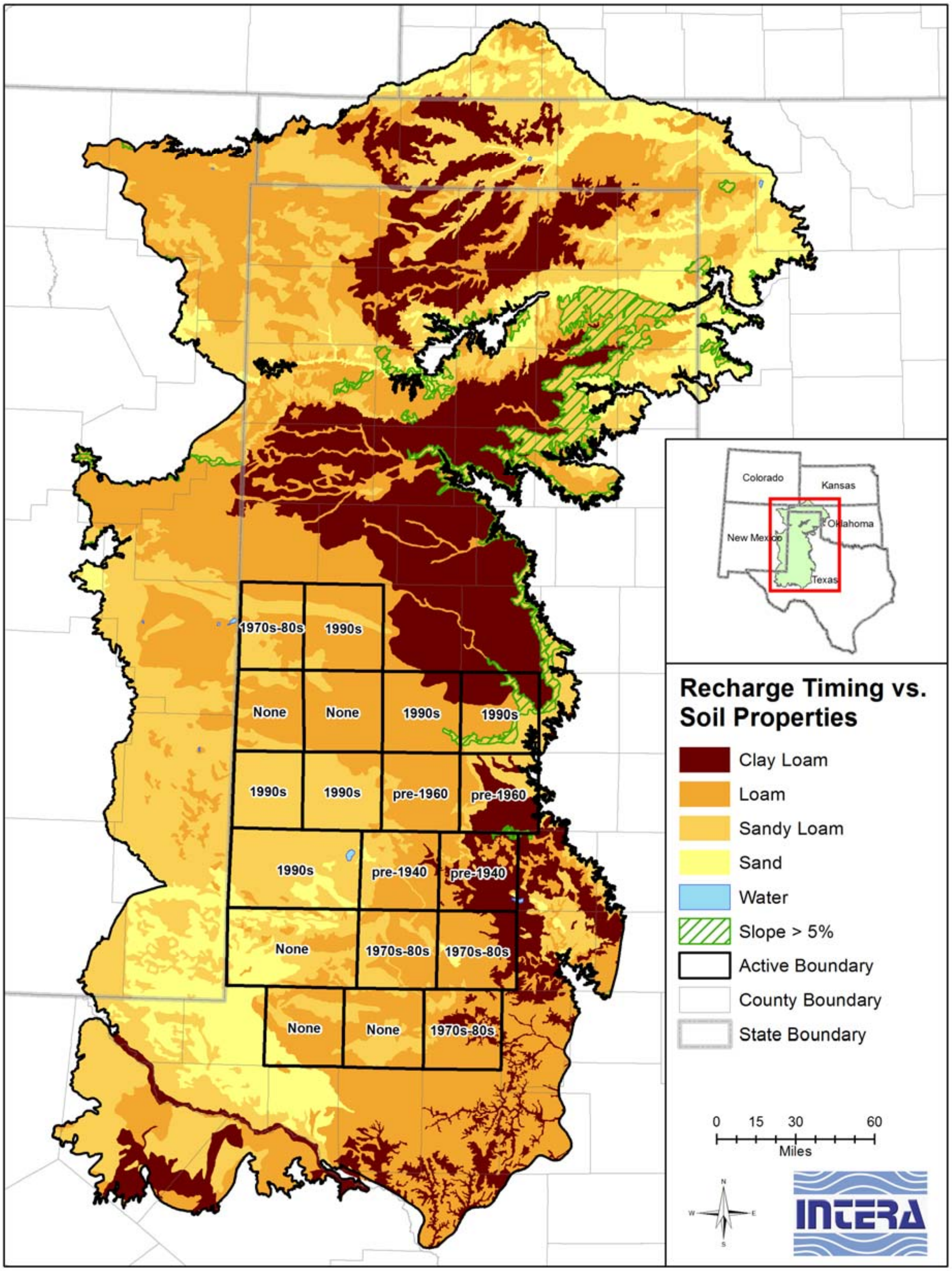


Figure 4.4.14 Timing of recharge compared to soil type based on STATSGO (United States Department of Agriculture, 1994) in the Southern Ogallala Aquifer.

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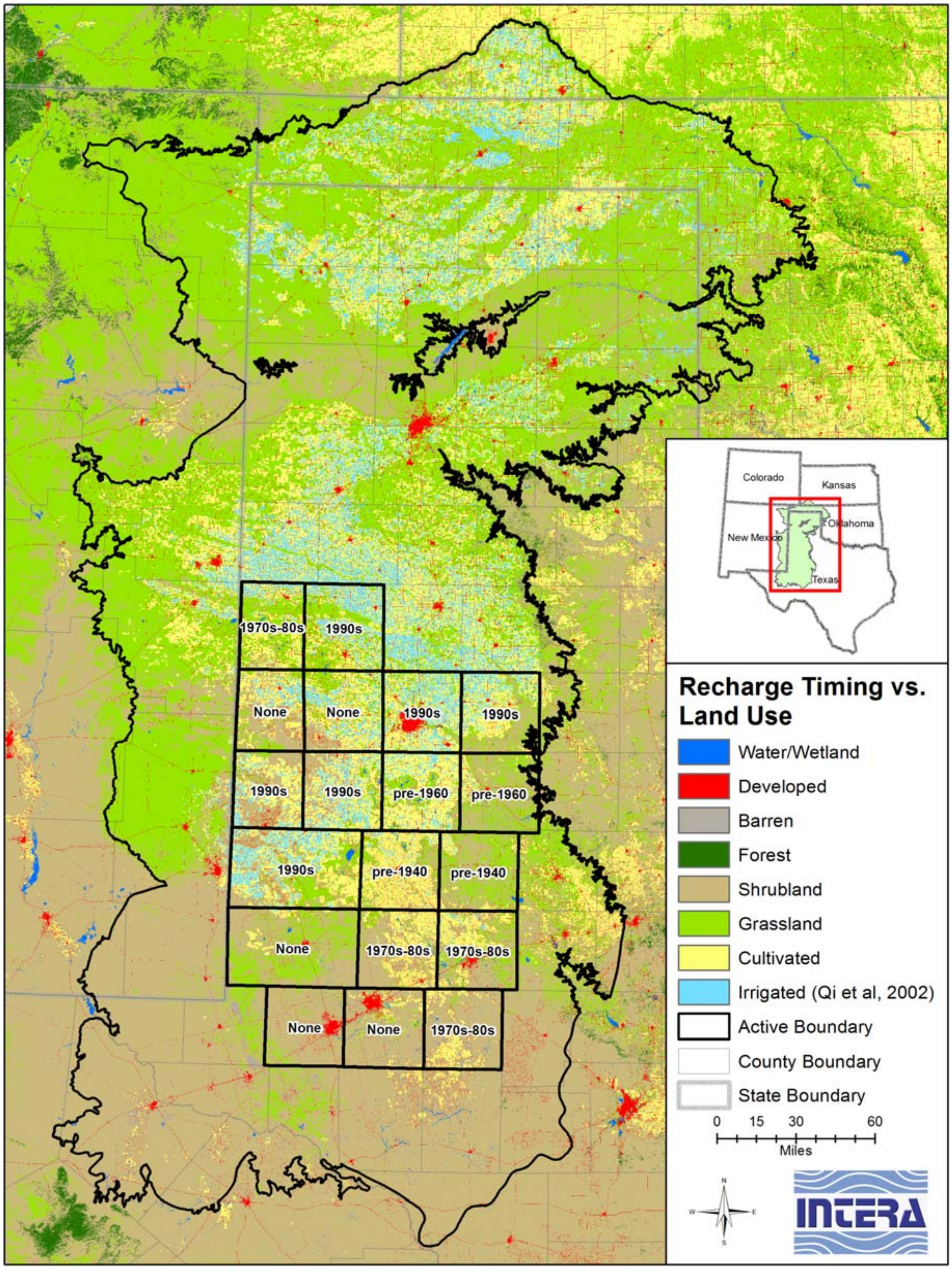

Figure 4.4.15 Timing of recharge compared to land use (Fry and others, 2011; Qi and others, 2002) in the Southern Ogallala Aquifer.

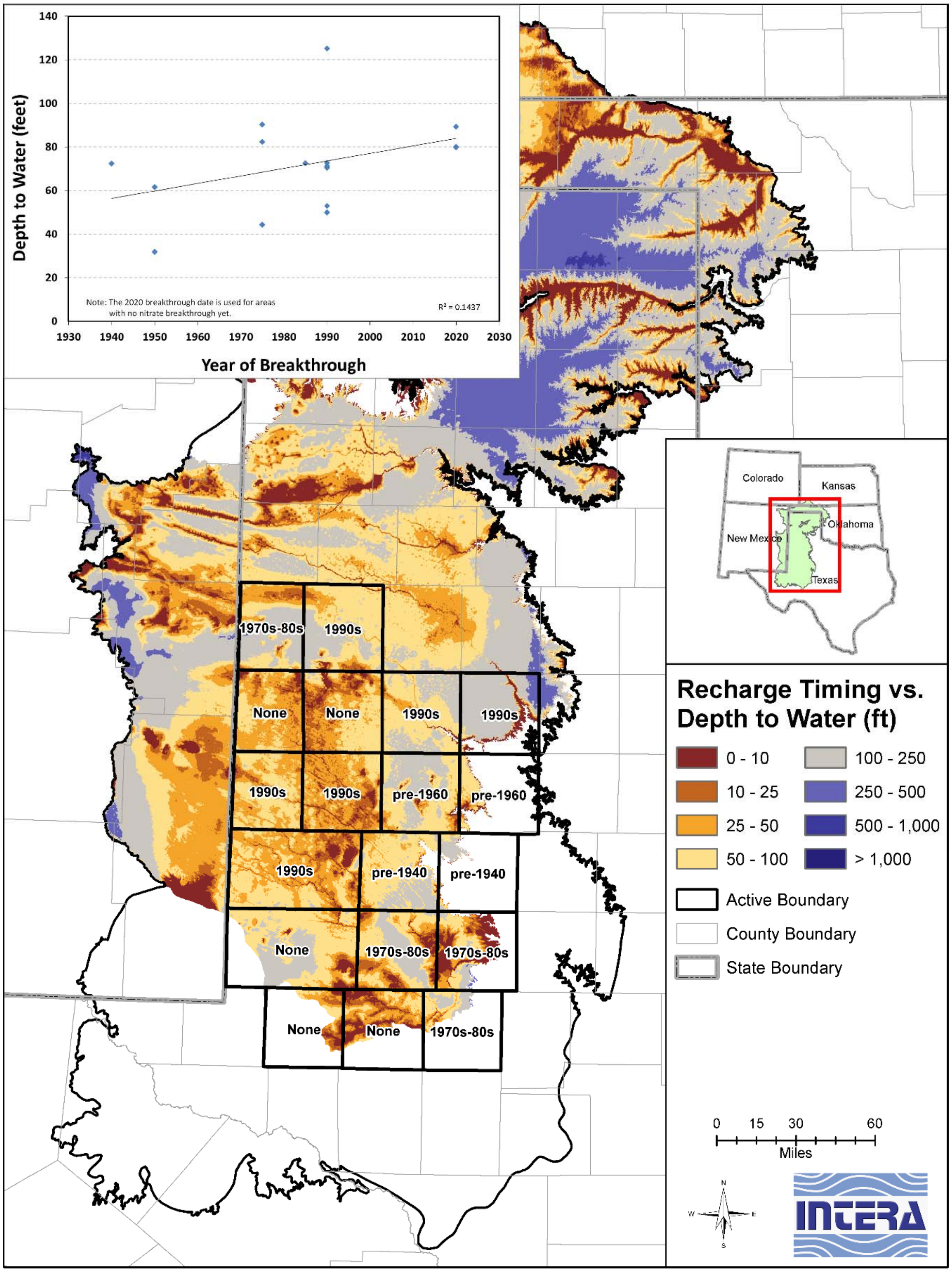

Figure 4.4.16 Timing of recharge compared to depth to water in the Southern Ogallala Aquifer.

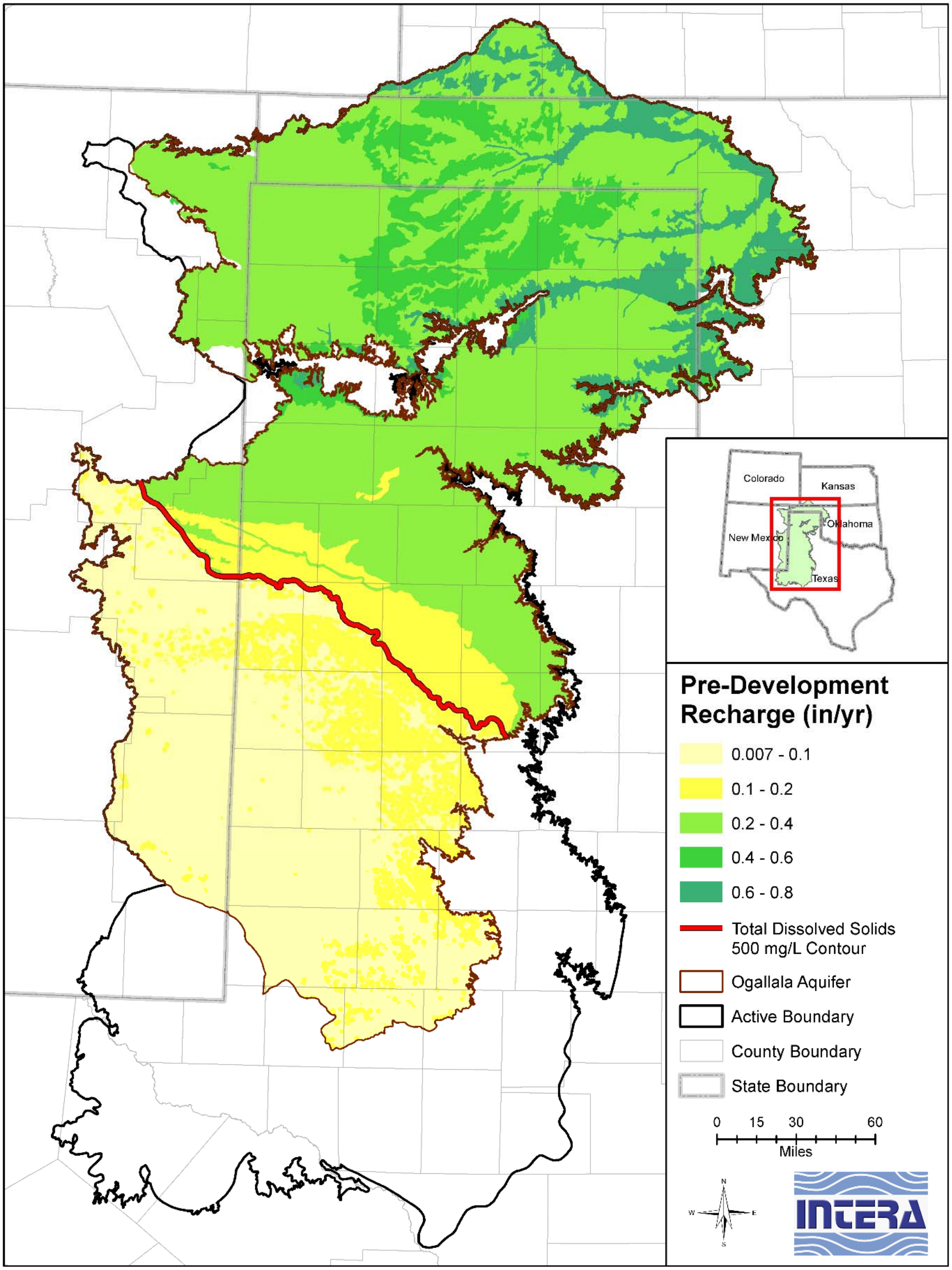

Figure 4.4.17 Pre-development recharge distribution in inches per year for the Ogallala Aquifer.

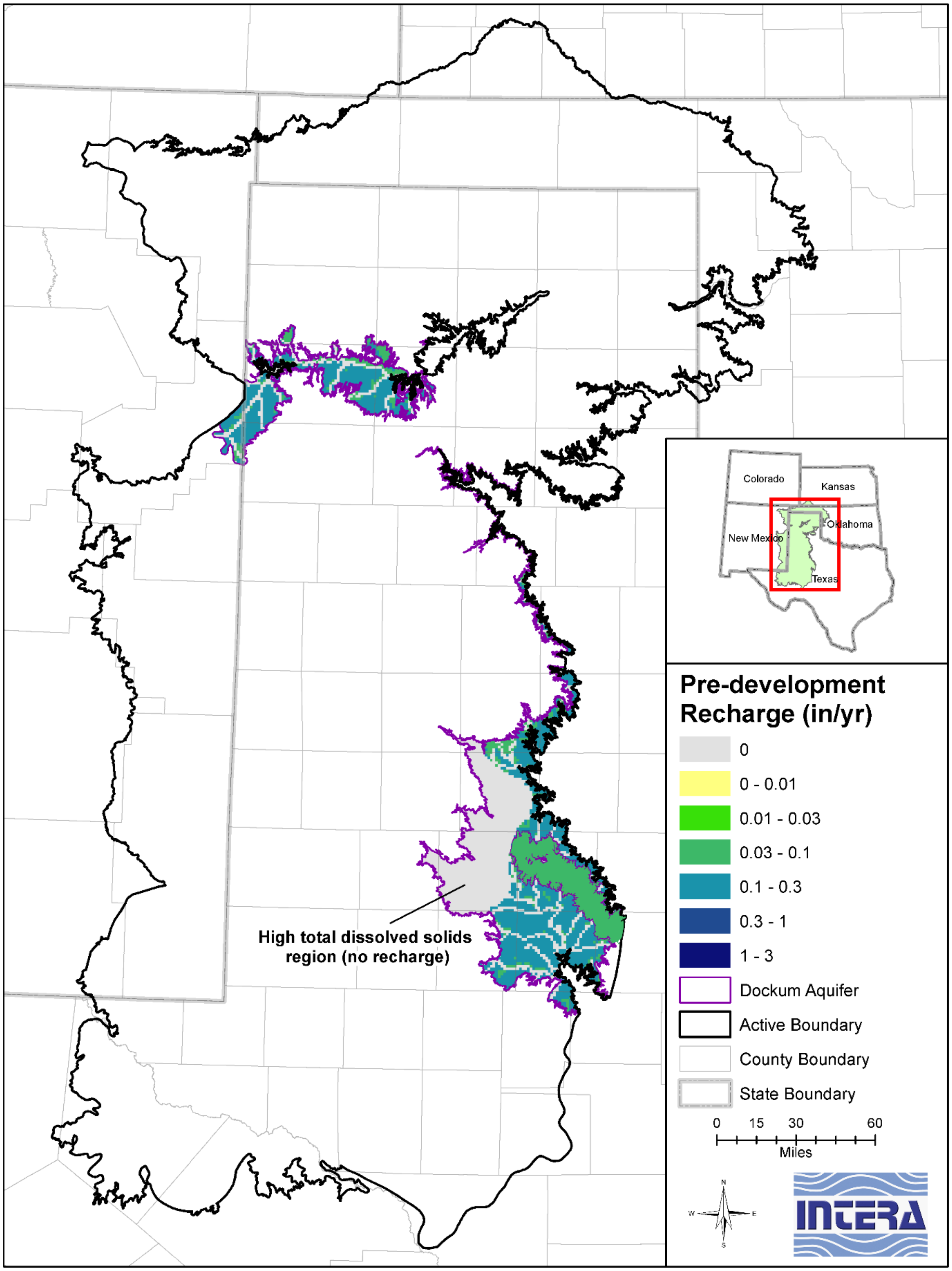

Figure 4.4.18 Pre-development recharge in inches per year for the Dockum Aquifer.

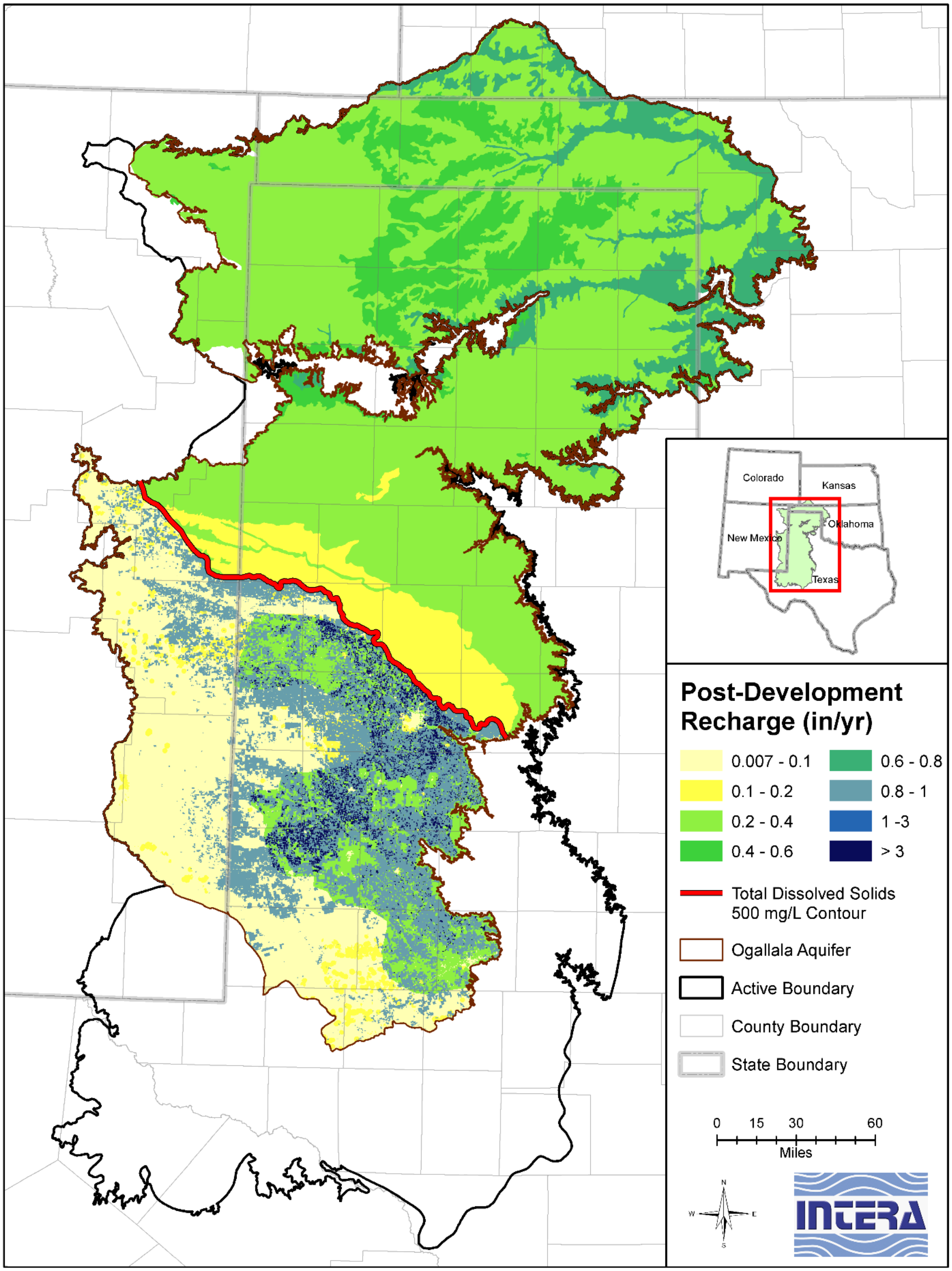

Figure 4.4.19 **Post-development recharge distribution in inches per year in the Ogallala Aquifer.**

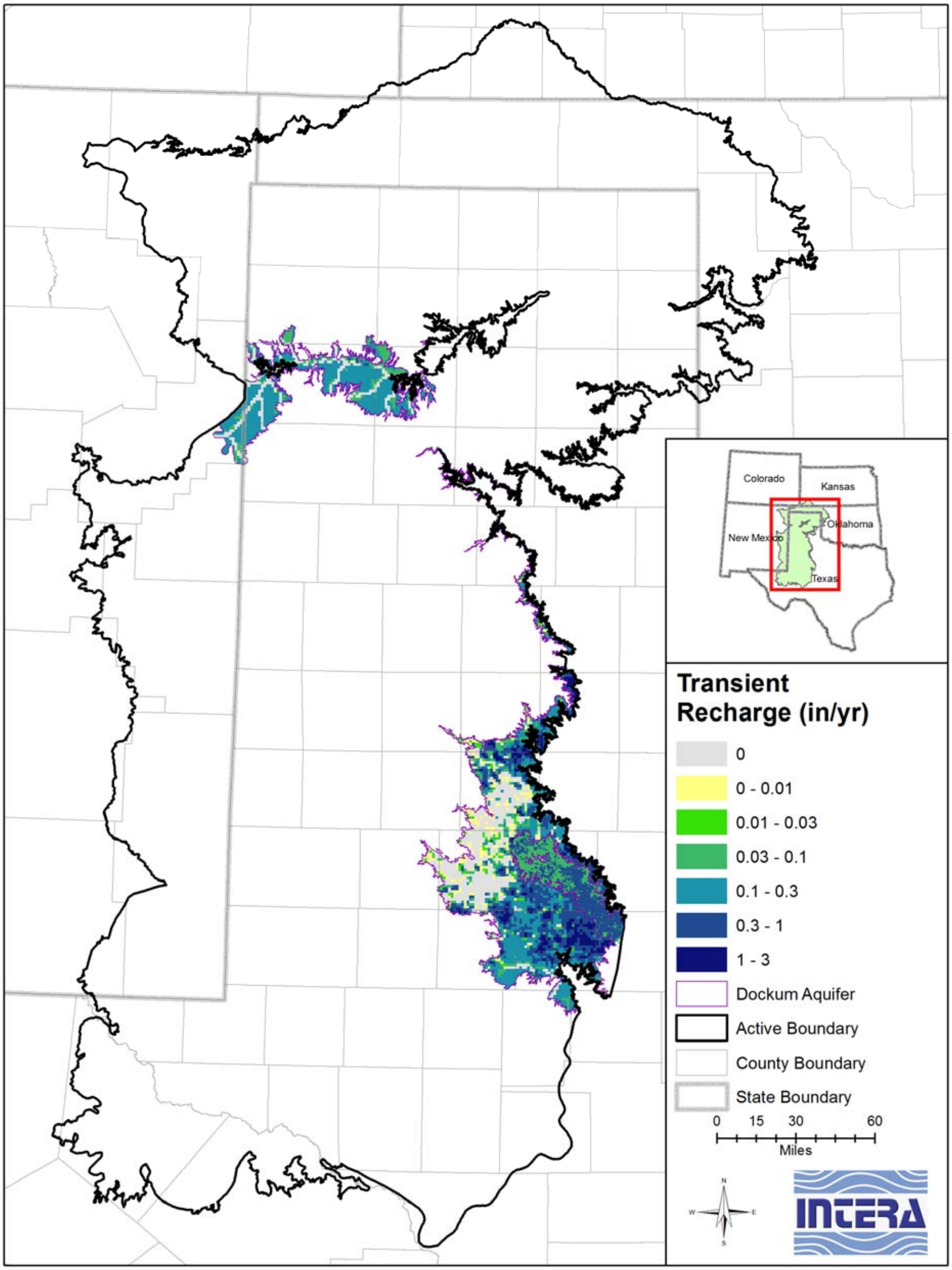

Figure 4.4.20 Post-Development recharge in inches per year in the Dockum Aquifer.

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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. Springs or seeps occur where the water table intersects the ground surface and there is discharge from an aquifer. Lakes can provide a potential site of focused recharge to an aquifer.

Generally, direct exchange between surface water and groundwater is limited to areas where a surface water feature intersects the aquifer outcrop. For the purposes of this study, the entire extent of the Ogallala Aquifer is considered outcrop, given its unconfined nature. However, surface water-groundwater interaction in the Dockum and Rita Blanca aquifers is assumed to be limited to the outcrop area. The Edwards-Trinity (High Plains) Aquifer does not outcrop within the study area and so is not considered a site of any major recharge or discharge.

4.5.1 Rivers and Streams

Three major rivers cross the study area: the Beaver (North Canadian), Canadian, and Pecos rivers (Figure 4.5.1). The Cimarron River drains the northernmost tip of the study area and forms the northern boundary for our model. Headwaters of the Washita, North Fork Red, Prairie Dog Town Fork Red, White, Double Mountain Fork Brazos, and Colorado rivers also drain the easternmost portion of the study area. This analysis focuses on identifying and quantifying the potential groundwater-surface water interaction occurring in areas where these rivers intersect aquifer outcrops. Potential sites for the Ogallala Aquifer include portions of the Cimarron, Beaver, Canadian, Washita, North Fork Red, Prairie Dog Town Fork Red, White, and Double Mountain Fork Brazos rivers. Potential sites for the Dockum Aquifer included portions of the Canadian, Colorado, Double Mountain Fork Brazos, White, and Prairie Dog Town Fork Red rivers. No major rivers intersect the Rita Blanca Aquifer outcrop.

While the southern portion of the Ogallala Aquifer has no major perennial rivers, it does have several major intermittent drainages, or "draws", most of which were formerly spring fed. The location of these draws may be controlled by underlying geologic structure, as they generally follow the northwest-southeast orientation of principal lineament trends (Fallin, 1989; Reeves and Reeves, 1996). Figure 4.5.1 shows the location of major draws overlying the southern portion of the Ogallala Aquifer. When flowing, Palo Duro, Frio, Tierra Blanca, and Tule creeks drain to the Red River; Running Water, Catfish, Blackwater, and Yellow House draws drain to the Brazos River; and Sulphur Springs, McKenzie, Sulphur, Lost, Wardswell, Seminole, Monument, Mustang, Midland, Johnson, and Monahans draws drain to the Colorado River. Though these draws are not currently important sources of surface water, they are useful in that they do show where springs likely occurred prior to groundwater development.

Figure 4.5.2 shows the locations of United States Geological Survey stream gages in the model area. Figure 4.5.3 shows hydrographs from select gages located on major rivers in the study area. The Cimarron River is the least flashy, in that the others show variations over orders of magnitude in daily flow. This trend is consistent with the precipitation distribution in the area (see Figure 2.1.6). Since precipitation is greater in the north, the recharge and, thus, base flow, should be steadier. In the north, the Cimarron and Canadian rivers are perennial, containing non-zero flow more than 97 percent of the time. Since precipitation decreases towards the south, the southern rivers are expected to be more sensitive to rain-runoff events, causing the dramatic spikes seen in the hydrographs on the Colorado and Brazos rivers. There is also less base flow expected under drier conditions, which would account for the dips seen in these hydrographs as well. They are both intermittent, containing no flow greater than 10 percent of the time. Since it is also located in the south, the Pecos River should also be intermittent. However, it is perennial at gage 08412500 and does not display as much variation in flow as the other southern rivers because its flow is regulated upstream by Red Bluff Reservoir.

There are no literature values available for streambed conductance in the model area. Due to uncertainty and considerations of scale, streambed conductance is typically a calibration parameter for regional groundwater models.

4.5.1.1 Gain/Loss Studies

Gain/loss studies are used to estimate gaining or losing conditions in a stream by performing a flow balance between two stream control points. The net gain, or loss, of flow between the two control points is attributed to stream gain or loss. The studies are performed at low-flow conditions because this method assumes that surface runoff is negligible. It is also important to characterize the timing, quantity and downstream propagation of all diversions and return flows occurring over the period of the study. Two reports documenting historical stream gain/loss studies were reviewed and summarized for Texas. The first is Slade and others (2002) who compiled the results of United States Geological Survey gain/loss studies conducted in Texas, and the second is by Baldys and Schalla (2011) who studied aquifer-stream interaction on the Brazos River. The Hemphill County Underground Water Conservation District also provided low-flow measurements collected during a water rights acquisition study (R.W. Harden and Associates, 2013).

4.5.1.1.1 United States Geological Survey Streamflow Gain-Loss Studies in Texas (Slade and others, 2002)

A comprehensive compilation of gain/loss studies in Texas was completed by Slade and others (2002). This compilation contains the results of 366 gain/loss studies conducted since 1918, which include 249 individual stream reaches throughout Texas. They document 14 gain/loss studies intersecting the High Plains Aquifer System (Figure 4.5.4). These studies are all located in the southern portion of the active model area and there are none on the Canadian River or above. There are five studies that include reaches that cross the Ogallala Aquifer and 12 studies that cross the Dockum Aquifer outcrop. Tables 4.5.1 and 4.5.2 summarize the results of the gain/loss studies crossing the Ogallala and Dockum aquifers, respectively. According to the compiled low-flow studies, Tierra Blanca Creek (studies 250 and 251) is consistently losing as it crosses the Ogallala Aquifer. Beals Creek (studies 37 through 39) alternates between losing and gaining reaches over the Ogallala Aquifer, but is also losing on average. Beals Creek transitions to slightly gaining as it crosses the Dockum Aquifer outcrop. Earlier studies of the Colorado River (studies 45 through 48, 52) show slightly gaining conditions over the Dockum Aquifer outcrop, but more recent studies (studies 42 through 44) indicate slightly losing conditions. The stretch of the Prairie Dog Town Fork Red River that crosses the Dockum Aquifer (study 247) is slightly gaining on average.

It is important to remember that gain-loss studies represent a snapshot of the river at a given time, rather than a long-term average. Streams can change both temporally (for example, be both gaining and losing within the same year) and spatially (for example, have a gaining stretch followed by a losing stretch). Inconsistencies can arise because analyzed measurements are typically recorded over a relatively short time span, but base flow has a strong climatically driven temporal component. This becomes problematic since groundwater flow models generally try to reproduce the average stream-aquifer interaction that may be integrated over a season or even a year. So we should be cautious in using the result from a gain/loss study as an average base flow to compare to model results.

4.5.1.1.2 United States Geological Survey Gain/Loss Studies for the Brazos River (Baldys and Schalla, 2011)

The United States Geological Survey conducted stream flow gain and loss measurements in 2010 and base flow analyses for 1966 to 2009 along the Brazos River and its tributaries (Baldys and Schalla, 2011). The study extended from the New Mexico-Texas state line to Waco, Texas. The gages they analyzed for gain/loss studies within the active model boundary are shown in Figure 4.5.5 and summarized in Table 4.5.3, along with their analysis results. None of the gages used in their base flow analysis fall within our study area.

Seasonal measurements of discharge and specific conductance were made in June and October 2010 along the Brazos River and its tributaries in order to characterize the gaining or losing nature of the stream. The study found that sites on the Salt Fork intersecting the Ogallala Aquifer have no flow in either season (sites SF 1 through 3), indicating no base flow input. The one site overlying the Dockum Aquifer outcrop (SF-4) has scant flow in both seasons, indicating some base flow input but very little. On the Double Mountain Fork Brazos River, two sites overlying the Ogallala Aquifer (DMF 1 and 2) have no flow in either season, but the two sites in the Dockum Aquifer outcrop (DMF 3 and 4) have flow in both seasons. However, this gain is attributed to discharges from the City of Lubbock's well field rather than to base flow input. The stretch between these two sites is actually a losing stretch. Another site on the South Fork Double Mountain Fork Brazos River also located in the Dockum Aquifer outcrop, contains some flow in October but not June, indicating some base flow input from the Dockum Aquifer, but again very little.

4.5.1.1.3 Hemphill County Surface Water Flow Measurements (R.W. Harden and Associates, 2013)

As part of Mesa Water's water rights acquisition and permitting process, R.W. Harden and Associates (2013) collected streamflow measurements at six sites on the Canadian and Washita rivers as well as Gageby and Wolf creeks (Figure 4.5.5 and Table 4.5.4). Streamflow was measured quarterly from December 2006 to March 2010, except during periods when total flow was not representative of base flow due to rain, high flow, or restricted flow. Because these measurements do not take into account delayed discharge, in-stream storage capacity or evapotranspiration, they only offer approximate base flow estimates. In addition, there is no gain/loss analysis provided for the stretches of river between measurement points. Wolf Creek (WC) and Gageby Creek (GC) have no sequential gages that would allow a gain/loss calculation, but since both seem to have perennial flow, we can assume that a portion of these creeks at or above the measurement point must be gaining. The Washita River has sequential gages (WR-4 and WR-5), but there are too few base flow measurements to allow a reliable gain/loss calculation. The few data points that are available seem to indicate that that stretch is losing. The Canadian River between sites CR-1 and CR-2 appears to be gaining according to base flow measurements. However, it is unclear whether or not there are other tributaries or sources of water contributing to that stretch. These low-flow values are, therefore, useful in establishing bounds for seasonal groundwater input to these streams but can't be used as quantitative base flow targets in our model.

4.5.1.2 Hydrograph Separation Studies

Hydrograph separation is a methodology whereby stream flow hydrograph data are analyzed and surface runoff is partitioned from the stream base flow component. The basic premise of this method is that the sharp peaks in the stream flow hydrograph represent surface runoff events, and the smooth, constant portion of the stream flow hydrograph represents base flow. The base flow for a stream is then assumed to be flow supplied by groundwater. There are several automated methods available to perform the hydrograph separation. Figure 4.5.6 shows the results of the hydrograph separation code Base Flow Index (Wahl and Wahl, 1995) for streamflow gage 07301410 located on Sweetwater Creek near Kelton, Texas in Wheeler County. This figure shows a relatively steady base flow component across orders of magnitude changes in overall flow. Once base flow is estimated using hydrograph separation, an estimated shallow areal recharge flux can be calculated by dividing the estimated base flow rate by the drainage area. However, a new hydrograph separation study and recharge calculation was not attempted in the current study. Accurate base flow calculation depends on a stream being perennial and unregulated by diversions or dams. The recharge calculation assumes that the actual contributing area is the same as the total topographically-defined drainage area, which is not necessarily the case in an arid environment. Only three of the United States Geological Survey gages in the area were perennial, with at least 10 years of flow data unregulated by diversion or dams, and had a contributing area that matched the total drainage area. Since these were small watersheds at the edge of the study area, they are not likely to be representative of much of the High Plains Aquifer System. The following section briefly summarizes another historical base flow analysis conducted in the active model area (Wolock, 2003a,b).

4.5.1.3 United States Geological Survey Conterminous United States Baseflow Study (Wolock, 2003a,b)

In 2003, the United States Geological Survey published a study for the entire conterminous United States that estimated the base flow component of streamflow at more than 19,000 United States Geological Survey stream gages (Wolock, 2003a). These point estimate values were then used to interpolate a 1-km grid raster dataset of base-flow index values that could be used to estimate base-flow index values even for streams with no gaged data (Wolock, 2003b). The base-flow index is the ratio of base flow to total stream flow, expressed as a percentage. The estimates of stream base flow were calculated using the Base Flow Index code (Wahl and Wahl, 1995).

Figure 4.5.7 plots the gage estimated base-flow index ratios in the study area after Wolock (2003a,b). In general, the base-flow index values in the northeastern and southeastern corners are higher than elsewhere in the model area, indicating a larger groundwater contribution. This is expected as these areas also generally receive more precipitation than the rest of the area (see Figure 2.1.6). Overall, the base-flow index values in the model area are all greater than zero, which indicates that most streams are on average and over the long term, gaining streams. However, this is inconsistent with the high number of ephemeral streams, particularly in the central-western portion of the model area. This inconsistency is likely due to the fact that none of the gages on these west-central ephemeral draws was included in the analysis (Figure 4.5.7). The study also does not discriminate between regulated and un-regulated gages so, while it is helpful for establishing an approximate spatial distribution of base flow, these numbers cannot be used as quantitative base flow targets for the model.

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. Several sources were used to find spring data for the

High Plains Aquifer System. In Texas, spring information was taken from the TWDB groundwater database (TWDB, 2013), Brune (2002), and a United States Geological Survey database of Texas springs reported in Heitmuller and Reece (2003). In New Mexico, spring information was taken from White and Kues (1992). In Oklahoma, spring information came from the United States Geological Survey National Water Information System database (United States Geological Survey, 2013b).

Figure 4.5.8 shows the locations of springs that flow or formerly flowed in the study area. Springs with recorded flow measurements are circled in black. The literature identified 666 springs or groups of springs in the study area, of which 194 flow out of the Ogallala Aquifer, 96 out of the Dockum Aquifer, three out of the Edwards-Trinity (High Plains) Aquifer and eight out of the Rita Blanca Aquifer. Six springs flowed from a combination of Ogallala and Dockum aquifers and three had sources described as a combination of Ogallala and Rita Blanca aquifers. The remainder flow from alluvium, formations older than the Dockum Aquifer, or unknown sources and so are not used in this discussion.

Many of the Ogallala Aquifer springs are located along the Eastern Caprock Escarpment (eastern edge of the active model boundary in figure) or clustered along draws in the central portion of the study area. As mentioned earlier, most draws in the area are, or formerly were, spring fed. Many of the Dockum Aquifer springs are also located along the Eastern Caprock Escarpment in addition to the Canadian and Colorado River outcrop areas.

Recorded flow measurements from springs in the study area are given in Table 4.5.5. One hundred and eighteen springs do, or at one time did, discharge at a rate greater than or equal to 100 gallons per minute (0.22 cubic feet per second). Figure 4.5.9 shows hydrographs from Roaring Springs and Chicken Springs, which both have multi-decadal time series of measured discharge. Roaring Springs, which issues from the Dockum Aquifer in Motley County, had a measured high flow of 1,125.4 gallons per minute (2.51 cubic feet per second) in 1946. The hydrograph 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 1978. Chicken Springs, which flows from the Ogallala and Dockum aquifers in Potter County, had a measured high flow of 1,521.6 gallons per minute (3.39 cubic feet per second) in 1956. Discharge from Chicken Springs steadily declined between about 1956 and 1962 and remained relatively stable from 1962 to 1978.

Throughout much of the state, including the study area, spring flows have shown a general decline over time. Brune (2002) notes that declining water levels due to pumping has resulted in reduced flow in many of the springs. However, most information regarding spring declines for minor springs is anecdotal and undocumented. Table 4.5.5 shows that only 74 springs have two or more recorded flow measurements. Of the springs with more than one measurement, 57 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. However, much of the data are point measurements and in some cases, the only available measurements were taken months apart and so are not indicative of longer-term trends. In addition, the data do not extend to the present, so the available measurements do not necessarily represent the current condition of these springs.

Information on springs with no recorded flow measurements is given in Table 4.5.6. Though lacking quantitative discharge data, they are still useful for creating our conceptual model. Because their locations are known, elevations were assigned based on the 10-m digital elevation model (see Figure 2.1.3) and used to constrain the pre-development water levels presented in Section 4.3.

4.5.3 Lakes and Reservoirs

There are no natural perennial lakes in the study area. However, eighteen reservoirs intersect the model area, thirteen of which have areas greater than one square mile (640 acres). Table 4.5.7 lists the names, owners, area, and year impounded for these reservoirs. Of these, eight overlie the Ogallala Aquifer, eight overlie the Dockum Aquifer outcrop, and one overlies both. Red Bluff Reservoir, one of the largest reservoirs intersecting the study area, overlies the Pecos Valley Aquifer. Figure 4.5.10 shows the locations of the reservoirs. Figure 4.5.11 shows the historical lake stage elevations from the United States Geological Survey National Water Information System database (United States Geological Survey, 2013b) for three of the reservoirs. The hydrograph for Lake Meredith, which intersects the Ogallala Aquifer, shows elevation fluctuations from about 2,842 to 2,909 feet above mean sea level with an average value of about 2,879 feet above mean sea level. The hydrograph for Red Bluff Reservoir, which intersects the Pecos Valley Aquifer, shows elevation fluctuations from about 2,795 to 2,824 feet above mean sea level with an average value of about 2,811 feet above mean sea level. The hydrograph for Lake Colorado City, which intersects the Dockum Aquifer outcrop, shows elevation fluctuations from about 2,049 to 2,072 feet above mean sea level with an average value of about 2,061 feet above mean sea level. Lake Meredith has shown the steadiest decline, losing almost 70 feet of elevation since 2000. But Red Bluff Reservoir and Lake Colorado City have also shown declines of tens of feet in recent years. The reservoirs located in outcrop areas provide potential locations for focused recharge to or discharge from the underlying aquifers.

Natural saline lakes and playa lakes, both of which are common in the High Plains, are also areas of potential surface water interaction with aquifers. There are nearly 40 larger saline lakes overlying the Southern Ogallala Aquifer (Wood and Jones, 1990; Reeves and Reeves, 1996). The names and locations of these lakes are shown in Table 4.5.8 and Figure 4.5.10, respectively. Saline lakes provide potential sites for shallow aquifer discharge. They occur in topographic depressions typically characterized by erosion of the Ogallala Formation on top of a topographic high in the underlying Cretaceous deposits. They are fed by precipitation runoff and shallow groundwater discharge from the Ogallala Aquifer and occasionally the Edwards-Trinity (High Plains) Aquifer. The total dissolved solids concentration can be significantly higher in these lakes compared to the Ogallala Aquifer due to evaporation (Wood and Jones, 1990).

There are also thousands of small playa lakes distributed across the study area (see Figure 4.5.10). These are fed by precipitation runoff and since most lie above the water table, they can provide potential sites for significant aquifer recharge. These can be particularly important in low permeability areas with little to no other sources of recharge. The impact of playas on recharge to the High Plains Aquifer System is discussed in further detail in Section 4.4.3.5.

Table 4.5.1 Summary of gain/loss studies intersecting the Ogallala Aquifer (Slade and others, 2002).

Study	Date	Gain or Loss (-) in Subreach (cfs)	Length of Subreach (river mile)	Aquifer	Total Gain or Loss (-) per Mile of Reach (cfs/mi)
Beals Cr - FM 87 to 0.5 mi above mouth					
37	2/24/1986	0.07	6.7	Ogallala, Dockum	0.01
		-0.04	4.2	Ogallala	-0.01
		5.15	6.2	Ogallala	0.83
		-5.14	2.2	Ogallala	-2.34
38	12/9-10/1986	-0.23	6.7	Ogallala, Dockum	-0.03
		7.52	4.2	Ogallala	1.79
		5.5	6.2	Ogallala	0.89
		-16.55	2.2	Ogallala	-7.52
Beals Cr - US 87 to 0.5 mi above mouth					
39	2/27-3/1/1989	2.15	2.2	Ogallala, Dockum	0.98
		-5.34	6.2	Ogallala	-0.86
		5.46	4.2	Ogallala	1.30
Tierra Blanca Cr - near Umbarger to near Canyon					
250	8/31/1941	0	2	Ogallala	0.00
		-0.2	1.8	Ogallala	-0.11
		-0.36	1.2	Ogallala	-0.30
		-0.2	1.6	Ogallala	-0.13
		-0.03	2.6	Ogallala	-0.01
		-0.83	1.7	Ogallala	-0.49
		-2.91	7	Ogallala	-0.42
251	9/28/1941	-0.62	9.2	Ogallala	-0.07
		-0.92	2.1	Ogallala	-0.44
		-0.04	3.2	Ogallala	-0.01
		-0.48	1.7	Ogallala	-0.28
		-0.54	1.7	Ogallala	-0.32

Table 4.5.2 Summary of gain/loss studies intersecting the Dockum Aquifer (Slade and others, 2002).

Study	Date	Gain or Loss (-) in Subreach (cfs)	Length of Subreach (river mile)	Aquifer	Total Gain or Loss (-) per Mile of Reach (cfs/mi)
Beals Creek - FM 87 to 0.5 mi above mouth					
37	2/24/1986	-0.11	14.7	Dockum	-0.01
		-0.23	17.6	Dockum	-0.01
		0.26	7.1	Dockum	0.04
38	12/9-10/1986	1.93	14.7	Dockum	0.13
		3.36	17.6	Dockum	0.19
		1.32	7.1	Dockum	0.19
Beals Creek - US 87 to 0.5 mi above mouth					
39	2/27-3/1/1989	1.34	14.7	Dockum	0.09
		0.17	24.7	Dockum	0.01
		0.1	6.7	Dockum	0.01
Colorado River - below Lake J.B. Thomas dam to FM 503 (08136700)					
42	2/24-26/1986	-0.25	7.7	Dockum	-0.03
		0.87	7	Dockum	0.12
		0.5	2.5	Dockum	0.20
		0.28	2.6	Dockum	0.11
		-8.2	0.9	Dockum	-9.11
		7.95	2	Dockum	3.98
		-4.65	9.5	Dockum	-0.49
		-0.36	9.3	Dockum	-0.04
		0.93	9.3	Dockum	0.10
		0.01	11.7	Dockum	0.00
43	1/6-9/1987	-37.2	7.7	Dockum	-4.83
		6	7	Dockum	0.86
		2.15	2.5	Dockum	0.86
		-0.8	2.6	Dockum	-0.31
		24.8	0.9	Dockum	27.56
		-24.35	2	Dockum	-12.18
		4.64	9.5	Dockum	0.49
		1.11	9.3	Dockum	0.12
		2.11	9.3	Dockum	0.23
		0.86	11.7	Dockum	0.07
44	2/27-3/1/1989	-9.38	7.7	Dockum	-1.22
		4.44	7	Dockum	0.63
		0.72	2.5	Dockum	0.29
		1.75	2.6	Dockum	0.67
		-22.64	0.9	Dockum	-25.16
		8.12	2	Dockum	4.06
		-0.1	9.5	Dockum	-0.01
		0.69	9.3	Dockum	0.07
		4.56	9.3	Dockum	0.49

Table 4.5.2, continued

Study	Date	Gain or Loss (-) in Subreach (cfs)	Length of Subreach (river mile)	Aquifer	Total Gain or Loss (-) per Mile of Reach (cfs/mi)
44	2/27-3/1/1989	0.78	11.7	Dockum	0.07
Colorado River - Bull Creek to Colorado City (08121000)					
45	2/14/1975	2.11	2.6	Dockum	0.81
		2.05	3.2	Dockum	0.64
		0.56	2.3	Dockum	0.24
		-0.78	6.2	Dockum	-0.13
		-0.17	6.2	Dockum	-0.03
		3.52	3.7	Dockum	0.95
		0.18	2.3	Dockum	0.08
		0.24	3.5	Dockum	0.07
		0.16	2.5	Dockum	0.06
		-0.04	2.9	Dockum	-0.01
		0.15	0.1	Dockum	1.50
46	11/13/1975	0.35	2.6	Dockum	0.13
		2.71	3.2	Dockum	0.85
		0.1	2.3	Dockum	0.04
		0.63	6.2	Dockum	0.10
		-0.04	6.2	Dockum	-0.01
		0.82	3.7	Dockum	0.22
		0.18	2.3	Dockum	0.08
		0.09	3.5	Dockum	0.03
		0.08	2.5	Dockum	0.03
		-0.01	2.9	Dockum	0.00
		0.05	0.1	Dockum	0.50
47	1/20/1976	0.08	2.6	Dockum	0.03
		-4.4	3.2	Dockum	-1.38
		0.07	2.3	Dockum	0.03
		0.57	6.2	Dockum	0.09
		-0.1	6.2	Dockum	-0.02
		1.02	3.7	Dockum	0.28
		0.34	2.3	Dockum	0.15
		-0.01	3.5	Dockum	0.00
		0.01	2.5	Dockum	0.00
		0.06	2.9	Dockum	0.02
		0.12	0.1	Dockum	1.20
48	3/2/1976	0.19	2.6	Dockum	0.07
		-4.74	3.2	Dockum	-1.48
		-0.24	2.3	Dockum	-0.10
		0.53	6.2	Dockum	0.09
		-0.24	6.2	Dockum	-0.04
		1.63	3.7	Dockum	0.44
		0.17	2.3	Dockum	0.07

Table 4.5.2, continued

Study	Date	Gain or Loss (-) in Subreach (cfs)	Length of Subreach (river mile)	Aquifer	Total Gain or Loss (-) per Mile of Reach (cfs/mi)
48	3/2/1976	0.28	3.5	Dockum	0.08
		0.08	2.5	Dockum	0.03
		-0.01	2.9	Dockum	0.00
		0.1	0.1	Dockum	1.00
Colorado River - near Vincent (08118000) to near Silver (08123900)					
52	4/8/1968	-0.07	7.5	Dockum	-0.01
		1.36	8	Dockum	0.17
		0.18	3.8	Dockum	0.05
		0.33	4.3	Dockum	0.08
		-0.77	3.4	Dockum	-0.23
		0.71	2.8	Dockum	0.25
		0.38	2.8	Dockum	0.14
		-0.2	5	Dockum	-0.04
		-0.05	2.3	Dockum	-0.02
		-0.02	5.6	Dockum	0.00
		0.45	10.3	Dockum	0.04
Prairie Dog Town Fork Red River - Lake Tanglewood to Wayside (07297910)					
247	2/6-9/1968	0.43	3.1	Dockum	0.14
		0.3	1.4	--	0.21
		-0.06	0.9	Dockum	-0.07
		-0.01	1.7	Dockum	-0.01

Table 4.5.3 Summary of analyzed gages from Baldys and Schalla (2011) in the study area.

USGS Gage Number	Station Name	Site Identifier	Discharge (ft^3/s)	
			June 6-9, 2010	Oct 16-19, 2010
341643102013700(1)	Running Water Draw at FM 2884 near Edmonson, TX	SF-1	no flow	no flow
8080700	Running Water Draw at Plainview, TX	SF-2	no flow	no flow
335939101293500(1)	Running Water Draw at FM 784 at Sandhill, TX	SF-3	no flow	no flow
8080900	White River below falls near Crosbyton, TX	SF-4	0.06	0.07 (est.)
335325101593700(1)	Blackwater Draw at FM 179 near Abernathy, TX	DMF-1	no flow	no flow
334137102005900(1)	Yellow House Draw at FM 1294 at Shallowater, TX	DMF-2	no flow	no flow
333047101393300(1)	North Fork Double Mountain Fork Brazos River at FM 400 near Lubbock, TX	DMF-3	22.83/6.90(2)	2.28/7.86(2)
331909101232900(1)	North Fork Double Mountain Fork Brazos River at FM 207 near Post, TX	DMF-4	2.78	3.17
8079600	Double Mountain Fork Brazos River at Justiceburg, TX	DMF-5	no flow	0.2

(1) All 15-digit gages were created solely for the purpose of the USGS study and so no historical data is available.
(2) Two given discharge values separated by a slash indicate replicate measurements.

Abbreviation key: USGS = United States Geological Survey; TX = Texas; ft^3/s = cubic feet per second; est. = estimated.

Table 4.5.4 Summary of streamflow measurements (in cubic feet per second) from R.W. Harden & Associates (2013).

		Canadian River-1 (CR-1)	Canadian River-2 (CR-2)	Gageby Creek (GC)	Washita River-4 (WR-4)	Washita River-5 (WR-5)	Wolf Creek (WC)
2006	**12/6/2006**	24.77	38.04	3.33	2.29	No Flow	0.51
2007	**3/21/2007**	42.19	71.92	4.63	6.8	10.2	1.48
	2nd QTR	Rain	Rain	Rain	Rain	Rain	Rain
	8/10/2007	Low Flow	8.25	3.51	No Flow	No Flow	2.31
	11/20/2007	16.2	29.88	4.33	9.67	5.19	1.48
2008	**3/27/2008**	32.4	61.34	4.05	7.13	7.36	3.46
	4/16/2008	25.36	43.43	2.67	5.77	3.47	2.94
	9/11/2008	21.87	39.89	5.54	High Flow	High Flow	Flow Restricted
	4th QTR.	Rain	Rain	Rain	Rain	Rain	Rain
2009	**4/9/2009**	38.78	68.54	4.75	13.53	Flow Restricted	Flow Restricted
	5/27/2009	44.11	103.28	6.41	11.29	High Flow	4.82
	8/25/2009	34.22	58.55	7.79	7.22	Flow Restricted	Flow Restricted
	11/5/2009	28.35	58.06	5.01	6.67	Flow Restricted	Flow Restricted
2010	**3/24/2010**	55.14	96.2	6.19	13.32	Flow Restricted	Flow Restricted

Table 4.5.5 Springs with flow measurements.

County	Spring Name/Number	Site Number*	Longitude (decimal Degrees)	Latitude (decimal Degrees)	Max Flow (gpm)	Date of Max Flow	Min Flow (gpm)	Date of Min Flow	# of Measure-ments	Geologic Source	Reference
Andrews, TX	Baird Springs	Andrews8	-102.304	32.1792	1.6	4/19/1979	1	3/21/1977	2	Ogallala	Brune
Armstrong, TX	Dripping Springs	Armstrong9	-101.385	34.92559	15	1940	seeps	8/1978	2	Dockum	Brune (2002)
Armstrong, TX	Harrell Springs	Armstrong13	-101.581	34.93126	10	1940	dry	8/1978	2	Dockum	Brune (2002)
Armstrong, TX	Hidden Springs	Armstrong15	-101.578	34.83499	30	8/11/1978	---	---	1	Dockum	Brune (2002)
Armstrong, TX	Pleasant Springs	Armstrong7	-101.48	34.78205	150.6	4/1/1940	19	8/7/1978	2	Unknown	Brune
Bailey, TX	White Springs	Bailey8	-102.685	33.89691	1.0	1977	---	---	1	Unknown	Brune
Bailey, TX	Alkali Springs	Bailey13	-102.751	33.95923	0.5	1936	---	---	1	Ogallala	Brune
Bailey, TX	no name	Bailey14	-102.707	33.88326	0.5	1936	---	---	1	Unknown	Brune
Briscoe, TX	Cottonwood and Red Rock Springs	Briscoe15	-101.13	34.39612	417	7/10/1979	---	---	1	Dockum	Brune (2002)
Briscoe, TX	Deer Springs	Briscoe5	-101.402	34.7052	301.2	9/9/1946	20.6	9/4/1978	3	Unknown	Brune
Briscoe, TX	Turkey Springs	Briscoe6	-101.365	34.70485	396.3	9/9/1946	39.6	9/4/1978	3	Unknown	Brune
Briscoe, TX	Cedar Springs	Briscoe7	-101.349	34.69016	253.6	9/9/1946	15.9	9/4/1978	3	Unknown	Brune
Briscoe, TX	no name	Briscoe8	-101.452	34.49767	206.1	9/10/1946	---	---	1	Dockum	Brune

Table 4.5.5, continued

County	Spring Name/Number	Site Number*	Longitude (decimal Degrees)	Latitude (decimal Degrees)	Max Flow (gpm)	Date of Max Flow	Min Flow (gpm)	Date of Min Flow	# of Measure-ments	Geologic Source	Reference
Briscoe, TX	no name	Briscoe9	-101.443	34.51293	150.6	9/10/1946	---	---	1	Unknown	Brune
Briscoe, TX	Las Lenquas Springs	Briscoe13	-101.21	34.33351	301.2	10/19/1967	30.1	9/5/1978	2	Ogallala	Brune
Briscoe, TX	BL-11-47-302	1147302 342150101080301	-101.134	34.36389	3.0	1/1/1969	---	---	1	Dockum	Heitmuller & Reece TWDB well database
Briscoe, TX	BL-11-47-505	1147505 341934101103601	-101.177	34.32611	90.0	1/1/1967	83	1/1/1938	2	Dockum	Heitmuller & Reece TWDB well database
Briscoe, TX	BL-11-47-504	1147504 341939101114701	-101.196	34.3275	3.0	1/1/1938	---	---	1	Dockum	Heitmuller & Reece TWDB well database
Briscoe, TX	BL-11-47-201	1147201 342007101120101	-101.2	34.33528	300.0	10/19/1967	10	1/1/1938	2	Dockum	Heitmuller & Reece TWDB well database
Briscoe, TX	BL-11-47-104	1147104 342038101130101	-101.217	34.34389	10.0	1/1/1946	---	---	1	Ogallala	Heitmuller & Reece TWDB well database
Briscoe, TX	BL-11-47-103	1147103 342134101131701	-101.221	34.35944	10.0	9/17/1946	---	---	1	Ogallala	Heitmuller & Reece TWDB well database
Briscoe, TX	BL-11-47-102	1147102 342221101125501	-101.215	34.3725	100.0	10/14/1967	---	---	1	Ogallala	Heitmuller & Reece TWDB well database
Briscoe, TX	BL-11-47-101	1147101 342223101131701	-101.221	34.37306	10.0	10/24/1938	---	---	1	Ogallala	Heitmuller & Reece TWDB well database

Table 4.5.5, continued

County	Spring Name/Number	Site Number*	Longitude (decimal Degrees)	Latitude (decimal Degrees)	Max Flow (gpm)	Date of Max Flow	Min Flow (gpm)	Date of Min Flow	# of Measure-ments	Geologic Source	Reference
Briscoe, TX	BL-11-39-703	1139703 342247101124701	-101.213	34.37972	10.0	10/24/1938	---	---	1	Ogallala	Heitmuller & Reece TWDB well database
Briscoe, TX	BL-11-39-601	1139601 342714101074201	-101.128	34.45389	40.0	3/21/1969	---	---	1	Other	Heitmuller & Reece
Briscoe, TX	BL-11-29-801	1129801 343205101250801	-101.419	34.53472	200.0	9/10/1946	---	---	1	Ogallala	Heitmuller & Reece TWDB well database
Briscoe, TX	BL-11-29-603	1129603 343232101245401	-101.415	34.54222	150.0	9/10/1946	---	---	1	Ogallala	Heitmuller & Reece TWDB well database
Briscoe, TX	BL-11-29-503	1129503 343308101250801	-101.419	34.55222	15.0	0	---	---	1	Other	Heitmuller & Reece TWDB well database
Briscoe, TX	BL-11-29-502	1129502 343327101254001	-101.428	34.5575	4.5	1/1/1946	---	---	1	Ogallala	Heitmuller & Reece TWDB well database
Briscoe, TX	BL-11-29-501	1129501 343332101254801	-101.43	34.55889	6.5	1/1/1946	---	---	1	Ogallala	Heitmuller & Reece TWDB well database
Briscoe, TX	BL-11-30-601	1130601 343340101171001	-101.286	34.56111	10.0	9/16/1969	---	---	1	Ogallala	Heitmuller & Reece TWDB well database
Briscoe, TX	BL-11-30-502	1130502 343420101194901	-101.33	34.57222	3.5	9/16/1946	---	---	1	Ogallala	Heitmuller & Reece TWDB well database
Briscoe, TX	BL-11-21-308	1121308 344330101224401	-101.379	34.725	250.0	1/1/1946	---	---	1	Dockum	Heitmuller & Reece TWDB well database

Table 4.5.5, continued

County	Spring Name/Number	Site Number*	Longitude (decimal Degrees)	Latitude (decimal Degrees)	Max Flow (gpm)	Date of Max Flow	Min Flow (gpm)	Date of Min Flow	# of Measure-ments	Geologic Source	Reference
Briscoe, TX	BL-11-21-306	1121306 344357101225001	-101.381	34.7325	200.0	1/1/1946	---	---	1	Dockum	Heitmuller & Reece TWDB well database
Briscoe, TX	BL-11-21-302	1121302 344358101235101	-101.398	34.73278	100.0	1/1/1946	---	---	1	Dockum	Heitmuller & Reece TWDB well database
Briscoe, TX	BL-11-21-303	1121303 344401101234401	-101.396	34.73361	80.0	1/1/1946	---	---	1	Dockum	Heitmuller & Reece TWDB well database
Briscoe, TX	BL-11-21-301	1121301 344402101240101	-101.4	34.73389	75.0	9/9/1946	---	---	1	Ogallala	Heitmuller & Reece TWDB well database
Briscoe, TX	BL-11-21-305	1121305 344409101223901	-101.378	34.73583	200.0	1/1/1946	---	---	1	Dockum	Heitmuller & Reece TWDB well database
Briscoe, TX	BL-11-21-304	1121304 344414101230101	-101.384	34.73722	50.0	1/1/1946	---	---	1	Dockum	Heitmuller & Reece TWDB well database
Briscoe, TX	Hulsey Springs	1113901 344430101233201	-101.392	34.74167	969.2	9/9/1946	102	6/23/1971	2	Unknown	Heitmuller & Reece
Cochran, TX	Silver Springs	Cochran5	-102.619	33.80019	10.0	4/13/1977	0.8	10/21/1978	2	Unknown	Brune
Coke, TX	DR-43-19-205	4319205 314412100404201	-100.678	31.73667	<0.2	2/12/1969	---	---	1	ET-P	Heitmuller & Reece TWDB well database
Coke, TX	DR-43-02-301	4302301 315741100460301	-100.768	31.96139	0.1	11/18/1968	---	---	1	ET-P	Heitmuller & Reece TWDB well database
Colfax, NM	26N.25E.12.314	Colfax8	-104.239	36.49833	100.0	4/7/1946	---	---	1	Alluvium	White & Kues

Table 4.5.5, continued

County	Spring Name/Number	Site Number*	Longitude (decimal Degrees)	Latitude (decimal Degrees)	Max Flow (gpm)	Date of Max Flow	Min Flow (gpm)	Date of Min Flow	# of Measure-ments	Geologic Source	Reference
Colfax, NM	26N.25E.12.400	Colfax9	-104.225	36.50933	40.0	--	---	---	1	Alluvium	White & Kues
Collingsworth, TX	DU-55-29-905	5529905 350844100320701	-100.535	35.14556	178.0	7/26/1967	---	---	1	Ogallala	Heitmuller & Reece TWDB well database
Collingsworth, TX	Wischkaemper Springs	Collingsworth3	-100.426	34.9851	791.2	5/18/1967	1613	6/24/1971	3	Alluvium	Brune
Collingsworth, TX	O'Hair Springs	Collingsworth4	-100.399	34.8894	609.9	1/24/1967	129	10/20/1938	4	Other	Brune
Collingsworth, TX	Baggett Springs	Collingsworth9	-100.399	34.8894	122.0	1967	636	8/20/1977	2	Unknown	Brune
Crosby, TX	Couch Springs	Crosby2 2323601 333930101073201	-101.126	33.65833	855.9	11/2/1938	---	---	1	Unknown	Heitmuller & Reece Brune
Crosby, TX	C Bar Springs	Crosby7	-101.439	33.40454	301	1938	8	4/1977	2	Dockum	Brune (2002)
Crosby, TX	L7 Springs	Crosby6	-101.136	33.51497	55	1938	0.8	4/1977	3	Dockum	Brune (2002)
Crosby, TX	Cottonwood Springs	Crosby1	-101.488	33.4617	206.1	1938	5.1	1975	2	Unknown	Brune
Crosby, TX	Rock House Springs	Crosby3	-101.231	33.79726	221.9	1938	9.8	1975	2	Unknown	Brune
Dallam, TX	Buffalo Springs	Dallam7 234202 362930102473201	-102.792	36.49167	554.2	8/7/1924 & 7/26/1957	3634	6/22/1971	6	Rita Blanca	Heitmuller & Reece Brune
Dawson, TX	Rock Crusher or Turner Springs	Dawson1 2802802 325312101491201	-101.827	32.88542	30.1	10/4/1978	3	6/28/1938	3	Ogallala	Heitmuller & Reece Brune TWDB well database

Table 4.5.5, continued

County	Spring Name/Number	Site Number*	Longitude (decimal Degrees)	Latitude (decimal Degrees)	Max Flow (gpm)	Date of Max Flow	Min Flow (gpm)	Date of Min Flow	# of Measure-ments	Geologic Source	Reference
De Baca, NM	2N.26E.15.214	De Baca2	-104.197	34.40333	seep	--	---	---	1	Unknown	White & Kues
De Baca, NM	2N.26E.36.313	De Baca3	-104.173	34.35167	10.0	2/26/1940	0.1	6/10/1940	2	Unknown	White & Kues
De Baca, NM	3N.28E.32.444	De Baca4	-104.014	34.44263	3.0	9/1/1966	---	---	1	Dockum	White & Kues
De Baca, NM	4N.28E.23.441	De Baca13	-103.969	34.55278	10.0	12/9/1965	---	---	1	Dockum	White & Kues
De Baca, NM	4N.28E.26.311	De Baca14	-103.958	34.53978	20.0	12/1/1965	---	---	1	Ogallala	White & Kues
De Baca, NM	1S.27E.22.333	De Baca18	-104.1	34.20556	1.0	3/1/1966	---	---	1	Dockum	White & Kues
Deaf Smith, TX	Big Springs	Deaf Smith4	-102.188	34.8416	15.1	1937	5.1	5/1/1977	2	Unknown	Brune
Dickens, TX	---	Dickens17	-100.958	33.64219	3	8/11/1979	---	---	1	Dockum	Brune (2002)
Dickens, TX	HY-22-25-202	2225202 333505100555401	-100.932	33.58472	4.5	1/1/1938	3.5	1/1/1969	2	Dockum	Heitmuller & Reece TWDB well database
Dickens, TX	HY-22-18-802	2218802 333731100490201	-100.817	33.62528	8.0	1/1/1967	3	1/1/1938	2	Dockum	Heitmuller & Reece TWDB well database
Dickens, TX	HY-22-25-201	2225201 333507100555601	-100.932	33.58528	2.5	1/1/1969	---	---	1	Dockum	Heitmuller & Reece TWDB well database
Dickens, TX	HY-22-18-801	2218801 333745100493701	-100.827	33.62917	15.0	1938	15	1/1/1967	2	Dockum	Heitmuller & Reece TWDB well database
Dickens, TX	Boggey Creek Spring	2217908 333853100545301	-100.915	33.64806	15.0	1/1/1938	---	---	1	Dockum	Heitmuller & Reece TWDB well database
Dickens, TX	HY-22-18-502	2218502 334034100494001	-100.828	33.67611	1.5	9/22/1938	---	---	1	Ogallala	Heitmuller & Reece TWDB well database

Table 4.5.5, continued

County	Spring Name/Number	Site Number*	Longitude (decimal Degrees)	Latitude (decimal Degrees)	Max Flow (gpm)	Date of Max Flow	Min Flow (gpm)	Date of Min Flow	# of Measure-ments	Geologic Source	Reference
Dickens, TX	HY-22-17-501	2217501 334051100554701	-100.93	33.68083	0.3	1/1/1938	---	---	1	Dockum	Heitmuller & Reece TWDB well database
Dickens, TX	HY-22-09-501	2209501 334820100562301	-100.94	33.80556	15.0	9/20/1938	---	---	1	Ogallala	Heitmuller & Reece TWDB well database
Dickens, TX	HY-22-10-401	2210401 334959100515001	-100.864	33.83306	16.0	1/1/1969	---	---	1	Dockum	Heitmuller & Reece TWDB well database
Donley, TX	JA-12-11-504	1211504 344844100401501	-100.671	34.81222	3.0	1/1/1941	---	---	1	Ogallala	Heitmuller & Reece TWDB well database
Donley, TX	JA-12-11-503	1211503 344858100401301	-100.67	34.81611	3.0	1/1/1941	---	---	1	Ogallala	Heitmuller & Reece TWDB well database
Donley, TX	JA-12-09-305	1209305 345033100542601	-100.907	34.8425	60.0	3/19/1968	---	---	1	Ogallala	Heitmuller & Reece TWDB well database
Donley, TX	JA-12-03-103	1203103 345853100442701	-100.741	34.98139	300.0	1/1/1919	0	1900/01/02	3	Ogallala	Heitmuller & Reece TWDB well database
Donley, TX	JA-12-03-104	1203104 345902100443801	-100.744	34.98389	< 1	12/29/1967	---	---	1	Ogallala	Heitmuller & Reece TWDB well database
Donley, TX	JA-12-02-303	1202303 345916100471001	-100.786	34.98778	200.0	1/4/1968	---	---	1	Ogallala	Heitmuller & Reece TWDB well database
Donley, TX	JA-12-02-304	1202304 345920100473001	-100.792	34.98889	222.0	1/4/1968	---	---	1	Ogallala	Heitmuller & Reece TWDB well database

Table 4.5.5, continued

County	Spring Name/Number	Site Number*	Longitude (decimal Degrees)	Latitude (decimal Degrees)	Max Flow (gpm)	Date of Max Flow	Min Flow (gpm)	Date of Min Flow	# of Measure-ments	Geologic Source	Reference
Donley, TX	JA-55-79-906	5579906 350001100535501	-100.899	35.00028	18.0	3/3/1941	---	---	1	Ogallala	Heitmuller & Reece
Donley, TX	JA-55-79-904	5579904 350222100544501	-100.913	35.03944	100.0	3/16/1968	---	---	1	Ogallala	Heitmuller & Reece
Donley, TX	JA-12-11-801	1211801 344625100412801	-100.691	34.77361	2.0	1/1/1941	---	---	1	Ogallala	Heitmuller & Reece TWDB well database
Donley, TX	JA-12-10-509	1210509 344800100483101	-100.809	34.8	11.0	3/5/1968	---	---	1	Ogallala	Heitmuller & Reece TWDB well database
Donley, TX	JA-12-10-510	1210510 344820100482201	-100.806	34.80556	6.0	3/5/1968	---	---	1	Ogallala	Heitmuller & Reece TWDB well database
Donley, TX	JA-12-12-414	1212414 344824100351101	-100.586	34.80667	3.0	5/20/1943	---	---	1	Ogallala	Heitmuller & Reece TWDB well database
Donley, TX	Parker Springs	1212413 344827100351001	-100.586	34.8075	5.0	5/19/1943	---	---	1	Ogallala	Heitmuller & Reece TWDB well database
Donley, TX	JA-12-12-408	1212408 344832100371201	-100.62	34.80889	140.0	1/5/1968	---	---	1	Ogallala	Heitmuller & Reece TWDB well database
Donley, TX	JA-12-12-407	1212407 344836100365801	-100.616	34.81	45.0	1/5/1968	---	---	1	Ogallala	Heitmuller & Reece TWDB well database
Donley, TX	East Spring	1210405 344845100504101	-100.845	34.8125	3.0	3/5/1968	---	---	1	Ogallala	Heitmuller & Reece TWDB well database
Donley, TX	Bitter Creek Springs	Donley9 1210605 344847100471001	-100.786	34.81306	775.0	3/5/1968	522	6/23/1971	2	Ogallala	Heitmuller & Reece TWDB well database Brune

Table 4.5.5, continued

County	Spring Name/Number	Site Number*	Longitude (decimal Degrees)	Latitude (decimal Degrees)	Max Flow (gpm)	Date of Max Flow	Min Flow (gpm)	Date of Min Flow	# of Measure-ments	Geologic Source	Reference
Donley, TX	JA-12-10-403	1210403 344903100512201	-100.856	34.8175	81.0	12/19/1967	---	---	1	Ogallala	Heitmuller & Reece TWDB well database
Donley, TX	JA-12-12-501	1212501 344909100344301	-100.579	34.81917	5.0	5/20/1943	---	---	1	Alluvium	Heitmuller & Reece TWDB well database
Donley, TX	JA-12-10-404	1210404 344912100512601	-100.857	34.82	56.0	12/19/1967	---	---	1	Ogallala	Heitmuller & Reece TWDB well database
Donley, TX	Indian Creek Spring 1	1211502 344913100402201	-100.673	34.82028	3.0	1/1/1941	---	---	1	Ogallala	Heitmuller & Reece TWDB well database
Donley, TX	JA-12-11-603	1211603 344916100385701	-100.649	34.82111	1.0	5/26/1943	---	---	1	Ogallala	Heitmuller & Reece TWDB well database
Donley, TX	JA-12-11-602	1211602 344917100394801	-100.663	34.82139	1.0	1/1/1941	---	---	1	Ogallala	Heitmuller & Reece TWDB well database
Donley, TX	West Spring	1210402 344920100504801	-100.847	34.82222	23.0	12/19/1967	---	---	1	Ogallala	Heitmuller & Reece TWDB well database
Donley, TX	JA-12-03-105	1203105 345802100444501	-100.746	34.96722	2.0	12/29/1967	---	---	1	Ogallala	Heitmuller & Reece TWDB well database
Donley, TX	JA-12-03-109	1203109 345835100434401	-100.729	34.97639	175.0	2/27/1966	---	---	1	Ogallala	Heitmuller & Reece TWDB well database
Donley, TX	JA-55-78-801	5578801 350222100550701	-100.919	35.03944	200.0	3/16/1968	---	---	1	Ogallala	Heitmuller & Reece
Donley, TX	JA-55-75-507	5575507 350356100552401	-100.923	35.06556	14.0	3/11/1941	---	---	1	Ogallala	Heitmuller & Reece

Table 4.5.5, continued

County	Spring Name/Number	Site Number*	Longitude (decimal Degrees)	Latitude (decimal Degrees)	Max Flow (gpm)	Date of Max Flow	Min Flow (gpm)	Date of Min Flow	# of Measure-ments	Geologic Source	Reference
Donley, TX	JA-55-91-107	5591107 350611100440901	-100.736	35.10306	5.0	0	---	---	1	Ogallala	Heitmuller & Reece
Donley, TX	JA-55-91-106	5591106 350629100442701	-100.741	35.10806	5.0	0	---	---	1	Ogallala	Heitmuller & Reece
Donley, TX	JA-55-91-105	5591105 350651100435801	-100.733	35.11417	5.0	0	---	---	1	Ogallala	Heitmuller & Reece
Donley, TX	JA-55-91-104	5591104 350706100442601	-100.741	35.11833	5.0	0	---	---	1	Ogallala	Heitmuller & Reece
Donley, TX	JA-55-91-103	5591103 350711100442601	-100.741	35.11972	5.0	0	---	---	1	Ogallala	Heitmuller & Reece
Donley, TX	JA-55-17-707	5517707 350731100430701	-100.719	35.12528	78.0	1/1/1968	---	---	1	Ogallala	Heitmuller & Reece
Donley, TX	JA-55-17-708	5517708 350737100430401	-100.718	35.12694	78.0	1/1/1968	---	---	1	Ogallala	Heitmuller & Reece
Donley, TX	JA-55-17-706	5517706 350758100431601	-100.721	35.13278	78.0	1/1/1968	---	---	1	Ogallala	Heitmuller & Reece
Donley, TX	JA-55-17-703	5517703 350802100435501	-100.732	35.13389	2.0	3/6/1968	---	---	1	Ogallala	Heitmuller & Reece
Donley, TX	JA-55-17-704	5517704 350804100431601	-100.721	35.13444	2.0	3/6/1968	---	---	1	Ogallala	Heitmuller & Reece
Donley, TX	JA-55-17-702	5517702 350808100435201	-100.731	35.13556	31.0	1/1/1968	---	---	1	Ogallala	Heitmuller & Reece
Donley, TX	JA-55-17-705	5517705 350809100431501	-100.721	35.13583	2.0	1/1/1968	---	---	1	Ogallala	Heitmuller & Reece
Donley, TX	---	557801	-100.918	35.03944	200.0	3/16/1968	---	---	1	Ogallala	TWDB well database
Donley, TX	---	557904	-100.912	35.03944	100.0	3/16/1968	---	---	1	Ogallala	TWDB well database
Donley, TX	---	557906	-100.898	35.00028	18.0	3/3/1941	---	---	1	Ogallala	TWDB well database
Donley, TX	---	557507	-100.923	35.06556	14.0	3/11/1941	---	---	1	Ogallala	TWDB well database
Donley, TX	---	559107	-100.735	35.10306	5.0	---	---	---	1	Ogallala	TWDB well database
Donley, TX	---	559106	-100.74	35.10806	5.0	---	---	---	1	Ogallala	TWDB well database
Donley, TX	---	559105	-100.732	35.11417	5.0	---	---	---	1	Ogallala	TWDB well database

Table 4.5.5, continued

County	Spring Name/Number	Site Number*	Longitude (decimal Degrees)	Latitude (decimal Degrees)	Max Flow (gpm)	Date of Max Flow	Min Flow (gpm)	Date of Min Flow	# of Measure-ments	Geologic Source	Reference
Donley, TX	---	559104	-100.74	35.11833	5.0	---	---	---	1	Ogallala	TWDB well database
Donley, TX	---	559103	-100.74	35.11972	5.0	---	---	---	1	Ogallala	TWDB well database
Donley, TX	---	551707	-100.718	35.12528	78.0	1968	---	---	1	Ogallala	TWDB well database
Donley, TX	---	551708	-100.717	35.12694	78.0	1968	---	---	1	Ogallala	TWDB well database
Donley, TX	---	551706	-100.721	35.13278	78.0	1968	---	---	1	Ogallala	TWDB well database
Donley, TX	---	551703	-100.731	35.13389	<2	3/6/1968	---	---	1	Ogallala	TWDB well database
Donley, TX	---	551704	-100.721	35.13444	<2	3/6/1968	---	---	1	Ogallala	TWDB well database
Donley, TX	---	551702	-100.731	35.13556	31.0	1968	---	---	1	Ogallala	TWDB well database
Donley, TX	---	551705	-100.72	35.13583	<2	1968	---	---	1	Ogallala	TWDB well database
Donley, TX	Cottonwood Springs	Donley13	-100.731	35.1145	247.3	3/6/1968	1703	8/4/1978	2	Unknown	Brune
Donley, TX	no name	Donley18	-100.98	35.0188	18.1	1941	---	---	1	Unknown	Brune
Donley, TX	Dunbar Springs	Donley19	-100.98	35.0188	313.2	3/16/1968	2953	8/5/1978	2	Unknown	Brune
Eddy, NM	24S.28E.27.411	Eddy29	-104.076	32.1875	<0.5	10/22/1947	---	---	1	Other	White & Kues
Ellis, OK	OK Wildlife Spring 1	355340099430801	-99.7193	35.89449	27.6	8/14/1992	---	---	1	Unknown	USGS NWIS
Ellis, OK	Davidson Ranch Spring 2	355906099364601	-99.6132	35.98505	1.1	8/21/1992	---	---	1	Unknown	USGS NWIS
Ellis, OK	Jenkins Springs	355947099531201	-99.8871	35.99643	123.0	7/27/1993	---	---	1	Unknown	USGS NWIS
Ellis, OK	Johnson Spring 1	355958099462801	-99.7748	35.99949	1.3	8/13/1992	---	---	1	Unknown	USGS NWIS
Ellis, OK	Gillispie Spring 1	360056099305401	-99.5154	36.0156	19.2	9/23/1992	---	---	1	Unknown	USGS NWIS
Ellis, OK	Word Springs	360107099475401	-99.7987	36.01866	20.0	7/22/1993	---	---	1	Unknown	USGS NWIS
Ellis, OK	Henderson Spring 3	360144099545901	-99.9168	36.0306	5.0	7/27/1993	---	---	1	Unknown	USGS NWIS

Table 4.5.5, continued

County	Spring Name/Number	Site Number*	Longitude (decimal Degrees)	Latitude (decimal Degrees)	Max Flow (gpm)	Date of Max Flow	Min Flow (gpm)	Date of Min Flow	# of Measure-ments	Geologic Source	Reference
Ellis, OK	Richards Spring	360202099513301	-99.8596	36.03393	0.3	7/20/1993	---	---	1	Unknown	USGS NWIS
Ellis, OK	Peck Spring 2	360240099540601	-99.9021	36.04449	21.1	9/11/1992	---	---	1	Unknown	USGS NWIS
Ellis, OK	Harris Spring 2	360251099295301	-99.4984	36.04755	9.3	8/28/1992	---	---	1	Unknown	USGS NWIS
Ellis, OK	Marvel Spring	360254099513301	-99.8596	36.04838	0.3	8/4/1993	---	---	1	Unknown	USGS NWIS
Ellis, OK	Cadwell Spring 2	360333099383501	-99.6434	36.05921	< 0.10	9/18/1992	---	---	1	Unknown	USGS NWIS
Ellis, OK	Harris Spring 1	360355099305901	-99.5168	36.06532	15.3	9/1/1992	---	---	1	Unknown	USGS NWIS
Ellis, OK	Redelsperger Springs	360445099510501	-99.8521	36.07532	450.0	7/20/1993	---	---	1	Unknown	USGS NWIS
Ellis, OK	Baker Spring 1	360459099273601	-99.4604	36.0831	5.1	9/23/1992	---	---	1	Unknown	USGS NWIS
Ellis, OK	Herbel Springs 2	360515099575101	-99.9646	36.08754	1.5	7/27/1993	---	---	1	Unknown	USGS NWIS
Ellis, OK	Coram Spring 3	360629099280101	-99.4673	36.1081	1.7	9/25/1992	---	---	1	Unknown	USGS NWIS
Ellis, OK	Knowles Spring	360632099562101	-99.9396	36.10893	0.5	8/4/1993	---	---	1	Unknown	USGS NWIS
Ellis, OK	Molloy Spring 3	361339099390801	-99.6526	36.22754	60.0	9/24/1993	---	---	1	Unknown	USGS NWIS
Ellis, OK	Berry Spring	361616099482601	-99.8054	36.27032	42.6	8/5/1993	---	---	1	Unknown	USGS NWIS
Ellis, OK	Miller Springs	362329099482101	-99.8062	36.39143	35.0	7/29/1993	---	---	1	Unknown	USGS NWIS
Ellis, OK	Eight-Mile Springs	362829099395201	-99.6648	36.47476	77.0	7/19/1993	---	---	1	Unknown	USGS NWIS
Ellis, OK	Dugger Spring 1	363209099471601	-99.7882	36.53587	54.0	9/29/1993	---	---	1	Unknown	USGS NWIS
Ellis, OK	Corless Spring	363444099525601	-99.8826	36.57892	30.0	9/29/1993	---	---	1	Unknown	USGS NWIS
Floyd, TX	Blue Hole Springs	Floyd2	-101.211	34.22177	221.9	11/4/1938	0	7/16/1978	4	Ogallala	Brune
Floyd, TX	Cold Springs	1156102 341456101072601	-101.124	34.24889	10.0	---	dry	1/1/1968	2	Dockum	Heitmuller & Reece TWDB well database
Floyd, TX	JW-11-64-604	1164604 340416101023101	-101.042	34.07111	140.0	0	---	---	1	Ogallala & Rita Blanca	Heitmuller & Reece
Floyd, TX	JW-11-64-203	1164203 340506101031101	-101.053	34.085	45.0	1/1/1968	---	---	1	Dockum	Heitmuller & Reece TWDB well database

Table 4.5.5, continued

County	Spring Name/Number	Site Number*	Longitude (decimal Degrees)	Latitude (decimal Degrees)	Max Flow (gpm)	Date of Max Flow	Min Flow (gpm)	Date of Min Flow	# of Measure-ments	Geologic Source	Reference
Floyd, TX	JW-11-64-204	1164204 340515101031801	-101.055	34.0875	5.0	1/1/1968	---	---	1	Dockum	Heitmuller & Reece TWDB well database
Floyd, TX	JW-11-64-205	1164205 340531101034401	-101.062	34.09194	35.0	1/1/1968	---	---	1	Dockum	Heitmuller & Reece TWDB well database
Floyd, TX	JW-11-64-206	1164206 340540101032601	-101.057	34.09444	10.0	1/1/1968	---	---	1	Dockum	Heitmuller & Reece TWDB well database
Floyd, TX	Watercress Pool	1164207 340541101030701	-101.052	34.09472	115.0	1/1/1968	---	---	1	Dockum	Heitmuller & Reece TWDB well database
Floyd, TX	JW-11-64-210	1164210 340615101044501	-101.079	34.10417	40.0	1/1/1937	35	1/1/1968	2	Ogallala & Rita Blanca	Heitmuller & Reece TWDB well database
Floyd, TX	JW-11-64-208	1164208 340623101035901	-101.066	34.10639	147.0	1/1/1968	---	---	1	Dockum	Heitmuller & Reece TWDB well database
Floyd, TX	Mud Spring	1164213 340657101043401	-101.076	34.11583	15.0	1/1/1968	---	---	1	Dockum	Heitmuller & Reece TWDB well database
Floyd, TX	JW-11-64-216	1164216 340707101035901	-101.066	34.11861	125.0	1/1/1968	---	---	1	Dockum	Heitmuller & Reece TWDB well database
Floyd, TX	JW-11-64-214	1164214 340714101044501	-101.079	34.12056	12.0	12/14/1968	1	8/24/1968	2	Ogallala	Heitmuller & Reece TWDB well database
Floyd, TX	JW-11-64-215	1164215 340724101043501	-101.076	34.12333	40.0	12/14/1968	25	8/24/1938	2	Ogallala	Heitmuller & Reece TWDB well database
Floyd, TX	JW-11-56-809	1156809 340817101031301	-101.054	34.13806	0.3	1/1/1938	---	---	1	Dockum	Heitmuller & Reece TWDB well database

Table 4.5.5, continued

County	Spring Name/Number	Site Number*	Longitude (decimal Degrees)	Latitude (decimal Degrees)	Max Flow (gpm)	Date of Max Flow	Min Flow (gpm)	Date of Min Flow	# of Measure-ments	Geologic Source	Reference
Floyd, TX	JW-11-56-808	1156808 340819101042301	-101.073	34.13861	1.0	9/6/1938	---	---	1	Ogallala	Heitmuller & Reece TWDB well database
Floyd, TX	JW-11-56-806	1156806 340854101044901	-101.08	34.14833	125.0	1/1/1938	---	---	1	Ogallala & Rita Blanca	Heitmuller & Reece TWDB well database
Floyd, TX	JW-11-56-702	1156702 340922101051701	-101.088	34.15611	75.0	12/2/1938	---	---	1	Ogallala	Heitmuller & Reece TWDB well database
Floyd, TX	JW-11-56-807	1156807 340939101035801	-101.066	34.16083	15.0	1/1/1938	---	---	1	Dockum	Heitmuller & Reece TWDB well database
Floyd, TX	JW-11-56-504	1156504 341011101032001	-101.056	34.16972	6.0	1/1/1938	---	---	1	Dockum	Heitmuller & Reece TWDB well database
Floyd, TX	JW-11-56-505	1156505 341102101032101	-101.056	34.18389	9.0	1/1/1938	---	---	1	Dockum	Heitmuller & Reece TWDB well database
Floyd, TX	JW-11-56-506	1156506 341151101044501	-101.079	34.1975	3.0	1/1/1938	---	---	1	Dockum	Heitmuller & Reece TWDB well database
Floyd, TX	JW-11-55-602	1155602 341155101090001	-101.149	34.19861	25.0	11/1/1938	---	---	1	Ogallala	Heitmuller & Reece TWDB well database
Floyd, TX	JW-11-55-603	1155603 341202101090501	-101.151	34.20056	75.0	11/1/1938	---	---	1	Ogallala	Heitmuller & Reece TWDB well database
Floyd, TX	JW-11-55-601	1155601 341212101083001	-101.142	34.20333	15.0	11/1/1938	---	---	1	Ogallala	Heitmuller & Reece TWDB well database

Table 4.5.5, continued

County	Spring Name/Number	Site Number*	Longitude (decimal Degrees)	Latitude (decimal Degrees)	Max Flow (gpm)	Date of Max Flow	Min Flow (gpm)	Date of Min Flow	# of Measure-ments	Geologic Source	Reference
Floyd, TX	JW-11-55-604	1155604 341218101093901	-101.161	34.205	25.0	11/1/1938	---	---	1	Ogallala	Heitmuller & Reece TWDB well database
Floyd, TX	JW-11-55-605	1155605 341226101093901	-101.161	34.20722	25.0	11/1/1938	---	---	1	Ogallala	Heitmuller & Reece TWDB well database
Floyd, TX	JW-11-56-214	1156214 341233101050001	-101.083	34.20917	2.0	0	---	---	1	Dockum	Heitmuller & Reece TWDB well database
Floyd, TX	Dripping Springs	1156105 341242101055601	-101.099	34.21167	2.0	1/1/1968	---	---	1	Dockum	Heitmuller & Reece TWDB well database
Floyd, TX	JW-11-55-304	1155304 341311101093401	-101.159	34.21972	20.0	11/3/1938	---	---	1	Ogallala	Heitmuller & Reece TWDB well database
Floyd, TX	JW-11-55-206	1155206 341319101120701	-101.202	34.22194	12.0	0	---	---	1	Dockum	Heitmuller & Reece TWDB well database
Floyd, TX	Blue Hole Springs	1155205 341320101115401	-101.198	34.22222	202.0	1/1/1968	---	---	1	Dockum	Heitmuller & Reece TWDB well database
Floyd, TX	JW-11-55-208	1155208 341328101102201	-101.173	34.22444	15.0	11/4/1938	---	---	1	Ogallala	Heitmuller & Reece TWDB well database
Floyd, TX	JW-11-55-204	1155204 341333101115201	-101.198	34.22583	193.0	1/1/1968	---	---	1	Dockum	Heitmuller & Reece TWDB well database
Floyd, TX	JW-11-55-207	1155207 341334101102301	-101.173	34.22611	8.0	11/4/1938	---	---	1	Ogallala	Heitmuller & Reece TWDB well database

