Groundwater Availability Model of the Edwards-Trinity (High Plains) Aquifer in Texas and New Mexico

Report No. _______

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Table of Contents

Table of Contents (Continued)

List of Figures

List of Figures (Continued)

List of Figures (Continued)

List of Figures (Continued)

List of Figures (Continued)

List of Tables

List of Appendices

Abstract

A numerical groundwater flow model was constructed for the Edwards-Trinity (High Plains) Aquifer in west Texas and eastern New Mexico, using the Southern Ogallala Groundwater Availability Model (Blandford and others, 2003) as a starting point for model construction. The Edwards-Trinity (High Plains) Aquifer lies beneath a region of about 9,000 square miles beneath the Southern High Plains. As part of this study, the geologic structure of the primary hydrogeologic units that form the Edwards-Trinity (High Plains) Aquifer system was determined based on geophysical logs from oil and gas wells, water well logs obtained from the Texas Commission on Environmental Quality and Texas Groundwater Conservation Districts, and existing publications. These units are the predominantly shale unit composed primarily of the Duck Creek and Kiamichi Formations, the predominantly limestone unit composed primarily of the Edwards Limestone and Comanche Peak Formations, and the basal Antlers Sand.

The geologic analysis identified regions where enhanced cross-formational flow between the Southern Ogallala and Edwards-Trinity (High Plains) Aquifers is likely to occur. These regions include the southern and eastern portions of the Edwards-Trinity (High Plains) Aquifer, where the Kiamichi and Duck Creek Formations are generally thin or absent, and limited areas within the central and western portions of the Edwards-Trinity (High Plains) Aquifer where these units have been eroded away, either in full or in part, in paleochannels. The geologic analysis also delineated regions where the Edwards-Trinity (High Plains) Aquifer is discontinuous or absent, and an updated aquifer extent was estimated that differs in certain areas from the existing Texas Water Development Board aquifer delineation. The largest differences in aquifer extent are in Gaines and Dawson Counties.

The model was constructed in such a way as to minimize, to the extent possible, non-uniqueness in aquifer parameter estimates and other model inputs. A steady-state model was developed for predevelopment (1930) conditions to determine hydraulic conductivity of the aquifers, recharge to the Southern Ogallala Aquifer, and cross-formational flow to and from the Edwards-Trinity (High Plains) Aquifer.

Results of the steady-state model indicate that, under predevelopment conditions, approximately half of the discharge from the combined Edwards-Trinity (High Plains) and Southern Ogallala Aquifers occurred at springs along draws and at the margins of salt lakes west of the eastern escarpment. The remainder of the discharge occurred at springs and seeps along the eastern escarpment, or as outflow to the Central Ogallala Aquifer near Amarillo. Only 3 percent of the total simulated spring flow emanated from the Edwards-Trinity (High Plains) Aquifer. Simulated predevelopment recharge to the Southern Ogallala Aquifer ranges from 0.03 inches per year to 0.08 inches per year, with the higher rates simulated in regions with lower-permeability soils in the northern part of the study area.

Results from the steady-state model were used as initial conditions for the transient model calibration, which was conducted for the period 1930 through 2000. Transient model calibration for Southern Ogallala Aquifer was conducted using 90 hydrographs for locations throughout the study area and all available observed water levels for the winters of 1989-1990 and 1999-2000. Relative to the existing Southern Ogallala Groundwater Availability Model, changes made in the

current model to maintain or improve model calibration include 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.

Transient model calibration for the Edwards-Trinity (High Plains) Aquifer was conducted using 18 hydrographs at locations distributed across the Edwards-Trinity (High Plains) Aquifer and all available observed 1980, 1990 and 1997 water level data from Edwards-Trinity (High Plains) Aquifer wells. The availability of observed data for the Edwards-Trinity (High Plains) Aquifer is very limited compared to the Southern Ogallala Aquifer. Even so, the transient model replicates the observed data quite well at most locations.

The vast majority of discharge simulated from the Southern Ogallala Aquifer (94 percent) for the year 1997 is from wells; less than 2 percent of the total discharge is to springs. Approximately 37 percent of the inflow to the aquifer is from recharge, and 63 percent is from aquifer storage, indicating that overall, the Southern Ogallala Aquifer is being mined. There is a high degree of variability throughout the aquifer, however. At many locations, water levels are relatively stable or even increasing.

Water budget components for the Edwards-Trinity (High Plains) Aquifer are a small fraction of those of the Southern Ogallala Aquifer. Groundwater in the Edwards-Trinity (High Plains) Aquifer has not been used to a significant extent except within Gaines, Dawson, and possibly southern Yoakum Counties. Model simulations indicate that where both the Southern Ogallala and Edwards-Trinity (High Plains) Aquifers occur in Gaines and Dawson Counties, up to 40 percent of the water pumped for irrigated agriculture is obtained from the Edwards-Trinity (High Plains) Aquifer. At other locations, only a limited number of wells penetrate the aquifer, and for the most part yields are not substantial. Utilization of groundwater from the aquifer in New Mexico is minimal. Most wells that penetrate the Edwards-Trinity (High Plains) Aquifer are also screened across the Southern Ogallala Aquifer.

Significant well yields might be obtained from Edwards-Trinity (High Plains) Aquifer at some locations, and the aquifer may serve as a beneficial supplement to Ogallala water supplies or as a primary supply where the Southern Ogallala Aquifer is dry or has low production capacity. However, Edwards-Trinity (High Plains) Aquifer water availability will generally be far less than that of the Southern Ogallala Aquifer.

Groundwater Availability Model of the Edwards-Trinity (High Plains) Aquifer in Texas and New Mexico

1.0 Introduction

The Edwards-Trinity (High Plains) Aquifer is designated as a minor aquifer in Texas and underlies approximately 9,000 square miles (mi^2) of the Southern Ogallala Aquifer, which is one of the largest and most significant aquifers in Texas. The Edwards-Trinity (High Plains) Aquifer occurs beneath the Southern High Plains in both Texas and New Mexico. The availability of water is critical to the economy of this region, as approximately 95 percent of groundwater pumped is used for irrigated agriculture. Livestock production, oil and gas production and related services, manufacturing, and wholesale and retail trade are also significant contributors to the region's economy.

The groundwater resources of this region have been studied since the early 1900s, when development of groundwater on a limited scale first began. Significant groundwater development began in the 1930s to 1940s, primarily for irrigated agriculture. Development continued rapidly through the 1950s, and groundwater has been used to sustain large regions of irrigated agriculture ever since. Previous studies, however, have focused largely on the Southern Ogallala Aquifer rather than the underlying Edwards-Trinity (High Plains) Aquifer, which is significantly less productive in most cases. In some regions, such as Gaines County, Texas, many wells draw water from both the Edwards-Trinity (High Plains) Aquifer and the Southern Ogallala Aquifer. An improved understanding of the hydrogeology and groundwater availability of the Edwards-Trinity (High Plains) Aquifer is necessary for improved water planning in the region. Prior to this study, there was no quantitative tool to assist with the evaluation of groundwater availability in the Edwards-Trinity (High Plains) Aquifer.

When developed appropriately in conjunction with observed data, a numerical groundwater flow model is a tool that can be used to estimate changes in water levels through time, subject to assumed groundwater demand. The numerical groundwater flow model described herein was developed for the Edwards-Trinity (High Plains) Aquifer as a tool to assist regional water planning efforts and planning activities of Texas Groundwater Conservation Districts (GCDs) who may rely on this aquifer. Because the Edwards-Trinity (High Plains) Aquifer lies beneath, and is in hydraulic communication with, the Southern Ogallala Aquifer, the Edward-Trinity (High Plains) Groundwater Availability Model (GAM) is a significant update to the Southern Ogallala GAM (Blandford and others, 2003).

2.0 Study Area

The Edwards-Trinity (High Plains) Aquifer underlies an area of about 9,000 mi^2 in western Texas and eastern New Mexico, encompassing all or part of 14 counties in Texas and 3 counties in New Mexico (fig. 1). The aquifer occurs almost entirely within the boundaries of Regional Water Planning Area O (Llano Estacado), but also occurs within the northwestern corner of Borden County, which is in Regional Water Planning Area F (fig. 2). The High Plains Underground Water Conservation District (HPUWCD) No. 1 covers all or portions of 8 counties underlain by the Edwards-Trinity (High Plains) Aquifer. Five other GCDs cover individual counties or portions of counties underlain by the aquifer (fig. 2).

The Edwards-Trinity (High Plains) Aquifer lies beneath the Southern Ogallala Aquifer, except at limited areas where the Ogallala Formation has been removed by erosion or where Ogallala Formation sediments are not saturated and therefore the aquifer does not exist (Section 2.2 and Section 4). The Southern Ogallala Aquifer, which encompasses an area of approximately 29,000 mi^2, extends north and south of the Edwards-Trinity (High Plains) Aquifer. Although the major goal of this study was to develop of a GAM for the Edwards-Trinity (High Plains) Aquifer, some new information was evaluated and utilized for the Southern Ogallala Aquifer as well. Consequently, the term “study area” as used in this report refers to the area coincident with the extent of the Southern Ogallala Aquifer.

Major drainages within the study area include the headwaters of the Red, Brazos, and Colorado Rivers. A small portion of the northern part of the study area drains to the Canadian River (fig. 3).

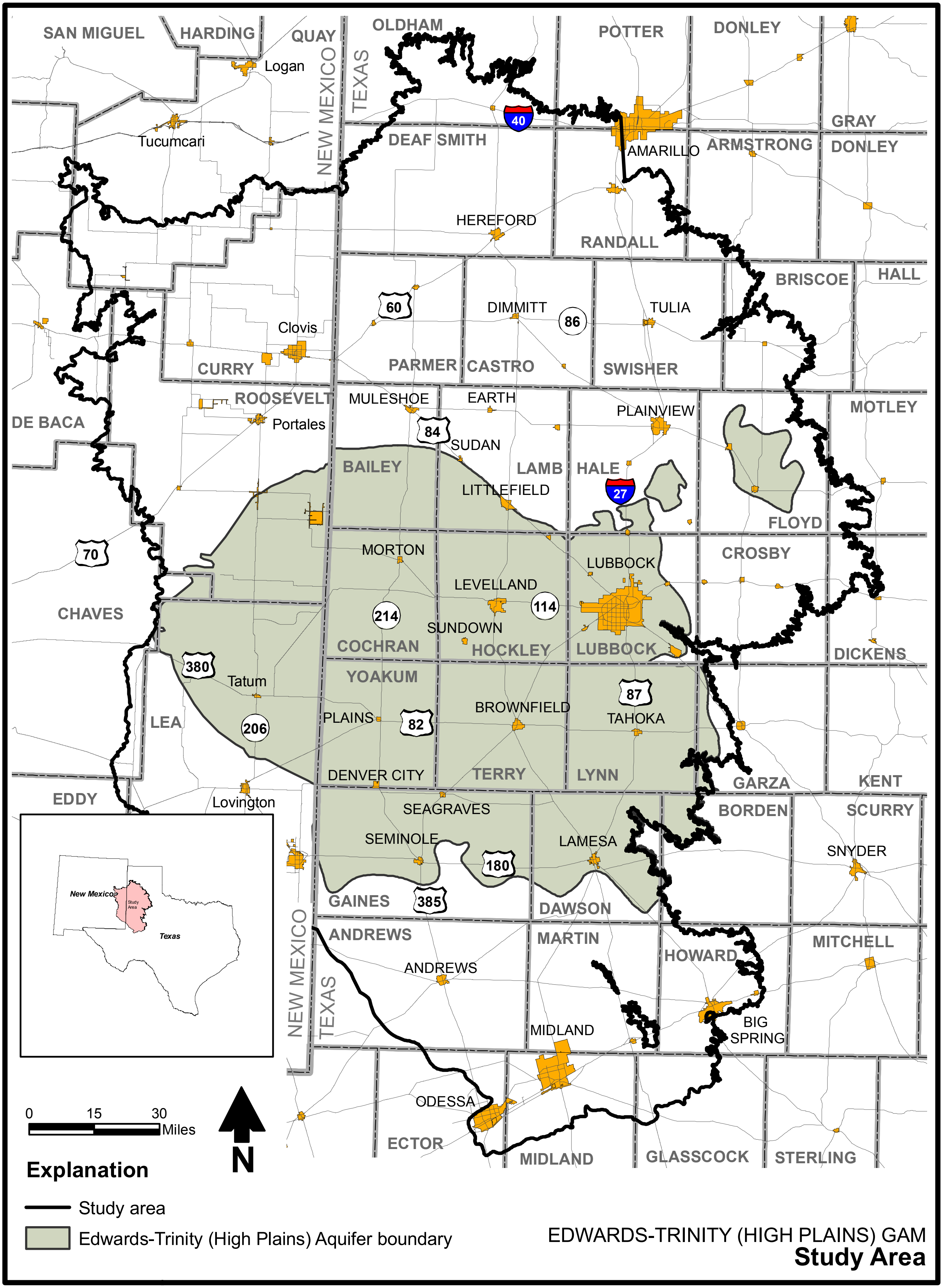
The main population center in the study area is Lubbock, Texas. Most of the study area is rural and sparsely populated (fig. 4).

2.1 Physiography and Climate

The study area lies in the Great Plains physiographic province (fig. 5). The study area occurs within that part of the High Plains south of the Canadian River and Palo Duro Canyon. The region is often referred to as the Llano Estacado, or “staked plains,” as named by Spanish explorers.

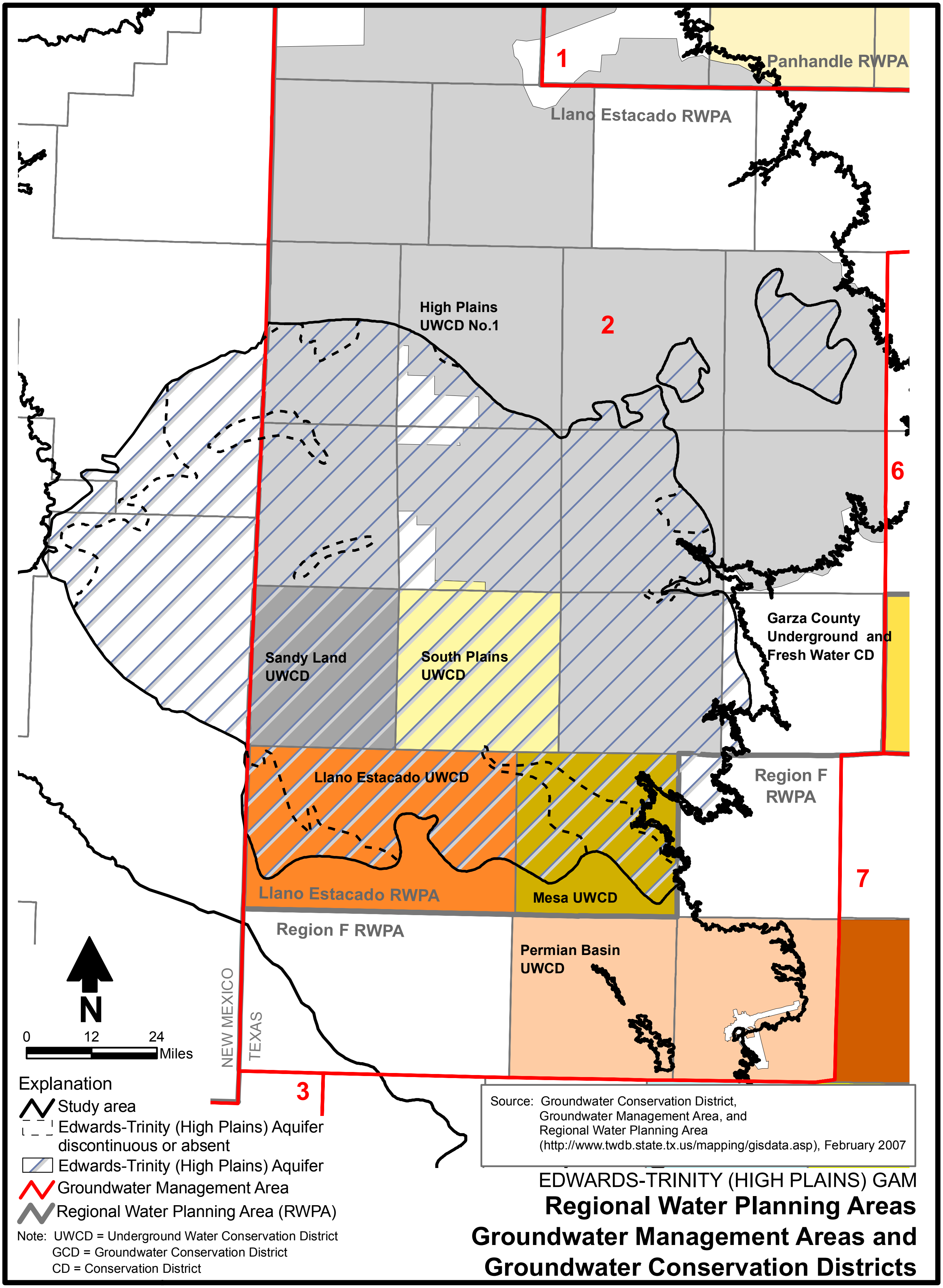
Regional physiographic features in and adjacent to the Edwards-Trinity (High Plains) Aquifer include:

- The broadly flat to slightly sloping High Plains surface, which is an extensive plain of minimal topographic relief
- Erosional escarpments to the west and east that border the High Plains
- A series of northwest- to southeast-trending draws that contain water only after heavy rains (fig. 3)
- Tens of thousands of closed drainage depressions known locally as playa basins or lakes, which may pond water after rainfall (fig. 6)



EDWARDS-TRINITY (HIGH PLAINS) GAM
Study Area

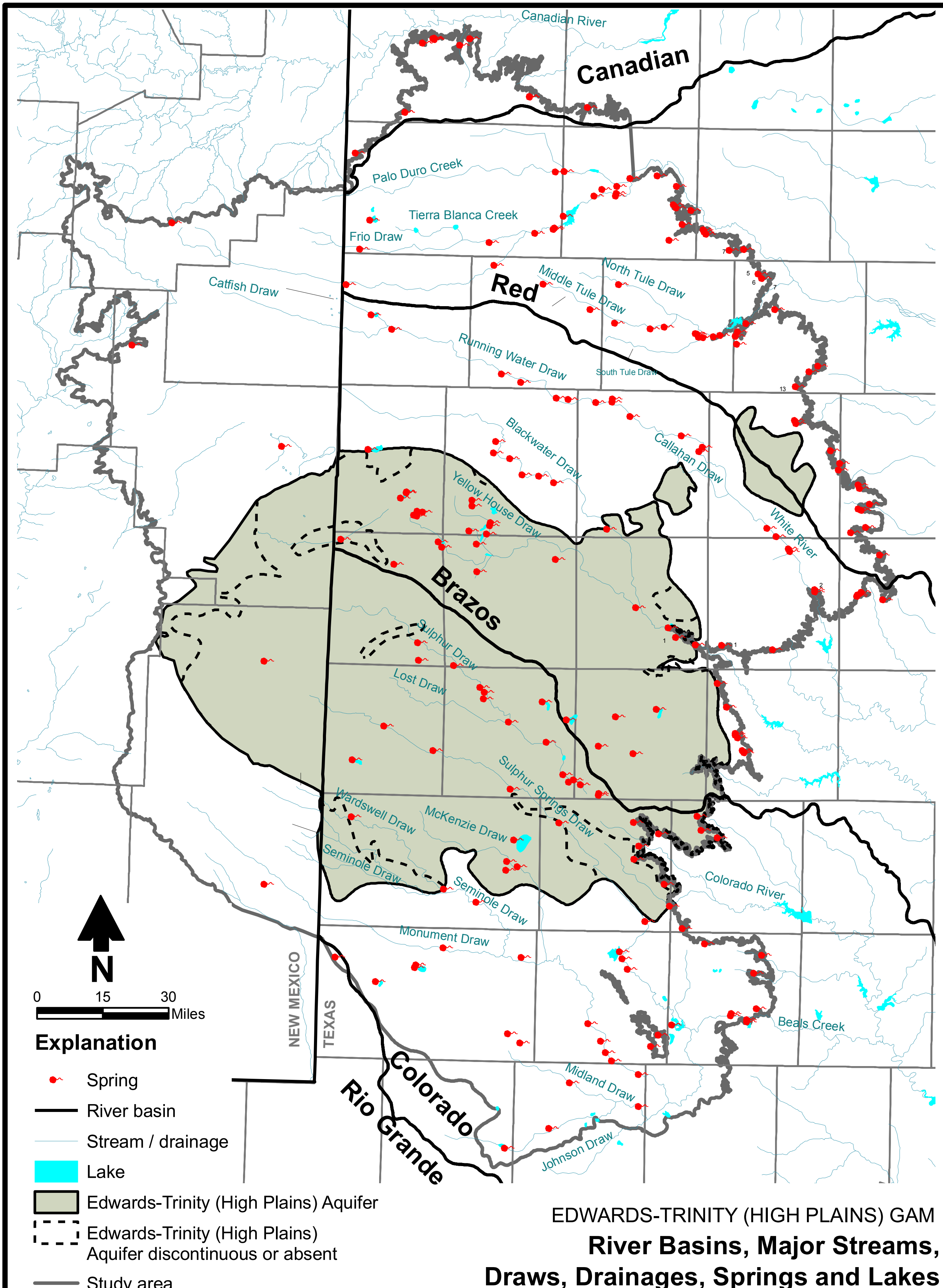
Figure 1



EDWARDS-TRINITY (HIGH PLAINS) GAM

Regional Water Planning Areas Groundwater Management Areas and Groundwater Conservation Districts

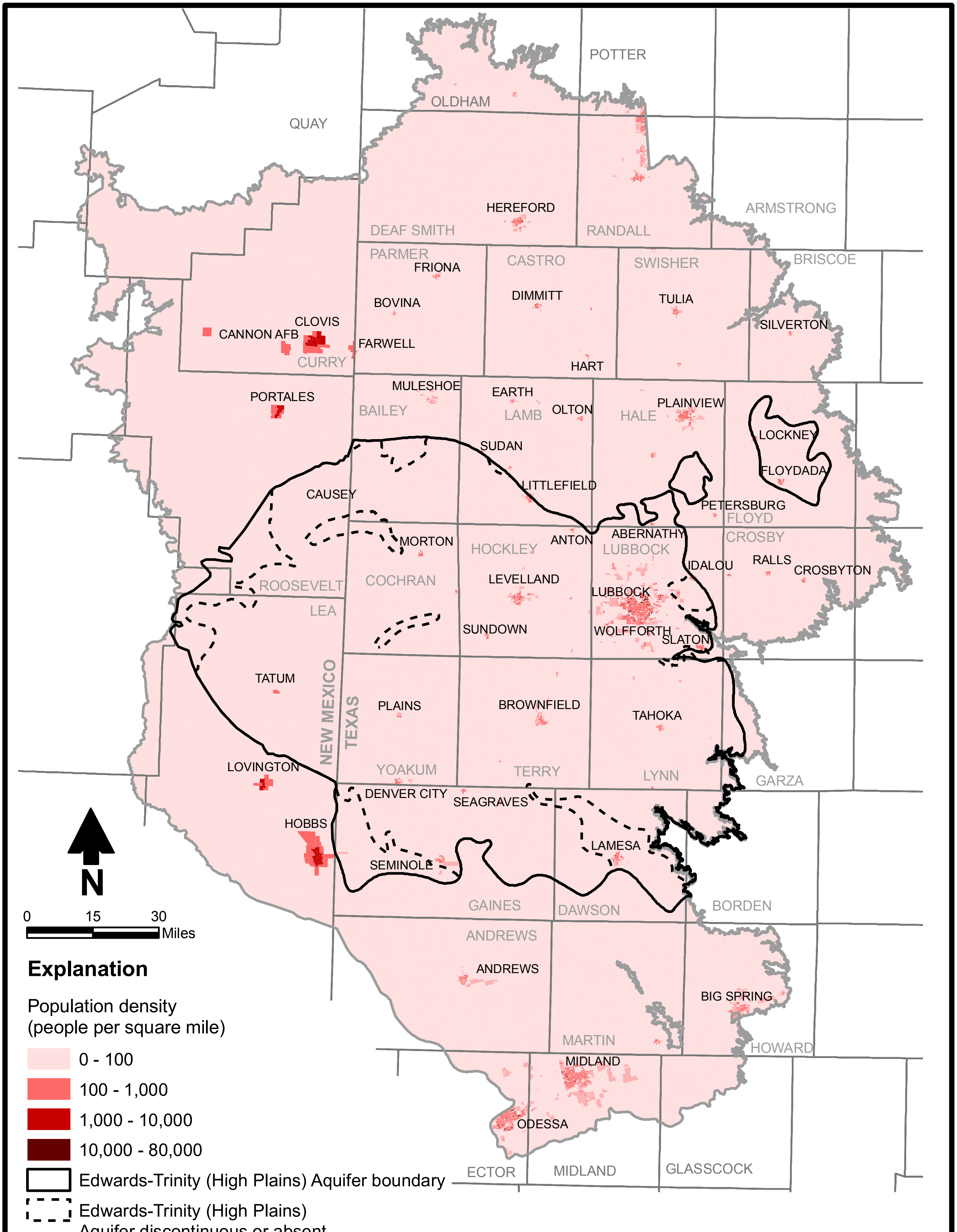
Figure 2



EDWARDS-TRINITY (HIGH PLAINS) GAM

River Basins, Major Streams, Draws, Drainages, Springs and Lakes

Figure 3

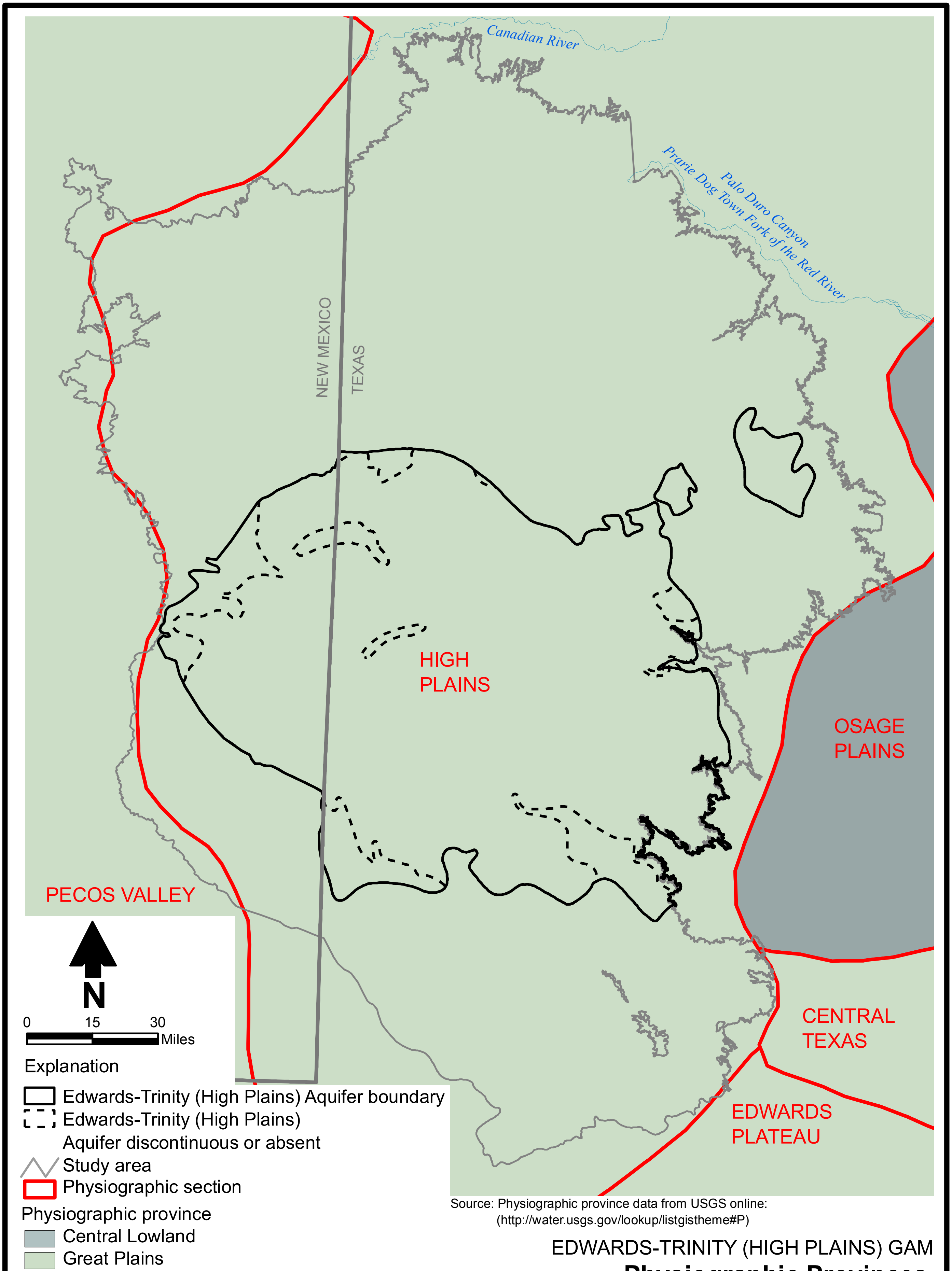


Source: U.S. Census Bureau

EDWARDS-TRINITY (HIGH PLAINS) GAM

2000 Population Density

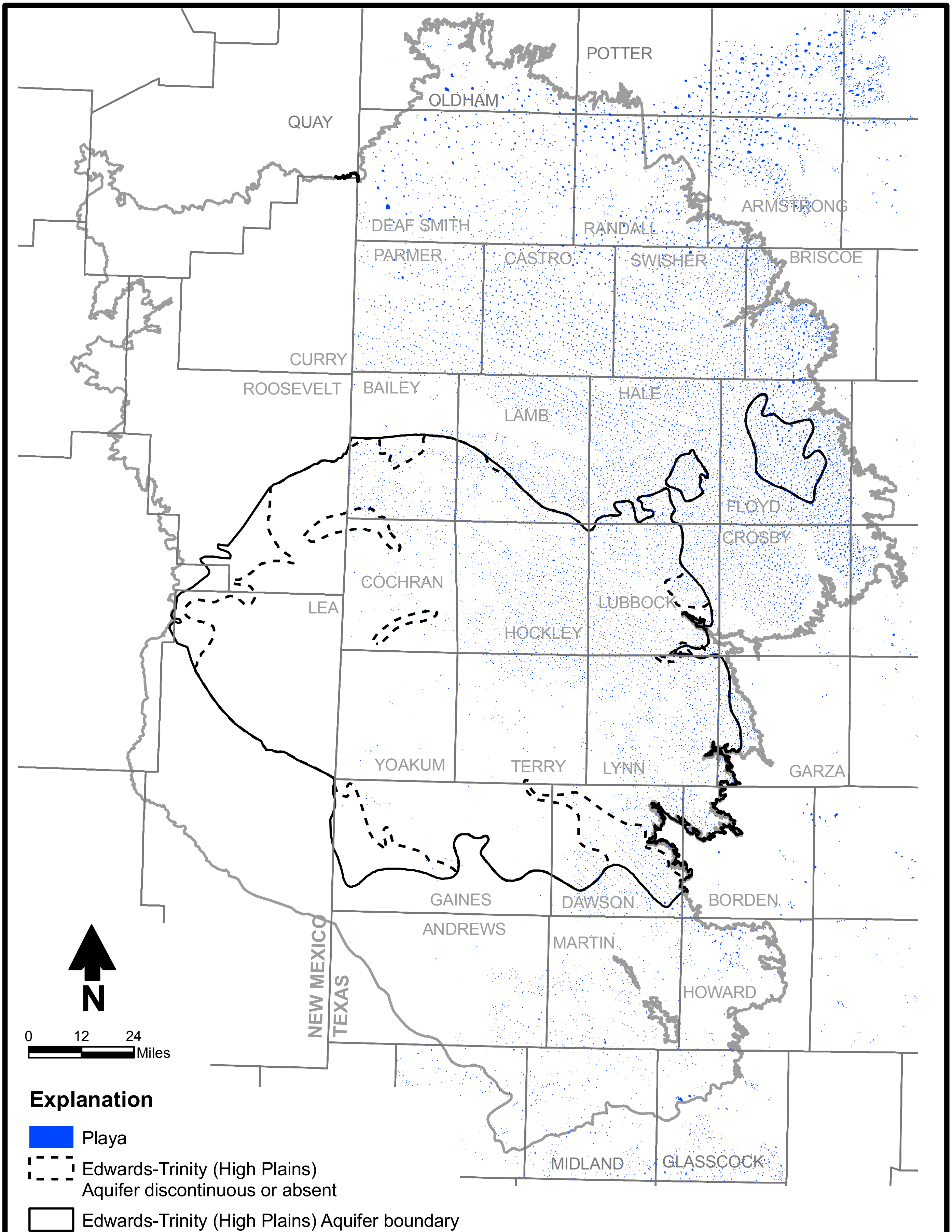
Figure 4



EDWARDS-TRINITY (HIGH PLAINS) GAM

Physiographic Provinces

Figure 5



EDWARDS-TRINITY (HIGH PLAINS) GAM

Playas in Texas Portion of Study Area

Figure 6

The Southern High Plains is bordered to the west by the Pecos River Valley and to the east by the Osage Plains (called the Rolling Plains on some physiographic maps). The erosional retreat of the High Plains Caprock Escarpment to the east and west and the incision of the Canadian and Pecos Rivers were strongly influenced by dissolution of buried Permian salt beds (Gustavson and Finley, 1985). The eastern escarpment is more eroded and incised than the western escarpment, indicating the influence of greater sapping effects of groundwater (Reeves and Reeves, 1996; Wood, 2002).

Land surface elevations range from over 5,000 feet above mean sea level (ft-MSL) in the far northwestern portion of the study area in Quay County, New Mexico to less than 2,500 ft-MSL in eastern Howard County, Texas. The regional slope of the land surface is approximately 100 feet per mile in a southeasterly direction (fig. 7).

The general distribution of soils within the study area is provided in Figure 8. The lowest-permeability soils (those that contain significant proportions of clay and silt) occur in the northern third of the study area in Texas, while the higher-permeability soils (primarily sand and silt loams) occur in the southern two thirds of the study area in Texas and throughout most of New Mexico.

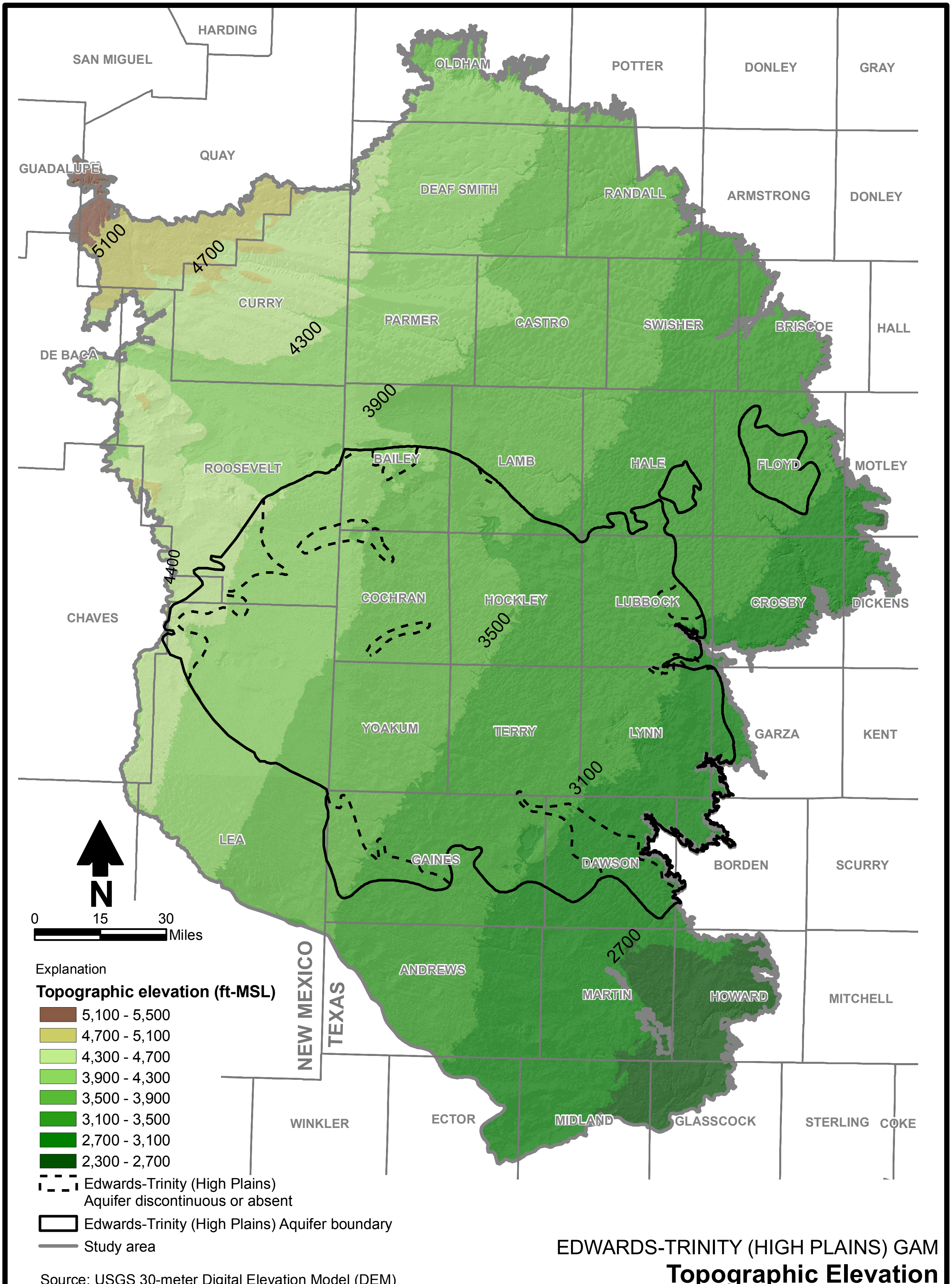
The study area is contained almost entirely within a Continental Steppe climate designation Figure 9. Average annual precipitation ranges from more than 21 inches per year (in/yr) in eastern portions of the Edwards-Trinity (High Plains) Aquifer to less than 17 in/yr in the western portion of the aquifer area (fig. 10). Observed average monthly precipitation at several climate stations is provided in Figure 11. About 80 percent of the average annual precipitation occurs during May through October (LERWPG, 2001), with peak monthly rainfall often occurring in June, September, and October.

Mean annual temperatures in the Edwards-Trinity (High Plains) Aquifer area range from 59 degrees Fahrenheit in the northeast to 64 degrees Fahrenheit in the southeast (fig. 12). Average annual lake evaporation ranges from approximately 61 in/yr in the far northwestern portion of the Edwards-Trinity (High Plains) Aquifer to about 73 in/yr in the far south-central portion of the aquifer (fig. 13). Peak evaporation occurs during the months of June, July, and August, with the highest evaporation occurring in July.

2.2 Geology

The regional geologic structure beneath and adjacent to the study area is illustrated in Figure 14). Also illustrated in Figure 14 are the locations of two regional geologic cross sections (A to A' and B to B') presented in Figure 15 to illustrate regional geological and structural features. A stratigraphic column with corresponding hydrogeologic unit descriptions and designations is provided in Table 1.

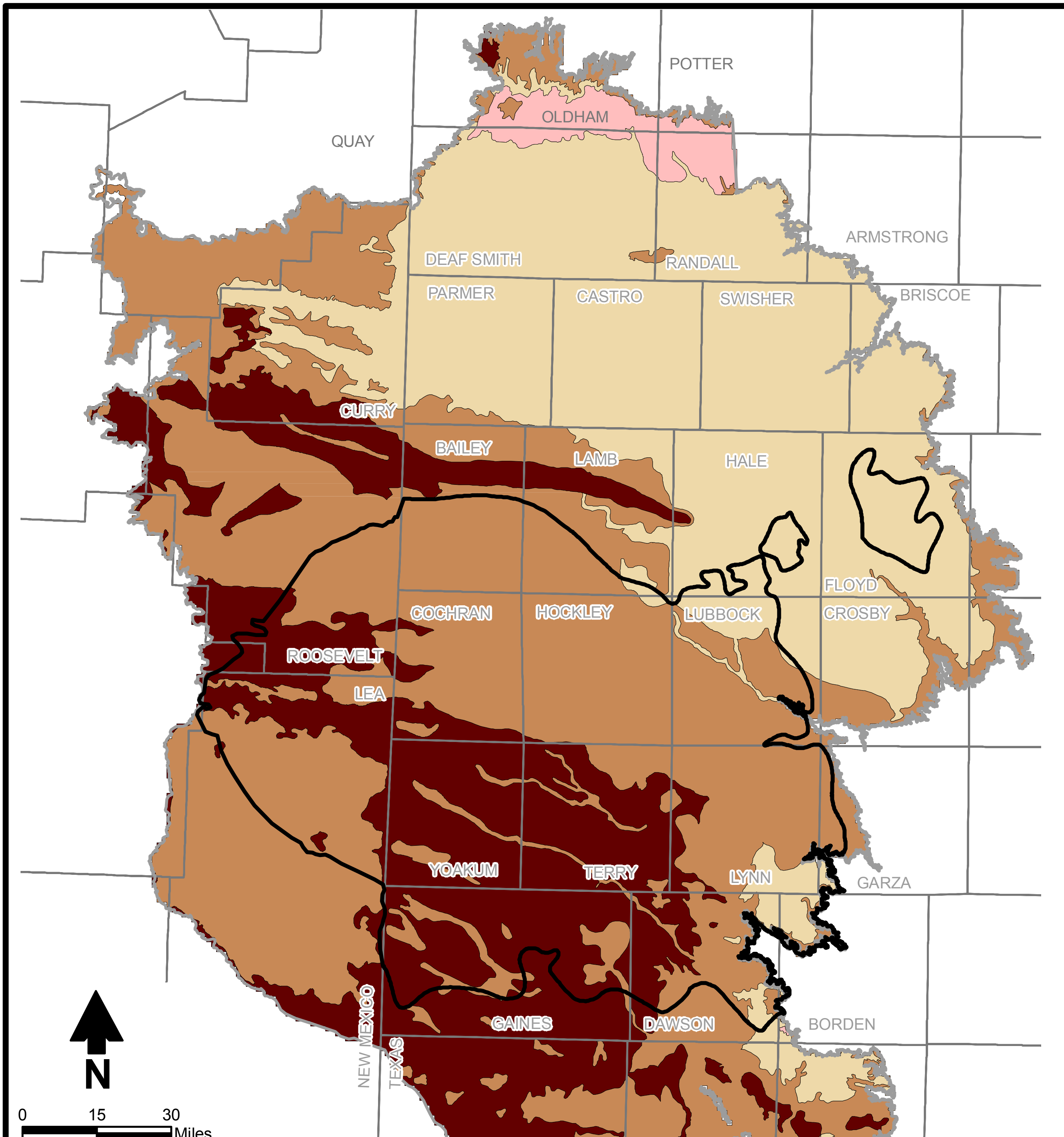
The study area includes several Paleozoic structural elements, basins that subsided and were filled in with sediment from 570 million to 245 million years ago (Dutton and others, 1982; Bassett and Bentley, 1983). The basins are separated by structurally positive areas, including arches and platforms, that did not subside to the same extent as the basins.



EDWARDS-TRINITY (HIGH PLAINS) GAM

Topographic Elevation

Figure 7



Explanation

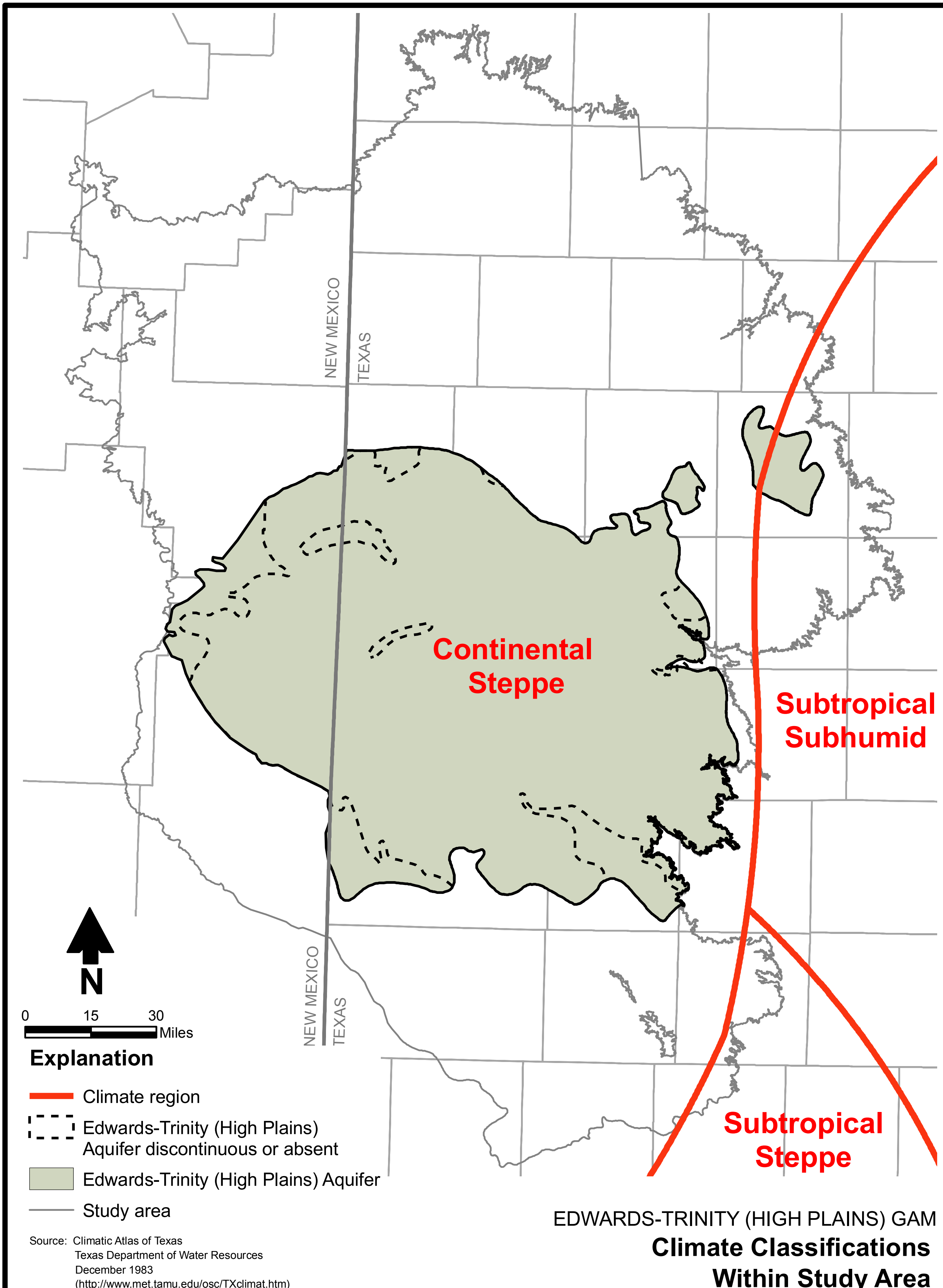
- Edwards-Trinity (High Plains) Aquifer boundary
- Study area
- High (sand, fine sand, loamy sand, loamy fine sand)
- Medium-high (sandy loam, fine sandy loam, sandy clay loam, loam, very gravelly loam)
- Medium-low (silt loam, silt, clay loam, clay)
- Low (sandy clay, silty clay loam, silty clay)

Source: Derived from U.S. Department of Agriculture, Soil Conservation Service, State Soil Geographic (STATSGO) database for Texas and New Mexico (1994)

EDWARDS-TRINITY (HIGH PLAINS) GAM

Generalized Soil Groupings

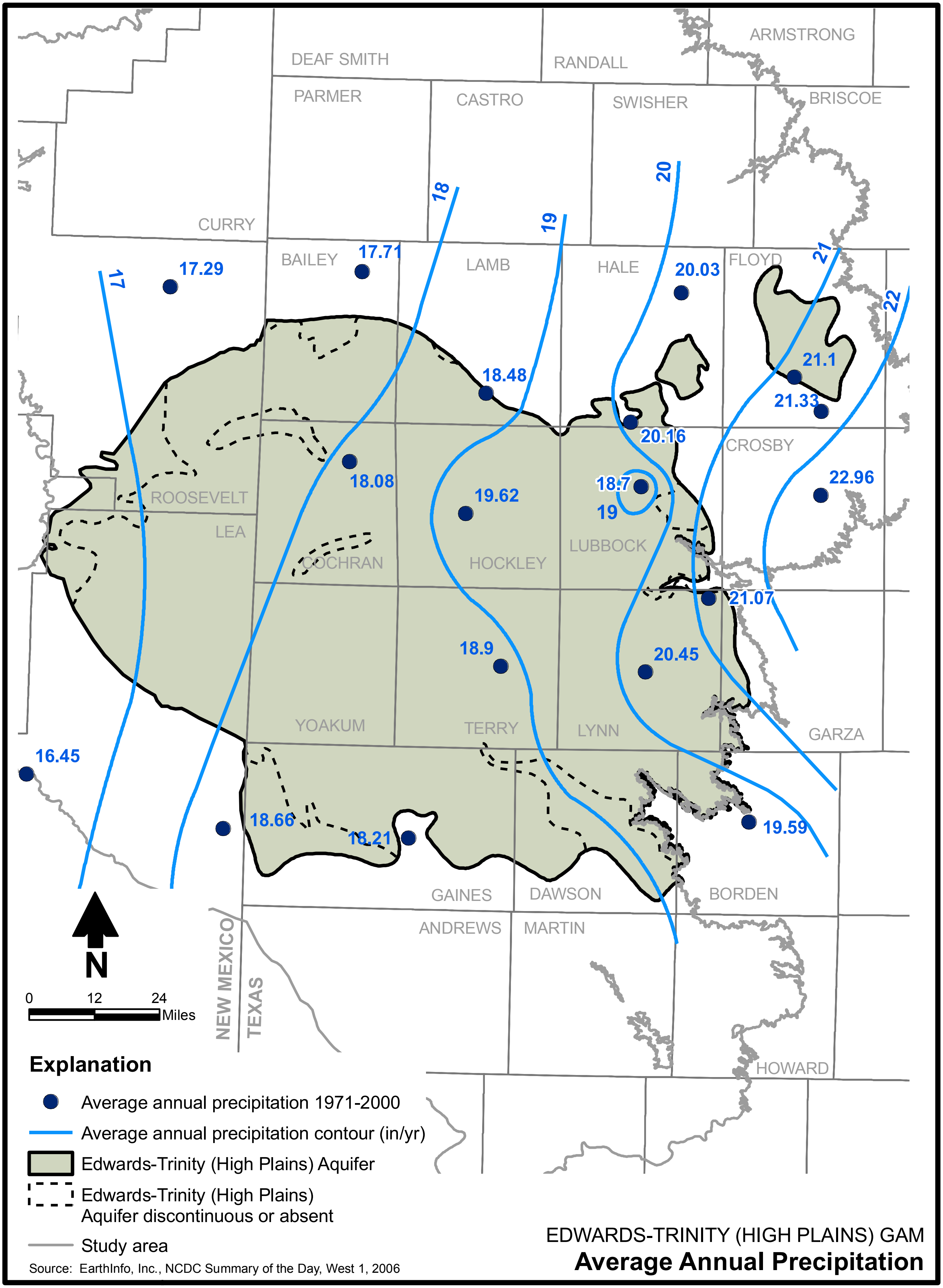
Figure 8



EDWARDS-TRINITY (HIGH PLAINS) GAM

Climate Classifications Within Study Area

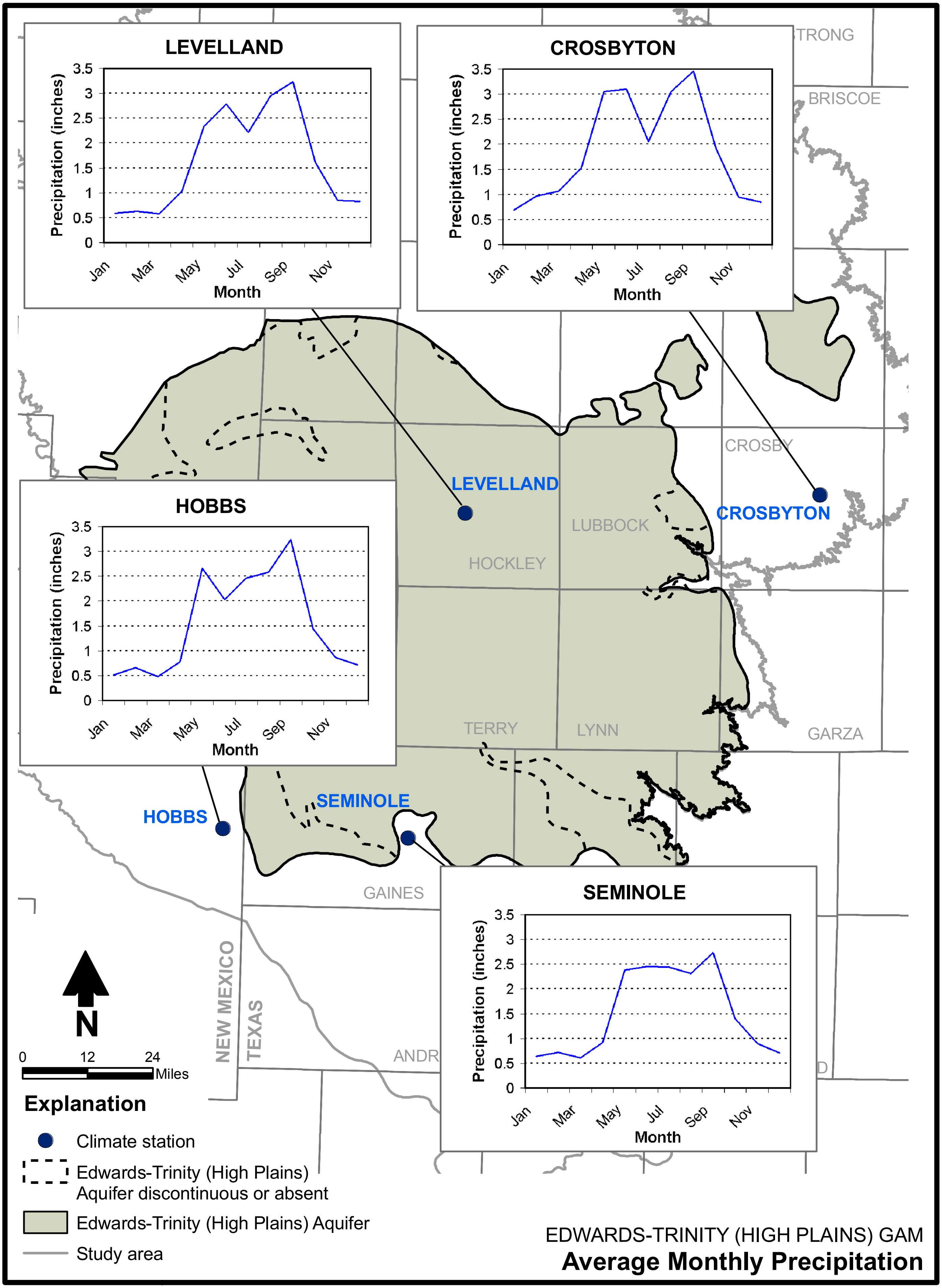
Figure 9



EDWARDS-TRINITY (HIGH PLAINS) GAM

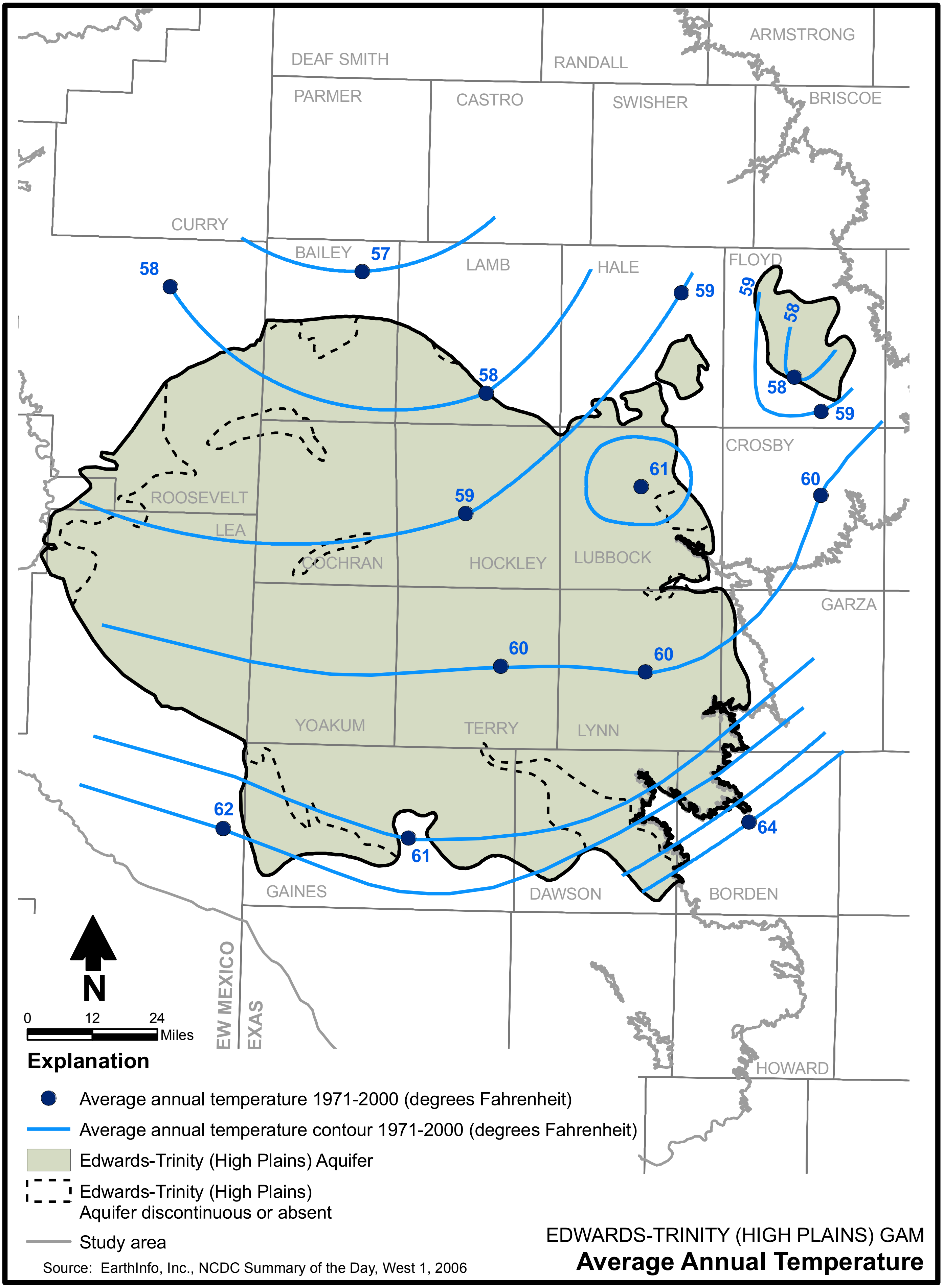
Average Annual Precipitation

Figure 10



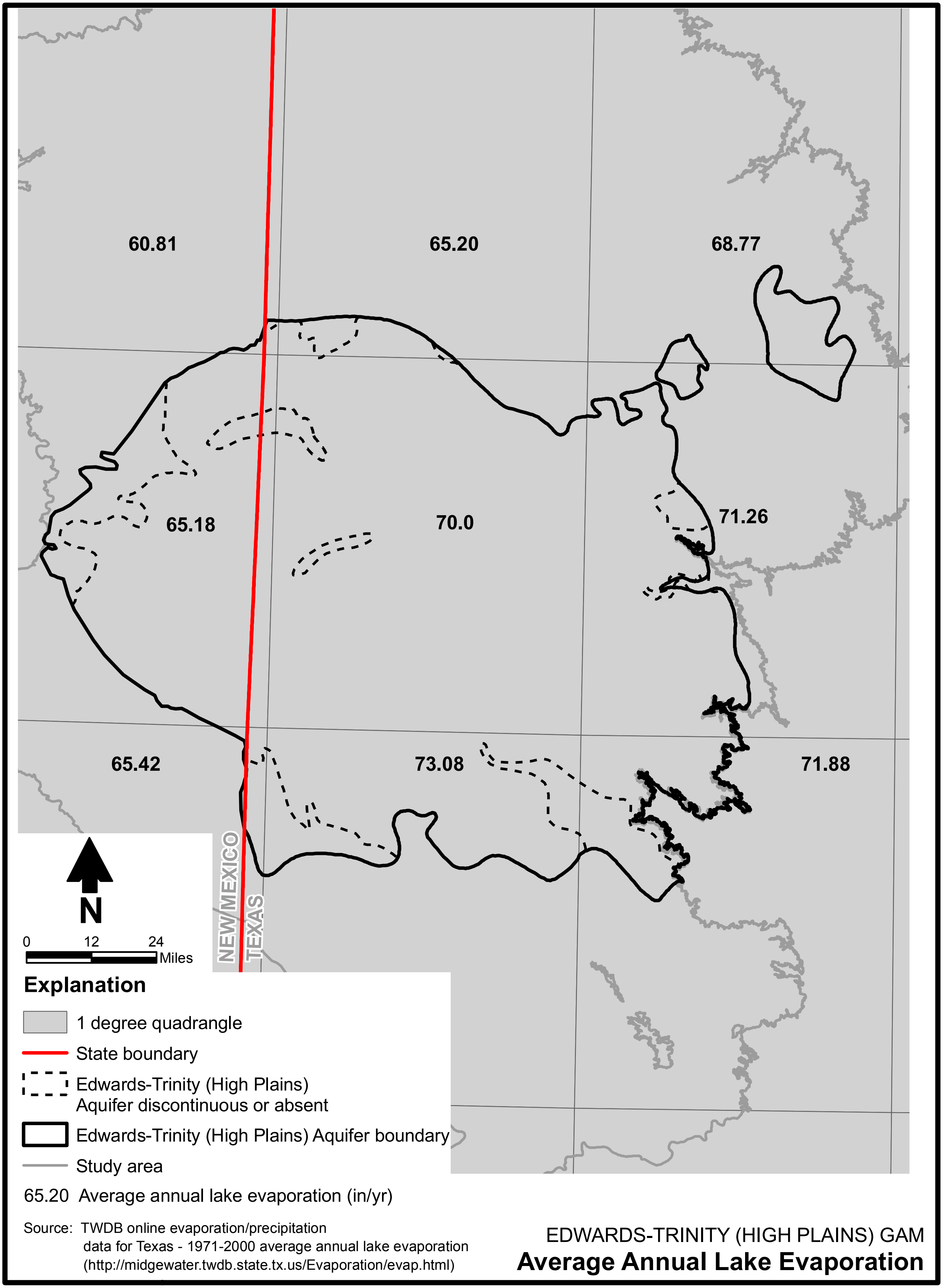
EDWARDS-TRINITY (HIGH PLAINS) GAM
Average Monthly Precipitation

Figure 11



EDWARDS-TRINITY (HIGH PLAINS) GAM
Average Annual Temperature

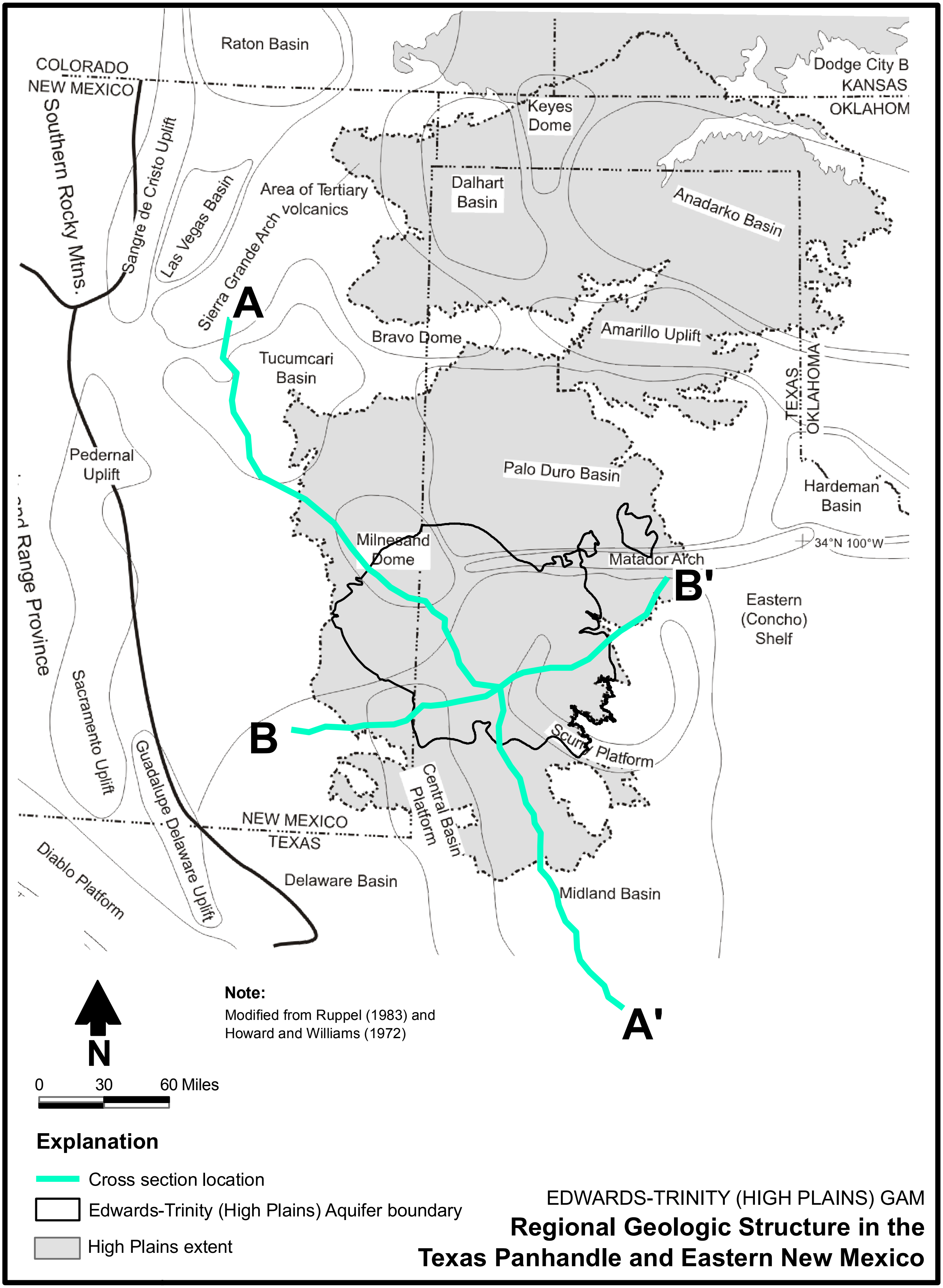
Figure 12



EDWARDS-TRINITY (HIGH PLAINS) GAM

Average Annual Lake Evaporation

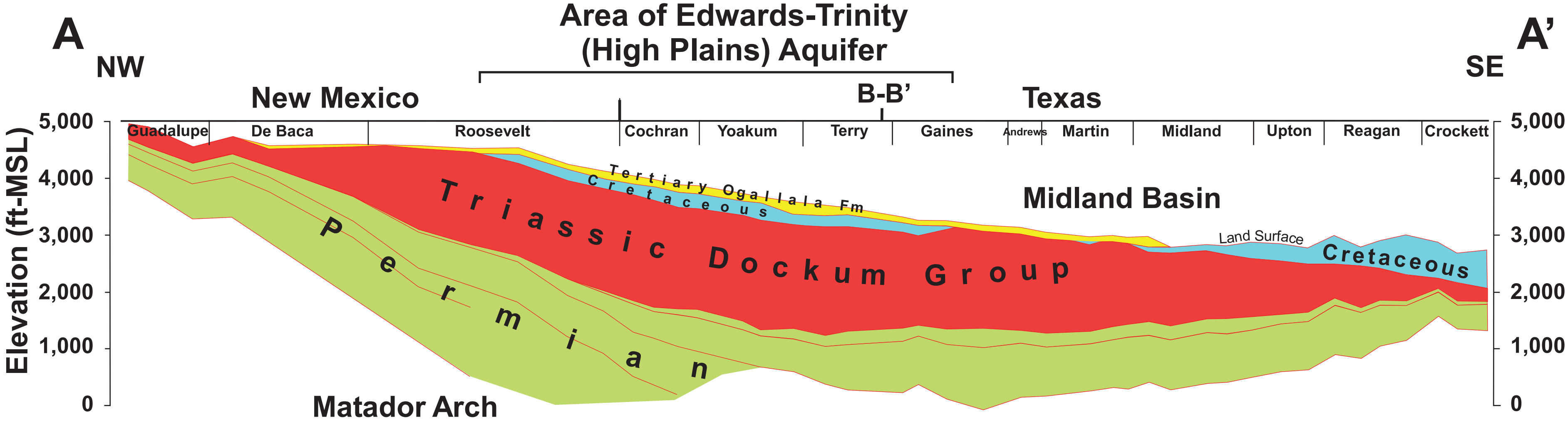
Figure 13

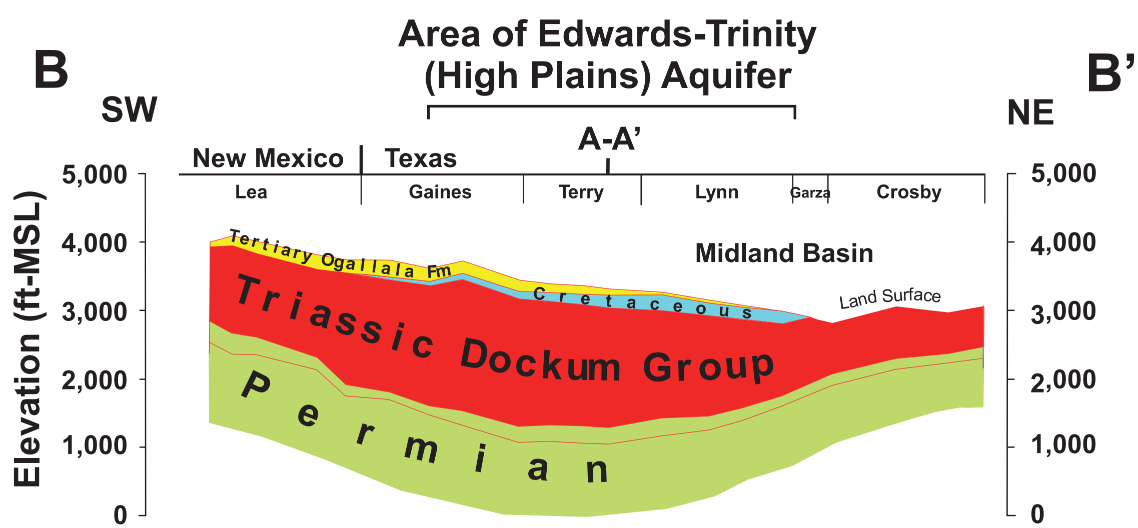


EDWARDS-TRINITY (HIGH PLAINS) GAM

Regional Geologic Structure in the Texas Panhandle and Eastern New Mexico

Figure 14





Note: Locations of cross sections shown on Figure 14.

EDWARDS-TRINITY (HIGH PLAINS) GAM

Geologic Cross Sections A-A' and B-B'

Figure 15

Table 1. Summary of Geologic and Hydrogeologic Units

System	Group	Formation	Geologic Description	Hydrogeologic Description	Hydrogeologic Units
Quaternary		Alluvium, eolian and lacustrine deposits	Sand, clay, silt, caliche, and gravel.	Generally yields small amounts of water to wells; may yield large amounts of water along stream valleys of Edwards Plateau.	Ogallala Aquifer
Tertiary		Ogallala	Tan, yellow, and reddish brown silt, clay, sand, and gravel. Caliche layers common near the surface.	Yields moderate to large amounts of water to wells across Southern High Plains. Yields small to moderate amounts of water in Andrews, Martin, Howard, Ector, Midland and Glasscock Counties.	
Cretaceous	Washita	Duck Creek	Yellow, sandy shale and thin gray to yellowish brown argillaceous limestone beds.	Yields small amounts of water locally to wells.	Aquitard
	Fredericksburg	Kiamichi	Gray to yellowish brown shale with thin interbeds of gray argillaceous limestone and yellow sandstone.	Yields small amounts of water locally to wells.	
		Edwards	Light gray to yellowish gray, thick to massive bedded, fine- to coarse-grained limestone.	Generally yields fairly small amounts of water to wells beneath Southern High Plains, but may yield large amounts of water locally due to fractures and solution cavities.	Edwards-Trinity (High Plains) Aquifer
		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.	Not known to yield water to wells.	
	Trinity	Antlers	White, gray, yellowish brown to purple, argillaceous, loosely cemented sand, sandstone, and conglomerate with interbeds of siltstone and clay.	Yields small to moderate amounts of water to wells.	
Triassic	Dockum	Chinle	Red, maroon to purple shale. Thin, discontinuous beds of sand and silt.	May yield small amounts of water to wells. Commonly known as “red beds”.	Aquitard
		Santa Rosa	Multi-colored fine- to coarse-grained micaceous sandstone with some claystone and shale interbeds.	Yields moderate amounts of water to wells.	Dockum
		Tecovas	Red to red-brown shale with fine-grained micaceous sand.	Not known to yield water to wells.	

Source: Adapted from Fallin, 1989; Walker, 1979; and Knowles and others, 1984

By the end of the Paleozoic Period, basins in the region of the study area were largely filled in. There was a gradational change from coastal marine to continental environments in the early Triassic Period, but the area remained near sea level (McGowen and others, 1979; Lucas, 2001). During the Cretaceous Period, the study area was flooded by seawater and was part of a seaway that ran north to south across the center of the North American continent.

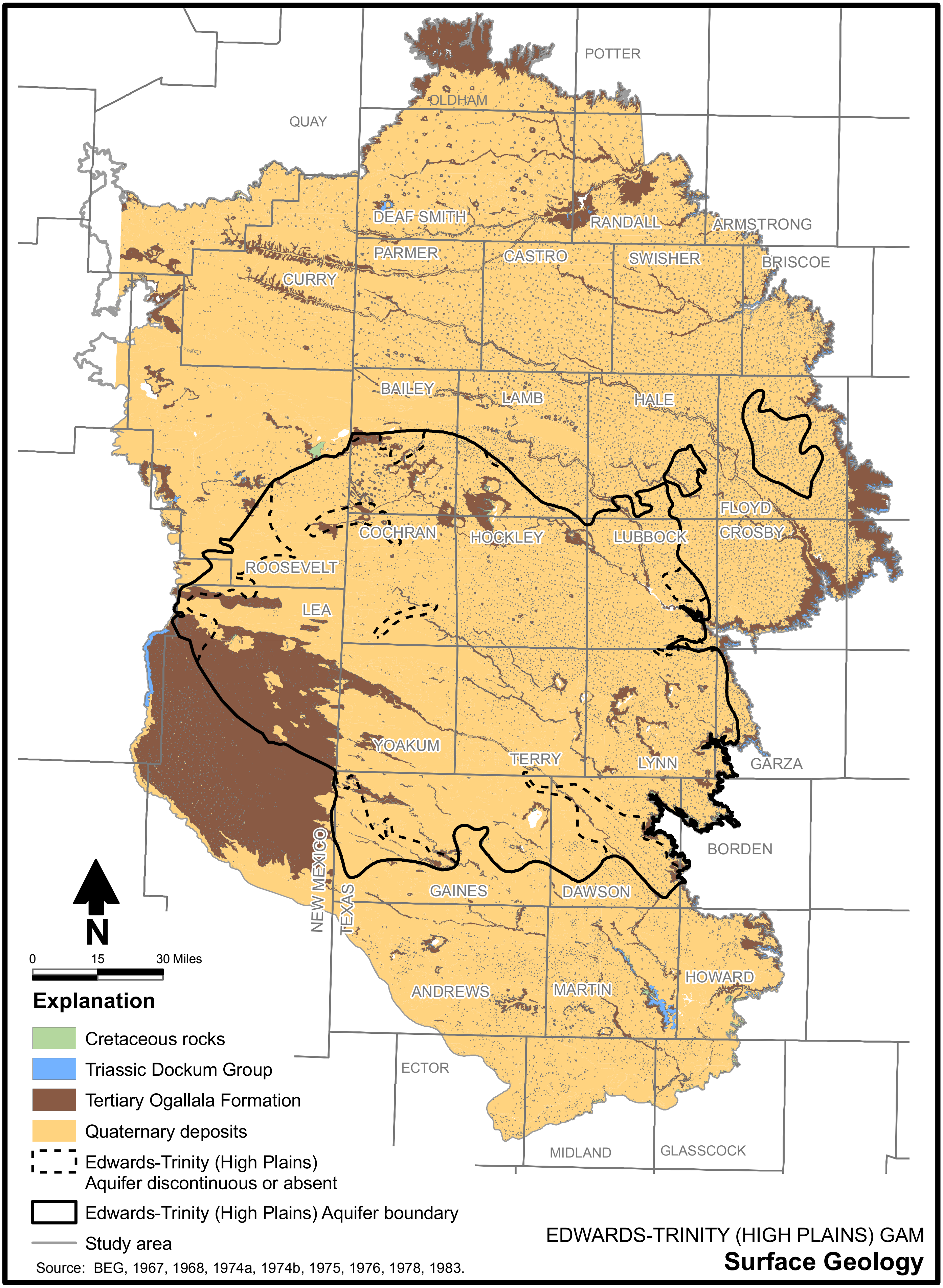
At the end of the Cretaceous Period, rise of the southern Rocky Mountains resulted in some uplift and eastward tilting of the area. During the Tertiary Period, the Ogallala Formation was deposited from sediments eroded from the southern Rockies. Additional uplift occurred during the Basin and Range tectonic event of the late Tertiary Period (Senger, 1991).

Figure 16 illustrates the surficial geology of the study area. Figure 16 is based on the digital versions of the Geologic Atlas of Texas maps compiled by the Texas Bureau of Economic Geology (BEG) that cover the study area (BEG, 1967, 1968, 1974a, 1974b, 1975, 1976, 1978, 1983). The study area is underlain mainly by the Tertiary Ogallala Formation and the Quaternary Blackwater Draw and Tule Formations. The Ogallala Formation ranges in thickness from 0 to more than 500 feet and consists of fluvial gravel, sand, and silt, and eolian sand and silt. Although the Ogallala Formation in areas north of Texas is subdivided into several members, the Texas section is not formally divided. The uppermost section of the Ogallala Formation is marked by several widespread calcretes and local silcretes, which form an erosion-resistant caprock.

The source of the Ogallala sediments within the study area has been interpreted as the Rocky Mountains to the northwest (e.g., Seni, 1980). Depositional environments of the Ogallala Formation have been interpreted as including coalescing alluvial fans or alluvial aprons (Johnson, 1901; Frye and Leonard, 1964; Seni, 1980; Reeves, 1984) or fluvial-dominated valley fill sequences confined within paleovalleys (Gustavson, 1996). In Texas, there are three major paleovalley systems, named the Panhandle, Clovis, and Slaton channels (Gustavson, 1996). In the lower part of the Ogallala, coarse fluvial sediments are concentrated along the major paleovalleys, and finer sediments are concentrated between channel axes. Within the study area, the paleovalleys are defined by a complex erosional surface that formed on the top of the lower Cretaceous geologic section or Triassic sediments, depending on location.

Gustavson and Winkler (1988) also identified a significant eolian component of the Ogallala Formation. Fluvial deposits of sand and gravel deposited in paleovalleys dominate the lower part of the Ogallala, while coeval eolian deposits dominate the drainage divides. Ogallala Formation lacustrine and eolian deposits subsequently blanketed the entire area. Gustavson (1996) interpreted the source of the eolian "cover sands" of the Quaternary Blackwater Draw and Tule Formations to be the Pecos and Canadian river valleys. The saturated part of the Ogallala Formation includes the predominantly coarse-grained basal part of the formation. Most of the fine-grained deposits in the upper Ogallala Formation lie above the water table.

Within a region of about 9,000 mi^2 in the central portion of the study area, the Ogallala Formation unconformably overlies Cretaceous formations (Gutentag and others, 1984; Knowles and others, 1984). The Cretaceous rocks make up the Edwards-Trinity (High Plains) minor aquifer (Nativ and Gutierrez, 1988; Ashworth and Hopkins, 1996). The Cretaceous section is as much as 250 feet thick and consists of up to six geologic formations:



POTTER
OLDHAM
QUAY
DEAF SMITH
RANDALL
ARMSTRONG
PARMER
CASTRO
SWISHER
BRISCOE
CURRY
BAILEY
LAMB
HALE
FLOYD
CROSBY
COCHRAN
HOCKLEY
LUBBOCK
ROOSEVELT
LEA
YOAKUM
TERRY
LYNN
GARZA
BORDEN
NEW MEXICO
TEXAS
GAINES
DAWSON
ANDREWS
MARTIN
HOWARD
ECTOR
MIDLAND
GLASSCOCK
N
0
15
30 Miles
Explanation
Cretaceous rocks
Triassic Dockum Group
Tertiary Ogallala Formation
Quaternary deposits
Edwards-Trinity (High Plains) Aquifer discontinuous or absent
Edwards-Trinity (High Plains) Aquifer boundary
Study area
Source: BEG, 1967, 1968, 1974a, 1974b, 1975, 1976, 1978, 1983.
EDWARDS-TRINITY (HIGH PLAINS) GAM
Surface Geology

Figure 16

- The Duck Creek and Kiamichi Formations are composed primarily of shale, but may also include thin interbeds of limestone or sandstone.
- The Edwards Formation consists of thick to massive bedded fine to coarse-grained limestone.
- The Comanche Peak Formation is composed primarily of argillaceous limestone with thin interbeds of shale.
- The Walnut Formation consists of sandstone, shale, and limestone.
- The Antlers Formation (Antlers Sand) consists of loosely cemented sand, sandstone, or conglomerate, often white or purple.

The Cretaceous rocks probably remain in this central area of the Southern High Plains because they were protected from more severe erosion due to their location within a structural basin (fig. 15).

The Cretaceous rocks that compose the Edwards-Trinity (High Plains) Aquifer are underlain by Triassic-age rocks of the Dockum Group, which were deposited in fluvial, deltaic, and lacustrine environments (McGowen and others, 1977, 1979). In portions of the study area that do not contain Cretaceous rocks, the Ogallala Formation lies unconformably on the Dockum Group. The Triassic section can be as much as 2,000 feet thick, and its low-permeability sediments in the upper portion of the section separate groundwater in the Southern Ogallala and Edwards-Trinity (High Plains) Aquifers from groundwater in Triassic sandstone units, referred to as the Dockum Aquifer.

2.3 Data Collection and Analysis

A significant amount of geologic and hydrogeologic information was collected specifically for this study. More than 1,900 drillers' reports and geophysical logs were collected to assist with construction of the stratigraphy of the Edwards-Trinity (High Plains) Aquifer. The geophysical logs were selected through a review of the BEG geophysical log database. Approximately 250 geophysical logs with good geographic distribution across the Edwards-Trinity (High Plains) Aquifer were initially obtained. Each log was reviewed for starting depth, types of geophysical log runs, and log quality. This process led to the selection of 111 geophysical logs for application during study. A site visit was also made to each of the groundwater districts in the study area to discuss data needs and availability and to obtain available geophysical logs, datasets, and/or drillers' reports to supplement sparse information in some areas.

The majority of the data were obtained at the Texas Commission on Environmental Quality (TCEQ) file room, where folders were pulled for each of the approximately 1,600 state well grid cells that cover the Edwards-Trinity (High Plains) Aquifer. Each driller's report within each folder (more than 10,000 drillers' reports) was reviewed, and an attempt was made to select at least one drillers' report from each state grid cell that penetrated the Cretaceous section, and in some cases two or three reports were pulled. Drillers' reports were selected using the best combination of the following criteria: data for wells that penetrated the Cretaceous and preferably the Dockum Formation (red beds), and detailed geologic description, location information, pump test data, screen interval, and water level information. Approximately 5,000 drillers' reports were copied and re-evaluated for usefulness. The second evaluation led to the selection of approximately 1,800 drillers' reports for consideration during this study. Each driller's report and geophysical log was stamped with a unique tracking number. Final data points in the database are illustrated in Figure 17.

In addition to the above data, locations and/or maps from various published BEG and TWDB reports were captured electronically and georeferenced in ArcGIS and used as guides to the interpretation and construction of three stratigraphic layers as follows:

- Duck Creek and Kiamichi clay and shales
- Edwards, Comanche Peak and Walnut Formations
- Antlers Formation

Key reports considered include Brand (1952), Knowles and others (1984), McGowen and others (1977), Fallin (1989), and Geologic Atlas of Texas (GAT) sheets (BEG, 1967, 1968, 1974a, 1974b, 1975, 1976, 1978, 1983).

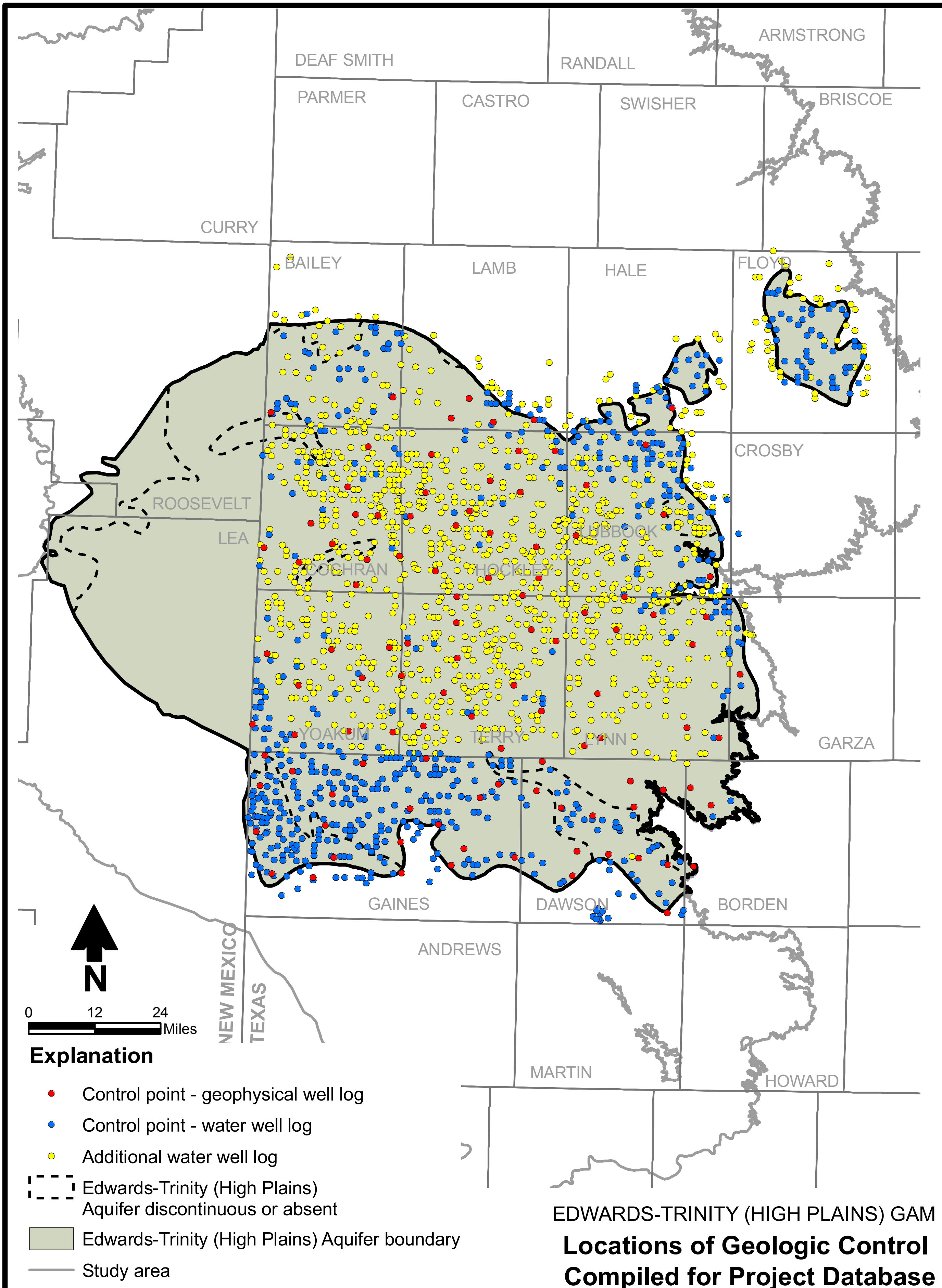
2.4 Stratigraphic Interpretation

The 111 geophysical logs, in conjunction with information from the published reports listed above, were used to build a stratigraphic framework of the Edwards-Trinity (High Plains) Aquifer. The quality and level of detail of information available from each of the geophysical logs used in this study was variable. Typically, the upper 500 feet or so of an oil and gas geophysical log is not focused on geologic detail. All geophysical logs included gamma ray curves, and most had either resistivity or neutron log runs to enhance the interpretation of the stratigraphy. Subjective confidence levels were assigned to each layer top and base selections in the database.

Drillers' logs and other information from various reports (e.g., Leggat, 1952, 1957; Rettman and Leggat, 1966) were used to fill in key information within the basic geologic framework determined from the geophysical logs. The drillers' reports are also highly variable in the quality and level of detail of information. It was discovered that some of the state grid cells assigned by the TCEQ to drillers' reports were incorrect, and each location was checked and re-located if necessary using a combination of survey, road maps, and other location descriptions within the drillers' reports. An attempt was made to be consistent in the selection of layer tops and bottoms while considering possible lithologic or stratigraphic variations.

2.5 Cretaceous Geologic Cross Sections

Two geologic cross sections focused on the Ogallala Formation and Cretaceous rocks are presented in Figures 18 and 19. Figure 18 is a geologic cross section from northwest to southeast across the Edwards-Trinity (High Plains) Aquifer (dip section), while Figure 19 is a cross section from southwest to northeast across the Edwards-Trinity (High Plains) Aquifer (strike section).



EDWARDS-TRINITY (HIGH PLAINS) GAM

Locations of Geologic Control Compiled for Project Database

Figure 17

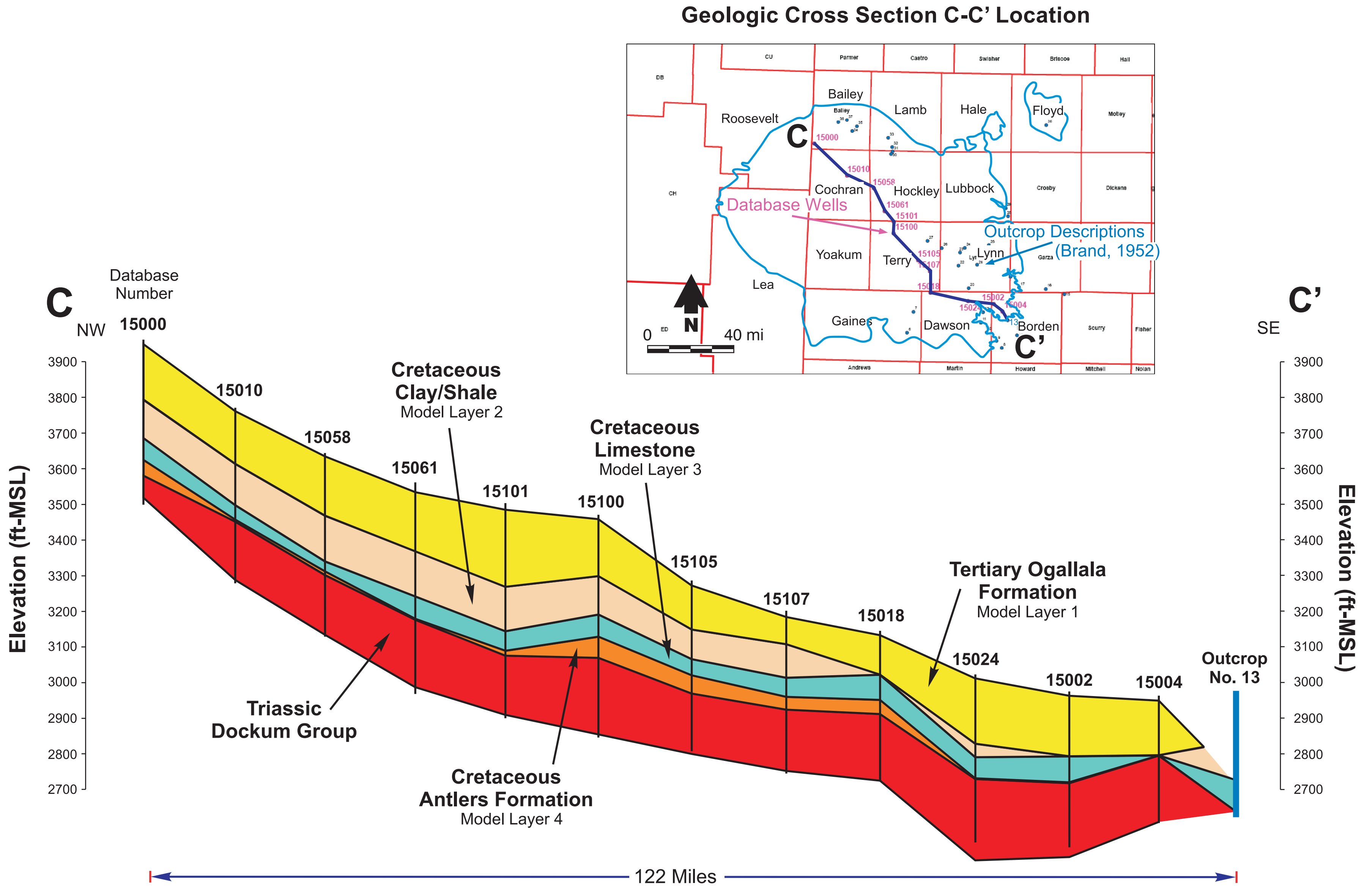
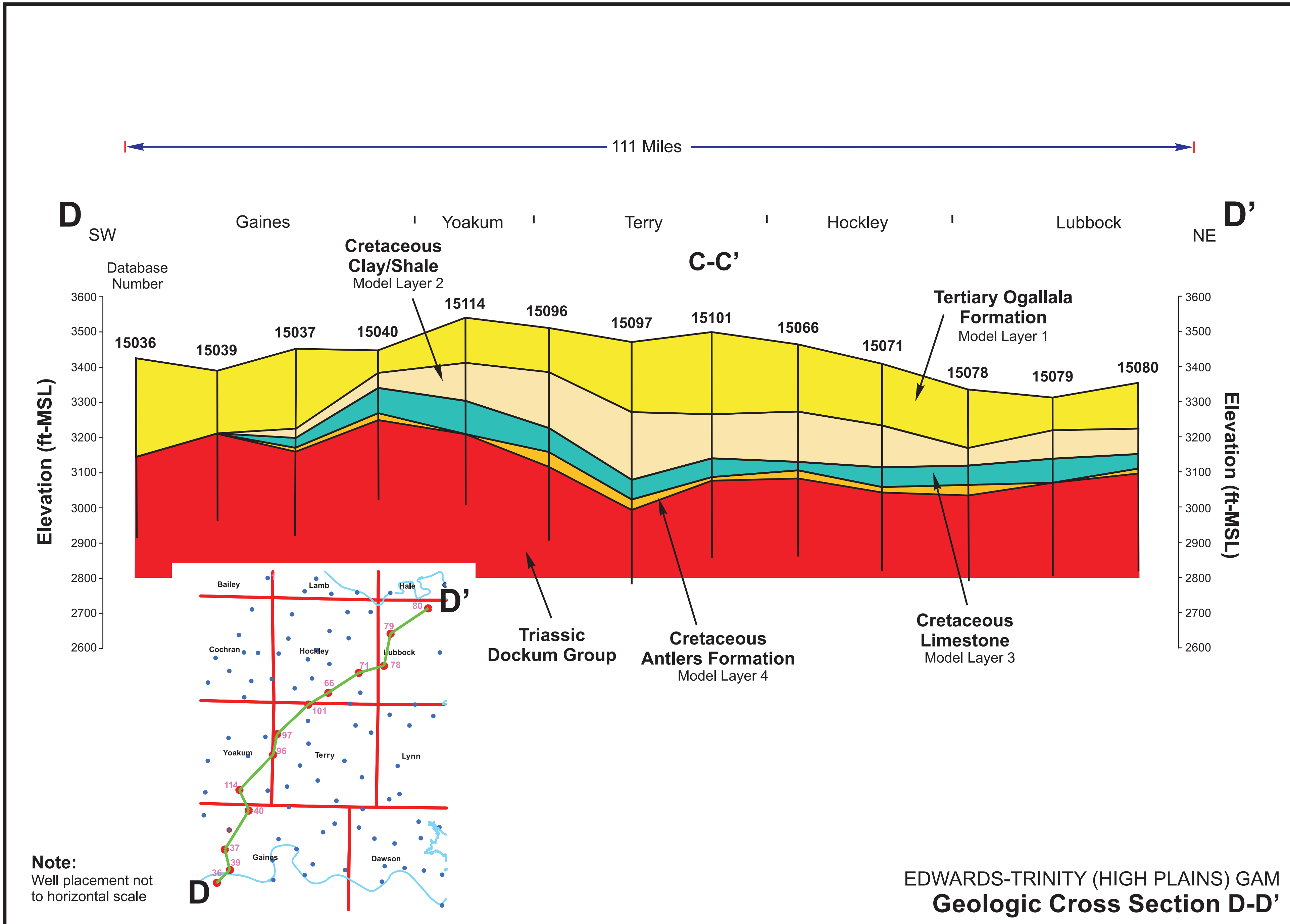


Figure 18

Note: Well placement not to horizontal scale

EDWARDS-TRINITY (HIGH PLAINS) GAM
Geologic Cross Section C-C'



EDWARDS-TRINITY (HIGH PLAINS) GAM

Geologic Cross Section D-D'

Figure 19

Each section illustrates the underlying topography of the top of the Dockum Group, the variable thickness of the three key stratigraphic layers selected to represent the Cretaceous rocks, and the variable thickness of the Ogallala Formation, all of which are key components of understanding the hydrogeology of the Edwards-Trinity (High Plains) Aquifer.

2.6 Edwards-Trinity (High Plains) Aquifer Extent

As a result of the data collection and analysis described above, a number of adjustments were made to the extent of the Edwards-Trinity (High Plains) Aquifer boundary currently used by the TWDB. Specifically, areas were identified within which geologic units that compose the Edwards-Trinity (High Plains) Aquifer were believed to be predominantly discontinuous or absent. These areas are marked as such (denoted by a dashed line) in numerous figures referenced in Sections 1 through 5. In the same series of figures, the solid line labeled as the Edwards-Trinity (High Plains) Aquifer boundary is the standard TWDB aquifer boundary.

Almost all of the figures introduced in Sections 6 through 9, and some figures introduced in earlier sections, refer to a "revised" Edwards-Trinity (High Plains) Aquifer boundary. This revised boundary is the aquifer boundary used during development of the Edwards-Trinity (High Plains) GAM and corresponds to the adjusted aquifer extent described above. All figures developed to illustrate GAM construction, calibration, or simulation results use the revised aquifer boundary.

3.0 Previous 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).

The most complete hydrogeological study of the Edwards-Trinity (High Plains) Aquifer to date was conducted by Fallin (1989). Nativ and Gutierrez (1988) were the first to consider the hydrogeology of the Cretaceous units beneath the Southern High Plains in detail.

4.0 Hydrogeologic Setting

This section describes the physical factors, either natural or man-made, that have a significant influence on groundwater flow in the aquifer. The hydrogeologic setting is based on (1) previous studies, some conducted as early as the 1930s, as referenced in the text, and (2) a significant database of geological and hydrogeological information collected and evaluated specifically for this study.

4.1 Hydrostratigraphy

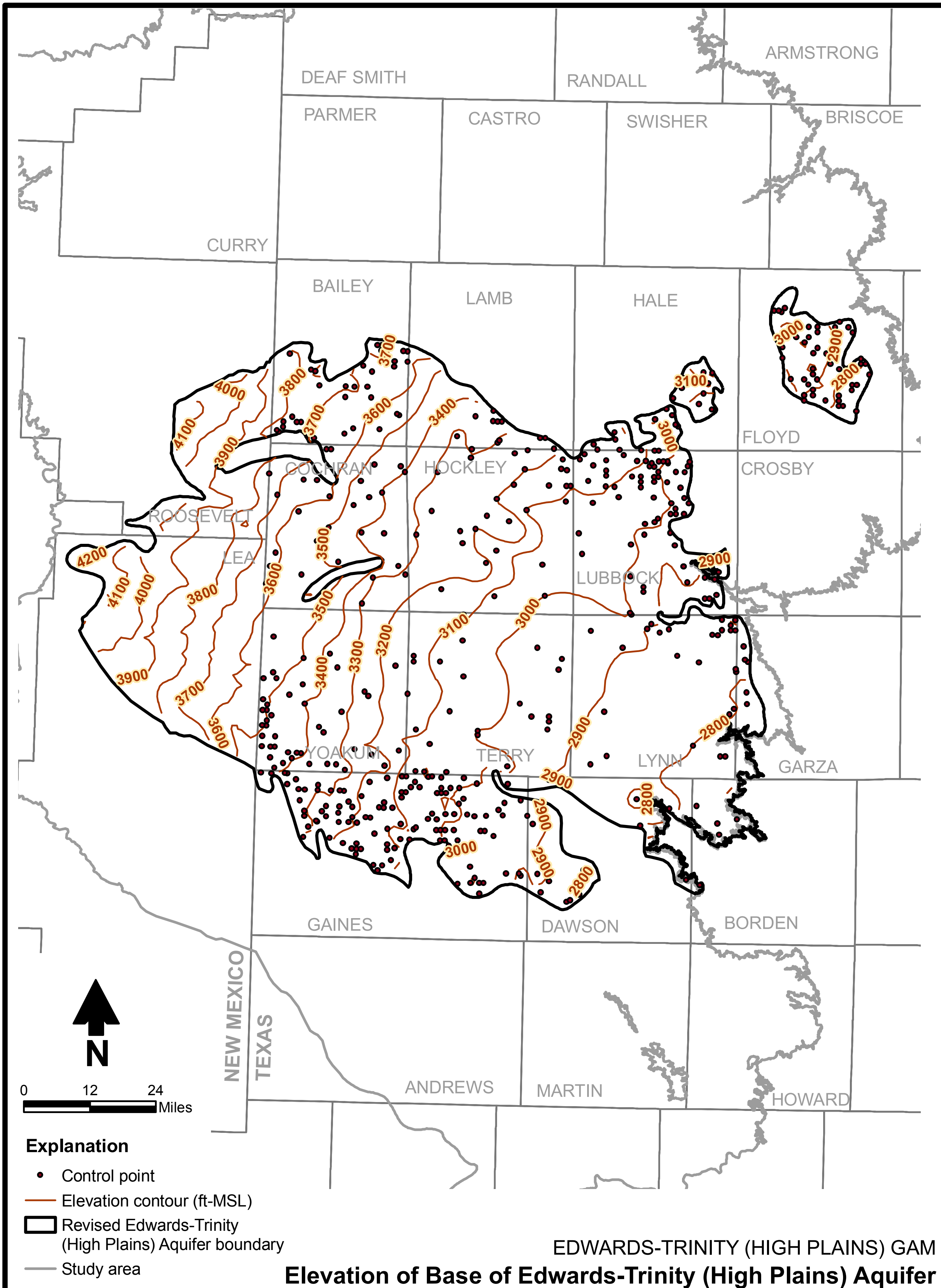
Table 1 illustrates the designation of hydrogeologic units in the study area and their correspondence to geology. Within the study area, geologic units that yield significant quantities of water to wells include the Ogallala Formation, the limestone of the Edwards and Comanche Peak Formations, and the Antlers Sand. Typically the Ogallala Formation is more productive than the Cretaceous aquifer units, but this is not always the case. The Duck Creek and Kiamichi Formations contain significant thicknesses of low-permeability sediments (e.g., clay) and generally function as aquitards that may confine groundwater in the lower Cretaceous rocks. The Walnut Formation may play a similar role and, where present, would tend to limit the vertical movement of water between the limestone units and the basal Antlers Sand.

The uppermost unit of the Triassic Dockum Group, the Chinle Formation, is a massive shale with some interbedded sandstones that typically yields only very small quantities of water to wells. This is the “red bed” unit that forms the base of either the Southern Ogallala Aquifer or the Edwards-Trinity (High Plains) Aquifer within the study area, depending on location.

4.2 Structure

Figures 20, 21, 22, and 23 illustrate the elevation of the base of Antlers Sand (equivalent to the base of the Edwards-Trinity [High Plains] Aquifer), the top of the Antlers Sand, the top of the predominantly limestone facies of the combined Comanche Peak and Edwards Formation, and the base of the Ogallala Formation, respectively. The control points used for computation are provided on each figure, with the exception of Figure 23 (which shows the base of the Ogallala Formation). This figure was developed using existing base of Ogallala Formation maps digitized from information provided by McReynolds (1996a through 1996o) and Knowles and others (1984) for the Southern Ogallala GAM (Blandford and others, 2003) for all Texas counties except Gaines and Dawson. For these two counties, the base of aquifer maps provided in Knowles and others (1984) included the Cretaceous rocks and the overlying Ogallala sediments. The base of the Ogallala Formation, therefore, was contoured for these counties using data collected as part of this study. The control points used to contour the base of the Ogallala Formation in Gaines and Dawson Counties are provided in Figure 23.

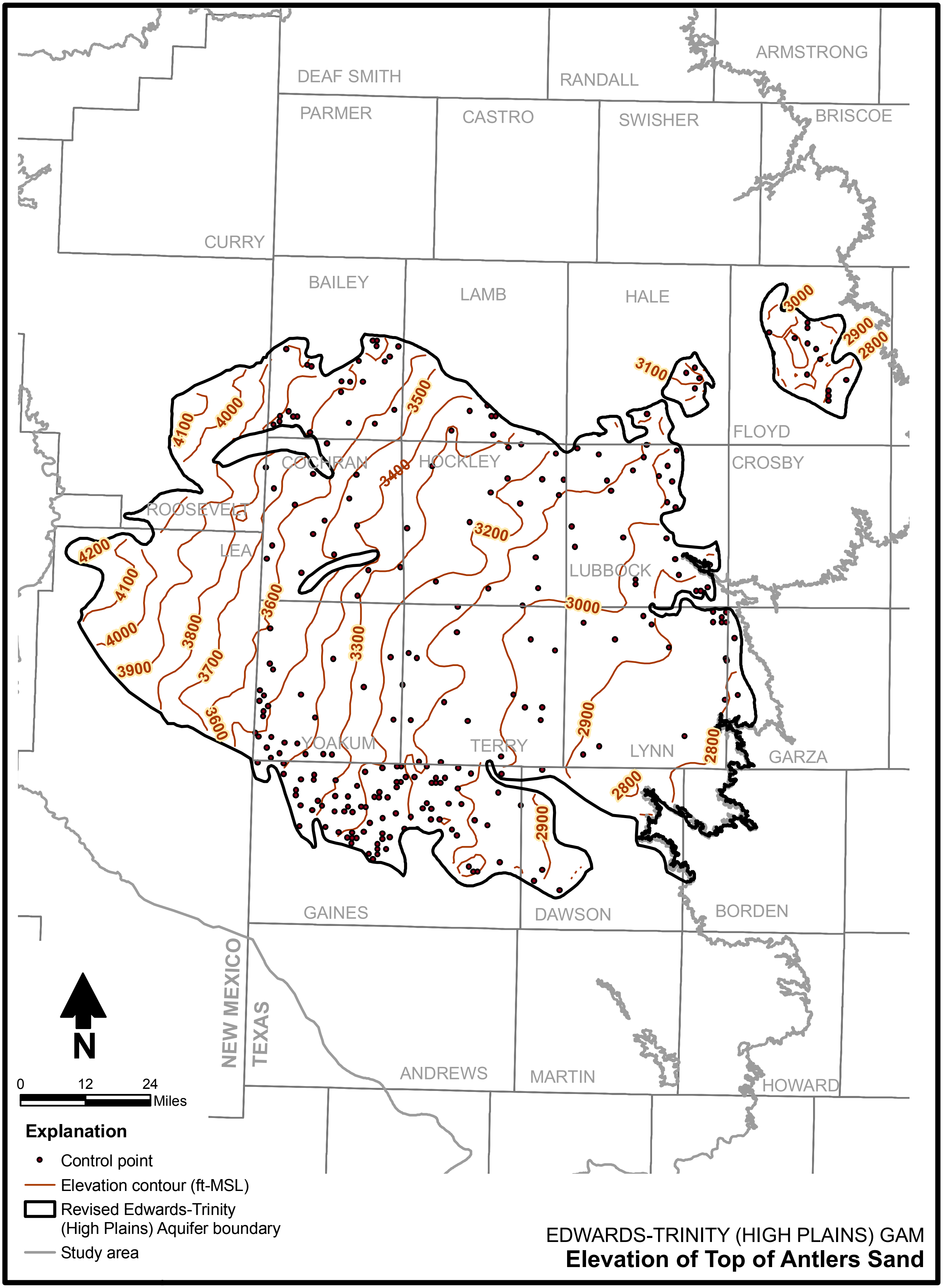
In Figures 20 through 23, the control points are for the Texas portion of the Edwards-Trinity (High Plains) Aquifer only. For the New Mexico portion of the aquifer, the working maps of Fallin (1989) obtained from the TWDB were digitized using scanned and georeferenced images. Fallin’s (1989) large-scale working maps could not be located for the Texas portion of the aquifer.



EDWARDS-TRINITY (HIGH PLAINS) GAM

Elevation of Base of Edwards-Trinity (High Plains) Aquifer

Figure 20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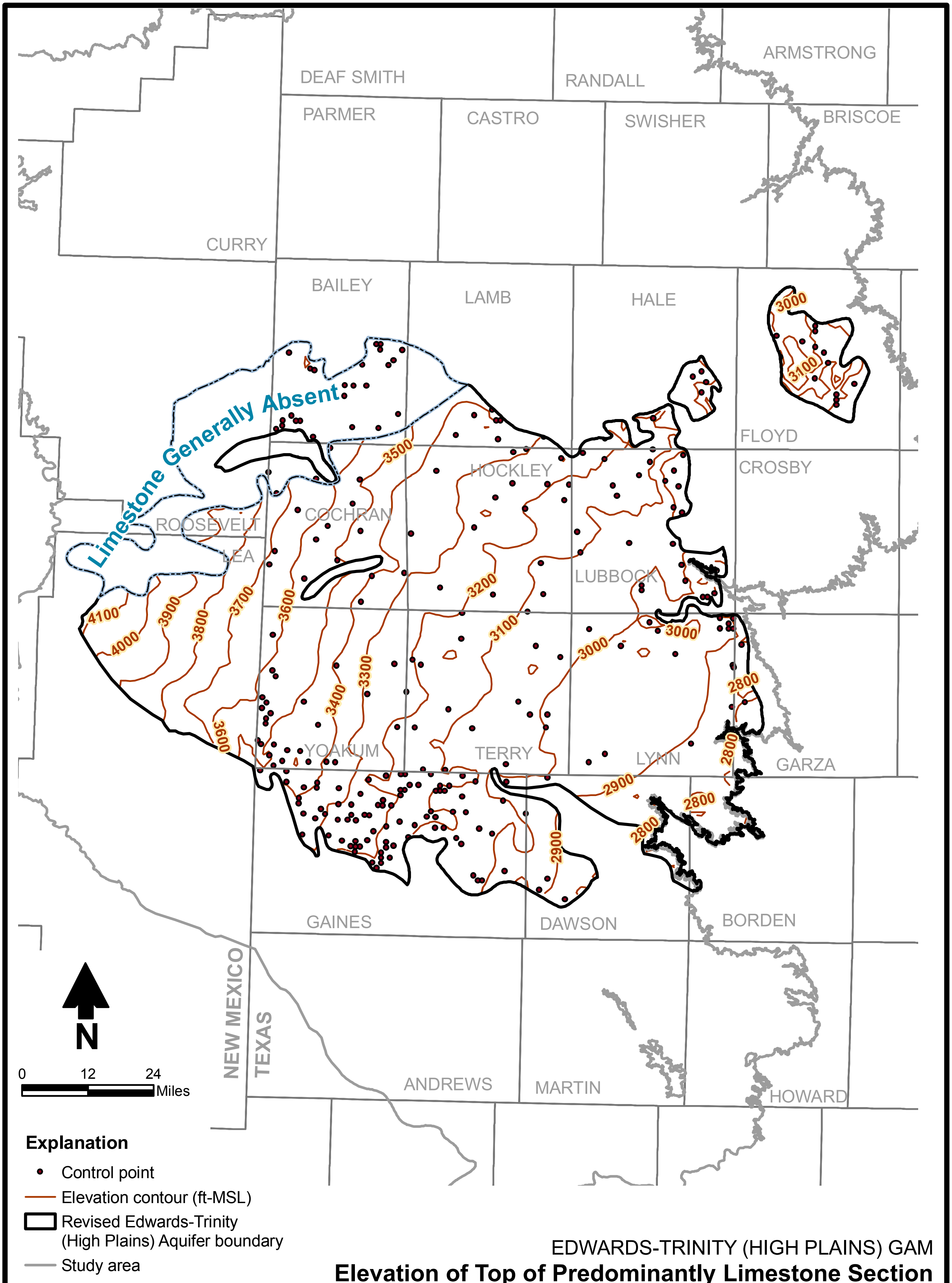
Miles
Explanation
Control point
Elevation contour (ft-MSL)
Revised Edwards-Trinity (High Plains) Aquifer boundary
Study area
EDWARDS-TRINITY (HIGH PLAINS) GAM
Elevation of Top of Antlers Sand

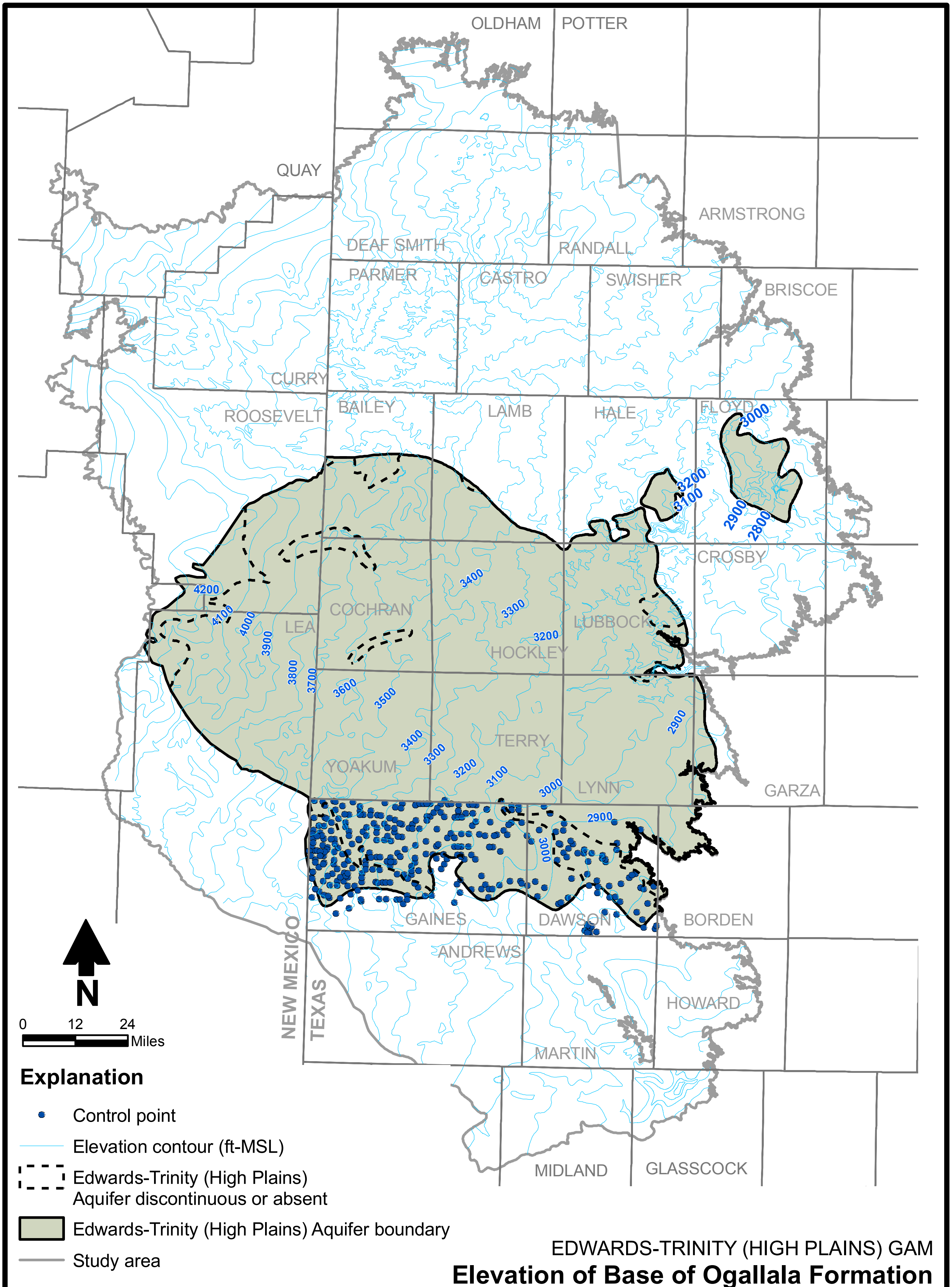
Figure 21



EDWARDS-TRINITY (HIGH PLAINS) GAM

Elevation of Top of Predominantly Limestone Section

Figure 22



EDWARDS-TRINITY (HIGH PLAINS) GAM

Elevation of Base of Ogallala Formation

Figure 23

The available information from the Fallin (1989) working maps included the base of the Antlers Sand, thickness of the Antlers Sand, thickness of the Cretaceous limestone, and base of the Ogallala Formation. This information was used to construct all of the necessary surfaces, with adjustments made as necessary near the state line for consistency with data and interpretations in the Texas portion of the study area. Limited adjustments were also made in New Mexico for physical reasonableness (e.g., layer thickness could not be negative) and for consistency with base of Ogallala Formation contours outside the Edwards-Trinity (High Plains) Aquifer extent. Also, in the far western extent of lower Cretaceous sediments in New Mexico, in Roosevelt and Chavez Counties, the Cretaceous shale is present, but the productive Cretaceous units (Antlers Sand and Cretaceous limestone) are generally absent (Fallin, 1989). The revised Edwards-Trinity (High Plains) Aquifer boundary, therefore, was moved east to exclude this region (see, for example, fig. 17).

Figures 20 through 23 illustrate the presence of a number of paleochannels that affect the elevation contours of each surface. The base of the Ogallala Formation surface (fig. 23) is the most complex one due to the greater number of data points available to contour the surface. The presence of numerous paleochannels beneath the Southern High Plains has been documented by many authors and is consistent with the geologic history of erosional surfaces on the top of the Dockum Group and the top of Cretaceous sediments. Paleochannels filled with Ogallala Formation sediments on the top of the Cretaceous rocks are primary sources of irrigation water and also indicate zones of preferred erosion that likely enhance hydraulic communication between Ogallala and Cretaceous sediments.

Figures 24, 25, and 26 illustrate the thickness of the Antlers Sand, the predominant limestone facies of the Comanche Peak and Edwards Formations, and the combined Kiamichi-Duck Creek Formations:

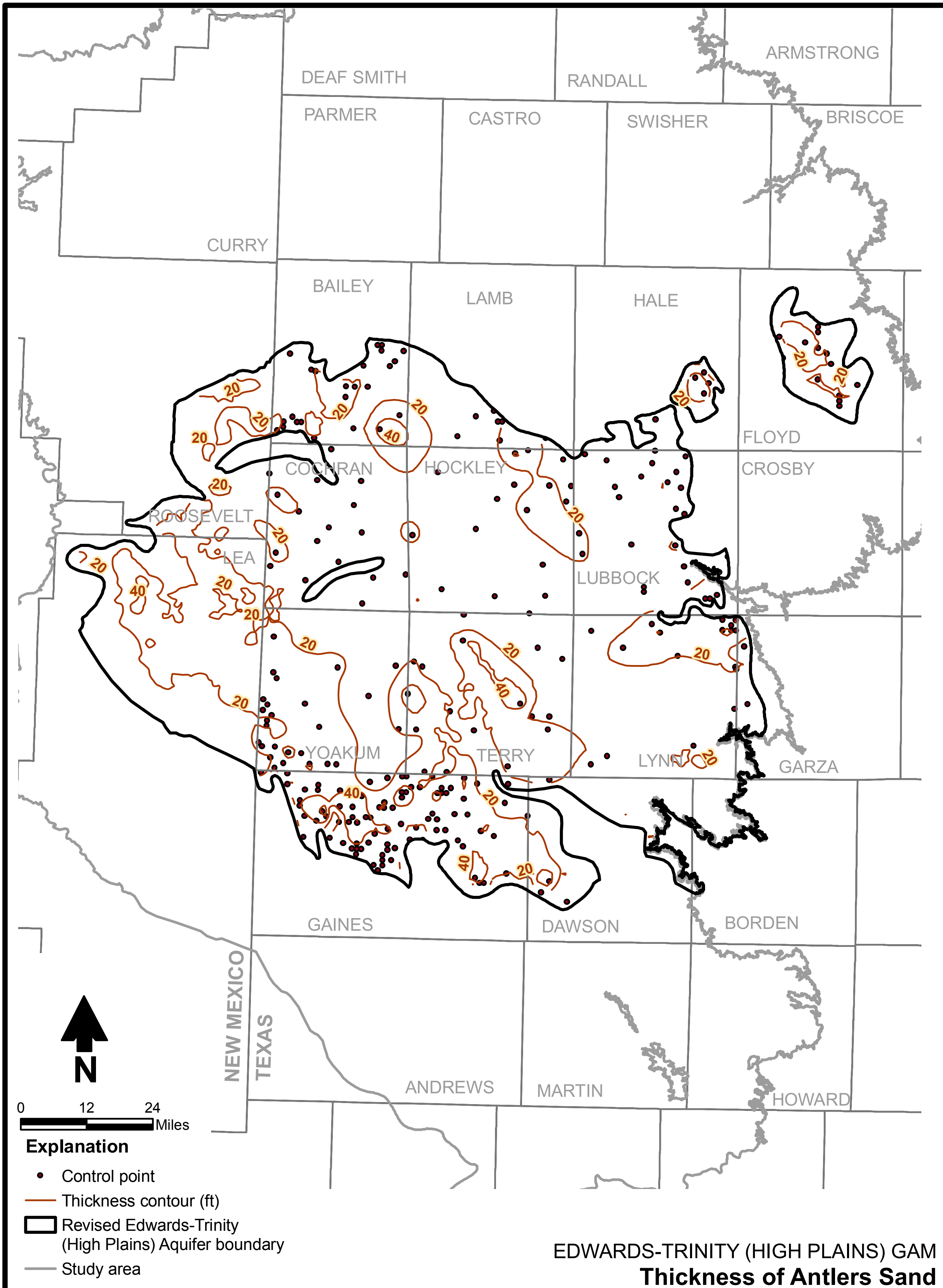
- Figure 24 illustrates that the Antlers Sand is fairly ubiquitous and ranges from about 10 to 40 feet in thickness.

- The combined Comanche Peak and Edwards limestones also occur throughout most of the Edwards-Trinity (High Plains) Aquifer extent and range in thickness from about 10 to 80 feet, although the thickness is as great as 100 feet in some areas (fig. 25). Limestone is generally absent throughout most of Bailey County and the northwestern portion of the Edwards-Trinity (High Plains) Aquifer.

- The combined thickness of Cretaceous shale composed primarily of the Duck Creek and Kiamichi Formations ranges from zero throughout the southern and far eastern portions of the Edwards-Trinity (High Plains) Aquifer to more than 100 feet throughout the central portions of the aquifer (fig. 26). In some zones within the central portion of the aquifer extent, however, the Duck Creek and Kiamichi Formations have been removed by erosion. These zones correspond to underlying paleochannels (i.e., the Duck Creek and Kiamichi Formations are generally thickest in the interchannel settings).

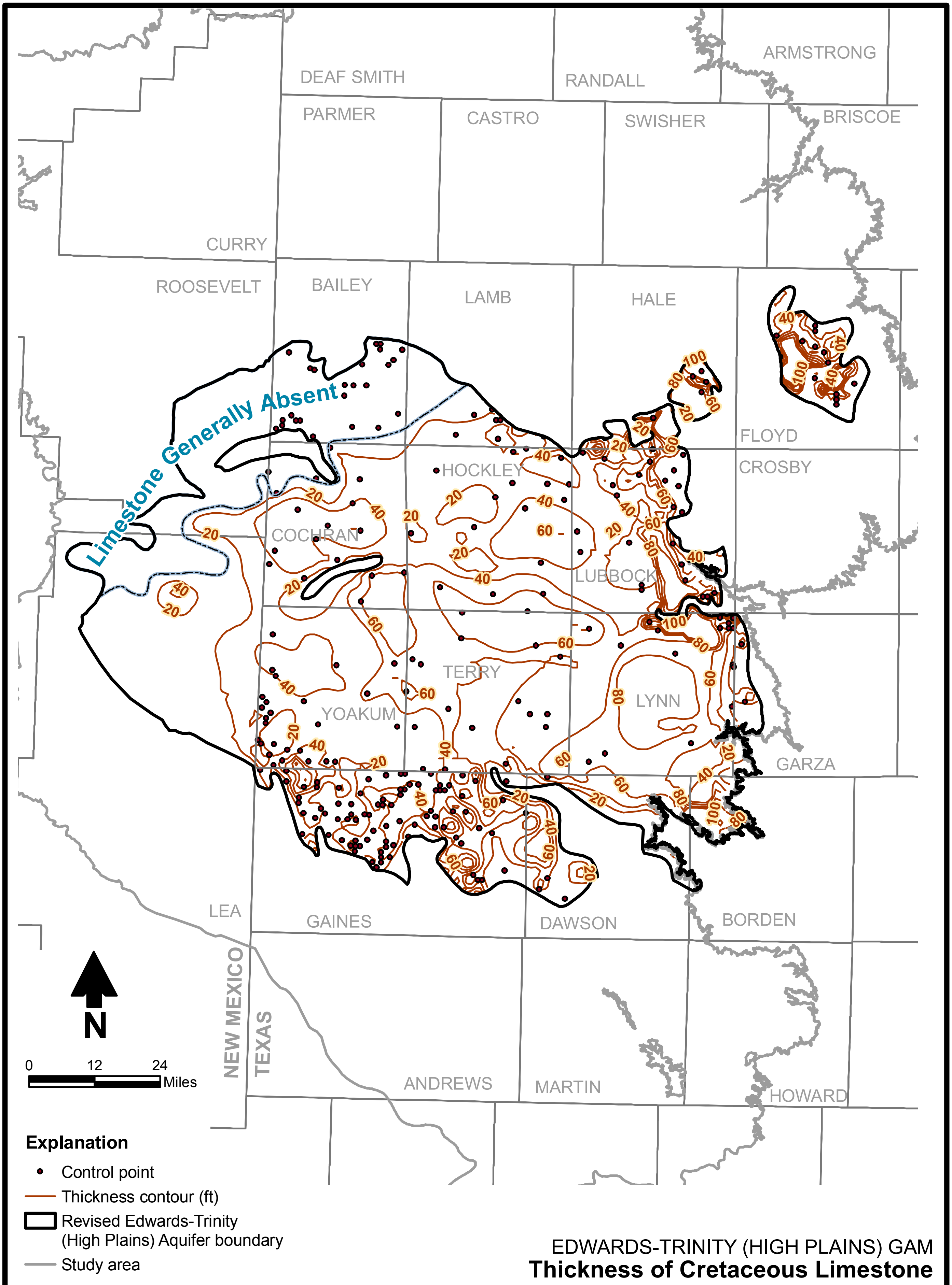
This series of structure figures (figs. 20 through 26) was developed as follows.

1. Contour maps were first developed based on observed data of the top of the Dockum Group and the thickness of the Antlers Sand and the Comanche Peak and Edwards



EDWARDS-TRINITY (HIGH PLAINS) GAM
Thickness of Antlers Sand

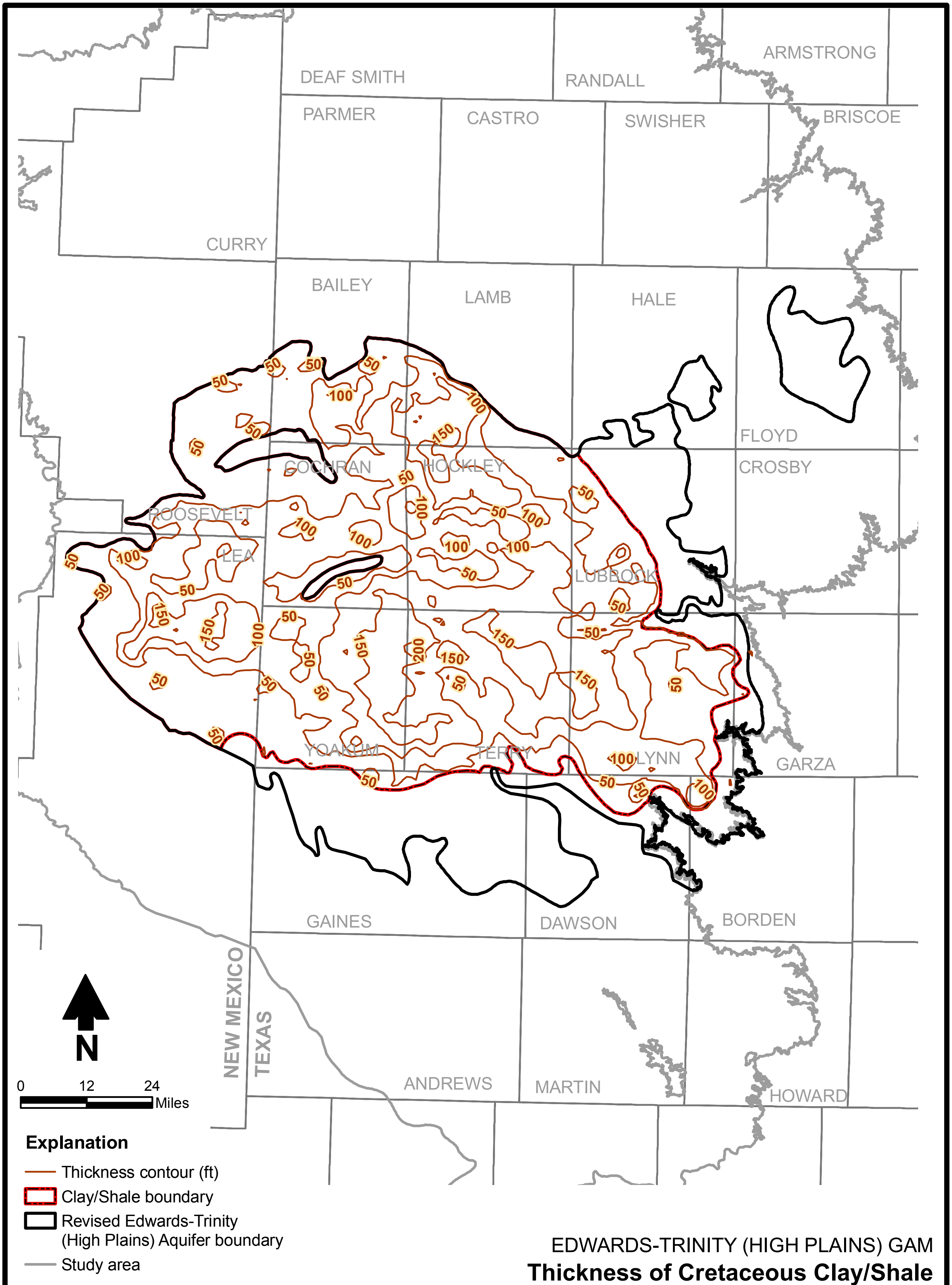
Figure 24



EDWARDS-TRINITY (HIGH PLAINS) GAM

Thickness of Cretaceous Limestone

Figure 25



EDWARDS-TRINITY (HIGH PLAINS) GAM

Thickness of Cretaceous Clay/Shale

Figure 26

limestones (note that there can be some thickness of interbedded sand and shale included in the limestone thickness numbers).

2. Starting with the top of Dockum elevation surface, the contoured thickness of the Antlers Sand was added to develop a top of Antlers Sand contour map.

3. The contoured limestone thickness was then added to the top of Antlers Sand elevation to develop a top of Cretaceous limestone surface.

4. Finally, the top of the limestone surface was subtracted from the base of Ogallala Formation surface to develop a thickness map of Cretaceous shale, which is composed primarily of the combined Duck Creek and Kiamichi Formations.

The top of Dockum (base of Edwards-Trinity [High Plains] Aquifer) elevation map was checked for consistency against top of Dockum contours outside the Edwards-Trinity (High Plains) Aquifer extent, and the Antlers Sand and limestone thickness maps were developed for consistency with the previous work of Fallin (1989) in the New Mexico portion of the study area. This process was repeated several times to eliminate inconsistencies among the various maps. The base of the Edwards-Trinity (High Plains) Aquifer elevation map was also compared to the top of Dockum Group elevation map provided by McGowen and others (1977). The elevation surface developed as part of this study is generally within several tens of feet of that estimated by McGowen and others (1977). In some regions, such as Hockley County, some more detailed features such as paleo-drainages are evident in Figure 20 that are not evident in the McGowen and others (1977) map.

4.3 Water Levels and Regional Groundwater Flow

Regional groundwater flow in the Edwards-Trinity (High Plains) Aquifer generally follows the regional slope of the land surface, which is to the southeast. Locally, the direction of groundwater flow is influenced by the presence of paleochannels incised into permeable Cretaceous rocks and springs, although the effects of these features are generally not discernable on regional-scale maps of the potentiometric surface. Groundwater tends to flow toward each of these features because paleochannels are generally zones of higher transmissivity and springs are points of groundwater discharge.

Groundwater that occurs in the Edwards-Trinity (High Plains) Aquifer is generally confined in that the water level in wells rises above the top of the permeable aquifer units. Groundwater in the aquifer may occur locally under unconfined (water table) conditions in the some of the far western portions of the study area in New Mexico and near the eastern escarpment where the water table has dropped beneath Ogallala sediments and occurs within the permeable portions of the Cretaceous rocks.

Water level information for Texas was obtained from the TWDB database (at http://wiid.twdb.state.tx.us/ims/wwm_drl/viewer.htm). For the New Mexico portion of the study area, water levels were obtained from the United States Geological Survey (USGS) Ground-Water Site Inventory (GWSI) (at http://waterdata.usgs.gov/tx/nwis/inventory). In general, available data for Edwards-Trinity (High Plains) Aquifer water levels are very limited. However, in Gaines and Dawson Counties, water levels in the Edwards-Trinity (High Plains)

Aquifer are believed to be the same as or very similar to those in the overlying Southern Ogallala Aquifer due to the absence of significant thicknesses of clay separating the Ogallala and permeable Cretaceous sediments. In these areas, therefore, available Ogallala water levels were used to develop regional Edwards-Trinity (High Plains) Aquifer potentiometric surface maps.

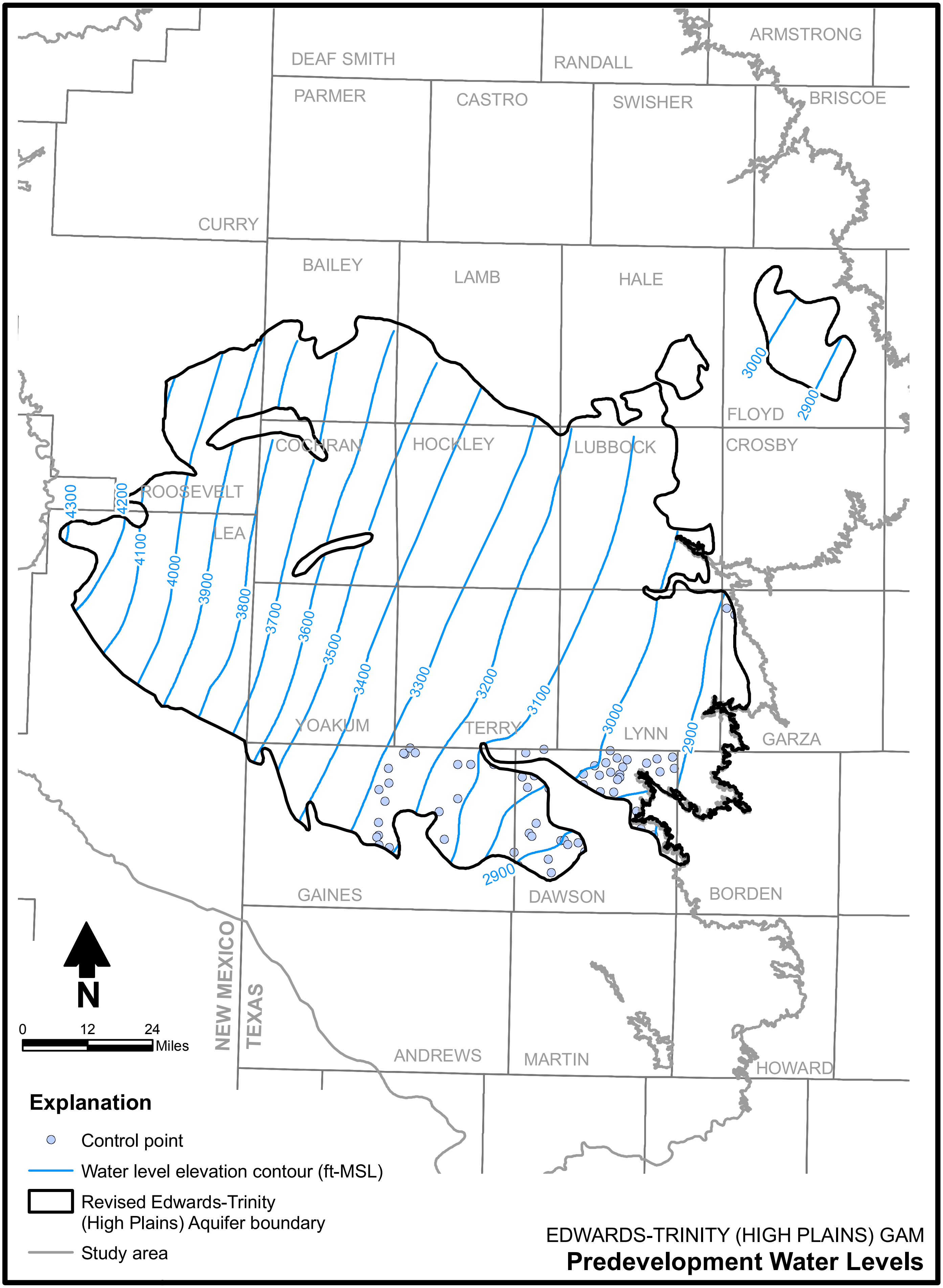
Figure 27 shows the estimated potentiometric surface prior to significant groundwater development within the Edwards-Trinity (High Plains) Aquifer. The data points used to construct this map are generally from around 1940 or earlier for Gaines and Dawson Counties in Texas. Later water level measurements were used to interpret the general configuration of the potentiometric surface north of Gaines and Dawson Counties, but early data points (about 1940 or earlier) are not available for contouring. As shown in Figure 27, groundwater flow under predevelopment conditions was generally to the southeast at an average hydraulic gradient of about 0.002 feet per foot (ft/ft), which is very similar to that of the Southern Ogallala Aquifer.

Figures 28 through 30 show the estimated potentiometric surface for the years 1980, 1990 and 1997, respectively. These maps illustrate that, for the most part, the direction of regional groundwater flow as well as the elevation of the potentiometric surface is relatively similar between time periods. Some of the changes that are evident from year to year may be due, at least in part, to the availability of data from additional water level observation points within the aquifer, rather than representing an actual change in the potentiometric surface.

Available Edwards-Trinity (High Plains) Aquifer hydrographs generally indicate historical changes in the potentiometric surface of several tens of feet, although changes greater than 100 feet have been observed at some wells (fig. 31). Since the vast majority of pumping that occurs from the aquifer is for irrigated agriculture, observed potentiometric surface levels likely mimic trends in groundwater use for irrigated agriculture. In addition, because the leakage between the Edwards-Trinity (High Plains) Aquifer and the overlying Southern Ogallala Aquifer is dependent upon the difference in hydraulic heads, some fluctuation in the potentiometric surface may be attributable to changes in leakage between aquifers. Also, as discussed in Section 5.0 (*Conceptual Model*), most wells that tap the Edwards-Trinity (High Plains) Aquifer are also screened in the overlying Southern Ogallala Aquifer, and therefore, water use (and corresponding changes in water levels) in one aquifer is directly connected to water use in the other. Water levels in some portions of the overlying Southern Ogallala Aquifer have increased significantly through time due to increased recharge attributable to changes in land use (Blandford and others, 2003; Scanlon and others, 2007); the effects of increased recharge are likely transmitted to the Edwards-Trinity (High Plains) Aquifer in some locations, such as Dawson County.

4.4 Recharge

The Edwards-Trinity (High Plains) Aquifer receives groundwater inflow primarily by downward leakage from the overlying Southern Ogallala Aquifer. The greatest exchange of water between aquifers likely occurs where the low-permeability clay layers of the Duck Creek and Kiamichi Formations are thin or absent. Figure 32 is a gray-scale representation of the calculated thickness of the combined shale thickness associated primarily with the Duck Creek and Kiamichi Formations. Distinct regions of zero or small shale thickness occur in southern and eastern portions of the Edwards-Trinity (High Plains) Aquifer and in other areas that often correspond to paleochannels filled with Ogallala sediments.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ROOSEVELT
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GARZA
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DAWSON
BORDEN
ANDREWS
MARTIN
HOWARD
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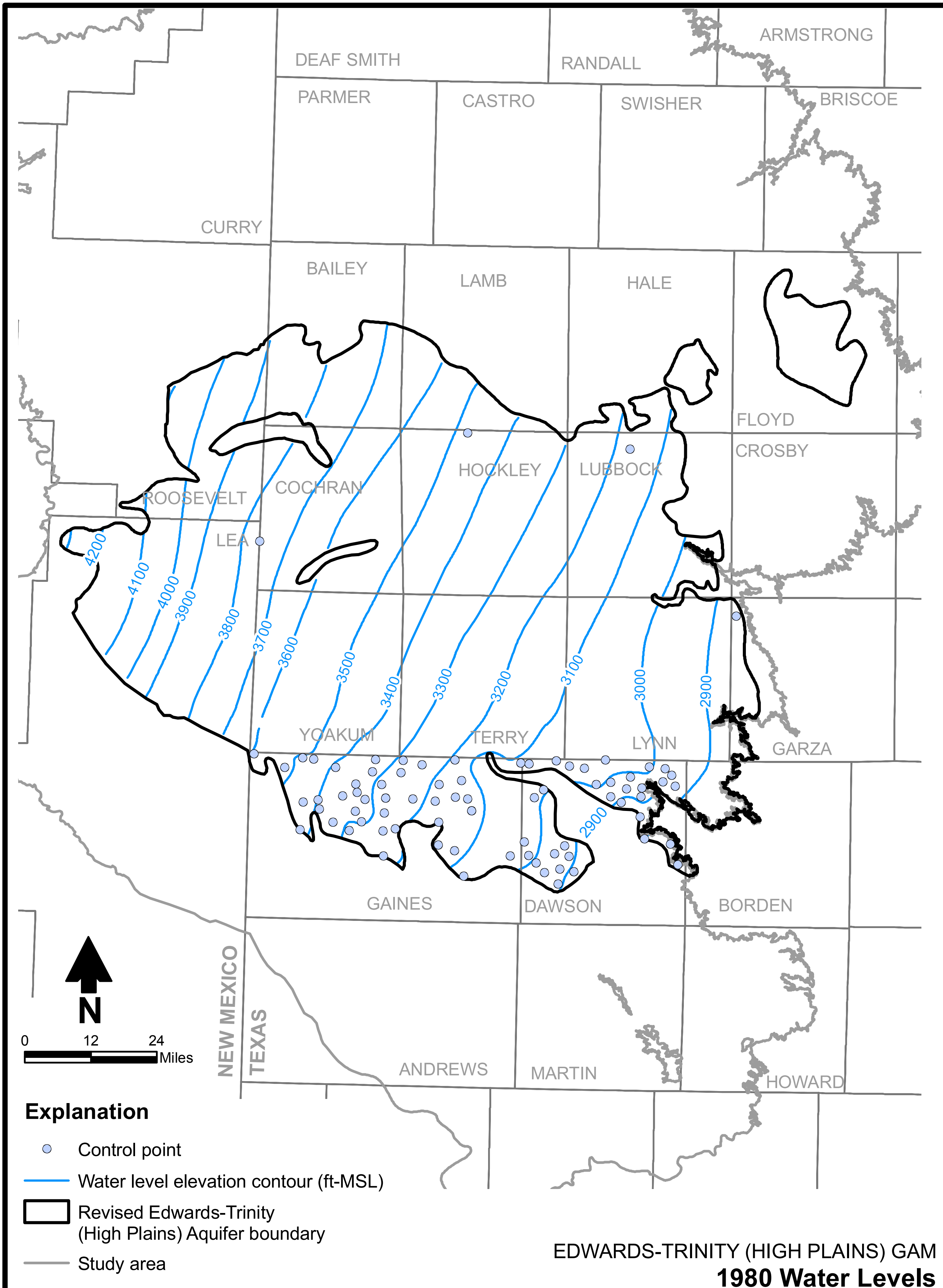
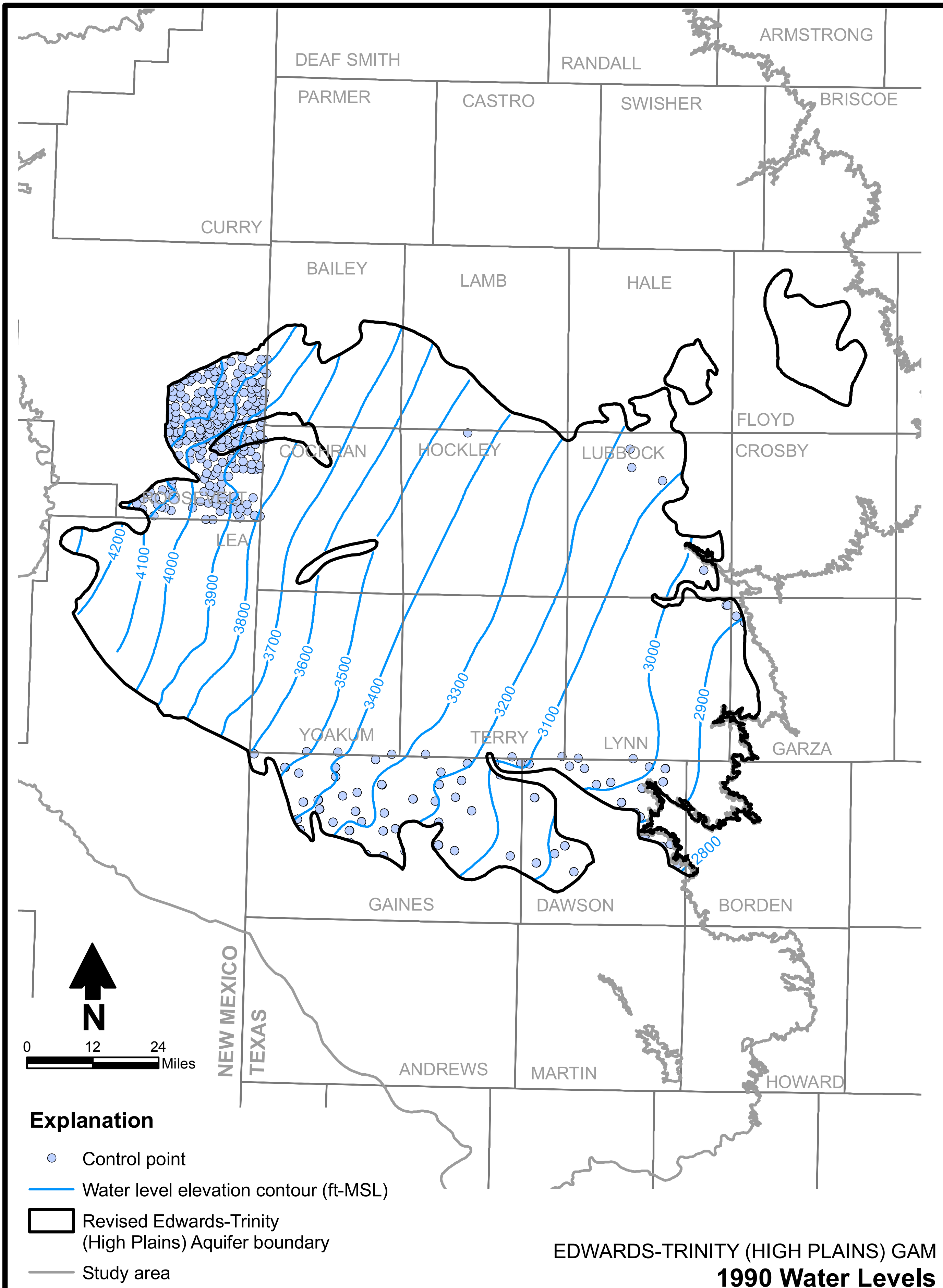
Explanation
Control point
Water level elevation contour (ft-MSL)
Revised Edwards-Trinity (High Plains) Aquifer boundary
Study area
EDWARDS-TRINITY (HIGH PLAINS) GAM
Predevelopment Water Levels
Figure 27



EDWARDS-TRINITY (HIGH PLAINS) GAM

1980 Water Levels

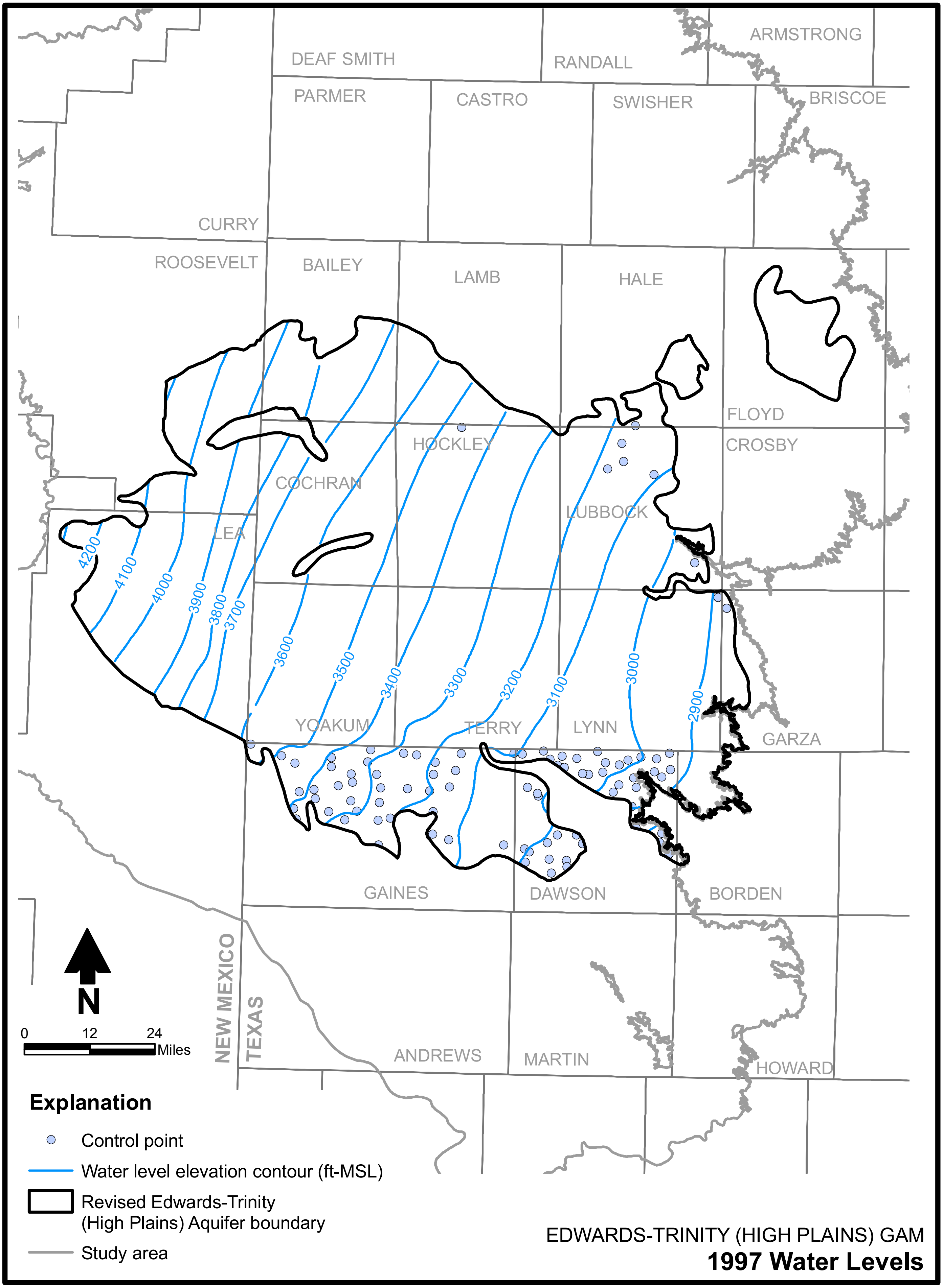
Figure 28



EDWARDS-TRINITY (HIGH PLAINS) GAM

1990 Water Levels

Figure 29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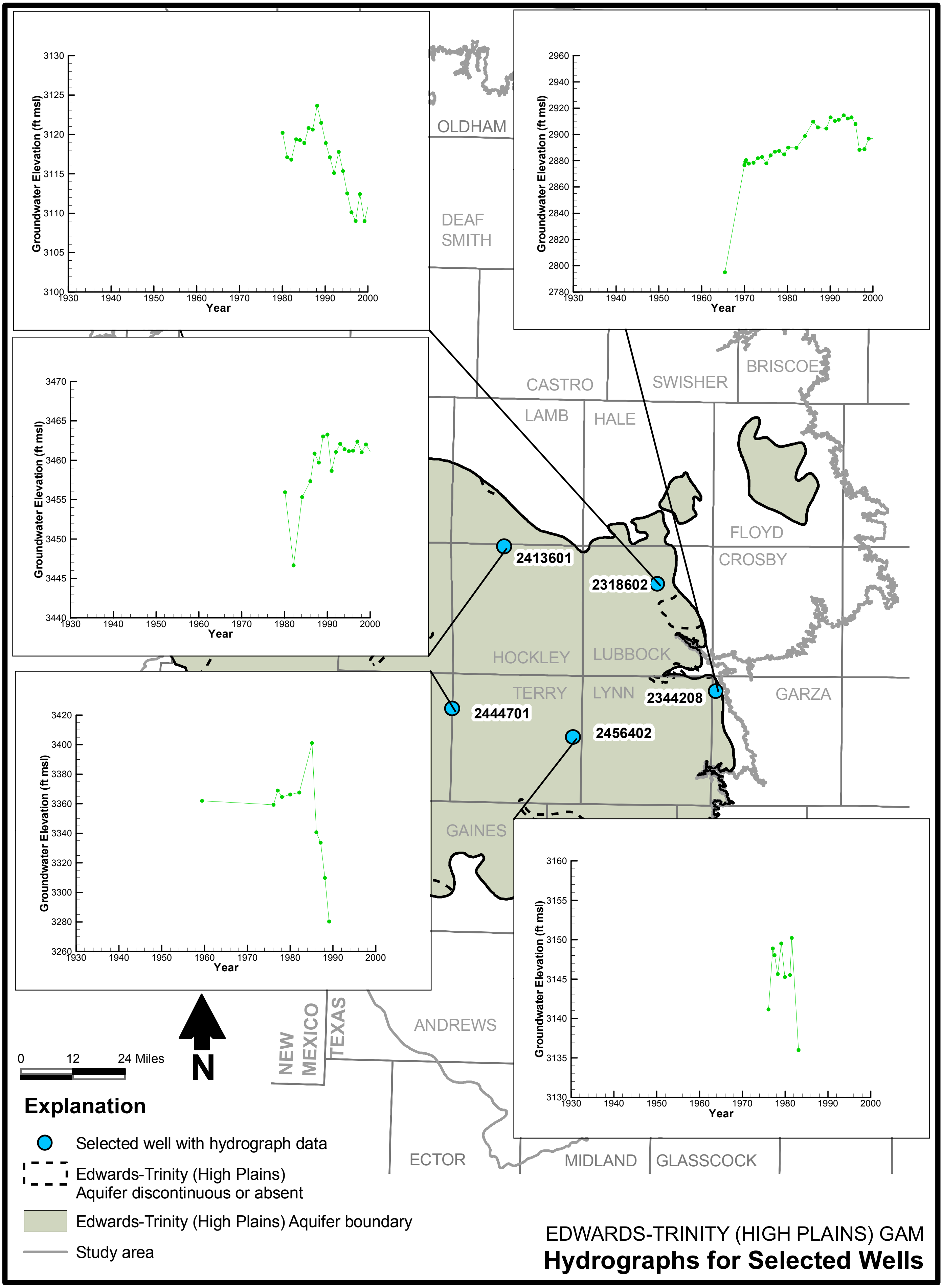
Explanation
Control point
Water level elevation contour (ft-MSL)
Revised Edwards-Trinity (High Plains) Aquifer boundary
Study area
EDWARDS-TRINITY (HIGH PLAINS) GAM
1997 Water Levels

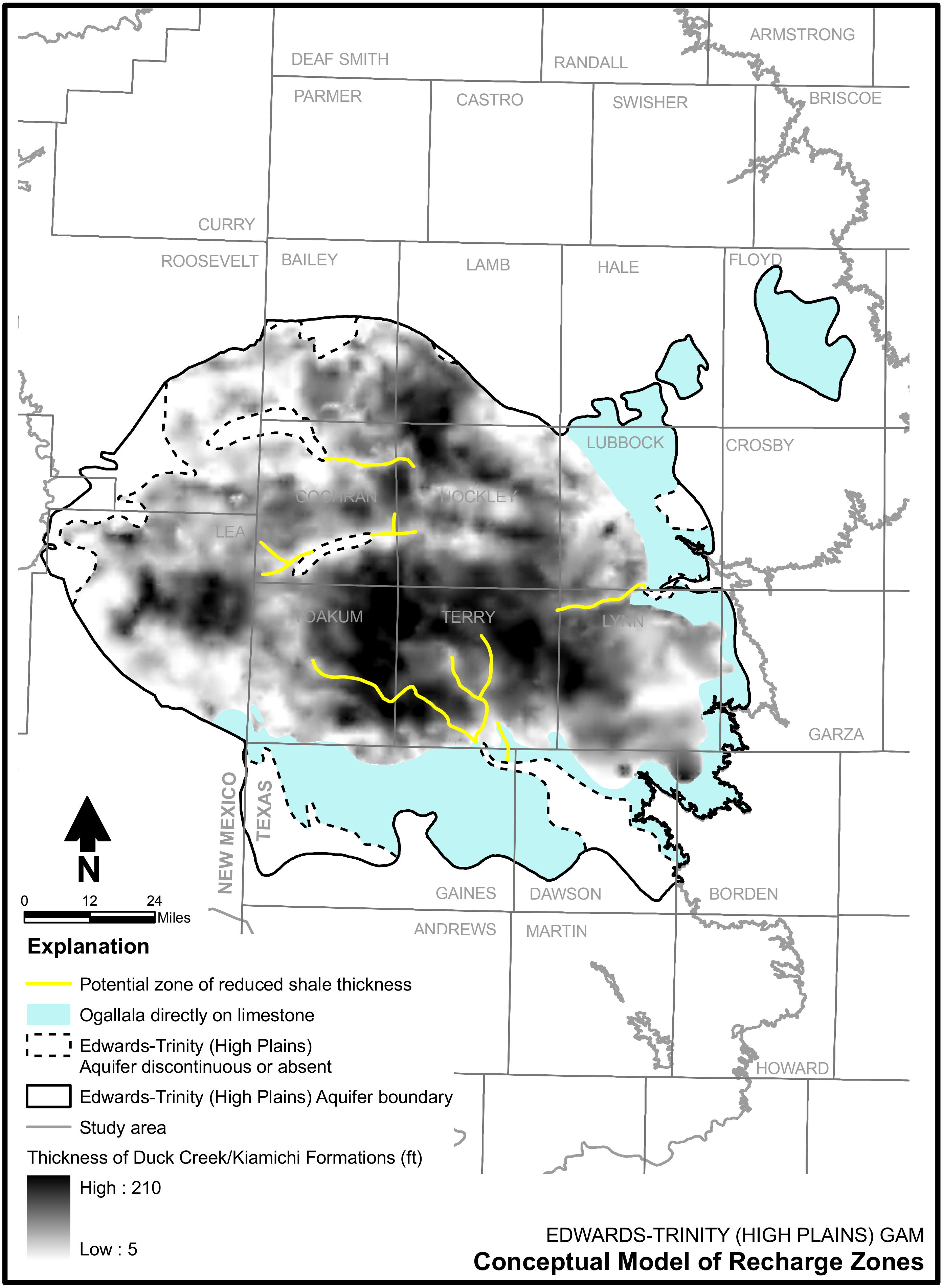
Figure 30



EDWARDS-TRINITY (HIGH PLAINS) GAM

Hydrographs for Selected Wells

Figure 31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Explanation
Potential zone of reduced shale thickness
Ogallala directly on limestone
Edwards-Trinity (High Plains) Aquifer discontinuous or absent
Edwards-Trinity (High Plains) Aquifer boundary
Study area
Thickness of Duck Creek/Kiamichi Formations (ft)
High : 210
Low : 5
EDWARDS-TRINITY (HIGH PLAINS) GAM
Conceptual Model of Recharge Zones

Figure 32

Significant groundwater inflow to the aquifer may also occur where past erosion has removed the Cretaceous formations entirely and groundwater in the Ogallala Formation is in direct contact with permeable portions of the Edwards, Comanche Peak, or Antlers Formations. Two such regions have been identified: one in south-central Cochran County and the other straddling the state line and the Cochran-Bailey County line. The second zone was first documented by Fallin (1989) and was confirmed and amended in Texas as part of this study. Both regions are coincident with significant paleochannels mapped in the base of Ogallala Formation (McReynolds, 1996a through 1996o), which indicates that other similar, but as yet unidentified, regions may exist.

In addition to regions where the Cretaceous section is entirely absent, there are also significant regions within the eastern and southern portions of the Edwards-Trinity (High Plains) Aquifer where Ogallala sediments are in direct contact with limestone of the Edwards or Comanche Peak Formations (fig. 32). Significant exchange of water between the Ogallala and Edwards-Trinity (High Plains) Aquifers can occur in these areas.

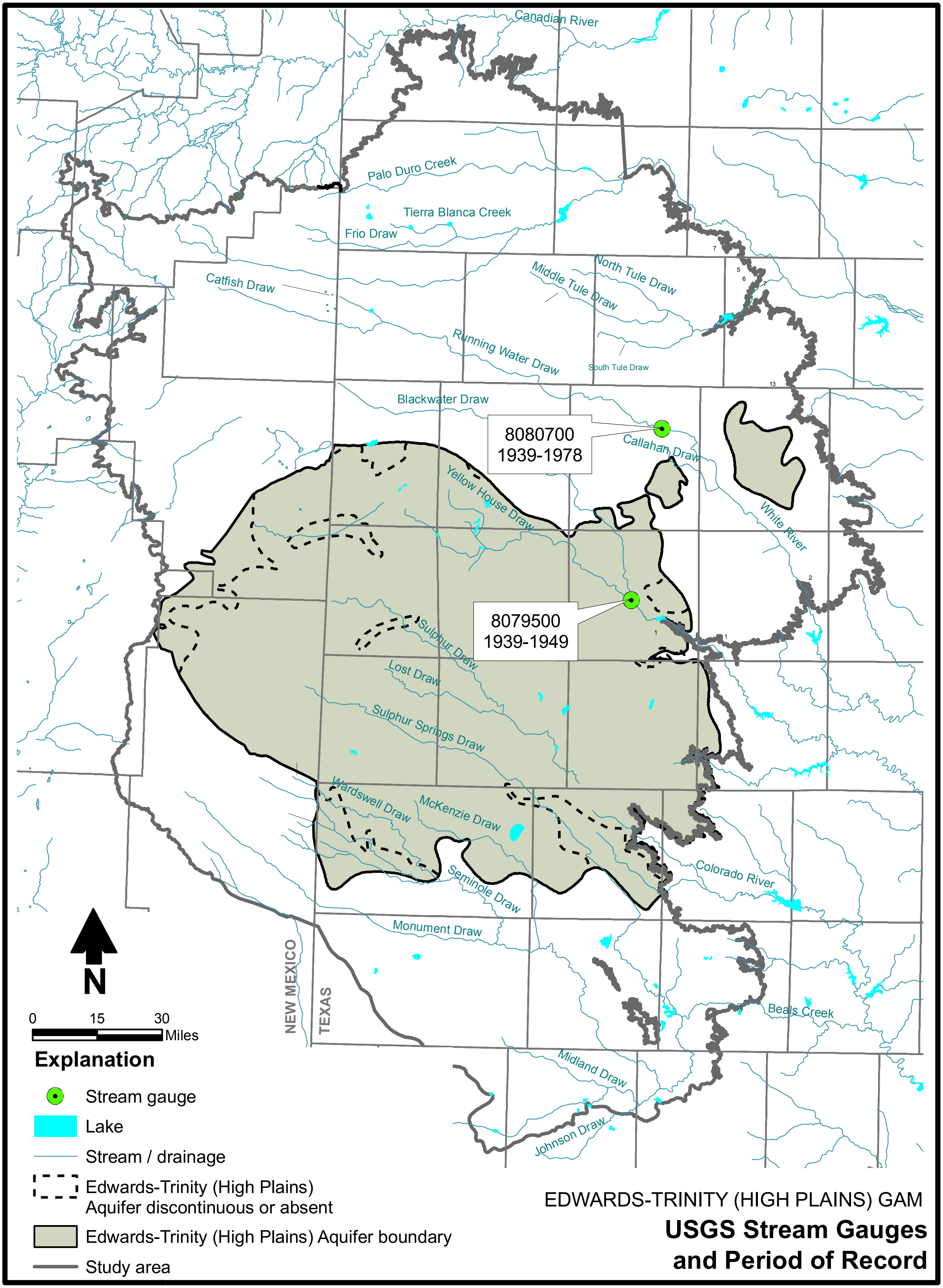
Groundwater inflow to the Edwards-Trinity (High Plains) Aquifer may also occur as upward groundwater flow from permeable layers of the Dockum Group into the Edwards-Trinity (High Plains) Aquifer (Nativ and Gutierrez, 1988). Inflow from this source, however, is poorly defined and believed to be small compared to downward leakage from the Southern Ogallala Aquifer.

There are no available published estimates of recharge or groundwater inflow to the Edwards-Trinity (High Plains) Aquifer. However, considering the aquifer hydraulic properties in relation to those of the Southern Ogallala Aquifer, as well as identified recharge rates to the Southern Ogallala Aquifer, average groundwater inflow to the Edwards-Trinity (High Plains) Aquifer is likely to be a small fraction of an inch when averaged over the aquifer area. Recharge to the overlying Southern Ogallala Aquifer, including significant changes that have occurred through time due to changes in land use and irrigation practices, is discussed in detail by Blandford and others (2003). The lack of significant quantities of rejected recharge to the Southern Ogallala Aquifer is also discussed by Blandford and others (2003). Since the primary source of groundwater inflow to the Edwards-Trinity (High Plains) Aquifer is downward seepage from the Southern Ogallala Aquifer, rejected recharge is not a significant component of the Edwards-Trinity (High Plains) Aquifer water balance.

4.5 Rivers, Streams, Springs, and Lakes

Figure 33 illustrates the major streams and the locations of surface water gauging stations within the study area. No perennial rivers or streams are located within the study area. Prior to significant groundwater development, however, small perennial streams fed by Ogallala and possibly Cretaceous springs did exist near the eastern Caprock escarpment, where the stream drainages are deeply incised (Baker, 1915; White and others, 1946).

The draws on the Southern High Plains are very long and narrow with limited drainage areas. The locations of some of the draws are apparently controlled by geologic structure, as they tend to be linear for large distances and are punctuated by sharp angular changes in direction. Reeves (1970) and Reeves and Reeves (1996) discuss the development of the major draws and illustrate that the principal lineament trends on the Southern High Plains are northwest-southeast,



Canadian River
Palo Duro Creek
Tierra Blanca Creek
Frio Draw
Catfish Draw
Middle Tule Draw
North Tule Draw
Running Water Draw
South Tule Draw
Blackwater Draw
8080700
1939-1978
Callahan Draw
Yellow House Draw
White River
8079500
1939-1949
Sulphur Draw
Lost Draw
Sulphur Springs Draw
Wardswell Draw
McKenzie Draw
Seminole Draw
Colorado River
Monument Draw
Beals Creek
Midland Draw
Johnson Draw
NEW MEXICO
TEXAS
N
0
15
30
Miles
Explanation
Stream gauge
Lake
Stream / drainage
Edwards-Trinity (High Plains) Aquifer discontinuous or absent
Edwards-Trinity (High Plains) Aquifer boundary
Study area
EDWARDS-TRINITY (HIGH PLAINS) GAM
USGS Stream Gauges and Period of Record

Figure 33

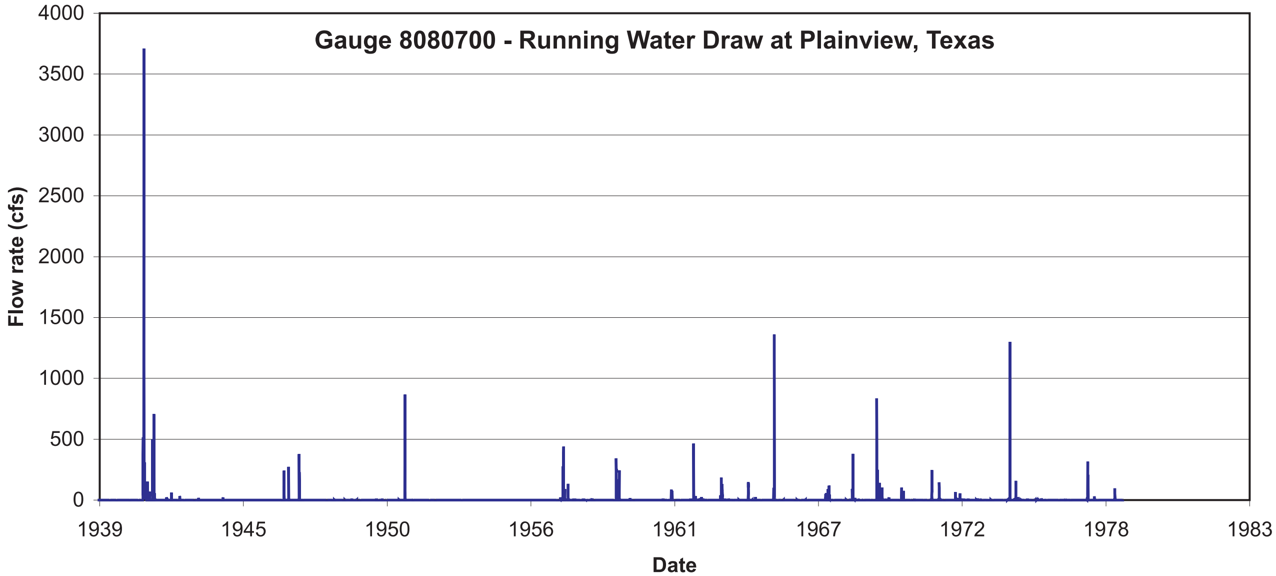
southwest-northeast, and north-south. Fallin (1989) states that major fracture trends in the Cretaceous section are oriented northwest-southeast and, to a lesser extent, northeast-southwest, and that the fractures trends are "especially well developed in Bordon, Dawson, Hale, Hockley, Lubbock, and Terry Counties." Sulphur Springs Draw, located between Natural Dam Lake in western Howard County and the town of Lamesa in central Dawson County, is an excellent example of this (fig. 33).

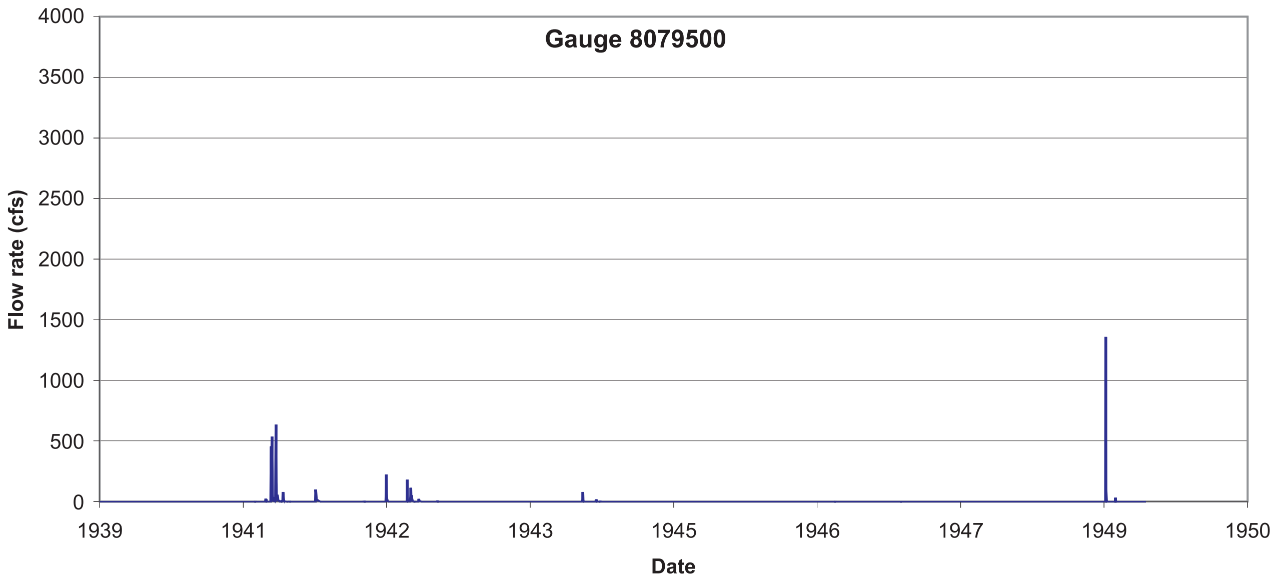
Some USGS stream gauges have been operated along several of the major draws at various times (fig. 33). Observed flows for two of these gauges are illustrated in Figure 34. These stream flow hydrographs illustrate that flow volumes are generally small and draws are dry except after significant storm events. In addition, the duration of flows is on the order of several days or less. Calhoun and others (2003) calculated an average storm flow duration of about 3 days for a gauge on the Prairie Dog Town Fork of the Red River near Canyon, in the northern part of the Southern High Plains.

Most of the playa lakes in the study area (fig. 6) lie above the water table and only hold water for some period of time after precipitation events (LERWPG, 2001). It has been estimated that playa lakes and salt lakes drain more than 90 percent of the land surface within the Southern High Plains (Wood and Jones, 1990). As discussed by Blandford and others (2003) and many other publications, previous studies have found substantially higher recharge rates beneath playa lakes as compared to inter-playa settings, at least under natural conditions.

In addition to the many thousands of playa lakes that cover the High Plains, there are approximately 40 substantially larger salt lakes within the study area (Wood and Jones, 1990; Reeves and Reeves, 1996). These lakes are significantly different hydrologically from playa lakes in that they are regions of groundwater discharge and typically lie within relatively large topographic depressions, some on the order of several tens of square miles. These lakes tend to occur in association with regional topographic highs on the Cretaceous section and where the Ogallala section is less than 200 feet thick (Reeves and Reeves, 1996). At most lake basins, a significant topographic depression occurs where the Ogallala Formation has been eroded away, and Cretaceous rocks crop out along the west and northwest margins of the lake basins. Although information is limited, most of the lakes may hold standing water only intermittently, and when they do have water, it is shallow (Wood and Jones, 1990; Baker, 1915). However, Leggat (1957) reported that Bull and Illusion Lakes in southwestern Lamb County usually contained water except during prolonged periods of drought.

Water in the lakes is a combination of runoff from precipitation and seepage from Southern Ogallala Aquifer and in some cases Edwards-Trinity (High Plains) Aquifer springs that occur along the lake basin margins, commonly on the west or northwest sides (fig. 35). Lake water is highly saline, with concentrations of total dissolved solids (TDS) ranging from several thousand to more than 400,000 milligrams per liter (mg/L), substantially higher than Ogallala Aquifer water (Wood and Jones, 1990). Wood and Jones (1990) show that the TDS concentrations in the lake water are high due to concentrations of salts in the closed lake basins caused by evaporation, and the TDS concentrations of many of the springs along the lake basin margins are elevated due to mixing of fresh aquifer water with saline lake water that has saturated portions of the aquifer beneath and immediately adjacent to the lakes.





EDWARDS-TRINITY (HIGH PLAINS) GAM

Stream Flow for USGS Stream Gauges 8080700 and 8079500

Figure 34

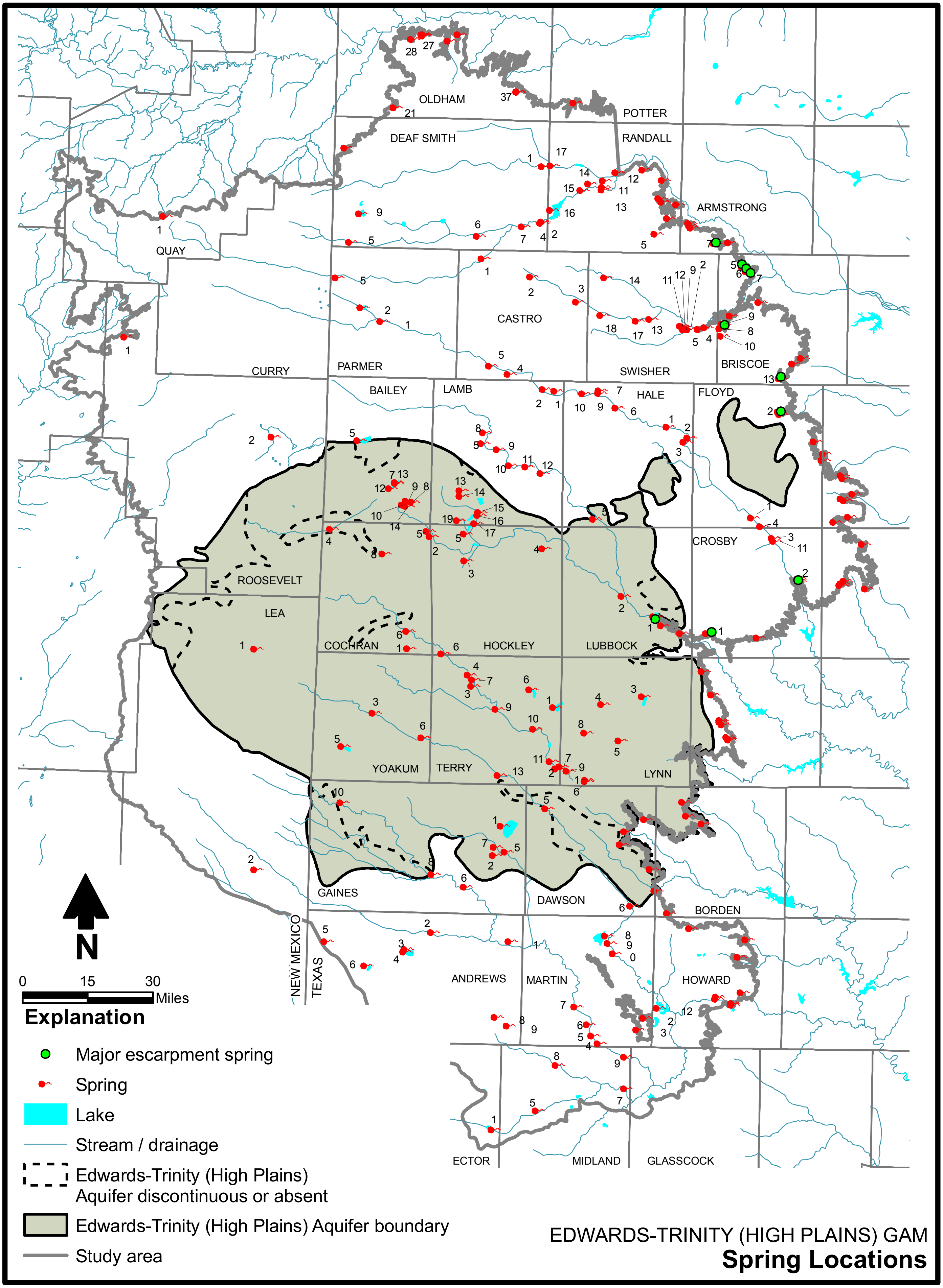

OLDHAM
POTTER
RANDALL
DEAF SMITH
ARMSTRONG
QUAY
CASTRO
CURRY
PARMER
SWISHER
BRISCOE
BAILEY
LAMB
HALE
FLOYD
CROSBY
ROOSEVELT
LEA
COCHRAN
HOCKLEY
LUBBOCK
YOAKUM
TERRY
LYNN
GAINES
DAWSON
BORDEN
NEW MEXICO
TEXAS
ANDREWS
MARTIN
HOWARD
ECTOR
MIDLAND
GLASSCOCK
N
0 15 30
Miles
Explanation
Major escarpment spring
Spring
Lake
Stream / drainage
Edwards-Trinity (High Plains) Aquifer discontinuous or absent
Edwards-Trinity (High Plains) Aquifer boundary
Study area
EDWARDS-TRINITY (HIGH PLAINS) GAM
Spring Locations

Figure 35

4.6 Hydraulic Properties

Information regarding hydraulic properties of the Edwards-Trinity (High Plains) Aquifer is very limited. Key hydraulic properties required for groundwater modeling include hydraulic conductivity and storage coefficient.

4.6.1 Hydraulic Conductivity

Hydraulic conductivity is a measure of the ease with which groundwater is able to flow through a porous medium. Mathematically, it is the amount of groundwater that an aquifer can transmit under a unit gradient in hydraulic head through a cross section of unit height and width. Transmissivity is the product of hydraulic conductivity and saturated thickness and varies as each of these aquifer attributes changes in space and time.

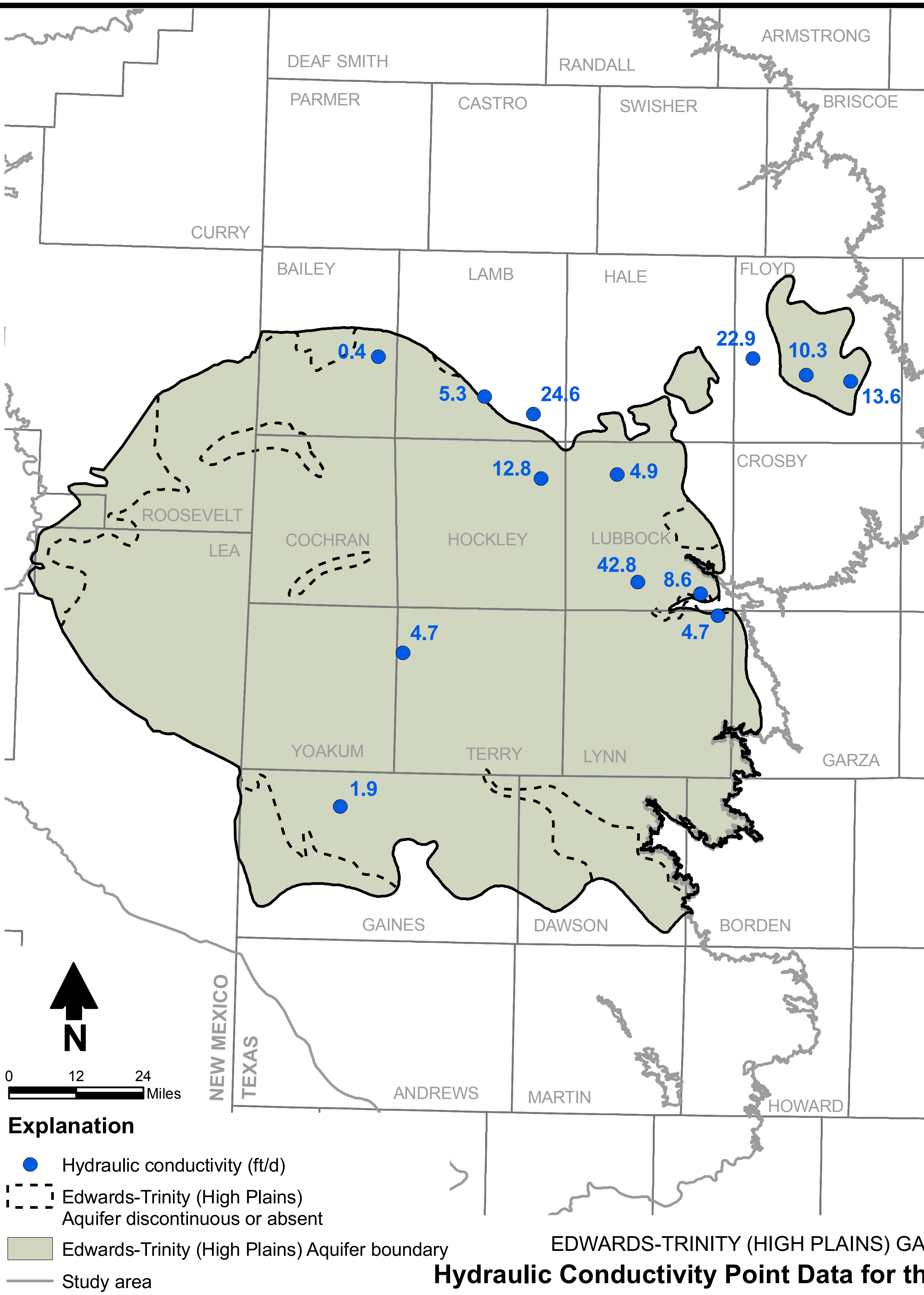
Hydraulic conductivity is controlled in part by the texture of the materials that make up the water-bearing parts of the aquifer. Variations in texture are influenced by the geological processes that deposited the sediments that make up the aquifer and the environments under which they were deposited. The hydraulic conductivity of various sediment types (e.g., clay, sand, gravel, or limestone) that may be encountered in a single borehole can vary by many orders of magnitude.

The hydraulic conductivity of the limestone rocks is highly dependent on the amount of fracturing and development of solution channels, called secondary permeability. Since historical groundwater flow and weathering activity experienced by a given section of limestone at a given location can vary dramatically, the hydraulic conductivity of the limestone can vary dramatically as well over short distances. Drillers' reports indicate that solution channels and secondary porosity are fairly prominent in Lubbock County.

When the drillers' reports were being reviewed at TCEQ, any reports that had aquifer testing information (single-well specific capacity tests) were collected. Of the available logs with specific capacity test information available, only 13 could be identified as being screened only in the Edwards-Trinity (High Plains) Aquifer. Documentation for a specific capacity test includes a single value for pumping rate, static depth to water, and depth to water after pumping the well for a given amount of time.

Transmissivity was estimated from specific capacity data using the solution based on Theis's non-equilibrium equation (Theis and others, 1963; Mace, 2001). In the calculation, storativity is assumed to be 0.001, which is representative of a predominantly confined aquifer response. The transmissivity was then divided by the screened interval of the well to estimate average hydraulic conductivity across the well screen. The available wells were screened across both limestone (Edwards and/or Comanche Peak) and Antlers Sand.

The results of this analysis are illustrated in Figure 36. The computed hydraulic conductivity for the producing interval of the Edwards-Trinity (High Plains) Aquifer ranges from 0.4 to 42.8 feet per day (ft/d). The two points outside the aquifer boundary in Figure 36 are in isolated portions of Cretaceous rock. The available data on hydraulic conductivity are insufficient to develop a correlation with geologic setting or material.



EDWARDS-TRINITY (HIGH PLAINS) GAM

Hydraulic Conductivity Point Data for the Edwards-Trinity (High Plains) Aquifer

Figure 36

4.6.2 Storativity

Storativity is the volume of water released from storage within the aquifer porous matrix per unit decline in hydraulic head. Storativity of the Edwards-Trinity (High Plains) Aquifer materials cannot be determined from specific capacity tests. Typical values for confined aquifer systems similar to the Edwards-Trinity (High Plains) Aquifer range from 0.0001 to 0.001. Where the aquifer is unconfined, the specific yield of the Antlers Sand may range from about 10 to 20 percent, while the specific yield of the producing limestone intervals is probably less than 10 percent, since the void spaces that can be drained are composed primarily of secondary porosity.

4.7 Discharge

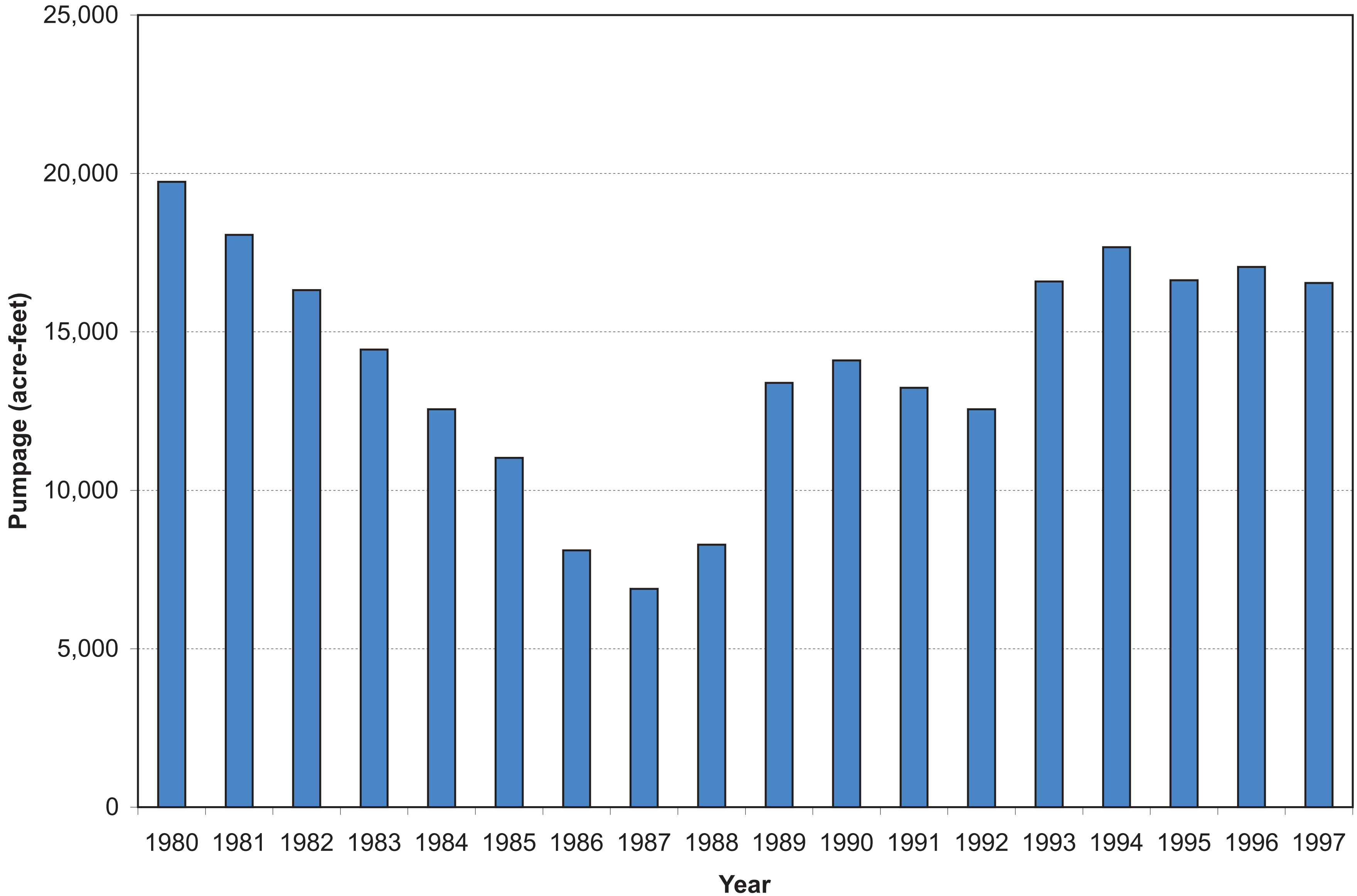
Groundwater discharge from the Edwards-Trinity (High Plains) Aquifer occurs through pumping, through outflow at numerous springs and seeps along the eastern escarpment and along the margins of salt lake basins, and through upward vertical leakage to the Southern Ogallala Aquifer. Model results indicate that under predevelopment conditions (generally prior to 1940), most discharge occurred as upward leakage to the Southern Ogallala Aquifer, while under post-development conditions, groundwater discharge from pumping greatly exceeds other components of discharge.

It is also possible that discharge occurs or has occurred through downward leakage to lower aquifer units, such as the Dockum Group. However, relative to other components in the regional water balance, this potential discharge is believed to be relatively small.

Estimated historical pumping for the Edwards-Trinity (High Plains) Aquifer for the period 1980 through 1997 is provided in Figure 37 and Table 2. The vast majority of pumping is for irrigated agriculture, but there is a small amount of livestock use as well. The total estimated groundwater pumping was highest, at almost 20,000 acre-feet, in 1980. This amount of pumping, which includes the entire Edwards-Trinity (High Plains) Aquifer extent, is substantially less than that obtained from the Southern Ogallala Aquifer. For example, Blandford and others (2003) estimated that pumping from the Southern Ogallala Aquifer for irrigated agriculture in Terry County alone was 75,000 to about 150,000 acre-feet per year (ac-ft/yr) over the same time period.

The distribution of irrigated acreage is illustrated in Figures 38 and 39. Both figures illustrate similar distributions of irrigated acreage, which tends to be most prevalent over paleochannels filled with Ogallala sediments. Ogallala paleochannel regions have greater saturated thickness and hydraulic conductivity, and therefore yield greater volumes of water. Available information indicates that, on a regional scale, areas of irrigated acreage have been fairly constant through time (Blandford and others, 2003).

Examination of Figures 38 and 39 illustrates that regions of irrigated agriculture can be correlated in some areas with the extent of the Cretaceous subcrop. For example, in Lamb County, very little irrigated acreage exists in the southwestern corner of the county, where the Cretaceous rocks exist. Likewise, in Hale and Floyd Counties, irrigated agriculture is very limited where isolated remnants of the Cretaceous section occur. In these regions, the ability of the Edwards-Trinity (High Plains) Aquifer (and the overlying Southern Ogallala Aquifer) to yield sufficient water to wells for irrigation purposes is limited.



Note: Total pumpage by year.

EDWARDS-TRINITY (HIGH PLAINS) GAM

Estimated Historical Groundwater Use

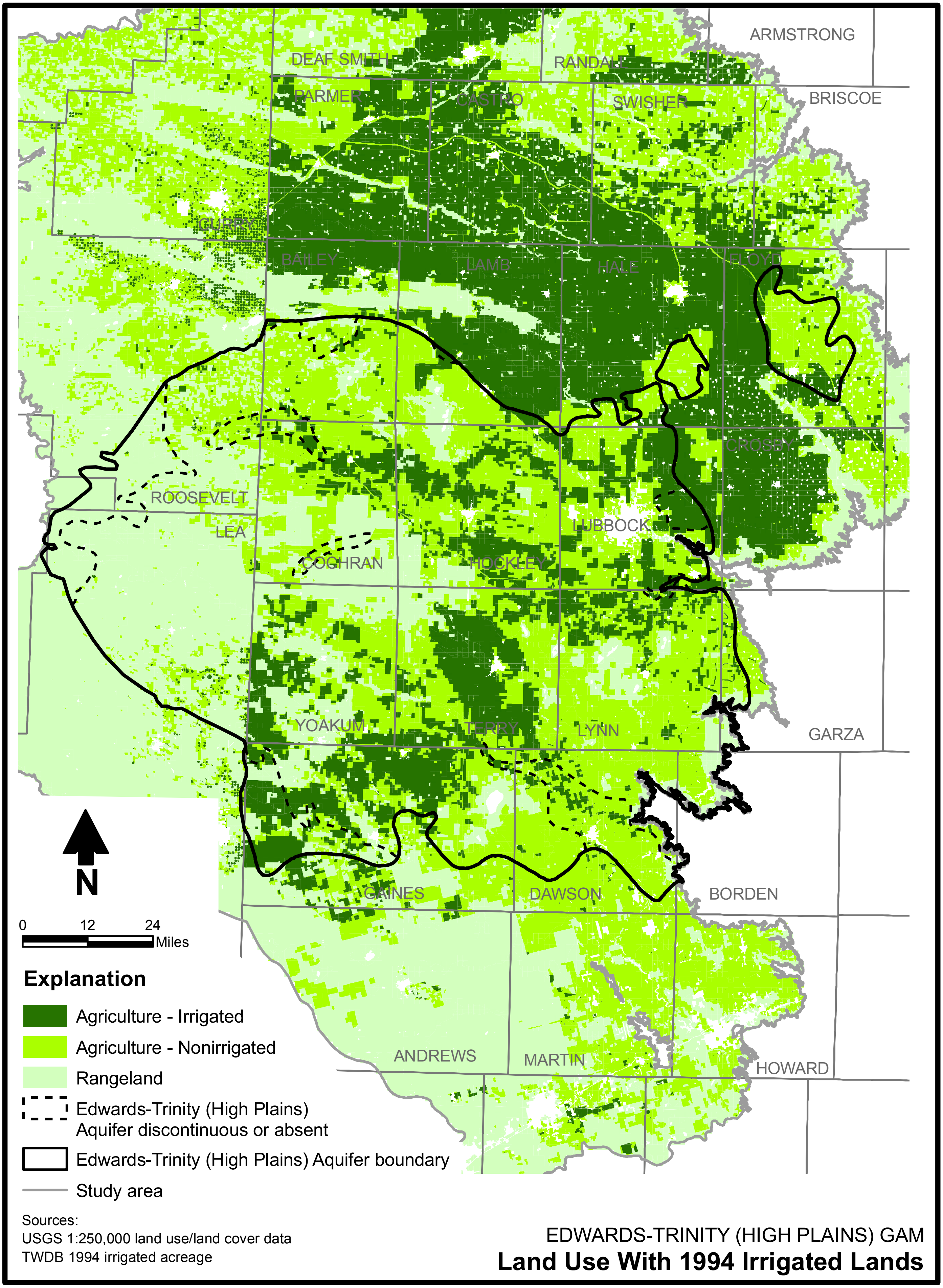
Figure 37

Table 2. Historical Pumping
Page 1 of 2

County	Pumping type	Pumping (acre-feet per year)									
		1980	1981	1982	1983	1984	1985	1986	1987	1988	1989
Bailey	Irrigation	152	253	202	155	108	111	85	70	62	140
	Livestock	37	42	47	52	57	69	106	73	55	55
Borden	Irrigation	5	5	4	4	3	4	7	7	7	3
	Livestock		3	3	3	3	3	5	2	2	2
Cochran	Irrigation	136	128	120	112	104	83	87	83	70	38
	Livestock	20	20.75	21.5	22.25	23	30	27	21	14	14
Dawson	Irrigation	141	118	96	74	52	71	32	32	48	106
	Livestock	8	12.75	17.5	22.25	27	24	28	21	23	22
Floyd	Irrigation	1,722	1,547	1,358	1,184	1,011	530	454	610	653	597
	Livestock	48	48.5	49	49.5	50	63	51	52	35	35
Gaines	Irrigation	7,915	7,018	6,122	5,226	4,330	4,346	2,982	2,457	3,777	5,659
	Livestock	29	31	33	35	37	42	37	36	25	25
Garza	Irrigation	15	14	13	12	11	6	4	4	9	13
Hale	Irrigation	6,195	5,884	5,646	5,284	4,912	4,100	3,040	2,502	2,260	4,013
	Livestock	7	7.5	8	8.5	9	12	12	11	6	5
Hockley	Irrigation	72	67	62	58	53	44	34	27	28	48
	Livestock	8	7.5	7	6.5	6	8	6	7	4	4
Lamb	Irrigation	299	289	278	268	258	182	178	117	111	102
Lubbock	Irrigation	365	361	382	375	371	310	255	236	399	591
Lynn	Irrigation	385	364	344	323	303	284	162	97	101	126
	Livestock	12	12.25	12.5	12.75	13	10	12	15	16	16
Terry	Irrigation	395	345	294	243	192	254	148	104	117	448
	Livestock	24	23.25	22.5	21.75	21	21	17	27	30	29
Yoakum	Irrigation	1,740	1,455	1,169	884	598	409	323	268	420	1,292
	Livestock	7	7.5	8	8.5	9	10	10	11	12	12

Table 2. Historical Pumping
Page 2 of 2

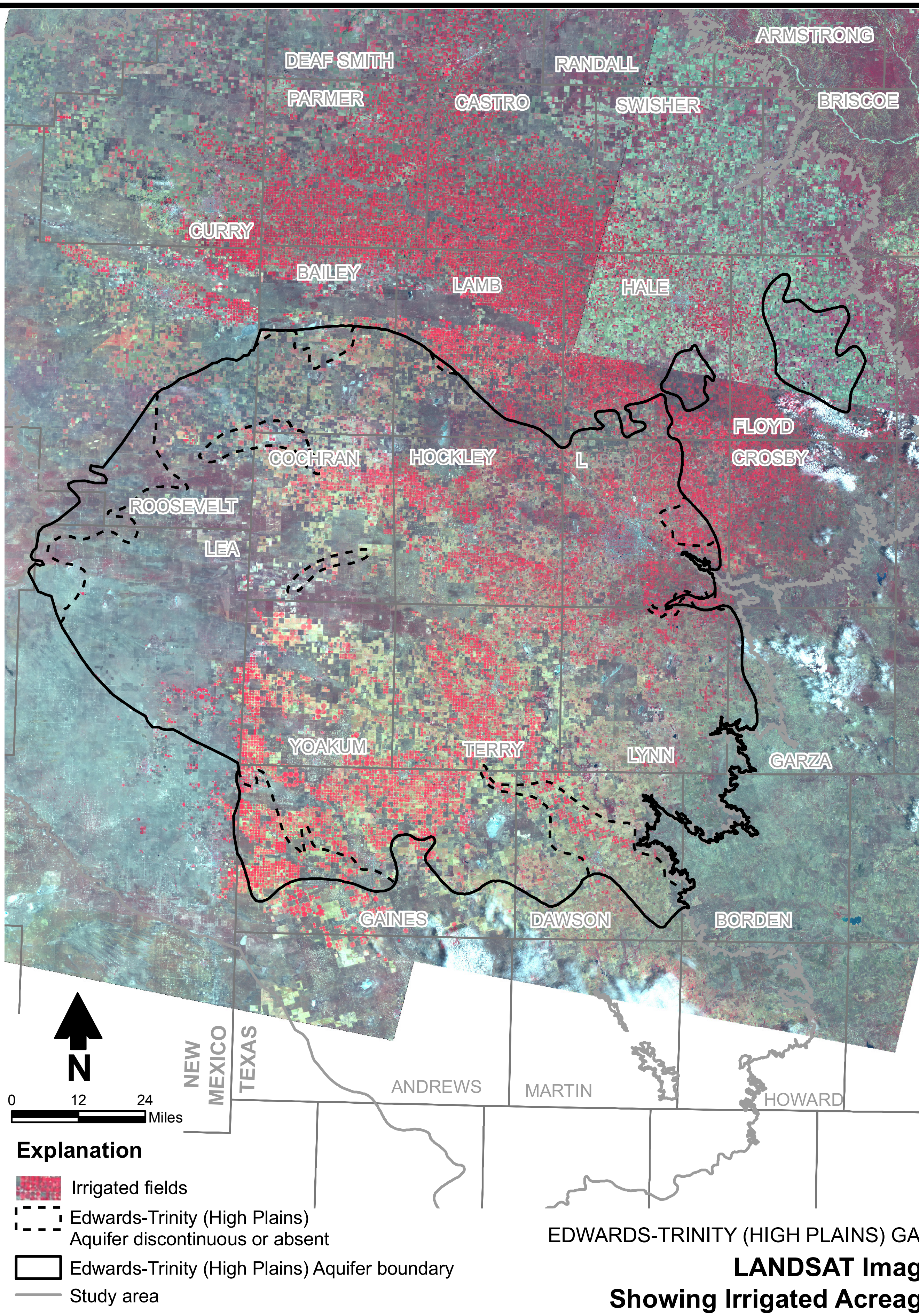
County	Pumping type	Pumping (acre-feet per year)							
		1990	1991	1992	1993	1994	1995	1996	1997
Bailey	Irrigation	157	143	131	163	135	148	178	125
	Livestock	60	61	86	104	94	111	106	83
Borden	Irrigation	3	6	6	9	11	16	54	103
	Livestock	2	2	2	2	4	4	3	3
Cochran	Irrigation	46	49	65	83	82	166	232	192
	Livestock	16	16	22	24	19	22	21	21
Dawson	Irrigation	140	167	226	384	292	521	1,418	1,399
	Livestock	22	23	38	38	27	34	38	54
Floyd	Irrigation	737	791	845	1,669	1,393	1,351	1,240	1,132
	Livestock	38	39	67	72	70	70	101	83
Gaines	Irrigation	6,024	6,603	6,887	7,588	9,317	7,307	6,449	6,605
	Livestock	28	29	56	59	65	69	105	97
Garza	Irrigation	9	7	3	8	10	13	22	18
Hale	Irrigation	4,103	2,723	2,393	3,831	3,428	3,758	3,826	3,503
	Livestock	6	6	13	14	15	17	17	18
Hockley	Irrigation	48	48	59	71	88	89	88	88
	Livestock	5	5	13	14	10	10	10	8
Lamb	Irrigation	168	136	53	179	144	180	182	164
Lubbock	Irrigation	716	541	225	686	669	849	743	689
Lynn	Irrigation	200	169	297	188	276	339	287	220
	Livestock	16	16	11	14	12	11	12	10
Terry	Irrigation	388	373	264	532	491	455	539	561
	Livestock	29	30	14	15	14	12	14	15
Yoakum	Irrigation	1,127	1,242	771	831	994	1,071	1,355	1,337
	Livestock	12	12	8	10	10	10	9	14



EDWARDS-TRINITY (HIGH PLAINS) GAM

Land Use With 1994 Irrigated Lands

Figure 38



EDWARDS-TRINITY (HIGH PLAINS) GAM

LANDSAT Image Showing Irrigated Acreage

Figure 39

No municipal or rural domestic pumping estimates are available for the Edwards-Trinity (High Plains) Aquifer in Texas. Rural domestic users would likely use the shallowest source of water for their limited needs, which would be the Southern Ogallala Aquifer. Although a number of municipalities overlie the Edwards-Trinity (High Plains) Aquifer, these, like the vast majority of other users, obtain their water supply from the Southern Ogallala Aquifer, supplemented in larger towns by imported water from the Canadian River Municipal Water Authority.

Estimated pumping from the Edwards-Trinity (High Plains) Aquifer in New Mexico is not available from published sources but is believed to be small. Cooper (1960) investigated the water resources of the Causey-Lingo area of New Mexico, which is just west of the state line where it is intersected by the Cochran-Bailey County line. Cooper (1960) believed that the principal water-bearing sediments in this area were unconsolidated sand and gravel of Cretaceous age. However, this is the same region in which Fallin (1989) identified a paleochannel where Cretaceous sediments had been eroded away and subsequently filled in with Ogallala Formation sediments. Pumping for irrigated agriculture in the Causey-Lingo area, therefore, is believed to be from the Southern Ogallala Aquifer for the most part. Although some small amounts of water are probably used for agriculture or other purposes in New Mexico, pumping from the Edwards-Trinity (High Plains) Aquifer was assumed to be negligible.

4.7.1 Discharge from Springs

The most complete documentation of discharge from springs in the Texas portion of the study area is provided by Brune (1981, 2002), who documents a number of measurements made during the 1970s and provides some historical estimates, measurements, or anecdotal evidence of earlier spring flows. Flows reported by Brune (1981, 2002) for springs in the study area range from seeps and trickles up to substantial flows on the order of hundreds of gallons per minute (gpm). The springs within the Texas portion of the study area documented by Brune (1981, 2002) and those within the New Mexico portion of the study area documented by White and Kues (1992) are illustrated in Figure 35 and listed in Table 3. The discharge values provided by Brune (1981, 2002) are, for the most part, viewed as general estimates of variable quality. Due to the lack of rigorous measurements conducted through time, as well as the general difficulty of accurately measuring flow at many springs in the study area, the magnitude of reported discharge values in Table 3 should be considered only a general guideline of the magnitude of discharge for any given spring.

In addition to the springs documented by Brune (1981, 2002), many others springs may exist or likely existed in the past. Although numerous springs are documented along the eastern escarpment, many springs also exist west of the escarpment along the major draws and their tributaries that incise the plains (fig. 35); these springs are Ogallala springs. Other springs occur west of the escarpment within the significant topographic depressions that contain salt lakes. Cretaceous rocks (most often Duck Creek or Kiamichi Formation) often crop out along the western and northwestern margins of the salt lake depressions. Springs along the salt lakes may discharge water from the Edwards-Trinity (High Plains) Aquifer, at least at some locations. Results of the Southern Ogallala GAM (Blandford and others, 2003) indicate that, under predevelopment conditions, approximately 40 to 50 percent of the groundwater discharge from the Ogallala Aquifer was from springs along the major draws and their tributaries and at salt lakes.

Table 3. Summary of Southern High Plains Springs
Page 1 of 9

County	Number	Name	Geologic Unit	Date Measured	Flow (L/s)	Flow (cfd)	Flow (gpm)
Andrews	1	No name		---	---	---	---
	2	No name		---	---	---	---
	3	No name	Ogallala	---	---	---	---
	4	No name		---	---	---	---
	5	No name		---	---	---	---
	6	Whalen Lake		---	---	---	---
	8	Baird Springs	Ogallala	3/21/1977	0.06	183	1
	8	Baird Springs	Ogallala	4/19/1979	0.1	305	1.6
Armstrong	7	Pleasant Springs		4/1/1940	9.5	28,983	150.6
	7	Pleasant Springs		8/7/1978	1.2	3,661	19
Bailey	7	Barnett Spring		---	---	---	---
	8	White Springs		1977	0.06	183	1
	9	No name		---	---	---	---
	10	No name		---	---	---	---
	12	No name	Ogallala	---	---	---	---
	13	Alkali Springs	Ogallala	1936	0.03	92	0.5
	14	No name		1936	0.03	92	0.5
Briscoe	5	Deer Springs		9/9/1946	19	57,966	301.2
	5	Deer Springs		6/23/1971	1.7	5,186	26.9
	5	Deer Springs		9/4/1978	1.3	3,966	20.6
	6	Turkey Springs		9/9/1946	25	76,271	396.3
	6	Turkey Springs		6/23/1971	3.1	9,458	49.1
	6	Turkey Springs		9/4/1978	2.5	7,627	39.6

L/s = Liters per second
cfd = Cubic feet per day
gpm= Gallons per minute
--- = Data not available

Table 3. Summary of Southern High Plains Springs
Page 2 of 9

County	Number	Name	Geologic Unit	Date Measured	Flow (L/s)	Flow (cfd)	Flow (gpm)
Briscoe (cont.)	7	Cedar Springs		9/9/1946	16	48,814	253.6
	7	Cedar Springs		6/23/1971	1.4	4,271	22.2
	7	Cedar Springs		9/4/1978	1	3,051	15.9
	8	No name	Tule and Dockum	9/10/1946	13	39,661	206.1
	9	No name		9/10/1946	9.5	28,983	150.6
	10	Mayfield Spring	Tule	---	---	---	---
	13	Las Lenquas Springs	Ogallala	10/19/1967	19	57,966	301.2
	13	Las Lenquas Springs	Ogallala	9/5/1978	1.9	5,797	30.1
Castro	1	No name		---	---	---	---
	2	No name	Ogallala	---	---	---	---
	3	No name		---	---	---	---
	4	No name		---	---	---	---
	5	Flagg Springs		---	---	---	---
Cochran	1	No name		---	---	---	---
	4	No name	Ogallala	---	---	---	---
	5	Silver Springs		4/13/1977	0.63	1,922	10
	5	Silver Springs		10/21/1978	0.05	153	0.8
	6	No name		---	---	---	---
	8	Morton Springs		---	---	---	---
Crosby	1	Cottonwood Springs		1938	13	39,661	206.1
	1	Cottonwood Springs		1975	0.32	976	5.1
	2	Couch Springs		11/2/1938	54	164,746	855.9
	3	Rock House Springs		1938	14	42,712	221.9

L/s = Liters per second
cfd = Cubic feet per day
gpm= Gallons per minute
--- = Data not available

Table 3. Summary of Southern High Plains Springs
Page 3 of 9

County	Number	Name	Geologic Unit	Date Measured	Flow (L/s)	Flow (cfd)	Flow (gpm)
Crosby (cont.)	3	Rock House Springs		1975	0.62	1,892	9.8
	11	Ericson Springs	Ogallala	---	---	---	---
Dawson	1	Rock Crusher or Turner Springs	Lower Cretaceous	6/28/1938	0.19	580	3.0
	1	Rock Crusher or Turner Springs	Lower Cretaceous	6/14/1975	0.63	1,922	9.99
	1	Rock Crusher or Turner Springs	Lower Cretaceous	10/4/1978	1.9	5,797	30.1
	5	No name		---	---	---	---
	6	No name		---	---	---	---
Deaf Smith	1	Fowler Springs		---	---	---	---
	2	Parker Springs		---	---	---	---
	4	Big Springs		1937	0.95	2,898	15.1
	4	Big Springs		5/1977	0.32	976	5.1
	5	Escarbada		---	---	---	---
	6	Punta de Agua or Source of Water		---	---	---	---
	7	Sulphur Springs		---	---	---	---
	9	Ojita de Garcia or Little Garcia Springs	Dockum	---	---	---	---
Ector	1	No name		---	---	---	---
Floyd	1	Massie Springs		---	---	---	---
	2	Blue Hole Springs	Ogallala	11/4/1938	14	42,712	221.9
	2	Blue Hole Springs	Ogallala	12/10/1968	13	39,661	206.1
	2	Blue Hole Springs	Ogallala	6/18/1975	0.63	1,922	10
	2	Blue Hole Springs	Ogallala	7/16/1978	0	0	0
	4	Montgomery Springs		---	---	---	---

L/s = Liters per second
cfd = Cubic feet per day
gpm= Gallons per minute
--- = Data not available

Table 3. Summary of Southern High Plains Springs
Page 4 of 9

County	Number	Name	Geologic Unit	Date Measured	Flow (L/s)	Flow (cfd)	Flow (gpm)
Gaines	1	Buffalo Springs		1963	0.01	18	0.1
	2	No name		---	---	---	---
	5	Balch Springs		3/18/1977	2.5	7,627	39.6
	6	No name		---	---	---	---
	7	No name		---	---	---	---
	8	Ward's Well		---	---	---	---
	10	Boar's Nest Springs		---	---	---	---
Hale	1	No name		---	---	---	---
	2	No name		---	---	---	---
	3	No name	Ogallala	---	---	---	---
	5	Eagle Springs		---	---	---	---
	6	Running Water Springs		---	---	---	---
	7	Jones Springs		---	---	---	---
	9	Morrison Springs		---	---	---	---
Hockley	10	Norfleet Springs		---	---	---	---
	2	Devil's Ink Well	Ogallala	---	---	---	---
	3	No name	Ogallala	---	---	---	---
	4	No name		---	---	---	---
	5	Yellow House Springs		---	---	---	---
	6	No name		---	---	---	---
Howard	12	No name		---	---	---	---
Lamb	1	King Springs	Ogallala	---	---	---	---
	2	No name		---	---	---	---

L/s = Liters per second
cfd = Cubic feet per day
gpm= Gallons per minute
--- = Data not available

Table 3. Summary of Southern High Plains Springs
Page 5 of 9

County	Number	Name	Geologic Unit	Date Measured	Flow (L/s)	Flow (cfd)	Flow (gpm)
Lamb (cont.)	5	Sod House Spring		---	---	---	---
	8	No name		---	---	---	---
	9	Rocky Ford Springs		5/1/1952	4.7	14,339	74.5
	9	Rocky Ford Springs		8/28/1952	0	0	0
	9	Rocky Ford Springs		11/1952	0	0	0
	10	No name		---	---	---	---
	11	Fieldton Springs		---	---	---	---
	12	Hart Springs		---	---	---	---
	13	Bull Springs	Tahoka	10/3/1978	Seeps		
	14	Roland Springs and Ponds	Ogallala	10/3/1978	Seeps		
	15	Illusion Springs	Tahoka	10/4/1978	1.6	4,881	25.4
	16	Yellow Springs	Tahoka	10/4/1978	0.14	427	2.2
	17	No name	Ogallala	10/4/1978	0.71	2,166	11.3
	19	Green Springs		10/21/1978	0.75	2,288	11.9
Lea	1	No name		---	---	---	---
	2	Monument Spring		---	---	---	---
Lubbock	1	Buffalo Springs		1937	8.5	25,932	134.7
	1	Buffalo Springs		1939	19	57,966	301.2
	1	Buffalo Springs		1969	96	292,882	1521.6
	1	Buffalo Springs		1970	93	283,729	1474.1
	1	Buffalo Springs		1971	85	259,322	1347.3
	1	Buffalo Springs		1972	57	173,898	903.5
	1	Buffalo Springs		1973	42	128,136	665.7

L/s = Liters per second
cfd = Cubic feet per day
gpm= Gallons per minute
--- = Data not available

Table 3. Summary of Southern High Plains Springs
Page 6 of 9

County	Number	Name	Geologic Unit	Date Measured	Flow (L/s)	Flow (cfd)	Flow (gpm)
Lubbock (cont.)	1	Buffalo Springs		1974	42	128,136	665.7
	1	Buffalo Springs		1975	62	189,153	982.7
	1	Buffalo Springs		1976	85	259,322	1347.3
	2	Lubbock Lake		---	---	---	---
Lynn	1	Saleh Lake and Seeps	Ogallala	---	---	---	---
	3	Tahoka Springs	Ogallala	12/13/1974	6	18,305	95.1
	4	Double Lakes Springs	Tahoka	12/12/1975	1	3,051	15.9
	4	Double Lakes Springs	Tahoka	9/9/1978	Seeps		
	5	Guthrie Springs		---	---	---	---
	6	Gooch Springs		10/26/1978	0.78	2,380	12.4
	7	New Moore Springs	Ogallala	12/13/1975	7.5	22,881	118.9
	7	New Moore Springs	Ogallala	10/25/1978	5.7	17,390	90.3
	8	No name	Tahoka	---	---	---	---
	9	Frost Springs		10/26/1978	4.2	12,814	66.6
Martin	2	No name	Ogallala	---	---	---	---
	3	Mulkey Springs		---	---	---	---
	4	Baldwin Springs		---	---	---	---
	5	Mustang Springs		---	---	---	---
	6	No name	Ogallala	---	---	---	---
	7	Kilpatrick Springs		---	---	---	---
	8	No name	Ogallala	---	---	---	---
	9	Soda Springs	Ogallala	4/20/1979	3.8	11,593	60.2
	10	Sulpher Springs	Ogallala	1936	0.63	1,922	10

L/s = Liters per second　　gpm= Gallons per minute
cfd = Cubic feet per day　　--- = Data not available

Table 3. Summary of Southern High Plains Springs
Page 7 of 9

County	Number	Name	Geologic Unit	Date Measured	Flow (L/s)	Flow (cfd)	Flow (gpm)
Martin (cont.)	10	Sulpher Springs	Ogallala	4/20/1979	0.13	397	2.1
Midland	5	No name		---	---	---	---
	7	No name		---	---	---	---
	8	No name	Quaternary Sand	---	---	---	---
	9	Mustang Springs		---	---	---	---
Motley	4	Burleson Springs		1938	8.8	26,847	139.5
	4	Burleson Springs		1968	8.8	26,847	139.5
Oldham	21	Rocky Dell Springs		---	---	---	---
	27	Joaquin Spring		---	---	---	---
	28	George Springs		---	---	---	---
	37	Cheyenne		1938	0.03	92	0.5
Parmer	1	No name	Ogallala	---	---	---	---
	2	No name	Ogallala	---	---	---	---
	5	No name		---	---	---	---
Quay	1	No name		---	---	---	---
Randall	5	South Cita Springs		8/10/1978	7.5	22,881	118.9
	11	T-Anchor Springs		---	---	---	---
	12	No name		---	---	---	---
	13	Thompson Springs		---	---	---	---
	14	Long Springs		---	---	---	---
	15	Carruth Springs		---	---	---	---
	16	No name		---	---	---	---
	17	Dean Springs		---	---	---	---

L/s = Liters per second
cfd = Cubic feet per day
gpm= Gallons per minute
--- = Data not available

Table 3. Summary of Southern High Plains Springs
Page 8 of 9

County	Number	Name	Geologic Unit	Date Measured	Flow (L/s)	Flow (cfd)	Flow (gpm)
Roosevelt	1	Spring No. 56		---	---	---	---
	2	Portales Spring		---	---	---	---
Swisher	2	Hackberry Springs		---	---	---	---
	4	Rogers Springs	Dockum	11/12/1945	0.32	976	5.1
	4	Rogers Springs	Dockum	9/7/1978	Seeps		
	5	Dead Horse Springs		---	---	---	---
	9	Dawson Springs		---	---	---	---
	11	No name		---	---	---	---
	12	Edwards Springs		---	---	---	---
	13	Poff Springs		---	---	---	---
	14	No name		---	---	---	---
	17	Maupin Springs		---	---	---	---
	18	Hardy Springs		---	---	---	---
Terry	1	Mound Springs		12/13/1975	4	12,203	63.4
	2	No name		---	---	---	---
	3	No name	Ogallala	---	---	---	---
	4	No name		---	---	---	---
	6	Rich Springs	Tahoka	1900	19	57,966	301.2
	6	Rich Springs	Tahoka	10/23/1978	1.2	3,661	19
	6	Rich Springs	Tahoka	5/18/1938	0.63	1,922	10
	7	No name		---	---	---	---
	9	No name		---	---	---	---
	10	No name		---	---	---	---

L/s = Liters per second
cfd = Cubic feet per day
gpm= Gallons per minute
--- = Data not available

Table 3. Summary of Southern High Plains Springs
Page 9 of 9

County	Number	Name	Geologic Unit	Date Measured	Flow (L/s)	Flow (cfd)	Flow (gpm)
Terry (cont.)	11	No name	Tahoka	---	---	---	---
	13	No name		---	---	---	---
Yoakum	3	No name		---	---	---	---
	5	No name		---	---	---	---
	6	No name		---	---	---	---

L/s = Liters per second
cfd = Cubic feet per day
gpm= Gallons per minute
--- = Data not available

Table 3 lists one spring specifically identified by Brune (1981, 2002) as emanating from lower Cretaceous rocks: Rock Crusher or Turner spring in Dawson County. Estimated discharge from this spring ranges from 3 gpm in 1938 to 30 gpm in 1978. Other springs listed in Table 3, such as Buffalo Springs along the margin of Cedar Lake in western Gaines County, likely emanate from Cretaceous rocks as well. Recorded discharge at Buffalo Springs is only 0.1 gpm in 1963. Although it is not possible to distinguish between Ogallala and Edwards-Trinity (High Plains) Aquifer springs based on existing information, at springs identified in areas where Cretaceous rocks outcrop, some unknown portion of spring flow likely occurs, or occurred, from the Edwards-Trinity (High Plains) Aquifer.

During 1938 and 1939, White and others (1946) conducted a detailed survey of groundwater discharge along a 75-mile stretch of the eastern escarpment, from Quitaque Creek to the Double Mountain Fork of the Brazos River across parts of Briscoe, Floyd, Motley, Dickens, and Crosby Counties. They also conducted a study of groundwater discharge within a 9,000-mi^2 area extending approximately 120 mi to the northwest of this portion of the eastern escarpment. This region contains isolated subcrops of Edwards-Trinity (High Plains) Aquifer, but Cretaceous rocks do not exist along the eastern escarpment within this region. As part of their study, White and others (1946) measured or estimated the discharge from all springs or seeps and estimated the amount of groundwater discharged through evapotranspiration along the escarpment and draw bottoms. For this portion of the study area, they estimated a total groundwater discharge of 25,000 to 30,000 ac-ft/yr (White and others, 1946).

4.7.2 Discharge to Streams and Lakes

As discussed in Section 4.7.1, discharge to salt lakes occurs through springs along the margins of the salt lake basins, some of which emanate from Cretaceous rocks. Observed or estimated discharge rates for these and other springs are provided in Table 3. Along the eastern margin of the study area, spring discharge prior to large-scale groundwater pumping was sufficient to form small perennial streams, as discussed in Section 4.5 (*Rivers, Streams, Springs, and Lakes*). Where lower Cretaceous rocks exist along the outcrop, such discharge was likely a combination of Southern Ogallala and Edwards-Trinity (High Plains) Aquifer water, or possibly only Edwards-Trinity (High Plains) Aquifer water (fig. 16). Quantitative estimates of the volumes of discharge to these streams are not available.

4.7.3 Evapotranspiration

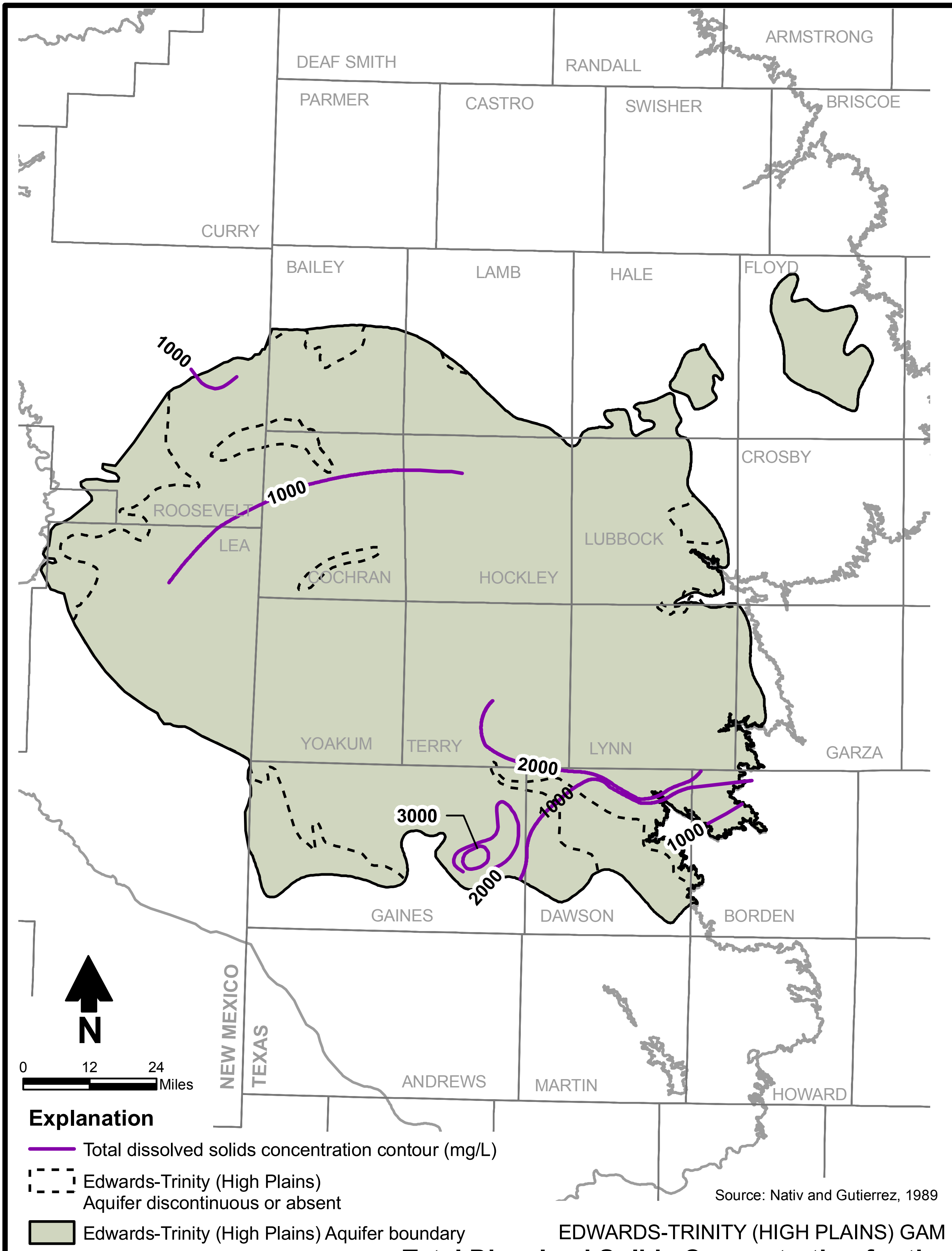
Discharge by evapotranspiration directly from the water table of the Edwards-Trinity (High Plains) Aquifer is believed to be negligible. Water table conditions within the aquifer likely occur only over small areas, and the water table would be at least several tens of feet below land surface, except in the immediate vicinity of springs.