Table 4.5.5, continued

County	Spring Name/Number	Site Number*	Longitude (decimal Degrees)	Latitude (decimal Degrees)	Max Flow (gpm)	Date of Max Flow	Min Flow (gpm)	Date of Min Flow	# of Measure-ments	Geologic Source	Reference
Floyd, TX	JW-11-55-209	1155209 341334101101501	-101.171	34.22611	5.0	11/4/1938	---	---	1	Ogallala	Heitmuller & Reece TWDB well database
Floyd, TX	JW-11-55-203	1155203 341353101113401	-101.193	34.23139	5.0	1/1/1938	---	---	1	Ogallala	Heitmuller & Reece TWDB well database
Floyd, TX	JW-11-55-202	1155202 341404101113701	-101.194	34.23444	10.0	1/1/1938	---	---	1	Ogallala	Heitmuller & Reece TWDB well database
Floyd, TX	JW-11-55-303	1155303 341453101093101	-101.159	34.24806	50.0	1/1/1938	19	1/1/1968	2	Dockum	Heitmuller & Reece TWDB well database
Floyd, TX	JW-11-47-804	1147804 341502101111701	-101.188	34.25056	100.0	11/4/1938	---	---	1	Ogallala	Heitmuller & Reece TWDB well database
Floyd, TX	Turkey Creek Falls Spring	1147902 341507101092101	-101.156	34.25194	58.0	1/1/1968	---	---	1	Dockum	Heitmuller & Reece TWDB well database
Floyd, TX	JW-11-47-904	1147904 341659101092301	-101.156	34.28306	0.5	10/13/1938	---	---	1	Ogallala	Heitmuller & Reece TWDB well database
Floyd, TX	JW-11-47-903	1147903 341701101094401	-101.162	34.28361	2.0	10/13/1938	---	---	1	Ogallala	Heitmuller & Reece TWDB well database
Floyd, TX	JW-11-47-803	1147803 341717101102901	-101.175	34.28806	18.0	11/19/1938	15	10/13/1938	2	Ogallala	Heitmuller & Reece TWDB well database
Floyd, TX	JW-11-47-502	1147502 341747101104501	-101.179	34.29639	15.0	11/19/1968	9	10/13/1938	2	Ogallala	Heitmuller & Reece TWDB well database

Table 4.5.5, continued

County	Spring Name/Number	Site Number*	Longitude (decimal Degrees)	Latitude (decimal Degrees)	Max Flow (gpm)	Date of Max Flow	Min Flow (gpm)	Date of Min Flow	# of Measure-ments	Geologic Source	Reference
Floyd, TX	JW-11-47-503	1147503 341839101105501	-101.182	34.31083	5.0	11/19/1968	3	10/25/1938	2	Ogallala	Heitmuller & Reece TWDB well database
Gaines, TX	Buffalo Springs	Gaines1	-102.296	32.81963	0.1	1963	---	---	1	Unknown	Brune
Gaines, TX	Balch Springs	Gaines5 2722205 324430102183201	-102.279	32.73259	39.6	3/18/1977	---	---	1	Unknown	Heitmuller & Reece Brune
Gaines, TX	KD-27-14-901	2714901 324701102171001	-102.286	32.78361	1.0	0	---	---	1	ET-HP	Heitmuller & Reece TWDB well database
Gaines, TX	KD-27-14-303	2714303 325017102170801	-102.286	32.83806	0.1	0	---	---	1	ET-HP	Heitmuller & Reece TWDB well database
Garza, TX	Barnum Springs	Garza6	-101.467	33.27971	dry	6/1979			1	Dockum	Brune (2002)
Garza, TX	Garza Springs	Garza2	-101.391	32.98524	seep	6/2/1979			1	Dockum	Brune (2002)
Garza, TX	OS Springs	Garza15	-101.164	33.1353	wet-weather seeps	6/1978			1	Dockum	Brune (2002)
Garza, TX	---	Garza16	-101.184	33.2369	seeps	6/5/1979			1	Dockum	Brune (2002)
Guadalupe, NM	8N.25E.22.313	Guadalupe20	-104.287	34.89833	3-5	12/1/1955	---	---	1	Dockum	White & Kues
Guadalupe, NM	8N.26E.18.421	Guadalupe21	-104.213	34.91598	2-3	11/4/1955	---	---	1	Ogallala	White & Kues
Guadalupe, NM	9N.25E.5.432	Guadalupe24	-104.305	35.0357	5-10	12/6/1955	---	---	1	Dockum	White & Kues
Guadalupe, NM	9N.26E.24.420	Guadalupe25	-104.128	34.99868	0.5	10/27/1953	---	---	1	Unknown	White & Kues

Table 4.5.5, continued

County	Spring Name/Number	Site Number*	Longitude (decimal Degrees)	Latitude (decimal Degrees)	Max Flow (gpm)	Date of Max Flow	Min Flow (gpm)	Date of Min Flow	# of Measure-ments	Geologic Source	Reference
Harding, NM	15N.32E.7.433	Harding17	-103.583	35.53611	3.0	4/1/1970	---	---	1	Unknown	White & Kues
Harding, NM	15N.32E. 8.422	Harding18	-103.55	35.54808	seep	7/15/1954	---	---	1	Alluvium	White & Kues
Harding, NM	15N.32E.14.330	Harding19	-103.487	35.52658	seep	7/15/1954	---	---	1	Alluvium	White & Kues
Harding, NM	19N.29E.6.424	Harding22	-103.623	35.70334	<1	3/1/1969	---	---	1	Ogallala	White & Kues
Harding, NM	23N.24E.21.400	Harding24	-104.388	36.20667	1	12/14/1966	---	---	1	Rita Blanca	White & Kues
Harper, OK	Cooper Spring	363612099335501	-99.5657	36.60337	0.0	8/13/1965	---	---	1	Alluvium	USGS NWIS
Harper, OK	Doby Spring	364952099463301	-99.7762	36.83114	4.5	7/25/1986	---	---	1	Unknown	USGS NWIS
Hartley, TX	XIT Springs	712601 354730102303201	-102.509	35.79167	14.0	2/1/1938	5	6/22/1971	2	Unknown	Heitmuller & Reece
Hartley, TX	Punta de Aqua Springs	Hartley3	-103.001	35.9581	57.7	1977	---	---	1	Ogallala	Brune
Hemphill, TX	Springer Springs	Hemphill8	-100.163	35.9297	79.1	6/21/1977	---	---	1	Ogallala	Brune
Hemphill, TX	Spring Creek Springs	Hemphill9	-100.06	35.9469	164.8	6/22/1977	---	---	1	Alluvium	Brune
Hemphill, TX	Oasis Springs	Hemphill10	-100.06	35.9469	214.3	6/23/1977	---	---	1	Alluvium	Brune
Howard, TX	PB-28-62-303	2862303 320707101163901	-101.278	32.11861	0.8	0	---	---	1	ET-P	Heitmuller & Reece TWDB well database
Howard, TX	German Springs	Howard15	-101.506	32.4886	56.0	5/28/1979	---	---	1	Alluvium	Brune
Hutchinson, TX	Camp Springs	Hutchinson14	-101.545	35.7441	1067.5	6/11/1978			1	Ogallala	Brune
Irion, TX	Yardley Springs	4342820 311540100480701	-100.802	31.26111	75.0	5/28/1936	---	---	1	ET-P	Heitmuller & Reece TWDB well database

Table 4.5.5, continued

County	Spring Name/Number	Site Number*	Longitude (decimal Degrees)	Latitude (decimal Degrees)	Max Flow (gpm)	Date of Max Flow	Min Flow (gpm)	Date of Min Flow	# of Measure-ments	Geologic Source	Reference
Irion, TX	Lopez Spring	4342405 311822100505301	-100.848	31.30611	25.0	7/17/1936	---	---	1	Alluvium	Heitmuller & Reece TWDB well database
Irion, TX	Dove Creek Springs	4351403	-100.735	31.18417	350	1967	---	---	1	ET-P	TWDB well database
Jeff Davis, TX	Augustine Spring	5210101 305213103512601	-103.857	30.87028	10.0	1/1/1990	---	---	1	Other	Heitmuller & Reece
Jeff Davis, TX	Phantom Lake spring	5202405 8425500	-103.85	30.93472	13 522	1990	556	1997	3	ET-P	TWDB well database Heitmuller & Reece
Kent, TX	Mackenzie Springs	Kent12	-100.927	32.99101	seeps	8/16/1979			1	Dockum	Brune (2002)
Kent, TX	Elkins Springs	Kent13 2901301 325930100533101	-100.892	32.99167	1.1	8/16/1979	---	---	1	Dockum	Heitmuller & Reece Brune (2002)
Lamb, TX	Rocky Ford Springs	Lamb9	-102.344	34.08019	74.5	5/1/1952	0	8/28/1952 & Nov 1952	3	Unknown	Brune
Lamb, TX	Bull Springs	Lamb13	-102.489	33.94002	seeps	10/3/1978	---	---	1	Alluvium	Brune
Lamb, TX	Roland Springs and Ponds	Lamb14	-102.489	33.92126	seeps	10/3/1978	---	---	1	Ogallala	Brune
Lamb, TX	Illusion Springs	Lamb15	-102.414	33.86782	25.4	10/4/1978	---	---	1	Alluvium	Brune
Lamb, TX	Yellow Springs	Lamb16	-102.417	33.8579	2.2	10/4/1978	---	---	1	Alluvium	Brune
Lamb, TX	no name	Lamb17	-102.428	33.82996	11.3	10/4/1978	---	---	1	Ogallala	Brune

Table 4.5.5, continued

County	Spring Name/Number	Site Number*	Longitude (decimal Degrees)	Latitude (decimal Degrees)	Max Flow (gpm)	Date of Max Flow	Min Flow (gpm)	Date of Min Flow	# of Measure-ments	Geologic Source	Reference
Lamb, TX	Green Springs	Lamb19	-102.498	33.83894	11.9	10/21/1978	---	---	1	Unknown	Brune
Lea, NM	11S.36E.11.133	Lea1	-103.297	33.39118	seep	2/7/1953	---	---	1	Unknown	White & Kues
Lipscomb, TX	Cold Springs	Lipscomb14	-100.034	36.0659	164.8	6/19/1977	---	---	1	Ogallala	Brune
Lubbock, TX	Buffalo Springs	Lubbock1 2327412 333230101423201	-101.703	33.53005	2742.2	1/7/1907	153	1/17/1937	3	Unknown	Heitmuller & Reece Brune
Lynn, TX	Tahoka Springs	Lynn3	-101.744	33.26108	95.1	12/13/1974	---	---	1	Ogallala	Brune
Lynn, TX	Double Lakes Springs	Lynn4	-101.905	33.23313	15.9	12/12/1975	seeps	9/9/1978	2	Alluvium	Brune
Lynn, TX	Gooch Springs	Lynn6	-101.966	32.97404	12.4	10/26/1978	---	---	1	Unknown	Brune
Lynn, TX	New Moore Springs	Lynn7	-102.066	33.02203	118.9	12/13/1975	90.3	10/25/1978	2	Ogallala	Brune
Lynn, TX	Frost Springs	Lynn9	-102.039	33.00706	66.6	10/26/1978	---	---	1	Unknown	Brune
Lynn, TX	SR-28-01-103	2801103 325825101574901	-101.964	32.97361	2.0	0	---	---	1	ET-HP	Heitmuller & Reece TWDB well database
Martin, TX	Soda Springs	Martin9 2833304 322730101533201	-101.863	32.43384	60.2	4/20/1979	---	---	1	Ogallala	Heitmuller & Reece Brune
Martin, TX	Sulphur Springs	Martin10 2833902 322430101523201	-101.842	32.39963	10.0	1936	2.1	4/20/1979	2	Ogallala	Heitmuller & Reece Brune
Mitchell, TX	---	2949801	-100.958	32.15346	12	---	---	---	1	Dockum	TWDB website
Mitchell, TX	TP-29-43-113	2943113 322003100440301	-100.734	32.33417	5.0	0	---	---	1	Dockum	Heitmuller & Reece TWDB well database

Table 4.5.5, continued

County	Spring Name/Number	Site Number*	Longitude (decimal Degrees)	Latitude (decimal Degrees)	Max Flow (gpm)	Date of Max Flow	Min Flow (gpm)	Date of Min Flow	# of Measure-ments	Geologic Source	Reference
Moore, TX	Vincent Springs	Moore12	-101.749	35.648	61.0	6/8/1978	---	---	1	Ogallala & Dockum	Brune
Motley, TX	Roaring Springs	Motley1 2210104 7307700	-100.865	33.85333	1539	1946	373	11/9/1966	152	Dockum	TWDB website Heitmuller and Reece Brune (2002)
Motley, TX	---	1164604 340416101023101	-101.042	34.07111	140	---	---	---	1	Ogallala & Dockum	Heitmuller and Reece TWDB well database
Motley, TX	Burleson Springs	Motley4	-101.029	34.082	139.5	1938	139.5	1968	2	Unknown	Brune
Motley, TX	Ballard Springs	2202102 335948100500801	-100.836	33.99667	15.0	1/1/1968	---	---	1	Dockum	Heitmuller & Reece TWDB well database
Motley, TX	TW-12-58-703	1258703 340009100522501	-100.874	34.0025	37.0	1/1/1968	---	---	1	Dockum	Heitmuller & Reece TWDB well database
Motley, TX	TW-22-09-104	2209104 335115100575301	-100.965	33.85417	45.0	1/1/1968	---	---	1	Ogallala	Heitmuller & Reece TWDB well database
Motley, TX	Panther Canyon Springs	2209203 335153100552501	-100.924	33.86472	5.0	1/1/1969	---	---	1	Ogallala	Heitmuller & Reece TWDB well database
Motley, TX	TW-22-01-503	2201503 335600100562301	-100.94	33.93333	37.5	1/1/1938	37.5	1/1/1968	2	Ogallala	Heitmuller & Reece TWDB well database
Motley, TX	TW-22-01-504	2201504 335633100553201	-100.926	33.9425	12.5	1/1/1938	12.5	1/1/1968	2	Dockum	Heitmuller & Reece TWDB well database
Motley, TX	TW-22-01-502	2201502 335645100570801	-100.952	33.94583	12.0	0	---	---	1	Ogallala	Heitmuller & Reece TWDB well database

Table 4.5.5, continued

County	Spring Name/Number	Site Number*	Longitude (decimal Degrees)	Latitude (decimal Degrees)	Max Flow (gpm)	Date of Max Flow	Min Flow (gpm)	Date of Min Flow	# of Measure-ments	Geologic Source	Reference
Motley, TX	TW-22-01-303	2201303 335942100525601	-100.882	33.995	4.0	1/1/1968	---	---	1	Dockum	Heitmuller & Reece TWDB well database
Motley, TX	Mott Camp Springs	1164908 340022101003501	-101.01	34.00611	10.0	8/30/1938	10	10/10/1968	2	Ogallala	Heitmuller & Reece TWDB well database
Motley, TX	TW-11-64-909	1164909 340129101010301	-101.018	34.02472	30.0	1/1/1968	10	1/1/1938	2	Ogallala	Heitmuller & Reece TWDB well database
Motley, TX	TW-12-57-803	1257803 340136100555601	-100.932	34.02667	37.0	1/1/1968	---	---	1	Dockum	Heitmuller & Reece TWDB well database
Motley, TX	TW-11-64-910	1164910 340151101010601	-101.018	34.03083	40.0	1/1/1968	---	---	1	Ogallala	Heitmuller & Reece TWDB well database
Motley, TX	TW-11-64-602	1164602 340408101005201	-101.014	34.06889	75.0	0	---	---	1	Dockum	Heitmuller & Reece TWDB well database
Oldham, TX	Brown's Camp Springs	Oldham17	-103.013	35.23395	40	5/1977	---	---	1	Dockum	Brune (2002)
Oldham, TX	Chisum Springs	Oldham2	-102.962	35.44914	30	5/5/1977	---	---	1	Dockum	Brune (2002)
Oldham, TX	Ojo Caballo or Horse Spring	Oldham4	-103.027	35.44914	1.00	1938	0.57	1977	2	Dockum	Brune (2002)
Oldham, TX	---	Oldham11	-102.305	35.5518	27	1938	seeps	5/1977	2	Dockum	Brune (2002)
Oldham, TX	Cheyenne	Oldham37	-102.294	35.27896	0.5	1938	---	---	1	Unknown	Brune
Oldham, TX	Bravo Springs	824901 353708103003201	-103.009	35.61889	18.0	6/22/1971	weak	7/20/1938	2	Unknown	Heitmuller & Reece

Table 4.5.5, continued

County	Spring Name/Number	Site Number*	Longitude (decimal Degrees)	Latitude (decimal Degrees)	Max Flow (gpm)	Date of Max Flow	Min Flow (gpm)	Date of Min Flow	# of Measure-ments	Geologic Source	Reference
Pecos, TX	Diamond Y Springs	4557801 310002102551101	-102.921	31.00111	193.0	5/10/1943	184	1/1/1992	2	ET-P	Heitmuller & Reece TWDB well database
Pecos, TX	US-53-02-201	5302201 305801102482601	-102.807	30.96694	193.0	10/16/1942	---	---	1	Unknown	Heitmuller & Reece
Pecos, TX	San Pedro Springs	5302202 305831102493201	-102.826	30.97528	2881.3	1/18/1949	0	7/10/1958	98	Unknown	Heitmuller & Reece
Pecos, TX	San Simon Springs	4558803 310131102473201	-102.792	31.02528	80.8	5/11/1943	---	---	1	Unknown	Heitmuller & Reece
Pecos, TX	Monument Springs	4549502 311016102554701	-102.93	31.17111	484.7	5/14/1938	0	2/22/1962	3	Unknown	Heitmuller & Reece
Pecos, TX	Bonebrake Spring	4549501 311018102553901	-102.928	31.17167	2.0	0	---	---	1	PVA	Heitmuller & Reece TWDB well database
Pecos, TX	Santa Rosa Spring	4541802 311606102573201	-102.959	31.26833	1979.2	1/13/1943	0	2/22/1962	3	PVA	Heitmuller & Reece TWDB well database
Pecos, TX	Bennett Springs	4557906	-102.91	31.00222	1.67	4/30/09	---	---	1	ET-P	TWDB well database
Pecos, TX	Comanche Springs	5301906	-102.877	30.88444	5200	2004	1395	1992	2	ET-P	TWDB well database
Potter, TX	Bonita or Pretty Springs	Potter16	-101.736	35.35837	73	7/4/1978	---	---	1	Ogallala & Dockum	Brune (2002)
Potter, TX	Chicken Springs	Potter21	-101.734	35.44331	1522	1956	285	1974	26	Ogallala & Dockum	Brune (2002)
Potter, TX	Pitcher Springs	Potter6	-101.912	35.48295	52	7/6/1978	---	---	1	Dockum	Brune (2002)

Table 4.5.5, continued

County	Spring Name/Number	Site Number*	Longitude (decimal Degrees)	Latitude (decimal Degrees)	Max Flow (gpm)	Date of Max Flow	Min Flow (gpm)	Date of Min Flow	# of Measure-ments	Geologic Source	Reference
Potter, TX	Quail Feather Springs	Potter12	-101.991	35.48861	43	7/6/1978	---	---	1	Dockum	Brune (2002)
Potter, TX	Sandoval Springs	Potter13	-102.138	35.49144	11	7/1978	---	---	1	Dockum	Brune (2002)
Potter, TX	Tecovas Spring	756102 351159102055701	-102.099	35.19972	44.9	8/13/1924	10	4/20/1937	2	Unknown	Heitmuller & Reece
Potter, TX	Coetas Springs	Potter20	-101.728	35.4724	123.6	7/7/1978	---	---	1	Ogallala	Brune
Potter, TX	Bonita/Pretty Springs	Potter16	-101.746	35.3578	75.8	7/4/1978	---	---	1	Ogallala & Dockum	Brune
Quay, NM	7N.30E.15.432	Quay1	-103.719	34.83037	seep	8/25/1953	---	---	1	Ogallala	White & Kues
Quay, NM	8N.27E.6.430	Quay2	-104.108	34.93829	2.0	11/2/1955	---	---	1	Rita Blanca	White & Kues
Quay, NM	8N.31E.12.320	Quay3	-103.602	34.93129	2.0	4/21/1955	---	---	1	Alluvium	White & Kues
Quay, NM	8N.32E.18.223	Quay4	-103.571	34.9166	5.0	4/16/1955	---	---	1	Alluvium	White & Kues
Quay, NM	8N.32E.35.114	Quay5	-103.506	34.87322	5.0	4/2/1955	---	---	1	Unknown	White & Kues
Quay, NM	9N.27E.36.244	Quay6	-104.021	34.96278	2.0	10/27/1953	---	---	1	Unknown	White & Kues
Quay, NM	9N.32E.24.322	Quay7	-103.494	34.99146	1.0	4/8/1955	---	---	1	Alluvium	White & Kues
Quay, NM	9N.32E.33.333	Quay8	-103.546	34.96697	25.0	4/16/1955	---	---	1	Alluvium	White & Kues
Quay, NM	9N.33E.24.312	Quay9	-103.382	34.99216	seep	2/14/1955	---	---	1	Unknown	White & Kues
Quay, NM	10N.33E.14.212	Quay13	-103.389	35.09221	seep	2/15/1955	---	---	1	Alluvium	White & Kues
Quay, NM	10N.35E.32.422	Quay14	-103.236	35.05653	3	12/1/1954	---	---	1	Alluvium	White & Kues
Quay, NM	10N.36E.8.233	Quay15	-103.13	35.1041	3	11/29/1954	---	---	1	Dockum	White & Kues
Quay, NM	10N.36E.18.224	Quay16	-103.152	35.08941	1	11/29/1954	---	---	1	Dockum	White & Kues
Quay, NM	12N.36E.5.231	Quay22	-103.135	35.2993	100.0	11/6/1954	---	---	1	Dockum	White & Kues
Quay, NM	13N.36E.27.332	Quay24	-103.089	35.33008	1.0	7/26/1957	---	---	1	Dockum	White & Kues
Quay, NM	14N.35E.34.343	Quay25	-103.214	35.38944	30.0	3/8/1957	---	---	1	Dockum	White & Kues

Table 4.5.5, continued

County	Spring Name/Number	Site Number*	Longitude (decimal Degrees)	Latitude (decimal Degrees)	Max Flow (gpm)	Date of Max Flow	Min Flow (gpm)	Date of Min Flow	# of Measure-ments	Geologic Source	Reference
Quay, NM	14N.35E.35.311	Quay26	-103.201	35.38694	150.0	3/8/1957	---	---	1	Dockum	White & Kues
Quay, NM	14N.37E.31.213	Quay27	-103.051	35.40056	3.0	3/31/1954	---	---	1	Dockum	White & Kues
Quay, NM	15N.34E.30.134	Quay28	-103.354	35.5008	300.0	6/3/1954	---	---	1	Ogallala	White & Kues
Quay, NM	15N.36E.24.214	Quay29	-103.059	35.52948	100.0	4/7/1954	---	---	1	Alluvium	White & Kues
Quay, NM	15N.37E.19.134	Quay30	-103.04	35.53018	50.0	4/7/1954	---	---	1	Alluvium	White & Kues
Quay, NM	16N.37E.18.423	Quay31	-103.045	35.61028	<1	5/22/1953	---	---	1	Ogallala	White & Kues
Randall, TX	CCC Springs	Randall7	-101.646	34.94215	6.0	5/11/1937	0.8	8/11/1978	2	Dockum	Brune (2002)
Randall, TX	South Cita Springs	Randall5	-101.722	34.81193	118.9	8/10/1978	---	---	1	Unknown	Brune
Reeves, TX	San Solomon Springs	5202611 8427500	-103.788	30.94292	29 904	1990	14 047	1997	2	ET-P	Heitmuller & Reece TWDB well database
Reeves, TX	Giffin Springs	5202610 8427000	-103.789	30.94765	3015	1990	1723	1997	2	ET-P	Heitmuller & Reece TWDB well database
Reeves, TX	Saragosa Spring	5202314 305851103453301	-103.759	30.98083	4106.5	11/6/1932	dry	2002	9	Alluvium	Heitmuller & Reece TWDB well database
Reeves, TX	West Sandia Spring	5203118 8429000	-103.738	30.98583	228.9	1971	dry	2002	2	Alluvium	Heitmuller & Reece TWDB well database

Table 4.5.5, continued

County	Spring Name/Number	Site Number*	Longitude (decimal Degrees)	Latitude (decimal Degrees)	Max Flow (gpm)	Date of Max Flow	Min Flow (gpm)	Date of Min Flow	# of Measure-ments	Geologic Source	Reference
Reeves, TX	Cowan Spring T-15	4658405 310356103503101	-103.842	31.06556	0.0	1/1/1959	---	---	1	ET-P	Heitmuller & Reece TWDB well database
Reeves, TX	Cowan Spring T-14	4658404 310410103502301	-103.84	31.06944	0.0	1/1/1959	---	---	1	ET-P	Heitmuller & Reece TWDB well database
Reeves, TX	Torrez or Coyote Spring	4641201 312003103573301	-103.959	31.33417	2.5	1/1/1970	---	---	1	ET-P	Heitmuller & Reece TWDB well database
Reeves, TX	Pecan Spring	4641202 312005103563401	-103.943	31.33472	27.5	1/1/1970	---	---	1	ET-P	Heitmuller & Reece TWDB well database
Reeves, TX	Hackberry Springs	4645101 312031103293201	-103.492	31.34194	0.0	3/26/1962	---	---	1	Unknown	Heitmuller & Reece
Scurry, TX	Dripping Springs	Scurry3	-101.385	34.92559	11	12/15/1975	---	---	1	Dockum	Brune (2002)
Scurry, TX	Camp Springs	Scurry2 2911702 324530100423101	-100.686	32.73613	904	4/8/1924	2.1	6/14/1975	3	Dockum	Heitmuller & Reece Brune (2002)
Scurry, TX	---	Scurry9	-101.128	32.9322	seeps	12/1975			1	Dockum	Brune (2002)
Scurry, TX	WZ-28-24-701	2824701 323755101072201	-101.123	32.63194	9.0	1/1/1961	---	---	1	Dockum	Heitmuller & Reece TWDB well database
Sterling, TX	XP-44-16-904	4416904 314529101001501	-101.004	31.75806	300.0	0	---	---	1	Unknown	Heitmuller & Reece
Sterling, TX	XP-44-07-903	4407903 315402101075301	-101.131	31.90056	150.0	0	---	---	1	Unknown	Heitmuller & Reece

Table 4.5.5, continued

County	Spring Name/Number	Site Number*	Longitude (decimal Degrees)	Latitude (decimal Degrees)	Max Flow (gpm)	Date of Max Flow	Min Flow (gpm)	Date of Min Flow	# of Measure-ments	Geologic Source	Reference
Sterling, TX	XP-43-01-605	4301605 315638100523601	-100.877	31.94389	3.0	0	---	---	1	Unknown	Heitmuller & Reece
Sterling, TX	XP-43-02-406	4302406 315700100505301	-100.848	31.95	93.0	0	---	---	1	Unknown	Heitmuller & Reece
Sterling, TX	XP-43-02-203	4302203 315801100493201	-100.826	31.96694	25.0	0	---	---	1	Unknown	Heitmuller & Reece
Sterling, TX	XP-43-02-107	4302107 315816100514801	-100.863	31.97111	3.0	0	---	---	1	Unknown	Heitmuller & Reece
Sterling, TX	XP-43-02-106	4302106 315821100515401	-100.865	31.9725	1.0	0	---	---	1	Unknown	Heitmuller & Reece
Sterling, TX	XP-43-01-307	4301307 315827100524601	-100.879	31.97417	25.0	0	---	---	1	Unknown	Heitmuller & Reece
Swisher, TX	Rogers Springs	Swisher4	-101.514	34.50057	5.1	11/12/1945	seeps	9/7/1978	2	Dockum	Brune
Terry, TX	Mound Springs	Terry1	-102.098	33.22026	63.4	12/13/1975	---	---	1	Unknown	Brune
Terry, TX	Rich Springs	Terry6	-102.194	33.27844	301.2	1900	10	5/18/1938	3	Alluvium	Brune
Terry, TX	XY-24-64-121	2464121 330600102070601	-102.118	33.1	1.0	7/27/1981	---	---	1	Alluvium	Heitmuller & Reece TWDB well database
Union, NM	18N.34E.12.241	Union1	-103.269	35.80833	10.0	9/8/1956	---	---	1	Rita Blanca	White & Kues
Union, NM	22N.33E.24.221	Union2	-103.367	36.12917	450.0	5/19/1956	---	---	1	Rita Blanca	White & Kues
Union, NM	22N.33E.36.112	Union3	-103.377	36.09806	150.0	5/19/1956	---	---	1	Rita Blanca	White & Kues
Union, NM	23N.29E.25.123	Union4	-103.805	36.20083	1.0	5/14/1955	---	---	1	Rita Blanca	White & Kues

Table 4.5.5, continued

County	Spring Name/Number	Site Number*	Longitude (decimal Degrees)	Latitude (decimal Degrees)	Max Flow (gpm)	Date of Max Flow	Min Flow (gpm)	Date of Min Flow	# of Measure-ments	Geologic Source	Reference
Union, NM	23N.33E.25.323	Union6	-103.376	36.19306	7.0	6/3/1954	---	---	1	Other	White & Kues
Union, NM	24N.29E.4.344	Union7	-103.85	36.34175	1.0	4/29/1955	---	---	1	Other	White & Kues
Union, NM	24N.31E.17.341	Union9	-103.663	36.3075	5.0	3/30/1955	---	---	1	Unknown	White & Kues
Union, NM	24N.31E.30.441	Union12	-103.671	36.27889	4.0	3/30/1955	---	---	1	Unknown	White & Kues
Union, NM	24N.32E.20.124	Union13	-103.544	36.29216	1.0	4/21/1955	---	---	1	Rita Blanca	White & Kues
Union, NM	24N.32E.31.432	Union14	-103.562	36.26623	5.0	5/17/1955	---	---	1	Rita Blanca	White & Kues
Union, NM	25N.35E.5.442	Union15	-103.227	36.42178	10-15	10/27/1954	---	---	1	Ogallala	White & Kues
Union, NM	26N.33E.30.223	Union16	-103.454	36.46583	15.0	10/18/1959	---	---	1	Rita Blanca	White & Kues
Union, NM	26N.35E.23.411	Union17	-103.171	36.47417	3.0	7/28/1954	---	---	1	Other	White & Kues
Union, NM	28N.33E.9.223	Union19	-103.417	36.67765	1.0	6/24/1955	---	---	1	Rita Blanca	White & Kues
Union, NM	29N.28E.12.113	Union22	-103.917	36.76778	450.0	7/11/1951	---	---	1	Other	White & Kues
Union, NM	29N.30E.34.111	Union23	-103.727	36.70583	105.0	10/10/1955	---	---	1	Rita Blanca	White & Kues
Union, NM	29N.32E.12.121	Union24	-103.476	36.76445	1.0	10/14/1955	---	---	1	Rita Blanca	White & Kues
Union, NM	29N.32E.27.211	Union25	-103.513	36.7171	seep	7/13/1955	---	---	1	Rita Blanca	White & Kues
Union, NM	29N.35E.5.231	Union26	-103.214	36.77008	2.0	6/27/1955	---	---	1	Rita Blanca	White & Kues
Union, NM	29N.36E.8.242	Union27	-103.108	36.7675	0.8	8/27/1954	---	---	1	Unknown	White & Kues
Wheeler, TX	Bronco Springs	538909 352230100163101	-100.275	35.375	27.0	6/24/1971	10	5/25/1967	2	Unknown	Heitmuller & Reece
Wheeler, TX	Rathjen Springs	Wheeler2 531609 353230100073101	-100.125	35.54167	179.3	7/14/1967	1567	6/24/1971	3	Ogallala	Heitmuller & Reece Brune
Wheeler, TX	Fort Elliot Springs	5294403 353243100282901	-100.475	35.54528	0.3	7/11/1967	0.02	6/24/1971	2	Ogallala	Heitmuller & Reece
Wheeler, TX	Bryant Spring	Wheeler13	-100.104	35.3549	230.8	1967	1885	1977	2	Ogallala	Brune
Wheeler, TX	Blakemore Springs	Wheeler8	-100.321	35.2322	247.3	8/17/1977	---	---	1	Other	Brune

Table 4.5.6 Springs with no flow measurements.

County	Spring Name/Number	Site Number*	Longitude (decimal Degrees)	Latitude (decimal Degrees)	Geologic Source	Reference
Andrews, TX	no name	Andrews1	-102.256	32.43268	Unknown	Brune
Andrews, TX	no name	Andrews2	-102.563	32.45858	Unknown	Brune
Andrews, TX	no name	Andrews3	-102.667	32.39994	Ogallala	Brune
Andrews, TX	no name	Andrews4	-102.672	32.39085	Unknown	Brune
Andrews, TX	no name	Andrews5	-102.984	32.41922	Unknown	Brune
Andrews, TX	Whalen Lake	Andrews6	-102.824	32.34145	Unknown	Brune
Andrews, TX	Scratch Springs	2733401 322630102593201	-102.992	32.44167	Unknown	Heitmuller & Reece
Armstrong, TX	AK-11-12-102	1112102 345024101350601	-101.584	34.84	Ogallala	Heitmuller & Reece TWDB well database
Bailey, TX	Barnett Spring	Bailey7	-102.75	33.96205	Unknown	Brune
Bailey, TX	no name	Bailey9	-102.706	33.90044	Unknown	Brune
Bailey, TX	no name	Bailey10	-102.72	33.88679	Unknown	Brune
Bailey, TX	no name	Bailey12	-102.774	33.9413	Ogallala	Brune
Bailey, TX	AR-10-50-802	1050802 340949102491101	-102.82	34.16361	Unknown	Heitmuller & Reece TWDB well database
Borden	Gavett Springs	2806501 325630101193101	-101.325	32.94167	Unknown	Heitmuller & Reece
Briscoe, TX	Mayfield Spring	Briscoe10	-101.447	34.47228	Alluvium	Brune
Briscoe, TX	BL-11-47-602	1147602 341845101082701	-101.141	34.3125	Dockum	Heitmuller & Reece TWDB well database
Briscoe, TX	BL-11-21-902	1121902 343745101232901	-101.391	34.62917	Ogallala	Heitmuller & Reece TWDB well database
Castro, TX	no name	Castro1	-102.422	34.71896	Unknown	Brune
Castro, TX	no name	Castro2	-102.224	34.66031	Ogallala	Brune
Castro, TX	no name	Castro3	-102.034	34.57953	Unknown	Brune
Castro, TX	no name	Castro4	-102.306	34.33312	Unknown	Brune
Castro, TX	Flagg Springs	Castro5	-102.383	34.35975	Unknown	Brune
Cimarron, OK	Saunders Spring	363407102565001	-102.946	36.56836	Rita Blanca	USGS NWIS

Table 4.5.6, continued

County	Spring Name/Number	Site Number*	Longitude (decimal Degrees)	Latitude (decimal Degrees)	Geologic Source	Reference
Cimarron, OK	no name	363604102534501	-102.896	36.60114	Rita Blanca	USGS NWIS
Cimarron, OK	Unnamed Spring	363610102543901	-102.911	36.6028	Unknown	USGS NWIS
Cimarron, OK	Hincke Spring	364435102583801	-102.978	36.74308	Alluvium	USGS NWIS
Cimarron, OK	James Spring 1	365019102381501	-102.638	36.83863	Rita Blanca	USGS NWIS
Cimarron, OK	Unnamed Spring	365042102391501	-102.655	36.84502	Rita Blanca	USGS NWIS
Cimarron, OK	James Spring 2	365052102375301	-102.632	36.8478	Rita Blanca	USGS NWIS
Cimarron, OK	James Spring 3	365052102380801	-102.636	36.8478	Rita Blanca	USGS NWIS
Cimarron, OK	Powelson Spring 1	365209102392401	-102.657	36.86919	Rita Blanca	USGS NWIS
Cimarron, OK	Powelson Spring 2	365233102391901	-102.656	36.87586	Rita Blanca	USGS NWIS
Cimarron, OK	Powelson Spring 3	365233102392701	-102.658	36.87586	Rita Blanca	USGS NWIS
Cochran, TX	no name	Cochran1	-102.686	33.40655	Unknown	Brune
Cochran, TX	no name	Cochran4	-103.006	33.79989	Ogallala	Brune
Cochran, TX	no name	Cochran6	-102.691	33.46436	Unknown	Brune
Cochran, TX	Morton Springs	Cochran8	-102.793	33.72204	Unknown	Brune
Colfax, NM	28N.26E.8.114	Colfax10	-104.202	36.67917	Rita Blanca	White & Kues
Colfax, NM	28N.26E.24.311	Colfax11	-104.132	36.64611	Rita Blanca	White & Kues
Colfax, NM	28N. 27E.20.133	Colfax12	-104.096	36.68	Rita Blanca	White & Kues
Colfax, NM	29N.26E.9.314	Colfax13	-104.184	36.75889	Alluvium	White & Kues
Colfax, NM	29N.27E.9.133	Colfax14	-104.078	36.76278	Alluvium	White & Kues
Crockett, TX	Live Oak Spring	5411814 304531101413101	-101.692	30.75861	Unknown	Heitmuller & Reece
Crosby, TX	Ericson Springs	Crosby11	-101.225	33.78785	Ogallala	Brune
Dawson, TX	no name	Dawson5	-102.12	32.88041	Unknown	Brune
Dawson, TX	no name	Dawson6	-101.776	32.55883	Unknown	Brune

Table 4.5.6, continued

County	Spring Name/Number	Site Number*	Longitude (decimal Degrees)	Latitude (decimal Degrees)	Geologic Source	Reference
De Baca, NM	1S.27E.14.121	De Baca17	-104.073	34.22438	Dockum	White & Kues
Deaf Smith, TX	Fowler Springs	Deaf Smith1	-102.185	35.03184	Unknown	Brune
Deaf Smith, TX	Parker Springs	Deaf Smith2	-102.183	34.84577	Unknown	Brune
Deaf Smith, TX	Escarbada	Deaf Smith5	-102.962	34.76238	Unknown	Brune
Deaf Smith, TX	Punta de Agua or Source of Water	Deaf Smith6	-102.443	34.79395	Unknown	Brune
Deaf Smith, TX	Sulphur Springs	Deaf Smith7	-102.262	34.82787	Unknown	Brune
Deaf Smith, TX	Ojita de Garcia or Little Garcia Springs	Deaf Smith9	-102.924	34.85862	Dockum	Brune
Deaf Smith, TX	Bridwell Springs	864302 350530103013201	-103.026	35.09167	Unknown	Heitmuller & Reece
Dickens, TX	Browning Springs	Dickens16	-100.859	33.6169	Dockum	Brune (2002)
Donley, TX	JA-12-10-609	1210609 344834100471601	-100.788	34.80944	Ogallala	Heitmuller & Reece TWDB well database
Donley, TX	JA-12-11-701	1211701 344612100433901	-100.728	34.77	Ogallala	Heitmuller & Reece TWDB well database
Donley, TX	JA-12-11-606	1211606 344848100373901	-100.628	34.81333	Ogallala	Heitmuller & Reece TWDB well database
Donley, TX	JA-12-10-608	1210608 344856100470401	-100.784	34.81556	Ogallala	Heitmuller & Reece TWDB well database
Ector, TX	no name	Ector1	-102.307	31.8019	Unknown	Brune
Eddy, NM	22S.30E.18.110	Eddy17	-103.929	32.39444	Unknown	White & Kues
Eddy, NM	23S.29E.4.430	Eddy20	-103.993	32.32778	Unknown	White & Kues
Ellis, OK	OK Wildlife Spring 3	355234099425201	-99.7148	35.87616	Unknown	USGS NWIS
Ellis, OK	OK Wildlife Spring 2	355337099431301	-99.7207	35.89366	Unknown	USGS NWIS

Table 4.5.6, continued

County	Spring Name/Number	Site Number*	Longitude (decimal Degrees)	Latitude (decimal Degrees)	Geologic Source	Reference
Ellis, OK	West Creek Spring 3	355404099435301	-99.7318	35.90116	Unknown	USGS NWIS
Ellis, OK	West Creek Spring 2	355411099435001	-99.7309	35.9031	Unknown	USGS NWIS
Ellis, OK	West Creek Spring 1	355419099435001	-99.7309	35.90532	Unknown	USGS NWIS
Ellis, OK	Grand Spring 1	355847099473601	-99.7937	35.97977	Unknown	USGS NWIS
Ellis, OK	Grand Spring 2	355848099474101	-99.7951	35.98005	Unknown	USGS NWIS
Ellis, OK	Johnson Spring 3	355903099470201	-99.7843	35.98421	Unknown	USGS NWIS
Ellis, OK	Davidson Ranch Spring 1	355917099363601	-99.6104	35.9881	Unknown	USGS NWIS
Ellis, OK	Johnson Spring 2	355958099462701	-99.7746	35.99949	Unknown	USGS NWIS
Ellis, OK	Flock Springs	360059099570001	-99.9504	36.01643	Unknown	USGS NWIS
Ellis, OK	Henderson Springs 4	360119099551601	-99.9215	36.02199	Unknown	USGS NWIS
Ellis, OK	Peck Spring 1	360123099462101	-99.7729	36.0231	Unknown	USGS NWIS
Ellis, OK	Henderson Spring 1	360132099551101	-99.9201	36.0256	Unknown	USGS NWIS
Ellis, OK	Henderson Spring 2	360134099550401	-99.9182	36.02616	Unknown	USGS NWIS
Ellis, OK	Trails End Farm Spring	360156099561901	-99.939	36.03227	Unknown	USGS NWIS
Ellis, OK	Harris Spring 3	360222099304701	-99.5134	36.03949	Unknown	USGS NWIS
Ellis, OK	Wayland Spring 1	360222099523201	-99.876	36.03949	Unknown	USGS NWIS
Ellis, OK	Wayland Springs 2	360226099524901	-99.8807	36.0406	Unknown	USGS NWIS
Ellis, OK	Elmer Knowles Spring	360245099480701	-99.8023	36.04588	Unknown	USGS NWIS
Ellis, OK	McCorkle Springs	360300099442701	-99.7912	36.05116	Unknown	USGS NWIS
Ellis, OK	Wagnon Spring 1	360321099374301	-99.629	36.05588	Unknown	USGS NWIS
Ellis, OK	Wagnon Spring 2	360321099374501	-99.6296	36.05588	Unknown	USGS NWIS
Ellis, OK	Cadwell Spring 3	360323099381101	-99.6368	36.05643	Unknown	USGS NWIS
Ellis, OK	Hutchison Spring 2	360336099303701	-99.5107	36.06005	Unknown	USGS NWIS

Table 4.5.6, continued

County	Spring Name/Number	Site Number*	Longitude (decimal Degrees)	Latitude (decimal Degrees)	Geologic Source	Reference
Ellis, OK	Hutchison Spring 1	360336099305001	-99.5143	36.06005	Unknown	USGS NWIS
Ellis, OK	Berry Spring 1	360342099300701	-99.5023	36.06171	Unknown	USGS NWIS
Ellis, OK	Davis Spring	360343099465601	-99.7826	36.06199	Unknown	USGS NWIS
Ellis, OK	Cadwell Spring 1	360349099384101	-99.6451	36.06366	Unknown	USGS NWIS
Ellis, OK	Baker Spring 4	360433099273801	-99.4609	36.07588	Unknown	USGS NWIS
Ellis, OK	Baker Spring 3	360441099273701	-99.4607	36.0781	Unknown	USGS NWIS
Ellis, OK	Baker Spring 2	360454099274801	-99.4637	36.08171	Unknown	USGS NWIS
Ellis, OK	Herbel Springs 1	360530099573701	-99.9607	36.09171	Unknown	USGS NWIS
Ellis, OK	Farris Springs	360620099572101	-99.9562	36.1056	Unknown	USGS NWIS
Ellis, OK	Pudwill Springs	360635099574501	-99.9629	36.10976	Unknown	USGS NWIS
Ellis, OK	Coram Spring 2	360637099275601	-99.4659	36.11032	Unknown	USGS NWIS
Ellis, OK	Coram Spring 1	360639099275501	-99.4657	36.11088	Unknown	USGS NWIS
Ellis, OK	Bowman Spring 4	360712099274801	-99.4637	36.12004	Unknown	USGS NWIS
Ellis, OK	Bowman Spring 2	360716099281201	-99.4704	36.12115	Unknown	USGS NWIS
Ellis, OK	Bowman Spring 1	360716099281401	-99.4709	36.12115	Unknown	USGS NWIS
Ellis, OK	Bowman Spring 3	360717099281001	-99.4698	36.12143	Unknown	USGS NWIS
Ellis, OK	Bowman Spring 5	360728099283501	-99.4768	36.12449	Unknown	USGS NWIS
Ellis, OK	Higginbotham Spring	361119099553701	-99.9273	36.18865	Unknown	USGS NWIS
Ellis, OK	Molloy Spring 1	361327099394501	-99.6629	36.22421	Unknown	USGS NWIS
Ellis, OK	Molloy Spring 2	361340099394001	-99.6615	36.22782	Unknown	USGS NWIS
Ellis, OK	Wayland Spring 3	361353099535301	-99.8985	36.23143	Unknown	USGS NWIS
Ellis, OK	Reininger Spring	361642099364401	-99.6126	36.27837	Unknown	USGS NWIS
Ellis, OK	Barnes Springs	361657099482301	-99.8062	36.28198	Unknown	USGS NWIS
Ellis, OK	Benbrook Spring	361925099362301	-99.6068	36.32365	Unknown	USGS NWIS
Ellis, OK	Harris Spring	362120099453901	-99.7612	36.35559	Unknown	USGS NWIS
Ellis, OK	Elliott Springs	362209099473001	-99.7921	36.36921	Unknown	USGS NWIS
Ellis, OK	Herber Springs	362215099474001	-99.7948	36.37087	Unknown	USGS NWIS
Ellis, OK	Brewers Spring	362845099383101	-99.6423	36.4792	Unknown	USGS NWIS
Ellis, OK	Murphy Springs	363036099415801	-99.6998	36.51004	Unknown	USGS NWIS
Ellis, OK	Dugger Spring 2	363126099470501	-99.7851	36.52392	Unknown	USGS NWIS
Ellis, OK	Burgess Springs	363328099395401	-99.6654	36.55781	Unknown	USGS NWIS
Floyd, TX	Massie Springs	Floyd1	-101.316	33.86475	Unknown	Brune
Floyd, TX	Montgomery Springs	Floyd4	-101.279	33.83642	Unknown	Brune
Gaines, TX	no name	Gaines2	-102.324	32.72021	Unknown	Brune
Gaines, TX	no name	Gaines6	-102.438	32.61236	Unknown	Brune
Gaines, TX	no name	Gaines7	-102.322	32.74822	Unknown	Brune
Gaines, TX	Ward's Well	Gaines8	-102.567	32.65272	Unknown	Brune

Table 4.5.6, continued

County	Spring Name/Number	Site Number*	Longitude (decimal Degrees)	Latitude (decimal Degrees)	Geologic Source	Reference
Gaines, TX	Boar's Nest Springs	Gaines10	-102.935	32.88474	Unknown	Brune
Garza, TX	Llano Springs	Garza8	-101.326	33.26272	Dockum	Brune (2002)
Garza, TX	Rocky Springs	Garza1	-101.077	33.01355	Dockum	Brune (2002)
Hale, TX	no name	Hale1	-101.661	34.16612	Unknown	Brune
Hale, TX	no name	Hale2	-101.577	34.13019	Unknown	Brune
Hale, TX	no name	Hale3	-101.591	34.11544	Ogallala	Brune
Hale, TX	Eagle Springs	Hale5	-101.951	33.85307	Unknown	Brune
Hale, TX	Running Water Springs	Hale6	-101.868	34.2268	Unknown	Brune
Hale, TX	Jones Springs	Hale7	-101.938	34.28405	Unknown	Brune
Hale, TX	Morrison Springs	Hale9	-101.94	34.27447	Unknown	Brune
Hale, TX	Norfleet Springs	Hale10	-102.004	34.27236	Unknown	Brune
Hansford, TX	Martin Springs	344201 362030101333201	-101.559	36.34167	Unknown	Heitmuller & Reece
Harper, OK	no name	364054099393701	-99.6607	36.6817	Alluvium	USGS NWIS
Harper, OK	no name	364203099564201	-99.9454	36.70087	Ogallala	USGS NWIS
Hartley, TX	no name	719101	-102.727	35.72893	Ogallala & Dockum	TWDB website
Hemphill, TX	Jo Spring	515302 355030100093101	-100.159	35.84167	Unknown	Heitmuller & Reece
Hockley, TX	Devil's Ink Well	Hockley2	-102.606	33.78316	Ogallala	Brune
Hockley, TX	no name	Hockley3	-102.464	33.70455	Ogallala	Brune
Hockley, TX	no name	Hockley4	-102.153	33.75047	Unknown	Brune
Hockley, TX	Yellow House Springs	Hockley5	-102.468	33.79518	Unknown	Brune
Hockley, TX	no name	Hockley6	-102.548	33.39247	Unknown	Brune
Hockley, TX	Silver Springs	2412401 334808102361801	-102.605	33.80222	Unknown	Heitmuller & Reece
Howard, TX	no name	Howard12	-101.665	32.21865	Unknown	Brune
Howard, TX	PB-28-45-806	2845806 321633101270401	-101.451	32.27583	Ogallala	Heitmuller & Reece TWDB well database
Howard, TX	PB-28-37-408	2837408 322555101292401	-101.49	32.43194	Ogallala	Heitmuller & Reece
Hutchinson, TX	White Deer Springs	623601 354130101073201	-101.126	35.69167	Unknown	Heitmuller & Reece
Irion, TX	Spring Creek Springs near Mertzon TX (Head Water spring)	4350201 8129000	-100.814	31.22139	ET-P	Heitmuller & Reece TWDB well database
Lamb, TX	King Springs	Lamb1	-102.116	34.28001	Ogallala	Brune
Lamb, TX	no name	Lamb2	-102.163	34.28417	Unknown	Brune
Lamb, TX	Sod House Spring	Lamb5	-102.407	34.09858	Unknown	Brune
Lamb, TX	no name	Lamb8	-102.401	34.13591	Unknown	Brune
Lamb, TX	no name	Lamb10	-102.293	34.02746	Unknown	Brune

Table 4.5.6, continued

County	Spring Name/Number	Site Number*	Longitude (decimal Degrees)	Latitude (decimal Degrees)	Geologic Source	Reference
Lamb, TX	Fieldton Springs	Lamb11	-102.226	34.02442	Unknown	Brune
Lamb, TX	Hart Springs	Lamb12	-102.166	34.00386	Unknown	Brune
Lea, NM	Monument Spring (19S.36E.25.123)	Lea2	-103.271	32.65269	Unknown	White & Kues
Lipscomb, TX	First Springs	445101 362030100293201	-100.492	36.34167	Unknown	Heitmuller & Reece
Loving, TX	Coyote Springs	4605701 315430103293201	-103.492	31.90833	Unknown	Heitmuller & Reece
Lubbock, TX	Lubbock Lake	Lubbock2	-101.832	33.5962	Unknown	Brune
Lubbock, TX	SP-23-27-713	2327713 333205101450001	-101.75	33.53472	Ogallala	Heitmuller & Reece TWDB well database
Lubbock, TX	SP-23-27-714	2327714 333208101435001	-101.731	33.53556	Ogallala	Heitmuller & Reece TWDB well database
Lubbock, TX	Pig Squeal Springs	2327804 333212101405801	-101.683	33.53667	Ogallala	Heitmuller & Reece TWDB well database
Lubbock, TX	SP-23-27-715	2327715 333214101440001	-101.733	33.53722	Ogallala	Heitmuller & Reece TWDB well database
Lubbock, TX	SP-23-27-716	2327716 333216101442901	-101.741	33.53778	Ogallala	Heitmuller & Reece TWDB well database
Lubbock, TX	SP-23-27-810	2327810 333220101420901	-101.703	33.53889	Ogallala	Heitmuller & Reece TWDB well database
Lynn, TX	Saleh Lake and Seeps	Lynn1	-101.965	32.97865	Ogallala	Brune
Lynn, TX	Guthrie Springs	Lynn5	-101.834	33.1125	Unknown	Brune
Lynn, TX	no name	Lynn8	-101.97	33.13607	Alluvium	Brune
Martin, TX	no name	Martin2	-101.718	32.18463	Ogallala	Brune
Martin, TX	Mulkey Springs	Martin3	-101.745	32.14581	Unknown	Brune
Martin, TX	Baldwin Springs	Martin4	-101.896	32.09661	Unknown	Brune
Martin, TX	no name	Martin6	-101.94	32.16043	Ogallala	Brune
Martin, TX	Kilpatrick Springs	Martin7	-101.991	32.21816	Unknown	Brune
Martin, TX	no name	Martin8	-101.873	32.45806	Ogallala	Brune
Martin, TX	Mustang Spring	Martin5 2849810 320830101563201	-101.922	32.12292	Unknown	Heitmuller & Reece Brune
Midland, TX	no name	Midland5	-102.135	31.86928	Unknown	Brune
Midland, TX	no name	Midland7	-101.789	31.94739	Unknown	Brune
Midland, TX	no name	Midland8	-102.059	32.02202	Alluvium	Brune
Midland, TX	Mustang Springs	Midland9	-101.791	32.05295	Unknown	Brune

Table 4.5.6, continued

County	Spring Name/Number	Site Number*	Longitude (decimal Degrees)	Latitude (decimal Degrees)	Geologic Source	Reference
Midland, TX	Peck's Spring	4410408 314850101513701	-101.86	31.81389	ET-P	Heitmuller & Reece TWDB well database
Midland, TX	TJ-45-15-203	4515203 315117102103601	-102.177	31.85472	ET-P	Heitmuller & Reece TWDB well database
Mitchell, TX	TP-28-40-811	2840811 322333101045001	-101.081	32.3925	Dockum	Heitmuller & Reece TWDB well database
Mitchell, TX	TP-29-25-702	2925702 323104100595801	-100.999	32.51778	Dockum	Heitmuller & Reece TWDB well database
Motley, TX	Wolf Springs	2201703 335230100593201	-100.992	33.875	Unknown	Heitmuller & Reece
Motley, TX	Miller Springs	1164304 340549101014001	-101.028	34.09694	Unknown	Heitmuller & Reece
Motley, TX		1258905	-100.779	34.01444	Dockum	TWDB well database
Ochiltree, TX	Wampus Cat Springs	340501 362530101043201	-101.076	36.425	Unknown	Heitmuller & Reece
Oldham, TX	Rocky Dell Springs	Oldham21	-102.794	35.21829	Unknown	Brune
Oldham, TX	Joaquin Spring	Oldham27	-102.683	35.46593	Unknown	Brune
Oldham, TX	George Springs	Oldham28	-102.731	35.44843	Unknown	Brune
Oldham, TX	Blue Goose Springs	733601 352530102543201	-102.909	35.425	Unknown	Heitmuller & Reece
Oldham, TX	Chavez Springs	725901 352930102523201	-102.876	35.49167	Unknown	Heitmuller & Reece
Oldham, TX	Pedarosa Springs	727202 353530102403201	-102.676	35.59167	Unknown	Heitmuller & Reece
Parmer, TX	no name	Parmer1	-102.826	34.49938	Ogallala	Brune
Parmer, TX	no name	Parmer2	-102.909	34.545	Ogallala	Brune
Parmer, TX	no name	Parmer5	-103.012	34.64268	Unknown	Brune
Pecos, TX	US-45-57-806	4557806 310030102551501	-102.921	31.00833	ET-P	Heitmuller & Reece TWDB well database
Pecos, TX	Euphrasia Spring	4557903 310157102534301	-102.895	31.0325	ET-P	Heitmuller & Reece TWDB well database
Potter, TX	Spring Grove Springs	Potter5	-101.935	35.2231	Dockum	Brune (2002)
Potter, TX	Alibates Springs	6278803 353215101401401	-101.671	35.5375	Alluvium	Heitmuller & Reece
Potter, TX		627803	-101.67	35.5375	Alluvium	TWDB well database
Potter, TX	Box Canyon Springs	Potter17	-101.746	35.3578	Unknown	Brune 2002
Randall, TX	T-Anchor Springs	Randall11	-101.937	34.96505	Unknown	Brune
Randall, TX	no name	Randall12	-101.936	34.98766	Unknown	Brune

Table 4.5.6, continued

County	Spring Name/Number	Site Number*	Longitude (decimal Degrees)	Latitude (decimal Degrees)	Geologic Source	Reference
Randall, TX	Thompson Springs	Randall13	-101.94	34.95648	Unknown	Brune
Randall, TX	Long Springs	Randall14	-101.995	34.97648	Unknown	Brune
Randall, TX	Carruth Springs	Randall15	-102.026	34.95423	Unknown	Brune
Randall, TX	no name	Randall16	-102.148	34.88596	Unknown	Brune
Randall, TX	Dean Springs	Randall17	-102.149	35.0348	Unknown	Brune
Randall, TX	Tub Springs	1103301 345730101383201	-101.642	34.95833	Unknown	Heitmuller & Reece
Reeves, TX	East Sandia Spring	5203115 8430000	-103.73	30.99083	Alluvium	Heitmuller & Reece TWDB well database
Reeves, TX	Petican Spring	4641102 312030103573201	-103.959	31.34167	Unknown	Heitmuller & Reece
Roberts, TX	Waterfield Springs	504503 355430100343101	-100.575	35.90833	Unknown	Heitmuller & Reece
Roberts, TX	Whitsell Springs	501102 355830100573201	-100.959	35.975	Unknown	Heitmuller & Reece
Roosevelt, NM	Spring No. 56 (3N.30E.33.400)	Roosevelt1	-103.86	34.42165	Unknown	White & Kues
Roosevelt, NM	Portales Spring (2S.35E.15.133)	Roosevelt2	-103.252	34.10268	Alluvium	White & Kues
Scurry, TX	WZ-28-24-808	2824808 323736101042701	-101.074	32.62667	Unknown	Heitmuller & Reece TWDB well database
Scurry, TX	WZ-28-24-807	2824807 323832101031001	-101.053	32.64222	Unknown	Heitmuller & Reece TWDB well database
Scurry, TX	Greene Springs	2919103 324230100433101	-100.725	32.70833	Unknown	Heitmuller & Reece
Scurry, TX	Deep Creek Springs	2816101 325030101053101	-101.092	32.84167	Unknown	Heitmuller & Reece
Sherman, TX	Coldwater Springs	343701 361530101443201	-101.742	36.25833	Unknown	Heitmuller & Reece
Sterling, TX	XP-44-08-309	4408309 315739101010301	-101.018	31.96083	Unknown	Heitmuller & Reece
Sterling, TX	XP-28-63-610	2863610 320301101095001	-101.164	32.05028	Unknown	Heitmuller & Reece
Swisher, TX	Hackberry Springs	Swisher2	-101.582	34.49261	Unknown	Brune
Swisher, TX	Dead Horse Springs	Swisher5	-101.54	34.4948	Unknown	Brune
Swisher, TX	Dawson Springs	Swisher9	-101.599	34.49294	Unknown	Brune
Swisher, TX	no name	Swisher11	-101.612	34.50447	Unknown	Brune
Swisher, TX	Edwards Springs	Swisher12	-101.605	34.50274	Unknown	Brune
Swisher, TX	Poff Springs	Swisher13	-101.737	34.52532	Unknown	Brune
Swisher, TX	no name	Swisher14	-101.922	34.66323	Unknown	Brune

Table 4.5.6, continued

County	Spring Name/Number	Site Number*	Longitude (decimal Degrees)	Latitude (decimal Degrees)	Geologic Source	Reference
Swisher, TX	Maupin Springs	Swisher17	-101.792	34.51858	Unknown	Brune
Swisher, TX	Hardy Springs	Swisher18	-101.935	34.53557	Unknown	Brune
Terry, TX	no name	Terry2	-102.085	33.01487	Unknown	Brune
Terry, TX	no name	Terry3	-102.426	33.28487	Ogallala	Brune
Terry, TX	no name	Terry4	-102.441	33.32245	Unknown	Brune
Terry, TX	no name	Terry7	-102.423	33.30702	Unknown	Brune
Terry, TX	no name	Terry9	-102.326	33.21013	Unknown	Brune
Terry, TX	no name	Terry10	-102.175	33.14564	Unknown	Brune
Terry, TX	no name	Terry11	-102.107	33.03911	Alluvium	Brune
Terry, TX	no name	Terry13	-102.313	32.98832	Unknown	Brune
Terry, TX	XY-24-64-107	2464107 330723102070801	-102.119	33.12306	Alluvium	Heitmuller & Reece TWDB well database
Terry, TX	XY-24-56-407	2456407 331007102064401	-102.112	33.16861	Ogallala	Heitmuller & Reece TWDB well database
Union, NM	23N.32E.16.121	Union5	-103.528	36.21664	Rita Blanca	White & Kues
Union, NM	24N.29E.10.141	Union8	-103.838	36.32485	Unknown	White & Kues
Union, NM	24N.31E.30.313	Union10	-103.685	36.28111	Unknown	White & Kues
Union, NM	24N.31E.30.434	Union11	-103.673	36.27778	Unknown	White & Kues
Union, NM	28N.32E.8.443	Union18	-103.544	36.67427	Other	White & Kues
Union, NM	28N.33E.18.141	Union20	-103.443	36.65736	Rita Blanca	White & Kues
Union, NM	29N.28E.11. 234	Union21	-103.919	36.76219	Rita Blanca	White & Kues
Wheeler, TX	ZB-55-32-202	5532202 351413100262701	-100.441	35.23694	Ogallala	Heitmuller & Reece
Wheeler, TX	ZB-54-57-706	5457706 351600100282801	-100.474	35.26667	Ogallala	Heitmuller & Reece
Wheeler, TX	ZB-54-52-203	5452203 352002100262901	-100.441	35.33389	Ogallala	Heitmuller & Reece
Wheeler, TX	ZB-53-66-603	5366603 352555100314501	-100.529	35.43194	Ogallala	Heitmuller & Reece
Wheeler, TX	ZB-53-74-402	5374402 352602100282101	-100.473	35.43389	Ogallala	Heitmuller & Reece
Wheeler, TX	ZB-53-94-407	5394407 352615100134001	-100.228	35.4375	Ogallala	Heitmuller & Reece
Wheeler, TX	ZB-53-96-610	5396610 352626100095301	-100.165	35.44056	Ogallala	Heitmuller & Reece
Wheeler, TX	ZB-53-86-608	5386608 352706100160701	-100.269	35.45167	Ogallala	Heitmuller & Reece

Table 4.5.6, continued

County	Spring Name/Number	Site Number*	Longitude (decimal Degrees)	Latitude (decimal Degrees)	Geologic Source	Reference
Wheeler, TX	ZB-53-85-509	5385509 352720100175701	-100.299	35.45556	Ogallala	Heitmuller & Reece
Wheeler, TX	ZB-53-71-103	5371103 352815100274801	-100.463	35.47083	Ogallala	Heitmuller & Reece
Wheeler, TX	ZB-53-27-702	5327702 353016100051001	-100.086	35.50444	Ogallala	Heitmuller & Reece
Wheeler, TX	ZB-52-98-816	5298816 353020100250601	-100.418	35.50556	Ogallala	Heitmuller & Reece
Wheeler, TX	ZB-53-19-903	5319903 353102100094601	-100.163	35.51722	Ogallala	Heitmuller & Reece
Wheeler, TX	ZB-53-27-701	5327701 353138100062701	-100.108	35.52722	Ogallala	Heitmuller & Reece
Wheeler, TX	ZB-53-07-706	5307706 353213100203701	-100.344	35.53694	Ogallala	Heitmuller & Reece
Wheeler, TX	ZB-53-09-902	5309902 353228100163901	-100.278	35.54111	Ogallala	Heitmuller & Reece
Wheeler, TX	ZB-52-96-608	5296608 353310100241601	-100.404	35.55278	Ogallala	Heitmuller & Reece
Wheeler, TX	ZB-52-95-503	5295503 353313100252001	-100.422	35.55361	Ogallala	Heitmuller & Reece
Wheeler, TX	no name	553202	-100.441	35.23694	Ogallala	TWDB well database
Wheeler, TX	no name	545706	-100.474	35.26667	Ogallala	TWDB well database
Wheeler, TX	no name	545203	-100.441	35.33389	Ogallala	TWDB well database
Wheeler, TX	no name	536603	-100.529	35.43194	Ogallala	TWDB well database
Wheeler, TX	no name	537402	-100.472	35.43389	Ogallala	TWDB well database
Wheeler, TX	no name	539407	-100.228	35.4375	Ogallala	TWDB well database
Wheeler, TX	no name	539610	-100.165	35.44056	Ogallala	TWDB well database
Wheeler, TX	no name	538608	-100.269	35.45167	Ogallala	TWDB well database
Wheeler, TX	no name	538509	-100.299	35.45556	Ogallala	TWDB well database
Wheeler, TX	no name	537103	-100.463	35.47083	Ogallala	TWDB well database
Wheeler, TX	no name	532702	-100.086	35.50444	Ogallala	TWDB well database
Wheeler, TX	no name	529816	-100.418	35.50556	Ogallala	TWDB well database
Wheeler, TX	no name	531903	-100.163	35.51722	Ogallala	TWDB well database
Wheeler, TX	no name	532701	-100.108	35.52722	Ogallala	TWDB well database
Wheeler, TX	no name	530706	-100.344	35.53694	Ogallala	TWDB well database
Wheeler, TX	no name	530902	-100.277	35.54111	Ogallala	TWDB well database
Wheeler, TX	no name	529403	-100.475	35.54528	Ogallala	TWDB well database
Wheeler, TX	no name	529608	-100.404	35.55278	Ogallala	TWDB well database

Table 4.5.6, continued

County	Spring Name/Number	Site Number*	Longitude (decimal Degrees)	Latitude (decimal Degrees)	Geologic Source	Reference
Wheeler, TX	no name	529503	-100.422	35.55361	Ogallala	TWDB well database
Winkler, TX	Willow Springs	4517503 314130102553201	-102.926	31.69167	Unknown	Heitmuller & Reece
Winkler, TX	Blue Mountain Springs	4502101 315930102513201	-102.859	31.99167	Unknown	Heitmuller & Reece
Yoakum, TX	no name	Yoakum3	-102.817	33.18753	Unknown	Brune
Yoakum, TX	no name	Yoakum5	-102.938	33.07298	Unknown	Brune
Yoakum, TX	no name	Yoakum6	-102.62	33.10937	Unknown	Brune

Table 4.5.7 Reservoirs intersecting the study area.

Reservoir Name	Owner/ Controlling Authority	Surface Area (acres)	Date Impounded	Aquifer
Lake Meredith(1)	Canadian River Municipal Water Authority	16,411	1965	Ogallala
Red Bluff Reservoir(1)	Red Bluff Water Control District	7,495	1936	Pecos Valley
Lake J B Thomas(1)	Colorado River Municipal Water District	7,282	1952	Dockum
Optima Lake(2)	Army Corps of Engineers	5,340	1978	Ogallala
Alan Henry Reservoir(1)	City of Lubbock	2,741	1993	Dockum
Palo Duro Reservoir(1)	Palo Duro River Authority	2,407	1991	Ogallala
Fort Supply Reservoir(2)	Army Corps of Engineers	1,820	1942	Ogallala
Lake Colorado City(1)	City of Colorado City	1,612	1949	Dockum
Champion Creek Reservoir(1)	City of Colorado City	1,560	1959	Dockum
Greenbelt Reservoir(1)	Greenbelt Municipal and Industrial Water Authority	2,025	1966	Ogallala
Mitchell County Reservoir(1)	Colorado River Municipal Water District	1,463	1991	Dockum
White River Lake[1]	White River Municipal Water District	1,642	1963	Dockum
Tule Creek Lake(1) (MacKenzie Reservoir)	Mackenzie Municipal Water Authority	910	1974	Dockum
Rita Blanca Lake(1)	United States Fish and Wildlife Service	524	1939	Ogallala
Bivins Lake(1) (Amarillo City Lake)	City of Amarillo	379	1927	Ogallala
Red Draw Lake(1)	Colorado River Municipal Water District	374	1985	Dockum
Buffalo Spring Lake(1)	Lubbock County Water Improvement District No. 1	200	1959	Ogallala/ Dockum
Lake Fryer(3) (Wolf Creek Lake)	Ochiltree County	86	1939	Ogallala

(1) Lake information from TWDB (2015).
(2) Lake information from OWRB (2015).
(3) Lake information from Texas Parks and Wildlife (2015).

Table 4.5.8 Saline lakes intersecting the study area.

Saline Lake Name	Source
Baileyboro	RR1996, WJ1990
Baird	RR1996
Buffalo	RR1996
Bull	RR1996, WJ1990
Cedar	RR1996, WJ1990
Coyote	RR1996, WJ1990
Double Lakes	RR1996, WJ1990
Frost	RR1996
Garcia	RR1996
Gooch	RR1996, WJ1990
Goose	WJ1990
Guthrie	RR1996, WJ1990
Illusion	WJ1990
Lane Salt Lake	RR1996, WJ1990
Lewiston	RR1996, WJ1990
Little Salt	WJ1990
McKenzie	RR1996, WJ1990
Mound	RR1996, WJ1990
Pauls	WJ1990
Ranger Lake	RR1996, WJ1990
Red Lake	RR1996
Rich	RR1996, WJ1990
Salt	WJ1990
Shafter	RR1996, WJ1990
Silver	RR1996, WJ1990
Soda	WJ1990
Tahoka	RR1996, WJ1990
Tule	RR1996
Twin Lakes	RR1996, WJ1990
Whalen	RR1996, WJ1990
White	WJ1990
Yellow	WJ1990
Unnamed 33	WJ1990
Unnamed 8	WJ1990

WJ1990 = Wood and Jones (1990)
RR1996 = Reeves and Reeves (1996)

Several saline lakes mentioned in Reeves and Reeves (1996) – Lazy S, Spring Creek, Brownfield, Anton, Shallowater, Yellow House, Roberts Ranch, Four Lakes, Cunavea Basin, House, Arch, Tierra Blanca, Patricia, Blanco, Canyon, and Lake Lomax – are not included since corresponding National Hydrography Dataset shapefiles were not available.

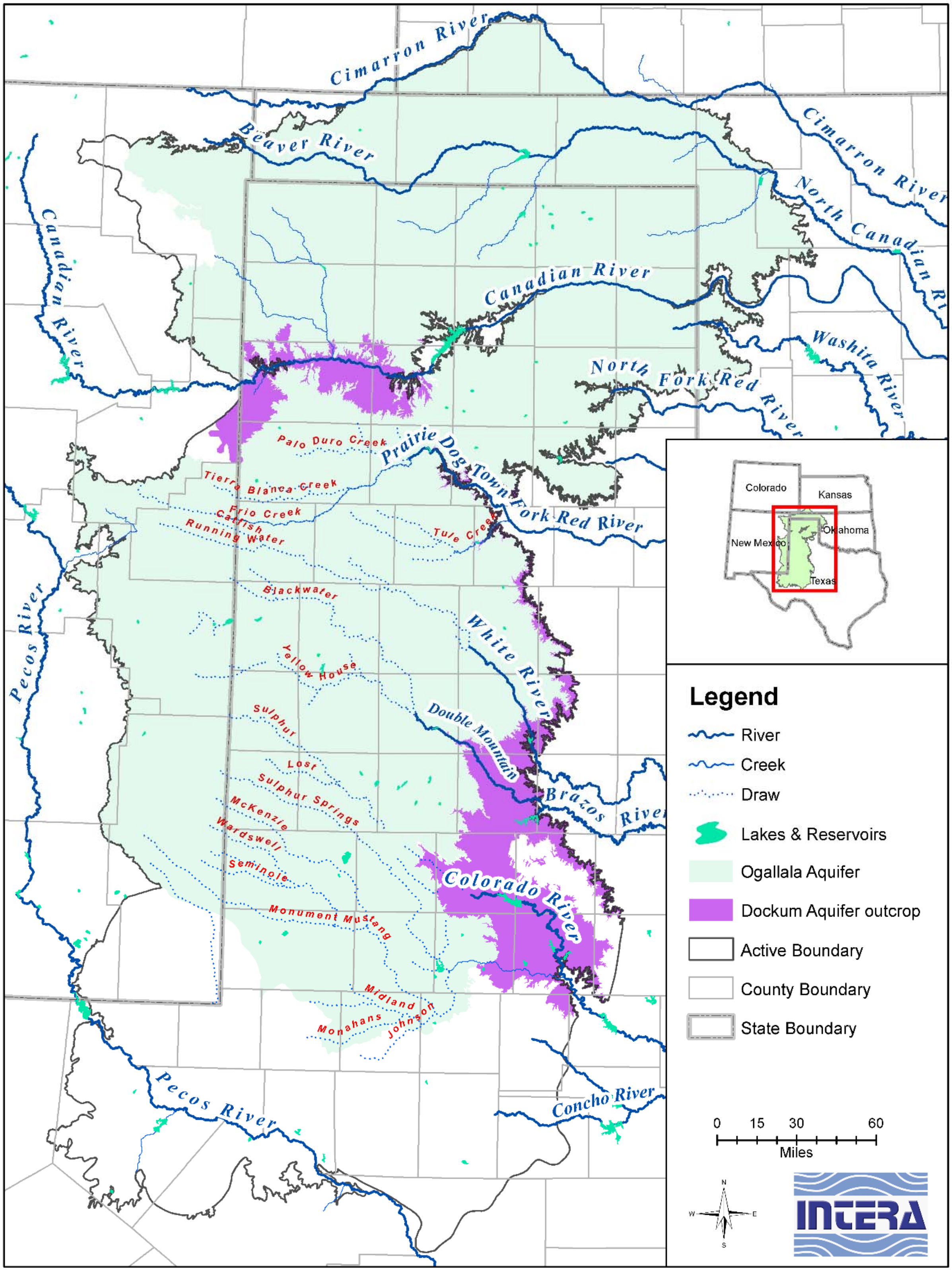

Figure 4.5.1 **Major rivers, streams, and draws in the study area.**

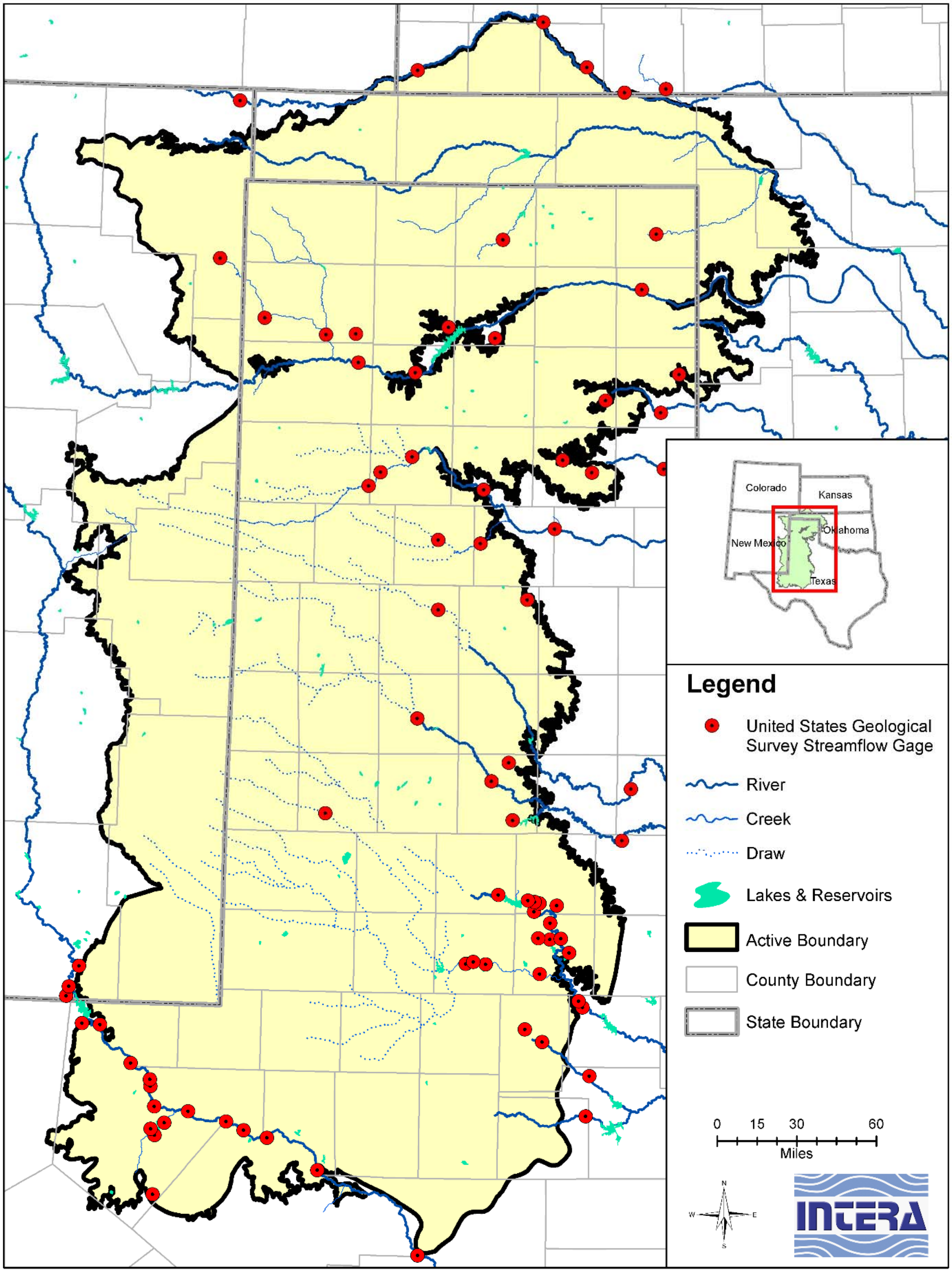

Figure 4.5.2 United States Geological Survey stream gages in the study area.

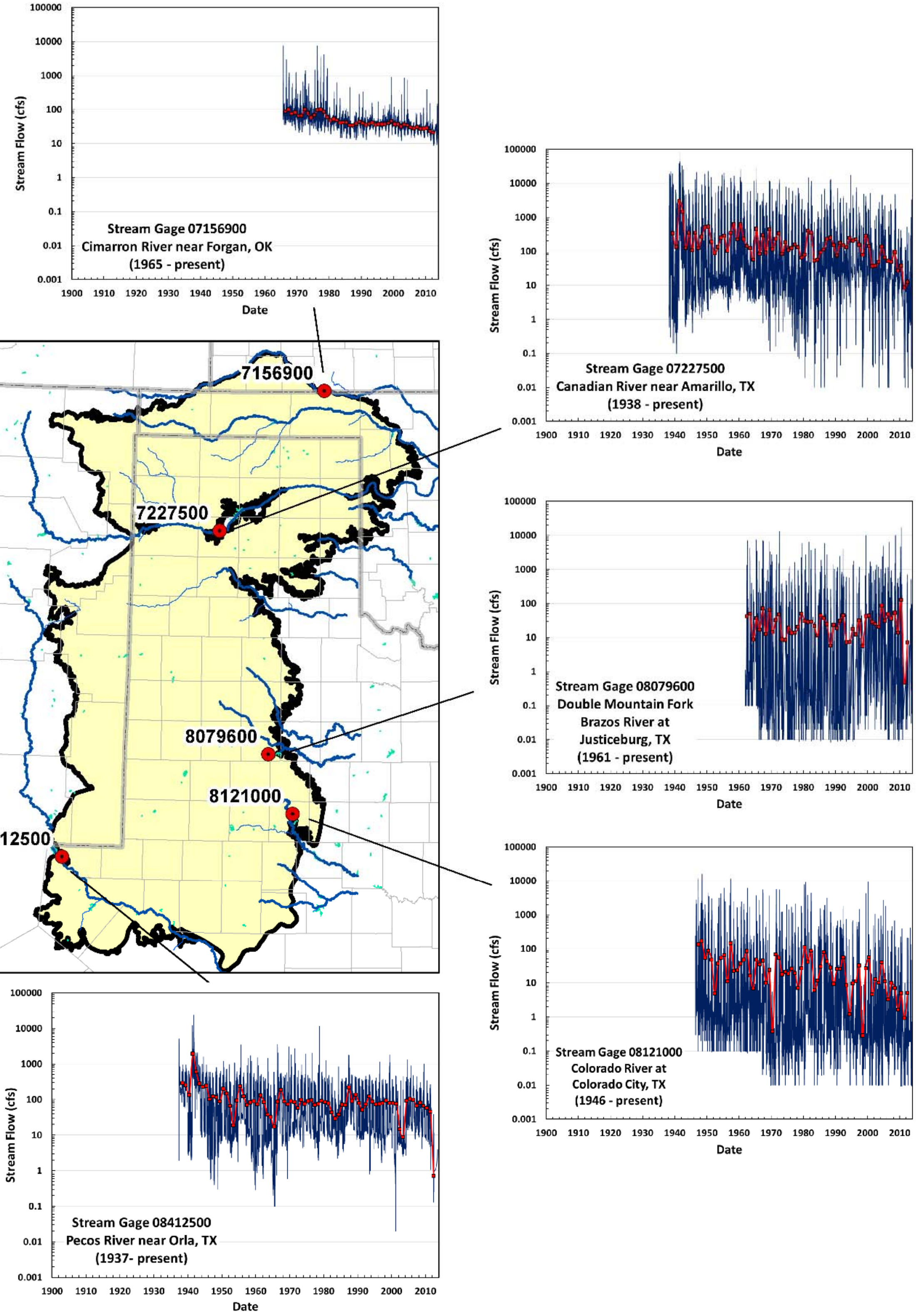

Figure 4.5.3 Select daily streamflow hydrographs for major rivers in the study area. Red line indicates average annual streamflow

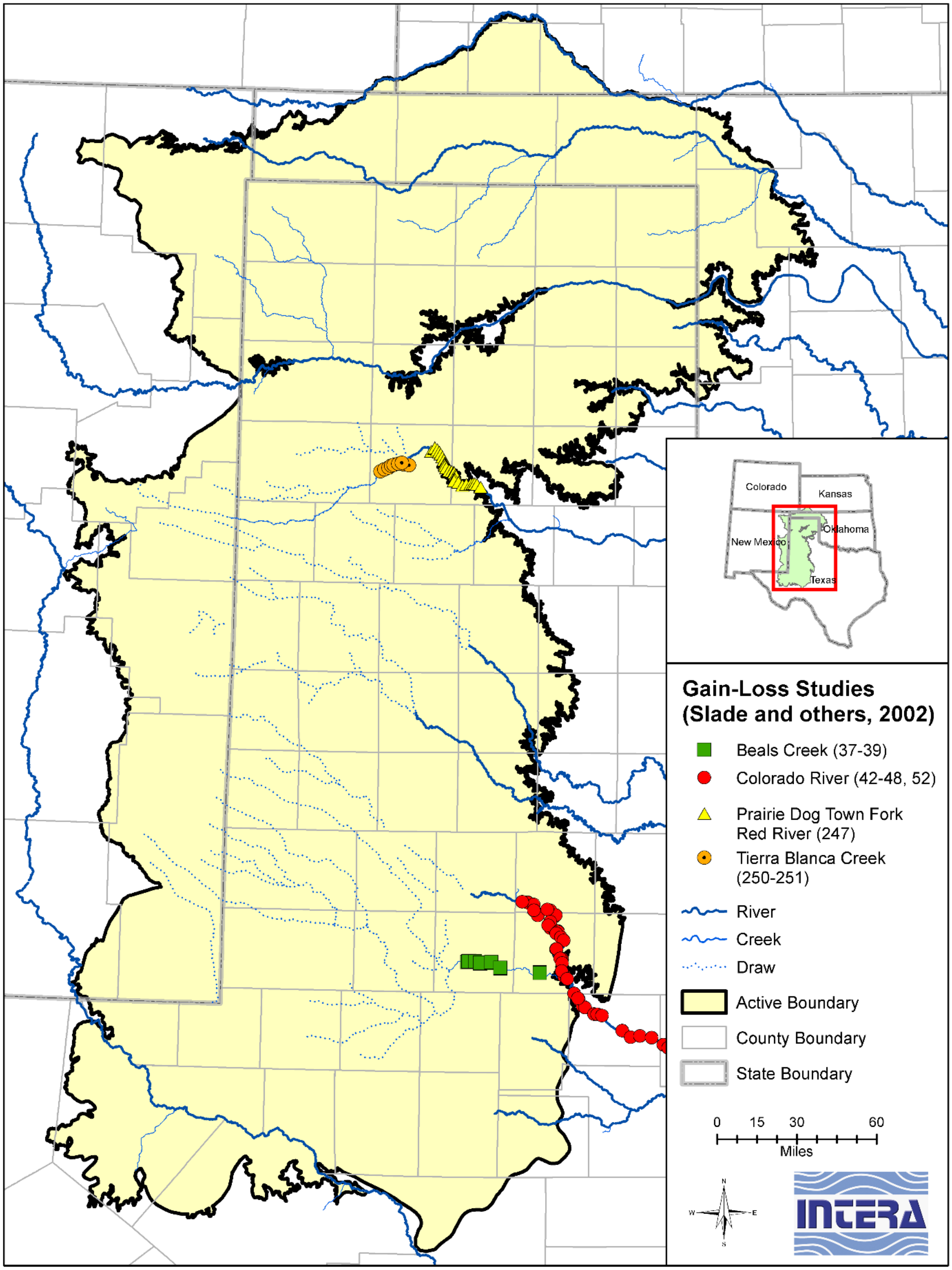

Figure 4.5.4 Slade and others (2002) stream gain/loss studies in the study area.

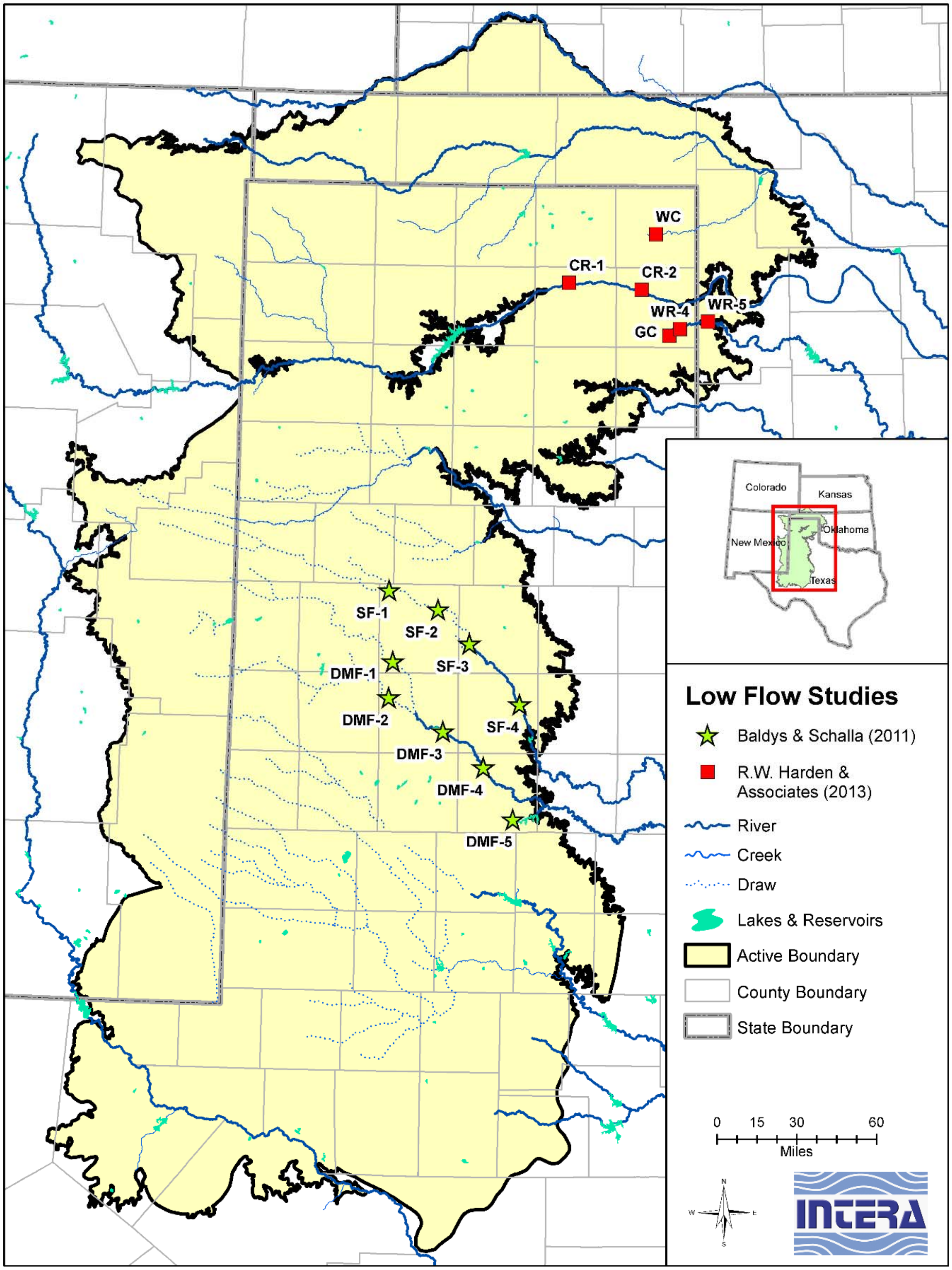

Figure 4.5.5 **Baldys and Schalla (2011) and R.W. Harden & Associates (2013) stream gain/loss studies in the study area.**

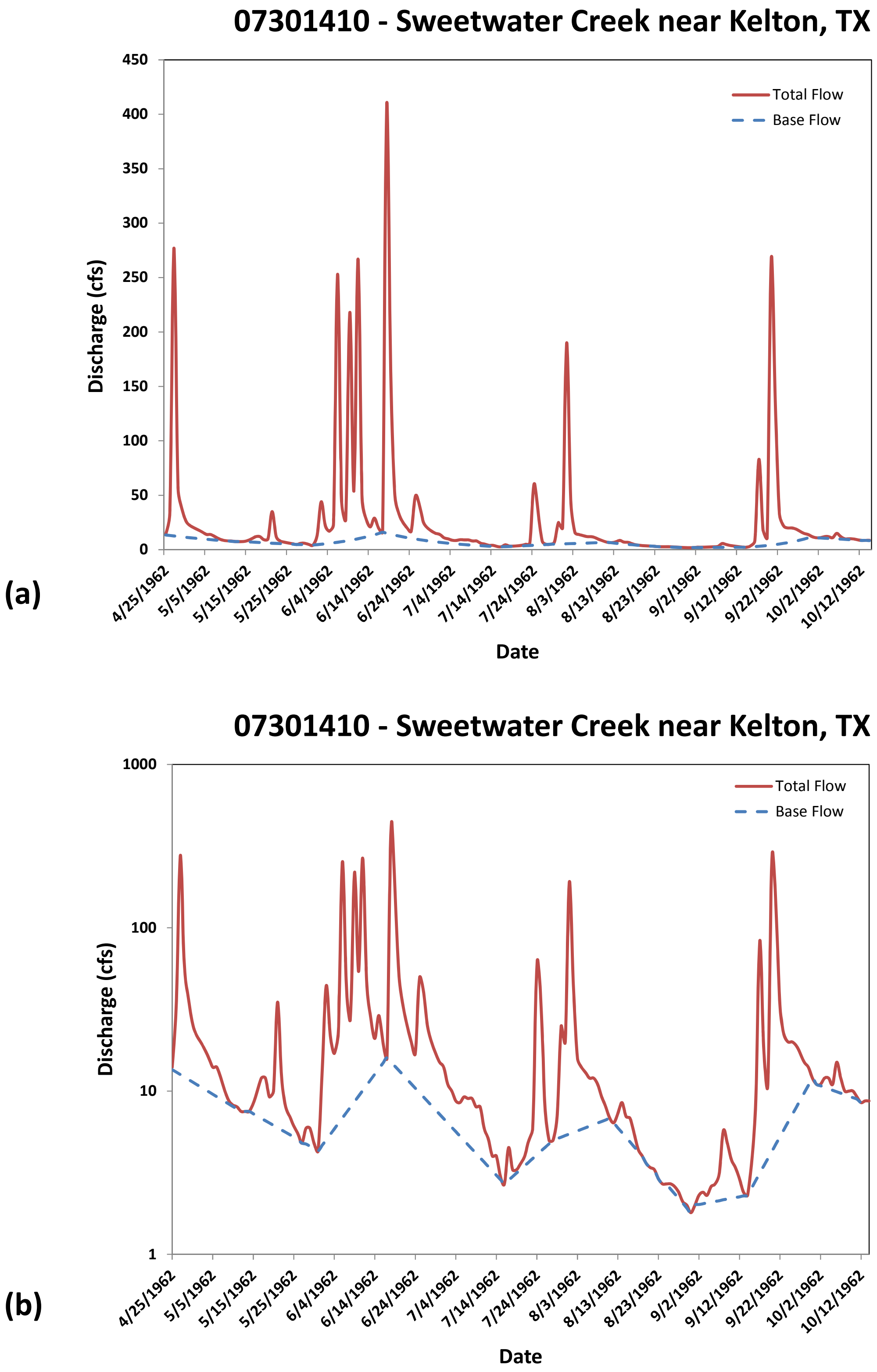

Figure 4.5.6 Example hydrograph separation for gage 07301410 located on the Sweetwater Creek on a (a) linear and (b) log y-axis.