4.8 Water Quality

The TDS of water in the Edwards-Trinity (High Plains) Aquifer generally ranges from about 1,000 to 2,000 mg/L, although some portions of the aquifer contain water that exceeds 3,000 mg/L (Nativ and Gutierrez, 1988; Fallin, 1989). For example, the TDS of Edwards-Trinity (High Plains) Aquifer water across much of central and southern Lynn County, northern Dawson

County, southeastern Terry County, and eastern Gaines County is 2,000 mg/L or greater. The highest TDS concentrations in the aquifer appear to occur at and in the general vicinity of salt lakes. Although only limited data are available for much of the aquifer, a map of TDS within the Edwards-Trinity (High Plains) Aquifer is provided in Figure 40.

Nativ and Gutierrez (1988) consider the potential for seepage between aquifer units based on water quality and interpreted hydraulic heads. TDS concentrations in the Southern Ogallala Aquifer are similar to those of the Edwards-Trinity (High Plains) Aquifer where the aquifers are coincident. North of the Edwards-Trinity (High Plains) Aquifer northern extent, however, Southern Ogallala Aquifer TDS concentrations are 400 mg/L or less. Nativ and Gutierrez (1988) note similarities of Southern Ogallala Aquifer water quality to Edwards-Trinity (High Plains) Aquifer water quality in Gaines and Lubbock Counties, and attribute the observations to upward cross-formational flow. Tritium and delta oxygen 18 values observed within the Southern Ogallala and Edwards-Trinity (High Plains) Aquifers also indicate that significant cross-formational groundwater flow occurs between these aquifers.



Total Dissolved Solids Concentration for the Edwards-Trinity (High Plains) Aquifer

Figure 40

5.0 Conceptual Model of Groundwater Flow

This section presents the overall interpretation of how groundwater flow occurs within the aquifer and how the flow is affected by various sources and mechanisms of groundwater recharge and discharge, as well as by the physical properties of the aquifer. The conceptual model of groundwater flow is presented graphically, in cross section form, in Figure 41.

As discussed in the Section 4.4 (*Recharge*), the Edwards-Trinity (High Plains) Aquifer receives groundwater inflow primarily by downward leakage from the overlying Southern Ogallala Aquifer. The greatest potential for exchange of water between aquifers likely occurs where the shales and clays of the Duck Creek and Kiamichi Formations are absent, thin, or relatively permeable (fig. 32), particularly where past erosion has removed the Duck Creek and Kiamichi Formations entirely and groundwater in the Ogallala Formation is in direct contact with the Edwards, Comanche Peak or Antlers Formations (fig. 41).

Water within the Edwards-Trinity (High Plains) Aquifer generally occurs under confined conditions, and therefore the direction of groundwater flow and the water level that would be observed in wells is defined by the potentiometric surface. The potentiometric surface of the Edwards-Trinity (High Plains) Aquifer slopes to the southeast, similar to the water table of the overlying Southern Ogallala Aquifer, and the regional direction of groundwater flow is therefore from northwest to southeast. The direction of groundwater flow is affected locally by points of discharge, such as springs and wells, and aquifer properties, such as thickness and hydraulic conductivity. The amount of existing water level data for the aquifer, however, is generally insufficient to determine detailed groundwater flow directions.

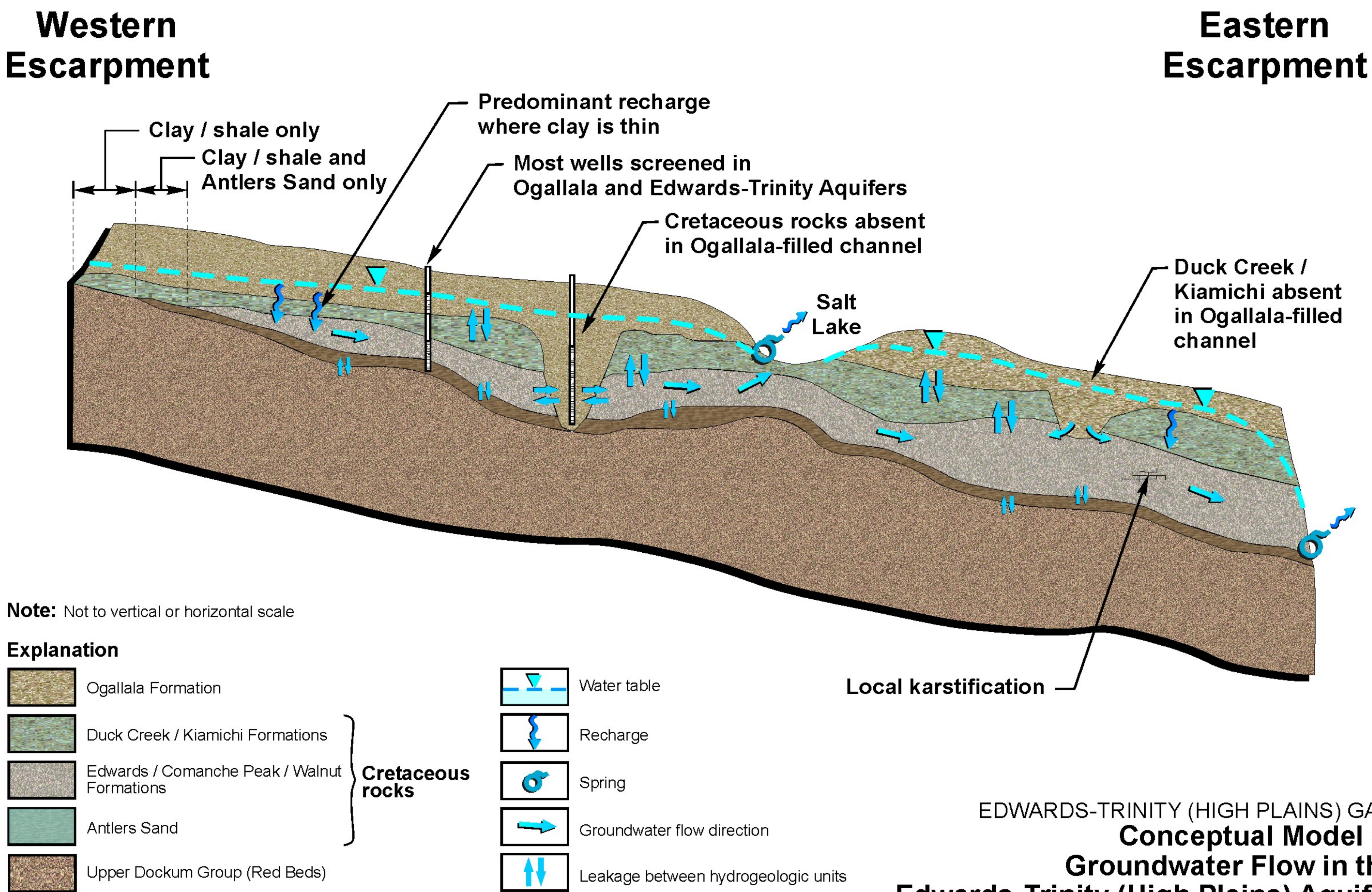
Seepage between hydrogeologic units occurs in accordance with the magnitude and direction (upward or downward) of the vertical hydraulic gradient and the vertical hydraulic conductivity of the sediments. Although available water level data are insufficient to determine in detail the magnitude and direction of leakage, some general conclusions can be made based on existing data:

- To the west and northwest, the direction of vertical leakage is probably downward, and these regions are ones of predominant recharge to the Edwards-Trinity (High Plains) Aquifer.

- At and in the immediate vicinity of springs that occur along the margins of salt lakes, there is a vertically upward component of groundwater flow.

- At springs that occur along the escarpment, the hydraulic gradient is laterally outward, and there is probably a downward component of seepage from overlying Southern Ogallala Aquifer sediments.

Throughout most of the aquifer area, vertical seepage may be upward or downward, depending on the relative difference between Edwards-Trinity (High Plains) and Southern Ogallala Aquifer water levels. Comparison of the 1990 potentiometric surface map presented in Section 4.3 of this report and the one presented in Blandford and others (2003) indicates a downward hydraulic gradient from the Southern Ogallala Aquifer to the Edwards-Trinity (High Plains) Aquifer in



EDWARDS-TRINITY (HIGH PLAINS) GAM

Conceptual Model of Groundwater Flow in the Edwards-Trinity (High Plains) Aquifer

Figure 41

Bailey and Yoakum Counties and very similar water levels between the two aquifers in Terry and Lynn Counties. Water levels available for comparison, however, are very limited.

Seepage between all aquifer units is locally enhanced where wells are present. Most wells on the Southern High Plains that penetrate the Edwards-Trinity (High Plains) Aquifer are also screened in the overlying Southern Ogallala Aquifer (fig. 41). Since most wells on the Southern High Plains are drilled for irrigation supply, there is typically no annular seal placed between aquifer units, and water can freely move up or down the annular space of the well in accordance with the local vertical hydraulic gradient, as well as within the well bore when the well is not pumping. Due to the relatively few number of wells completed in the Edwards-Trinity (High Plains) Aquifer in Texas, this component of seepage may be relatively small, but it will affect observed water levels in Edwards-Trinity (High Plains) Aquifer wells (i.e., the observed water levels most likely reflect, to an unknown degree, a combined Edwards-Trinity [High Plains] Aquifer and Southern Ogallala Aquifer water level). In the New Mexico portion of the aquifer, thousands of shot holes have been drilled through the Ogallala Formation into the Edwards-Trinity (High Plains) Aquifer for oil and gas exploration. Each shot hole is a potential conduit for groundwater flow between aquifer units, and the number of holes may have reduced or eliminated potential differences in hydraulic head between the Ogallala and Edwards-Trinity (High Plains) Aquifers (Fallin, 1989).

Discharge from the Edwards-Trinity (High Plains) Aquifer occurs at springs and seeps along the eastern caprock escarpment and at a number of large salt lakes west of the escarpment, as upward leakage to the Southern Ogallala Aquifer where the hydraulic head in the Edwards-Trinity (High Plains) Aquifer is greater than that in the Ogallala Aquifer, and as discharge to wells, primarily for irrigation and domestic supply. Return flow from Edwards-Trinity (High Plains) Aquifer irrigation water will recharge the overlying Ogallala Aquifer, and probably very little, if any, Edwards-Trinity (High Plains) Aquifer water pumped for irrigation or other uses actually returns to the aquifer as return flow.

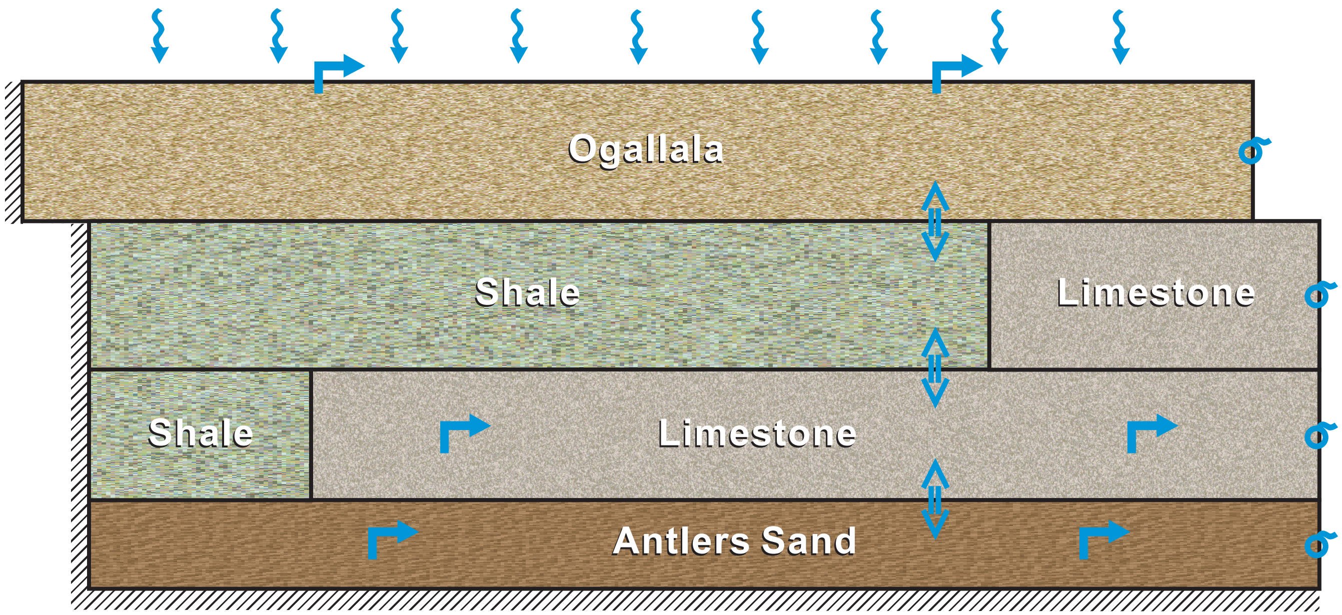
Some of the same features identified as primary sources of recharge are also regions of discharge under post-development conditions. The paleochannels filled by Ogallala sediments are heavily pumped for irrigation, and it is likely that irrigation pumping of Ogallala water within the paleochannels (fig. 41) actually draws water from the Edwards-Trinity (High Plains) Aquifer. Whereas regions where the clay-rich Duck Creek and Kiamichi Formations have been removed by erosion may have served as zones of recharge, the same areas may have changed to regions of Edwards-Trinity (High Plains) Aquifer discharge with the onset of large-scale pumping for irrigation in the Southern Ogallala Aquifer.

Some amount of groundwater inflow to, or outflow from, the Edwards-Trinity (High Plains) Aquifer also occurs due to seepage from permeable layers of the Dockum Group (Nativ and Gutierrez, 1988). Exchange of water between the Edwards-Trinity (High Plains) and Dockum Aquifers, however, is poorly defined and is believed to be small compared to the amount of seepage from or to the Southern Ogallala Aquifer. For the purposes of this study, seepage between the Edwards-Trinity (High Plains) and Dockum Aquifers is assumed to be negligible, although sensitivity analyses are conducted to evaluate the effects of this assumption on the model (Sections 8.5 and 9.5).

Groundwater flow in the aquifer is also significantly affected by aquifer properties. Changes in aquifer storage are governed by storage coefficients indicative of confined groundwater conditions, which are generally 100 to 1,000 times lower than the specific yield of approximately 15 percent commonly assumed for the overlying Southern Ogallala Aquifer. Since groundwater within the Edwards and Comanche Peak limestones occurs primarily in fractures and solution channels, the specific storage (the volume of water released per unit volume of aquifer per unit decline in hydraulic head) of these units is probably less than that of the underlying Antlers Sand, which has some significant primary porosity.

Available information on aquifer hydraulic conductivity is insufficient to develop a detailed correlation with geology. However, observed hydraulic conductivity values for the combined Edwards, Comanche Peak and Antlers Formations are generally equivalent to the medium to low range of values determined for the overlying Ogallala Formation. Very high hydraulic conductivities have been observed in limited, highly karstified zones of the Edwards and Comanche Peak limestones, but available information suggests that such high-permeability zones are not extensive on a regional scale.

Implementation of the conceptual model into a numerical model of groundwater flow within the Southern Ogallala and Edwards-Trinity (High Plains) Aquifers is illustrated in Figure 42. The numerical model consists of four model layers. Model layer 1 represents the Southern Ogallala Aquifer, and model layer 4 represents the Antlers Sand. Model layer 2 represents shale across much of the model domain, or where shale is predominantly absent, the top 5 feet of limestone. Model layer 3 represents limestone over most of the model domain, or where limestone is absent, the bottom 5 feet of shale. Additional details regarding model construction are provided in Section 6.0.



Explanation

- Cross-formational flow
- Recharge
- Discharge by springs and seeps
- No-flow boundary
- Pumping

EDWARDS-TRINITY (HIGH PLAINS) GAM

Schematic Illustration of the Translation of the Conceptual Model of Groundwater Flow into the Numerical Model

Figure 42

6.0 Model Design

Model design is the process of translating the conceptual model of groundwater flow into a mathematical (in this case numerical) model. The model design consists of selecting the computer code used to simulate groundwater flow, developing the model grid that the computations will be based on, assigning all input parameters and fluxes (e.g., pumping and recharge) to the model grid, and implementing appropriate boundary conditions to represent internal or external model boundaries.

6.1 Code and Processor

In accordance with TWDB specifications for the GAMs, the USGS computer code commonly known as MODFLOW-2000 (Harbaugh and others, 2000) was applied to simulate groundwater flow in the Edwards-Trinity (High Plains) and Southern Ogallala Aquifers. MODFLOW-2000 has been applied extensively to simulate groundwater flow throughout the world for numerous hydrogeological settings and different types of aquifers. The code is well tested, validated, and documented, and it is in the public domain. It also is versatile in that it can simulate a variety of boundary conditions (e.g., prescribed and general head, rivers, drains, and evapotranspiration) and aquifer types (e.g., confined or unconfined). All MODFLOW-2000 features (packages) applied during development of the Edwards-Trinity (High Plains) Aquifer GAM are publicly available.

The software package Groundwater Vistas Version 5.17 (Rumbaugh and Rumbaugh, 2007) was applied to facilitate model development, calibration, and analysis of simulation results. This proprietary software package is not part of MODFLOW-2000, but was developed to facilitate the development of groundwater models using MODFLOW.

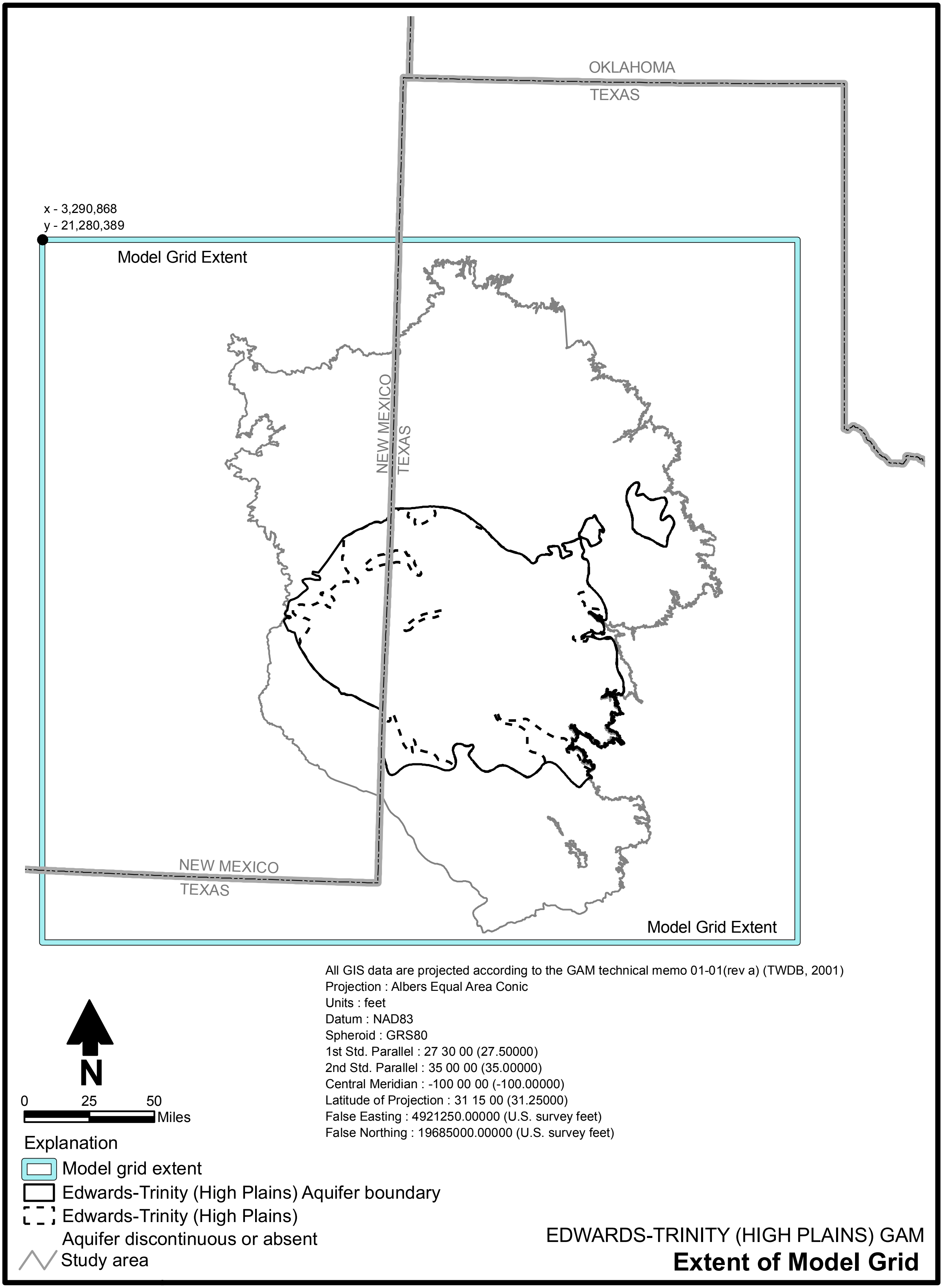
MODFLOW-2000 requires that model inputs be provided in a consistent set of units. In accordance with TWDB requirements, all model inputs are provided in length and time units of feet and days, respectively.

6.2 Layers and Grid

Discretization is the process of dividing the study area into a series of model blocks or cells, referred to as the model grid. Since the Edwards-Trinity (High Plains) GAM is a three-dimensional model, the model grid consists of multiple model layers. The model grid encompasses both the Edwards-Trinity (High Plains) and Southern Ogallala Aquifers.

The model grid for the Edwards-Trinity (High Plains) Aquifer GAM consists of 313,200 cells (270 rows by 290 columns by 4 layers), of which 57,873 are active. An active model cell is one where either a boundary condition is prescribed or a hydraulic head is simulated. The model grid is divided into 1-mi^2 cells in the horizontal dimension.

The areal extent of the model grid and pertinent specifications are illustrated in Figure 43; it is the same as that applied in the Southern Ogallala GAM (Blandford and others, 2003). The entire model grid is not plotted in Figure 43 because the individual cells would be nearly indiscernible at the scale of the map. However, the model grid for Lamb and Hale Counties is provided in Figure 44 as an illustration of the relative size of individual model cells.

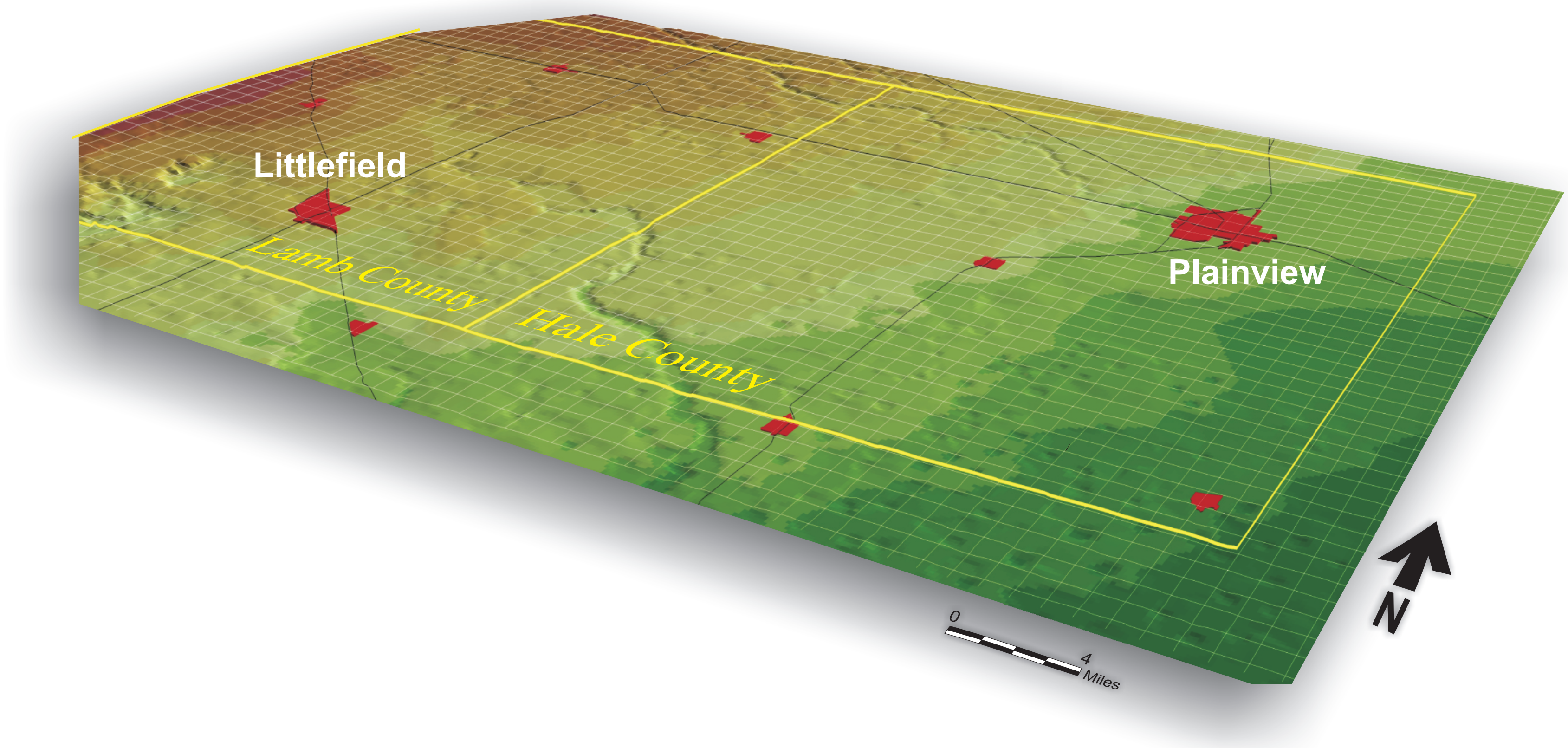


All GIS data are projected according to the GAM technical memo 01-01(rev a) (TWDB, 2001)
Projection : Albers Equal Area Conic
Units : feet
Datum : NAD83
Spheroid : GRS80
1st Std. Parallel : 27 30 00 (27.50000)
2nd Std. Parallel : 35 00 00 (35.00000)
Central Meridian : -100 00 00 (-100.00000)
Latitude of Projection : 31 15 00 (31.25000)
False Easting : 4921250.00000 (U.S. survey feet)
False Northing : 19685000.00000 (U.S. survey feet)

EDWARDS-TRINITY (HIGH PLAINS) GAM

Extent of Model Grid

Figure 43



Note: Scale based on perspective view

EDWARDS-TRINITY (HIGH PLAINS) GAM

Illustration of Model Grid for Lamb and Hale Counties

Figure 44

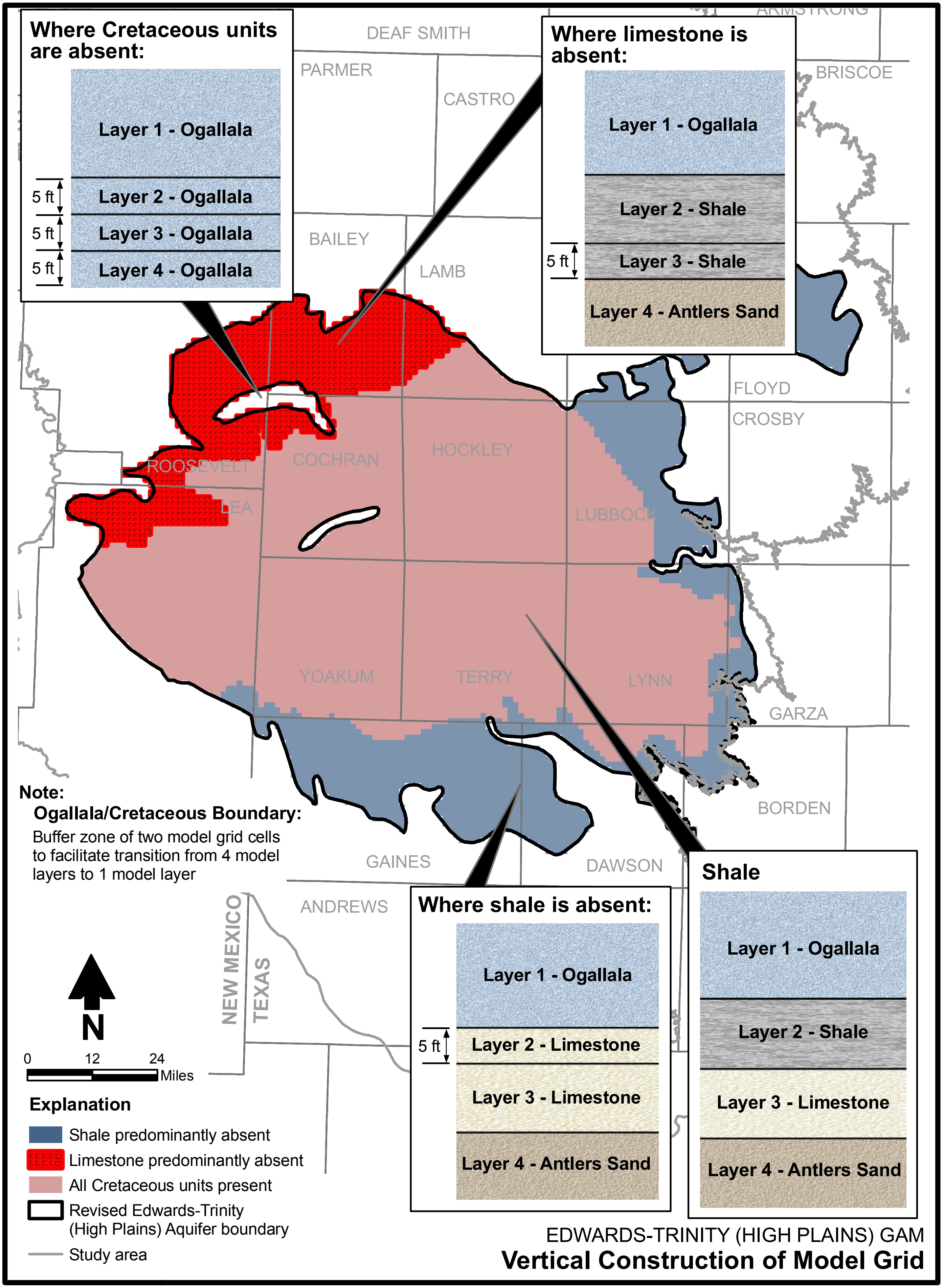
In the vertical dimension, the active model domain consists of 4 model layers of variable thickness designed to represent the Southern Ogallala and Edwards-Trinity (High Plains) Aquifers. Model layers are numbered from shallowest to deepest. Model layer 1, the shallowest layer, is unconfined, while model layers 2 through 4 are mixed type, meaning that they are treated as confined if the simulated hydraulic head is above the top of the layer and unconfined if the simulated hydraulic head occurs between the top elevation and bottom elevation of the layer. If the simulated hydraulic head drops below the bottom of a given layer, the model cell(s) at which this occurred is called "dry" and is automatically removed from the simulation.

For portions of the model domain where the full thickness of the lower Cretaceous geologic section is present, the model layers are conceptualized as follows:

- Model layer 1 represents the Southern Ogallala Aquifer.
- Model layer 2 represents the combined thickness of Cretaceous shale, primarily composed of the Duck Creek and Kiamichi Formations.
- Model layer 3 represents the combined thickness of the predominantly limestone rocks (primarily Edwards and Comanche Peak Formations).
- Model layer 4 represents the Antlers Sand.

At some locations, one or more of the hydrogeologic units defined above may be missing; therefore, an approach was developed to assign appropriate material types and hydraulic properties to each of the active model layers, as illustrated in Figure 45. Within the southern and eastern portions of the Edwards-Trinity (High Plains) Aquifer, significant thicknesses of shale are absent and Ogallala sediments lie directly on limestone. In these areas model layer 2 was assigned to be 5 feet of limestone that occurs on top of the remaining thickness of limestone represented by model layer 3. In the far northwestern extent of the aquifer, limestone is generally absent and significant thicknesses of shale lie directly on top of Antlers Sand. In this area the thickness of model layer 3 was set to 5 feet with the properties of shale, and the remainder of the shale thickness was assigned to model layer 2. The Cretaceous formations have been eroded away entirely in two known areas: in southern Cochran County and along the border of Cochran and Bailey Counties extending into New Mexico (fig. 45). Within these two "islands" where Cretaceous rocks are absent, all four model layers represent the thickness of Ogallala sediments.

Outside the extent of the Edwards-Trinity (High Plains) Aquifer, only model layer 1 is active to simulate groundwater flow within the Southern Ogallala Aquifer. A transition zone of two model cells was implemented at the Edwards-Trinity (High Plains) Aquifer boundary to avoid an abrupt change from four active model layers to one. At the first model cell adjacent to, but outside, the Edwards-Trinity (High Plains) Aquifer boundary, model layers 1 through 3 are active, with assigned hydraulic properties equal to those of the Ogallala Aquifer. At the second model cell adjacent to, but outside, the Edwards-Trinity (High Plains) Aquifer boundary, model layers 1 and 2 are active, with assigned hydraulic properties equal to those of the Ogallala Aquifer.



Where Cretaceous units are absent:
Layer 1 - Ogallala
Layer 2 - Ogallala
Layer 3 - Ogallala
Layer 4 - Ogallala
5 ft
5 ft
5 ft
Where limestone is absent:
Layer 1 - Ogallala
Layer 2 - Shale
Layer 3 - Shale
Layer 4 - Antlers Sand
5 ft
Where shale is absent:
Layer 1 - Ogallala
Layer 2 - Limestone
Layer 3 - Limestone
Layer 4 - Antlers Sand
5 ft
Shale
Layer 1 - Ogallala
Layer 2 - Shale
Layer 3 - Limestone
Layer 4 - Antlers Sand
DEAF SMITH
PARMER
CASTRO
BRISCOE
BAILEY
LAMB
FLOYD
CROSBY
ROOSEVELT
COCHRAN
HOCKLEY
LEA
LUBBOCK
YOAKUM
TERRY
LYNN
GARZA
BORDEN
GAINES
DAWSON
ANDREWS
NEW MEXICO
TEXAS
Note:
Ogallala/Cretaceous Boundary:
Buffer zone of two model grid cells to facilitate transition from 4 model layers to 1 model layer
N
0 12 24 Miles
Explanation
Shale predominantly absent
Limestone predominantly absent
All Cretaceous units present
Revised Edwards-Trinity (High Plains) Aquifer boundary
Study area
EDWARDS-TRINITY (HIGH PLAINS) GAM
Vertical Construction of Model Grid

Figure 45

Figures 46 through 49 illustrate the active model cells and applied boundary conditions for model layers 1 through 4, respectively. The two-cell transition zone described above is evident in these figures, in two model cells for model layer 2 (fig. 47) and in one model cell for model layer 3 (fig. 48). There are no transition cells outside the extent of the Edwards-Trinity (High Plains) Aquifer for model layer 4 (fig. 49). Boundary conditions are discussed in Section 6.4 (*Model Boundaries*).

6.3 Initial Model Input Parameters

For the Edwards-Trinity (High Plains) Aquifer GAM, the initial model input parameters for model cells that represent the Southern Ogallala Aquifer were the same as the final model input parameters developed for the Southern Ogallala GAM (Blandford and others, 2003). Figures 50 through 52 illustrate the initial model input values for horizontal hydraulic conductivity, specific yield, and predevelopment recharge, respectively. The vertical hydraulic conductivity of the Southern Ogallala Aquifer sediments was assumed to be one-tenth of the horizontal hydraulic conductivity.

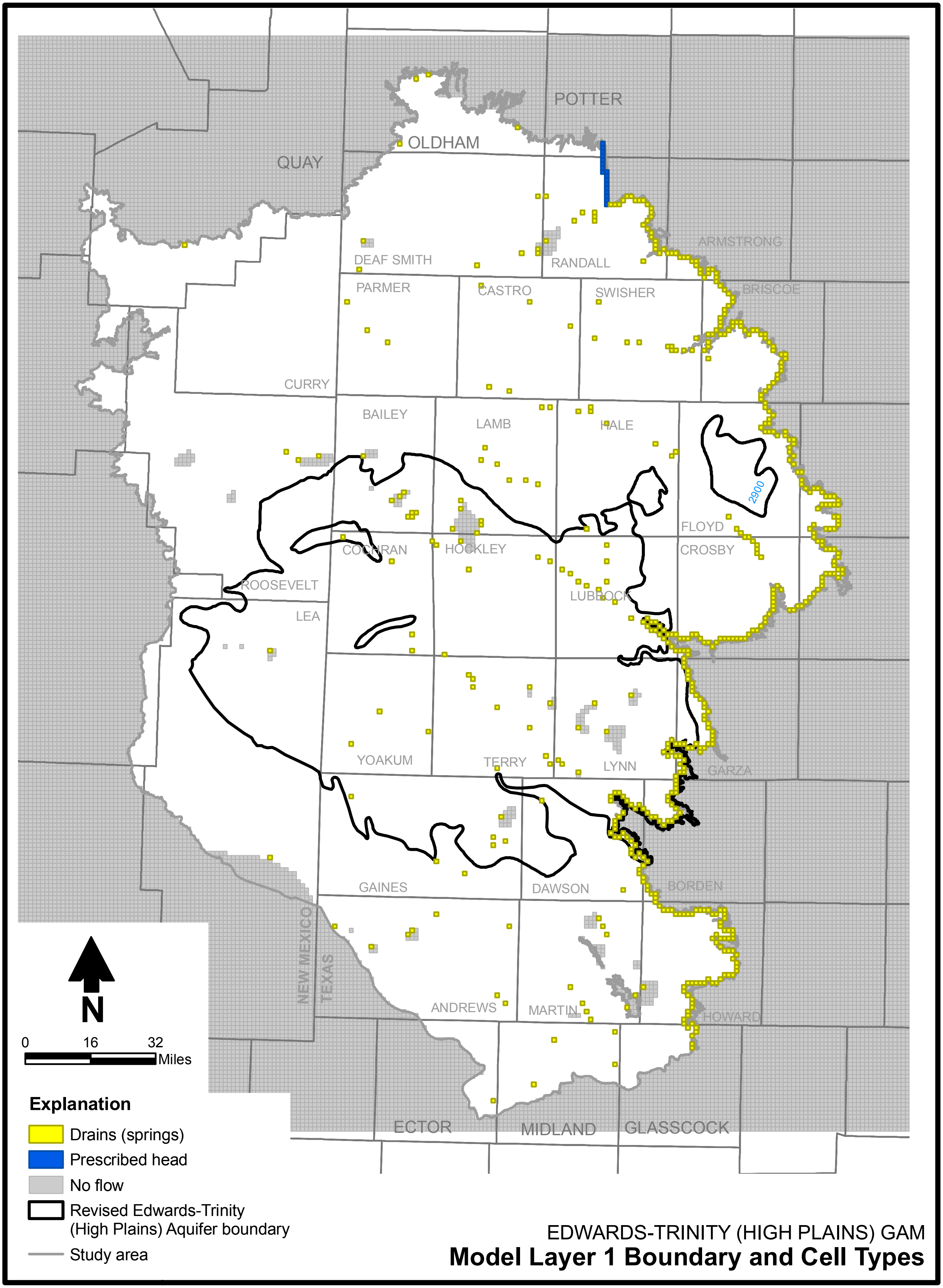
Comparison of Figures 50 and 51 with Figure 23 illustrates the approach followed by Blandford and others (2003), where aquifer hydraulic conductivity and specific yield are assigned higher values within paleochannels than within inter-channel regions. Comparison of Figure 52 with Figures 6 and 8 indicates that greater recharge is assigned within regions of lower-permeability soils and greater playa density. This approach is consistent with the conceptual model that recharge under predevelopment conditions occurred almost exclusively at playa lakes, and that recharge is greater in areas where playa density and runoff to playas is greater (low-permeability soils). Additional details and explanation of the derivation of these parameters are provided by Blandford and others (2003).

Initial model input parameters for the shale, limestone, and Antlers Sand hydrogeologic units had to be selected; these included horizontal hydraulic conductivity, vertical hydraulic conductivity, confined storage coefficient, and specific yield. Due to the limited availability of data for each of these parameters, initial values were assumed to be constant, as provided in Table 4.

Table 4. Initial Model Input Parameters for Edwards-Trinity (High Plains) Aquifer Hydrogeologic Units

Material	Hydraulic Conductivity (ft/d)		Specific Yield (dimensionless)	Specific Storage (1/ft)
	Horizontal	Vertical		
Shale	0.1	0.001	0.1	3×10^{-6}
Limestone	10	1	0.05	3×10^{-6}
Antlers Sand	10	1	0.15	3×10^{-6}

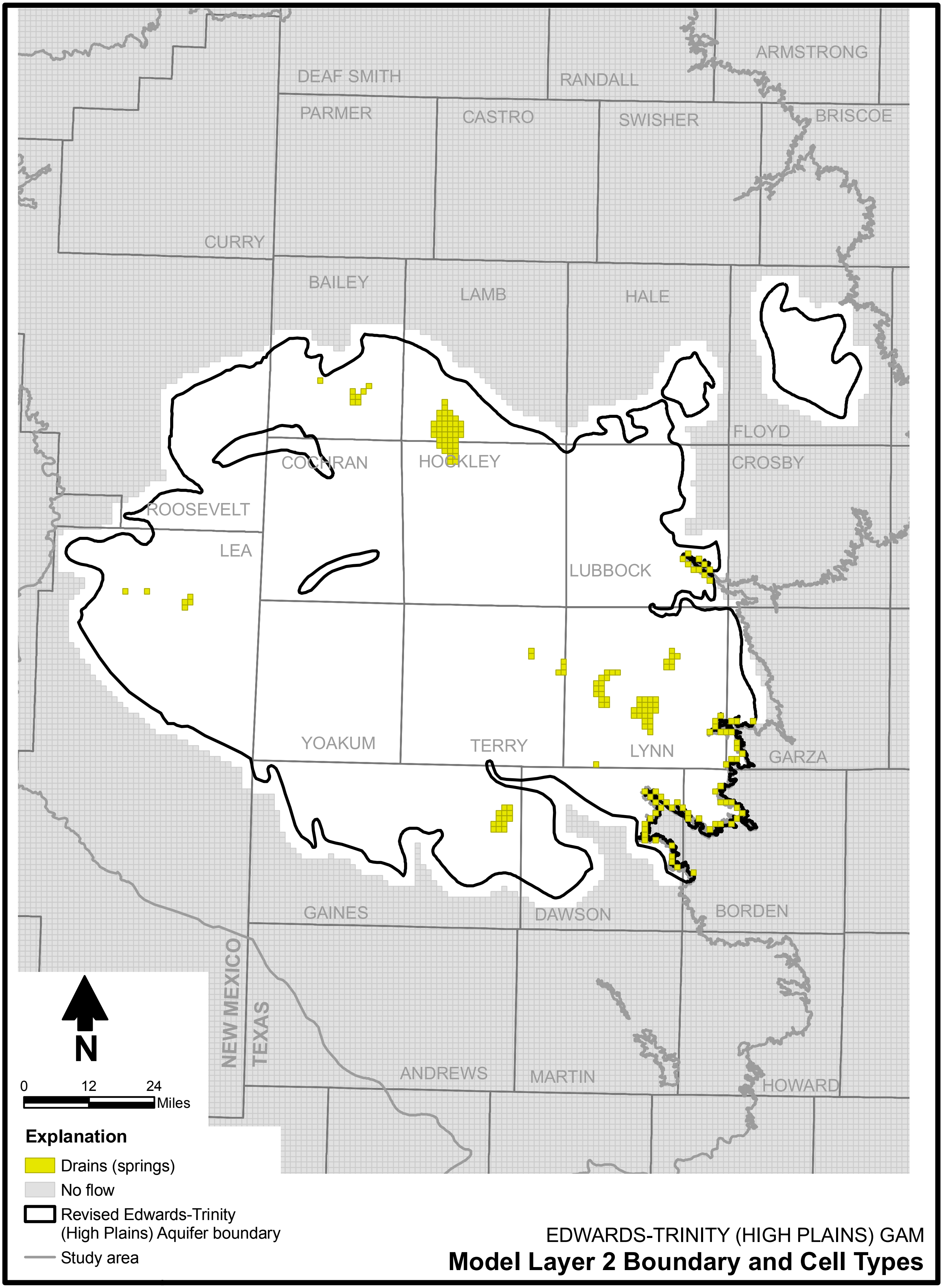
ft/d = Feet per day



EDWARDS-TRINITY (HIGH PLAINS) GAM

Model Layer 1 Boundary and Cell Types

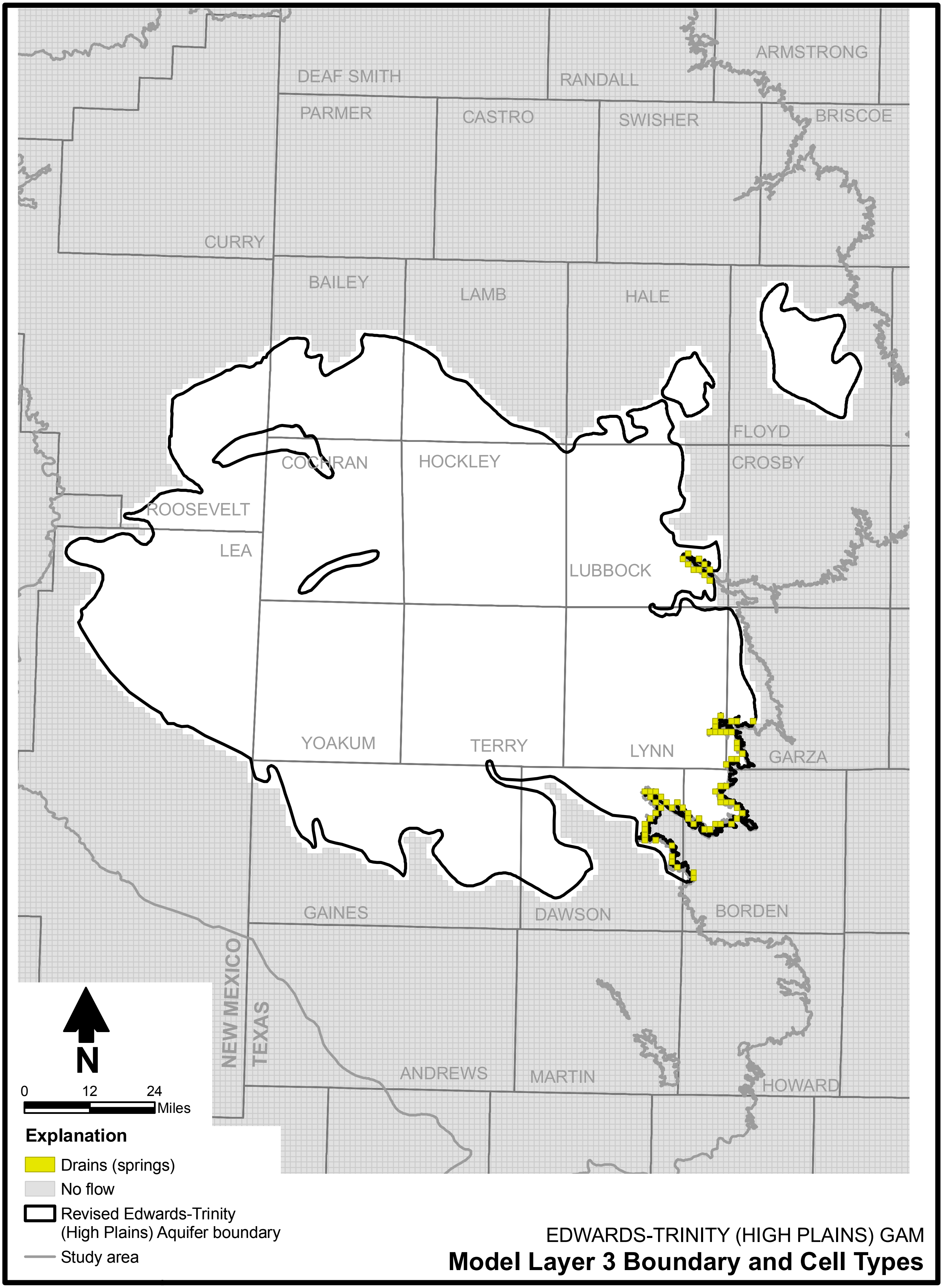
Figure 46



EDWARDS-TRINITY (HIGH PLAINS) GAM

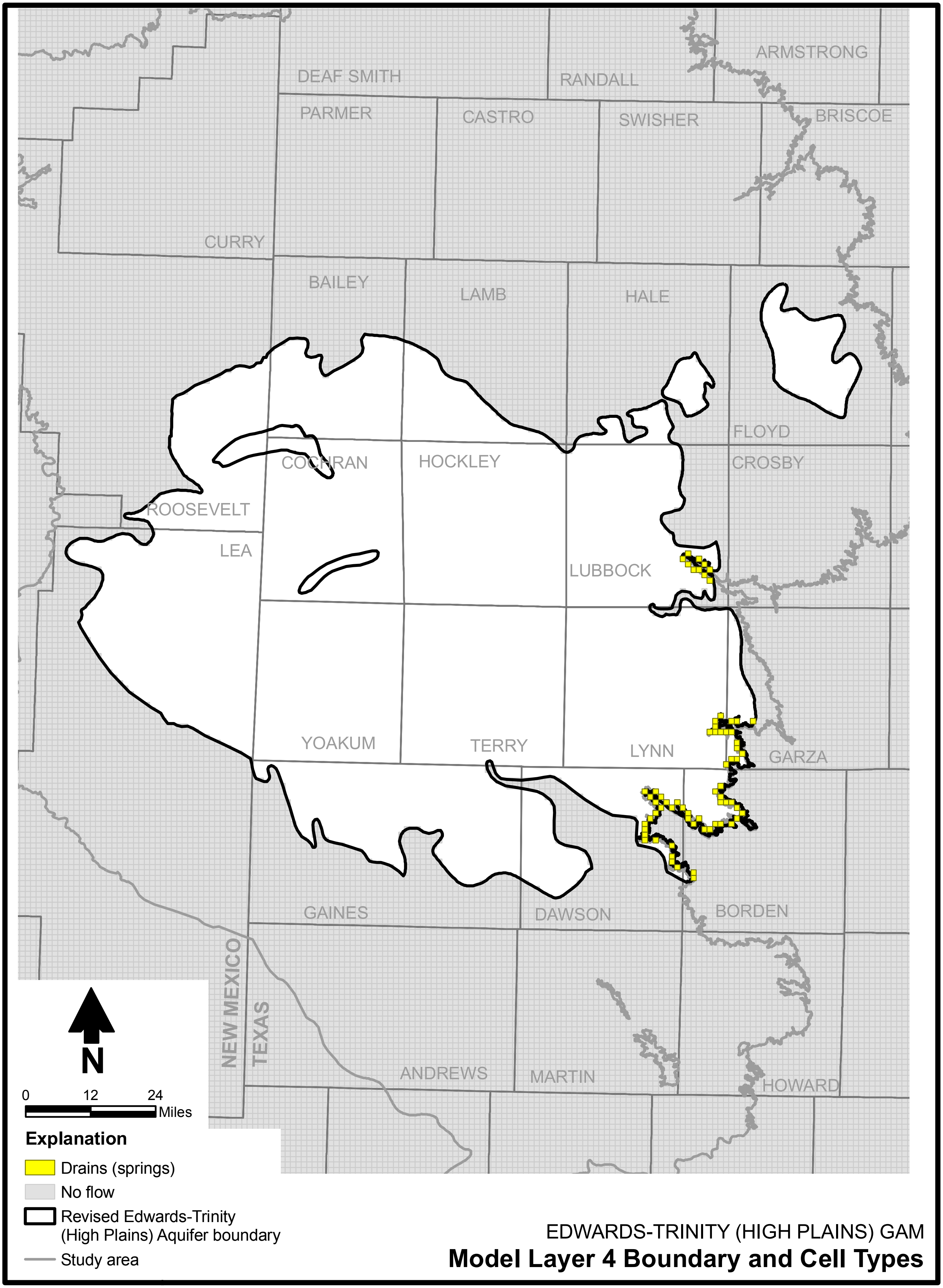
Model Layer 2 Boundary and Cell Types

Figure 47



EDWARDS-TRINITY (HIGH PLAINS) GAM
Model Layer 3 Boundary and Cell Types

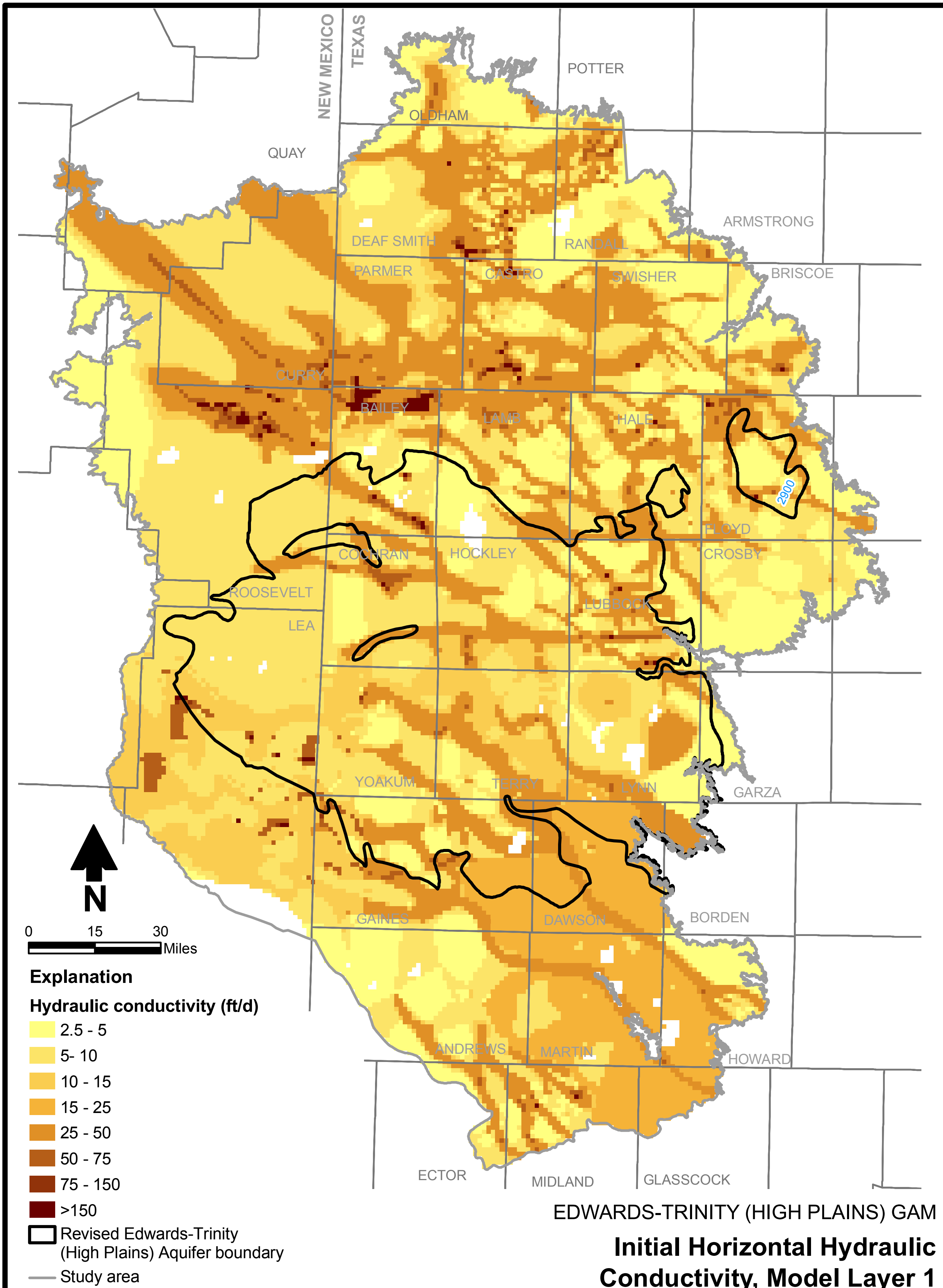
Figure 48



EDWARDS-TRINITY (HIGH PLAINS) GAM

Model Layer 4 Boundary and Cell Types

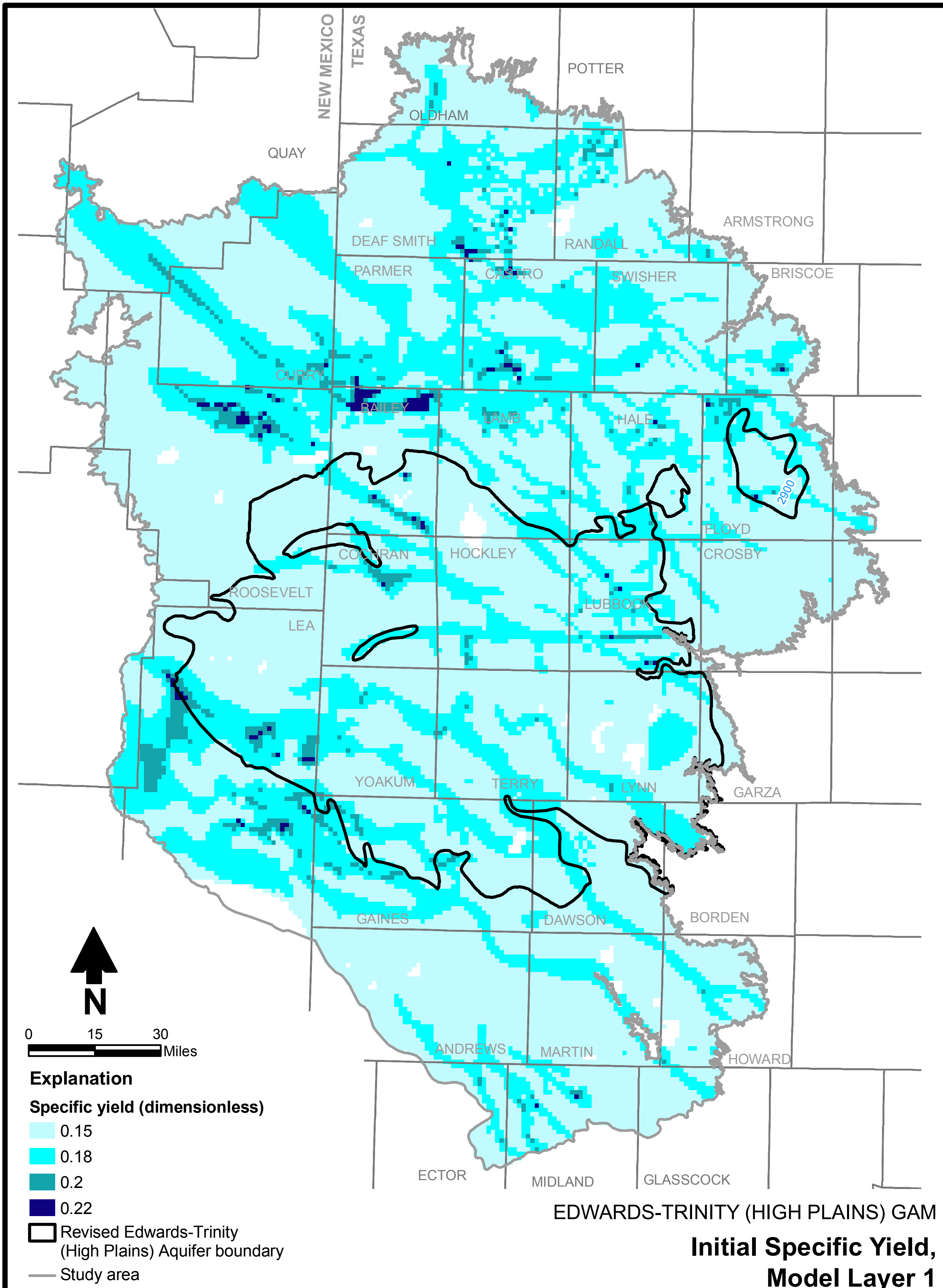
Figure 49



EDWARDS-TRINITY (HIGH PLAINS) GAM

Initial Horizontal Hydraulic Conductivity, Model Layer 1

Figure 50



EDWARDS-TRINITY (HIGH PLAINS) GAM

Initial Specific Yield, Model Layer 1

Figure 51

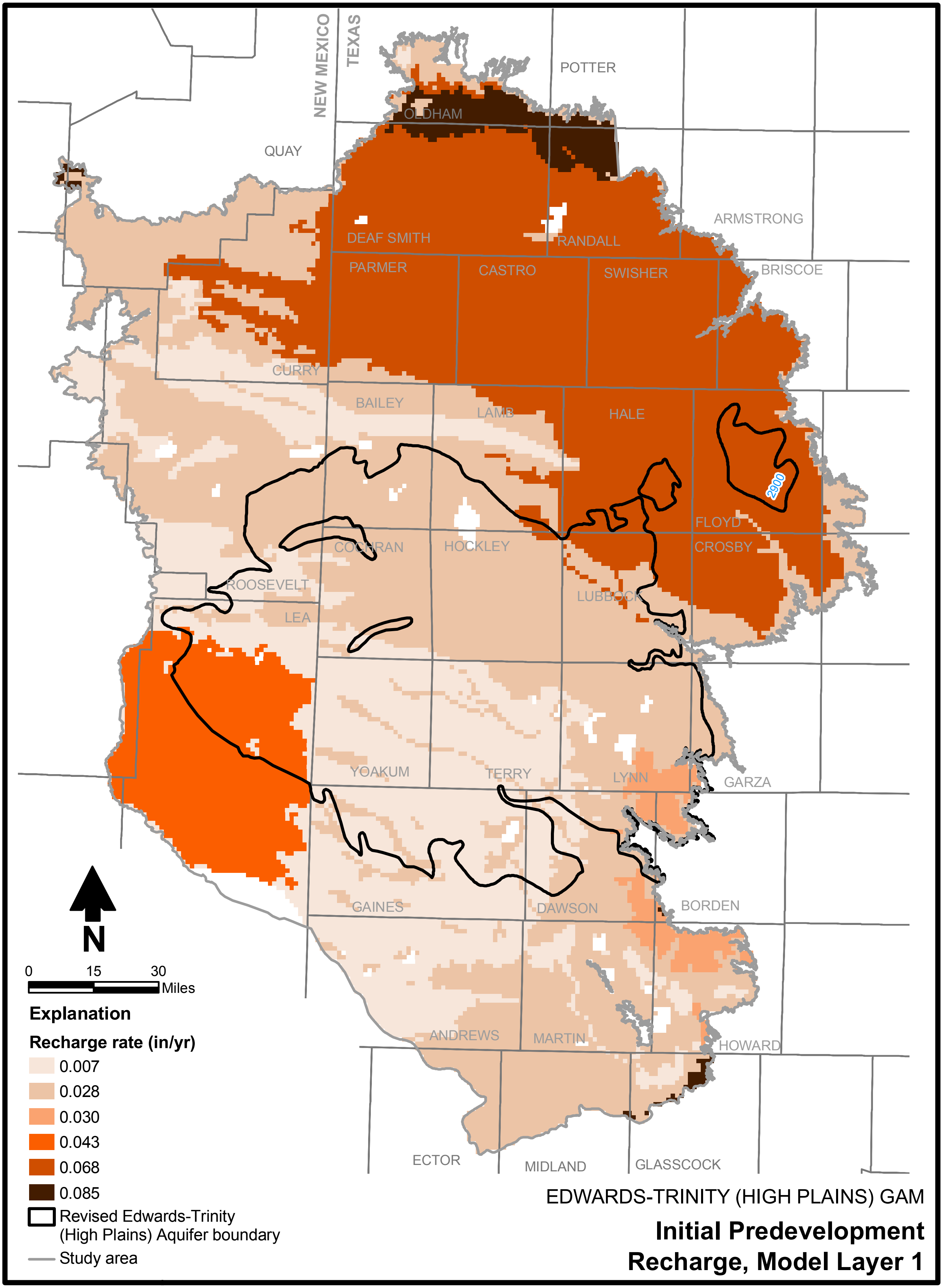

NEW MEXICO
TEXAS
POTTER
OLDHAM
QUAY
ARMSTRONG
DEAF SMITH
RANDALL
PARMER
CASTRO
SWISHER
BRISCOE
CURRY
BAILEY
LAMB
HALE
2900
FLOYD
COCHRAN
HOCKLEY
CROSBY
ROOSEVELT
LUBBOCK
LEA
YOAKUM
TERRY
LYNN
GARZA
GAINES
DAWSON
BORDEN
ANDREWS
MARTIN
HOWARD
ECTOR
MIDLAND
GLASSCOCK
N
0
15
30
Miles
Explanation
Recharge rate (in/yr)
0.007
0.028
0.030
0.043
0.068
0.085
Revised Edwards-Trinity (High Plains) Aquifer boundary
Study area
EDWARDS-TRINITY (HIGH PLAINS) GAM
Initial Predevelopment Recharge, Model Layer 1

Figure 52

6.4 Model Boundaries

The assigned boundary conditions for model layer 1 (fig. 46) include numerous springs along the eastern caprock escarpment, along draws that cross the High Plains, and at the margins of salt lakes. The western, northern, and southern boundaries of model layer 1 are no-flow, except in parts of the northern boundary, where several springs are documented (Brune, 1981, 2002). A no-flow boundary is one at which no exchange of groundwater occurs across the model boundary. Salt lakes and their associated topographic basins were also treated as regions of no flow, as these are typically areas of thin or zero aquifer thickness.

Along the far northeastern model boundary, west of Amarillo, prescribed hydraulic head cells were used during the predevelopment (steady-state) and post-development (transient) calibrations in model layer 1. The prescribed hydraulic head values were based on observed data in the TWDB water level database for wells near the boundary. Groundwater flow across this boundary represents the only connection between the Southern and Central Ogallala Aquifers (the Central Ogallala Aquifer is sometimes called the Northern Ogallala Aquifer in Texas). A detailed description of the assignment of model layer 1 boundary conditions is provided by Blandford and others (2003) and is not repeated here.

The assigned boundary conditions for model layer 2 (fig. 47) include springs along the eastern escarpment, where limestone units crop out within Lubbock, Garza, Borden and Dawson Counties, and drain cells (potential springs) in the bottoms of the major salt lake basins.

Boundary conditions for model layers 3 and 4 consist exclusively of springs along the eastern escarpment (figs. 48 and 49). Other than areas where drain conditions are used to simulate spring flow, no additional boundary conditions are applied for the Edwards-Trinity (High Plains) Aquifer. This approach is consistent with the conceptual model of groundwater flow, where all water within the aquifer is derived from seepage, primarily from the overlying Southern Ogallala Aquifer.

7.0 Modeling Approach

This section provides an overview of the model calibration approach, an introduction to and overview of model calibration assessment, and an overview of calibration targets applied during development of the Edwards-Trinity (High Plains) Aquifer GAM. Since the Edwards-Trinity (High Plains) Aquifer GAM is based on, and is essentially an upgrade to, the Southern Ogallala GAM, model calibration used observed data from both aquifers.

7.1 Model Calibration Approach

The overall modeling approach consisted of calibrating a steady-state, predevelopment model, and then calibrating a transient, post-development model. Model calibration was conducted for observed hydrogeologic conditions in both the Edwards-Trinity (High Plains) Aquifer and the Southern Ogallala Aquifer. Specifically, the steady-state model was calibrated to observed hydraulic heads within the Edwards-Trinity (High Plains) and Southern Ogallala Aquifers. Outflows at the 10 largest springs, 9 of which emanate from the Southern Ogallala Aquifer along the eastern escarpment, were reviewed qualitatively. Buffalo Springs near Lubbock (fig. 35) may contribute some flow from the Edwards-Trinity (High Plains) Aquifer, since outcrop of Antlers Sand is mapped immediately downstream of the springs (BEG, 1967), which are now covered by a lake.

The steady-state model is useful to determine average aquifer hydraulic conductivity and recharge under natural conditions without the added complexity of significant groundwater pumping, recharge from return flow and changes in land use, and effects of specific yield. The simulated hydraulic heads from the steady-state model served as the initial (starting) condition for the transient, post-development simulation.

Much of the Southern High Plains did not experience significant groundwater development until 1940 (Luckey and others, 1986), but significant groundwater pumping existed at least in the Lubbock area during the 1930s (Lang, 1945). Accordingly, the steady-state model was calibrated to average hydrogeologic conditions at or about 1930.

The transient (post-development) calibration was used to determine, in conjunction with observed data and anecdotal information, rates of irrigation return flow, enhanced recharge beneath agricultural areas, and specific yield. During the transient model calibration, hydraulic conductivity and recharge for non-agricultural areas were not changed from the steady-state model. However, estimates of agricultural pumping were changed for several selected counties and years.

This sequence of simulation and model parameter estimation was followed to minimize, to the extent possible, the problem of non-unique simulation results. Model results are non-unique when changes in multiple aquifer parameters, all within reasonable limits, lead to the same or similar simulation results.

7.2 Model Calibration Assessment

Calibration statistics are presented in terms of mean-absolute error (MAE), mean error (ME) and root-mean-squared error (RMSE). These terms are defined as follows:

$$MAE = \frac{1}{n} \sum_{i=1}^{n} Abs \left(h_{obs} - h_{sim}\right)$$

$$ME = \frac{1}{n} \sum_{i=1}^{n} \left(h_{obs} - h_{sim}\right)$$

$$RMSE = \left[\frac{1}{n} \sum_{i=1}^{n} \left(h_{obs} - h_{sim}\right)^2\right]^{0.5}$$

where n = number of water level observations

h_{obs} = observed water level

h_{sim} = simulated water level

Abs = absolute value

The primary goal of model calibration is to reduce the value of each of these statistics to the extent possible, using model input values consistent with observed data or realistic estimates. The observed values in the above equations are often referred to as calibration targets. Although the calibration statistics are presented in terms of observed and simulated hydraulic head, the same approach of comparing observed and simulated values can be applied to other parameters that can be simulated using a groundwater flow model, such as spring flow.

The ME is a simple average of the difference between observed and simulated water levels, and therefore positive values will offset negative values. A positive value of ME indicates that, on average, simulated hydraulic heads are lower than observed hydraulic heads, while a negative value indicates the opposite.

MAE is similar to the ME, with the important distinction that the sum of the absolute values of the residuals is calculated, thereby eliminating the offset that occurs by adding positive and negative values. The MAE, therefore, is always positive, and represents the average difference between observed and simulated hydraulic head values. The MAE is the primary calibration statistic selected by the TWDB for evaluation of GAM calibration; the TWDB requires that the MAE be less than 10 percent of the observed hydraulic head drop that occurs across the model domain.

The RMSE is not required by the TWDB but is a common model calibration statistic that is computed in groundwater modeling and is therefore included here. The RMSE is similar to the MAE, although negative values of the difference between observed and simulated hydraulic heads are eliminated by squaring the difference, and then the square root of the sum is determined prior to computing the average. This approach is analogous to the computation of the variance that would be conducted for a linear regression. A common modeling guideline for the RMSE is the same as the TWDB requirement for the MAE, that the RMSE should be less than 10 percent of the observed hydraulic head drop that occurs across the model domain.

Other model calibration criteria set by the TWDB are:

- The residuals between observed and simulated hydraulic heads (model error) should not be spatially biased due to the locations of observations.

- The simulated mass balance (the difference between total model inflows and total model outflows) should be less than 1 percent and preferably less than 0.1 percent.

7.3 Model Calibration Targets

Calibration targets were identified for both the Edwards-Trinity (High Plains) and Southern Ogallala Aquifers. Calibration targets for the Edwards-Trinity (High Plains) Aquifer consist of available observed hydraulic heads and water level maps for predevelopment conditions and the years 1980, 1990 and 1997. In addition, 18 hydrographs for wells determined to be completed in the Edwards-Trinity (High Plains) Aquifer were used to evaluate the transient model calibration. Existing observed data concerning spring flow from the Edwards-Trinity (High Plains) Aquifer are not sufficient to be used as targets for model calibration.

The model calibration targets for the Southern Ogallala Aquifer were the observed data compiled for development of the Southern Ogallala GAM, as documented by Blandford and others (2003). The steady-state model was calibrated to the estimated water level contours and observed hydraulic heads under predevelopment conditions. The transient model was calibrated to observed changes in water levels at 90 locations distributed throughout the study area in irrigated and non-irrigated regions and to observed water levels for all available points in the study area for the winters of 1989-1990 and 1999-2000. Changes in simulated spring flows were also examined, but insufficient historical information is available to conduct detailed comparisons of model output with observed values through the transient simulation period.

7.4 Sensitivity Analysis

Sensitivity analysis is the process of changing selected model input parameters within reasonable ranges to evaluate the effects of changing the parameter(s) on simulation results. Model input parameters that have a significant (large) effect on model output are called “sensitive” parameters, while input parameters that have little or no influence on simulation results when they are changed are called “insensitive” parameters. Sensitivity analysis was conducted for both the steady-state and transient calibrated groundwater flow models.

8.0 Steady-State Model

The steady-state (predevelopment) model represents average hydrogeologic conditions at or about 1930. Steady-state groundwater flow conditions were solved for by running the model in transient mode for a long period of time until the rate of change in storage was very small, thereby approximating steady-state conditions (for steady-state conditions the rate of change in groundwater storage is zero). The period of time and time step parameters are not significant in the context of the steady-state simulation because they have no physical meaning in terms of dates or water level observations. This approach was followed because the direct steady-state solution in MODFLOW would not converge. The steady-state model calibration, water budget, and sensitivity analysis for the Edwards-Trinity (High Plains) and Ogallala Aquifers are presented in Sections 8.1 through 8.5.

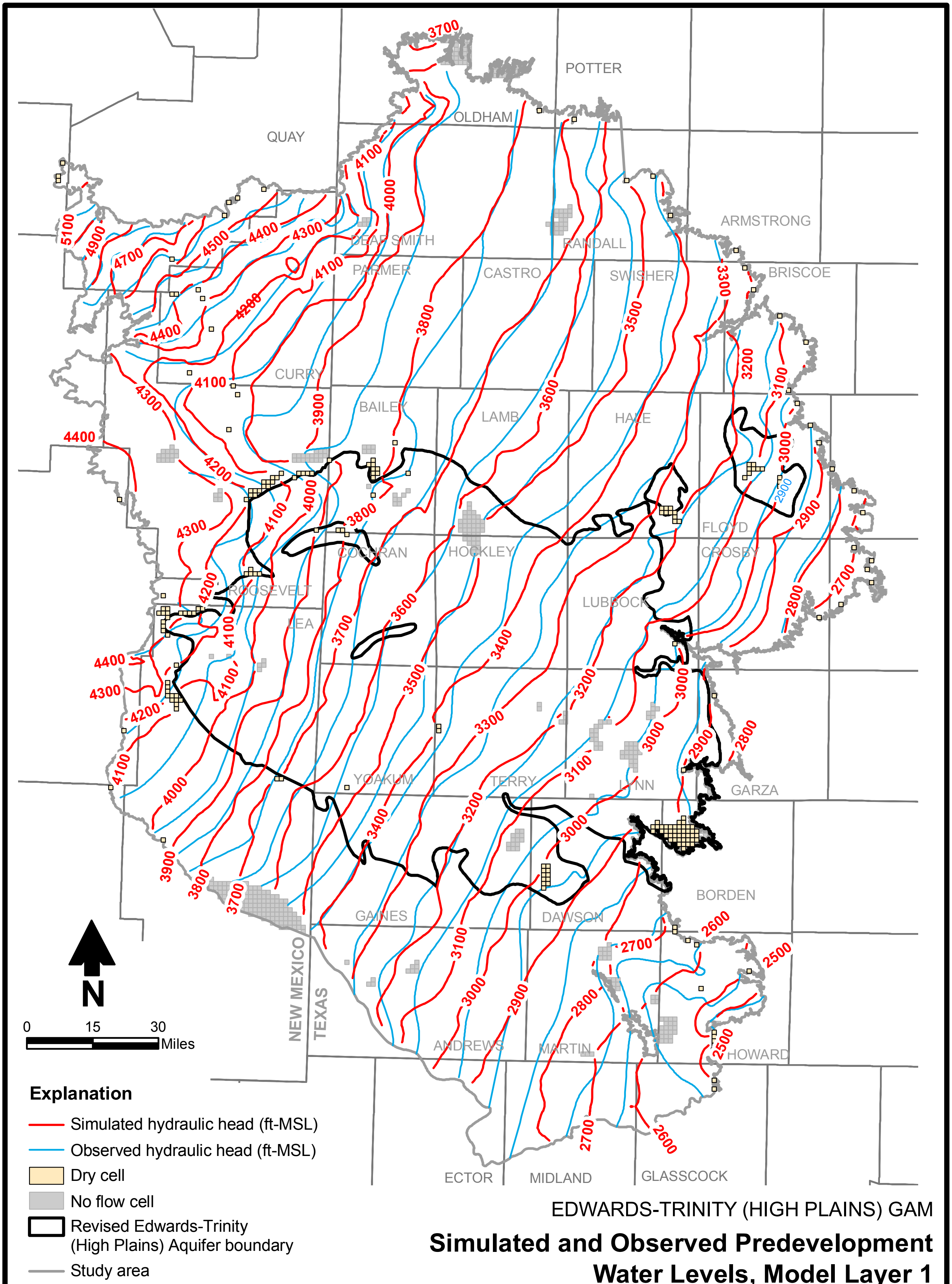
8.1 Calibration Results for the Southern Ogallala Aquifer

Steady-state model calibration was achieved primarily through changes in hydraulic conductivity implemented for model layers 2 through 4. During the model calibration process, the match between observed and simulated values was consistently checked for both the Edwards-Trinity (High Plains) and Ogallala Aquifers. The steady-state model calibration results are detailed below.

Figure 53 presents the simulated and observed water levels under predevelopment conditions for the Southern Ogallala Aquifer, which is represented as model layer 1 at most model locations. Details of the construction of the observed Southern Ogallala Aquifer water table map are provided by Blandford and others (2003). For the most part, the hydraulic gradient and the direction of groundwater flow simulated in the model are reasonably consistent with the observed data. A small number of dry cells are simulated for model layer 1 adjacent to the Edwards-Trinity (High Plains) Aquifer boundary in New Mexico and in Bailey, Cochran, Hale, Floyd, and Dawson Counties in Texas. In the northwest corner of Borden County, a significant zone of dry cells is simulated adjacent to a peninsular region of the eastern caprock escarpment, where limited saturated thickness would be expected.

A comparison of the observed and simulated water levels is provided in Figure 54, which also lists the model calibration statistics. The MAE is 26 feet, indicting that, on average, the simulated predevelopment water levels differ from observed values by 26 feet. The MAE divided by the observed range in hydraulic heads of 2,318 feet is 1.1 percent, far below the maximum allowable value of 10 percent set for this statistic by the TWDB. The ME is –8 feet, indicating that, on average, simulated water levels are slightly greater than the observed water levels. The Southern Ogallala Aquifer MAE and ME calculated for the Edwards-Trinity (High Plains) GAM are identical to those documented in the previous Southern Ogallala GAM (Blandford and others, 2003).

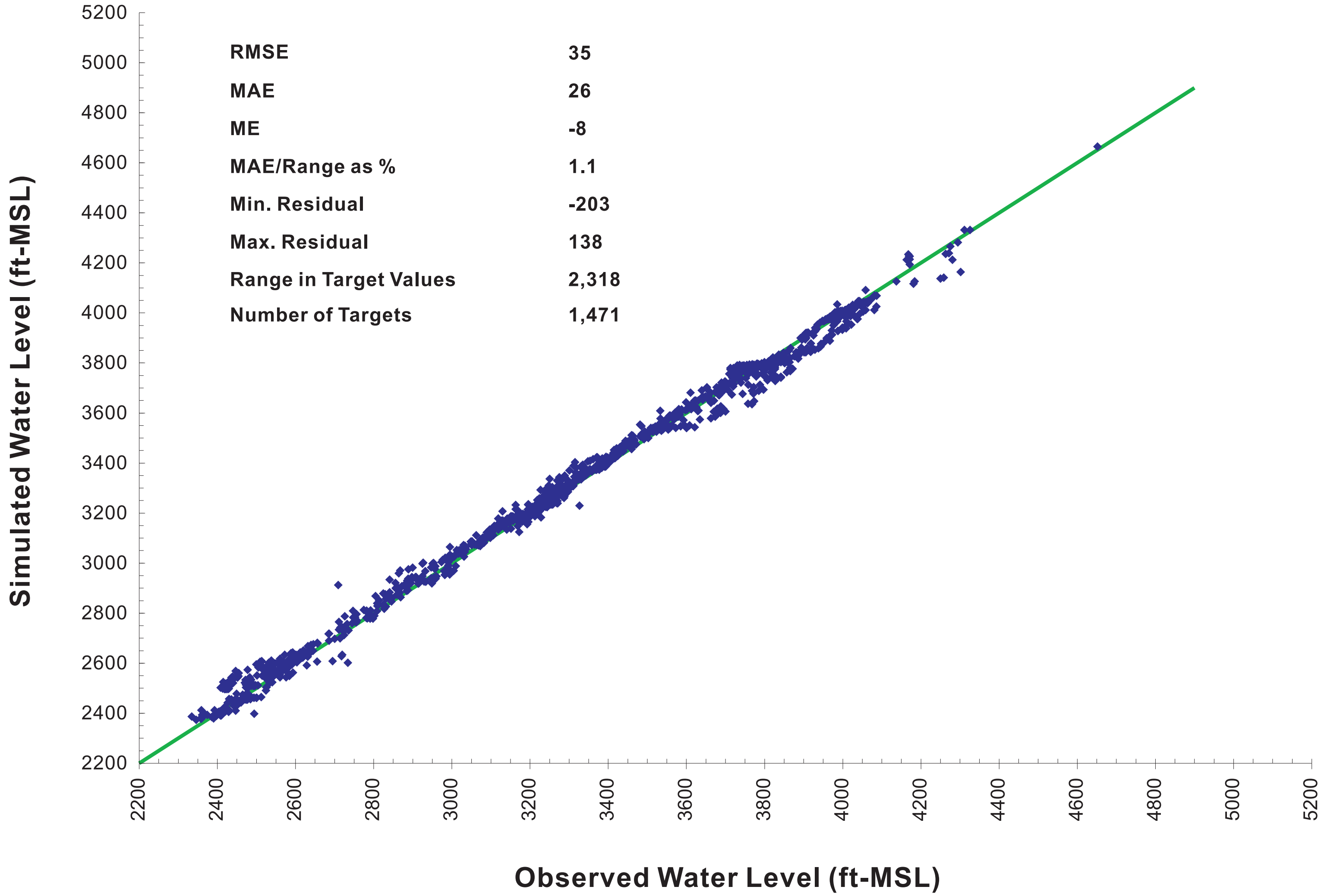
Figure 55 illustrates the magnitude of the difference between simulated and observed water levels, as well as whether they are higher or lower than observed values. As shown in Figure 55, simulated hydraulic heads in the steady-state model tend to be uniformly over- or under-estimated in three regions:



EDWARDS-TRINITY (HIGH PLAINS) GAM

Simulated and Observed Predevelopment Water Levels, Model Layer 1

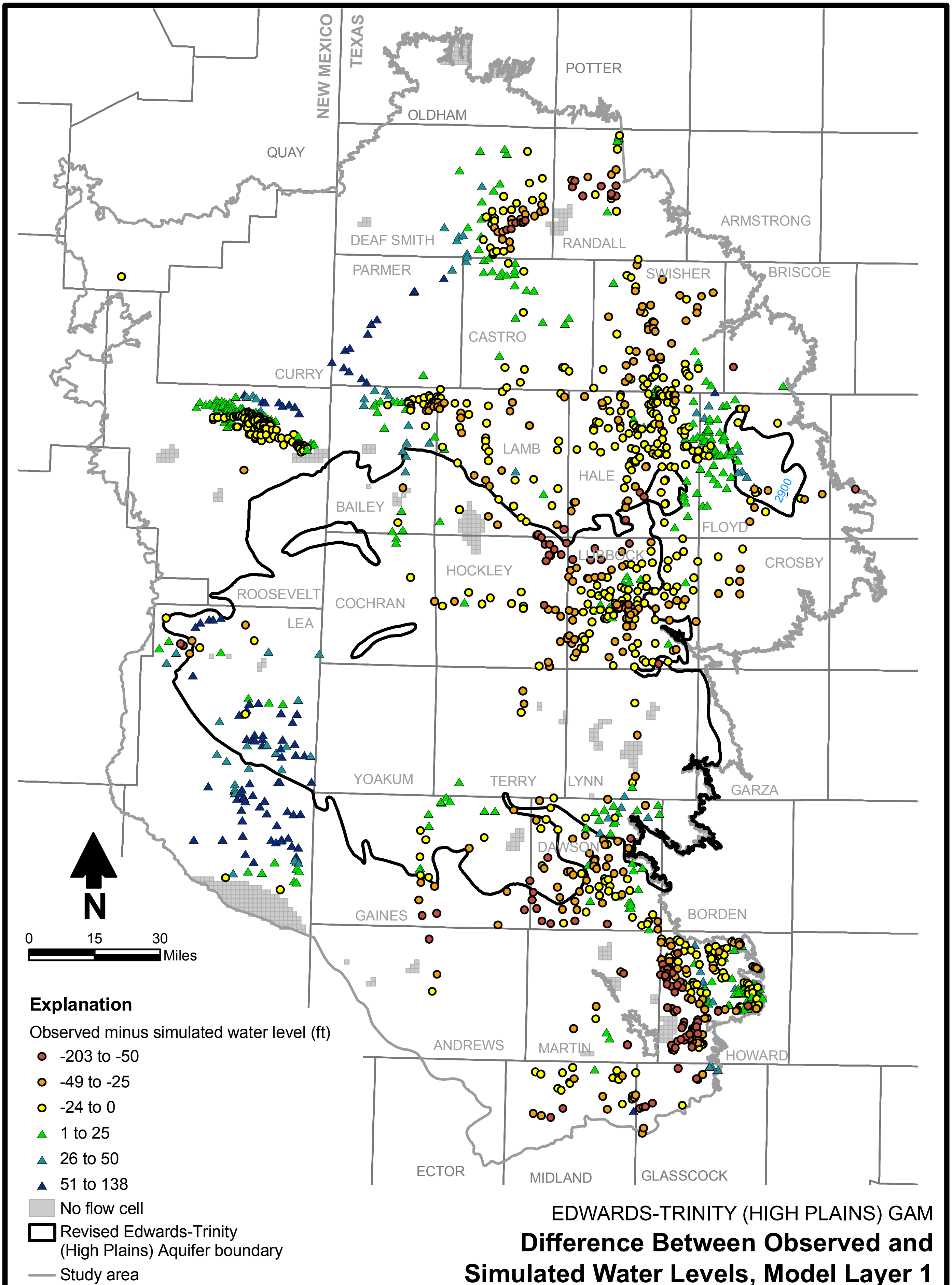
Figure 53



EDWARDS-TRINITY (HIGH PLAINS) GAM

Simulated Versus Observed Predevelopment Water Levels
Model Layer 1

Figure 54



EDWARDS-TRINITY (HIGH PLAINS) GAM

Difference Between Observed and Simulated Water Levels, Model Layer 1

Figure 55

- In Lea County, New Mexico and the adjoining western Gaines County, Texas, simulated water levels are consistently lower than observed water levels.
- In southwestern Parmer County, Texas and southeastern Curry County, New Mexico, the model simulates water levels significantly lower than those that have been observed or interpolated (although early water level observations are limited in this area).
- In the far southeastern portion of the model in parts of eastern Martin County and western Howard County, simulated water levels are higher than those observed.

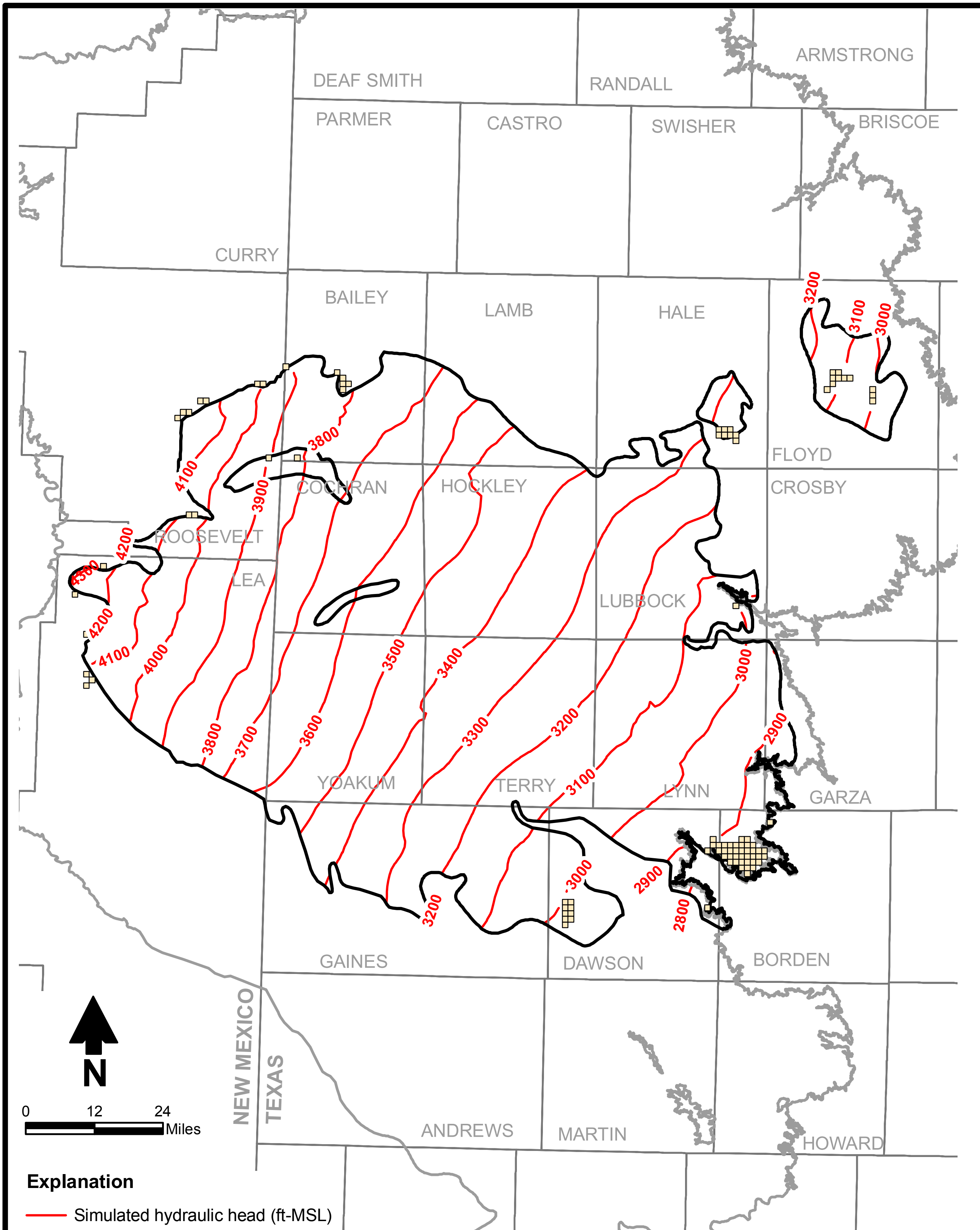
In summary, the steady-state (predevelopment) calibration for the Southern Ogallala Aquifer is nearly identical to that presented in the Southern Ogallala GAM (Blandford and others, 2003). Additional discussion of model calibration efforts and results applicable to model layer 1 of the Edwards-Trinity (High Plains) Aquifer GAM can be found in that document.

8.2 Calibration Results for the Edwards-Trinity (High Plains) Aquifer

Figures 56 through 58 illustrate the simulated and observed predevelopment water level data for model layers 2 through 4, respectively. No observed data are available for model layer 2, which represents primarily clay and shale units associated with the Duck Creek and Kiamichi Formations. Because simulation results for this model layer could therefore not be calibrated, observed water level contours are not provided on Figure 56. The simulated water levels illustrated in Figures 57 (model layer 3, predominantly limestone units) and 58 (model layer 4, Antlers Sand) are virtually identical since the horizontal hydraulic conductivity of each unit is similar and the vertical connection between model layers is good. In subsequent figures, therefore, the simulation results for model layers 3 and 4 are not distinguished, and the simulated hydraulic heads for layer 4 are used in the plots. Layers 3 and 4 were not combined in the model, however, because the specific yield assigned to each layer is different (Section 9.3.2), which could be important for some predictive simulations. In addition, maintaining separate model layers that correspond to distinct hydrogeologic units will likely prove useful during future model updates that might be conducted as additional information becomes available.

Review of Figures 57 and 58 also illustrates that for the most part the hydraulic gradient and the direction of groundwater flow simulated in the model is reasonably consistent with the observed data, particularly in the southern portion of the Edwards-Trinity (High Plains) Aquifer, where observed predevelopment data are available. The simulated and observed hydraulic head contours do not match as well within the northern and northeastern portions of the aquifer, but the observed predevelopment water levels had to be estimated in these areas and are not necessarily appropriate for model calibration. A very limited number of dry cells occur in model layers 2 and 3 (figs. 56 and 57) in the northeastern portion of Borden County adjacent to the escarpment and near the edge of the Edwards-Trinity (High Plains) Aquifer extent.

A comparison of the observed and simulated water levels is provided in Figure 59, which also lists the model calibration statistics. The MAE is 22 feet, indicting that, on average, the simulated predevelopment water levels differ from observed values by 22 feet. The MAE divided by the observed range in hydraulic heads of 461 feet is 4.8 percent, about one-half the allowable value of 10 percent set for this statistic by the TWDB. The ME is –8 feet, indicating that, on average, simulated water levels are slightly greater than the observed values.



Explanation

Simulated hydraulic head (ft-MSL)

Dry cell

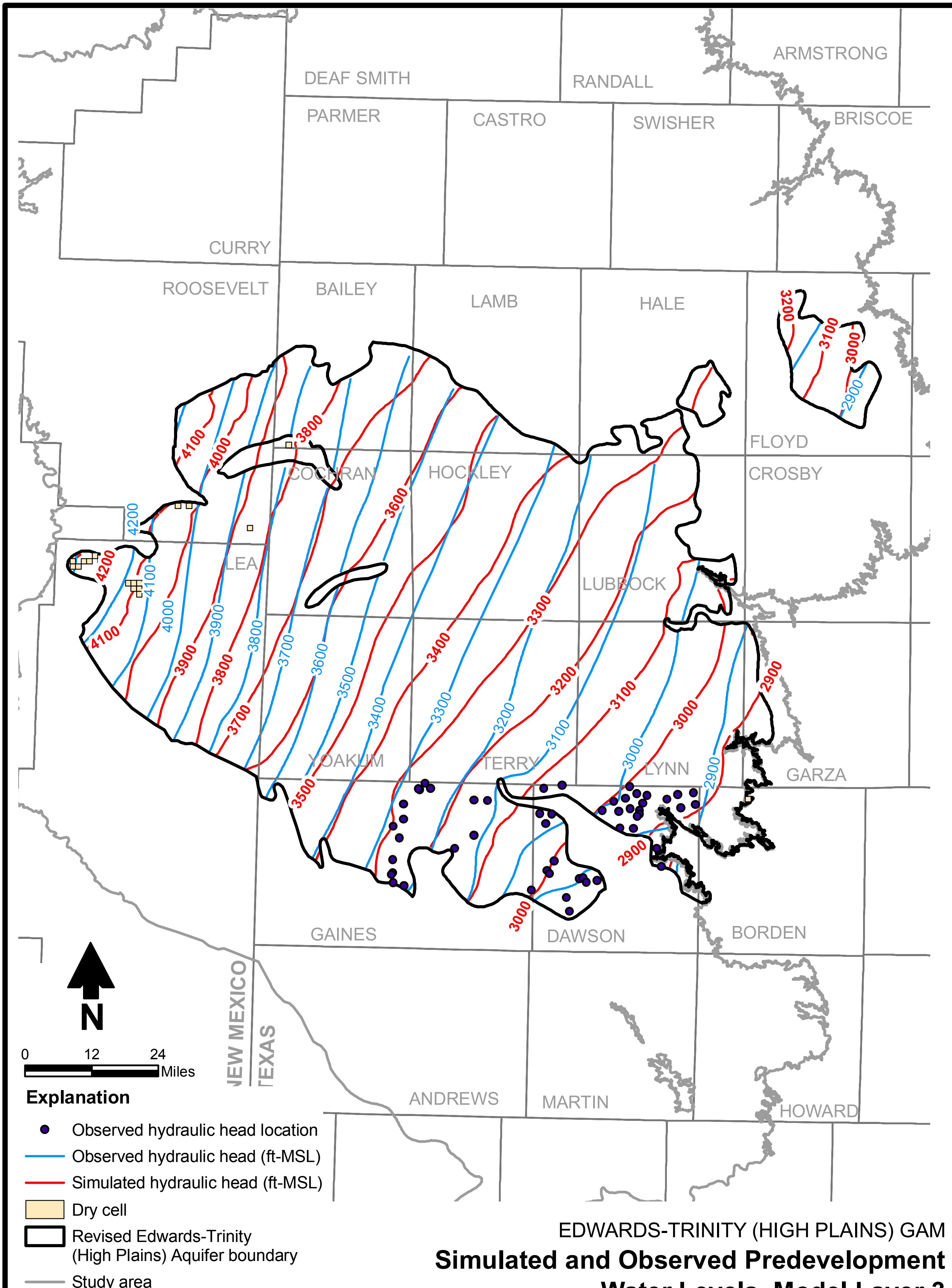
Revised Edwards-Trinity (High Plains) Aquifer boundary

Study area

EDWARDS-TRINITY (HIGH PLAINS) GAM

Simulated Predevelopment Water Levels, Model Layer 2

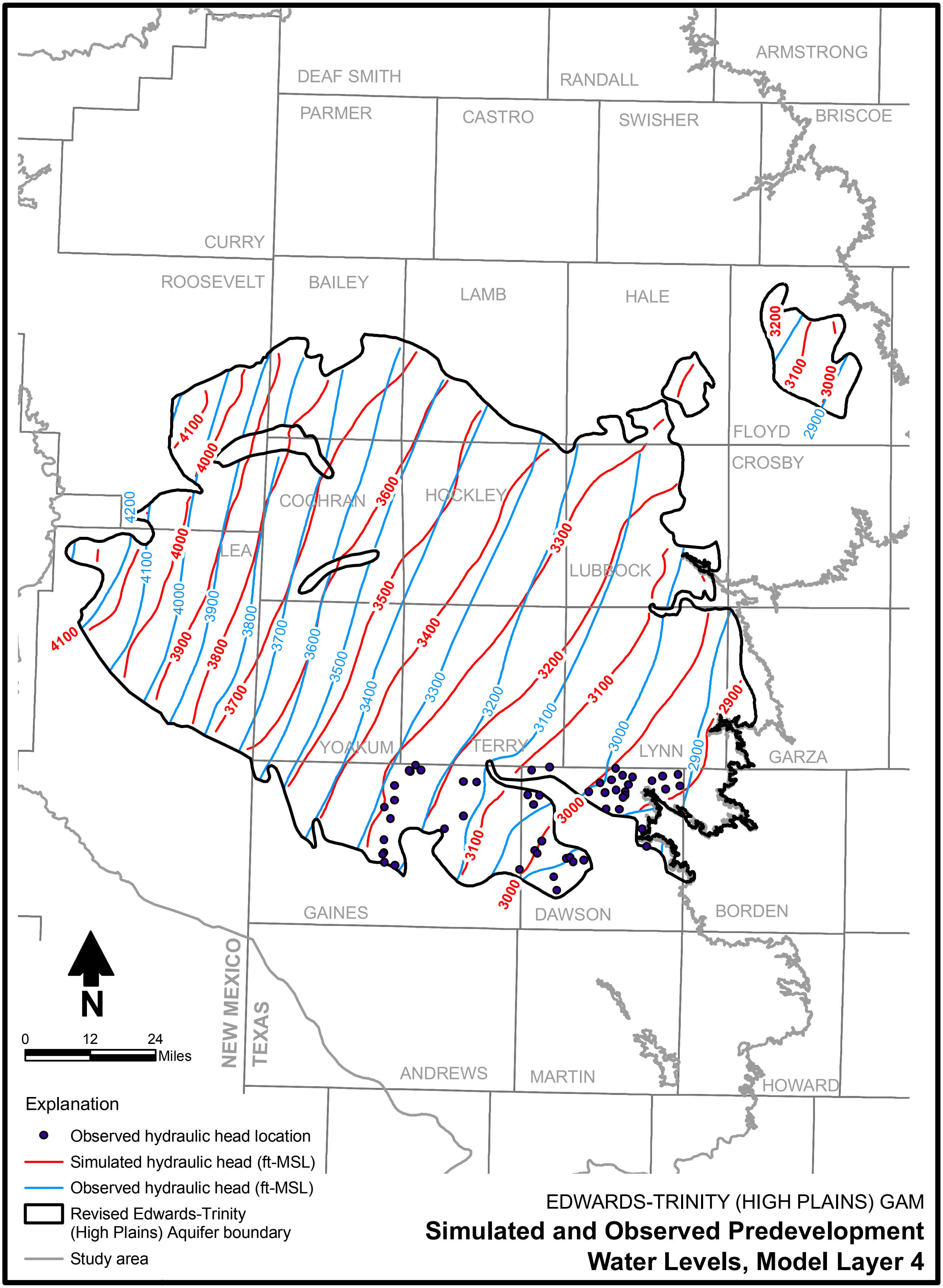
Figure 56



EDWARDS-TRINITY (HIGH PLAINS) GAM

Simulated and Observed Predevelopment Water Levels, Model Layer 3

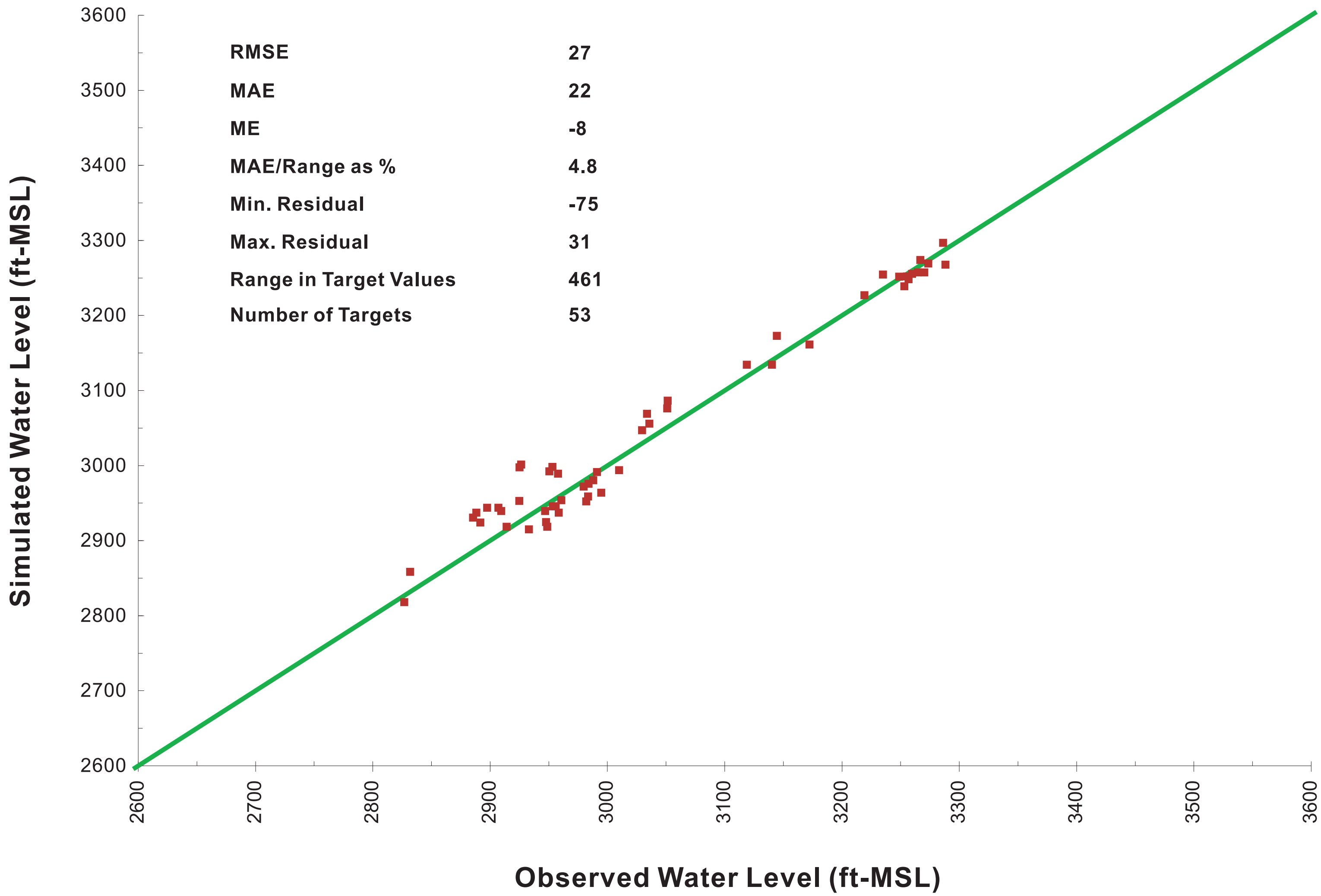
Figure 57



EDWARDS-TRINITY (HIGH PLAINS) GAM

Simulated and Observed Predevelopment Water Levels, Model Layer 4

Figure 58



EDWARDS-TRINITY (HIGH PLAINS) GAM

Simulated Versus Observed Predevelopment Water Levels
Model Layers 3 and 4

Figure 59

Figure 60 illustrates the magnitude of the difference between simulated and observed water levels, as well as whether they are higher or lower than observed values. Shown on this figure are a zone in western Dawson County where simulated water levels are higher than observed water levels and a zone in northeastern Dawson County where the opposite is true.

The available information on observed spring flow from the Edwards-Trinity (High Plains) Aquifer is not sufficient to make any quantitative comparisons.

8.3 Model Parameters

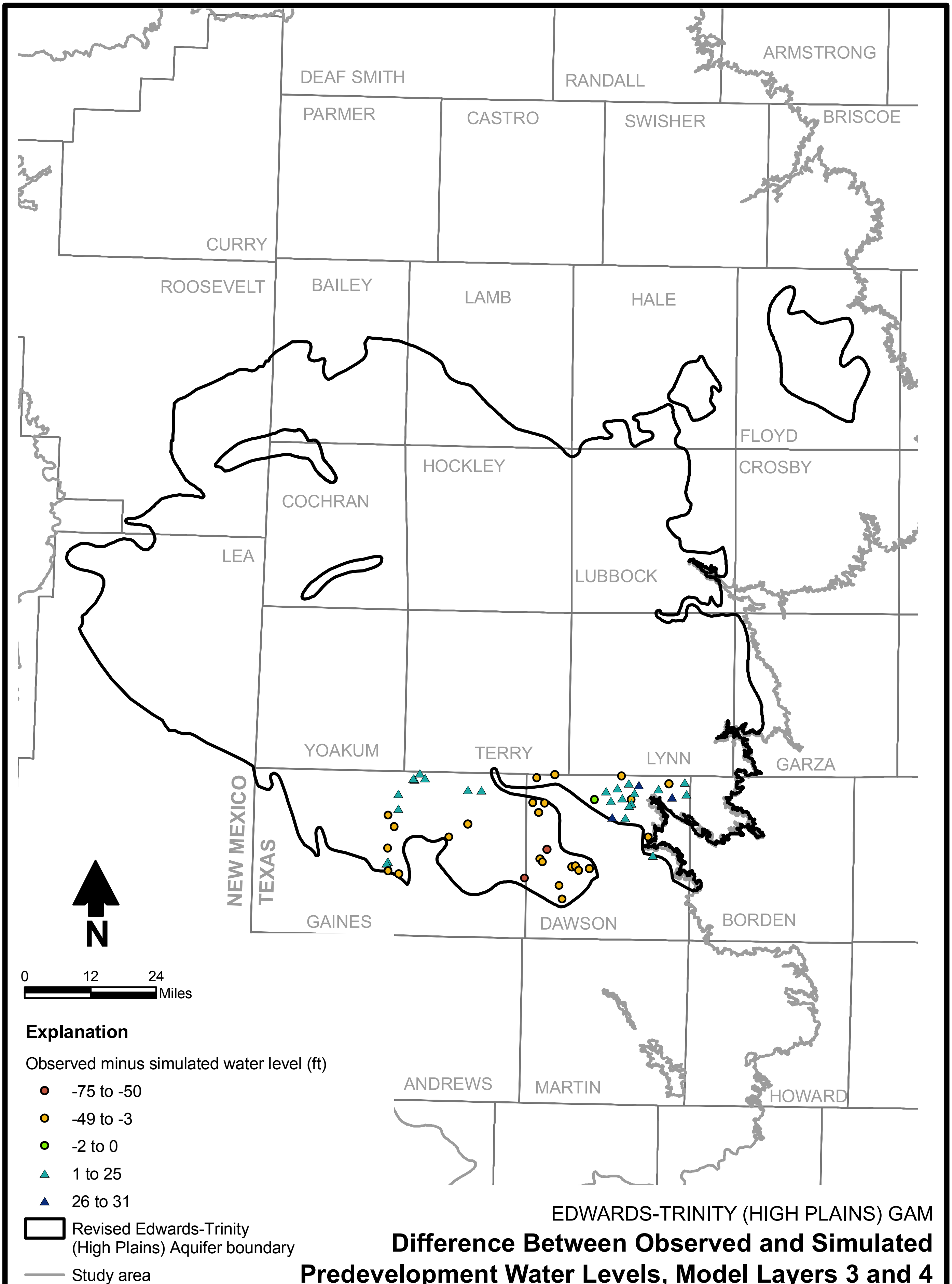
The final calibrated recharge rates for predevelopment conditions range from 0.03 to 0.08 in/yr (fig. 61). The simulated recharge rates are highest in the northern part of the model, where the soil types are the least permeable, consistent with the conceptual model of groundwater recharge implemented in the Southern Ogallala GAM (Blandford and others, 2003). The recharge rates are very similar to those used in the previous model, the only change being that some recharge zones have been grouped and simplified (i.e., compare figs. 61 and 52).

If the conceptual model that most of the recharge to the aquifer occurs through playas is valid for predevelopment conditions, then it is reasonable that more recharge would occur in regions of lower-permeability soils, because there would be more runoff to playas after precipitation events. This hypothesis is suggested by Wood and Sanford (1995), but they acknowledge the lack of actual field data to demonstrate this possibility. They do note, however, that playas in the northern part of the study area tend to be larger and deeper and to occur more frequently. Comparison of Figures 6 and 8 illustrates that playas do occur more frequently (the coverage is more dense) in the northern portion of the Southern High Plains Aquifer, where the lower-permeability soil types are present. Gustavson and others (1995) illustrated quantitatively that playa basins in more permeable sandy soils are smaller and shallower than those that developed in less permeable clayey soils. They also determined that more runoff occurs to playa basins formed in clayey soils than to those formed in loamy soils (Gustavson and others, 1995).

The simulated recharge rate for much of the northern third of the model domain is 0.07 in/yr (fig. 61). This value is nearly identical to the rates of 0.05 to 0.0625 in/yr back-calculated from groundwater discharge estimates made by White and others (1946) for the same approximate area.

The simulated direction of groundwater flow through the base of model layer 1 is illustrated in Figure 62. In areas where Ogallala sediments directly overlay the predominantly limestone units, such as in Gaines, Dawson, Lubbock Floyd, and Hale Counties, the simulated vertical direction of groundwater flow is highly variable. Where significant thicknesses of clay and shale occur (fig. 26), groundwater flow is predominantly downward from the Southern Ogallala Aquifer to the Edwards-Trinity (High Plains) Aquifer. However, where the mapped thickness of clay or shale is reduced, simulated groundwater flow tends to be upward. Compare, for example, Figures 32 and 62.

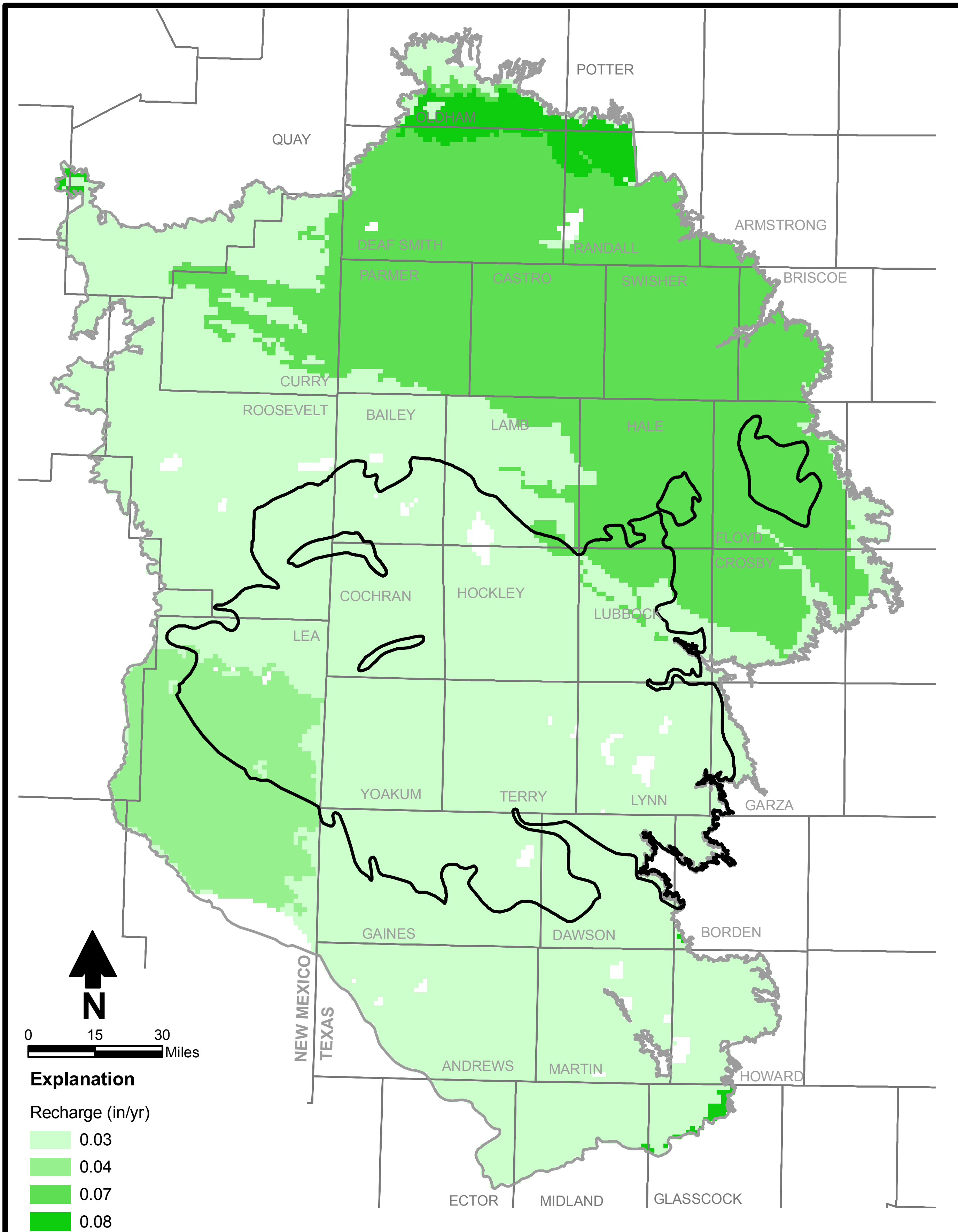
The horizontal hydraulic conductivity applied for model layer 1 is nearly the same as that applied for the Southern Ogallala GAM (Blandford and others, 2003). Some minor adjustments were made in the vicinity of Lubbock (fig. 63). These changes have a local effect in the vicinity of Lubbock, but have no significant effect on the regional model calibration for layer 1.



EDWARDS-TRINITY (HIGH PLAINS) GAM

Difference Between Observed and Simulated Predevelopment Water Levels, Model Layers 3 and 4

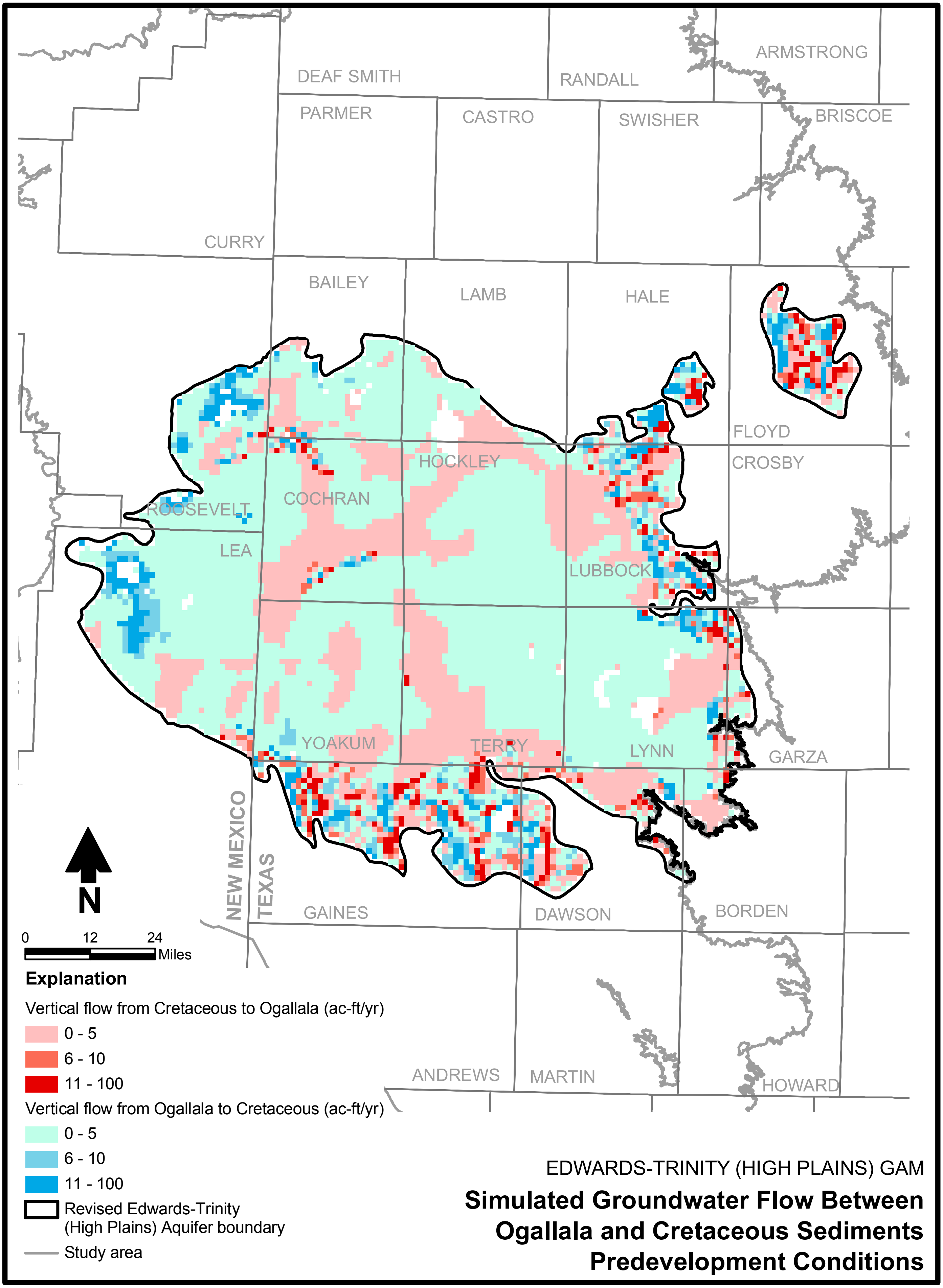
Figure 60



EDWARDS-TRINITY (HIGH PLAINS) GAM

Calibrated Predevelopment Recharge

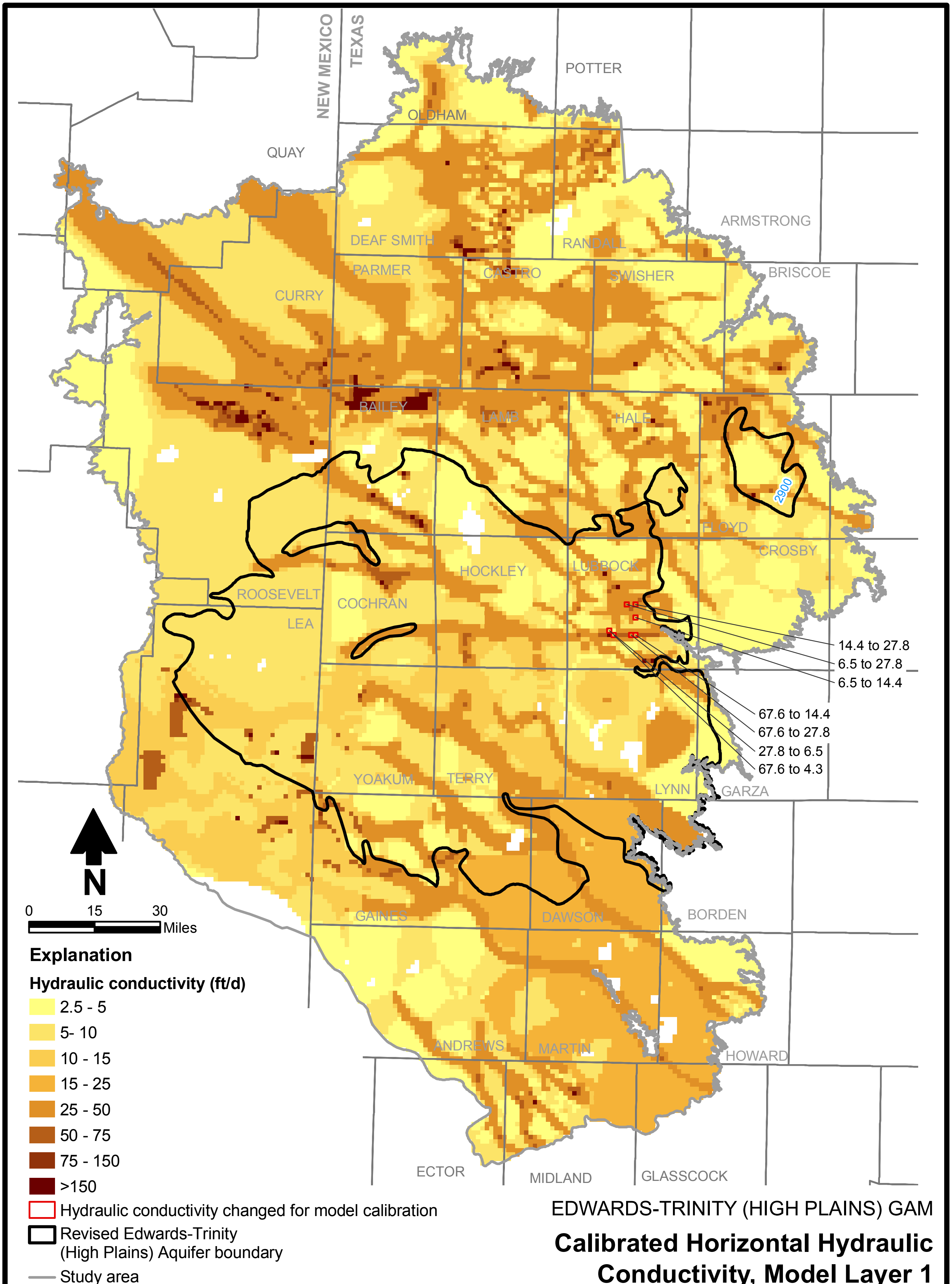
Figure 61



EDWARDS-TRINITY (HIGH PLAINS) GAM

Simulated Groundwater Flow Between Ogallala and Cretaceous Sediments Predevelopment Conditions

Figure 62



EDWARDS-TRINITY (HIGH PLAINS) GAM

Calibrated Horizontal Hydraulic Conductivity, Model Layer 1

Figure 63

The average Southern Ogallala Aquifer hydraulic conductivity in the final model is 15.7 feet per day (ft/d), the same as in the Southern Ogallala GAM. Where multiple model layers were used to represent the Southern Ogallala Aquifer, such as within the two regions within the Edwards-Trinity (High Plains) Aquifer extent where Cretaceous sediments are absent, the same values for aquifer parameters were assumed for each layer.

Figures 64 through 66 illustrate the final calibrated horizontal hydraulic conductivity values used for model layers 2, 3 and 4, respectively. For model layer 2 (fig. 64), the horizontal hydraulic conductivity ranges from 0.001 ft/d for shale to 2.5 ft/d for limestone (the first 5 feet of model layer 2 is assumed to be limestone where shale and clay are predominantly absent). For model layer 3 (fig. 65), the horizontal hydraulic conductivity also ranges from 0.001 ft/d for shale to 2.5 ft/d for limestone; only the bottom 5 feet of layer 3 in the northwestern portion of the model domain, where limestone is absent, is assumed to be shale. For model layer 4 (fig. 66), a uniform horizontal hydraulic conductivity value of 5 ft/d was applied. The calibrated vertical hydraulic conductivity value used for Ogallala sediments, limestone, and Antlers Sand is one-tenth that of the horizontal hydraulic conductivity. The calibrated vertical hydraulic conductivity value for shale is one-hundredth that of the horizontal value, or 0.00001 ft/d.

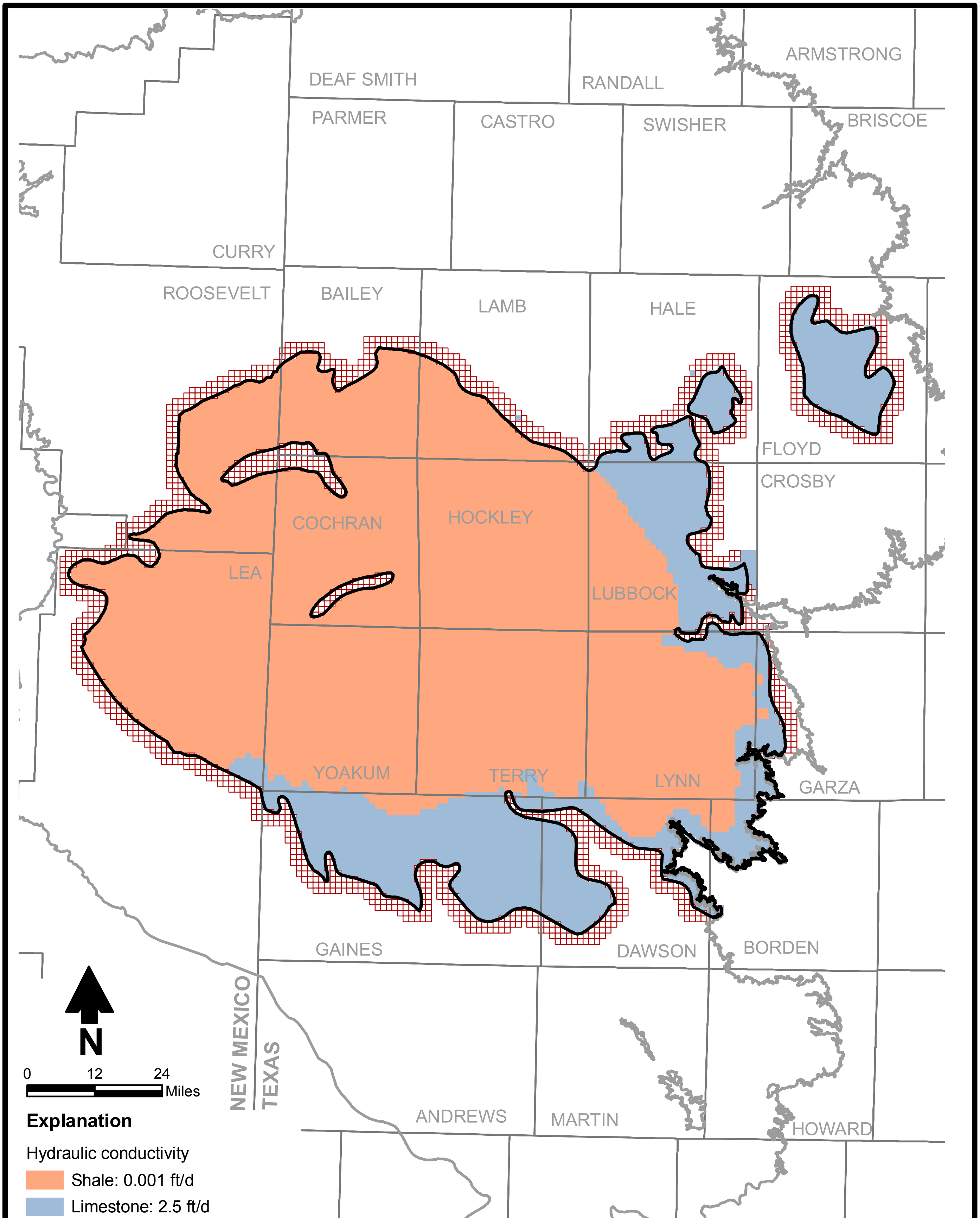
Each of these values is reasonably consistent with the observed data and the various aquifer material types. Although the hydraulic conductivity values applied for the Edwards-Trinity (High Plains) Aquifer units are less than the geometric mean for observed data of 7.8 ft/d, this result is not unexpected because a significant number of less productive Edwards-Trinity (High Plains) wells were likely not tested, and available observed values may therefore be biased toward more productive (and therefore higher hydraulic conductivity) locations.

Due to the limited availability of aquifer test and observed water level data, the decision was made to keep the variation in hydraulic properties used for the Edwards-Trinity (High Plains) Aquifer to a minimum to avoid over-calibration of the model to the extent possible.

8.4 Water Budget

The steady-state calibration water budget is provided in Table 5. Total simulated recharge to the aquifer system is 60,567 ac-ft/yr, 99 percent of which occurs to the Ogallala Aquifer. Approximately 91 percent of simulated outflow occurs from Ogallala Aquifer springs, about 3 percent occurs from Edwards-Trinity (High Plains) Aquifer springs, and 6 percent occurs as groundwater underflow from the Southern Ogallala Aquifer to the Northern Ogallala Aquifer in the vicinity of Amarillo. The overall mass balance discrepancy is less than 1 percent.

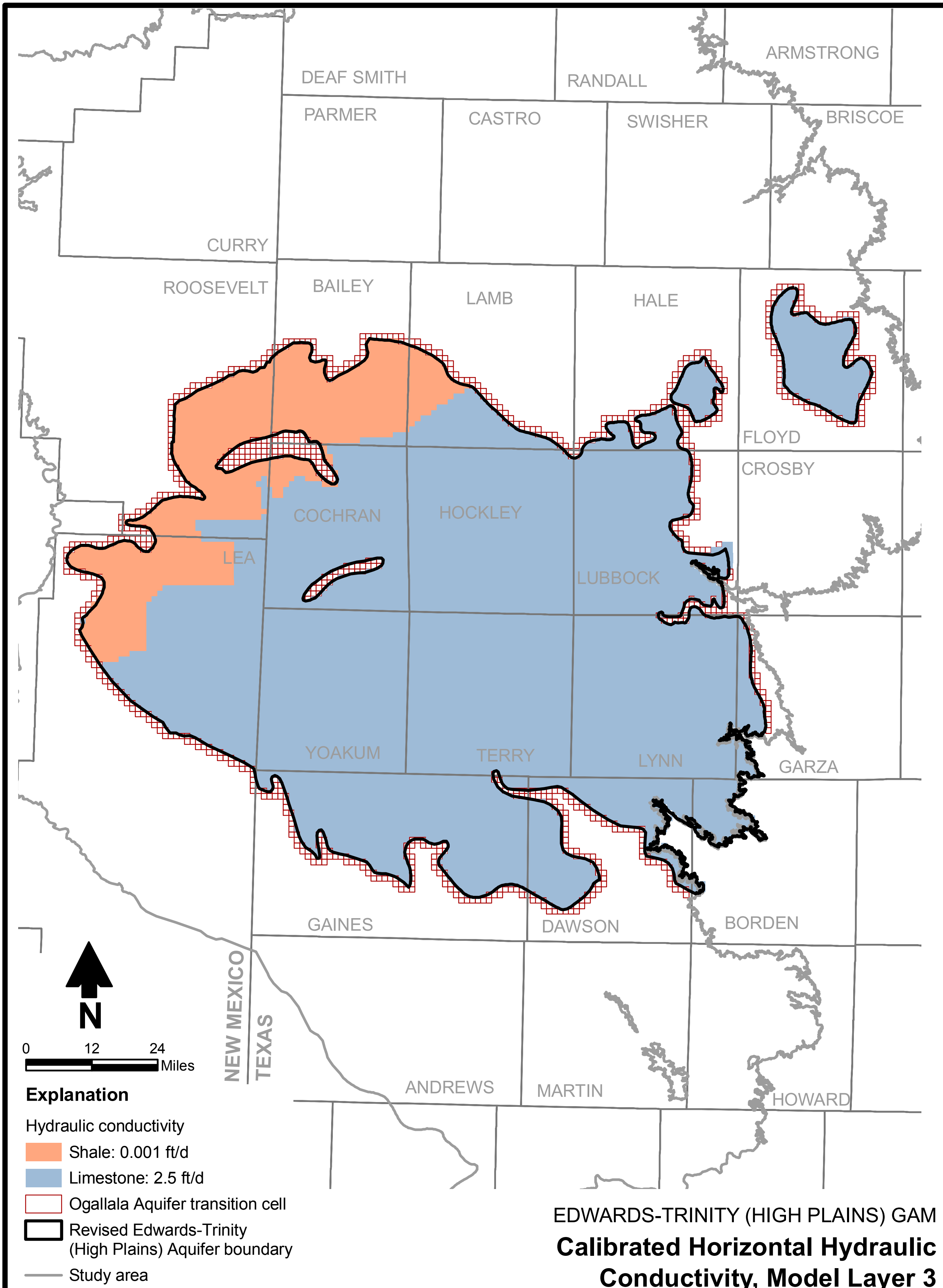
The steady-state water budget by county and GCD for predevelopment conditions is provided in Appendix A.



EDWARDS-TRINITY (HIGH PLAINS) GAM

Calibrated Horizontal Hydraulic Conductivity, Model Layer 2

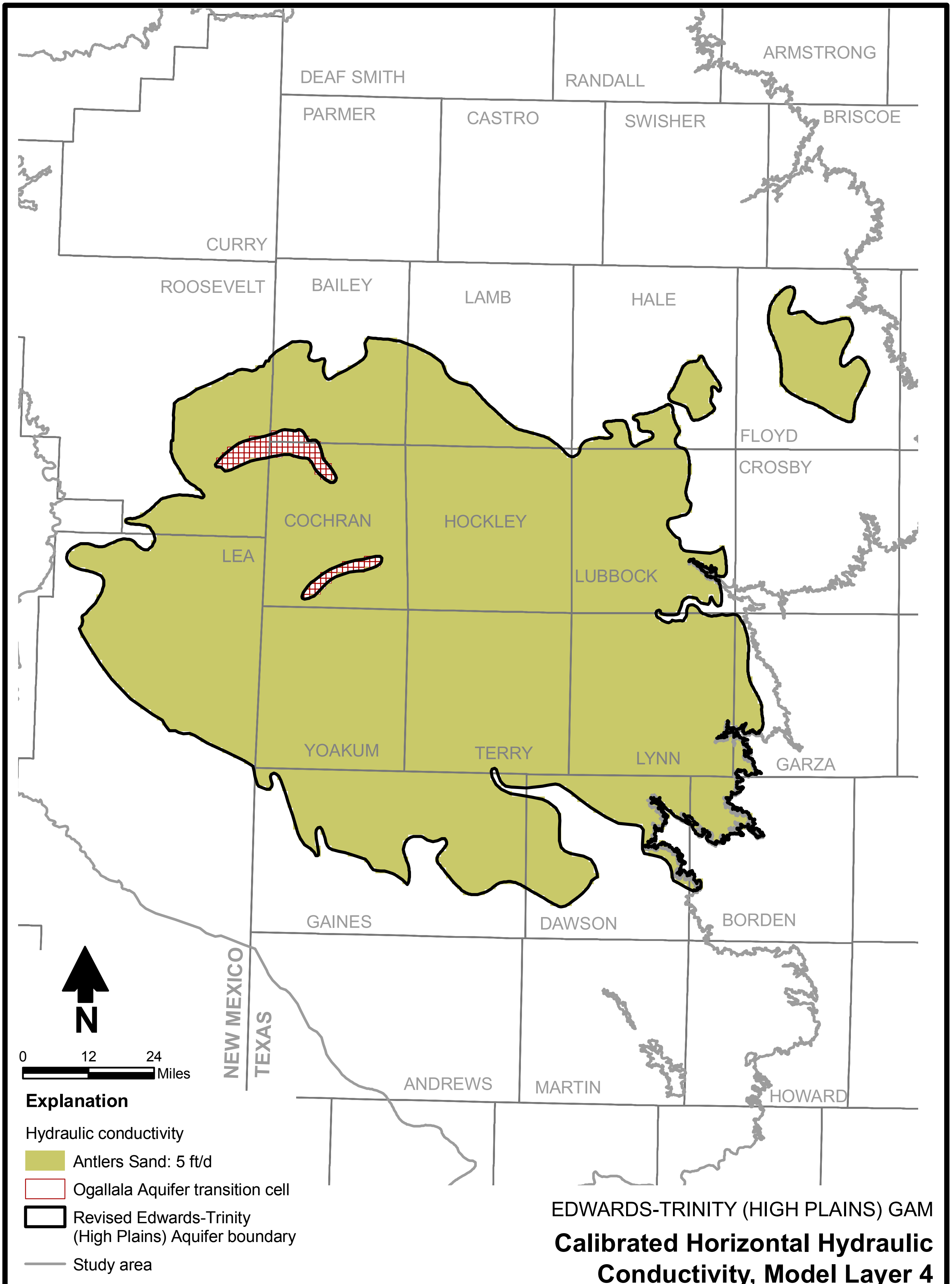
Figure 64



EDWARDS-TRINITY (HIGH PLAINS) GAM

Calibrated Horizontal Hydraulic Conductivity, Model Layer 3

Figure 65



Calibrated Horizontal Hydraulic Conductivity, Model Layer 4

Figure 66

Table 5. Steady-State Model Water Budget

	Amount (ac-ft/yr)				
Component	Layer 1	Layer 2	Layer 3	Layer 4	Total
Inflows					
Recharge	59,881	475	197	15	60,567
Total Inflows	59,881	475	197	15	60,567
Outflows					
Prescribed head	3,945	—	—	—	3,945
Drains	55,369	340	854	477	57,039
Total outflows	59,314	340	854	477	60,984
No. of dry cells	212	97	18	0	327
Percent discrepancy –0.69					

8.5 Sensitivity Analysis

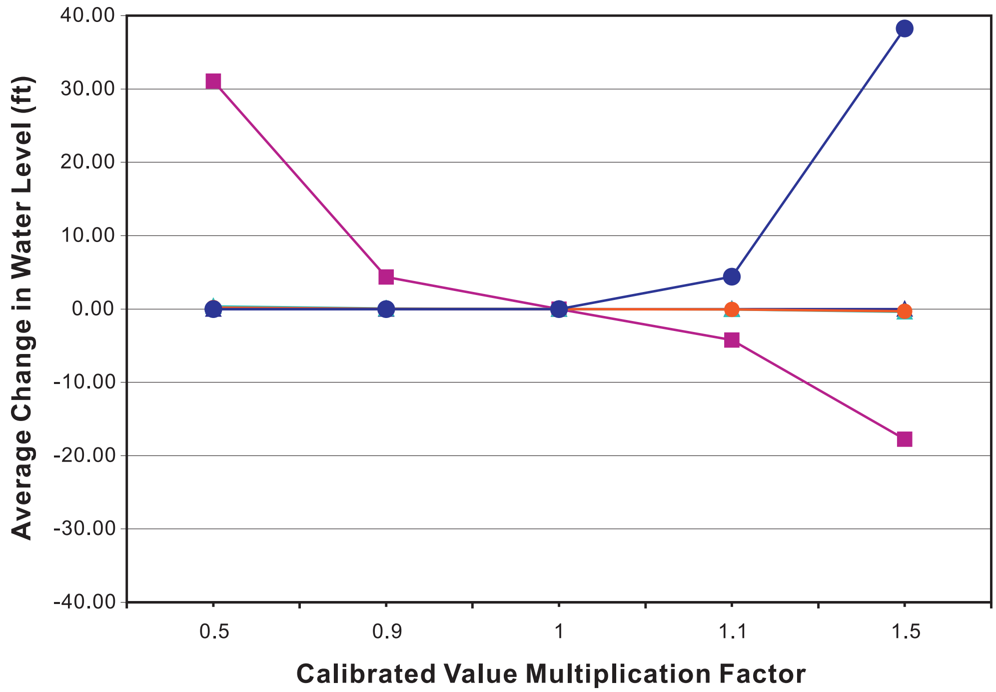
Sensitivity analyses for the steady-state model were conducted for horizontal and vertical hydraulic conductivity for each hydrogeologic unit (i.e., Ogallala sediments, and Cretaceous shale, limestone, and Antlers Sand), prescribed hydraulic head in the northeastern portion of the model domain near Amarillo, recharge, drain conductance, and seepage to or from the Dockum Aquifer. Each of these input parameters, except for horizontal hydraulic conductivity and prescribed hydraulic head, was increased and decreased uniformly by a factor of 5 and 10. Horizontal hydraulic conductivity and prescribed hydraulic head were increased uniformly by 10 percent and 50 percent above the calibrated value and decreased by 10 percent and 50 percent below the calibrated value. The sensitivity analysis results are presented in terms of the average difference between calibrated model water levels and sensitivity run water levels at (1) the calibration points and (2) all active model cells within a given layer. The sensitivity model runs are provided for both model layer 1 (Southern Ogallala Aquifer) and model layers 3 and 4 (Edwards-Trinity [High Plains] Aquifer).

Since cross-formational flow between the Edwards-Trinity (High Plains) Aquifer and the Dockum Aquifer is set to zero in the calibrated model, the leakage rate determined during development of the Dockum Aquifer GAM (Ewing and others, 2008) was applied as a groundwater flux to model layer 4 in order to conduct the Dockum leakage sensitivity analysis. The leakage rates determined from the Dockum Aquifer GAM are both upward (inflow from the Dockum Aquifer to the Edwards-Trinity [High Plains] Aquifer) and downward (outflow from the Edwards-Trinity [High Plains] Aquifer to the Dockum Aquifer). Based on the simulated values in Ewing and others (2008) for their predevelopment period, the inflow to the Edwards-Trinity (High Plains) Aquifer from the Dockum Aquifer is 4,729 ac-ft/yr, while the outflow from the Edwards-Trinity (High Plains) Aquifer to the Dockum Aquifer is 7,750 ac-ft/yr. The applied leakage rates should be considered as very approximate potential values, subject to a high degree of uncertainty, because (1) no observed hydraulic head data are available for the Dockum Aquifer that lies beneath large portions of the Edwards-Trinity (High Plains) Aquifer, and (2) TDS of Dockum Aquifer water is very high beneath large portions of the Edwards-Trinity (High Plains) Aquifer and the effects of the high salinity are not accounted for in the Dockum Aquifer GAM. Details regarding the Dockum Aquifer are provided in Ewing and others (2008).

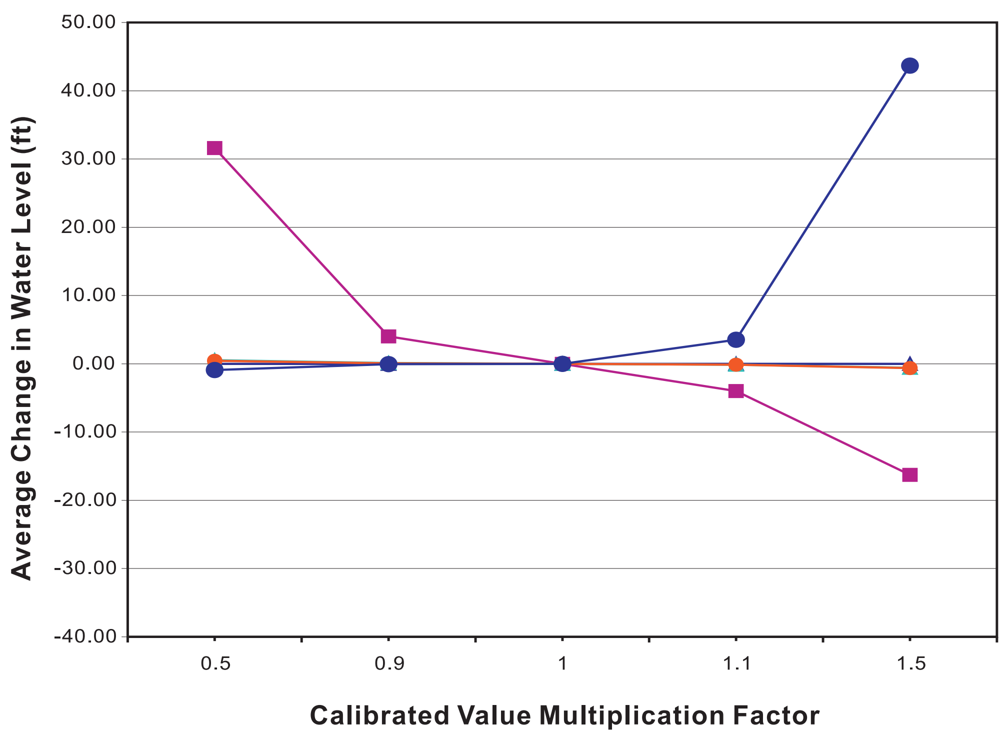
The model sensitivity to horizontal hydraulic conductivity and prescribed hydraulic head is presented in Figures 67 (Southern Ogallala Aquifer) and 68 (Edwards-Trinity [High Plains] Aquifer). Both figures indicate that the model is sensitive to changes in horizontal hydraulic conductivity of the Southern Ogallala Aquifer but insensitive to changes in the horizontal hydraulic conductivity of the shale, limestone, and Antlers Sand units that lie beneath the Southern Ogallala Aquifer. The model is also insensitive to changes in prescribed hydraulic head along the far northeastern boundary, except for model layer 1 when the prescribed head is increased by 50 percent (fig. 67).

The model sensitivity to vertical hydraulic conductivity is presented in Figures 69 (Southern Ogallala Aquifer) and 70 (Edwards-Trinity [High Plains] Aquifer). These figures indicate that the model is relatively insensitive to changes in vertical hydraulic conductivity, with the exception of decreasing the vertical hydraulic conductivity of the shale (fig. 70b).

Sensitivity of the steady-state model to recharge, drain conductance (divided into escarpment and interior drains), and leakage to and from the Dockum Aquifer is illustrated in Figures 71 and 72 for the Southern Ogallala Aquifer and Edwards-Trinity (High Plains) Aquifer, respectively. Figure 71 indicates that Southern Ogallala Aquifer water levels are moderately sensitive to decreases in drain conductance, but are insensitive to increases in drain conductance. Conversely, simulated Southern Ogallala Aquifer water levels are sensitive to increases in Dockum Aquifer leakage, but insensitive to decreases in Dockum Aquifer leakage (note that prescribed Dockum Aquifer leakage applied in the sensitivity analysis leads to both inflow to, and outflow from, the Edwards-Trinity [High Plains] Aquifer). Figure 72 indicates that, like the Southern Ogallala Aquifer water levels, Edwards-Trinity (High Plains) Aquifer water levels are moderately sensitive to decreases in drain conductance, but are insensitive to increases in drain conductance. Also like the Southern Ogallala Aquifer water levels, Edwards-Trinity (High Plains) Aquifer water levels are very sensitive to increases in prescribed Dockum Aquifer leakage (fig. 72b), but insensitive to decreases in prescribed Dockum Aquifer leakage.

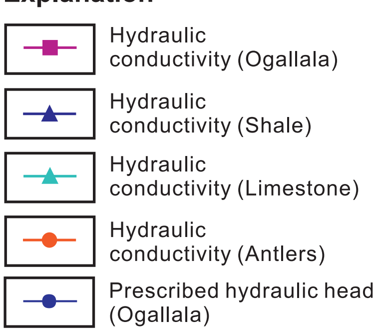


(a) Change at calibration points



(b) Change at all active model cells
(scale changed to plot highest value)

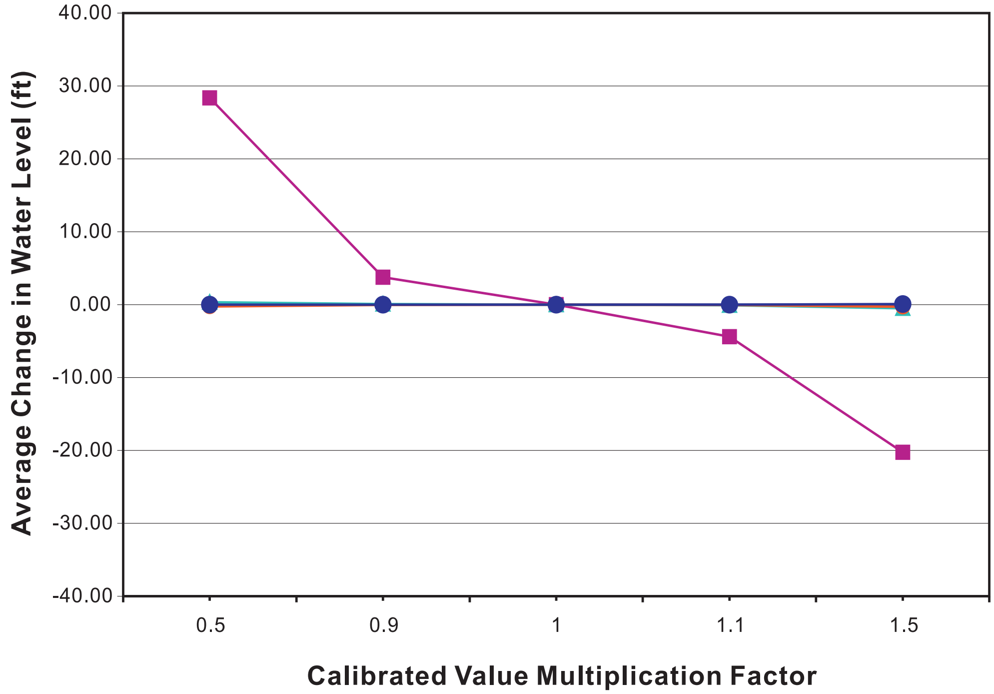
Explanation



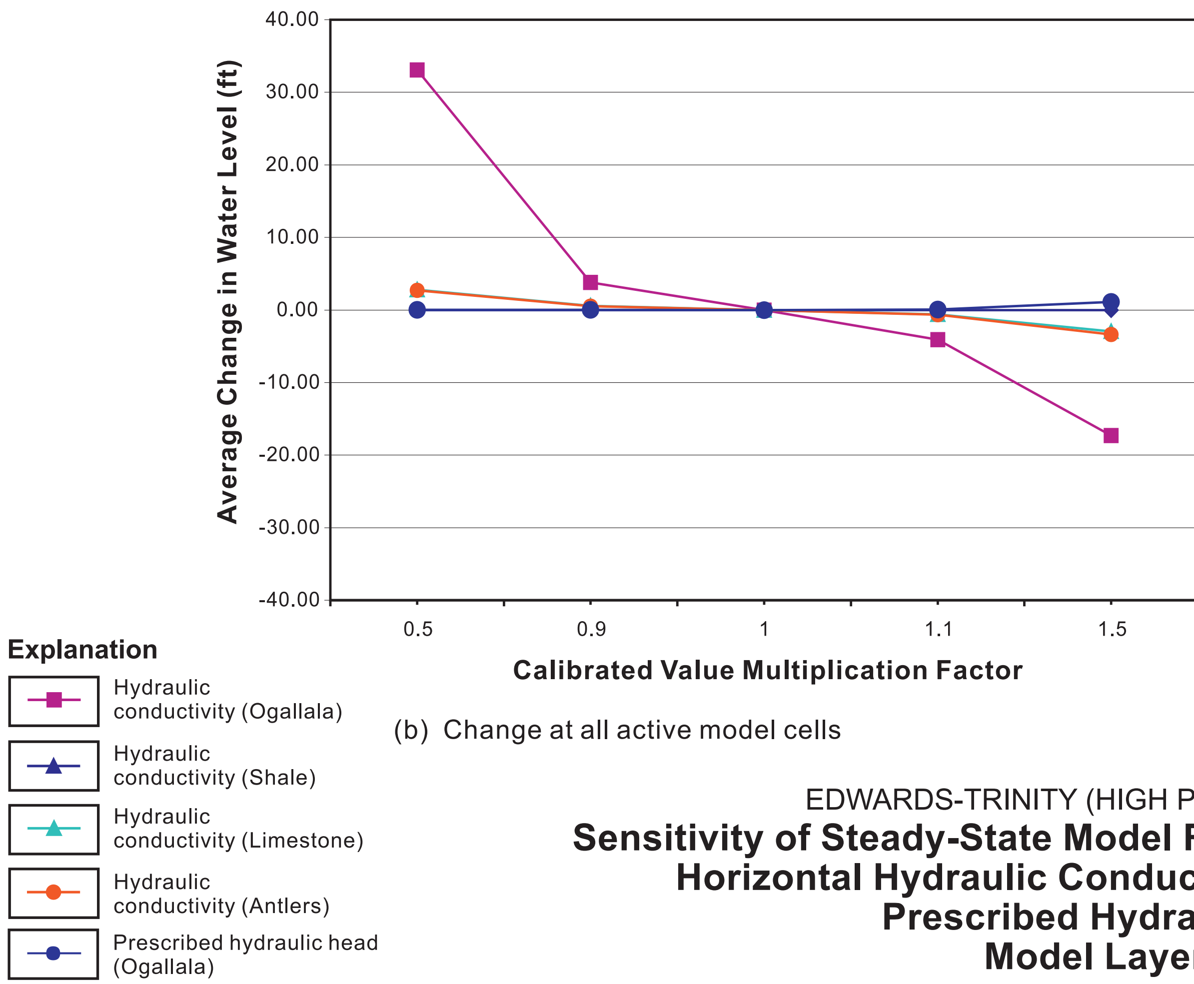
EDWARDS-TRINITY (HIGH PLAINS) GAM

Sensitivity of Steady-State Model Results to Horizontal Hydraulic Conductivity and Prescribed Hydraulic Head Model Layer 1

Figure 67



(a) Change at calibration points

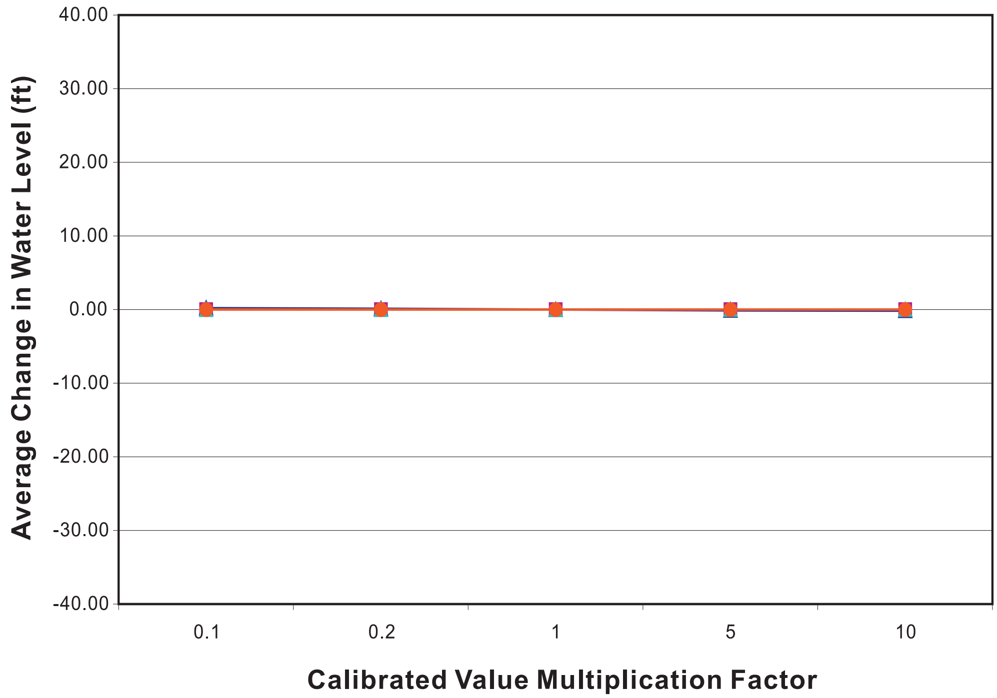


(b) Change at all active model cells

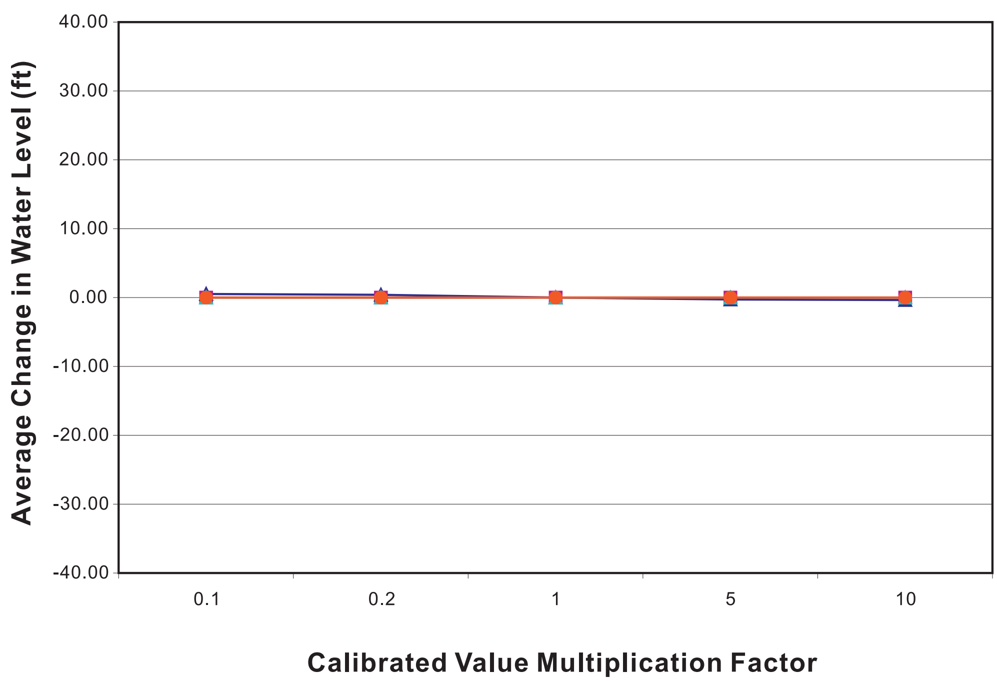
EDWARDS-TRINITY (HIGH PLAINS) GAM

Sensitivity of Steady-State Model Results to Horizontal Hydraulic Conductivity and Prescribed Hydraulic Head Model Layers 3 and 4

Figure 68



(a) Change at calibration points



(b) Change at all active model cells

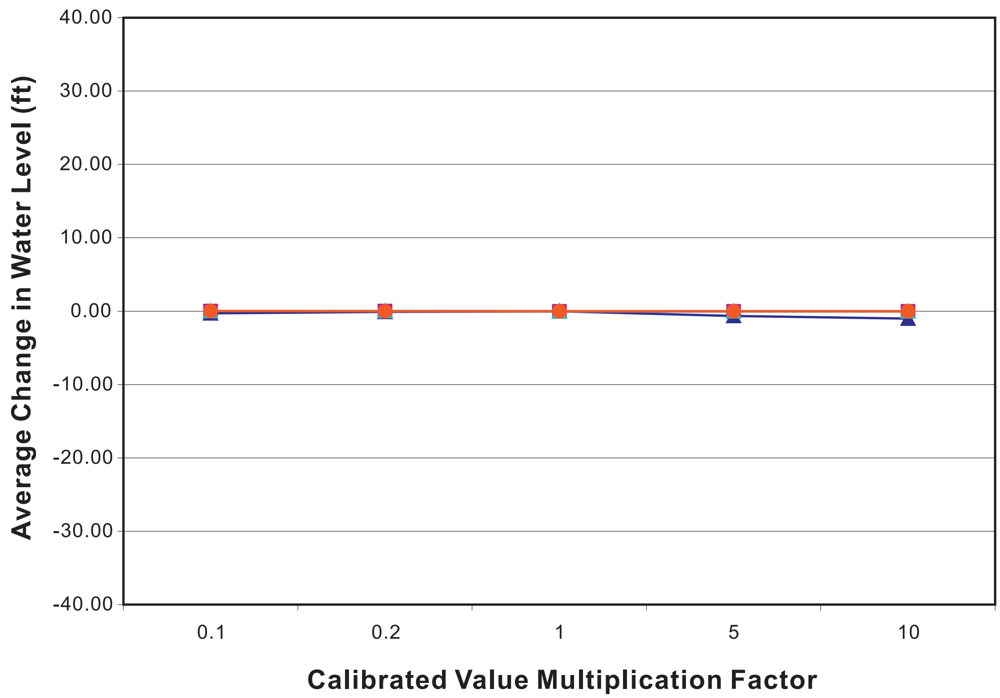
Explanation

- Ogallala
- Shale
- Limestone
- Antlers

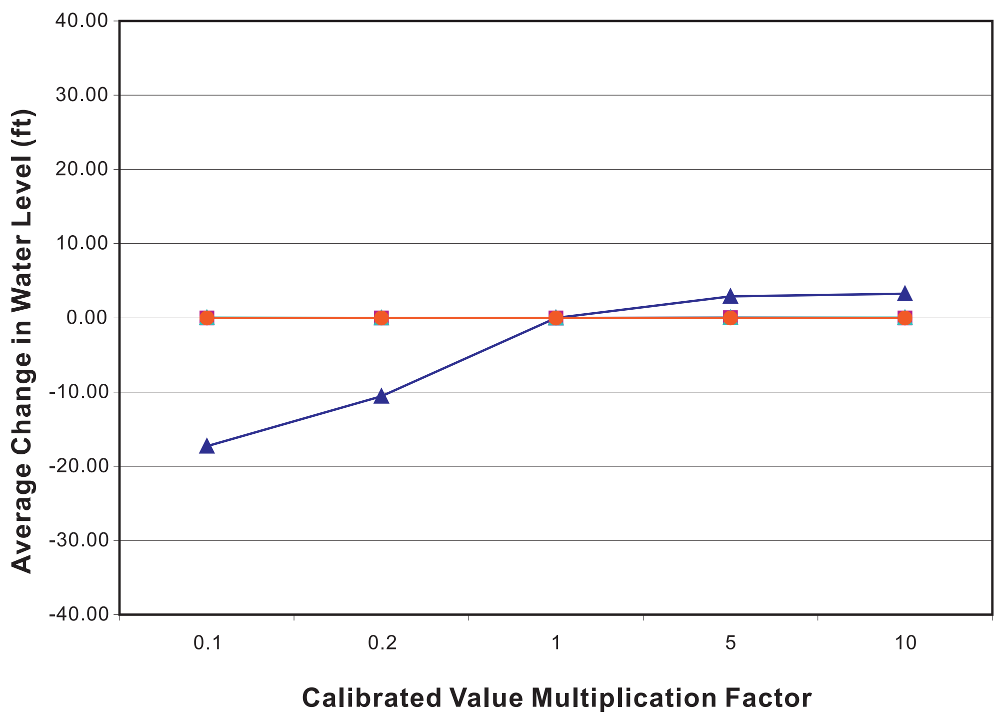
EDWARDS-TRINITY (HIGH PLAINS) GAM

Sensitivity of Steady-State Model Results to Vertical Hydraulic Conductivity Model Layer 1

Figure 69



(a) Change at calibration points



(b) Change at all active model cells

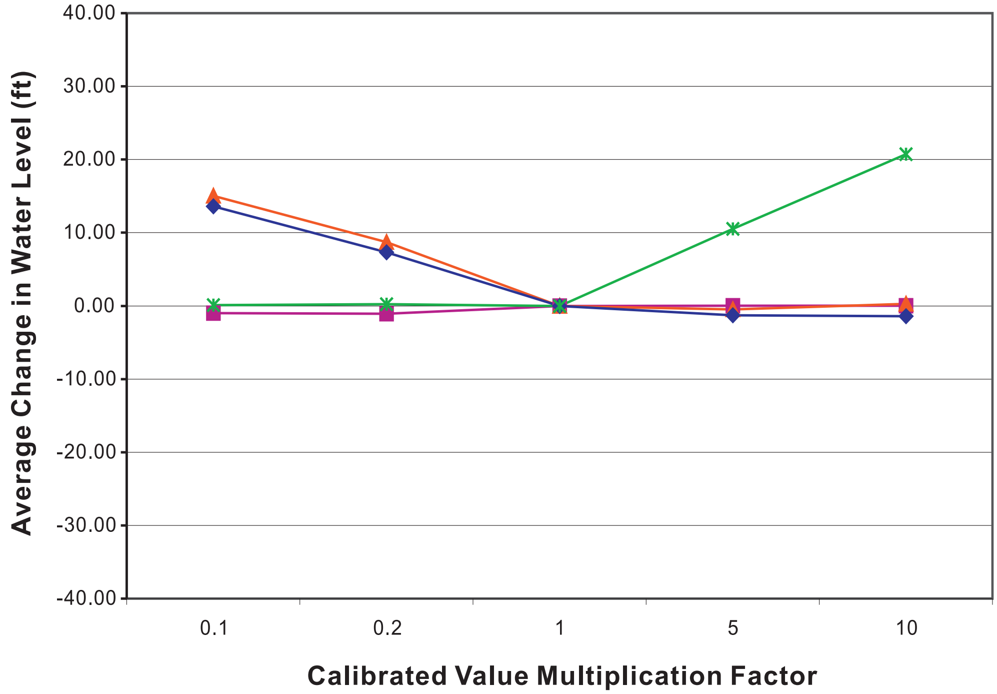
Explanation

- Ogallala
- Shale
- Limestone
- Antlers

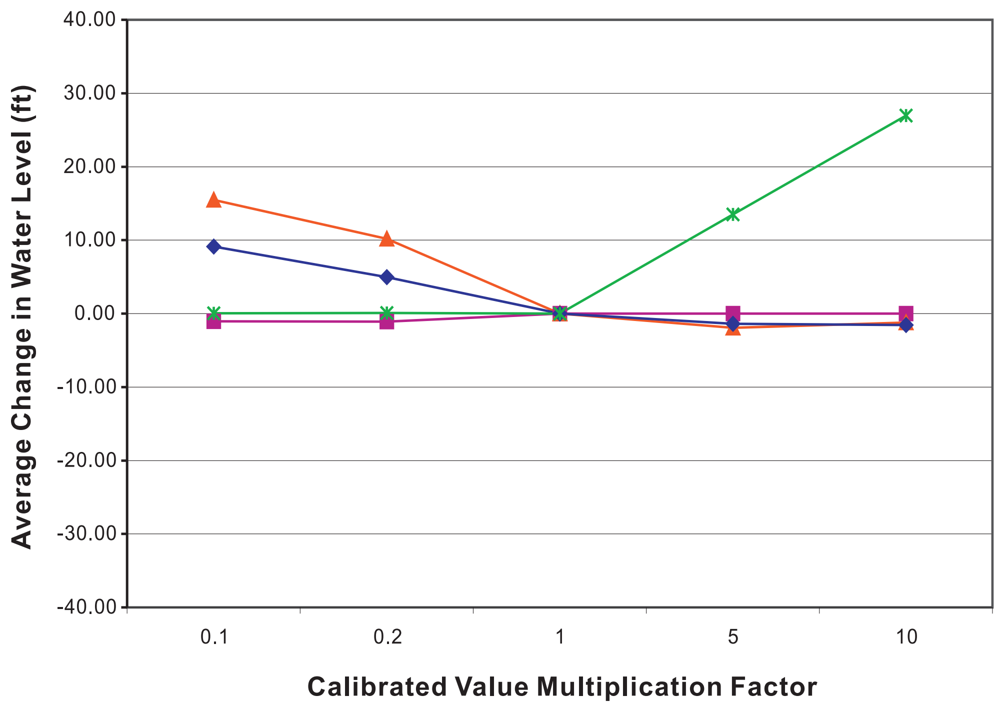
EDWARDS-TRINITY (HIGH PLAINS) GAM

Sensitivity of Steady-State Model Results to Vertical Hydraulic Conductivity Model Layers 3 and 4

Figure 70



(a) Change at calibration points



(b) Change at all active model cells

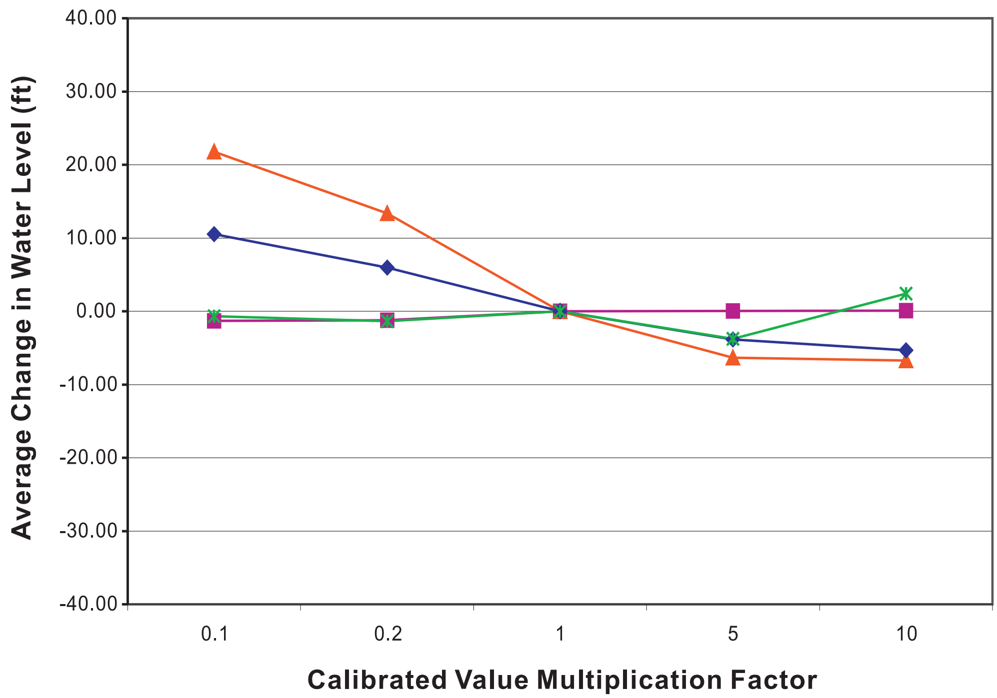
Explanation

- Recharge
- Escarpment drain conductance
- Interior drain conductance
- Dockum leakage

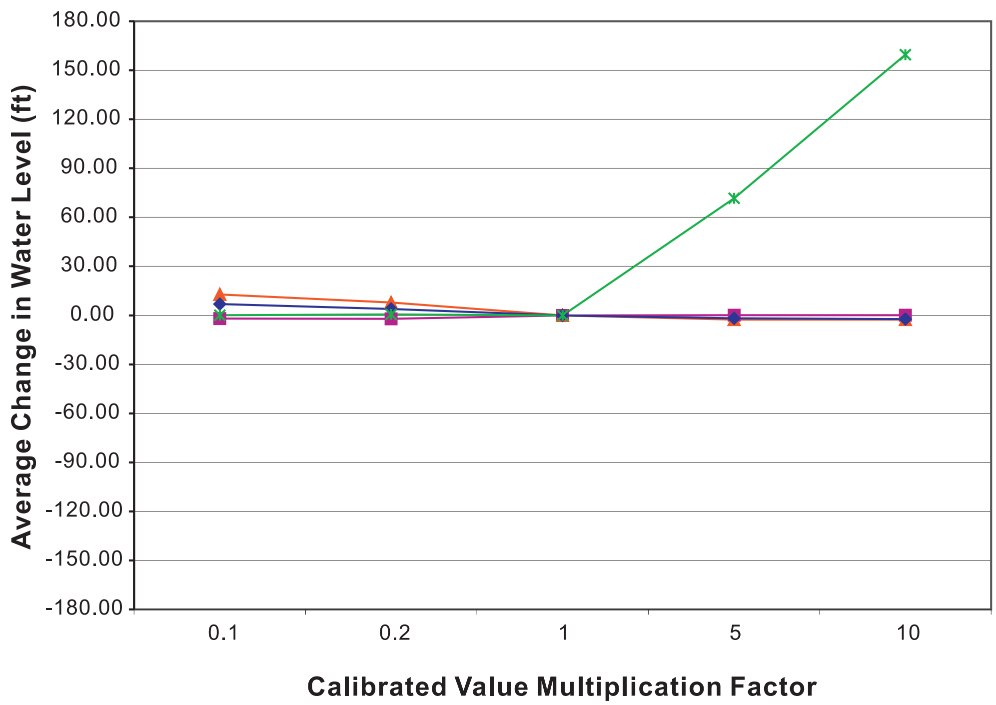
EDWARDS-TRINITY (HIGH PLAINS) GAM

Sensitivity of Steady-State Model Results to Recharge, Drain Conductance, and Dockum Leakage Model Layer 1

Figure 71



(a) Change at calibration points



(b) Change at all active model cells (scale changed to plot highest value)

Explanation

- Recharge
- Escarpment drain conductance
- Interior drain conductance
- Dockum leakage

EDWARDS-TRINITY (HIGH PLAINS) GAM

Sensitivity of Steady-State Model Results to Recharge, Drain Conductance, and Dockum Leakage Model Layers 3 and 4

Figure 72

9.0 Transient Model

The transient model simulates water levels in the aquifer system for the period of 1930 through 2000. This period is divided into 71 annual stress periods, and each stress period is divided into 4 time steps. As required by the TWDB, the steady-state model is included as the first stress period of the transient simulation (representing the period prior to 1930), thereby leading to a total of 72 stress periods (Table 6).

Table 6. Transient Model Simulation Stress Periods

Year	Stress Period	Year	Stress Period	Year	Stress Period
Pre-1930	1	1953	25	1977	49
1930	2	1954	26	1978	50
1931	3	1955	27	1979	51
1932	4	1956	28	1980	52
1933	5	1957	29	1981	53
1934	6	1958	30	1982	54
1935	7	1959	31	1983	55
1936	8	1960	32	1984	56
1937	9	1961	33	1985	57
1938	10	1962	34	1986	58
1939	11	1963	35	1987	59
1940	12	1964	36	1988	60
1941	13	1965	37	1989	61
1942	14	1966	38	1990	62
1943	15	1967	39	1991	63
1944	16	1968	40	1992	64
1945	17	1969	41	1993	65
1946	18	1970	42	1994	66
1947	19	1971	43	1995	67
1948	20	1972	44	1996	68
1949	21	1973	45	1997	69
1950	22	1974	46	1998	70
1951	23	1975	47	1999	71
1952	24	1976	48	2000	72

Simulation results from the steady-state model were used as initial conditions for the transient model. Boundary conditions in the transient model were also the same as those in the steady-state model, with the exception that the prescribed hydraulic heads along the northern model boundary west of Amarillo were changed through time to represent observed changes in water levels in that area. Assignment of groundwater pumping, recharge, and storage properties for the transient model are discussed in Section 9.3 (*Model Parameters*).

9.1 Calibration Results for the Southern Ogallala Aquifer

The calibrated transient model results for the Southern Ogallala Aquifer are overall very similar to those of the previous Southern Ogallala GAM (Blandford and others, 2003). In the Edwards-Trinity (High Plains) Aquifer GAM, however, groundwater flow within the Cretaceous hydrogeologic units is simulated in conjunction with that in the Southern Ogallala Aquifer sediments. This modification is a significant enhancement to the previous model and will lead to more realistic predictions. Although adjustments to the previous model calibration were made in Lubbock, Hockley, and Yoakum Counties, the most significant improvement in model calibration was realized in Lubbock County where changes from the previous GAM are most extensive.

The simulated and observed 1990 water levels for the Southern Ogallala Aquifer are shown in Figure 73. The simulated directions of groundwater flow and hydraulic gradients are similar to the observed values for most of the study area. Figure 73 also illustrates model cells that are dry, where the simulated water level fell below the bottom of the aquifer at some point during the simulation. Relatively small (with respect to the size of the entire model) areas of dry cells occur in southern Parmer and northern Bailey Counties in Texas and in southeastern Curry and northeastern Roosevelt Counties in New Mexico, which are regions of significant agricultural pumping. In these and other areas, such as southwestern Yoakum County, simulated regions of dry cells occur where starting hydraulic heads in the model are lower than the observed water levels, due to the results of the steady-state simulation.

Other isolated regions of dry cells occur throughout the model domain at various places, most often near the edge of the Southern Ogallala Aquifer boundary or where subcrops of the Edwards-Trinity (High Plains) Aquifer occur. Although the Southern Ogallala Aquifer saturated thicknesses is generally diminished in these boundary and transition areas, the aquifer for the most part is probably not dry at these locations. Given the uncertainties in the model, it is expected that some simulated dry cells will occur in regions of limited saturated thickness.

A comparison of the observed and simulated water levels is provided in Figure 74, which also lists the model calibration statistics. The MAE is 36 feet, indicting that, on average, the simulated 1990 water levels differ from observed values by 36 feet. The MAE divided by the observed range in hydraulic heads of 2,772 feet is 1.3 percent, far below the maximum allowable value of 10 percent set for this statistic by the TWDB. The ME is –3 feet, indicating that, on average, simulated water levels are slightly greater than the observed water levels.

Figure 75 illustrates the magnitude of the difference between simulated and observed water levels, as well as whether they are higher or lower than observed values. The points shown in Figure 75 correspond to the locations where the data available to construct Figure 74 were measured.

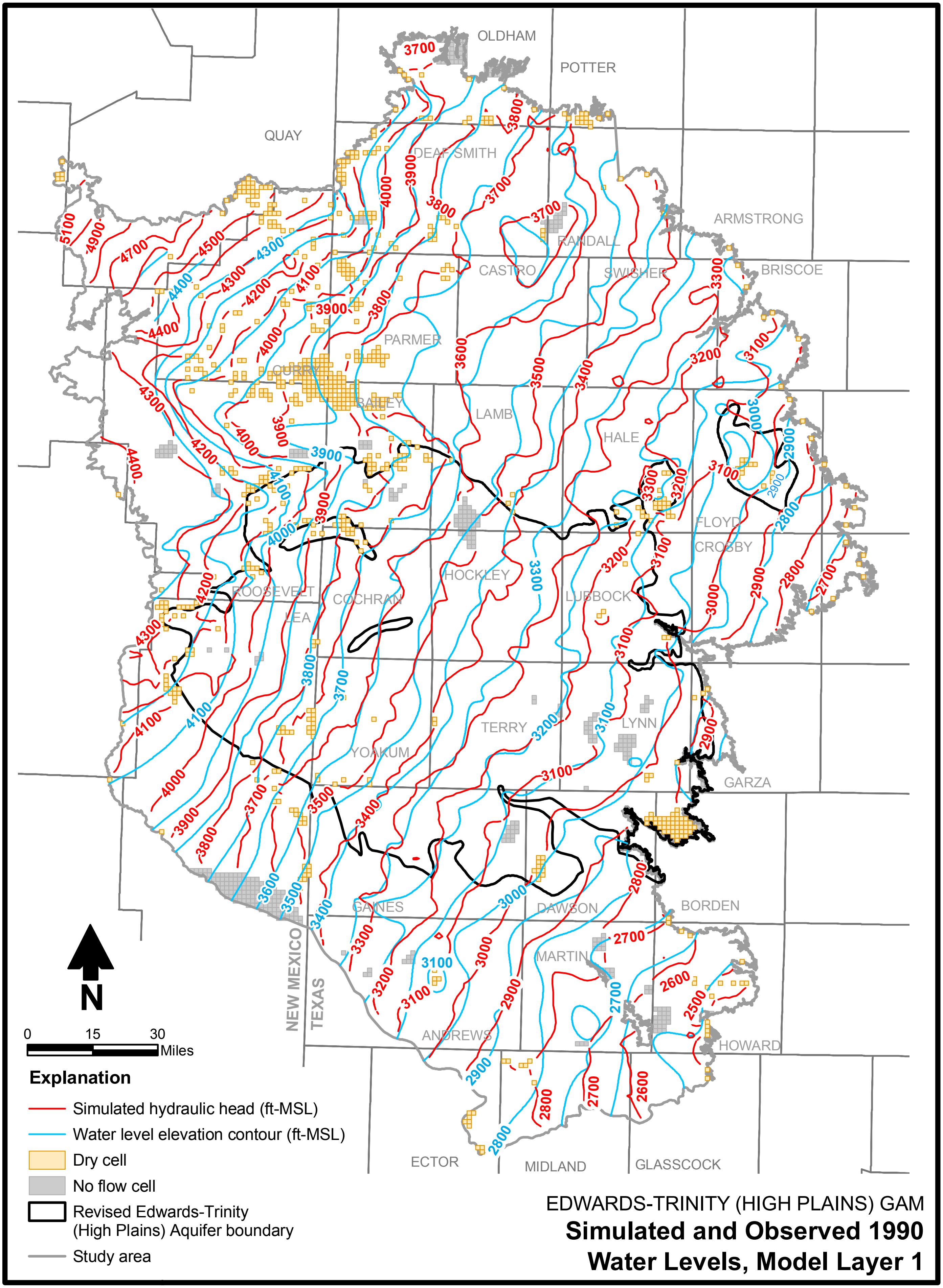
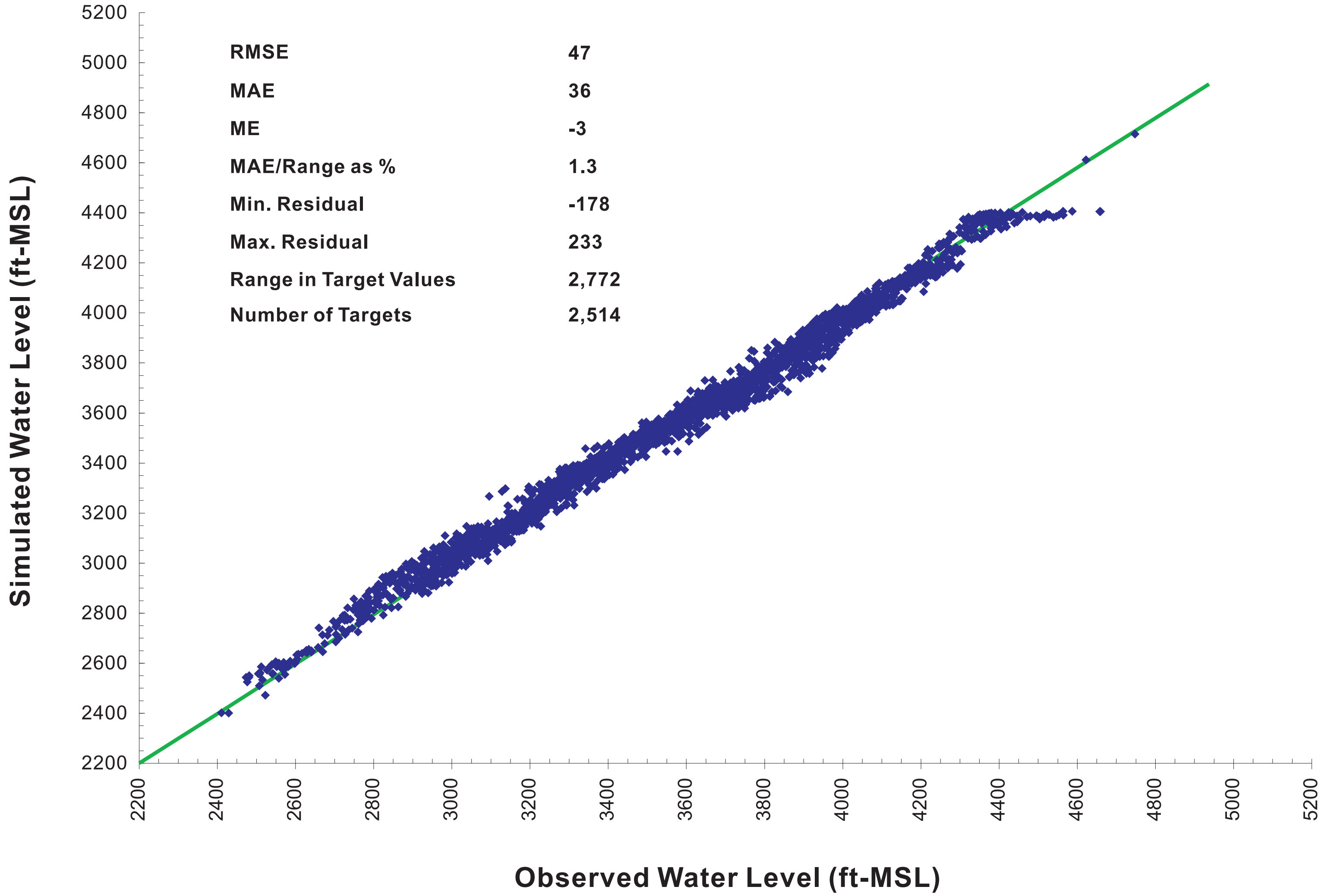

OLDHAM
POTTER
QUAY
DEAF SMITH
ARMSTRONG
RANDALL
CASTRO
SWISHER
BRISCOE
PARMER
CURRY
BAILEY
LAMB
HALE
FLOYD
CROSBY
HOCKLEY
ROOSEVELT
COCHRAN
LEA
LUBBOCK
TERRY
LYNN
YOAKUM
GARZA
GAINES
DAWSON
BORDEN
MARTIN
ANDREWS
HOWARD
ECTOR
MIDLAND
GLASSCOCK
NEW MEXICO
TEXAS
N
0 15 30
Miles
Explanation
Simulated hydraulic head (ft-MSL)
Water level elevation contour (ft-MSL)
Dry cell
No flow cell
Revised Edwards-Trinity (High Plains) Aquifer boundary
Study area
EDWARDS-TRINITY (HIGH PLAINS) GAM
Simulated and Observed 1990
Water Levels, Model Layer 1

Figure 73

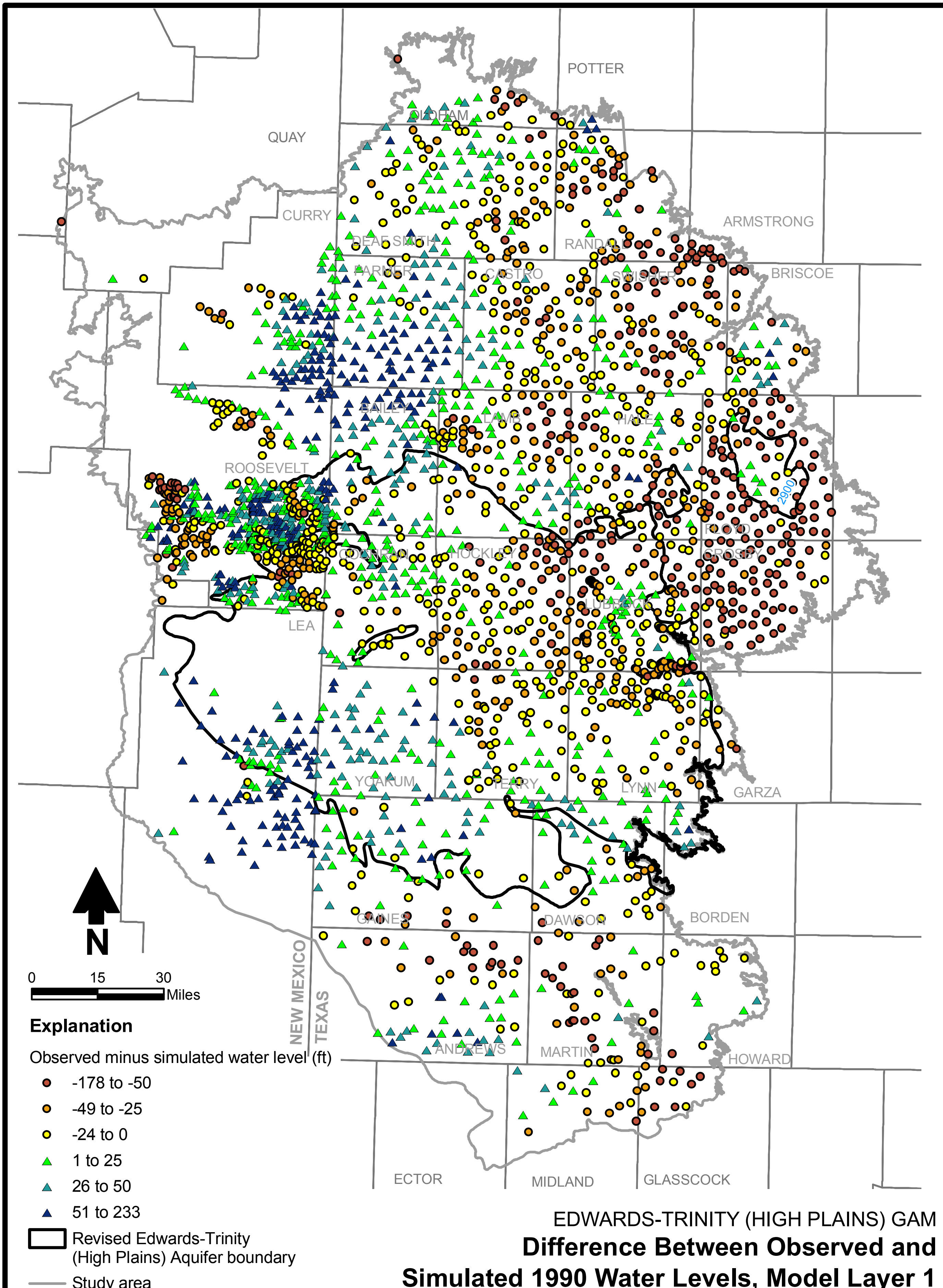


EDWARDS-TRINITY (HIGH PLAINS) GAM

Simulated Versus Observed 1990 Water Levels

Model Layer 1

Figure 74



EDWARDS-TRINITY (HIGH PLAINS) GAM

Difference Between Observed and Simulated 1990 Water Levels, Model Layer 1

Figure 75

As shown in Figure 75, simulated 1990 hydraulic heads in the transient model are generally within 25 feet of the observed value. However, simulated values tend to be lower than observed values in some of the western counties (e.g., Bailey, Parmer and Yoakum), and conversely, simulated values tend to be higher than observed values in some eastern counties (e.g., Floyd and Crosby). This trend is also evident in Figure 74, where the higher simulated water levels tend to fall below the 45-degree best fit line, while the lower simulated water levels tend to fall above the best fit line.

Figures 76 through 78 present the same water level comparisons as Figures 73 through 75, but for the year 2000. The trends seen in the 1990 water levels are also applicable to the 2000 water level comparisons. Comparison of Figures 76 and 73 illustrates that the number of simulated dry cells increases somewhat over the 10-year simulation period from 1990 to 2000. The year 2000 calibration statistics (fig. 77) are also very good, with an ME of –9 feet, an MAE of 33 feet and the MAE divided by the observed range in hydraulic heads of 1.8 percent.

The goal of the transient simulation was to match the trends in observed water levels through time, to the extent possible, while maintaining a reasonable set of model input parameters. The starting points for the simulated water levels are generally different from the observed data because they were taken from the steady-state modeling results. The simulated and observed water levels of each of the 90 hydrographs used in the transient model calibration for model layer 1 are provided in Appendix B.

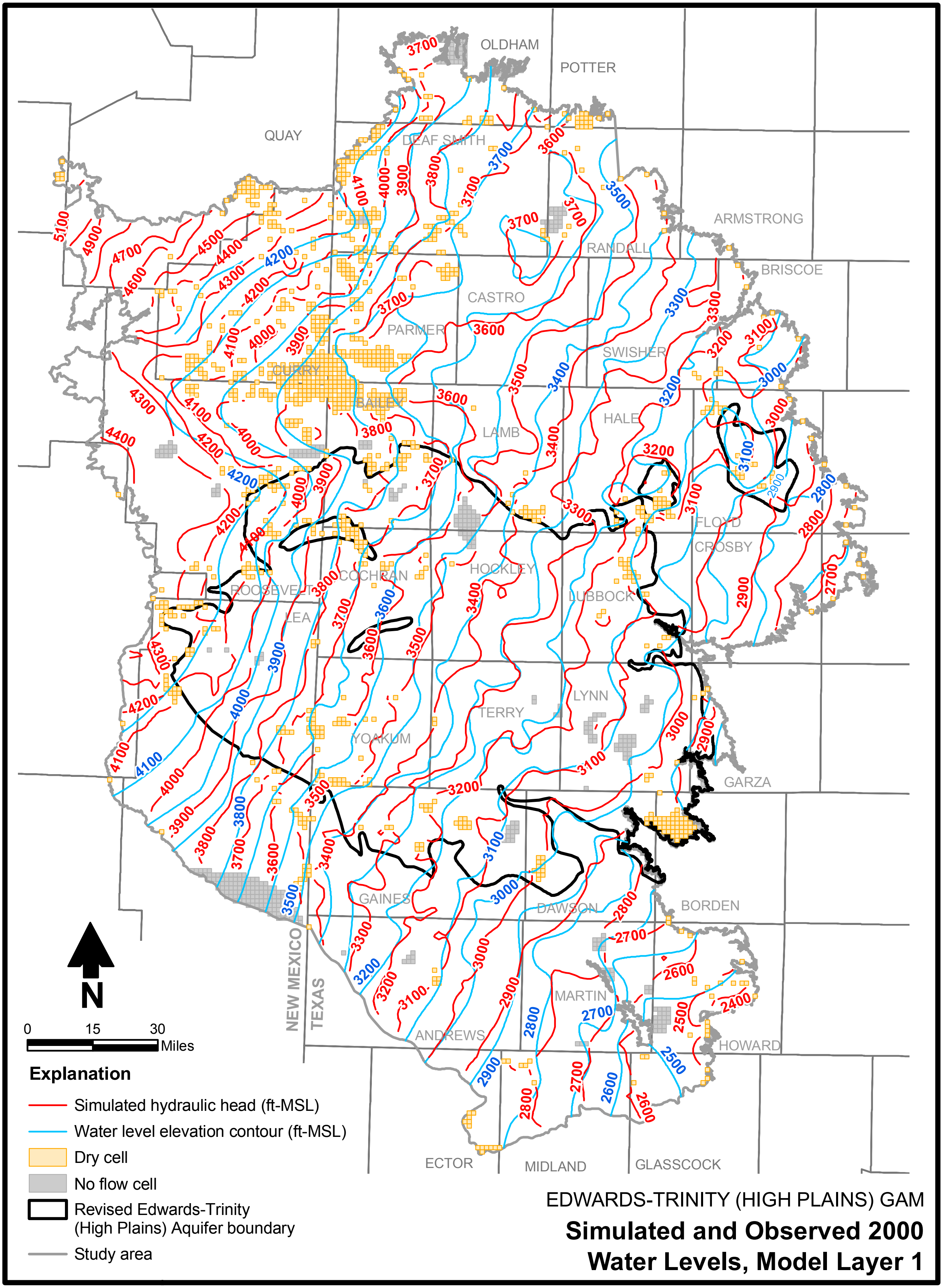
Examples of simulated and observed hydrographs for Southern Ogallala Aquifer wells are provided in Figures 79 and 80 for the northern and southern half of the study area, respectively. As illustrated in the figures, a reasonable match between simulated and observed water level trends was obtained for regions of significant drawdown (e.g., Parmer and Hale Counties), regions of fairly stable water levels or less substantial drawdown (e.g., Terry and Gaines Counties), and regions of rising water levels (e.g., Dawson County and the Lubbock area in Lubbock County).

9.2 Calibration Results for the Edwards-Trinity (High Plains) Aquifer

The simulated 1980 water levels for model layer 2 are provided in Figure 81, and the simulated and observed 1980 water levels representative of model layers 3 and 4 (Cretaceous limestone and Antlers Sand) are provided in Figure 82. As noted in Section 8.0 (*Steady-State Model*), observed water levels representative of model layer 2 could not be located, and the simulated water levels for model layers 3 and 4 are essentially identical. Therefore, observed data believed to be representative of water-producing units in the Cretaceous limestone and/or Antlers Sand are compared to water levels simulated for model layer 4.

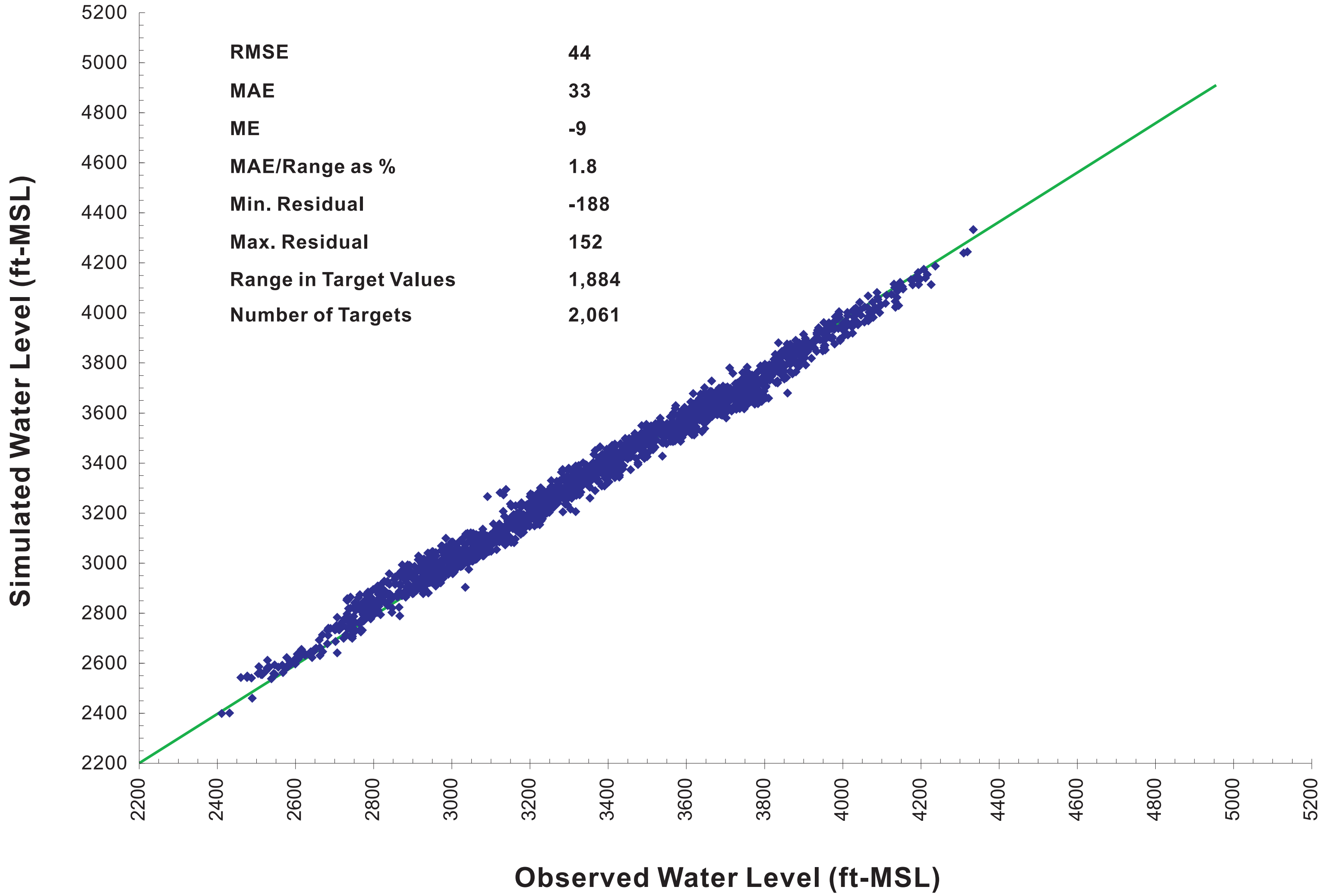
The observation data control points provided in Figure 82 are divided into three types of data that should be considered during the interpretation of water levels:

- The Edwards-Trinity (High Plains) Aquifer control points represent wells where the screened interval appears to correspond to producing zones exclusive to the Edwards-Trinity (High Plains) Aquifer. Note, however, that even if the screened interval of the well is adjacent to Edwards-Trinity (High Plains) Aquifer units only, the well annular space may not be sealed off from the overlying Southern Ogallala Aquifer.



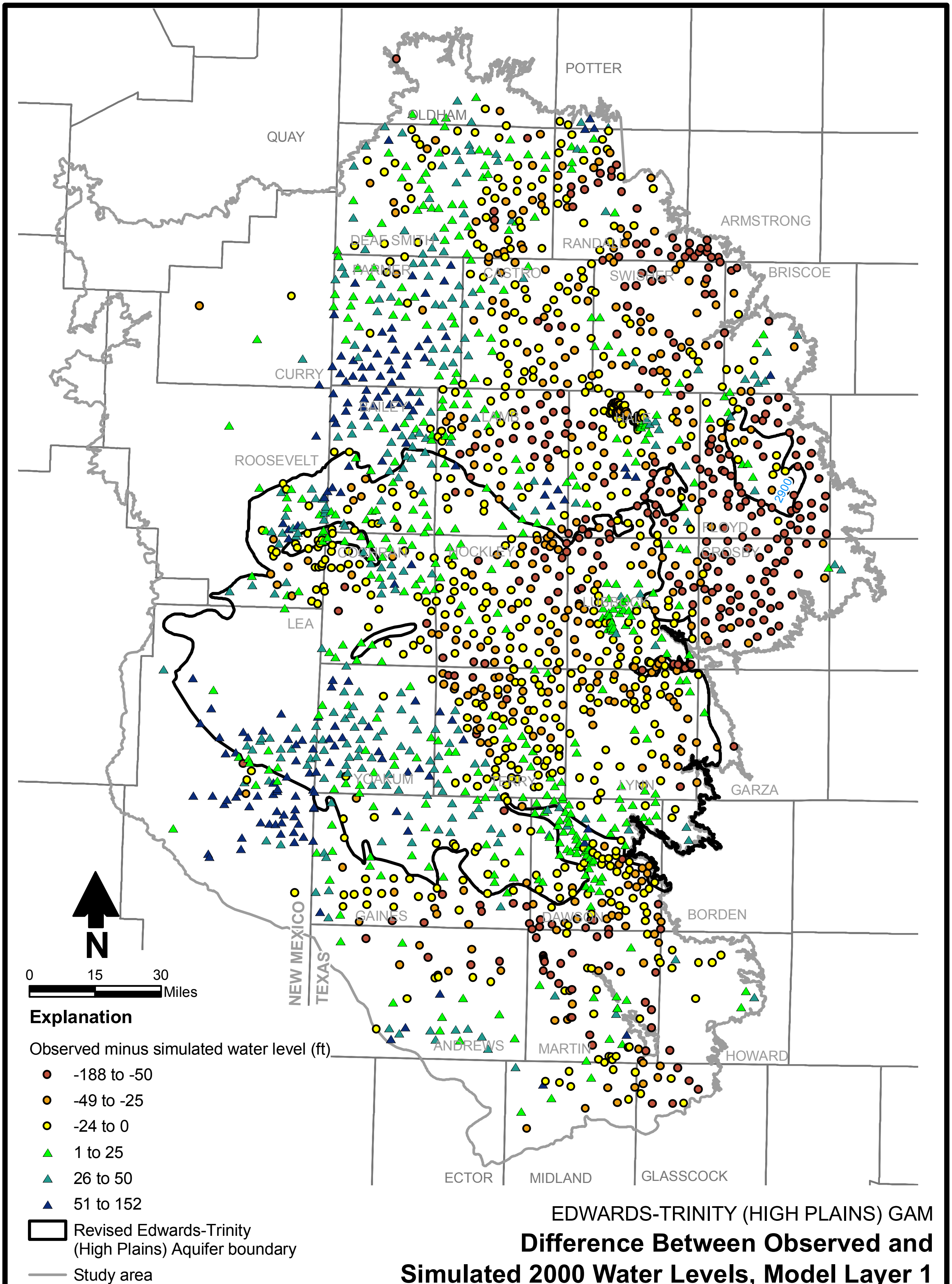
OLDHAM
POTTER
QUAY
DEAF SMITH
RANDALL
ARMSTRONG
BRISCOE
CASTRO
PARMER
SWISHER
CURRY
BAILEY
LAMB
HALE
FLOYD
CROSBY
COCHRAN
HOCKLEY
LUBBOCK
ROOSEVELT
LEA
LYNN
TERRY
YOAKUM
GARZA
GAINES
DAWSON
BORDEN
MARTIN
ANDREWS
HOWARD
ECTOR
MIDLAND
GLASSCOCK
NEW MEXICO
TEXAS
N
0 15 30 Miles
Explanation
Simulated hydraulic head (ft-MSL)
Water level elevation contour (ft-MSL)
Dry cell
No flow cell
Revised Edwards-Trinity (High Plains) Aquifer boundary
Study area
EDWARDS-TRINITY (HIGH PLAINS) GAM
Simulated and Observed 2000 Water Levels, Model Layer 1

Figure 76



EDWARDS-TRINITY (HIGH PLAINS) GAM
Simulated Versus Observed 2000 Water Levels
Model Layer 1

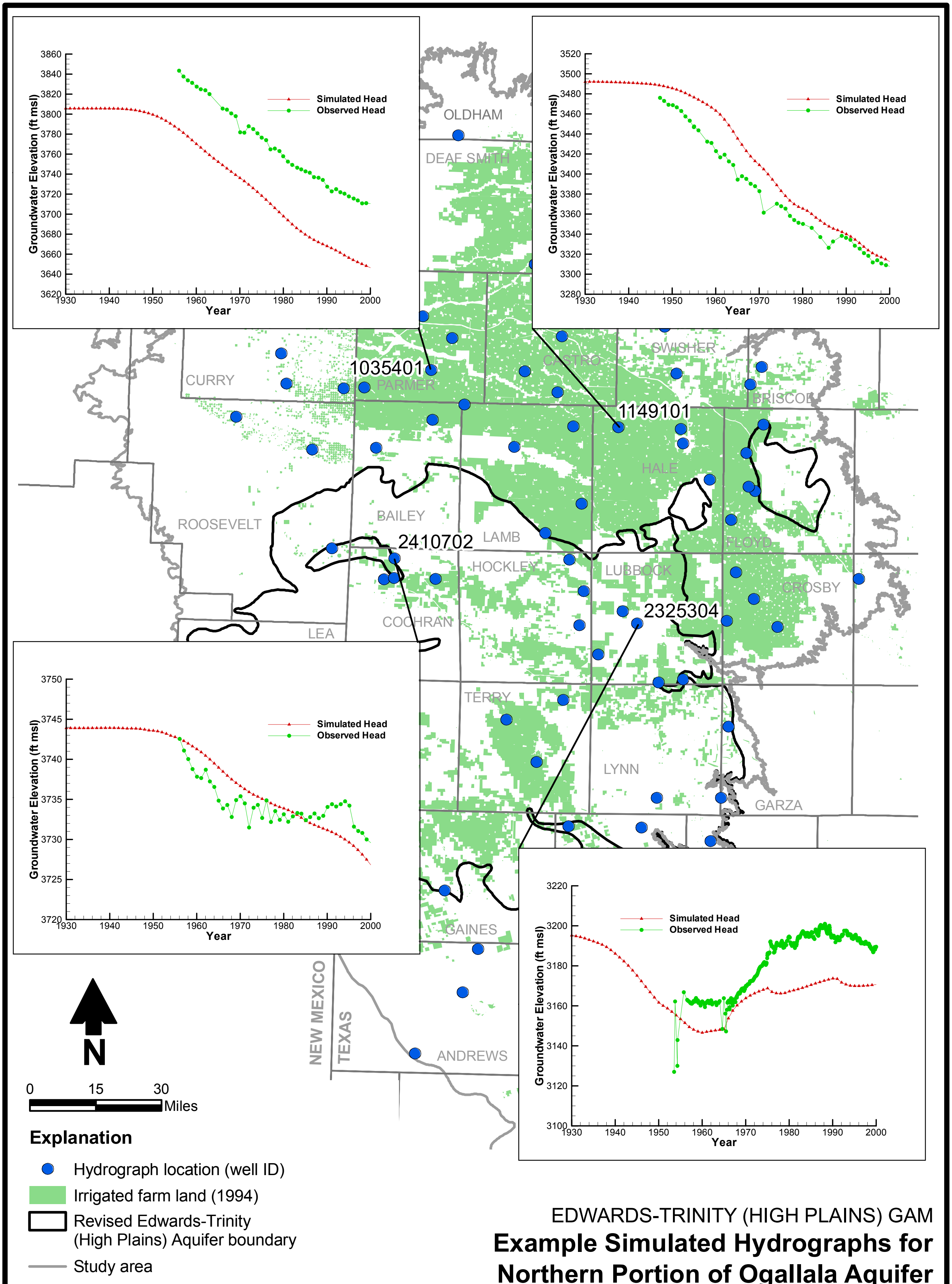
Figure 77



EDWARDS-TRINITY (HIGH PLAINS) GAM

Difference Between Observed and Simulated 2000 Water Levels, Model Layer 1

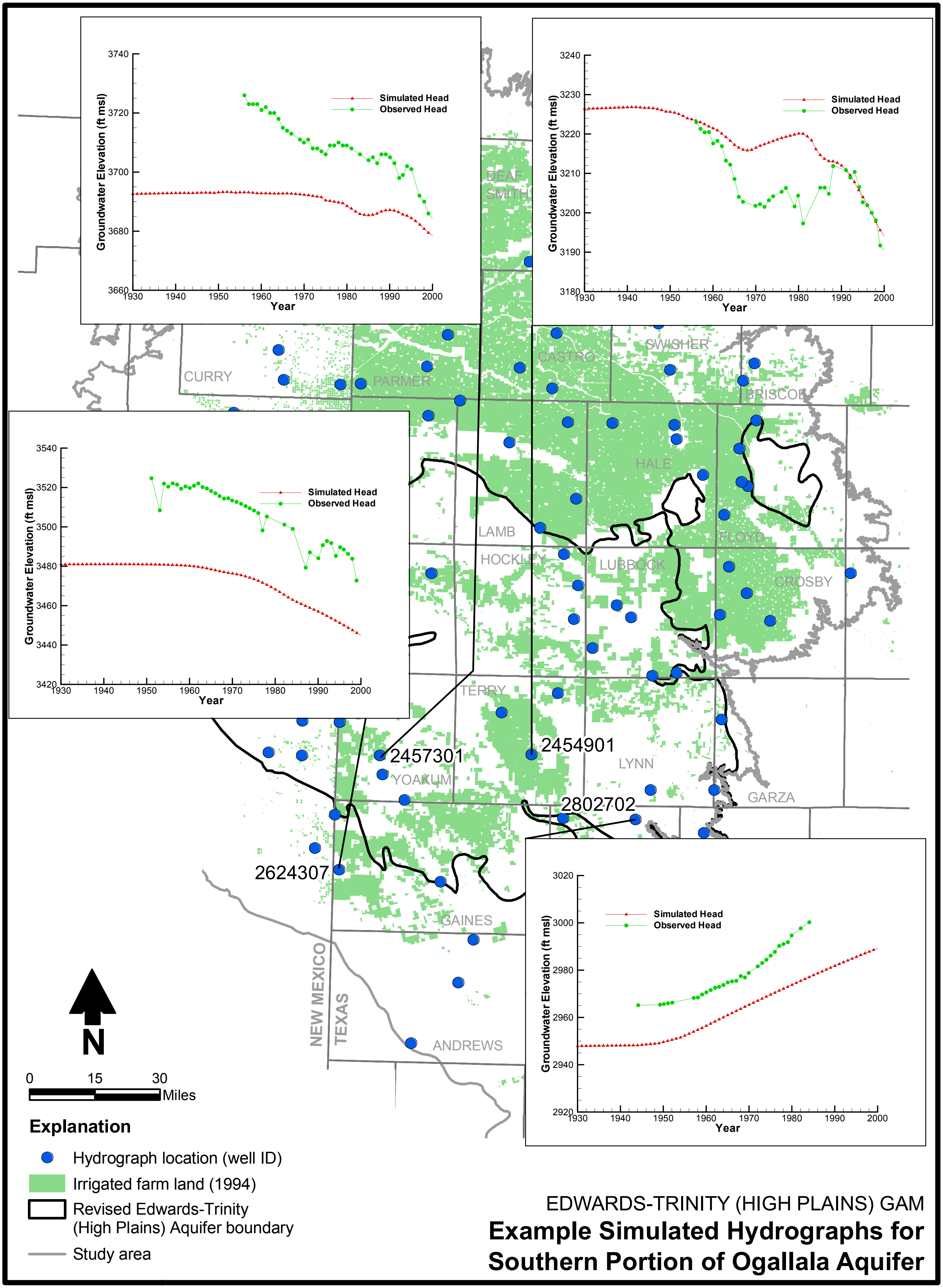
Figure 78



EDWARDS-TRINITY (HIGH PLAINS) GAM

Example Simulated Hydrographs for Northern Portion of Ogallala Aquifer

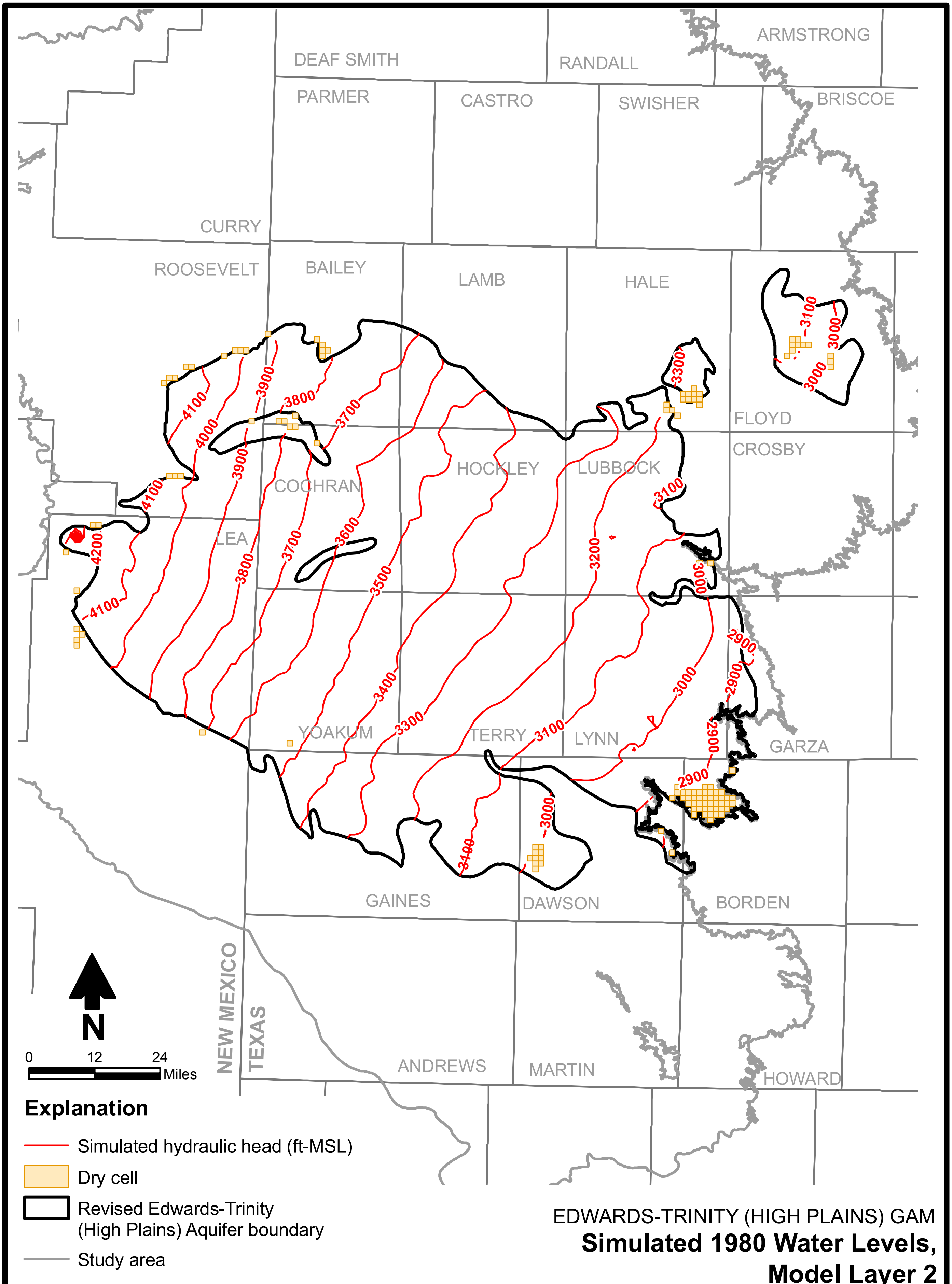
Figure 79



EDWARDS-TRINITY (HIGH PLAINS) GAM

Example Simulated Hydrographs for Southern Portion of Ogallala Aquifer

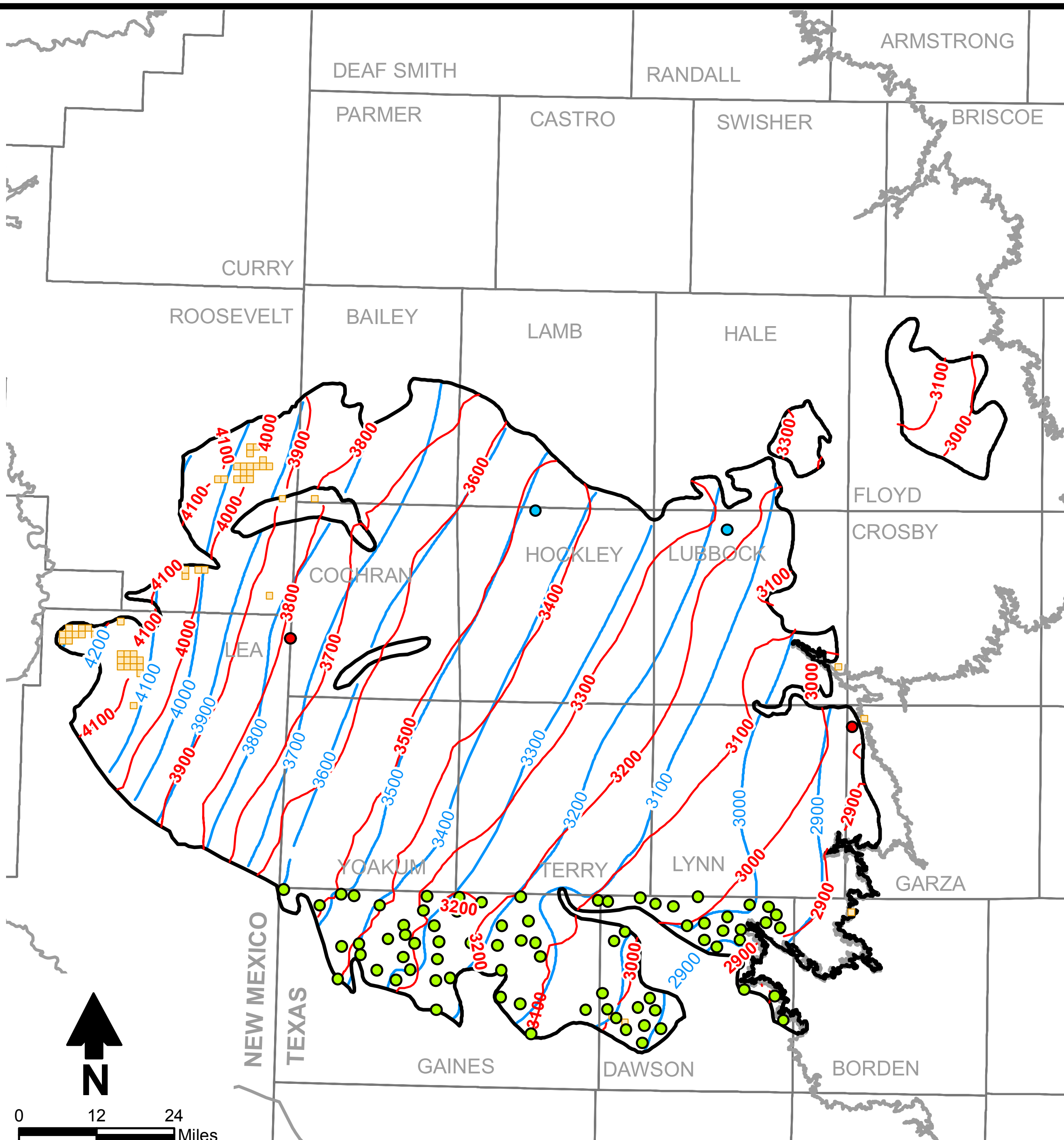
Figure 80



EDWARDS-TRINITY (HIGH PLAINS) GAM

Simulated 1980 Water Levels, Model Layer 2

Figure 81



Explanation

- Edwards-Trinity (High Plains) Aquifer control point
- Combined aquifer control point
- Gaines or Dawson County control point
- Simulated hydraulic head (ft-MSL)
- Observed hydraulic head (ft-MSL)
- Dry cell
- Revised Edwards-Trinity (High Plains) Aquifer boundary
- Study area

EDWARDS-TRINITY (HIGH PLAINS) GAM

Simulated and Observed 1980 Water Levels, Model Layers 3 and 4

Figure 82

- The combined aquifer control points represent wells that appear to be open to both the Southern Ogallala and Edwards-Trinity (High Plains) Aquifers. Observed water levels at these locations are therefore expected to be indicative of an average water level affected by hydrogeologic conditions in each aquifer. In some areas where a thick sequence of shale separates the two aquifers (e.g., Terry County), water levels in each aquifer at the same location may be substantially different. In other regions where the shale is thin or non-existent (e.g., north-central Lubbock County), a substantial difference in water levels is less likely.

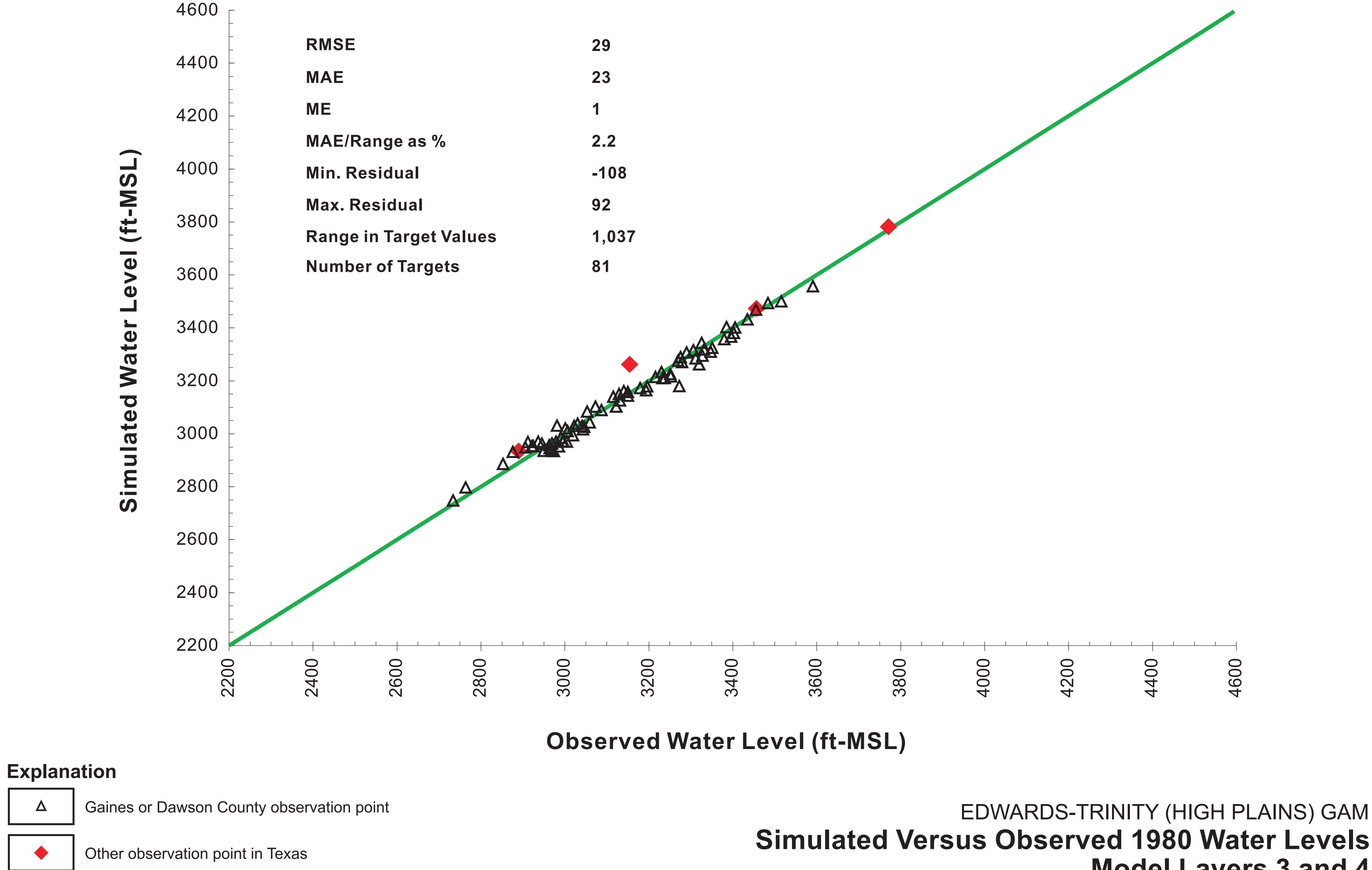
- The Gaines or Dawson County control points occur in one of these counties within the southern portion of the Edwards-Trinity (High Plains) Aquifer. In this area no significant thickness of shale separates the Southern Ogallala and Edwards-Trinity (High Plains) Aquifers, and numerous wells are completed through and screened across both aquifer units. Observed water levels at these locations are considered representative of average water levels indicative of hydrologic conditions within both aquifers. Note that for the predevelopment calibration figures (figs. 57 and 58), this is the only type of control point used.

Review of the 1980 simulated and observed water level contours indicates that the simulated directions of groundwater flow and hydraulic gradients are similar to the observed values. Figure 82 also illustrates the existence of a limited number of additional dry cells relative to the predevelopment period in the western (New Mexico) portion of the model domain, where saturated thickness is very limited (compare figs. 82 and 57).

A comparison of the observed and simulated water levels is provided in Figure 83, which also lists the model calibration statistics. The MAE is 23 feet, indicting that, on average, the simulated 1980 water levels differ from observed values by 23 feet. The MAE divided by the observed range in hydraulic heads of 1,037 feet is 2.2 percent, far below the maximum allowable value of 10 percent set for this statistic by the TWDB. The ME is 1 foot, indicating that, on average, simulated water levels are slightly lower than the observed water levels (fig. 83).

Figure 84 illustrates the magnitude of the difference between simulated and observed water levels, as well as whether simulated water levels are higher or lower than observed values. The points shown in Figure 84 correspond to the locations where the data available to construct Figure 83 were measured. As shown in Figure 84, simulated Edwards-Trinity (High Plains) water levels are generally lower than observed values in much of Gaines and Dawson Counties, except at some locations near the aquifer boundary, where simulated water levels tend to be higher than observed values.