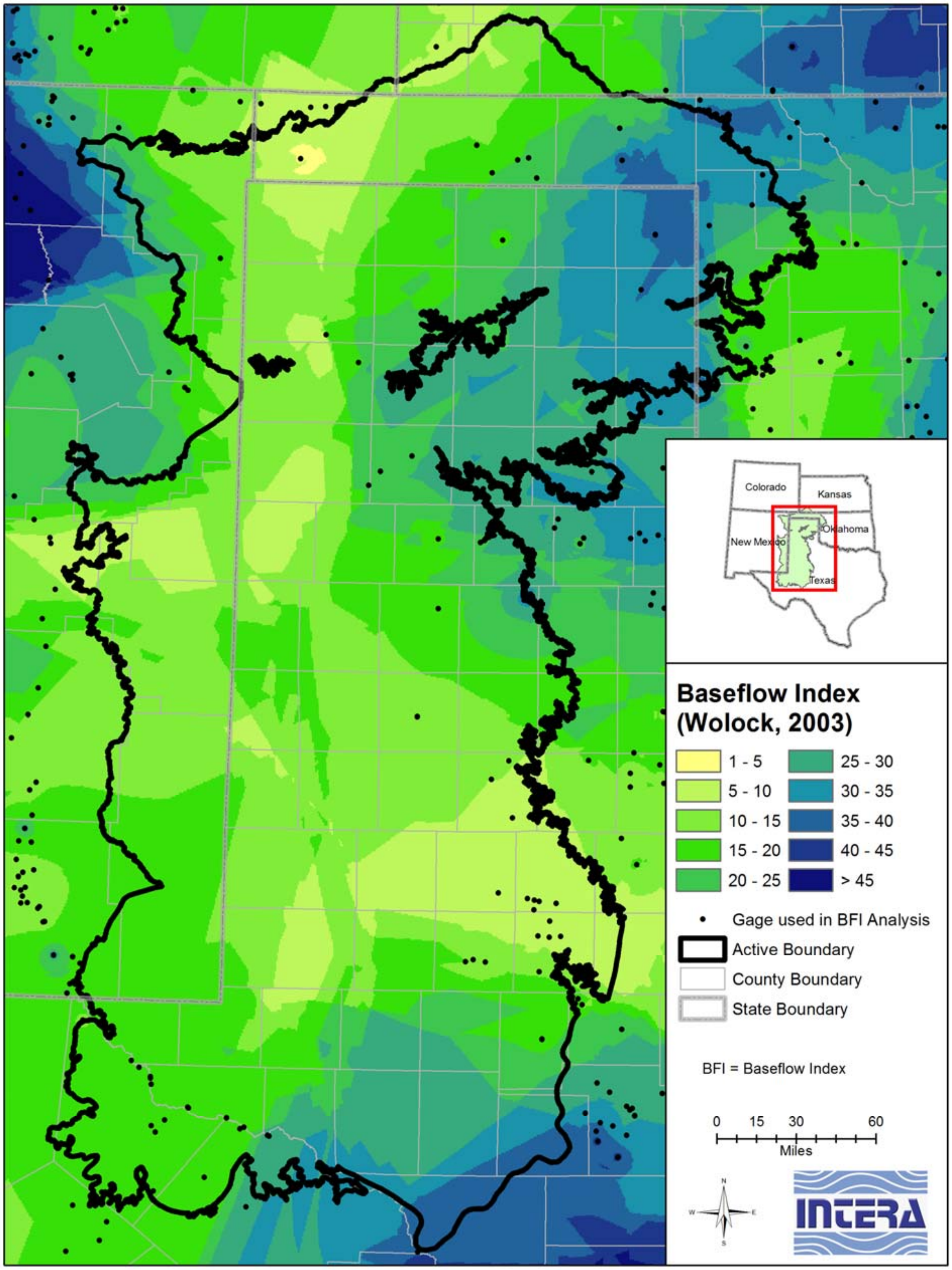

Figure 4.5.7 **Base flow index values from Wolock (2003a,b).**

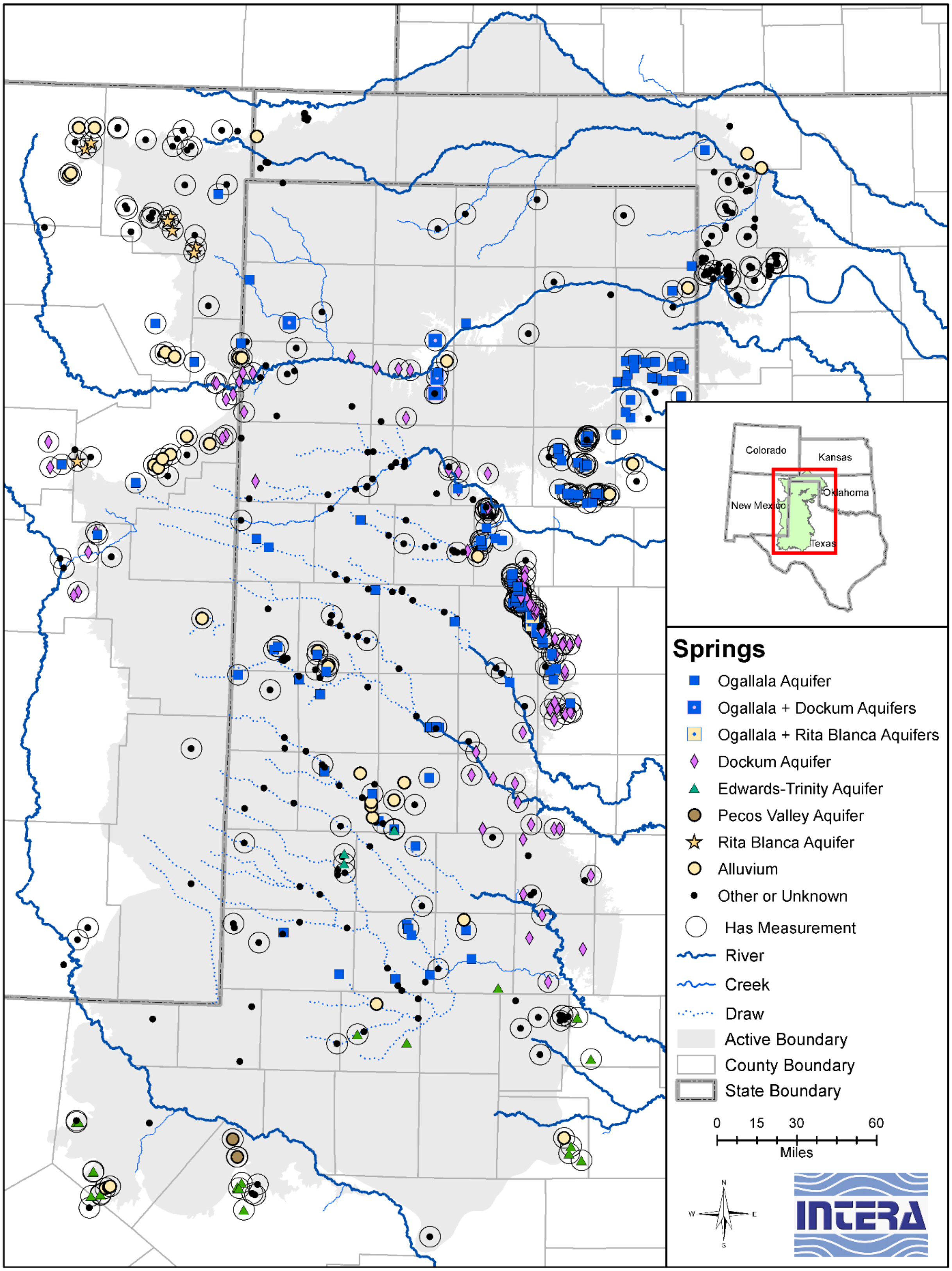

Figure 4.5.8 **Springs in the study area.**

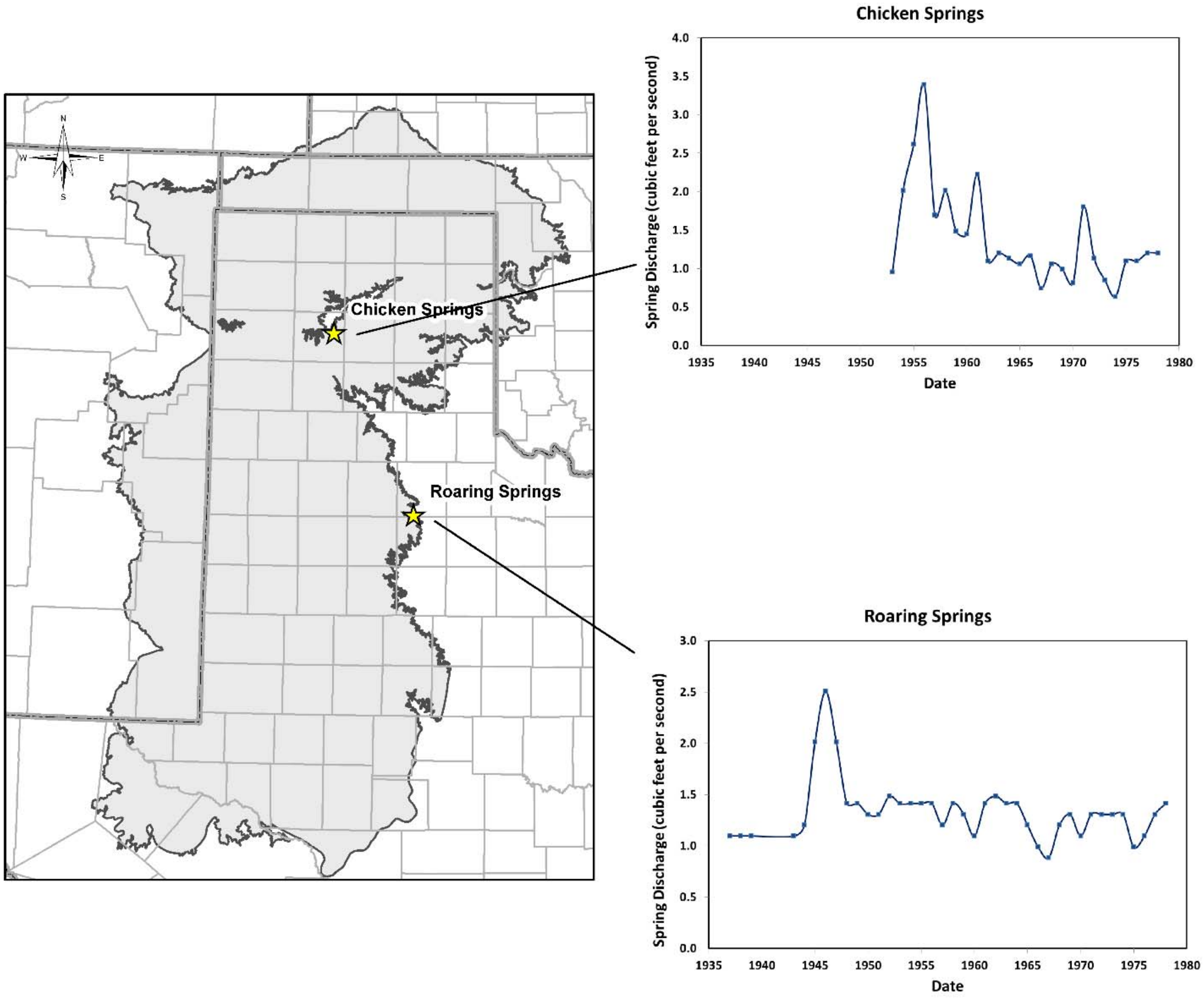

Figure 4.5.9 Spring flow hydrographs for select springs in the study area.

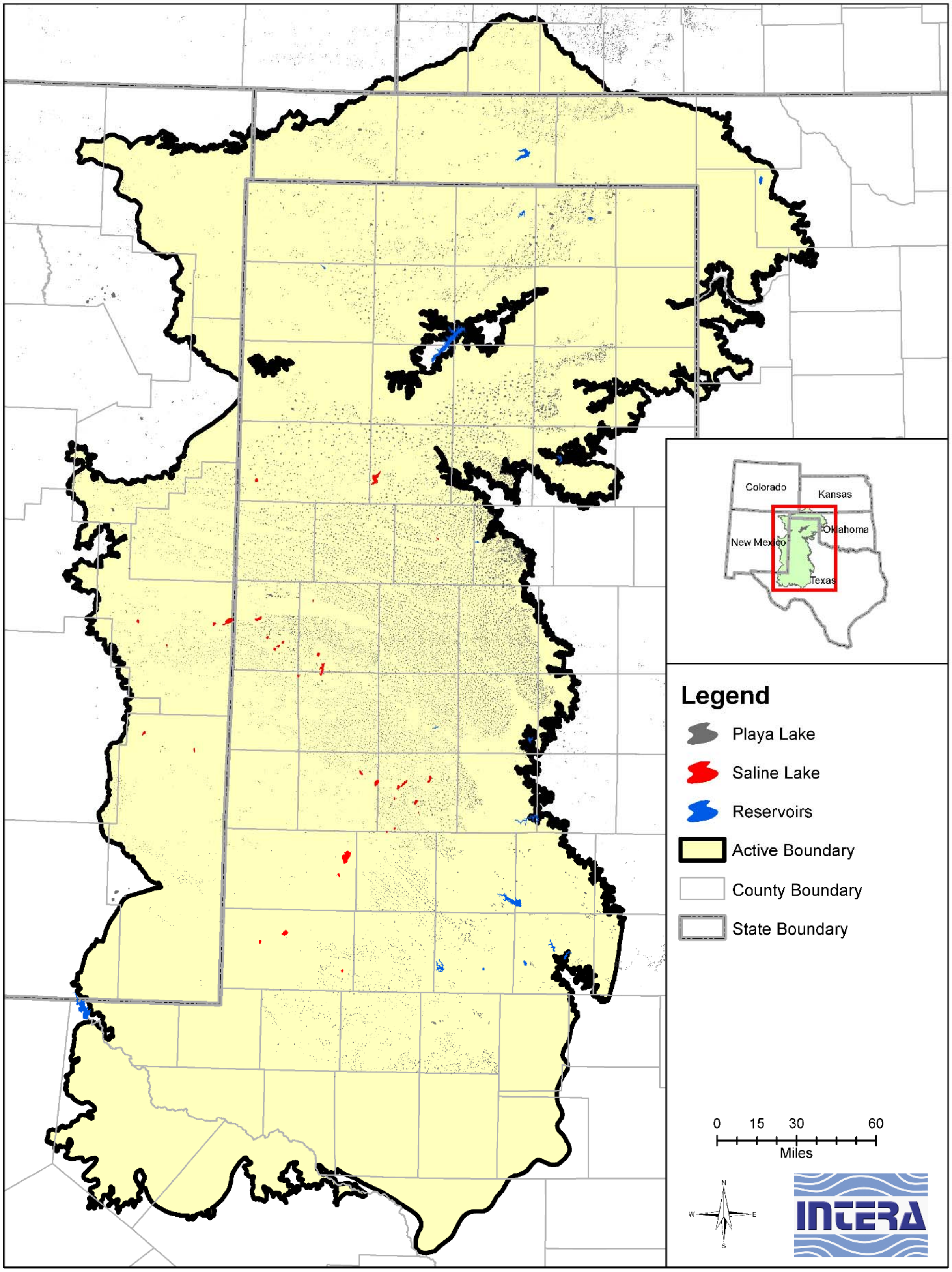

Figure 4.5.10 Surface water bodies in the study area.

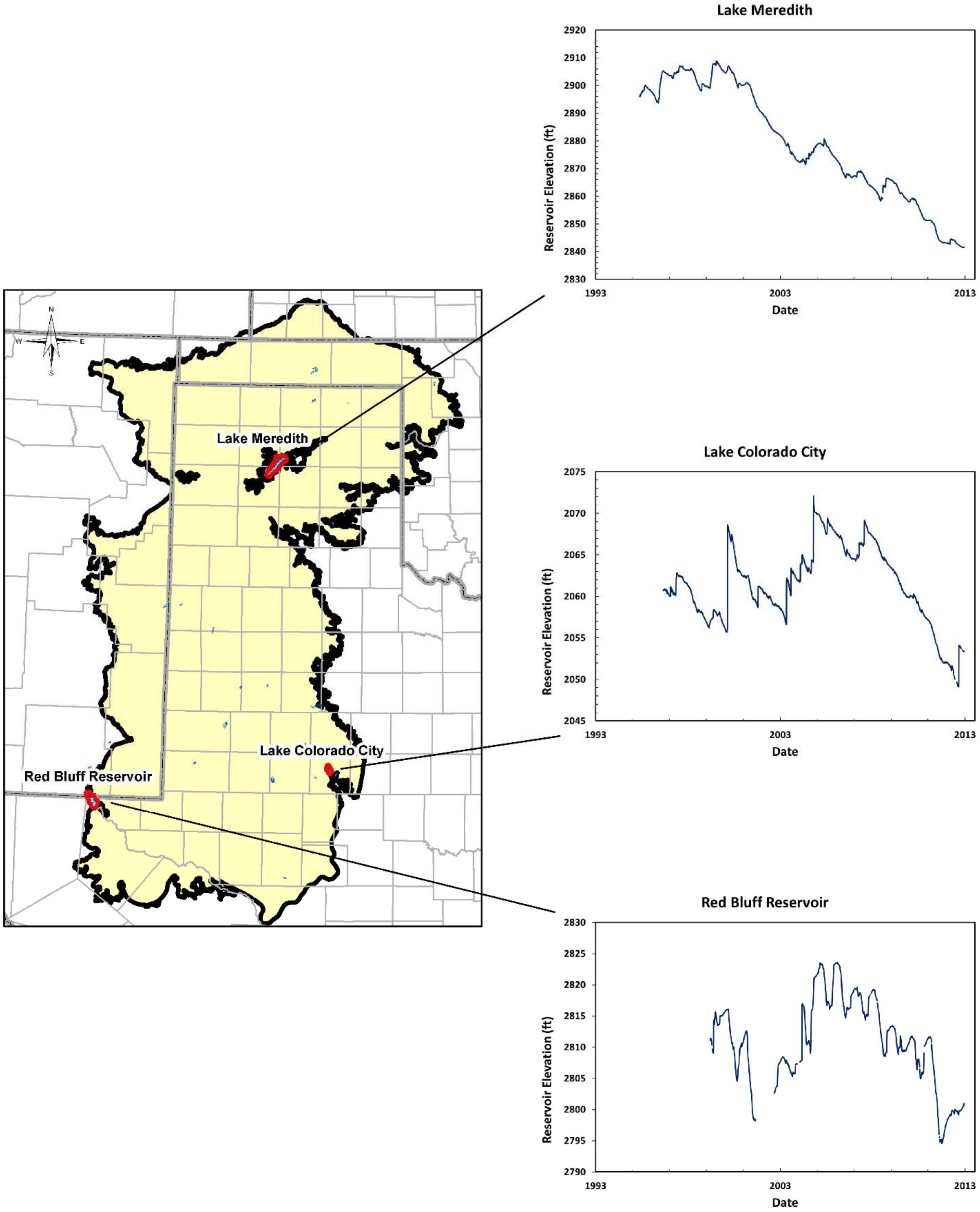

Figure 4.5.11 Select lake elevation time-series for major reservoirs in the study area.

4.6 Hydraulic Properties

Because adjusting aquifer hydraulic properties is an integral part of model calibration, it is important to first develop a sound conceptual framework that sets upper and lower bounds on representative aquifer property values. Otherwise, if aquifer hydraulic parameters are poorly constrained, the modeler runs the risk of producing a model that adequately matches historical water levels and streamflows but cannot reliably be used to make predictions of future aquifer conditions because it has unrealistic hydraulic properties. In this section, we assemble aquifer property information from both past groundwater availability models as well as our current analyses and integrate that data in a way that can be implemented in the High Plains Aquifer System groundwater availability model.

The ability of the aquifer to transmit groundwater to a well can vary greatly depending on factors such as aquifer lithology, structural deformation, fracturing, and thickness of overburden. Several hydraulic properties are used to describe groundwater flow in aquifers. For this analysis, we considered hydraulic conductivity, transmissivity, and storage properties gathered from several sources. The following section reviews the sources of available data describing hydraulic properties in the Ogallala, Edwards-Trinity (High Plains), and Dockum aquifers.

4.6.1 Data Sources

Hydraulic property data was largely sourced from previous TWDB groundwater availability models of the aquifers of the High Plains Aquifer System (Blandford and others, 2003; 2008; Ewing and others, 2008) as well as a model of the Northern Ogallala Aquifer in Texas (Dutton and others, 2001a; INTERA, Inc., and Dutton, 2010). We also solicited additional data that was either not incorporated in the original models, or has been collected since their publication. These data include unpublished aquifer pumping test results from various municipalities and Groundwater Conservation Districts. The lithologic (sand fraction) data is newly generated based on the geophysical log analyses described in Section 4.2. These data complement the sand fraction values from Seni (1980) that were used as secondary data to inform property distributions in previous studies.

4.6.2 Property Estimates from Calibration

With previous groundwater availability modeling studies specifically covering each of the aquifers in the High Plains Aquifer System (with the exception of the Rita Blanca Aquifer, which has not been treated independently), in most cases we have full property distributions available without requiring any additional analysis. However, the "final" property distributions in those previous models have for the most part been adjusted during model calibration from initial estimates. For example, in Dutton and others (2001a), thousands of specific capacity estimates were used, overlain on maps of depositional systems, to hand-contour horizontal hydraulic conductivity. The result comprised the initial estimate. During calibration, the horizontal hydraulic conductivity was adjusted in some areas of the model to better fit head calibration targets.

While the changes that were made during calibration of previous models will likely prove informative during the calibration of the current model, our initial estimates of hydraulic properties will be based on previous initial estimates of hydraulic properties, rather than the final calibrated property fields. The current model is the first to combine all of the aquifers of the High Plains Aquifer System and, thus, may behave somewhat differently than previous models, due to interaction between the aquifers, especially the Ogallala Aquifer and Dockum Group. Therefore, we felt the correct approach was to start from the property estimates made from analyzing measured data, and approach the calibration from a "clean slate" perspective.

4.6.3 Lithology

When data are sparse, lithology can potentially be a useful and reliable proxy for hydraulic conductivity and other aquifer hydraulic properties (Folk, 1980; Carmen, 1939; Lambe and Whitman, 1969; Masch and Denny, 1966; Cade and others, 1994). The hydraulic conductivity of a deposit will generally increase with increases in the percentage of sand, in the average size of the sand grains, and in the sorting of the deposits. Since the spatial distribution of lithological information is typically better known than that of hydraulic properties, defining a relationship between sand content and hydraulic conductivity can be useful for assigning aquifer properties in a model grid.

In the lithological analysis for the current model (see Section 4.2), we established a net sand thickness distribution for each of the aquifers. These distributions compare favorably with past work in the area. Seni (1980) provides a net sand distribution for the Ogallala Aquifer in Texas. Although the net sand thickness distribution developed for the current model includes areas outside of Texas, it agrees well with the Seni (1980) distribution within Texas (Figure 4.6.1).

The previous Dockum Aquifer groundwater availability model (Ewing and others, 2008) provides net sand distributions for the upper and lower Dockum Group. Although the aquifer extents used in the current model differ from the earlier work, the net sand distributions agree in areas of overlap (Figures 4.6.2 and 4.6.3). The previous Edwards-Trinity (High Plains) Aquifer groundwater availability model (Blandford and others, 2008) did not provide a net sand thickness distribution that we could compare to the current model.

Because the sand content is consistently high across the entire extent of the Ogallala Aquifer, we do not expect to see major variation in hydraulic conductivity due solely to changes in sand content. Indeed, a direct comparison of hydraulic conductivity to net sand thickness and to sand percent shows no measurable relationship. This is likely due to the uncertainty associated with drillers' log data. An analysis of variance between groups defined by ranges of net sand thickness or sand percent does show some statistically significant relationships that tie increasing sand content to increasing log hydraulic conductivity values (Alan Dutton, personal communication.). Because the changes are small, we will not adjust the initial conceptualization of hydraulic conductivity values according to net sand thickness or sand percent distributions.

Ewing and others (2008) took into account sand content when developing the hydraulic conductivity distribution for the Dockum Aquifer. Transmissivity values derived from specific capacity values were converted to hydraulic conductivity values using the net sand thickness rather than the full screen length since the clay layers were not considered to contribute a significant amount of water. The hydraulic conductivity values used in the model are these derived "sand" hydraulic conductivity values multiplied by the sand fraction, resulting in an effective hydraulic conductivity. There was, however, no demonstrable correlation between the derived sand hydraulic conductivity and net sand thickness in either the upper and lower Dockum Group. In general, we expect higher hydraulic conductivity values in areas of higher sand content.

Blandford and others (2008) did not have sufficient data to create a relationship between hydraulic conductivity and geologic setting within the Edwards-Trinity (High Plains) Aquifer. However, for the initial model distribution, they did assume that the hydraulic conductivity in the Antlers Sand and limestone portions of the aquifer was much higher (10 feet per day) than the shale portions of the aquifer (0.1 feet per day).

4.6.4 Correlation of Hydraulic Conductivity to Depth

Since the size and distribution of pores in the sand matrix control groundwater flow, the compaction and cementation that occurs as sediment is buried can lead to a decrease in hydraulic conductivity with depth. Previous work did not mention any measurable relationship between hydraulic conductivity and depth in either the Ogallala Aquifer or the Edwards-Trinity (High Plains) Aquifer (Blandford and others, 2003, 2008). Ewing and others (2008) did find that hydraulic conductivity did appear to decrease slightly with depth in the lower Dockum Group. In the upper Dockum Group, where data was scarcer, they found no measurable correlation between hydraulic conductivity and depth.

4.6.5 Horizontal Hydraulic Conductivity

Hydraulic conductivity is a measure of the ease with which groundwater can flow through an aquifer expressed in units of length per time (for example, feet per day) or rate per area (for example, gallons per day per square foot). Higher hydraulic conductivity indicates that the aquifer will allow more water movement under the same hydraulic gradient. Field-scale hydraulic conductivity can be estimated from various types of aquifer performance tests, including slug tests (local near-well estimate), specific capacity tests (relatively near-well estimate), or multi-hour to multi-day aquifer pumping tests (integrated estimate over radius of influence, the size which depends on the duration of the test).

Aquifer pumping tests can be used to estimate the transmissivity of an aquifer, which is the effective aquifer thickness multiplied by the hydraulic conductivity of the aquifer. To calculate hydraulic conductivity, the transmissivity value is divided by the effective aquifer thickness for the aquifer pumping tests. The effective aquifer thickness is often taken as the well screen length. However, since a well screen is unlikely to extend across the entire thickness of an aquifer (and so is smaller than the full aquifer thickness) this approach can produce an upper bound of hydraulic conductivity. The lower bound could be estimated by dividing the transmissivity by the full aquifer thickness.

Because high quality data from multi-day aquifer pumping tests are scarce, another method of estimating hydraulic conductivity values uses specific capacity measurements, which are much more commonly available. Where transmissivity is not directly measured, it can be determined from an empirical relationship between transmissivity and specific capacity. This relationship is established by plotting transmissivity against specific capacity for wells that have both measurements recorded. Because of the many assumptions involved in this method, these values are considered more uncertain than the values determined using the previous methods. However, using specific capacity measurements can greatly improve data coverage and so is useful for providing a general idea of reasonable hydraulic conductivity values in an area with few direct measurements.

The following sections provide hydraulic conductivity estimates compiled for the Ogallala and Edwards-Trinity (High Plains) aquifers and the Dockum Group. The literature review did not provide any data specific to the Rita Blanca Aquifer. Because the Rita Blanca Aquifer is hydraulically connected to the Ogallala Aquifer, its properties are often assumed to be similar to the Ogallala Aquifer. However, it likely has a lower effective hydraulic conductivity than the Ogallala Aquifer due to its lower sand percent (Figure 4.2.23). There is no evidence in the literature of regional horizontal anisotropy in the High Plains Aquifer System, so this discussion does not include horizontal anisotropy estimates.

4.6.5.1 Ogallala Aquifer

Blandford and others (2003) developed the hydraulic conductivity distribution of the Southern Ogallala Aquifer using data from 7,938 well locations. Only 118 of these values are field or lab measurements of transmissivity or conductivity, while the rest are calculated using specific capacity data. The mean hydraulic conductivity value derived from specific capacity tests did not differ significantly from the mean value of reported hydraulic conductivity measurements. The spatial distribution of initial hydraulic conductivity accounts for the influence of paleochannels as mapped in Naing (2002). Blandford and others (2003) established that the hydraulic conductivity for the Southern Ogallala Aquifer ranges from 0.01 to 2,600 feet per day, with a geometric mean of approximately 6.8 feet per day. The updated Southern Ogallala and Edwards-Trinity (High Plains) aquifers model (Blandford and others, 2008) did not include any additional hydraulic conductivity data for the Ogallala Aquifer.

The Northern Ogallala Aquifer model (Dutton and others, 2001a) used specific capacity data from 1,341 wells to calculate transmissivity and hydraulic conductivity in the Northern Ogallala Aquifer. They established that the geometric mean of hydraulic conductivity in the Northern Ogallala Aquifer is about 14.8 feet per day with a standard deviation of 5 to 44 feet per day. This distribution of hydraulic conductivity used in the model was adjusted by hand to match maps of depositional systems within the Ogallala Formation as given in Seni (1980).

The update to the Northern Ogallala Aquifer model (INTERA, Inc., and Dutton, 2010) introduced several new data sources for hydraulic conductivity data in the Ogallala Aquifer. These include four additional aquifer pumping tests each from the City of Amarillo, Mesa Water Inc. and their consultants, and the Panhandle Groundwater Conservation District in Carson, Potter, and Roberts counties. These 12 new values largely agreed with the original hydraulic conductivity distribution produced by Dutton and others (2001a) and only required local changes to the distribution within a few square miles of each new data point.

Additional data compiled for this report include aquifer pumping test data from the City of Clarendon, the Canadian River Municipal Water Authority, the City of Amarillo via the Panhandle Groundwater Conservation District, and the South Plains Underground Water Conservation District. The locations of these datasets are shown in Figure 4.6.4 and the data is given in Tables 4.6.1 through 4.6.4. Most of the values reported by the South Plains Underground Water Conservation District are significantly higher than previous estimates of hydraulic conductivity in this region. As the new values were derived from specific capacity measurements, this difference could be due simply to the uncertainty inherent in establishing a specific-capacity/transmissivity relationship. Since this area has good existing data coverage, we have reserved inclusion of this data in the updated hydraulic conductivity distribution for the Ogallala Aquifer. During calibration of the numerical model, we will examine the sensitivity to inclusion of this higher hydraulic conductivity data.

The initial horizontal hydraulic conductivity distribution used in the current model is shown in Figure 4.6.5. Hydraulic conductivity values for the South Ogallala Aquifer and the portion of the Northern Ogallala Aquifer within Texas are derived from the hydraulic conductivity contours presented in Naing (2002), the same data used to develop the hydraulic conductivity distribution in Blandford and others (2003). The hydraulic conductivity values for the Northern Ogallala Aquifer outside of Texas are derived from the hydraulic conductivity contours presented in Dutton and others (2001a). The contours from Naing (2002) and Dutton and others (2001a) were converted to points and additional hydraulic conductivity point values from the City of Clarendon, the City of Amarillo, and the Canadian River Municipal Water Authority datasets were also added. These combined hydraulic conductivity point values were used to create a hydraulic conductivity distribution using the TopoToRaster interpolation function in ArcGIS.

Figure 4.6.5 shows an increase in average hydraulic conductivity in the Ogallala Aquifer moving north from Texas into Oklahoma and Kansas. This trend appears in the original hydraulic conductivity estimate of Dutton and others (2001a) (see Figure 20 of that work), and was maintained in the current initial estimate. We will assess whether this trend affects model performance during calibration. Regardless of the results of that assessment, the trend is expected to have a minimal effect on the model performance as a tool for making availability assessments in Texas.

4.6.5.2 Edwards-Trinity (High Plains) Aquifer

Information on the hydraulic properties of the Edwards-Trinity (High Plains) Aquifer is very limited. Blandford and others (2008) found no reported hydraulic conductivity values and were only able to locate 13 wells with specific capacity test information that were screened only in the Edwards-Trinity (High Plains) Aquifer. Using a transmissivity/specific-capacity relationship, they calculated that the hydraulic conductivity for the Edwards-Trinity (High Plains) Aquifer ranges from 0.4 to 42.8 feet per day. For the initial model distribution, they assumed that the hydraulic conductivity was 0.1 feet per day for the shale layer and 10 feet per day in both the Antlers Sand and limestone layers. Since the current model does not distinguish between the different geologic layers within the Edwards-Trinity (High Plains) Aquifer, these initial hydraulic conductivity values were weighted by the thickness of each layer to produce a composite hydraulic conductivity for the entire aquifer. The resulting initial hydraulic conductivity distribution used for the current model is shown in Figure 4.6.6.

4.6.5.3 Dockum Group

Ewing and others (2008) collected three published conductivity values and 45 measured transmissivity values for the Dockum Group. Using a relationship between transmissivity and specific capacity, 19 additional hydraulic conductivity values were calculated from reported specific capacity values for the upper Dockum Group and 414 for the lower Dockum Group. As mentioned before, these derived values are effectively “sand” hydraulic conductivities and were multiplied by sand fraction before implementation in the model. The sand hydraulic conductivities for the upper Dockum Group ranged from 0.41 to 20 feet per day with a mean value of 8.1 feet per day. In the lower Dockum Group, the range of hydraulic conductivity was 0.59 to 61 feet per day with a mean of 6.6 feet per day. Since Ewing and others (2008) did not include the section of upper Dockum Group north of the Canadian River, and we could find no specific capacity estimates in that region of the upper Dockum Group, the initial sand hydraulic conductivity was defined as the median value of the sand hydraulic conductivity in the southern portion (7 feet per day). The initial horizontal hydraulic conductivity distributions for the upper and lower Dockum Group are shown in Figures 4.6.7 and 4.6.8, respectively. These were derived by multiplying the sand hydraulic conductivity distributions provided in Ewing and others (2008) by the sand fractions developed in Section 4.2. Because Ewing and others (2008) decreased the estimates of horizontal hydraulic conductivity to about 20 percent of their initial estimate during calibration, these initial estimates for both the upper and lower Dockum Group may also be revised downward during calibration of the High Plains Aquifer System groundwater availability model.

The sand hydraulic conductivity distribution for the Lower Dockum Aquifer incorporated additional aquifer pumping test data from the City of Canyon that was compiled for this report. The locations of these new data points are shown in Figure 4.6.9. Using drawdown and discharge data from these tests, we were able to calculate transmissivity values using the Cooper-Jacob straight line approximation (Cooper and Jacob, 1946). Table 4.6.5 summarizes the aquifer pumping test data and calculated hydraulic conductivity values. The calculated hydraulic conductivity values range from 7.7 to 76.5 feet per day, with an average value of 37.93 feet per day.

4.6.6 Vertical Hydraulic Conductivity

At very small scales, the vertical and horizontal hydraulic conductivities may differ by very little. However, at thicknesses of several hundred feet and greater, the differences between the vertical and horizontal conductivities can be very large. In areas where the aquifer is thought to be largely structurally intact, the vertical hydraulic conductivity is limited by the hydraulic conductivity of the lower permeability units. For instance, a continuous low permeability clay layer in the middle of a sandy aquifer could greatly impede vertical flow in what would otherwise be a high permeability system. This could create a difference of several orders of magnitude between vertical and horizontal hydraulic conductivity. The presence of clays and shales will generally have the largest effect on vertical conductivity, and we will use the estimates of sand and clay fractions determined for this study (and from previous studies) to inform the distribution of vertical conductivity during calibration.

Because vertical hydraulic conductivity is not measurable at the large scale typical of a regional model grid, it is usually a calibrated model parameter. Indeed, 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 section below provides vertical hydraulic conductivity estimates produced during the calibration process of past models in the study region.

4.6.6.1 Ogallala Aquifer

In the Southern Ogallala Aquifer, Blandford and others (2008) produced a model-calibrated vertical hydraulic conductivity value that is one-tenth of the horizontal hydraulic conductivity. Because Dutton and others (2001a) was a single-layer model, no vertical hydraulic conductivity value was defined for the northern portion of the Ogallala Aquifer.

In general, we would expect the Ogallala Aquifer to have a higher vertical conductivity than the units that underlie it. Therefore, vertical conductivity of underlying units, including the Dockum, Edwards-Trinity (High Plains), and Rita Blanca aquifers, will likely control the overall vertical conductance between the two aquifers.

4.6.6.2 Edwards-Trinity (High Plains) Aquifer

Blandford and others (2008) defined vertical hydraulic conductivity values for the different geologic layers of the Edwards-Trinity (High Plains) Aquifer. Shale layers had a model-calibrated vertical hydraulic conductivity value of 0.00001 feet per day, or 1/100th of the horizontal hydraulic conductivity. Limestone and Antlers Sand layers had a model-calibrated vertical hydraulic conductivity value that was 1/10th of the horizontal hydraulic conductivity value.

4.6.6.3 Dockum Group

A model of the Palo Duro Basin in Texas (Senger and others, 1987) gives a model-calibrated vertical hydraulic conductivity value for the Dockum Group that is four orders of magnitude lower than the horizontal hydraulic conductivity. Ewing and others (2008) estimated the initial distribution of vertical hydraulic conductivity in the upper and lower Dockum Group using the harmonic mean of the sand hydraulic conductivity (5 feet per day) and clay hydraulic conductivity (5×10^{-4} feet per day), weighted according to the sand fraction. Model-calibrated vertical hydraulic conductivity values in the Dockum Aquifer ranged from 2.5×10^{-4} to 5×10^{-3} feet per day.

In most of the study area, the lower Dockum Group consists of the Santa Rosa Formation overlain by the Tecovas Formation. The Tecovas Formation is composed mainly of shale and sandy shale, which limits the connection with overlying units. However, in places where the Tecovas Formation is absent, the connection with overlying units could be enhanced by direct contact with the Santa Rosa Formation which consists mainly of sandstone. Wells with Santa Rosa Formation directly overlain by the Ogallala Aquifer were identified during the process of picking geologic surfaces. Gamma, resistivity or other geophysical logs were used to pick the top of the Santa Rosa Formation and the presence or absence of the Tecovas Formation in 212 of the wells. The majority of picks were derived from gamma logs as few high-quality resistivity or other geophysical logs were available. High gamma and low resistivity responses on the geophysical logs indicate clay and were used to pick the top of the Tecovas Formation shales, where present. Low gamma and higher resistivity responses indicated sandstone and were used to pick the top of the Santa Rosa Formation. Figure 4.6.10 provides example geophysical log interpretations comparing a well where the Tecovas Formation is present and one where it is absent. Figure 4.6.11 shows the distribution of wells where the Lower Dockum Group is directly overlain by the Ogallala Aquifer and indicates whether the Tecovas Formation is present or absent at those locations.

4.6.7 Storage Properties

Water is released from storage differently in confined and unconfined aquifers. In confined aquifers, the release of water is dominated by changes in pressure head. Water is released due to pressure-induced changes in the arrangement and bulk density of the aquifer matrix as well as in the density of the water. In confined aquifers, these processes are described using the term specific storage, defined as the volume of water a unit volume of aquifer releases from storage per unit decline in head (Freeze and Cherry, 1979). The dimensionless storage coefficient in confined aquifers is the product of the specific storage and the thickness of the aquifer.

In unconfined aquifers, released water comes from the draining of the pore spaces of the aquifer. Specific yield is defined as the volume of water that an aquifer releases from storage per unit surface area of aquifer per unit decline in water table (Freeze and Cherry, 1979). As in confined aquifers, there is some release due to change in the aquifer matrix but this is small compared to specific yield.

4.6.7.1 Ogallala Aquifer

Since the Ogallala Aquifer is generally unconfined, specific yield is the most important storage property to consider. In Blandford and others (2003), specific yield values for the Southern Ogallala Aquifer ranged from 15 to 22 percent with an average of 16 percent. Blandford and others (2008) cite a specific yield value of 15 percent, likely since this is a commonly assumed value for the Ogallala Aquifer (Mullican and others, 1997; Luckey and others, 1986). In the Northern Ogallala Aquifer, Dutton and others (2001a) established a specific yield distribution by merging Texas values from Knowles and others (1984) with non-Texas values from Luckey and Becker (1999). The Luckey and Becker (1999) distribution was based on Gutentag and others (1984). The Knowles and others (1984) estimates were based on a large-scale drilling program with laboratory analysis of the resulting cores. Specific yield values in the final Dutton and others (2001a) coverage ranged from 0.04 to 0.28. Figure 4.6.12a shows the combined specific yield coverages from Blandford and others (2003) in the Southern Ogallala Aquifer and Dutton and others (2001a) in the Northern Ogallala Aquifer.

McGuire and others (2012) also created a specific yield distribution for the entire Ogallala Aquifer based on data from Gutentag and others (1984) and Cederstrand and Becker (1998), which were based on analyses of drillers' logs. Specific yield values from McGuire and others (2012) ranged from 0.025 to 0.28 for the Ogallala Aquifer (Figure 4.6.12b).

Since specific yield is correlated to porosity, estimates of porosity from geophysical logs can be used to estimate specific yield. However, porosity estimates require a neutron porosity log, and, as there were only a handful of these logs available in the log database, there was insufficient data to make revised specific yield estimates. Rather, the current study relies on previous studies for estimates of specific yield.

4.6.7.2 Edwards-Trinity (High Plains) Aquifer

The Edwards-Trinity (High Plains) Aquifer has both unconfined (a small area) and confined portions. There are no recorded storativity values available for any Edwards-Trinity (High Plains) Aquifer wells. Instead, Blandford and others (2008) assumed a constant specific storage value of 3×10^{-6} per foot. Where the aquifer is unconfined, they assumed the specific yield of the Antlers Sand portion of the aquifer ranges from about 10 to 20 percent. In the producing Edwards and Comanche Peak limestone intervals, the specific yield was assumed to be less than 10 percent, since drainage is largely due to secondary porosity from fractures and solution channels, rather than primary porosity. The initial specific yield values were thus set at 0.05 for limestone and 0.15 for Antlers Sand. Shale was assumed to be 0.1. The literature value for specific yield in shale and limestone is generally lower, ranging from 0.005 to 0.05 (Sterrett, 2007). Sensitivity to specific yield will be tested during calibration and the specific yield values will be adjusted, if necessary.

4.6.7.3 Dockum Group

The Dockum Aquifer also has both unconfined and confined portions. For the confined portion, a literature review reported in Ewing and others (2008) defined a storativity range from 5×10^{-5} to 2×10^{-3} with a geometric mean of 1.6×10^{-4}. Due to the scarcity of data, however, specific storage in the Ewing and others (2008) model was calculated by combining the specific storage for sand (3×10^{-6}) and the specific storage for clay (7.5×10^{-6}), weighted according to the sand fraction. The distribution of specific storage used for the upper and lower Dockum Group is shown in Figures 4.6.13 and 4.6.14, respectively.

There are no reported estimates of specific yield for the Dockum Aquifer. Instead, Ewing and others (2008) assume a value of 0.15 for the unconfined portions of the aquifer. This value is based on combining reasonable ranges for material similar to the sediments in the study area (0.03 to 0.28) given by Domenico and Schwartz (1998) and for unconfined aquifers (0.1 to 0.3) given by Lohman (1972). Since the literature review did not provide any data specific to storage properties in the Rita Blanca Aquifer, specific yield values in the outcrop and specific storage values in the subcrop were estimated using the same methodology as for the Dockum Aquifer.

Table 4.6.1 New hydraulic conductivity values from the City of Clarendon.

Well ID	State Well Number	Latitude (decimal degrees)	Longitude (decimal degrees)	Hydraulic Conductivity (feet per day)
---	---	34.940555	-100.887777	168.1

Table 4.6.2 New hydraulic conductivity values from the City of Amarillo.

Well ID	State Well Number	Latitude (decimal degrees)	Longitude (decimal degrees)	Hydraulic Conductivity (feet per day)
Well #505	236195	35.467222	-101.698055	11.7
Well #507	236196	35.460000	-101.703611	8.1
Well #508	236197	35.460000	-101.681388	8.8
Well #509	236198	35.461388	-101.615000	27.9
Well #510	236201	35.448055	-101.688333	12.4
Well #511	236203	35.448333	-101.680000	11.1
Well #512	5235206-235207	35.443888	-101.640000	11.4
Well #513	235229	35.436111	-101.660277	7.4
Well #514	235237	35.433611	-101.651388	10.4
Well #515	236207	35.438055	-101.617222	16.1
Well #516	236208	35.390000	-101.661666	29.1
Well #517	235242	35.384722	-101.639722	13.0
Well #518	235249	35.404444	-101.626388	13.8
Well #520	236210	35.375000	-101.643888	13.7
Well #521	242507	35.454444	-101.644722	6.1
Well #522	235260	35.450277	-101.621111	12.2

Table 4.6.3 New hydraulic conductivity values from the Canadian River Municipal Water Authority.

Well ID	State Well Number	Latitude (decimal degrees)	Longitude (decimal degrees)	Hydraulic Conductivity (feet per day)
---	---	35.760765	-100.820143	15.5
---	---	35.740522	-100.829313	18.1
---	---	35.745773	-100.785255	16.6
---	---	35.749829	-100.821984	22.4
---	---	35.754081	-100.810225	17.8

Table 4.6.4 New hydraulic conductivity values from the South Plains Underground Water Conservation District.

State Well Number	Latitude (decimal degrees)	Longitude (decimal degrees)	Hydraulic Conductivity (feet per day)
24-37-9371	33.40493	-102.38635	17.6
24-39-7761	33.38308	-102.23906	8.6
24-44-9571	33.26471	-102.52582	0.1
24-44-9752	33.25544	-102.53344	3.0
24-45-1991	33.33416	-102.46003	71.2
24-45-6652	33.31072	-102.39535	13.2
24-45-7972	33.23587	-102.46351	19.5
24-45-8713	33.26039	-102.45795	37.3
24-45-9551	33.27016	-102.39394	57.1
24-46-4181	33.32135	-102.36869	13.5
24-46-4311	33.33067	-102.34624	6.6
24-46-4312	33.3321	-102.3459	6.4
24-46-4522	33.31702	-102.35577	40.0
24-46-4523	33.31828	-102.35373	16.0
24-46-4541	33.31321	-102.36012	5.3
24-46-4621	33.31501	-102.34111	92.8
24-46-6191	33.32246	-102.27907	119.6
24-46-6192	33.32246	-102.28115	55.8
24-46-6244	33.32433	-102.27768	83.9
24-46-7351	33.28674	-102.33958	39.9
24-46-8831	33.2608	-102.30671	10.2
24-46-8841	33.25753	-102.31903	112.3
24-47-2161	33.3699	-102.1947	9.5
24-47-2491	33.35	-102.1974	1.2
24-47-2663	33.35244	-102.16987	33.9
24-47-2831	33.34481	-102.18399	15.3
24-47-2932	33.34682	-102.17004	27.8
24-47-3561	33.35438	-102.14067	10.0
24-47-3771	33.33702	-102.16658	9.3
24-47-3821	33.34474	-102.13855	30.3
24-47-3843	33.33911	-102.14828	24.7
24-47-3874	33.33652	-102.14845	29.9
24-47-5213	33.3294	-102.1917	69.1
24-47-5242	33.32507	-102.1927	18.9
24-47-5371	33.366	-102.17576	89.6
24-47-5431	33.3185	-102.195	5.6

Table 4.6.4, continued

State Well Number	Latitude (decimal degrees)	Longitude (decimal degrees)	Hydraulic Conductivity (feet per day)
24-47-5442	33.3125	-102.2072	6.2
24-47-6211	33.33039	-102.15178	10.0
24-47-6212	33.33046	-102.14849	4.7
24-47-6263	33.32694	-102.14034	6.6
24-47-6322	33.3293	-102.13283	10.2
24-47-6551	33.31295	-102.13773	46.8
24-47-6612	33.31363	-102.13705	38.2
24-47-6641	33.31279	-102.13863	44.8
24-47-6751	33.29808	-102.15761	2.6
24-48-4191	33.32141	-102.11291	23.2
24-52-6241	33.2001	-102.5268	208.0
24-52-9361	33.16095	-102.50283	42.0
24-52-9381	33.15462	-102.50645	49.4
24-52-9382	33.1546	-102.50808	69.4
24-52-9392	33.1553	-102.50176	6.0
24-52-9393	33.15722	-102.50321	136.4
24-52-9395	33.15458	-102.50417	64.2
24-52-9396	33.15452	-102.49999	54.0
24-52-9397	33.15455	-102.50201	95.9
24-53-2761	33.21682	-102.4466	104.3
24-53-5321	33.20724	-102.42472	34.6
24-53-5392	33.19749	-102.41922	11.1
24-53-5673	33.18061	-102.43034	6.6
24-53-5893	33.16887	-102.4332	284.0
24-53-6692	33.1819	-102.37842	6.1
24-53-8632	33.15067	-102.42088	203.6
24-53-9441	33.14423	-102.4141	346.2
24-53-9471	33.14182	-102.41272	565.5
24-53-9472	33.14044	-102.41434	232.8
24-53-9572	33.14182	-102.39972	198.2
24-53-9882	33.12723	-102.39675	94.0
24-54-2132	33.24658	-102.3214	107.4
24-54-2551	33.22822	-102.31258	486.4
24-54-3242	33.24118	-102.27394	27.5
24-54-3273	33.24066	-102.27697	27.8
24-54-3756	33.21576	-102.2831	29.7
24-54-4885	33.19874	-102.35621	5.0
24-54-5411	33.19184	-102.32993	58.5

Table 4.6.4, continued

State Well Number	Latitude (decimal degrees)	Longitude (decimal degrees)	Hydraulic Conductivity (feet per day)
24-54-5441	33.18534	-102.33101	41.8
24-54-5851	33.17384	-102.31323	252.1
24-54-5972	33.16751	-102.30481	345.9
24-54-6211	33.20427	-102.27479	26.8
24-54-6381	33.19443	-102.25949	85.8
24-54-7122	33.16341	-102.36592	112.7
24-54-7261	33.15857	-102.35098	31.1
24-54-7451	33.14441	-102.36684	67.5
24-54-7883	33.12842	-102.35558	285.8
24-54-8771	33.12726	-102.33029	32.4
24-54-8941	33.1339	-102.3042	78.9
24-54-9663	33.14659	-102.25429	96.8
24-54-9711	33.13648	-102.28705	138.6
24-55-1171	33.23992	-102.24958	72.0
24-55-1553	33.22995	-102.23074	110.5
24-55-1581	33.22558	-102.23109	185.0
24-55-1961	33.21545	-102.2114	92.1
24-55-2361	33.24386	-102.16922	13.0
24-55-2721	33.22126	-102.2034	331.4
24-55-3173	33.2396	-102.16368	10.0
24-55-3744	33.2156	-102.16436	138.7
24-55-4231	33.20641	-102.22681	11.4
24-55-4352	33.19978	-102.21548	1656.2
24-55-4492	33.18168	-102.2484	12.8
24-55-4834	33.1772	-102.2259	110.2
24-55-5471	33.18197	-102.20629	14.6
24-55-5932	33.17751	-102.17118	11.6
24-55-5982	33.16974	-102.17133	23.3
24-60-8731	33.03988	-102.58994	6.3
24-60-9951	33.00537	-102.50685	25.6
24-61-3382	33.11482	-102.28198	270.2
24-61-3761	33.09015	-102.4073	56.5
24-61-4921	33.05122	-102.46307	91.9
24-61-5331	33.0807	-102.42011	72.3
24-61-6281	33.07213	-102.39754	15.4
24-61-6521	33.06796	-102.39661	67.2
24-61-7292	33.03218	-102.47554	94.4
24-61-8472	33.01537	-102.45597	72.0

Table 4.6.4, continued

State Well Number	Latitude (decimal degrees)	Longitude (decimal degrees)	Hydraulic Conductivity (feet per day)
24-61-8851	33.00805	-102.4387	17.1
24-61-9682	33.01448	-102.38354	19.4
24-61-9791	33.00267	-102.40682	3.6
24-62-1241	33.11932	-102.35917	139.3
24-62-1251	33.11827	-102.35641	59.2
24-62-1313	33.12083	-102.34506	131.5
24-62-1421	33.10899	-102.36774	51.0
24-62-1431	33.10897	-102.36194	235.2
24-62-1461	33.10534	-102.365	1097.0
24-62-1552	33.10646	-102.35243	157.8
24-62-1581	33.0979	-102.35638	32.4
24-62-1681	33.09766	-102.33893	117.7
24-62-1871	33.10003	-102.34249	27.3
24-62-2291	33.11546	-102.30751	707.0
24-62-3112	33.12273	-102.28992	221.7
24-62-3132	33.1211	-102.28535	100.7
24-62-3213	33.12201	-102.27545	37.1
24-62-3661	33.10558	-102.25455	7.5
24-62-4581	33.05821	-102.35375	125.1
24-62-4671	33.05883	-102.34595	317.7
24-62-5291	33.07335	-102.3075	13.4
24-62-6582	33.06009	-102.27186	243.6
24-62-6672	33.05788	-102.26302	433.4
24-62-9651	33.02261	-102.25485	161.5
24-63-2341	33.11757	-102.1787	38.0
24-63-3192	33.11471	-102.15725	27.8
24-63-3542	33.10521	-102.15121	83.0
24-63-4771	33.04441	-102.24887	100.5
24-63-5942	33.04843	-102.17813	31.6
24-63-8221	33.04021	-102.18608	68.4
24-63-8231	33.03829	-102.18275	53.0
24-63-8232	33.03829	-102.18443	58.0
24-63-7142	33.03425	-102.24783	156.3
24-63-7821	33.01078	-102.22828	119.6
24-63-8371	33.03219	-102.17831	20.4
27-04-2254	32.99113	-102.56342	76.1
27-04-2892	32.96119	-102.55451	10.6
27-04-3171	32.98898	-102.53831	30.4

Table 4.6.4, continued

State Well Number	Latitude (decimal degrees)	Longitude (decimal degrees)	Hydraulic Conductivity (feet per day)
27-05-1592	32.97287	-102.47313	82.6
27-05-3121	32.99637	-102.40906	33.5
27-06-1181	32.98922	-102.36646	86.6
27-06-1572	32.97689	-102.36042	11.2
27-06-1643	32.97714	-102.3437	7.2
27-06-1832	32.96959	-102.34905	26.0
27-06-2851	32.96685	-102.31046	35.3
27-07-2522	32.98558	-102.18936	55.2
27-08-1862	33.96493	-102.09871	19.3

Table 4.6.5 New hydraulic conductivity values from the City of Canyon.

State Well Number	GSE (feet above mean sea level)	Number of Screens	Total Screen Length (feet)	Flow Rate (gallons per minute)	Slope on Semi-log plot	Transmissivity (square feet per day)	Hydraulic Conductivity (feet per day)
G1910001AC	3616	1	70	375	2.5	5351.6	76.5
G1910001AA	3624	1	70	402	5.4	2623.6	37.5
G1910001AB	3612	1	70	402	8.4	1677.1	24.0
G1910001AD	3594	1	70	402	6.2	2277.6	32.5
G1910001AE	3527	1	50	303	6.4	1655.7	33.1
G1910001U	3586	1	60	411	31.5	459.9	7.7
G1910001W	3615	1	70	700	6.5	3792.6	54.2
G1910001X	3633	1	70	250	5.2	1683.4	24.0
G1910001Y	3627	1	70	300	2.7	3911.4	55.9
G1910001Z	3624	1	70	310	4.6	2373.8	33.9

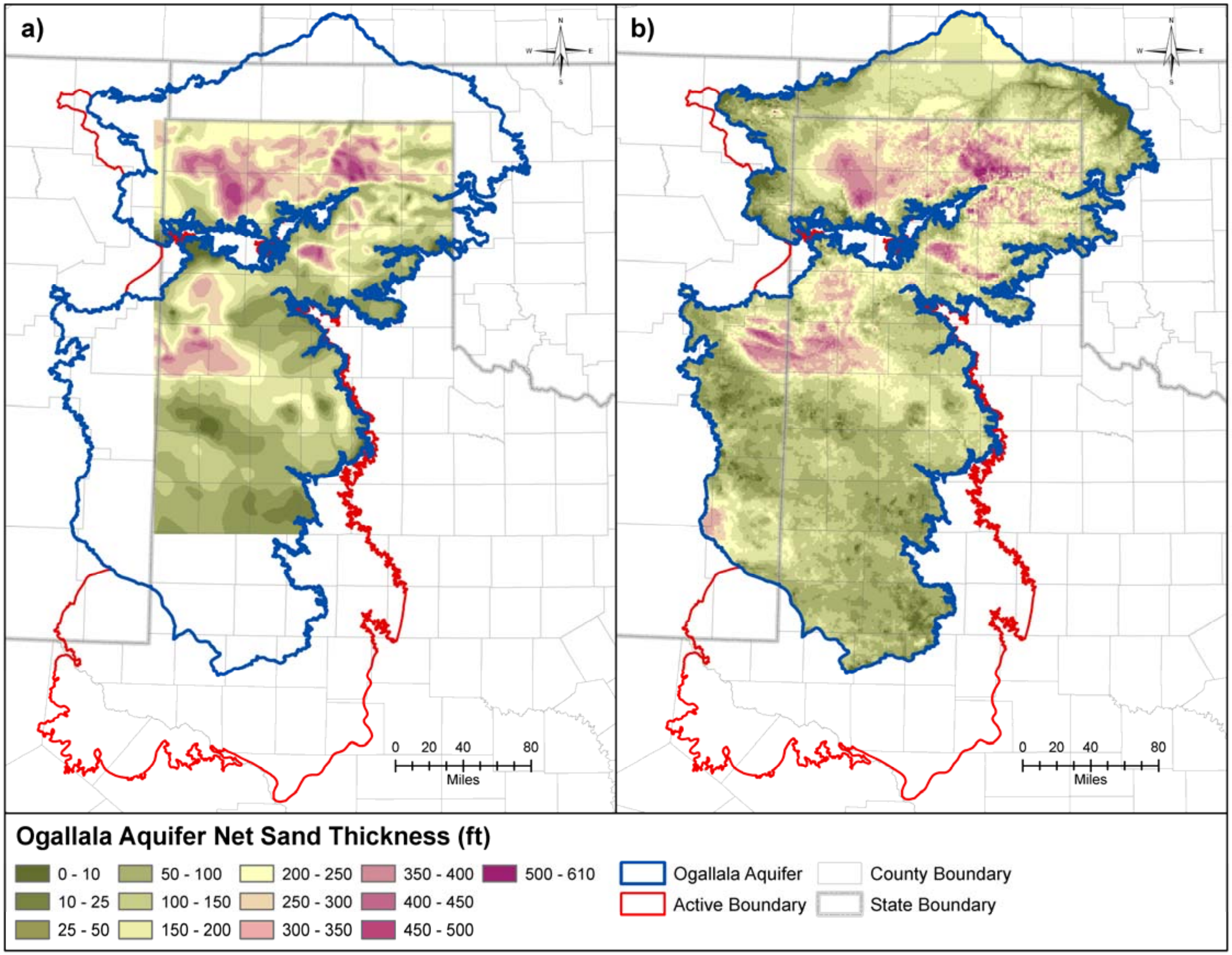

Figure 4.6.1 Comparison of Ogallala Aquifer net sand thickness in feet from (a) Seni (1980) and (b) this report.

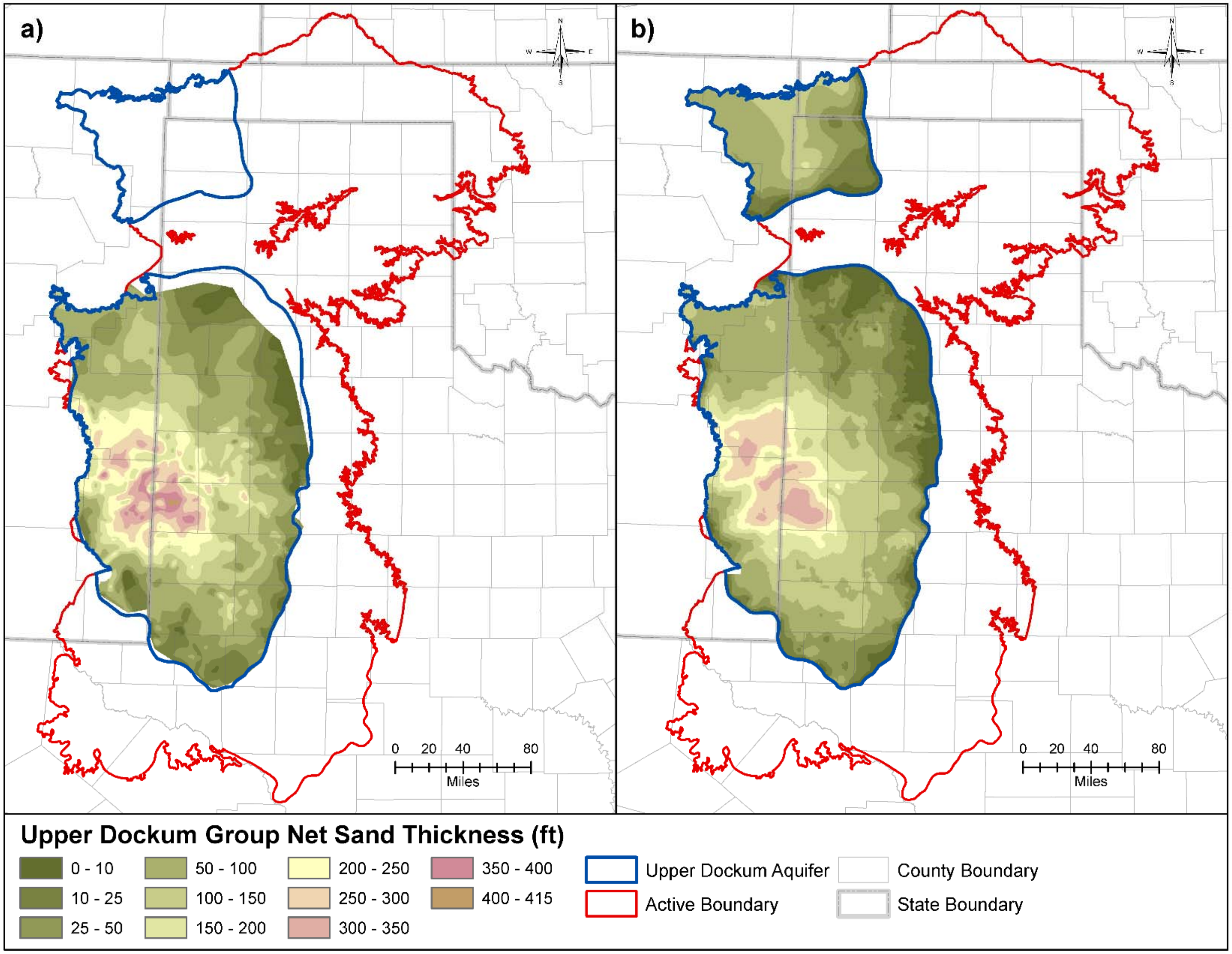

Figure 4.6.2 Comparison of upper Dockum Group net sand thickness in feet from (a) Ewing and others (2008) and (b) this report.

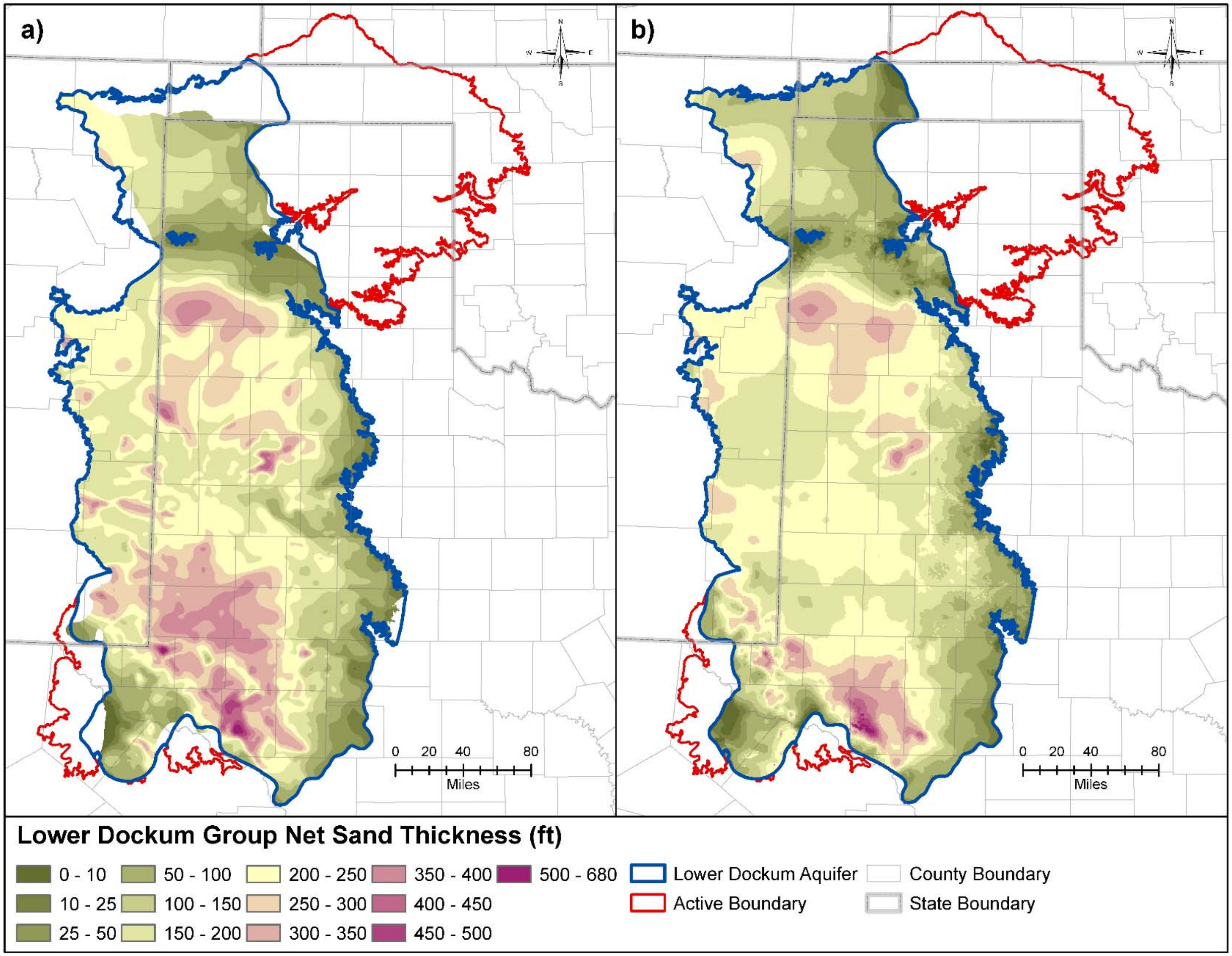

Figure 4.6.3 Comparison of lower Dockum Group net sand thickness in feet from (a) Ewing and others (2008) and (b) this report.

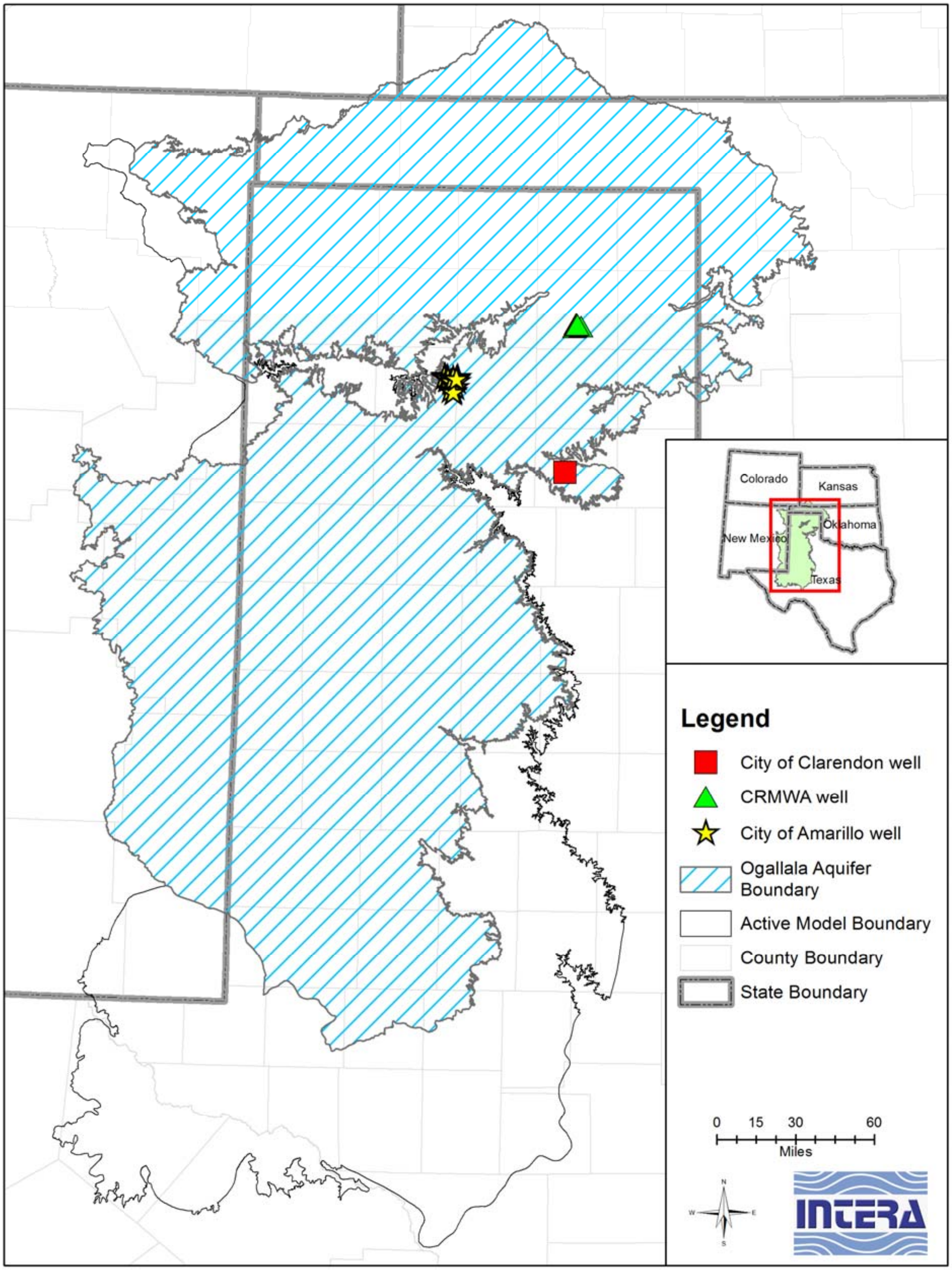

Figure 4.6.4 **Location of new hydraulic conductivity data in the Ogallala Aquifer.**

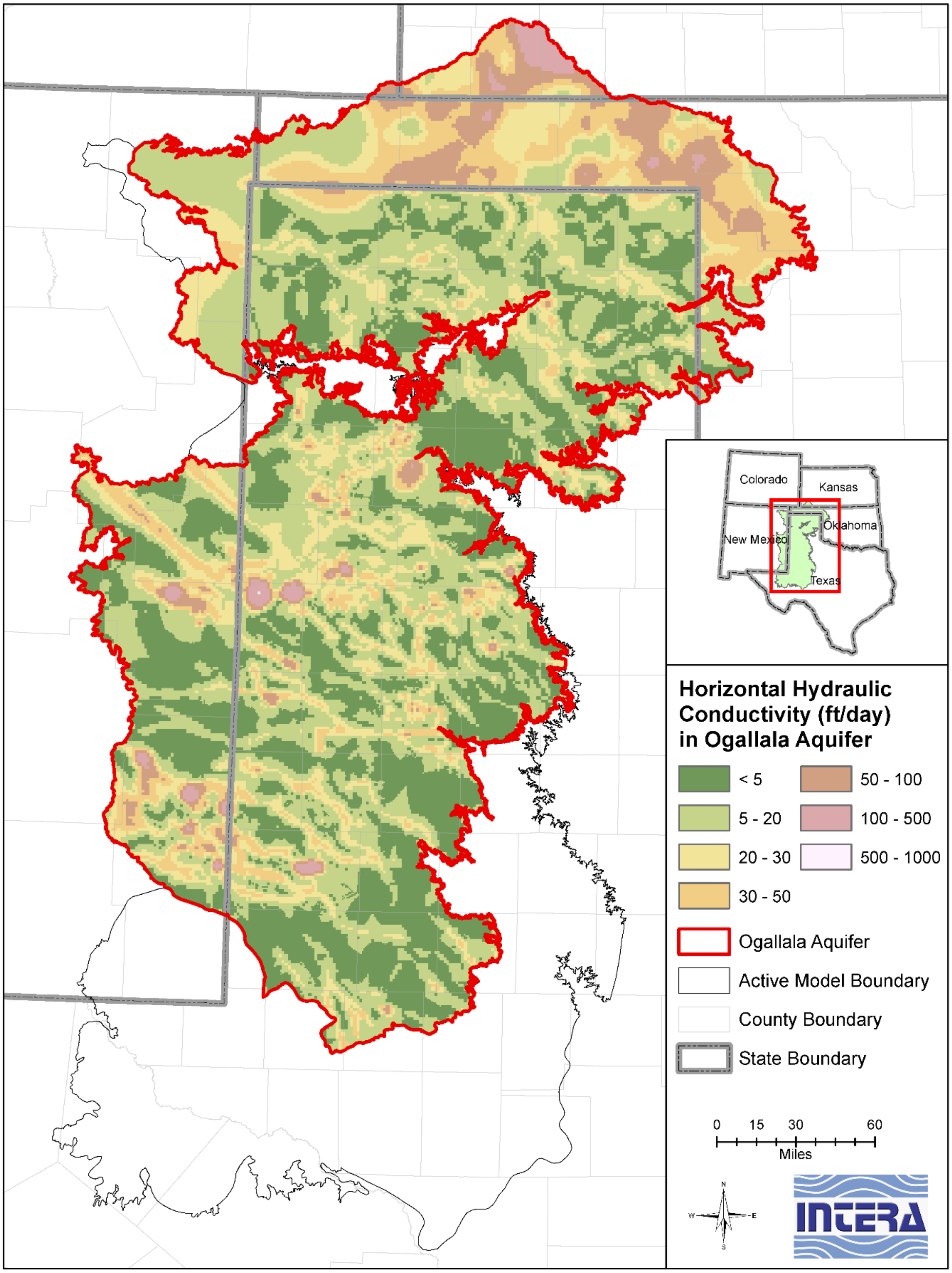

Figure 4.6.5 **Hydraulic conductivity distribution in feet per day in the Ogallala Aquifer (modified from Naing, 2002 and Dutton and others, 2001a).**

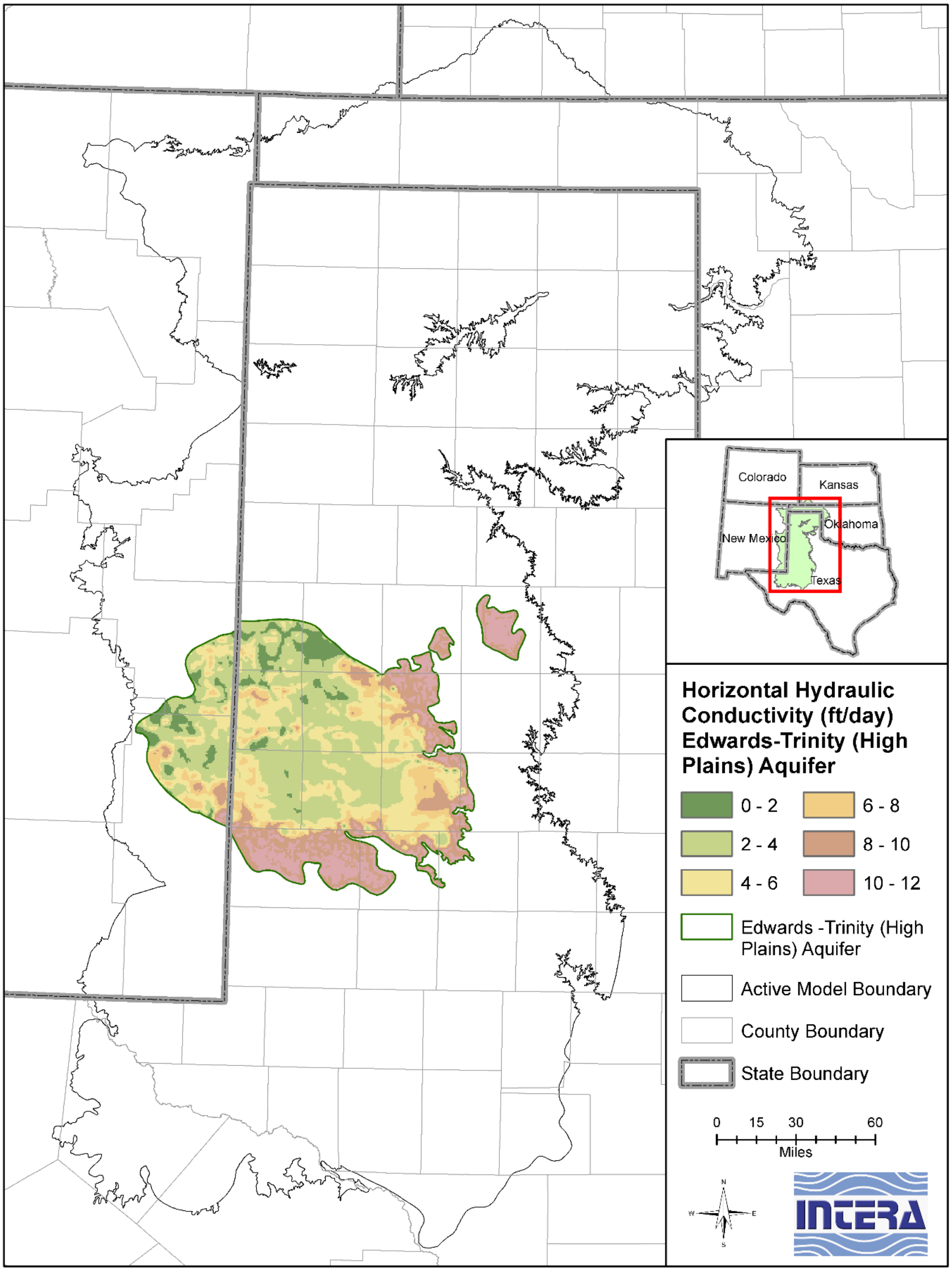

Figure 4.6.6 Hydraulic conductivity distribution in feet per day in the Edwards-Trinity (High Plains) Aquifer (modified from Blandford and others, 2008).

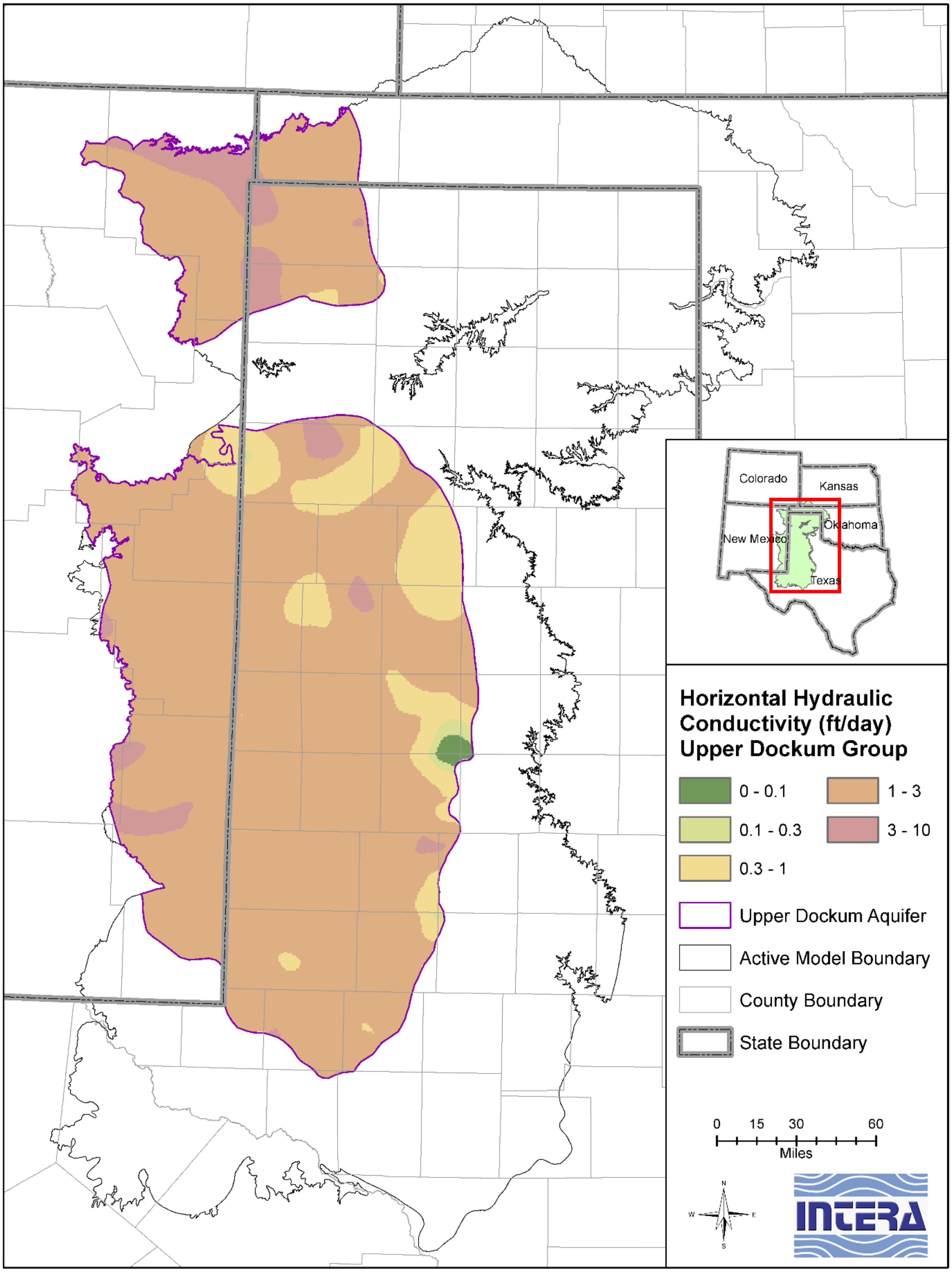

Figure 4.6.7 **Hydraulic conductivity distribution in feet per day in the upper Dockum Group.**

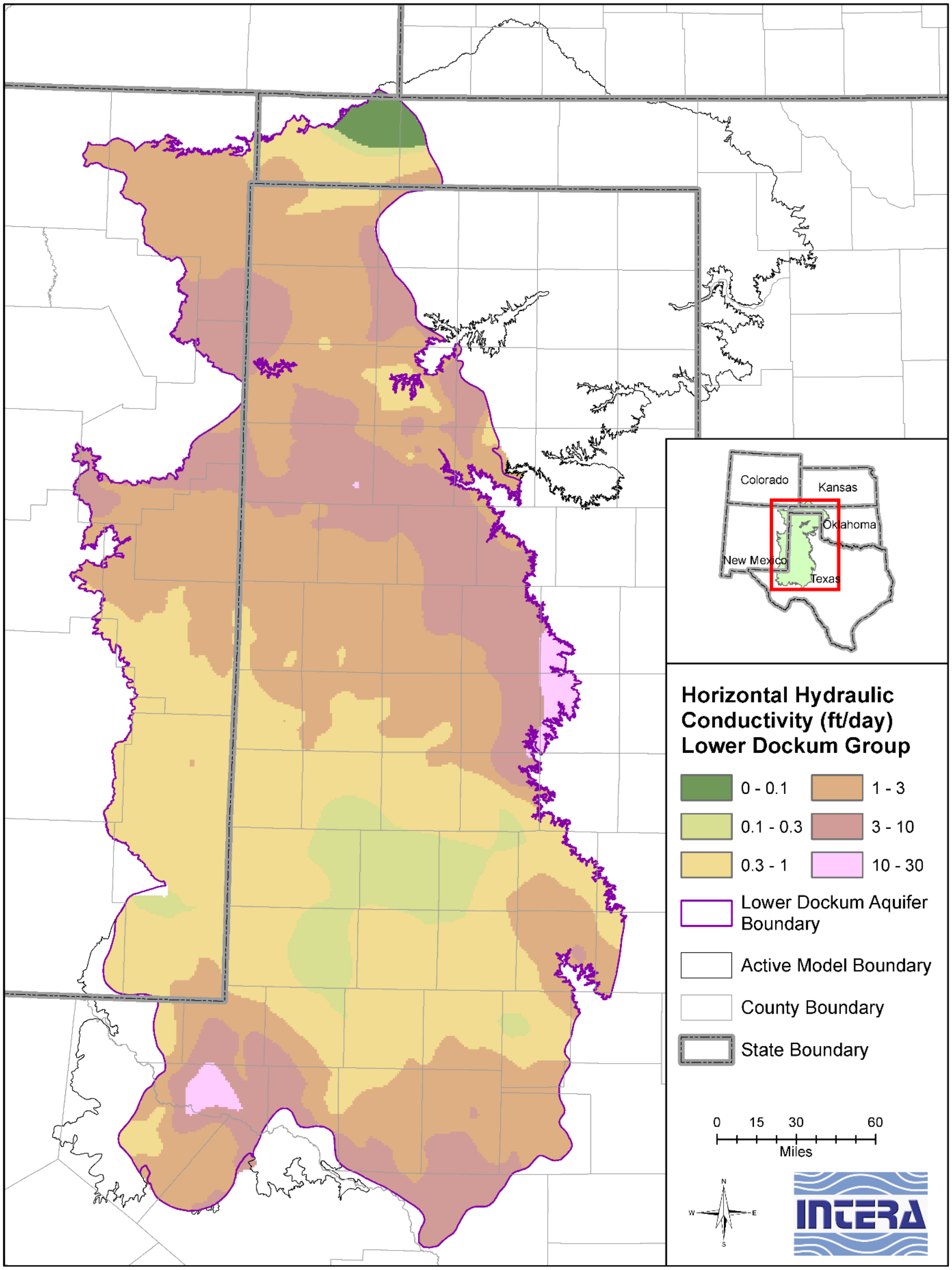

Figure 4.6.8 Hydraulic conductivity distribution in feet per day in the lower Dockum Group.

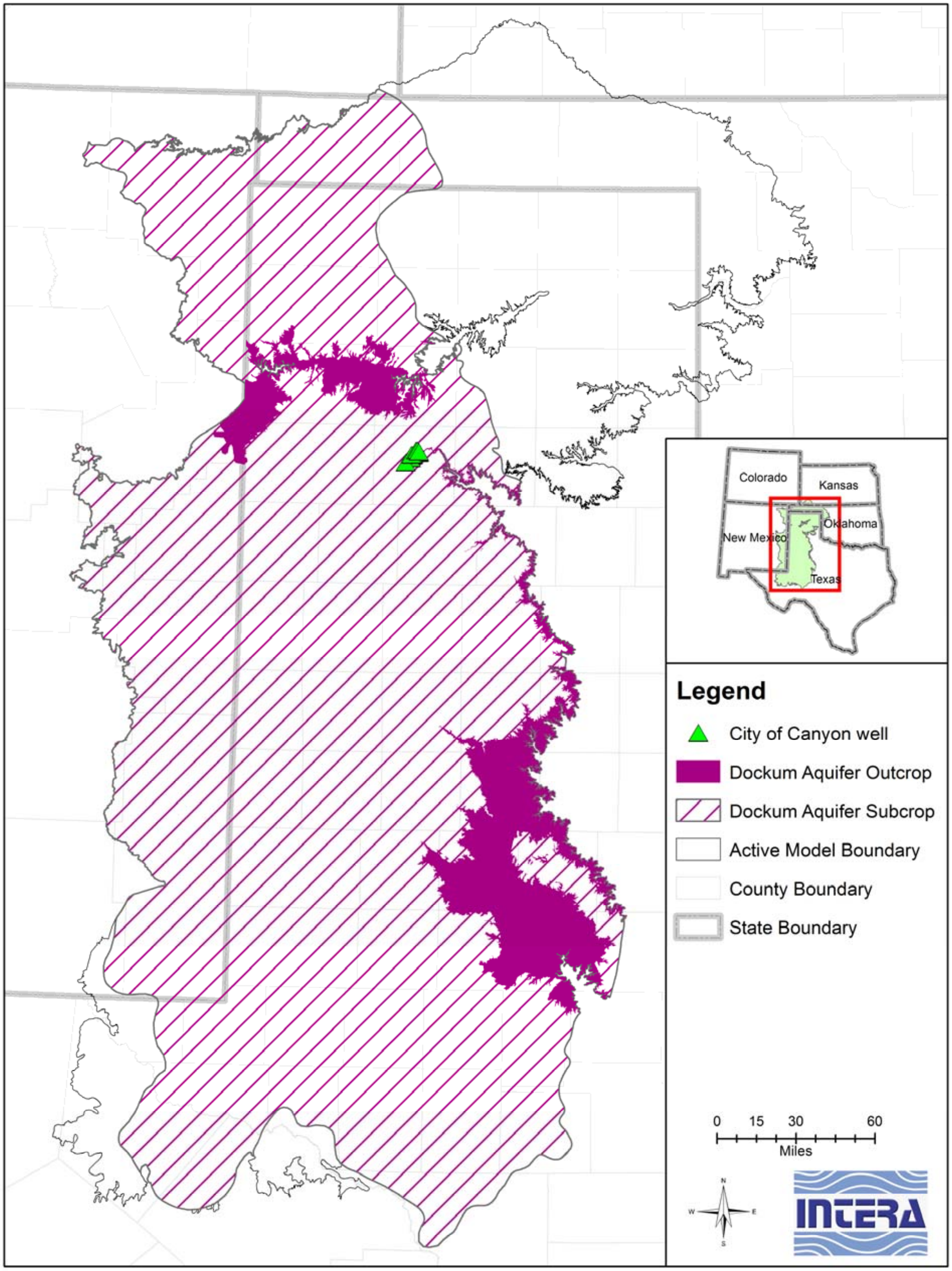

Figure 4.6.9 Location of new Dockum Aquifer aquifer pumping tests for the City of Canyon wellfield.

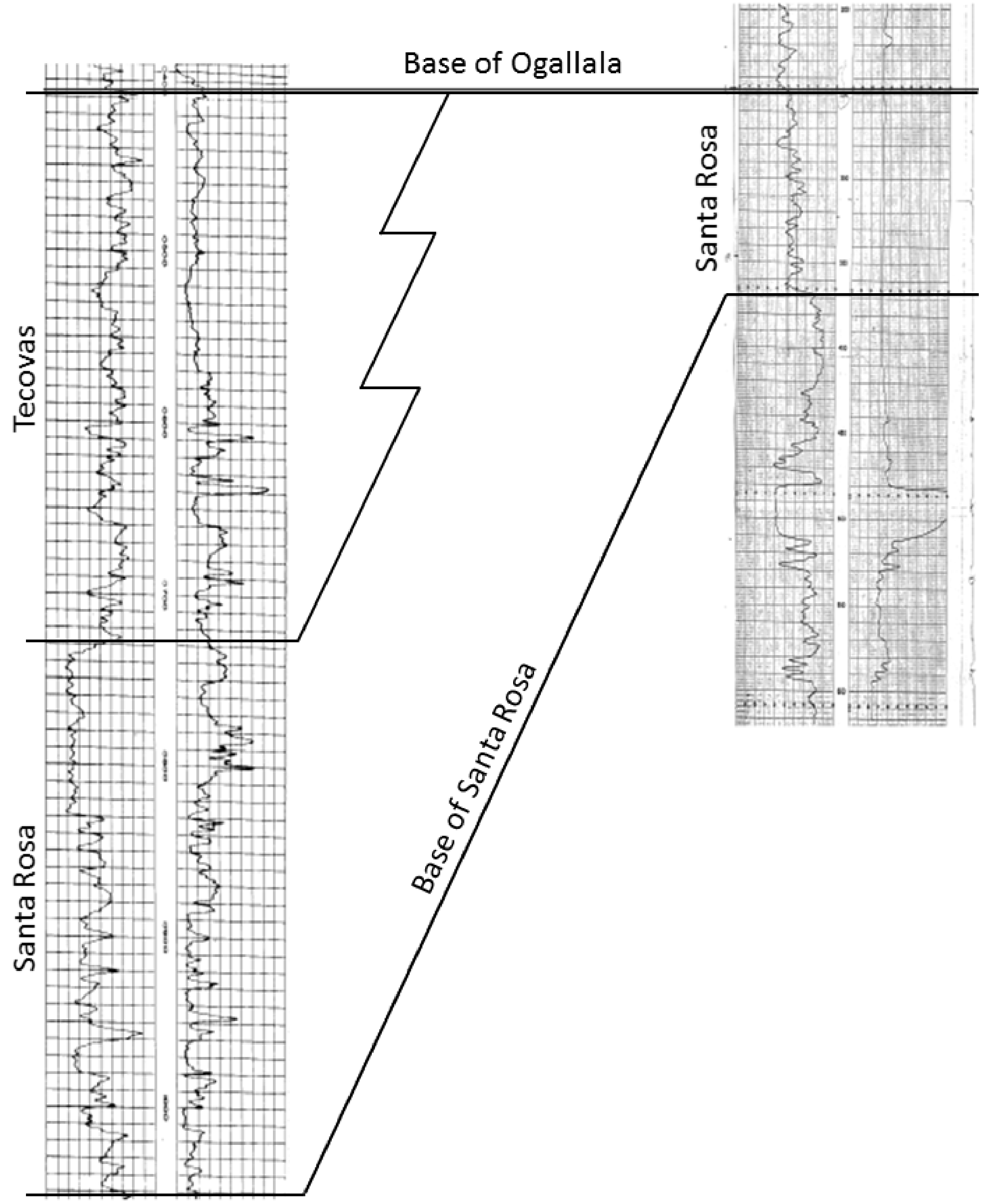

Figure 4.6.10 Example geophysical log interpretations of wells where Tecovas Formation is present (left) and absent (right).