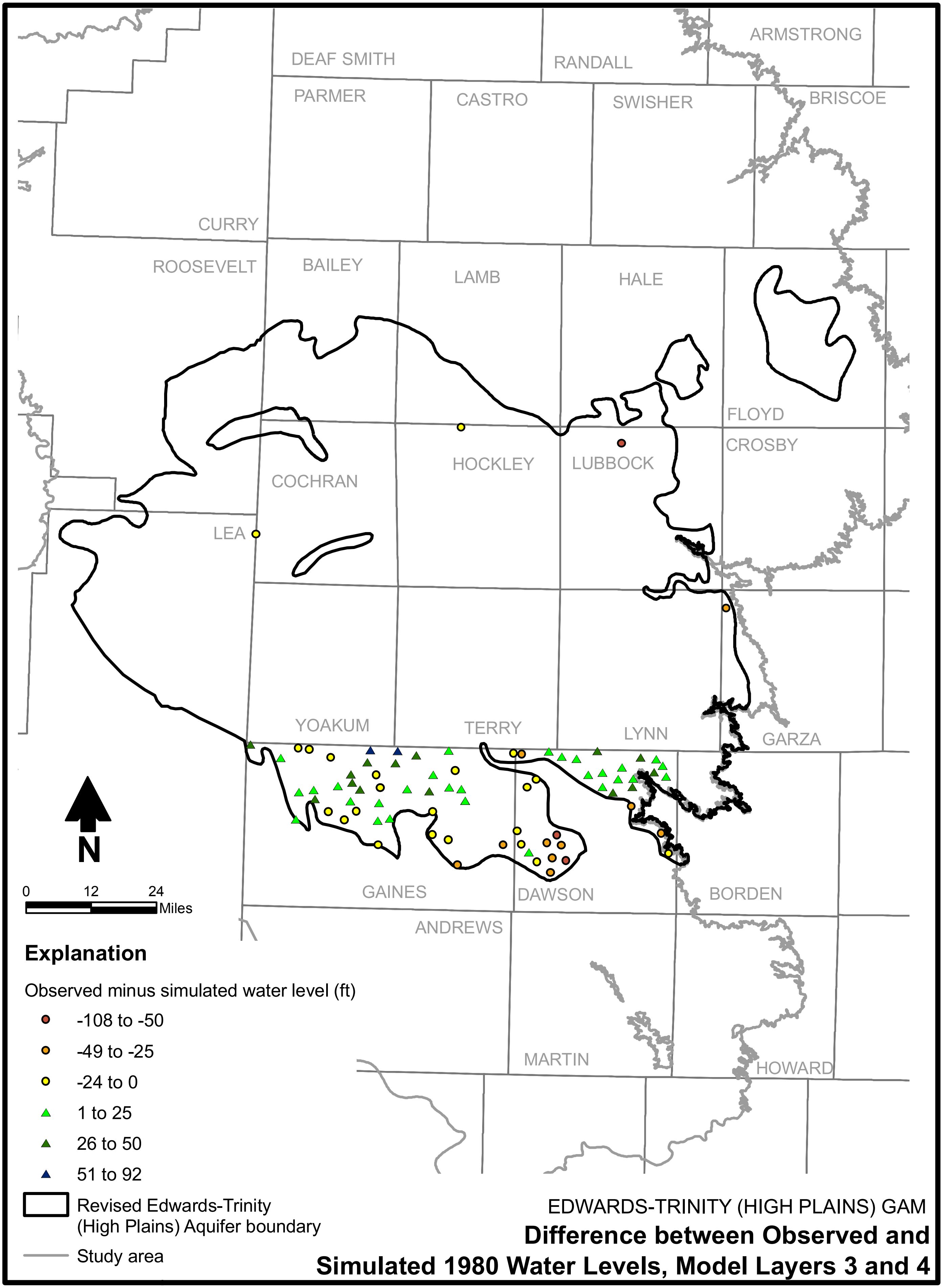
The simulated 1990 water levels for model layer 2 are provided in Figure 85, and the simulated and observed 1990 water levels representative of model layers 3 and 4 are provided in Figure 86. As noted for the 1980 time period, the simulated directions of groundwater flow and hydraulic gradients are similar to the observed values. The number of simulated dry cells in the western portion of the model domain, where the aquifer saturated thickness is limited, is similar to the 1980 calibration results. Also indicated in Figure 86 are a large number of locations where observed water levels were available for model calibration in the northwestern portion of the Edwards-Trinity (High Plains) Aquifer in New Mexico.



EDWARDS-TRINITY (HIGH PLAINS) GAM

Simulated Versus Observed 1980 Water Levels
Model Layers 3 and 4

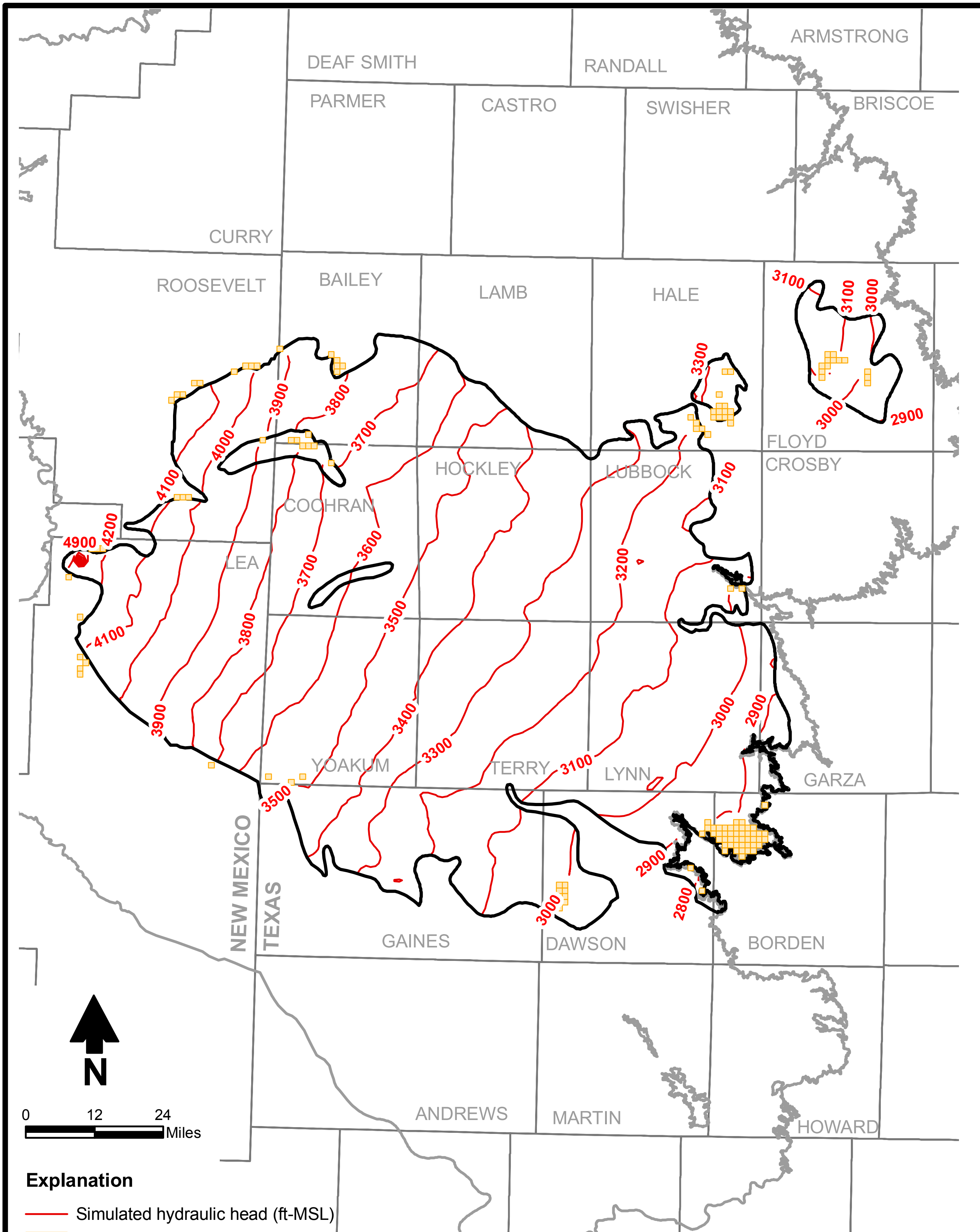
Figure 83



EDWARDS-TRINITY (HIGH PLAINS) GAM

Difference between Observed and Simulated 1980 Water Levels, Model Layers 3 and 4

Figure 84



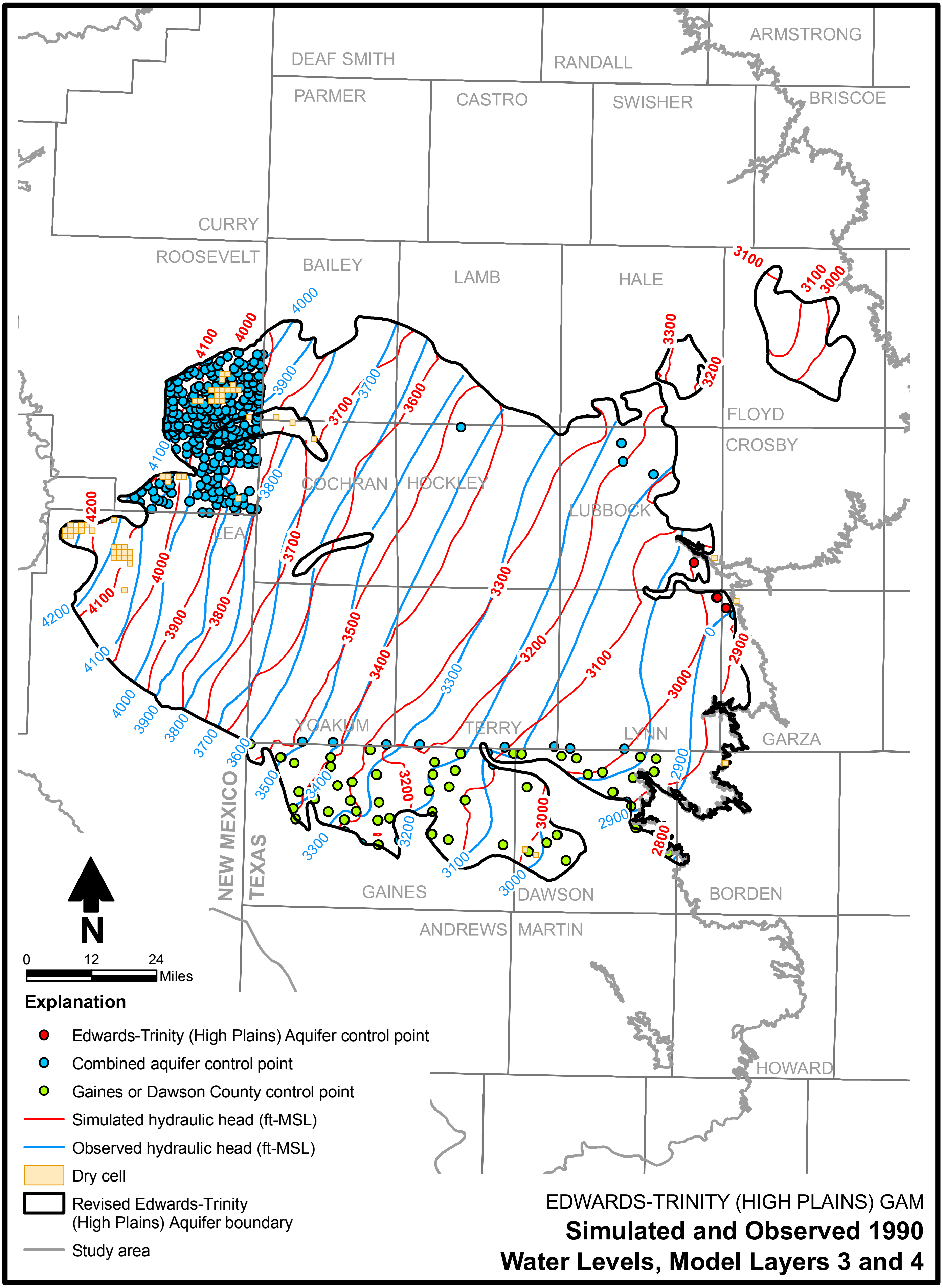
Explanation

- Simulated hydraulic head (ft-MSL)
- Dry cell
- Revised Edwards-Trinity (High Plains) Aquifer boundary
- Study area

EDWARDS-TRINITY (HIGH PLAINS) GAM

Simulated 1990 Water Levels, Model Layer 2

Figure 85



EDWARDS-TRINITY (HIGH PLAINS) GAM

Simulated and Observed 1990 Water Levels, Model Layers 3 and 4

Figure 86

A comparison of the observed and simulated 1990 water levels is provided in Figure 87, which also lists the model calibration statistics. The MAE is 36 feet, and the MAE divided by the observed range in hydraulic heads of 1,495 feet is 2.4 percent. The ME is 26 feet, indicating that, on average, simulated water levels are lower than the observed water levels (fig. 87).

Figure 88 illustrates the magnitude of the difference between simulated and observed water levels for 1990, as well as whether they are higher or lower than observed values. The points shown in Figure 88 correspond to the locations where the data available to construct Figure 87 were measured. The difference between observed and simulated water levels for 1990 (fig. 88) is similar to that observed for 1980 for the Texas portion of the Edwards-Trinity (High Plains) Aquifer. In New Mexico, simulated water levels are both higher and lower than observed values, with higher simulated water levels clustered adjacent to and south of the area in southeastern Roosevelt County where there is an island of Southern Ogallala Aquifer surrounded by Edwards-Trinity (High Plains) Aquifer.

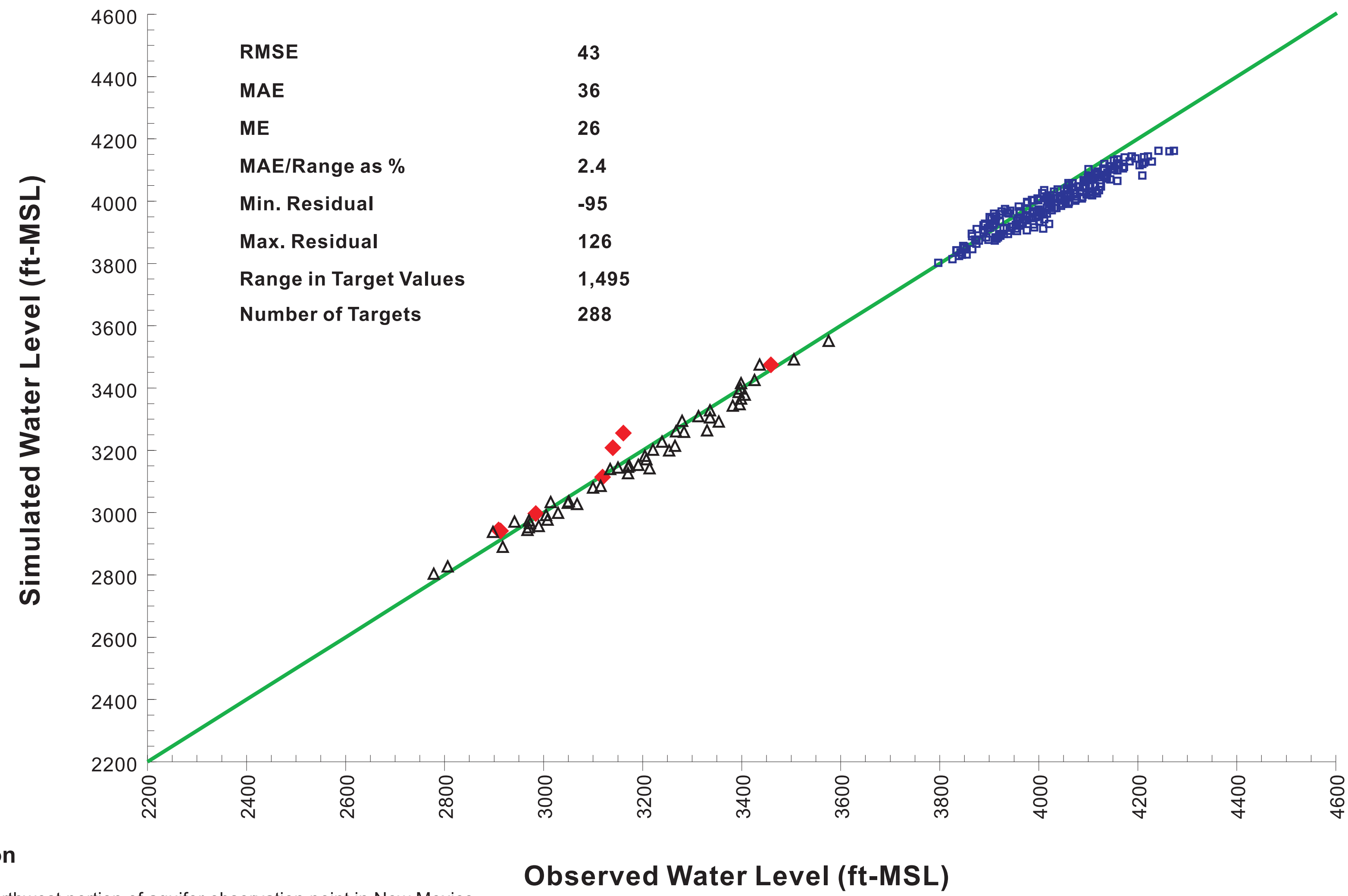
The simulated 1997 water levels for model layer 2 are provided in Figure 89, and the simulated and observed 1997 water levels representative of model layers 3 and 4 are provided in Figure 90. As noted for the 1980 and 1990 time periods, the simulated directions of groundwater flow and hydraulic gradients are similar to the observed values. The number of simulated dry cells in the western portion of the model domain is also similar to the 1980 and 1990 simulation results.

A comparison of the observed and simulated water levels is provided in Figure 91, which also lists the model calibration statistics. The MAE is 25 feet, and the MAE divided by the observed range in hydraulic heads is 3.0 percent. The ME is 9 feet, indicating that, on average, simulated water levels are lower than the observed water levels (fig. 91).

Figure 92 illustrates the magnitude of the difference between simulated and observed water levels for 1997, as well as whether they are higher or lower than observed values. The points shown in Figure 92 correspond to the locations where data available to construct Figure 91 were measured. The difference between observed and simulated water levels for 1997 (fig. 92) is similar to that observed for 1990.

Simulated and observed water levels through time for 5 observation well locations are provided in Figure 93. Overall, simulated water levels and observed water levels are in good agreement both in terms of absolute value as well as general trends. Steep declines or rises in observed water levels evident in some of the hydrographs (e.g. well 2444701 near the Yoakum-Terry county line) are not replicated by the model. This result is to be expected, since significant changes in water levels are most likely attributable to pumping at or near the observation well, which is not known.

The simulated and observed water levels of each of the 18 Edwards-Trinity (High Plains) Aquifer hydrographs used in the transient model calibration are provided in Appendix C. The simulated hydraulic head for each model layer at the observation well location is plotted on each hydrograph; where a single simulated hydraulic head line is evident in the figure, the simulated hydraulic heads are nearly identical for each model layer. The plots are constructed in this manner to provide a range of possible simulated hydraulic head values to compare against observed water levels for wells that are screened across multiple aquifer units.



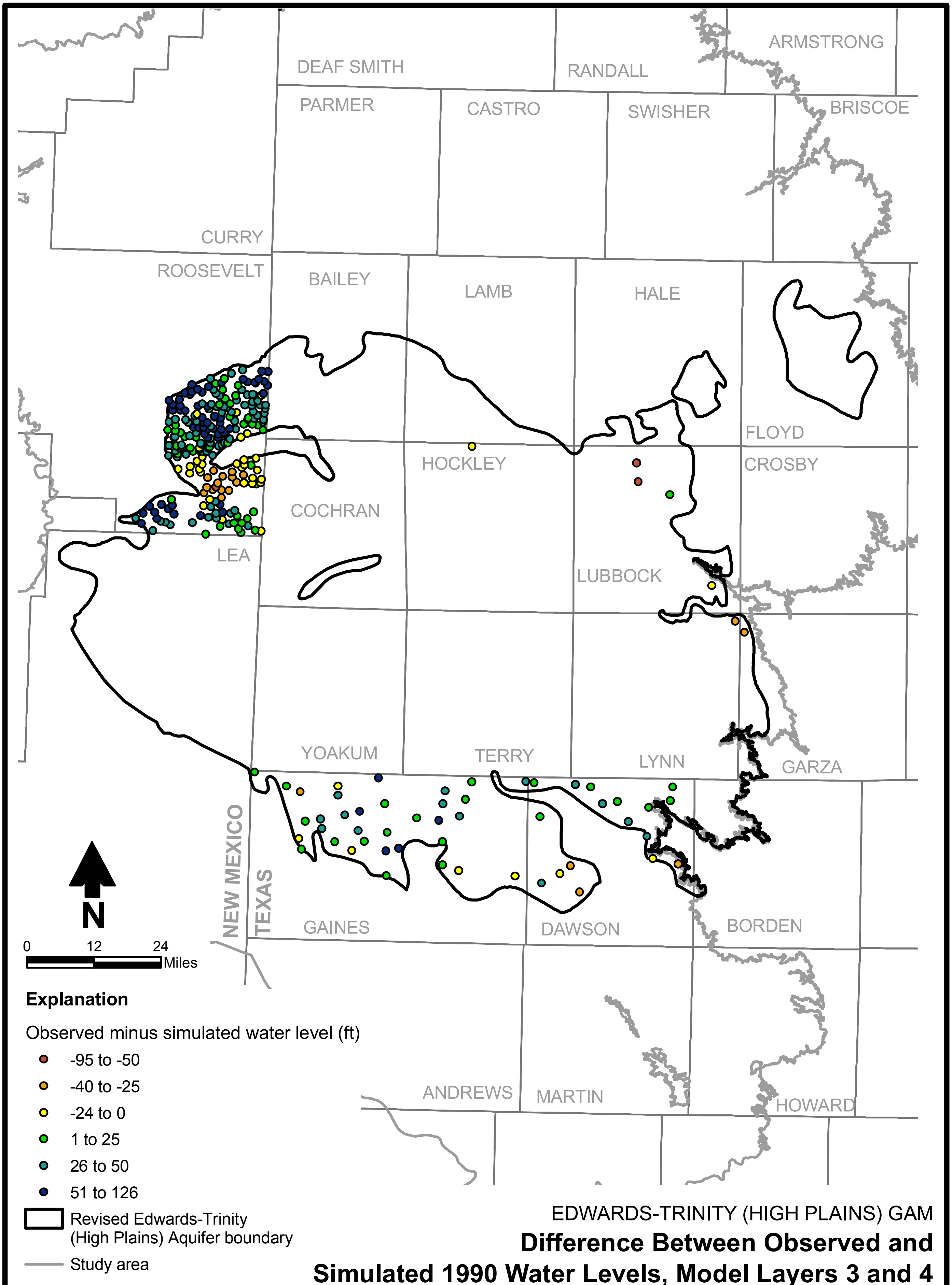
Explanation

□	Northwest portion of aquifer observation point in New Mexico
△	Gaines or Dawson County observation point
◆	Other observation point in Texas

EDWARDS-TRINITY (HIGH PLAINS) GAM

Simulated Versus Observed 1990 Water Levels
Model Layers 3 and 4

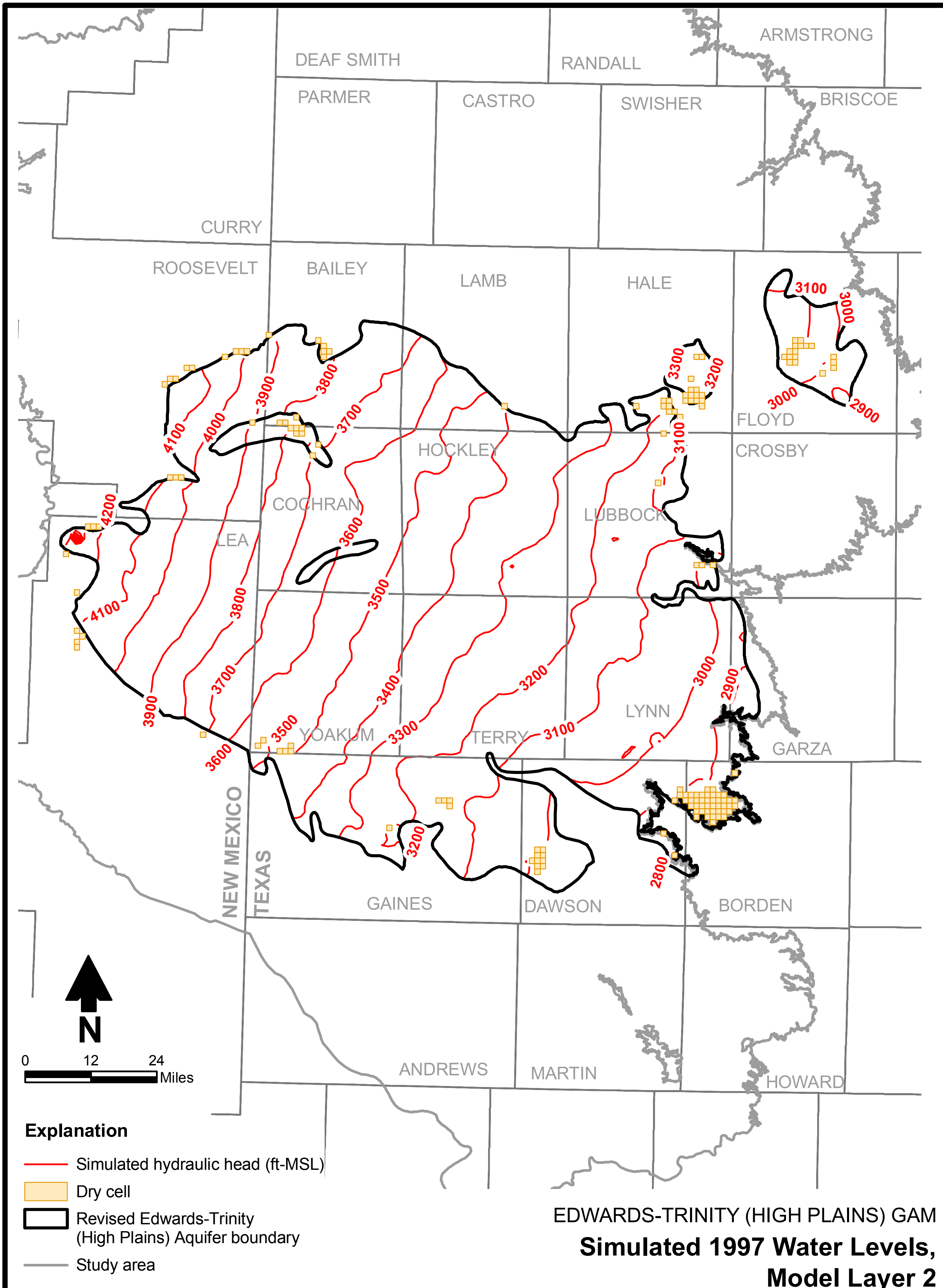
Figure 87



EDWARDS-TRINITY (HIGH PLAINS) GAM

Difference Between Observed and Simulated 1990 Water Levels, Model Layers 3 and 4

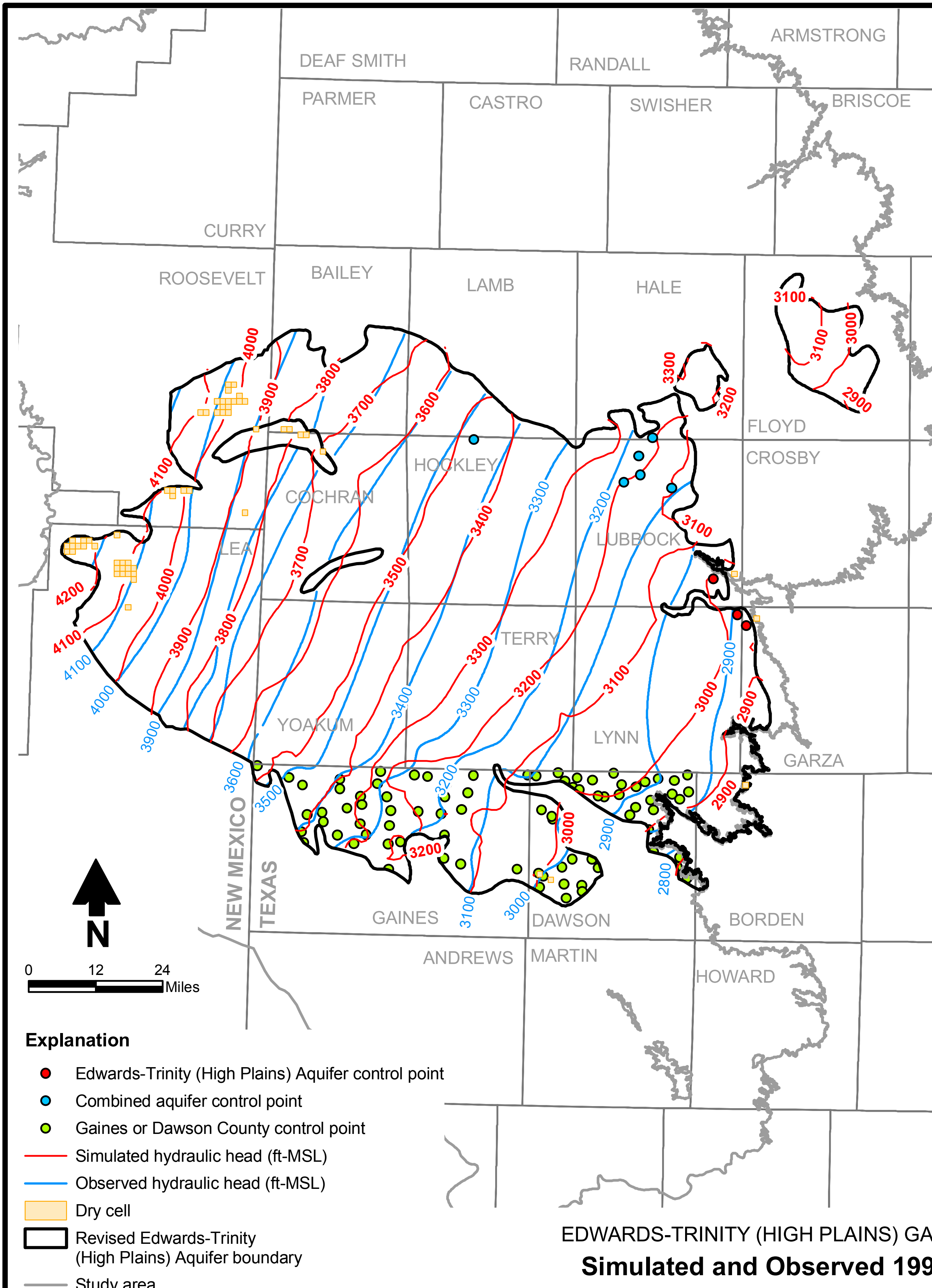
Figure 88



EDWARDS-TRINITY (HIGH PLAINS) GAM

Simulated 1997 Water Levels, Model Layer 2

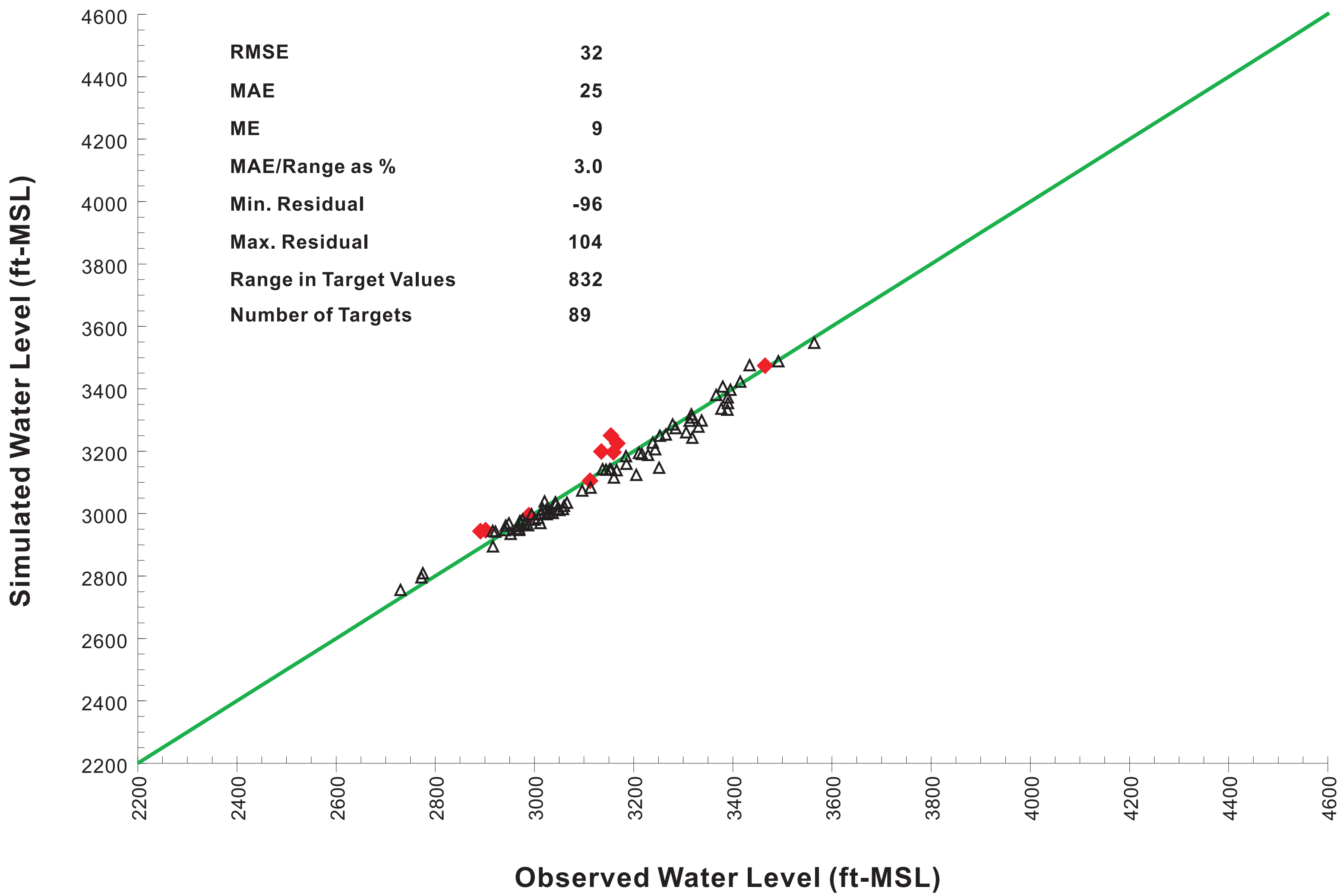
Figure 89



EDWARDS-TRINITY (HIGH PLAINS) GAM

Simulated and Observed 1997 Water Levels, Model Layers 3 and 4

Figure 90



Explanation

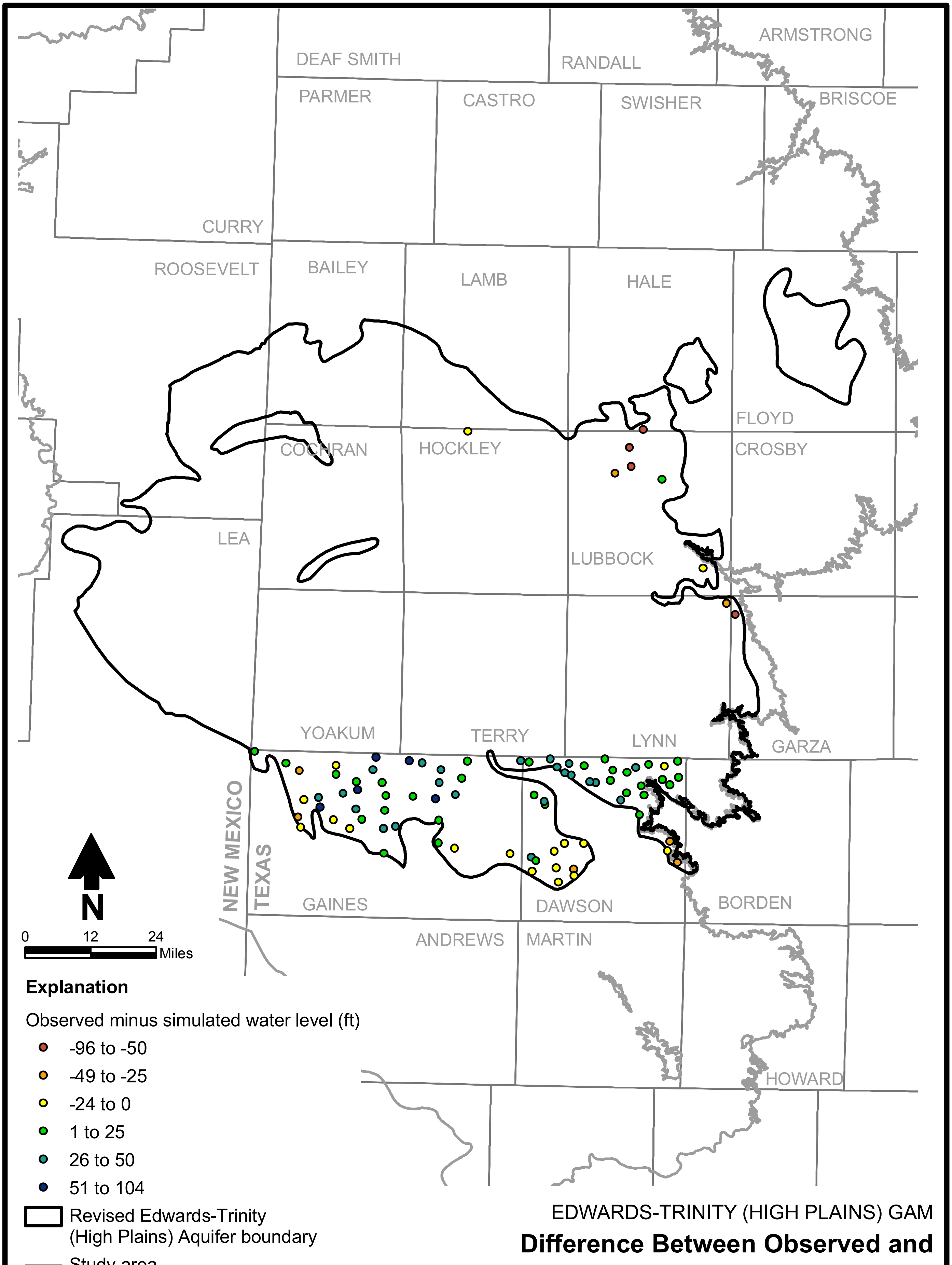
Gaines or Dawson County observation point

Other observation point in Texas

EDWARDS-TRINITY (HIGH PLAINS) GAM

Simulated Versus Observed 1997 Water Levels
Model Layers 3 and 4

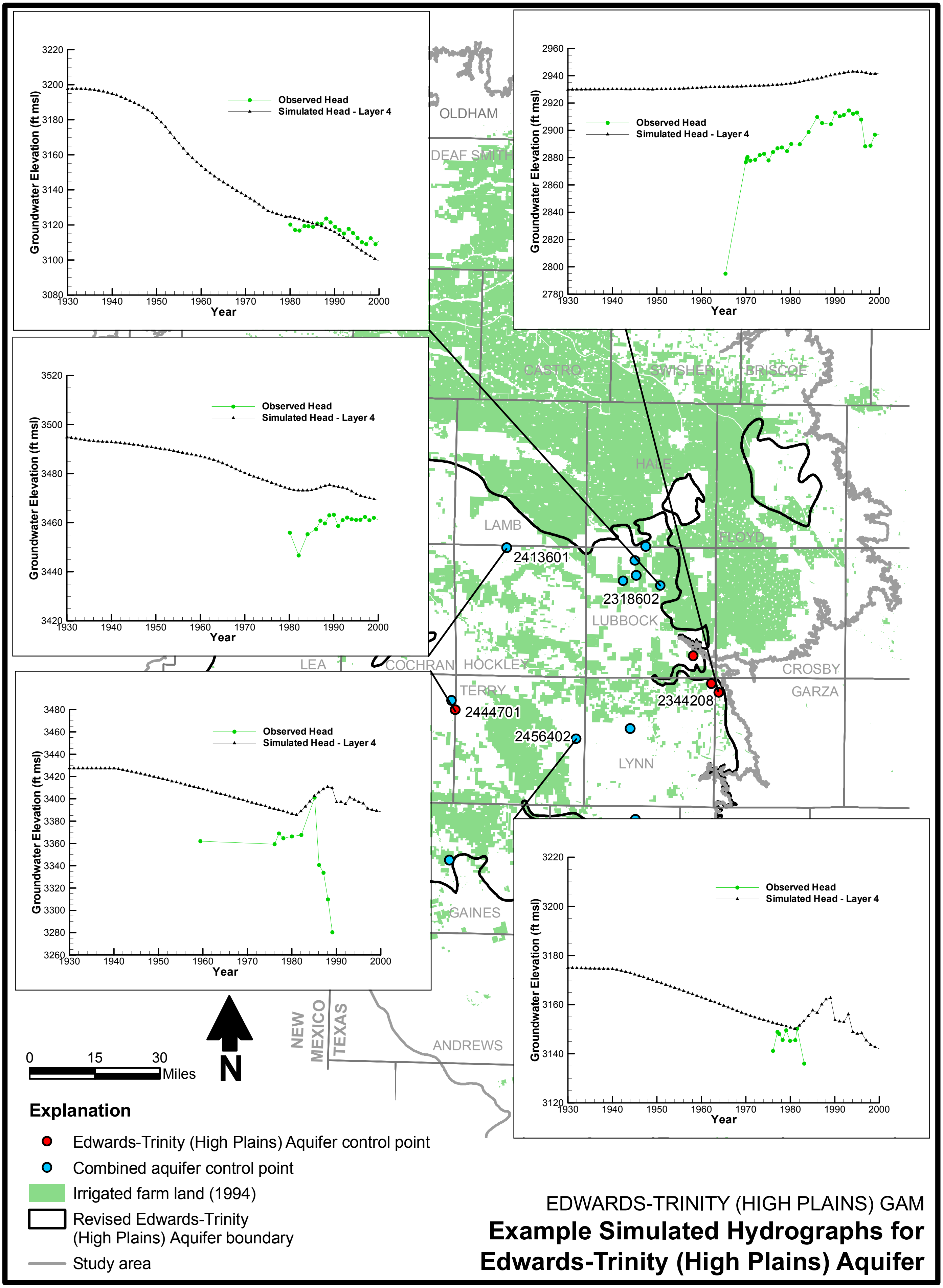
Figure 91



EDWARDS-TRINITY (HIGH PLAINS) GAM

Difference Between Observed and Simulated 1997 Water Levels, Model Layers 3 and 4

Figure 92



EDWARDS-TRINITY (HIGH PLAINS) GAM

Example Simulated Hydrographs for Edwards-Trinity (High Plains) Aquifer

Figure 93

Figures 94 through 96 illustrate the simulated direction of groundwater flow at the base of model layer 1 for 1980, 1990 and 1997 conditions, respectively. Comparison of Figures 94 through 96 with Figure 62, which is the equivalent figure for the steady-state simulation, indicates that the overall pattern of vertical flow is relatively similar between steady-state conditions and those of later time periods. There are, however, a number of areas where the direction or magnitude of groundwater flow between aquifer units has changed in accordance with local pumping and recharge conditions. For example, in western and central Gaines County, the simulated groundwater flow has a strong downward component from the Southern Ogallala Aquifer to the Edwards-Trinity (High Plains) Aquifer. Farther to the north, such as in Yoakum and Terry Counties, the extent of many regions where upward flow from the Edwards-Trinity (High Plains) Aquifer to the Southern Ogallala Aquifer was simulated under predevelopment conditions (fig. 62) has been reduced or eliminated during the transient simulation period (figs. 94 through 96). In southeastern Hockley County, a region of downward flow under predevelopment conditions changes to simulated upward flow by 1980, probably due to pumping in the Southern Ogallala Aquifer for irrigated agriculture.

9.3 Model Parameters

Transient model input parameters that are different than those used in the steady-state model are discussed in Sections 9.3.1 through 9.3.4.

9.3.1 Recharge

Simulated recharge to the Southern Ogallala Aquifer (model layer 1) was increased significantly through time following the same approach and procedure documented in the Southern Ogallala GAM (Blandford and others, 2003). As noted in that report, the primary reason for increased recharge through time appears to be the effects of changes in land use. For the Edwards-Trinity (High Plains) Aquifer GAM, enhanced recharge in the vicinity of the City of Lubbock was also implemented in accordance with the approach and values documented by DBS&A (2007). In addition to enhanced recharge of 0.5 in/yr applied in the Lubbock urban area, prescribed volumes of recharge were assigned to individual playas within the Lubbock urban area using the MODFLOW well package.

The recharge applied to the uppermost active model layer (predominantly model layer 1) as of the year 2000 is illustrated in Figure 97. As illustrated in the figure, applied recharge in the transient model ranges from 2.5 in/yr under irrigated agricultural lands with high-permeability soils down to 0.25 in/yr for non-irrigated agricultural lands in regions of low-permeability soils, lesser amounts of average annual precipitation, or relatively steady observed water levels through time. In rangeland areas, assigned recharge was maintained at the predevelopment assigned value (fig. 61).

Although the distribution of recharge applied in the transient model is for the most part a function of land use and soil type, some values were adjusted on a regional basis so that simulation results would better match observed water levels. For example, a higher rate of recharge was applied to non-irrigated lands in Lynn, Dawson, Garza, and Borden Counties than was assigned to adjacent areas with the same land use and similar soil types. This adjustment was required to match observed water levels, although it is unknown why recharge in these

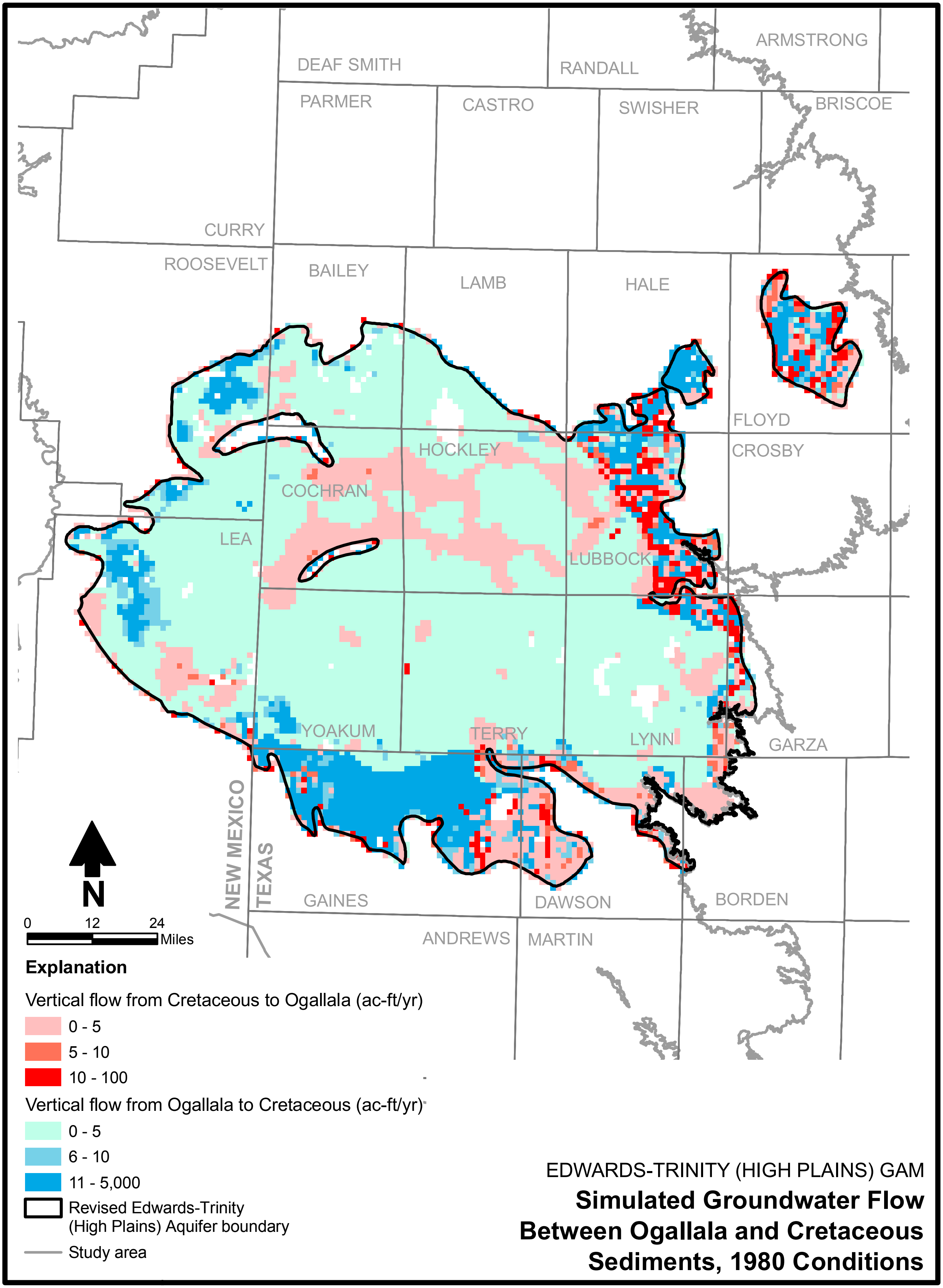
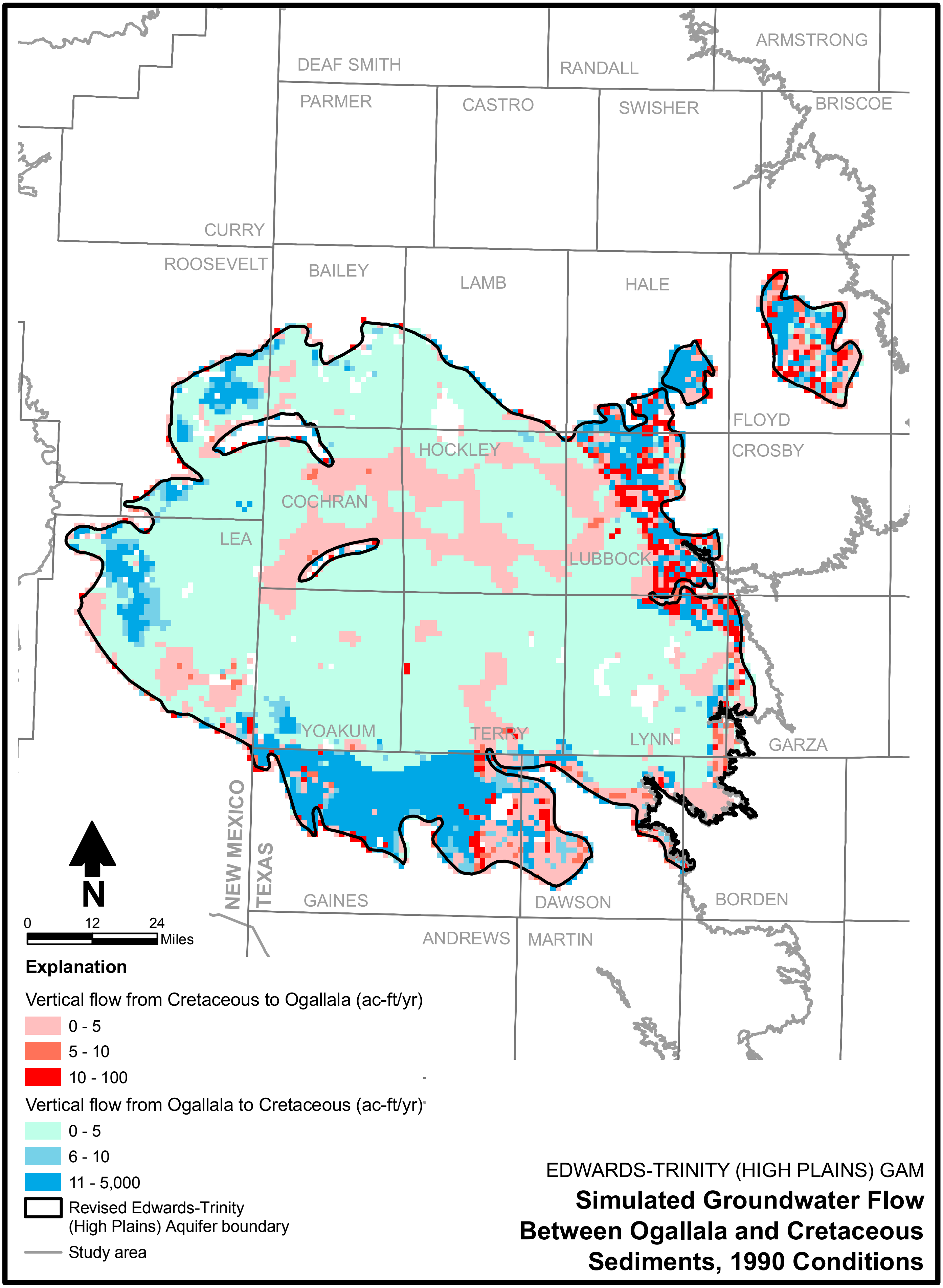

DEAF SMITH
RANDALL
ARMSTRONG
PARMER
CASTRO
SWISHER
BRISCOE
CURRY
ROOSEVELT
BAILEY
LAMB
HALE
FLOYD
CROSBY
HOCKLEY
COCHRAN
LEA
LUBBOCK
YOAKUM
TERRY
LYNN
GARZA
NEW MEXICO
TEXAS
GAINES
DAWSON
BORDEN
ANDREWS
MARTIN
N
0 12 24
Miles
Explanation
Vertical flow from Cretaceous to Ogallala (ac-ft/yr)
0 - 5
5 - 10
10 - 100
Vertical flow from Ogallala to Cretaceous (ac-ft/yr)
0 - 5
6 - 10
11 - 5,000
Revised Edwards-Trinity (High Plains) Aquifer boundary
Study area
EDWARDS-TRINITY (HIGH PLAINS) GAM
Simulated Groundwater Flow Between Ogallala and Cretaceous Sediments, 1980 Conditions

Figure 94



DEAF SMITH
RANDALL
ARMSTRONG
PARMER
CASTRO
SWISHER
BRISCOE
CURRY
ROOSEVELT
BAILEY
LAMB
HALE
FLOYD
HOCKLEY
CROSBY
COCHRAN
LEA
LUBBOCK
YOAKUM
TERRY
LYNN
GARZA
NEW MEXICO
TEXAS
GAINES
DAWSON
BORDEN
ANDREWS
MARTIN
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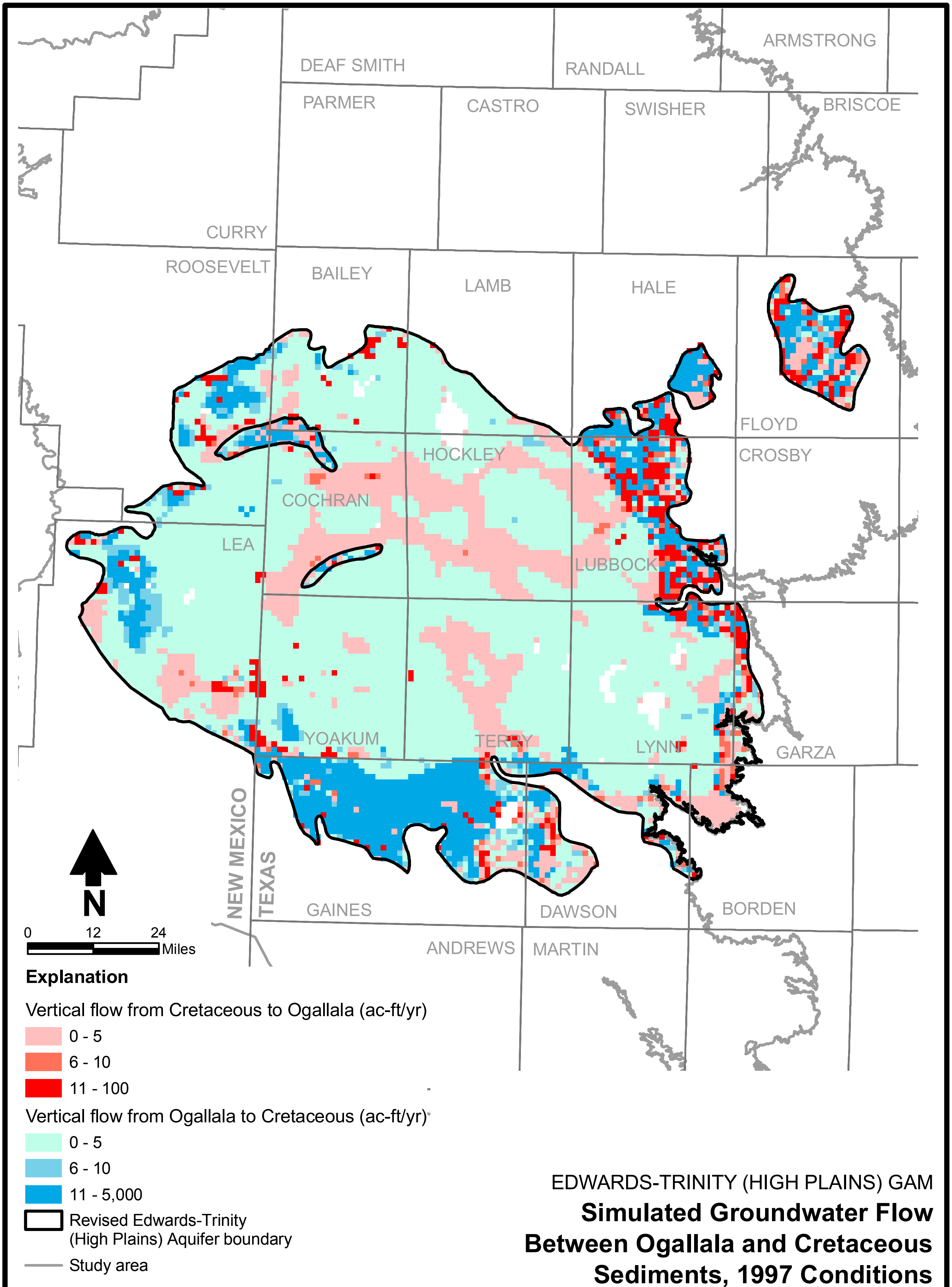
0 12 24
Miles
Explanation
Vertical flow from Cretaceous to Ogallala (ac-ft/yr)
0 - 5
5 - 10
10 - 100
Vertical flow from Ogallala to Cretaceous (ac-ft/yr)
0 - 5
6 - 10
11 - 5,000
Revised Edwards-Trinity (High Plains) Aquifer boundary
Study area
EDWARDS-TRINITY (HIGH PLAINS) GAM
Simulated Groundwater Flow Between Ogallala and Cretaceous Sediments, 1990 Conditions

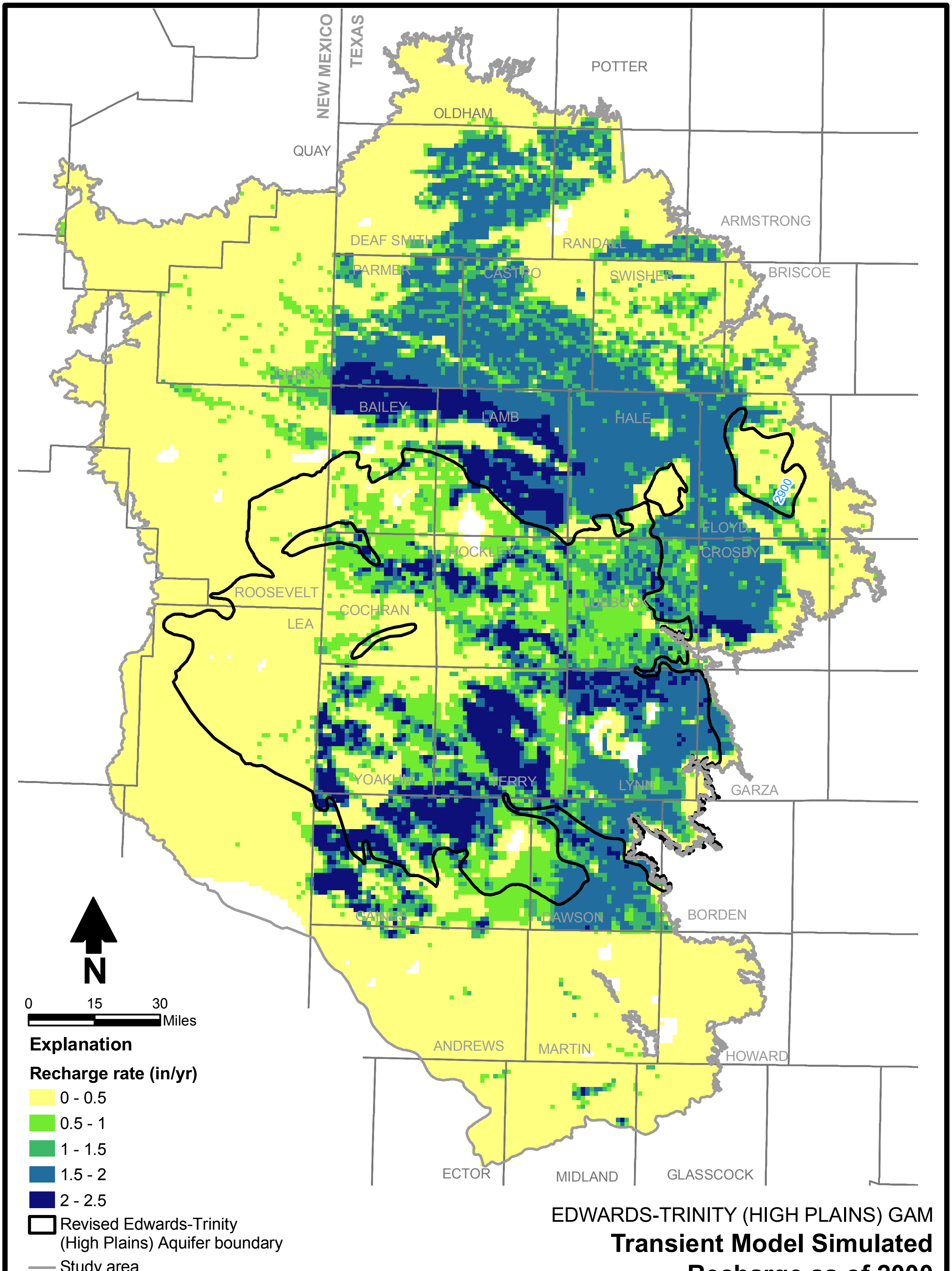
Figure 95



EDWARDS-TRINITY (HIGH PLAINS) GAM

Simulated Groundwater Flow Between Ogallala and Cretaceous Sediments, 1997 Conditions

Figure 96



EDWARDS-TRINITY (HIGH PLAINS) GAM

Transient Model Simulated Recharge as of 2000

Figure 97

counties is apparently larger than recharge in adjacent areas with similar average annual precipitation and soils. Although changes in recharge will obviously not occur precisely along county boundaries, a suitable alternative for adjusting recharge was not identified (Blandford and others, 2003).

9.3.2 Storage Coefficient

The specific yield of the Southern Ogallala Aquifer was not changed during the transient model calibration, and therefore the calibrated specific yield for model layer 1 is the same as that provided in Figure 51. Although adjusted during model calibration, the other storage coefficient values were also maintained at the initial estimated value (Table 4) in the final calibrated model. The specific storage for model layers 2 through 4, therefore, is 3×10^{-6} per foot. During the model simulation, the specific storage is multiplied by the model layer thickness to obtain a storage coefficient representative of the entire layer thickness so long as the simulated water level remains above the top of the layer.

The specific yields for shale, limestone, and Antlers Sand were also maintained at 0.1, 0.05, and 0.15, respectively. The specific yield is applied when changes in hydraulic head occur within an unconfined aquifer. Throughout most of the active model domain that contains these Edwards-Trinity (High Plains) Aquifer hydrogeologic units, the simulated water level is higher than the top of each unit and the specific yield value does not affect the simulation results.

9.3.3 Southern Ogallala Aquifer Pumping

The distribution of Southern Ogallala Aquifer pumping for irrigated agriculture as of the year 2000 is illustrated in Figure 98. Pumping was assigned in accordance with the methodology developed for the Southern Ogallala GAM (Blandford and others, 2003), where a greater proportion of pumping is assigned to model cells that have larger production capacity (defined as the saturated thickness times hydraulic conductivity). Greater rates of groundwater pumping, therefore, are assigned to paleochannel regions where saturated thickness and hydraulic conductivity tend to be greater than in adjacent areas (compare fig. 98 with figs. 23 and 63).

Assigned pumping for irrigated agriculture was changed for some counties from that used in the Southern Ogallala GAM to better match observed water levels. In the Southern Ogallala GAM, pumping for irrigated agriculture was interpolated between certain years for which pumping estimates were available, either from the TWDB or from estimates conducted as part of the GAM project (Blandford and others, 2003).

In some areas, observed water levels were not consistent with the assumed distribution of pumping. For example, if observed water levels were stable or trending upward, it is not likely that pumping would be increasing substantially during that time period. Adjustments were made for selected early annual pumping estimates (prior to 1990) for Cochran, Crosby, and Lubbock Counties. For these counties, estimated pumping for years that had a specific value was not changed; changes were made only to the estimated values for selected years without data. Assigned municipal pumping for the City of Lubbock was also changed based on data and analysis presented by DBS&A (2007). A detailed description of changes to previous Southern Ogallala GAM pumping and a table of pumping used in the Edwards-Trinity (High Plains) Aquifer GAM are provided in Appendix D.

(Figure)

98 Southern Ogallala Aquifer Pumping Distribution as of 2000

9.3.4 Edwards-Trinity (High Plains) Aquifer Pumping

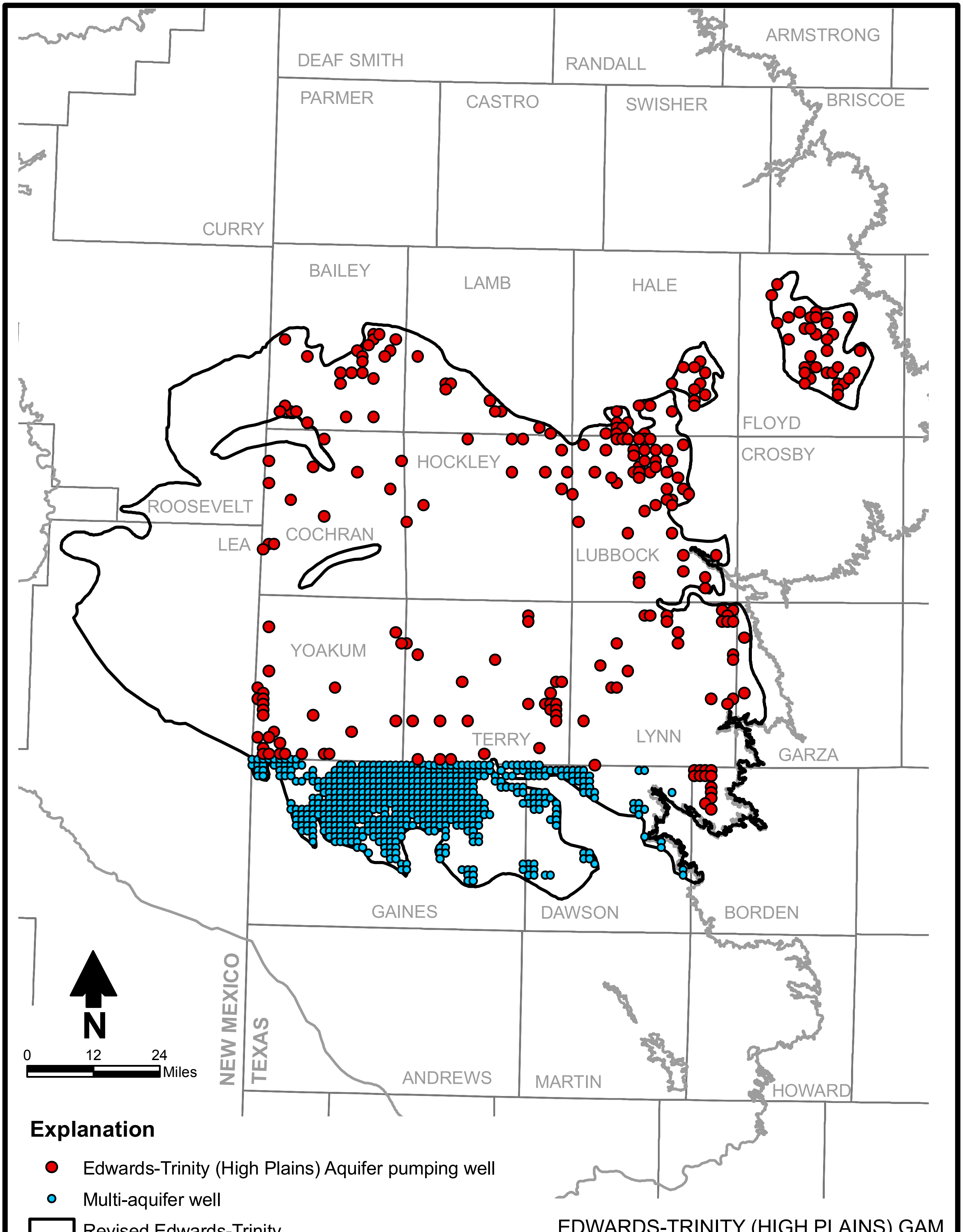
Pumping for the Edwards-Trinity (High Plains) Aquifer was assigned in accordance with Figure 99. Pumping from the Edwards-Trinity (High Plains) Aquifer for counties north of Dawson and Gaines Counties was assigned to the identified well locations. The well locations were either (1) queried from the TWDB database using the aquifer type designation, or (2) identified as a well location for which Edwards-Trinity (High Plains) Aquifer well logs were available based on the review and analysis of TCEQ well records conducted as part of this study. The total estimated pumping within a county was divided equally among the total number of identified well locations. This approach was considered the best one for these counties because, unlike the Southern Ogallala Aquifer, pumping centers for the Edwards-Trinity (High Plains) Aquifer may not correspond with areas of intense irrigated acreage. In fact, the case might be made that Edwards-Trinity (High Plains) Aquifer wells are more likely to be used where pumping from the Southern Ogallala Aquifer is limited due to poor yield, thereby forcing land owners to investigate and use deeper water sources.

In Gaines and Dawson Counties, where the Cretaceous shale is relatively thin or non-existent and saturated Ogallala Formation sediments are in direct hydraulic communication with Cretaceous limestone and Antlers Sand (fig. 45), an alternative approach to the assignment of pumping was taken. Many wells in these counties are completed in both the Southern Ogallala and Edwards-Trinity (High Plains) Aquifers. In these counties, therefore, the Multi-Node Well (MNW) package for MODFLOW (Halford and Hanson, 2002) was applied for model cells within the Edwards-Trinity (High Plains) Aquifer that were assigned irrigation pumping. In order to use the MNW package, the total pumping rate of the well through time is specified by the user, along with information about the well's screened intervals(s). This information allows the model to determine which layers the well is screened in, and the MNW package will calculate, for each time step, the relative contribution to the total well discharge provided by each model layer. The computation is based on the saturated thickness and aquifer properties of each model layer that the well penetrates. In essence, therefore, the pumping amount for each model layer for each time step at each multi-node well location is determined by the model, rather than by the user. Finally, because the MNW package considers groundwater flow to a single well bore from multiple aquifers, it is possible for groundwater flow to occur within the well bore between aquifers (i.e., one aquifer can recharge another). This process occurs at some places in the GAM, but the magnitude is insignificant (a fraction of 1 percent of the assigned pumping).

The portion of groundwater pumping for irrigated agriculture that comes from the Edwards-Trinity (High Plains) Aquifer in Gaines and Dawson Counties, as determined by the MNW package for the transient simulation period, is provided in Figure 100. The proportion of Edwards-Trinity (High Plains) Aquifer pumping to the total pumping ranges from approximately 20 to 40 percent.

9.4 Water Budget

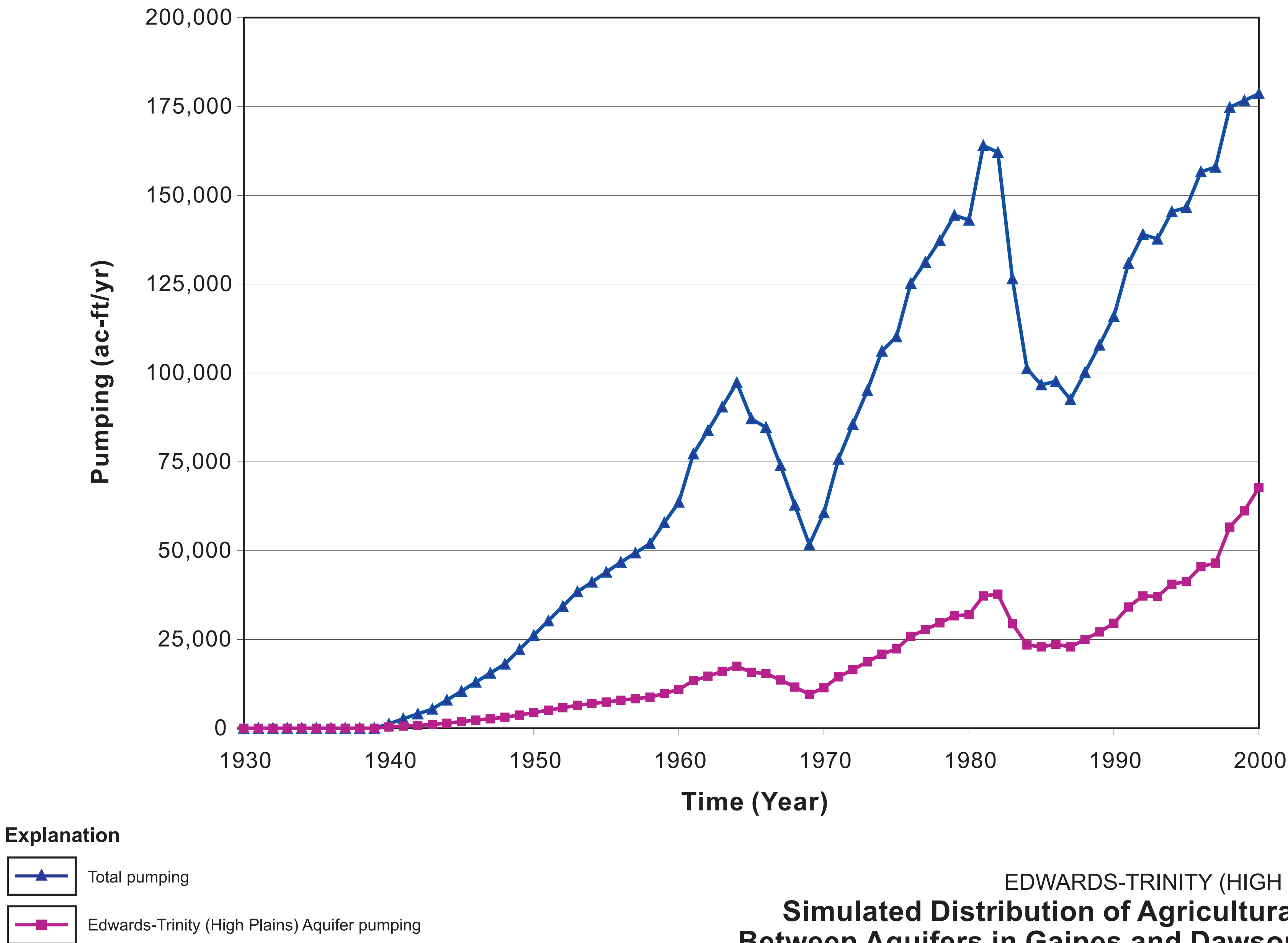
The transient model simulated water budgets for 1980, 1990 and 1997 are provided in Tables 7, 8, and 9, respectively. The simulated mass balance discrepancy is below 1 percent for each period. Each table illustrates that the predominant outflow from the aquifer system (about 95 percent) is due to groundwater pumping, primarily for irrigated agriculture.



EDWARDS-TRINITY (HIGH PLAINS) GAM

Assignment of Edwards-Trinity (High Plains) Aquifer Pumping

Figure 99



EDWARDS-TRINITY (HIGH PLAINS) GAM

Simulated Distribution of Agricultural Pumping Between Aquifers in Gaines and Dawson Counties

Figure 100

Table 7. Transient Model Water Budget, 1980

	Amount (ac-ft/yr)				
Component	Layer 1	Layer 2	Layer 3	Layer 4	Total
Inflows					
Storage	1,929,432	749	1,228	160	1,931,569
Prescribed head	304	0	0	0	304
Wells	10,483	0	114	114	10,711
Recharge	1,060,294	0	0	0	1,060,294
Total Inflows	3,000,513	749	1,342	274	3,002,878
Outflows					
Storage	194,928	383	223	252	195,786
Prescribed head	1,207	0	0	0	1,207
Wells	2,714,574	1,988	18,576	25,507	2,760,645
Drains	43,300	250	864	474	44,888
Total outflows	2,954,010	2,621	19,662	26,233	3,002,527
No. of dry cells	590	120	53	0	763
Percent discrepancy 0.01					

ac-ft/yr = Acre-feet per year

Table 8. Transient Model Water Budget, 1990

	Amount (ac-ft/yr)				
Component	Layer 1	Layer 2	Layer 3	Layer 4	Total
Inflows					
Storage	1,546,313	831	1,245	213	1,548,602
Prescribed head	816	0	0	0	816
Wells	11,270	0	104	103	11,477
Recharge	1,049,846	0	0	0	1,049,846
Total Inflows	2,608,245	831	1,350	316	2,610,741
Outflows					
Storage	138,804	418	224	180	139,626
Prescribed head	903	0	0	0	903
Wells	2,387,471	1,781	15,666	21,998	2,426,917
Drains	42,013	263	879	480	43,636
Total outflows	2,569,191	2,461	16,770	22,659	2,611,081
No. of dry cells	770	131	56	0	957
Percent discrepancy –0.01					

ac-ft/yr = Acre-feet per year

Table 9. Transient Model Water Budget, 1997

	Amount (ac-ft/yr)				
Component	Layer 1	Layer 2	Layer 3	Layer 4	Total
Inflows					
Storage	1,747,742	2,272	4,979	669	1,755,663
Prescribed head	1,106	0	0	0	1,106
Wells	10,437	0	121	108	10,666
Recharge	1,034,807	0	0	0	1,034,807
Total Inflows	2,794,091	2,272	5,100	777	2,802,241
Outflows					
Storage	109,190	358	118	178	109,844
Prescribed head	774	0	0	0	774
Wells	2,590,182	2,931	23,194	33,531	2,649,838
Drains	41,109	266	886	482	42,743
Total outflows	2,741,255	3,555	24,199	34,192	2,803,199
No. of dry cells	1,010	153	58	0	1,221
Percent discrepancy –0.03					

ac-ft/yr = Acre-feet per year

The largest sources of groundwater inflows are depletion of groundwater storage (approximately 60 percent) and recharge that has been substantially increased due to changes in land use (approximately 40 percent). Note that for each period, more than 100,000 ac-ft/yr of water is simulated as an outflow to groundwater storage; this volume of water is due to rising water levels in regions such as a portion of Dawson County. Inflow due to wells in each of these tables represents recharge assigned to specific playas in the vicinity of Lubbock, as determined by DBS&A (2007).

Another point illustrated by Tables 7 through 9 is that each water budget component for the Edwards-Trinity (High Plains) Aquifer (model layers 2 through 4) is substantially less than that of the Southern Ogallala Aquifer (model layer 1). This observation illustrates that, relative to the Southern Ogallala Aquifer, the Edwards-Trinity (High Plains) Aquifer is a substantially smaller and more limited water supply.

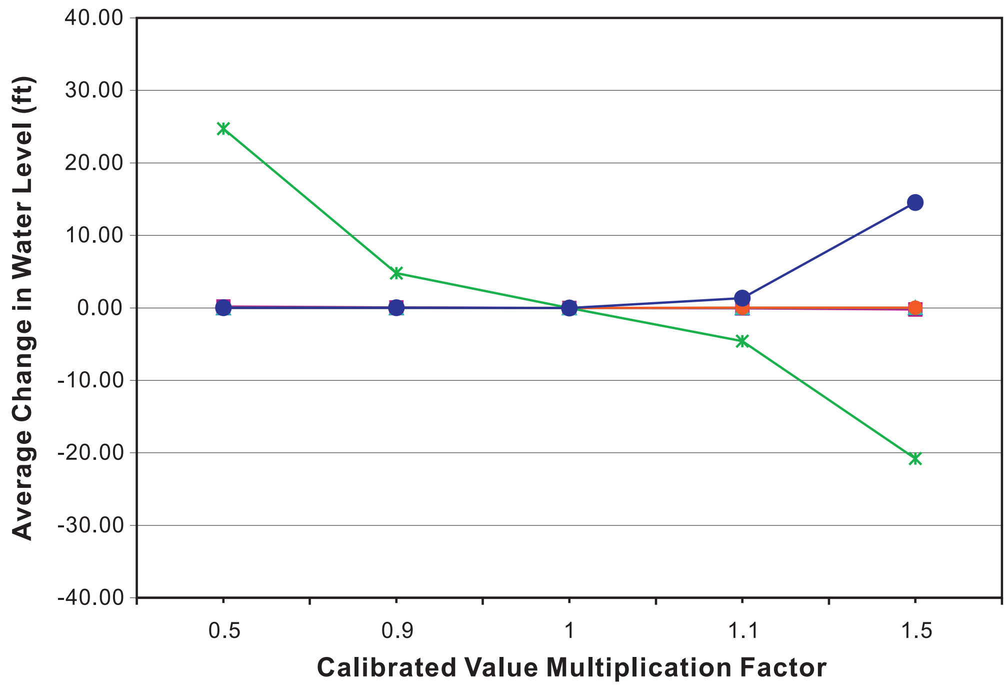
The simulated water budget by county and GCD for 1997 is provided in Appendix A.

9.5 Sensitivity Analysis

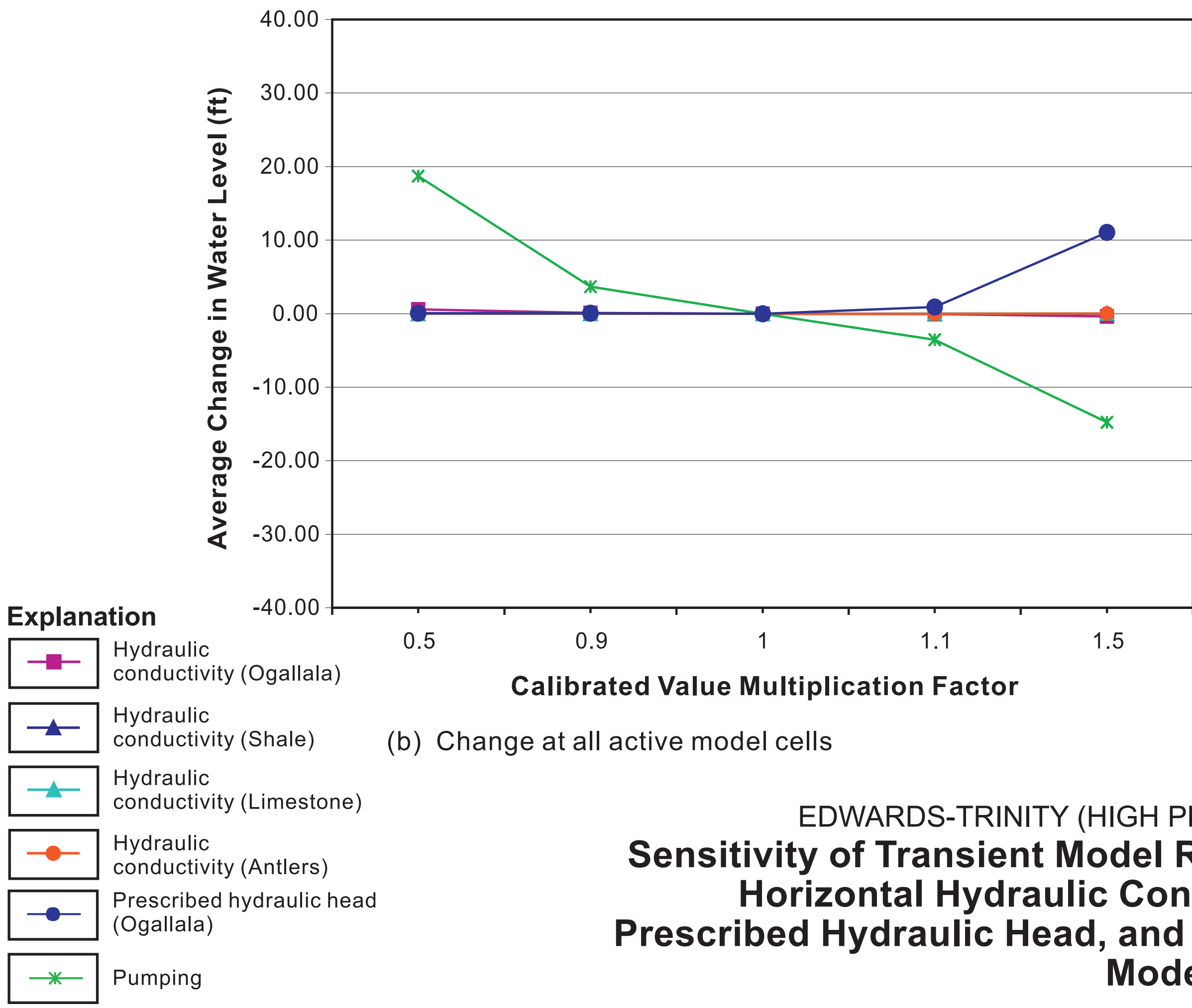
Sensitivity analyses for the transient model were conducted for horizontal and vertical hydraulic conductivity for each hydrogeologic unit (i.e., Ogallala sediments, and Cretaceous shale, limestone, and Antlers Sand), prescribed hydraulic head in the northeastern portion of the model domain near Amarillo, recharge, drain conductance, seepage between the Edwards-Trinity (High Plains) Aquifer and the Dockum Aquifer, specific storage, specific yield and pumping. Each of these input parameters, except for horizontal hydraulic conductivity, prescribed hydraulic head and pumping, was increased and decreased uniformly by a factor of 5 and 10. Horizontal hydraulic conductivity, prescribed hydraulic head, and pumping were increased uniformly by 10 percent and 50 percent above the calibrated value and decreased by 10 percent and 50 percent below the calibrated value. The sensitivity analysis results are presented in terms of the average difference between calibrated model water levels and sensitivity run water levels at (1) the calibration points and (2) all active model cells within a given layer. The sensitivity model runs are provided for both model layer 1 (Southern Ogallala Aquifer) and model layers 3 and 4 (Edwards-Trinity [High Plains] Aquifer). As was done for the steady-state model sensitivity analysis, the leakage rate between the Edwards-Trinity (High Plains) and Dockum Aquifers determined during development of the Dockum Aquifer GAM (Ewing and others, 2008) was applied to conduct the sensitivity analysis for the transient model. Based on the simulated values in Ewing and others (2008) for the period 1980 to 1997, the average inflow to the Edwards-Trinity (High Plains) Aquifer from the Dockum Aquifer is 9,011 ac-ft/yr, while the average outflow from the Edwards-Trinity (High Plains) Aquifer to the Dockum Aquifer is very similar, at 8,446 ac-ft/yr.

The model sensitivity to horizontal hydraulic conductivity, prescribed hydraulic head at the northeastern model boundary, and groundwater pumping is presented in Figures 101 (Southern Ogallala Aquifer) and 102 (Edwards-Trinity [High Plains] Aquifer). Both figures indicate that the model is relatively insensitive to changes in horizontal hydraulic conductivity of either the Southern Ogallala or Cretaceous hydrogeologic units. This result is different from that of the steady-state model, which was found to be sensitive to changes in Southern Ogallala Aquifer hydraulic conductivity. The model is also insensitive to changes in prescribed hydraulic head along the far northeastern boundary, except for model layer 1 when the prescribed head is increased by 50 percent (fig. 101). Both aquifers are sensitive to increases and decreases in pumping, although the Southern Ogallala Aquifer (fig. 101) is more sensitive to changes in pumping than the Edwards-Trinity (High Plains) Aquifer (fig. 102).

The model sensitivity to vertical hydraulic conductivity is presented in Figures 103 (Southern Ogallala Aquifer) and 104 (Edwards-Trinity [High Plains] Aquifer). These figures indicate that the transient model is insensitive to changes in vertical hydraulic conductivity of each hydrogeologic unit except for the Cretaceous shale. Simulated Edwards-Trinity (High Plains) Aquifer hydraulic heads are sensitive to changes in vertical hydraulic conductivity of the shale (fig. 104). Higher shale vertical hydraulic conductivity leads to higher simulated hydraulic heads in model layers 3 and 4, while decreasing the vertical hydraulic conductivity has the opposite effect (fig. 104).



(a) Change at calibration points

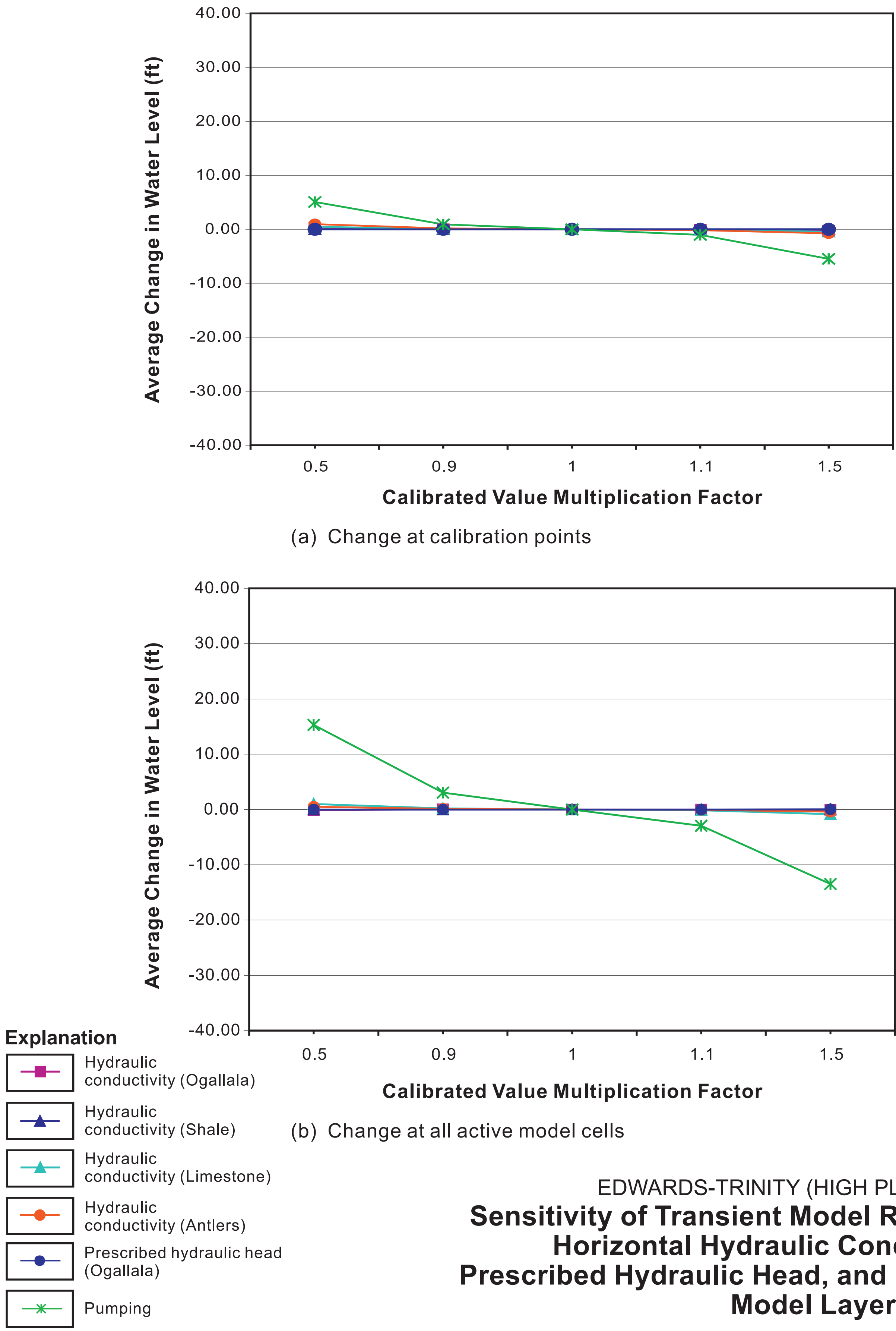


(b) Change at all active model cells

EDWARDS-TRINITY (HIGH PLAINS) GAM

Sensitivity of Transient Model Results to Horizontal Hydraulic Conductivity, Prescribed Hydraulic Head, and Pumping Model Layer 1

Figure 101



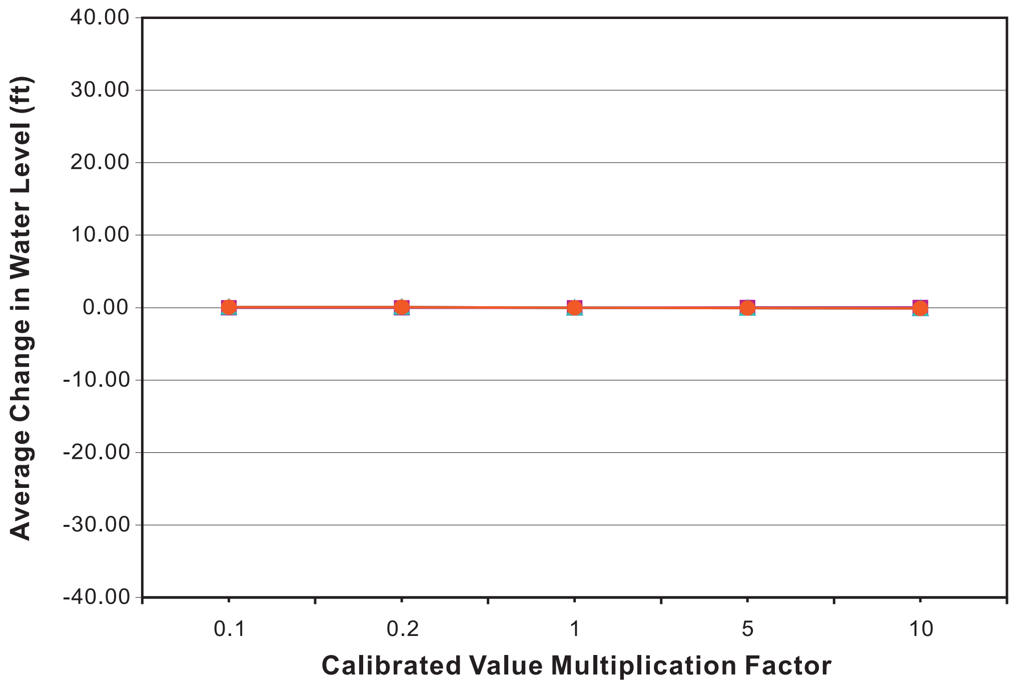
(a) Change at calibration points

(b) Change at all active model cells

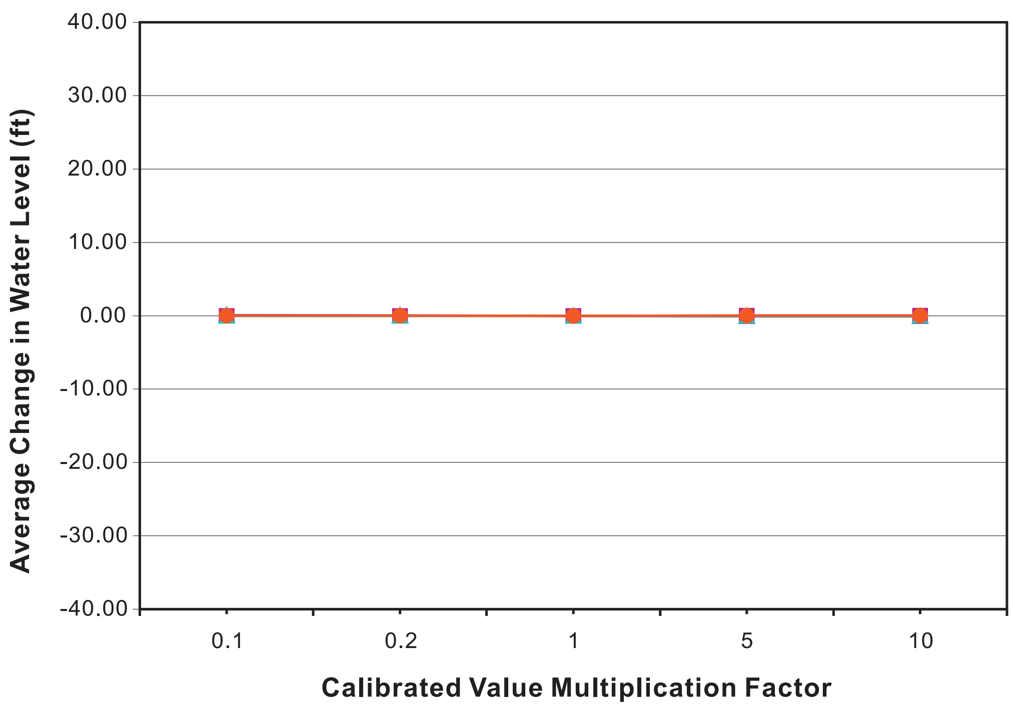
EDWARDS-TRINITY (HIGH PLAINS) GAM

Sensitivity of Transient Model Results to Horizontal Hydraulic Conductivity, Prescribed Hydraulic Head, and Pumping Model Layers 3 and 4

Figure 102



(a) Change at calibration points



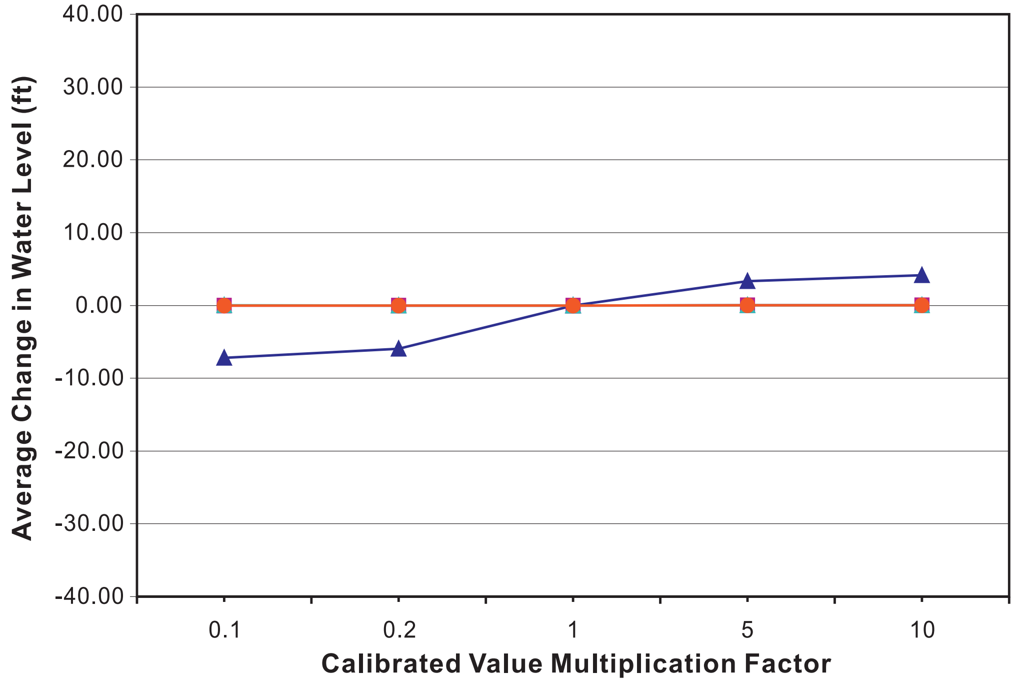
(b) Change at all active model cells

Explanation

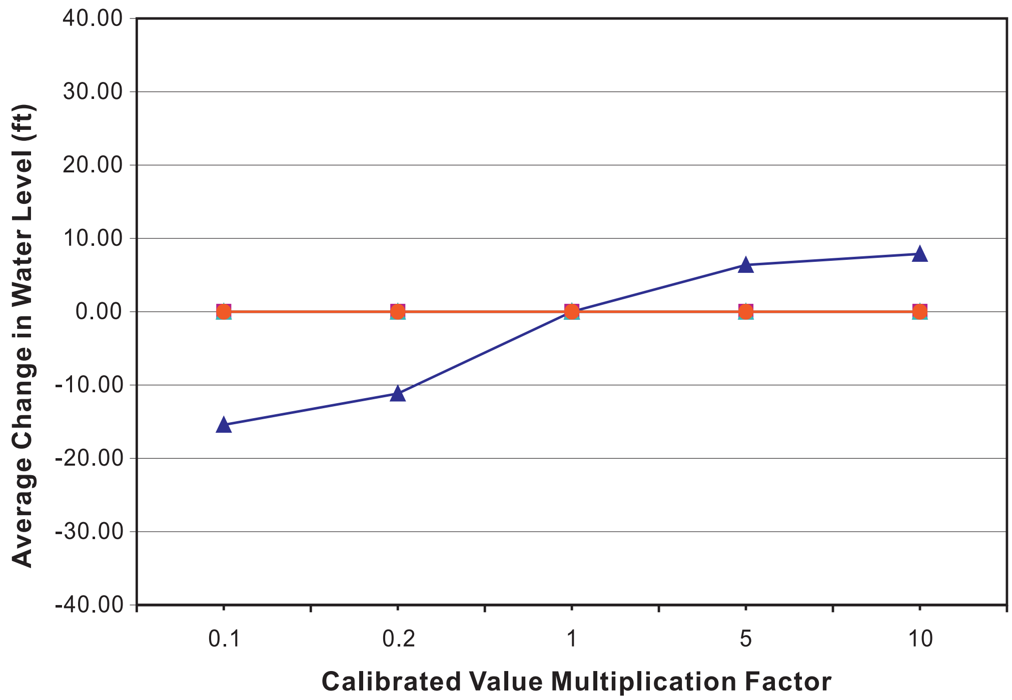
EDWARDS-TRINITY (HIGH PLAINS) GAM

Sensitivity of Transient Model Results to Vertical Hydraulic Conductivity Model Layer 1

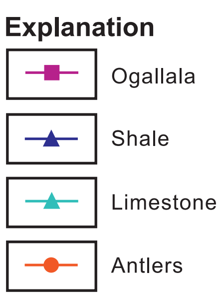
Figure 103



(a) Change at calibration points



(b) Change at all active model cells



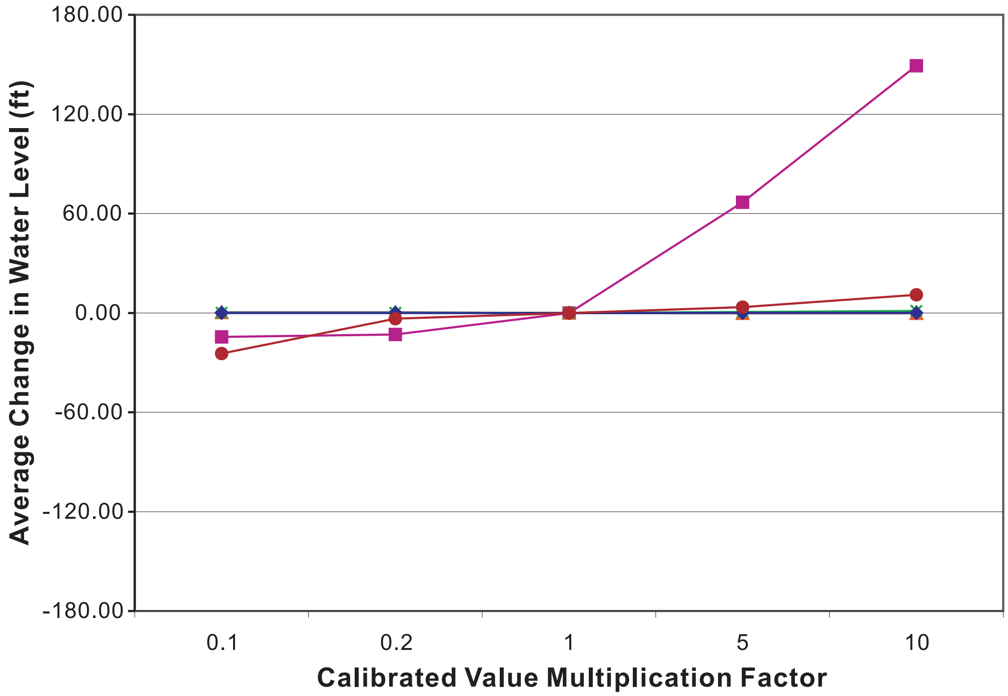
EDWARDS-TRINITY (HIGH PLAINS) GAM

Sensitivity of Transient Model Results to Vertical Hydraulic Conductivity Model Layers 3 and 4

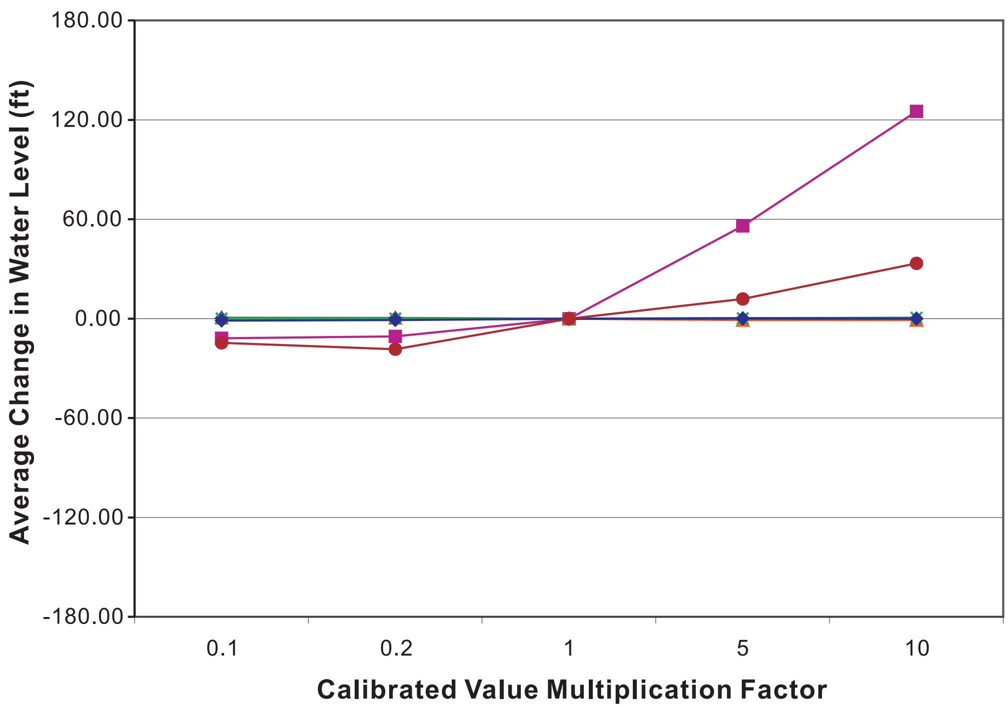
Figure 104

Sensitivity of the transient model to recharge, drain conductance (divided into escarpment and interior drains), leakage to and from the Dockum Aquifer, specific storage, and specific yield is illustrated in Figures 105 and 106 for the Southern Ogallala Aquifer and Edwards-Trinity (High Plains) Aquifer, respectively. Figure 105 indicates that Southern Ogallala Aquifer water levels are sensitive to changes in recharge (very sensitive to increases in recharge) and sensitive to changes in specific yield. Southern Ogallala Aquifer water levels are insensitive to drain conductance, leakage between the Edwards-Trinity (High Plains) and Dockum Aquifers, and specific storage.

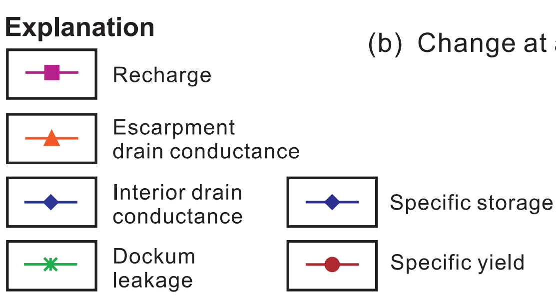
Figure 106 indicates that Edwards-Trinity (High Plains) Aquifer water levels are also very sensitive to increases in recharge. Unlike the Southern Ogallala Aquifer hydraulic heads, simulated hydraulic heads for model layers 3 and 4 are sensitive to increases in the prescribed Dockum Aquifer leakage rate to or from the Edwards-Trinity (High Plains) Aquifer, but insensitive to decreases in prescribed Dockum Aquifer leakage. Simulated hydraulic heads in model layers 3 and 4 are insensitive to drain conductance and storage coefficients.



(a) Change at calibration points



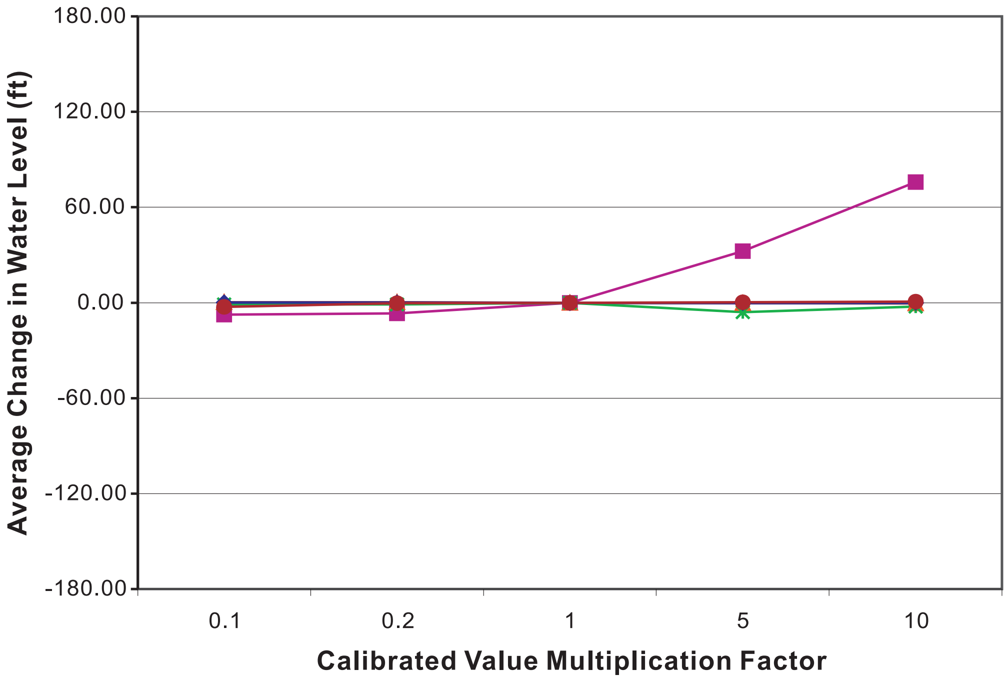
(b) Change at all active model cells



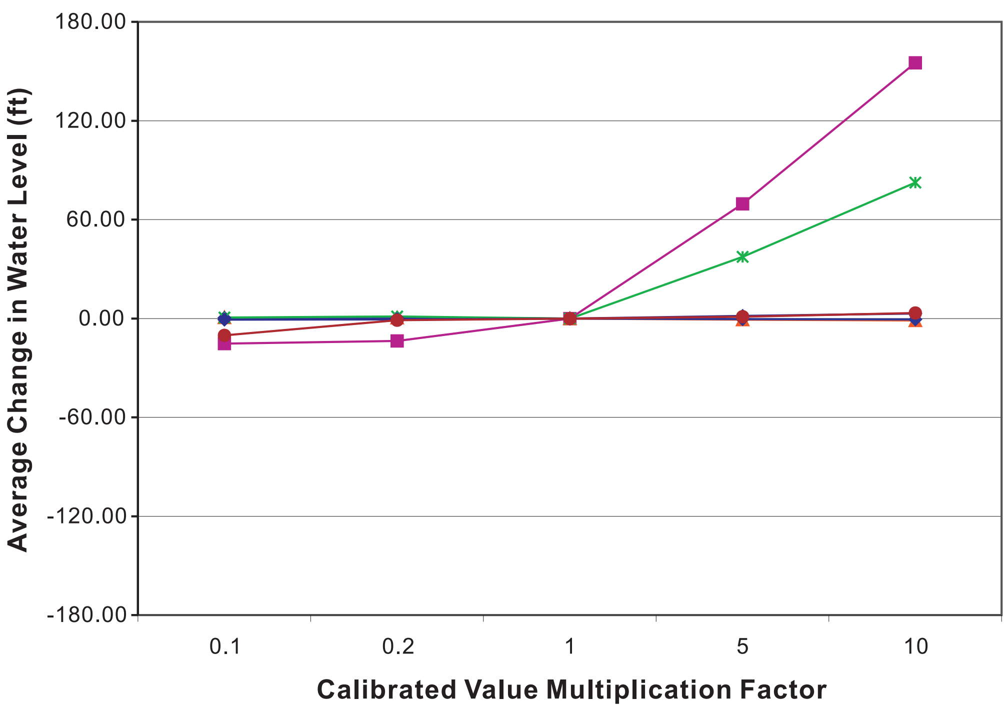
EDWARDS-TRINITY (HIGH PLAINS) GAM

Sensitivity of Transient Model Results to Recharge, Storage Coefficient, Drain Conductance, and Dockum Leakage Model Layer 1

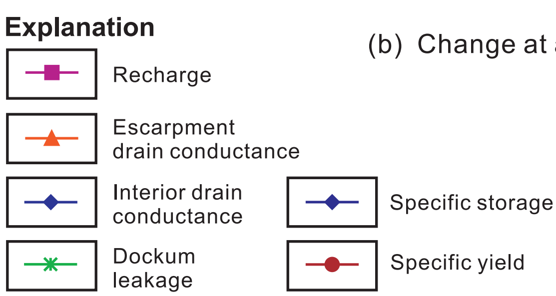
Figure 105



(a) Change at calibration points



(b) Change at all active model cells



EDWARDS-TRINITY (HIGH PLAINS) GAM

Sensitivity of Transient Model Results to Recharge, Storage Coefficient, Drain Conductance, and Dockum Leakage Model Layers 3 and 4

Figure 106

10.0 Limitations of the Model

The Edwards-Trinity (High Plains) Aquifer GAM, which also serves as an update to the Southern Ogallala GAM (Blandford and others, 2003), was developed for regional analysis and is generally applicable on the scale of at least a county. Although the model may serve as a useful starting point for conducting site-specific analysis (e.g., computation of water levels at a sub-county scale), it should not be used for local analysis without evaluation of its suitability and/or modification for such applications. Appropriate modifications may consist of refining the model grid in the horizontal and/or vertical dimensions and comparing historical simulation results to additional observed data in the region of interest. The original Southern Ogallala GAM was used successfully in this way for conducting detailed analyses within Lubbock, Bailey and Hockley Counties (DBS&A, 2005, 2007).

In addition, all groundwater flow models have limitations based on data constraints and the methodology used to construct them. One of the basic assumptions intrinsic in using a model for predictive purposes is that the hydrologic system will behave in the future as it did in the past if similar stresses (such as pumping and recharge) are applied. This assumption may or may not be valid as water levels in deeper portions of the aquifer decline even further. As the saturated thickness of the aquifer changes, average aquifer parameters such as hydraulic conductivity and specific yield can also change. Although true of all aquifer units considered in the Edwards-Trinity (High Plains) Aquifer GAM, this potential limitation is most applicable to the Southern Ogallala Aquifer.

A large number of springs both inside the model domain and along the eastern escarpment were simulated using drain nodes in the model. Because information on spring flow is very limited for the study area, detailed calibration of the model to observed spring flow could not be conducted. The model might provide a sense of general changes in overall spring flow, but it should not be used to estimate or predict flow at individual springs.

Additional limitations of the model are intrinsic to the available data sets used to create it. As discussed throughout this report, some of the model input parameters are relatively unconstrained and in many cases simply not known. Although reasonable estimates of hydraulic parameters, recharge, and pumping rates were used in the modeling, errors certainly exist within the construct of the model due to errors in estimated inputs. In general, the magnitude of such errors is reduced in regions where greater amounts of observed data are available. Observed aquifer properties for the Edwards-Trinity (High Plains) Aquifer, as well as observed hydraulic head data to calibrate to, are lacking for large portions of the aquifer extent.

Finally, for a number of regions in the model, the simulated predevelopment water levels, and therefore the starting water levels for the transient simulation, are either high or low relative to observed values. This situation is unavoidable given that a "perfect" match between observed and simulated water levels is not achievable. For the most part, however, general trends in water levels are reasonably replicated in the transient model for both the Edwards-Trinity (High Plains) and Southern Ogallala Aquifers. It is recommended, therefore, that the model be used to simulate expected trends in water levels, rather than absolute values of water levels.

11.0 Recommended Future Improvements

Throughout much of the Edwards-Trinity (High Plains) Aquifer, data concerning aquifer properties, water levels, and pumping volumes are very limited. As additional data are collected in the future, the Edwards-Trinity (High Plains) GAM or subsequent models can be refined and updated to account for the additional information. Model improvements likely to yield the greatest benefit in terms of improved predictive simulations would be those based on better information regarding the magnitude and distribution of recharge and groundwater pumping, and the spatial distribution of aquifer properties such as hydraulic conductivity. Improved estimates of leakage to and from the Dockum Aquifer based on observed data may also be beneficial.

12.0 Summary and Conclusions

A numerical groundwater flow model was constructed for the Edwards-Trinity (High Plains) Aquifer in west Texas and eastern New Mexico, using the Southern Ogallala GAM (Blandford and others, 2003) as a starting point for model construction. The Edwards-Trinity (High Plains) Aquifer lies beneath a region of about 9,000 mi^2 beneath the Southern High Plains. Significant effort was expended during this study to develop the geologic structure of the primary hydrogeologic units that form the Edwards-Trinity (High Plains) Aquifer system. These units are the predominantly shale unit composed primarily of the Duck Creek and Kiamichi Formations, the predominantly limestone unit composed primarily of the Edwards Limestone and Comanche Peak Formations, and the basal Antlers Sand. This structure was determined based on geophysical logs from oil and gas wells, water well logs obtained from the TCEQ and GCDs, and existing publications.

The geologic analysis identified regions where enhanced cross-formational flow between the Southern Ogallala and Edwards-Trinity (High Plains) Aquifers is likely to occur. These regions include the southern and eastern portions of the Edwards-Trinity (High Plains) Aquifer, where the Kiamichi and Duck Creek Formations are generally thin or absent, and limited areas within the central and western portions of the Edwards-Trinity (High Plains) Aquifer where these units have been eroded away, either in full or in part, in paleochannels. The geologic analysis also delineated regions where the Edwards-Trinity (High Plains) Aquifer is discontinuous or absent, and an updated aquifer extent was estimated that differs in certain areas from the existing TWDB aquifer delineation. The largest differences in aquifer extent are in Gaines and Dawson Counties.

The model was constructed in such a way as to minimize, to the extent possible, non-uniqueness in aquifer parameter estimates and other model inputs. A steady-state model was developed for predevelopment (1930) conditions to determine hydraulic conductivity of the aquifers, recharge to the Southern Ogallala Aquifer, and cross-formational flow to and from the Edwards-Trinity (High Plains) Aquifer.

Results of the steady-state model indicate that, under predevelopment conditions, approximately half of the discharge from the combined Southern Ogallala and Edwards-Trinity (High Plains) Aquifers occurred at springs along draws and at the margins of salt lakes west of the eastern escarpment. The remainder of the discharge occurred at springs and seeps along the eastern escarpment, or as outflow to the Central Ogallala Aquifer near Amarillo. Only 3 percent of the total simulated spring flow emanated from the Edwards-Trinity (High Plains) Aquifer. Simulated predevelopment recharge to the Southern Ogallala Aquifer ranges from 0.03 in/yr to 0.08 in/yr, with the higher rates simulated in regions with lower-permeability soils in the northern part of the study area.

Results from the steady-state model were used as initial conditions for the transient model calibration, which was conducted for the period 1930 through 2000. Transient model calibration for Southern Ogallala Aquifer was conducted using 90 hydrographs for locations throughout the study area and all available observed water levels for the winters of 1989-1990 and 1999-2000. Relative to the existing Southern Ogallala GAM, changes made in the current model to maintain or improve model calibration include 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.

Transient model calibration for the Edwards-Trinity (High Plains) Aquifer was conducted using 18 hydrographs at locations distributed across the aquifer extent and all available observed 1980, 1990 and 1997 water level data from Edwards-Trinity (High Plains) Aquifer wells. The availability of observed data for the Edwards-Trinity (High Plains) Aquifer is very limited compared to the Southern Ogallala Aquifer. Even so, the transient model replicates the observed data quite well at most locations.

The vast majority of discharge simulated from the Southern Ogallala Aquifer (94 percent) for the year 1997 is from wells; less than 2 percent of the total discharge is to springs. Approximately 37 percent of the inflow to the aquifer is from recharge, and 63 percent is from aquifer storage, indicating that overall, the Southern Ogallala Aquifer is being mined. There is a high degree of variability throughout the aquifer, however. At many locations, water levels are relatively stable or even increasing.

Water budget components for the Edwards-Trinity (High Plains) Aquifer are a small fraction of those of the Southern Ogallala Aquifer. Groundwater in the Edwards-Trinity (High Plains) Aquifer has not been used to a significant extent except within Gaines, Dawson, and possibly southern Yoakum Counties. Model simulations indicate that where both the Southern Ogallala and Edwards-Trinity (High Plains) Aquifers occur in Gaines and Dawson Counties, up to 40 percent of the water pumped for irrigated agriculture is obtained from the Edwards-Trinity (High Plains) Aquifer. At other locations, only a limited number of wells penetrate the aquifer, and for the most part yields are not substantial. Utilization of groundwater from the aquifer in New Mexico is minimal. Most wells that penetrate the Edwards-Trinity (High Plains) Aquifer are also screened across the Southern Ogallala Aquifer.

Significant well yields might be obtained from Edwards-Trinity (High Plains) Aquifer at some locations, and the aquifer may serve as a beneficial supplement to Ogallala water supplies or as a primary supply where the Southern Ogallala Aquifer is dry or has low production capacity. However, Edwards-Trinity (High Plains) Aquifer water availability will generally be far less than that of the Southern Ogallala Aquifer.

13.0 Acknowledgments

The input and assistance of all of the participants of the Stakeholder Advisory Forums are gratefully acknowledged. In particular, we thank Mr. Jason Coleman, Director of the South Plains UWCD, Mr. Harvey Everheart, Director of the Mesa UWCD, and Mr. Mike McGregor, former Director of the Llano Estacado UWCD, for their input and insights. Mr. Ray Brady provided useful opinions and information regarding the hydrogeology of Yoakum and Gaines Counties. We also thank Mr. Richard Smith of the TWDB for technical and contract management support throughout the duration of the project. And finally, we gratefully acknowledge the assistance of Mr. Jim Conkwright, Director of the HPUWCD No. 1, who not only provided input and data concerning the Edwards-Trinity (High Plains) Aquifer, but also hosted each of the Stakeholder Advisory Forums at the District offices in Lubbock, Texas.

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Appendix A

Simulated Water Budgets by County and Groundwater Conservation District

Steady-State Calibration Water Budget by County, Ogallala Aquifer (Model Layer 1)

County	Inflows (ac-ft/yr)							Outflows (ac-ft/yr)						
	Prescribed Head	Recharge	Storage	Wells	Lateral Flow	Vertical Flow	Total	Prescribed Head	Drains	Storage	Wells	Lateral Flow	Vertical Flow	Total
ANDREWS	0	1,219	0	0	2,143	0	**3,362**	0	924	0	0	2,460	0	**3,385**
ARMSTRONG	0	218	0	0	902	0	**1,119**	0	1,014	0	0	104	0	**1,118**
BAILEY	0	1,103	0	0	4,076	144	**5,322**	0	111	0	0	4,980	242	**5,332**
BORDEN	0	100	0	0	776	73	**949**	0	903	0	0	0	39	**942**
BRISCOE	0	1,361	0	0	3,021	0	**4,382**	0	3,607	0	0	774	0	**4,381**
CASTRO	0	3,256	0	0	7,308	0	**10,564**	0	0	0	0	0	10,570	**10,570**
COCHRAN	0	1,078	0	0	1,469	455	**3,002**	0	24	0	0	2,657	334	**3,015**
CROSBY	0	2,110	0	0	5,898	0	**8,008**	0	6,514	0	0	1,496	0	**8,010**
DAWSON	0	1,074	0	0	4,383	1,188	**6,644**	0	2,434	0	0	3,357	865	**6,655**
DEAF SMITH	0	5,209	0	0	828	0	**6,037**	0	642	0	0	5,399	0	**6,040**
DICKENS	0	251	0	0	1,371	0	**1,623**	0	1,617	0	0	0	0	**1,617**
ECTOR	0	319	0	0	344	0	**664**	0	57	0	0	609	0	**666**
FLOYD	0	3,229	0	0	9,032	1,616	**13,876**	0	7,377	0	0	4,926	1,576	**13,880**
GAINES	0	1,360	0	0	5,604	3,102	**10,066**	0	2,195	0	0	5,148	2,757	**10,100**
GARZA	0	213	0	0	1,177	387	**1,778**	0	1,693	0	0	0	76	**1,769**
GLASSCOCK	0	362	0	0	946	0	**1,308**	0	619	0	0	690	0	**1,309**
HALE	0	3,526	0	0	9,180	1,252	**13,957**	0	1,193	0	0	11,372	1,396	**13,960**
HOCKLEY	0	1,368	0	0	3,454	55	**4,876**	0	117	0	0	4,509	264	**4,890**
HOWARD	0	736	0	0	2,145	0	**2,881**	0	2,874	0	0	0	0	**2,874**
LAMB	0	1,857	0	0	7,261	86	**9,204**	0	2,697	0	0	6,387	131	**9,215**

ac-ft/yr = Acre-feet per year

Steady-State Calibration Water Budget by County, Ogallala Aquifer (Model Layer 1)

County	Inflows (ac-ft/yr)							Outflows (ac-ft/yr)						
	Prescribed Head	Recharge	Storage	Wells	Lateral Flow	Vertical Flow	Total	Prescribed Head	Drains	Storage	Wells	Lateral Flow	Vertical Flow	Total
LUBBOCK	0	1,981	0	0	6,545	1,550	**10,076**	0	4,830	0	0	3,621	1,634	**10,085**
LYNN	0	1,247	0	0	1,702	549	**3,499**	0	422	0	0	2,111	978	**3,511**
MARTIN	0	1,202	0	0	4,759	0	**5,960**	0	3,829	0	0	2,136	0	**5,965**
MIDLAND	0	790	0	0	1,205	0	**1,994**	0	1,044	0	0	954	0	**1,998**
MOTLEY	0	160	0	0	1,954	0	**2,113**	0	1,965	0	0	149	0	**2,114**
OLDHAM	0	1,435	0	0	64	0	**1,499**	0	468	0	0	1,032	0	**1,500**
PARMER	0	3,069	0	0	4,479	0	**7,548**	0	0	0	0	7,555	0	**7,555**
POTTER	0	191	0	0	403	0	**594**	341	0	0	0	253	0	**594**
RANDALL	0	2,586	0	0	3,966	0	**6,552**	3,604	1,872	0	0	1,076	0	**6,552**
SWISHER	0	3,263	0	0	6,064	0	**9,328**	0	2,944	0	0	6,378	0	**9,322**
TERRY	0	851	0	0	2,683	211	**3,745**	0	470	0	0	3,172	129	**3,770**
YOAKUM	0	699	0	0	1,632	117	**2,447**	0	0	0	0	2,128	341	**2,469**
Total	**0**	**47,421**	**0**	**0**	**106,774**	**10,783**		**3,945**	**54,454**	**0**	**0**	**85,433**	**21,331**	

ac-ft/yr = Acre-feet per year

Steady-State Calibration Water Budget by Groundwater Conservation District, Ogallala Aquifer (Model Layer 1)

Groundwater Conservation District	Inflows (ac-ft/yr)							Outflows (ac-ft/yr)						
	Prescribed Head	Recharge	Storage	Wells	Lateral Flow	Vertical Flow	Total	Prescribed Head	Drains	Storage	Wells	Lateral Flow	Vertical Flow	Total
GARZA COUNTY	0	213	0	0	1,177	387	**1,778**	0	1,693	0	0	0	76	**1,769**
GLASSCOCK	0	362	0	0	946	0	**1,308**	0	619	0	0	690	0	**1,309**
HIGH PLAINS NO. 1	0	28,325	0	0	19,284	5,676	**53,286**	2,953	18,811	0	0	25,082	6,527	**53,374**
LLANO ESTACADO	0	1,360	0	0	5,604	3,102	**10,066**	0	2,195	0	0	5,148	2,757	**10,100**
MESA	0	1,074	0	0	4,383	1,188	**6,644**	0	2,434	0	0	3,357	865	**6,655**
PANHANDLE	0	22	0	0	448	0	**470**	341	88	0	0	41	0	**470**
PERMIAN BASIN	0	1,904	0	0	5,626	0	**7,530**	0	5,245	0	0	2,292	0	**7,537**
SANDY LAND	0	699	0	0	1,632	117	**2,447**	0	0	0	0	2,128	341	**2,469**
SOUTH PLAINS	0	879	0	0	2,756	211	**3,845**	0	470	0	0	3,266	136	**3,871**
Total	**0**	**34,836**	**0**	**0**	**41,857**	**10,680**		**3,294**	**31,555**	**0**	**0**	**42,004**	**10,702**	

ac-ft/yr = Acre-feet per year

Steady-State Calibration Water Budget by County, Edwards-Trinity (High Plains) Aquifer (Model Layers 2 through 4)

County	Inflows (ac-ft/yr)							Outflows (ac-ft/yr)						
	Prescribed Head	Recharge	Storage	Wells	Lateral Flow	Vertical Flow	Total	Prescribed Head	Drains	Storage	Wells	Lateral Flow	Vertical Flow	Total
BAILEY	0	33	0	0	156	242	**431**	0	12	0	0	277	144	**433**
BORDEN	0	158	0	0	102	39	**299**	0	222	0	0	0	73	**295**
COCHRAN	0	0	0	0	588	334	**922**	0	0	0	0	469	455	**924**
CROSBY	0	0	0	0	0	0	**0**	0	0	0	0	0	0	**0**
DAWSON	0	103	0	0	600	865	**1,567**	0	310	0	0	71	1,188	**1,568**
FLOYD	0	40	0	0	0	1,576	**1,616**	0	0	0	0	0	1,616	**1,616**
GAINES	0	21	0	0	611	2,757	**3,389**	0	55	0	0	232	3,102	**3,389**
GARZA	0	29	0	0	341	76	**446**	0	55	0	0	0	387	**443**
HALE	0	36	0	0	12	1,396	**1,444**	0	0	0	0	193	1,252	**1,444**
HOCKLEY	0	17	0	0	461	264	**742**	0	35	0	0	652	55	**742**
LAMB	0	47	0	0	135	131	**313**	0	58	0	0	169	86	**313**
LUBBOCK	0	11	0	0	567	1,634	**2,211**	0	518	0	0	143	1,550	**2,211**
LYNN	0	86	0	0	538	978	**1,602**	0	391	0	0	662	549	**1,603**
TERRY	0	0	0	0	780	129	**908**	0	10	0	0	697	211	**918**
YOAKUM	0	0	0	0	638	341	**980**	0	0	0	0	865	117	**981**
Total	**0**	**582**	**0**	**0**	**5,528**	**10,761**		**0**	**1,666**	**0**	**0**	**4,431**	**10,783**	

ac-ft/yr = Acre-feet per year

Steady-State Calibration Water Budget by Groundwater Conservation District, Edwards-Trinity (High Plains) Aquifer (Model Layers 2 through 4)

Groundwater Conservation District	Inflows (ac-ft/yr)							Outflows (ac-ft/yr)						
	Prescribed Head	Recharge	Storage	Wells	Lateral Flow	Vertical Flow	Total	Prescribed Head	Drains	Storage	Wells	Lateral Flow	Vertical Flow	Total
GARZA COUNTY	0	29	0	0	341	76	**446**	0	55	0	0	0	387	**443**
HIGH PLAINS NO. 1	0	208	0	0	1,349	6,527	**8,084**	0	921	0	0	1,490	5,676	**8,087**
LLANO ESTACADO	0	21	0	0	611	2,757	**3,389**	0	55	0	0	232	3,102	**3,389**
MESA	0	103	0	0	600	865	**1,567**	0	310	0	0	71	1,188	**1,568**
SANDY LAND	0	0	0	0	638	341	**980**	0	0	0	0	865	117	**981**
SOUTH PLAINS	0	0	0	0	799	136	**935**	0	10	0	0	724	211	**945**
Total	**0**	**361**	**0**	**0**	**4,338**	**10,702**		**0**	**1,351**	**0**	**0**	**3,381**	**10,680**	

ac-ft/yr = Acre-feet per year

Water Budget by County, Ogallala Aquifer (Model Layer 1), Transient Simulation (Post-Development Conditions, 1997)

County	Inflows (ac-ft/yr)							Outflows (ac-ft/yr)						
	Prescribed Head	Recharge	Storage	Wells	Lateral Flow	Vertical Flow	Total	Prescribed Head	Drains	Storage	Wells	Lateral Flow	Vertical Flow	Total
ANDREWS	0	4,648	16,825	0	2,553	0	**24,025**	0	492	1,006	19,764	2,752	0	**24,014**
ARMSTRONG	0	3,071	40	0	120	0	**3,230**	0	1,054	1,156	630	391	0	**3,231**
BAILEY	0	24,919	33,185	0	1,487	217	**59,808**	0	11	5,585	51,449	2,133	671	**59,849**
BORDEN	0	2,533	1,777	0	1,388	96	**5,794**	0	1,171	1,570	2,811	80	164	**5,795**
BRISCOE	0	7,499	9,783	0	1,485	0	**18,767**	0	3,399	982	12,880	1,508	0	**18,770**
CASTRO	0	60,603	207,825	0	2,311	0	**270,739**	0	0	0	264,443	6,492	0	**270,935**
COCHRAN	0	23,919	56,404	0	1,251	971	**82,546**	0	0	3,319	75,162	1,948	1,508	**81,938**
CROSBY	0	42,308	59,795	0	4,009	0	**106,112**	0	4,350	450	98,773	2,576	0	**106,149**
DAWSON	0	62,042	50,692	0	6,436	1,446	**120,617**	0	3,394	22,592	83,889	6,734	3,968	**120,578**
DEAF SMITH	0	56,691	119,121	0	2,697	0	**178,508**	0	379	90	176,003	2,154	0	**178,626**
DICKENS	0	1,101	4,352	0	2,032	0	**7,484**	0	1,599	125	5,757	0	0	**7,480**
ECTOR	0	681	3,456	0	420	0	**4,556**	0	0	332	3,896	330	0	**4,558**
FLOYD	0	41,716	86,902	0	6,338	2,285	**137,241**	0	4,409	56	125,337	4,538	3,062	**137,402**
GAINES	0	92,766	164,477	0	4,344	1,960	**263,547**	0	2,270	3,856	209,015	6,304	42,429	**263,875**
GARZA	0	8,865	4,397	0	2,643	698	**16,603**	0	2,068	2,474	11,782	0	260	**16,584**
GLASSCOCK	0	1,162	2,344	0	1,175	0	**4,682**	0	606	226	2,961	889	0	**4,682**
HALE	0	71,148	146,986	0	6,278	2,714	**227,127**	0	0	0	215,292	6,328	5,633	**227,253**
HOCKLEY	0	46,359	78,486	0	2,597	247	**127,690**	0	50	396	122,548	4,360	401	**127,755**
HOWARD	0	4,369	1,229	0	2,381	0	**7,979**	0	2,845	2,112	3,015	0	0	**7,972**
LAMB	0	75,844	126,675	0	2,014	568	**205,101**	0	354	2,915	195,049	6,228	676	**205,223**

ac-ft/yr = Acre-feet per year

Water Budget by County, Ogallala Aquifer (Model Layer 1), Transient Simulation (Post-Development Conditions, 1997)

County	Inflows (ac-ft/yr)							Outflows (ac-ft/yr)						
	Prescribed Head	Recharge	Storage	Wells	Lateral Flow	Vertical Flow	Total	Prescribed Head	Drains	Storage	Wells	Lateral Flow	Vertical Flow	Total
LUBBOCK	0	52,626	100,027	10,436	5,968	3,863	**172,921**	0	2,234	2,843	161,859	2,080	3,981	**172,996**
LYNN	0	69,270	11,245	0	946	881	**82,342**	0	1,358	29,413	42,521	6,657	2,387	**82,336**
MARTIN	0	7,588	5,895	0	7,878	0	**21,361**	0	3,394	5,556	10,386	2,011	0	**21,347**
MIDLAND	0	4,386	7,015	0	875	0	**12,276**	0	872	833	9,281	1,291	0	**12,278**
MOTLEY	0	456	425	0	1,711	0	**2,592**	0	1,940	0	475	170	0	**2,586**
OLDHAM	0	3,081	8,410	0	505	0	**11,997**	0	459	974	9,705	862	0	**12,000**
PARMER	0	52,662	120,812	0	2,989	0	**176,463**	0	0	298	174,636	1,650	0	**176,584**
POTTER	27	519	3,932	0	1,039	0	**5,517**	60	0	0	5,460	0	0	**5,521**
RANDALL	1,079	23,844	31,653	0	610	0	**57,186**	714	1,053	332	52,311	2,797	0	**57,207**
SWISHER	0	35,042	62,116	0	5,893	0	**103,050**	0	363	1,054	98,838	2,856	0	**103,111**
TERRY	0	71,027	77,867	0	2,312	151	**151,357**	0	944	5,861	139,040	4,439	1,154	**151,439**
YOAKUM	0	39,586	65,173	0	1,696	404	**106,859**	0	0	3,461	99,608	1,730	1,699	**106,498**
Total	**1,106**	**992,332**	**1,669,321**	**10,436**	**86,382**	**16,501**		**774**	**41,068**	**99,866**	**2,484,578**	**82,290**	**67,993**	

ac-ft/yr = Acre-feet per year

Water Budget by Groundwater Conservation District, Ogallala Aquifer (Model Layer 1), Transient Simulation (Post-Development Conditions, 1997)

Groundwater Conservation District	Inflows (ac-ft/yr)							Outflows (ac-ft/yr)						
	Prescribed Head	Recharge	Storage	Wells	Lateral Flow	Vertical Flow	Total	Prescribed Head	Drains	Storage	Wells	Lateral Flow	Vertical Flow	Total
GARZA COUNTY	0	8,865	4,397	0	2,643	698	**16,603**	0	2,068	2,474	11,782	0	260	**16,584**
GLASSCOCK	0	1,162	2,344	0	1,175	0	**4,682**	0	606	226	2,961	889	0	**4,682**
HIGH PLAINS NO. 1	1,079	630,242	1,165,495	10,436	17,693	11,743	**1,836,688**	281	9,223	44,608	1,740,467	24,426	18,167	**1,837,172**
LLANO ESTACADO	0	92,766	164,477	0	4,344	1,960	**263,547**	0	2,270	3,856	209,015	6,304	42,429	**263,875**
MESA	0	62,042	50,692	0	6,436	1,446	**120,617**	0	3,394	22,592	83,889	6,734	3,968	**120,578**
PANHANDLE	27	61	311	0	139	0	**538**	60	83	0	184	211	0	**538**
PERMIAN BASIN	0	11,895	7,022	0	9,041	0	**27,958**	0	4,888	7,638	13,142	2,269	0	**27,937**
SANDY LAND	0	39,586	65,173	0	1,696	404	**106,859**	0	0	3,461	99,608	1,730	1,699	**106,498**
SOUTH PLAINS	0	71,287	78,197	0	2,168	151	**151,802**	0	944	5,861	139,200	4,714	1,166	**151,885**
Total	**1,106**	**917,907**	**1,538,107**	**10,436**	**45,335**	**16,402**		**341**	**23,476**	**90,716**	**2,300,248**	**47,275**	**67,690**	

ac-ft/yr = Acre-feet per year

Water Budget by County, Edwards-Trinity (High Plains) Aquifer (Model Layers 2 through 4), Transient Simulation (Post-Development Conditions, 1997)

County	Inflows (ac-ft/yr)							Outflows (ac-ft/yr)						
	Prescribed Head	Recharge	Storage	Wells	Lateral Flow	Vertical Flow	Total	Prescribed Head	Drains	Storage	Wells	Lateral Flow	Vertical Flow	Total
BAILEY	0	0	101	0	174	671	**946**	0	0	41	395	282	217	**935**
BORDEN	0	0	74	0	208	164	**446**	0	208	32	106	0	96	**442**
COCHRAN	0	0	1,035	0	632	1,508	**3,175**	0	0	0	2,191	566	971	**3,728**
DAWSON	0	0	321	19	772	3,968	**5,080**	0	362	52	3,085	133	1,446	**5,078**
FLOYD	0	0	524	0	0	3,062	**3,586**	0	0	0	1,215	0	2,285	**3,500**
GAINES	0	0	2,179	210	776	42,429	**45,594**	0	55	0	43,047	411	1,960	**45,472**
GARZA	0	0	15	0	509	260	**784**	0	56	0	18	0	698	**772**
HALE	0	0	718	0	26	5,633	**6,376**	0	0	0	3,521	173	2,714	**6,408**
HOCKLEY	0	0	193	0	461	401	**1,055**	0	19	0	96	693	247	**1,055**
LAMB	0	0	69	0	183	676	**928**	0	15	0	164	148	568	**895**
LOVING	0	0	0	0	0	0		0	0	0	0	0	0	
LUBBOCK	0	0	352	0	794	3,981	**5,127**	0	473	0	689	85	3,863	**5,110**
LYNN	0	0	36	0	320	2,387	**2,743**	0	439	94	230	1,123	881	**2,767**
TERRY	0	0	283	0	715	1,154	**2,153**	0	0	0	1,086	916	151	**2,153**
YOAKUM	0	0	1,739	0	1,022	1,699	**4,460**	0	0	0	3,393	718	404	**4,515**
Total	**0**	**0**	**7,640**	**229**	**6,592**	**67,993**		**0**	**1,626**	**219**	**59,235**	**5,248**	**16,501**	

ac-ft/yr = Acre-feet per year

Water Budget by Groundwater Conservation District, Edwards-Trinity (High Plains) Aquifer (Model Layers 2 through 4), Transient Simulation (Post-Development Conditions, 1997)

Groundwater Conservation District	Inflows (ac-ft/yr)							Outflows (ac-ft/yr)						
	Prescribed Head	Recharge	Storage	Wells	Lateral Flow	Vertical Flow	Total	Prescribed Head	Drains	Storage	Wells	Lateral Flow	Vertical Flow	Total
GARZA COUNTY	0	15	0	509	260	784	**1,568**	56	0	18	0	698	775	**1,547**
HIGH PLAINS NO. 1	0	3,005	0	1,358	18,167	22,530	**45,061**	916	145	8,455	1,746	11,743	23,005	**46,010**
LLANO ESTACADO	0	2,179	210	776	42,429	45,594	**91,188**	55	0	43,047	411	1,960	45,475	**90,947**
MESA	0	321	19	772	3,968	5,080	**10,160**	362	52	3,085	133	1,446	5,078	**10,156**
SANDY LAND	0	1,739	0	1,022	1,699	4,460	**8,920**	0	0	3,393	718	404	4,515	**9,029**
SOUTH PLAINS	0	287	0	730	1,166	2,183	**4,367**	0	0	1,086	946	151	2,186	**4,369**
Total	**0**	**7,546**	**229**	**5,167**	**67,690**	**80,631**		**1,389**	**197**	**59,083**	**3,954**	**16,402**	**81,034**	

ac-ft/yr = Acre-feet per year

Appendix B

Southern Ogallala Aquifer Simulated and Observed Hydrographs from Transient Model Calibration

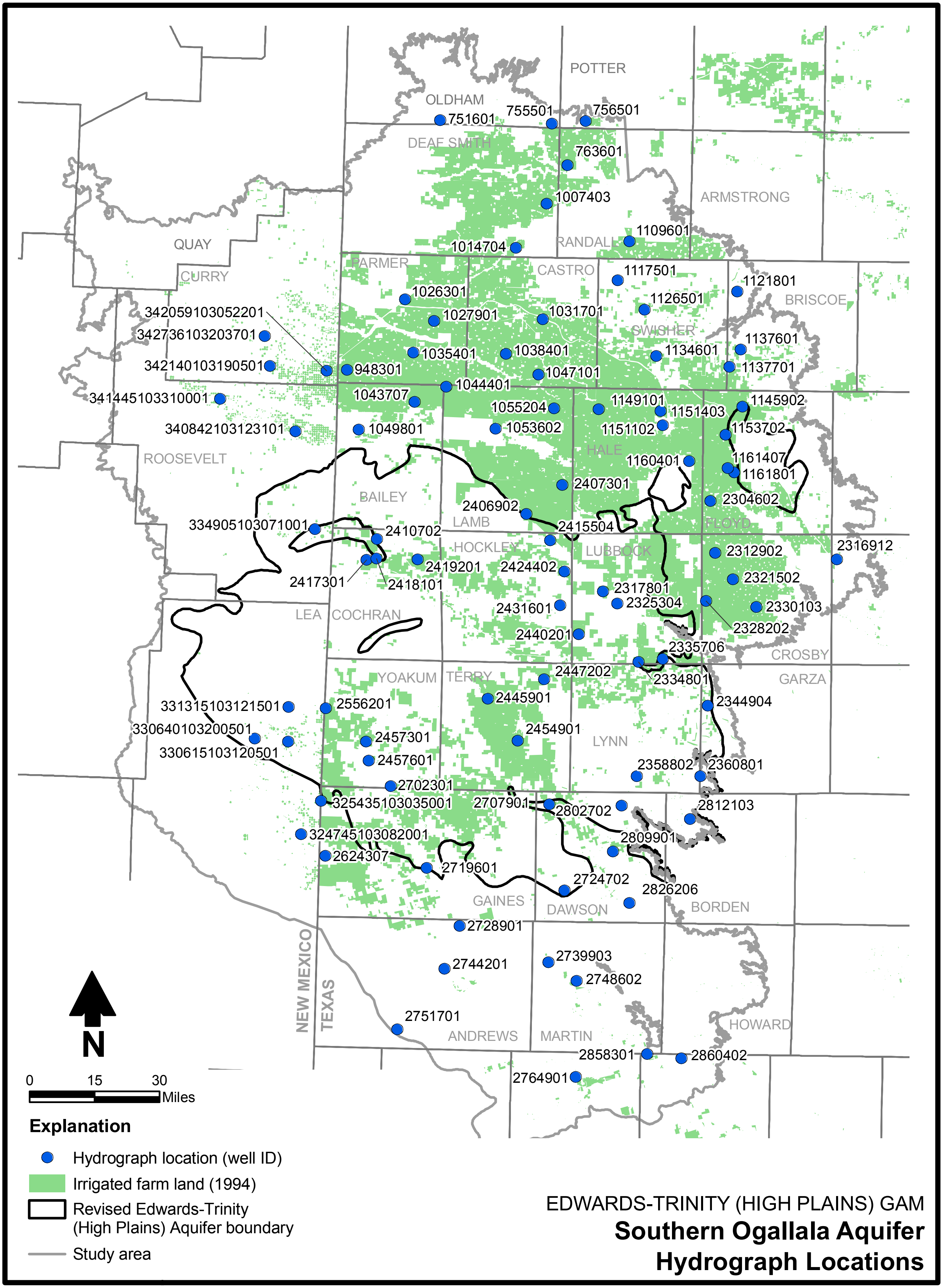
POTTER
OLDHAM
DEAF SMITH
ARMSTRONG
RANDALL
QUAY
CURRY
PARMER
CASTRO
SWISHER
BRISCOE
ROOSEVELT
BAILEY
LAMB
HALE
FLOYD
HOCKLEY
LUBBOCK
LEA
COCHRAN
CROSBY
YOAKUM
TERRY
GARZA
LYNN
GAINES
DAWSON
BORDEN
NEW MEXICO
TEXAS
ANDREWS
MARTIN
HOWARD
751601
755501
756501
763601
1007403
1109601
1014704
1117501
1121801
1026301
1126501
1027901
1031701
1137601
1035401
1038401
1134601
1137701
948301
1047101
1044401
1043707
1055204
1149101
1145902
1151403
1049801
1053602
1151102
1153702
1160401
1161407
1161801
2407301
2304602
2406902
2415504
2410702
2419201
2424402
2312902
2316912
2417301
2418101
2317801
2321502
2325304
2330103
2431601
2328202
2440201
2335706
2447202
2334801
2445901
2344904
2556201
2457301
2454901
2457601
2358802
2360801
2702301
2707901
2802702
2812103
2809901
2624307
2719601
2724702
2826206
2728901
2739903
2744201
2748602
2751701
2858301
2860402
2764901
342059103052201
342736103203701
342140103190501
341445103310001
340842103123101
334905103071001
331315103121501
330640103200501
330615103120501
325435103035001
324745103082001
N
0
15
30
Miles
Explanation
Hydrograph location (well ID)
Irrigated farm land (1994)
Revised Edwards-Trinity (High Plains) Aquifer boundary
Study area
EDWARDS-TRINITY (HIGH PLAINS) GAM
Southern Ogallala Aquifer
Hydrograph Locations

Figure B-1

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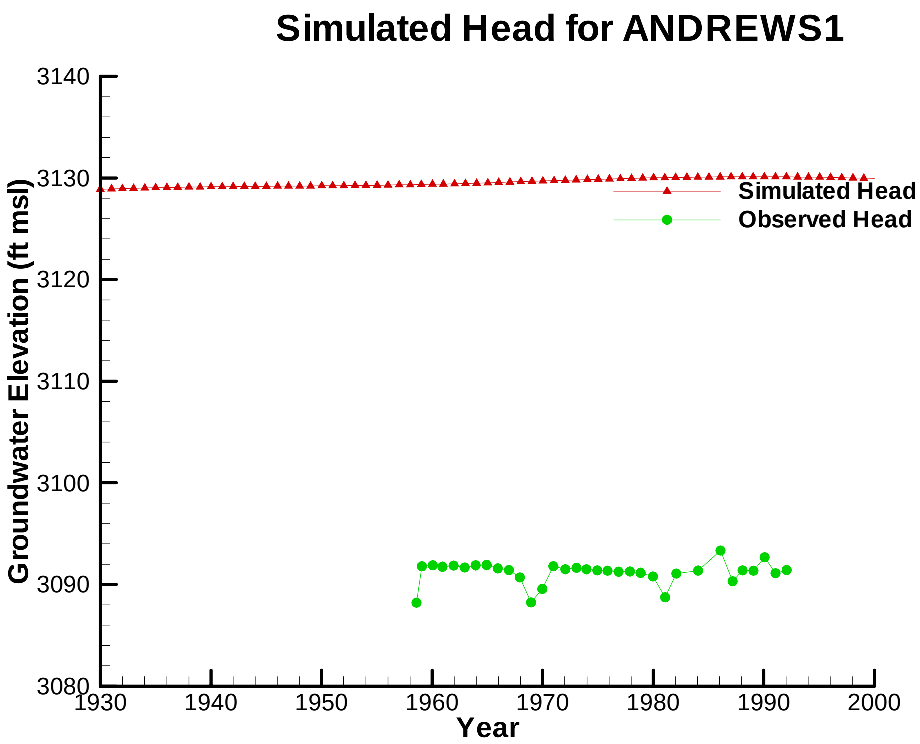
Table B-1. Well Locations

Name	Well ID	X-Coordinate	Y-Coordinate
ANDREWS1	2728901	4151430.44	20150514.67
ANDREWS2	2744201	4133013.62	20098137.35
ANDREWS3	2751701	4075341.60	20023780.13
BAILEY1	1043707	4096906.53	20790090.92
BAILEY2	1049801	4028543.99	20755921.39
BORDEN1	2812103	4432587.56	20280676.80
BRISCOE1	1121801	4490034.68	20924412.34
BRISCOE2	1137601	4494481.77	20853670.96
BRISCOE3	1137701	4480884.20	20832578.24
CASTRO1	1031701	4253131.03	20890595.60
CASTRO2	1038401	4208299.29	20848326.49
CASTRO3	1047101	4247580.17	20822922.64
COCHRAN1	2410702	4050544.96	20622511.52
COCHRAN2	2417301	4037974.81	20597035.28
COCHRAN3	2419201	4100515.60	20597782.14
COCHRAN4	2418101	4050265.001	20598828.43
CROSBY1	2312902	4463317.10	20605637.39
CROSBY2	2321502	4484910.85	20573575.80
CROSBY3	2328202	4452393.40	20547193.30
CROSBY4	2330103	4513456.675	20539510.7
CURRY1	342736103203701	3914051.53	20870087.99
CURRY2	342140103190501	3920413.12	20833972.53
CURRY3	342059103052201	3989482.84	20827709.58
DAWSON1	2802702	4349389.98	20296887.27
DAWSON2	2809901	4338417.61	20241370.66
DAWSON3	2724702	4279696.94	20193831.08
DAWSON4	2707901	4260900	20298678
DAWSON5	2826206	4358922	20178429
DEAFSMITH1	1007403	4257942.46	21031823.64
DEAFSMITH2	1014704	4220354.00	20978161.94
DICKENS1	2316912	4611569.84	20597895.30
FLOYD1	1145902	4496281.90	20784336.69
FLOYD2	1153702	4475863.26	20749888.19
FLOYD3	1161801	4486416.36	20703593.45
FLOYD4	2304602	4457513.08	20668896.60
FLOYD5	1161407	4478435.862	20708980.47
GAINES1	325435103035001	3982648.90	20303015.94
GAINES2	2624307	3988041.65	20236028.94
GAINES3	2719601	4111466.79	20221121.46
GARZA1	2344904	4454058.42	20419104.22
GARZA2	2360801	4445065.68	20333172.58
GLASSCOCK1	2858301	4380174.94	19994188.07
GLASSCOCK2	2860402	4422010.72	19988593.48
HALE1	1149101	4321156.00	20780757.27
HALE2	1151102	4396539.39	20778578.02

Table B-1. Well Locations

Name	Well ID	X-Coordinate	Y-Coordinate
HALE3	1160401	4431650.61	20717610.15
HALE4	1151403	4399199.536	20761306.13
HOCKLEY1	2415504	4262136.77	20620825.59
HOCKLEY2	2424402	4279348.81	20582848.26
HOCKLEY3	2431601	4274274.16	20541727.70
LAMB1	1044401	4135509.78	20808177.93
LAMB2	1055204	4266898.33	20781848.48
LAMB3	2407301	4277001.63	20688348.37
LAMB4	2406902	4233110.83	20652892.21
LAMB5	1053602	4195280.898	20756914.4
LEA1	331315103121501	3942962.99	20417571.69
LEA2	330640103200501	3901926.92	20378786.14
LEA3	330615103120501	3942588.62	20375069.27
LEA4	324745103082001	3958502.08	20262160.34
LUBBOCK1	2317801	4326383.19	20558805.86
LUBBOCK2	2440201	4297100.77	20506163.37
LUBBOCK3	2334801	4369821.60	20472713.22
LUBBOCK4	2325304	4344096.97	20543920.14
LUBBOCK5	2335706	4399079.298	20476402.39
LYNN1	2358802	4367780.98	20332925.80
MARTIN1	2748602	4293982.91	20083165.95
MARTIN2	2739903	4259729.408	20105689.38
MIDLAND1	2764901	4293030.03	19965706.41
OLDHAM1	751601	4127901.53	21133994.17
OLDHAM2	755501	4263992.75	21129589.64
PARMER1	1026301	4084857.98	20915230.69
PARMER2	1027901	4120326.66	20888570.57
PARMER3	1035401	4094885.36	20849923.87
PARMER4	948301	4014049.37	20828963.65
POTTER1	756501	4305150.83	21132728.06
RANDALL1	763601	4283251.28	21078835.35
RANDALL2	1109601	4358426.29	20985658.08
ROOSEVELT1	341445103310001	3859447.17	20793733.46
ROOSEVELT2	340842103123101	3951380.75	20754207.50
ROOSEVELT3	334905103071001	3974980.21	20634397.03
SWISHER1	1117501	4344278.05	20938382.60
SWISHER2	1126501	4377181.37	20902614.23
SWISHER3	1134601	4391479.50	20846042.98
TERRY1	2447202	4254567.38	20451211.87
TERRY2	2445901	4185937.28	20427740.73
TERRY3	2454901	4222271.07	20376336.29
YOAKUM1	2556201	3988154.13	20415782.85
YOAKUM2	2457301	4037313.88	20375268.62
YOAKUM3	2457601	4040806.32	20351989.58
YOAKUM4	2702301	4067382.065	20320938.14


Simulated Head for ANDREWS1
Groundwater Elevation (ft msl)
Year
Simulated Head
Observed Head
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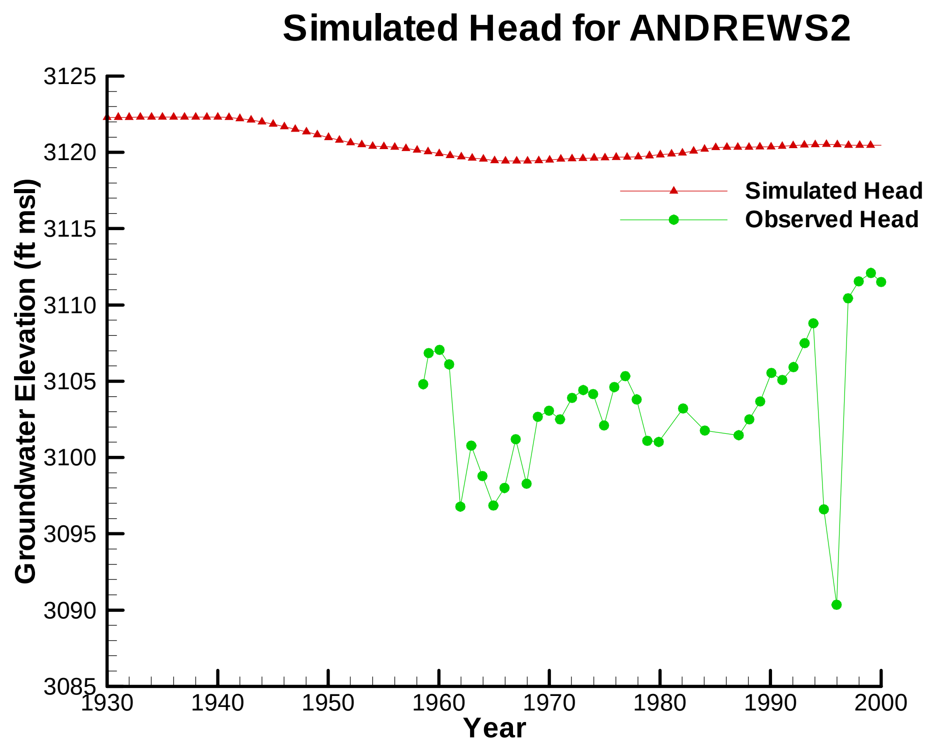
3090
3100
3110
3120
3130
3140
1930
1940
1950
1960
1970
1980
1990
2000


Simulated Head for ANDREWS2
Groundwater Elevation (ft msl)
Year
Simulated Head
Observed Head
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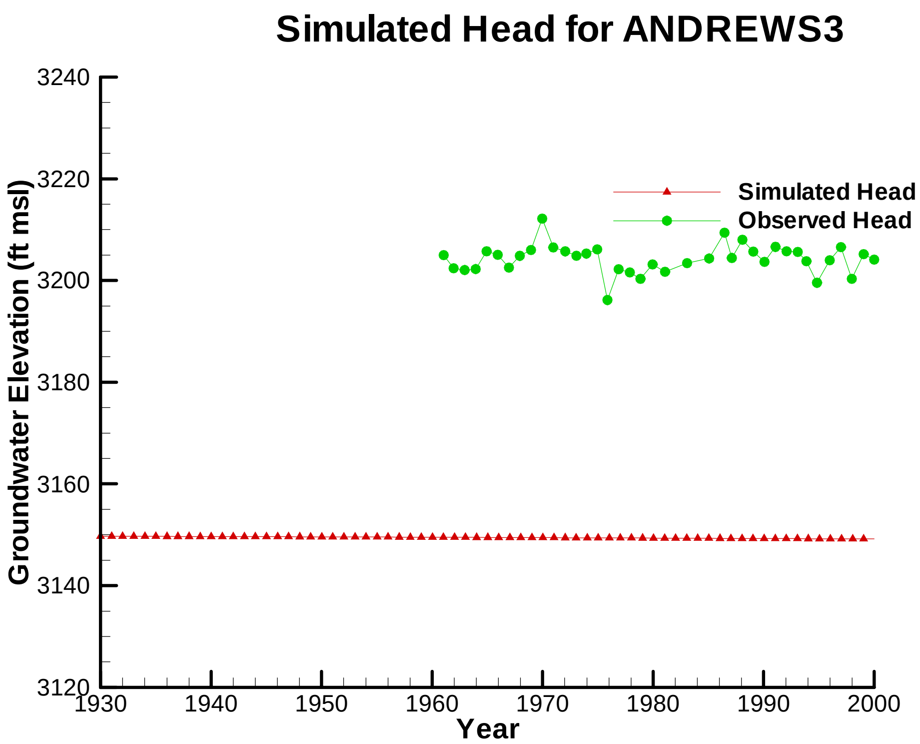
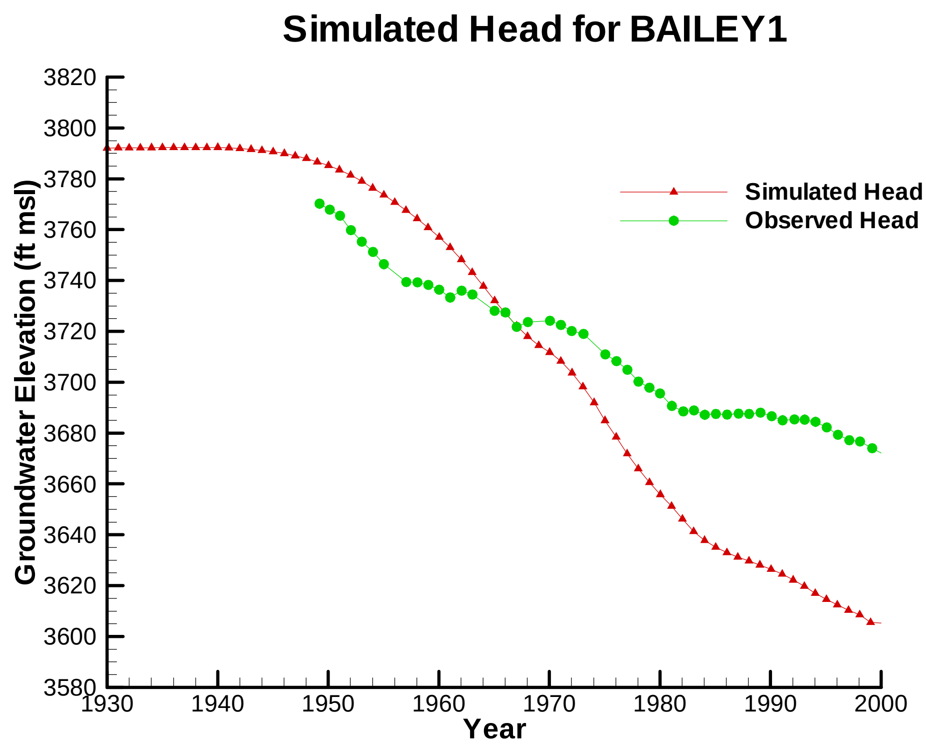
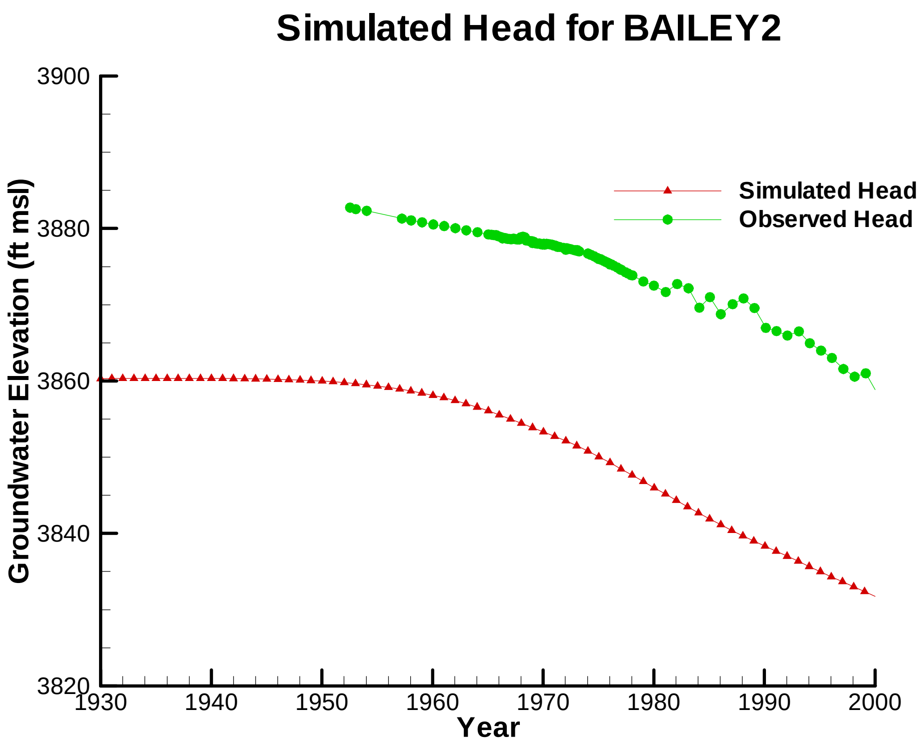
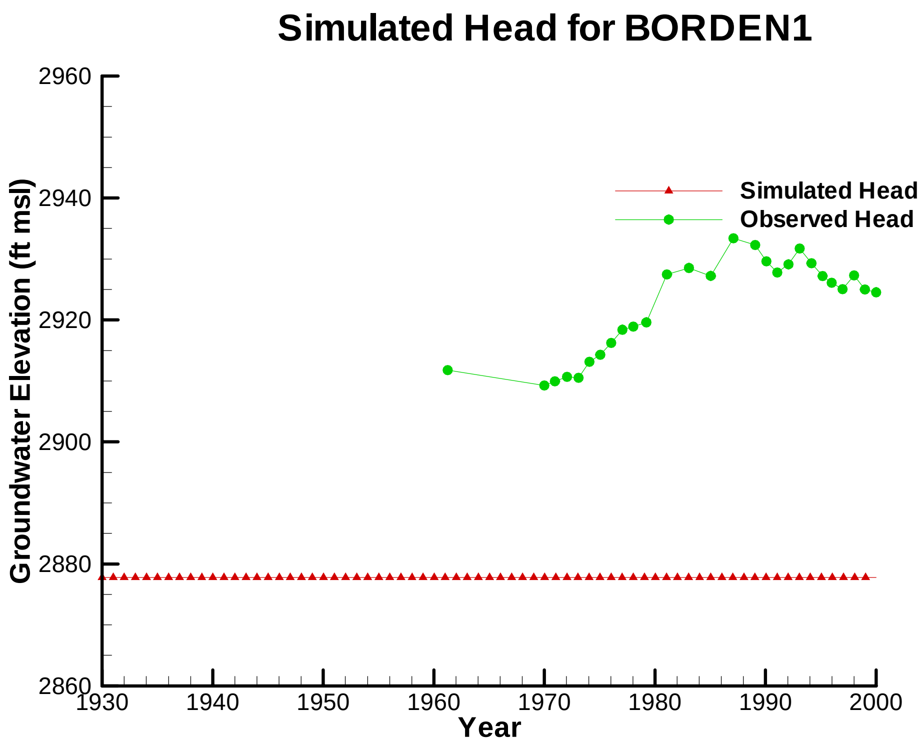
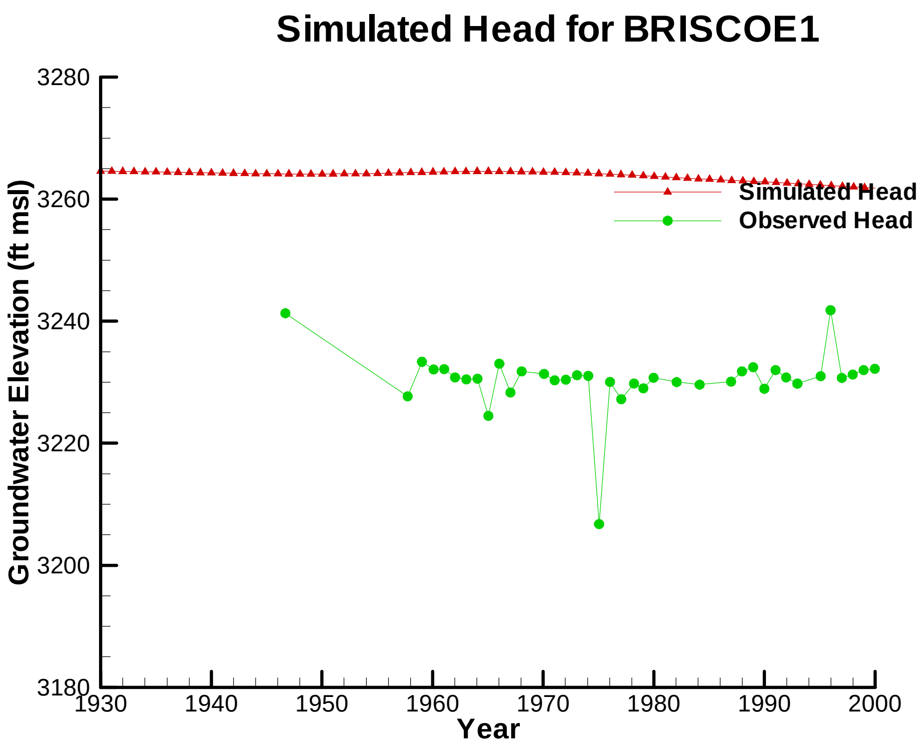
3090
3095
3100
3105
3110
3115
3120
3125
1930
1940
1950
1960
1970
1980
1990
2000

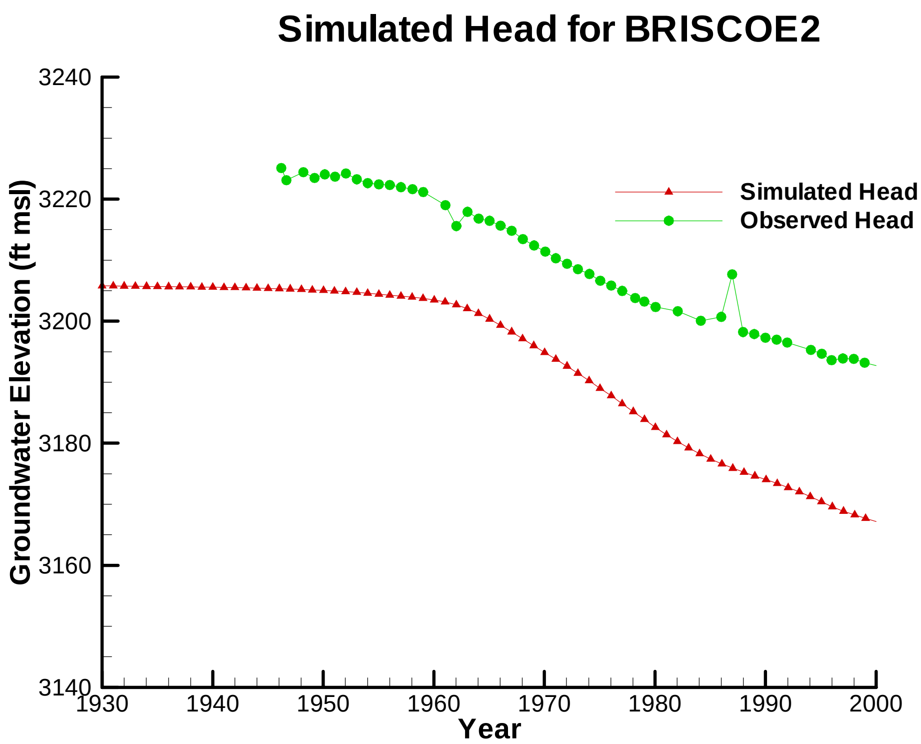

Simulated Head for ANDREWS3
Groundwater Elevation (ft msl)
Year
Simulated Head
Observed Head
3120
3140
3160
3180
3200
3220
3240
1930
1940
1950
1960
1970
1980
1990
2000

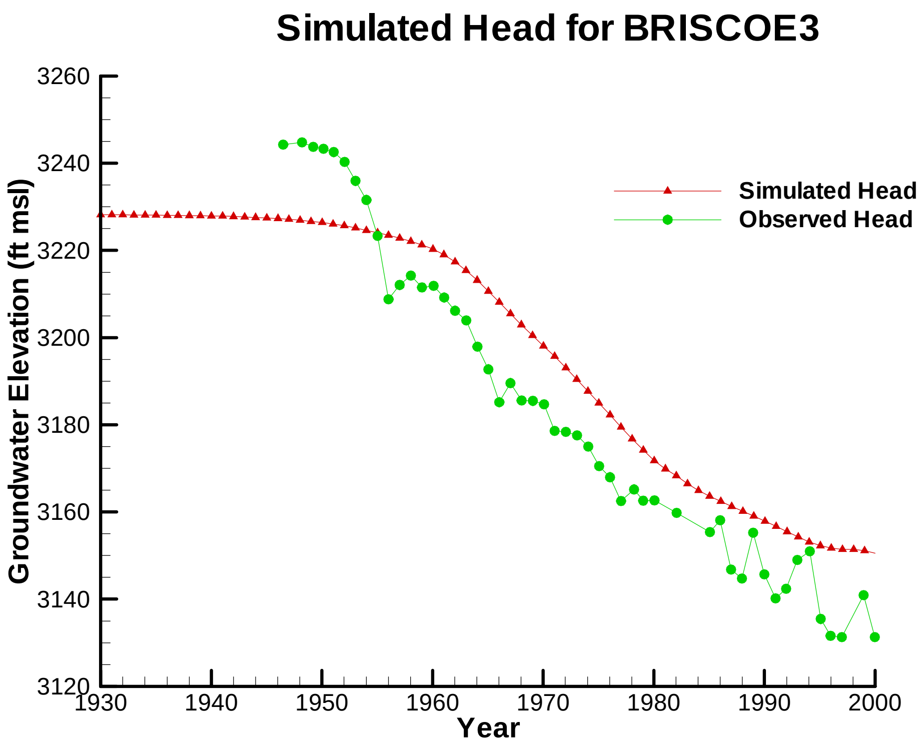

Simulated Head for BAILEY1
Groundwater Elevation (ft msl)
Year
Simulated Head
Observed Head
3580
3600
3620
3640
3660
3680
3700
3720
3740
3760
3780
3800
3820
1930
1940
1950
1960
1970
1980
1990
2000


Simulated Head for BAILEY2
Simulated Head
Observed Head
Groundwater Elevation (ft msl)
Year
3900
3880
3860
3840
3820
1930
1940
1950
1960
1970
1980
1990
2000


Simulated Head for BORDEN1
Simulated Head
Observed Head
Groundwater Elevation (ft msl)
Year
2960
2940
2920
2900
2880
2860
1930
1940
1950
1960
1970
1980
1990
2000


Simulated Head for BRISCOE1
Simulated Head
Observed Head
Groundwater Elevation (ft msl)
Year
3280
3260
3240
3220
3200
3180
1930
1940
1950
1960
1970
1980
1990
2000


Simulated Head for BRISCOE2
Simulated Head
Observed Head
Groundwater Elevation (ft msl)
Year
3240
3220
3200
3180
3160
3140
1930
1940
1950
1960
1970
1980
1990
2000


Simulated Head for BRISCOE3
Groundwater Elevation (ft msl)
Year
Simulated Head
Observed Head
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3180
3200
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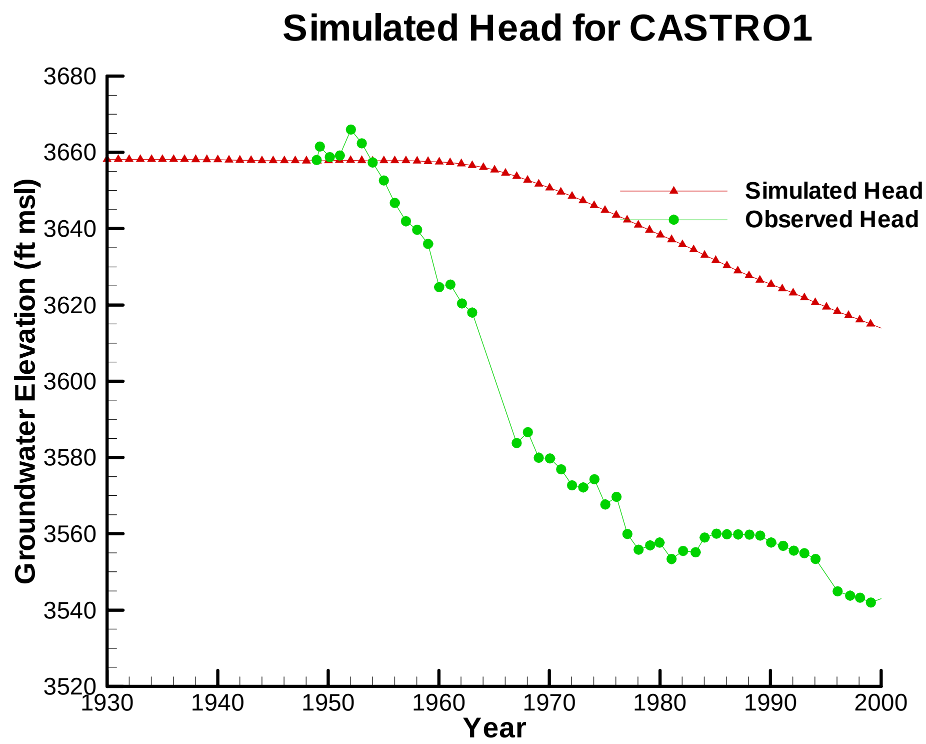
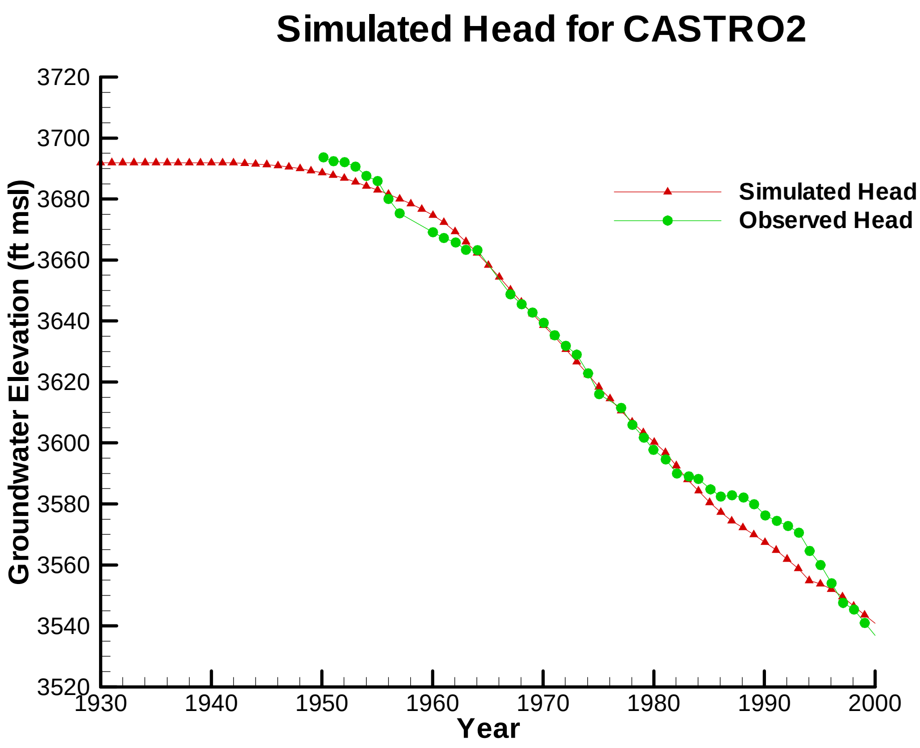
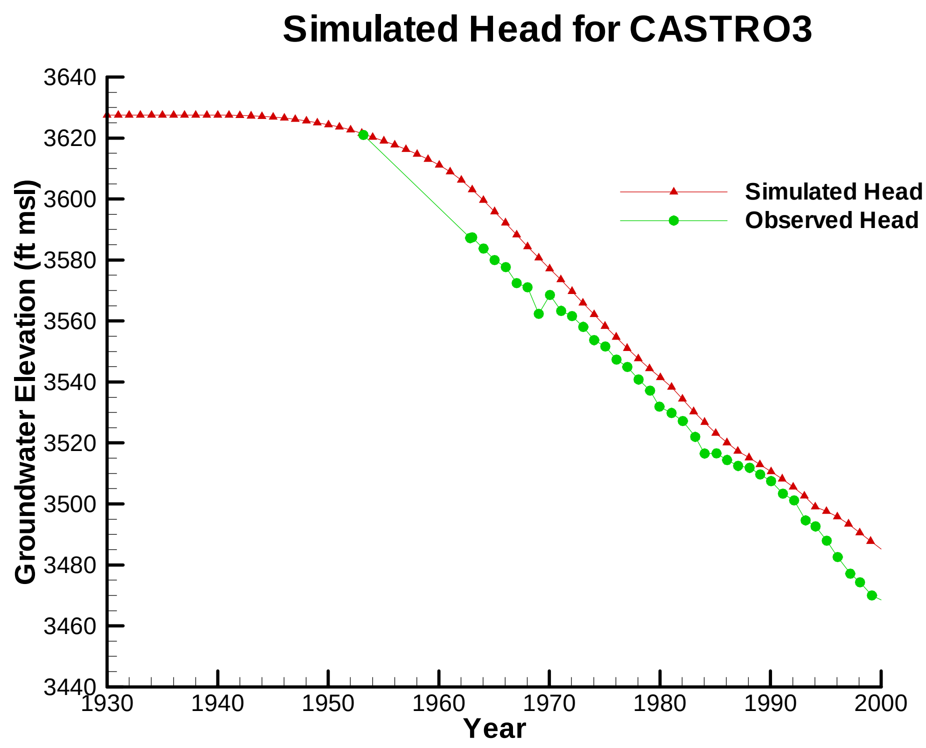
1960
1970
1980
1990
2000


Simulated Head for CASTRO1
Groundwater Elevation (ft msl)
Year
Simulated Head
Observed Head
3520
3540
3560
3580
3600
3620
3640
3660
3680
1930
1940
1950
1960
1970
1980
1990
2000


Simulated Head for CASTRO2
Groundwater Elevation (ft msl)
Year
Simulated Head
Observed Head
3520
3540
3560
3580
3600
3620
3640
3660
3680
3700
3720
1930
1940
1950
1960
1970
1980
1990
2000


Simulated Head for CASTRO3
Groundwater Elevation (ft msl)
Year
Simulated Head
Observed Head
3440
3460
3480
3500
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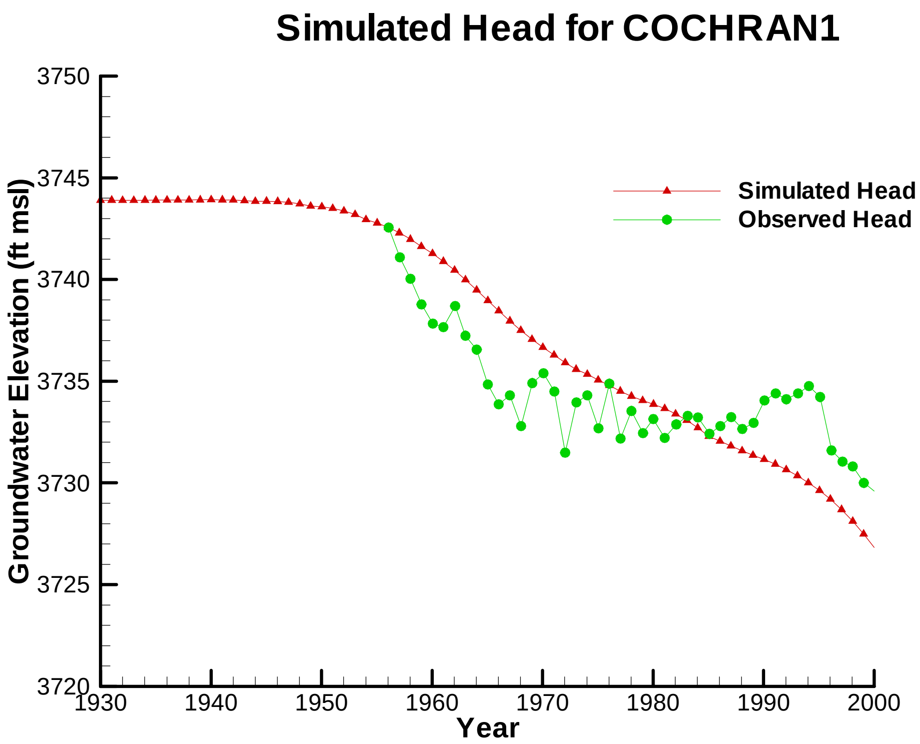
3540
3560
3580
3600
3620
3640
1930
1940
1950
1960
1970
1980
1990
2000


Simulated Head for COCHRAN1
Groundwater Elevation (ft msl)
Year
Simulated Head
Observed Head
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3725
3730
3735
3740
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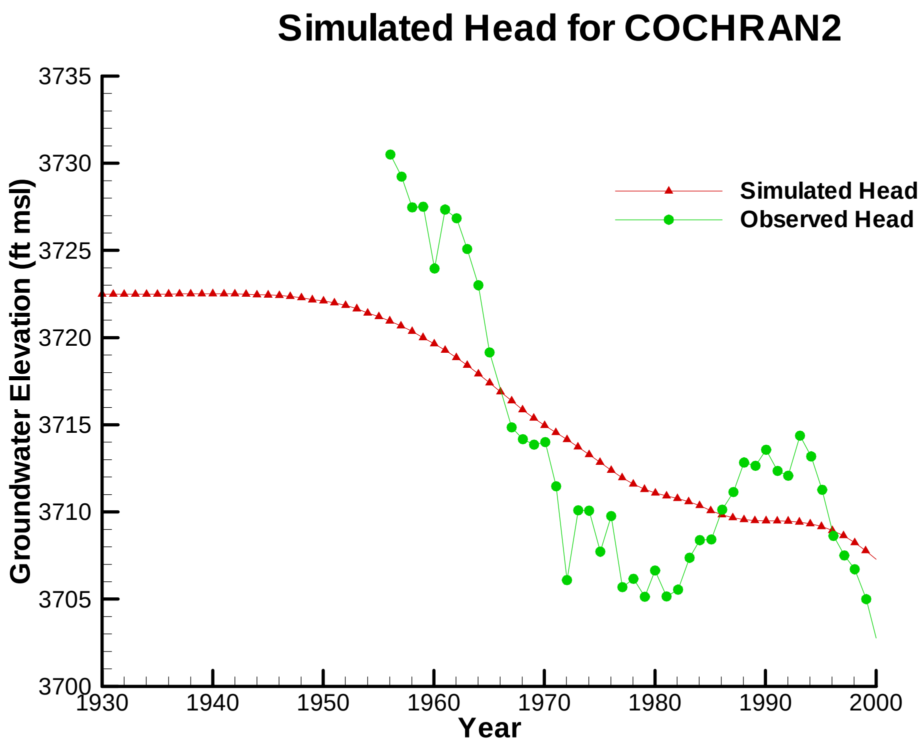
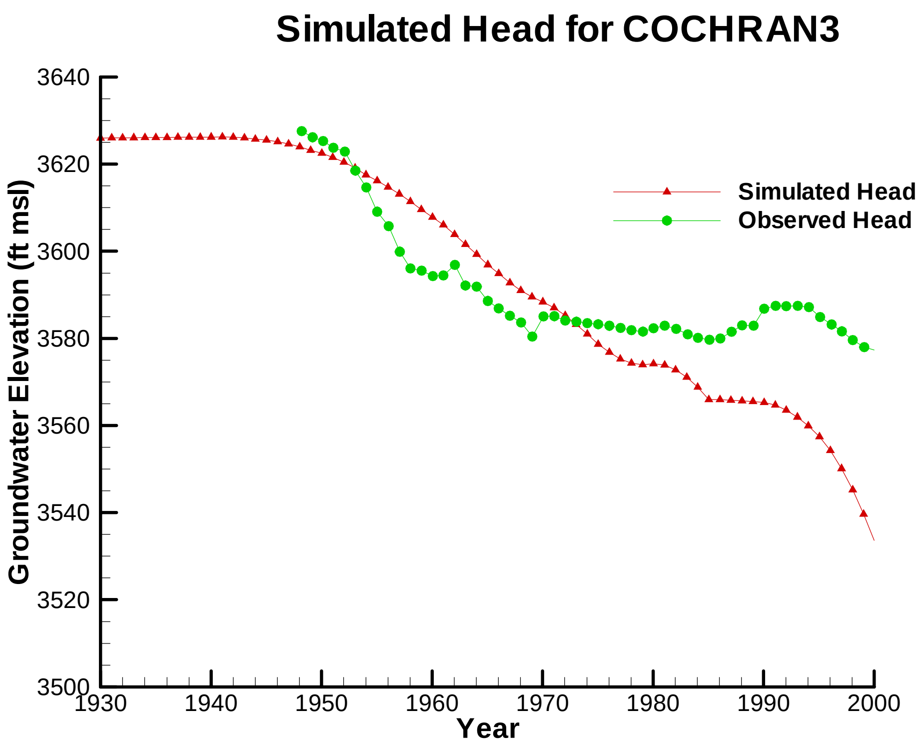
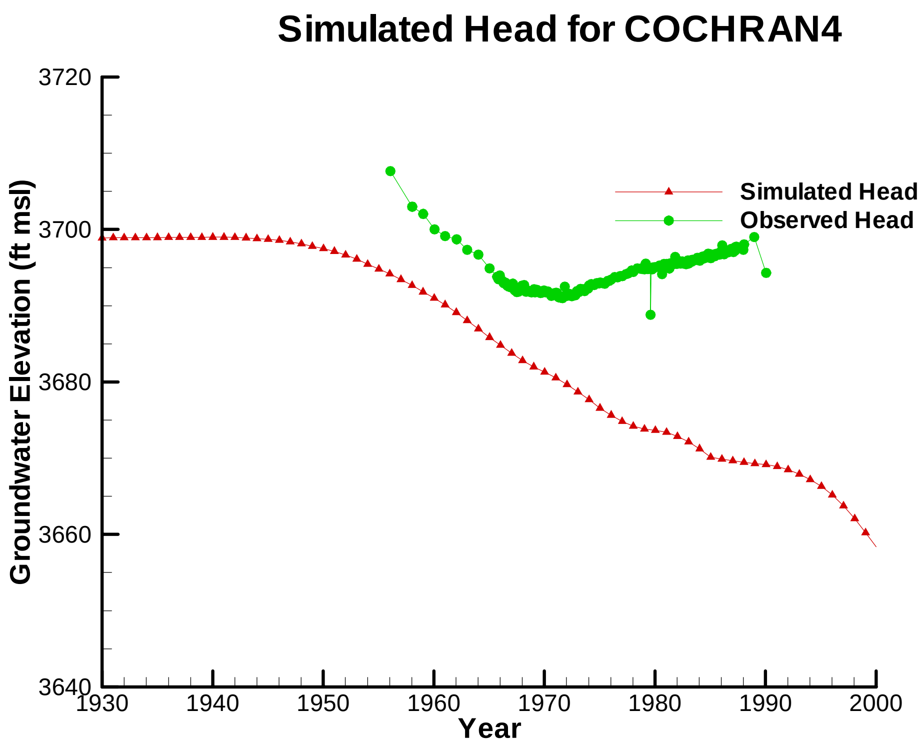
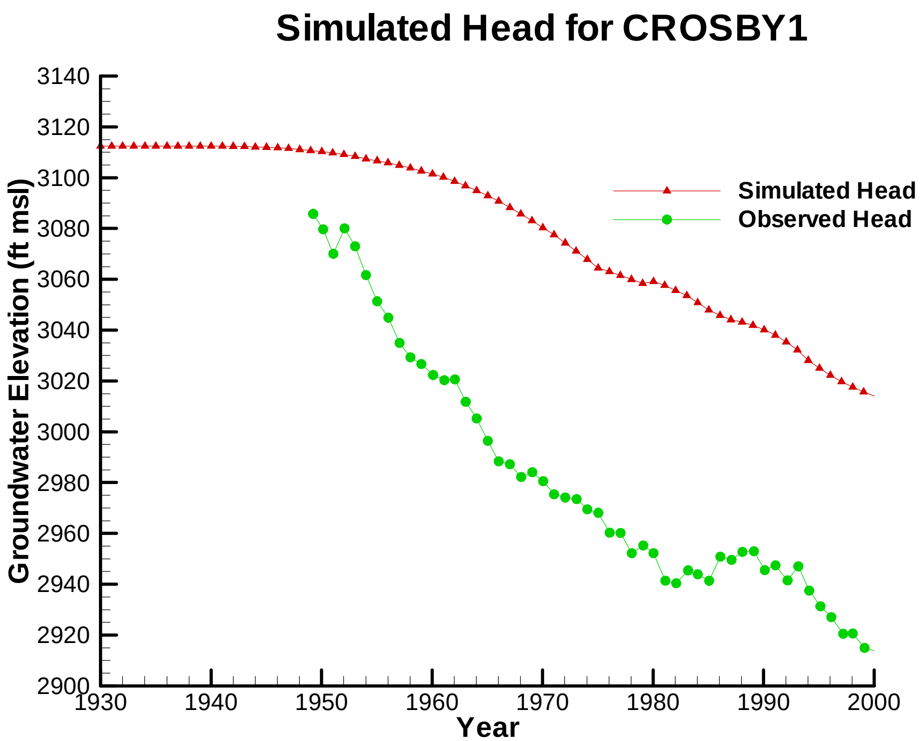
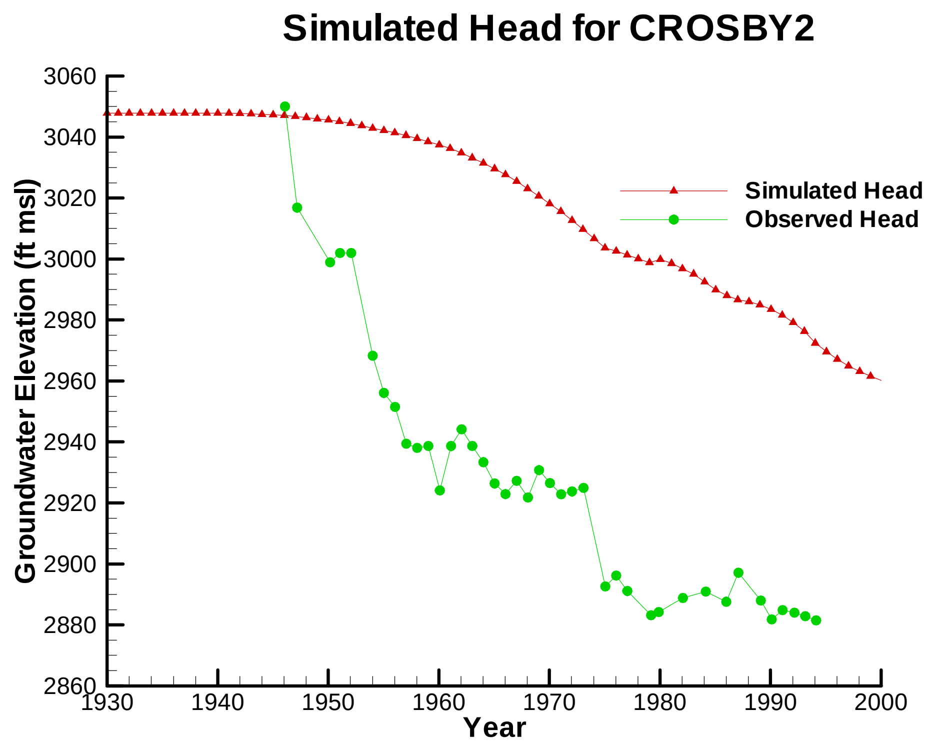
1960
1970
1980
1990
2000

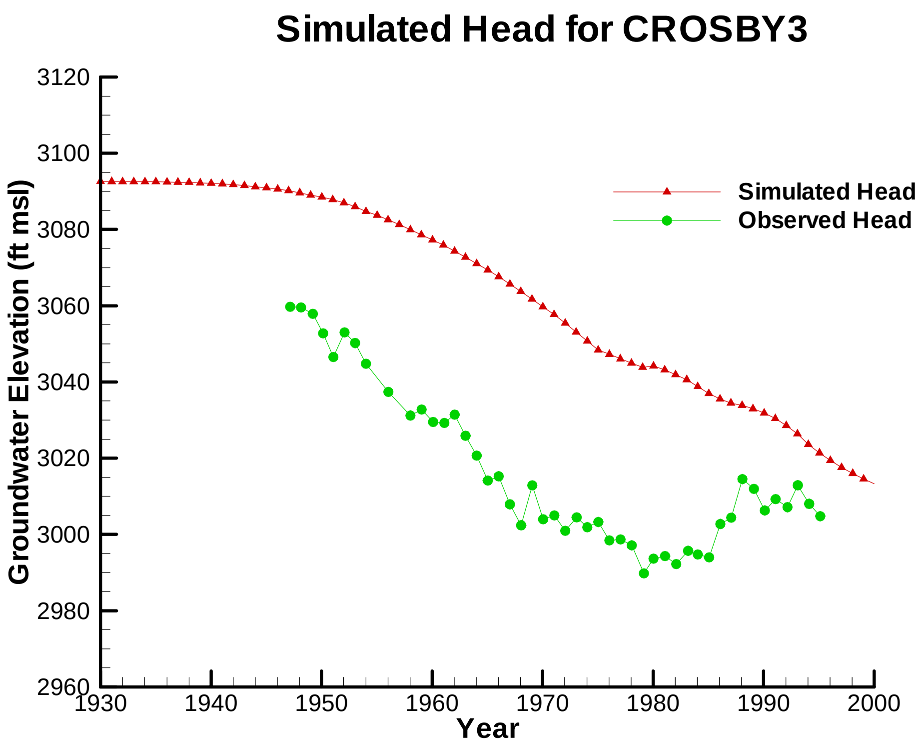

Simulated Head for COCHRAN2
Groundwater Elevation (ft msl)
Year
Simulated Head
Observed Head
3700
3705
3710
3715
3720
3725
3730
3735
1930
1940
1950
1960
1970
1980
1990
2000

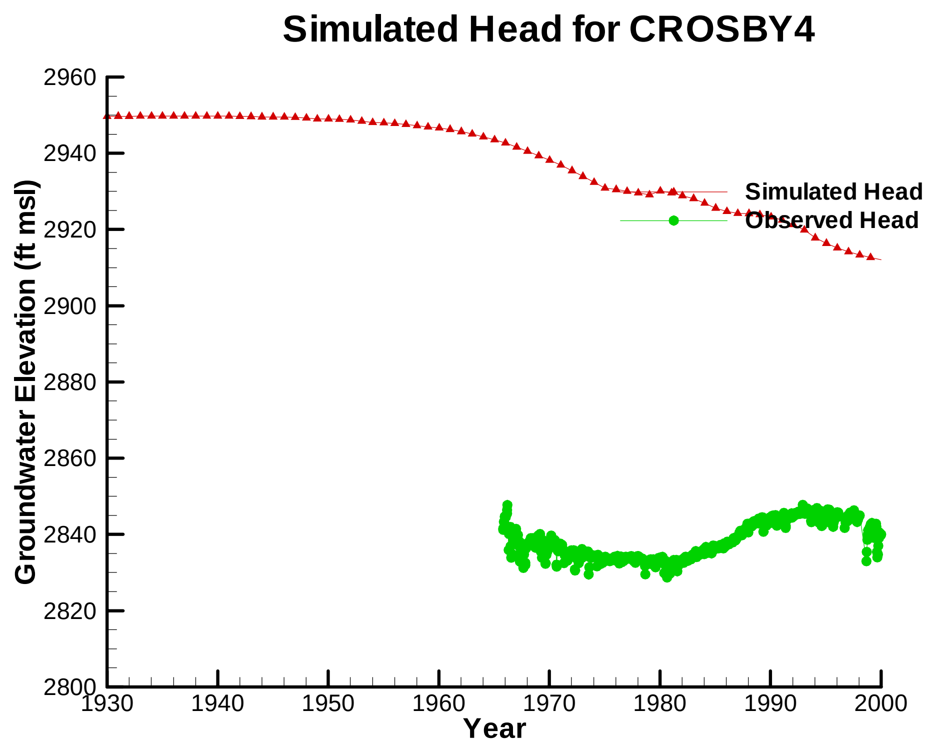

Simulated Head for COCHRAN3
Groundwater Elevation (ft msl)
Year
Simulated Head
Observed Head
3500
3520
3540
3560
3580
3600
3620
3640
1930
1940
1950
1960
1970
1980
1990
2000

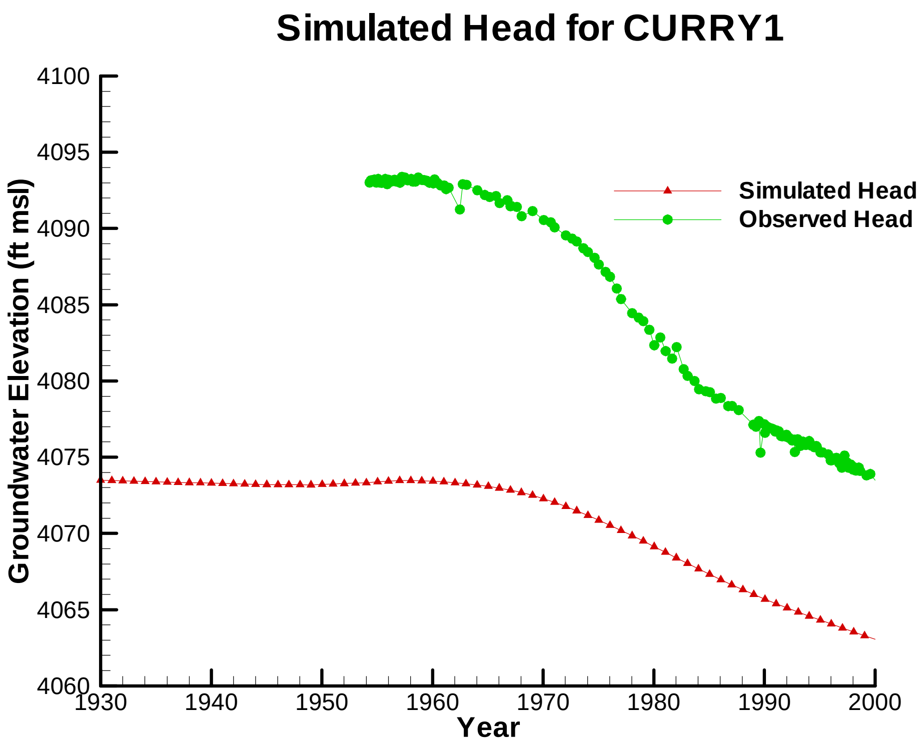

Simulated Head for COCHRAN4
Groundwater Elevation (ft msl)
Year
Simulated Head
Observed Head
3640
3660
3680
3700
3720
1930
1940
1950
1960
1970
1980
1990
2000

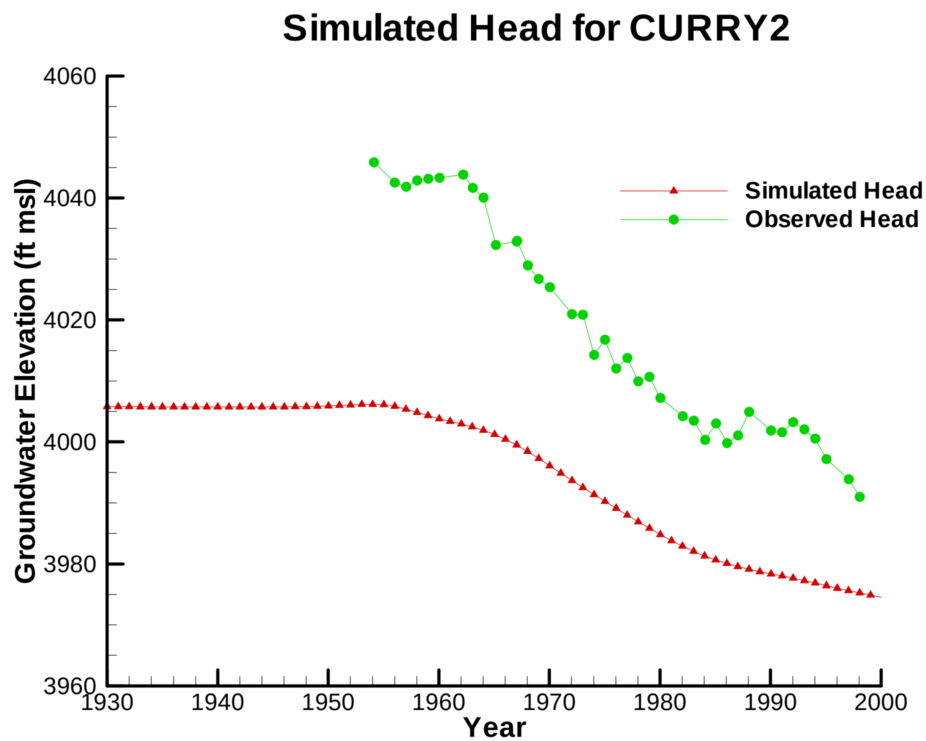

Simulated Head for CROSBY1
Groundwater Elevation (ft msl)
Year
Simulated Head
Observed Head

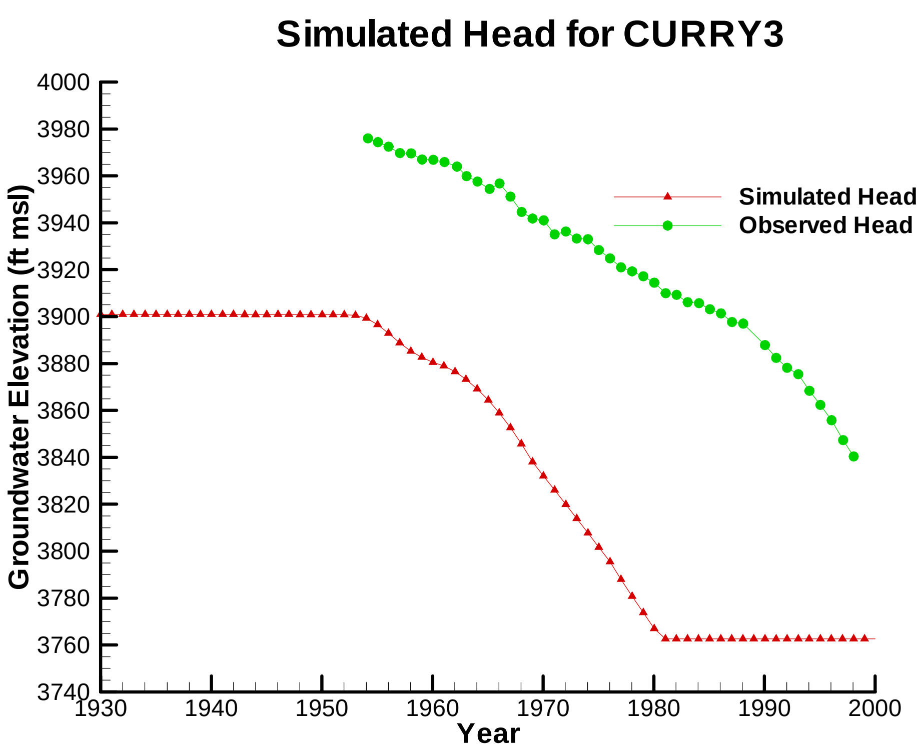

Simulated Head for CROSBY2
Groundwater Elevation (ft msl)
Year
Simulated Head
Observed Head

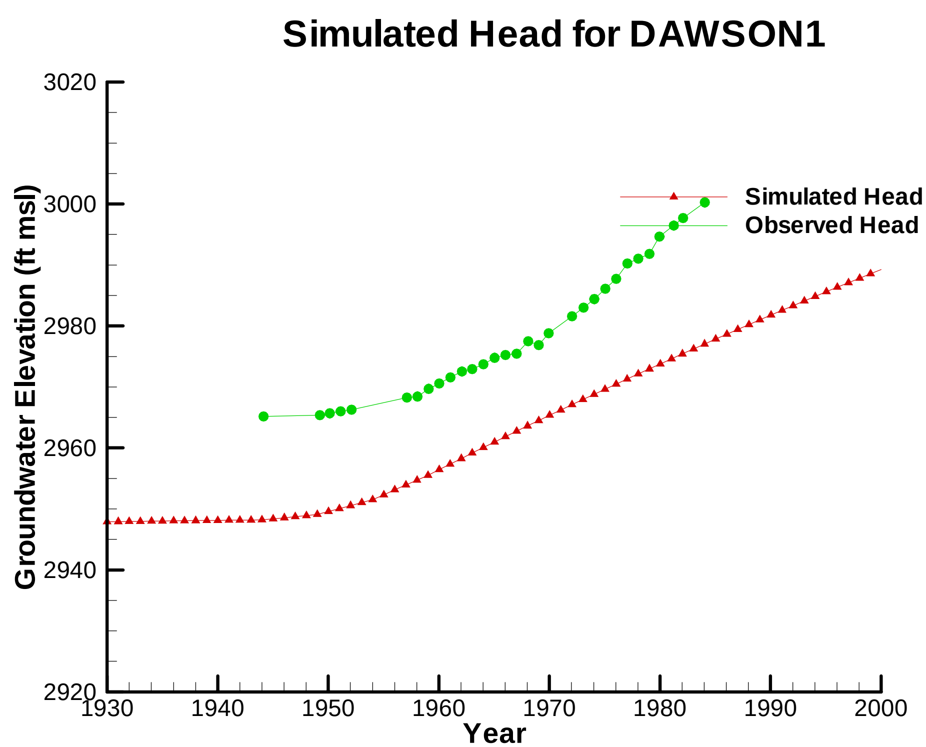

Simulated Head for CROSBY3
Groundwater Elevation (ft msl)
Year
Simulated Head
Observed Head

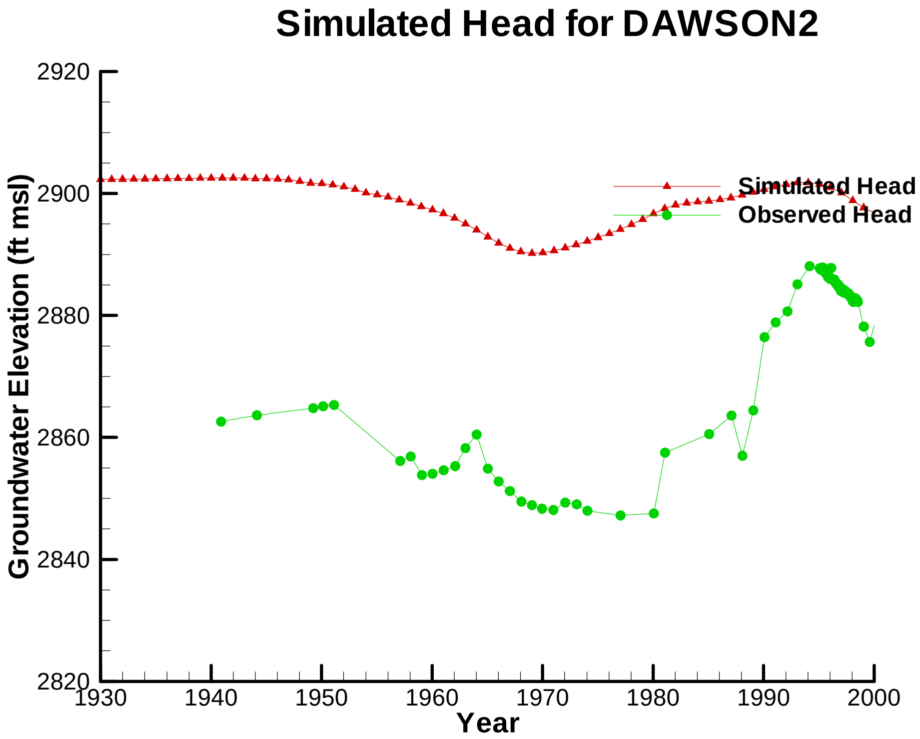

Simulated Head for CROSBY4
Groundwater Elevation (ft msl)
Year
Simulated Head
Observed Head

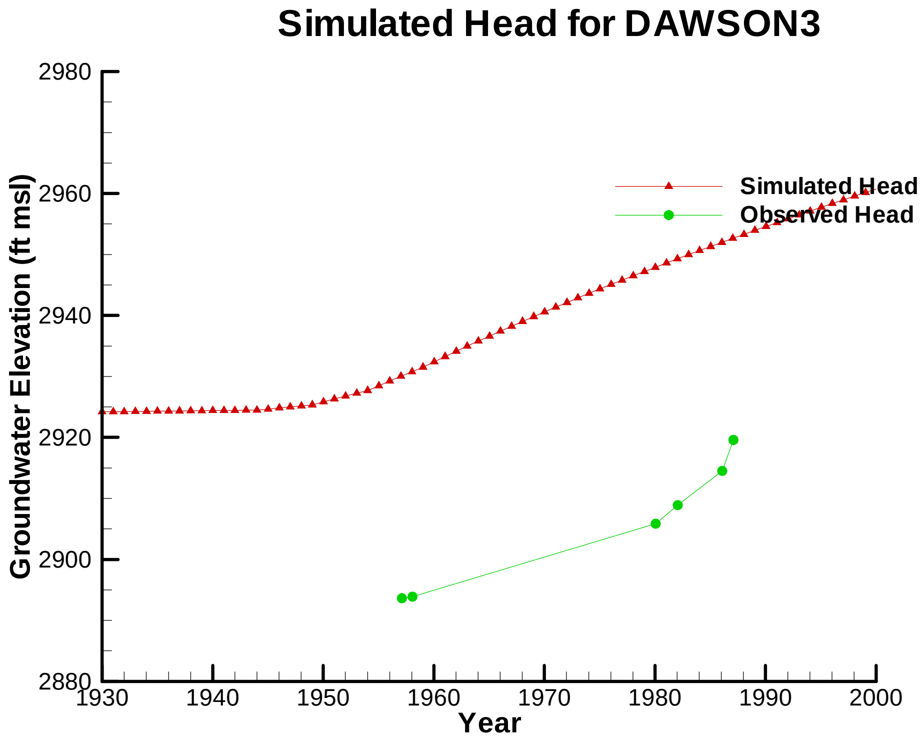

Simulated Head for CURRY1
Simulated Head
Observed Head
Groundwater Elevation (ft msl)
Year
4100
4095
4090
4085
4080
4075
4070
4065
4060
1930
1940
1950
1960
1970
1980
1990
2000

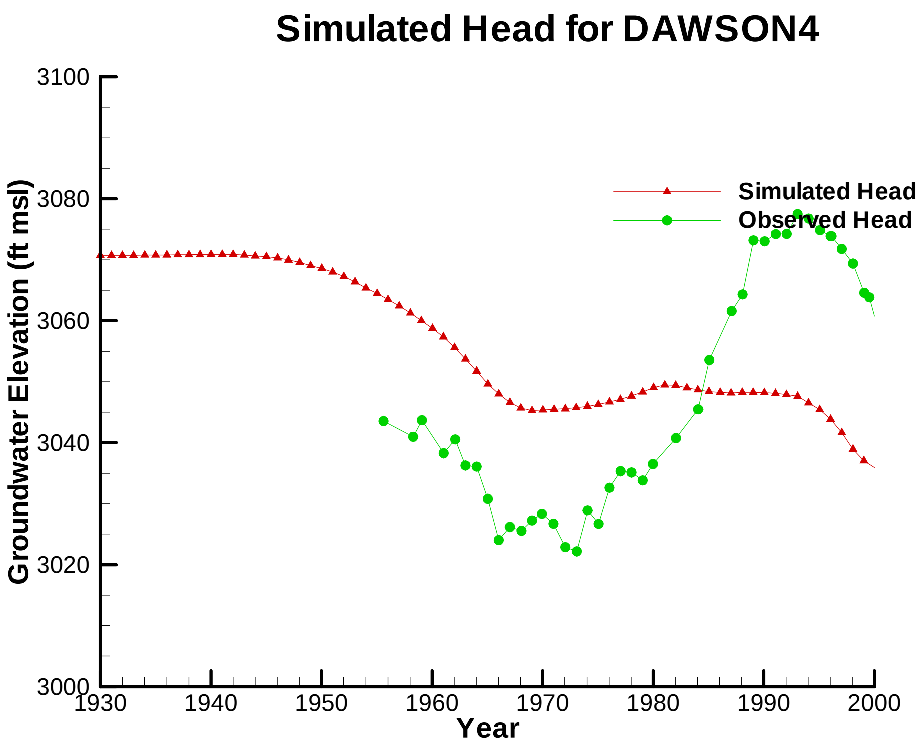

Simulated Head for CURRY2
Simulated Head
Observed Head
Groundwater Elevation (ft msl)
Year
4060
4040
4020
4000
3980
3960
1930
1940
1950
1960
1970
1980
1990
2000

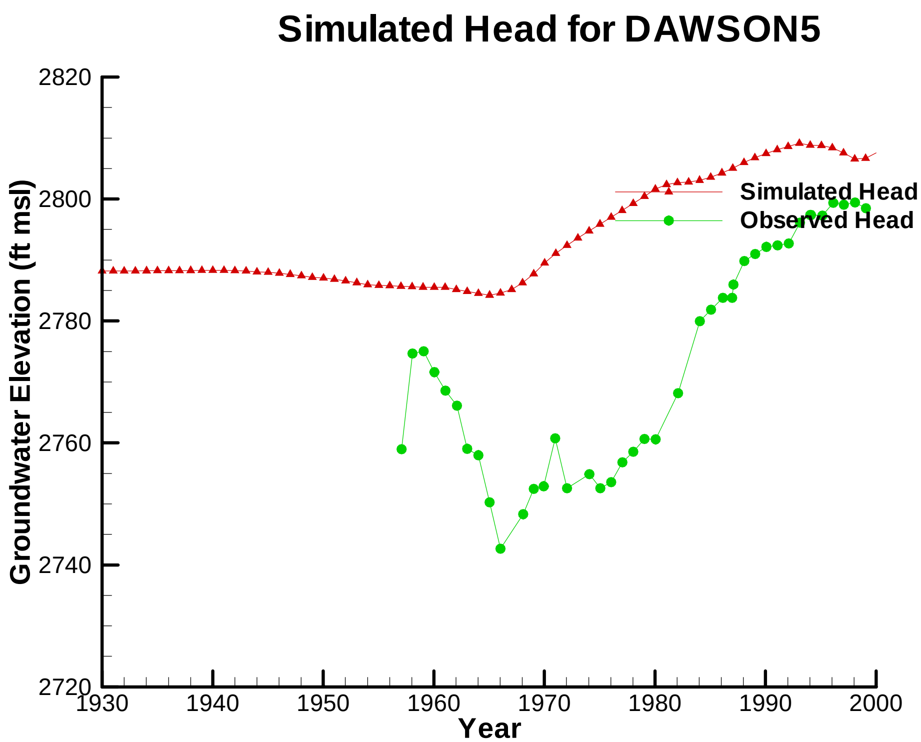

Simulated Head for CURRY3
Simulated Head
Observed Head
Groundwater Elevation (ft msl)
Year
4000
3980
3960
3940
3920
3900
3880
3860
3840
3820
3800
3780
3760
3740
1930
1940
1950
1960
1970
1980
1990
2000

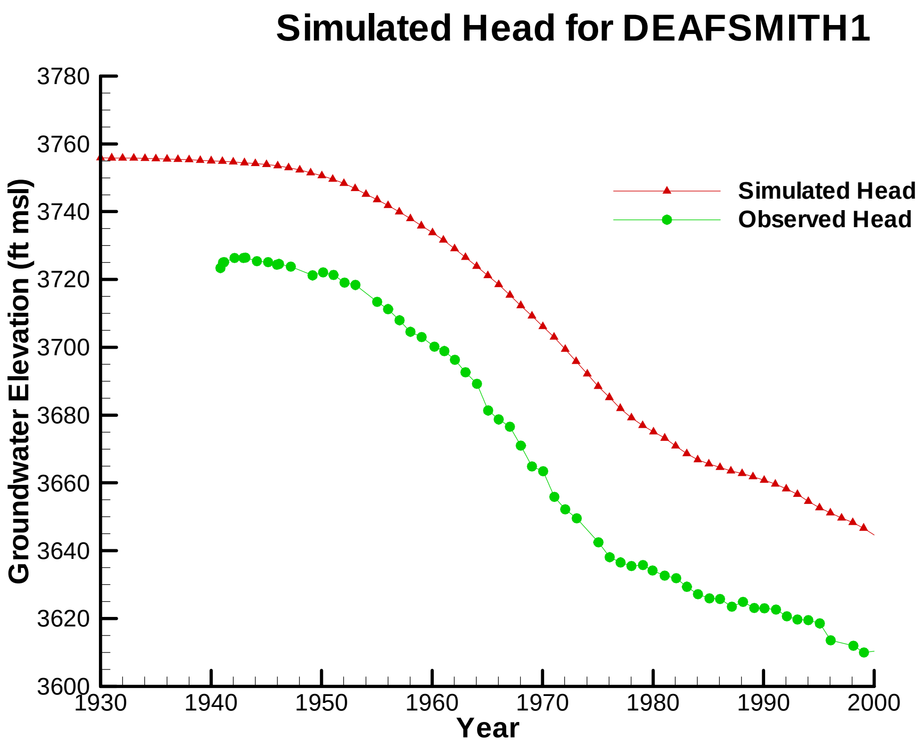

Simulated Head for DAWSON1
Simulated Head
Observed Head
Groundwater Elevation (ft msl)
Year
3020
3000
2980
2960
2940
2920
1930
1940
1950
1960
1970
1980
1990
2000

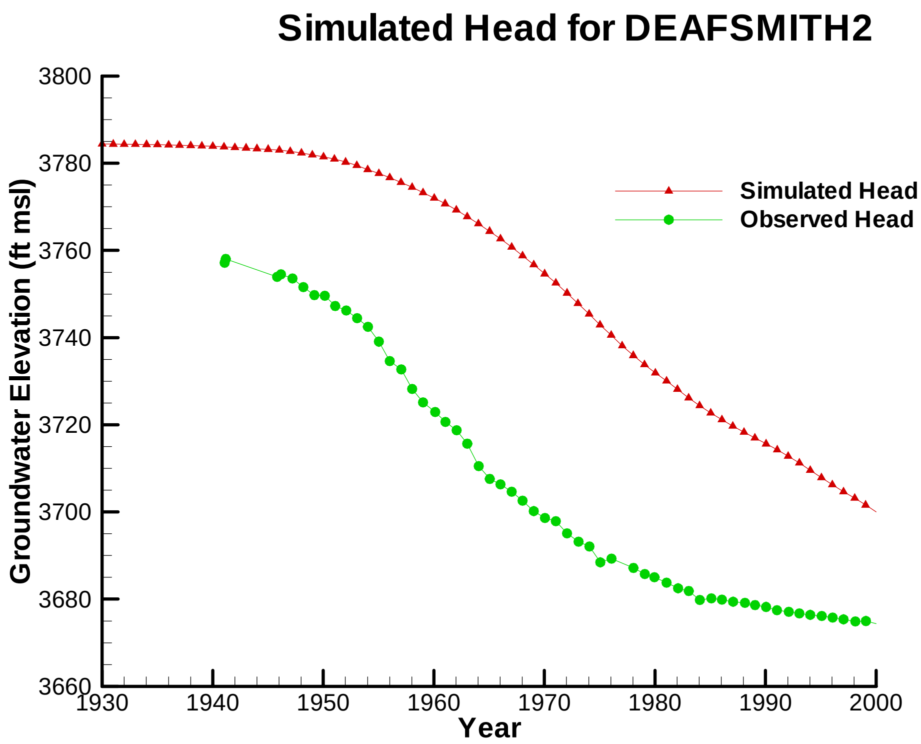

Simulated Head for DAWSON2
Simulated Head
Observed Head
Groundwater Elevation (ft msl)
Year
2820
2840
2860
2880
2900
2920
1930
1940
1950
1960
1970
1980
1990
2000

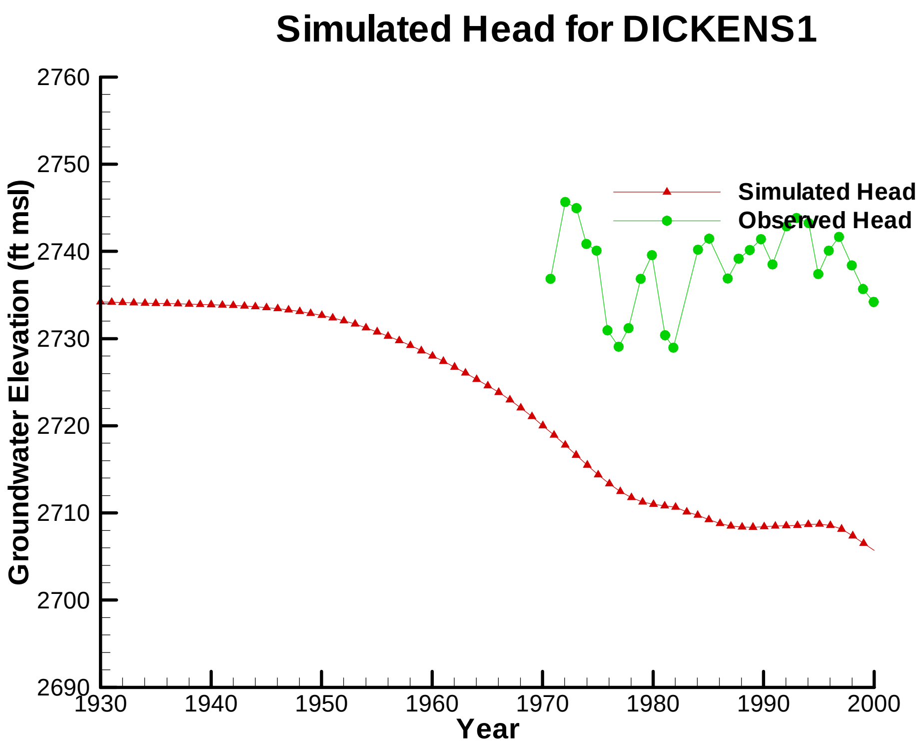

Simulated Head for DAWSON3
Simulated Head
Observed Head
Groundwater Elevation (ft msl)
Year
2880
2900
2920
2940
2960
2980
1930
1940
1950
1960
1970
1980
1990
2000

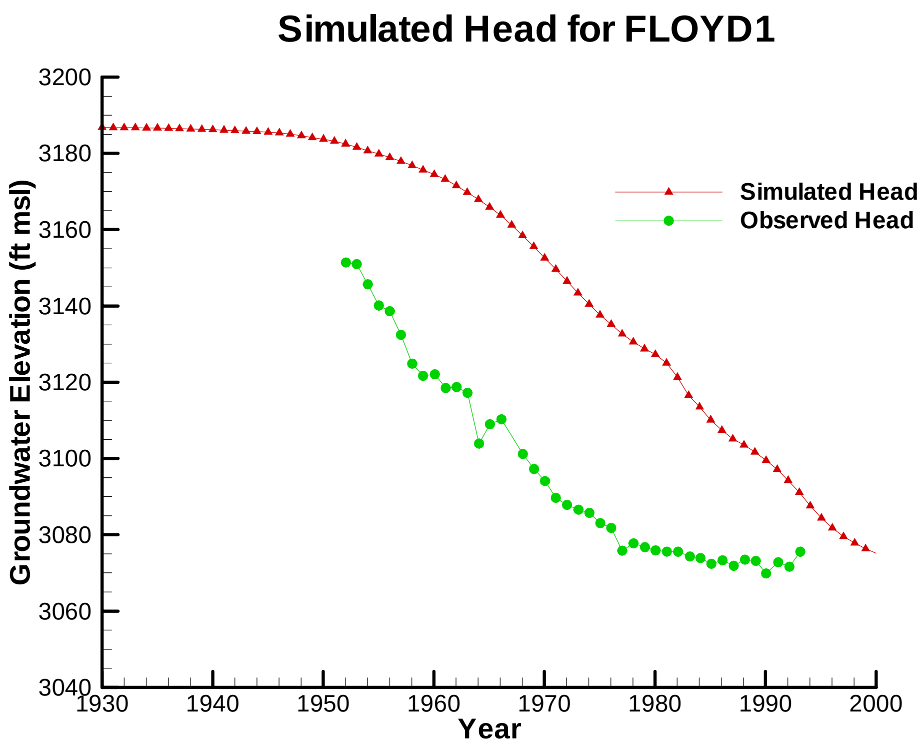

Simulated Head for DAWSON4
Simulated Head
Observed Head
Groundwater Elevation (ft msl)
Year
3000
3020
3040
3060
3080
3100
1930
1940
1950
1960
1970
1980
1990
2000