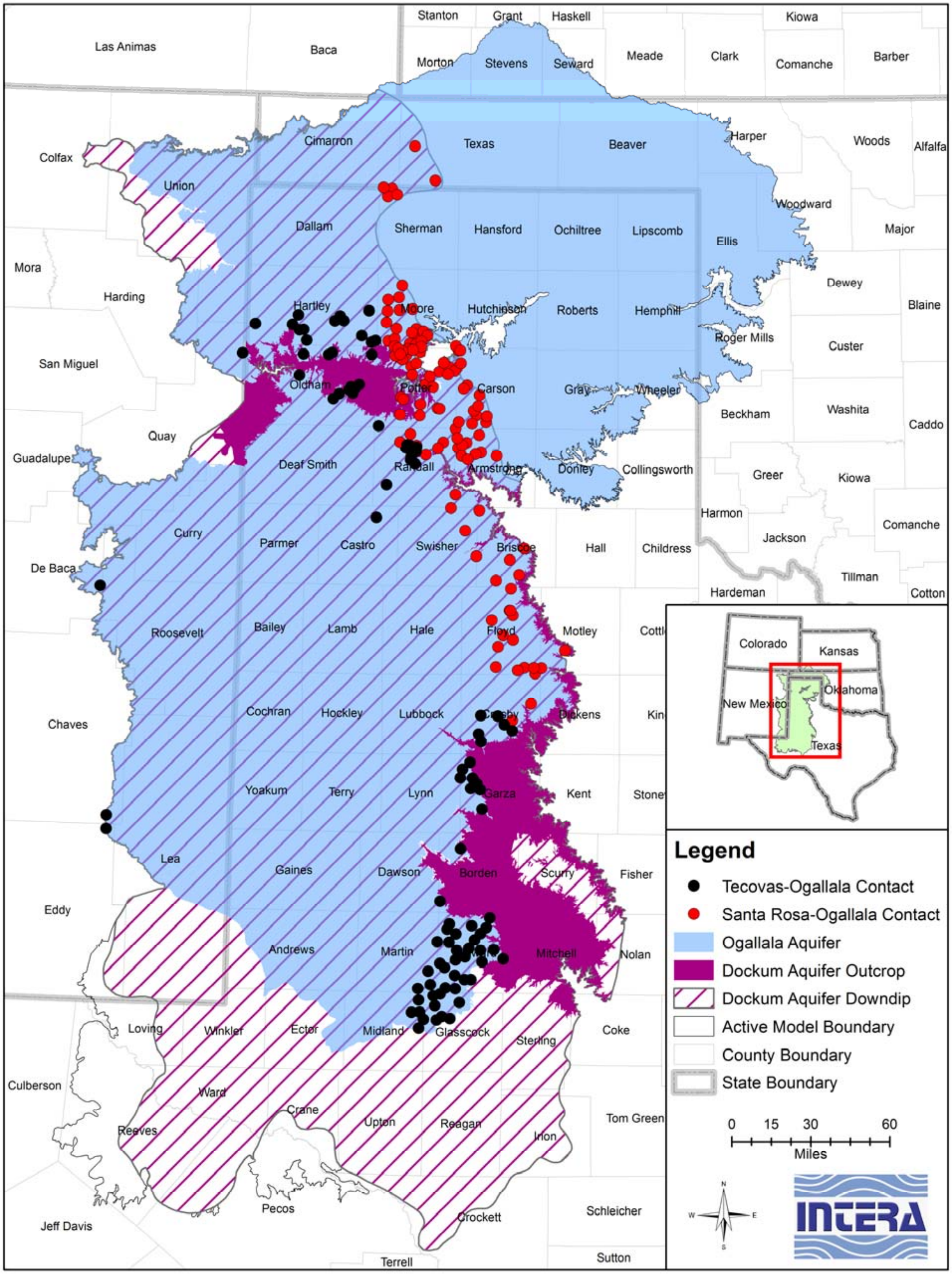

Figure 4.6.11 **Location of wells where lower Dockum Group is directly overlain by the Ogallala Aquifer.**

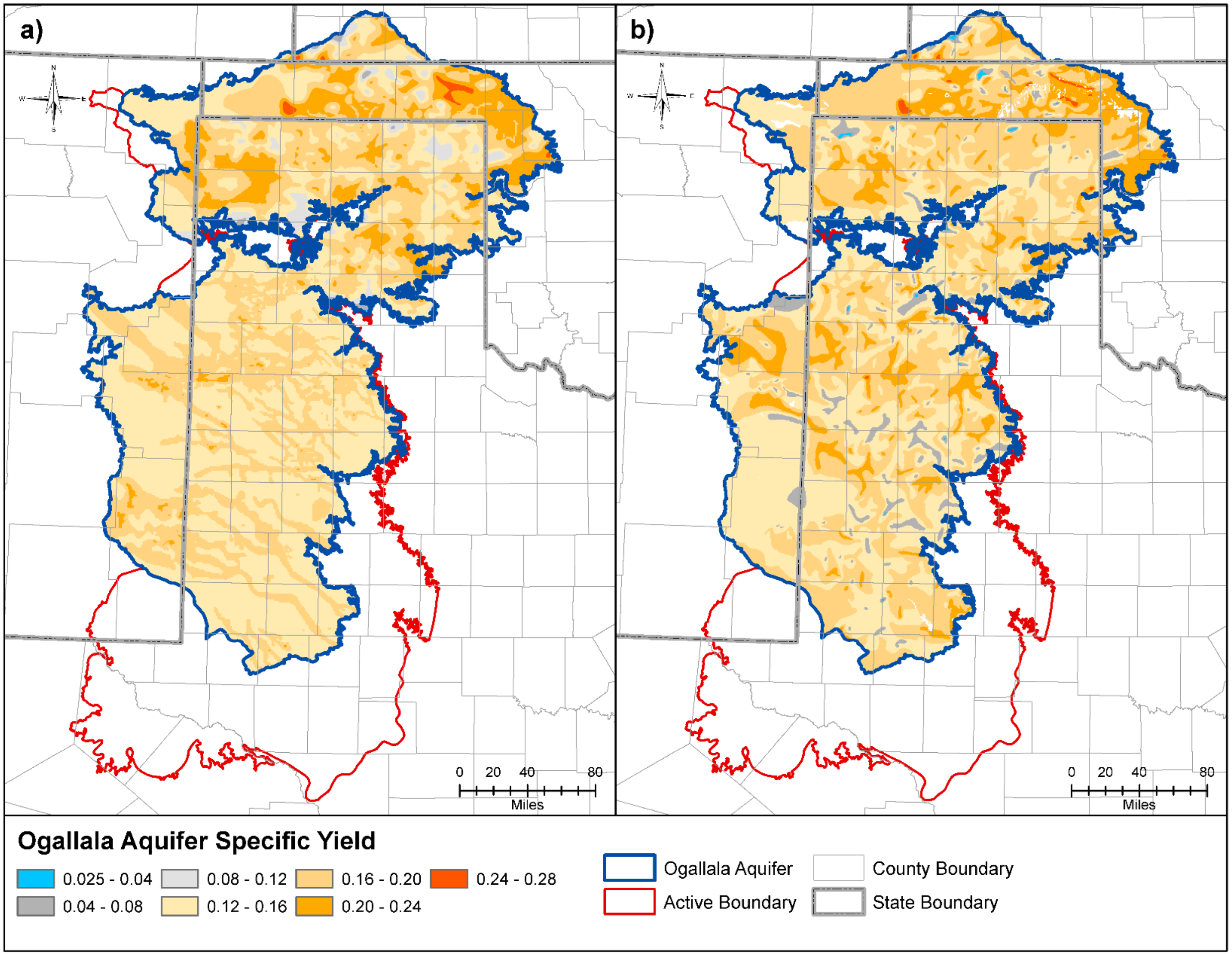

Figure 4.6.12 Specific yield distribution in the Ogallala Aquifer from (a) Dutton and others (2001a) and Blandford and others (2008) and (b) McGuire and others (2012).

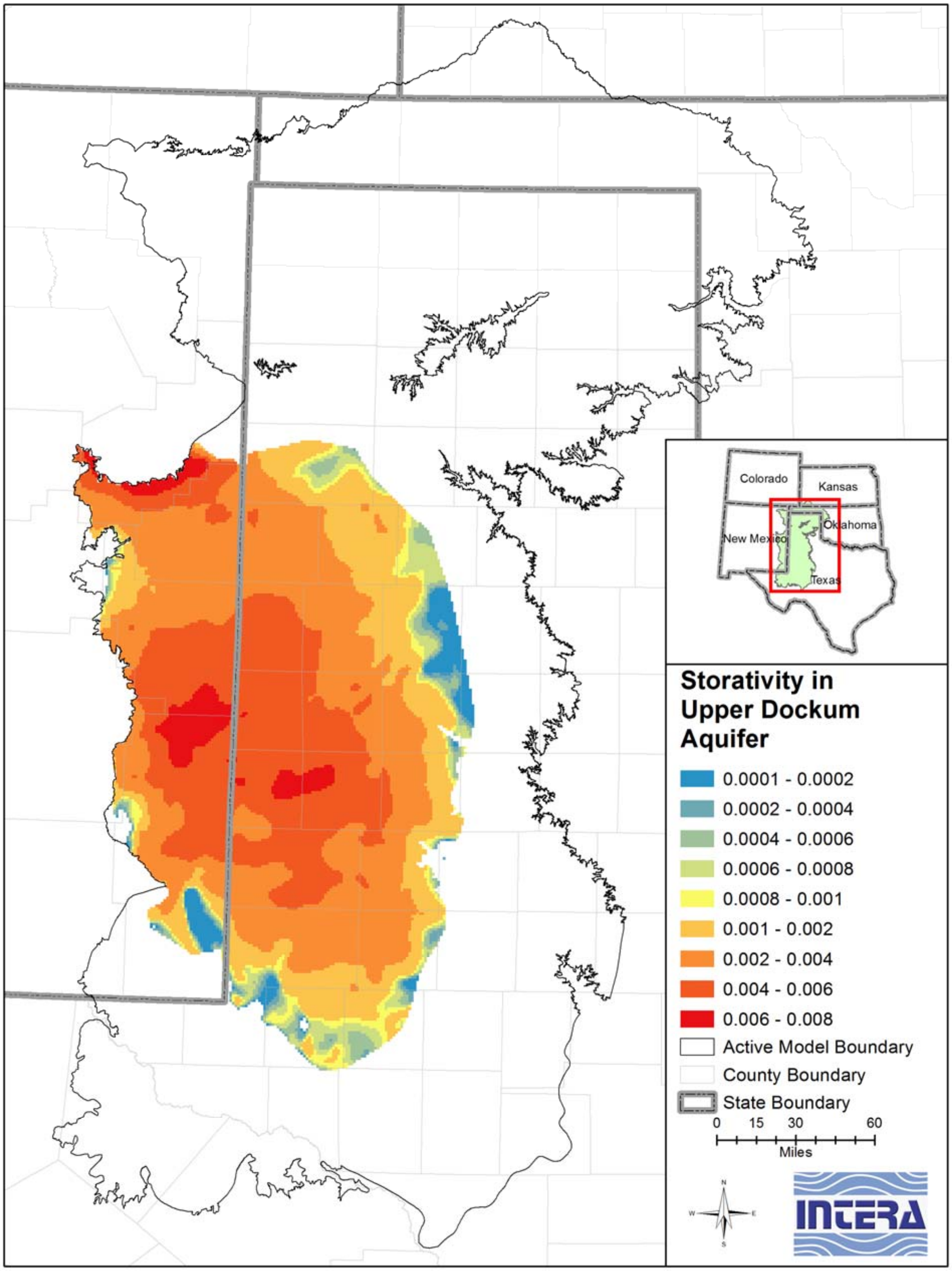

Figure 4.6.13 Storage coefficient of the upper Dockum Group (Ewing and others, 2008).

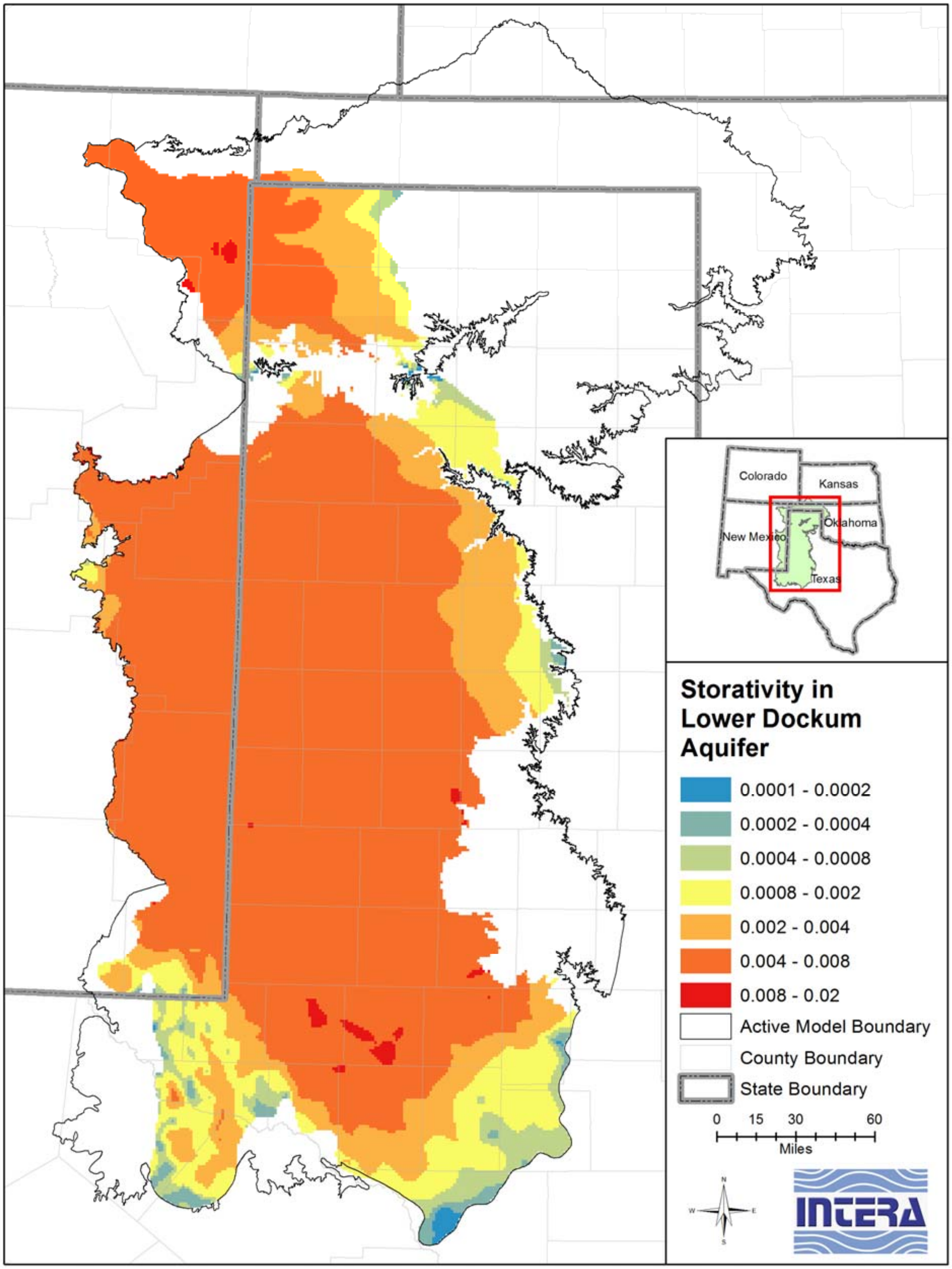

Figure 4.6.14 Storage coefficient of the lower Dockum Group (Ewing and others, 2008).

4.7 Aquifer Discharge

Discharge refers to water moving out of an aquifer by either natural or anthropogenic processes. Natural processes include evapotranspiration, cross-formational flow, and discharge to streams, springs, and other surface water bodies. The most important anthropogenic discharge mechanism is groundwater pumping.

4.7.1 Natural Aquifer Discharge

Under pre-development conditions, without any pumping, aquifer recharge and discharge are balanced. Natural aquifer discharge occurs as base flow to streams, springs and seeps, groundwater evapotranspiration, and cross-formational flow. Recharge that discharges through surficial features is sometimes termed “rejected recharge”. This discharging water has the potential to be captured by pumping, if the water table is lowered to the point where gradients are affected, and natural discharge is decreased. The plethora of springs and seeps from the Ogallala Aquifer observed by Gould (1906, 1907) in stream valleys is an example of recharge rejected by the aquifer prior to its development. The decrease in flow to springs in the Ogallala Aquifer post-development is an example of capture of “rejected recharge”.

Natural aquifer discharge through stream base flow is discussed in Sections 4.5.1. Discharge through springs is discussed in Section 4.5.2. Cross-formational flow is discussed in Section 4.3.6. Refer to these sections for additional information on these discharge mechanisms. The remaining natural discharge mechanism, groundwater evapotranspiration, is the focus of this section.

Evapotranspiration is the combined process of soil water evaporation near the land surface and the uptake in the root zone and subsequent transpiration of water by vegetation. For the purposes of groundwater modeling, two types of evapotranspiration are distinguished: vadose zone evapotranspiration and groundwater evapotranspiration. Evapotranspiration in the vadose zone captures infiltrating water before it reaches the water table. Groundwater evapotranspiration is plant uptake or surface evaporation of groundwater. Here, the focus is groundwater evapotranspiration, since it is the type implemented in the groundwater model. Vadose zone evapotranspiration is accounted for in the recharge estimate as discussed in Section 4.4.

Groundwater evapotranspiration occurs primarily in riparian buffer strips adjacent to streams (Scanlon and others, 2005a). Since riparian zones are not specifically mapped in Texas, two methods can be used to define the location of groundwater evapotranspiration. Either a fixed buffer around streams can be defined as riparian areas, or topographically lower areas can be assumed to be likely regions of groundwater evapotranspiration. In general, the goal is to limit the potential for groundwater evapotranspiration to regions where the water table is near ground surface. Both approaches likely produce similar results, although some combination may be necessary if the stream coverage does not have adequate resolution to define all of the discharge areas. The potential for groundwater evapotranspiration is expected near rivers and streams crossing the Ogallala Aquifer and the outcrops of the Rita Blanca and Dockum aquifers.

Scanlon and others (2005a) summarize the conceptual approach to estimating groundwater evapotranspiration. In general, if water tables are very near the surface, evapotranspiration will be close to the potential evapotranspiration, assuming there is some type of vegetative cover. Potential evapotranspiration and reference evapotranspiration are terms often used interchangeably. Reference evapotranspiration is defined as the evapotranspiration rate from a reference vegetation, often a short grass, that has unlimited available water. Potential evapotranspiration should not be confused with “pan evaporation”, which is the rate of water evaporation from an open pan. Potential evapotranspiration can be related to pan evaporation by the use of pan coefficients; however, since potential evaporation can be estimated with basic climate data, pan evaporation is not used in the calculation of potential evapotranspiration.

When the water table is below ground surface but still in the main vegetation root zone, evapotranspiration will occur at the unhindered vegetative evapotranspiration rate, ETV_{max}. This can be estimated by (Scanlon and others, 2005a):

$$ETV_{max} = PET * K_c \tag{4.7.1}$$

where

K_c is the vegetation coefficient

PET is the potential evapotranspiration

Thus, to parameterize groundwater evapotranspiration, three parameters must be estimated: potential evapotranspiration, vegetation coefficient, and rooting depth. Rooting depth and vegetation coefficient are specific to the type of vegetation, so a necessary prerequisite is some knowledge of the types of vegetation in the riparian areas in the model region. The following paragraphs discuss potential evaporation in the study area, how the types of vegetation in the model region were estimated, and the corresponding vegetation coefficients and rooting depths.

Borrelli and others (1998) provide an estimate of long-term potential evapotranspiration in Texas, based on the Penman-Monteith method, as reproduced in Figure 4.7.1 for the study area. This figure shows that the long-term average potential evapotranspiration ranges from about 59 to 78 inches per year, increasing from northeast to southwest. Although evapotranspiration varies considerably with seasons, it does not vary significantly year to year (annual average basis). For this reason, the assumption is made that potential evapotranspiration is constant throughout a transient simulation, where annual stress periods are used.

The National Land Cover Database 2006 (Fry and others, 2011) provides detailed land use data for the entire conterminous United States. Figure 4.7.2 shows land use coverage for the study area. Unfortunately, this dataset does not specifically identify riparian vegetation or riparian zones. To determine whether different types of vegetation are identified in areas near rivers, a coverage of the major rivers and streams in the area including a one-mile riparian buffer was created and intersected with the vegetation coverage. The distribution of vegetation types for this subset was calculated and compared to the vegetation distribution in the entire model region, as shown in Figure 4.7.3. With the exception of cultivated crops, the relative frequency of each vegetation type is very similar, indicating that either markedly atypical vegetation does not naturally occur near streams, or the vegetation coverage does not contain sufficient resolution to discriminate the riparian areas. Lacking higher resolution information, the potential for discharge through groundwater evapotranspiration was assumed to occur within riparian areas defined by a buffer around streams.

Scanlon and others (2005a) provides a database of estimates of vegetation coefficient and rooting depths for many types of vegetation. Table 4.7.1 shows estimates for several vegetation types in the Amarillo region according to Scanlon and others (2005a).

Using the Simplified-Surface-Energy-Balance (SSEB) Model, Houston and others (2013) calculated average annual actual evapotranspiration during the period 2000 to 2009 for the Ogallala Aquifer. These values, shown in Figure 4.7.4, range from 5 to 48 inches per year, with the highest values clustered around rivers and streams. A comparison of the calculated groundwater evapotranspiration for the model to the actual evaporation estimated by Houston and others (2013) could provide a consistency check of the model values, as they should not be greater than actual evapotranspiration.

4.7.2 Aquifer Discharge through Pumping

Under pre-development conditions, a long-term dynamic equilibrium exists where aquifer recharge is balanced by aquifer discharge. This hydraulic condition is generally referred to as a steady-state system. Human activities alter the dynamic equilibrium of the pre-development flow system through groundwater pumping withdrawals, changes in recharge through development and irrigation return flow, and changes in vegetation. From the groundwater perspective, groundwater withdrawals due to pumping almost always have the greatest impact on aquifer hydraulics.

Groundwater removed by pumping is supplied through reduced natural groundwater discharge, decreased groundwater storage, and sometimes increased recharge. The observable impact resulting from pumping is declines in water levels. Throughout much of the High Plains Aquifer System, groundwater withdrawals exceed the amount of recharge, and water levels have declined fairly consistently through time. Water-level declines in excess of 200 feet have occurred in the Ogallala Aquifer in several areas over the last 50 to 60 years (see Section 4.3). However, there are also areas where water levels have risen over the last few years (see Section 4.3). For an aquifer system that has experienced significant groundwater loss through pumping and associated changes in water levels, accurate definition of pumping is an important parameter required for development of a reliable model.

Data from various sources was integrated in estimating pumping. These data included:

- Water use surveys provided by the TWDB for the periods 1980 to 2008 (TWDB, 2013b) and 2000 to 2012 (TWDB, 2013c).
- TWDB irrigation survey data for the years 1958, 1964, 1969, 1974, 1979, 1984, and 1989 (TWDB, 1991).
- Agricultural water demands for the years 1952 to 1956, 1982 to 1984, 1987, 1992 to 1994, and 1997 estimated by Amosson and others (2003).

- Metered pumping data for the years 2008 to 2012 from the North Plains Groundwater Conservation District (Hallmark, 2013).
- Historical pumping estimates for the years 1950 to 2008 from the Northern Ogallala Aquifer groundwater availability model Update to Support the 2011 [Region A] Water Plan (INTERA, Inc. and Dutton, 2010).
- Historical pumping estimates for the years 1940 to 2000 from the Southern Ogallala Aquifer groundwater availability model (Blandford and others, 2003).
- Historical pumping estimates for the years 1930 to 2000 from the Edwards-Trinity (High Plains) Aquifer groundwater availability model (Blandford and others, 2008).
- Historical pumping estimates for the years 1950 to 1997 from the Dockum Aquifer groundwater availability model (Ewing and others, 2008).

Aquifers considered for pumping are: the Ogallala Aquifer, the Dockum Aquifer, the Edwards-Trinity (High Plains) Aquifer, and the Rita Blanca Aquifer. Pumping for each of these aquifers is discussed in subsequent sections. Pumping is considered for the following seven categories: irrigation, municipal, manufacturing, mining, power, livestock, and rural domestic. Because the Edwards-Trinity (Plateau) and Pecos Valley aquifers will not be explicitly modeled in the High Plains Aquifer System groundwater availability model (they will be treated as boundary conditions), pumping in those aquifers is not estimated as part of this study.

4.7.2.1 Northern Ogallala Aquifer Pumping

Most groundwater discharge from the Northern Ogallala Aquifer is through pumping, of which irrigation is the dominant type of water use. Pumping estimates for the Northern Ogallala Aquifer were based on three data sources: the most updated Northern Ogallala Aquifer groundwater availability model (INTERA, Inc. and Dutton, 2010), metered data obtained from the North Plains Groundwater Conservation District (Hallmark, 2013), and water use survey data provided by the TWDB for the period 2000 to 2012 (TWDB, 2013c).

The updated Northern Ogallala Aquifer groundwater availability model (INTERA, Inc. and Dutton, 2010) incorporates historical pumping from 1950 to 2008. The methodology they followed to estimate historical pumping is summarized below:

- Pumping in the updated model was based on pumping from earlier versions of the Northern Ogallala Aquifer groundwater availability model (Dutton and others, 2001a; Dutton, 2004), which estimated historical pumping from 1950 through 1998. The 2004 groundwater availability model reconstructed historical groundwater withdrawals in the period 1950 to 1998 from the following sources.
    - Pumping for municipal, industrial, irrigation, livestock, mining, and power uses during 1958, 1964, 1969, and 1974 was taken from worksheets compiled by Knowles and others (1984).
    - Pumping for 1980 to 1996 was tallied from a groundwater-summary database compiled by the TWDB (Dutton and Reedy, 2000).
    - Decadal estimates of irrigation withdrawal for 1950 to 1997 were made by the Texas Agricultural Experiment Station on the basis of rainfall and irrigation efficiencies (Dutton and Reedy, 2000).
    - Pumping estimates were modified as appropriate to reflect pumping only from the Ogallala Aquifer.
- The updated model by INTERA, Inc. and Dutton (2010) used the same estimates as the 2004 groundwater availability model for historical irrigation, livestock, and rural domestic pumping for all Texas counties for the period 1950 to 1997.
- The updated model extended historical irrigation pumping for all Texas counties from 1998 through 2008. The new estimates were based on metered data received from the North Plains and Panhandle Groundwater Conservation Districts along with irrigation demand estimates developed by Freese and Nichols.
- The updated model extended historical livestock and rural domestic pumping for all Texas counties from 1998 through 2008 using demand estimates developed by Freese and Nichols.
- INTERA, Inc. and Dutton (2010) updated municipal, manufacturing, mining, and power pumping for all Texas counties using information provided by the TWDB, which enumerated annual water use by individual large and small surveyed entities.

Information from the TWDB was supplemented or replaced as appropriate where more accurate data were available.

- Historical pumping in all non-Texas counties for all water use categories was kept the same as the 2004 groundwater availability model, which derived these data from the digital files of Luckey and Becker (1999).

After reviewing the pumping estimates from the updated Northern Ogallala Aquifer groundwater availability model (INTERA, Inc. and Dutton, 2010), it was decided that those estimates provided the most reliable source of information for regional pumping for the aquifer. Thus, all historical pumping estimates for the period between 1950 and 2008 for the Northern Ogallala Aquifer in the High Plains Aquifer System groundwater availability model were kept consistent with the updated Northern Ogallala Aquifer groundwater availability model (INTERA, Inc. and Dutton, 2010). Pumping was assumed to be zero in 1930. Pumping for the years between 1930 and 1950 was linearly interpolated between zero in 1930 and the value in the updated Northern Ogallala Aquifer groundwater availability model in 1950.

For the period from 2009 to 2012, two pumping data sources were available: TWDB water use survey data for the years 2000 through 2011 (2012 pumping was missing or incomplete for many counties in the TWDB water use survey data) and irrigation pumping volumes provided by the North Plains Groundwater Conservation District from their metering program for the years 2006 through 2012. For counties completely within the North Plains Groundwater Conservation District boundary, the metered data was fairly consistent with the TWDB water use survey data between 2006 and 2011. These counties include Hansford, Lipscomb, Ochiltree, and Sherman. A good match between the metered data and the water use survey data for Hartley County, which is only partially within the North Plains Groundwater Conservation District, was also found. Figures 4.7.5 shows the model historical pumping from the updated Northern Ogallala Aquifer groundwater availability model compared to the TWDB water use survey data and the metered pumping volumes from the North Plains Groundwater Conservation District for Hansford County, which lies completely within the District. Figure 4.7.6 shows the same comparison for Dallam County, which is partially within the North Plains Groundwater Conservation District boundary.

Based on these comparisons, the North Plains Groundwater Conservation District metered data were used to extend irrigation pumping from 2009 to 2012 for all counties lying completely within the District boundary. Non-irrigation pumping for these counties was extended using the TWDB water use survey data from 2009 to 2011. For counties partially located within the North Plains Groundwater Conservation District, the TWDB water use survey data were used to extend pumping from 2009 to 2011 for all water use categories, including irrigation. Due to missing data in 2012 in the TWDB water use survey, 2012 pumping levels were kept the same as 2011 levels when using the TWDB water use survey data.

A United States Geological Survey study with remote-sensing based water-balance estimates (Stanton and others (2011) was evaluated for additional pumping information in the study area. Stanton and others (2011) tested different approaches for estimating water-budget components of the Ogallala Aquifer during the pre-development (1940 to 1949) and current (2000 to 2009) time periods. The study provides insight into how sensitive soil-water-balance models can be to changes in input parameters, particularly precipitation and actual evapotranspiration. While the models discussed do provide estimates of pumping for Texas, it should be noted that estimating pumping was not the focus of the study. The models were not calibrated to actual independent hydrologic measurements and so, the pumping estimates should be considered uncertain. During the 2000 to 2009 time period, their SOil-WATer-Balance Model estimated an average annual pumping estimate of 2.4 million acre-feet in Texas and their Soil-Water-Balance Model estimated 4.5 million acre-feet. This second estimate compares favorably with the 2000 to 2009 average pumping estimated from the TWDB water use survey (4.7 million acre-feet). It is promising that one of the models did roughly agree with the TWDB water use survey, which is used as the "gold standard" for estimating pumping in the current report. However, in general, the Stanton and others (2011) study does not otherwise provide additional helpful information for checking and/or correcting the current study's pumping estimates.

For non-Texas (New Mexico, Oklahoma, and Kansas) counties, pumping from 1950 through 2008 was taken from the updated Northern Ogallala Aquifer groundwater availability model. Pumping was linearly extended back to 1930 (assuming zero pumping for that year) and kept constant at 2008 levels for the period 2009 through 2012.

Figure 4.7.7 shows total pumping by category for the Texas portion of the Northern Ogallala Aquifer. Figure 4.7.8 shows total pumping for the non-Texas portion of the Northern Ogallala Aquifer.

4.7.2.2 Southern Ogallala Aquifer Pumping

Similar to the Northern Ogallala Aquifer, the Southern Ogallala Aquifer is also dominated by irrigation pumping, which accounts for approximately 95 percent or more of total groundwater withdrawal (Blandford and others, 2003). This part of the Ogallala Aquifer was originally modeled by Blandford and others (2003) as part of the Southern Ogallala Aquifer groundwater availability model and later updated in the Edwards-Trinity (High Plains) Aquifer groundwater availability model (Blandford and others 2008). Historical pumping for the original model (Blandford and others, 2003) extended from 1940 through 2000.

Irrigation pumping estimates for the original Southern Ogallala Aquifer groundwater availability model were based on a study conducted by Amosson and others (2003). That study estimated pumping for irrigated agriculture for the years 1982, 1983, 1984, 1987, 1992, 1993, 1994, and 1997 based on a water balance approach. Their procedure involved using weather data, crop types, acreages, irrigation technologies, and other relevant data from the region. Observed water levels were used to validate the crop demand estimates where available. Pre-1980 irrigation pumping estimates were based on irrigation surveys provided by the TWDB for both Southern Ogallala Aquifer groundwater availability models.

Blandford and others (2003) assumed that irrigation return flows contributed a significant amount of recharge to the aquifer. They accounted for this by reducing the amount of pumping assigned in their model. The return flows estimated by Blandford and others (2003) are given in Table 4.7.2. Using these estimates, they reduced pumping for the different decadal periods by a proportionate amount. As discussed in Section 4.4, new analyses of recharge and irrigation return flow in the Ogallala Aquifer indicate that irrigation return flow has not occurred in many of the counties where the "high percentage return flow" assumption was made (for example, Hale, Floyd, Parmer, and Castro counties). Additionally, many high producing counties with evidence of return flow (for example, Lamb, and Lubbock counties), show that return flow did not reach the water table until the 1990s, too late to have made any difference during the time of proposed peak production. Therefore, the pumping estimates presented here do not account for return flow. In Section 4.7.2.7, a discussion is provided as to whether these high demands, which required the percentage adjustment by Blandford and others (2008), are plausible given the estimated change in storage during that time period.

Blandford and others (2003) provide pumping estimates for the original Southern Ogallala Aquifer groundwater availability model, without accounting for return flows, in Appendix C of their report. Blandford and others (2008) updated these pumping estimates by modifying irrigation pumping for individual districts to assist in model calibration. Those modifications are described in Appendix D of their report. The post-calibration pumping estimates from Blandford and others (2008) were not considered applicable to the current modeling study, especially as return flows are handled differently in this study. Therefore, the pre-calibration pumping estimates without the effect of return flows as given in Appendix C of Blandford and others (2003), were used as the basis for historical pumping in the Southern Ogallala Aquifer for the current model. That pumping is consistent with the Amosson and others (2003) irrigation demands for 1982, 1983, 1984, 1987, 1992, 1993, 1994, and 1997 and the irrigation survey data provided by the TWDB (1991) for groundwater withdrawals for the years 1958, 1964, 1969, 1974, and 1979.

Amosson and others (2003) also estimated irrigation demands for the years 1952 through 1956 (consistent with the drought of record for much of the southern High Plains). Those estimates were based on climatic conditions in the 1950s but assumed the same crop acreage and irrigation practices as in 1997. Use of these 1950s estimates from Amosson and others (2003) was investigated when evaluating approaches to updating historical irrigation pumping for the Southern Ogallala Aquifer. The 1950s estimates from Amosson and others (2003) provide useful information on potential trends in irrigation water use in the 1950s. However, direct use of those data was not considered because they were not developed using crop acreages and irrigation practices applicable to the 1950s. During the numerical modeling phase, these estimates may be used to guide calibration efforts.

For the current model of the High Plains Aquifer System, 1958 pumping from Blandford and others (2003) was interpolated back to zero pumping in 1930. The year 1958 was chosen as this was the earliest year with reliable irrigation pumping estimate from the irrigation survey (TWDB, 1991). For most counties, the interpolation followed the trend in irrigated acreage for the southern High Plains provided by Luckey and others (1986) and shown in Table 4.7.3. The periods 1930 through 1939, 1940 through 1944, 1945 through 1949, 1950 through 1954, and 1954 through 1959 were on average 0, 8, 33, 73, and 100 percent, respectively, of the 1958 estimated pumping number. For several counties, records of early (pre-1940) irrigation districts suggest the possibility that pumping may have been significant in these counties in early years. These included Bailey, Briscoe, Castro, Crosby, Deaf Smith, Floyd, Hale, Hockley, Lamb, Lubbock, Parmer, and Swisher counties. For these counties, pumping was interpolated linearly between 1930 and 1958.

For the intermediate years not included in the Amosson and others (2003) data, Blandford and others (2003) estimated irrigation pumping through linear interpolation. The TWDB water use survey data provide information on irrigation pumping trends in these intermediate years as well as beyond 1997. Therefore, the Amosson and others (2003) data were merged with the TWDB irrigation pumping trends using a scaling methodology to interpolate between the values for years given in Amosson and others (2003). This was done as follows:

- For all years with an Amosson and others (2003) estimate, pumping was maintained at the value given by Amosson and others (2003).
- For the intermediate years, the ratio between the average of Amosson and others (2003) pumping estimates for the beginning and ending of the period and the average TWDB water use survey pumping for the period was taken. For example, for the period between 1987 and 1992 the ratio (r) was calculated as:

$$r = \frac{\left(Q_{Amosson,1987} + Q_{Amosson,1992}\right)/2}{\left(\sum_{y=1987}^{y=1992} Q_{TWDB,y}\right)/5} \tag{4.7.2}$$

where $Q_{\text{Amosson, 1987}}$ and $Q_{\text{Amosson, 1992}}$ are the Amosson and others (2003) estimates for the years 1987 and 1992, and $Q_{\text{TWDB, y}}$ is the TWDB estimates for years from 1987 to 1992.

- The pumping estimates for the intermediate years were calculated as the product of the TWDB pumping for the years and the calculated ratio.
- For years beyond 1997, the ratio was kept the same as for the 1994 to 1997 period.
- The TWDB values used in the calculation for the years 1980 through 1999 are based on the TWDB water use survey data from 1980 to 2008 (TWDB, 2013b) and the values used

for the years 2000 to 2011 are based on the TWDB water use survey data from 2000 to 2012 (TWDB, 2013c). Due to incomplete data for 2012 in the TWDB water use survey, pumping for 2012 was kept at the same level as that for 2011.

The final pumping estimates developed for the High Plains Aquifer System groundwater availability model are consistent with the pre-calibrated irrigation pumping estimates from the Southern Ogallala Aquifer groundwater availability model (Blandford and others, 2003) without accounting for return flows for the period between 1958 to 1984, as well as the years 1987, 1992, 1993, 1994, and 1997. Pre-1958 pumping either follows trends based on Luckey and others (1986) or were interpolated linearly between 1930 and 1958. For intermediate years between the Amosson and others (2003) estimates, as well as for the period from 1997 to 2012, the pumping estimates follow the trends in the TWDB water use survey data but the magnitudes are scaled to be commensurate with the Amosson and others (2003) estimates for the period.

Figures 4.7.9 through 4.7.18 show the developed irrigation pumping estimates for select counties along with the different data sources used to develop the estimates (that is, pre-calibrated/no return flow irrigation pumping from the original Southern Ogallala Aquifer groundwater availability model (Blandford and others, 2003), irrigation survey data (TWDB, 1991), Amosson and others (2003) estimates, and the TWDB water use survey data).

Counties such as Deaf Smith, Hale, Lubbock, Parmer, and Swisher counties are among those with early irrigation districts and, thus, follow a linear trend between 1930 and 1958. Counties such as Gaines, Midland, Randall, Terry, and Yoakum counties did not have early irrigation districts and, thus, follow the trend from Luckey and others (1986), which rises slowly beginning in 1930 and ramps up rapidly in the 1950s. Current estimates are consistent with the irrigation survey (TWDB, 1991) between 1958 and 1979 and with the pre-calibrated pumping estimates for the years 1958 through 1984 from Blandford and others (2003). The only exception is for Yoakum and Terry counties where Blandford and others (2003) reduced pre-1980 pumping. For the sake of consistency, the estimates for this model maintain consistency with the estimates in the TWDB irrigation survey (TWDB, 1991) for these years. All estimates are consistent with the Amosson and others (2003) estimates for the years 1982, 1983, 1984, 1987, 1992, 1993, 1994, and 1997. Trends in the intermediate years (1985, 1986, 1988, 1989, 1990, 1991, 1995, 1996, 1998, and beyond) are consistent with the TWDB water use surveys data, while maintaining the same magnitude as the Amosson and others (2003) estimates.

For most counties, the 1950s estimates from Amosson and others (2003) (which were not used directly in the estimation process) are fairly consistent with the interpolated levels in the 1950s (see Figures 4.7.9 through 4.7.18). Gaines, Parmer, Terry, and Yoakum counties are some of the counties where developed pumping estimates are higher or lower that the 1950 Amosson and others (2003) estimates.

Non-irrigation pumping in both the original and updated Southern Ogallala Aquifer groundwater availability models was based on TWDB water use surveys data for respective non-irrigation categories. Consistent with this approach, the current non-irrigation pumping estimates were taken from the water use survey data for the years 1980 to 2011. Pre-1980 non-irrigation pumping was taken from the previous Southern Ogallala Aquifer groundwater availability models (Blandford and others, 2003, 2008). Due to incomplete data for the year 2012 in the TWDB water use survey data, pumping in 2012 was assumed to be the same as in 2011.

Pumping for all New Mexico counties in the Southern Ogallala Aquifer (Curry, Lea, Quay, and Roosevelt counties) was taken from the previous groundwater availability models without any modifications. Pumping was linearly extracted back to 1930 (assuming zero for that year) and kept constant at 1997 levels for the period 1998 through 2012.

Figure 4.7.19 shows the estimated pumping by category developed for the Southern Ogallala Aquifer for the Texas portion of the aquifer. Figure 4.7.20 shows the total pumping for the Southern Ogallala Aquifer outside of Texas.

4.7.2.3 Dockum Group Pumping

Historical pumping estimates for the years 1950 through 1997 are available from the Dockum Aquifer groundwater availability model (Ewing and others, 2008). Ewing and others (2008) used estimates provided by the TWDB in a pumpage geodatabase for historical pumping in all Texas counties from 1980 through 1997. The geodatabase included estimates for municipal, manufacturing, power generation, mining, livestock, and irrigation. Rural domestic pumping, which consists primarily of unreported domestic water use, was estimated based on population density data provided by the TWDB. Ewing and others (2008) estimated pre-1980 pumping by interpolating 1980 pumping to 1950 assuming a regional trend based on total irrigation water use reported in the TWDB irrigation surveys for the years 1958, 1964, 1969, 1974, and 1979 (TWDB, 1981).

Ewing and others (2008) based pumping in New Mexico counties on countywide pumping estimates from the New Mexico Office of the State Engineer (Sorensen, 1977, 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 5 year increments.

Historical pumping estimates for Dockum Group are also available from the water use surveys obtained from the TWDB for the period 1980 to 2008 and 2000 to 2012 (TWDB, 2013b,c).

Pumping from the Dockum Aquifer groundwater availability model (Ewing and others, 2008) and the TWDB water use surveys were combined in estimating pumping for the current model. Pumping from the Dockum Aquifer groundwater availability model was taken for the years 1980 to 1997. Consistent with the Dockum Aquifer groundwater availability model, pre-1980 pumping was interpolated back to 1930 using ratios based on regional irrigation pumping trends from the TWDB irrigation survey for the years 1958, 1958, 1964, 1969, 1974, and 1979 (TWDB, 1981). Since the TWDB irrigation estimates only go back to 1958, 1930 pumping was assumed to be 10 percent of 1958 levels. Table 4.7.4 shows the percentage of 1980 pumping used for pre-1980 estimates. Intermediate years not shown in the table were interpolated linearly.

Post-1997 pumping for all categories was estimated based on the 2000 to 2012 TWDB water use survey (TWDB, 2013c). Pumping for 1998 and 1999 was kept constant at 1997 levels. In some instances, the Dockum Aquifer groundwater availability model has pumping for counties or categories that were not found in the latest TWDB water use survey data. In such instances, 1997 levels from Ewing and others (2008) were kept constant until 2012.

Figure 4.7.21 shows the estimated pumping by category developed for the Dockum Group for the Texas portion of the aquifer. Figure 4.7.22 shows the total pumping for the Dockum Group in New Mexico.

4.7.2.4 Edwards-Trinity (High Plains) Aquifer Pumping

Blandford and others (2008) estimated historical pumping in the Edwards-Trinity (High Plains) Aquifer based on the TWDB pumpage geodatabase. The TWDB water use surveys (TWDB, 2013b,c) contain more updated estimates for pumping. Therefore, the pumping estimates from Blandford and others (2008) were updated using the TWDB water use survey data (TWDB, 2013b,c). Pumping for 1930 to 1980 was taken directly from the Edwards-Trinity (High Plains) Aquifer groundwater availability model. Since only total pumping is available from that groundwater availability model, the pumping was split between categories (irrigation and livestock were the only categories mentioned by Blandford and others, 2008) using the 1980 ratios from the TWDB water use survey data. Pumping for 1980 to 1999 was taken from the TWDB water use survey data for the years 1980 to 2008 (TWDB, 2013b). Pumping for the years 2000 to 2012 was taken from the TWDB water use survey data for the years 2000 to 2012 (TWDB, 2013c). The original groundwater availability model has only irrigation and livestock pumping, however, the water use surveys report pumping for several other categories (for example, municipal, mining, and manufacturing).

Pumping in Gaines and Dawson counties was considered as a special case by Blandford and others (2008). In these counties, the Cretaceous-age shale separating the Ogallala Aquifer from the Edwards-Trinity (High Plains) Aquifer is relatively thin (or non-existent). Therefore, multiple wells are completed into both aquifers. Blandford and others (2008) simulated these wells used the Multi-Node Well package in MODFLOW, which only requires total pumping for wells screened in two or more aquifers, splitting the pumping based on saturated thickness and properties for the respective aquifers. Thus, the pumping estimates by Blandford and others (2008) for the Edwards-Trinity (High Plains) Aquifer in Gaines and Dawson counties are model dependent and could not be directly used for the current model. Therefore, pumping in these two counties for the Edwards-Trinity (High Plains) Aquifer was estimated as follows:

- For irrigation pumping, the average ratio of Edwards-Trinity (High Plains) Aquifer pumping to Ogallala Aquifer pumping in 1984 and 1985, using data from the TWDB water use survey, was calculated and applied to the estimated Ogallala Aquifer pumping from 1930 through 1980.
- For other pumping categories, the average ratio of each category to irrigation pumping in 1984 and 1985 in the TWDB water use survey data was calculated and applied to the estimated irrigation pumping to obtain pre-1980 pumping
- Post-1980 pumping for all categories was taken from the TWDB water use survey data.

For some counties, pumping for some years was missing or reported as zero in the TWDB water use survey data. In these cases, linear interpolation was used to estimate pumping for the missing years or the years with zero pumping. For example, the irrigation pumping in the TWDB water use survey data for Dawson, Gaines, Lynn, and Terry counties was zero in the years 1994 through 1999 and were linearly interpolated using the non-zero data in 1993 and 2000.

Figure 4.7.23 shows the estimated pumping by category developed for the Edwards-Trinity (High Plains) Aquifer. Blandford and others (2008) investigated pumping from the Edwards-Trinity (High Plains) Aquifer in New Mexico and determined that it was small and could be neglected in the model. The same assumption is made for the High Plains Aquifer System groundwater availability model.

4.7.2.5 Rita Blanca Aquifer Pumping

Dallam County is the only county with any pumping from the Rita Blanca Aquifer. The TWDB water use surveys are the only available data source for pumping in the Rita Blanca Aquifer. Though the North Plains Groundwater Conservation District does provide metered well data in Dallam County, it does not explicitly differentiate between Rita Blanca Aquifer and Ogallala Aquifer wells and so, no metered pumping can be specifically assigned to the Rita Blanca Aquifer.

Rita Blanca Aquifer pumping estimates for the years 1980 through 2012 were based on the TWDB water use survey data. Pre-1980 pumping in the Rita Blanca Aquifer was estimated according to the ratio of 1980 pumping in the Rita Blanca Aquifer to 1980 pumping in the Ogallala Aquifer in Dallam County, using pre-1980 Northern Ogallala Aquifer pumping estimates (from Section 4.7.2.1). The TWDB water use survey data shows a sharp increase (approximately one order of magnitude) in pumping from the Rita Blanca Aquifer in 2004 and subsequent years. This is due to the fact that the TWDB changed the contribution of pumping between the Rita Blanca and Ogallala aquifers in 2004 and subsequent years. However, the 2003 ratio of pumping in the Rita Blanca Aquifer to pumping in the Ogallala Aquifer in Dallam County is considered more reasonable. Therefore, post-2003 pumping in the Rita Blanca Aquifer is estimated according to the 2003 ratio, using Ogallala Aquifer pumping estimates (from Section 4.7.2.1) for the years 2004 through 2012.

Figure 4.7.24 shows the estimated pumping by category developed for the Rita Blanca Aquifer. Evidence of production in the Rita Blanca Aquifer is seen in hydrographs showing downward trends in Union County. Because no pumping estimates were available from previous models, pumping in the Rita Blanca Aquifer for Union County was estimated during calibration of the numerical model (Deeds and Jigmond, 2015).

4.7.2.6 Summary of Pumping

Historical pumping for the aquifers of the High Plains Aquifer System region were estimated based on multiple sources of information. Given the inherent uncertainty in the estimation process at each stage, the most reliable and plausible data source was chosen. To summarize:

- For the Northern Ogallala Aquifer, pumping was based on the existing updated Northern Ogallala Aquifer groundwater availability model (INTERA, Inc. and Dutton, 2010) from 1950 to 2008. Pumping was linearly extrapolated back to 1930 from 1950 levels. Where available, North Plains Groundwater Conservation District metering data was used to estimate irrigation pumping from 2008 to 2012. For counties without metering data or for counties only partially within the North Plains Groundwater Conservation District, the TWDB water use survey data were used to estimate post-2008 irrigation pumping. For all counties and all other pumping categories, the TWDB water use survey data were used to estimate post-1980 pumping.

- For the Southern Ogallala Aquifer, irrigation pumping between 1958 and 1980 was based on the original Southern Ogallala Aquifer groundwater availability model (Blandford and others, 2003) and TWDB irrigation surveys (TWDB, 1991). Pumping estimates taken from Blandford and others (2003) were corrected for their assumption of irrigation return flows. Irrigation pumping after 1980 was based on crop water demand estimates made by Amosson and others (2003) and the TWDB water use survey data, which were used to fill the gaps between years with Amosson and other (2003) estimates. Pumping in 1958 was extrapolated to 1930 based on early estimates of pumping from Luckey and others (1986) and the existence of early irrigation districts. Non-irrigation pumping was based on the Ogallala Aquifer pumping in the Edwards-Trinity (High Plains) groundwater availability model (Blandford and others, 2008). Post-2008 non-irrigation pumping was based on the TWDB water use survey data.

- Pumping for the Dockum Group was taken from the Dockum Aquifer groundwater availability model (Ewing and others, 2008) and the TWDB water use surveys. Pre-1950 pumping was based on trends in regional irrigation pumping taken from the TWDB irrigation survey (TWDB, 1981).
- Pumping in the Edwards-Trinity (High Plains) Aquifer was taken as a combination of model pumping from Blandford and others (2008) and pumping estimates from the TWDB water use surveys.
- Pumping in the Rita Blanca Aquifer was taken from the TWDB water use surveys.
- In all cases, corrections and adjustments were made when pumping estimates did not seem reasonable or gaps existed in the data.

Figures 4.7.25 through 4.7.33 show county-wide pumping for the Ogallala, Dockum, Edwards-Trinity (High Plains), and Rita Blanca aquifers for the years 1950, 1980, and 2010. Tables 4.7.5 through 4.7.27 show pumping estimates by category for all Texas counties (grouped by Groundwater Conservation District, where applicable) for each of the four aquifers every decade from 1940 to 1990 and then every 5 years from 1990 to 2010. Tables of power and rural domestic pumping estimates for the Edwards-Trinity (High Plains) Aquifer are not included because there is no pumping from the aquifer for those two categories. Tables 4.7.28 through 4.7.30 show non-Texas pumping for the Ogallala, Rita Blanca, and Dockum aquifers for the same years. The pumping numbers shown in Tables 4.7.5 through 4.7.30 are rounded to the nearest acre-foot. If a county did not have any pumping from an aquifer in any year for a water use category, that county is not included in the table for that aquifer and water use category. In some tables, the pumping value given for all years for a county is zero, indicating that pumping for that aquifer and water use category is estimated to be zero in that county for the years shown in the table. These counties are included in the table because, even though pumping is estimated to be zero for the years shown in the table, pumping from that aquifer and that water use category is non-zero in the county for at least one year from 1930 through 2012.

4.7.2.7 Comparison of Demand-Based Pumping Estimates to Estimated Change in Storage

The previous sections present the development of pumping estimates for the High Plains Aquifer System groundwater availability model based on historical estimates of pumping from a number of sources. In this section, those developed pumping estimates are referred to as demand-based estimates of pumping. For an unconfined aquifer, historical estimates of pumping can also be developed through calculation of the change in aquifer storage volume with time. This section presents calculations of estimated pumping based on changes in aquifer storage and compares those estimates to the demand-based estimates presented in the previous sections. The purpose for this comparison was to evaluate the consistency between historical demand-based estimates of pumping with observed water-level declines in the Ogallala Aquifer. This comparison is important because the primary use of groundwater from the Ogallala Aquifer is for irrigation purposes, and estimating historical irrigation pumping using a demand-based approach is difficult and results in large uncertainty. The following text first introduces and describes the approach for estimating pumping based on changes in aquifer storage and then represents and discusses the comparison between the pumping estimates from both approaches.

4.7.2.7.1 Introduction and Description of Approach

Because the Ogallala Aquifer is primarily unconfined, declines in water levels correspond to drainage of water from aquifer storage. Estimating the change in storage requires only the change in water level and the specific yield of the aquifer, that is:

$$\Delta S = \Delta h \cdot S_y \qquad (4.7.3)$$

where ΔS is the change in storage per unit area of aquifer, Δh is the change in head (water level), and S_y is the average specific yield for that area of the aquifer.

Equation 4.7.3 was used to estimate the change in storage in the Ogallala Aquifer for comparison to demand-based estimates of pumping. A direct comparison requires the assumption that sources of input to the aquifer are small compared to production, including recharge and any cross-formational flow from underlying formations. This assumption will be further addressed later in this section.

In performing these estimates, three lessons were immediately learned:

1. The estimates of change in storage are very sensitive to data control, both in time and space. The method will fail in areas that lack dense monitoring networks.

2. Even in data-dense regions, significant drawdown is required in order for the method to work consistently. The method will fail in areas that have small to medium historical production totals.
3. Long-time integration is often required to achieve #2. The method will not generally work year-to-year.

With these lessons in mind, the analysis was performed at several different time scales and with different data control. First, the decline estimate shown in Figure 4.3.30 was used to calculate a change in storage by county over the historical period. This estimate is considered to be most representative of the change in storage between 1950 and the present, since few data were available prior to 1950. Second, the difference between the 1950 water-level surface (Figure 4.3.27), the 1980 water-level surface (Figure 4.3.28), and the 2010 water-level surface (Figure 4.3.29) were used to estimate 30-year changes in storage (that is, 1950 to 1980 and 1980 to 2010).

Note that the decline surface shown in Figure 4.3.30 was not produced by subtracting the 2010 water level surface from the 1950 water-level surface, but rather was created by analyzing wells with long-term water-level records. Figure 4.3.30 is expected to be more accurate, where decline data are available, than taking the simple difference between two estimated water-level surfaces. However, the decline shown in Figure 4.3.30 is also expected to be biased somewhat low (less decline) in areas where long-term decline data are not available. Thus, the 1950 to 2010 water-level difference was also analyzed to help provide a second estimate.

The estimates discussed above are based on water level and decline surfaces that were produced using careful data analysis, supplemental data where water-level measurements were not available, and professional judgment. This type of approach could not be used for making surfaces at very short time intervals (that is, every 3 to 5 years) for the historical period within the resources of this study. Therefore, an automated tool that could quickly produce estimates of aquifer storage for any given county and year was developed. This automated tool has the advantage of speed, but the disadvantage of not having an analyst’s eye on every step of the process. The tool was developed using ArcMap as a front-end, and utilizes ArcObjects libraries in the background. The workflow is as follows:

1. The user points the tool to the TWDB groundwater database, accessing a view (query) that screens water-level measurements by county, aquifer, and measurement code.
2. The user indicates which months of the year are considered "winter months", and a range of years to process.
3. The tool queries the database, splits the water-level measurements out by year, and creates point coverages in ArcMap containing measurements by year. Some additional processing occurs, such as querying the 10-meter digital elevation model at each well location to ensure that the land surface datum shown in the database is reasonable.
4. The tool then interpolates the water levels by year, and does a basic volume calculation using the surface of the base of the Ogallala Aquifer and a coverage of specific yield. For the application presented here, combined estimates of specific yield from the previous northern and Southern Ogallala Aquifer groundwater availability models were used.
5. Finally, the tool uses coverages of county and groundwater conservation district boundaries to estimate volumes by county and district for the specified years.

The results from this tool were tested by comparing estimates to those produced by Mullican (2012) in a study for the High Plains Water District that estimated the change in volume in storage for the period 2003 to 2012. The comparison is shown in Figure 4.7.34. Note that partial counties Deaf Smith and Randall are not shown on the figure, since the volume tool does not clip single counties to the district boundary. In general, the results are quite comparable, given the automated nature of the volume tool compared to the expert-aided approach in the Mullican (2012) study.

4.7.2.7.2 Results and Discussion

A basic comparison was made between the historical demand-based pumping estimates presented in Sections 4.7.2.1 and 4.7.2.2 and the estimates of change in aquifer storage volume. Figure 4.7.35 shows the results of the 60-year (1950 to 2010) comparison between the demand-based pumping estimates, the storage change estimate based on the decline analysis (Figure 4.3.30), and the change in water-level surfaces from 1950 to 2010 (Figures 4.3.27 and 4.3.29), as discussed above. The top seven producing counties all show demand-based estimates that exceed the estimates of change in storage, often by double the amount. The two change in storage estimates are not always consistent, with the decline-based estimate typically producing the lower value.

Figure 4.7.36 shows, for Hale County, a comparison of the demand-based estimates of pumping to the storage change rate estimates over various integration periods. The 60-year changes (same as Figure 4.7.35) are shown, along with 30-year (1950 to 1980 and 1980 to 2010) changes, which are based on the water-level and decline estimates (Figures 4.3.27 through 4.3.30). In addition, decadal estimates were made using the volume tool. The well counts for each year where the volume tool calculated a value of storage are also shown on the plot. The result from the volume tool is shown only for those years where more than 50 wells with measurements were available. The sensitivity of the estimate (or the variability in the estimate) to the number of wells was reviewed to arrive at this number. The rates of storage change shown in Figure 4.7.36 were calculated by dividing the estimated change in storage by the duration of the integration period (that is, 60, 30, or 10 years). The rate from 1930 to 1950 was assumed to increase linearly from zero in 1930 to the 1950 estimate.

Figure 4.7.36 shows a large difference between the demand-based pumping estimate and the estimate based on storage change, especially in the period from 1950 to 1980. While the decadal estimate follows the same basic shape as the demand-based estimate, it is significantly lower over the 1950 to 1980 period. The previous Southern Ogallala Aquifer groundwater availability model (Blandford and others, 2008) dealt with this discrepancy by proposing that a large percentage of the irrigation water (55 to 40 percent over that 30-year period) was returned directly to the water table in the same year that it was produced (see Table 4.7.2). However, the recharge analysis described in Section 4.4 indicates that little if any irrigation return flow has occurred in Hale County, since there are only limited elevated nitrates at the water table. If 500,000 to 700,000 acre-feet per year of irrigation water (corresponding to a flux rate of 9.5 to 13 inches per year) were returned to the water table on an annual basis over two decades, significant nitrates at the water table would be expected. Based on the results from a borehole in Hale County under irrigated conditions, Scanlon and others (2010a) report that the chloride and nitrate profiles in the vadose zone indicate that irrigation water has reached less than 10 feet below ground surface (that is, irrigation return flow has not reached the water table.)

With a lack of evidence for return flow, the proposed reason for the discrepancy between the rate of storage change and the demand-based pumping estimate is due to overestimation of groundwater production in the period before 1980. Figure 4.7.37 shows estimates of irrigated and total farm acreage in Hale County for 1935 (no estimate of irrigated acreage is available that year), 1954, 1974, 1997, and 2007 based on a USDA agricultural census data (U.S. Department of Agriculture, 1935, 1954, 1974, 1997, 2007). The estimate of irrigated acreage does not increase from 1954 to 1974. While data is not available from the census for the intervening years, the overall trend does not favor the extreme peaking that occurs in the demand-based pumping curve.

Because Hale County was an early area of declining water levels, it is not expected that the change in storage would exactly match production, since water would move laterally in from adjacent counties where water-level elevations are higher. However, the experience of Blandford and others (2008) and the storage change analysis would indicate that the demand-based pumping estimate should be revised downward in the peak years of 1960 to 1975. The last 30 years should be able to remain relatively unmodified from the original estimate.

Figures 4.7.38 and 4.7.39 show the comparison for Floyd and Parmer counties, respectively, which are examples of high production counties where the rate of storage change and the demand-based pumping curve are more closely matched. In Floyd County, where the various time integrated averages of storage change fall above and below the demand curve through time, the demand-based pumping curve looks plausible compared to the storage change. With the exception of a peak in the late 1950s, the demand curve in Parmer County looks plausible compared to the storage change.

Figures 4.7.40 through 4.7.43 show more example comparisons for counties that are more like Hale County, where the peak demand-based pumping estimate in the 1960s and 1970s seems to greatly exceed the rate of storage change. Although Lamb County shows evidence of some irrigation return flow starting in the 1990s, (see Section 4.4) this would not account for the large difference in the two estimates for the period 1955 through 1970 (see Figure 4.7.40). Castro, Swisher, and Bailey counties are similar, with large differences in approximately the same time period, and the curves from the demand and storage-based estimates coming together in the 1990s.

The implications of this analysis are that in the historical period, prior to around 1980, the large peak demands reported in the irrigation surveys will likely be adjusted downward for the model based on the estimates of the rate of storage change during that period. The numerical model will help inform the amount of influence from adjoining counties and, thus, the amount of downward adjustment that must occur.

Table 4.7.1 Estimates of vegetation coefficient and rooting depth for several vegetation types in the study area (from Scanlon and others, 2005a).

Vegetation Type	Vegetation Coefficient	Rooting Depth (feet)
Shrubland	0.44	14
Grassland	0.53	2.5
Conifer	0.34	10
Cropland	0.6*	7
Unknown	0.5	

*estimated from analogs

Table 4.7.2 Return flow estimates by Blandford and others (2003) for Texas and New Mexico.

Period	Return Flow[1] (percent)	
	Texas	New Mexico
1940 – 1960	55	55
1961 – 1965	50	50
1966 – 1970	45	50
1971 – 1975	40	50
1976 – 1980	35	40
1981 – 1985	25	40
1986 – 1990	20	35
1991 – 1995	15	25
1996 – 2000	10	20

(1) Assumed to occur in the same year as pumping.

Table 4.7.3 Estimated total irrigation pumping in the Southern High Plains Aquifer from Luckey and others (1986) and calculated percentage of 1955 to 1959 pumping.

Period	Total Irrigation Pumping (million acre-feet per year)	Percentage of 1955 to 1959
1930 - 1939	0.0	0
1940 - 1944	0.5	8
1945 - 1949	2.1	33
1950 - 1954	4.6	73
1955 - 1959	6.3	100

Table 4.7.4 Percentage of 1980 pumping used to extrapolate 1980 pumping to 1930 for the Dockum Group.

Year	Percent of 1980 Pumping
1930	2
1950	15
1960	30
1970	84
1975	105
1976	105
1977	104
1978	104
1979	104
1980	100

Table 4.7.5 Irrigation pumping by county for the Ogallala Aquifer.

County	Pumping (acre-feet per year)									
	1940	1950	1960	1970	1980	1990	1995	2000	2005	2010
Garza County Underground Water Conservation District										
Garza County	1,000	8,550	16,005	16,321	9,939	4,737	9,618	17,624	17,157	10,707
Gateway Groundwater Conservation District										
Motley County	11	96	206	491	338	466	509	207	192	137
Glasscock Groundwater Conservation District										
Glasscock County	62	529	1,274	3,069	3,796	3,191	6,870	3,231	4,031	5,209
Hemphill County Underground Water Conservation District										
Hemphill County	50	100	249	724	445	0	2,062	3,779	2,802	4,413
High Plains Underground Water Conservation District										
Bailey County	91,745	183,491	289,427	223,081	249,358	150,545	109,753	96,696	34,351	32,482
Castro County	126,598	253,196	447,750	548,139	432,545	386,429	200,723	233,765	135,994	163,445
Cochran County	7,252	62,007	114,278	69,362	62,883	45,952	76,006	76,854	45,501	42,586
Crosby County	49,696	99,391	155,581	219,207	70,193	140,575	138,691	107,627	70,383	75,667
Deaf Smith County	145,462	290,924	427,910	488,180	310,276	218,014	188,776	260,777	99,298	123,653
Floyd County	65,334	130,667	204,738	302,249	222,260	190,861	187,230	165,037	80,924	71,321
Hale County	205,626	411,251	752,373	709,405	393,384	433,094	317,711	264,221	174,469	157,754
Hockley County	58,934	117,867	242,670	240,857	109,941	141,593	167,258	172,581	89,391	97,885
Lamb County	141,422	282,844	491,739	393,874	365,426	398,156	286,408	286,108	182,791	138,372
Lubbock County	104,023	208,046	265,275	207,562	101,133	281,441	224,155	192,891	90,037	86,893
Lynn County	5,300	45,316	79,356	33,258	38,143	59,464	61,448	108,380	58,323	51,101
Parmer County	276,406	552,811	707,297	515,775	545,253	391,918	266,196	257,241	180,459	158,826
Randall County	9,398	49,183	106,640	86,956	56,593	37,435	48,500	48,603	57,784	22,994
Swisher County	94,652	189,304	333,892	390,685	208,865	151,529	154,732	138,242	133,121	90,948
District Total	*1,381,847*	*2,876,299*	*4,618,928*	*4,428,592*	*3,166,251*	*3,027,008*	*2,427,587*	*2,409,022*	*1,432,826*	*1,313,928*
Llano Estacado Underground Water Conservation District										
Gaines County	10,231	87,476	197,339	179,673	416,931	315,632	310,005	262,781	249,988	202,029
Mesa Underground Water Conservation District										
Dawson County	7,008	59,916	119,672	40,003	20,920	31,744	48,530	106,790	74,611	57,755
North Plains Groundwater Conservation District										
Dallam County	19,469	38,938	86,005	142,477	239,149	354,383	295,179	308,143	331,694	330,452
Hansford County	10,256	20,512	50,619	205,214	176,758	100,225	126,716	138,217	111,281	130,000
Hartley County	6,748	13,496	33,740	152,787	252,511	197,536	162,948	289,008	294,622	340,554
Hutchinson County	7,732	15,465	38,662	61,638	81,865	38,208	30,499	63,112	44,909	39,548

Table 4.7.5, continued

County	**Pumping (acre-feet per year)**									
	1940	**1950**	**1960**	**1970**	**1980**	**1990**	**1995**	**2000**	**2005**	**2010**
North Plains Groundwater Conservation District, continued										
Lipscomb County	636	1,272	3,179	5,376	20,883	12,363	23,641	24,897	28,695	34,200
Moore County	17,824	35,647	88,531	213,301	236,385	186,717	160,740	165,940	143,991	161,473
Ochiltree County	4,031	8,061	19,860	92,239	107,819	55,462	41,108	104,220	66,191	61,800
Sherman County	17,537	35,073	87,683	358,352	321,687	235,590	176,483	294,265	231,996	250,700
District Total	*84,232*	*168,463*	*408,278*	*1,231,384*	*1,437,056*	*1,180,483*	*1,017,314*	*1,387,802*	*1,253,379*	*1,348,726*
Panhandle Groundwater Conservation District										
Armstrong County	3,515	7,124	17,451	13,132	10,403	5,675	4,061	8,436	6,413	3,940
Carson County	13,109	26,218	65,546	98,232	111,736	80,925	71,722	106,015	83,780	59,823
Donley County	1,004	2,008	4,514	11,567	11,533	21,097	14,000	25,170	27,700	24,981
Gray County	1,549	3,098	7,698	18,286	11,215	8,780	12,535	24,186	22,707	22,610
Potter County	1,989	8,344	19,707	28,155	23,362	8,339	18,736	4,164	4,933	1,904
Roberts County	737	1,475	3,677	8,221	6,132	3,696	4,679	1,548	6,816	7,362
Wheeler County	377	753	1,613	2,876	4,288	192	2,583	7,374	9,987	9,624
District Total	*22,280*	*49,020*	*120,205*	*180,468*	*178,669*	*128,704*	*128,315*	*176,893*	*162,336*	*130,243*
Permian Basin Underground Water Conservation District										
Howard County	102	874	1,744	1,604	4,450	5,398	2,318	5,711	3,342	7,940
Martin County	2,712	23,185	42,338	29,315	14,365	11,466	11,509	14,606	16,186	36,236
District Total	*2,814*	*24,059*	*44,083*	*30,919*	*18,815*	*16,864*	*13,827*	*20,317*	*19,528*	*44,177*
Sandy Land Underground Water Conservation District										
Yoakum County	4,527	38,709	65,882	87,166	120,293	73,717	103,941	113,541	114,156	178,219
South Plains UWC										
Terry County	9,039	77,284	147,162	75,560	79,433	159,874	162,875	213,480	145,146	144,437
No Groundwater Conservation District										
Borden County	54	461	775	698	565	1,151	1,477	1,877	2,614	1,614
Briscoe County	8,318	16,636	37,796	58,479	51,349	31,021	23,999	30,355	47,142	33,324
Dickens County	350	2,994	5,500	8,295	3,320	2,265	2,232	3,984	4,751	3,796
Ector County	0	0	1,904	3,688	3,503	1,505	1,617	251	126	88
Midland County	497	4,252	6,458	10,270	7,403	6,137	6,585	2,789	2,147	1,704
Oldham County	1,607	13,743	28,930	30,405	21,286	7,958	15,151	7,067	14,986	9,347
Andrews County	113	968	6,597	2,014	11,890	8,874	11,139	13,270	22,120	16,097
Irrigation Total	**1,534,040**	**3,429,553**	**5,827,243**	**6,388,218**	**5,552,203**	**5,001,331**	**4,293,654**	**4,775,059**	**3,570,038**	**3,505,951**

Table 4.7.6 Municipal pumping by county for the Ogallala Aquifer.

County	Pumping (acre-feet per year)									
	1940	**1950**	**1960**	**1970**	**1980**	**1990**	**1995**	**2000**	**2005**	**2010**
Garza County Underground Water Conservation District										
Garza County	0	0	0	0	0	125	112	5	2	94
Gateway Groundwater Conservation District										
Motley County	0	0	0	0	0	3	2	0	0	0
Glasscock Groundwater Conservation District										
Glasscock County	0	0	0	0	0	2	2	0	0	18
Hemphill County Underground Water Conservation District										
Hemphill County	155	310	275	712	1,377	575	465	463	536	731
High Plains Underground Water Conservation District										
Bailey County	1,205	1,477	3,434	2,419	3,123	1,425	1,236	8,362	904	8,699
Castro County	291	345	829	1,098	2,303	3,357	3,418	2,957	1,214	1,359
Cochran County	229	*419*	464	575	534	930	904	692	396	555
Crosby County	130	124	72	189	273	462	439	285	211	311
Deaf Smith County	1,957	3,285	4,389	4,972	7,768	4,372	4,153	3,787	2,845	5,098
Floyd County	716	708	821	1,135	1,123	239	856	483	572	349
Hale County	1,851	3,090	4,447	2,790	3,376	5,130	4,963	4,146	3,868	4,439
Hockley County	455	852	2,445	1,602	1,276	1,745	2,003	1,163	892	1,355
Lamb County	1,566	1,797	6,989	4,009	4,576	3,405	3,547	3,472	2,674	2,217
Lubbock County	4,564	12,404	14,448	3,519	3,264	12,652	19,642	2,801	9,647	9,372
Lynn County	748	694	570	153	351	497	548	230	301	298
Parmer County	453	445	714	1,215	1,690	2,248	2,059	1,674	1,175	1,604
Randall County	8,123	18,205	34,368	15,601	35,301	35,202	35,083	37,817	29,194	5,771
Swisher County	438	572	851	1,452	1,240	453	1,013	808	704	457
District Total	*22,726*	*44,417*	*74,839*	*40,730*	*66,198*	*72,117*	*79,864*	*68,678*	*54,594*	*41,882*
Llano Estacado Underground Water Conservation District										
Gaines County	874	961	1,580	1,732	2,108	2,881	3,001	2,612	2,429	3,210
Mesa Underground Water Conservation District										
Dawson County	1,404	1,796	1,910	1,509	25	836	634	1,109	1,222	794
North Plains Groundwater Conservation District										
Dallam County	580	1,159	1,112	1,551	1,641	1,625	2,038	2,765	3,644	2,295
Hansford County	245	489	745	1,203	1,216	1,303	1,086	1,197	1,061	1,090
Hartley County	192	385	449	746	881	879	738	1,308	1,153	1,976
Hutchinson County	1,603	3,206	2,729	2,633	2,770	2,253	3,335	4,743	3,801	6,152
Lipscomb County	97	194	345	452	686	801	750	930	659	837
Moore County	513	1,027	1,311	1,943	4,415	5,522	5,198	6,668	6,277	5,328
Ochiltree County	361	722	1,242	1,290	1,348	2,454	1,662	2,087	2,031	2,282
Sherman County	118	235	304	485	761	534	600	692	529	633
District Total	*3,709*	*7,418*	*8,238*	*10,303*	*13,719*	*15,371*	*15,407*	*20,390*	*19,155*	*20,593*
Panhandle Groundwater Conservation District										
Armstrong County	31	62	88	162	184	309	334	357	330	336
Carson County	3,357	6,713	9,471	4,504	10,532	11,068	10,908	12,203	9,026	23,124
Donley County	416	832	683	578	830	545	509	567	507	613
Gray County	1,280	2,560	3,676	4,046	1,093	2,779	2,922	826	1,554	1,567
Potter County	147	295	420	157	434	570	566	544	376	743

Table 4.7.6, continued

County	Pumping (acre-feet per year)									
	1940	**1950**	**1960**	**1970**	**1980**	**1990**	**1995**	**2000**	**2005**	**2010**
Panhandle Groundwater Conservation District, continued										
Roberts County	29	59	81	182	189	192	164	139	34,852	15,839
Wheeler County	362	725	861	1,421	1,396	747	688	768	735	1,126
District Total	*5,623*	*11,247*	*15,279*	*11,050*	*14,657*	*16,210*	*16,091*	*15,404*	*47,380*	*43,349*
Permian Basin Underground Water Conservation District										
Howard County	0	0	0	0	0	507	544	0	0	883
Martin County	2,316	2,309	3,732	1,374	31	1,574	1,397	1,222	2,036	333
District Total	*2,316*	*2,309*	*3,732*	*1,374*	*31*	*2,081*	*1,941*	*1,222*	*2,036*	*1,217*
Sandy Land Underground Water Conservation District										
Yoakum County	453	375	906	1,073	1,168	1,793	1,321	1,356	1,262	1,361
South Plains Underground Water Conservation District										
Terry County	1,184	1,412	1,727	286	761	528	1,013	189	263	545
No Groundwater Conservation District										
Borden County	0	0	0	0	0	3	14	0	89	57
Briscoe County	127	111	123	141	106	34	38	20	0	29
Dickens County	0	0	0	0	0	12	9	0	0	31
Ector County	588	4,263	2,352	17	0	245	246	3,358	0	614
Midland County	798	2,864	6,855	1,777	0	7,901	3,156	836	2,601	2,601
Oldham County	23	46	157	514	2,801	2,522	558	445	570	119
Andrews County	9	267	1,937	2,206	2,842	3,226	3,141	3,142	2,700	3,058
Municipal Total	**39,986**	**77,795**	**119,909**	**73,423**	**105,791**	**126,463**	**127,016**	**119,228**	**134,841**	**120,303**

Table 4.7.7 Manufacturing pumping by county for the Ogallala Aquifer.

County	Pumping (acre-feet per year)									
	1940	**1950**	**1960**	**1970**	**1980**	**1990**	**1995**	**2000**	**2005**	**2010**
Glasscock Groundwater Conservation District										
Glasscock County(1)	0	0	0	0	0	0	0	0	0	0
High Plains Underground Water Conservation District										
Bailey County	0	0	0	0	0	147	153	264	0	0
Castro County	5	6	8	0	936	392	150	95	95	54
Cochran County	1	1	1	1	0	0	0	0	0	0
Crosby County	0	0	0	0	0	0	0	0	2	0
Deaf Smith County	12	16	25	6,618	5,294	685	1,164	1,270	7	4
Floyd County	0	0	0	0	0	0	53	0	0	0
Hale County	0	0	62	2,519	5,494	1,467	2,123	2,050	1,442	1,115
Hockley County	6	7	6	13	14	0	0	0	0	0
Lamb County	0	0	0	0	0	0	0	0	0	1
Lubbock County	43	117	183	2,014	1,385	240	214	302	333	335
Lynn County(1)	0	0	0	0	0	0	0	0	0	0
Parmer County	0	0	0	0	216	1,500	1,378	2,061	1,908	1,552
Randall County	0	1	1	7	4	0	0	0	0	0
Swisher County(1)	0	0	0	0	0	0	0	0	0	0
District Total	*67*	*147*	*286*	*11,173*	*13,343*	*4,431*	*5,235*	*6,043*	*3,788*	*3,061*

Table 4.7.7, continued

County	Pumping (acre-feet per year)									
	1940	1950	1960	1970	1980	1990	1995	2000	2005	2010
Llano Estacado Underground Water Conservation District										
Gaines County	162	178	103	212	164	303	369	0	0	0
Mesa Underground Water Conservation District										
Dawson County	0	0	0	0	0	44	27	0	0	0
North Plains Groundwater Conservation District										
Hansford County	516	1,031	986	612	486	237	526	174	174	59
Hutchinson County	7,547	15,095	22,096	17,207	10,364	9,590	9,072	8,695	7,167	17,196
Moore County	3,032	6,063	9,367	12,753	7,863	3,510	4,168	4,018	5,607	4,057
Sherman County	0	0	0	4	1	0	0	0	0	0
District Total	*11,095*	*22,189*	*32,449*	*30,577*	*18,713*	*13,337*	*13,766*	*12,886*	*12,948*	*21,312*
Panhandle Groundwater Conservation District										
Carson County	3,620	7,239	9,413	8,426	7,246	6,423	5,275	5,960	1,433	5,446
Gray County	536	1,073	1,720	3,729	3,735	3,499	3,794	4,003	3,434	458
Potter County	201	348	976	1,488	1,650	47	52	9	2	4
Roberts County	0	0	0	0	0	3	1	1	1	1
Wheeler County	0	0	0	68	40	0	0	0	0	14
District Total	*4,357*	*8,659*	*12,109*	*13,711*	*12,671*	*9,972*	*9,122*	*9,973*	*4,869*	*5,924*
Permian Basin Underground Water Conservation District										
Howard County	1	2	1	0	32	301	360	129	33	1,167
Martin County	0	0	0	0	0	30	44	0	0	0
District Total	*1*	*2*	*1*	*0*	*32*	*331*	*404*	*129*	*33*	*1,167*
South Plains Underground Water Conservation District										
Terry County	110	132	10	90	27	0	5	1	2	2
No Groundwater Conservation District										
Briscoe County(1)	0	0	0	0	0	0	0	0	0	0
Midland County	1	3	7	7	0	58	193	109	0	1
Andrews County	1	2	6	4	2	0	0	0	0	24
Manufacturing Total	**15,794**	**31,313**	**44,972**	**55,774**	**44,952**	**28,476**	**29,120**	**29,140**	**21,640**	**31,491**

(1) County has non-zero pumping for at least one year between 1930 and 2012.

Table 4.7.8 Mining pumping by county for the Ogallala Aquifer.

County	Pumping (acre-feet per year)									
	1940	1950	1960	1970	1980	1990	1995	2000	2005	2010
Garza County Underground Water Conservation District										
Garza County	0	0	0	0	4	21	1,138	0	0	0
Hemphill County Underground Water Conservation District										
Hemphill County	0	0	0	0	0	0	0	1,183	3,070	7,777
High Plains Underground Water Conservation District										
Bailey County	0	0	0	0	0	16	18	0	0	0
Cochran County	8	14	14	14	1	924	1,142	0	0	0
Crosby County	0	0	0	0	195	490	490	182	185	185
Floyd County	0	0	0	1	1	63	64	0	0	0

Table 4.7.8, continued

County	**Pumping (acre-feet per year)**									
	1940	**1950**	**1960**	**1970**	**1980**	**1990**	**1995**	**2000**	**2005**	**2010**
High Plains Underground Water Conservation District, continued										
Hale County	0	0	15	594	1,295	166	312	0	0	0
Hockley County	189	205	181	416	424	2,630	2,952	1	1	171
Lamb County	0	0	0	0	3	76	125	0	0	0
Lubbock County	8	22	34	377	259	191	1,255	0	0	0
Lynn County	0	0	0	0	0	116	227	0	0	0
Randall County	0	0	0	0	0	10	21	0	0	0
Swisher County	0	0	0	0	0	0	6	0	0	0
District Total	*205*	*241*	*244*	*1,401*	*2,177*	*4,682*	*6,612*	*183*	*185*	*356*
Llano Estacado Underground Water Conservation District										
Gaines County	1,741	1,912	1,112	2,279	1,761	2,904	7,765	402	445	5,217
Mesa Underground Water Conservation District										
Dawson County	17	20	20	20	7	654	781	32	36	28
North Plains Groundwater Conservation District										
Hansford County	0	0	0	0	0	0	0	0	0	143
Hutchinson County	1	2	3	3	0	0	0	0	0	135
Lipscomb County	0	0	0	0	0	0	0	0	0	409
Moore County	4	8	10	58	24	8	6	3	0	16
Ochiltree County	0	0	0	5	3	2	1	1	1	39
District Total	*5*	*11*	*13*	*66*	*27*	*10*	*7*	*4*	*1*	*742*
Panhandle Groundwater Conservation District										
Armstrong County	0	0	0	0	0	2	2	0	0	0
Carson County	122	245	383	240	65	21	0	1	1	7
Gray County	14	28	25	71	26	0	0	0	0	0
Potter County	54	78	250	462	495	65	130	31	19	0
Roberts County	0	0	0	7	0	2	1	1	0	0
Wheeler County	0	0	0	0	0	0	0	0	0	658
District Total	*191*	*350*	*658*	*779*	*586*	*91*	*133*	*34*	*20*	*665*
Permian Basin Underground Water Conservation District										
Howard County	9	12	9	1	196	154	82	0	2	1
Martin County	1	1	0	1	10	681	852	41	36	44
District Total	*10*	*13*	*9*	*2*	*206*	*835*	*934*	*41*	*38*	*46*
Sandy Land Underground Water Conservation District										
Yoakum County	3,005	2,941	4,905	5,278	4,029	3,404	6,660	0	0	0
South Plains Underground Water Conservation District										
Terry County	546	651	49	445	135	561	276	0	0	0
No Groundwater Conservation District										
Borden County	0	0	0	0	0	306	0	0	0	0
Ector County	196	1,422	3,387	4,673	302	3,762	5,308	0	0	0
Midland County	70	251	504	483	3	0	0	0	749	585
Oldham County	0	0	0	0	2	172	220	1	1	0
Andrews County	329	730	1,660	1,067	472	3,569	3,184	77	72	0
Mining Total	**6,315**	**8,541**	**12,560**	**16,493**	**9,710**	**20,972**	**33,018**	**1,958**	**4,619**	**15,416**

Table 4.7.9 Power pumping by county for the Ogallala Aquifer.

County	Pumping (acre--feet per year)									
	1940	**1950**	**1960**	**1970**	**1980**	**1990**	**1995**	**2000**	**2005**	**2010**
High Plains Underground Water Conservation District										
Lamb County	14	16	15	9	157	12,587	12,813	14,553	14,197	13,945
Lubbock County[(1)]	0	0	0	0	0	0	0	0	0	0
District Total	*14*	*16*	*15*	*9*	*157*	*12,587*	*12,813*	*14,553*	*14,197*	*13,945*
North Plains Groundwater Conservation District										
Moore County	378	756	1,313	1,085	1,131	359	319	396	108	43
Panhandle Groundwater Conservation District										
Potter County	190	381	735	624	0	229	197	171	108	303
Sandy Land Underground Water Conservation District										
Yoakum County	685	671	1,119	1,204	919	0	0	0	0	0
No Groundwater Conservation District										
Oldham County[(1)]	0	0	0	0	2	0	0	0	0	0
Power Total	**1,267**	**1,823**	**3,182**	**2,921**	**2,207**	**13,175**	**13,329**	**15,121**	**14,412**	**14,291**

(1) County has non-zero pumping for at least one year between 1930 and 2012.

Table 4.7.10 Livestock pumping by county for the Ogallala Aquifer.

County	Pumping (acre-feet per year)									
	1940	**1950**	**1960**	**1970**	**1980**	**1990**	**1995**	**2000**	**2005**	**2010**
Garza County Underground Water Conservation District										
Garza County	110	110	110	110	44	33	41	4	5	8
Gateway Groundwater Conservation District										
Motley County	14	14	14	14	14	12	9	2	17	17
Glasscock Groundwater Conservation District										
Glasscock County	362	362	362	362	243	31	24	35	31	30
Hemphill County Underground Water Conservation District										
Hemphill County	38	76	139	135	363	306	538	680	534	902
High Plains Underground Water Conservation District										
Bailey County	790	790	790	790	688	1,052	1,964	1,603	2,175	2,454
Castro County	2,505	2,505	2,505	2,505	3,161	2,702	7,426	6,671	7,553	8,478
Cochran County	852	852	852	852	630	459	676	130	145	343
Crosby County	393	393	393	393	346	220	222	73	56	56
Deaf Smith County	3,469	3,469	3,469	3,469	5,849	6,836	14,446	2,251	9,765	9,912
Floyd County	531	531	531	531	867	628	1,178	662	571	841
Hale County	1,757	1,757	1,757	1,757	1,506	674	2,039	2,037	2,277	2,792
Hockley County	395	395	395	395	438	257	520	367	178	285
Lamb County	1,131	1,131	1,131	1,131	1,092	1,734	3,418	1,658	3,478	3,554
Lubbock County	1,576	1,576	1,576	1,576	1,155	1,509	2,042	609	922	716
Lynn County	251	251	251	251	162	201	142	116	99	70
Parmer County	3,496	3,496	3,496	3,496	3,496	3,839	7,900	6,480	6,613	7,748
Randall County	1,531	1,545	1,565	1,585	1,681	1,775	3,014	2,041	2,822	2,156
Swisher County	2,747	2,747	2,747	2,747	2,747	3,118	5,271	2,735	3,872	2,918
District Total	*21,423*	*21,438*	*21,458*	*21,477*	*23,818*	*25,004*	*50,258*	*27,434*	*40,527*	*42,323*

Table 4.7.10, continued

County	Pumping (acre-feet per year)									
	1940	**1950**	**1960**	**1970**	**1980**	**1990**	**1995**	**2000**	**2005**	**2010**
Llano Estacado Underground Water Conservation District										
Gaines County	480	480	480	480	468	413	1,005	449	361	139
Mesa Underground Water Conservation District										
Dawson County	200	200	200	200	85	57	86	89	74	175
North Plains Groundwater Conservation District										
Dallam County	73	146	264	252	1,303	1,502	2,707	3,461	3,078	1,956
Hansford County	0	0	132	638	1,563	1,369	2,064	2,132	1,675	2,631
Hartley County	29	59	110	122	1,263	825	1,561	1,921	2,082	3,371
Hutchinson County	27	54	97	115	57	31	46	133	163	314
Lipscomb County	6	12	20	23	36	44	33	229	288	716
Moore County	61	123	235	224	1,473	1,625	3,153	2,841	2,346	2,026
Ochiltree County	67	133	273	275	981	98	164	1,387	1,124	1,300
Sherman County	40	80	151	213	1,391	1,900	3,108	3,166	3,700	1,947
District Total	*303*	*606*	*1,281*	*1,861*	*8,066*	*7,393*	*12,835*	*15,270*	*14,456*	*14,260*
Panhandle Groundwater Conservation District										
Armstrong County	636	663	707	702	1,026	351	342	356	402	383
Carson County	41	82	160	60	498	530	760	745	534	609
Donley County	0	0	0	0	0	0	0	0	0	495
Gray County	0	0	0	0	0	0	0	0	0	1,106
Potter County	21	21	23	22	22	6	6	10	77	627
District Total	*698*	*766*	*890*	*784*	*1,546*	*887*	*1,108*	*1,112*	*1,013*	*3,220*
Permian Basin Underground Water Conservation District										
Howard County	192	192	192	192	181	145	169	137	92	115
Martin County	248	248	248	248	128	310	251	544	55	103
District Total	*440*	*440*	*440*	*440*	*309*	*455*	*420*	*681*	*147*	*218*
Sandy Land Underground Water Conservation District										
Yoakum County	80	80	80	80	80	129	122	118	245	159
South Plains Underground Water Conservation District										
Terry County	132	132	132	132	132	156	66	92	155	208
No Groundwater Conservation District										
Borden County	122	122	122	122	46	16	39	7	18	19
Briscoe County	135	135	135	135	543	123	188	94	90	98
Dickens County	195	195	195	195	76	27	18	8	38	31
Ector County	95	95	95	95	79	11	10	7	10	10
Midland County	81	81	81	81	81	107	167	118	108	94
Oldham County	28	28	28	28	28	31	51	36	142	373
Andrews County	225	225	225	225	232	139	267	199	204	182
Livestock Total	**25,162**	**25,586**	**26,467**	**26,957**	**36,253**	**35,331**	**67,252**	**46,434**	**58,176**	**62,465**

Table 4.7.11 Rural domestic pumping by county for the Ogallala Aquifer.

County	**Pumping (acre-feet per year)**									
	1940	**1950**	**1960**	**1970**	**1980**	**1990**	**1995**	**2000**	**2005**	**2010**
Garza County Underground Water Conservation District										
Garza County	0	0	0	0	118	133	125	61	15	15
Hemphill County Underground Water Conservation District										
Hemphill County	16	31	57	56	149	126	221	279	219	352
High Plains Underground Water Conservation District										
Bailey County	221	395	483	452	384	346	321	310	48	30
Castro County	1	1	2	2	533	486	478	479	177	167
Cochran County	144	262	285	241	252	300	301	185	6,997	6,360
Crosby County	403	419	454	402	321	223	230	224	1,333	1,983
Deaf Smith County	1	2	2	2	682	557	562	599	9	4
Floyd County	505	536	639	575	398	264	280	275	1,148	1,148
Hale County	494	1,082	1,474	1,371	1,037	860	1,204	1,104	204	204
Hockley County	304	574	642	596	827	778	866	935	1,542	1,565
Lamb County	480	551	606	503	756	592	629	536	44	44
Lubbock County	506	1,300	2,243	2,579	2,650	2,903	3,501	3,449	2,577	3,056
Lynn County	416	583	582	497	458	321	375	292	341	248
Parmer County	136	218	426	469	557	613	495	499	142	142
Randall County	6	12	25	38	150	224	380	840	1,721	1,468
Swisher County	0	0	0	0	0	0	0	0	0	0
District Total	*3,616*	*5,936*	*7,864*	*7,727*	*9,003*	*8,465*	*9,623*	*9,726*	*16,283*	*16,418*
Llano Estacado Underground Water Conservation District										
Gaines County	126	407	609	576	557	726	740	778	18,091	19,652
Mesa Underground Water Conservation District										
Dawson County	197	712	713	621	583	467	470	616	2,363	2,363
Mesquite Groundwater Conservation District										
Collingsworth County	0	0	0	0	0	0	0	1	1	0
North Plains Groundwater Conservation District										
Dallam County	5	9	17	16	85	97	176	225	200	190
Hansford County	0	0	25	123	301	264	398	411	323	350
Hartley County	7	14	26	28	296	193	366	450	487	548
Hutchinson County	19	38	68	80	39	21	32	83	80	72
Lipscomb County	6	13	21	26	39	47	35	248	313	379
Moore County	23	46	88	84	554	612	1,187	1,070	885	923
Ochiltree County	14	28	57	58	206	21	34	293	241	224
Sherman County	2	4	8	11	72	99	161	164	190	210
District Total	*76*	*152*	*311*	*426*	*1,593*	*1,355*	*2,390*	*2,944*	*2,720*	*2,895*
Panhandle Groundwater Conservation District										
Armstrong County	8	16	30	28	108	94	92	96	101	75
Carson County	32	64	125	47	388	413	592	581	420	281
Donley County	53	106	185	104	47	32	48	213	216	189
Gray County	97	194	344	261	942	134	280	649	580	564
Potter County	86	173	355	282	971	897	1,084	1,467	1,033	1,998

Table 4.7.11, continued

County	Pumping (acre-feet per year)									
	1940	**1950**	**1960**	**1970**	**1980**	**1990**	**1995**	**2000**	**2005**	**2010**
Panhandle Groundwater Conservation District, continued										
Roberts County	16	32	61	55	51	54	37	122	82	81
Wheeler County	43	87	152	137	318	99	146	339	288	256
District Total	*336*	*672*	*1,251*	*914*	*2,825*	*1,722*	*2,279*	*3,468*	*2,720*	*3,444*
Permian Basin Underground Water Conservation District										
Howard County	2	2	1	1	826	674	822	837	1,104	702
Martin County	308	464	426	402	283	297	322	388	383	473
District Total	*309*	*465*	*428*	*404*	*1,109*	*971*	*1,143*	*1,224*	*1,487*	*1,175*
No Groundwater Conservation District										
Borden County	1	1	1	1	69	61	63	62	2,040	2,012
Briscoe County	215	241	245	197	198	187	183	74	3	5
Midland County	1	1	1	1	1,916	2,694	2,712	2,958	7,123	11,283
Oldham County	182	229	279	318	163	2,060	489	437	2,719	2,623
Andrews County	2	33	205	163	294	635	791	846	252	214
Rural Domestic Total	**5,077**	**8,882**	**11,963**	**11,404**	**18,577**	**19,602**	**21,228**	**23,477**	**56,036**	**62,450**

Table 4.7.12 Total pumping by county for the Ogallala Aquifer.

County	Pumping (acre-feet per year)									
	1940	1950	1960	1970	1980	1990	1995	2000	2005	2010
Garza County Underground Water Conservation District										
Garza County	1,110	8,660	16,115	16,431	10,105	5,049	11,034	17,694	17,179	10,824
Gateway Groundwater Conservation District										
Motley County	25	110	220	505	352	481	520	209	210	153
Glasscock Groundwater Conservation District										
Glasscock County	424	891	1,636	3,431	4,039	3,224	6,896	3,266	4,062	5,258
Hemphill County Underground Water Conservation District										
Hemphill County	258	517	720	1,627	2,333	1,006	3,287	6,384	7,161	14,175
High Plains Underground Water Conservation District										
Bailey County	93,961	186,153	294,133	226,742	253,552	153,530	113,445	107,235	37,477	43,665
Castro County	129,400	256,054	451,094	551,745	439,478	393,366	212,195	243,967	145,034	173,502
Cochran County	8,485	63,556	115,895	71,045	64,299	48,565	79,029	77,862	53,040	49,843
Crosby County	50,621	100,327	156,500	220,191	71,327	141,970	140,072	108,391	72,170	78,202
Deaf Smith County	150,901	297,694	435,794	503,242	329,870	230,464	209,102	268,685	111,923	138,671
Floyd County	67,085	132,443	206,729	304,490	224,649	192,055	189,661	166,457	83,215	73,658
Hale County	209,727	417,180	760,128	718,436	406,091	441,391	328,352	273,558	182,261	166,304
Hockley County	60,284	119,899	246,339	243,880	112,920	147,003	173,599	175,046	92,003	101,261
Lamb County	144,614	286,340	500,481	399,527	372,011	416,550	306,940	306,328	203,183	158,134
Lubbock County	110,720	223,464	283,760	217,626	109,846	298,936	250,808	200,051	103,516	100,371
Lynn County	6,715	46,843	80,759	34,159	39,114	60,600	62,740	109,018	59,064	51,716
Parmer County	280,491	556,971	711,934	520,956	551,211	400,118	278,028	267,955	190,297	169,872
Randall County	19,058	68,946	142,599	104,186	93,729	74,646	86,998	89,301	91,520	32,389
Swisher County	97,837	192,623	337,490	394,884	212,852	155,100	161,022	141,785	137,697	94,323
District Total	*1,429,899*	*2,948,493*	*4,723,635*	*4,511,109*	*3,280,947*	*3,154,294*	*2,591,992*	*2,535,639*	*1,562,400*	*1,431,913*
Llano Estacado Underground Water Conservation District										
Gaines County	13,613	91,415	201,224	184,952	421,990	322,859	322,885	267,023	271,315	230,246
Mesa Underground Water Conservation District										
Dawson County	8,825	62,644	122,514	42,353	21,620	33,802	50,528	108,637	78,305	61,114
Mesquite Groundwater Conservation District										
Collingsworth County	0	0	0	0	0	0	0	1	1	0
North Plains Groundwater Conservation District										
Dallam County	20,126	40,253	87,398	144,296	242,178	357,606	300,100	314,594	338,616	334,893
Hansford County	11,016	22,032	52,507	207,790	180,324	103,398	130,790	142,131	114,514	134,274

Table 4.7.12, continued

County	Pumping (acre-feet per year)									
	1940	1950	1960	1970	1980	1990	1995	2000	2005	2010
North Plains Groundwater Conservation District, continued										
Hartley County	6,977	13,953	34,324	153,683	254,951	199,433	165,613	292,687	298,344	346,449
Hutchinson County	16,930	33,860	63,655	81,676	95,095	50,102	42,984	76,766	56,120	63,416
Lipscomb County	745	1,490	3,565	5,877	21,644	13,255	24,459	26,303	29,955	36,541
Moore County	21,836	43,671	100,855	229,448	251,844	198,352	174,770	180,936	159,213	173,866
Ochiltree County	4,472	8,945	21,432	93,867	110,357	58,037	42,969	107,988	69,588	65,645
Sherman County	17,696	35,392	88,146	359,065	323,912	238,123	180,352	298,287	236,416	253,489
District Total	*99,798*	*199,596*	*451,883*	*1,275,701*	*1,480,305*	*1,218,308*	*1,062,037*	*1,439,692*	*1,302,766*	*1,408,572*
Panhandle Groundwater Conservation District										
Armstrong County	4,191	7,865	18,276	14,024	11,720	6,430	4,830	9,245	7,247	4,735
Carson County	20,281	40,561	85,099	111,509	130,466	99,381	89,257	125,506	95,193	89,291
Donley County	1,473	2,946	5,381	12,248	12,409	21,674	14,557	25,950	28,424	26,277
Gray County	3,476	6,953	13,463	26,393	17,010	15,191	19,531	29,663	28,274	26,306
Potter County	2,689	9,639	22,465	31,189	26,934	10,154	20,771	6,396	6,548	5,579
Roberts County	783	1,566	3,819	8,465	6,372	3,947	4,882	1,812	41,750	23,283
Wheeler County	782	1,565	2,626	4,501	6,043	1,038	3,416	8,481	11,010	11,678
District Total	*33,675*	*71,096*	*151,128*	*208,330*	*210,954*	*157,816*	*157,245*	*207,054*	*218,446*	*187,148*
Permian Basin Underground Water Conservation District										
Howard County	306	1,081	1,948	1,799	5,685	7,179	4,294	6,813	4,574	10,809
Martin County	5,584	26,207	46,745	31,340	14,816	14,358	14,375	16,800	18,696	37,190
District Total	*5,890*	*27,288*	*48,692*	*33,139*	*20,501*	*21,537*	*18,669*	*23,613*	*23,270*	*47,999*
Sandy Land Underground Water Conservation District										
Yoakum County	8,750	42,776	72,891	94,800	126,489	79,043	112,044	115,015	115,663	179,738
South Plains Underground Water Conservation District										
Terry County	11,011	79,610	149,079	76,513	80,488	161,119	164,235	213,762	145,566	145,191
No Groundwater Conservation District										
Andrews County	679	2,225	10,629	5,679	15,732	16,443	18,522	17,534	25,347	19,574
Borden County	177	584	899	822	680	1,536	1,593	1,946	4,761	3,702
Briscoe County	8,795	17,123	38,299	58,952	52,196	31,365	24,408	30,543	47,236	33,456
Dickens County	545	3,189	5,695	8,490	3,396	2,304	2,259	3,992	4,790	3,858
Ector County	879	5,780	7,737	8,473	3,884	5,523	7,181	3,616	136	712
Midland County	1,448	7,452	13,907	12,619	9,403	16,898	12,813	6,810	12,728	16,269
Oldham County	1,840	14,046	29,394	31,265	24,281	12,743	16,468	7,987	18,419	12,463
Aquifer Total	**1,627,642**	**3,583,493**	**6,046,297**	**6,575,191**	**5,769,695**	**5,245,350**	**4,584,617**	**5,010,416**	**3,859,761**	**3,812,365**

Table 4.7.13 Irrigation pumping by county for the Dockum Group.

County	Pumping (acre-feet per year)									
	1940	1950	1960	1970	1980	1990	1995	2000	2005	2010
Garza County Underground Water Conservation District										
Garza County	5	10	19	52	62	37	51	189	184	115
Gateway Groundwater Conservation District										
Motley County	5	10	19	54	64	70	93	642	597	425
High Plains Underground Water Conservation District										
Crosby County	272	544	1,058	2,961	3,515	2,700	3,434	2,391	1,566	1,665
Deaf Smith County	239	478	929	2,602	3,088	2,878	2,828	2,989	2,989	1,786
Floyd County	124	249	484	1,355	1,608	688	1,261	3,182	1,570	1,384
Hale County	19	38	73	205	243	152	139	130	130	130
Randall County	42	85	165	463	549	321	350	395	649	368
Swisher County	17	34	66	185	219	143	197	443	427	800
District Total	*713*	*1,427*	*2,775*	*7,769*	*9,222*	*6,882*	*8,209*	*9,530*	*7,331*	*6,133*
Lone Wolf Groundwater Conservation District										
Mitchell County	249	498	968	2,711	3,218	1,593	410	5,549	5,931	9,443
North Plains Groundwater Conservation District										
Dallam County	135	270	525	1,468	1,743	1,966	2,343	2,757	2,757	2,757
Hartley County	57	114	221	618	734	607	710	840	840	840
Moore County	334	668	1,298	3,635	4,315	5,576	4,845	2,012	2,008	1,122
Sherman County	43	87	169	473	562	442	487	485	485	485
District Total	*569*	*1,138*	*2,213*	*6,196*	*7,354*	*8,591*	*8,385*	*6,094*	*6,090*	*5,204*
Panhandle Groundwater Conservation District										
Armstrong County	5	9	18	51	60	52	37	82	53	30
Carson County	25	49	96	268	318	250	142	91	91	91
Potter County	25	50	96	270	320	81	255	116	169	37
District Total	*54*	*108*	*210*	*588*	*698*	*383*	*434*	*288*	*313*	*158*
Permian Basin Underground Water Conservation District										
Howard County	1	3	5	14	17	46	20	322	189	448
Santa Rita Groundwater Conservation District										
Reagan County	59	118	230	644	765	1,651	1,896	60	47	74
Sterling County Underground Water Conservation District										
Sterling County	1	3	5	15	18	11	8	8	8	8
West Texas Groundwater Conservation District										
Nolan County	46	91	178	497	590	529	424	4,855	5,313	7,990
No Groundwater Conservation District										
Briscoe County	1	2	4	12	14	12	7	26	41	29
Dickens County	1	2	3	8	10	6	4	41	49	39
Oldham County	23	45	88	248	294	130	174	158	341	213
Pecos County	73	147	286	800	950	631	820	772	772	772
Reeves County	8	15	30	84	100	33	190	180	180	180
Scurry County	617	1,234	2,401	6,722	7,979	998	776	2,660	3,586	5,857
Upton County	14	28	54	152	181	146	206	99	52	150
Ward County	3	6	12	33	39	7	11	37	15	11
Winkler County	7	13	25	71	84	0	0	0	0	0
Irrigation Total	**2,449**	**4,898**	**9,527**	**26,672**	**31,659**	**21,756**	**22,118**	**31,511**	**31,039**	**37,249**

Table 4.7.14 Municipal pumping by county for the Dockum Group.

County	Pumping (acre-feet per year)									
	1940	**1950**	**1960**	**1970**	**1980**	**1990**	**1995**	**2000**	**2005**	**2010**
Clear Fork Groundwater Conservation District										
Fisher County	0	0	0	0	0	0	0	0	19	62
Crockett County Groundwater Conservation District										
Crockett County	0	0	0	0	0	0	0	0	0	1
Garza County Underground Water Conservation District										
Garza County	0	0	0	0	0	0	0	0	0	47
Gateway Groundwater Conservation District										
Motley County	0	0	0	0	0	0	0	0	0	8
High Plains Underground Water Conservation District										
Crosby County	0	0	0	0	0	0	0	0	0	9
Deaf Smith County	0	0	0	0	0	0	0	0	0	30
Floyd County	0	0	0	0	0	0	0	0	0	42
Randall County	0	0	0	0	0	0	0	0	0	2,643
Swisher County	0	0	0	0	0	0	0	0	0	60
District Total	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*2,784*
Lone Wolf Groundwater Conservation District										
Mitchell County	10	19	37	104	124	132	198	854	1,747	1,385
Mesa Underground Water Conservation District										
Dawson County	0	0	0	0	0	0	0	0	0	6
North Plains Groundwater Conservation District										
Hartley County	0	0	0	0	0	0	0	0	0	20
Moore County	0	0	0	0	0	0	0	0	0	7
District Total	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*27*
Panhandle Groundwater Conservation District										
Armstrong County	0	0	0	0	0	0	0	0	0	11
Carson County	0	0	0	0	0	0	0	0	0	17
Potter County	0	0	0	0	0	0	0	0	0	1,085
District Total	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*1,113*
Permian Basin Underground Water Conservation District										
Howard County	0	0	0	0	0	0	0	0	0	62
Sterling County Underground Water Conservation District										
Sterling County	0	0	0	0	0	0	0	0	0	1
Wes-Tex Groundwater Conservation District										
Nolan County	14	28	55	154	183	238	232	188	336	262
No Groundwater Conservation District										
Borden County	0	0	0	0	0	0	0	0	0	22
Briscoe County	0	0	0	0	0	0	0	7	7	16
Crane County	0	0	0	0	0	0	0	0	0	12
Dickens County	0	0	0	0	0	0	0	0	0	24
Ector County	0	0	0	0	0	0	0	0	0	115
Loving County	0	0	0	0	0	0	0	0	0	0

Table 4.7.14, continued

County	Pumping (acre-feet per year)									
	1940	1950	1960	1970	1980	1990	1995	2000	2005	2010
No Groundwater Conservation District, continued										
Oldham County	0	0	0	0	0	0	0	340	338	291
Reeves County	121	243	472	1,321	1,568	967	916	1,011	1,011	1,011
Scurry County	0	0	0	0	0	0	0	77	132	663
Upton County	0	0	0	0	0	0	0	0	0	7
Ward County	0	0	0	0	0	0	0	0	0	43
Winkler County	186	372	724	2,026	2,405	1,835	1,973	1,968	1,619	1,506
Municipal Total	**331**	**662**	**1,288**	**3,606**	**4,280**	**3,172**	**3,319**	**4,445**	**5,208**	**9,469**

Table 4.7.15 Manufacturing pumping by county for the Dockum Group.

County	Pumping (acre-feet per year)									
	1940	1950	1960	1970	1980	1990	1995	2000	2005	2010
Clear Fork Groundwater Conservation District										
Fisher County	0	0	0	0	0	0	0	158	159	127
No Groundwater Conservation District										
Ector County	7	14	27	76	90	42	6	34	212	9
Scurry County	2	3	7	19	22	1	0	0	0	0
Winkler County	1	1	2	6	7	2	1	1	1	34
Manufacturing Total	**9**	**18**	**36**	**100**	**119**	**45**	**7**	**193**	**372**	**170**

Table 4.7.16 Mining pumping by county for the Dockum Group.

County	Pumping (acre-feet per year)									
	1940	1950	1960	1970	1980	1990	1995	2000	2005	2010
High Plains Underground Water Conservation District										
Hockley County	43	86	168	471	559	922	504	571	571	571
South Plains Underground Water Conservation District										
Terry County(1)	0	0	0	0	0	1	0	0	0	0
No Groundwater Conservation District										
Crane County	0	0	0	0	0	0	407	442	461	39
Ector County	0	0	0	0	0	0	0	922	452	452
Loving County	1	2	4	12	14	2	0	0	0	0
Oldham County	57	114	221	618	734	195	188	52	97	97
Scurry County	56	112	218	609	723	239	160	167	212	154
Winkler County	23	46	90	253	300	452	326	202	217	101
Mining Total	**180**	**361**	**701**	**1,963**	**2,330**	**1,811**	**1,585**	**2,356**	**2,009**	**1,413**

(1) County has non-zero pumping for at least one year between 1930 and 2012.

Table 4.7.17 Power pumping by county for the Dockum Group.

County	Pumping (acre-feet per year)									
	1940	1950	1960	1970	1980	1990	1995	2000	2005	2010
No Groundwater Conservation District										
Scurry County	1	1	2	7	8	0	0	0	0	0
Winkler County	30	60	117	329	390	33	40	67	67	67
Andrews County	1	1	2	7	8	32	1	0	0	0
Power Total	**31**	**63**	**122**	**342**	**406**	**65**	**41**	**67**	**67**	**67**

Table 4.7.18 Livestock pumping by county for the Dockum Group.

County	Pumping (acre-feet per year)									
	1940	1950	1960	1970	1980	1990	1995	2000	2005	2010
Clear Fork Groundwater Conservation District										
Fisher County	1	1	3	8	9	14	11	8	35	48
Crockett County Groundwater Conservation District										
Crockett County	0	0	0	0	0	0	0	2	2	1
Garza County Underground Water Conservation District										
Garza County	1	1	2	7	8	8	10	16	22	30
Gateway Groundwater Conservation District										
Motley County	0	0	0	0	0	0	0	7	54	51
High Plains Underground Water Conservation District										
Crosby County	4	8	15	42	50	1	1	68	59	53
Deaf Smith County	0	1	2	5	6	4	4	99	30	94
Floyd County	1	2	5	13	16	12	22	355	424	117
Hockley County	0	0	0	0	0	0	0	32	18	24
Randall County	9	18	36	99	118	110	187	254	277	306
District Total	*15*	*29*	*57*	*160*	*190*	*127*	*214*	*807*	*808*	*595*
Lone Wolf Groundwater Conservation District										
Mitchell County	4	8	15	42	50	38	42	35	61	79
Mesa Underground Water Conservation District										
Dawson County	0	0	0	0	0	0	0	4	4	9
North Plains Groundwater Conservation District										
Hartley County	51	102	198	555	659	429	814	284	621	674
Panhandle Groundwater Conservation District										
Armstrong County	0	0	0	0	0	0	0	55	93	51
Potter County	1	3	5	15	18	28	26	1	9	9
District Total	*1*	*3*	*5*	*15*	*18*	*28*	*26*	*56*	*102*	*60*
Permian Basin Underground Water Conservation District										
Howard County	0	1	2	4	5	5	6	28	19	24
Sterling County Underground Water Conservation District										
Sterling County	0	0	0	0	0	0	0	8	7	6
Wes-Tex Groundwater Conservation District										
Nolan County	3	5	10	29	34	14	24	11	50	48

Table 4.7.18, continued

County	Pumping (acre-feet per year)									
	1940	1950	1960	1970	1980	1990	1995	2000	2005	2010
No Groundwater Conservation District										
Borden County	0	0	0	0	0	0	0	6	19	15
Briscoe County	0	0	0	0	0	0	0	33	32	35
Crane County	1	2	4	10	12	22	24	46	30	24
Dickens County	0	0	0	0	0	0	0	10	46	39
Ector County	1	1	2	6	7	19	19	5	4	4
Loving County	0	1	2	4	5	3	5	17	45	16
Oldham County	4	9	17	47	56	75	121	95	458	290
Reeves County	4	8	16	45	53	46	62	23	20	9
Scurry County	6	12	23	65	77	28	41	51	108	132
Upton County	1	2	5	13	15	13	16	11	10	7
Ward County	0	1	2	4	5	7	5	15	9	13
Winkler County	1	3	5	14	17	13	14	12	6	8
Andrews County	0	0	0	0	0	5	9	3	3	3
Livestock Total	**95**	**191**	**371**	**1,040**	**1,234**	**900**	**1,471**	**1,593**	**2,574**	**2,220**

Table 4.7.19 Rural domestic pumping by county for the Dockum Group.

County	Pumping (acre-feet per year)									
	1940	1950	1960	1970	1980	1990	1995	2000	2005	2010
Clear Fork Groundwater Conservation District										
Fisher County	0	0	1	2	2	2	1	1	1	1
Crockett County Groundwater Conservation District										
Crockett County	0	0	1	3	3	3	3	3	3	3
Garza County Underground Water Conservation District										
Garza County	1	1	3	8	9	14	19	13	13	13
Gateway Groundwater Conservation District										
Motley County	1	2	3	8	10	7	7	7	7	7
High Plains Underground Water Conservation District										
Crosby County	1	2	4	11	13	10	10	10	10	10
Deaf Smith County	0	1	2	4	5	4	4	4	4	4
Floyd County	0	1	1	3	4	1	2	2	2	2
Lubbock County	0	0	1	2	2	3	5	3	3	3
Randall County	32	63	123	344	408	450	473	438	438	438
District Total	*33*	*67*	*130*	*364*	*432*	*468*	*494*	*457*	*457*	*457*
Lone Wolf Groundwater Conservation District										
Mitchell County	2	5	9	26	31	28	41	40	40	40
Mesa Underground Water Conservation District										
Dawson County	0	0	0	1	1	2	1	2	2	2
North Plains Groundwater Conservation District										
Hartley County	0	1	2	5	6	6	7	8	8	8

Table 4.7.19, continued

County	Pumping (acre-feet per year)									
	1940	1950	1960	1970	1980	1990	1995	2000	2005	2010
Panhandle Groundwater Conservation District										
Armstrong County	3	7	13	36	43	44	45	46	46	46
Carson County	2	5	9	25	30	30	30	30	30	30
Potter County	29	59	114	319	379	353	375	332	332	332
District Total	*35*	*70*	*136*	*381*	*452*	*427*	*450*	*408*	*408*	*408*
Permian Basin Underground Water Conservation District										
Howard County	0	1	2	5	6	6	7	7	7	7
Sterling County Underground Water Conservation District										
Sterling County	0	0	1	2	2	3	3	3	3	3
Wes-Tex Groundwater Conservation District										
Nolan County	1	2	4	11	13	15	10	5	5	5
No Groundwater Conservation District										
Borden County	5	10	20	55	65	58	56	56	56	56
Briscoe County	0	0	1	2	2	1	1	1	1	1
Crane County	2	5	9	25	30	30	28	27	27	27
Dickens County	1	2	4	10	12	9	7	6	6	6
Ector County	0	0	0	1	1	1	1	0	0	0
Loving County	0	0	1	3	3	3	3	2	2	2
Oldham County	8	17	33	91	108	108	106	105	105	105
Pecos County	0	1	2	4	5	5	5	5	5	5
Reeves County	0	1	1	3	4	4	4	4	4	4
Scurry County	9	18	35	98	116	141	146	259	259	259
Upton County	4	9	17	47	56	54	48	45	45	45
Ward County	5	11	21	59	70	66	61	58	58	58
Winkler County	2	3	6	17	20	17	16	15	15	15
Andrews County	0	0	0	1	1	1	1	1	1	1
Rural Domestic Total	**113**	**226**	**439**	**1,230**	**1,460**	**1,479**	**1,526**	**1,538**	**1,538**	**1,538**

Table 4.7.20 Total pumping by county for the Dockum Group.

County	Pumping (acre-feet per year)									
	1940	1950	1960	1970	1980	1990	1995	2000	2005	2010
Clear Fork Groundwater Conservation District										
Fisher County	1	2	3	9	11	16	12	168	214	238
Crockett County Groundwater Conservation District										
Crockett County	0	0	1	3	3	3	3	5	5	5
Garza County Underground Water Conservation District										
Garza County	6	12	24	67	79	59	80	218	218	205
Gateway Groundwater Conservation District										
Motley County	6	11	22	62	74	77	100	656	658	492

Table 4.7.20, continued

County	Pumping (acre-feet per year)									
	1940	1950	1960	1970	1980	1990	1995	2000	2005	2010
High Plains Underground Water Conservation District										
Crosby County	277	554	1,077	3,014	3,578	2,711	3,445	2,469	1,635	1,737
Deaf Smith County	240	479	933	2,611	3,099	2,886	2,836	3,092	3,023	1,914
Floyd County	126	252	490	1,372	1,628	701	1,285	3,538	1,996	1,545
Hale County	19	38	73	205	243	152	139	130	130	130
Hockley County	43	86	168	471	559	922	504	603	589	595
Lubbock County	0	0	1	2	2	3	5	3	3	3
Randall County	83	166	323	906	1,075	881	1,010	1,087	1,364	3,755
Swisher County	17	34	66	185	219	143	197	443	427	861
District Total	*805*	*1,609*	*3,130*	*8,764*	*10,403*	*8,399*	*9,421*	*11,365*	*9,167*	*10,540*
Lone Wolf Groundwater Conservation District										
Mitchell County	265	530	1,030	2,884	3,423	1,791	691	6,478	7,778	10,947
Mesa Underground Water Conservation District										
Dawson County	0	0	0	1	1	2	1	6	6	17
North Plains Groundwater Conservation District										
Dallam County	135	270	525	1,468	1,743	1,966	2,343	2,757	2,757	2,757
Hartley County	108	216	421	1,179	1,399	1,042	1,531	1,132	1,469	1,543
Moore County	334	668	1,298	3,635	4,315	5,576	4,845	2,012	2,008	1,129
Sherman County	43	87	169	473	562	442	487	485	485	485
District Total	*620*	*1,241*	*2,413*	*6,756*	*8,019*	*9,026*	*9,206*	*6,386*	*6,719*	*5,913*
Panhandle Groundwater Conservation District										
Armstrong County	8	16	31	87	103	96	82	182	192	138
Carson County	27	54	105	293	348	280	172	121	121	138
Potter County	55	111	216	604	717	462	656	449	510	1,462
District Total	*90*	*181*	*351*	*984*	*1,168*	*838*	*910*	*752*	*823*	*1,738*
Permian Basin Underground Water Conservation District										
Howard County	2	4	8	24	28	57	33	357	215	541
Santa Rita Underground Water Conservation District										
Reagan County	60	121	234	656	779	1,657	1,904	61	47	75
South Plains Underground Water Conservation District										
Terry County	0	0	0	0	0	1	0	0	0	0
Sterling County	2	3	6	17	20	14	11	19	18	18
District Total	*2*	*3*	*6*	*17*	*20*	*15*	*11*	*19*	*18*	*18*
Wes-Tex Groundwater Conservation District										
Nolan County	63	127	247	691	820	796	690	5,058	5,703	8,306
No Groundwater Conservation District										
Andrews County	1	1	3	8	9	38	11	4	4	4
Borden County	5	10	20	55	65	58	56	62	75	93

Table 4.7.20, continued

County	Pumping (acre-feet per year)									
	1940	1950	1960	1970	1980	1990	1995	2000	2005	2010
No Groundwater Conservation District, continued										
Briscoe County	1	2	5	13	16	13	8	68	81	80
Crane County	3	6	13	35	42	52	459	515	518	103
Dickens County	2	3	7	19	22	15	11	56	100	108
Ector County	8	15	29	83	98	62	26	961	668	580
Kent County	0	0	1	3	3	3	3	5	38	33
Loving County	2	3	7	19	22	8	8	19	47	18
Oldham County	92	184	359	1,004	1,192	508	589	751	1,339	996
Pecos County	74	148	287	805	955	636	825	777	777	777
Reeves County	133	267	519	1,453	1,725	1,050	1,172	1,218	1,215	1,203
Scurry County	690	1,381	2,686	7,519	8,925	1,407	1,123	3,214	4,296	7,064
Upton County	19	39	76	212	252	213	270	155	107	209
Ward County	9	18	34	96	114	80	77	110	82	125
Winkler County	249	499	970	2,715	3,223	2,352	2,370	2,264	1,924	1,730
Aquifer Total	**3,210**	**6,419**	**12,486**	**34,956**	**41,491**	**29,231**	**30,070**	**41,708**	**42,844**	**52,159**

Table 4.7.21 Irrigation pumping by county for the Edwards-Trinity (High Plains) Aquifer.

County	Pumping (acre-feet per year)									
	1940	1950	1960	1970	1980	1990	1995	2000	2005	2010
Garza County Underground Water Conservation District										
Garza County	0	4	8	11	15	0	0	189	184	115
High Plains Underground Water Conservation District										
Bailey County	4	63	128	162	212	787	0	0	0	0
Cochran County	4	45	87	119	146	52	0	0	0	0
Floyd County	42	462	883	1,303	1,723	747	1,382	0	0	0
Hale County	151	1,663	3,175	4,687	6,199	1,426	4,811	13,508	8,918	8,063
Hockley County	2	19	37	54	72	0	0	0	0	0
Lamb County	7	80	153	226	299	0	0	0	0	0
Lubbock County	9	98	187	276	365	0	0	1,483	691	668
Lynn County	9	103	197	291	385	155	484	1,335	722	619
District Total	*228*	*2,534*	*4,847*	*7,119*	*9,402*	*3,167*	*6,677*	*16,326*	*10,330*	*9,350*
Llano Estacado Underground Water Conservation District										
Gaines County	834	7,135	6,110	5,563	12,909	9,688	12,291	12,485	11,877	9,598
Mesa Underground Water Conservation District										
Dawson County	126	1,075	1,646	550	288	530	1,210	1,994	1,398	1,071

Table 4.7.21, continued

County	Pumping (acre-feet per year)									
	1940	1950	1960	1970	1980	1990	1995	2000	2005	2010
Sandy Land Underground Water Conservation District										
Yoakum County	42	467	892	1,317	1,741	230	0	0	0	0
South Plains Underground Water Conservation District										
Terry County	10	106	202	299	395	834	0	0	0	0
No Groundwater Conservation District										
Borden County	0	1	3	4	5	26	0	0	0	0
Irrigation Total	**1,241**	**11,322**	**13,707**	**14,863**	**24,756**	**14,475**	**20,178**	**30,994**	**23,789**	**20,134**

Table 4.7.22 Municipal pumping by county for the Edwards-Trinity (High Plains) Aquifer.

County	Pumping (acre-feet per year)									
	1940	1950	1960	1970	1980	1990	1995	2000	2005	2010
High Plains Underground Water Conservation District										
Floyd County	0	0	0	0	112	16	16	0	0	0
Hale County	0	0	0	0	65	67	72	0	0	22
Hockley County	0	0	0	0	13	11	13	0	0	26
Lamb County	0	0	0	0	0	0	0	0	0	13
Lynn County	0	0	0	0	10	6	16	0	0	0
District Total	*0*	*0*	*0*	*0*	*200*	*100*	*117*	*0*	*0*	*61*
Llano Estacado Underground Water Conservation District										
Gaines County	0	0	0	0	34	38	38	0	0	125
Mesa Underground Water Conservation District										
Dawson County	0	0	0	0	30	82	95	0	0	3
Sandy Land Underground Water Conservation District										
Yoakum County	0	0	0	0	16	20	18	0	0	0
South Plains Underground Water Conservation District										
Terry County	0	0	0	0	101	53	60	0	0	16
Municipal Total	**0**	**0**	**0**	**0**	**381**	**293**	**328**	**0**	**0**	**206**

Table 4.7.23 Manufacturing pumping by county for the Edwards-Trinity (High Plains) Aquifer.

County	Pumping (acre-feet per year)									
	1940	1950	1960	1970	1980	1990	1995	2000	2005	2010
Llano Estacado Underground Water Conservation District										
Gaines County(1)	0	0	0	0	0	0	0	0	0	0

(1) County has non-zero pumping for at least one year between 1930 and 2012.

Table 4.7.24 Mining pumping by county for the Edwards-Trinity (High Plains) Aquifer.

County	Pumping (acre-feet per year)									
	1940	1950	1960	1970	1980	1990	1995	2000	2005	2010
High Plains Underground Water Conservation District										
Bailey County	0	0	0	0	0	4	5	0	0	0
Cochran County	0	0	0	0	179	0	0	0	0	0
District Total	*0*	*0*	*0*	*0*	*179*	*4*	*5*	*0*	*0*	*0*
Llano Estacado Underground Water Conservation District										
Gaines County	0	0	0	0	530	436	0	0	0	0
Sandy Land Underground Water Conservation District										
Yoakum County	0	0	0	0	415	69	135	0	0	0
South Plains Underground Water Conservation District										
Terry County	0	0	0	0	240	132	0	0	0	0
No Groundwater Conservation District										
Borden County	0	0	0	0	0	36	0	0	0	0
Mining Total	**0**	**0**	**0**	**0**	**1,364**	**677**	**140**	**0**	**0**	**0**

Table 4.7.25 Livestock pumping by county for the Edwards-Trinity (High Plains) Aquifer.

County	Pumping (acre-feet per year)									
	1940	1950	1960	1970	1980	1990	1995	2000	2005	2010
Garza County Underground Water Conservation District										
Garza County	0	0	0	0	0	0	0	2	3	4
High Plains Underground Water Conservation District										
Bailey County	1	15	31	39	52	60	111	0	0	0
Cochran County	1	7	13	17	21	16	22	11	14	16
Floyd County	1	13	25	36	48	38	70	0	0	0
Hale County	0	2	4	5	7	6	17	0	0	0
Hockley County	0	2	4	6	8	5	10	64	36	49
Lynn County	0	3	6	9	12	16	11	9	8	5
District Total	*3*	*42*	*82*	*114*	*148*	*141*	*241*	*83*	*58*	*70*
Llano Estacado Underground Water Conservation District										
Gaines County	4	35	30	27	63	28	69	180	145	55
Mesa Underground Water Conservation District										
Dawson County	10	83	126	42	22	22	34	7	6	13
Sandy Land Underground Water Conservation District										
Yoakum County	0	2	4	5	7	12	10	5	9	6
South Plains Underground Water Conservation District										
Terry County	1	6	12	18	24	29	12	0	0	0
No Groundwater Conservation District										
Borden County	0	0	0	0	0	2	4	6	19	15
Livestock Total	**18**	**167**	**254**	**206**	**264**	**234**	**370**	**283**	**239**	**164**

Table 4.7.26 Total pumping by county for the Edwards-Trinity (High Plains) Aquifer.

County	Pumping (acre-feet per year)									
	1940	1950	1960	1970	1980	1990	1995	2000	2005	2010
Garza County Underground Water Conservation District										
Garza County	0	4	8	11	15	0	0	191	187	118
Sandy Land Underground Water Conservation District										
Yoakum County	43	469	895	1,322	2,179	331	163	5	9	6
South Plains Underground Water Conservation District										
Terry County	10	112	215	317	760	1,048	72	0	0	16
High Plains Underground Water Conservation District										
Bailey County	5	78	159	201	264	851	116	0	0	0
Cochran County	4	51	99	136	347	68	22	11	14	16
Floyd County	43	475	907	1,339	1,883	801	1,468	0	0	0
Hale County	151	1,665	3,179	4,693	6,271	1,499	4,900	13,508	8,918	8,085
Hockley County	2	21	41	61	93	16	23	64	36	75
Lamb County	7	80	153	226	299	0	0	0	0	13
Lubbock County	9	98	187	276	365	0	0	1,483	691	668
Lynn County	10	107	203	300	407	177	511	1,344	730	624
District Total	*232*	*2,576*	*4,929*	*7,232*	*9,929*	*3,412*	*7,040*	*16,410*	*10,389*	*9,481*
Llano Estacado Underground Water Conservation District										
Gaines County	838	7,169	6,140	5,590	13,536	10,190	12,398	12,664	12,021	9,779
Mesa Underground Water Conservation District										
Dawson County	135	1,158	1,772	592	340	634	1,339	2,000	1,403	1,087
No Groundwater Conservation District										
Borden County	0	1	3	4	5	64	4	6	19	15
Aquifer Total	**1,258**	**11,490**	**13,961**	**15,069**	**26,765**	**15,679**	**21,016**	**31,276**	**24,028**	**20,504**

Table 4.7.27 Total pumping by category for the Rita Blanca Aquifer.

Category	Pumping (acre-feet per year)									
	1940	1950	1960	1970	1980	1990	1995	2000	2005	2010
North Plains Groundwater Conservation District - Dallam County										
Irrigation	541	1,082	1,911	3,166	6,506	6,554	4,843	5,641	4,644	4,165
Municipal	12	25	19	27	31	18	15	411	163	146
Manufacturing	0	0	0	0	0	0	0	0	9	8
Mining(a)										
Power(a)										
Livestock	2	5	7	7	34	39	71	72	75	68
Rural Domestic(a)										
Aquifer Total	**556**	**1,111**	**1,937**	**3,200**	**6,571**	**6,611**	**4,929**	**6,124**	**4,891**	**4,386**

(a) no pumping from the aquifer for this category

Table 4.7.28 Non-Texas pumping for the Ogallala Aquifer.

County	Pumping (acre-feet per year)									
	1940	**1950**	**1960**	**1970**	**1980**	**1990**	**1995**	**2000**	**2005**	**2010**
New Mexico										
Curry County	1,579	2,153	72,671	289,185	244,820	102,862	130,821	125,854	126,001	126,001
Lea County	4,748	98,507	113,132	132,607	114,796	63,148	50,614	58,694	58,707	58,647
Quay County	1,889	6,919	2,319	9,094	12,014	879	1,379	1,623	1,195	1,195
Roosevelt County	26,998	53,460	86,599	170,665	160,682	92,457	107,426	104,381	104,339	104,339
Union County	356	233	4,482	9,925	12,861	13,223	12,367	10,529	11,671	12,354
State Total	**35,569**	**161,272**	**279,203**	**611,476**	**545,173**	**272,568**	**302,606**	**301,081**	**301,914**	**302,536**
Oklahoma										
Beaver County	374	839	15,054	36,096	41,250	36,488	35,727	40,372	43,886	45,323
Cimarron County	44,530	886	37,846	120,709	88,554	71,498	69,381	79,587	87,208	90,776
Ellis County	164	655	3,413	12,600	24,884	38,564	39,711	45,447	49,401	50,782
Harper County	325	127	6,464	8,398	11,873	11,158	10,977	12,544	13,636	14,045
Roger Mills County	835	1	21	68	85	79	78	88	95	97
Texas County	117	1,669	88,864	266,681	242,339	221,897	218,487	248,375	269,899	277,548
State Total	**46,343**	**4,177**	**151,661**	**444,553**	**408,984**	**379,684**	**374,360**	**426,413**	**464,125**	**478,572**
Kansas										
Morton County	0	191	3,888	10,761	10,136	9,143	8,996	10,280	11,175	11,510
Seward County	1	327	11,969	29,982	39,118	41,817	41,774	47,740	51,894	53,451
Stevens County	20	649	51,392	114,044	149,510	159,128	158,881	181,568	197,369	203,291
State Total	**21**	**1,167**	**67,249**	**154,788**	**198,764**	**210,087**	**209,651**	**239,588**	**260,439**	**268,252**

Table 4.7.29 Non-Texas pumping for the Rita Blanca Aquifer.

County	Pumping (acre-feet per year)									
	1940	**1950**	**1960**	**1970**	**1980**	**1990**	**1995**	**2000**	**2005**	**2010**
New Mexico										
Union County	4,916	8,471	7,554	7,232	7,481	7,602	8,640	10,119	4,916	8,471
State Total	**4,916**	**8,471**	**7,554**	**7,232**	**7,481**	**7,602**	**8,640**	**10,119**	**4,916**	**8,471**

Table 4.7.30 Non-Texas pumping for the Dockum Aquifer.

County	Pumping (acre-feet per year)									
	1940	**1950**	**1960**	**1970**	**1980**	**1990**	**1995**	**2000**	**2005**	**2010**
New Mexico										
Curry County	39	78	151	422	501	653	524	508	508	508
Lea County	224	449	873	2,445	2,902	2,363	2,622	2,975	2,975	2,975
Quay County	391	781	1,520	4,255	5,050	3,818	5,684	3,997	3,997	3,997
Roosevelt County	20	41	80	223	265	353	245	245	245	245
State Total	**674**	**1,349**	**2,623**	**7,345**	**8,718**	**7,187**	**9,075**	**7,725**	**7,725**	**7,725**

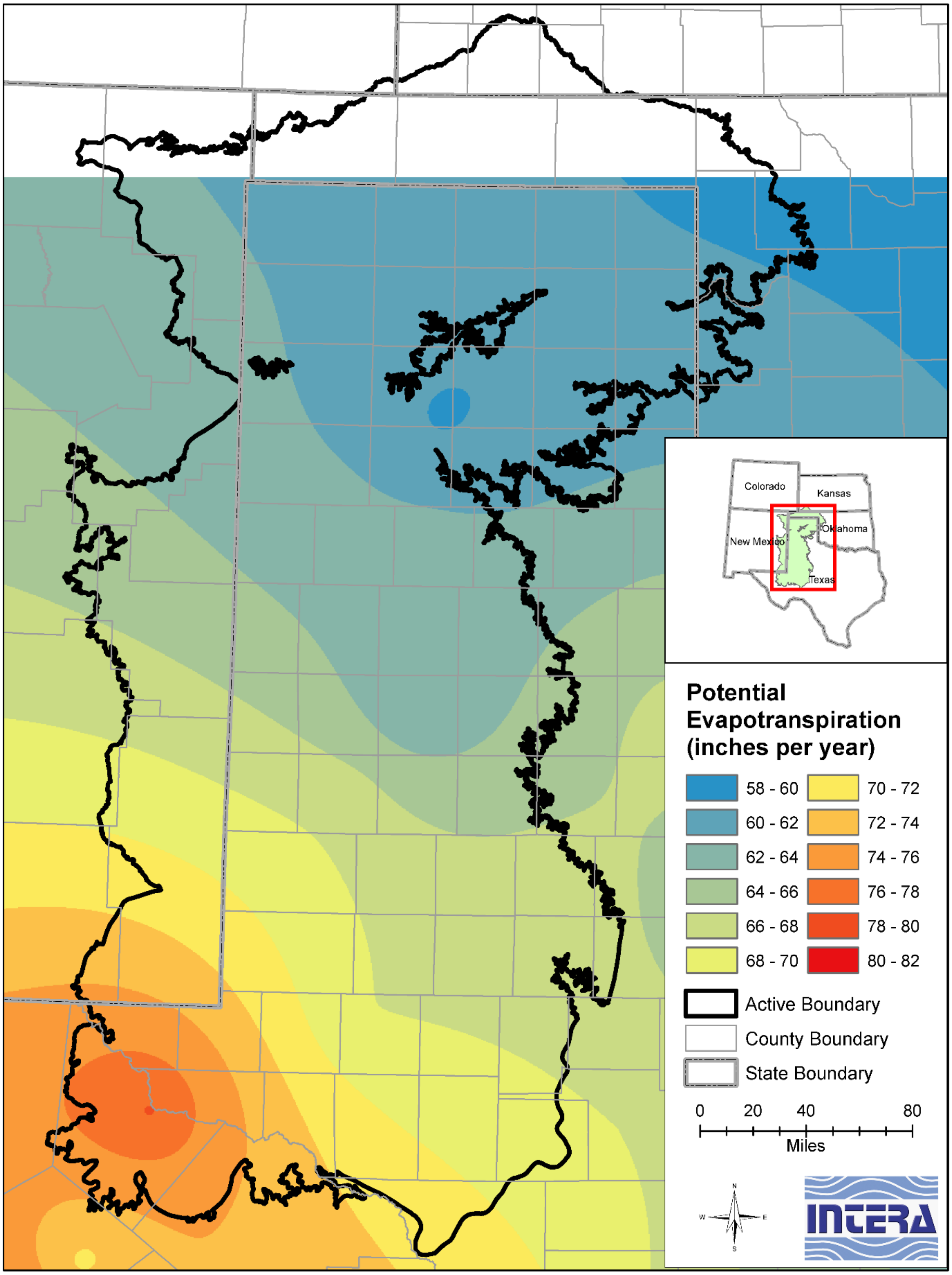

Figure 4.7.1 **Potential evapotranspiration in inches per year in the study area (Borrelli and others, 1998)**

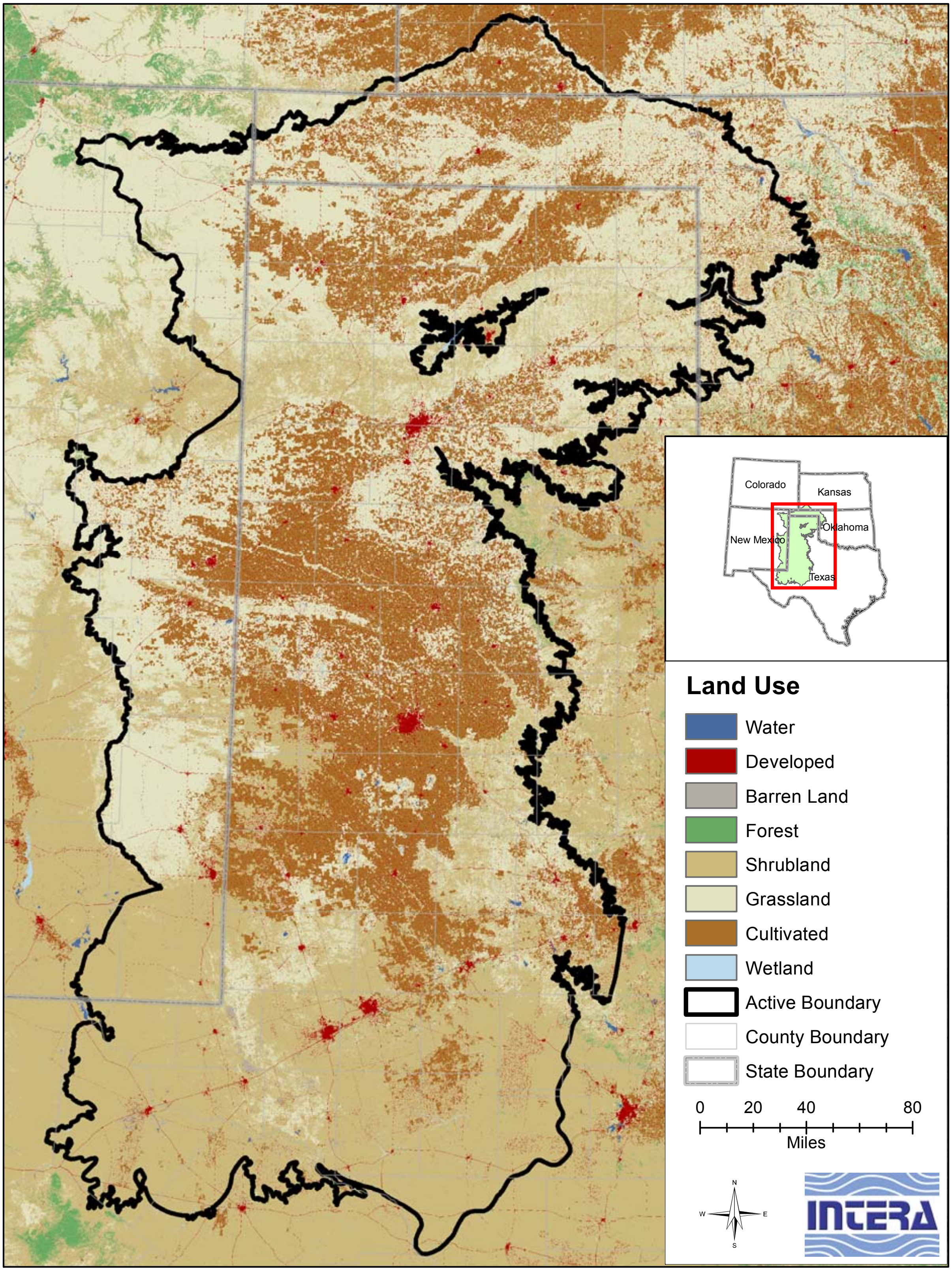

Figure 4.7.2 Land use in the study area (Fry and others, 2011).

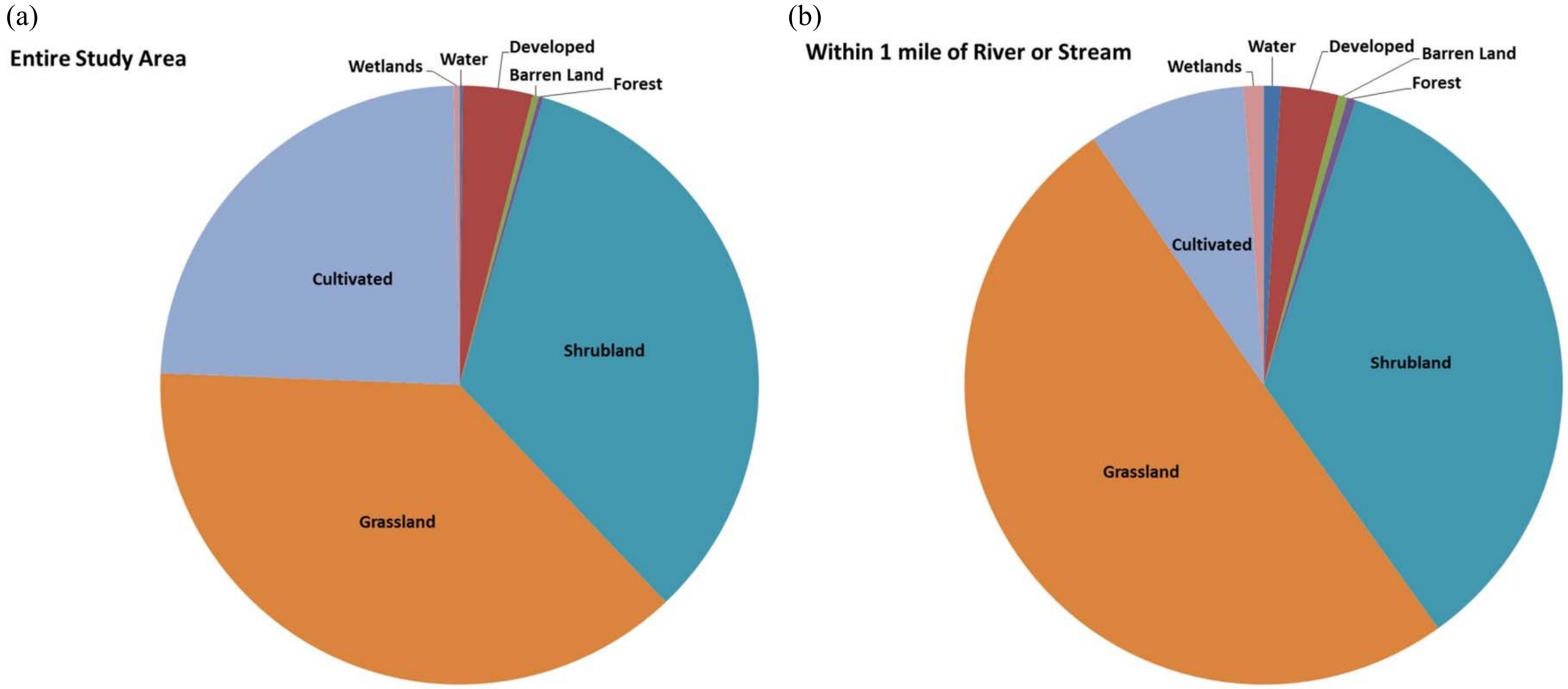

Figure 4.7.3 Land use distribution in the (a) entire study area and (b) within 1 mile of a river or stream.

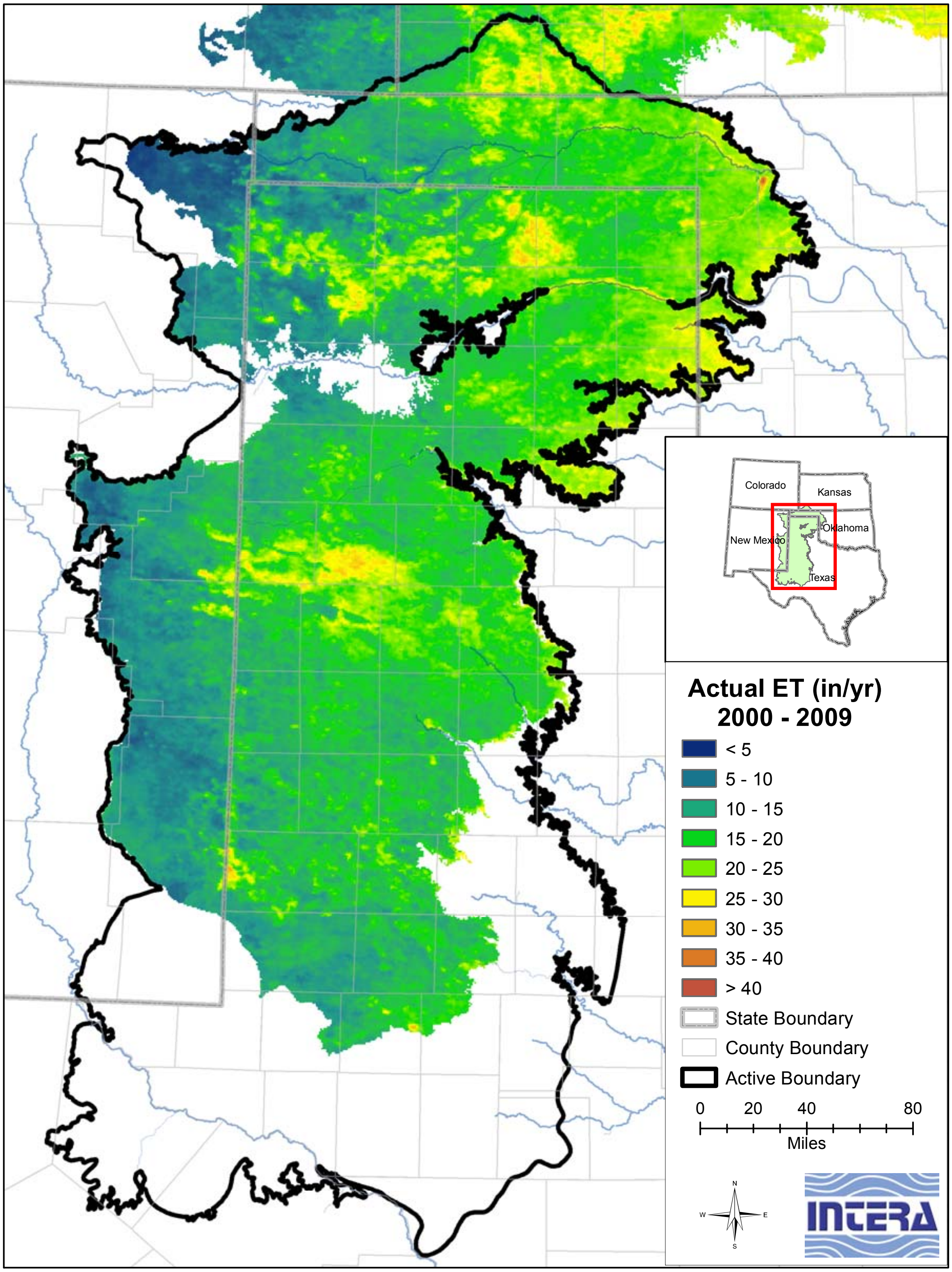

Figure 4.7.4 Actual evapotranspiration in inches per year in the Ogallala Aquifer (Houston and others, 2013).

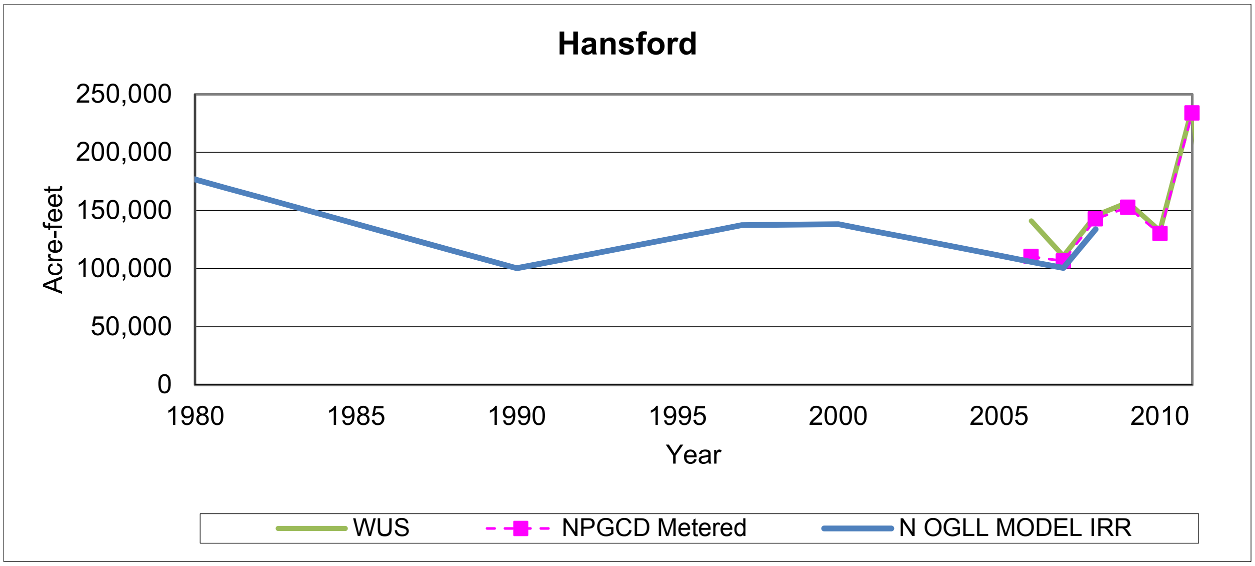

Figure 4.7.5 **Comparison of pumping estimates from the updated Northern Ogallala Aquifer groundwater availability model (N OGLL MODEL IRR), the TWDB water use survey data (WUS), and the North Plains Groundwater Conservation District metered data for Hansford County (NPGCD Metered), which lies completely with the North Plains Groundwater Conservation District.**

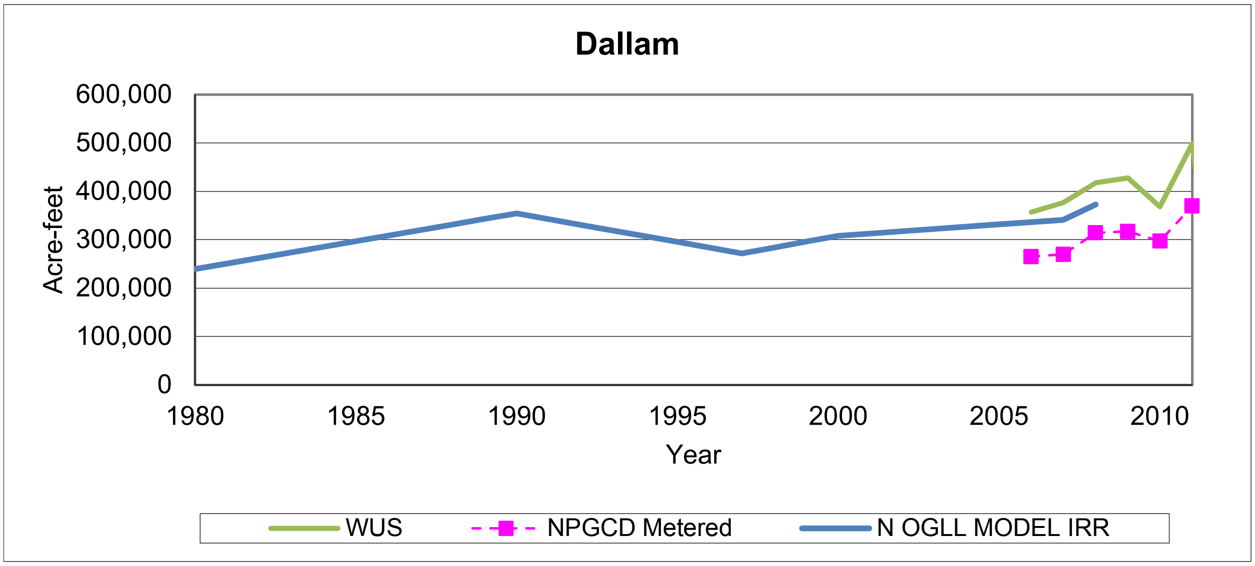

Figure 4.7.6 **Comparison of pumping estimates from the updated Northern Ogallala Aquifer groundwater availability model (N OGLL MODEL IRR), the TWDB water use survey data (WUS), and the North Plains Groundwater Conservation District metered data for Dallam County (NPGCD Metered), which lies partially within the North Plains Groundwater Conservation District.**

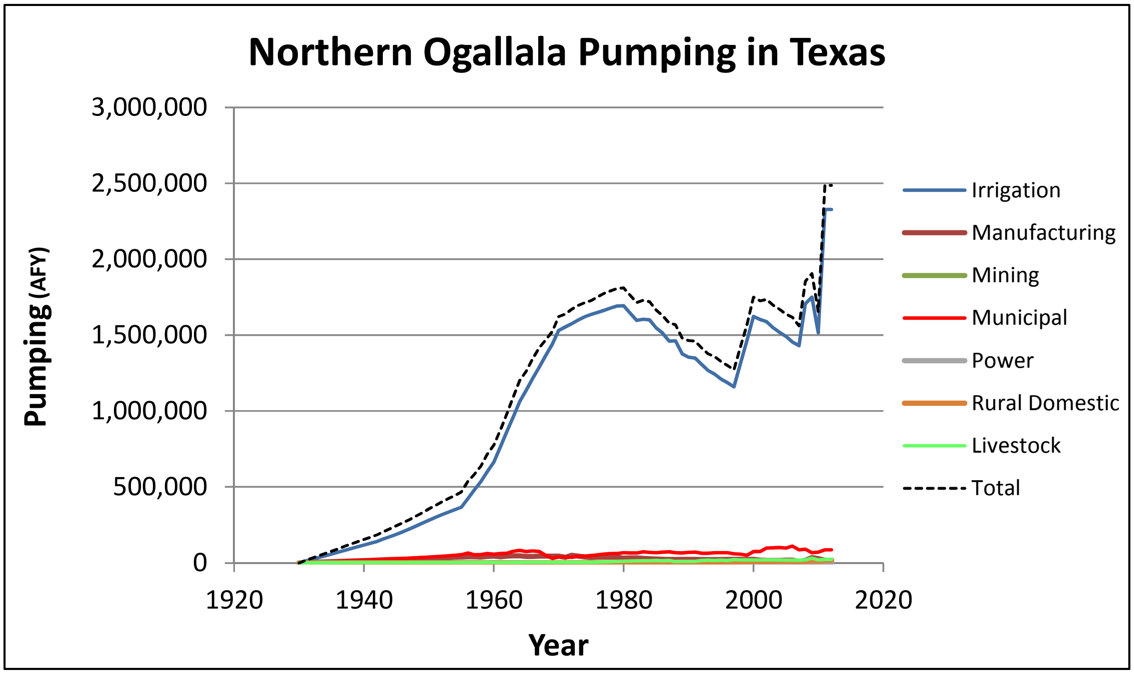

Figure 4.7.7 Estimated pumping in acre-feet per year in the Texas portion of the Northern Ogallala Aquifer.

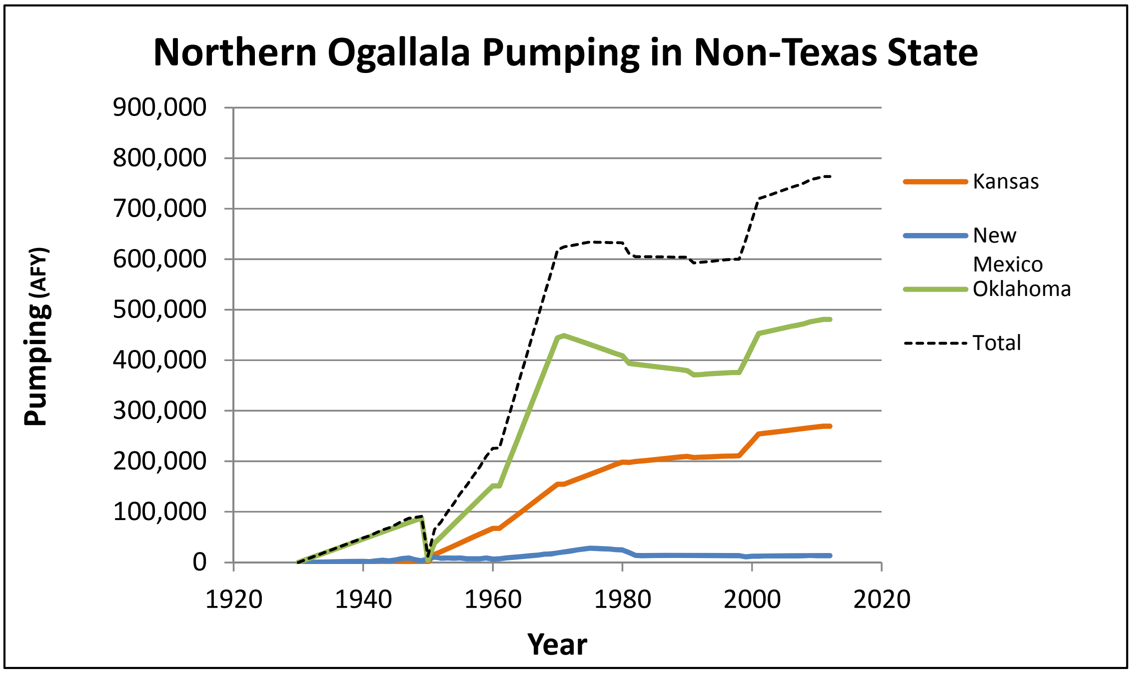

Figure 4.7.8 Estimated pumping in acre-feet per year in the non-Texas portion of the Northern Ogallala Aquifer.

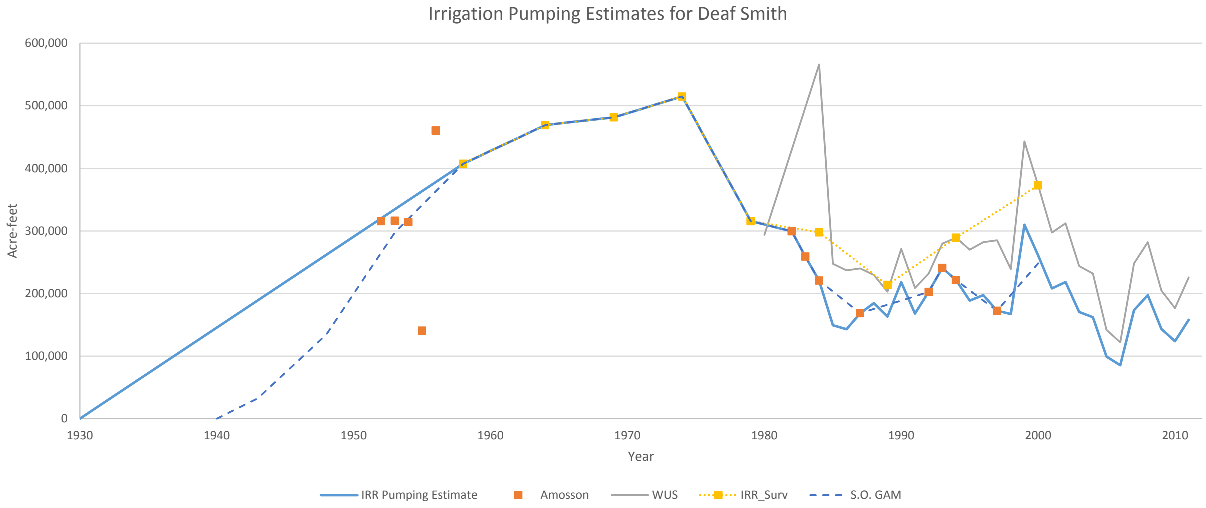

Figure 4.7.9 **Comparison of estimated irrigation pumping for Deaf Smith County between the current model, the Amosson and others (2003) data, the TWDB water use survey data , the TWDB irrigation survey data (TWDB, 1991), and the pre-calibrated/no return flow pumping estimates from the original Southern Ogallala Aquifer groundwater availability model (Blandford and others, 2003).**

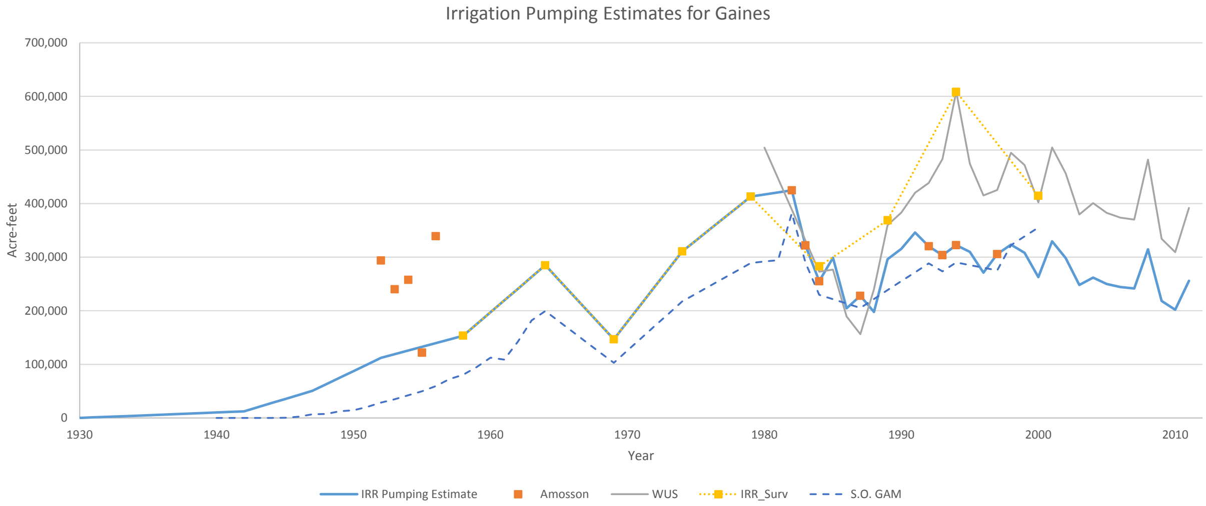

Figure 4.7.10 **Comparison of estimated irrigation pumping for Gaines County between the current model, the Amosson and others (2003) data, the TWDB water use survey data , the TWDB irrigation survey data (TWDB, 1991), and the pre-calibrated/no return flow pumping estimates from the original Southern Ogallala Aquifer groundwater availability model (Blandford and others, 2003).**

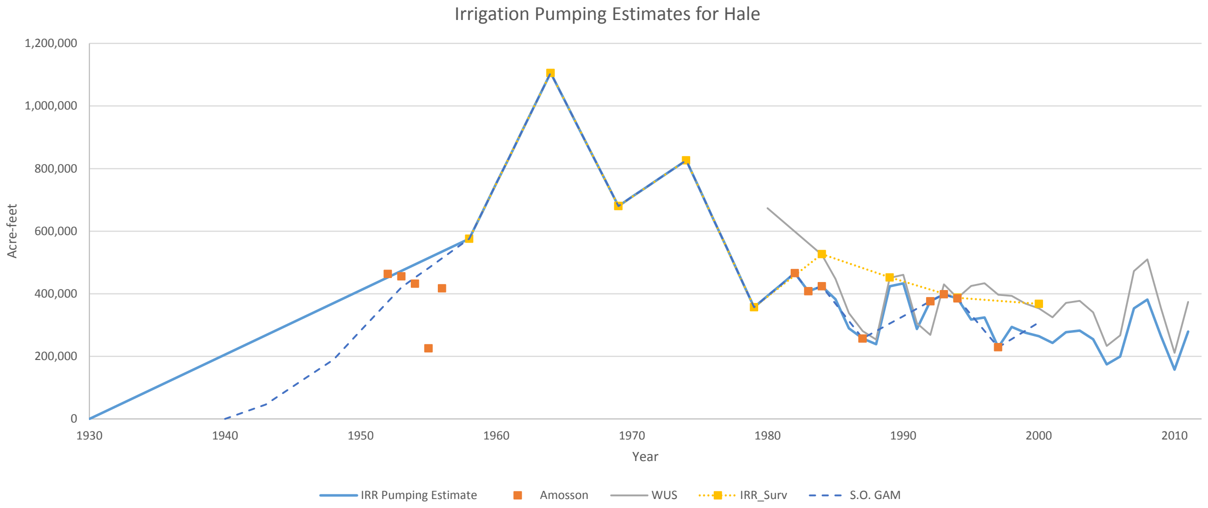

Figure 4.7.11 **Comparison of estimated irrigation pumping for Hale County between the current model, the Amosson and others (2003) data, the TWDB water use survey data , the TWDB irrigation survey data (TWDB, 1991), and the pre-calibrated/no return flow pumping estimates from the original Southern Ogallala Aquifer groundwater availability model (Blandford and others, 2003).**

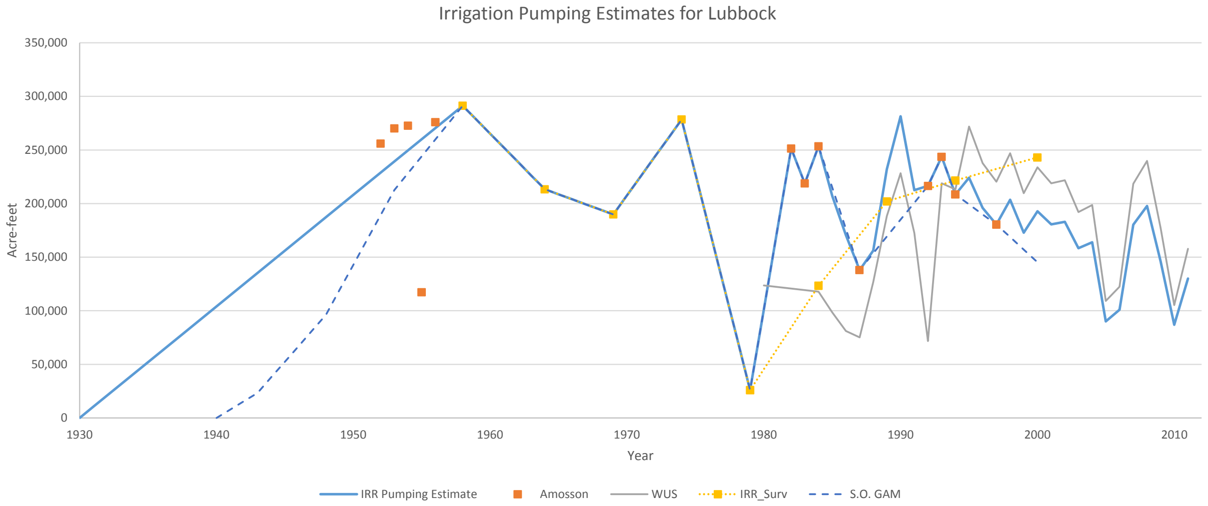

Figure 4.7.12 **Comparison of estimated irrigation pumping for Lubbock County between the current model, the Amosson and others (2003) data, the TWDB water use survey data , the TWDB irrigation survey data (TWDB, 1991), and the pre-calibrated/no return flow pumping estimates from the original Southern Ogallala Aquifer groundwater availability model (Blandford and others, 2003).**

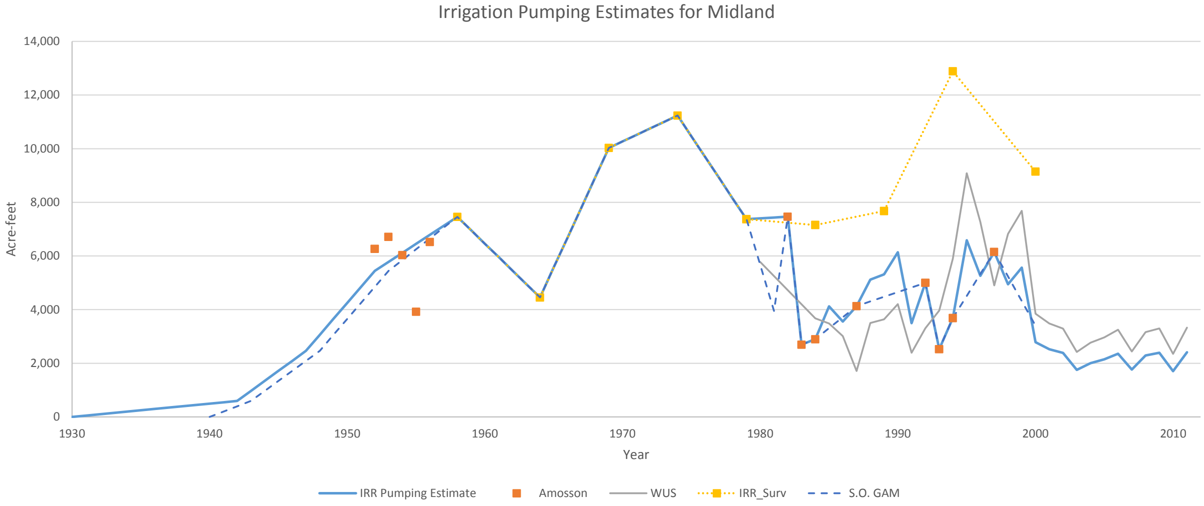

Figure 4.7.13 **Comparison of estimated irrigation pumping for Midland County between the current model, the Amosson and others (2003) data, the TWDB water use survey data , the TWDB irrigation survey data (TWDB, 1991), and the pre-calibrated/no return flow pumping estimates from the original Southern Ogallala Aquifer groundwater availability model (Blandford and others, 2003).**

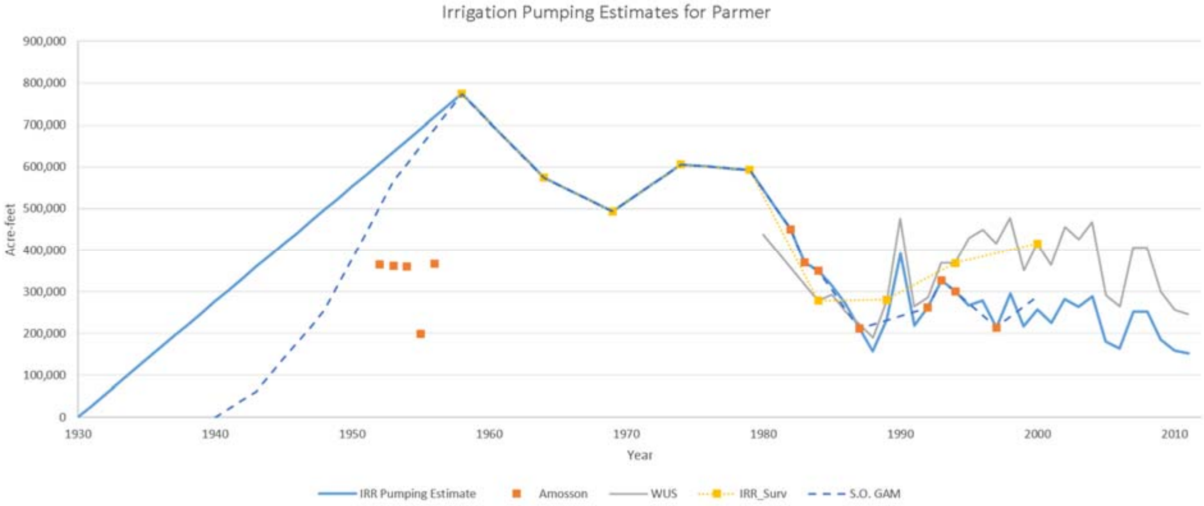

Figure 4.7.14 **Comparison of estimated irrigation pumping Parmer County between the current model, the Amosson and others (2003) data, the TWDB water use survey data , the TWDB irrigation survey data (TWDB, 1991), and the pre-calibrated/no return flow pumping estimates from the original Southern Ogallala Aquifer groundwater availability model (Blandford and others, 2003).**

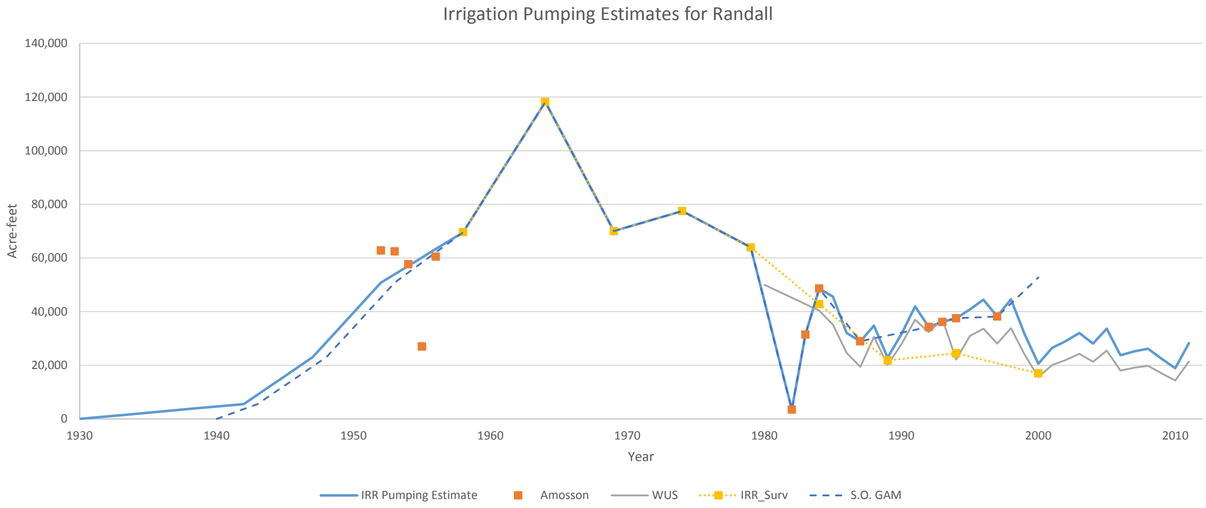

Figure 4.7.15 **Comparison of estimated irrigation pumping for Randall County between the current model, the Amosson and others (2003) data, the TWDB water use survey data , the TWDB irrigation survey data (TWDB, 1991), and the pre-calibrated/no return flow pumping estimates from the original Southern Ogallala Aquifer groundwater availability model (Blandford and others, 2003).**

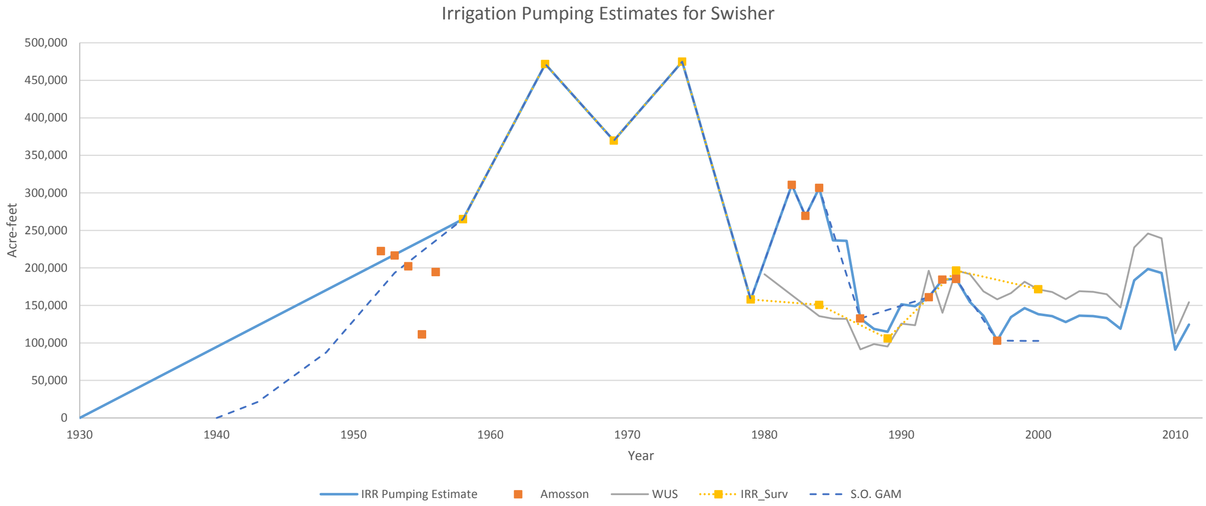

Figure 4.7.16 **Comparison of estimated irrigation pumping for Swisher County between the current model, the Amosson and others (2003) data, the TWDB water use survey data , the TWDB irrigation survey data (TWDB, 1991), and the pre-calibrated/no return flow pumping estimates from the original Southern Ogallala Aquifer groundwater availability model (Blandford and others, 2003).**

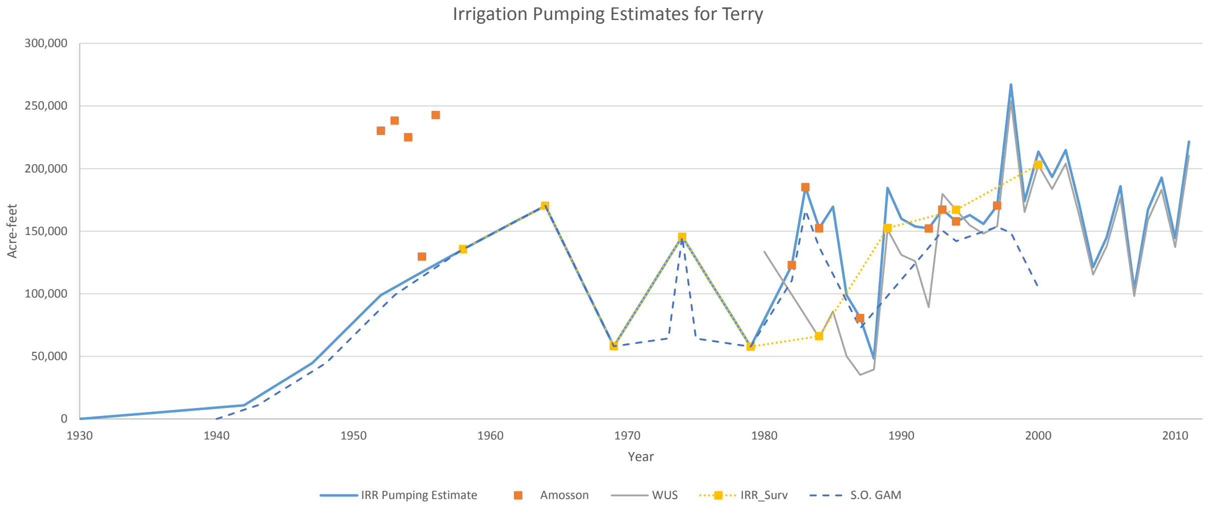

Figure 4.7.17 **Comparison of estimated irrigation pumping for Terry County between the current model, the Amosson and others (2003) data, the TWDB water use survey data , the TWDB irrigation survey data (TWDB, 1991), and the pre-calibrated/no return flow pumping estimates from the original Southern Ogallala Aquifer groundwater availability model (Blandford and others, 2003).**

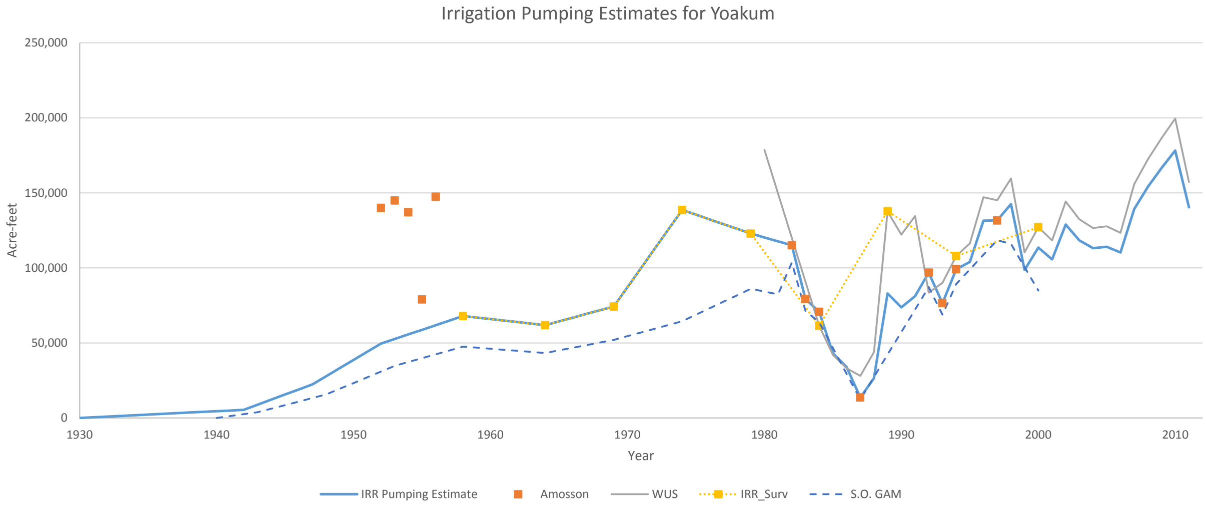

Figure 4.7.18 **Comparison of estimated irrigation pumping for Yoakum County between the current model, the Amosson and others (2003) data, the TWDB water use survey data , the TWDB irrigation survey data (TWDB, 1991), and the pre-calibrated/no return flow pumping estimates from the original Southern Ogallala Aquifer groundwater availability model (Blandford and others, 2003).**

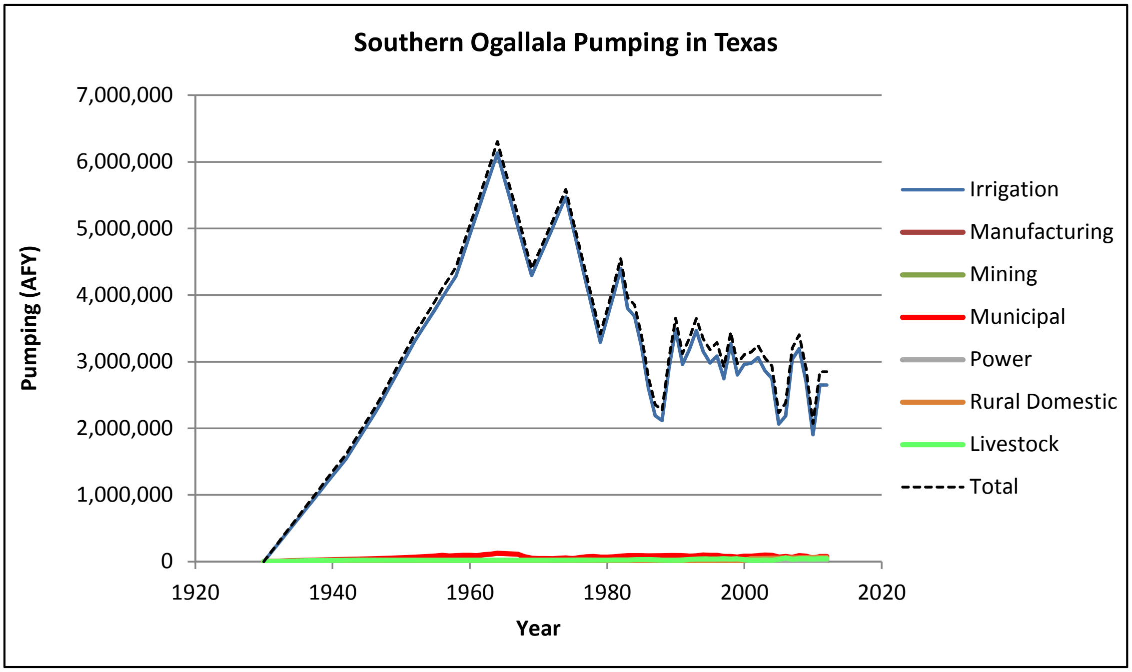

Figure 4.7.19 **Estimated pumping in acre-feet per year in the Texas portion of the Southern Ogallala Aquifer.**

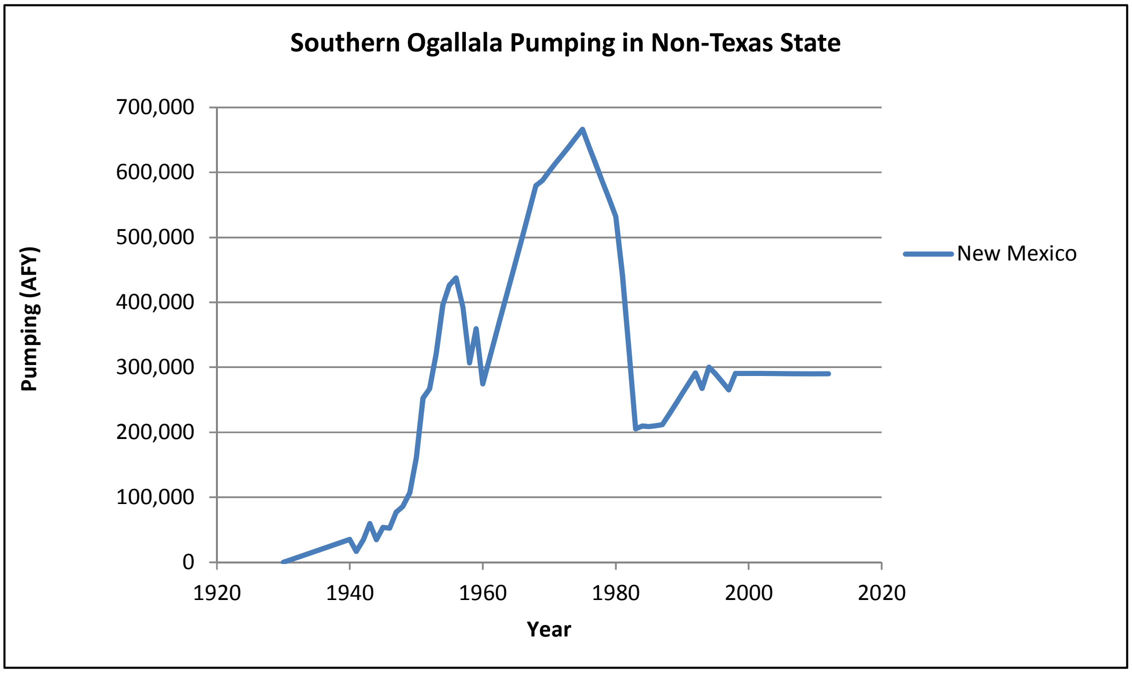

Figure 4.7.20 **Estimated pumping in acre-feet per year in the non-Texas portion of the Southern Ogallala Aquifer**

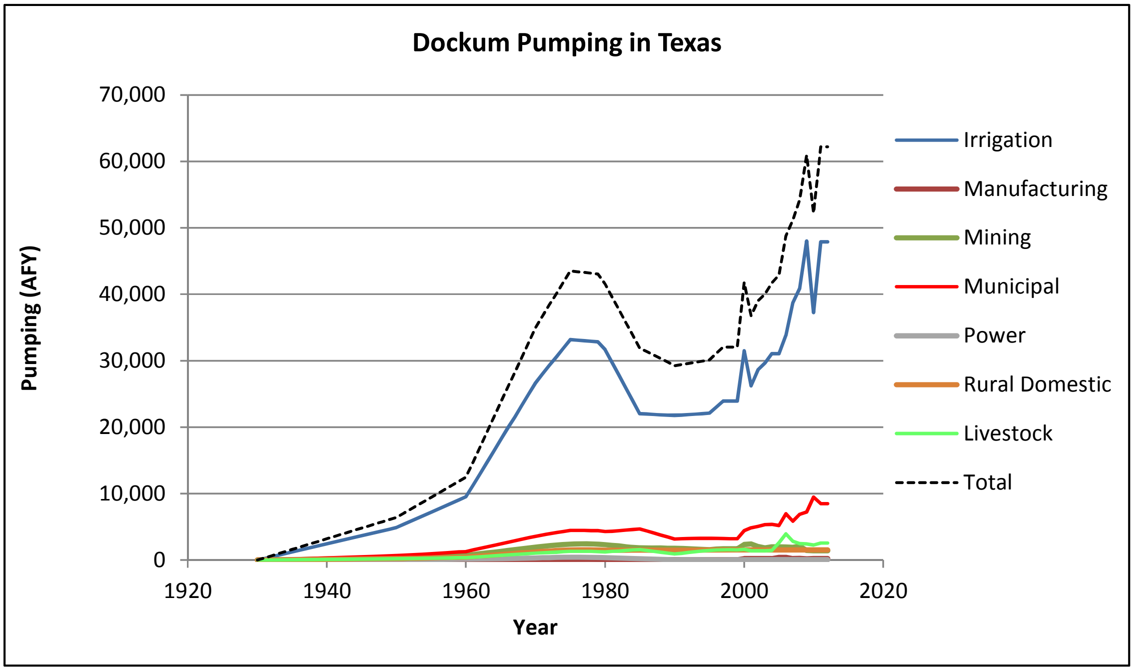

Figure 4.7.21 Estimated pumping in acre-feet per year in the Texas portion of the Dockum Group.