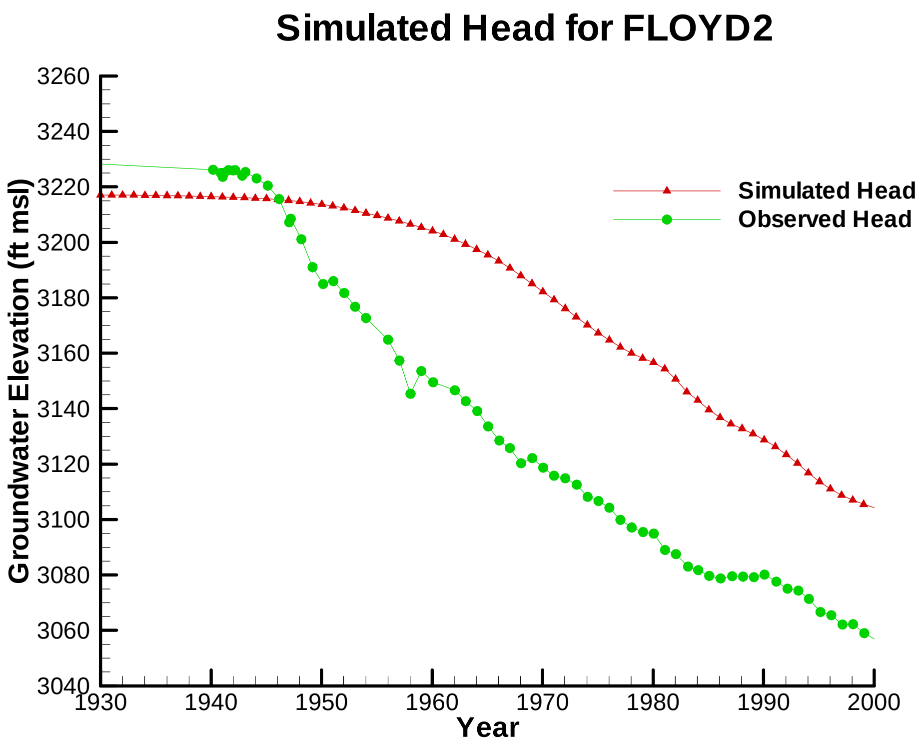

Simulated Head for DAWSON5
Simulated Head
Observed Head
Groundwater Elevation (ft msl)
Year
2720
2740
2760
2780
2800
2820
1930
1940
1950
1960
1970
1980
1990
2000

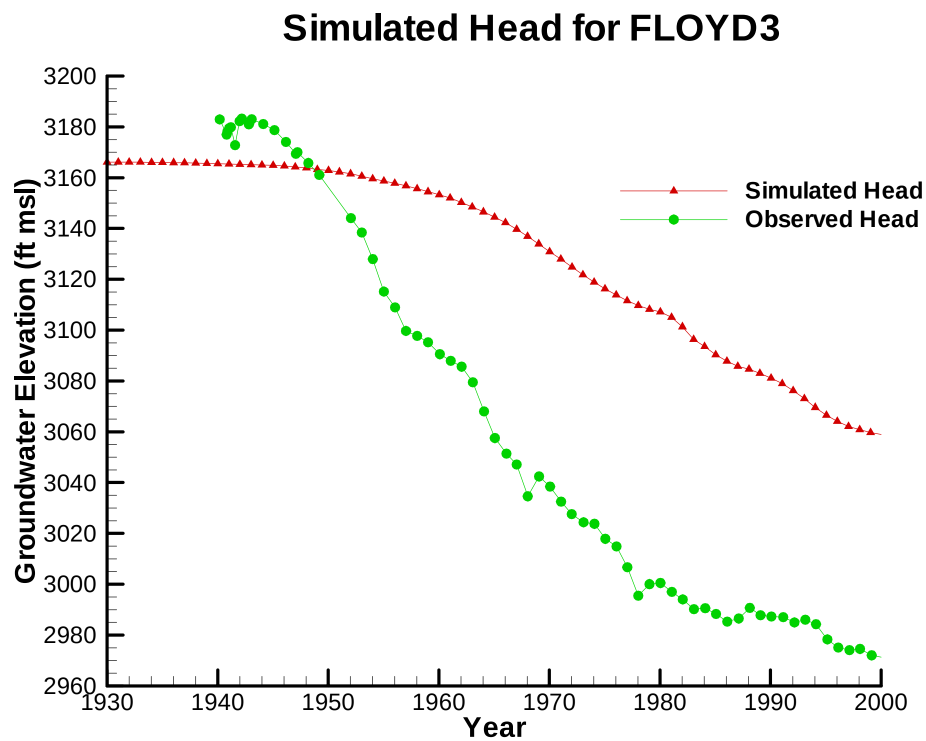

Simulated Head for DEAFSMITH1
Groundwater Elevation (ft msl)
Year
Simulated Head
Observed Head
3600
3620
3640
3660
3680
3700
3720
3740
3760
3780
1930
1940
1950
1960
1970
1980
1990
2000

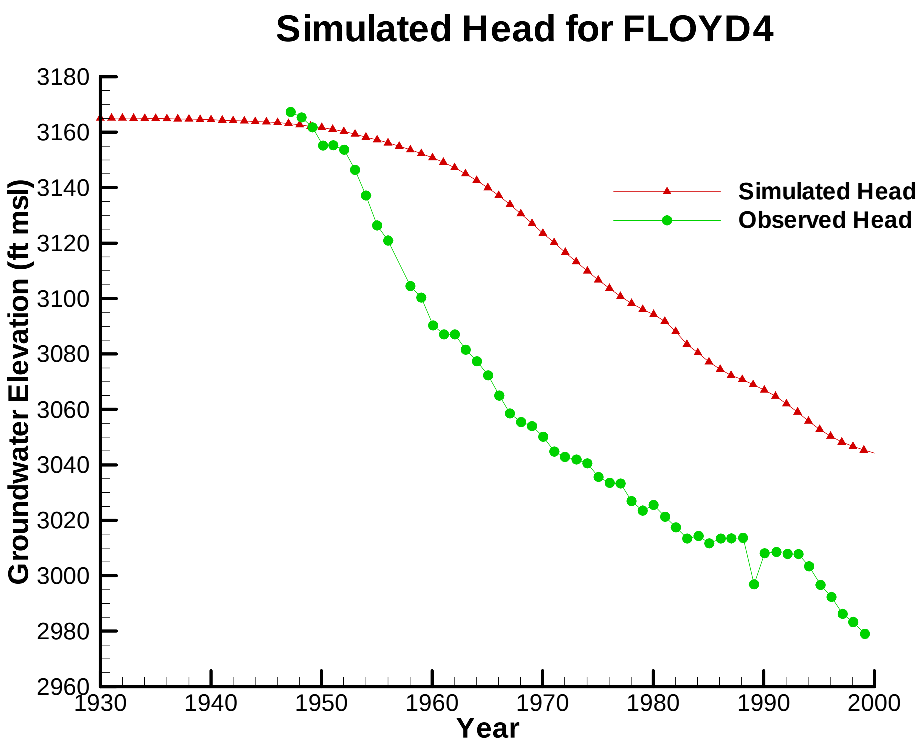

Simulated Head for DEAFSMITH2
Groundwater Elevation (ft msl)
Year
Simulated Head
Observed Head
3660
3680
3700
3720
3740
3760
3780
3800
1930
1940
1950
1960
1970
1980
1990
2000

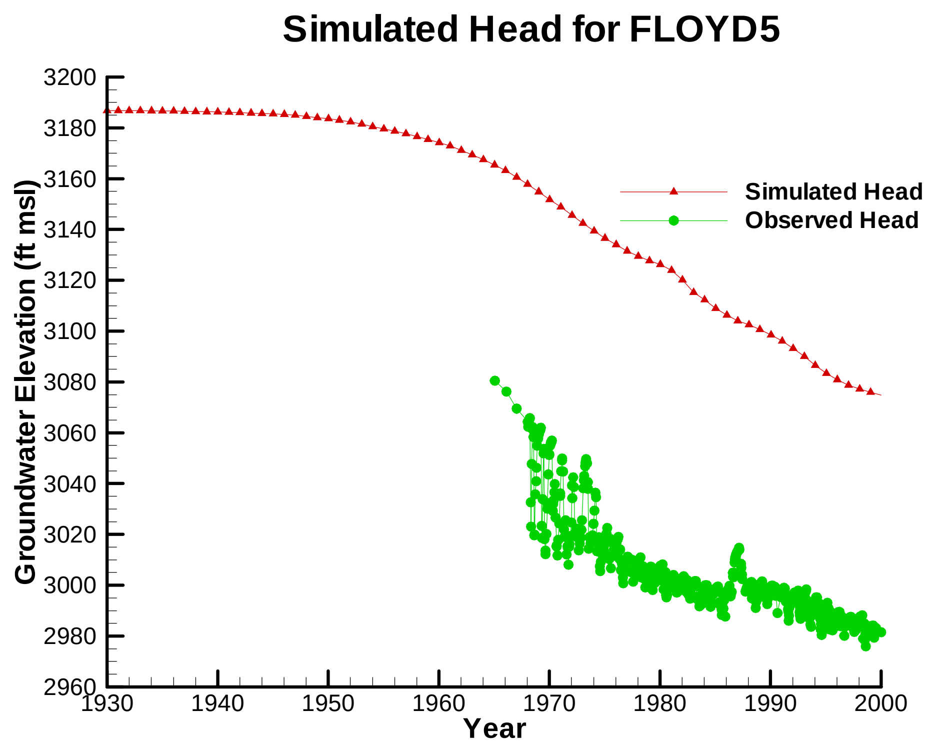

Simulated Head for DICKENS1
Groundwater Elevation (ft msl)
Year
Simulated Head
Observed Head
2690
2700
2710
2720
2730
2740
2750
2760
1930
1940
1950
1960
1970
1980
1990
2000


Simulated Head for FLOYD1
Groundwater Elevation (ft msl)
Year
Simulated Head
Observed Head
3040
3060
3080
3100
3120
3140
3160
3180
3200
1930
1940
1950
1960
1970
1980
1990
2000

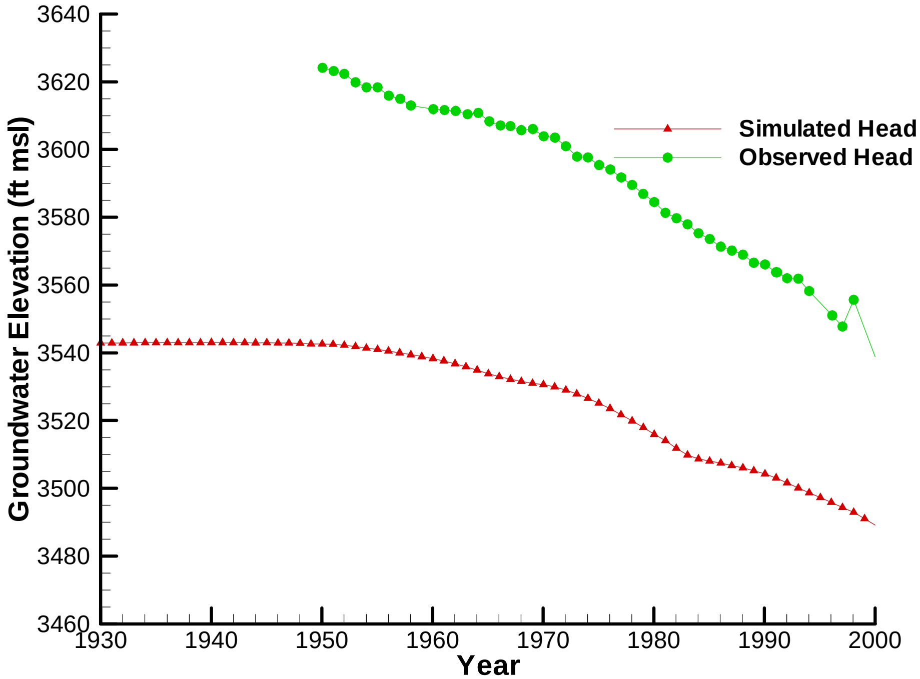

Simulated Head for FLOYD2
Simulated Head
Observed Head
Groundwater Elevation (ft msl)
Year
3260
3240
3220
3200
3180
3160
3140
3120
3100
3080
3060
3040
1930
1940
1950
1960
1970
1980
1990
2000


Simulated Head for FLOYD3
Simulated Head
Observed Head
Groundwater Elevation (ft msl)
Year
3200
3180
3160
3140
3120
3100
3080
3060
3040
3020
3000
2980
2960
1930
1940
1950
1960
1970
1980
1990
2000

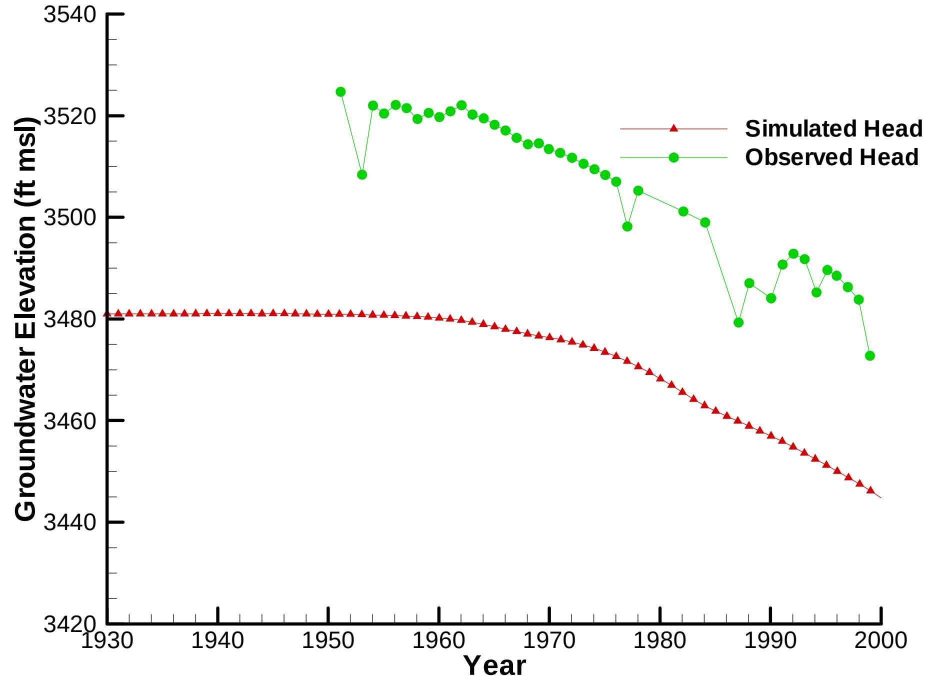

Simulated Head for FLOYD4
Simulated Head
Observed Head
Groundwater Elevation (ft msl)
Year
3180
3160
3140
3120
3100
3080
3060
3040
3020
3000
2980
2960
1930
1940
1950
1960
1970
1980
1990
2000


Simulated Head for FLOYD5
Simulated Head
Observed Head
Groundwater Elevation (ft msl)
Year
3200
3180
3160
3140
3120
3100
3080
3060
3040
3020
3000
2980
2960
1930
1940
1950
1960
1970
1980
1990
2000

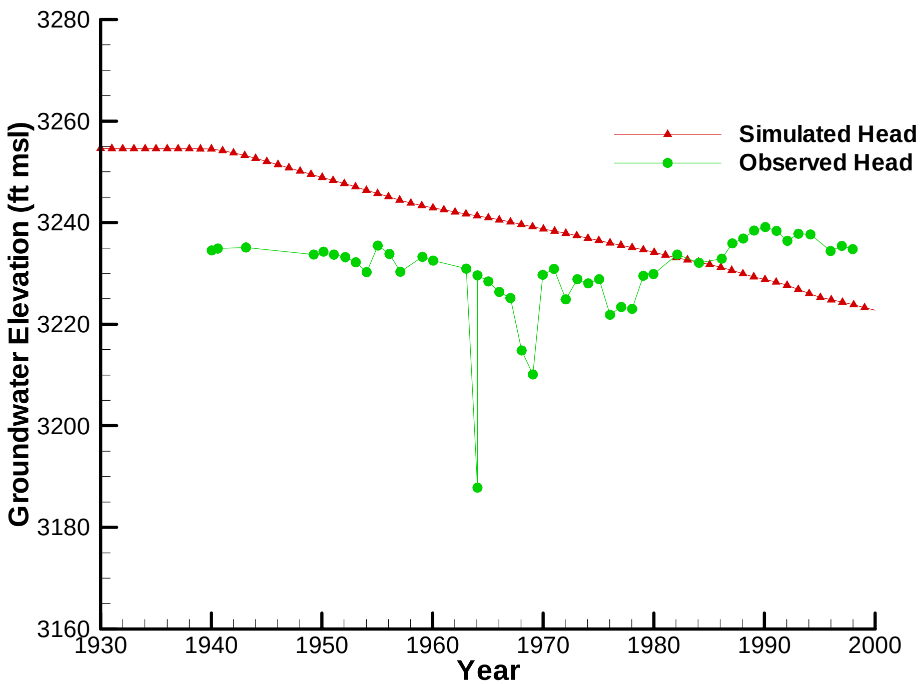
Simulated Head for GAINES1



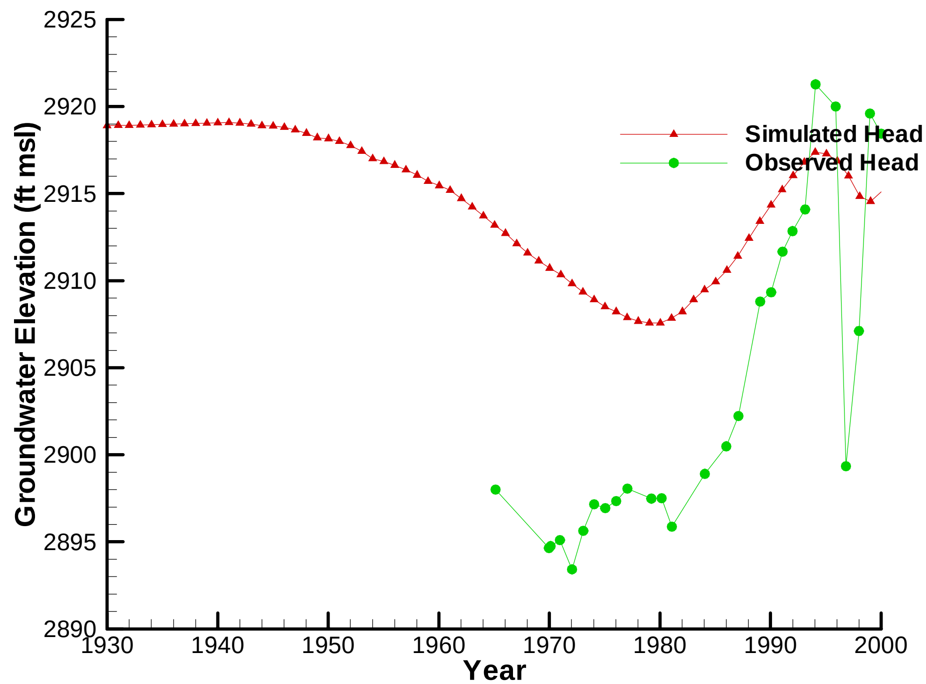
Simulated Head for GAINES2

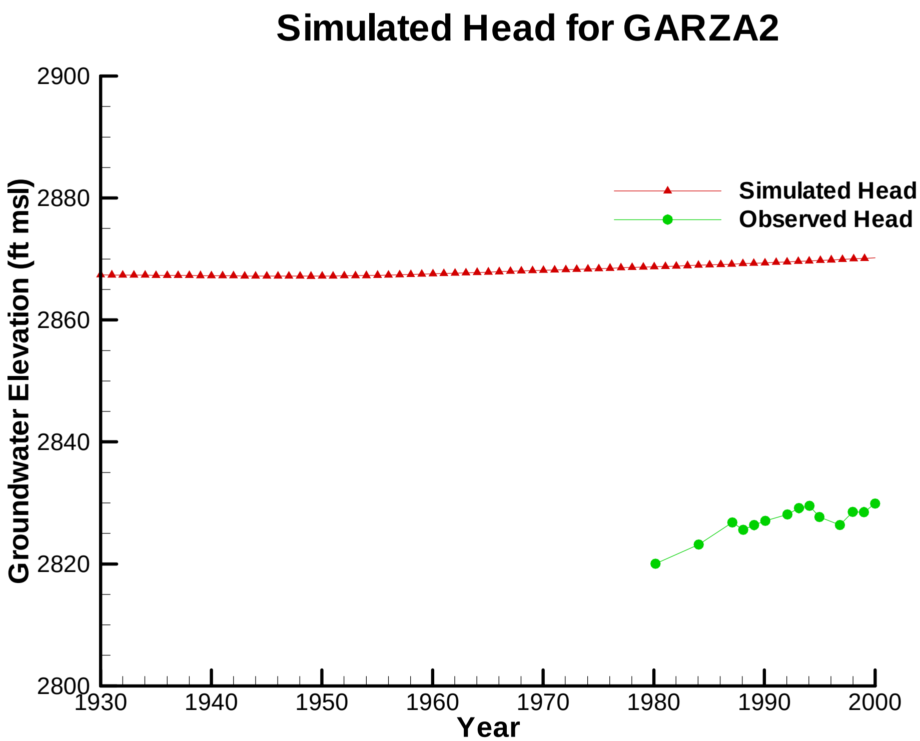


Simulated Head for GAINES3

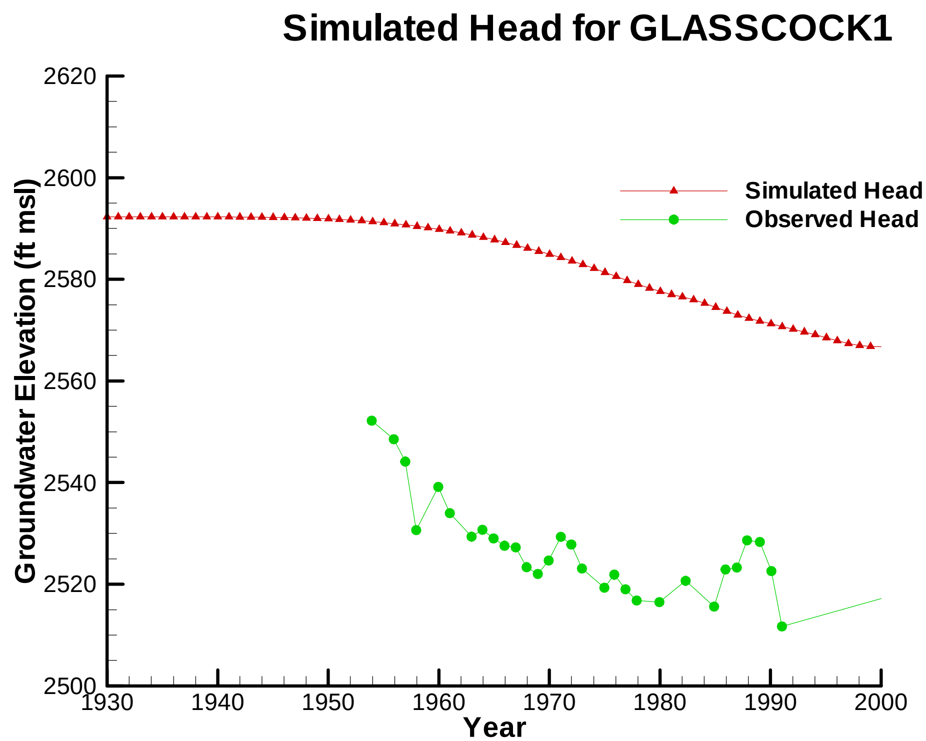


Simulated Head for GARZA1

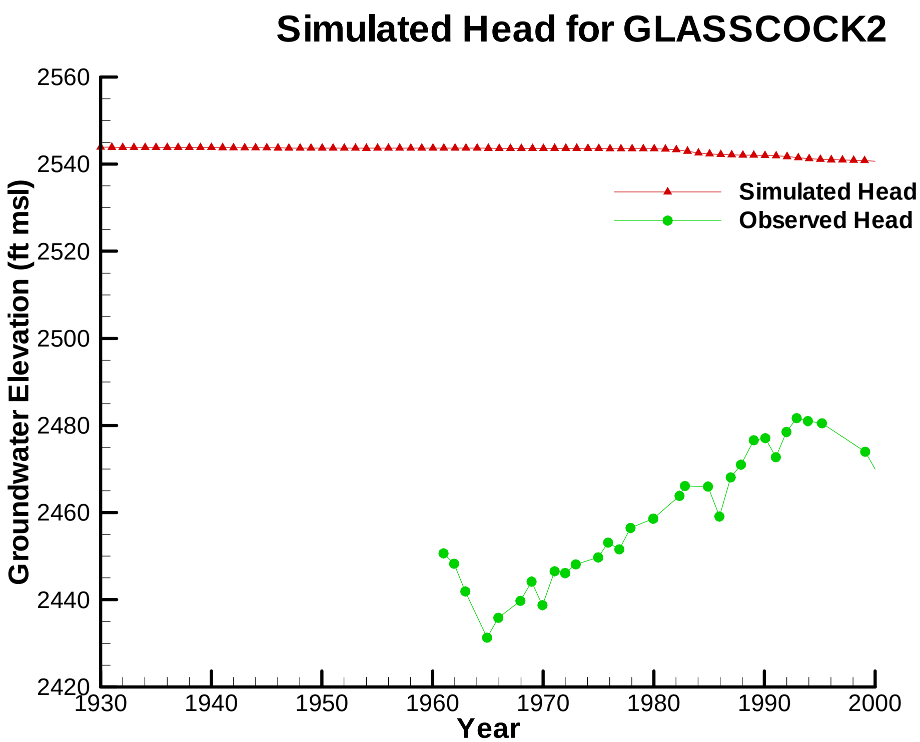




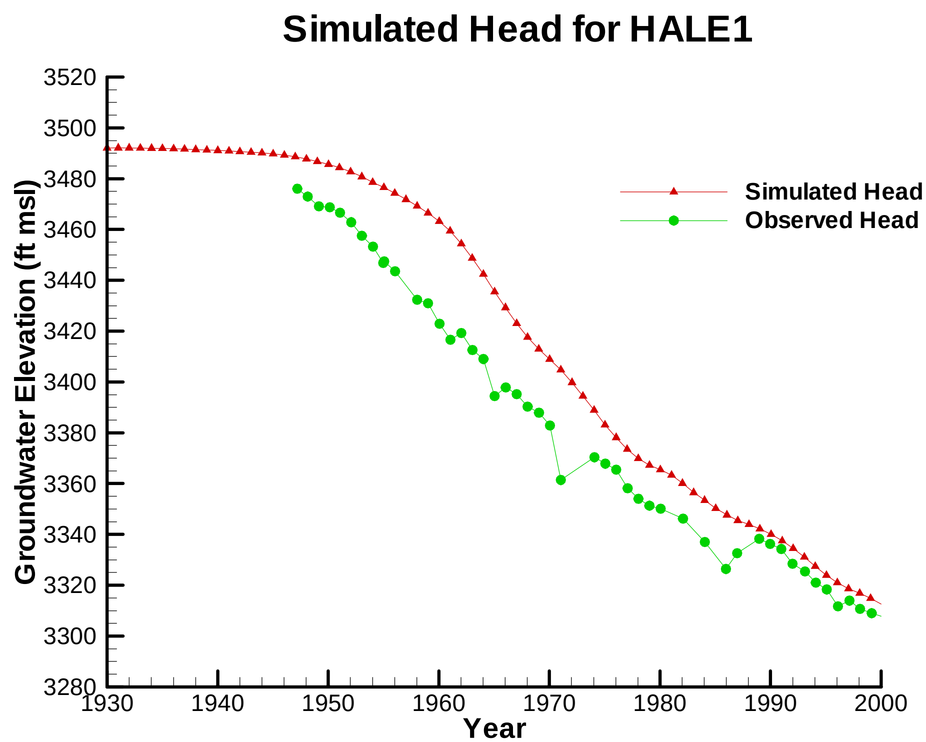
Simulated Head for GARZA2
Groundwater Elevation (ft msl)
Year
Simulated Head
Observed Head
2800
2820
2840
2860
2880
2900
1930
1940
1950
1960
1970
1980
1990
2000



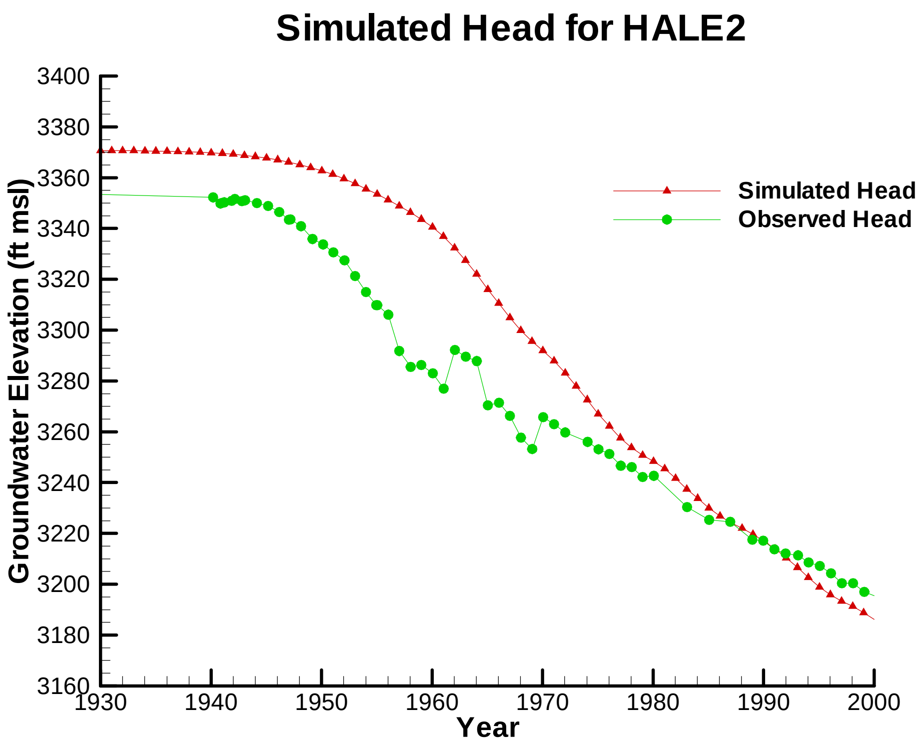
Simulated Head for GLASSCOCK1
Groundwater Elevation (ft msl)
Year
Simulated Head
Observed Head
2500
2520
2540
2560
2580
2600
2620
1930
1940
1950
1960
1970
1980
1990
2000



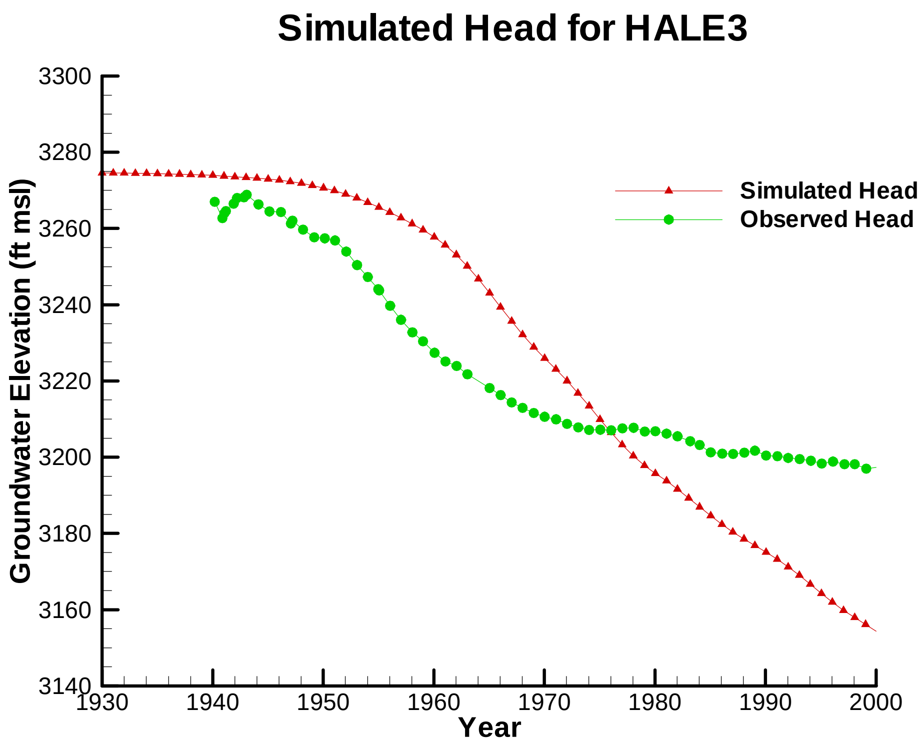
Simulated Head for GLASSCOCK2
Groundwater Elevation (ft msl)
Year
Simulated Head
Observed Head
2420
2440
2460
2480
2500
2520
2540
2560
1930
1940
1950
1960
1970
1980
1990
2000



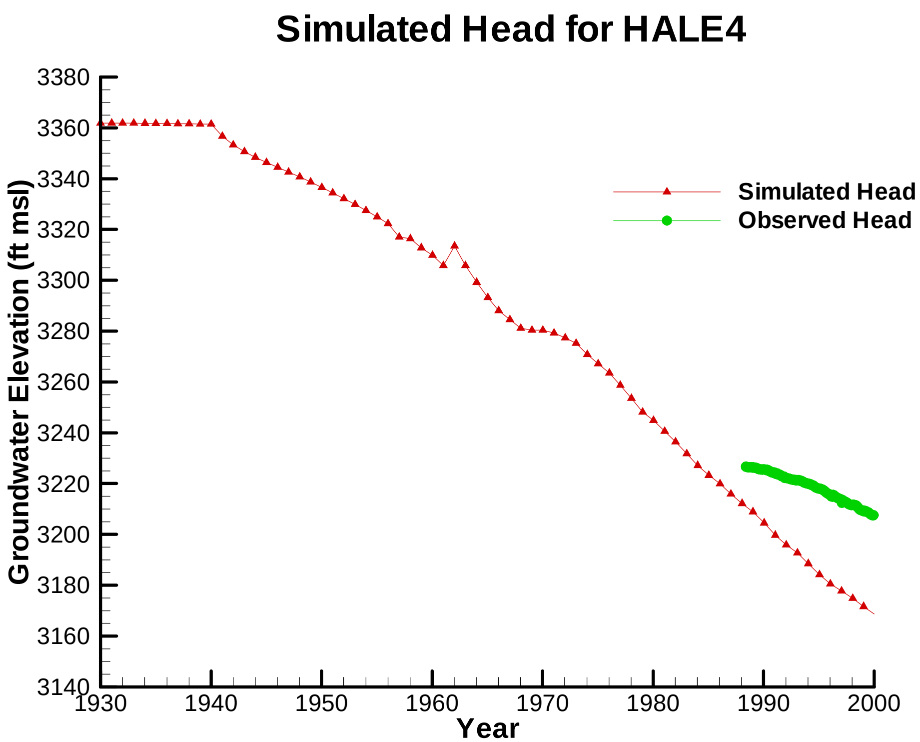
Simulated Head for HALE1
Groundwater Elevation (ft msl)
Year
Simulated Head
Observed Head
3280
3300
3320
3340
3360
3380
3400
3420
3440
3460
3480
3500
3520
1930
1940
1950
1960
1970
1980
1990
2000



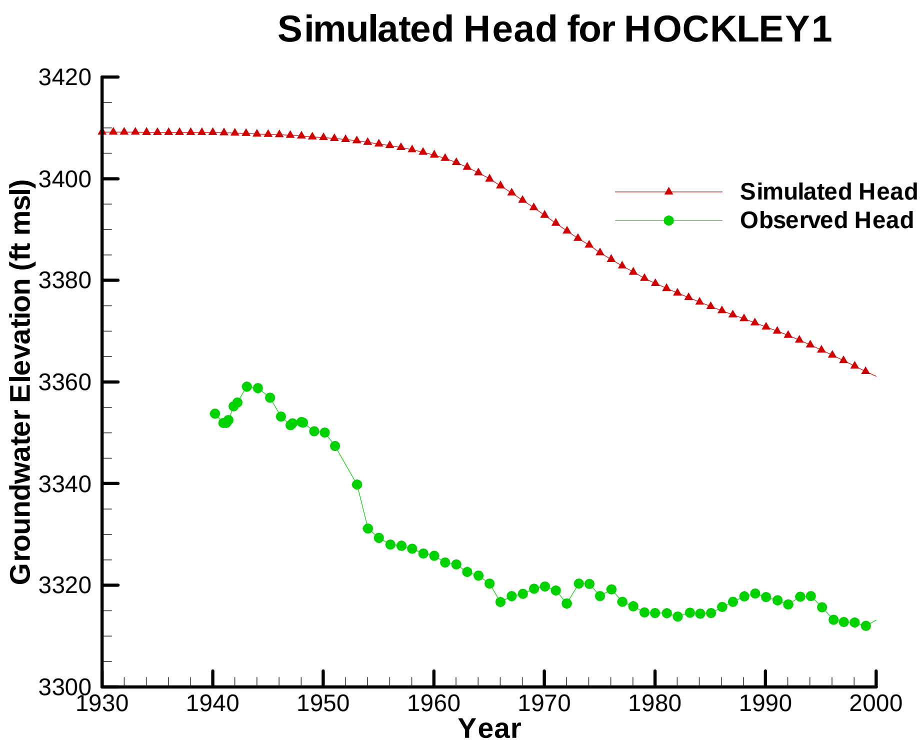
Simulated Head for HALE2
Simulated Head
Observed Head
Groundwater Elevation (ft msl)
Year
3400
3380
3360
3340
3320
3300
3280
3260
3240
3220
3200
3180
3160
1930
1940
1950
1960
1970
1980
1990
2000



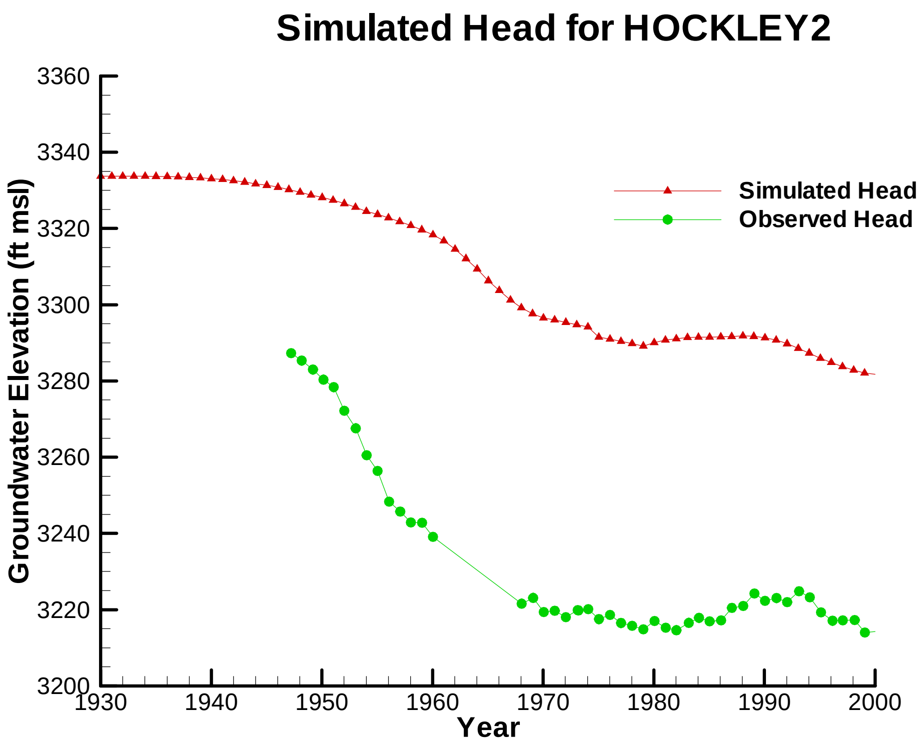
Simulated Head for HALE3
Simulated Head
Observed Head
Groundwater Elevation (ft msl)
Year
3300
3280
3260
3240
3220
3200
3180
3160
3140
1930
1940
1950
1960
1970
1980
1990
2000

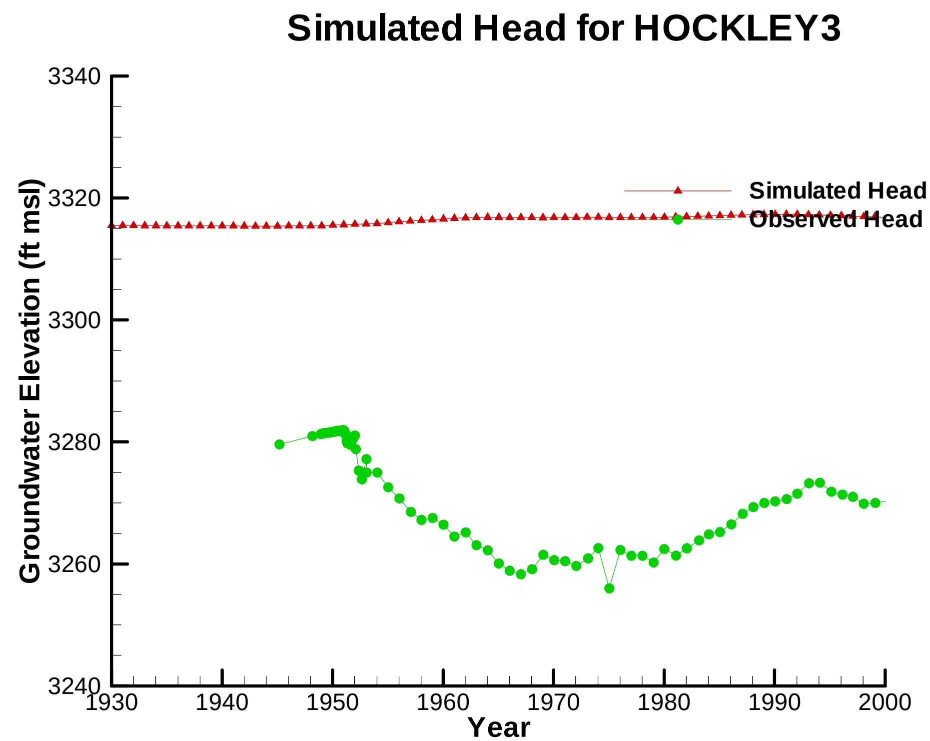


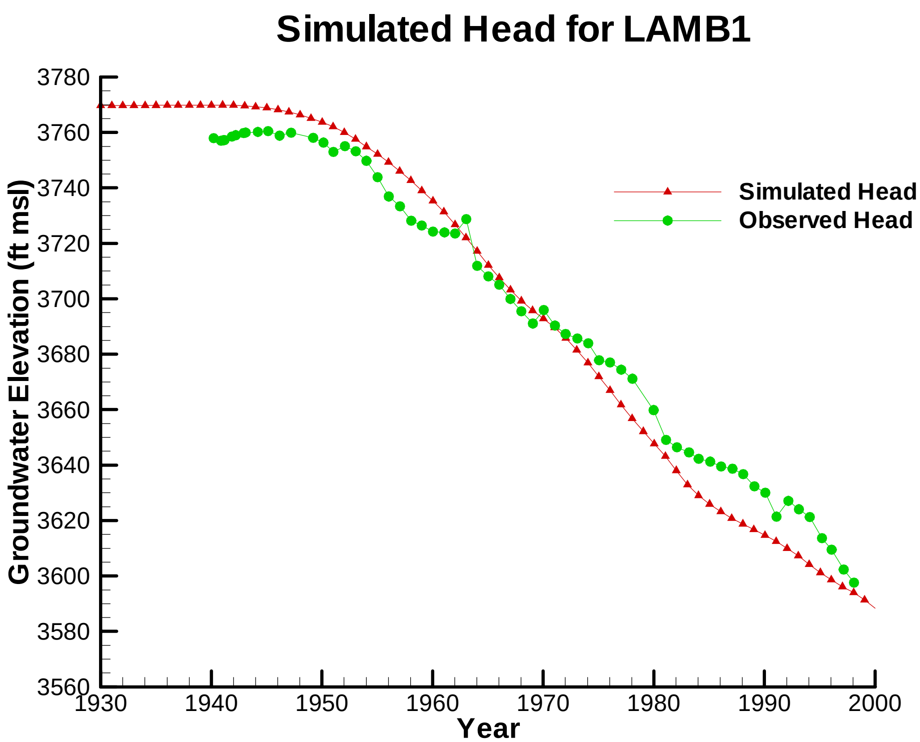
Simulated Head for HALE4
Simulated Head
Observed Head
Groundwater Elevation (ft msl)
Year
3380
3360
3340
3320
3300
3280
3260
3240
3220
3200
3180
3160
3140
1930
1940
1950
1960
1970
1980
1990
2000

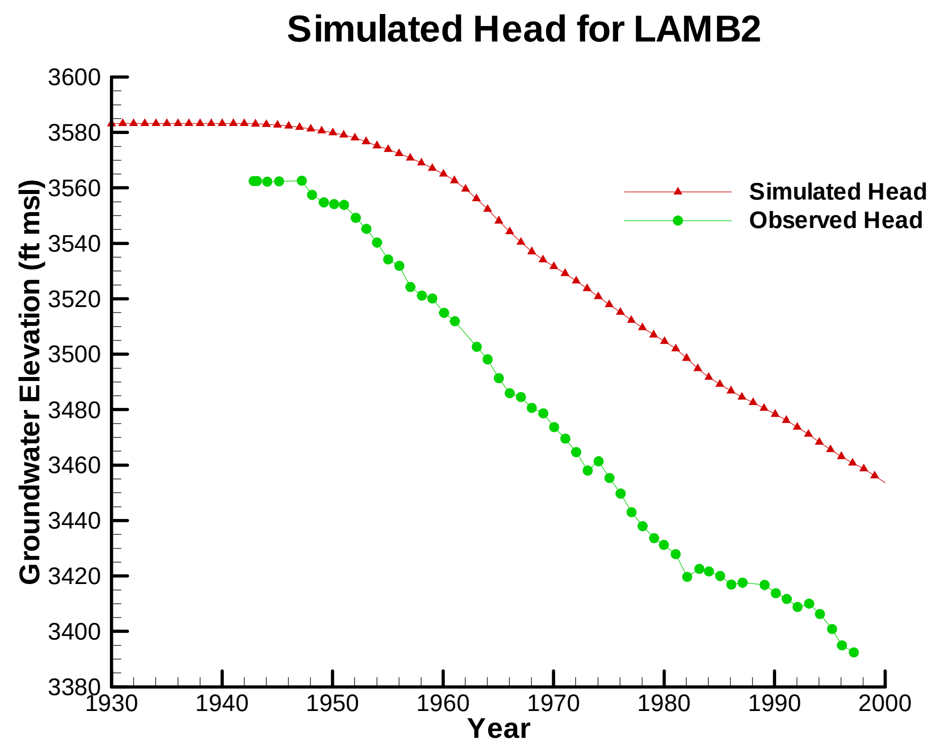


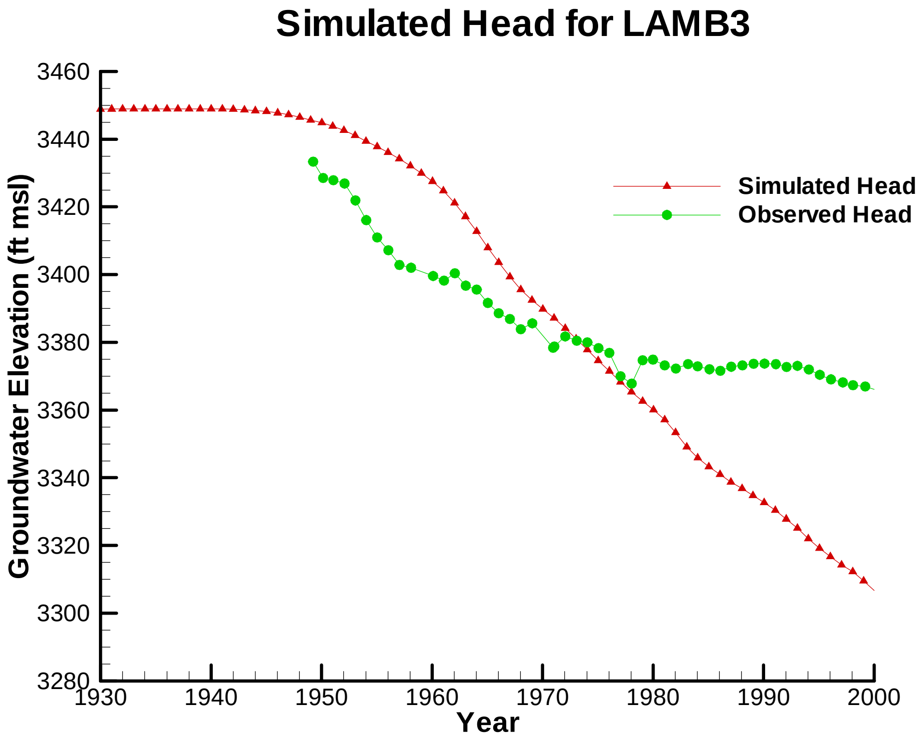
Simulated Head for HOCKLEY1
Simulated Head
Observed Head
Groundwater Elevation (ft msl)
Year
3420
3400
3380
3360
3340
3320
3300
1930
1940
1950
1960
1970
1980
1990
2000

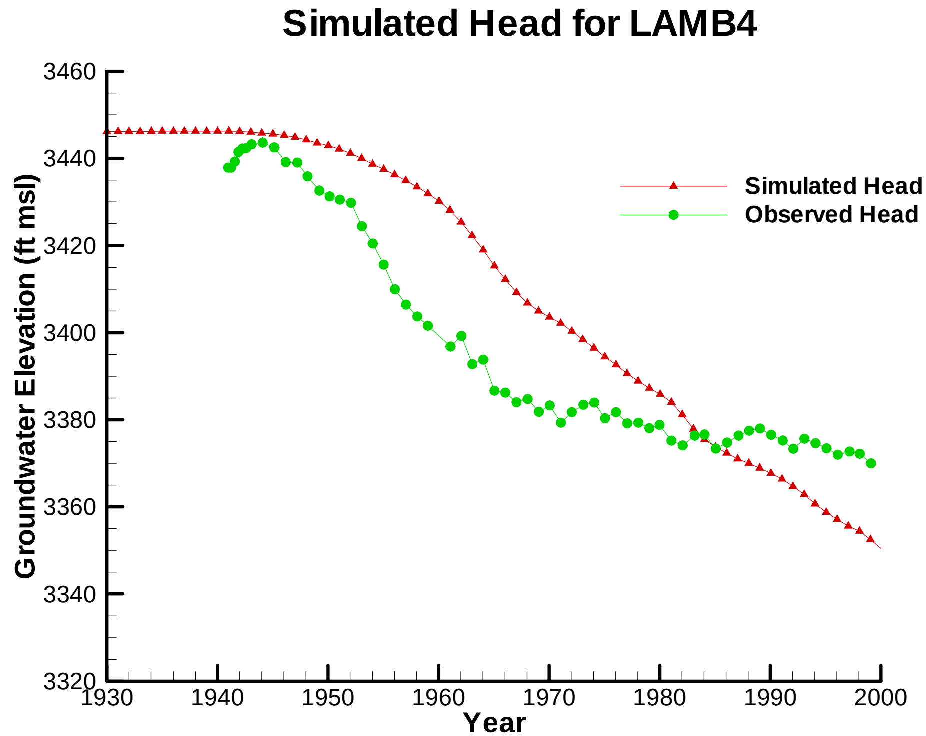

Simulated Head for HOCKLEY2
Groundwater Elevation (ft msl)
3360
3340
3320
3300
3280
3260
3240
3220
3200
1930
1940
1950
1960
1970
1980
1990
2000
Year
Simulated Head
Observed Head

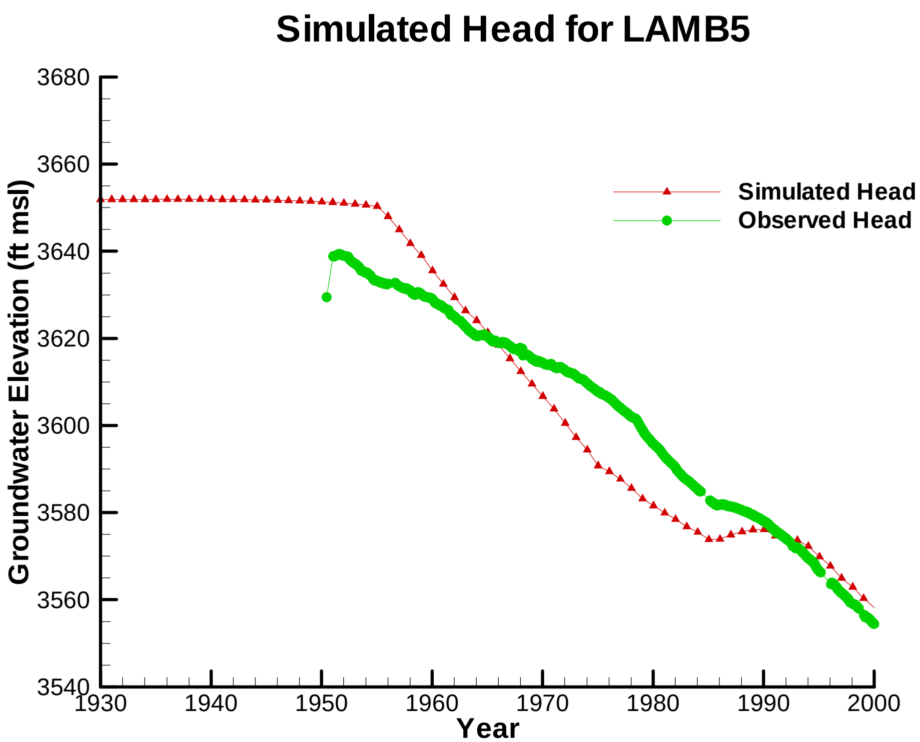

Simulated Head for HOCKLEY3
Groundwater Elevation (ft msl)
3340
3320
3300
3280
3260
3240
1930
1940
1950
1960
1970
1980
1990
2000
Year
Simulated Head
Observed Head

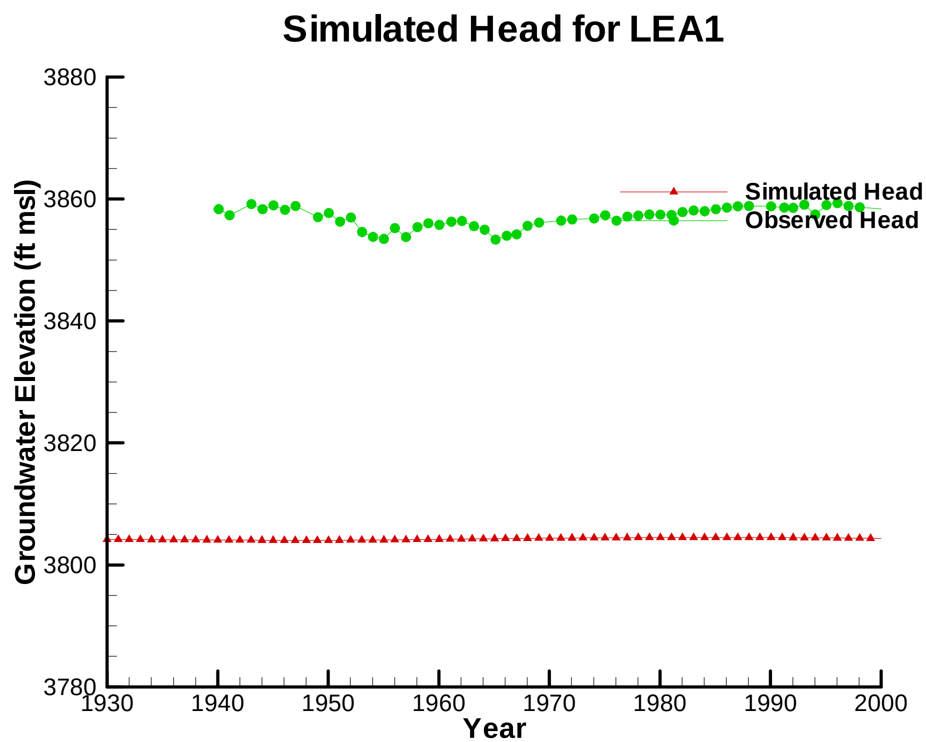

Simulated Head for LAMB1
Groundwater Elevation (ft msl)
3780
3760
3740
3720
3700
3680
3660
3640
3620
3600
3580
3560
1930
1940
1950
1960
1970
1980
1990
2000
Year
Simulated Head
Observed Head

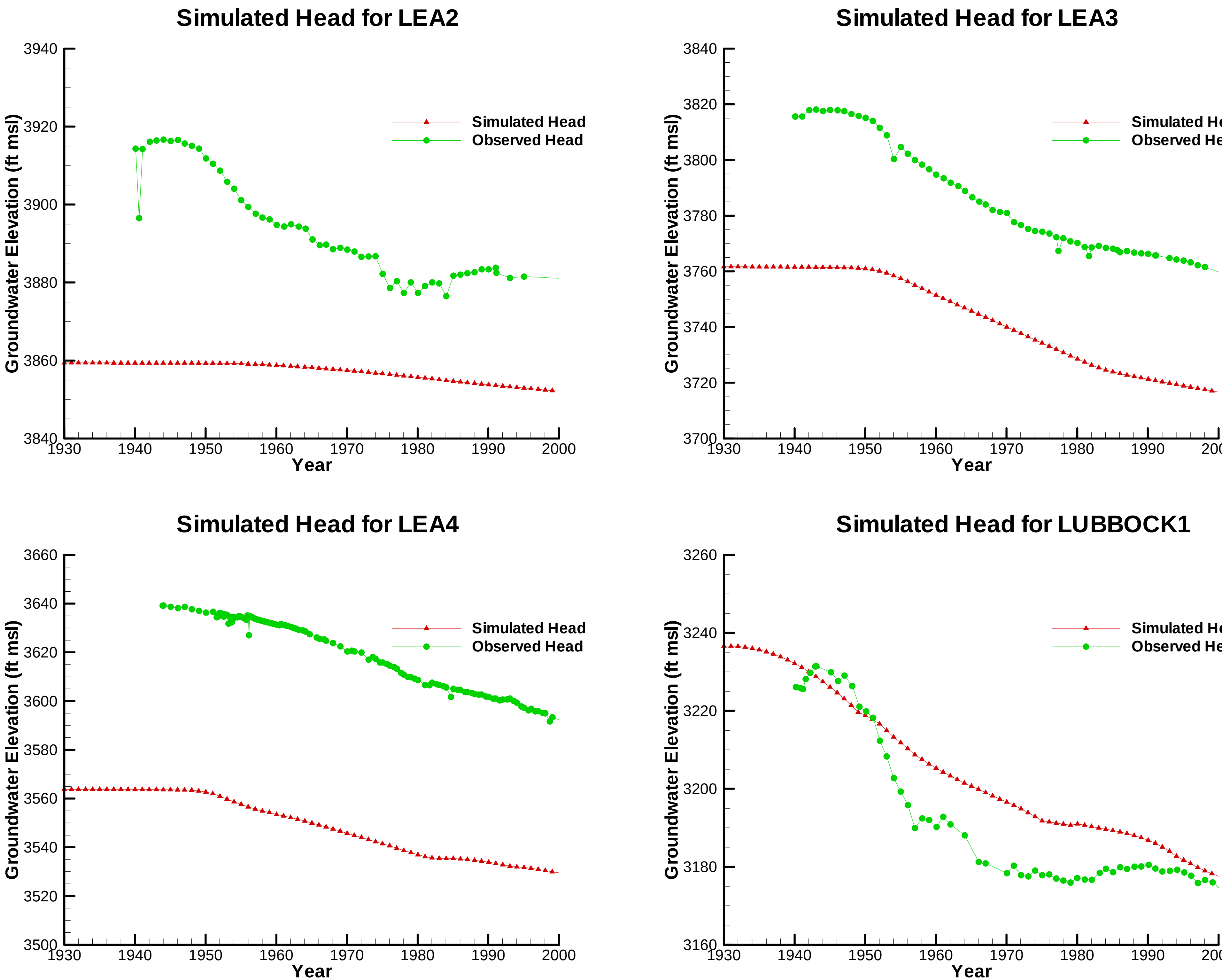

Simulated Head for LAMB2
Groundwater Elevation (ft msl)
3600
3580
3560
3540
3520
3500
3480
3460
3440
3420
3400
3380
1930
1940
1950
1960
1970
1980
1990
2000
Year
Simulated Head
Observed Head


Simulated Head for LAMB3
Groundwater Elevation (ft msl)
Year
Simulated Head
Observed Head
3280
3300
3320
3340
3360
3380
3400
3420
3440
3460
1930
1940
1950
1960
1970
1980
1990
2000

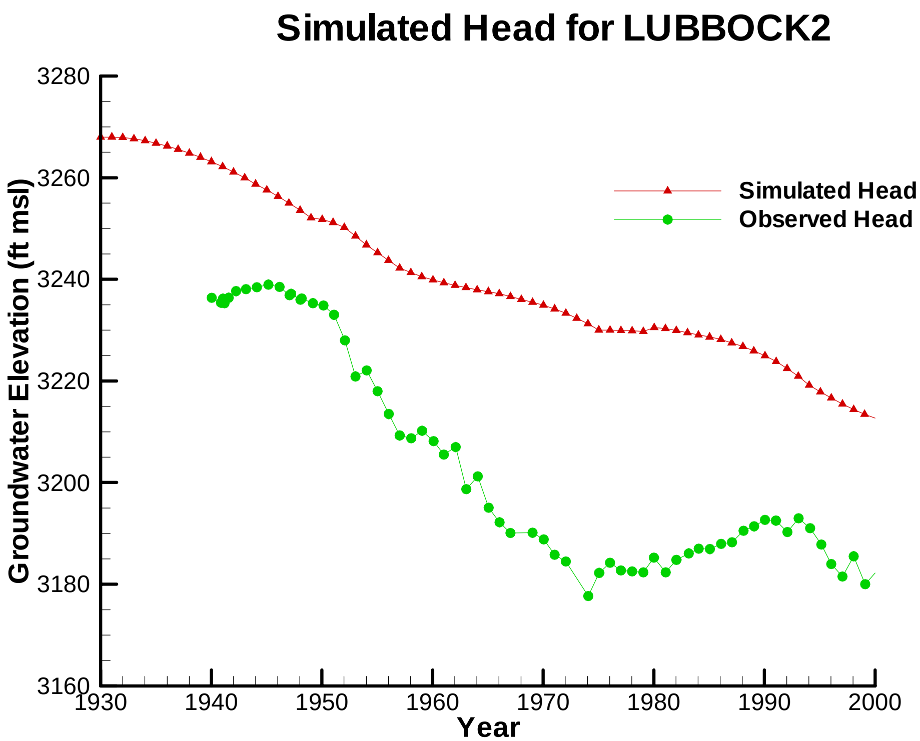

Simulated Head for LAMB4
Groundwater Elevation (ft msl)
Year
Simulated Head
Observed Head
3320
3340
3360
3380
3400
3420
3440
3460
1930
1940
1950
1960
1970
1980
1990
2000

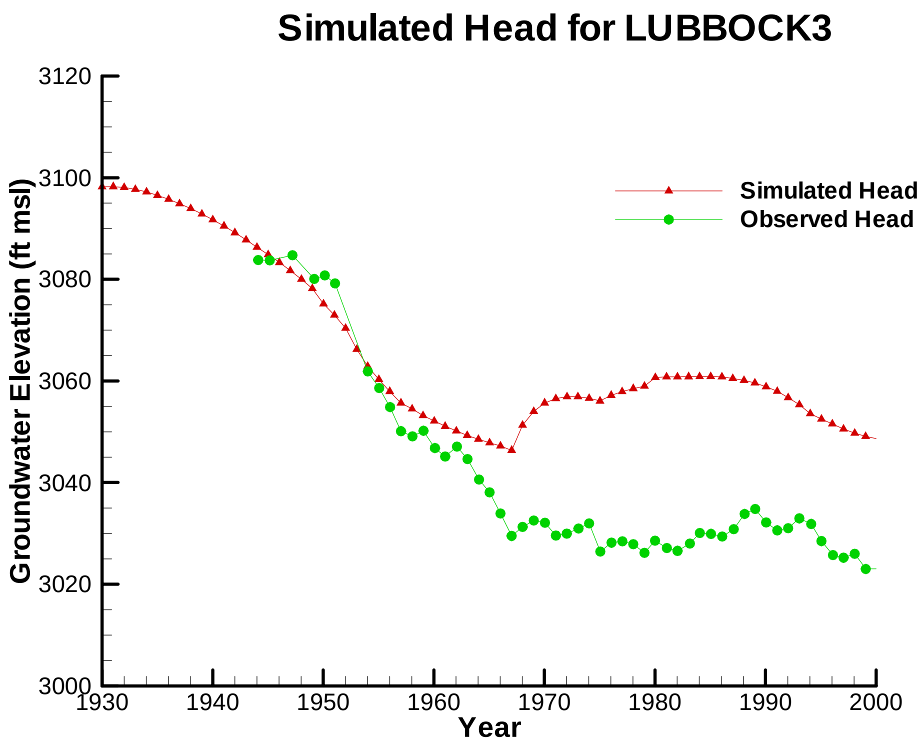

Simulated Head for LAMB5
Groundwater Elevation (ft msl)
Year
Simulated Head
Observed Head
3540
3560
3580
3600
3620
3640
3660
3680
1930
1940
1950
1960
1970
1980
1990
2000

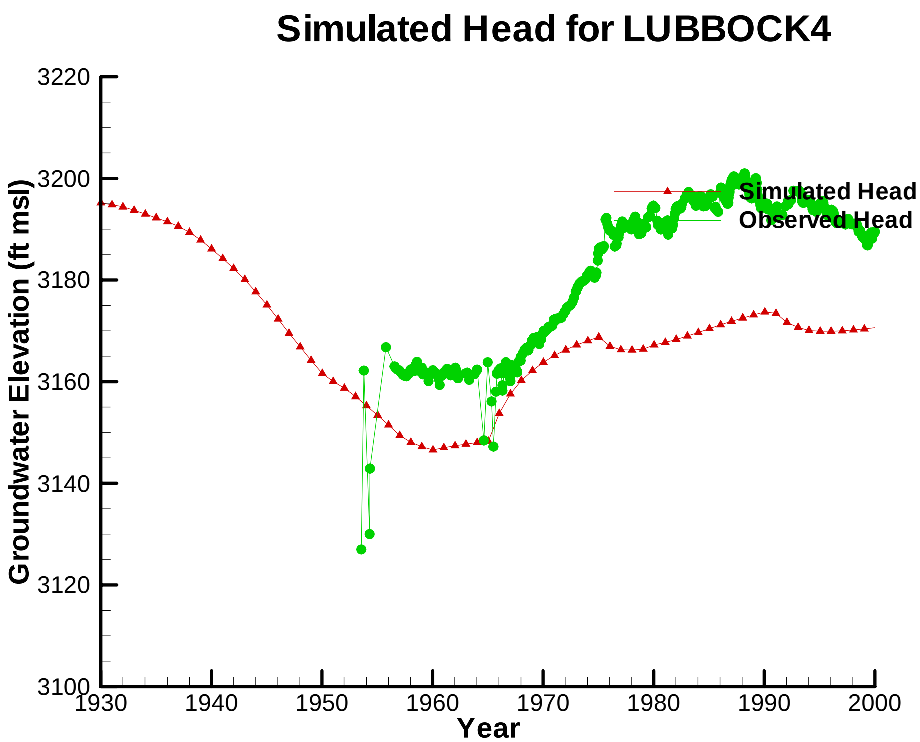

Simulated Head for LEA1
Groundwater Elevation (ft msl)
Year
Simulated Head
Observed Head
3780
3800
3820
3840
3860
3880
1930
1940
1950
1960
1970
1980
1990
2000

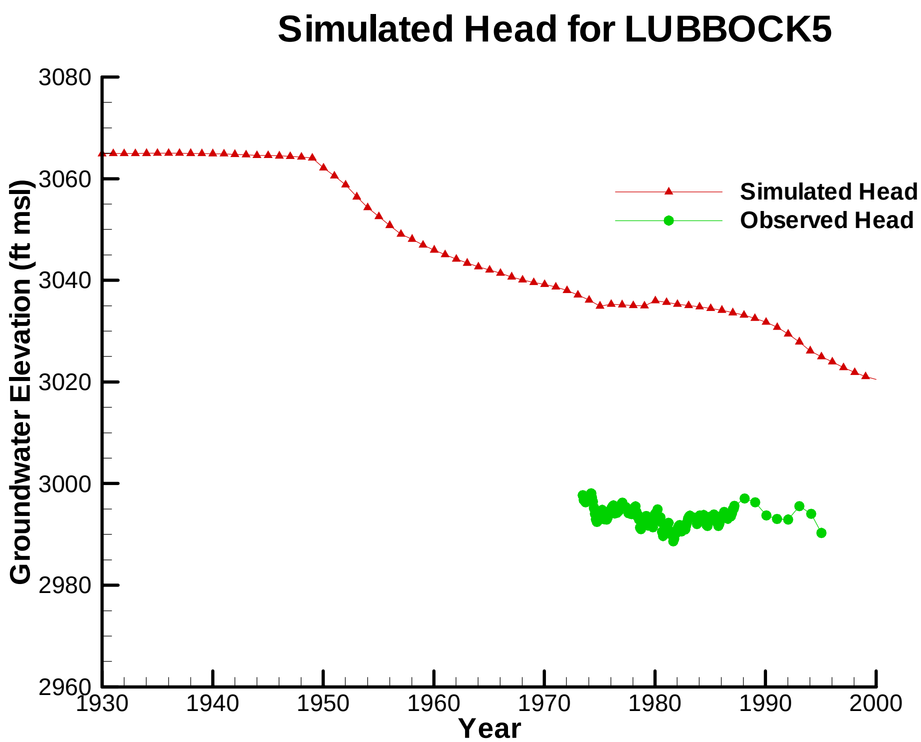


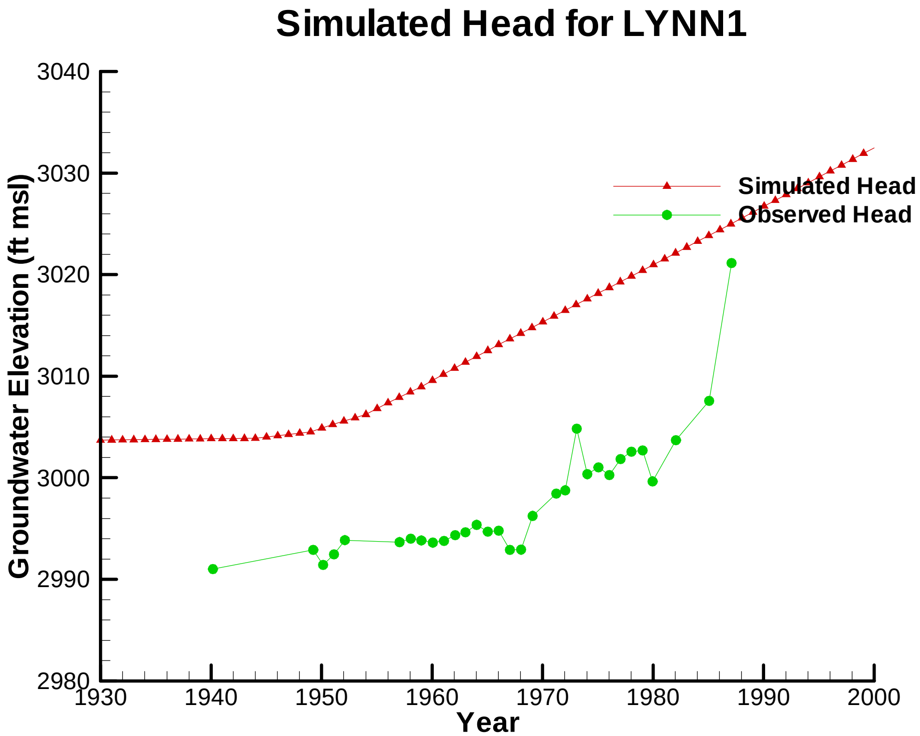
Simulated Head for LEA2
Simulated Head
Observed Head
Groundwater Elevation (ft msl)
Year
3840
3860
3880
3900
3920
3940
1930
1940
1950
1960
1970
1980
1990
2000
Simulated Head for LEA3
Simulated Head
Observed Head
Groundwater Elevation (ft msl)
Year
3700
3720
3740
3760
3780
3800
3820
3840
1930
1940
1950
1960
1970
1980
1990
2000
Simulated Head for LEA4
Simulated Head
Observed Head
Groundwater Elevation (ft msl)
Year
3500
3520
3540
3560
3580
3600
3620
3640
3660
1930
1940
1950
1960
1970
1980
1990
2000
Simulated Head for LUBBOCK1
Simulated Head
Observed Head
Groundwater Elevation (ft msl)
Year
3160
3180
3200
3220
3240
3260
1930
1940
1950
1960
1970
1980
1990
2000

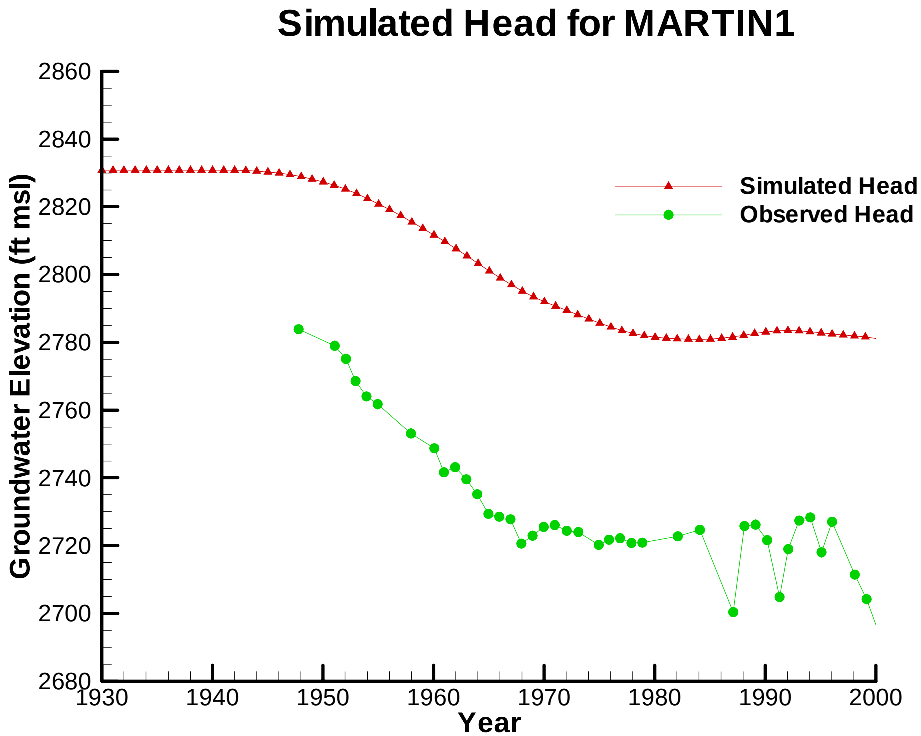

Simulated Head for LUBBOCK2
Groundwater Elevation (ft msl)
Year
Simulated Head
Observed Head
3160
3180
3200
3220
3240
3260
3280
1930
1940
1950
1960
1970
1980
1990
2000

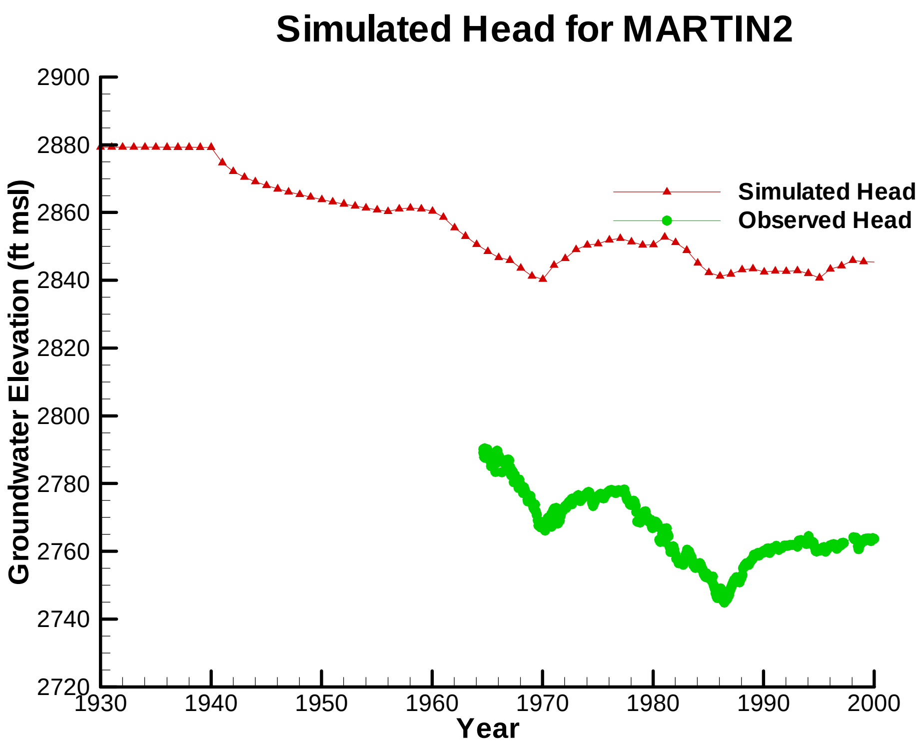

Simulated Head for LUBBOCK3
Groundwater Elevation (ft msl)
Year
Simulated Head
Observed Head
3000
3020
3040
3060
3080
3100
3120
1930
1940
1950
1960
1970
1980
1990
2000

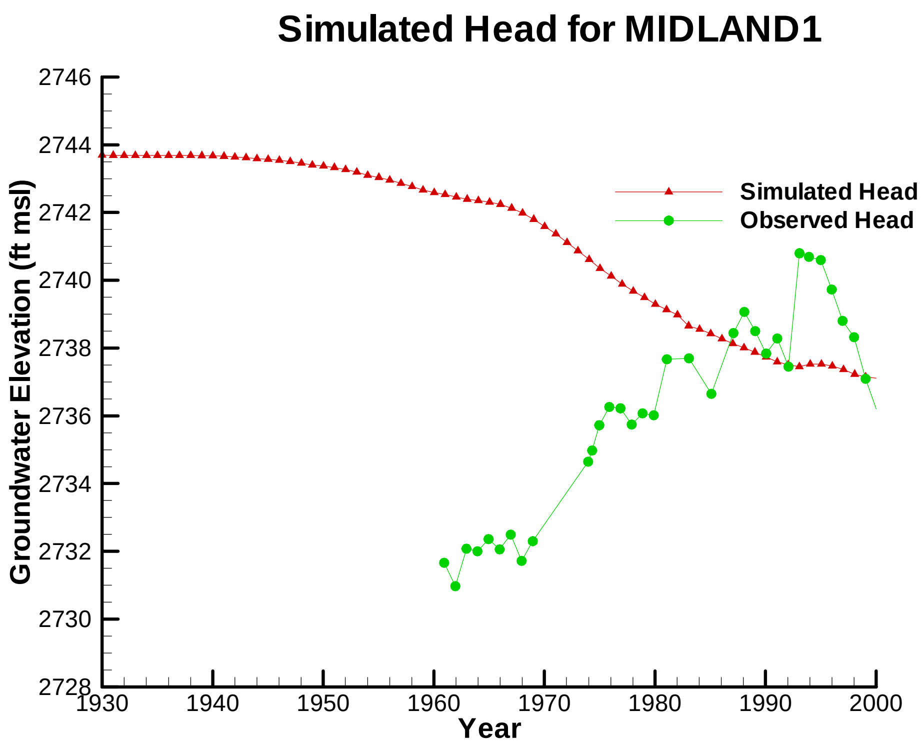

Simulated Head for LUBBOCK4
Groundwater Elevation (ft msl)
Year
Simulated Head
Observed Head
3100
3120
3140
3160
3180
3200
3220
1930
1940
1950
1960
1970
1980
1990
2000

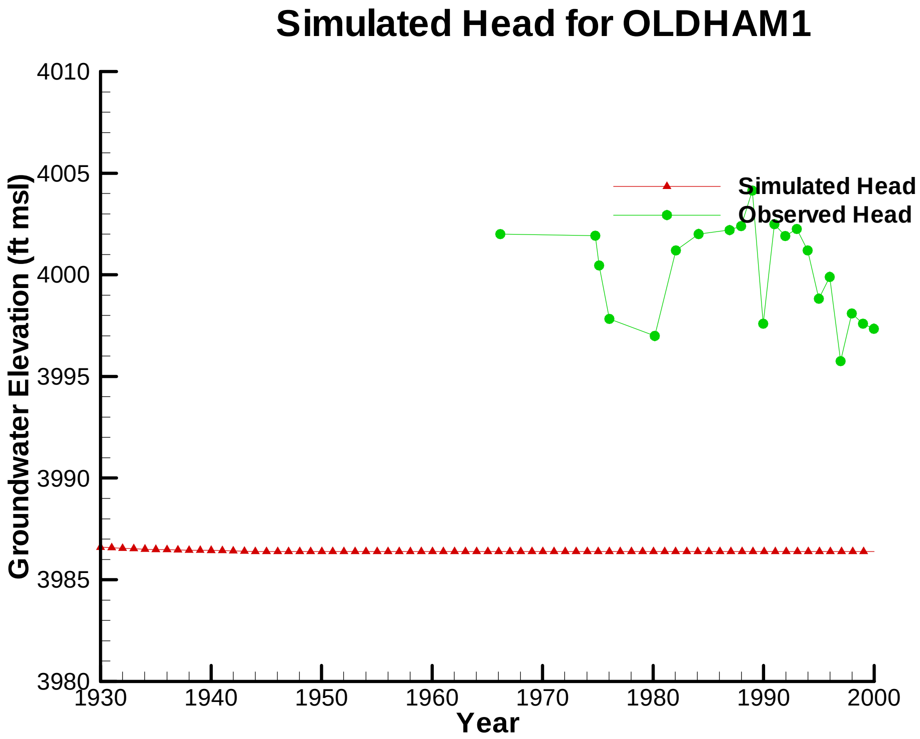

Simulated Head for LUBBOCK5
Groundwater Elevation (ft msl)
Year
Simulated Head
Observed Head
2960
2980
3000
3020
3040
3060
3080
1930
1940
1950
1960
1970
1980
1990
2000

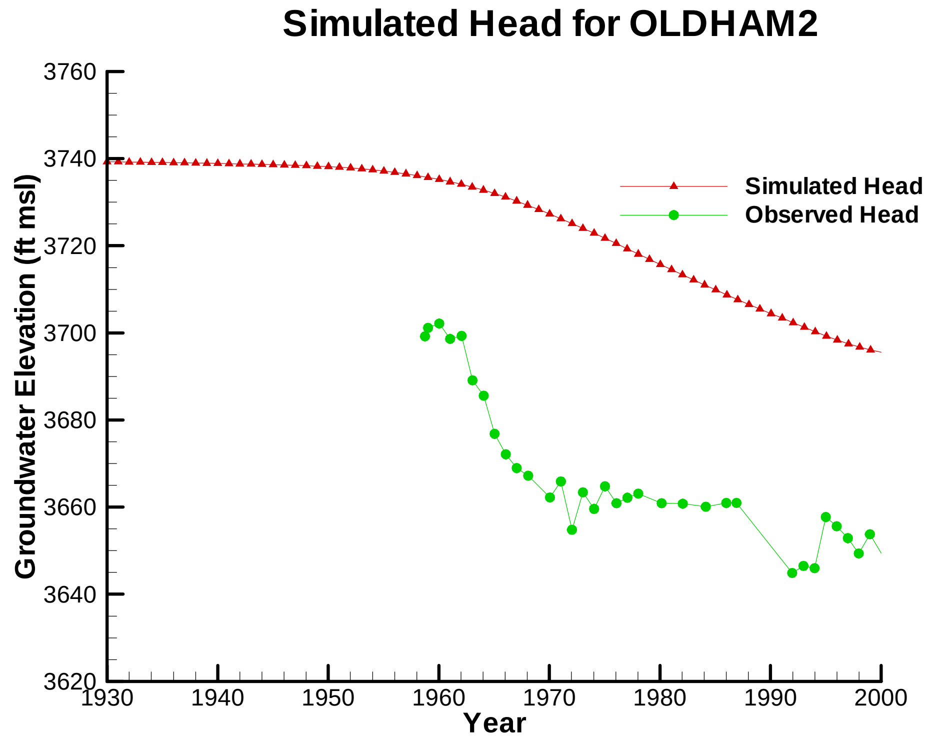

Simulated Head for LYNN1
Simulated Head
Observed Head
Groundwater Elevation (ft msl)
Year
3040
3030
3020
3010
3000
2990
2980
1930
1940
1950
1960
1970
1980
1990
2000

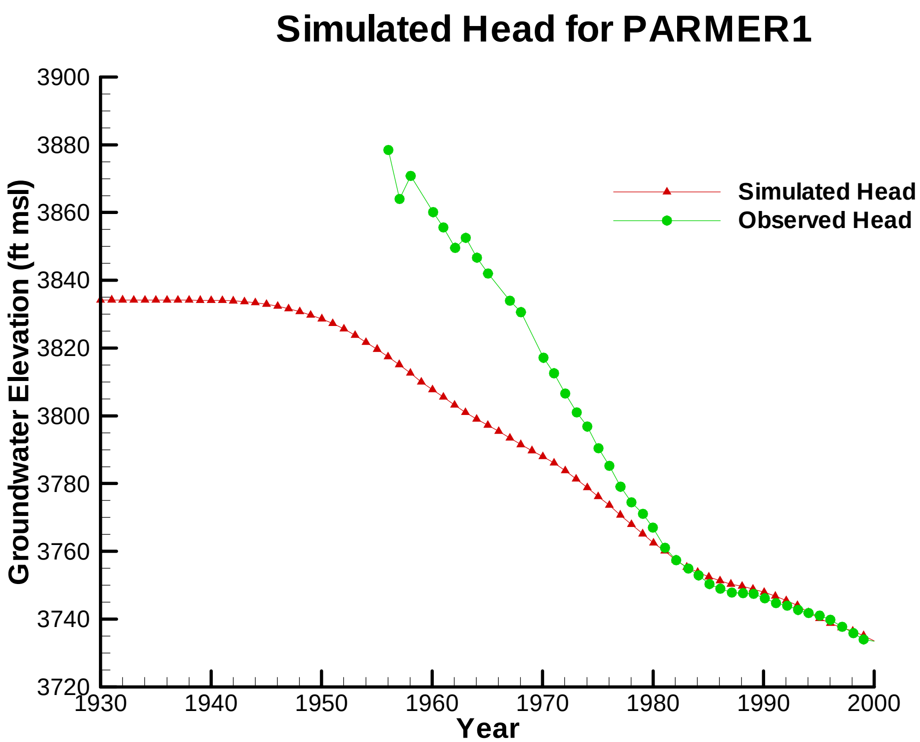

Simulated Head for MARTIN1
Simulated Head
Observed Head
Groundwater Elevation (ft msl)
Year
2860
2840
2820
2800
2780
2760
2740
2720
2700
2680
1930
1940
1950
1960
1970
1980
1990
2000

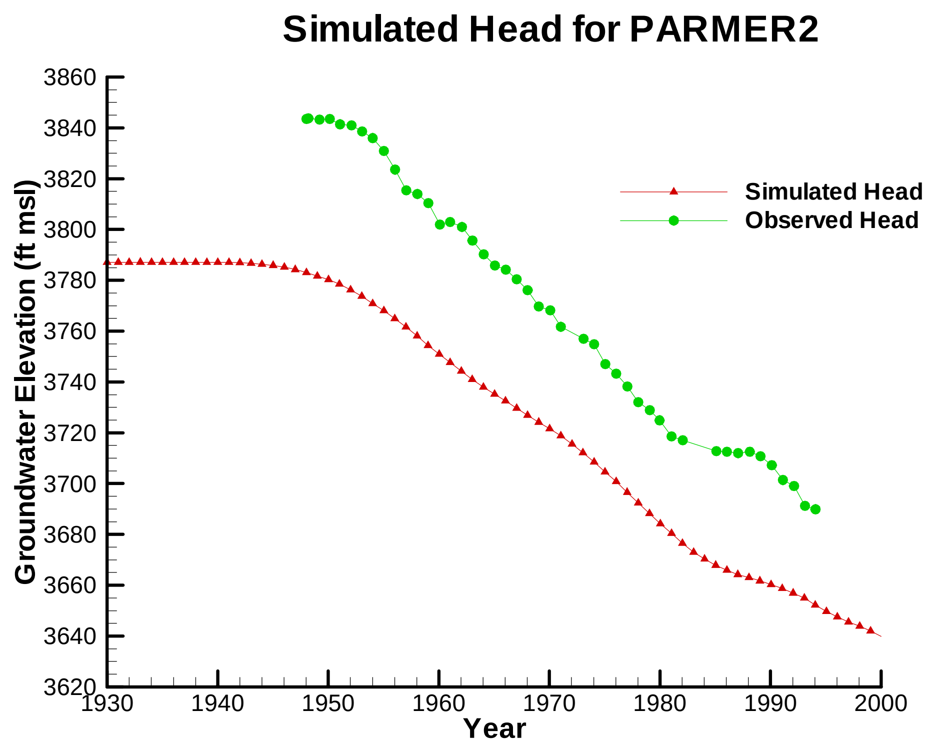

Simulated Head for MARTIN2
Simulated Head
Observed Head
Groundwater Elevation (ft msl)
Year
2900
2880
2860
2840
2820
2800
2780
2760
2740
2720
1930
1940
1950
1960
1970
1980
1990
2000

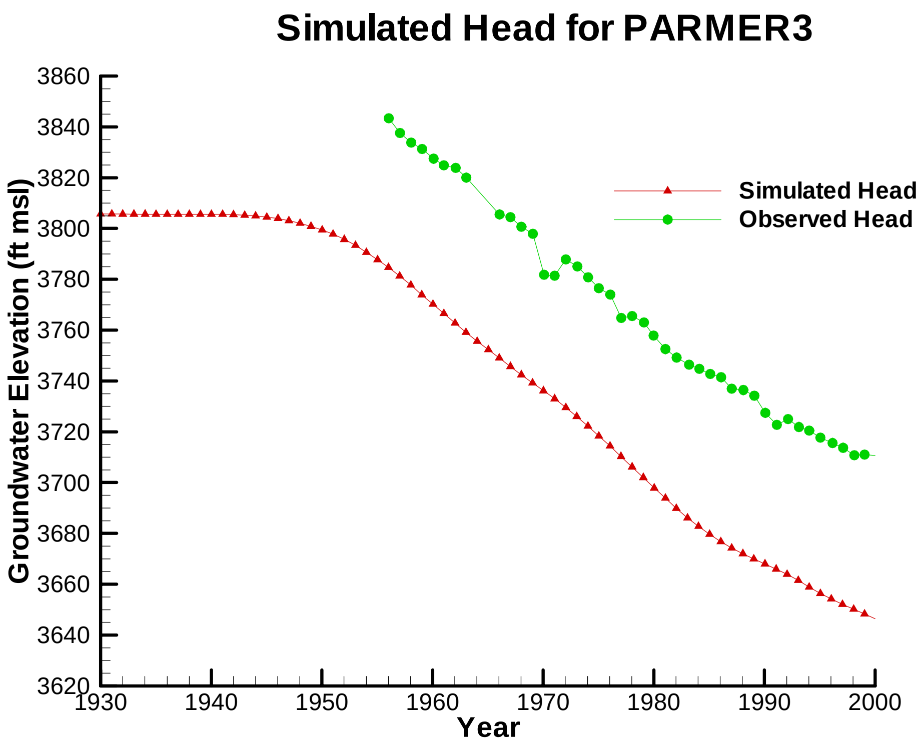

Simulated Head for MIDLAND1
Simulated Head
Observed Head
Groundwater Elevation (ft msl)
Year
2746
2744
2742
2740
2738
2736
2734
2732
2730
2728
1930
1940
1950
1960
1970
1980
1990
2000

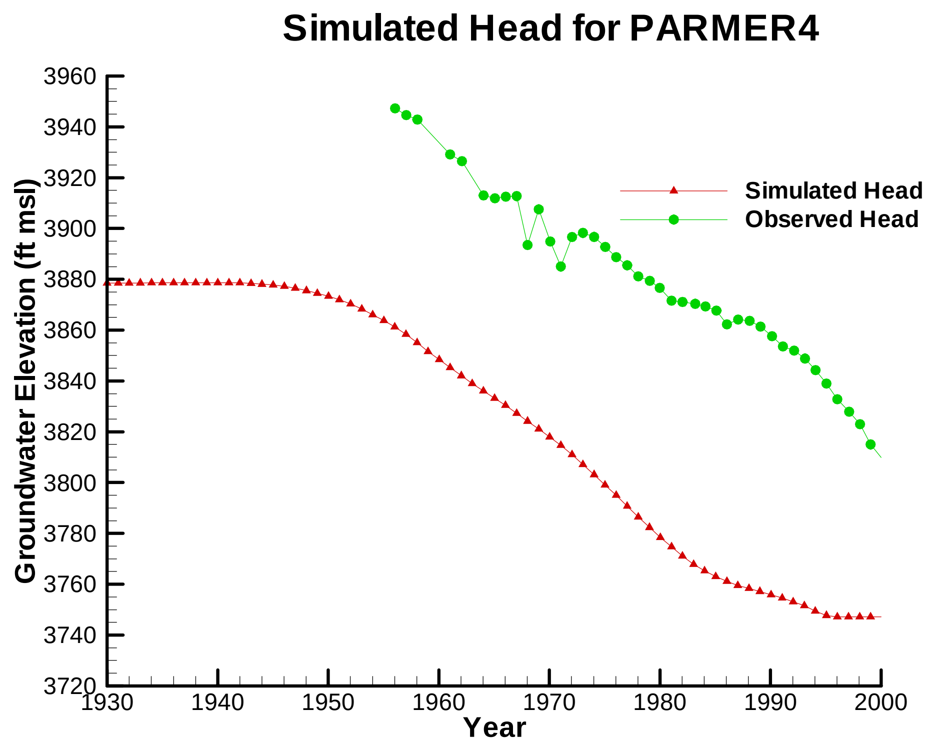

Simulated Head for OLDHAM1
Groundwater Elevation (ft msl)
Year
Simulated Head
Observed Head
4010
4005
4000
3995
3990
3985
3980
1930
1940
1950
1960
1970
1980
1990
2000

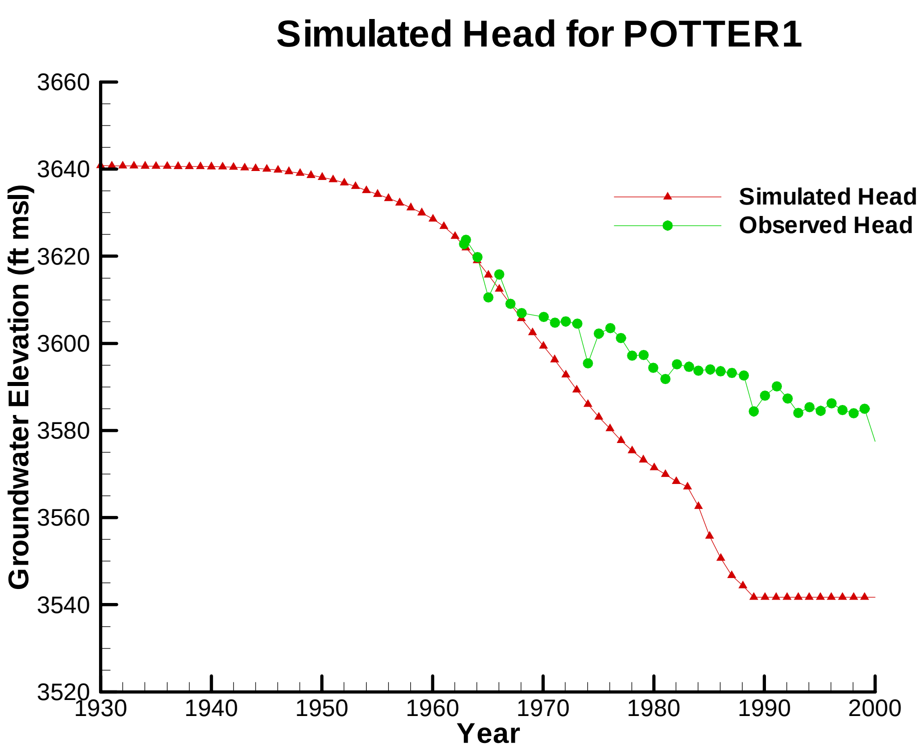

Simulated Head for OLDHAM2
Groundwater Elevation (ft msl)
Year
Simulated Head
Observed Head
3760
3740
3720
3700
3680
3660
3640
3620
1930
1940
1950
1960
1970
1980
1990
2000

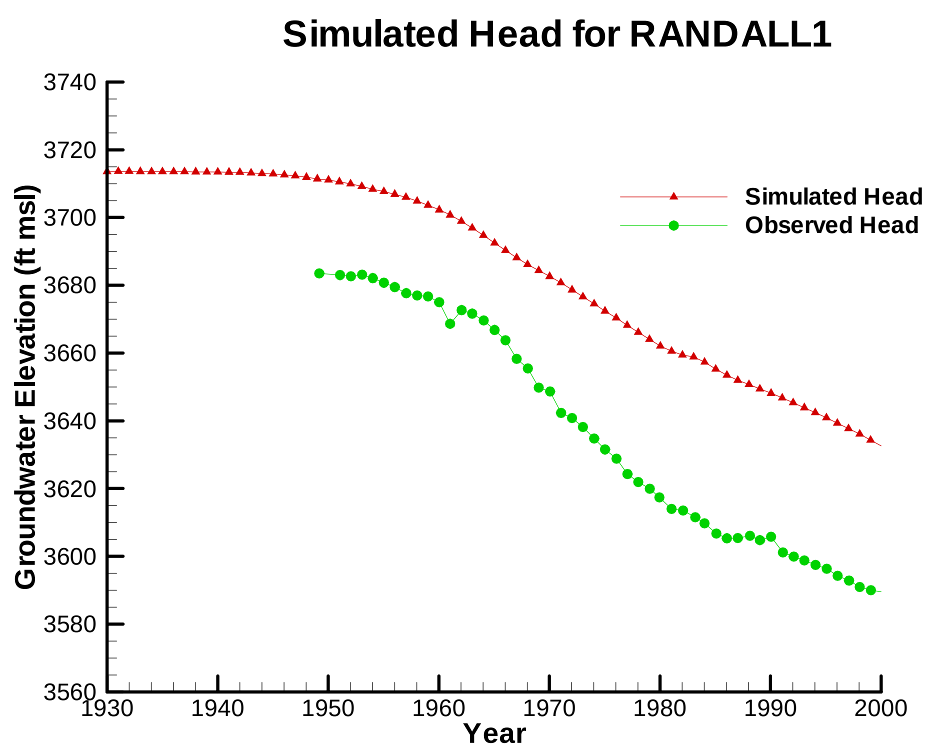

Simulated Head for PARMER1
Groundwater Elevation (ft msl)
Year
Simulated Head
Observed Head
3900
3880
3860
3840
3820
3800
3780
3760
3740
3720
1930
1940
1950
1960
1970
1980
1990
2000


Simulated Head for PARMER2
Groundwater Elevation (ft msl)
Year
Simulated Head
Observed Head
3860
3840
3820
3800
3780
3760
3740
3720
3700
3680
3660
3640
3620
1930
1940
1950
1960
1970
1980
1990
2000









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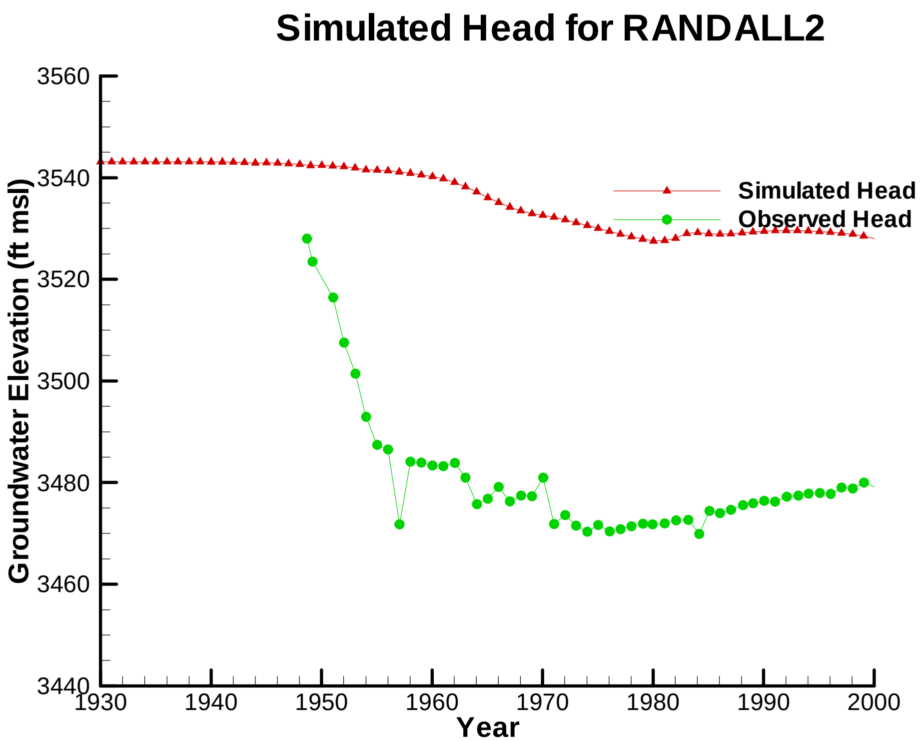
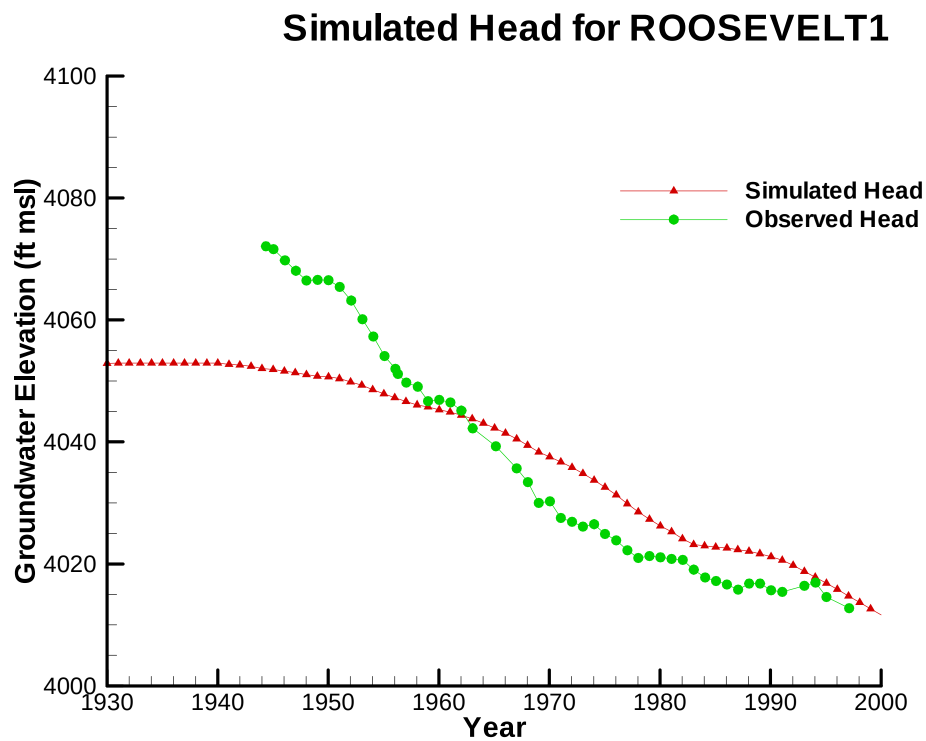
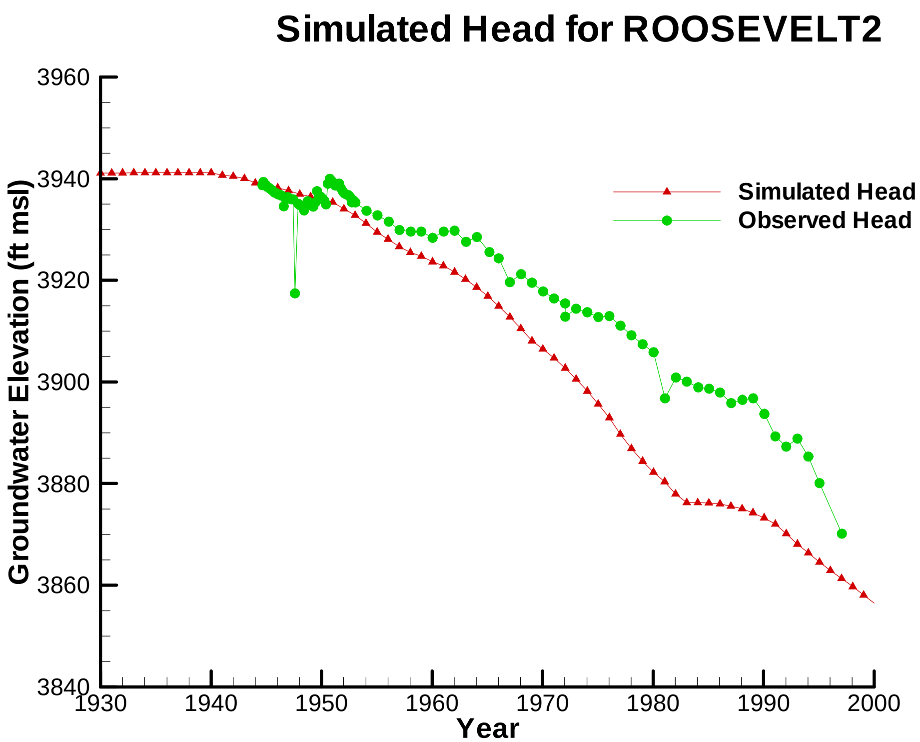
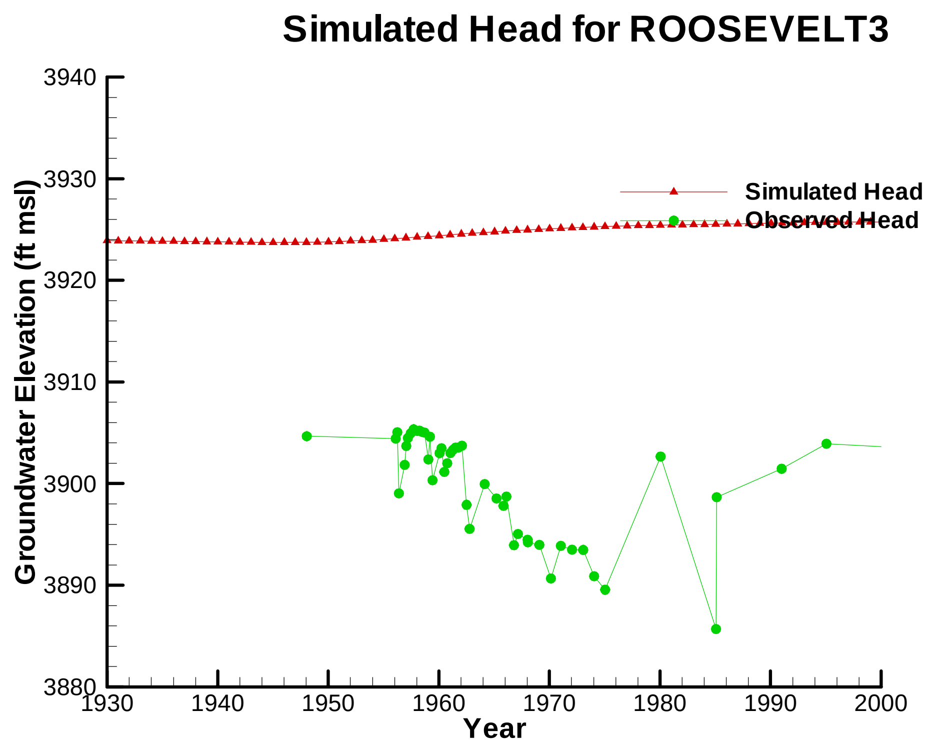
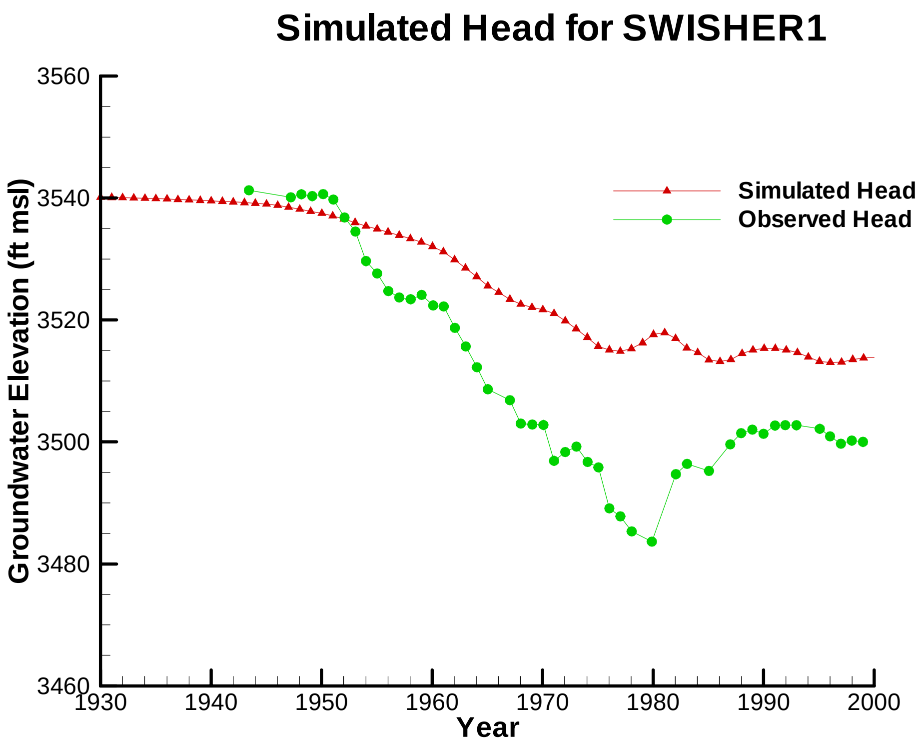

Simulated Head for RANDALL2
Simulated Head
Observed Head
Groundwater Elevation (ft msl)
Year
3560
3540
3520
3500
3480
3460
3440
1930
1940
1950
1960
1970
1980
1990
2000

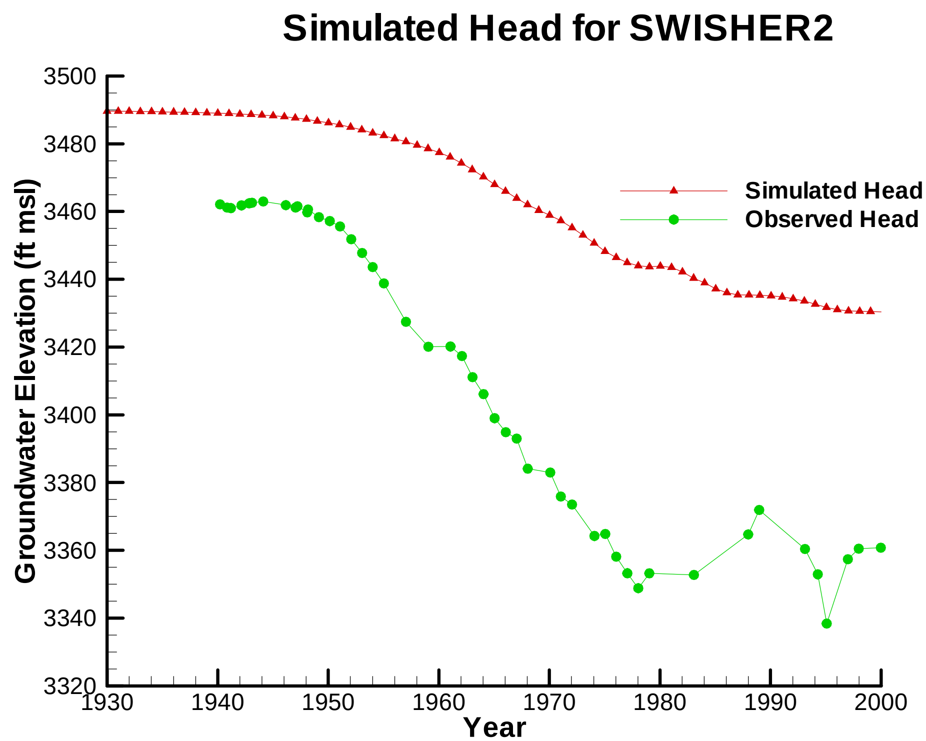

Simulated Head for ROOSEVELT1
Simulated Head
Observed Head
Groundwater Elevation (ft msl)
Year
4100
4080
4060
4040
4020
4000
1930
1940
1950
1960
1970
1980
1990
2000


Simulated Head for ROOSEVELT2
Simulated Head
Observed Head
Groundwater Elevation (ft msl)
Year
3960
3940
3920
3900
3880
3860
3840
1930
1940
1950
1960
1970
1980
1990
2000