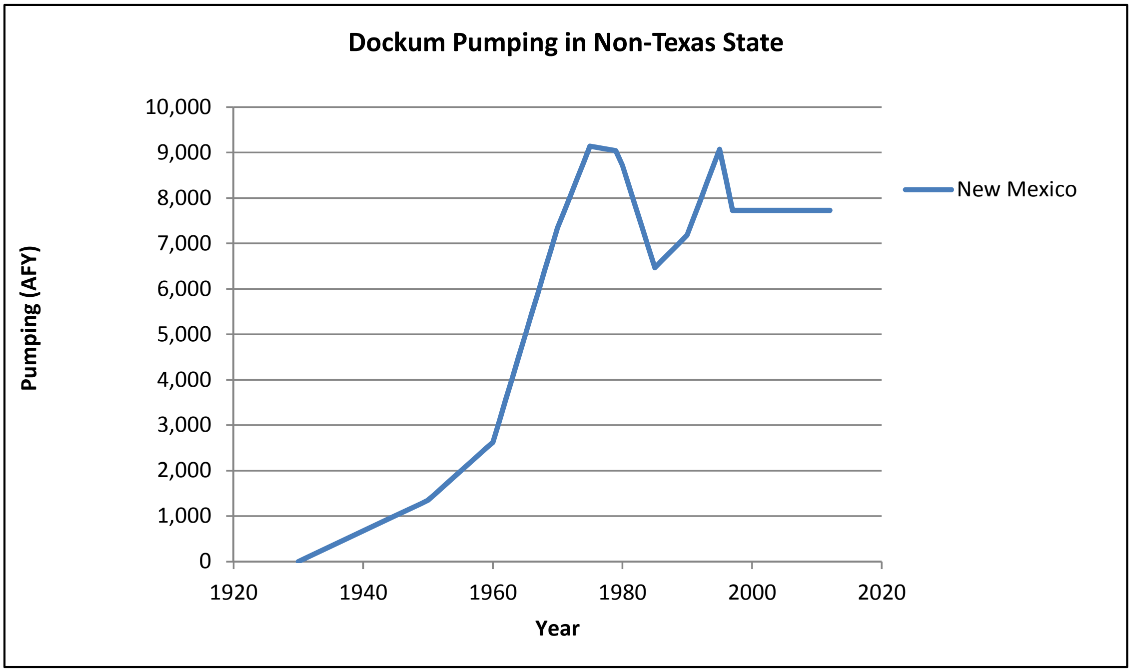

Figure 4.7.22 Estimated pumping in acre-feet per year in the non-Texas portion of the Dockum Group.

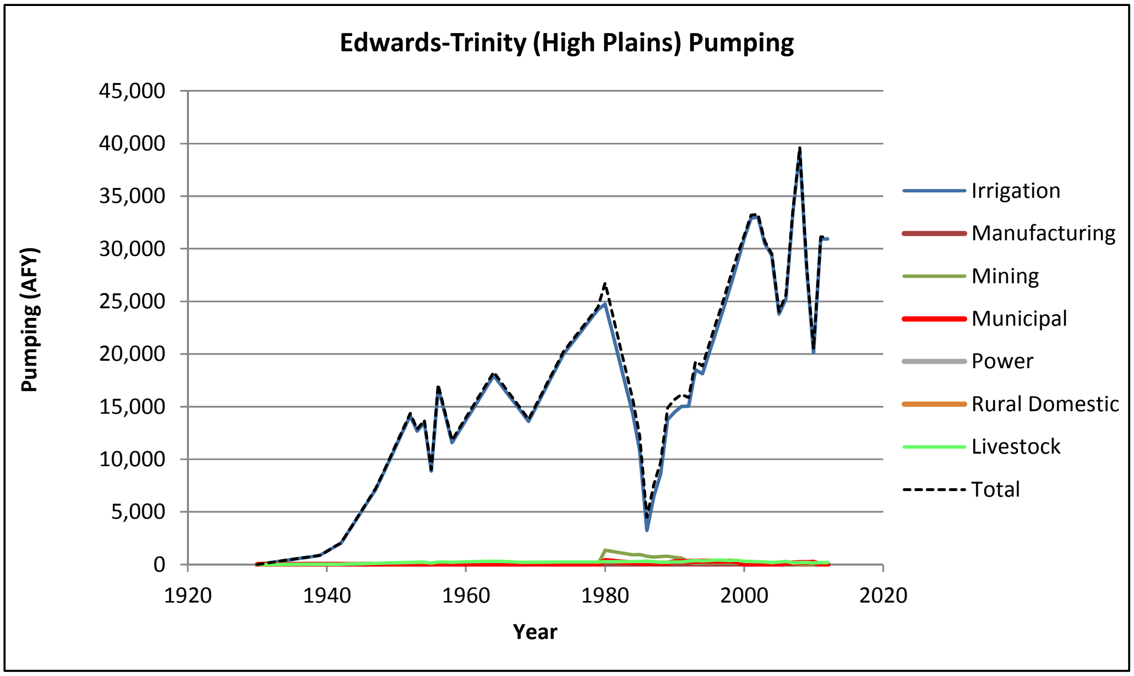

Figure 4.7.23 Estimated pumping in acre-feet per year in the Edwards-Trinity (High Plains) Aquifer.

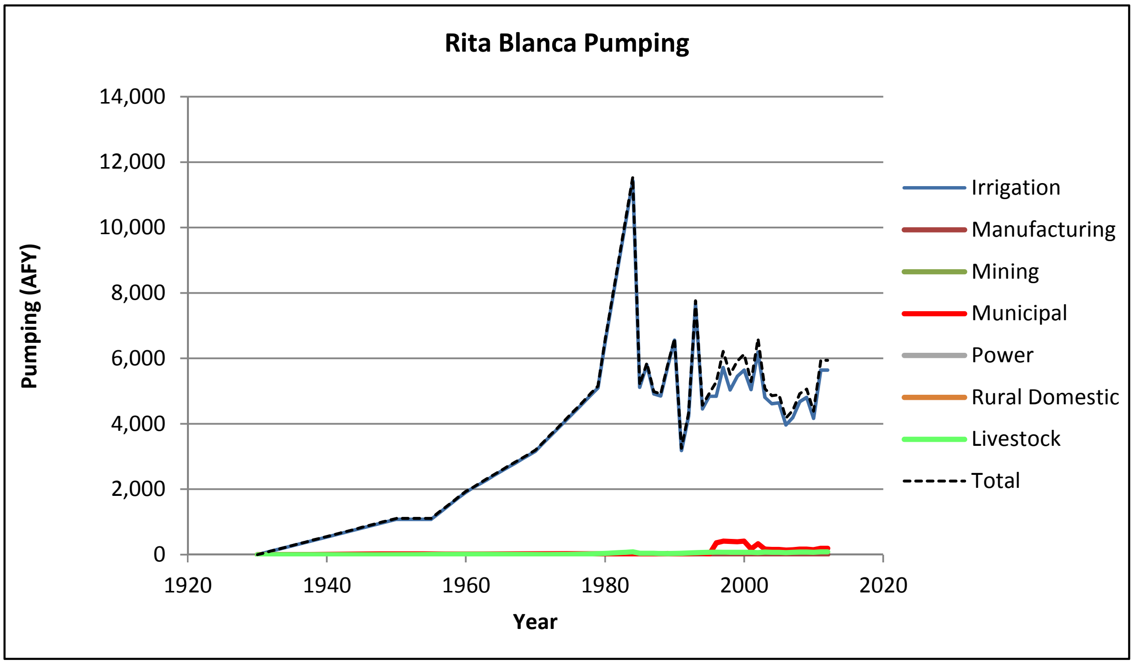

Figure 4.7.24 Estimated pumping in acre-feet per year in the Rita Blanca Aquifer.

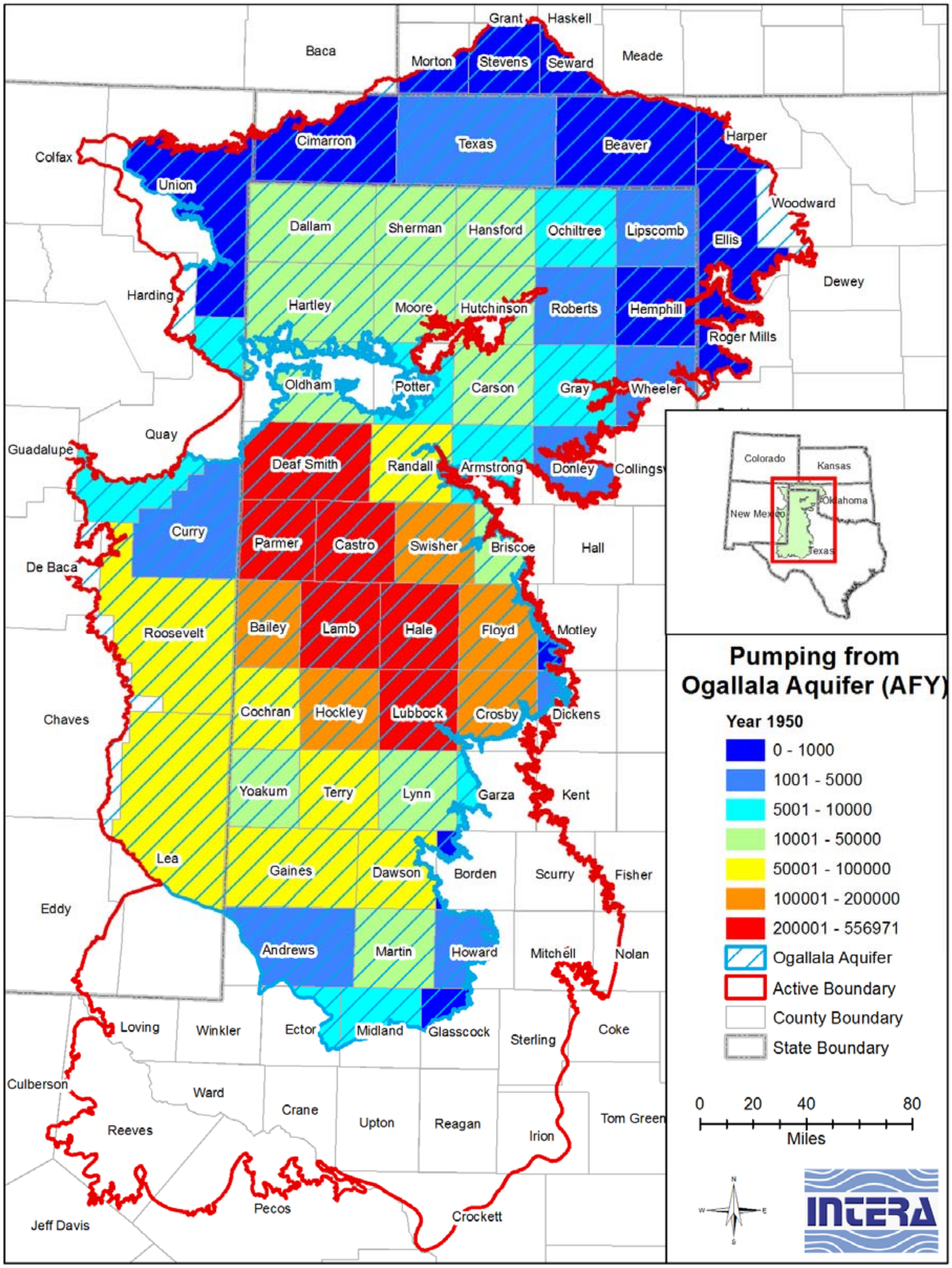

Figure 4.7.25 Estimated county-wide pumping in acre-feet in the Ogallala Aquifer for the year 1950.

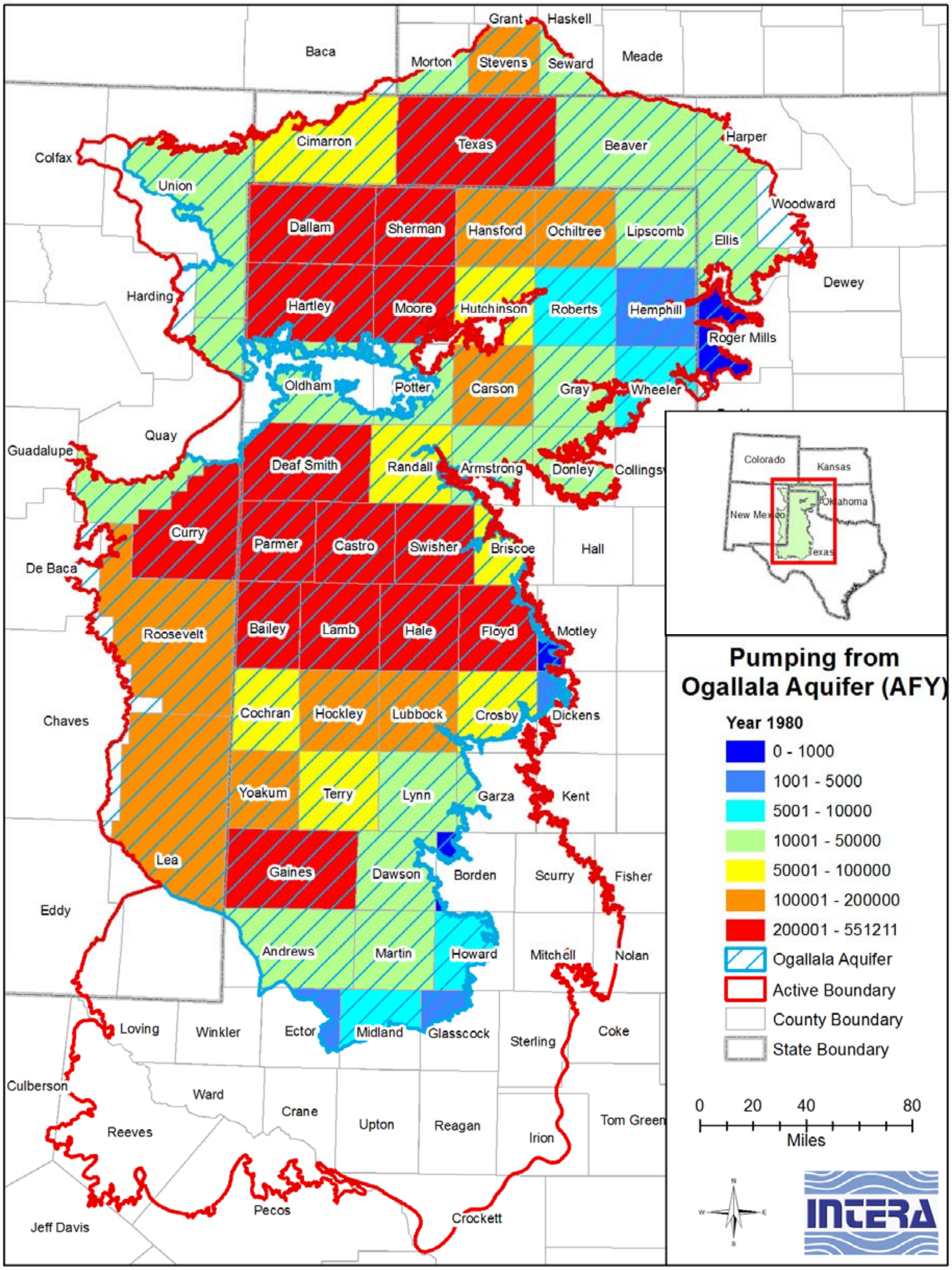

Figure 4.7.26 Estimated county-wide pumping in acre-feet in the Ogallala Aquifer for the year 1980.

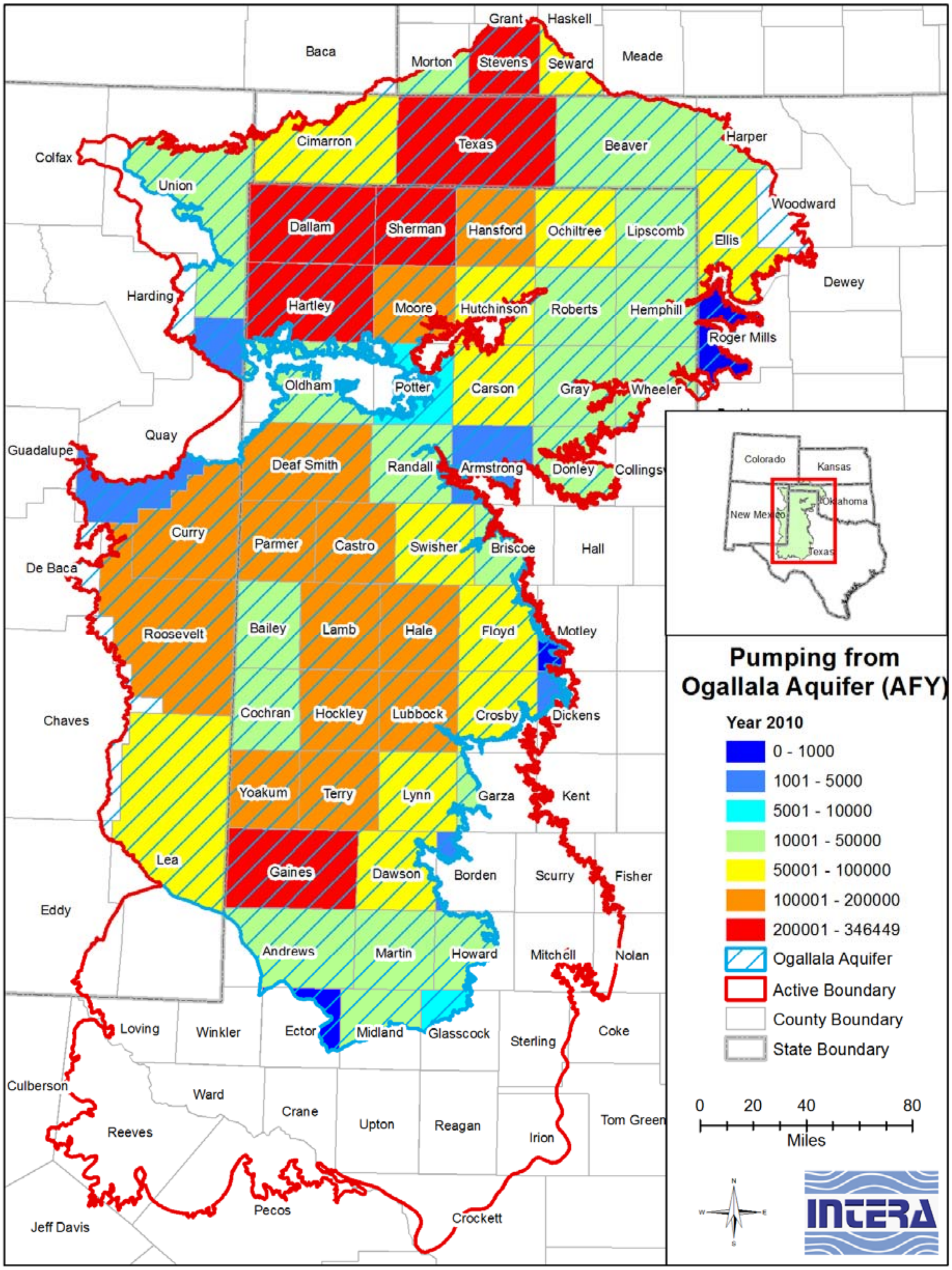

Figure 4.7.27 **Estimated county-wide pumping in acre-feet in the Ogallala Aquifer for the year 2010.**

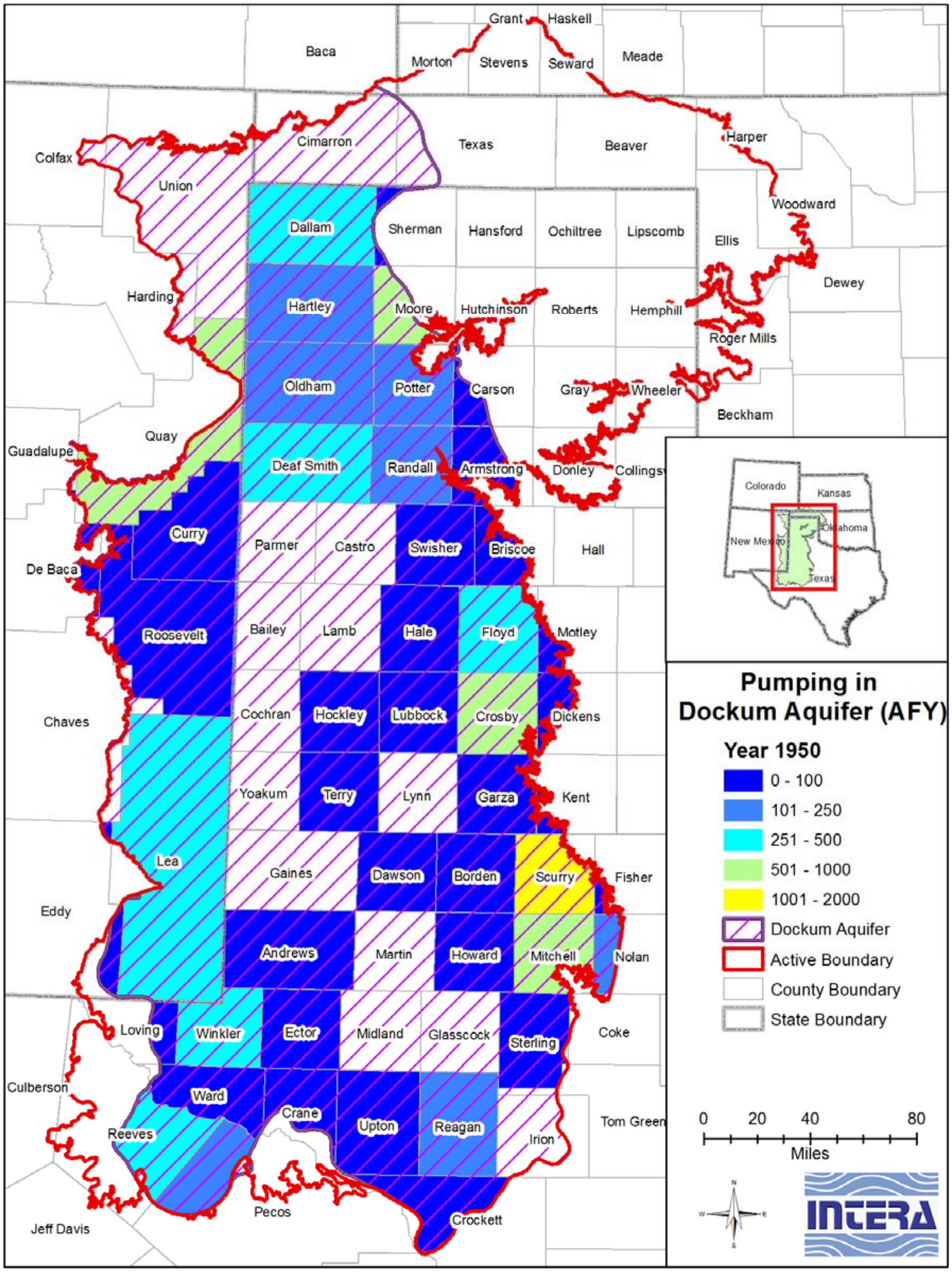

Figure 4.7.28 **Estimated county-wide pumping in acre-feet in the Dockum Group for the year 1950.**

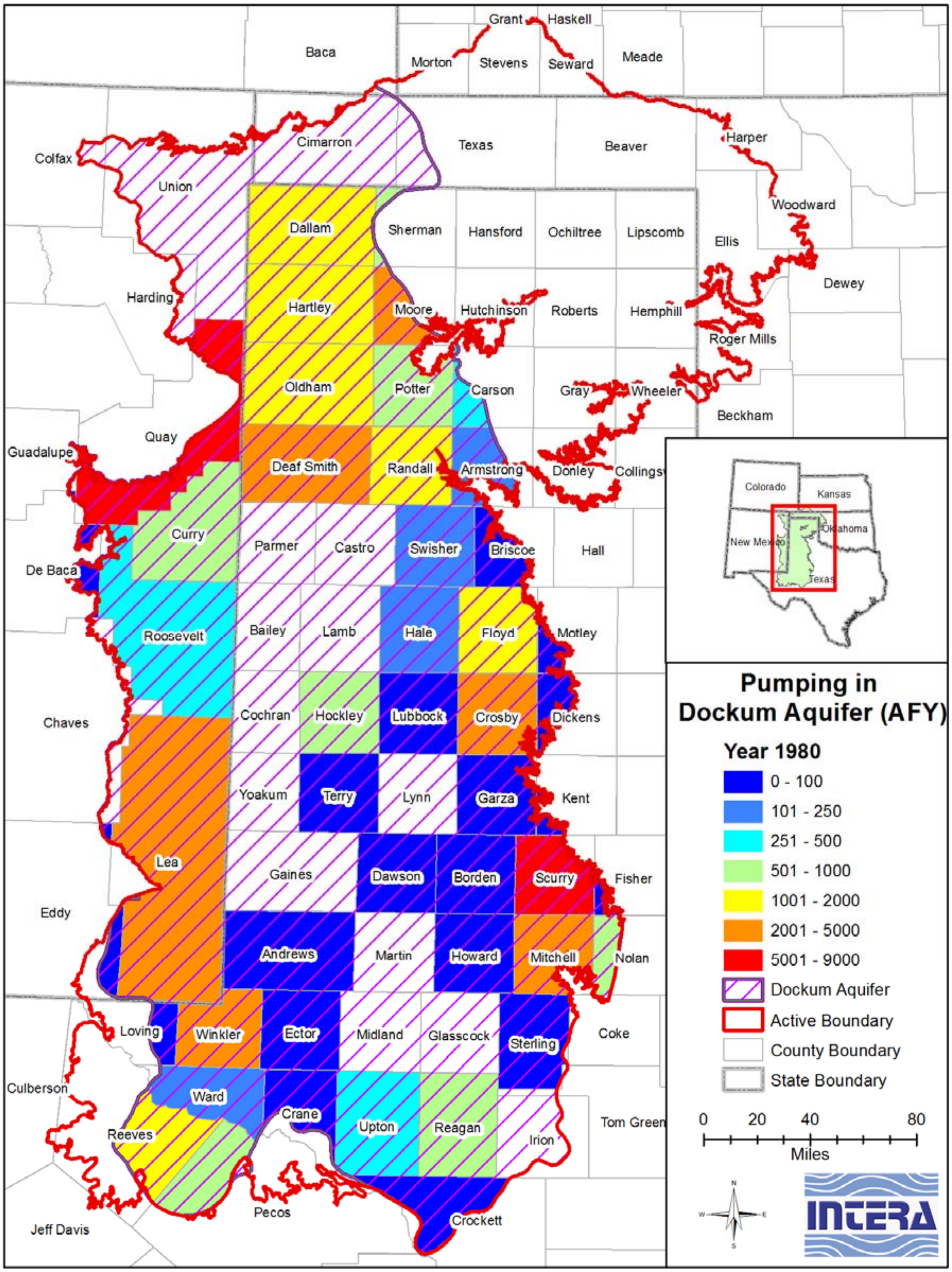

Figure 4.7.29 Estimated county-wide pumping in acre-feet in the Dockum Group for the year 1980.

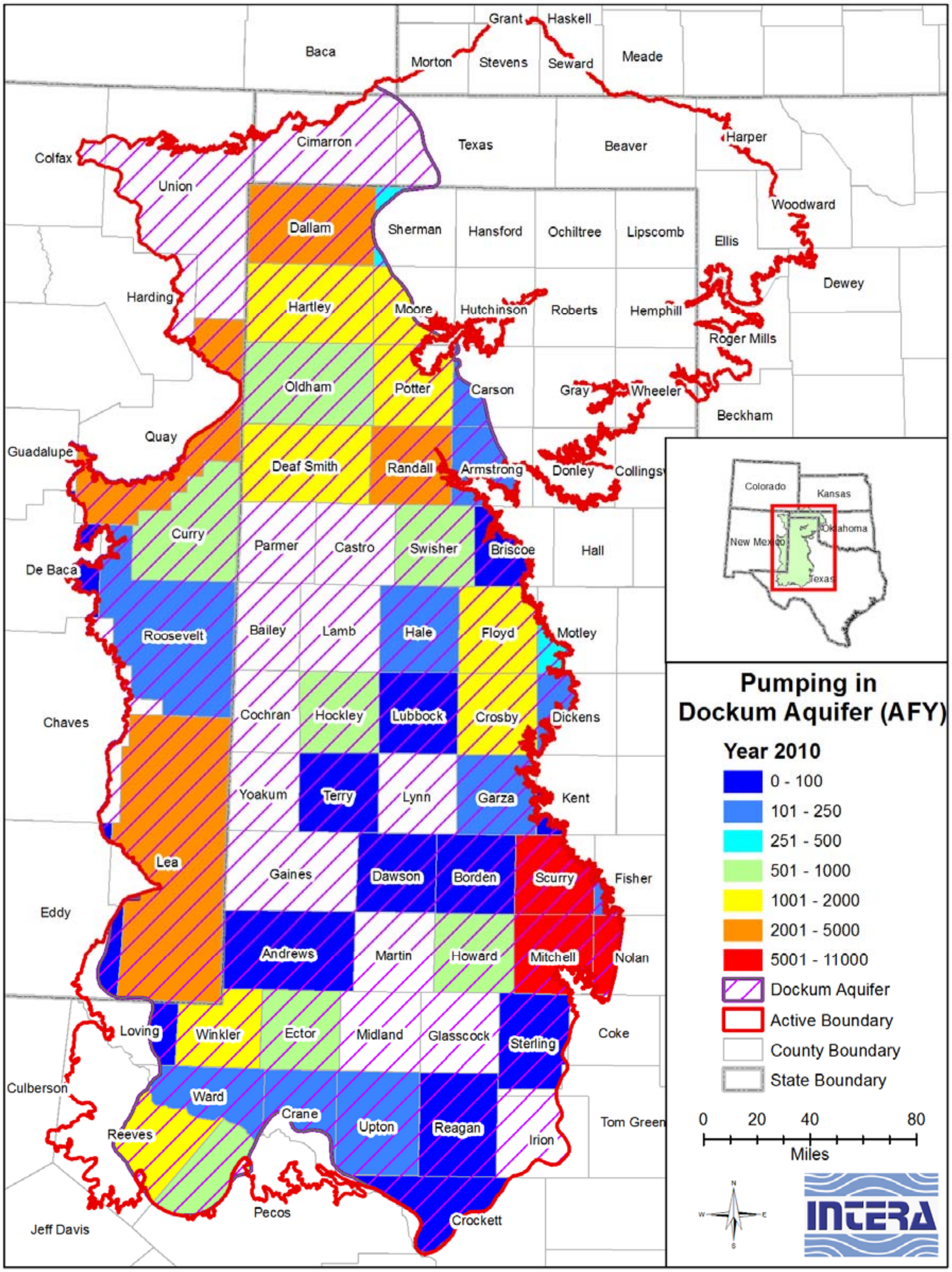

Figure 4.7.30 Estimated county-wide pumping in acre-feet in the Dockum Group for the year 2010.

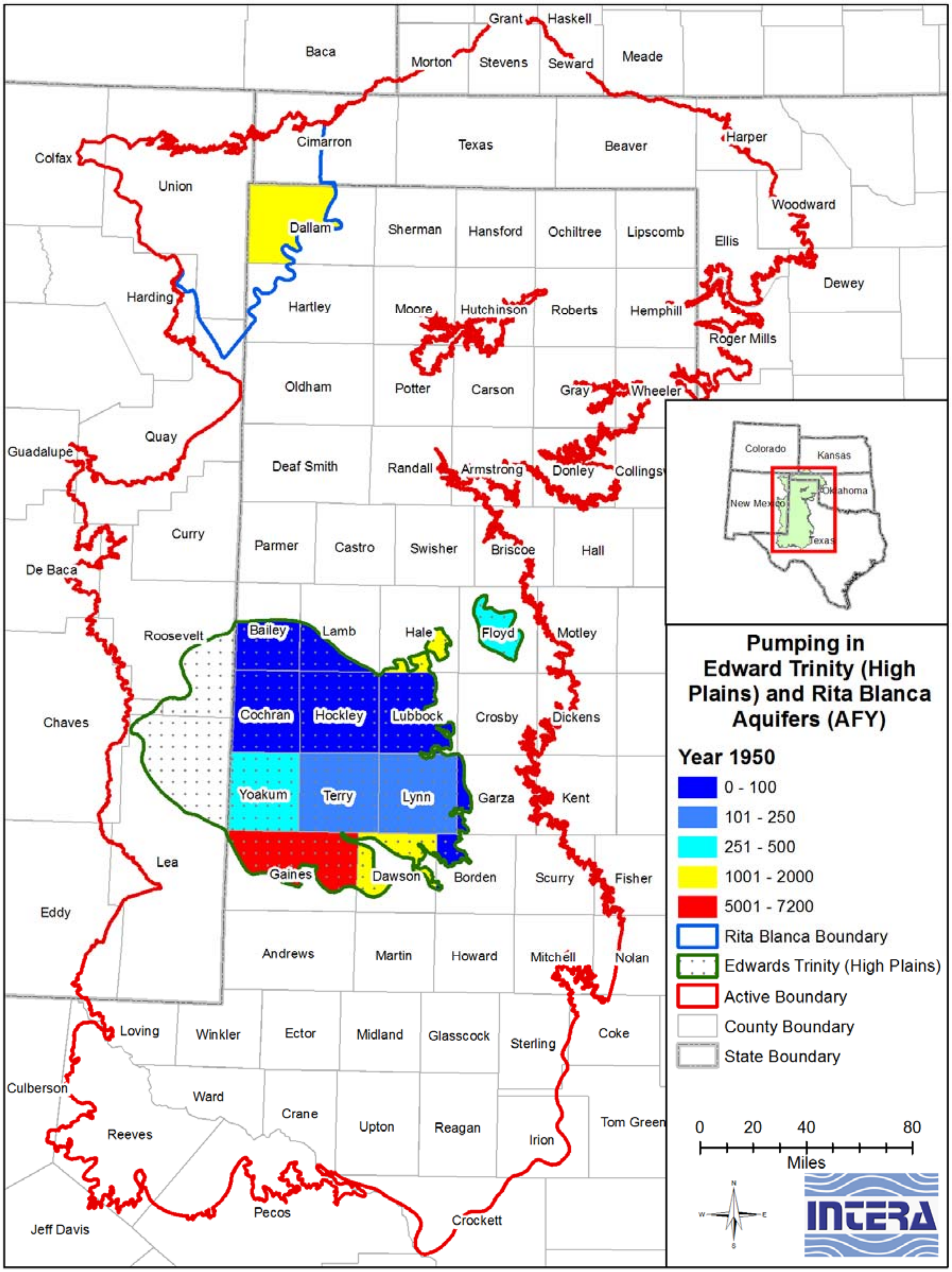

Figure 4.7.31 Estimated county-wide pumping in acre-feet in the Edwards-Trinity (High Plains) and Rita Blanca aquifers for the year 1950.

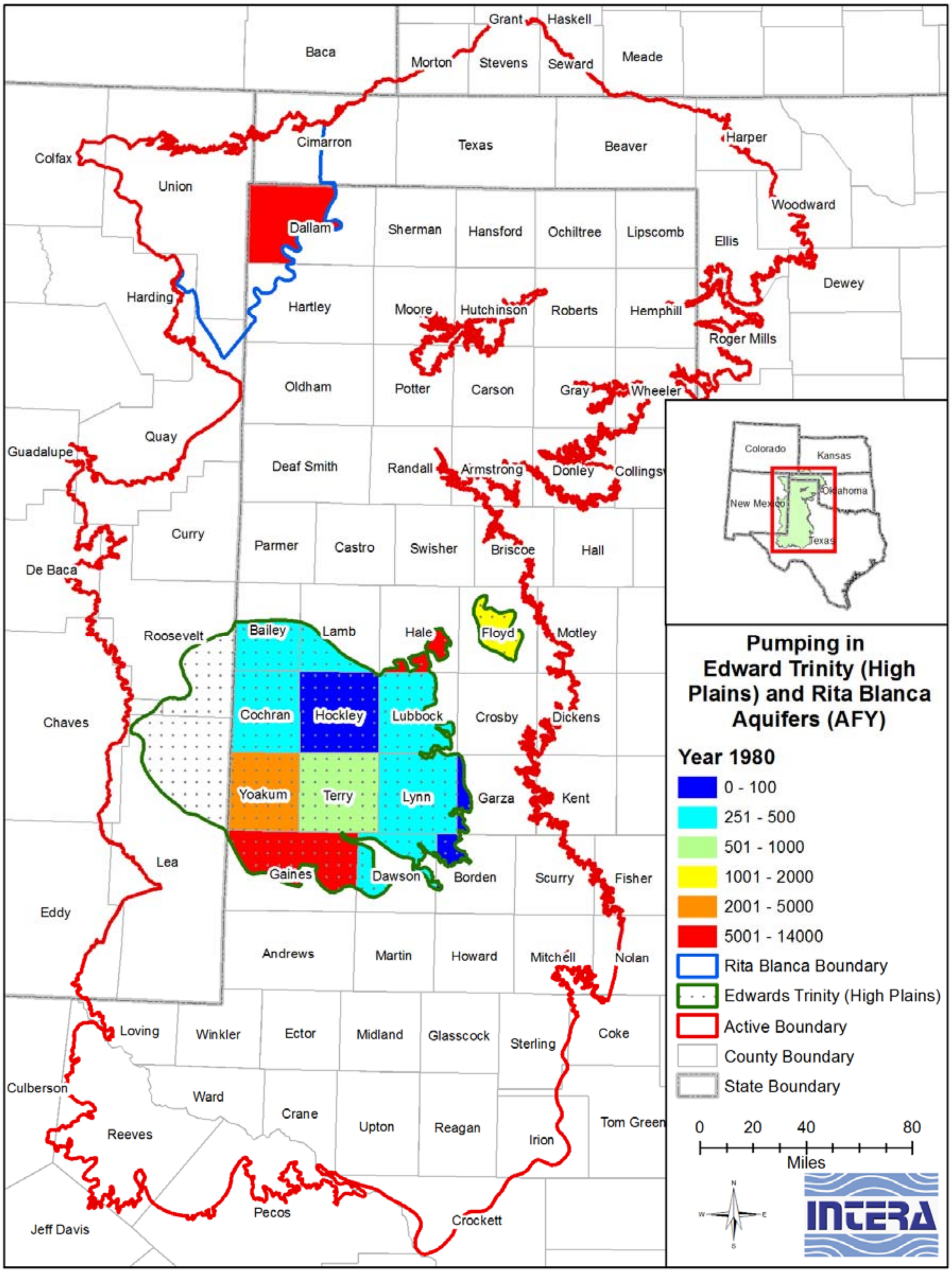

Figure 4.7.32 Estimated county-wide pumping in acre-feet in the Edwards-Trinity (High Plains) and Rita Blanca aquifers for the year 1980.

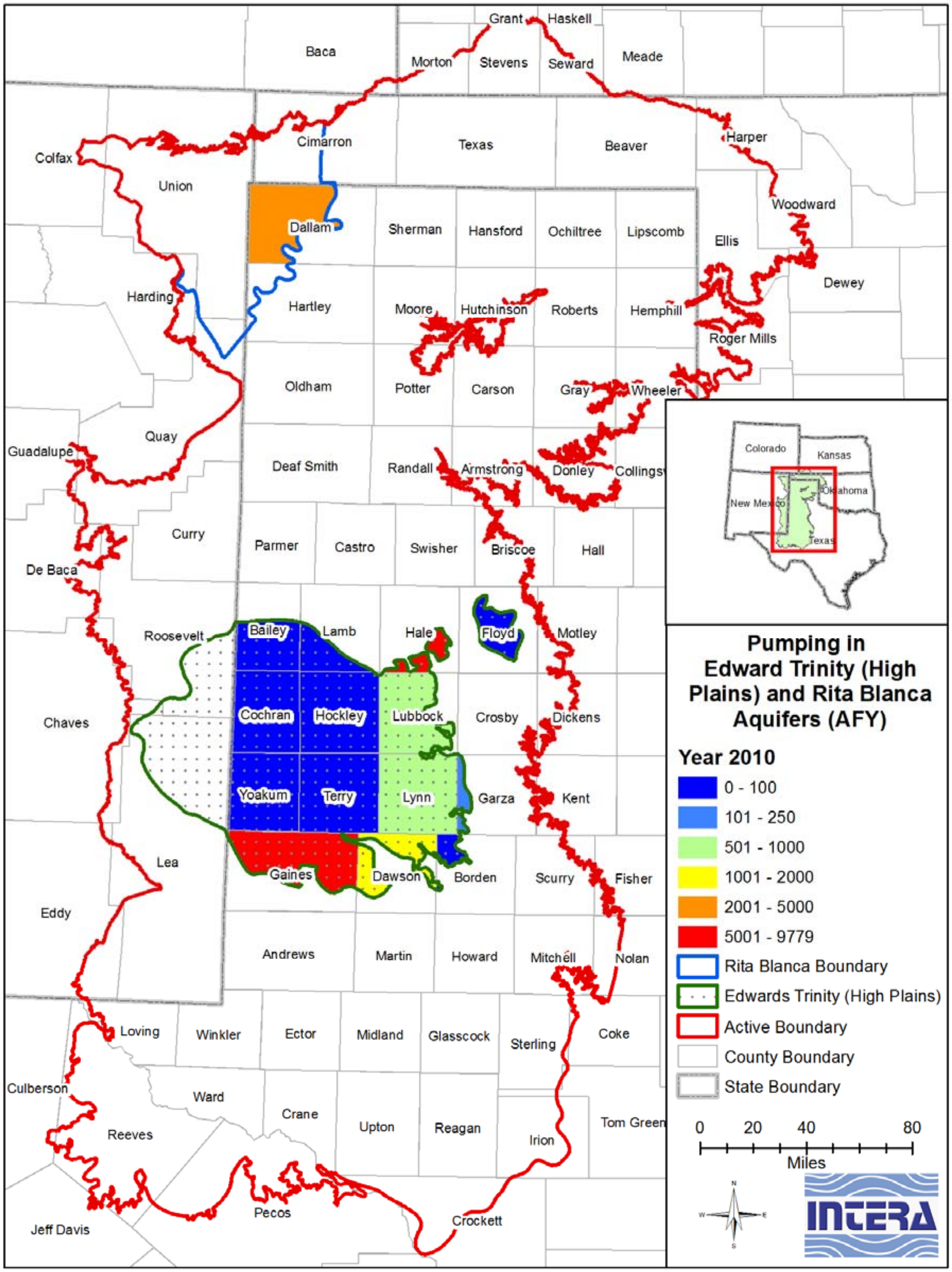

Figure 4.7.33 Estimated county-wide pumping in acre-feet in the Edwards-Trinity (High Plains) and Rita Blanca aquifers for the year 2010.

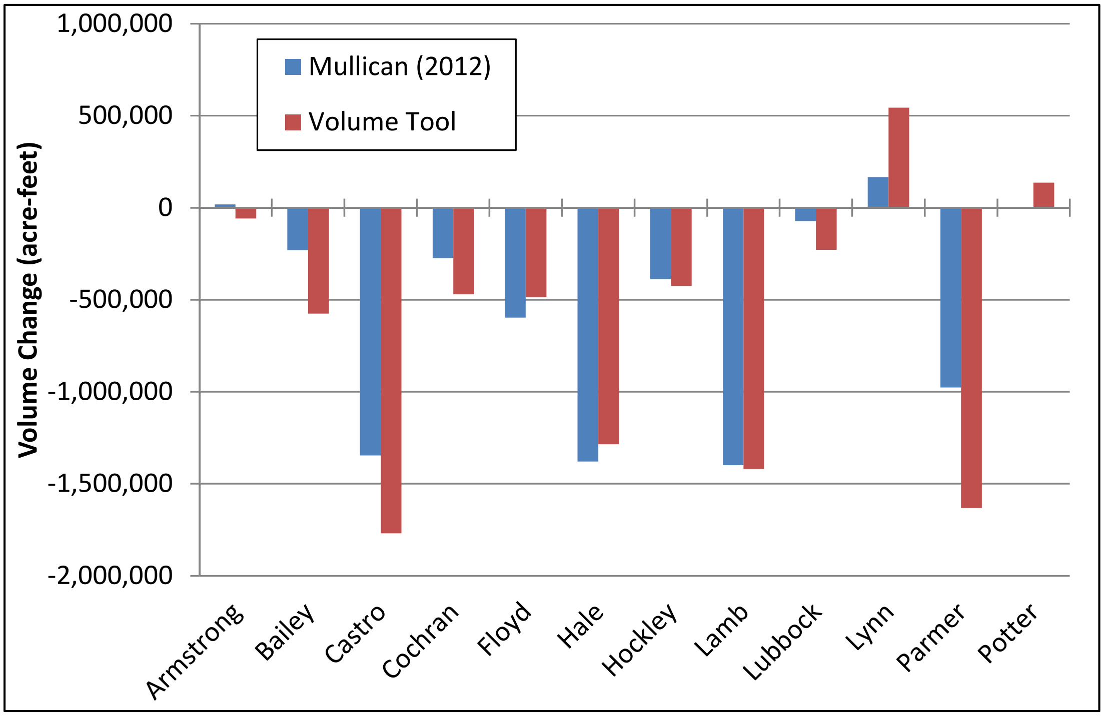

Figure 4.7.34 **Comparison of 2003 to 2013 results from the volume tool and the Mullican (2012) study for counties in the High Plains Water District.**

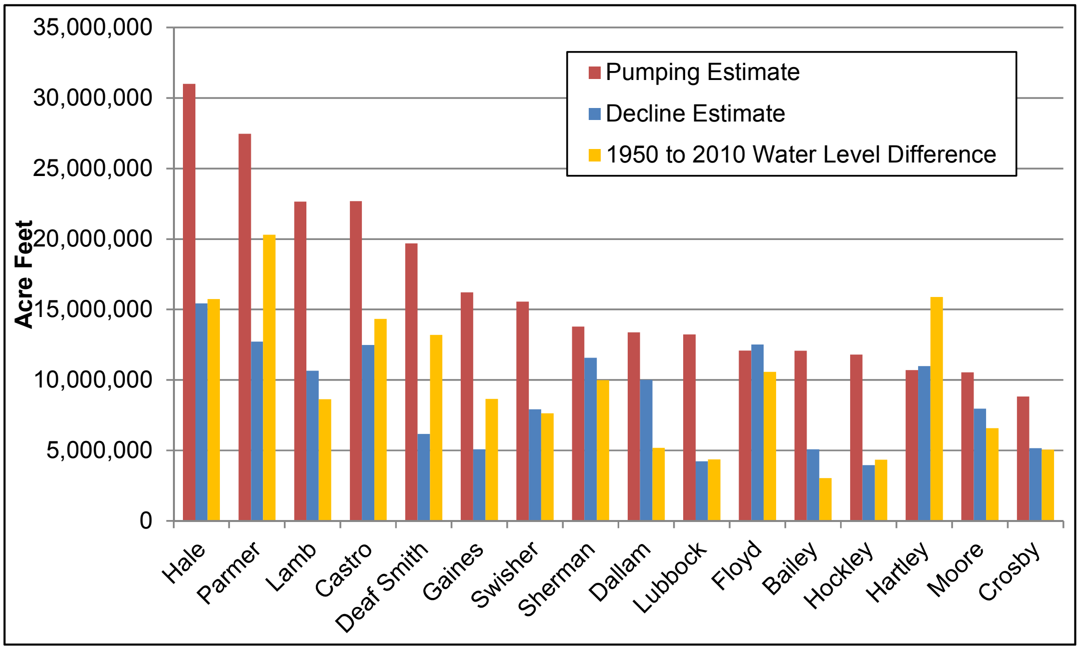

Figure 4.7.35 **Comparison of demand based pumping estimate from 1950 to 2010 with the two estimates of change in volume in storage.**

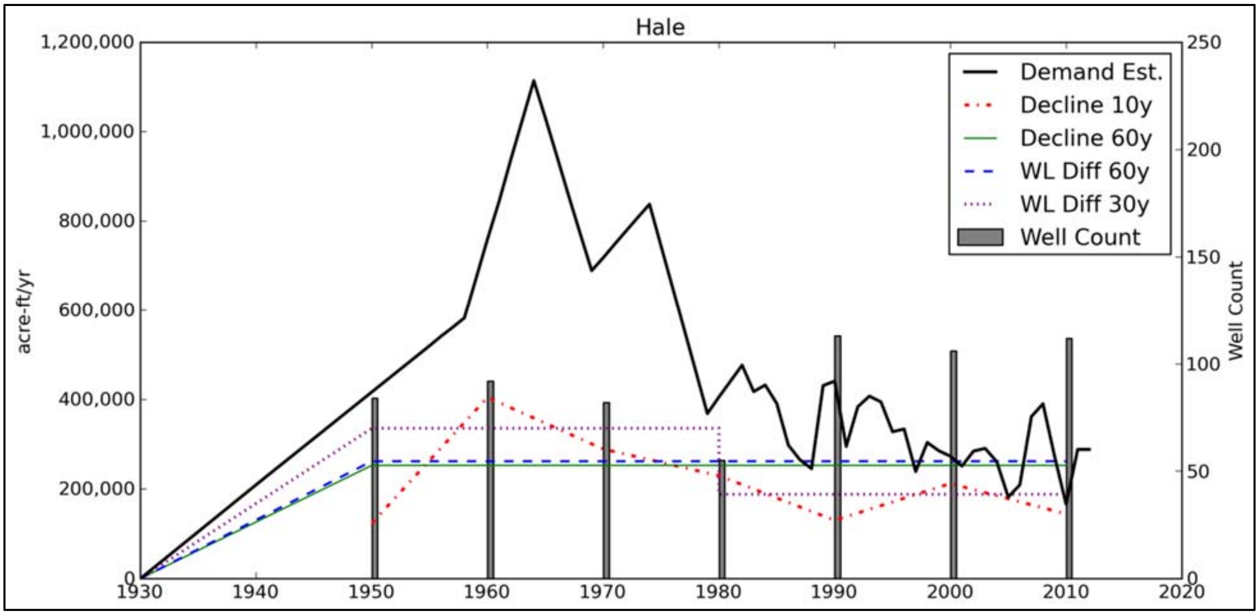

Figure 4.7.36 Hale County comparison of demand based pumping estimate to estimates of rate of change in storage over 60-, 30-, and 10-year integration periods.

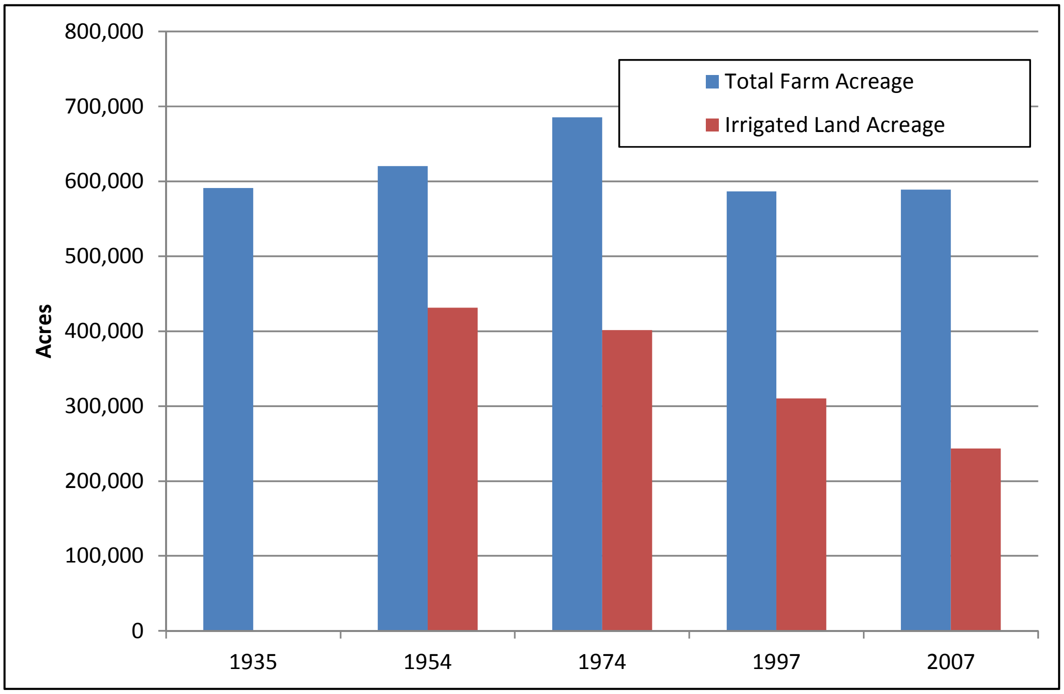

Figure 4.7.37 Irrigated and total farm acreage in Hale County from United States Department of Agriculture census data (United States Department of Agriculture, 1935, 1954, 1974, 1997, 2007). No irrigated land acreage estimate was available in 1935.

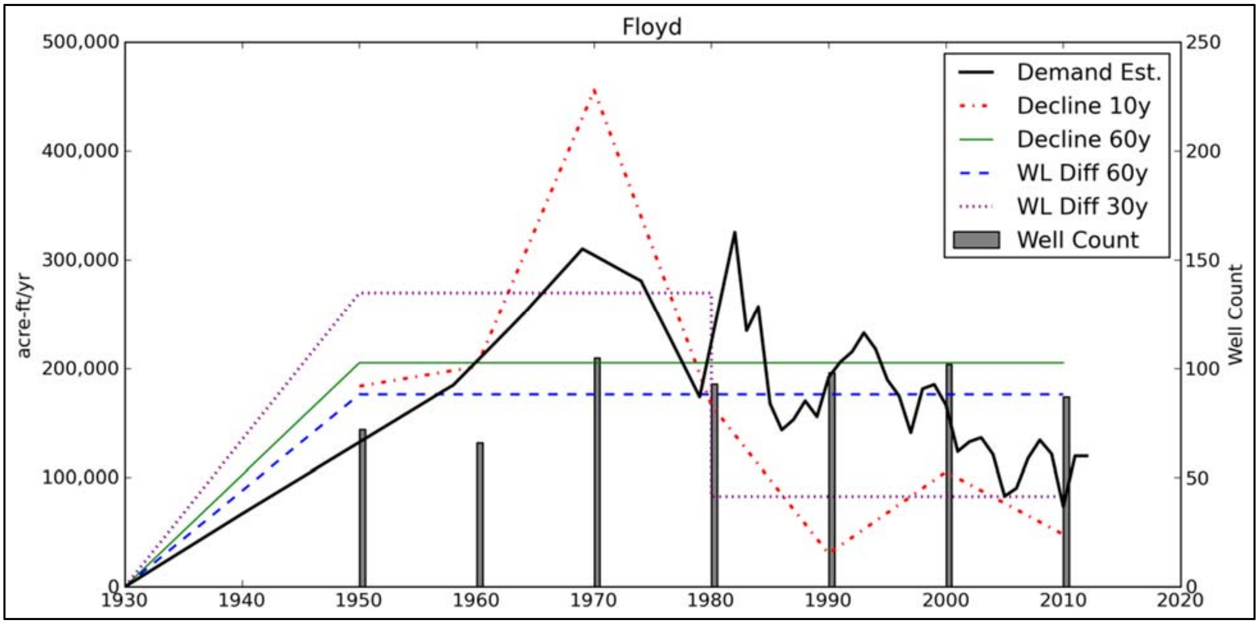

Figure 4.7.38 **Floyd County comparison of demand based pumping estimate to estimates of rate of change in storage over 60-, 30-, and 10-year integration periods.**

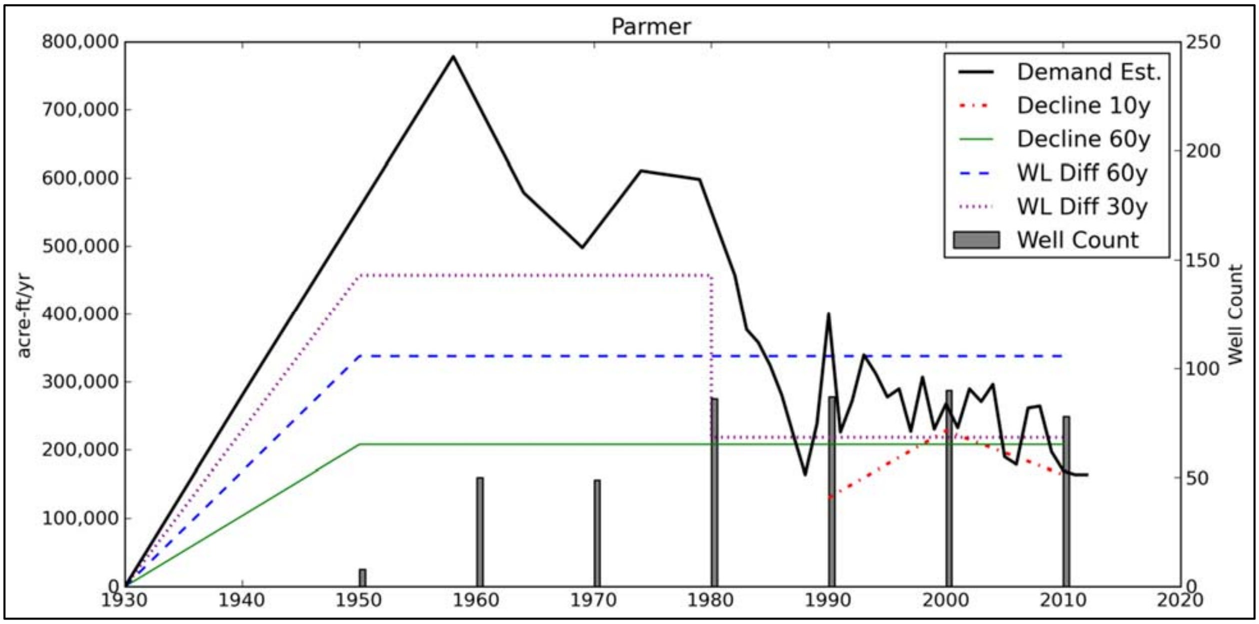

Figure 4.7.39 **Parmer County comparison of demand based pumping estimate to estimates of rate of change in storage over 60-, 30-, and 10-year integration periods.**

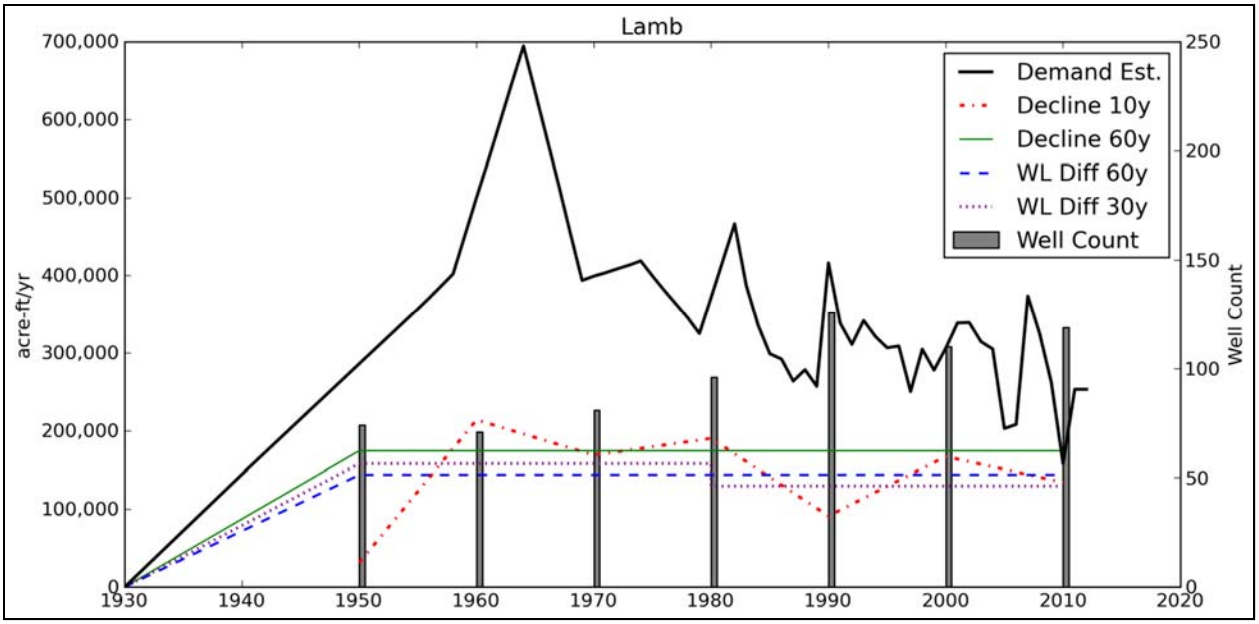

Figure 4.7.40 Lamb County comparison of demand based pumping estimate to estimates of rate of change in storage over 60-, 30-, and 10-year integration periods.

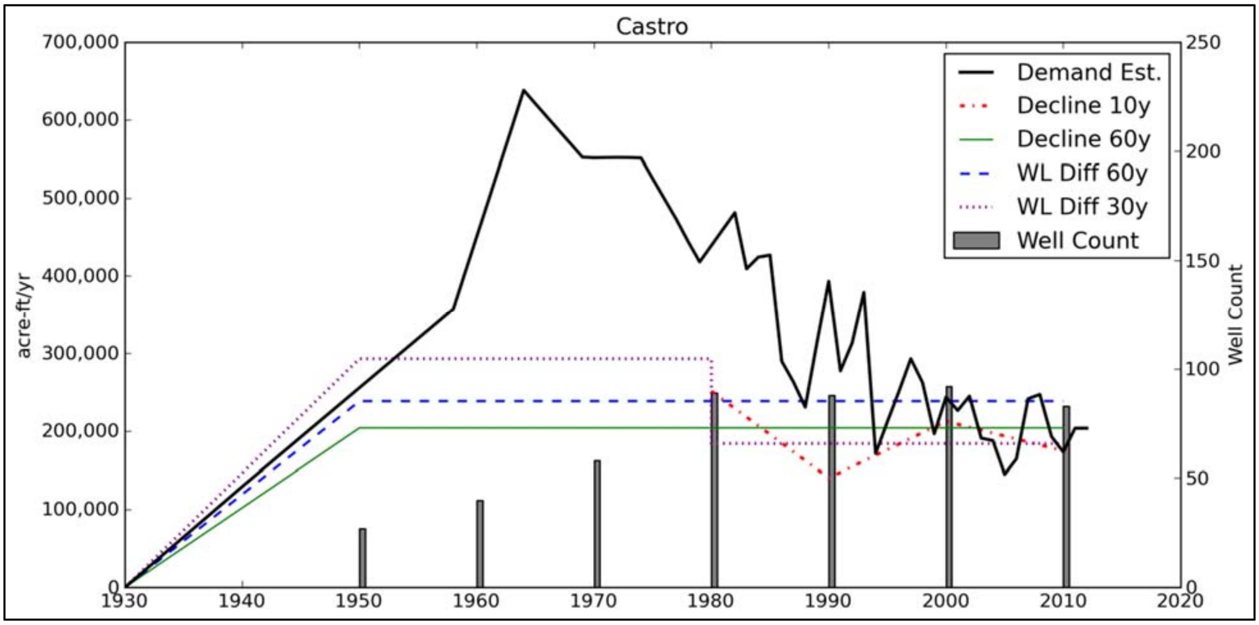

Figure 4.7.41 Castro County comparison of demand based pumping estimate to estimates of rate of change in storage over 60-, 30-, and 10-year integration periods.

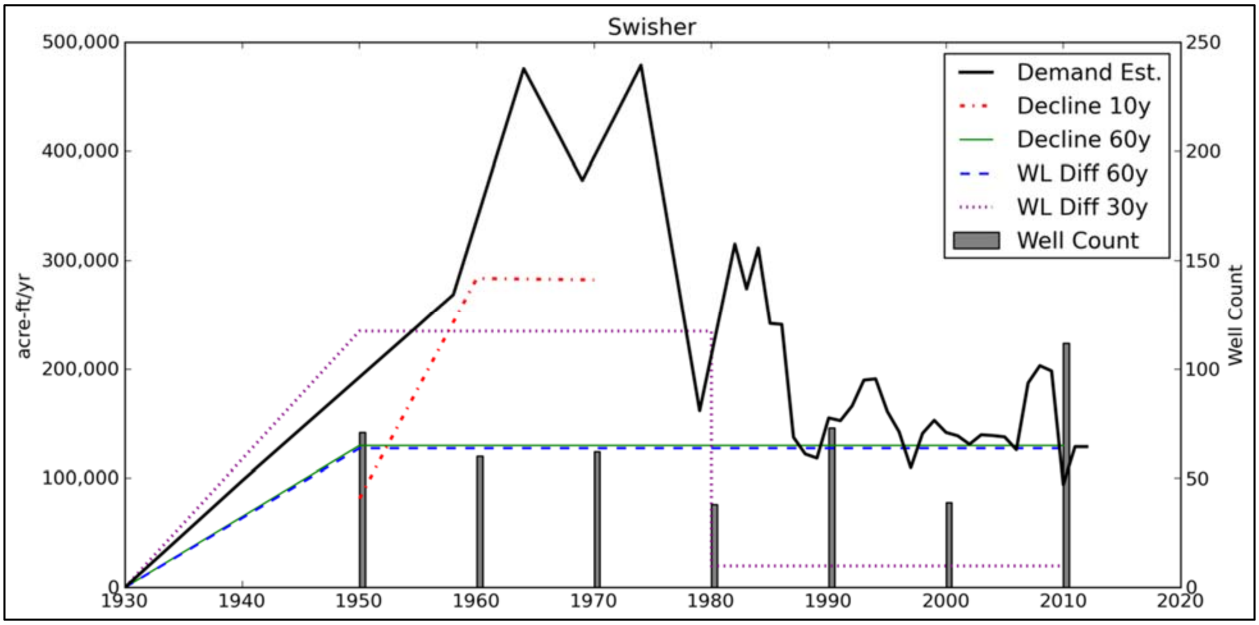

Figure 4.7.42 Swisher County comparison of demand based pumping estimate to estimates of rate of change in storage over 60-, 30-, and 10-year integration periods.

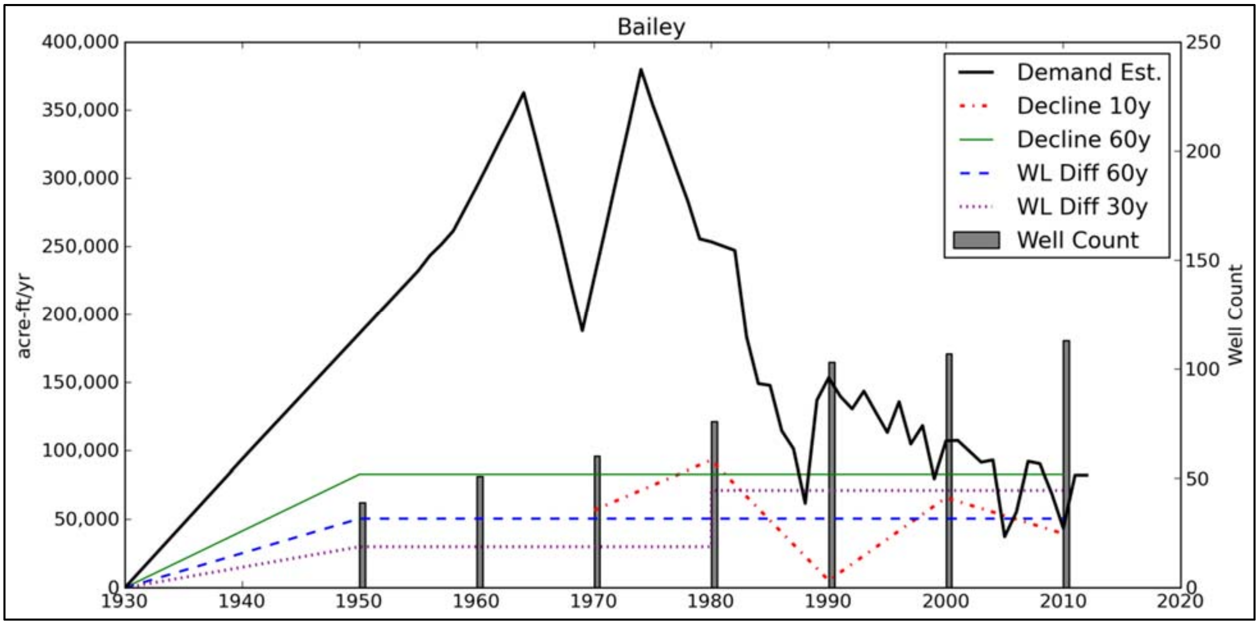

Figure 4.7.43 Bailey County comparison of demand based pumping estimate to estimates of rate of change in storage over 60-, 30-, and 10-year integration periods.

4.8 Water Quality

Considerable variation occurs in the water quality characteristics of the four aquifers comprising the High Plains Aquifer System. Not only do the aquifers display very different hydrochemical characteristics from one another, but they can have significant internal variability as well. Therefore, the quality of water depends greatly on both the aquifer into which a well is drilled and its physical location within the aquifer. Of the aquifers in this study, the Tertiary-age Ogallala Aquifer has historically been the most important, as it produces freshwater throughout most of its extent. In the northwest, the Ogallala Aquifer overlies the Jurassic-age Rita Blanca Aquifer, a small, but also mostly fresh minor aquifer. In the central portion of the study area, the Ogallala Aquifer overlies the Cretaceous-age Edwards-Trinity (High Plains) Aquifer, a slightly saline minor aquifer. The Triassic-age Dockum Group underlies much of the study area, but generally only produces freshwater in its outcrops. Elsewhere, salinity in the Dockum Group increases with depth towards the center of the Midland Basin and can reach over 50,000 milligrams per liter. In the southwestern portion of the study area, where the Ogallala Aquifer is absent, the Quaternary-age Pecos Valley Aquifer produces fresh to moderately saline water in the east and slightly to moderately saline water in the west. The outcropping Cretaceous-age Edwards-Trinity (Plateau) Aquifer provides hard, but mostly freshwater in the southeastern portion of the study area. Please note that, in the discussion above, salinity terms are consistent with United States Geological Survey (2012) terminology, which defines “fresh” as having a total dissolved solids concentration less than 1,000 milligrams per liter, “slightly saline” as 1,000 to 3,000 milligrams per liter, “moderately saline” as 3,000 to 10,000 milligrams per liter, and “very saline” as greater than 10,000 milligrams per liter.

4.8.1 Previous Studies

Given their economic importance, the aquifers of the High Plains Aquifer System have been the subject of numerous reports that include water-quality discussions. In general, previous work has focused on assembling all available data in order to characterize the water chemistry of each aquifer. This approach typically treats each aquifer as an individual entity with little to no emphasis on interaction between the aquifers. On their own, hydrochemical assessments of individual aquifers are of limited use for analyzing the High Plains Aquifer System as an interconnected system. Given the distinct chemical characteristics of each aquifer, water chemistry can help highlight mixing zones created by cross-formational flow. A few studies have taken advantage of these chemistry differences to illustrate potential connections between the aquifers in the High Plains Aquifer System.

Because it is the largest source of freshwater in most of the study area, the quality of groundwater in the Ogallala Aquifer has attracted particular scrutiny. Cross-formational flow into the Ogallala Aquifer is especially of interest since sufficiently large inputs from surrounding formations with poorer water quality could potentially degrade local or regional water quality in the Ogallala Aquifer.

Several studies have focused on identifying areas where there is hydrochemical evidence for potential cross-formational flow into the Ogallala Aquifer. Nativ (1988) noted that the hydrochemical facies of the groundwater in the Ogallala Aquifer (sodium-bicarbonate or sodium-chloride type) is similar to that of the groundwater in the Dockum Group in parts of Deaf Smith, Parmer, Dickens, Howard, Garza, and Crosby counties, Texas and Curry County, New Mexico (Figure 4.8.1). These areas coincide with areas near the Dockum Aquifer outcrop where the hydraulic head gradient could make upward flow from the Dockum Aquifer feasible. In portions of the Midland Basin, Nativ (1988) also found that groundwater in the Ogallala Aquifer has similar hydrochemical facies, isotopic ($\delta^{18}O$ and δD) composition and tritium values to the underlying Edwards-Trinity (High Plains) Aquifer (Figure 4.8.1). These areas also largely coincide with regions where the hydraulic head gradient favors upward flow from the Edwards-Trinity (High Plains) Aquifer into the Ogallala Aquifer (Nativ and Gutierrez, 1988). Adding further support to the existence of cross-formational flow from the Edwards-Trinity (High Plains) Aquifer, a mass-balance calculation based on major ion concentrations in a nearby well field in Hale County indicated that 8 to 17 percent of the Ogallala Aquifer groundwater could be contributed by lateral cross-formational flow from the Edwards-Trinity (High Plains) Aquifer (McMahon and others, 2004b).

Mehta and others (2000) mapped two plumes with anomalously high chloride and sulfate concentrations and depleted isotopic signatures in parts of Carson, Gray, and Roberts counties, Texas, that cover a combined area greater than 386 square miles (Figure 4.8.1). Though the total dissolved solids concentrations of the surrounding Northern Ogallala Aquifer is generally less than 400 milligrams per liter, these plumes had elevated total dissolved solids ranging from 400 to greater than 2,000 milligrams per liter. A model of the plumes indicate that the higher salinity groundwater inputs originate from underlying salt-bearing Permian-age formations (Mehta and others, 2000). Sodium-chloride type water found in the Ogallala Aquifer near the western Caprock Escarpment (Figure 4.8.1) is also thought to be due to water interacting with Permian-age salt deposits and then flowing upward through the Dockum Group (Langman, 2008). McMahon (2001) attributes the increased salinity of Ogallala Aquifer groundwater along the Cimarron River Valley to the upward flow of halite-dissolution brines from underlying Permian-age beds as well (Figure 4.8.1).

Outside the Ogallala Aquifer, evidence of water chemistry changes due to cross-formational flow is poorly documented and studies are more uncommon. Nativ and Gutierrez (1988) identified areas in the northwest section of the Edwards-Trinity (High Plains) Aquifer where the hydraulic head gradient could favor upward flow from the underlying Dockum Group. In this region, the Dockum Group contains sodium-mixed anion type water transitioning to sodium-chloride type (Dutton and Simpkins, 1986), similar to the sodium-mixed anion type water and abundance of sodium and chloride in the Edwards-Trinity (High Plains) Aquifer above (Nativ and Gutierrez, 1988). This suggests the existence of cross-formational flow here. Elevated sulfate levels in the Pecos Valley Aquifer in Reeves County are attributed to flow from the underlying Rustler Formation (Ashworth, 1990).

With some exceptions, as mentioned above, the hydraulic head gradients in the aquifers of the study area generally favor downward flow into underlying formations. Whether or not downward flow actually occurs and the rate at which it occurs is a function of the permeability of the contact between the two aquifers and the presence of intervening confining units. And even when aquifers are thought to be hydraulically connected, there are few documented instances in which downward mixing creates noticeable changes in water chemistry. Scanlon and others (2005b) note that elevated natural arsenic concentrations in the Edwards-Trinity Aquifer only occur in areas where it is overlain by the Ogallala Aquifer. For instance, elevated arsenic concentrations are seen along the northern edge of the Edwards-Trinity (Plateau) Aquifer where it underlies the Ogallala Aquifer, but not elsewhere in the aquifer. The Ogallala Aquifer has elevated natural arsenic levels in the southern portion that decreases northward. Elevated arsenic levels are seen in the southern portion of the Edwards-Trinity (High Plains) Aquifer where it underlies this higher-arsenic section of the Ogallala Aquifer, but not seen in the northern portion where it underlies a lower-arsenic section of the Ogallala Aquifer. These data indicate some impact to the water quality in the Edwards-Trinity (High Plains) Aquifer due to downward flow from the Ogallala Aquifer. In Sterling County, the Dockum Group transitions to a calcium-bicarbonate type water similar to groundwater in the Edwards-Trinity (Plateau) Aquifer. Since this corresponds with an area where the Dockum Group is in hydrologic contact with the Edwards-Trinity (Plateau) Aquifer (Walker, 1979), this has been interpreted as evidence of downward groundwater movement (Ashworth and Christian, 1989; Bradley and Kalaswad, 2003). The Dockum Group is noted to transition to a calcium-sulfate-mixed anion-type water when overlain by the Pecos Valley Aquifer (Bradley and Kalaswad, 2003), also potentially indicating downward movement.

Besides cross-formational flow, groundwater chemistry can also offer insight into the rate and path of surface recharge to an aquifer. Dutton (1995), for instance, used isotopic composition ($\delta^{18}O$ and δD) and other age tracers (^{14}C and ^{3}H) in High Plains groundwater to establish that unconfined Ogallala Group groundwater was young (0 to 1,000 years) and derived from meteoric input. Confined Dockum Group groundwater was older (15,000 to 35,000 years) and derived from vertical leakage from the Ogallala Aquifer above. Tritium values show a stratification of age in the Ogallala Aquifer, in that groundwater at the water table is typically less than 50 years old whereas deep Ogallala Aquifer water is greater than 50 years old (McMahon, 2001; McMahon and others, 2004b). The appearance of recent agricultural inputs such as nitrate and pesticides in groundwater can also be used to establish recent origin. Fahlquist (2003) used the presence of nitrate and pesticides combined with tritium values to date water in southern Ogallala Aquifer wells as less than 50 years old.

Changes in groundwater chemistry can also provide information on surface processes, both natural and anthropogenic. These surface processes can potentially affect all aquifers in outcrop areas where they are essentially unconfined. Most available documentation focuses on the Ogallala and Pecos Valley aquifers, which are unconfined throughout much of their extent. Some saline plumes in the Ogallala Aquifer are thought to be the result of eolian sediment transport from saline lake basins and the subsequent dissolution and transport of salts to the water table (Wood and Sanford, 1995b). While that process is largely natural, most other surface processes with an impact on groundwater are anthropogenic. Irrigation, in what is otherwise an arid to semi-arid area, mobilizes dissolved solids in the unsaturated zone and increases groundwater flux rate and thus transport of dissolved solids to the water table (McMahon and others, 2006). Before recharging, irrigation water can undergo evaporation at the surface and become more saline, also increasing the amount of dissolved solids transported to the water table. This is likely the source of salinity in the Pecos Valley Aquifer in Reeves County and northwest Pecos County (Ashworth, 1990). The application of fertilizer and pesticides at the surface leads to the appearance of these anthropogenic contaminants at the water table. McMahon and others (2004b) identified a distinct stratification in the groundwater chemistry of the Ogallala Aquifer with shallow water near the water table showing high total dissolved solids, nitrate and pesticide levels and dilute deep water showing little to no contamination. High nitrate levels found in the Pecos Valley Aquifer in parts of Reeves and Pecos counties are also likely due to agricultural surface application (Ashworth, 1990). Contamination from surface industrial waste can also change groundwater chemistry. Local high-salinity portions of the Pecos Valley Aquifer in Winkler and Loving counties are attributed to the improper surface disposal of oil-field brines (Ashworth, 1990).

Even without the direct input of agricultural and industrial contamination, humans can also alter groundwater chemistry by simple water withdrawal. Declines in water level can induce changes in the flow system that then manifest themselves as changes in water chemistry. Water-level declines have induced recharge from the Pecos River, introducing its poor quality (high total dissolved solids) water to portions of the Pecos Valley and Edwards-Trinity (Plateau) aquifers in northwestern Pecos and north-central Reeves counties (Ashworth, 1990; Barker and Ardis, 1996). While the stratification of water quality in the Ogallala Aquifer has prevented the contamination of deep wells, future water-level declines could eventually pull saline, nitrate-contaminated water, currently isolated at the water table, into deeper wells.

Deep wells, particularly oil and gas wells, can lead to contamination when poorly cased wells leak and introduce shorter flow paths for poorer quality water from deeper formations. Nativ (1988) suggested that formation brines leaking from old oil and gas wells contributed to the higher total dissolved solids levels found in the Southern Ogallala Aquifer compared to the Northern Ogallala Aquifer. High chloride in Edwards-Trinity (Plateau) Aquifer groundwater has also been blamed on oil field brine leakage from poorly cased or plugged wells in north-central Pecos County (Rees and Buckner, 1980).

Due to the temporal scarcity of water quality measurements, few studies have been able to use water chemistry to quantify changes due to irrigation and other agricultural practices over time, or to establish any pre-development water chemistry baseline. Groundwater dating techniques combined with nitrogen isotope data have been used to establish pre- and post-development nitrate concentrations in the Ogallala Aquifer (McMahon and others, 2004a; McMahon and Böhlke, 2006). These show that pre-development nitrate concentrations remained steady for thousands of years and began to sharply increase in the 1940s and 1950s, coincident with greater agricultural activity and fertilizer application. Dutton (2005) did also identify a slightly increasing nitrate trend in the Dockum Group from the 1930s to the 2000s. While groundwater chemistry does demonstrate some impact from agricultural input over the past half-century, data are insufficient to quantify recharge amounts and rates of different constituents and relate them to specific changes in irrigation practices at the timescale of our model.

4.8.2 Data Sources and Methods of Analysis

The water-quality data used in the current analysis is from the TWDB groundwater database for wells located within Texas and from the United States Geological Survey National Water Information System database for wells located outside of Texas. If a well had screen information or total depth, the well was assigned to an aquifer based on the updated structural surfaces created for this project (see Section 4.2). Wells that were screened across several aquifers were not included in the analysis since the water chemistry would not be representative of either aquifer. Because of the scarcity of data, we also included data from wells without screen information that were designated as Edwards-Trinity (High Plains) Aquifer or Rita Blanca Aquifer wells in the TWDB groundwater database.

This groundwater water quality analysis included 4,919 wells completed within the Ogallala Aquifer, 818 wells within the lower Dockum Group, 80 wells in the upper Dockum Group, 22 in the Rita Blanca Aquifer, and 58 in the Edwards-Trinity (High Plains) Aquifer. 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.

4.8.3 Drinking Water Quality

Screening levels for drinking water supply are based on the maximum contaminant levels established by the Environmental Protection Agency. 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).

Tables 4.8.1 through 4.8.5 summarizes the occurrence and levels of some commonly measured groundwater quality constituents in the Ogallala Aquifer, upper and lower Dockum Group, Rita Blanca Aquifer, and Edwards-Trinity (High Plains) Aquifer, respectively.

Total dissolved solids, a measure of salinity, 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 secondary maximum contaminant level of 500 milligrams per liter in approximately 38 percent of the sampled Ogallala wells, 50 percent of the sampled upper Dockum Group wells, 67 percent of the sampled lower Dockum Group wells, 6 percent of the sampled Rita Blanca Aquifer wells, and 93 percent of the sampled Edwards-Trinity (High Plains) wells. Figure 4.8.2 shows the spatial distribution of total dissolved solids in Ogallala Aquifer groundwater, Figure 4.8.3 shows Dockum Group groundwater, and Figure 4.8.4 shows Rita Blanca and Edwards-Trinity (High Plains) aquifers groundwater.

The concentration of total dissolved solids in groundwater in the Ogallala Aquifer is low in the northern portion of the aquifer but increases significantly in the southern portion. The total dissolved solids in groundwater in the Dockum Group generally increases with depth toward the center of the depositional basin. Groundwater in the Dockum Group that is sufficiently fresh to meet safe-drinking water standards is limited to the shallower areas near and on the outcrop of the Dockum Aquifer. All available Rita Blanca Aquifer groundwater samples are fresh. Edwards-Trinity (High Plains) Aquifer groundwater is also generally fresh, but does increase in total dissolved solids towards the south.

Sulfate and chloride are major components of total dissolved solids. The secondary maximum contaminant level for both sulfate and chloride is 250 milligrams per liter. Fourteen percent of sampled Ogallala Aquifer wells, 24 percent of sampled upper Dockum Group wells, 43 percent of lower Dockum Group wells, and 59 percent of the Edwards-Trinity (High Plains) Aquifer wells exceeded this level for sulfate. Eleven percent of sampled Ogallala Aquifer wells, 22 percent of sampled upper Dockum Group wells, 31 percent of lower Dockum Group wells, and 56 percent of the Edwards-Trinity (High Plains) Aquifer wells exceeded this level for chloride. None of the sampled Rita Blanca Aquifer wells exceeded 250 milligrams per liter for either sulfate or chloride.

Fluoride is a naturally-occurring element found in most rocks. At very low concentrations, fluoride is a beneficial nutrient. For instance, 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. This level is exceeded in 51 percent of the sampled Ogallala wells, 28 percent of the sampled lower Dockum Group wells, 59 percent of the sampled upper Dockum Group wells, 10 percent of the sampled Rita Blanca Aquifer wells, and 64 percent of the sampled Edwards-Trinity (High Plains) wells. At concentrations above the primary maximum contaminant level of 4 milligrams per liter, fluoride can cause a type of bone disease. This level is exceeded in 17 percent of the sampled Ogallala Aquifer wells, 9 percent of the sampled upper Dockum Group wells, 4 percent of the sampled lower Dockum Group wells, 5 percent of the sampled Rita Blanca Aquifer wells, and 22 percent of the sampled Edwards-Trinity (High Plains) wells.

Nitrate, which is often indicative of agricultural contamination, is another potentially hazardous constituent of drinking water. Since high concentrations of nitrate can cause serious illness in infants younger than 6 months old, the EPA established a primary maximum contaminant level of 10 milligrams of nitrate per liter as nitrogen. This level is exceeded in 5 percent of the sampled Ogallala Aquifer wells, 10 percent of the upper Dockum Group wells, 11 percent of the lower Dockum Group wells, and 14 percent of the Edwards-Trinity (High Plains) Aquifer wells. None of the available Rita Blanca Aquifer samples exceeded 10 milligrams per liter.
Figures 4.8.5 through 4.8.7 show the distribution of nitrate in groundwater samples in the Ogallala Aquifer, Dockum Group, Rita Blanca Aquifer, and Edwards-Trinity (High Plains) Aquifer, respectively.

Arsenic can be another hazardous, but often naturally-occurring, component of groundwater. Since long-term exposure can cause various forms of cancer, arsenic has a primary maximum concentration of 10 micrograms per liter. This level is exceeded in 19 percent of Ogallala aquifer wells, 27 percent of upper Dockum Group wells, 7 percent of lower Dockum Group wells, and 27 percent of Edwards-Trinity (High Plains) Aquifer wells. None of the available Rita Blanca Aquifer samples exceeded 10 micrograms per liter. Figures 4.8.8 through 4.8.10 show the distribution of arsenic in groundwater samples in the Ogallala Aquifer, Dockum Group, Rita Blanca Aquifer, and Edwards-Trinity (High Plains) Aquifer, respectively.

4.8.4 Irrigation Water Quality

The utility of groundwater from the High Plains Aquifer System for crop irrigation was evaluated based on its salinity hazard, sodium hazard, and concentration of chloride. Although crops can differ in their tolerance of high salinity, saline irrigation water is generally undesirable as it limits the ability of plants to take up water from soils. The salinity hazard classification system of the United States Salinity Laboratory (1954) classifies waters with electrical conductivity over 750 micromhos as a high salinity hazard, and those with electrical conductivity over 2,250 micromhos as a very high salinity hazard. Of the wells in the Ogallala Aquifer with chemical analyses, groundwater from 43 percent have exhibited a high salinity hazard and 8 percent exhibited a very high salinity hazard. In the upper and lower Dockum aquifers, 68 and 73 percent exhibited a high salinity hazard, respectively, and 14 and 31 percent have exhibited a very high salinity hazard, respectively. In the Rita Blanca Aquifer, only one well showed a high salinity hazard and none had a very high salinity hazard. In the Edwards-Trinity (High Plains), 96 percent exhibited a high salinity hazard and 54 percent have exhibited a very high salinity hazard.

Groundwater with a high sodium concentration compared to other major ion concentrations can negatively affect soil cultivation and permeability in irrigated land. A sodium hazard condition generally results when the sodium concentration in water is in excess of 60 percent of total cations. The sodium hazard of groundwater is typically calculated in terms of sodium adsorption ratio (United States Salinity Laboratory, 1954):

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

where the sodium (Na), calcium (Ca), and magnesium (Mg) concentrations are expressed in milliequivalents per liter. The United States Salinity Laboratory (1954) classifies groundwater into low (less than 10), medium (10 to 18), high (18 to 26), and very high (greater than 26) sodium adsorption ratio ranges. In the Ogallala Aquifer, less than 1 percent of the wells fall into the high or very high categories. In the upper Dockum Group, 8 percent of groundwater samples have a high sodium hazard and 5 percent have a very high sodium hazard. In the lower Dockum Group, 19 percent of groundwater samples have a high sodium hazard and 16 percent have a very high sodium hazard. In the Edwards-Trinity (High Plains) Aquifer, 11 percent of groundwater samples have a high sodium hazard and 5 percent have a very high sodium hazard. None of the Rita Blanca Aquifer samples show a high or very high sodium hazard. The sodium hazard (sodium adsorption ratio) of groundwater for the Ogallala Aquifer, Dockum Group, Rita Blanca Aquifer, and Edwards-Trinity (High Plains) Aquifer are shown in Figures 4.8.11 through 4.8.13, respectively.

Chloride is another constituent potentially toxic to crops at higher concentrations. Most crops cannot tolerate chloride levels above 1,000 milligrams per liter for an extended period of time (Tanji, 1990). Only 2 percent of the sampled Ogallala Aquifer wells have a chloride concentration greater than 1,000 milligrams per liter. However, this chloride concentration is exceeded in 4 percent of upper Dockum Group wells, 12 percent of lower Dockum Group wells, and 18 percent of Edwards-Trinity (High Plains) Aquifer wells. None of the Rita Blanca Aquifer wells had a chloride concentration that exceeded 1,000 milligrams per liter. The chloride distributions for the Ogallala Aquifer, Dockum Group, Rita Blanca Aquifer, and Edwards-Trinity (High Plains) Aquifer are shown in Figures 4.8.14 through 4.8.16.

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

Constituent	Type of Standard	Screening Level	Units	Number of Results	Mean Value (*Std Dev*)	Number (%) of Results Exceeding Screening Level
Fluoride	Primary maximum contaminant level[1]	4	mg/L	4232	2.45 (1.61)	740 (17%)
Nitrate	Primary maximum contaminant level[1]	10	mg/L as N	4376	3.07 (10.02)	215 (5%)
Arsenic	Primary maximum contaminant level[1]	10	µg/L	1295	9.15 (11.45)	241 (19%)
pH	Secondary maximum contaminant level[1]	6.5 to 8.5	-	4321	7.70 (0.38)	26 (1%)
Chloride	Secondary maximum contaminant level[1]	250	mg/L	4780	133.60 (632.25)	504 (11%)
Fluoride	Secondary maximum contaminant level[1]	2	mg/L	4232	2.45 (1.61)	2142 (51%)
Sulfate	Secondary maximum contaminant level[1]	250	mg/L	4751	158.73 (562.97)	643 (14%)
Total Dissolved Solids	Secondary maximum contaminant level[1]	500	mg/L	4681	701.42 (1686.50)	1781 (38%)
Specific Conductance	Irrigation Salinity Hazard- High[2]	750	µmhos/cm	4298	1854 (3225.52)	1854 (43%)
Specific Conductance	Irrigation Salinity Hazard - Very High[2]	2250	µmhos/cm	4298	1854 (3225.52)	352 (8%)
Sodium Adsorption Ratio	Sodium hazard – High[2]	18	-	4573	1.84 (2.35)	14 (0.3%)
Sodium Adsorption Ratio	Sodium hazard –Very High[2]	26	-	4573	1.84 (2.35)	6 (0.1%)
Chloride	Irrigation Hazard[3]	1000	mg/L	4780	133.60 (632.25)	83 (2%)

[1] Environmental Protection Agency Drinking Water Standards
[2] United States Salinity Laboratory (1954)
[3] Tanji (1990)

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

Table 4.8.2 Occurrence and levels of some commonly measured groundwater quality constituents in the lower Dockum Group.

Constituent	Type of Standard	Screening Level	Units	Number of Results	Mean Value (*Std Dev*)	Number (%) of Results Exceeding Screening Level
Fluoride	Primary maximum contaminant level[1]	4	mg/L	710	1.72 (1.16)	28 (4%)
Nitrate	Primary maximum contaminant level[1]	10	mg/L as N	747	4.01 (9.24)	85 (11%)
Arsenic	Primary maximum contaminant level[1]	10	µg/L	236	6.53 (13.91)	16 (7%)
pH	Secondary maximum contaminant level[1]	6.5 to 8.5	-	739	7.71 (0.47)	30 (4%)
Chloride	Secondary maximum contaminant level[1]	250	mg/L	834	816.33 (4199)	255 (31%)
Fluoride	Secondary maximum contaminant level[1]	2	mg/L	710	1.72 (1.16)	198 (28%)
Sulfate	Secondary maximum contaminant level[1]	250	mg/L	834	613.77 (4435)	359 (43%)
Total Dissolved Solids	Secondary maximum contaminant level[1]	500	mg/L	825	2507.7 (12121)	552 (67%)
Specific Conductance	Irrigation Salinity Hazard- High[2]	750	µmhos/cm	738	3322 (9189.6)	539 (73%)
Specific Conductance	Irrigation Salinity Hazard - Very High[2]	2250	µmhos/cm	738	3322 (9189.6)	228 (31%)
Sodium Adsorption Ratio	Sodium hazard – High[2]	18	-	832	12.56 (23.63)	162 (19%)
Sodium Adsorption Ratio	Sodium hazard –Very High[2]	26	-	832	12.56 (23.63)	133 (16%)
Chloride	Irrigation Hazard[3]	1000	mg/L	834	816.33 (4199)	97 (12%)

[1] Environmental Protection Agency Drinking Water Standards
[2] United States Salinity Laboratory (1954)
[3] Tanji (1990)

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

Table 4.8.3 Occurrence and levels of some commonly measured groundwater quality constituents in the upper Dockum Group.

Constituent	Type of Standard	Screening Level	Units	Number of Results	Mean Value *(Std Dev)*	Number (%) of Results Exceeding Screening Level
Fluoride	Primary maximum contaminant level[1]	4	mg/L	78	2.28 (1.18)	7 (9%)
Nitrate	Primary maximum contaminant level[1]	10	mg/L as N	68	3.99 (4.82)	7 (10%)
Arsenic	Primary maximum contaminant level[1]	10	µg/L	33	8.91 (8.69)	9 (27%)
pH	Secondary maximum contaminant level[1]	6.5 to 8.5	-	74	7.73 (0.43)	4 (5%)
Chloride	Secondary maximum contaminant level[1]	250	mg/L	79	200.70 (437.97)	17 (22%)
Fluoride	Secondary maximum contaminant level[1]	2	mg/L	78	2.28 (1.18)	46 (59%)
Sulfate	Secondary maximum contaminant level[1]	250	mg/L	79	215.79 (280.91)	19 (24%)
Total Dissolved Solids	Secondary maximum contaminant level[1]	500	mg/L	76	878.82 (1012.67)	38 (50%)
Specific Conductance	Irrigation Salinity Hazard- High[2]	750	µmhos/cm	71	1375.27 (1611.02)	48 (68%)
Specific Conductance	Irrigation Salinity Hazard - Very High[2]	2250	µmhos/cm	71	1375.27 (1611.02)	10 (14%)
Sodium Adsorption Ratio	Sodium hazard – High[2]	18	-	79	5.34 (10.56)	6 (8%)
Sodium Adsorption Ratio	Sodium hazard –Very High[2]	26	-	79	5.34 (10.56)	4 (5%)
Chloride	Irrigation Hazard[3]	1000	mg/L	79	200.70 (437.97)	3 (4%)

[1] Environmental Protection Agency Drinking Water Standards
[2] United States Salinity Laboratory (1954)
[3] Tanji (1990)

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

Table 4.8.4 Occurrence and levels of some commonly measured groundwater quality constituents in the Rita Blanca Aquifer.

Constituent	Type of Standard	Screening Level	Units	Number of Results	Mean Value (*Std Dev*)	Number (%) of Results Exceeding Screening Level
Fluoride	Primary maximum contaminant level[1]	4	mg/L	21	1.28 (0.91)	1 (5%)
Nitrate	Primary maximum contaminant level[1]	10	mg/L as N	18	2.25 (1.29)	0 (0%)
Arsenic	Primary maximum contaminant level[1]	10	µg/L	8	5.90 (4.40)	0 (0%)
pH	Secondary maximum contaminant level[1]	6.5 to 8.5	-	20	7.70 (0.31)	0 (0%)
Chloride	Secondary maximum contaminant level[1]	250	mg/L	21	15.31 (9.34)	0 (0%)
Fluoride	Secondary maximum contaminant level[1]	2	mg/L	21	1.28 (0.91)	2 (10%)
Sulfate	Secondary maximum contaminant level[1]	250	mg/L	21	36.60 (18.90)	0 (0%)
Total Dissolved Solids	Secondary maximum contaminant level[1]	500	mg/L	18	306.61 (69.90)	1 (6%)
Specific Conductance	Irrigation Salinity Hazard- High[2]	750	µmhos/cm	21	515.38 (146.48)	1 (5%)
Specific Conductance	Irrigation Salinity Hazard - Very High[2]	2250	µmhos/cm	21	515.38 (146.48)	0 (0%)
Sodium Adsorption Ratio	Sodium hazard – High[2]	18	-	20	0.69 (0.35)	0 (0%)
Sodium Adsorption Ratio	Sodium hazard –Very High[2]	26	-	20	0.69 (0.35)	0 (0%)
Chloride	Irrigation Hazard[3]	1000	mg/L	21	15.31 (9.34)	0 (0%)

[1] Environmental Protection Agency Drinking Water Standards
[2] United States Salinity Laboratory (1954)
[3] Tanji (1990)

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

Table 4.8.5 Occurrence and levels of some commonly measured groundwater quality constituents in the Edwards-Trinity (High Plains) Aquifer.

Constituent	Type of Standard	Screening Level	Units	Number of Results	Mean Value (*Std Dev*)	Number (%) of Results Exceeding Screening Level
Fluoride	Primary maximum contaminant level[1]	4	mg/L	45	2.96 (1.37)	10 (22%)
Nitrate	Primary maximum contaminant level[1]	10	mg/L as N	50	4.75 (4.58)	7 (14%)
Arsenic	Primary maximum contaminant level[1]	10	μg/L	15	8.97 (7.68)	4 (27%)
pH	Secondary maximum contaminant level[1]	6.5 to 8.5	-	52	7.72 (0.39)	0 (0%)
Chloride	Secondary maximum contaminant level[1]	250	mg/L	57	573.61 (900.13)	32 (56%)
Fluoride	Secondary maximum contaminant level[1]	2	mg/L	45	2.96 (1.37)	29 (64%)
Sulfate	Secondary maximum contaminant level[1]	250	mg/L	56	587.98 (883.64)	33 (59%)
Total Dissolved Solids	Secondary maximum contaminant level[1]	500	mg/L	55	2076.36 (2548.45)	51 (93%)
Specific Conductance	Irrigation Salinity Hazard- High[2]	750	μmhos/cm	52	3320.54 (3539.37)	50 (96%)
Specific Conductance	Irrigation Salinity Hazard - Very High[2]	2250	μmhos/cm	52	3320.54 (3539.37)	28 (54%)
Sodium Adsorption Ratio	Sodium hazard – High[2]	18	-	55	7.79 (10.69)	6 (11%)
Sodium Adsorption Ratio	Sodium hazard –Very High[2]	26	-	55	7.79 (10.69)	3 (5%)
Chloride	Irrigation Hazard[3]	1000	mg/L	57	573.61 (900.13)	10 (18%)

[1] Environmental Protection Agency Drinking Water Standards
[2] United States Salinity Laboratory (1954)
[3] Tanji (1990)

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

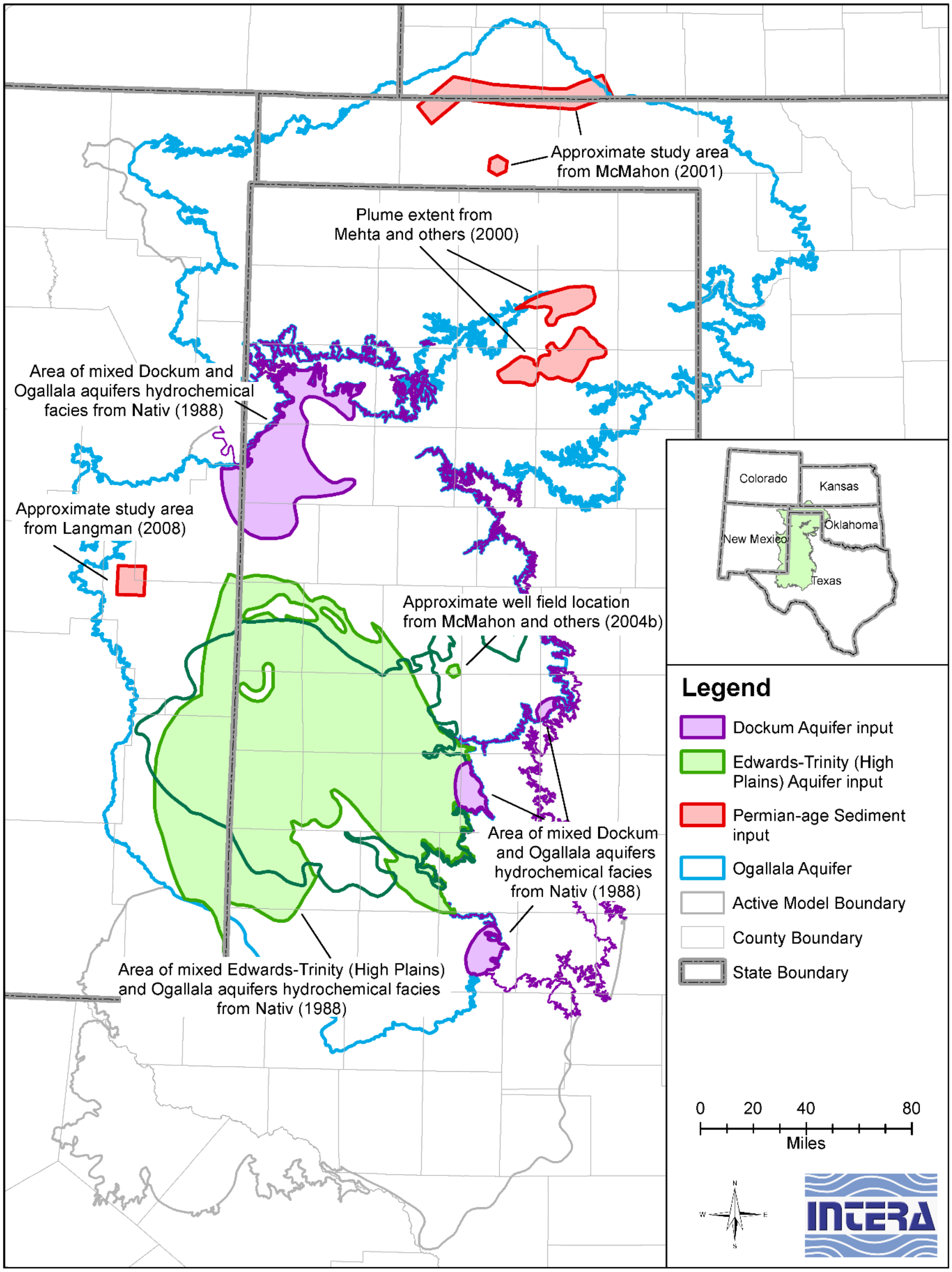

Figure 4.8.1 **Potential locations and source of cross-formational flow from underlying aquifers into the Ogallala Aquifer.**

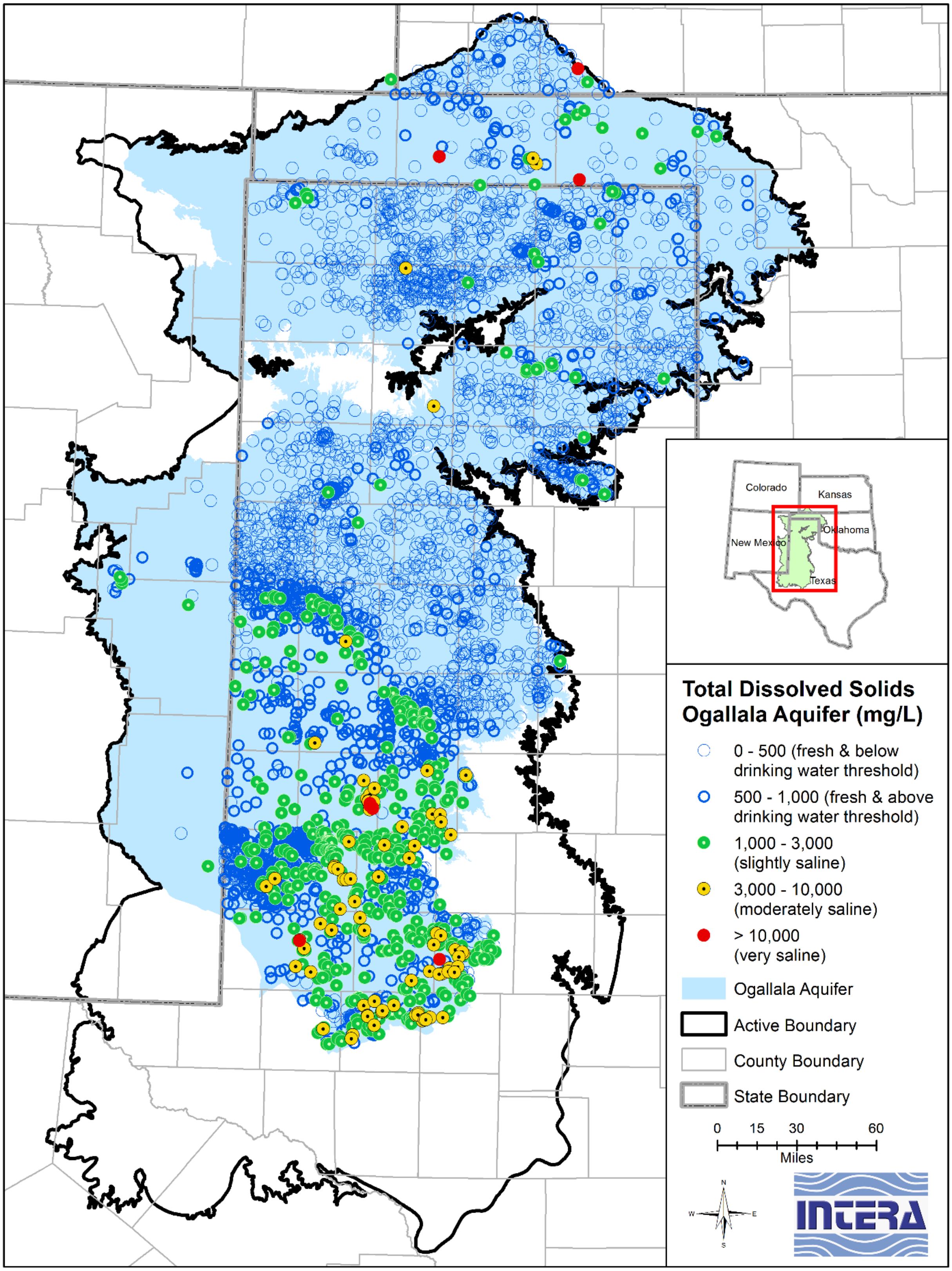

Figure 4.8.2 **Total dissolved solids concentration in the Ogallala Aquifer (TWDB, 2013a).**

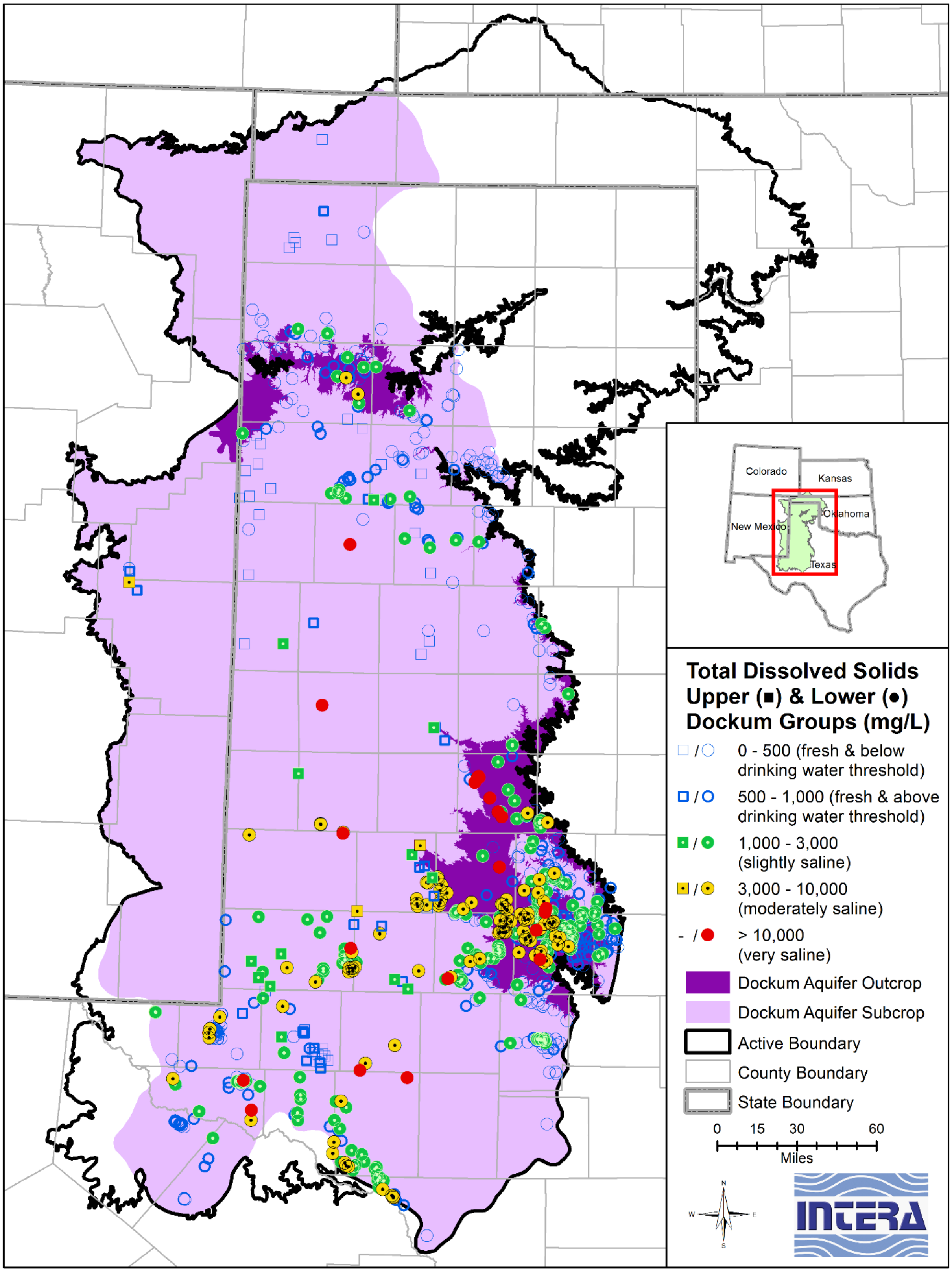

Figure 4.8.3 Total dissolved solids concentration in the Dockum Group (TWDB, 2013a).

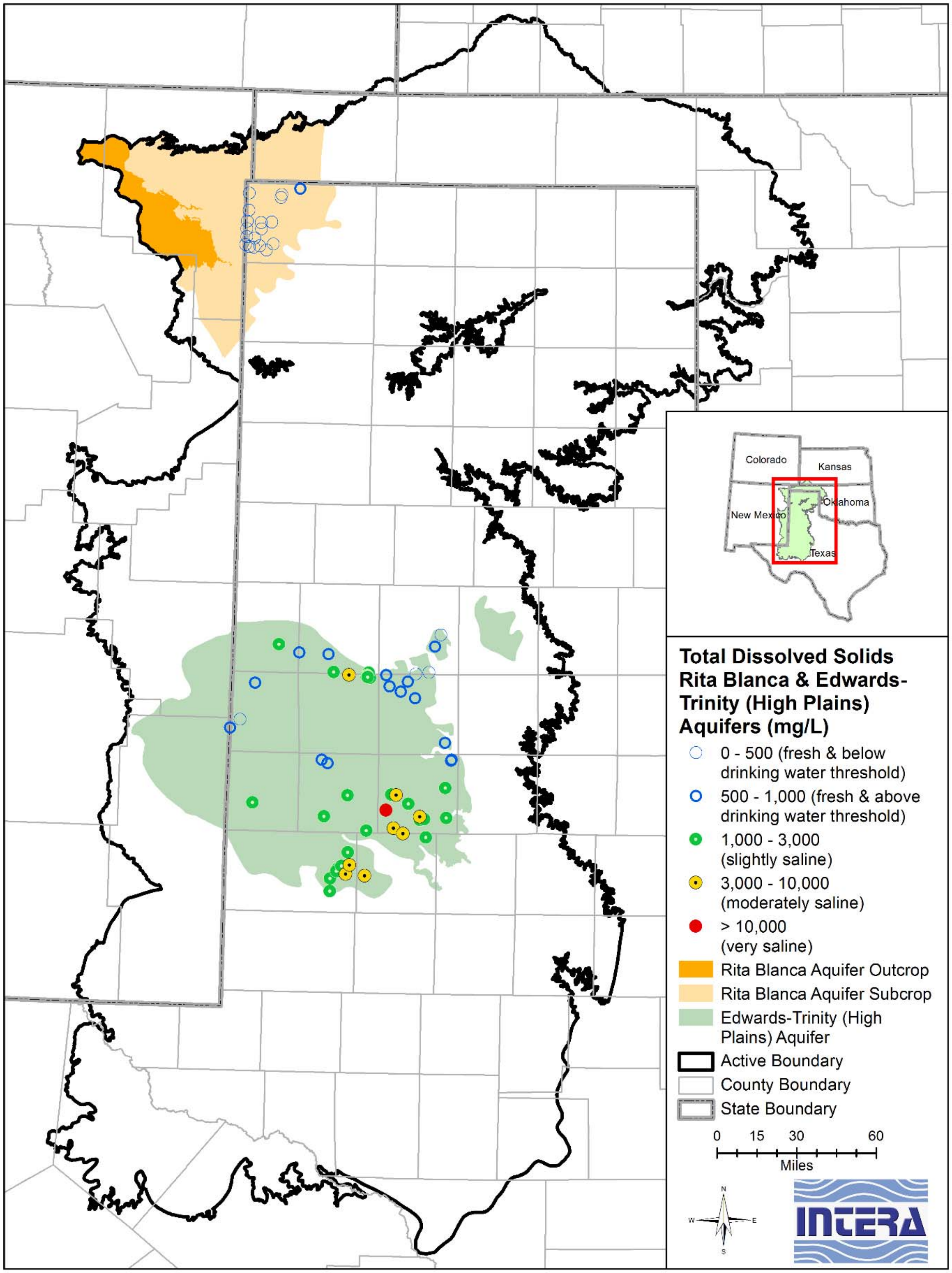

Figure 4.8.4 **Total dissolved solids concentration in the Rita Blanca and Edwards-Trinity (High Plains) aquifers (TWDB, 2013a).**

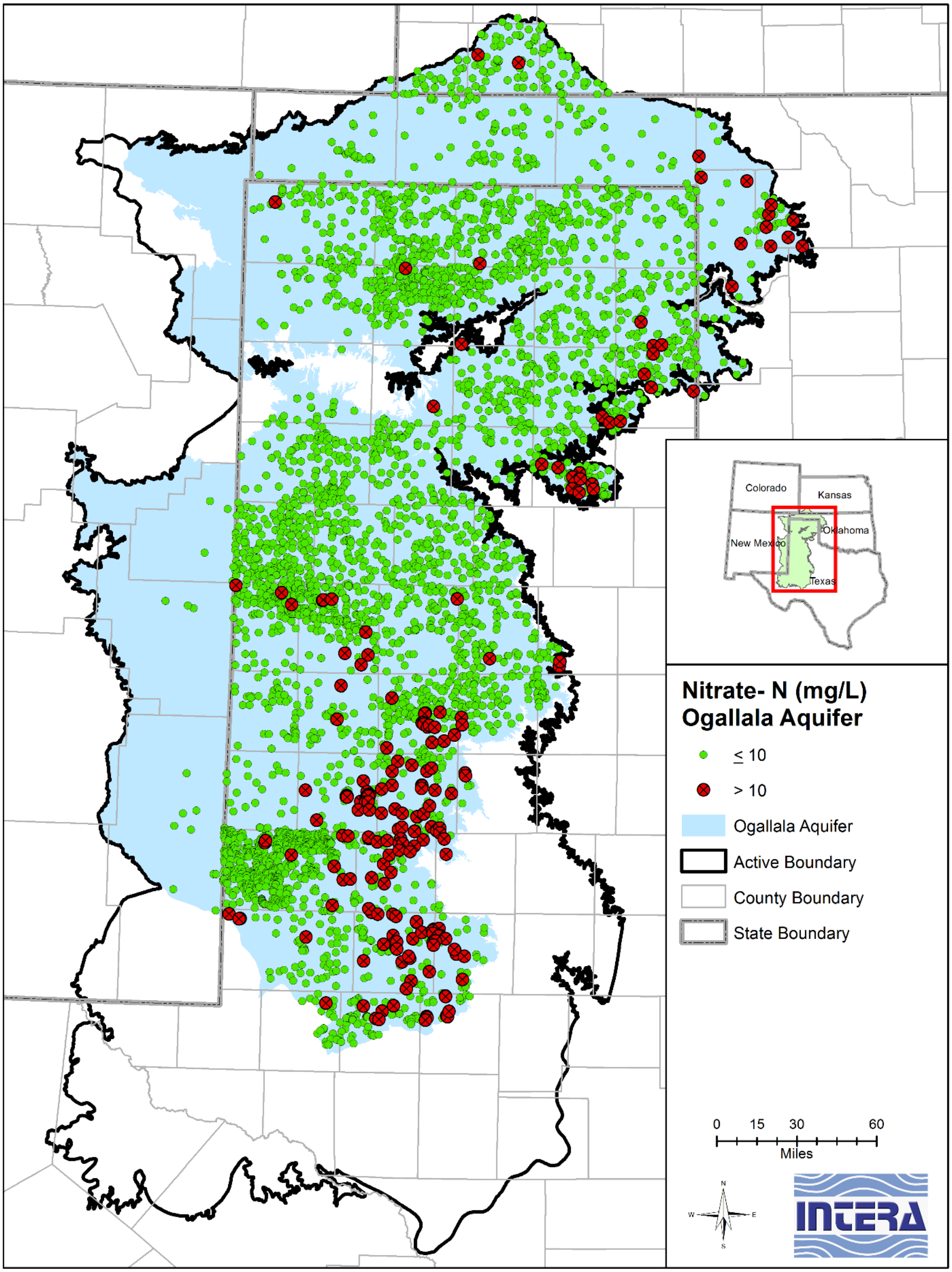

Figure 4.8.5 Nitrate concentration in the Ogallala Aquifer (TWDB, 2013a).

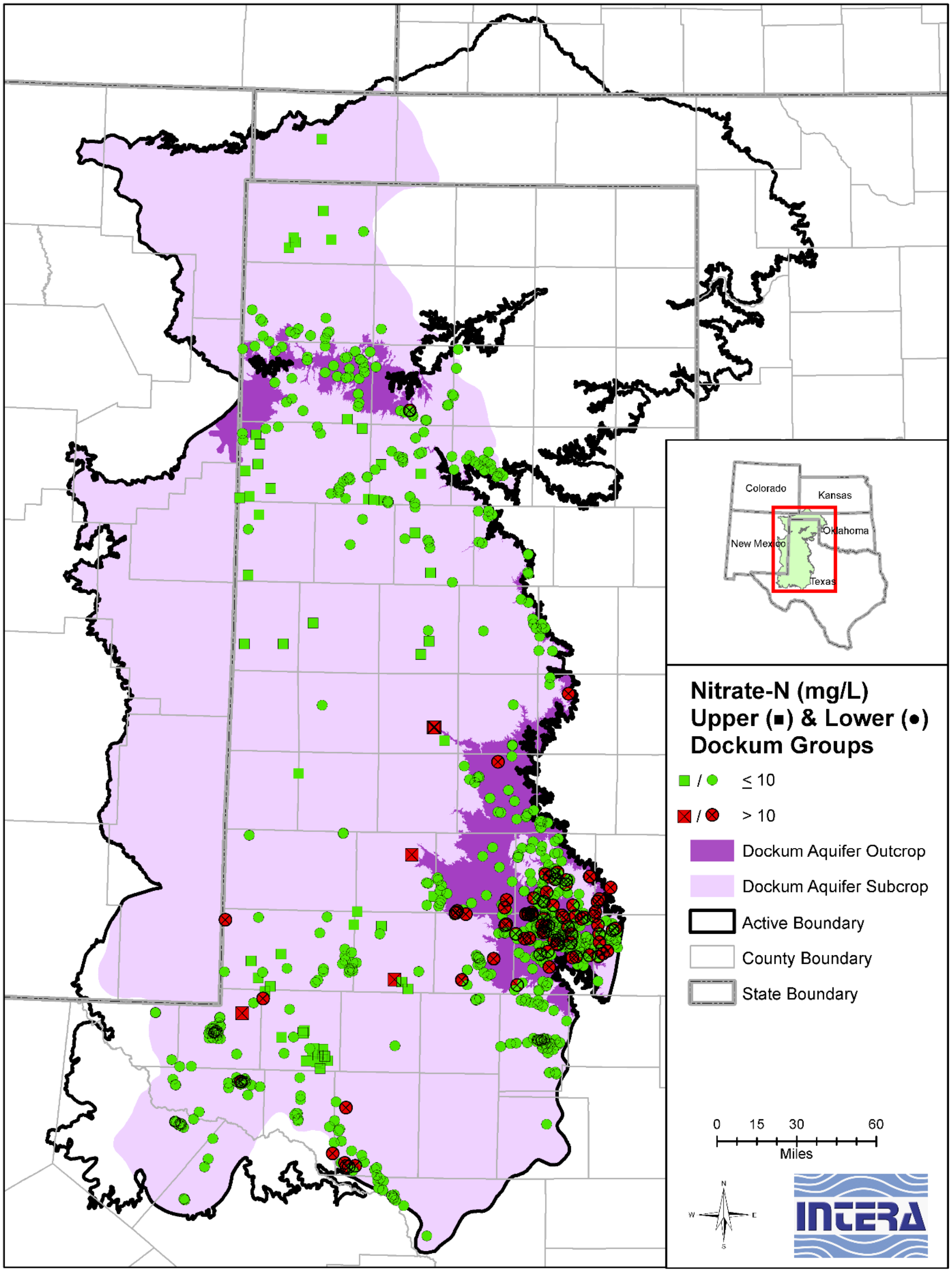

Figure 4.8.6 **Nitrate concentration in the Dockum Group (TWDB, 2013a).**

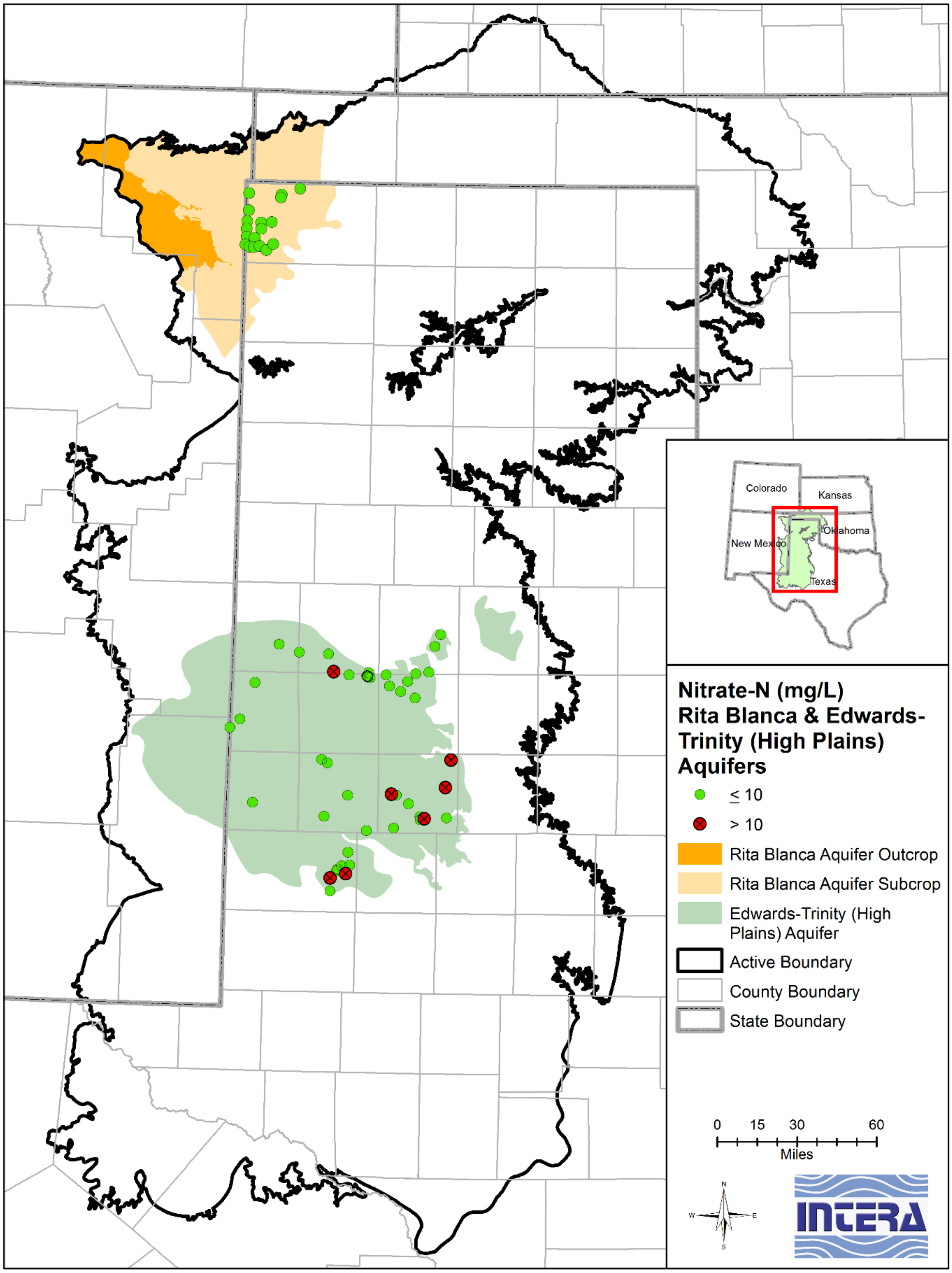

Figure 4.8.7 Nitrate concentration in the Rita Blanca and Edwards-Trinity (High Plains) aquifers (TWDB, 2013a).

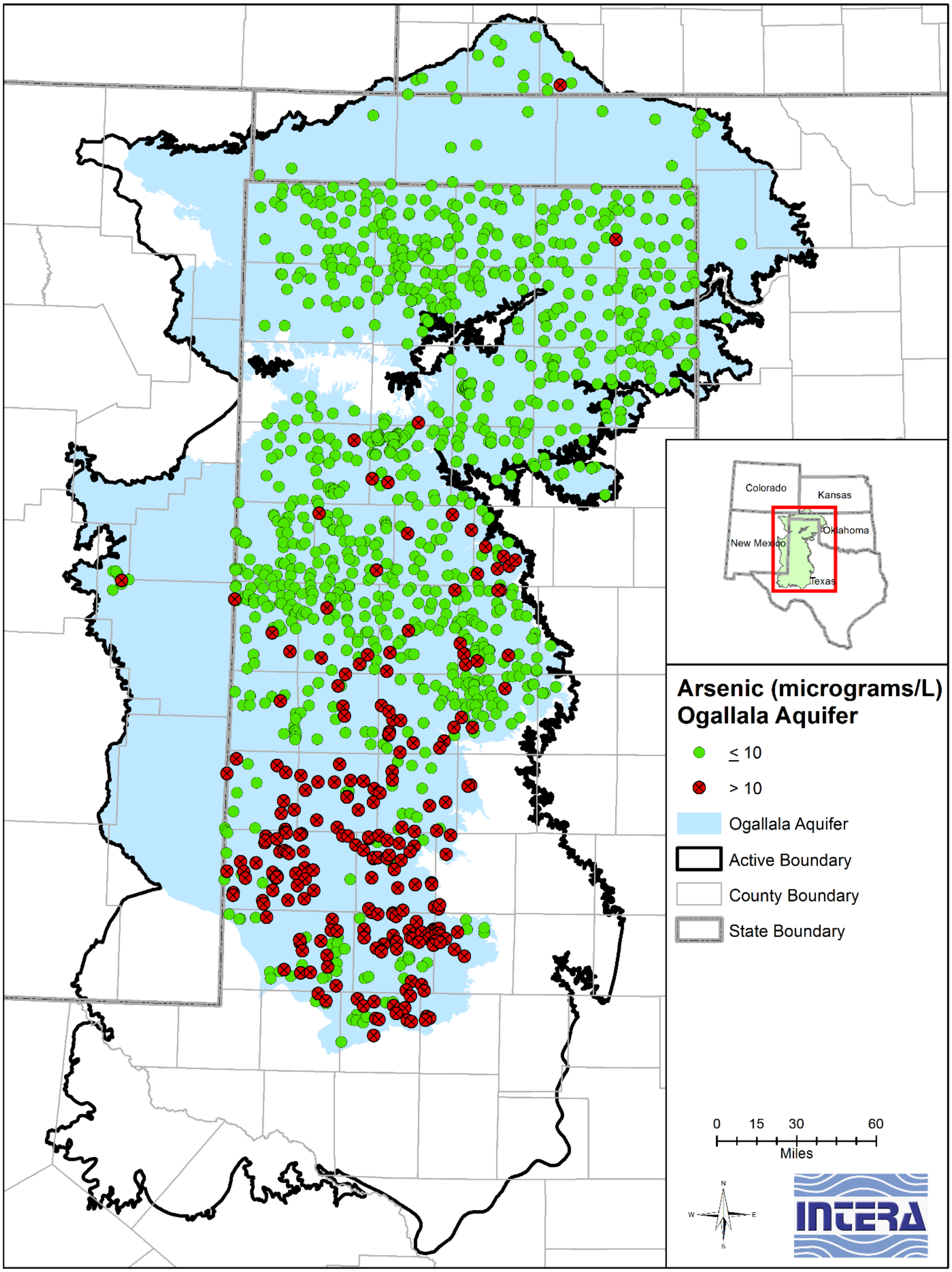

Figure 4.8.8 Arsenic concentration in the Ogallala Aquifer (TWDB, 2013a).

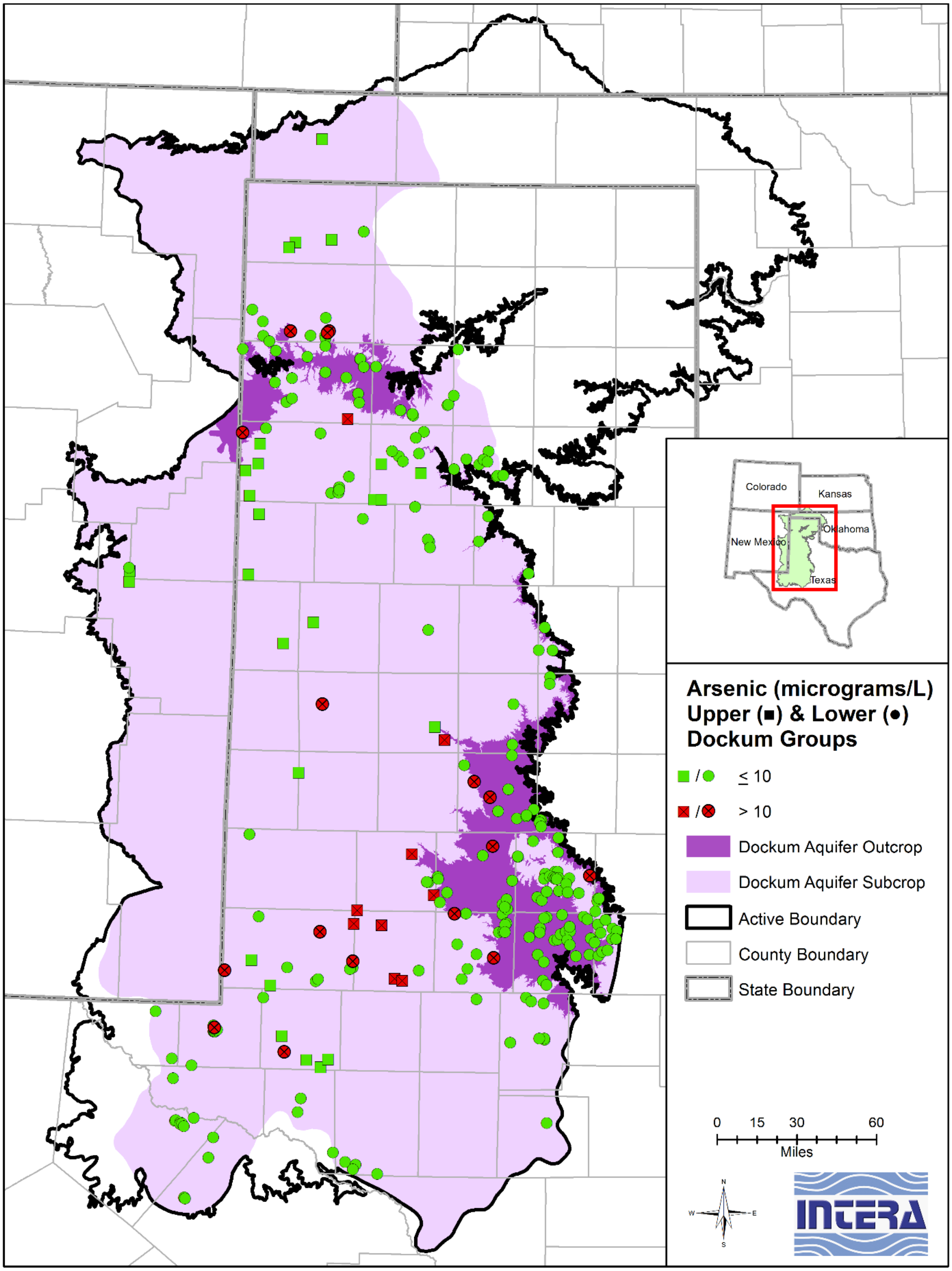

Figure 4.8.9 Arsenic concentration in the Dockum Group (TWDB, 2013a).

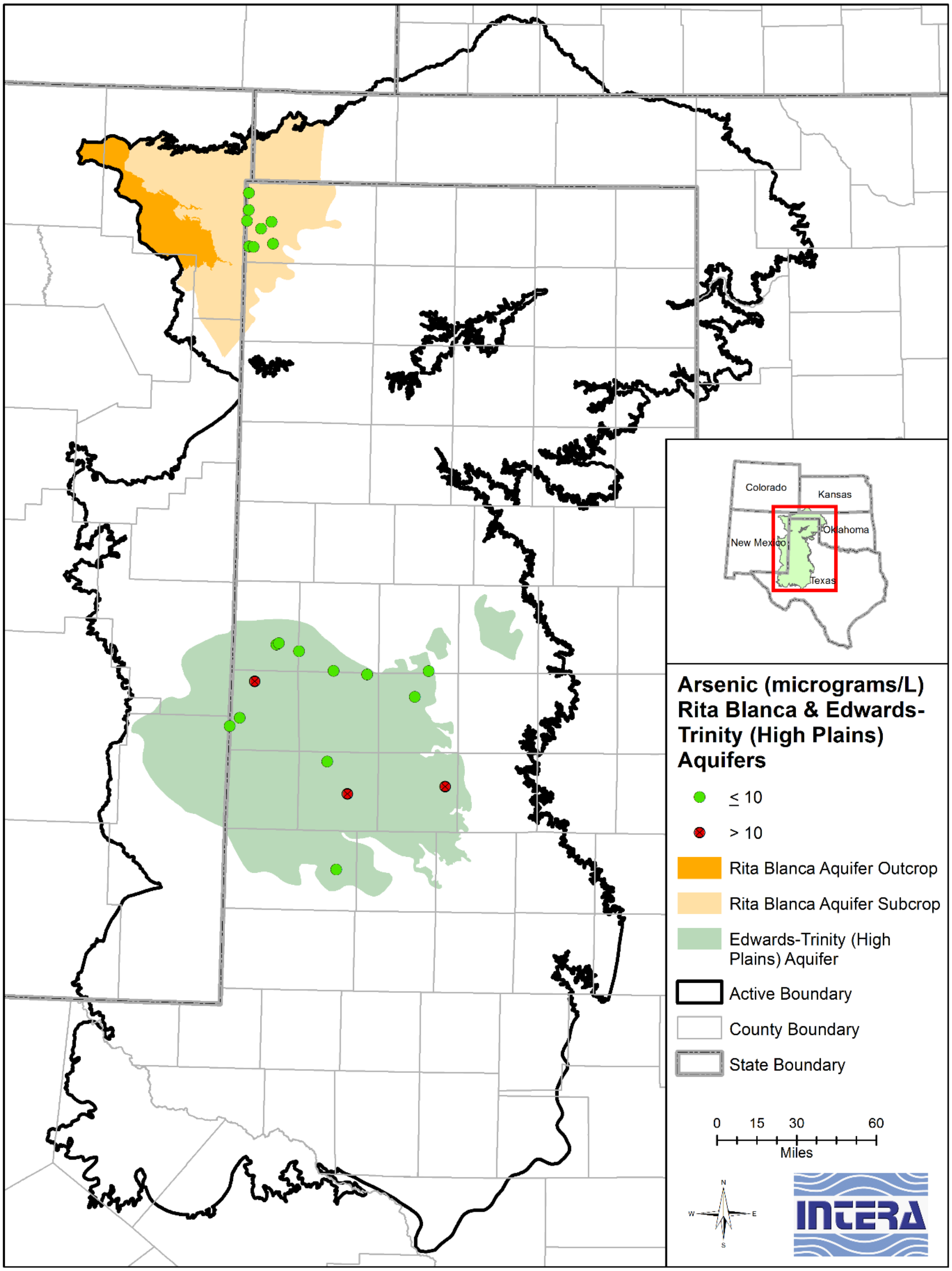

Figure 4.8.10 **Arsenic concentration in the Rita Blanca and Edwards-Trinity (High Plains) aquifers (TWDB, 2013a).**

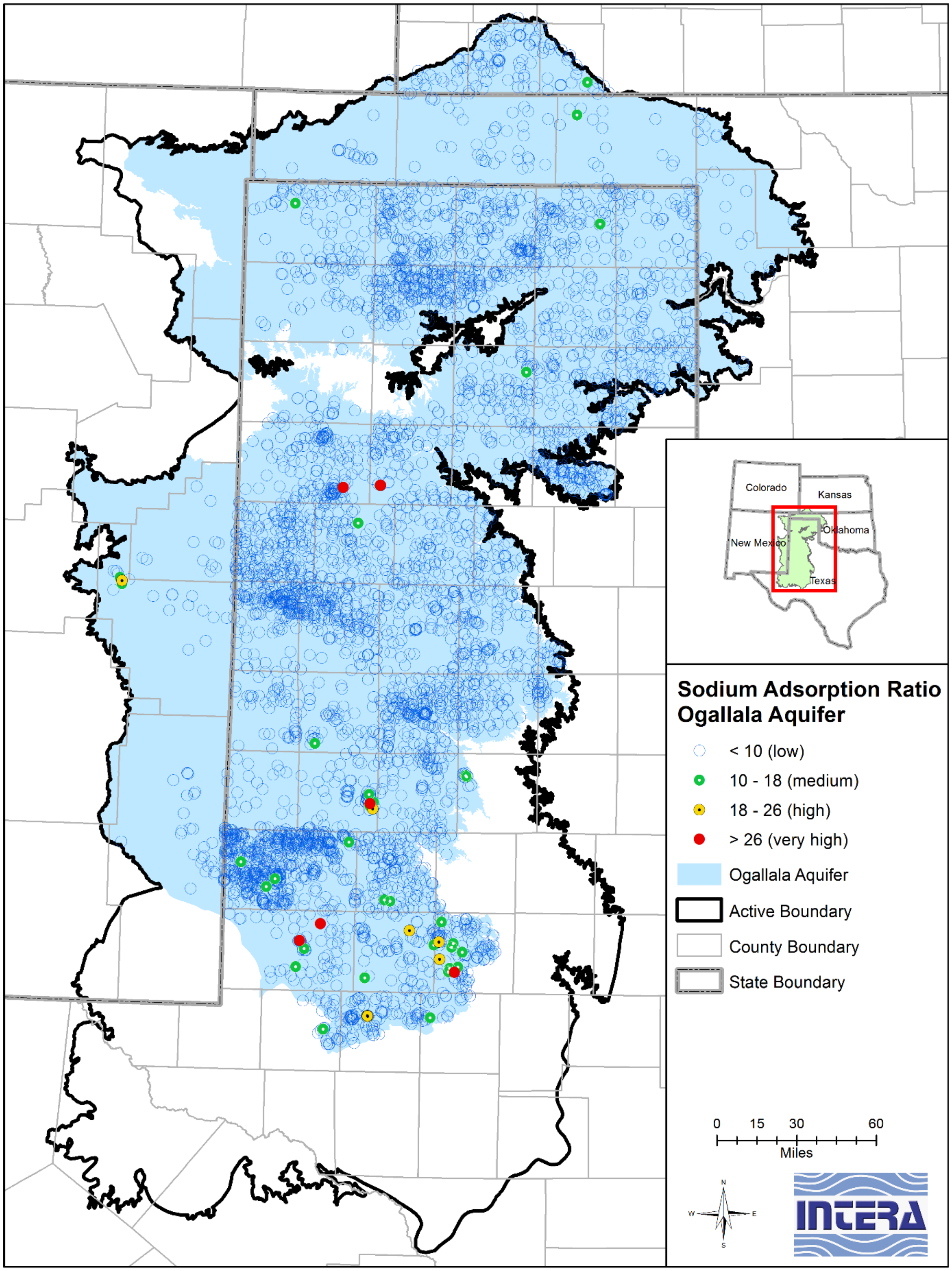

Figure 4.8.11 Sodium adsorption ratio in the Ogallala Aquifer (TWDB, 2013a).

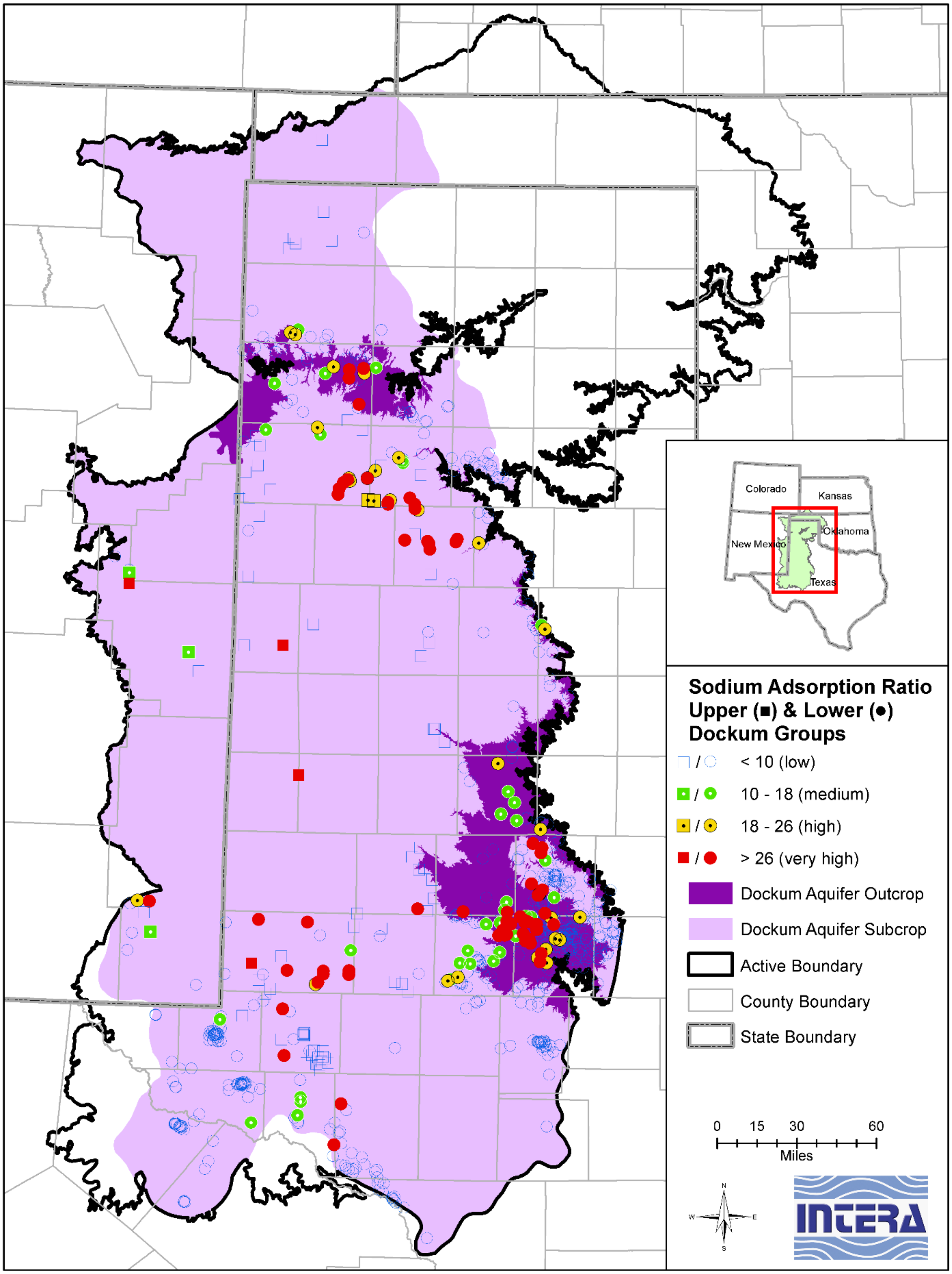

Figure 4.8.12 **Sodium adsorption ratio in the Dockum Group (TWDB, 2013a).**

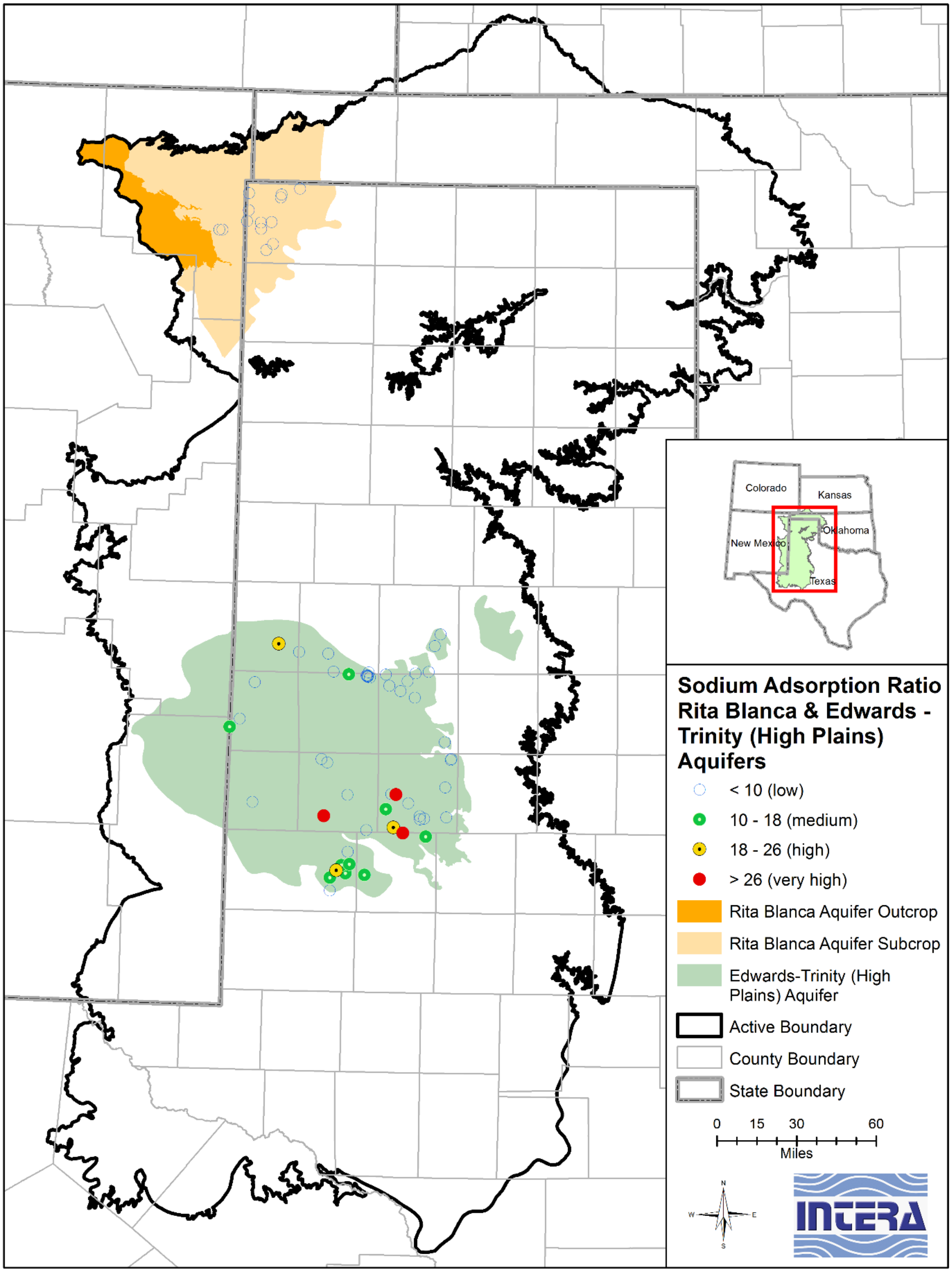

Figure 4.8.13 **Sodium adsorption ratio in the Rita Blanca and Edwards-Trinity (High Plains) aquifers (TWDB, 2013a).**

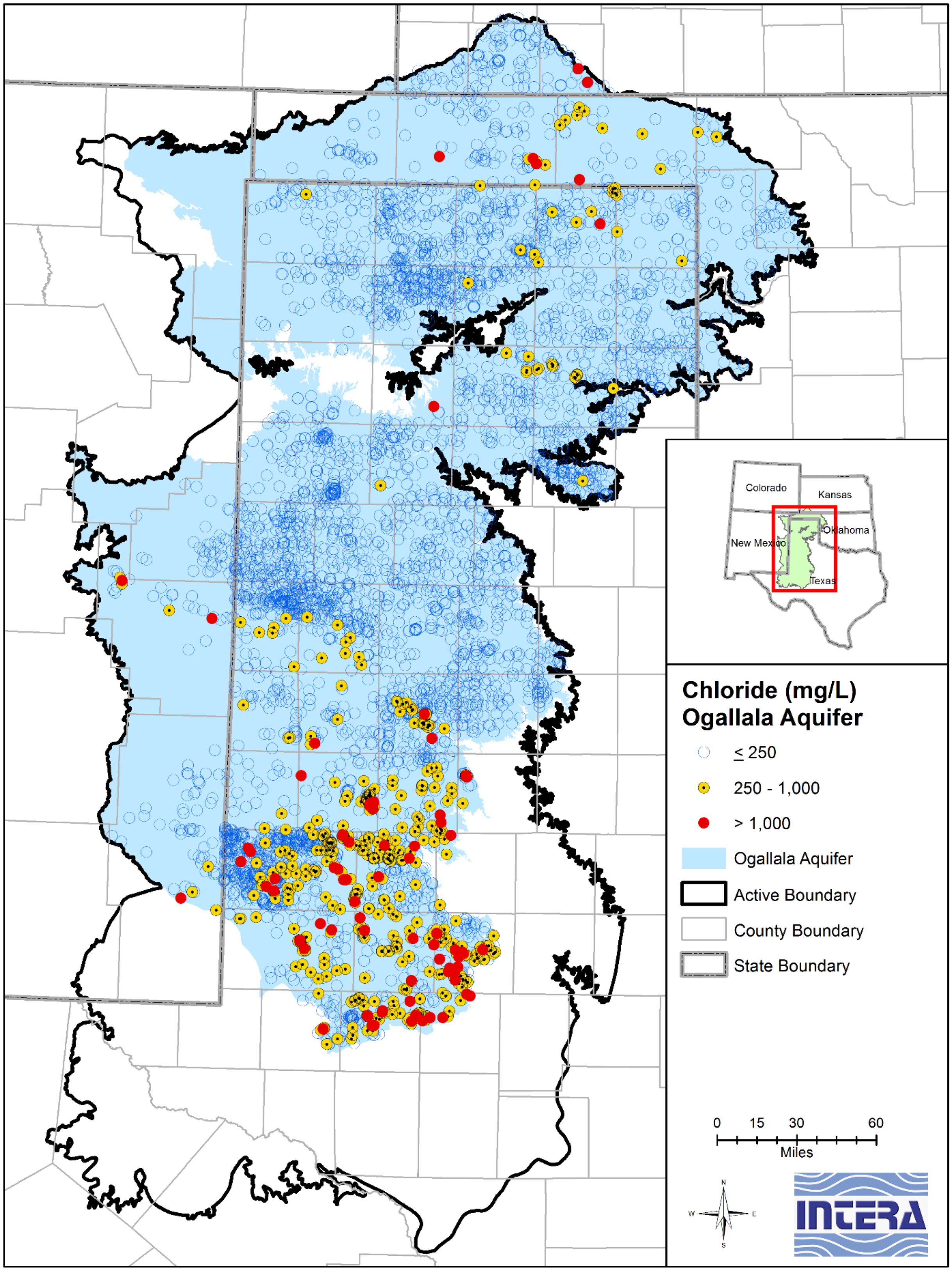

Figure 4.8.14 **Chloride concentration in the Ogallala Group (TWDB, 2013a).**

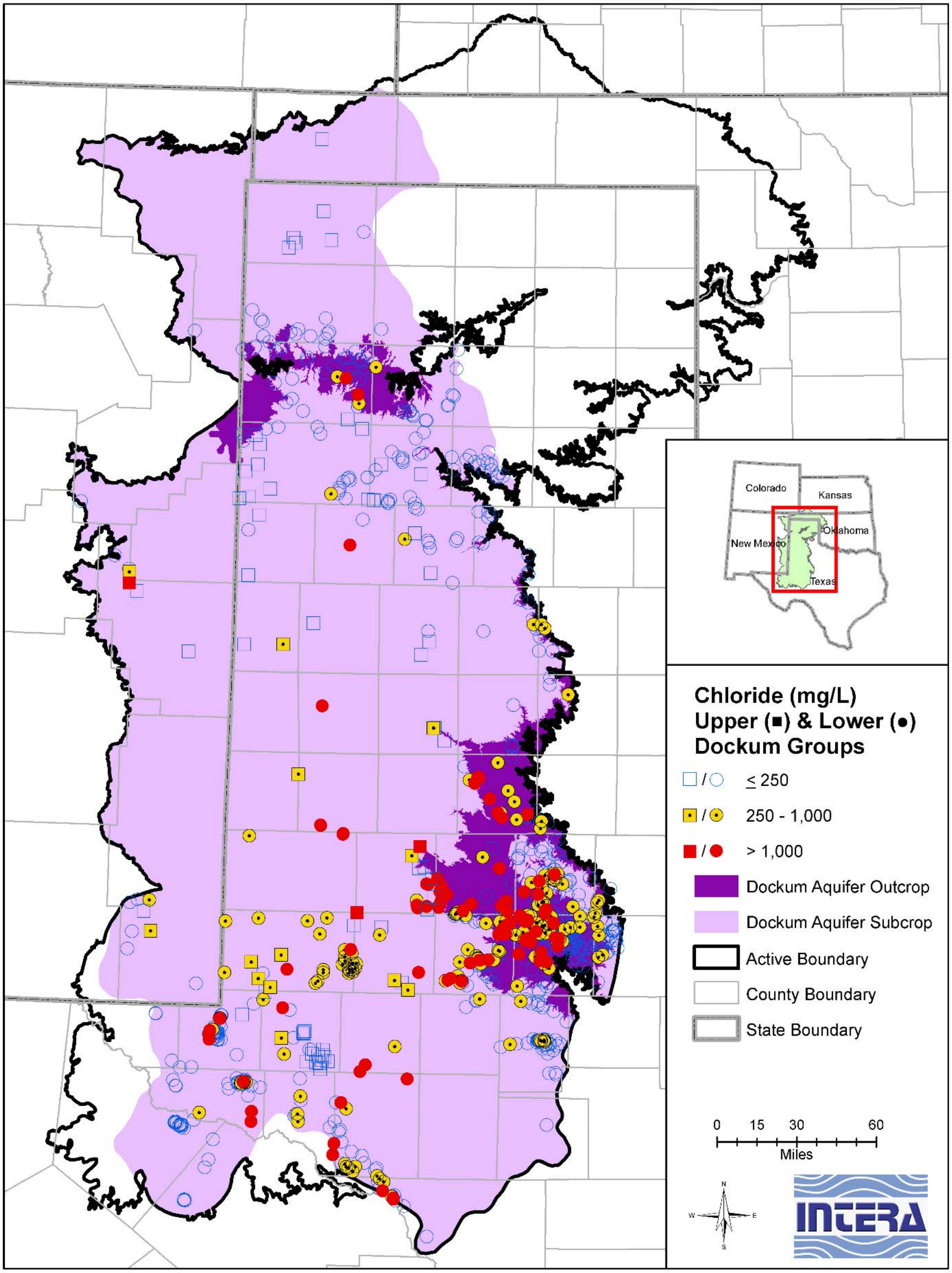

Figure 4.8.15 Chloride concentration in the Dockum Group (TWDB, 2013a).

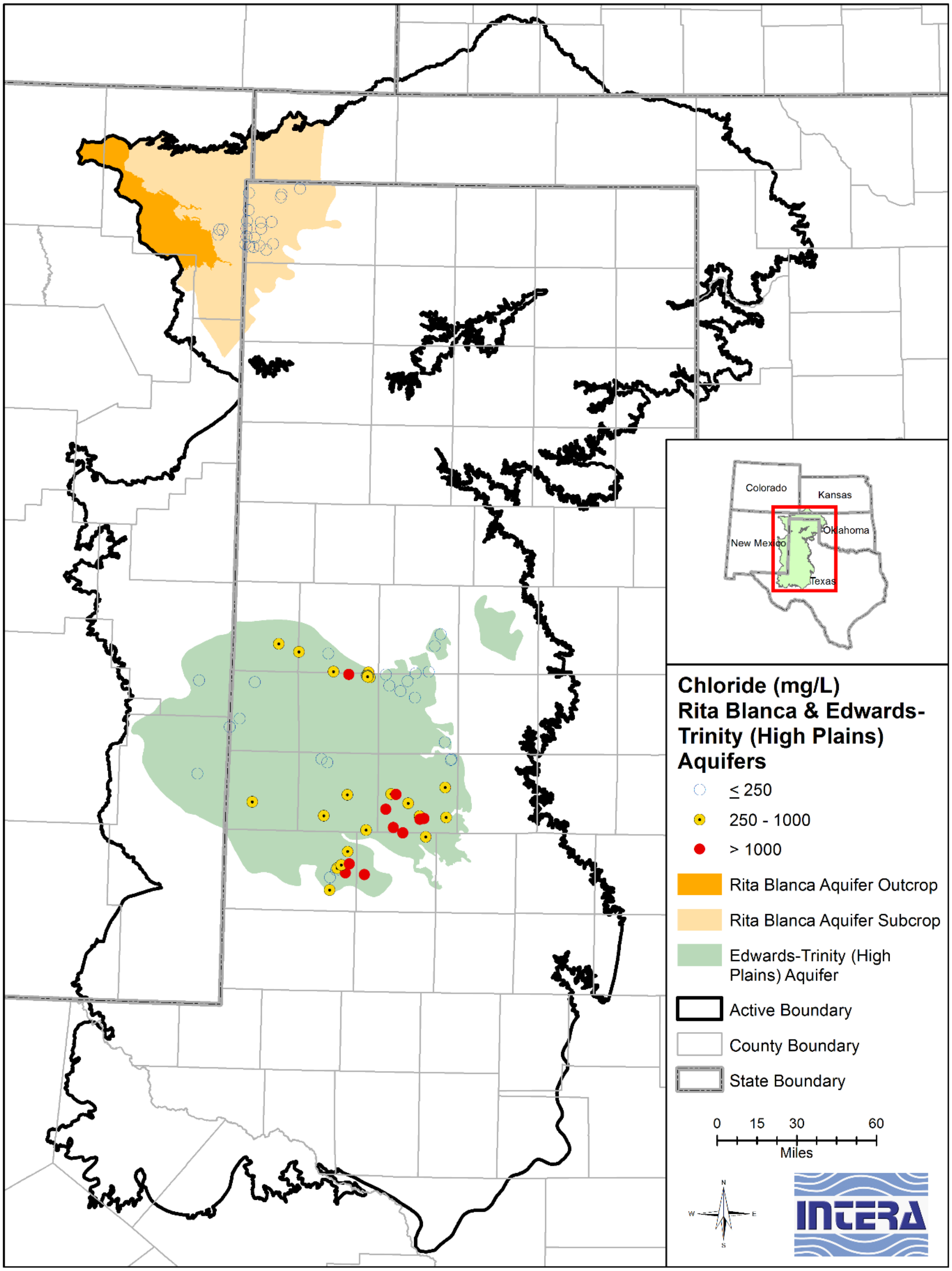

Figure 4.8.16 **Chloride concentration in the Rita Blanca and Edwards-Trinity (High Plains) aquifers (TWDB, 2013a).**

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5.0 Conceptual Model of Groundwater Flow for the High Plains Aquifer System Groundwater Availability Model

The conceptual model for groundwater flow in the High Plains Aquifer System 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. In addition to identifying the hydrostratigraphic layers of the aquifer, the conceptual model also describes factors influencing groundwater flow through the aquifer, defines the mechanisms of recharge and natural aquifer discharge, and quantifies anthropogenic stresses such as pumping. These components of the model are discussed below.

The steady-state model will represent the High Plains Aquifer System in its pre-development condition, which is represented as conditions prior to about 1930. Although cultivation was well under way by 1930, groundwater irrigation was minimal, and the effects of land use on percolation had yet to strongly impact recharge at the water table. Under steady-state conditions, the aquifer system is unaffected by anthropogenic activities and is in long-term dynamic equilibrium. In this pre-development state, aquifer recharge is balanced by aquifer discharge resulting in no net change in groundwater storage. Figure 5.0.1 shows the location of two cross-sections in the study area. Figure 5.0.2 shows the structure cross-section W1-E1 in the northern part of the study area, annotated with pre-development recharge and discharge features. The lower half of the figure is a block schematic with similar annotation showing the proposed numerical model layer scheme. The formations dip strongly from west to east, following land surface. The Ogallala Aquifer is largely unconfined and, under pre-development conditions, was recharged by precipitation, with focused recharge occurring in playa lakes. Groundwater flow generally followed the topography, with west to east flow in the Northern Ogallala Aquifer. These regional flow patterns were locally diverted in topographically low areas. Discharge occurred through springs, streams, and saline lakes. Some discharge occurred through evapotranspiration in riparian areas. Some discharge exited the aquifer as cross-formational flow, recharging the underlying aquifers, such as the Rita Blanca Aquifer.

Except in its outcrop area, the Rita Blanca Aquifer is overlain by the Ogallala Aquifer. Under pre-development conditions, the aquifer was recharged by precipitation in the outcrop area and by downward flow from the Ogallala Aquifer in some areas. In general, groundwater flowed downdip towards the southeast. Discharge occurred at springs and small streams in the Rita Blanca Aquifer outcrop and as cross-formational flow to the underlying Dockum Aquifer.

The Edwards-Trinity (High Plains) Aquifer is largely under confined conditions, and is overlain by the Ogallala Aquifer throughout its entire extent. Under pre-development conditions, recharge occurred through downward flow from the Ogallala Aquifer. Because the upper formations (Duck Creek and Kiamichi) of the Edwards-Trinity (High Plains) Aquifer exhibit high shale and clay content, the greatest potential for interaction occurs where these formations are thin or eroded away. Regional groundwater flow in the aquifer was to the southeast. Some discharge occurred at surficial saline lakes and as cross-formational flow downward into the Dockum Aquifer.

The upper and lower Dockum aquifers are under confined conditions except in outcrop areas. Under pre-development conditions, the aquifer was recharged by precipitation in the outcrop where the lower Dockum Aquifer is exposed. This recharge did not move very far downdip but, rather, discharged locally to springs and streams. The subcrop of the Dockum Group is no longer an active groundwater flow system and has received little to no recharge since the Pleistocene. The shallow active portion of the Dockum Aquifer near the outcrops receives recharge from the overlying Ogallala, Edwards-Trinity (High Plains), and Pecos Valley aquifers. The locations where cross-formational flow recharges the Dockum Aquifer is generally limited to areas where the upper Dockum Aquifer is missing and the lower Dockum Aquifer is relatively shallow, as is the case along the eastern edge of the aquifer. In areas where the upper Dockum Aquifer is present, its low permeability mudstone likely restricts downward flow from the overlying Ogallala and Edwards-Trinity (High Plains) aquifers. Some small amount of groundwater may also flow vertically from the overlying Edwards-Trinity (Plateau) Aquifer to the Dockum Aquifer.

The transient model will represent the High Plains Aquifer System during its post-development stage. In this period, human activities altered the dynamic equilibrium of the pre-development flow system through pumping withdrawals, changes in recharge through development and irrigation return flow, and changes in vegetation. Figure 5.0.3 shows the structure cross-section W2-E2 in the southern part of the study area, annotated with post-development recharge and discharge features.

In the Ogallala Aquifer, post-development irrigation pumping has significantly lowered the Ogallala Aquifer water table and locally affected groundwater flow direction as discussed in Section 4.3. Pumping is now the largest discharge mechanism in the Ogallala Aquifer. Most of the pumping discharge is offset by a decrease in aquifer storage. Figure 5.0.4 shows a plot of the estimated drawdown from pre-development water levels versus the pre-development saturated thickness in the Southern Ogallala Aquifer (Scanlon and others, 2010a). Drawdown is based on the difference between the earliest water level available (average 1958) and 2002 water levels. The values shown are representative of the northern and southern portions of the Southern Ogallala Aquifer, separated by the 500 milligram per liter total dissolved solids contour (see Figure 5.0.1). In both portions, the largest amount of pumping and corresponding drawdown clearly occurred where the initial saturated thickness was largest. This relationship can help guide where to place pumping in the model. Some of the pumping discharge is offset by capture, with decreased discharge to springs, streams, and other surface discharge features. Many springs have either experienced reduced flow or dried up completely. Streams and draws that were originally fed by springs or aquifer discharge also have reduced or no flow.

As discussed in Section 4.4, post-development conversion of rangeland to cultivated land increased percolation in certain local areas due to changes in the soil character, and decreases in evapotranspiration and runoff. Irrigation return flow also increased percolation. However, enhanced percolation does not immediately appear as recharge to the water table. In some counties, such as Dawson, the enhanced percolation recharged the Ogallala Aquifer early, prior to 1940. Some areas in that region show steady or increasing water levels, indicating recharge in excess of discharge. Other counties in the Southern Ogallala Aquifer region show evidence of enhanced recharge from cultivation and/or irrigation beginning in the 1970s through 1990s. In the Northern Ogallala Aquifer region, unsaturated zone borehole profiles indicate that the conversion to cultivated agricultural land has had little to no impact on recharge, likely due to the presence of restrictive underlying soil layers. Post-development recharge in this region therefore remains close to pre-development rates.

Similar to the Ogallala Aquifer, the Rita Blanca Aquifer generally shows a decline in water levels due to increased pumping discharge, which is balanced by reduced groundwater storage, less cross-formational flow, and reduced groundwater storage. The decline in the Edwards-Trinity (High Plains) Aquifer water levels is not as pronounced or as uniformly distributed as in the Ogallala or Rita Blanca aquifers. The increased discharge from pumping is balanced by decreased discharge to saline lakes, less cross-formational flow, and reduced groundwater storage.

The upper Dockum Aquifer does not show a change from pre-development conditions north of the Canadian River. In the southern portion of the aquifer, minor water-level declines are observed across the entire aquifer with higher declines concentrated in northeastern Deaf Smith County and south-central Swisher County as described in Section 4.3. The increase in discharge via pumping is likely balanced by a decrease in discharge as cross-formational flow.

As shown in Section 4.3, the lower Dockum Aquifer has shown a more consistently distributed decline in water level than in the upper Dockum Aquifer. The highest declines are seen in northwestern Pecos County and along the border of Curry and Roosevelt counties, New Mexico. In a few local areas, particularly in the Colorado River outcrop area, increased recharge due to irrigation return flow appears to offset this increased discharge through pumping. Elsewhere, discharge through pumping is offset by reduced natural discharge to springs and streams in outcrop areas and cross-formational flow.

Figures 5.0.2 and 5.0.3 contain block schematics of the formations presented in the cross-sections, and their proposed numerical model layer representations. The numerical model will consist of four layers. In the northern and central portions of the study area, Layer 1 represents the Ogallala Aquifer. In the southern portion of the study area, Layer 1 will represent the Pecos Valley Aquifer. Although the Pecos Valley Aquifer is not explicitly modeled as part of the High Plains Aquifer System, it is included to provide a reasonable head boundary for the underlying Dockum Aquifer in areas where the Ogallala Aquifer is absent. Layer 2 represents the Rita Blanca Aquifer in the northern portion of the study area, the Edwards-Trinity (High Plains) Aquifer in the central portion of the study area, and the Edwards-Trinity (Plateau) Aquifer in the southern portion of the study area. Like the Pecos Valley Aquifer, the Edwards-Trinity (Plateau) Aquifer is not considered part of the High Plains Aquifer System, but is included in the model to provide a reasonable head boundary for the underlying Dockum Aquifer. Model Layers 3 and 4 represent the upper and lower Dockum aquifers, respectively, in all areas of the model. The top of the Permian-age sediments forms the no-flow bottom boundary of the model.

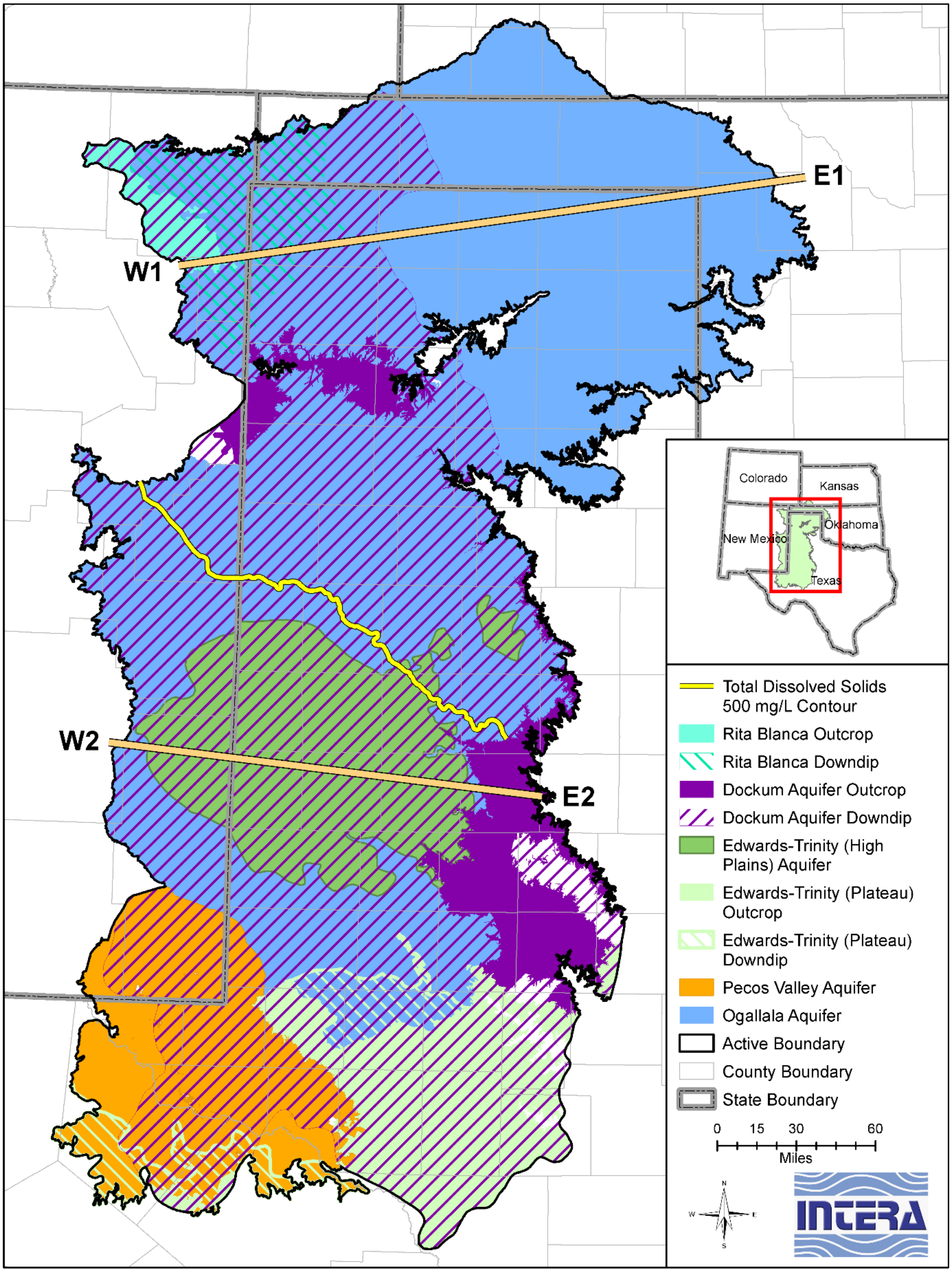

Figure 5.0.1 **Location of cross-sections shown in Figures 5.0.2 and 5.0.3.**

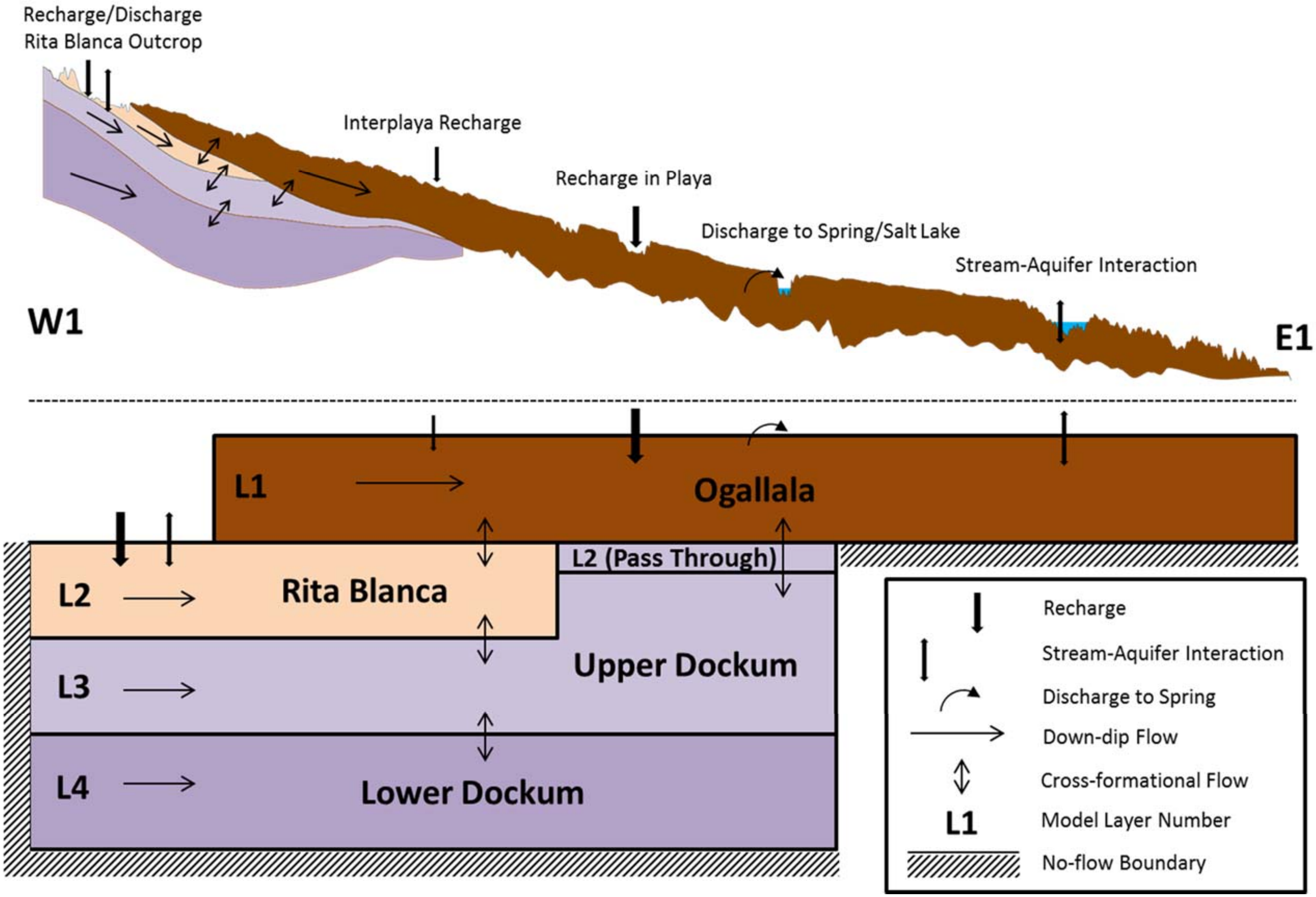

Figure 5.0.2 **Cross-section W1 – E1, annotated with pre-development recharge and discharge components. The block schematic shows proposed numerical model layer scheme.**

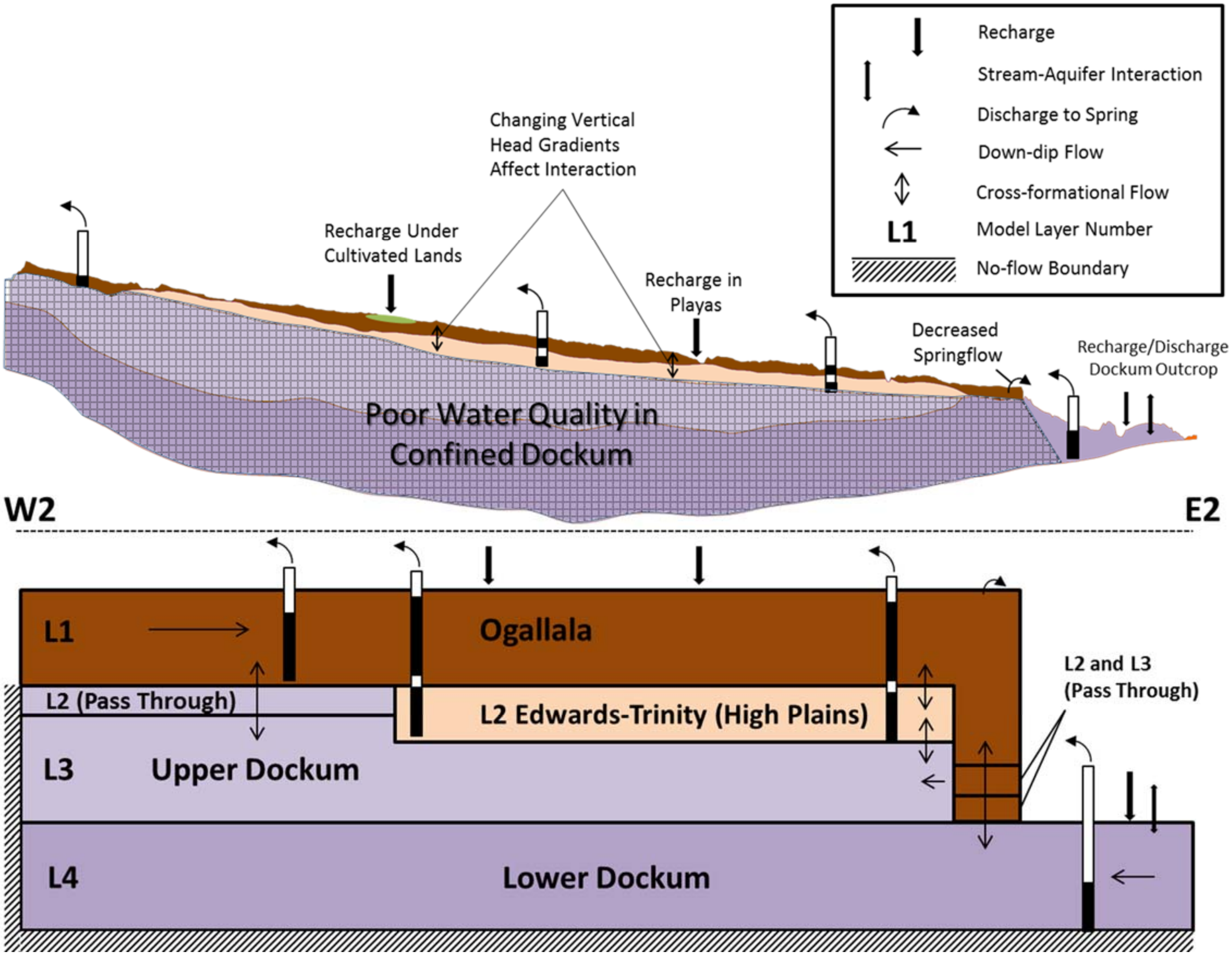

Figure 5.0.3 **Cross-section W2 – E2, annotated with post-development recharge and discharge components. The block schematic shows proposed numerical model layer scheme.**

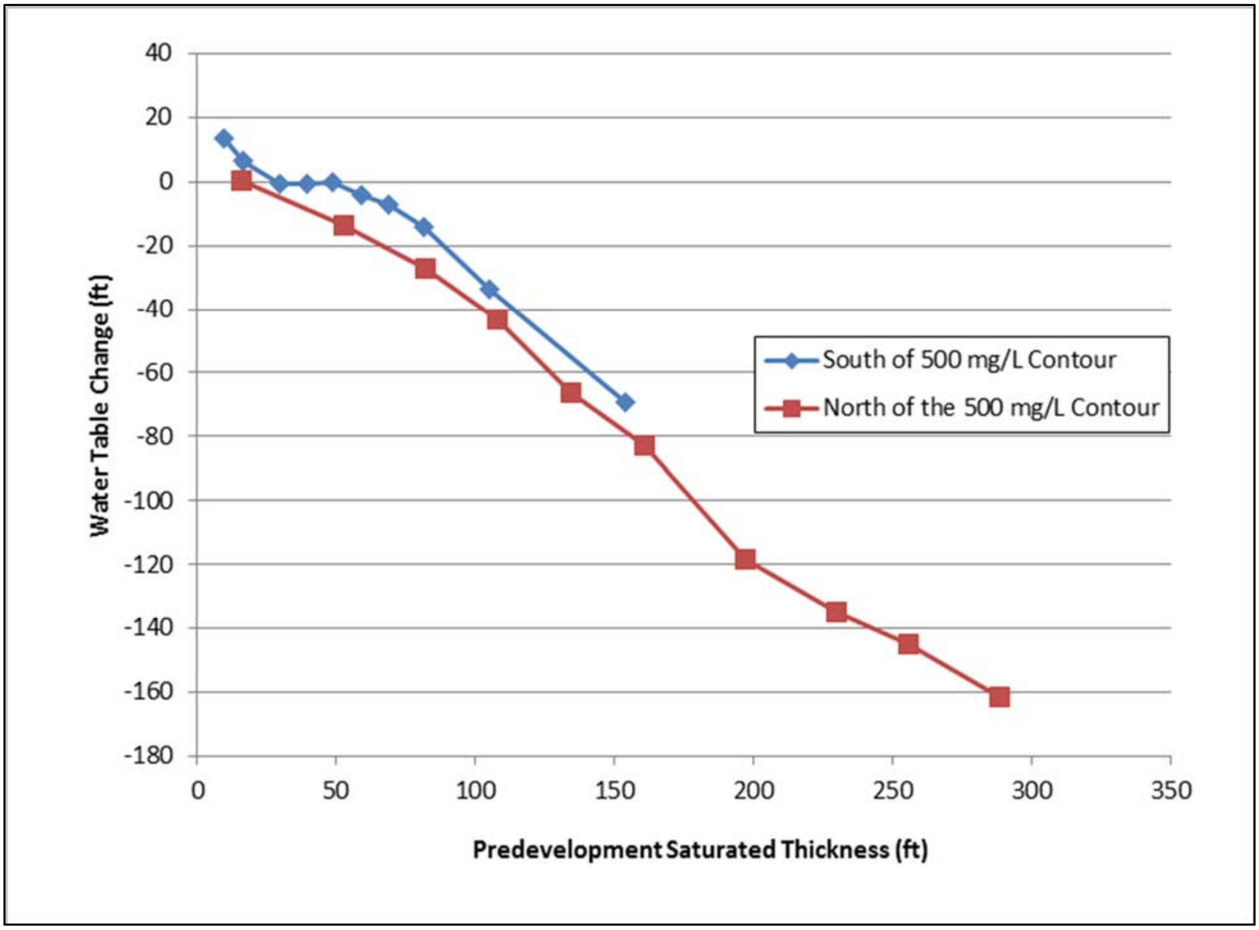

Figure 5.0.4 **Pre-development saturated thickness versus historical change in water level (from pre-development to 2002) in the Southern Ogallala Aquifer (Scanlon and others, 2010a).**

6.0 Future Improvements

In this section, recommendations for potential future improvements in the conceptual model are provided. Additional ideas may occur through the continued stakeholder process and the development of the numerical model. The recommendations are approximately grouped when applicable, according to the sections in Chapter 4.

Hydrostratigraphy and Structure

The current work provides a regional structural framework based on geophysical log analysis, with supplemental local estimates of Ogallala Aquifer bottom from driller log analyses, where available. As additional analyses, either geophysical log or driller log, become available, they could be added to the dataset used to build the surfaces, improving resolution in those areas.

Hydraulic Heads

The Ogallala Aquifer contains an extensive water level monitoring network. However, the minor aquifers, including the Dockum, Rita Blanca, and Edwards Trinity (High Plains) aquifers, have fewer measurements. Wells are often only partially completed in the minor aquifers making interpretation of water levels challenging. As these minor aquifers continue to be developed, new wells and data will become available to help refine the water level estimates. This is especially true for analyzing vertical flow between the aquifers, which is currently difficult to assess using water levels because of sparcity of data, and lack of nearby well pairs clearly screened in different units.

Recharge

Recharge has been studied extensively in the Ogallala Aquifer. Additional field studies in the Dockum Aquifer outcrop could help improve estimates of recharge in the aquifer.

Hydraulic Properties

Similar to water levels, continued development of the minor aquifers should bring access to more aquifer tests and geophysical logs to help increase resolution of hydraulic conductivity data. What would be especially useful would be an aquifer test specifically in one formation, with monitoring in the over- or underlying formation, to allow for some estimate of the vertical conductivity between the formations. Continued development of the minor aquifers will cause cross-formational flow to become an increasingly important factor, especially given the difference in water quality among the aquifers that compose the High Plains Aquifer System.

Pumping

The vast majority of agricultural pumping in the Ogallala does not have rate measurements at the wellhead or at the pivot. In the absence of these measurements, other strategies, such as GIS-based analyses of crop water use, might improve estimates of production.

Water Quality

Similar to water levels and hydraulic properties, additional wells in the minor aquifers will bring additional water quality information that could be useful in improving the characterization of water quality in the minor aquifers. Additionally, characterization of the brackish portions of the aquifers is becoming more important. Data is currently somewhat limited in many of the fresh-brackish transition zones, especially in the Dockum Aquifer.

7.0 Acknowledgements

We would like to acknowledge several organizations and individuals who contributed to the development of the conceptual model for the High Plains Aquifer GAM. The North Plains Groundwater Conservation District, Panhandle Groundwater Conservation District, and High Plains Underground Water Conservation District No. 1 all contributed financially to this project. These Districts, as well as the Hemphill County Underground Water Conservation District, Mesa Underground Water Conservation District, Permian Basin Underground Water Conservation District, South Plains Underground Water Conservation District, and Llano Estacado Underground Water Conservation District, provided valuable data and other support. Local knowledge from these Districts proved especially valuable in development of the conceptual model.

We would like to thank the cities of Amarillo, Lubbock, Canyon, and Morton, as well as the Canadian River Municipal Water Authority and the Red River Authority of Texas, for the data and support they provided.

We would like to thank both the Mesa Underground Water Conservation District and the city of Amarillo for hosting Stakeholder Advisory Forums.

Senior technical expert Steven Seni provided expert review of the hydrostratigraphy and structure. Dr. Paul Colaizzi provided expert input on historical irrigation practices in the High Plains.

We would like to thank Wade Oliver of INTERA, Inc. for his review of this conceptual model report. Finally, we would like to thank Judy Ratto of INTERA, Incorporated for her efforts in editing and production of this report.

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APPENDIX A

Comments and Responses
for
Review of "Draft Conceptual Model for the High Plains Aquifer System Groundwater Availability Model" Report and deliverables for TWDB Contract No. 1248301494 dated March 31, 2015

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Appendix A

Comments and Responses
for
Review of "Draft Conceptual Model for the High Plains Aquifer System Groundwater Availability Model" Report and deliverables for TWDB Contract No. 124801494 dated March 31, 2015

Attachment 1

The following report and data review comments shall be addressed and included in the final draft deliverables due March 31, 2015. Please note the items listed under suggestions are editorial in context and are not contractually required; however, adjustments noted may improve the readability of the report.

Draft conceptual report comments:

General comments to be addressed

1. Please refrain from using acronyms such as DEM, TDS, GAM, GCD, UWCD, and HPAS or please insert a Glossary Section defining these and other abbreviations used repeatedly in the text and then please consistently use the same acronyms throughout the report in the text, tables, and figures.

   Acronyms removed.

2. In the final report for the Conceptual model please insert a page before the Table of Contents for sealing the report per the Occupation Code, Title 6, Subtitle A, Chapters 1001 and 1002.

   Seal page added.

3. Please be consistent in the text, figure legends, figure captions, and throughout the report when referring to the Rita Blanca Aquifer. Rita Blanca appears throughout the report without "Aquifer" as the modifier. Please revise text with the "Aquifer" modifier, as appropriate.

   Text revised accordingly.

4. Please use consistent modifiers such as aquifer or appropriate geologic nomenclature when discussing Dockum, Ogallala, and so forth.

   Text revised accordingly.

5. Please cite references when discussing characteristics, features, and uses of aquifers in Chapters 1 and 2.

References added.

6. Please label contours on the map figures more carefully and please attempt to not label contours when the label obscures the entire contour.

   Contour maps with stretched colormap symbology were replaced with non-contoured maps with color block symbology to improve readability.

7. Hydraulic properties (hydraulic conductivity) and water levels are stated throughout the report to two decimal points of accuracy. Please explain the reason/justification for use of that level of accuracy. Please clarify if the same level of accuracy will be used during calibration to produce the final numerical model.

   See Comments 118 and 239.

8. Legend titles in the figures appear to contain unexplained abbreviations (Kh) or lack correct terminology (such as adding the term “Aquifer” after the name of the aquifer). Please check and correct such Legends.

   Figure legends corrected where applicable.

Specific comments to be addressed

9. Page 1.0-1, Section 1.0, Paragraph 1: please update the reference section regarding the citation Ashworth and Hopkins (1995). Please note the report by Ashworth and Hopkins (1995) was updated in 2011(please see the newer TWDB Report 380 located http://www.twdb.texas.gov/publications/reports/numbered_reports/doc/R380_AquifersofTexas.pdf).

   Reference updated

10. Page 1.0-1, Section 1.0, Paragraph 3: please re-state the first sentence in the text to reflect that this report documents the conceptual model for the High Plains Aquifer System and that the results of this analysis will form the foundation for the development of a groundwater availability model.

    Text edited accordingly.

11. Page 1.0-1, Section 1.0, Paragraph 3: per Exhibit B, Attachment 1 of the Contract, Section 4, page 14, please re-word this paragraph to clearly state two reports will be produced for this project: the final conceptual model report (at least 8 chapters and an appendix with responses to these comments) and a separate report for the numerical model/calibration (9 chapters with three appendices of which one appendix will include draft comments with responses).

Text edited accordingly.

12. Page 1.0-1, Section 1.0, Paragraph 4: please clarify citation TWDB, 2012. The reference section lists, “TWDB, 2012, Precipitation and lake evaporation data for Texas: website; http://www.twdb.texas.gov/surfacewater/conditions/evaporation/index.asp” which does not appear to be the appropriate reference for the corresponding state water plan.

    Reference and citation corrected.

13. Page 1.0-2, Section 1.0, Paragraphs 1 and 2: please cite sources for discussion of aquifers and please refer to figures 1.0.1 and 1.0.2, as appropriate.

    Citations and figure references added.

14. Page 1.0-2, Section 1.0, Paragraph 1, Sentence 1 and in Paragraph 2: please be consistent in use of the term total dissolved solids for defining water quality; for example, the term slightly saline is defined as between 1000 to 2000 mg/l and later brackish to brine is defined as anything more than 1000 mg/l. Please explain the various terms clearly, consistently, and please cite references in the text and reference section.

    Text edited for clarity and salinity definitions added.

15. Page 1.0-2, Section 1.0, Paragraph 3, Sentence 1: per Table 2.2.1, layers 3 and 4 will represent the Upper and Lower Dockum Group not Upper and Lower Dockum formations. Please clarify and adjust text as needed. Please be consistent throughout the remainder of the report.

    Corrected.

16. Page 1.0-2, Section 1.0, Paragraph 4, Sentence 1: please clarify citation TWDB, 2007a. The reference section lists only the following for 2007:“TWDB, 2007, Maps & GIS data, GIS data, Groundwater Management Areas: website; http://www.twdb.state.tx.us/mapping/gisdata.asp “ Note: a more appropriate citation for this sentence would be to directly quote Texas Water Code § 16.051 (http://www.statutes.legis.state.tx.us/Docs/WA/htm/WA.16.htm#16.051).

    Incorrect citation removed and replaced with an in-line citation for Texas Water Code § 16.051

17. Page 1.0-3, Section 1.0, Paragraph 3, Sentence 1: please provide a reference for the standard modeling protocol in the text and reference section such as ASTM standards or possibly Anderson and Woessner, 1992.

    Reference added.

18. Page 1.0-5, Section 1.0, Figure 1.0.1: please correct the northern boundary for the Edwards-Trinity (Plateau) Aquifer where it underlies the Ogallala Aquifer. Also, please use map symbols consistent with TWDB major aquifers map symbols.

    Boundary fixed and colors changed to be more similar to TWDB maps.

19. Page 2.0-1, Section 2.0, Paragraph 2: please update the text with references for the various observations concerning the aquifers being discussed.

    Citations and figure references added.

20. Page 2.0-1, Section 2.0, Paragraph 2, Sentence 3: please update the text to reflect the Ogallala Aquifer overlies the Rita Blanca Aquifer in the northwest part of the study area instead of the northeast part of the study area.

    Corrected.

21. Page 2.0-1, Section 2.0, Paragraph 2: per Table 2.2.1, please use Group instead of Formation when discussing the "Dockum" geologically in the report (please see comment 15).

    Corrected.

22. Page 2.0-1, Section 2.0, Paragraph 2: text discusses the inclusion of the brackish portion of the Dockum Aquifer in the active model boundary because it may be a target for brackish water development. Text suggests or infers that the developed numerical model will be able to handle variable-density flow. Please clarify in the text of the report.

    Text added to clarify that the numerical model will not be simulating transport or variable density flow.

23. Page 2.0-2, Section 2.0, Paragraph 1: please show and label Cimarron River on a figure, for example Figure 2.0.4, as this appears to be discussed throughout the text as the northernmost model boundary. In addition, please cite associated figure in the text.

    Cimarron River labelled in figure and figure reference added.

24. Page 2.0-3, Section 2.0, paragraph 2, Sentence 5: Figure 2.0.8 refers to New Mexico Declared Groundwater Basins and shows Carlsbad, Capitan, Lea County … Canadian River, Clayton. Text refers to Declared Underground Water Basins and designated groundwater basins both and names only Clayton, Carlsbad, Canadian River, and Roswell. Please clarify in the text of the report and/or revise text and/or figure so they agree.

    Text updated to match figure. Figure and text corrected to "Declared Underground Water Basins"

25. Page 2.0-8, Section 2.0, Figure 2.0.2: please revise figure to more accurately show the extents of the aquifers included in the High Plains Aquifer System modeling study. Using two separate maps to show major and minor aquifers included in the High Plains Aquifer System modeling study may be less confusing. Also, please use map symbols consistent with TWDB major aquifers map symbols.

    The purpose of this map is to illustrate how all the aquifers of the High Plains Aquifer System are spatially related with each other, which is not immediately clear when the aquifers are split out into different maps. Later maps (Figure 2.0.5 and 2.0.6) provide separate maps of just major and just minor aquifers, respectively, if necessary. This map has been revised so that colors more closely match the aquifer symbols used by TWDB.

26. Page 2.0-11, Section 2.0, Figure 2.0.5: please use map symbols consistent with TWDB major aquifers map symbols.

    Map symbols changed to be consistent with TWDB aquifer map symbols.

27. Page 2.0-12, Section 2.0, Figure 2.0.6: please use map symbols consistent with TWDB major aquifers map symbols.

    Map symbols changed to be consistent with TWDB aquifer map symbols.

28. Page 2.0-15, Figure 2.0.9: please associate groundwater conservation district with GCD, underground water conservation district with UWCD, management district with MD, groundwater management district with GMD in the legend or caption. Please re-consider color scheme for non-Texas groundwater management areas as the same colors are used in Texas and the bold border does not appear very distinguishable. In addition, please re-visit TWDB, 2010 citation as reference section lists TWDB, 2010a and TWDB, 2010b. Please note that TWDB 2010b was not referenced in the report

    Abbreviation key added to the caption, map symbols for non-Texas groundwater management areas changed. Citation corrected and the unused citation removed from the reference section.

29. Page 2.0-17, Section 2.0, Figure 2.0.11: please correct map legend to correlate with map colors used for river sub-basins.

    Figure revised so that sub-basins are symbolized according to river basin and the delineation of river basins and sub-basins is less confusing.

30. Page 2.1-2, Section 2.1, Paragraph 3: text discusses climate classification by Larkin and Bomar, 1983. Figure 2.1.4 displays the climatic divisions in the study area as defined by National Oceanic and Atmospheric Administration National Climatic Data Center with the Larkin and Bomar areas outlined but not labeled. The text is unclear how the Lamar and

Bomar and National Oceanic and Atmospheric Administration National Climatic Data Center classifications correlate, please clarify in the text of the report. At a minimum please label the Larkin and Bomar classification in Figure 2.1.4. Or another option is to include just a figure of climate classification by Larkin and Bomar, 1983 with the areas labeled and delineated that are discussed in the text. Please note that LP-192 (Bomar and Larkin, 1983) was updated in 2005 with Digital Climatic Atlas of Texas (https://www.twdb.texas.gov/groundwater/docs/Texas_Digital_Climate_Atlas.pdf).

Figure 2.1.4 has been modified to just include the Larkin and Bomar climatic divisions. References to the NCDC climatic divisions have been removed from the figure and text as their inclusion was confusing and did not add significant information to the discussion. The new climatic divisions presented in the 2005 Digital Climatic Atlas of Texas were not included. They are not descriptive but rather intended as useful boundaries for statistical climatic analyses, whereas the purpose here is to just briefly describe climatic conditions in the study area, as done in the original Larkin and Bomar (1983) reference.

31. Page 2.1-4, Section 2.1, Figure 2.1.1: please correct map legend to correlate with map colors used for physiographic sections.

    Figure 2.1.1 modified so that the individual physiographic sections are represented in the legend.

32. Page 2.1-5, Section 2.1, Figure 2.1.2: please correct map legend to correlate with map colors used for ecological regions.

    Figure 2.1.2 modified so that the individual ecological regions are represented in the legend.

33. Page 2.1-6, Figure 2.1.3: text on page 2.1-2 (Paragraph 1, last sentence) states,” The drainage features of the major rivers can be seen in the topography in much of the study area, particularly the Canadian, Beaver, and Pecos rivers, which have created deeply incised valleys in some places”. For clarity, please label these features on the figure.

    Rivers and labels added to the map.

34. Page 2.1-11, Section 2.1, Figure 2.1.8: please label horizontal dashed lines or add information as to what they represent in the figure caption; for example, do these represent the mean or median values?

    Text added to the caption to explain that these indicate the mean annual precipitation over the period of record.

35. Page 2.1-12, Section 2.1, Figure 2.1.9: please add period of record used for the mean monthly precipitation charts in the legend or caption.

Period of record for each station added to the figure.

36. Page 2.1-13, Section 2.1, Figure 2.1.10: please add period of record used for the annual lake evaporation rates in the legend or caption. Per https://www.twdb.texas.gov/surfacewater/conditions/evaporation/index.asp gross lake surface evaporation data are available from 1954 through 2012.

    Period of record (1954 - 2011) added to the caption.

37. Page 2.1-14, Section 2.1, Figure 2.1.11: please add period of record used for the average monthly lake evaporation rates in the legend or caption. Per https://www.twdb.texas.gov/surfacewater/conditions/evaporation/index.asp gross lake surface evaporation data are available from 1954 through 2012.

    Period of record (1954 - 2011) added to the caption.

38. Pages 2.2-1 to 2.2-6, Section 2.2: please consistently capitalize Aquifer in High Plains Aquifer System, please use parenthesis for Edwards-Trinity (Plateau) and Edwards-Trinity (High Plains) aquifers, please add modifier to “Aquifer” to Rita Blanca, and please use modifier “Group” when referencing Dockum Group as a geologic unit. Please update the text of the rest of the report as needed.

    Corrected.

39. Page 2.2-7, Section 2.2, Table 2.2.1: please add source reference for general descriptions or the entire table.

    References added to the caption.

40. Page 2.2-12, Figure 2.2.5: please include legend identifying the patterns shown; for example, sand and shale units.

    Legend added to the figure.

41. Page 2.2-13, Figure 2.2.6, Section 2.2.3: please include location map for cross-section.

    Location map added as Figure 2.2.7.

42. Page 3.1-3, Section 3.1, Paragraph 3, Sentence 2: please provide reference for Texas A&M Texas Agricultural Extension Service.

    Reference added.

43. Page 3.1-7, Section 3.1.5, Paragraph 3: please clarify citation of McGowan and others, 1975 and please update the text and/or reference section with this reference.

Done

44. Pages 3.2-1 to 3.2-5, Section 3.2.1: per Exhibit B of the contract (page 18) this section of the conceptual report should compare and contrast modeling efforts to each other and the new modeling effort as described in Section 3.1[of Exhibit B], as applicable. Discussion must include how new modeling effort will be an improvement over previous modeling efforts with respect to determining regional groundwater availability. Please update this section of the report with how this new modeling effort will be an improvement over previous modeling efforts.

    Section 3.2.5 added to address key model improvements.

45. Page 3.2-9, Figure 3.2.2; please update legend and caption to indicate the groundwater availability model for the northern portion of the Ogallala Aquifer also includes the Rita Blanca Aquifer as noted in the text in Section 3.2.2 on page 3.2-6. In addition, please use a thicker line symbol for the active model and thinner line symbols for the previous models to prevent obscuring the active model boundary where it coincides with previous model boundaries.

    Text in Section 3.2.2 revised to clarify that the Rita Blanca Aquifer is not explicitly included in the Northern Ogallala groundwater availability model. Rather portions of the Rita Blanca subcrop that underlie the Ogallala Aquifer happened to be included in the model but were basically treated as part of the Ogallala Aquifer. The boundary shown in the map shows the actual boundary of the Northern Ogallala groundwater availability model used by Dutton and others (2001a) and so was not changed. However, the figure has been modified to make all model boundaries clearer.

46. Pages 4.1-1 to 4.1-2, Section 4.1: please see comment 40—please consistently capitalize Aquifer in High Plains Aquifer System, please use parenthesis for Edwards-Trinity (Plateau) and Edwards-Trinity (High Plains) aquifers, please add modifier to “Aquifer” to Rita Blanca, and please use modifier “Group” when referencing Dockum Group as a geologic unit.

    Corrected

47. Page 4.1-1, Paragraph 3, Sentence 3 and last Sentence: please provide reference for comparison between Rita Blanca Aquifer and Dockum Aquifer, and also for Edwards-Trinity aquifers.

    The text comparing the Rita Blanca Aquifer with the Dockum Aquifer is misleading and has been removed to avoid confusion. Citations and descriptive text have been added to the discussion of the Edwards-Trinity aquifers.

48. Page 4.1-3, Section 4.1, Table 4.1.1: please define shaded areas within table in the caption or in a footnote.

Explanatory footnote added.

49. Page 4.1-4, Figure 4.1.1: please increase the range of colors and possibly increase the size of the color scale. Currently, only a high of 3105, low of 0, and possibly a mid-range value of 1550 is discernable. Please consider adding more values on the scale.

    Figure revised with a better color scale.

50. Page 4.1-5, Section 4.1, Figure 4.1.2: please update map to show Edwards-Trinity (Plateau) and Pecos Valley aquifers to be consistent with Figure 4.1.3.

    Figure revised to include Edwards-Trinity (Plateau) and Pecos Valley aquifers

51. Pages 4.1-6 and 4.1-7, Figures 4.1.3 and 4.1.4: please clarify what “Kd”, “ET Plateau”, and “ETHP” refers to on the cross-section and please explain/define all acronyms on Figures 4.1.3 and 4.1.4 either in a legend or in the caption. Also please consider improving the resolution and quality of the cross-sections and labels (some labels appear bold and others are regular font).

    Abbreviation key added to the captions. Higher-resolution images used for Figures 4.1.3 and 4.1.4.

52. Page 4.2-1, Section 4.2: please refer to this section as “Hydrostratigraphic Framework”, rather than “Structure” per Exhibit B, Attachment 1, page 19 of the contract.

    Done.

53. Page 4.2-2, Section 4.2, Paragraph 2, last Sentence: the gamma-log database has been quantified. However, the resistivity-log database was not quantified. Please state the number of resistivity logs obtained for the analysis.

    Text added to indicate that we used 732 resistivity logs.

54. Page 4.2-3, Section 4.2.3, Paragraph 2: text cites Bebout and Meador, 1985; however, the Reference Section lists Bebout and Meadow, 1985. Please clarify the spelling of the second author and adjust the text accordingly.

    “Meadow” replaced with “Meador” in the reference section.

55. Page 4.2-4, Section 4.2.4, Paragraph 1: text references Figure 4.2.2 when describing four wells; however, Figure 4.2.2 shows more than four wells and the specific ones discussed in the text do not appear to be highlighted. Please adjust figure or add a new figure highlighting the location of the cores discussed in the text.

    Johns (1989) wells added to the figure.

56. Page 4.2-6, List item 6: please list the two counties in the Seni (1980) study in the text of the report.

    Text revised to clarify that the data mostly falls in Randall County and the surrounding area.

57. Page 4.2-8, Section 4.2.6, Paragraph 2: text cites Bebout and Meador, 1985; however, the Reference Section lists Bebout and Meadow, 1985. Please clarify the spelling of the second author and adjust the text accordingly.

    “Meadow” replaced with “Meador” in the reference section.

58. Page 4.2-10, Section 4.2, Figure 4.2.1: please update map to show Edwards-Trinity (Plateau) and Pecos Valley aquifers to be consistent with related cross-sections shown in figures 4.2.3 to 4.2.9.

    Edwards-Trinity (Plateau) and Pecos Valley aquifers added to Figure 4.2.1.

59. Page 4.2-11, Section 4.2, Figure 4.2.2: please update map to show Edwards-Trinity (Plateau) and Pecos Valley aquifers to be consistent with related cross-sections shown in figures 4.2.3 to 4.2.9.

    Edwards-Trinity (Plateau) and Pecos Valley aquifers added to Figure 4.2.2

60. Pages 4.2-14, 4.2-15, 4.2-29, and 4.2-30, Figures 4.2.14, 4.2.15, 4.2.18, and 4.2.19: please change “Aquifer” to “Group” in the caption. The portions of the Dockum Group with higher salinity concentrations are not considered part of the official boundaries of the Dockum Aquifer. Please either include the boundaries of the geologic units or change your gradient colors since white denotes great thicknesses and areas not contoured are shown in white (some showing location of geophysical logs).

    “Aquifer” replaced with “Group”. Color gradient changed in the figures to improve readability.

~~61.~~ Page 4.2-19, Figure 4.2-10: please correct spelling of Ogallala in legend; please either spell out the abbreviations or provide what they represent in the caption or legend; and please include references for data shown.

Spelling corrected, abbreviation key included in caption and references added.

62. Page 4.2-20, Section 4.2, Figure 4.2.11A: please use a constant contour interval for labeling contours such as 200 or 500 or 1000 with thicker contour line symbols for the constant label intervals. It should help with labeling errors such as the 3800 contour on the Texas-Oklahoma border being labeled 3700 just to the south of the border.

    Contours removed and the stretched colormap replaced with color blocks so that

intervals are clearer.

63. Page 4.2-21, Section 4.2, Figure 4.2.11B: please use a constant contour interval for labeling contours such as 200 or 500 or 1000 with thicker contour line symbols for the constant label intervals. It should help with labeling errors such as the 3700 contour on the Texas-New Mexico border being labeled 3900 just to the southwest of the border.

    Contours removed and the stretched colormap replaced with color blocks so that intervals are clearer.

64. Section 4.2, Figures 4.2.12 through 4.2.19: please use a constant contour interval for labeling contours such as 100, 200, 500, or 1000 with thicker contour line symbols for the constant label intervals.

    Contours removed and the stretched colormap replaced with color blocks so that intervals are clearer.

65. Page 4.2-23, Figure 4.2.13; please add Edwards-Trinity (Plateau) Aquifer to the list of aquifers in the caption.

    Edwards-Trinity (Plateau) Aquifer added to the list of aquifers.

66. Pages 4.2-26 to 4.2-27, Figures 4.2.16A and 4.2.16B: please either include the boundaries of the Ogallala Aquifer (and Pecos Valley Aquifer in Figure 4.2.16B) or change your gradient colors since white denotes great thicknesses and areas not contoured are shown in white. Also please add “Aquifer(s)” to the Title in the Legend “Thickness of Ogallala and Pecos Valley (ft)

    Figures 4.2.16A and 4.2.16B replaced with single figure (Figure 4.2.16). Contours removed and the stretched colormap replaced with color blocks so that intervals are clearer. “Aquifers” added to the legend title.

67. Page 4.2-28, Figure 4.2.17: same as previous review comment; please include aquifer boundaries and/or change the color gradient schema. For example, in the area of the Edwards-Trinity (High Plains) Aquifer the placement of the geophysical log locations along the perimeter suggests the thickness is around 1,097 feet. Also please add “Aquifer(s)” to the Title in the Legend “Thickness of Rita Blanca & Edwards-Trinity (ft)”

    Contours removed and the stretched colormap was replaced with color blocks so that intervals are clearer. “Aquifer” added to the legend title.

68. Page 4.2-29, Figure 4.2.18: please add “Aquifer(s)” to the Title in the Legend “Thickness of Upper Dockum (ft)”

    As per Comment #60, “Group” rather than “Aquifer” added to the legend title.

69. Page 4.2-30, Figure 4.2.19: the legend indicates this figure is the base of the lower Dockum; however the caption indicates this is the thickness of the Lower Dockum. Please clarify and adjust so legend and caption agree. Please add "Aquifer(s)" to the Title in the Legend "Thickness of … (ft)"

    Legend title corrected to "Thickness." As per Comment #60, "Group" rather than "Aquifer" added to the legend title.

70. Pages 4.2-31 to 4.2-32, Figures 4.2.20 and 4.2.21: please explain/define all acronyms on Figures 4.1.3 and 4.1.4 either in a legend or in the caption. Please note that the colors in the legend do not appear to match the colors used in the figure.

    Abbreviation key added to caption. Figures revised so that the legend matches the cross-section colors.

71. Page 4.2-33, Section 4.2, Figure 4.2.22: please correct the legend to correspond to the map as there are no areas that contain a sand percent of less than 20 percent.

    Legend corrected.

72. Page 4.2-34, Section 4.2, Figure 4.2.23: please correct the legend to correspond to the map as there are no areas that contain a sand percent of greater than 80 percent.

    Legend corrected.

73. Page 4.2-35, Section 4.2, Figure 4.2.24: please correct the legend to correspond to the map as there are no areas that contain a sand percent of greater than 50 percent.

    Legend corrected. Higher threshold (60 percent) chosen because there is a small area with a value slightly greater than 50 percent in the northern section.

74. Pages 4.2-35, 4.2-36, 4.2-39, and 4.2-40, Figures 4.2.24, 4.2.25, 4.2.28, and 4.2.29: please change "Aquifer" to "Group" in the caption. The portions of the Dockum Group with higher salinity concentrations are not considered part of the official boundaries of the Dockum Aquifer.

    Captions revised to read "Dockum Group" instead of "Dockum Aquifer"

75. Page 4.2-36, Section 4.2, Figure 4.2.25: please correct the legend to correspond to the map as there are no areas that contain a sand percent of greater than 80 percent.

    Legend corrected.

76. Section 4.2, Figures 4.2.26 through 4.2.31: please be careful with contour labeling to avoid obscuring smaller areas or the contour altogether and please consider using fewer labels when possible. The contours maps shown in Section 4.3 are good templates for the contour

map figures in Section 4.2.

Since the contours in this section were generally confusing rather than helpful, contours were removed from all figures and the stretched colormap symbology was replaced with color block symbology so that intervals are clearer and the maps are more readable.

77. Page 4.3-1, Section 4.3.1: historical data was already compiled along with data from other sources in previous model development; please explain in the text of the report why source data from pre-existing groundwater availability models was not used and then supplemented with other resources for the time period from the late 1990s to more recent times.

    Text added to Section 4.3.1 explaining why water-level data were recompiled from the various sources rather than supplementing data historically compiled for the previous groundwater availability models of the individual aquifers in the High Plains Aquifer System.

78. Page 4.3-3, Section 4.3.1, Paragraph 1: please clarify in the text and on Figure 4.3.5 (page 4.3-59) the reasoning for listing wells undetermined in Hansford, Ochiltree, Roberts, Hemphill, Donnelly, and Gray counties when only the Ogallala Aquifer is mapped as the groundwater source for these counties (Figure 4.2.3 on page 4.2-12 suggests underlying Permian units are mostly shale) and in Mitchell County where the upper Dockum Group appears as the sole groundwater source (Figure 4.28 on page 4.2-17 suggests underlying Permian units are shale and limestone).

    Figure and text revised to indicate wells with unknown completions and wells that were not used. The wells in Hansford, Ochiltree, Roberts, Hemphill, Donnelly, Gray, and Mitchell counties were relabeled as "not used". The water-level data for these wells were not used because the reported maximum depth to water is greater than the reported total depth of the well. Due to the potential uncertainty in the well data, the limited number of these wells, and the availability of water-level data from numerous other wells in the areas of these wells, the impact of not using these wells in the analysis of water levels was considered to be negligible.

79. Pages 4.3-14 to 4.3-16, Subsection Ogallala Aquifer: please cite Table 4.3.4 when discussing water level trends not shown in a hydrograph in Figures 4.3.19, 4.3 20, and 4.3.21. For example, Hansford, Roberts, Potter, Armstrong, Randall, Briscoe, and Crosby counties do not have hydrographs however trends are summarized in Table 4.3.4 and discussed in the text of this section.

    Text modified to indicate that the discussion is primarily based on the information in Table 4.3.4, with only example trends shown in the figures.

80. Page 4.3-16, Sub-section Rita Blanca Aquifer: please update Figure 4.3.22 with a hydrograph in Cimarron County, Oklahoma since this is discussed in the text of this section

and not included in Table 4.3.4.

A hydrograph from Cimarron County, Oklahoma added to Figure 4.3.22

81. Pages 4.3-17 and 4.3-18, Subsection Lower Dockum Aquifer: please cite Table 4.3.4 when discussing water level trends not shown in a hydrograph in Figure 4.3.24; for example, Deaf Smith, Swisher, Crosby, Floyd, Sterling, Upton, Loving, Martin, Reeves, Pecos, Glasscock, and Ector counties.

    Text modified to indicate that the discussion is primarily based on the information in Table 4.3.4, with only example trends shown in the figures.

82. Page 4.3-20, Section 4.3.4, Paragraph 2, last sentence: please explain in the text of the report why maximum water levels were used rather than averages for the Rita Blanca, Edwards-Trinity (High Plains), and Dockum aquifers when wells had multiple measurements over a selected time period. Maximum water levels were discussed in previous sections when trying to determine pre-development; however, continuing this logic for post-development is unclear and appears to create a bias in the analysis.

    Water-level surfaces for the Rita Blanca, Edwards-Trinity (High Plains), and Dockum aquifers revised using average water levels. Text modified to reflect this change and all affected figures also revised.

83. Page 4.3-20, Section 4.3.4, Ogallala Aquifer, Paragraph 2, last sentence: text discusses a shift of water level contours of 3,400 and 3,600 feet from 1980 to 2010 in four counties in Figures 4.3.28 and 4.3.29; however, the corresponding counties are not labeled in these figures. Please label counties in the figures so that the figure and text agree.

    Labels added for counties that intersect the Ogallala Aquifer.

84. Pages 4.3-21 and 4.3-30, Sub-section Ogallala Aquifer and Figure 4.3.30: text cites examples of water level declines and compares by county. Please update Figure 4.3.30 by labeling the counties in the background so reader can follow the discussion.

    Labels added for counties that intersect the Ogallala Aquifer.

85. Pages 4.3-22 to 4.3-23, Sub-sections Rita Blanca Aquifer, Edwards-Trinity (High Plains) Aquifer, Upper Dockum Aquifer, and Lower Dockum Aquifer: text cites examples of water level declines and compares by county. Please update Figures 4.3.34, 4.3.38, and 4.3.42 by labeling the counties in the background so reader can follow the discussion.

    Labels added for counties that intersect the aquifers.

86. Page 4.3-25, Section 4.36, last paragraph: please clarify in the text whether elevated concentrations of arsenic are naturally occurring throughout the Ogallala Aquifer or just in the vicinity of the Edwards-Trinity (High Plains) Aquifer. The logic presented appears to

suggest the source of the elevated natural arsenic is the Edwards-Trinity (High Plains) Aquifer and therefore flow from the Edwards-Trinity (High Plains) Aquifer to the Ogallala Aquifer appears more reasonable than the reverse.

Text revised for clarity

87. Page 4.3-66, Figure 4.3.12: please provide interpretation of abbreviations either in the legend or caption; for example, DEM, in this figure and in all other figures of the report, as needed.

    Explanation of the DEM abbreviation added below the figure.

88. Page 4.3-81, Figure 4.3.27: the figure indicates several predevelopment water levels were used as control points for the 1950 Ogallala water-level map; however, the text on page 4.3-20 Section 4.3.4 does not mention that. If the preD (+) values were used; please discuss in the text. If they were not used please remove from Figure 4.3.27. In addition, please provide interpretation of abbreviations either in the legend or caption—preD and DEM.

    Text added to discuss the two pre-development water levels in Lea County, New Mexico used as control points for the 1950 surface. Explanations of abbreviations added below the figure.

89. Page 4.3-84, Figure 4.3.30: Top Control Point label in legend is marked as “pre-1930 to post 2005”; however, based on the text that should be post 2009. If 2009 is correct please update legend to say, “pre-1930 to post 2009” or revise text so figure and text agree.

    The figure legend is correct. Text added and modified to agree with the figure legend.

90. Pages 4.4-18 to 4.4-20, Sections 4.4.5 and 4.4.6: please clarify in the text in more detail why the western portion of the Colorado River outcrop for the Dockum Aquifer (Borden, Dawson, and Garza counties) is a no recharge zone in pre-development and has recharge in post development. The explanation for pre-development seemed to justify keeping it a no recharge zone in post development—irrigating crops with groundwater having total dissolved solid concentrations greater than 5,000 milligrams per liter is not typical.

    Recharge was increased in this area only in the small percent where cropland is present, based on land use distribution. The agricultural activity may be dryland farming, or growers may have found areas of the outcrop where groundwater TDS is low enough for use. Agricultural activity typically enhances recharge through disturbance of native vegetation and reworking of soil, so the proposed slight increase in recharge in these areas is not dependent on irrigation even being present. Text has been slightly revised to clarify that enhanced recharge is due to agricultural land use change, with no distinction between rainfed and irrigated cropland.

91. Pages 4.4-19, 4.4-38, and 4.4-40, Section 4.4.6, Figures 4.4.17 and 4.4.19: text on page 4.4-19 states recharge distribution remains the same as predevelopment in the northern portion

of the Ogallala Aquifer and the northern parts of the southern portion of the Ogallala Aquifer. Please use the same scale in Figures 4.4.17 and 4.4.19 so a comparison between the figures can easily be done.

Color scales adjusted to be consistent.

92. Page 4.4-21, Table 4.4.1: please either define methods in more detail without abbreviations, use footnotes, and/or cross reference to text that explains the approach in more detail. For example, Regional GW model (Dutton and others, 2001a) should be Regional groundwater model—northern Ogallala Aquifer, Texas

    Table revised.

93. Page 4.4-21, Table 4.4.2: please give complete names for each region; for example, Central High Plains, rather than CHP, Colorado River rather than Colorado, and so forth. Please provide map delineating these sub-regions and cross reference table to figure.

    Sub area names revised to be consistent with Figure 4.4.1. Text added to table caption to refer readers to Figure 4.4.1.

94. Page 4.4-23, Section 4.4, Figure 4.4.2: please use different line symbol for Dockum Aquifer outcrop boundary to avoid confusion with water bodies or remove water bodies altogether from the map. Also, the greater than 5 percent slope area does not correlate to Figure 4.4.3 for slope based on elevation model.

    The symbol for the Dockum Aquifer outcrop boundary was changed. Water bodies shown here are part of the STATSGO dataset, not a separate shapefile and so were not removed. The greater than 5 percent slope threshold in Figure 4.4.2 is based on the average slope value of an entire STATSGO map unit and is therefore not expected to match Figure 4.4.3 exactly. Text has been added to Section 4.4.3.3 to clarify this.

95. Page 4.4-24, Figure 4.4.3; please cite data source per contract Exhibit B. Please spell percent instead of using %. Please review figure caption to determine if this percent slope is based on 30-meter or 10-meter DEM (there was no 30-meter DEM in the geodatabase) and cite accordingly.

    Citation added. "%" symbol replaced. The text and caption are correct – slope was calculated from the 30-m digital elevation model. The 30-m digital elevation model was not included in the geodatabase because it does not appear in any figures in the report. The slope raster shown here, however, is included in the geodatabase.

96. Page 4.4-28, Figure 4.4.7: please cite reference for data.

    Reference added. Text revised to clarify that playa density is calculated based on the playa coverage given in Figure 4.4.6.

97. Page 4.4-30, Figure 4.4.9: please cite reference for data and spell out abbreviations in legend or caption.

    Reference added and abbreviations fixed.

98. Page 4.4-35, Figure 4.4.14: please cite reference for soil properties.

    Reference added

99. Page 4.4-36, Figure 4.4.15: please cite reference for land use.

    Reference added

100. Pages 4.4-38 and 4.4-40, Figures 4.4.17 and 4.4.19: the contour line (total dissolved solids equal 500 milligrams per liter) is indistinguishable from the active boundary line. Please adjust so it is easier to distinguish between the two. Please include a discussion in Section 4.4.6 on why this was used as the boundary for different recharge approaches. Please see comment 1 for using abbreviations such as TDS.

     Contour color changed to improve visibility. Explanatory text added to Section 4.4.5. Abbreviation fixed.

101. Page 4.4-39, Figure 4.4.18: please see comment 1 for using abbreviations such as TDS.

     Abbreviation fixed.

102. Pages 4.5-1 to 4.5-9, Chapter 4.5: Per Exhibit B, Attachment 1, Section 3.1.7, page 8, any specific or general information on streambed conductance shall also be addressed. Please update this chapter to include this discussion.

     We could find no literature specific to the region on streambed conductance. Because of uncertainty (and considerations of scale), streambed conductance is typically a calibration parameter for regional groundwater models. We added text to this effect in Section 4.5.1.

103. Page 4.5-1, Section 4.5.1: text discusses major rivers, draws, and refers to Figure 4.5.1. Please update figure with labels of the rivers and major draws discussed in the text so reader can follow the discussion. In addition, please clarify what the hatching in the figure signifies and update the legend accordingly.

     Labels added. Hatching removed.

104. Page 4.5-4, Section 4.5.1.1.3, Paragraph 1, Sentence 2: please remove this sentence as it appears speculative.

Sentence removed.

105. Page 4.5-4, Section 4.5.1.1.3, 6th sentence: Text lists Wolf Creek (WC) and Gageby Creek (WC). Please verify if this should be Wolf Creek (WC) and Gageby Creek (GC) and please update text as necessary for clarity.

    Corrected.

106. Page 4.5-55, Table 4.57: Please cite reference for source of data and update reference section, if needed.

    References added.

107. Page 4.5-57, Section 4.5, Figure 4.5.1: please correct the legend symbols to correspond to the map feature symbols.

    Map updated.

108. Page 4.5-58, Section 4.5, Figures 4.5.2, 4.2.3, 4.5.4, 4.5.5, 4.5.8, 4.5.9, 4.5.10, and 4.5.11: please explain the purpose for displaying the selected aquifer outcrops and not others within the caption or remove the aquifer outcrops as they serve no purpose for showing the gage locations.

    Aquifer outcrops removed from figures.

109. Page 4.5-60, Figure 4.5.4: legend is missing symbols for aquifer outcrops. Please update legend as needed for clarity.

    Aquifer outcrops removed from figure.

110. Chapter 4.6: per Exhibit B, Attachment 1 of the contract (Section 3.1.8, page 8), states horizontal anisotropy shall also be defined, discussed, and estimated, if appropriate. Please update the chapter to include a discussion on horizontal anisotropy.

    We found no evidence in the literature for regional horizontal anisotropy in the High Plains Aquifer System. We added text to this effect at the end of Section 4.6.5.

111. Section 4.6.5: per Exhibit B, Attachment 1 of the contract (Section 4.4.1, pages 18-20), please include histograms of hydraulic conductivity, storativity, and specific storage (if applicable) for each model layer.

    Histograms were not included. The hydraulic conductivity and specific yield coverages developed for the current model were based on existing coverages developed in previous reports, not point data. Text modified in Section 4.6.5.1 to clarify this point. Information on the raw data used to create these existing coverages is available in the source material reports. Any new data points added during this

study (that is Tables 4.6.1, 4.6.2, 4.6.3, and 4.6.5) were only used to modify the existing coverage in place, not added to an original raw point dataset. The small sample size of these additional datasets was not appropriate for histogram plotting and also, would be misleading since it is not representative of all of the data used to create the final coverages. No point measurements for specific storage were available to create a histogram.

112. Section 4.6.5, pages 4.6-4 to 4.6-8: per Exhibit A (pages 9 and 14, paragraph 4) of the contract, specific yield will be revised based on new geophysical data, primarily porosity measurements from geophysical logs. The Conceptual Model report makes no mention of this analysis being performed. The report mentions the range of values for the study, 0.025 to 0.28 (page 4.6-10), but does not mention where those values came from. Please document the source of the specific yield values in the text of the report. If the geophysical log analysis was not performed please explain why in the text of the report.

    Specific yield would be correlated to porosity and other factors, but estimates of porosity based on geophysical logs require a neutron porosity log. There were only a handful of these logs available in the log database, therefore these estimates were not possible, and we relied on previous studies for estimates of specific yield. Text has been added to this effect in Section 4.6.7.1. Text has also been modified to clarify that the range 0.025 to 0.28 refers to Dutton and others (2001a) and that the range 0.025 - 0.28 refers to McGuire and others (2012).

113. Page 4.6-6, Paragraph 3, Section 4.6.5, and Figures 4.6.5, 4.67, and 4.6.8: per Exhibit B (page 19) of the contract please include locations of point values of hydraulic conductivity on the figures, if feasible.

    The hydraulic conductivity coverages shown in Figures 4.6.5 – 4.6.8 were created based on existing coverages developed in previous reports, not point data. The few new data points incorporated into the existing coverages are shown in Figure 4.6.4 for the Ogallala Aquifer and Figure 4.6.9 for the Dockum Aquifer.

114. Page 4.6-8, Section 4.6.5.3, Paragraph 2, Sentence 2: sentence refers to Lower Dockum data points on Figure 4.6.6. Please revise the figure reference to Figure 4.6.9 where the points are shown.

    Corrected.

115. Page 4.6-10, Section 4.6.7.1, Sentence 1: please explain the reasoning for determining the Rita Blanca Aquifer is unconfined; while it outcrops in New Mexico, it underlies the Ogallala Aquifer in Texas. Per Figure 4.2.3, it appears the Rita Blanca is bounded by clay lenses grading into mostly clay in Texas.

    Text corrected. Rita Blanca discussion moved to Dockum section since the estimation of specific yield in the outcrop and specific storage in the subcrop was performed

more similarly to the Dockum Aquifer than the Ogallala Aquifer.

116. Page 4.6-10, Section 4.6.7.1, Paragraphs 3 and 4, last sentence each: text refers to specific yield shown in Figures 4.6.7a and 4.6.7b. Please change figure references in the text to Figures 4.6.10a and 4.6.10b.

     Corrected.

117. Page 4.6-11, Section 4.6.7.3, Paragraph 2, last sentence: text refers to storage coefficient in the Dockum Aquifer shown in Figures 4.6.8 and 4.6.9. Please change figure references in the text to Figures 4.6.11 and 4.6.12.

     Corrected.

118. Page 4.6-17, Tables 4.6.4-4.6.5: hydraulic conductivity values are stated in varying decimal point accuracy. Please be consistent while stating hydraulic properties. Also please explain if final numerical modeling report will contain calibrated hydraulic properties with such accuracy.

     The data provided to us from the represented cities and districts were reported with varying decimal point accuracy. We have amended all the hydraulic conductivity values in the report tables to one decimal place for consistency. The numerical modeling report will use a similar representation. However, the "accuracy" of the calibrated values for the numerical model will not be explicitly calculated. The calibration is based on goodness of fit to the output metrics.

119. Page 4.6-22-4.6.25, Figures 4.6.5-4.6.8: Please explain the abbreviation Kh or use Horizontal hydraulic conductivity instead.

     Abbreviation fixed.

120. Page 4.7-3, Section 4.7.1, Paragraph 3: text discusses riparian zones. The U.S. Fish and Wildlife Service National Wetlands Inventory include mapped riparian zones—please see http://www.fws.gov/wetlands/Other/Riparian-Product-Summary.html for more information concerning downloading the dataset. Using the Wetlands Mapper, riparian zones were included in the dataset for the study area. Please consider investigating this dataset for applying evapotranspiration in the study area.

     Upon review of the riparian coverage, we found that many areas along streams that appear to be influenced by the stream (that is, are green and vegetated) were inconsistently reflected in the coverage. Therefore we decided not to use the coverage as the basis for evapotranspiration in the numerical model. This is discussed in the numerical model report as well.

121. Pages 4.7-4 to 4.7-22 Section 4.7.2: per Exhibit A (page 11, paragraph 3) of the contract, in addition to the change in storage estimates which were compared to demand based

pumping estimates, a remote-sensing based water-balance estimates will be evaluated such as the USGS study from Stanton [and others] (2011) for comparison to estimates of groundwater pumping. The remote-sensing analysis is not documented in the conceptual model report. If the analysis was not performed, please explain why in the text of report. Otherwise please discuss this in the text of the report.

Text added to Section 4.7.2.1 to explain why these pumping estimates were not incorporated.

122. Pages 4.7-5 to 4.7-8, 4.7-15, Section 4.7.2.1 and 4.7.2.5, and Figure 4.7.6: it is unclear how pumping in Dallam County will be adjusted. Existing models combined the Rita Blanca Aquifer with the Ogallala Aquifer and all associated pumping with both aquifers should have been applied in the model. It is assumed with this new model that pumping from the Rita Blanca Aquifer (Section 4.7.2.5) will be applied in the associated model layer; however, the text does not discuss reducing the pumping for the Ogallala Aquifer layer to reflect this refinement (note pumping from the model in Figure 4.7.6 should be the combination of pumping from the Ogallala and Rita Blanca aquifers). Please clarify in the text of the report. In addition, please clarify in Section 4.7.2.5 that North Plains Groundwater Conservation District did not have metered data for wells completed in the Rita Blanca Aquifer. And finally Section 4.7.2.5 on page 4.7-16 states pumping in the Rita Blanca Aquifer in New Mexico was assumed negligible; however, hydrographs in wells 363041103054601 and 361847103064701 indicate 40 feet to over 100 feet decline in water levels, please clarify in the text.

    Section 4.7.2.5 explains how assignments of Rita Blanca Aquifer pumping were based on the 2003 ratio of Rita Blanca Aquifer pumping to Ogallala Aquifer pumping for post-2004 and on the 1980 ratio for pre-1980 pumping. Text reworded slightly for clarity. Text also added to indicate that the North Plains Groundwater Conservation District does not explicitly delineate between Rita Blanca and Ogallala wells, therefore the metered data also makes no such delineation. Pumping in the Rita Blanca was added for Union County (Table 4.7.29). Text in Section 4.7.5 revised to reflect this.

123. Page 4.7-6, Section 4.7.2.1 and Reference Section: please clarify if the year should be 2002 instead of 2000 in the two citations of Dutton and Reedy on page 4.7-6 as the Reference Section only lists 2002 for Dutton and Reddy (please clarify if this should be Reedy instead of Reddy). In addition, the reference possibly has several typos: "…wate rin".., "…Planning Regiona A…', and "…The Univeristy of Texas…"

    Corrected.

124. Page 4.7-11, Section 4.7.2.2, Paragraph 3: text references Figures 4.7.11 to 4.7.18, please update to Figures 4.7.9 to 4.7.18 as Figures 4.7.9 and 4.7.10 were not cited elsewhere in the report. In addition, please remove data for S.O. GAM after 2000 in Figures 4.7.9 to 4.7.18 (assume S.O. GAM is the southern portion of the Ogallala Aquifer and the Edwards-Trinity (High Plains) model) as the model calibration ended in 2000.

Figure numbers corrected. The S.O GAM estimates for 2000 – 2010 were extrapolated based on 2000 levels and come very close to the other estimates presented. However, to avoid confusion, the 2000 – 2010 S.O. GAM values have been removed from the figures.

125. Page 4.7.12, Section 4.7.2.2, Paragraph 2: text references Figures 4.7.11 to 4.7.18, please update to Figures 4.7.9 to 4.7.18 as Figures 4.7.9 and 4.7.10 were not cited elsewhere in the report.

Corrected.

126. Pages 4.7-17 to 4.7.22 and Figures 4.7.36, 4.7.38 to 4.7.43: please clarify in the text in Section 4.7.2.7 how 'Demand Est' in the graphs in Figures 4.7.36, 4.738 to 4.7.43 relates the total pumping for the Ogallala Aquifer in Table 4.7.12 as this is unclear. The values plotted on the graphs appear to be significantly different; for example the maximum pumping in Hale County is 760,128 acre-feet in 1960 per Table 4.7.12 and on Figure 4.7.36 pumping/Demand Est is over 1,000,000 acre-feet for around the same timeframe.

Table 4.7.12 shows total pumping every 10 years, whereas the figure plots the full time-series. In the case of Hale County (Figure 4.7.36), the maximum of > 1,000,000 acre-feet is reached in the year 1964, and this year is not reported in Table 4.7.12. However, the value at 1960 (measured along the line before the 1964 peak) does match the value Table 4.7.12. For a better illustration, you can see that the "Demand Est" for Hale in Figure 4.7.36 is very close to the irrigation pumping estimate (which represents the majority of pumping) given in Figure 4.7.11, which also shows the full time series rather than 10 year intervals.

127. Page 4.7-49, Figure 4.7.1: the legend appears to be reversed—red should be maximum values of 79-82 and blue should be minimum values of 58-61. Please verify and correct as necessary.

Figure corrected.

128. Page 4.8-1, Section 4.8, Paragraph 1: please adjust the following text," In the ~~northeast~~ [northwest], the Ogallala Aquifer overlies the Jurassic-age Rita Blanca Aquifer, a small, but also mostly fresh minor aquifer."

Corrected.

129. Page 4.8-2, Section 4.8.1, Paragraph 2: text cites McMahon and others (2001); however, reference section only lists McMahon, 2001. Please update text or reference section so they are in agreement.

Citation corrected.

130. Page 4.8-4, Section 4.8.1, Paragraph 2: text cites Wood and Sanford (1995); however, reference section has two references for Wood and Sanford in 1995. Please update text to “a” or “b” to clarify which reference was used.

     Citation corrected.

131. Page 4.8-8, Section 4.8.3, Paragraph 3, and Page 4.8-25, Figure 4.8.10: text states none of the samples in the Rita Blanca Aquifer exceeded 10 micrograms per liter for arsenic; however, Figure 4.8.10 indicates four samples exceeded 10 micrograms per liter for arsenic. Please re-visit text and figure so they agree.

     The text is correct. The figures erroneously highlighted samples with values equal to the threshold of 10 micrograms per liter. The figure (as well as the other figures in this chapter) have been revised so that the highlighted samples only include values *exceeding* the threshold and do not include values equal to the threshold. This approach is consistent with the statistics shown in Tables 4.8.1-4.8.5 and discussed in the text. Note that Figures 4.8.2-4.8.4 and 4.8.14-4.8.16 have been revised to use 500 mg/L total dissolved solids and 250 mg/L chloride thresholds, respectively, to be consistent with the EPA drinking water thresholds used in the text and tables, rather than the Texas drinking water thresholds.

132. Page 4.8-16, Figure 4.8.1: please adjust the reference for McMahon and others, 2004 to McMahon and others, 2004b, so text and figure agree.

     Citation corrected.

133. Pages 4.8-16 and 4.8-17, Figures 4.8.1 and 4.8.2: Please clarify in the text the inconsistencies of total dissolved solids plotted in Figure 4.8.2 as “fresh” in areas noted in Figure 4.8.1 as areas with elevated salinities and/or poor water quality. For example, northern saline plume (Mehta and others, 2000) shows all freshwater in Figure 4.8.2 as well as the area of mixed Dockum and Ogallala in Deaf Smith and Parmer counties (Nativ, 1988).

     Since Mehta and others (2000) define the “saline” plumes based on comparison to the low-salinity Northern Ogallala Aquifer, their total dissolved solids “saline” threshold is 400 mg/L, much lower than the 1,000 mg/L threshold used in Figure 4.8.2. The word “saline” has therefore been removed from the discussion of the Mehta and others (2000) study, as it is confusing and inconsistent with the word’s use in the rest of the current report. The area in Deaf Smith and Parmer discussed in Nativ (1988) is defined based on a hydrochemical facies analysis. This depends on the chemical make-up of the water, rather than absolute value of total dissolved solids and so is not necessarily expected to be visible in Figure 4.8.2. In general, evidence of cross-formational flow and mixing is more subtle than drastic changes in water chemistry that cause exceedances of drinking or agricultural water standards. The text has been revised to clarify this point.

134. Pages 4.8-17 to 4.8-31, Figures 4.8.2 to 4.8.16: please cite references for data sources for these figures in the legend or caption.

    Citations added.

135. Pages 4.8-18, 4.8-21, 4.8-24, 4.8-27, and 4.8-30, Figures 4.8.3, 4.8.6, 4.8.9, 4.8.12, and 4.8-30: please explain in the legend or caption the significance of the two symbols used for each concentration range.

    Explanatory text added to figure legends.

136. Page 5.0-3, paragraph 1, Sentence 4: please explain Figure 5.0.4 and what is implied by the correlation between initial saturated thickness and pumping.

    This relationship can help guide where to place pumping in the model. Text added to that effect.

137. Page 5.0-3, paragraph 2, last Sentence: since recharge is an important factor in the numerical model, please explain the reason (hypothesis) for enhanced percolation not reaching the water table and how this will be handled in the different regions of the numerical model.

    Text revised to be consistent with the Section 4.4 discussion of recharge in the northern Ogallala Aquifer. The actual implementation of the timing of enhanced recharge in different regions is discussed in the numerical model report.

138. Page 5.0-5, Figure 5.0.1: please clarify if the Dockum Aquifer outcrop areas should be shown as downdip as noted and please revise figure as necessary.

    Hatching removed from Dockum outcrop area.

139. Page 5.0-7, Figure 5.0.3: figure caption says figure is annotated with pre-development features; however, figure shows pumping wells and text mentions post-development recharge and discharge. Please review figure caption and update for consistency and clarity as necessary. Suggest lining up the blocks for L2 and L3 in the Ogallala shaded area to L2 Edwards-Trinity (High Plains) block and L3 Upper Dockum block.

    Figure caption corrected. No changes were made to the figure. The figure needs to represent thin passthrough layers, hence the offset.

140. Page 5.0-8, Section 5.0, Figure 5.0.4: please clarify for what aquifer or aquifers the water level change represent, for what period of time, and whether this is averaged over model or aquifer(s).

    Relevant information added to the caption.

141. Page 8.0-23, References: the TWDB website URL is now www.twdb.texas.gov/ : it is no longer www.twdb.state.tx.us. Please revise 10 TWDB references to the current TWDB website URL.

Corrected.

Draft BRACS comments to be addressed:

142. Please provide readme file within the BRACS_db folder with a brief explanation of the database and its contents.

Added.

143. 108 digital (LAS) geophysical well logs are referenced on page 4.2-1. Please provide these logs to TWDB.

Added.

144. Bracs Database table HP_GAM_tblWell_Geology stratigraphic records need to be edited so that the top, bottom, and thickness (if known) of each distinct geologic unit are listed in one record. The present data has many records in which the top of a unit and the base of a unit are in two separate records.

Corrected.

145. Bracs Database table HP_GAM_tblWell_Geology stratigraphic records need to be edited so that missing top, bottom, and thickness values are recorded, if known. The present data has many records that are incomplete but could be made complete.

Corrected.

146. Bracs Database table HP_GAM_tblWell_Geology records need to be edited so that missing information in the following fields is added: [source_geologic_data], [initials], and [last_change].

Corrected.

147. Bracs Database table HP_GAM_tblWell_Geology records need to be edited so that the [source_geologic_data] is accurate. There are hundreds of records showing base of Ogallala that indicate a geophysical well log was used for this stratigraphic pick. We assume water well reports were used for many of these wells.

Corrected.

148. Bracs Database table HP_GAM_tblWell_Location field [well_type] records need to be edited so that the full name (tblLkWellType field well_type) is listed in this field and not

the well type code (tblLkWellType field well_type_code).

Corrected.

149. Bracs Database table HP_GAM_tblWell_Location field [county_name] contains a number of misspelled names: armstron; deaf smi; hutchins; 0; roosevel. Please correct.

    Corrected.

150. Bracs Database table HP_GAM_tblWell_Location records of wells do not have any well owner , depth, drill date, or corresponding records in the table HP_GAM_tblBracs_ForeignKey from the following sources: DBS&A, 2012; DBS&A, 2013; Hemphill County UWCD, 2013. If there are any attributes of these wells that can be added to Bracs Database to support the identification of these wells, please provide it. For example, wells from the source PGCD, 2013 have a state well number in the foreign key table that will allow identification of additional data.

    All data that INTERA has is contained within this table.

151. Bracs Database table HP_GAM_tblGeophysicalLog_Header field [gl_digital_file_name] requires the filename without the file extension.

    Corrected.

Draft geodatabase comments to be addressed

152. Please add metadata information to the geodatabase and also provide the spatial reference information.

    Metadata added to the geodatabase as a whole, including spatial reference information.

153. Please add field descriptions to the metadata for all feature classes having measured values and include the units of the measured values.

    Done.

154. Please check the CountyBoundaries feature class within the Boundary feature dataset for spatial drift and correct or replace with more accurate feature class. The CountyBoundaries feature class does not overlay properly with either the USCounties feature class or our own TWDB_Counties_GAM shape file and has drifted over a mile in some places. Any and all derivative data created with the CountyBoundaries feature class may need to be revised.

    “CountyBoundaries” and “USCounties” feature classes removed from the geodatabase and replaced with the “County_Boundary_GAM” feature class. This feature class is in agreement with the Strategic Mapping Program (StratMap) county

boundaries within Texas. No derivative data dependent on this boundary feature class were created and so further revision was not required.

155. Please consider not using the CONMNETTXStateBoundaries feature class as it too has the same drift issue as the CountyBoundaries feature class (in previous comment).

"CONMNETTXStateBoundaries" feature class removed from the geodatabase and replaced with the "State_Boundary_GAM" feature class. This feature class is in agreement with the Strategic Mapping Program (StratMap) county boundaries within Texas.

156. Please revise the metadata to describe why the TWDB_PecosValleyAquifer feature class does not match the "official" TWDB boundary for the Pecos Valley Aquifer or correct the TWDB_PecosValleyAquifer feature class and any derivative data that may have been created from this feature class.

Metadata updated to indicate it is based on the TWDB brackish aquifer delineation (Meyers and others, 2012) because it includes portions of the aquifer in New Mexico, rather than truncating at the state line like the official TWDB "Major Aquifers" boundary.

157. Please revise the metadata to describe why the TWDB_EdTrinAquiferOutcrop feature class does not match the "official" TWDB boundary for the Edwards-Trinity (Plateau) Aquifer or correct the TWDB_EdTrinAquiferOutcrop feature class.

Metadata updated to indicate it has been clipped to current active model boundary.

158. Please revise the metadata to describe why the TWDB_CapitanReef feature class does not match the "official" TWDB boundary for the Capitan Reef Complex Aquifer or correct the TWDB_CapitanReef feature class.

Metadata updated to indicate it has been clipped to current active model boundary.

159. Please revise the metadata to describe why the TWDB_RustlerAquifer feature class does not match the "official" TWDB boundary for the Rustler Aquifer or correct the TWDB_RustlerAquifer feature class.

Metadata updated to indicate it has been clipped to current active model boundary.

160. Please revise the metadata to describe why the TWDB_LipanAquifer feature class does not match the "official" TWDB boundary for the Lipan Aquifer or correct the TWDB_LipanAquifer feature class.

Metadata updated to indicate it has been clipped to current active model boundary.

161. Please review the OgIslandBoundary feature class for accuracy in Nolan County where Ogallala Formation outcrop should not overlap with Edwards and/or Trinity group outcrops.

OgIslandBoundary feature class corrected so that there is no overlap.

162. Please provide the precipitation attribute values or join tables for the precipitation point feature classes within the Climate feature dataset. The locations alone are of little use without any measured values attribute data.

Two tables (Figure_2_1_8_AnnualPPT and Figure_2_1_9_MonthlyPPT) added to the geodatabase, containing the annual and monthly precipitation data for selected precipitation gages used to create Figures 2.1.8 and 2.1.9.

163. Please provide potential evapotranspiration data shown in Figure 4.7.1 of the conceptual report.

"Borrelli_PET" raster dataset added to the ClimatePRISm raster catalog in the geodatabase.

164. Please provide actual evapotranspiration data used for Figure 4.7.4 of the conceptual model report.

"Houston_AET" raster dataset added to the ClimatePRISm raster catalog in the geodatabase.

165. Please provide derivative data used for Figure 4.7.3 of the conceptual model report.

Data from Figure 4.7.3 added to the geodatabase as the table "Figure_4_7_3_LandUseDistribution".

166. Please provide pumping estimate data used for Figures 4.7.5 through 4.7.24 of the conceptual model report.

Data from Figures 4.7.5 and 4.7.6 added to the geodatabase as the table "Figs_4_7_5_and_6_PumpingComparison". Data from Figures 4.7.9 through 4.7.18 added to the geodatabase as the table "Figs_4_7_9_thru_18_PumpingComparison." Data from Figures 4.7.7, 4.7.19, 4.7.21, 4.7.23 and 4.7.24 were already included in the geodatabase as table "Pumping_cnty_aq_cat_TX". This has been renamed "Figs_4_7_7_and_19_23_24_pumping_cnty_aq_cat_TX" for clarity. Data from Figures 4.7.8, 4.7.20, and 4.4.22 were already included in the geodatabase as table "pumping_cnty_aq". This has been renamed "Figs_4_7_8_and_20_22_pumping_cnty_aq" for clarity.

167. Please provide volumetric change data used for Figure 4.7.34 of the conceptual model report.

Data from Figure 4.7.34 added to the geodatabase as the table “Fig_4_7_34_VolToolVsMullican”

168. Please provide volumetric change in storage data used for Figures 4.7.35, 4.7.36, and 4.7.38 through 4.7.43 of the conceptual model report

Data from Figure 4.7.35 added to the geodatabase as the table “Fig_4_7_35_PumpingStorage”. Data from Figures 4.7.36 and 4.7.38 through 4.7.43 have been added to the geodatabase as the table “Figs_4_7_36_and_4_7_38_thru_43_PumpingVsStorageChange”

169. Please provide Irrigated and total farm acreage data used for Figure 4.7.37 of the conceptual report.

Data from Figure 4.7.37 added to the geodatabase as the table “Fig_4_7_37_HaleCountyIrrigation”

170. Please provide the time series stream flow gage data used in Figure 4.5.3 for Section 4.5 of the conceptual model report and not just the location data.

Data from Figure 4.5.3 added to the geodatabase as the tables “Fig_4_5_3_DailyStreamflow” and “Fig_4_5_3_AnnualStreamflow”

171. Please provide the time series stream flow and base flow gage data used in Figure 4.5.6 for Section 4.5 of the conceptual model report and not just the location data.

Data from Figure 4.5.6 added to the geodatabase as the table “Fig_4_5_6_ExHydSep”

172. Please provide the time series spring flow gage data used in Figure4.5.9 for Section 4.5 of the conceptual model report and not just the location data.

Data from Figure 4.5.9 added to the geodatabase as the table “Fig_4_5_9_Springs”

173. Please provide the low flow gage data used in Figure 4.5.11 for Section 4.5 of the conceptual model report and not just the location data. [Revision 3/6/2015: TWDB clarified that this comment refers to Figure 4.5.5, not Figure 4.5.11]

Discharge data added to the “BaldysSchalla”, “HardenHemphillLowFlow” and “SladeStudies” feature classes.

174. Please provide the time series reservoir stage data used in Figures for Section 4.5 of the conceptual model report and not just the location data. [Revision 3/6/2015: TWDB clarified that this comment refers to Figure 4.5.11]

Data from Figure 4.5.11 added to the geodatabase as the table

"Fig_4_5_11_Reservoirs"

175. Please provide hydraulic conductivity data for South Plains Underground Conservation District listed in Table 4.6.4 of the conceptual model report.

Data from Table 4.6.4 added to the geodatabase as the table "Table_4_6_4_SPUWCD_K"

176. Please provide measured groundwater quality constituents used for Tables 4.8.1 through 4.8.5 of the conceptual model report.

The water quality data used to create Table 4.8.1 through 4.8.5 are already included in the geodatabase as fields in the corresponding feature classes located in feature dataset "WaterQuality". Data used for Table 4.8.1 are included in the feature class "Og_WQ_pts", data for Table 4.8.2 are included in "LD_WQ", data for Table 4.8.3 are included in "UD_WQ", data for Table 4.8.4 are included in "RB_WQ", and data for Table 4.8.5 are included in "ETHP_WQ_pts2".

177. Please provide water table change data used for Figure 5.0.4 of the conceptual model report.

Data from Figure 5.0.4 added to the geodatabase as the table "Fig_5_0_4_DD_vs_SatThick"

178. Please provide additional metadata for Geology raster catalog with regard to units and vertical references for thicknesses and top and base elevations.

Metadata for the Geology raster catalog updated with additional information.

179. Please provide metadata for the (DEM) elevation raster dataset.

The DEM elevation raster dataset removed since it was a duplicate of the raster already included in the "GeomorphologyDEM" raster catalog.

180. Please define (for the Layer Properties Source tab) the coordinate system for the dem_gam_ft raster dataset within the GeomorphologyDEM raster catalog.

The raster is in the GAM projected coordinate system. Information about this coordinate system (such as datum) is included in the Spatial Reference section in the Layer Properties Source tab. The definition of this coordinate system is also included in the metadata for the geodatabase as a whole.

181. Please provide additional metadata with regard to attributes and units for the STATSGO_Soils feature class within the Soil feature database.

Additional metadata added.

182. Please provide additional metadata with regard to Slope_x10_Model_Area_Gam raster dataset values and the PlayaDensity_Proj raster dataset values in the SoilGrids raster catalog.

     Additional metadata added.

183. Please provide additional metadata with regard to both landuse classifications attributes for the NLCD_GAM raster dataset and the irrigation attributes for the Qi_irrig raster dataset within the ConservationLandUse raster catalog.

     Additional metadata added.

184. Please provide tabular data for Tables 4.7.1 through 4.7.4 used in the conceptual model report.

     Tabular data for Tables 4.7.1 through 4.7.4 have been added to the geodatabase as tables "Table_4_7_1_VegCoeffsRootDepth", "Table_4_7_2_TX_NM_ReturnFlow", "Table_4_7_3_TotIrrPump_Luckey", and "Table_4_7_4_Percent1980Pumping".

185. Please provide additional metadata with regard to units for SOgPreD, SOgPostD_NLCD, SOg_Rech_Irr, PostDOgls, and WolockBFI raster datasets within the RechargeGrids raster catalog.

     Additional metadata added.

186. Please add to metadata for the SubsurfaceHydroHydraulics raster catalog additional information relating OBJECTID number to specific subsurface hydraulics raster datasets.

     Additional metadata added.

187. Please review the ETHP_Kh and Ogallala_Kh_Clp raster datasets within the SubsurfaceHydroHydraulics raster catalog for negative conductivity values or else please explain further the concept of using negative conductivity values in the conceptual model.

     "ETHP_Kh" and "Ogallala_Kh_Clp" raster datasets removed and replaced with corrected rasters "ETHP_Kh2" and "Og_Kh" containing no negative conductivity values.

188. Please provide additional metadata for SubSurfaceHydroWL raster catalog with regard to units and vertical references for water level and water level decline/change elevations.

     Done

189. Please provide additional metadata for all feature classes within the Subsurface_Hydro feature dataset with regard to attribute field descriptions and units of measure for all applicable attribute fields with measured values.

Done.

190. Please remove unused field label_UD_pd10 for WL_surface_cntrl_pts_v2 feature class within the SubsurfaceHydro feature dataset or populated with appropriate values.

Done

191. Please remove unused field UD_outside for CM_WL_data_wells_v3_GAM feature class within the SubsurfaceHydro feature dataset or populated with appropriate values.

Done

192. Please include attribute fields with contour values for all line feature classes within the SubsurfaceHydro feature dataset:
    a) ETHP_1980v1
    b) ETHP_preDv5
    c) lowD_1950v2
    d) lowD_1980v2
    e) lowD2010v1
    f) lowD_preD_2010_decline
    g) lowD_preDv10
    h) Og_1950_v5
    i) Og_1980_v1
    j) Og_2010_v1
    k) Og_preDv4
    l) Og_WLdec_v1
    m) RB_1980_v1
    n) RB_2010_v2
    o) RB_preD_v3
    p) upD_1950_v1
    q) upD_1980_v1
    r) upD_2010_v1
    s) upD_preD_2010_decline
    t) upD_preD_v4
    u) RB_preD_2010_decline

Done

193. Please add metadata (including units for values) to all the raster datasets in the HPAS_GAM_Draft_Aquifer_Surfaces_Mar2014 folder.

Folder removed from the geodatabase.

194. Please review for accuracy the anomalous values in Permian_Top raster dataset in the HPAS_GAM_Draft_Aquifer_Surfaces_Mar2014 folder for an area within Lea County near the intersection of US HWY 62 and STATE HWY 176.

Folder removed from the geodatabase.

195. Please provide uncorrupted ogpvanetsand_1 raster dataset (with appropriate metadata) or remove from geodatabase if not used for modeling purposes.

“ogpvanetsand_1” raster dataset removed from the geodatabase.

196. Please review and correct negative net sand thickness values in the OgSeniNetSand raster dataset within the GeologyGrids raster catalog.

“OgSeniNetSand” raster dataset removed and replaced with corrected raster “OgSeniNetS”, containing no negative net sand thicknesses.

197. Please review and correct negative net limestone percent values in the ETHP_LSPerc raster dataset within the GeologyGrids raster catalog.

“ETHP_LSPerc” raster dataset removed and replaced with corrected raster “ETHP_LSPer2”, containing no negative limestone percent values.

198. Please review and correct negative net limestone values in the ETHPNetLime raster dataset within the GeologyGrids raster catalog and also provide metadata description for this raster dataset.

“ETHPNetLime” raster dataset removed and replaced with corrected raster “ETHPNetLS”, containing no negative net limestone values. Metadata added.

199. Please review and remove unnecessary duplicate raster datasets between GeologyGrids raster catalog within geodatabase and raster datasets within HPAS_GAM_Draft_Aquifer_surfaces folder.

“HPAS_GAM_Draft_Aquifer_surfaces” folder removed from the geodatabase.

200. Please provide additional metadata for all feature classes within the Geology feature dataset with regard to attribute field descriptions and units of measure for all applicable attribute fields with measured values.

Done.

201. Please review all attribute fields for each of the feature classes within the Geology feature datasets and check for duplicate and/or unnecessary attribute fields with different names

and clean up attributes table.

Done.

202. Please provide metadata for CrossSectionWell feature class within Geology feature dataset and also provide additional metadata information on how the user can relate or join the CrossSectionWell feature class points with actual geophysical/log data and also add a field attribute for section line labels.

    Additional metadata and cross-section field added.

203. Please provide additional metadata information on how the user can relate or join the GeophysicalLogWells feature class within the Geology Feature dataset with actual geophysical log data.

    Additional metadata added.

204. Please provide metadata for SupplementalNPGCDData feature class within Geology feature dataset.

    Additional metadata added.

205. Please provide metadata for SupplementalLipscombData feature class within Geology feature dataset.

    Additional metadata added.

206. Please provide metadata for SupplementalSeniData feature class within Geology feature dataset.

    Additional metadata added.

207. Please provide additional metadata information on how the user can relate or join the Cross_section_well_region feature class within Geology feature dataset with actual geophysical/log data and also add a field attribute for section line labels.

    Additional metadata and cross-section field added.

208. Please provide additional metadata information on how the user can relate or join the ref_logs feature class within Geology feature dataset with actual geophysical/log data.

    Additional metadata added.

209. Please add label field for RegCrossSectionLines feature class within Geology feature dataset for section line name/labels.

Additional metadata and cross-section field added.

210. Please include attribute field for cross-section line labels for the CrossSectionModel feature class within the Geology feature dataset.

Additional metadata and cross-section field added.

211. Please provide spatial reference information for the all raster catalogs and/or all raster datasets contained within them.

Metadata added to the raster catalogs noting that rasters are in the GAM coordinate system. The definition of the GAM coordinate system is included in the metadata description added for the geodatabase as a whole, per Comment #151.

General suggestions for Draft geodatabase

212. Please consider moving the EvapGrids and EvapGridsSelect feature classes from the SurfaceHydro feature dataset to the Climate feature dataset.

Done.

213. Please consider using a raster mosaic data model structure instead of the raster catalog for the (DEM) elevation datasets and/or please consider not using duplicates (DEM raster catalog and GeomorphologyDEM raster catalog) for the elevation datasets to help reduce the size of the geodatabase.

Duplicate DEM removed. Official DEM is contained in "GeomorphologyDEM" raster catalog.

214. Please consider using, for each of the raster catalogs within the geodatabase, the same format used for the Contents listing of the raster datasets within the raster catalog in the metadata description to make it easier to correlate between the Contents listing and the metadata description. In other words, please consider listing an individual metadata description for each raster dataset within the raster catalogs that includes both the name and OBJECTID for each raster dataset.

Done.

Suggestions for Conceptual Model Report:

General suggestions

215. Please check for grammar, spelling, and punctuation throughout the report.

Text revised throughout report where needed.

216. Please capitalize Aquifer when discussing one aquifer and please use lower case when referencing more than one.

Text revised throughout report where needed.

217. Please consider using the term “subcrop” instead of “downdip” for aquifers or formations that do not have a regional dip such as the Edwards-Trinity (Plateau) Aquifer.

“Downdip” replaced with “subcrop” throughout report, where appropriate.

218. Value range scales on the figures are sized differently and only marked with minimum and maximum values (e.g. Figures 4.2.11A - 4.2.19). Please put more values on the value scale ranges and resize them to be consistent.

Value range scales adjusted on figures throughout the report, where appropriate.

Specific suggestions

219. Page 1.0-1, Section 1.0, Paragraph 4, Sentence 1: please add modifier “Aquifer” when referencing “Rita Blanca”, as applicable. Please see review comment number 3.

Corrected

220. Page 1.0-1, Section 1.0, Paragraph 4, and the remainder of the report: please replace “%” with “percent”.

Corrected

221. Page 1.0-2, Section 1.0, Paragraph 1, Sentence 6: please add modifier “Aquifer” when referencing “Rita Blanca”, as applicable. Please see review comment number 3.

Corrected

222. Page 1.0-2, Section 1.0, Paragraph 3, Sentence 1: please consider rewording “…GAM numerical model…” to possibly “…numerical groundwater availability model…” or simply “…groundwater availability model …” as stating groundwater availability model numerical model appears redundant.

Revised to avoid redundancy

223. Page 1.0-3, Section 1.0, Paragraph 1, Sentence 1: please consider re-wording this sentence since groundwater availability is now considered a policy decision. One possible revision,” Groundwater models provide a tool to estimate [the effects of] various water use strategies and [help] to determine the cumulative effects of increased water use and drought.”

Corrected

224. Page 1.0-3, Section 1.0, Paragraph 3 and the remainder of the report: please use “for example” instead of e.g.

Except for direct quotes, “e.g.” was replaced with “for example” throughout the report.

225. Page 1.0-5, Figure 1.0.1: please consider moving the labels for the Trinity, Carrizo-Wilcox, and Edwards aquifers to outside the footprint of Texas, like was done for the Seymour Aquifer, so it is easier to read. In addition, please consider using the term “subcrop” instead of “downdip” for areas of aquifers that lie beneath the land surface.

Labels highlighted so that they are easier to read. “Downdip” replaced with “subcrop” throughout the report.

226. Page 2.0-3, Section 2.0, paragraph 1, sentence 1: Please change “State Water Plan is updated about every 5 years” to “State Water Plan is updated every 5 years”, please remove “about”.

Corrected

227. Page 2.0-3, Section 2.0, Paragraph 1: please adjust grammar for verb agreement,” Small portions of the Region B, Brazos G (Region G), and Far West Texas (Region E) Regional Water Planning Groups are located in or near the study area ~~is~~ [are] also included.

Corrected

228. Page 2.0-3, Section 2.0, Paragraph 2, Sentence 1: please consider replacing, “…roughly corresponding to groundwater basin boundaries.” to “…roughly corresponding to TWDB defined aquifer flow boundaries.”

Corrected

229. Page 2.0-4, Section 2.0, Paragraph 2, Sentence 8: please consider replacing,”… tend to gain flow from the underlying sediments” to “…tend to gain flow from the underlying [saturated] sediments and/or underlying aquifers”.

Corrected

230. Page 2.1-2, Section 2.1, Paragraph 3, Sentence 2: please consider rephrasing “this type of climate is typical of continent interiors” to “continental interiors”

Corrected

231. Pages 2.2-1 through 2.2-5, Sections 2.2.1 Tectonic History and 2.2.2 Depositional Environments: much of the information in Section 2.2.1 is repeated in Section 2.2.2. Suggest consider merging the two sections.

Merging the two sections was considered. However, the two sections were not merged because doing so would have reduced the clarity of both the tectonic history discussion and the depositional environments discussion. Although the two sections were not merged, text was modified in each section to eliminate the repeating of information in both sections.

232. Page 4.2-1, Section 4.2.1, Paragraph 1, Sentence 2: please clarify and possibly re-word the following,' Large amounts of time and effort were spent up front searching for, evaluating the quality of, and ~~depth calibrating~~ [interpreting lithologic elevations for geologic units (depth calibrating) in] well logs.". In other words, define what depth calibration means to the layperson.

Text added to explain the depth calibration process.

233. Page 4.2-1, Section 4.2.1, Paragraph 2, Sentence 2: please check the grammar in the following sentence," Although the image files are just pictures of well logs, the depth calibration process in Petra allows us to make interpretations directly on the images that are automatically saved to [a] database at correct[ed and compatible] depth and thickness [elevations]."

Text revised for grammar and clarity.

234. Page 4.2-1, Section 4.2, Paragraph 3, last Sentence: Figure 4.2.1 appears to be a plot of the location of logs and not the logs themselves. Please consider modifying the sentence to reflect this.

Text modified to "log locations"

235. Page 4.2-21, Figure 4.2.11B: please adjust Pecos Valley Aquifers to singular—Pecos Valley Aquifer.

Corrected.

236. Page 4.3-20, Subsection Ogallala Aquifer, last paragraph: please adjust the following, "These surfaces were construct[ed]~~ing~~ using only water-level data for control."

Corrected

237. Page 4.3-24, Section 4.3.6: suggest consider adding some maps to the section on Cross Formational Flow indicating general areas of cross-formational flow based on literature.

No changes were made. The discussion on cross-formational flow is based on a

literature review. Areas where these studies identify the likelihood of cross-formational flow are in some cases more specifically explained or shown on figures, sometimes must be inferred from figures, but sometimes only general descriptions of the areas are provided. In addition, areas of cross-formational flow are not always consistent between the literature studies. Therefore, the availability of the information in the literature is considered to be insufficient to create maps indicating general areas of cross-formational flow.

238. Page 4.3-25, Section 4.3.6, Paragraph 1: please consistently refer to Prof. Ronit Nativ's work using female pronouns; this section currently references "her" work and "his" work.

     Corrected

239. Pages 4.3-29 to 4.3-40, Table 4.3.3: please define abbreviations used for "Water-Level Source in the caption or in footnotes. Please consider only reporting water levels to the tenth decimal.

     Abbreviation key added as footnotes to the table. Water levels values revised to report only the tenth decimal.

240. Page 4.3-76, Figure 4.3.22, the titles for hydrographs of wells in Union, Lea, and Roosevelt counties New Mexico have the word "Aquifer" truncated to varying degrees. Please adjust titles so that the word "Aquifer" is complete. In addition, please provide in a legend or caption the meaning of the abbreviation ET(HP).

     Truncation fixed. Abbreviation key added to the caption.

241. Page 4.3.-77, Figure 4.3.23: the word "Aquifer" is truncated in the title for hydrograph 1010701. Please adjust title so that the word "Aquifer" is complete.

     Truncation fixed.

242. Page 4.4-10, Section 4.4.3.5, paragraph 3, sentence 2: please correct spelling of playas (…individual plays …).

     Corrected.

243. Page 4.4-12, Section 4.4.4.2, Paragraph 3: please re-word the following sentence for clarity," Monitoring at different stations generally variously beginning in the late 1970's to the early 1980's."

     Corrected.

244. Page 4.4-15, Section 4.4.4.5, Paragraph 1: please introduce total dissolved solids (TDS) prior to using acronym and/or please insert into glossary.

Corrected.

245. Pages 4.4-15 to 4.4-17, Section 4.4.4.5: please clarify if overlaying Figure 2.1.6 (precipitation patterns 1981 to 2010 or possibly using averaged precipitation for the analysis timeframe) to Figures 4.4.14, 4.4.15, and/or 4.4.16 shows a stronger correlation. It appears that areas without recharge also correspond to bands of low precipitation and areas with early recharge breakthroughs are in areas with higher precipitation (or please clarify if this is circular reasoning as the approach used is not clear).

    The conceptualization is that precipitation is not the major driver for increased recharge, but rather the occurrence of agricultural activity. We don't see any obvious correlation in breakthrough times with precipitation. If it were true, the most northeastern county should have the earliest breakthrough and get steadily later towards the southwest (since precipitation decreases from northeast to southwest). However, the wettest, most northeastern county (Crosby) actually broke through much more recently (1990's) than the one just southeast of it (Lynn) which broke through pre-1960. Other counties with similar precipitation values break through at very different times, supporting our conceptualization that recharge depends on factors other than precipitation.

246. Page 4.4-25, Figure 4.4.4: suggest either replacing this figure with a table of values for Farm Acreage or also including a table. It is difficult with this figure to compare values. In addition, please do not use scientific notation for y-axis and please indent footnotes so it is easier to distinguish groups from county lists or bold the group names.

    Data labels added to chart. Y-axis fixed. Footnotes indented for readability.

247. Page 4.4-29, Figure 4.48: please cite reference for data. Please clarify in the text if this was developed using Figures 2.1.3 and 4.3.27.

    Reference added. Text added to clarify that it was calculated using Figures 2.1.3 and 4.3.12.

248. Pages 4.4-31 to 4.4-34, Figures 4.4.10 to 4.413: please use at least 10-point font for the legend in each of these figures.

    Font size increased.

249. Page 4.4-37, Figure 4.4.16; suggest adding R^2 value to slope of inset graph.

    Added.

250. Pages 4.5-16 to 4.5-43, Table 4.5.5: Please include state in a column or break the table by state as Ellis County appears to occur in Oklahoma and in Texas (although outside the study area).

State added to the county name column.

251. Pages 4.5-44 to 4.5-55, Table 4.5.6: Please include state in a column or break the table by state as Ellis County appears to occur in Oklahoma and in Texas (although outside the study area).

State added to the county name column.

252. Page 4.5-58, Figure 4.5.2: Please do not use USGS abbreviation and spell out United States Geological Survey. Please clarify why the two gages that are to the left of the legend are included when they are not on the main river and are down gradient of the recharge zone (possibly in Kent and Fisher counties).

Abbreviation fixed. Unnecessary gages removed.

253. Page 4.6-22, Figure 4.6.5: please insert a space in "OgallalaBoundary" (and please check other figures) and please define abbreviation Kh (in legend or caption).

Corrected.

254. Pages 4.6-23 to 4.6-25, Figures 4.6.6 to 4.6.8: please define abbreviation Kh (in legend or caption).

Corrected.

255. Page 4.7-1, Section 4.7, Paragraph 2, Sentence 3: "that discharges" repeats at the beginning of the sentence. Suggest removing redundant set.

Corrected.

256. Page 4.7-6, first dark bullet: please re-word, "The updated model of INTERA, Inc. and Dutton (2010)…" to "The updated model ~~of~~ [by] INTERA, Inc. and Dutton (2010)…"

Corrected.

257. Page 4.7-16, Section 4.7.2.6, Bullet 1: please update text from,"…pumping was based on the ~~exiting~~ [existing] updated…"

Corrected.

258. Page 4.7-18, Subsection Introduction and Description of Approach: please change this section from text to a numbered subsection 4.7.2.6.1.

Done.

259. Page 4.7-19 Subsection Introduction and Description of Approach, Paragraph 3: please correct grammar in the following sentence,” Therefore, an automated tool that could quickly produce~~s~~ estimates of aquifer storage for any given county and year was developed.

Corrected.

260. Page 4.7-20, Subsection Results and Discussion: please change this section from text to a numbered subsection 4.7.2.6.2.

Done.

261. Pages 4.7-63 through 4.7-71, Figures 4.7.25 through 4.7.33: suggest removing these figures as they appear to confuse the reader instead of enlighten. For example, figures show pumping for the Dockum Aquifer in counties where the aquifer does not exist. The pumping is very low according to the tables, but that is not obvious in the figures.

No changes made. The comment is unclear as the figures are just a graphical representation of the tables provided in the section. Most of the area that falls outside of the “official” Dockum Aquifer boundary is indeed symbolized as blank (no pumping). Sections with non-zero pumping that do overlap the saline portion of the Dockum Group have negligible pumping and the color symbology reflects this. Perhaps it is slightly misleading to apply the color over an entire county even if the value represents pumping in only a small portion of the county. However, since the tables in the chapter are presented on a county basis, this is the most appropriate way to represent the data on a map.

262. Page 7.0-1, Section 7.0, Paragraph 1, Sentence 1: conceptual is misspelled and sentence contains 2 periods. Please review and correct.

Corrected.

263. Page 7.0-1, Section 7.0, Paragraph 1; please update High Plains Water District to High Plains Underground Water Conservation No. 1.

Corrected.

264. Page 7.0-1, Section 7.0, Paragraph 1, Sentences 3 and 4: valuable and development are misspelled. Please review and correct.

Corrected.

265. Page 8.0-2, References, Ashworth and Christian, 1989: please correct the spelling of Reagan County.

Corrected.

266. Page 8.0-2, References, Baldys and Schalla, 2011: please verify if title "…of the Brazos River form the New Mexico…" should be "…of the Brazos River [from] the New Mexico…"

Corrected.

267. Page 8.0-6, References: please replace Regiona in Dutton and Reddy and Dutton and others, 2000 with either Region or Regional.

Corrected to "Region A"

268. Page 8.0-6, References, Dutton and Simpkins, 1986: please correct the spelling of hydrogeochemistry.

Corrected.

269. Page 8.0-6, References, Dutton and others, 2001b: please correct the spelling of hydrogeologic, guidebook, conference, and authors name Reddy should be Reedy.

Corrected.

270. Page 8.0-11, References, Klemt, 1981: please adjust the font to be consistent with the rest of the report.

Done.

271. Page 8.0-14, References, McGuire, 2012: please correct spelling of predevelopment.

Done.

272. Page 8.0-16, References, Mullican, 2012: please update author to Mullican, W.F., III and please change "2-11" to "2011".

Done.

273. Page 8.0-18, References, Ozdogan and Gutman, 2008: please adjust the font to be consistent with the rest of the report.

Done.

274. Page 8.0-21, References, Sorenson, 1997: please correct the spelling of Technical.

Done.

275. Page 8.0-26, References: Wilson, B.C., 1992, Wilson and Lucero,1997, and Wilson and others, 2003: title should be “Water use by categories …” rather than “Water use be categories …” Please review and correct if necessary.

Corrected.