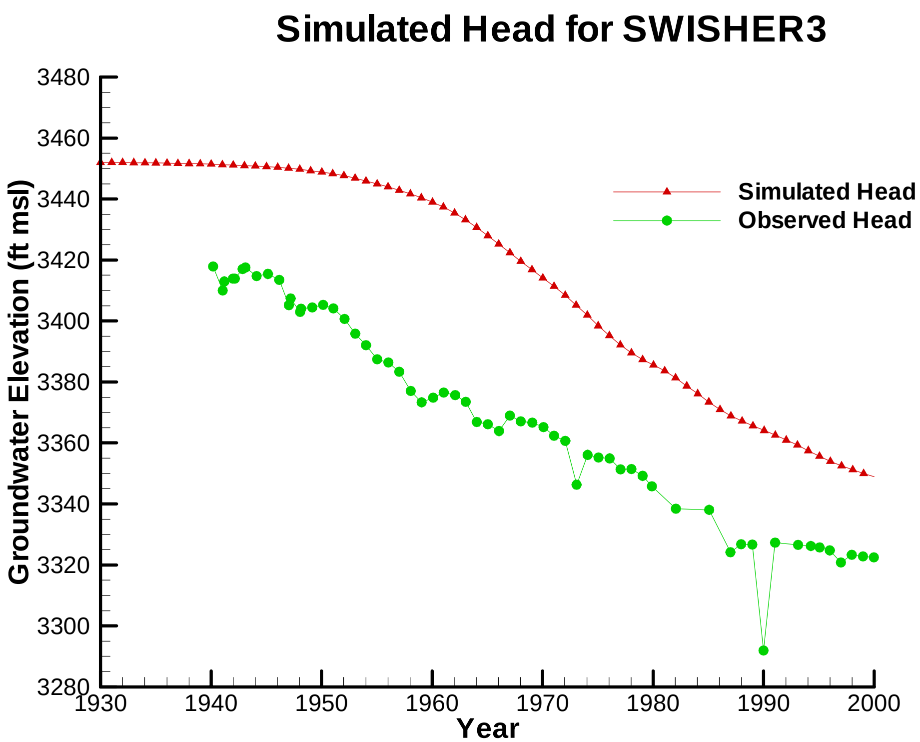

Simulated Head for ROOSEVELT3
Simulated Head
Observed Head
Groundwater Elevation (ft msl)
Year
3940
3930
3920
3910
3900
3890
3880
1930
1940
1950
1960
1970
1980
1990
2000



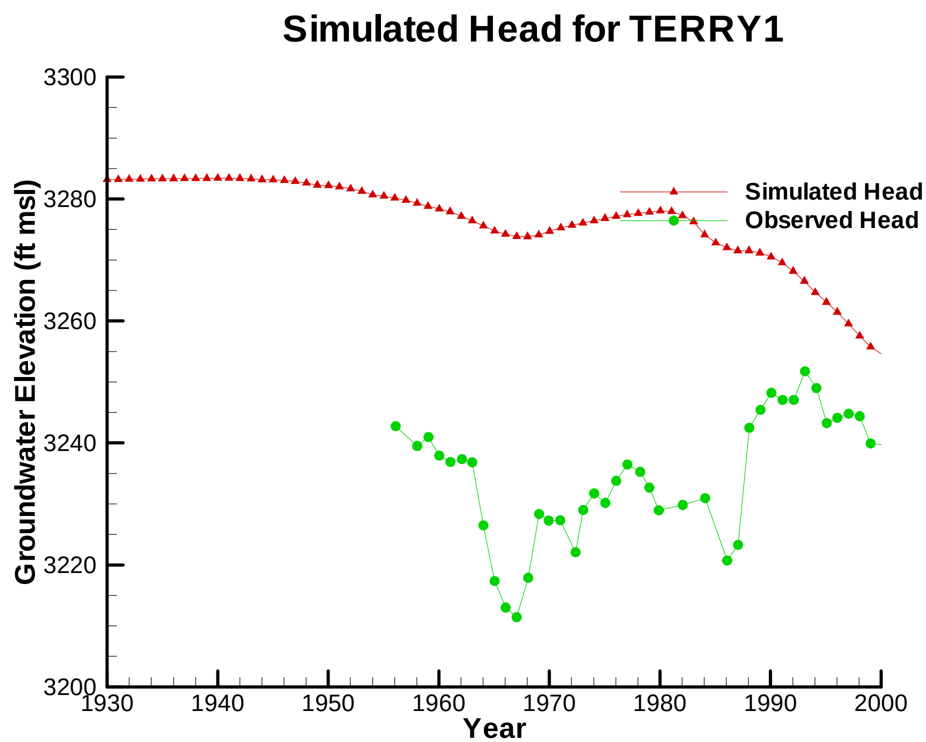
Simulated Head for SWISHER1
Simulated Head
Observed Head
Groundwater Elevation (ft msl)
Year



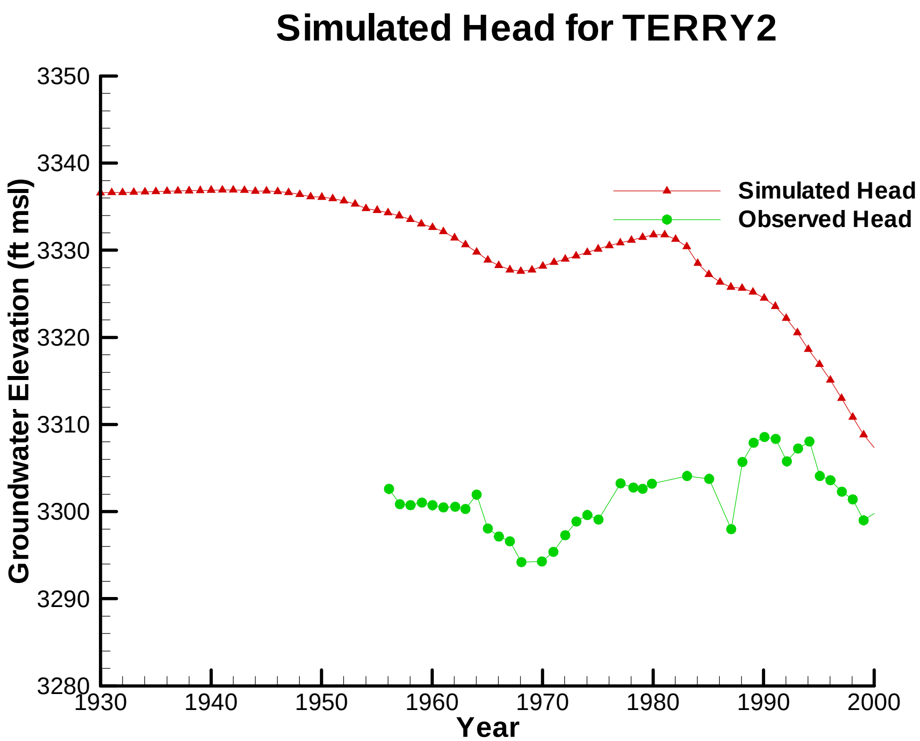
Simulated Head for SWISHER2
Simulated Head
Observed Head
Groundwater Elevation (ft msl)
Year



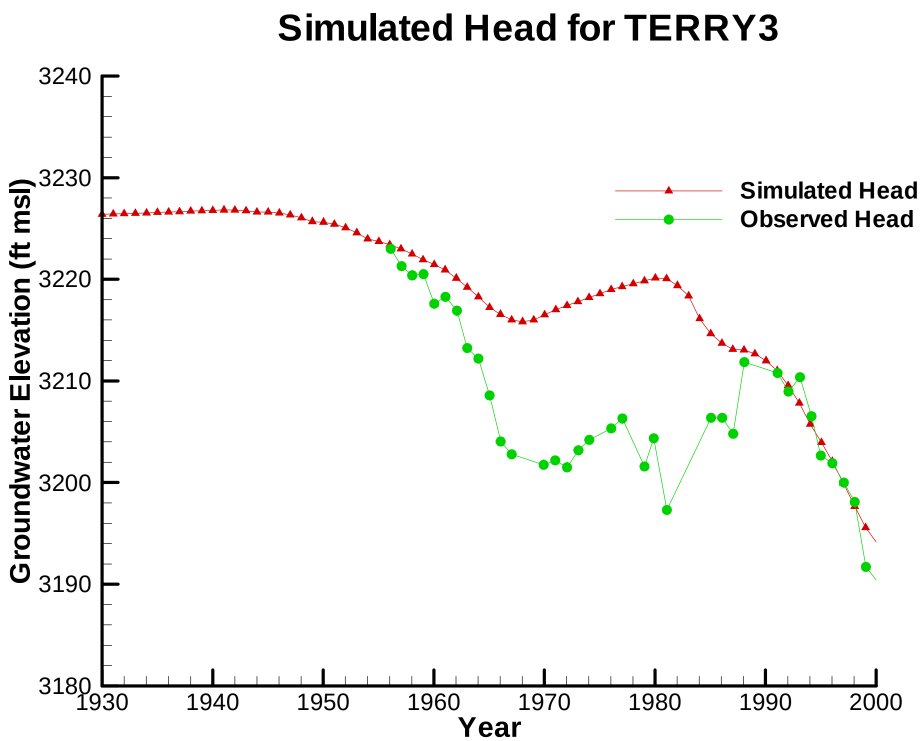
Simulated Head for SWISHER3
Simulated Head
Observed Head
Groundwater Elevation (ft msl)
Year



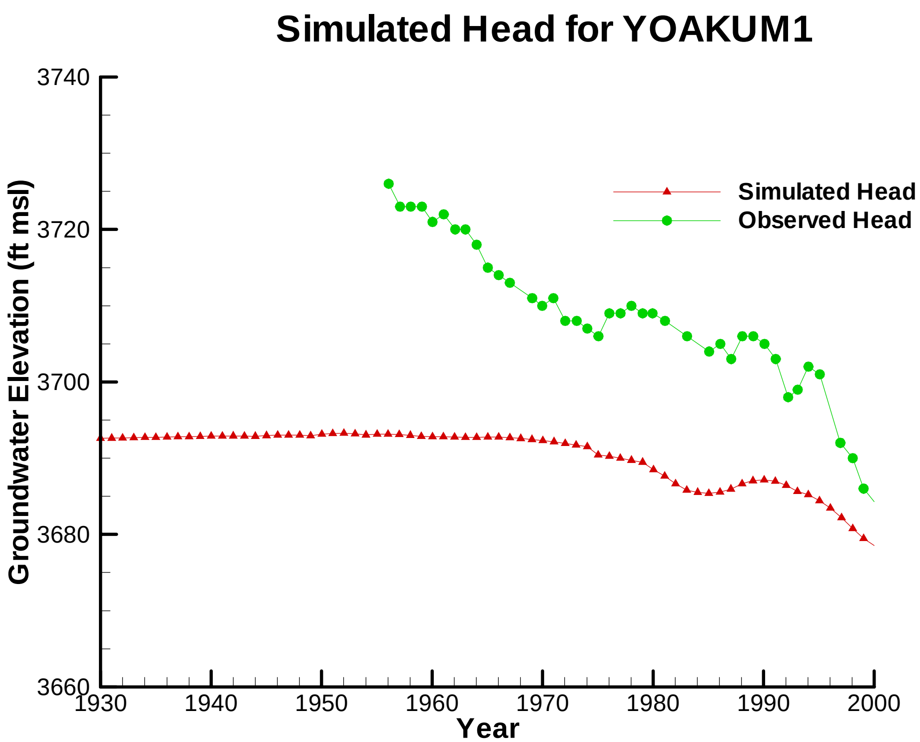
Simulated Head for TERRY1
Simulated Head
Observed Head
Groundwater Elevation (ft msl)
Year



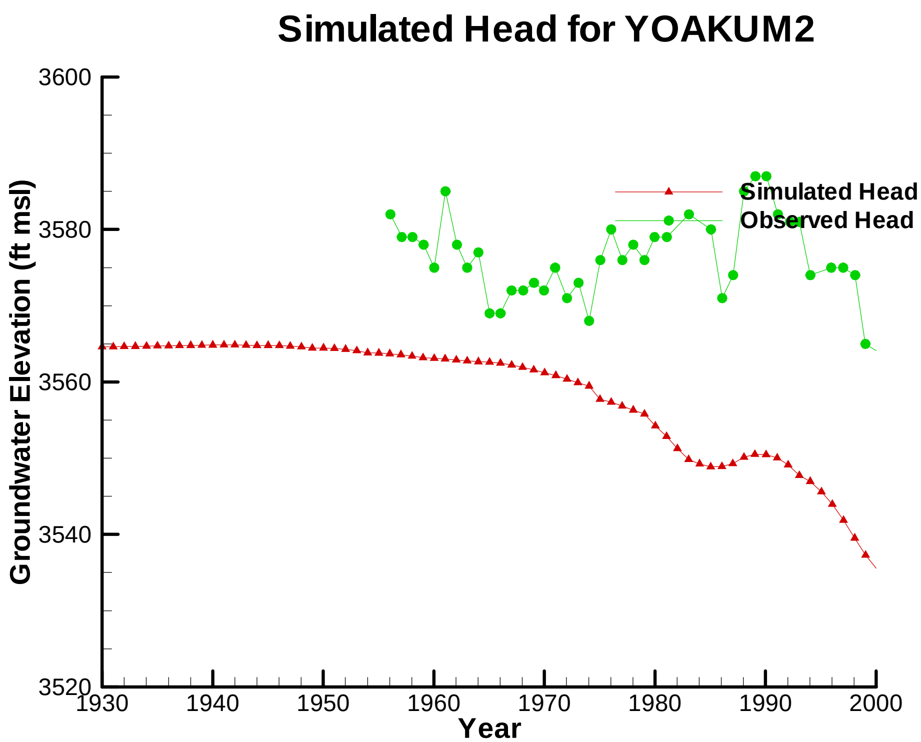
Simulated Head for TERRY2
Groundwater Elevation (ft msl)
Year
Simulated Head
Observed Head
3280
3290
3300
3310
3320
3330
3340
3350
1930
1940
1950
1960
1970
1980
1990
2000



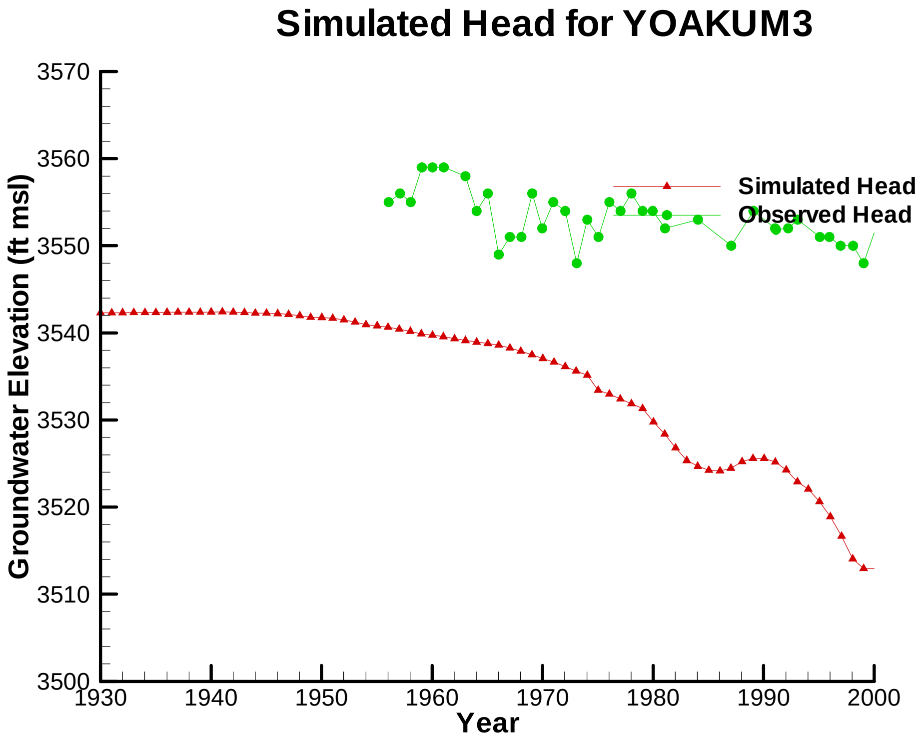
Simulated Head for TERRY3
Groundwater Elevation (ft msl)
Year
Simulated Head
Observed Head
3180
3190
3200
3210
3220
3230
3240
1930
1940
1950
1960
1970
1980
1990
2000

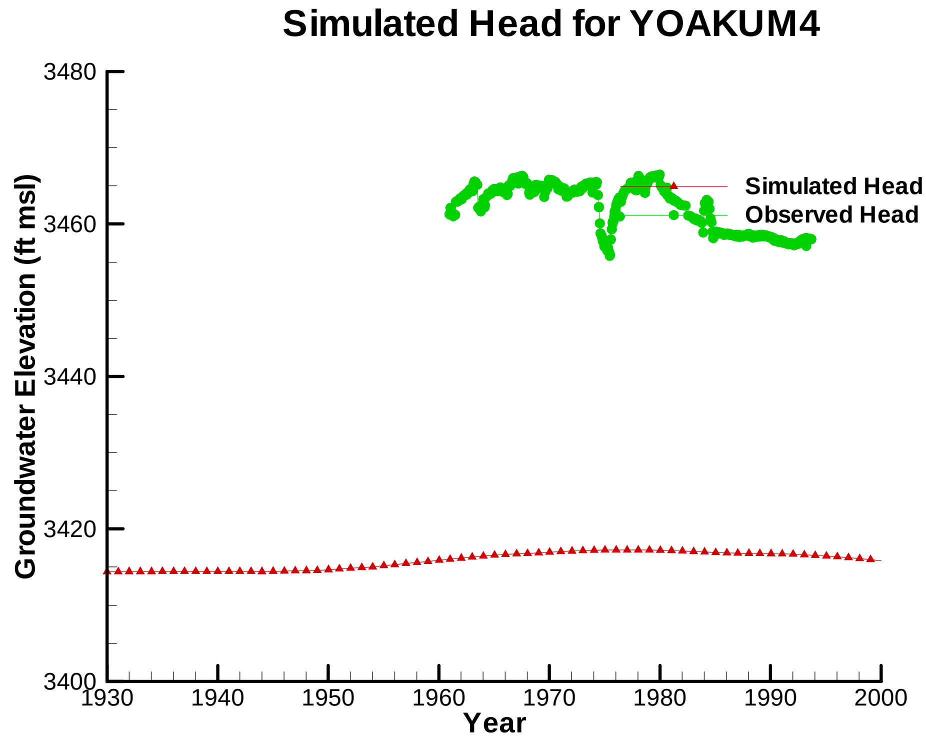


Simulated Head for YOAKUM1
Groundwater Elevation (ft msl)
Year
Simulated Head
Observed Head
3660
3680
3700
3720
3740
1930
1940
1950
1960
1970
1980
1990
2000



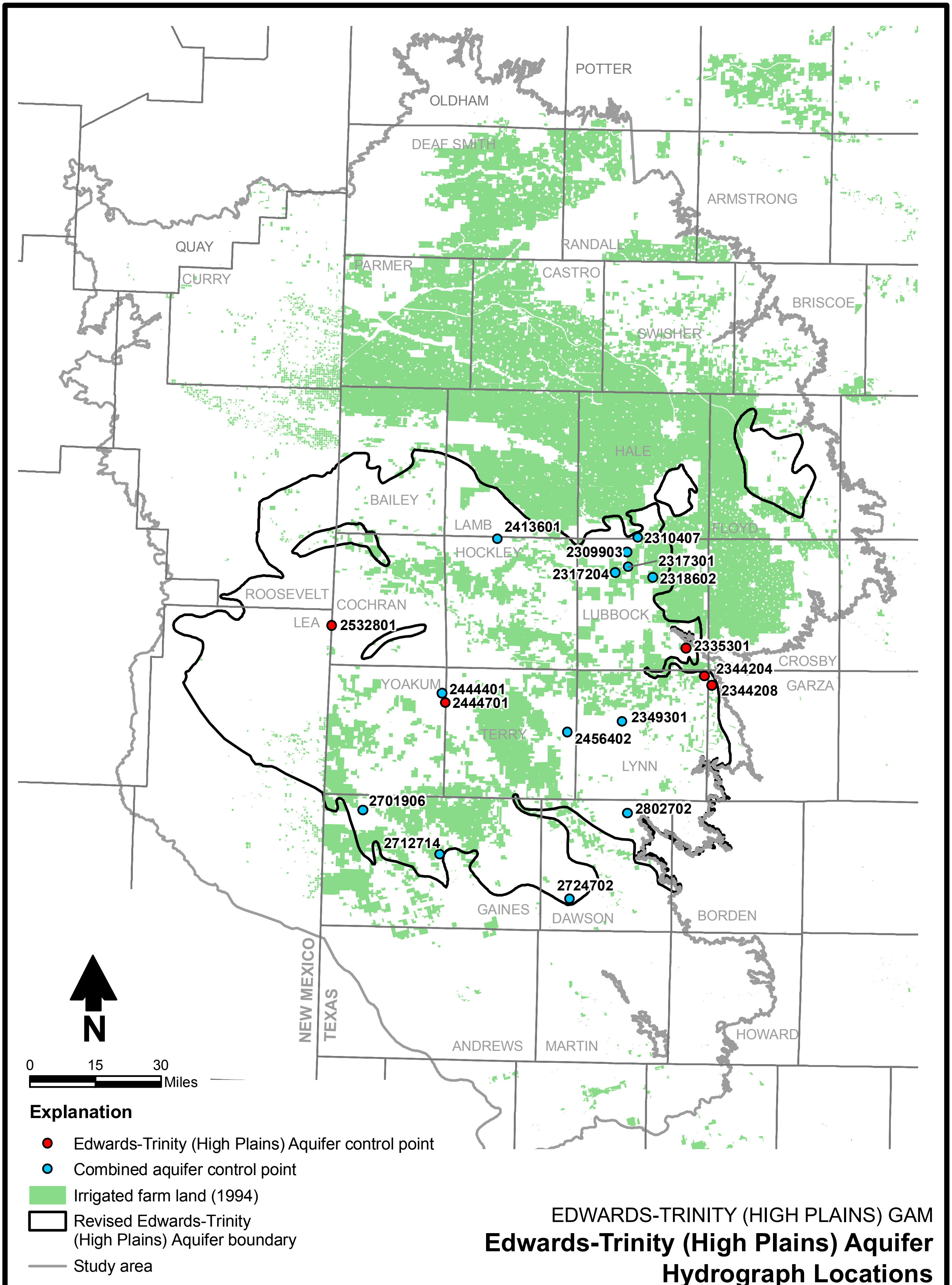
Simulated Head for YOAKUM2
Groundwater Elevation (ft msl)
Year
Simulated Head
Observed Head
3520
3540
3560
3580
3600
1930
1940
1950
1960
1970
1980
1990
2000


Simulated Head for YOAKUM3
Groundwater Elevation (ft msl)
Year
Simulated Head
Observed Head
3500
3510
3520
3530
3540
3550
3560
3570
1930
1940
1950
1960
1970
1980
1990
2000


Simulated Head for YOAKUM4
Groundwater Elevation (ft msl)
Year
Simulated Head
Observed Head
3400
3420
3440
3460
3480
1930
1940
1950
1960
1970
1980
1990
2000

Appendix C

Edwards-Trinity (High Plains) Aquifer Simulated and Observed Hydrographs from Transient Model Calibration



EDWARDS-TRINITY (HIGH PLAINS) GAM

Edwards-Trinity (High Plains) Aquifer Hydrograph Locations

Figure C-1

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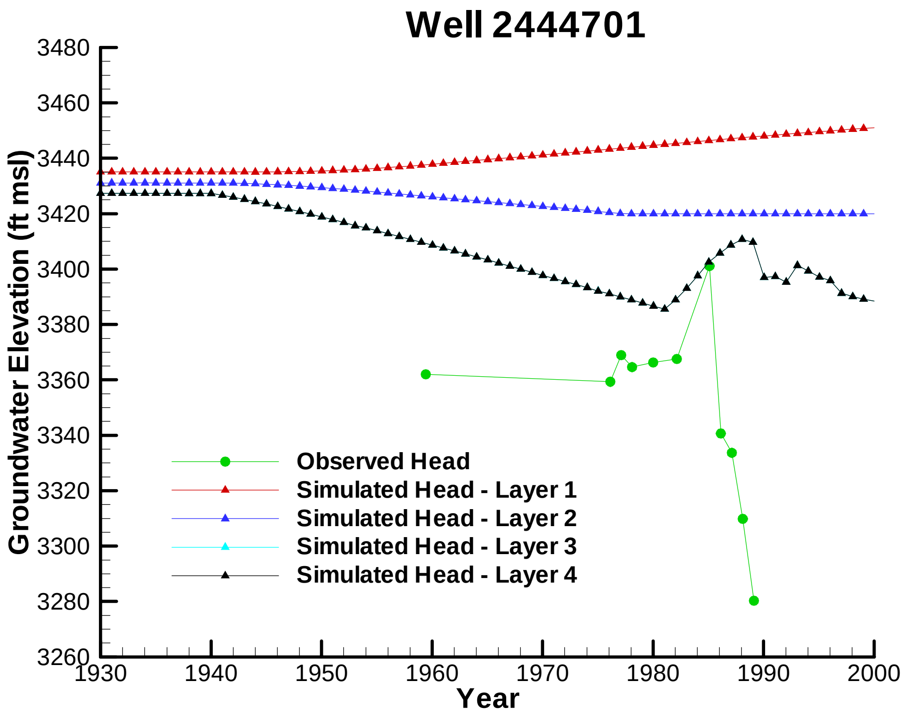
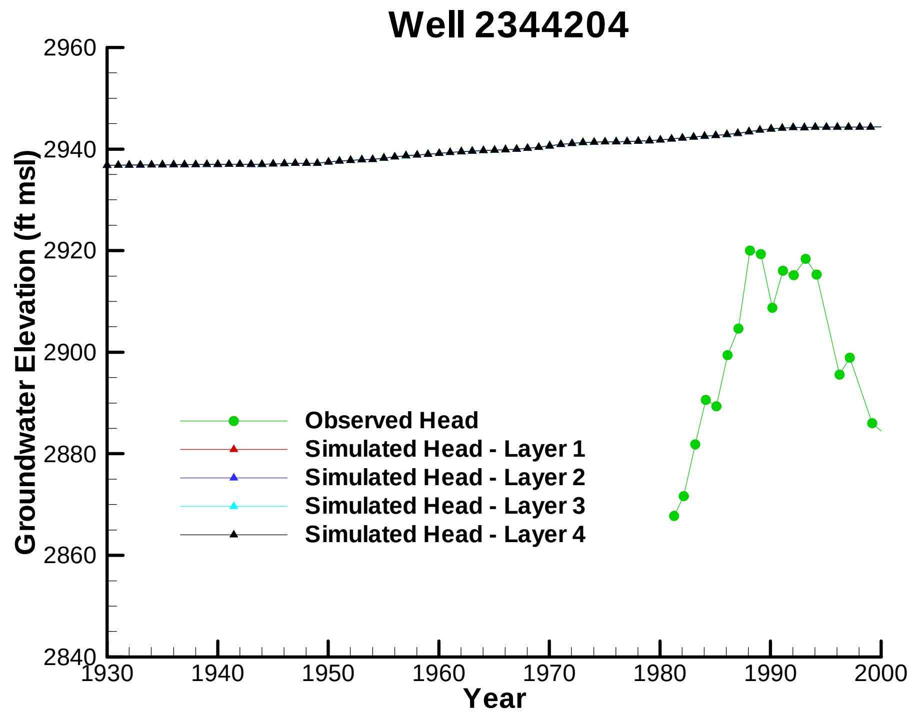
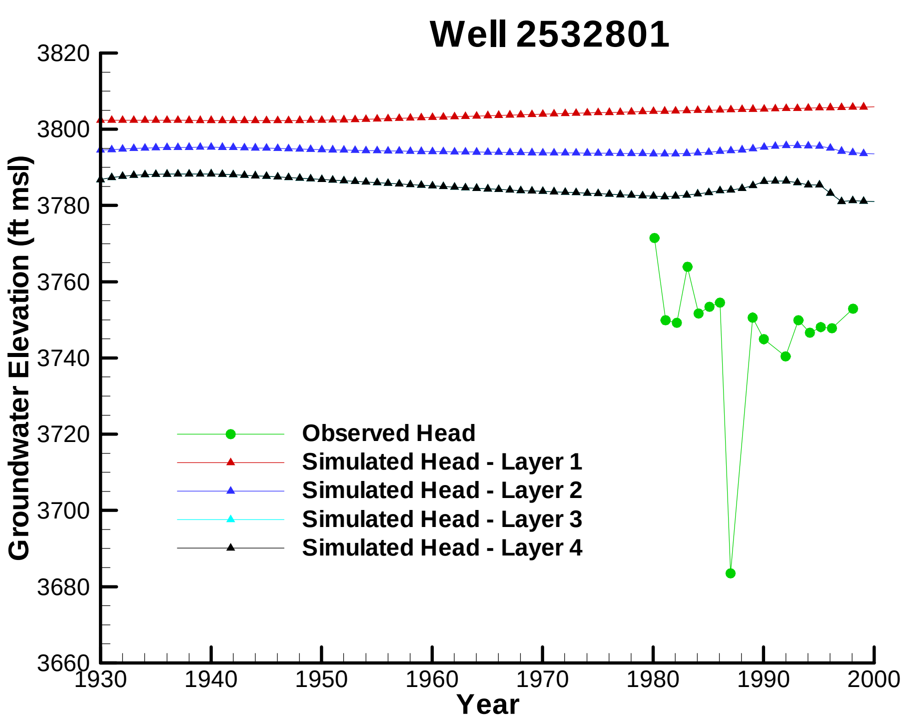
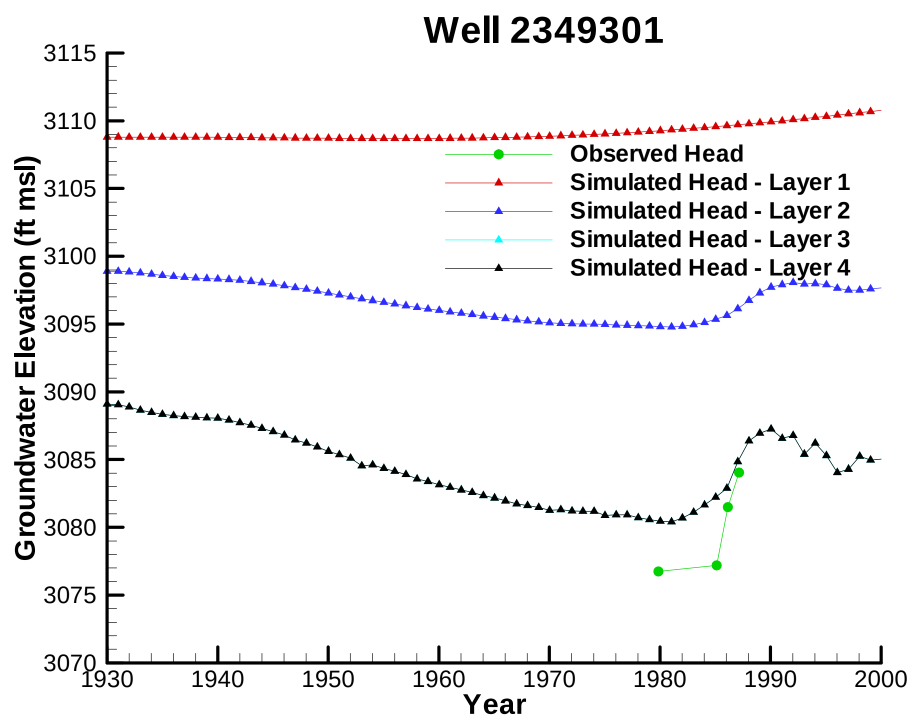
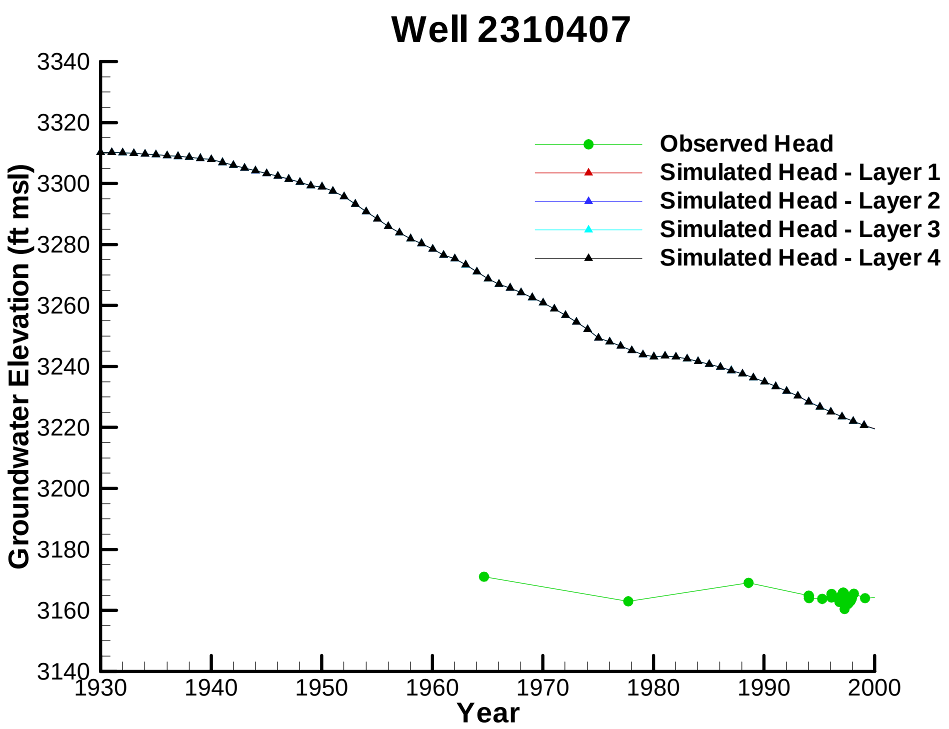
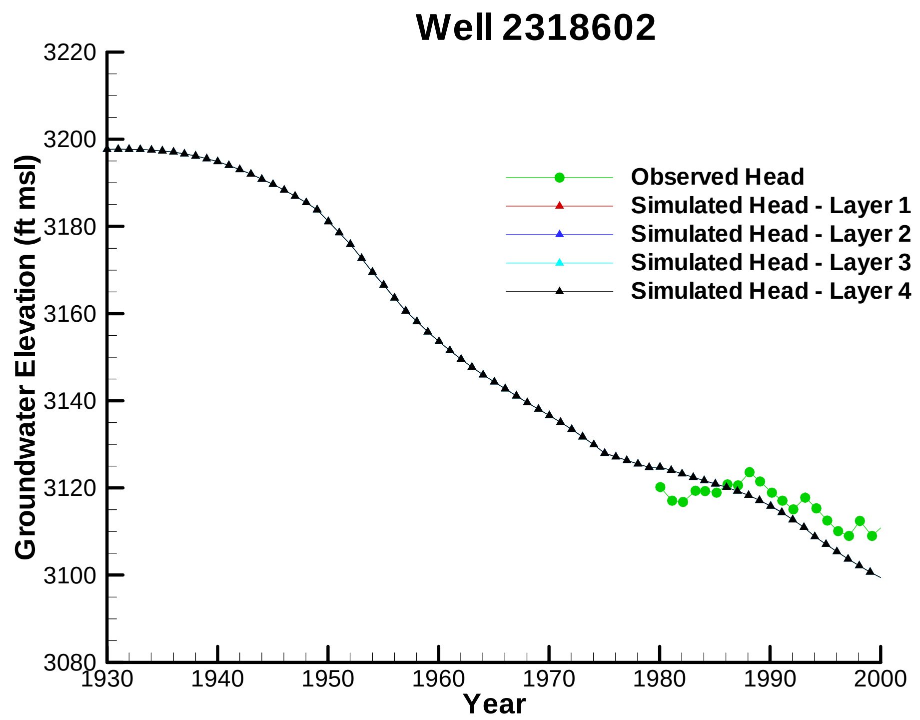

Well 2444701
Groundwater Elevation (ft msl)
Year
3480
3460
3440
3420
3400
3380
3360
3340
3320
3300
3280
3260
1930
1940
1950
1960
1970
1980
1990
2000
Observed Head
Simulated Head - Layer 1
Simulated Head - Layer 2
Simulated Head - Layer 3
Simulated Head - Layer 4

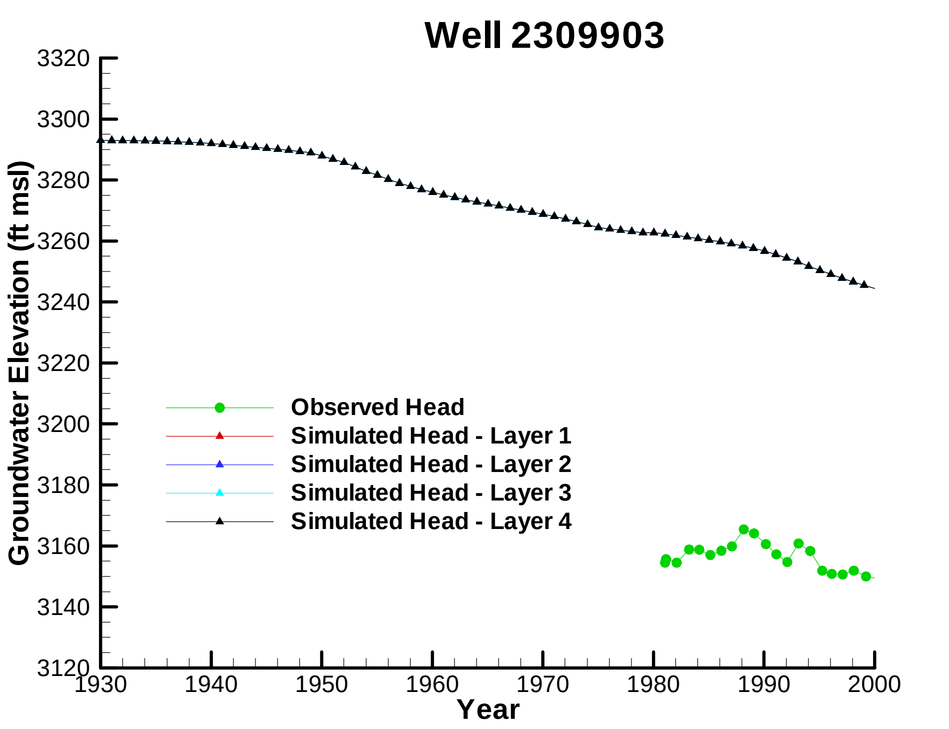

Well 2344204
Groundwater Elevation (ft msl)
Year
2960
2940
2920
2900
2880
2860
2840
1930
1940
1950
1960
1970
1980
1990
2000
Observed Head
Simulated Head - Layer 1
Simulated Head - Layer 2
Simulated Head - Layer 3
Simulated Head - Layer 4

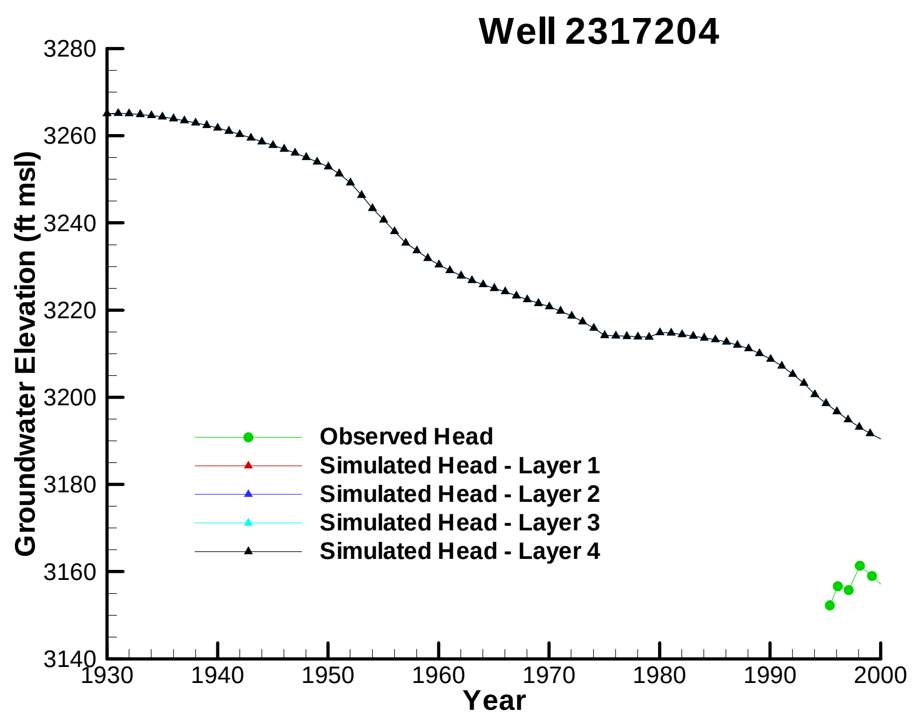

Well 2532801
Groundwater Elevation (ft msl)
Year
3820
3800
3780
3760
3740
3720
3700
3680
3660
1930
1940
1950
1960
1970
1980
1990
2000
Observed Head
Simulated Head - Layer 1
Simulated Head - Layer 2
Simulated Head - Layer 3
Simulated Head - Layer 4

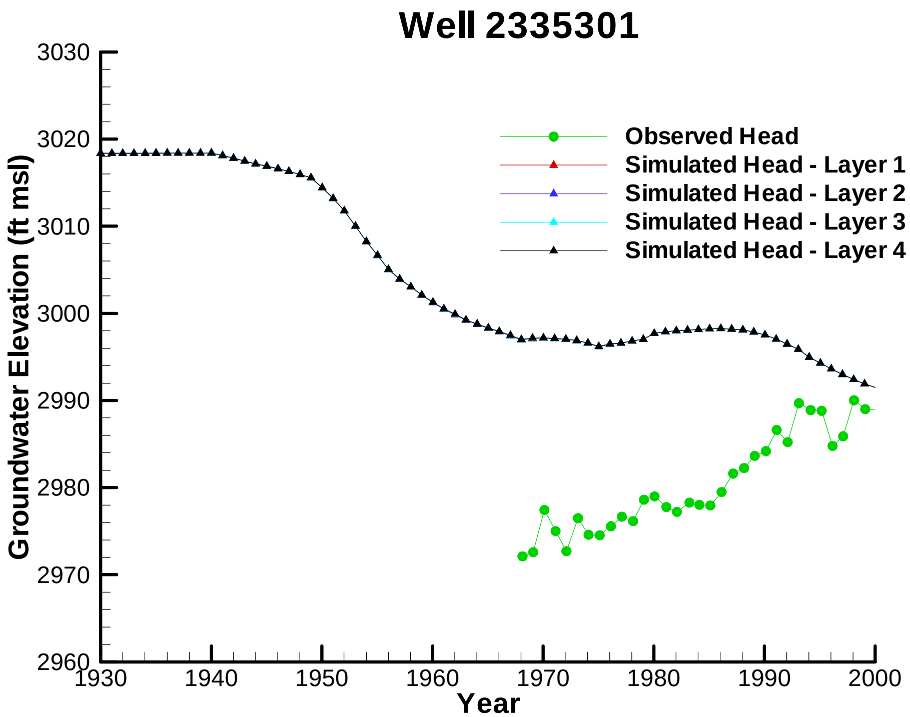

Well 2349301
Groundwater Elevation (ft msl)
Year
3115
3110
3105
3100
3095
3090
3085
3080
3075
3070
1930
1940
1950
1960
1970
1980
1990
2000
Observed Head
Simulated Head - Layer 1
Simulated Head - Layer 2
Simulated Head - Layer 3
Simulated Head - Layer 4

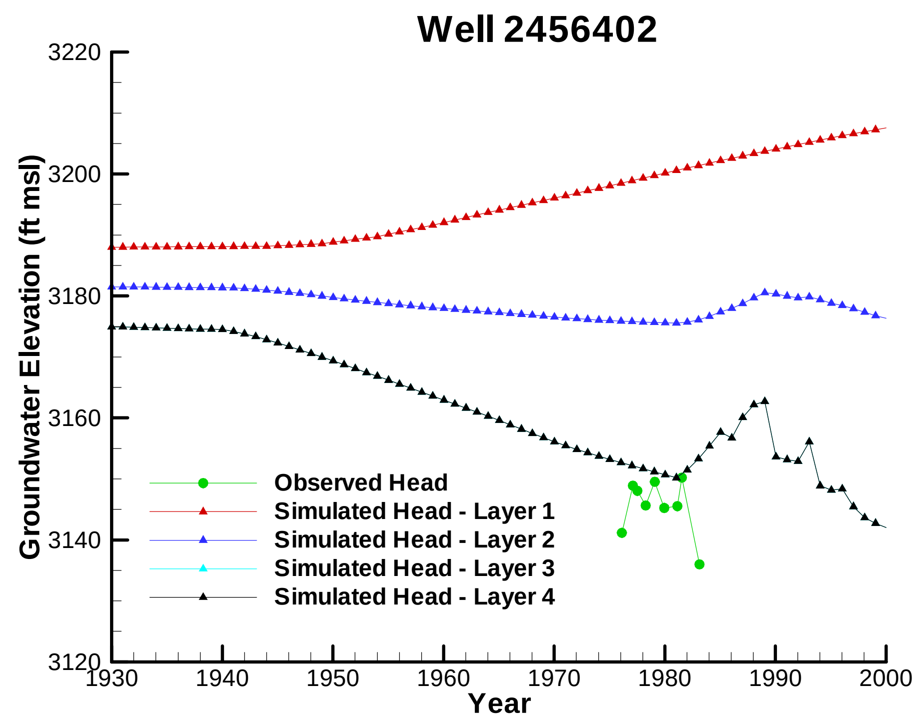

Well 2310407
Groundwater Elevation (ft msl)
Year
Observed Head
Simulated Head - Layer 1
Simulated Head - Layer 2
Simulated Head - Layer 3
Simulated Head - Layer 4

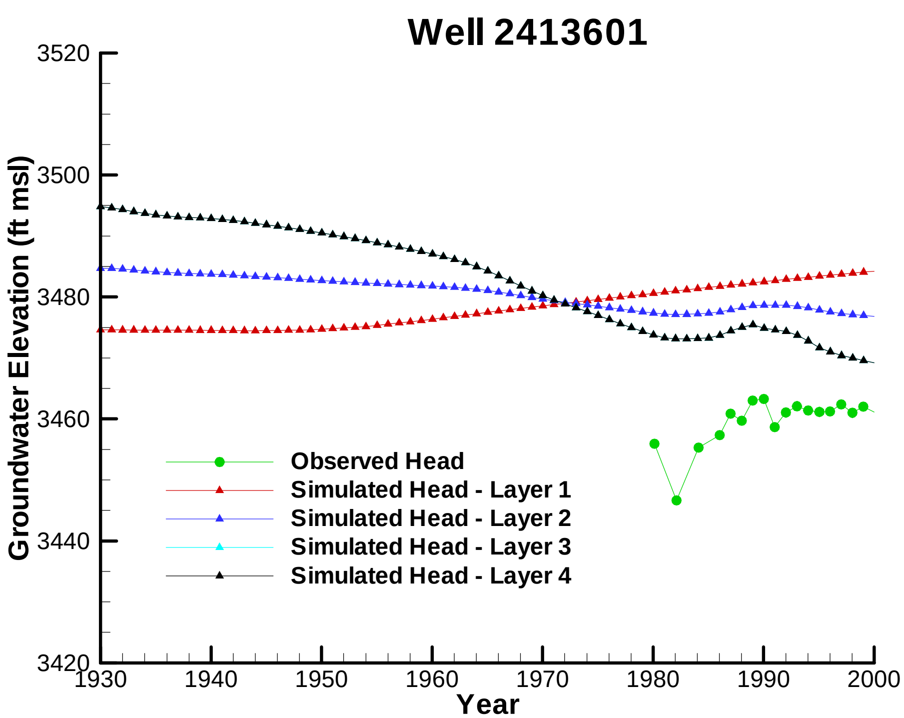

Well 2318602
Groundwater Elevation (ft msl)
Year
Observed Head
Simulated Head - Layer 1
Simulated Head - Layer 2
Simulated Head - Layer 3
Simulated Head - Layer 4

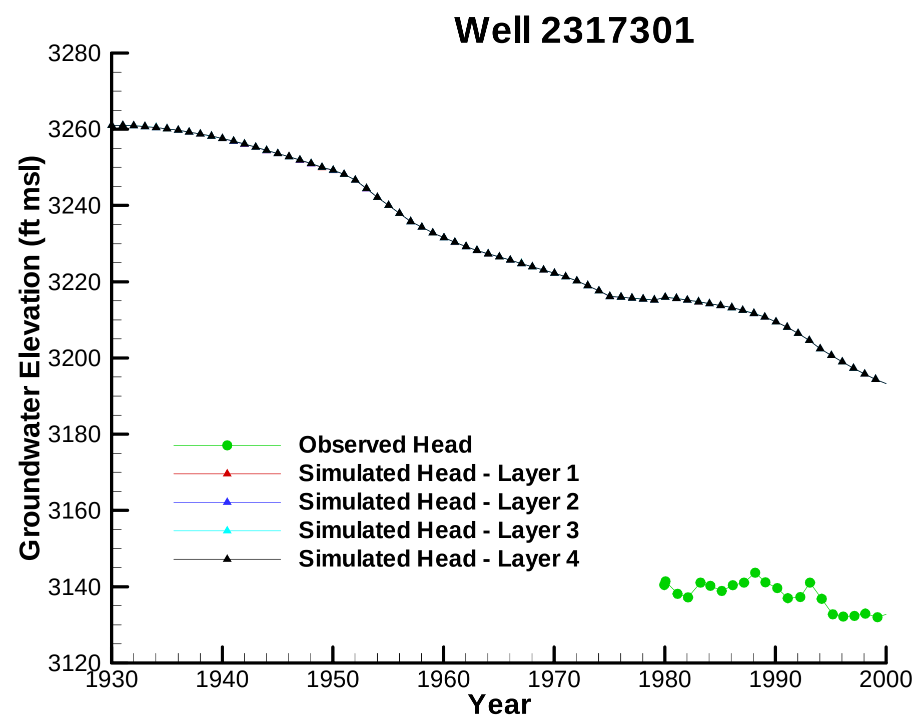

Well 2309903
Groundwater Elevation (ft msl)
Year
Observed Head
Simulated Head - Layer 1
Simulated Head - Layer 2
Simulated Head - Layer 3
Simulated Head - Layer 4

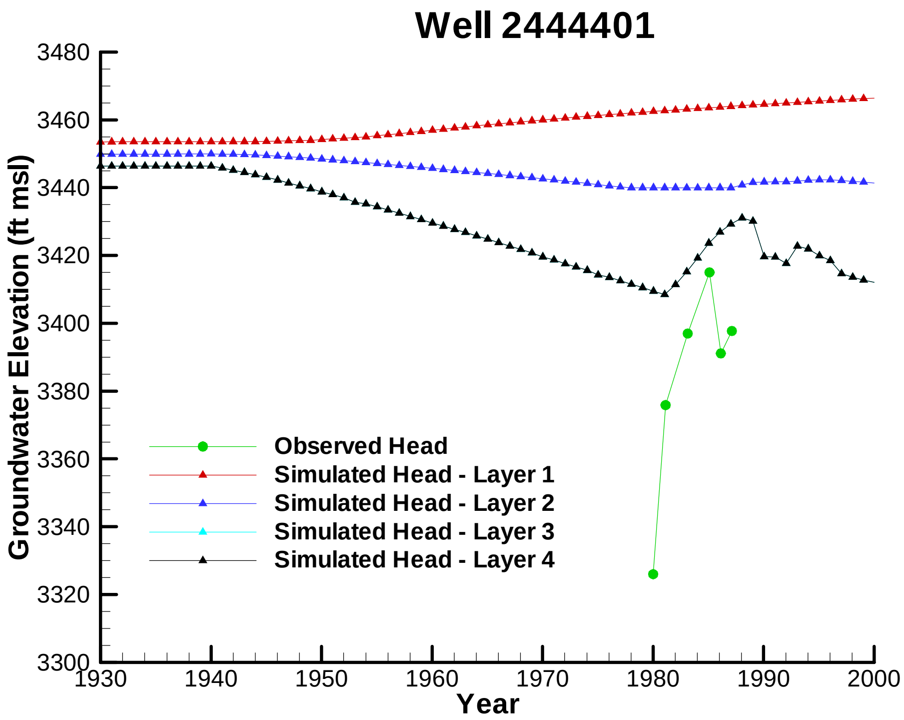

Well 2317204
Groundwater Elevation (ft msl)
Year
Observed Head
Simulated Head - Layer 1
Simulated Head - Layer 2
Simulated Head - Layer 3
Simulated Head - Layer 4


Well 2335301
Groundwater Elevation (ft msl)
3030
3020
3010
3000
2990
2980
2970
2960
1930
1940
1950
1960
1970
1980
1990
2000
Year
Observed Head
Simulated Head - Layer 1
Simulated Head - Layer 2
Simulated Head - Layer 3
Simulated Head - Layer 4

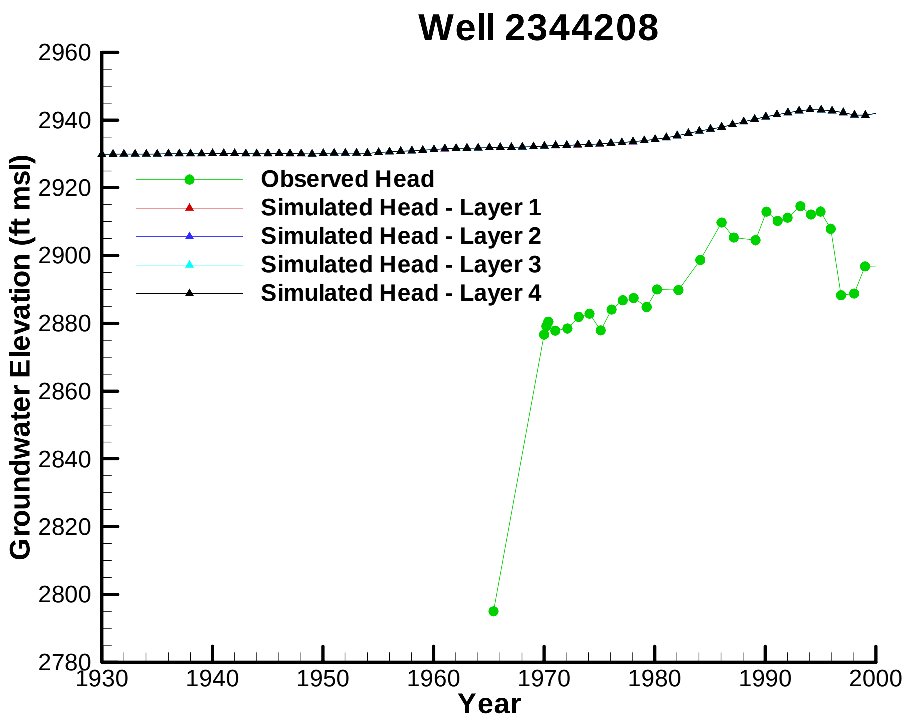

Well 2456402
Groundwater Elevation (ft msl)
3220
3200
3180
3160
3140
3120
1930
1940
1950
1960
1970
1980
1990
2000
Year
Observed Head
Simulated Head - Layer 1
Simulated Head - Layer 2
Simulated Head - Layer 3
Simulated Head - Layer 4


Well 2413601
Groundwater Elevation (ft msl)
3520
3500
3480
3460
3440
3420
1930
1940
1950
1960
1970
1980
1990
2000
Year
Observed Head
Simulated Head - Layer 1
Simulated Head - Layer 2
Simulated Head - Layer 3
Simulated Head - Layer 4

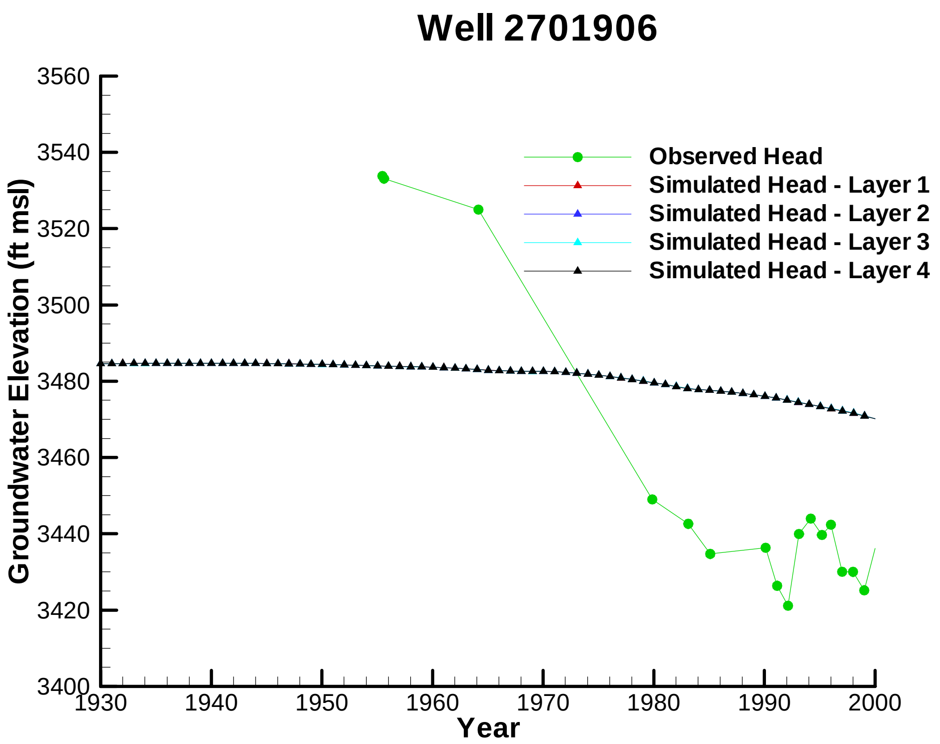

Well 2317301
Groundwater Elevation (ft msl)
3280
3260
3240
3220
3200
3180
3160
3140
3120
1930
1940
1950
1960
1970
1980
1990
2000
Year
Observed Head
Simulated Head - Layer 1
Simulated Head - Layer 2
Simulated Head - Layer 3
Simulated Head - Layer 4

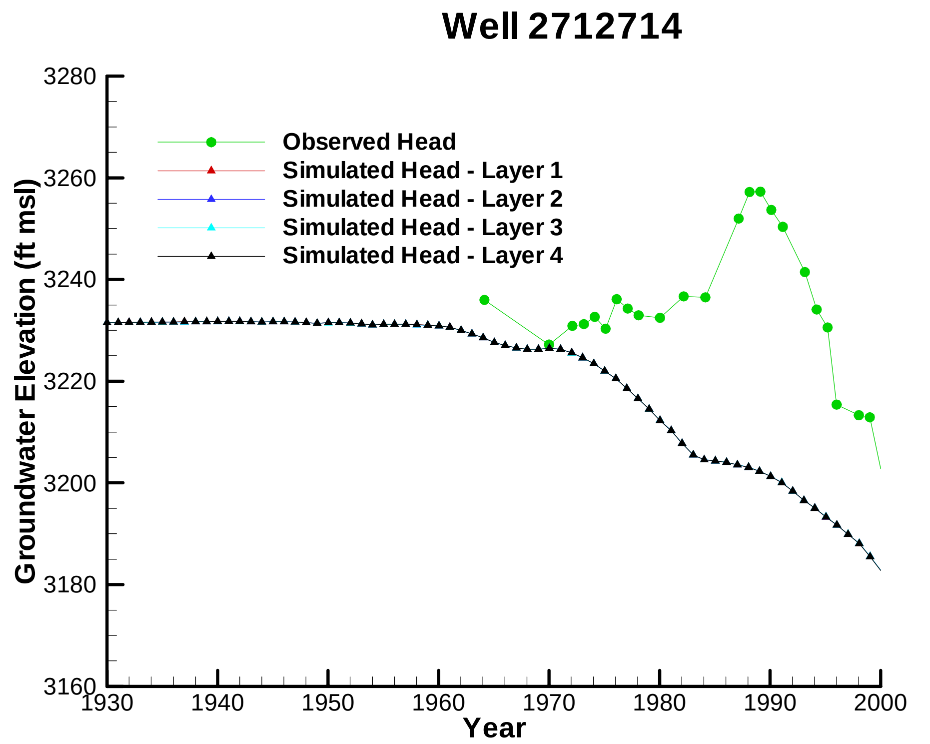


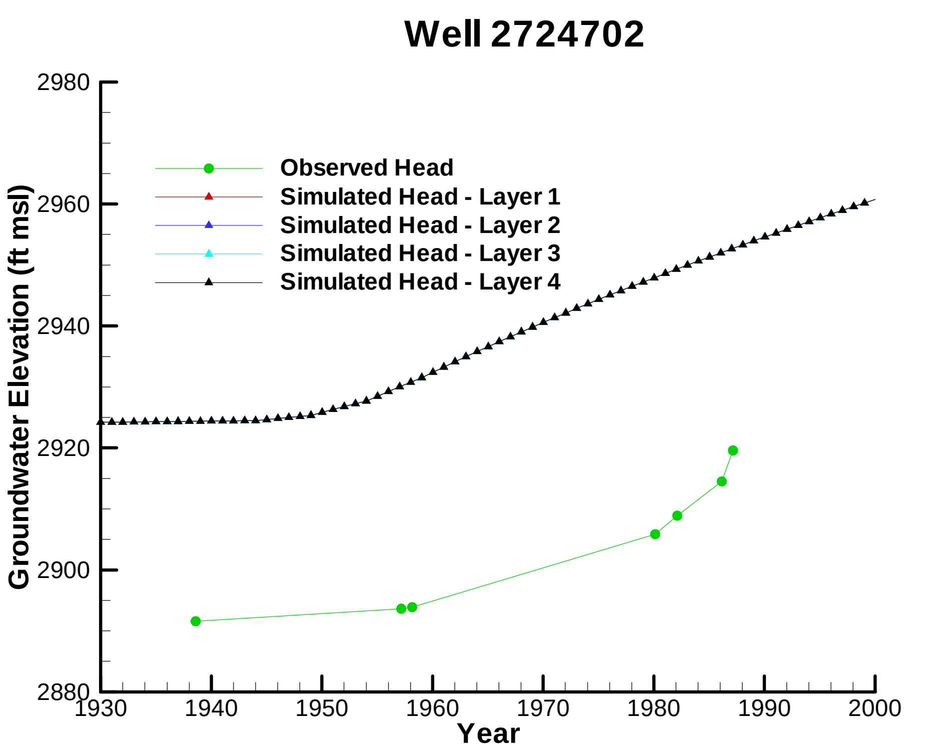
Well 2444401
Groundwater Elevation (ft msl)
Year
3480
3460
3440
3420
3400
3380
3360
3340
3320
3300
1930
1940
1950
1960
1970
1980
1990
2000
Observed Head
Simulated Head - Layer 1
Simulated Head - Layer 2
Simulated Head - Layer 3
Simulated Head - Layer 4

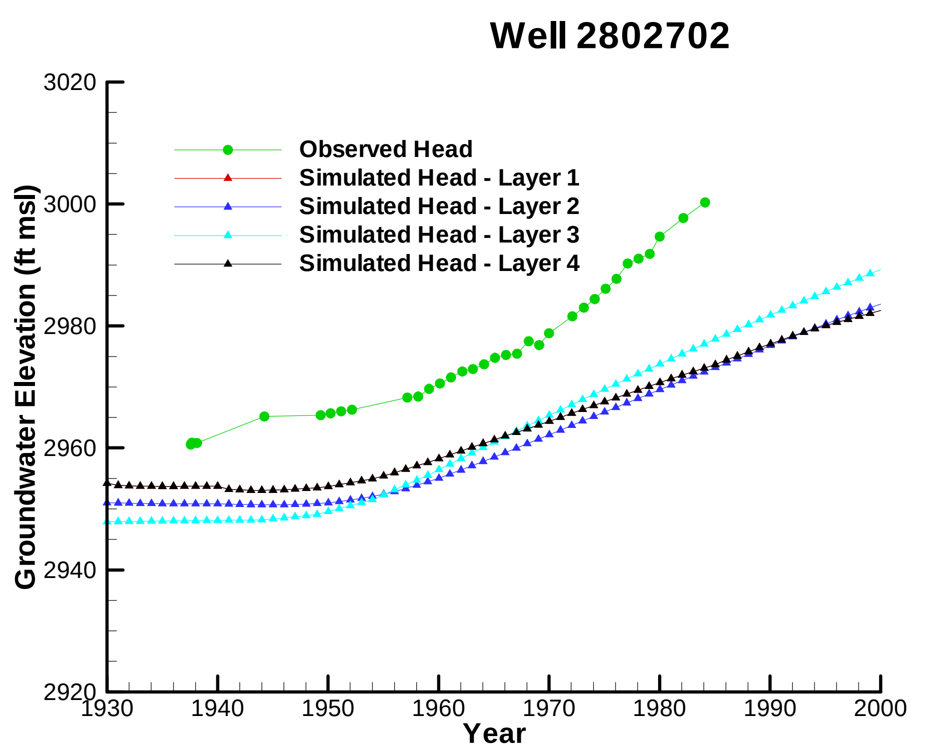


Well 2344208
Groundwater Elevation (ft msl)
Year
2960
2940
2920
2900
2880
2860
2840
2820
2800
2780
1930
1940
1950
1960
1970
1980
1990
2000
Observed Head
Simulated Head - Layer 1
Simulated Head - Layer 2
Simulated Head - Layer 3
Simulated Head - Layer 4


Well 2701906
Groundwater Elevation (ft msl)
Year
Observed Head
Simulated Head - Layer 1
Simulated Head - Layer 2
Simulated Head - Layer 3
Simulated Head - Layer 4


Well 2712714
Groundwater Elevation (ft msl)
Year
Observed Head
Simulated Head - Layer 1
Simulated Head - Layer 2
Simulated Head - Layer 3
Simulated Head - Layer 4


Well 2724702
Groundwater Elevation (ft msl)
Year
Observed Head
Simulated Head - Layer 1
Simulated Head - Layer 2
Simulated Head - Layer 3
Simulated Head - Layer 4


Well 2802702
Groundwater Elevation (ft msl)
Year
Observed Head
Simulated Head - Layer 1
Simulated Head - Layer 2
Simulated Head - Layer 3
Simulated Head - Layer 4

Appendix D

Documentation of Pumping Changes from Southern Ogallala GAM

Appendix D. Documentation of Pumping Changes from Southern Ogallala GAM

Table D-1 summarizes changes to assumed pumping for irrigated agriculture implemented in the Edwards-Trinity (High Plains) Groundwater Availability Model (GAM) versus the Southern Ogallala GAM (Blandford and others, 2003). Table D-2 provides the pumping used for irrigated agriculture for the Southern Ogallala Aquifer for each year in the transient simulation. Changes were made for three reasons:

1. To implement early pumping in selected counties prior to 1941
2. To correct some minor errors in the previous GAM because of incorrect data entry from the Texas Water Development Board (TWDB) irrigation pumping estimates
3. To enhance model calibration to transient historical conditions.

Each of these categories of changes is discussed below.

The current model begins at 1930 rather than 1940. Reports that discuss early groundwater pumping indicate that pumping and associated drawdown occurred during the 1930s in Lubbock, Floyd, Hale, Swisher, and Deaf Smith Counties (White and others, 1946; Bonnen and others, 1952). In the current model, early pumping was interpolated from zero in 1930 up to the value used in the GAM for 1943 for Deaf Smith, Floyd, Hale, and Swisher Counties.

Numerous counties have very small changes in assigned agricultural pumping that have no effect on simulation results. These changes were implemented for consistency with referenced data sources. For certain years in the Southern Ogallala GAM, where pumping estimates were taken from TWDB estimates, the “All Irrigation” estimated use was applied rather than the “Ground Water Supplied” estimate. For some counties this makes no difference because the values are the same, but for some counties the numbers are different. This correction affected certain years for Andrews, Borden, Briscoe, Dawson, Dickens, Ector, Gaines, Garza, Howard, Lynn, Midland, Motley, Parmer, Potter, Randall, and Terry Counties. Again, these changes are minimal and have no discernible effect on simulation results, but were implemented for consistency and completeness.

The most significant changes to pumping were made to assist with model calibration. These changes were made due to consideration of observation well hydrographs for Cochran, Crosby, Hockley, Lubbock, and Yoakum Counties. Pumping during the years for which agricultural pumping estimates were available were not adjusted; rather the interpolation approach between years was adjusted to better match observed water level conditions. TWDB pumping estimates are available for the years 1958, 1964, 1969, 1974, 1979, 1984, 1989, 1994, and 2000. In the Southern Ogallala GAM (Blandford and others, 2003), alternative pumping estimates completed as part of that study were implemented beginning in 1982 and subsequent years. The changes made to these counties and the reason(s) for the changes are provided below.

Cochran County. In Cochran County, the TWDB estimated groundwater pumping of 27,082 acre-feet per year (ac-ft/yr) for 1989 was also applied to the previous years of 1985 through 1988. These previous years were interpolated from the results of a study conducted as part of the Southern Ogallala GAM (Blandford and others, 2003). TWDB values were also applied for 1994 and 2000, and intermediate years were interpolated between these values. Based on review of monitor well water levels, the previous values used in the Southern Ogallala GAM appeared to be too high for the 1980s and the 1990s.

Crosby County. For Crosby County the long-term average pumping of 121,345 ac-ft/yr estimated for the Southern Ogallala GAM (Blandford and others, 2003) was applied for the years 1975 through 1978 and 1980 through 1982. From 1982 forward, applied pumping is the same as that applied by Blandford and others (2003).

Hockley County. For Hockley County, a constant value of 161,837 ac-ft/yr, which is the long-term average pumping provided in the Southern Ogallala GAM (Blandford and others, 2003), was applied for the periods 1970 through 1973 and 1975 through 1978. The TWDB estimates were used for the adjoining years 1969, 1974, and 1979. Interpolation of TWDB data led to a greater amount of estimated pumping than likely occurred based on the observed water levels.

Lubbock County. For Lubbock County, the estimated 1984 TWDB value of 114,907 ac-ft/yr was applied to the period 1980 through 1983 as well. Prior to 1983, TWDB values were used for available years and intermediate years were interpolated. Values estimated in the Southern Ogallala GAM (Blandford and others, 2003) were used for 1987, 1992, 1993, and 1997, and intermediate values were interpolated. Prior to 1958 (the first year a TWDB estimate is available), pumping values were taken from DBS&A (2007). Essentially, the 1958 value of 291,264 ac-ft/yr was applied for 1957 and 1951. Values for years prior to 1951 were obtained through linear interpolation from the 1951 value to zero as of 1930. For the intervening years of 1952 through 1956, a constant value of 378,643 ac-ft/yr was applied, which was calculated by taking 130 percent of the estimated 1958 TWDB pumping estimate. Based on hydrographs in Lubbock County, it appears that pumping was higher during this period, which also corresponds with a period of drought.

Yoakum County. For Yoakum County, the TWDB estimate of 138,651 ac-ft/yr for 1974 is believed to be abnormally high because it represented a year of low precipitation and low irrigation efficiency due to high winds. Therefore, for the years adjacent to 1974 (1970 through 1973 and 1975 through 1978), the TWDB-estimated value for 1969 of 74,295 ac-ft/yr was used. This value appeared to represent a more typical pumping estimate for this period of time.

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Table D-1. Summary of Changes in Pumping for Irrigated Agriculture Between Current Model and Southern Ogallala GAM (Blandford and others, 2003)

County	1930	1931	1932	1933	1934	1935	1936	1937	1938	1939	1940	1941	1942	1943	1944	1945
Andrews	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Armstrong	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Bailey	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Borden	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Briscoe	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Castro	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cochran	0	0	0	0	0	0	0	0	0	0	0	***921***	***1,843***	***2,764***	***4,491***	***6,218***
Crosby	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Curry	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dawson	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Deaf smith	0	***2,506***	***5,013***	***7,519***	***10,026***	***12,532***	***15,039***	***17,545***	***20,051***	***22,558***	***25,064***	***16,709***	***8,355***	0	0	0
Dickens	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ector	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Floyd	0	***1,161***	***2,321***	***3,482***	***4,642***	***5,803***	***6,963***	***8,124***	***9,285***	***10,445***	***11,606***	***7,737***	***3,869***	0	0	0
Gaines	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Garza	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Glasscock	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hale	0	***3,543***	***7,086***	***10,629***	***14,172***	***17,715***	***21,259***	***24,802***	***28,345***	***31,888***	***35,431***	***23,621***	***11,810***	0	0	0
Hockley	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Howard	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lamb	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lea	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lubbock	0	***13,870***	***27,739***	***41,609***	***55,479***	***69,349***	***83,218***	***97,088***	***110,958***	***124,827***	***138,697***	***144,800***	***150,902***	***157,005***	***156,312***	***155,618***
Lynn	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Martin	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Midland	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Motley	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Oldham	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Parmer	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Potter	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Quay	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Randall	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Roosevelt	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Swisher	0	***1,631***	***3,262***	***4,893***	***6,524***	***8,155***	***9,786***	***11,417***	***13,047***	***14,678***	***16,309***	***10,873***	***5,436***	0	0	0
Terry	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Yoakum	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table D-1. Summary of Changes in Pumping for Irrigated Agriculture Between Current Model and Southern Ogallala GAM (Blandford and others, 2003)

County	1946	1947	1948	1949	1950	1951	1952	1953	1954	1955	1956	1957	1958	1959	1960
Andrews	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Armstrong	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Bailey	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Borden	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Briscoe	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Castro	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cochran	***7,946***	***9,673***	***11,401***	***14,164***	***16,928***	***19,692***	***22,456***	***25,219***	***27,085***	***28,950***	***30,816***	***32,681***	***34,547***	***33,678***	***32,809***
Crosby	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Curry	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dawson	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Deaf smith	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dickens	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ector	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Floyd	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Gaines	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Garza	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Glasscock	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hale	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hockley	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Howard	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lamb	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lea	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lubbock	***154,925***	***154,231***	***153,538***	***144,106***	***134,675***	***125,244***	***189,322***	***166,020***	***150,292***	***134,564***	***118,836***	***15,728***	0	0	0
Lynn	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Martin	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Midland	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Motley	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Oldham	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Parmer	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Potter	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Quay	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Randall	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Roosevelt	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Swisher	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Terry	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Yoakum	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table D-1. Summary of Changes in Pumping for Irrigated Agriculture Between Current Model and Southern Ogallala GAM (Blandford and others, 2003)

County	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975
Andrews	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-50
Armstrong	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Bailey	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Borden	0	0	0	0	-3	-6	-10	-13	-16	-16	-17	-17	-18	-18	-19
Briscoe	0	0	0	0	-73	-147	-220	-294	-367	-499	-631	-762	-894	-1,026	-884
Castro	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cochran	31,940	31,071	30,202	29,333	23,466	17,600	11,733	5,867	0	0	0	0	0	0	0
Crosby	0	0	0	0	-341	-681	-1,022	-1,362	-1,703	-1,760	-1,816	-1,873	-1,929	-1,986	-73,513
Curry	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dawson	0	0	0	0	-5	-9	-14	-18	-23	-18	-14	-9	-5	0	0
Deaf smith	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dickens	0	0	0	0	-127	-254	-381	-508	-635	-561	-488	-414	-341	-267	-236
Ector	0	0	0	0	-198	-397	-595	-794	-992	-853	-715	-576	-438	-299	-303
Floyd	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Gaines	0	0	0	0	-10	-20	-30	-40	-50	-40	-30	-20	-10	0	0
Garza	0	0	0	0	-19	-38	-56	-75	-94	-75	-56	-38	-19	0	0
Glasscock	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hale	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hockley	0	0	0	0	0	0	0	0	0	-79,020	-105,181	-131,343	-157,504	0	-123,568
Howard	0	0	0	0	-25	-50	-74	-99	-124	-128	-132	-136	-140	-144	-120
Lamb	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lea	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lubbock	0	0	0	0	0	0	0	0	0	-1,625	-3,250	-4,875	-6,500	-8,125	-113,016
Lynn	0	0	0	0	-37	-73	-110	-146	-183	-168	-153	-138	-123	-108	-181
Martin	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Midland	0	0	0	0	0	0	0	0	0	-341	-682	-1,022	-1,363	-1,704	-1,863
Motley	0	0	0	0	0	0	0	0	0	-12	-24	-36	-48	-60	-55
Oldham	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Parmer	0	0	0	0	-96	-191	-287	-382	-478	-479	-480	-481	-482	-483	-490
Potter	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-840
Quay	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Randall	0	0	0	0	-207	-413	-620	-826	-1,033	-1,033	-1,033	-1,033	-1,033	-1,033	-1,213
Roosevelt	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Swisher	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Terry	0	0	0	0	0	0	0	0	0	-2,114	-4,229	-6,343	-8,458	-10,572	-8,458
Yoakum	0	0	0	0	0	0	0	0	0	-3,562	-7,124	-10,687	-14,249	46,545	-23,972

Table D-1. Summary of Changes in Pumping for Irrigated Agriculture Between Current Model and Southern Ogallala GAM (Blandford and others, 2003)

County	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989
Andrews	-100	-150	-200	-250	-167	-83	0	0	0	0	0	0	0	0
Armstrong	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Bailey	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Borden	-20	-21	-22	-23	-15	-8	0	0	0	0	0	0	0	0
Briscoe	-742	-599	-457	-315	-210	-105	0	0	0	0	0	0	0	0
Castro	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cochran	0	0	0	0	-21,208	-42,416	-63,624	-17,854	-16,232	-45,728	-28,388	-11,049	-16,888	-22,726
Crosby	-35,570	2,372	40,315	-40,708	51,152	24,047	0	0	0	0	0	0	0	0
Curry	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dawson	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Deaf smith	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dickens	-205	-174	-143	-112	-75	-37	0	0	0	0	0	0	0	0
Ector	-307	-311	-315	-319	-213	-106	0	0	0	0	0	0	0	0
Floyd	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Gaines	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Garza	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Glasscock	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hale	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hockley	-63,471	-3,374	56,723	0	-45,743	-91,486	-145,087	-104,322	-61,813	-41,209	-20,604	0	0	0
Howard	-96	-72	-48	-24	-16	-8	0	0	0	0	0	0	0	0
Lamb	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lea	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lubbock	-62,530	-12,045	38,441	-17,667	13,774	-61,379	-136,532	-95,506	-38,302	-40,862	-32,567	-34,487	-38,413	-42,339
Lynn	-255	-328	-402	-475	-317	-158	0	0	0	0	0	0	0	0
Martin	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Midland	-2,022	-2,182	-2,341	-2,500	-1,667	-833	0	0	0	0	0	0	0	0
Motley	-51	-46	-42	-37	-25	-12	0	0	0	0	0	0	0	0
Oldham	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Parmer	-497	-503	-510	-517	-345	-172	0	0	0	0	0	0	0	0
Potter	-1,680	-2,520	-3,360	-4,200	-2,800	-1,400	0	0	0	0	0	0	0	0
Quay	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Randall	-1,394	-1,574	-1,755	-1,935	-1,290	-645	0	0	0	0	0	0	0	0
Roosevelt	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Swisher	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Terry	-6,343	-4,229	-2,114	0	0	0	0	0	0	0	0	0	0	0
Yoakum	-30,133	-36,295	-42,456	0	0	0	0	0	0	0	0	0	0	0

Table D-1. Summary of Changes in Pumping for Irrigated Agriculture Between Current Model and Southern Ogallala GAM (Blandford and others, 2003)

County	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
Andrews	0	0	0	0	0	0	0	0	0	0	0
Armstrong	0	0	0	0	0	0	0	0	0	0	0
Bailey	0	0	0	0	0	0	0	0	0	0	0
Borden	0	0	0	0	0	0	0	0	0	0	0
Briscoe	0	0	0	0	0	0	0	0	0	0	0
Castro	0	0	0	0	0	0	0	0	0	0	0
Cochran	***-22,309***	***-21,891***	***-21,474***	***-19,669***	***-13,749***	***-1,409***	***10,931***	***23,271***	***38,118***	***60,288***	***82,457***
Crosby	0	0	0	0	0	0	0	0	0	0	0
Curry	0	0	0	0	0	0	0	0	0	0	0
Dawson	0	0	0	0	0	0	0	0	0	0	0
Deaf smith	0	0	0	0	0	0	0	0	0	0	0
Dickens	0	0	0	0	0	0	0	0	0	0	0
Ector	0	0	0	0	0	0	0	0	0	0	0
Floyd	0	0	0	0	0	0	0	0	0	0	0
Gaines	0	0	0	0	0	0	0	0	0	0	0
Garza	0	0	0	0	0	0	0	0	0	0	0
Glasscock	0	0	0	0	0	0	0	0	0	0	0
Hale	0	0	0	0	0	0	0	0	0	0	0
Hockley	0	0	0	0	0	0	0	0	0	0	0
Howard	0	0	0	0	0	0	0	0	0	0	0
Lamb	0	0	0	0	0	0	0	0	0	0	0
Lea	0	0	0	0	0	0	0	0	0	0	0
Lubbock	***-46,265***	***-35,429***	***-38,200***	***-42,995***	***-36,794***	***-35,143***	***-21,088***	***-20,049***	***-18,747***	***-17,446***	***-16,145***
Lynn	0	0	0	0	0	0	0	0	0	0	0
Martin	0	0	0	0	0	0	0	0	0	0	0
Midland	0	0	0	0	0	0	0	0	0	0	0
Motley	0	0	0	0	0	0	0	0	0	0	0
Oldham	0	0	0	0	0	0	0	0	0	0	0
Parmer	0	0	0	0	0	0	0	0	0	0	0
Potter	0	0	0	0	0	0	0	0	0	0	0
Quay	0	0	0	0	0	0	0	0	0	0	0
Randall	0	0	0	0	0	0	0	0	0	0	0
Roosevelt	0	0	0	0	0	0	0	0	0	0	0
Swisher	0	0	0	0	0	0	0	0	0	0	0
Terry	0	0	0	0	0	0	0	0	0	0	0
Yoakum	0	0	0	0	0	0	0	0	0	0	0

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Table D-2. Pumping for Southern Ogallala Aquifer Irrigated Agriculture Used in Edwards-Trinity (High Plains) GAM

County	1930	1931	1932	1933	1934	1935	1936	1937	1938	1939	1940	1941
Andrews	0	0	0	0	0	0	0	0	0	0	0	45
Armstrong	0	0	0	0	0	0	0	0	0	0	0	574
Bailey	0	0	0	0	0	0	0	0	0	0	0	6,850
Borden	0	0	0	0	0	0	0	0	0	0	0	22
Briscoe	0	0	0	0	0	0	0	0	0	0	0	1,035
Castro	0	0	0	0	0	0	0	0	0	0	0	9,453
Cochran	0	0	0	0	0	0	0	0	0	0	0	2,321
Crosby	0	0	0	0	0	0	0	0	0	0	0	3,711
Curry	0	0	0	0	0	0	0	0	0	0	0	0
Dawson	0	0	0	0	0	0	0	0	0	0	0	2,803
Deaf Smith	0	2,506	5,013	7,519	10,026	12,532	15,039	17,545	20,051	22,558	25,064	27,571
Dickens	0	0	0	0	0	0	0	0	0	0	0	280
Ector	0	0	0	0	0	0	0	0	0	0	0	0
Floyd	0	1,161	2,321	3,482	4,642	5,803	6,963	8,124	9,285	10,445	11,606	12,766
Gaines	0	0	0	0	0	0	0	0	0	0	0	4,092
Garza	0	0	0	0	0	0	0	0	0	0	0	400
Glasscock	0	0	0	0	0	0	0	0	0	0	0	309
Hale	0	3,543	7,086	10,629	14,172	17,715	21,259	24,802	28,345	31,888	35,431	38,974
Hockley	0	0	0	0	0	0	0	0	0	0	0	4,400
Howard	0	0	0	0	0	0	0	0	0	0	0	41
Lamb	0	0	0	0	0	0	0	0	0	0	0	10,560
Lea	0	0	0	0	0	0	0	0	0	0	3,200	1,550
Lubbock	0	13,870	27,739	41,609	55,479	69,349	83,218	97,088	110,958	124,827	138,697	152,567
Lynn	0	0	0	0	0	0	0	0	0	0	0	2,120
Martin	0	0	0	0	0	0	0	0	0	0	0	1,085
Midland	0	0	0	0	0	0	0	0	0	0	0	663
Motley	0	0	0	0	0	0	0	0	0	0	0	64
Oldham	0	0	0	0	0	0	0	0	0	0	0	643
Parmer	0	0	0	0	0	0	0	0	0	0	0	20,638
Potter	0	0	0	0	0	0	0	0	0	0	0	267
Quay	0	0	0	0	0	0	0	0	0	0	1,570	580
Randall	0	0	0	0	0	0	0	0	0	0	0	2,320
Roosevelt	0	0	0	0	0	0	0	0	0	0	25,800	9,750
Swisher	0	1,631	3,262	4,893	6,524	8,155	9,786	11,417	13,047	14,678	16,309	17,940
Terry	0	0	0	0	0	0	0	0	0	0	0	3,616
Yoakum	0	0	0	0	0	0	0	0	0	0	0	1,811

Table D-2. Pumping for Southern Ogallala Aquifer Irrigated Agriculture Used in Edwards-Trinity (High Plains) GAM

County	1942	1943	1944	1945	1946	1947	1948	1949	1950	1951	1952	1953
Andrews	91	136	221	306	391	476	561	697	833	968	1,104	1,240
Armstrong	1,147	1,721	2,796	3,872	4,947	6,023	7,098	8,819	10,539	12,260	13,981	15,702
Bailey	13,701	20,551	33,395	46,240	59,084	71,928	84,773	105,324	125,875	146,426	166,977	187,528
Borden	43	65	105	145	186	226	267	331	396	461	525	590
Briscoe	2,070	3,105	5,046	6,987	8,928	10,869	12,810	15,915	19,020	22,126	25,231	28,336
Castro	18,905	28,358	46,082	63,806	81,529	99,253	116,977	145,335	173,693	202,051	230,409	258,767
Cochran	4,641	6,962	11,314	15,665	20,016	24,368	28,719	35,681	42,643	49,605	56,568	63,530
Crosby	7,421	11,132	18,089	25,047	32,004	38,961	45,919	57,051	68,183	79,314	90,446	101,578
Curry	0	0	0	0	0	0	0	0	0	0	5,985	41,200
Dawson	5,606	8,409	13,665	18,921	24,177	29,432	34,688	43,098	51,507	59,916	68,325	76,735
Deaf Smith	30,077	32,583	52,948	73,313	93,677	114,042	134,407	166,990	199,574	232,157	264,740	297,324
Dickens	560	840	1,366	1,891	2,416	2,941	3,466	4,307	5,147	5,987	6,828	7,668
Ector	0	0	0	0	0	0	0	0	0	0	0	0
Floyd	13,927	15,087	24,517	33,947	43,376	52,806	62,235	77,323	92,410	107,497	122,585	137,672
Gaines	8,185	12,277	19,951	27,624	35,297	42,971	50,644	62,921	75,199	87,476	99,754	112,031
Garza	800	1,200	1,950	2,700	3,450	4,200	4,950	6,150	7,350	8,550	9,750	10,950
Glasscock	619	928	1,508	2,087	2,667	3,247	3,827	4,755	5,683	6,610	7,538	8,466
Hale	42,517	46,060	74,848	103,635	132,423	161,211	189,998	236,058	282,118	328,179	374,239	420,299
Hockley	8,801	13,201	21,452	29,703	37,953	46,204	54,455	67,656	80,857	94,058	107,259	120,460
Howard	82	123	199	276	353	429	506	629	751	874	996	1,119
Lamb	21,119	31,679	51,478	71,277	91,076	110,875	130,674	162,353	194,031	225,710	257,388	289,067
Lea	3,500	6,000	3,500	6,500	3,500	19,000	39,000	60,000	95,000	153,000	166,000	165,000
Lubbock	166,437	180,306	194,176	208,046	221,915	235,785	249,655	263,525	277,394	291,264	378,643	378,643
Lynn	4,240	6,360	10,335	14,310	18,285	22,260	26,235	32,595	38,955	45,316	51,676	58,036
Martin	2,169	3,254	5,288	7,322	9,355	11,389	13,423	16,677	19,931	23,185	26,439	29,693
Midland	1,326	1,989	3,233	4,476	5,719	6,962	8,206	10,195	12,184	14,174	16,163	18,152
Motley	128	192	312	432	552	672	792	984	1,176	1,369	1,561	1,753
Oldham	1,286	1,929	3,134	4,340	5,545	6,751	7,956	9,885	11,814	13,743	15,672	17,600
Parmer	41,277	61,915	100,612	139,308	178,005	216,702	255,399	317,314	379,229	441,144	503,058	564,973
Potter	533	800	1,300	1,800	2,300	2,800	3,300	4,100	4,900	5,700	6,500	7,300
Quay	2,500	3,300	2,500	4,250	6,600	7,750	4,300	2,300	6,600	8,000	5,300	5,700
Randall	4,639	6,959	11,308	15,657	20,007	24,356	28,705	35,664	42,623	49,582	56,541	63,500
Roosevelt	23,500	45,000	23,500	37,500	37,000	45,000	37,000	37,000	52,000	84,000	82,000	101,000
Swisher	19,571	21,202	34,453	47,705	60,956	74,207	87,459	108,661	129,863	151,065	172,267	193,469
Terry	7,231	10,847	17,626	24,405	31,185	37,964	44,743	55,590	66,437	77,284	88,131	98,978
Yoakum	3,622	5,433	8,828	12,224	15,619	19,015	22,410	27,843	33,276	38,709	44,142	49,574

Table D-2. Pumping for Southern Ogallala Aquifer Irrigated Agriculture Used in Edwards-Trinity (High Plains) GAM

County	1954	1955	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965
Andrews	1,332	1,424	1,516	1,607	1,699	4,148	6,597	9,046	11,495	13,944	16,393	13,354
Armstrong	16,863	18,025	19,186	20,348	21,509	25,221	28,933	32,646	36,358	40,070	43,782	41,819
Bailey	201,399	215,271	229,143	243,015	256,887	273,157	289,427	305,698	321,968	338,238	354,508	320,583
Borden	633	677	721	764	808	792	775	759	742	726	709	707
Briscoe	30,433	32,529	34,625	36,721	38,817	50,906	62,994	75,083	87,171	99,260	111,348	108,219
Castro	277,908	297,050	316,192	335,333	354,475	401,113	447,750	494,388	541,025	587,663	634,300	617,167
Cochran	68,229	72,929	77,628	82,328	87,027	89,225	91,422	93,620	95,818	98,015	100,213	93,233
Crosby	109,092	116,606	124,120	131,634	139,148	147,365	155,581	163,798	172,015	180,231	188,448	193,580
Curry	102,600	138,380	156,000	140,000	105,490	95,000	70,000	95,978	121,956	147,933	173,911	199,889
Dawson	82,411	88,087	93,763	99,440	105,116	112,394	119,672	126,950	134,227	141,505	148,783	127,460
Deaf Smith	319,318	341,312	363,305	385,299	407,293	417,602	427,910	438,219	448,528	458,836	469,145	471,621
Dickens	8,235	8,802	9,370	9,937	10,504	10,752	11,001	11,249	11,497	11,746	11,994	12,851
Ector	0	0	0	0	0	952	1,904	2,856	3,808	4,760	5,712	5,113
Floyd	147,856	158,040	168,224	178,408	188,592	199,831	211,070	222,309	233,548	244,787	256,026	268,350
Gaines	120,318	128,605	136,893	145,180	153,467	175,403	197,339	219,276	241,212	263,148	285,084	257,434
Garza	11,760	12,570	13,380	14,190	15,000	15,502	16,005	16,507	17,009	17,512	18,014	17,689
Glasscock	9,092	9,718	10,345	10,971	11,597	13,760	15,924	18,087	20,250	22,414	24,577	26,499
Hale	451,390	482,480	513,571	544,661	575,752	664,063	752,373	840,684	928,995	1,017,305	1,105,616	1,020,526
Hockley	129,371	138,282	147,192	156,103	165,014	203,842	242,670	281,499	320,327	359,155	397,983	361,326
Howard	1,202	1,285	1,367	1,450	1,533	1,639	1,744	1,850	1,956	2,061	2,167	1,985
Lamb	310,450	331,833	353,216	374,599	395,982	443,860	491,739	539,617	587,495	635,374	683,252	624,377
Lea	163,000	170,000	160,000	140,000	107,000	149,000	105,000	107,052	109,105	111,157	113,210	115,262
Lubbock	378,643	378,643	378,643	291,264	291,264	278,270	265,275	252,281	239,287	226,292	213,298	208,608
Lynn	62,329	66,622	70,915	75,208	79,501	79,429	79,356	79,284	79,212	79,139	79,067	67,912
Martin	31,889	34,086	36,282	38,479	40,675	41,507	42,338	43,170	44,002	44,833	45,665	42,369
Midland	19,495	20,838	22,180	23,523	24,866	23,196	21,526	19,857	18,187	16,517	14,847	18,563
Motley	1,882	2,012	2,142	2,271	2,401	2,674	2,947	3,220	3,492	3,765	4,038	4,657
Oldham	18,902	20,204	21,506	22,808	24,110	26,520	28,930	31,341	33,751	36,161	38,571	36,874
Parmer	606,766	648,558	690,351	732,143	773,936	740,617	707,297	673,978	640,659	607,339	574,020	557,779
Potter	7,840	8,380	8,920	9,460	10,000	12,091	14,183	16,274	18,365	20,457	22,548	22,207
Quay	5,000	5,400	3,400	3,200	3,000	4,500	2,000	2,620	3,240	3,860	4,480	5,101
Randall	68,197	72,894	77,592	82,289	86,986	97,108	107,230	117,352	127,473	137,595	147,717	135,476
Roosevelt	117,250	104,250	109,250	98,250	79,250	98,500	85,000	94,144	103,289	112,433	121,578	130,722
Swisher	207,780	222,092	236,403	250,715	265,026	299,459	333,892	368,325	402,757	437,190	471,623	451,226
Terry	106,299	113,621	120,943	128,264	135,586	141,374	147,162	152,950	158,737	164,525	170,313	147,862
Yoakum	53,241	56,909	60,576	64,243	67,910	66,896	65,882	64,868	63,853	62,839	61,825	64,319

Table D-2. Pumping for Southern Ogallala Aquifer Irrigated Agriculture Used in Edwards-Trinity (High Plains) GAM

County	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977
Andrews	10,315	7,276	4,237	1,198	2,014	2,830	3,646	4,462	5,278	5,999	6,720	7,440
Armstrong	39,856	37,894	35,931	33,968	33,236	32,504	31,772	31,040	30,308	26,814	23,320	19,825
Bailey	286,658	252,733	218,808	184,883	223,081	261,279	299,478	337,676	375,874	351,136	326,398	301,661
Borden	705	704	702	700	682	664	646	628	610	544	478	412
Briscoe	105,090	101,960	98,831	95,702	96,965	98,229	99,492	100,756	102,019	100,622	99,225	97,829
Castro	600,034	582,900	565,767	548,634	548,139	547,644	547,150	546,655	546,160	519,274	492,388	465,503
Cochran	86,253	79,272	72,292	65,312	69,362	73,413	77,463	81,514	85,564	74,070	62,576	51,083
Crosby	198,711	203,843	208,974	214,106	217,448	220,789	224,131	227,472	230,814	121,345	121,345	121,345
Curry	225,867	251,844	277,822	227,850	228,030	228,210	228,390	228,570	228,750	228,930	221,456	213,981
Dawson	106,137	84,815	63,492	42,169	39,984	37,799	35,615	33,430	31,245	26,936	22,627	18,318
Deaf Smith	474,097	476,573	479,049	481,525	488,180	494,835	501,489	508,144	514,799	474,980	435,162	395,343
Dickens	13,709	14,566	15,424	16,281	16,029	15,777	15,525	15,273	15,021	12,650	10,279	7,909
Ector	4,514	3,914	3,315	2,716	2,834	2,953	3,071	3,190	3,308	3,321	3,334	3,348
Floyd	280,674	292,998	305,322	317,646	311,597	305,548	299,498	293,449	287,400	265,314	243,227	221,141
Gaines	229,784	202,135	174,485	146,835	179,633	212,431	245,230	278,028	310,826	331,267	351,708	372,150
Garza	17,364	17,040	16,715	16,390	16,245	16,101	15,956	15,812	15,667	14,912	14,158	13,403
Glasscock	28,420	30,342	32,263	34,185	38,369	42,552	46,736	50,919	55,103	51,874	48,644	45,415
Hale	935,436	850,347	765,257	680,167	709,405	738,643	767,881	797,119	826,357	732,475	638,594	544,712
Hockley	324,668	288,011	251,353	214,696	161,837	161,837	161,837	161,837	345,502	161,837	161,837	161,837
Howard	1,802	1,620	1,437	1,255	1,476	1,697	1,918	2,139	2,360	2,054	1,749	1,443
Lamb	565,501	506,626	447,750	388,875	393,874	398,874	403,873	408,873	413,872	395,104	376,336	357,569
Lea	117,315	119,367	121,420	123,472	123,114	122,755	122,397	122,038	121,680	121,321	117,709	114,097
Lubbock	203,919	199,229	194,540	189,850	205,937	222,024	238,110	254,197	270,284	114,907	114,907	114,907
Lynn	56,758	45,603	34,449	23,294	33,090	42,886	52,682	62,478	72,274	65,382	58,490	51,599
Martin	39,074	35,778	32,483	29,187	29,315	29,442	29,570	29,697	29,825	26,985	24,145	21,305
Midland	22,280	25,996	29,713	33,429	33,894	34,359	34,823	35,288	35,753	33,017	30,280	27,544
Motley	5,275	5,894	6,512	7,131	7,005	6,878	6,752	6,625	6,499	5,787	5,075	4,362
Oldham	35,176	33,479	31,781	30,084	30,405	30,726	31,046	31,367	31,688	28,695	25,702	22,708
Parmer	541,539	525,298	509,058	492,817	515,296	537,776	560,255	582,735	605,214	602,629	600,044	597,459
Potter	21,866	21,526	21,185	20,844	21,541	22,237	22,934	23,630	24,327	22,765	21,202	19,640
Quay	5,721	6,341	6,961	5,686	6,972	8,257	9,543	10,829	12,115	13,400	12,597	11,793
Randall	123,235	110,994	98,753	86,512	88,380	90,247	92,115	93,982	95,850	92,284	88,718	85,152
Roosevelt	139,867	149,011	158,156	125,475	134,420	143,365	152,310	161,255	170,200	179,145	168,659	158,172
Swisher	430,829	410,431	390,034	369,637	390,685	411,733	432,782	453,830	474,878	411,493	348,108	284,722
Terry	125,411	102,959	80,508	58,057	57,497	56,936	56,376	55,815	55,255	55,746	56,238	56,729
Yoakum	66,813	69,307	71,801	74,295	74,295	74,295	74,295	74,295	138,651	74,295	74,295	74,295

Table D-2. Pumping for Southern Ogallala Aquifer Irrigated Agriculture Used in Edwards-Trinity (High Plains) GAM

County	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989
Andrews	8,161	8,882	11,724	14,565	17,407	34,009	11,563	9,802	8,040	6,279	6,567	6,856
Armstrong	16,331	12,837	8,603	4,368	134	98	125	109	93	77	90	103
Bailey	276,923	252,185	241,234	230,283	219,333	162,324	131,751	116,946	102,142	87,338	92,800	98,263
Borden	346	280	550	820	1,089	0	168	427	687	947	1,377	1,807
Briscoe	96,432	95,035	76,566	58,097	39,628	34,208	28,312	26,388	24,463	22,538	24,182	25,826
Castro	438,617	411,731	432,545	453,358	474,172	401,774	416,520	362,757	308,994	255,231	264,962	274,692
Cochran	39,589	28,095	37,259	46,424	55,588	64,753	73,917	27,082	27,082	27,082	27,082	27,082
Crosby	121,345	2,380	121,345	121,345	124,402	158,593	163,163	132,632	102,102	71,572	87,992	104,412
Curry	206,507	199,032	191,558	195,052	134,694	96,177	102,397	94,998	87,598	80,199	85,876	91,552
Dawson	14,009	9,700	20,920	32,140	43,361	41,475	38,078	33,129	28,179	23,229	24,836	26,442
Deaf Smith	355,525	315,706	310,276	304,847	299,417	259,146	220,633	203,275	185,916	168,558	175,327	182,096
Dickens	5,538	3,167	4,338	5,510	6,681	3,578	4,952	3,710	2,469	1,228	1,390	1,552
Ector	3,361	3,374	3,290	3,206	3,122	0	0	941	1,882	2,823	2,258	1,694
Floyd	199,054	176,968	225,799	274,630	323,462	233,128	255,234	220,680	186,125	151,571	164,023	176,475
Gaines	392,591	413,032	402,774	392,515	382,257	289,984	229,689	221,556	213,423	205,290	221,904	238,517
Garza	12,649	11,894	9,939	7,984	6,029	6,587	7,353	6,044	4,736	3,427	3,599	3,770
Glasscock	42,185	38,956	27,689	16,421	5,154	5,515	5,167	4,486	3,805	3,124	3,354	3,584
Hale	450,831	356,949	393,384	429,819	466,255	408,155	423,736	368,185	312,635	257,084	280,884	304,684
Hockley	161,837	45,017	56,205	67,394	70,724	80,794	90,863	84,668	78,473	72,278	88,764	105,251
Howard	1,138	832	4,434	8,036	11,638	3,104	3,812	3,164	2,515	1,867	2,940	4,012
Lamb	338,801	320,033	350,219	380,405	410,591	337,142	289,552	267,542	245,531	223,520	231,753	239,985
Lea	110,484	106,872	103,260	75,046	46,833	26,548	23,083	29,932	36,782	43,631	46,344	49,057
Lubbock	114,907	8,313	114,907	114,907	114,907	114,907	114,907	122,587	130,268	137,948	153,652	169,356
Lynn	44,707	37,815	37,826	37,837	37,848	48,882	53,493	45,285	37,076	28,868	36,918	44,968
Martin	18,465	15,625	14,365	13,105	11,846	13,505	9,509	7,879	6,250	4,621	6,337	8,053
Midland	24,807	22,071	17,202	12,334	7,465	2,693	2,898	3,309	3,719	4,130	4,304	4,479
Motley	3,650	2,938	2,158	1,378	598	433	555	518	482	445	431	418
Oldham	19,715	16,722	21,286	25,850	30,414	26,995	24,085	22,358	20,632	18,906	18,730	18,554
Parmer	594,874	592,289	544,908	497,527	450,146	369,520	349,416	303,510	257,604	211,698	221,608	231,519
Potter	18,077	16,515	14,853	13,192	11,530	25,692	37,689	29,737	21,785	13,833	13,590	13,347
Quay	10,990	10,186	9,383	6,490	469	299	311	309	306	304	311	318
Randall	81,586	78,020	53,189	28,359	3,528	31,438	48,629	42,073	35,516	28,960	30,031	31,103
Roosevelt	147,686	137,199	126,713	146,245	123,539	62,509	62,394	64,003	65,612	67,221	74,362	81,503
Swisher	221,337	157,952	208,865	259,777	310,690	269,198	306,589	248,572	190,556	132,539	138,235	143,931
Terry	57,221	57,712	75,337	92,963	110,588	166,635	137,174	115,615	94,057	72,499	85,396	98,293
Yoakum	74,295	122,912	116,458	110,003	103,549	71,398	63,702	46,573	29,444	12,315	27,290	42,266

Table D-2. Pumping for Southern Ogallala Aquifer Irrigated Agriculture Used in Edwards-Trinity (High Plains) GAM

County	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
Andrews	7,144	7,432	7,720	5,136	5,963	9,745	13,527	17,309	17,012	16,715	16,418
Armstrong	116	129	143	117	129	107	85	63	2,291	4,519	6,747
Bailey	103,725	109,188	114,650	126,044	112,432	102,866	93,301	83,736	116,760	140,481	164,201
Borden	2,236	2,666	3,096	0	2,803	3,824	4,844	5,864	4,182	2,501	819
Briscoe	27,470	29,115	30,759	36,299	33,584	27,208	20,831	14,455	19,110	23,766	28,421
Castro	284,423	294,154	303,885	368,552	160,445	200,976	241,508	282,039	273,989	265,938	257,888
Cochran	33,338	39,594	45,849	52,105	58,361	68,632	78,902	89,173	99,444	109,714	119,985
Crosby	120,832	137,252	153,672	193,050	154,332	139,208	124,083	108,959	101,561	94,164	86,766
Curry	97,229	102,906	108,583	115,350	138,782	123,490	108,197	92,905	118,523	118,523	118,523
Dawson	28,049	29,656	31,262	53,333	54,051	67,834	81,617	95,400	75,758	56,117	36,475
Deaf Smith	188,864	195,633	202,402	240,951	221,386	205,100	188,813	172,527	197,727	222,927	248,127
Dickens	1,715	1,877	2,039	1,279	2,060	3,548	5,036	6,524	5,613	4,703	3,792
Ector	1,129	565	0	0	0	1,181	2,361	3,542	4,237	4,932	5,627
Floyd	188,926	201,378	213,830	231,136	215,910	190,142	164,373	138,604	127,998	117,392	106,786
Gaines	255,131	271,745	288,359	273,429	290,208	285,230	280,251	275,273	322,347	338,835	355,323
Garza	3,942	4,113	4,285	5,390	8,998	10,915	12,831	14,748	10,385	6,022	1,660
Glasscock	3,814	4,044	4,274	4,073	5,324	5,681	6,038	6,395	5,562	4,729	3,896
Hale	328,485	352,285	376,085	398,524	385,001	333,003	281,006	229,009	255,399	281,788	308,178
Hockley	121,737	138,223	154,710	157,774	167,341	156,015	144,689	133,363	126,689	105,196	83,704
Howard	5,085	6,157	7,230	3,837	2,473	2,893	3,313	3,733	4,055	4,378	4,700
Lamb	248,217	256,449	264,681	290,859	271,773	250,205	228,638	207,070	247,625	265,172	282,719
Lea	51,770	54,484	57,197	32,847	34,537	38,665	42,793	46,921	46,745	46,745	46,745
Lubbock	185,060	200,764	216,468	243,639	208,500	199,146	189,791	180,437	168,727	157,016	145,306
Lynn	53,018	61,068	69,117	54,541	54,445	52,036	49,627	47,218	40,966	34,713	28,461
Martin	9,769	11,486	13,202	14,166	12,568	11,773	10,979	10,184	11,419	12,653	13,888
Midland	4,653	4,828	5,002	2,530	3,686	4,508	5,329	6,151	5,235	4,320	3,404
Motley	404	391	377	238	442	430	418	406	811	1,217	1,622
Oldham	18,377	18,201	18,025	11,776	18,144	21,201	24,257	27,314	26,859	26,403	25,948
Parmer	241,429	251,339	261,250	327,375	300,227	271,614	243,001	214,388	239,047	263,705	288,364
Potter	13,104	12,861	12,618	11,275	12,038	13,541	15,045	16,548	16,862	17,176	17,490
Quay	325	332	339	158	184	255	326	397	499	499	499
Randall	32,174	33,246	34,317	36,216	37,554	37,766	37,978	38,190	43,034	47,878	52,722
Roosevelt	88,644	95,785	102,926	95,996	103,046	101,732	100,417	99,103	98,687	98,687	98,687
Swisher	149,627	155,324	161,020	184,368	185,382	157,950	130,517	103,085	102,958	102,832	102,705
Terry	111,189	124,086	136,983	150,511	142,005	145,810	149,616	153,421	148,647	126,826	105,005
Yoakum	57,241	72,217	87,192	68,850	89,216	98,970	108,724	118,479	116,070	100,498	84,925

Appendix E

Draft Conceptual Model Report Comments and Responses

Edwards-Trinity (High Plains) GAM
Conceptual Model Report
Comments

Global comments -

Please capitalize ‘aquifer’ when it appears as part of an aquifer name.

Comment implemented.

Please change term ‘Southern Ogallala aquifer’ to ‘Ogallala Aquifer’.

Aquifer name not changed to maintain consistency with TWDB terminology and other references that could not be changed, such as ‘Southern Ogallala GAM’. ‘Aquifer’ has been capitalized.

In figures, please change ‘High Plains boundary’ to ‘Ogallala boundary’.

Comment implemented.

The area where the Edwards-Trinity (High Plains) Aquifer is discontinuous or absent that straddles the Texas-New Mexico border has a solid line that should be changed to a dashed line.

Comment implemented.

The term ‘recharge’ should be used only to describe groundwater inflows from precipitation. Because the Edwards-Trinity (High Plains) Aquifer is not widely exposed at land surface, please substitute the term ‘recharge’ in the text with ‘groundwater inflow’.

Comment implemented.

In the Discharge Section, please discuss why there is apparently no municipal or rural domestic pumping from the Edwards-Trinity (High Plains) Aquifer. Please discuss pumping from the Edwards-Trinity (High Plains) Aquifer in New Mexico.

Comment implemented.

In the Water quality section, please add more details, such as, groundwater major element compositions, potential indicators of cross-formational flow from Dockum Aquifer, and a water quality map.

Comment implemented.

Page	Paragraph	Sentence	Comment
1	3		Please change ‘Underground Water Conservation Districts (UWCDs)’ to ‘Groundwater Conservation Districts (GCDs)’ *Comment implemented*
1	3		Please spell out ‘GAM’ (groundwater availability model [ing]). *Comment implemented.*
1	4		Please change ‘Planning Area F’ to ‘Regional Water Planning Area F’ *Comment implemented.*
2	4		The Pecos Valley and Edwards Plateau sections of the great Plains physiographic province lie outside of the study area, please delete all reference to them. *Comment implemented.*
2	8		Please point out that the Edwards-Trinity (High Plains) aquifer is not exposed at land surface and that consequently soils do not have a direct influence on the aquifer hydrology. *Comment implemented.*
2	9		Please delete the phrase ‘,during growing season’ *Comment implemented.*
2	10		The grid with 63 in/yr of average annual lake evaporation occurs in the <u>western</u> part of the study area, not the <u>north. Please correct text.</u> *Comment implemented.*
2	10	1	Physiography and Climate Section on page 2 describes spatial variability of precipitation however per contract Exhibit B, Attachment 1, Section 3.3.1,Physiography and Climate, bullets: this section should include descriptions and maps of spatial and temporal variability. Please add discussion on temporal variability. *Comment implemented.*

Page	Paragraph	Sentence	Comment
2	10	2	Physiography and Climate Section on page 2 describes spatial variability of evaporation however per contract Exhibit B, Attachment 1, Section 3.3.1,Physiography and Climate, bullets: this section should include descriptions and maps of spatial and temporal variability. Please add discussion on temporal variability. *Comment implemented.*
3	1		There is no reference to the Permian basin in Figure 14. Please either delete the first reference to Figure 14 in this paragraph or add 'Permian basin' to the figure. *Comment implemented. Term was removed from the text.*
3	2		It is not clear how this paragraph is relevant to the study. Please either delete it or revise the text. *Text revised but not deleted; it provides general geologic background of the study area.*
3	5		Please make the legend in Figure 17 consistent with formation names that appear in the text. *Comment implemented.*
3	6		Please include a more detailed description of the Cretaceous formations in this paragraph. *Comment implemented.*
4	6	1	Data Collection and Analysis Section on page 4 cites Brand (1953), please update the References Section with related information. *Comment implemented.*
5	2	1	Stratigraphic Interpretation Section on page 5 cites Leggat (1952), please update the References Section with related information. *Comment implemented.*
5	4	3	Previous Work Section on page 5 cites Blandford and Blazer (2004), please update the References Section with related information. *Comment implemented.*

Page	Paragraph	Sentence	Comment
6	3		Please change ‘top of Dockum Group’ to ‘base of Antlers Sand’. *Comment implemented.*
7	2		Please discuss any differences between the top of the Dockum Group in this study and McGowen and others (1977). *Comment implemented.*
8	1	7	Water Levels and Regional Groundwater Flow Section cites Scanlon and others (2007), please update the References Section with related information. *Comment implemented.*
8	3		Please change ‘removed the Cretaceous formations’ to ‘removed the Duck Creek and Kiamichi formations’. *Statement is as intended* - *comment not implemented.*
8	4		Please change ‘the Cretaceous section’ to ‘the Duck Creek and Kiamichi formations’. *Statement is as intended* - *comment not implemented.*
8	5		Please change ‘Some recharge…’ to ‘Groundwater inflow to the Edwards-Trinity (High Plains) Aquifer …’ *Comment implemented.*
11	1		Please add references for the storativity and specific yield values cited. *Comment implemented.*
11	4		Please clarify how Figure 40 shows irrigated land. There should be a legend indicating color codes for irrigated land in the satellite photo. *Comment implemented.*

Figures	Comments
2	Suggest updating labels for Regional Water Planning Groups to gray to match outline color in legend and possibly using a larger font size to distinguish this category from groundwater conservation districts. *Comment implemented.*

Figures	Comments
3	Please clarify why the Canadian and Red rivers are solid lines and Brazos is dashed. Also suggest using blue or another color to highlight rivers as the dashed and solid lines represent discontinuous or absent aquifer and model boundaries and it is difficult to determine which is which. *Figure amended and river basin boundaries made consistent between one another.*
4	Suggest labeling cities within the study area in this figure. *Figure amended.*
5	Please focus figure on the study area. *Figure amended.*
7	Please change elevation intervals to logical intervals arranged in decreasing order (e.g., 4,000 – 3,600, 3,600 – 3,200, …). *Figure amended.*
10	Please add additional isohyetal lines around precipitation station in Lubbock County with 18.7 average annual precipitation as this value is not between 19 and 20 inches per year. *Figure amended.*
12	Please add additional isothermal lines delineating weather station in Floyd County as average annual temperature values shown of 58 is not between 59 and 60 degrees Fahrenheit. The outline of aquifer should be a solid line. *Figure amended.*
13	Please specify units of lake evaporation. *Figure amended.*
16	Figure 16 cites Walker (1979) as a source, please update the References Section with related information. *Comment implemented.*
NA	Per contract Exhibit B, Attachment 1, Section 4.4.2, Final Report Section 4.8 states maps of water quality (total dissolved solids and any other constituents of concern) should be included. Please update the report with a figure showing total dissolved *Figure added.*
17	Please replace codes with formation names in legend. Suggest simplification to reduce size of the legend and make the figure more meaningful to readers. *Figure amended.*

Figures	Comments
18	Please adjust outline of the aquifer to a solid line *Figure amended.*
19 & 20	Please revise text on hydrogeologic unit nomenclature to be consistent with those in Figure 16. *Text consistent with Figure 16 already - comment not implemented.*
21	Please change figure caption to ‘Elevation of Base of Edwards-Trinity (High Plains) Aquifer. *Figure amended.*
22 through 24	Please reduce the number of contours *Figure amended.*
21 through 27	Please label contours to be consistent with Figures 28 through 31 *Figure amended.*
25 through 27	Suggest using color fill to supplement the contour lines to help convey complexity of surface. *Suggestion not implemented.*
27	Please reduce the number of contours. *Figure amended.*
36 & Table 2	Please adjust figure and table to show springs and lakes that receive discharge from the Edwards-Trinity (High Plains) Aquifer. *The geologic unit that each spring emanates from is already listed in Table 2 if it was available from the source data. For most of the springs, the aquifer is not designated in the source data.*
38	Please add New Mexico pumping to this figure *New Mexico Edwards-Trinity (High Plains) Aquifer pumping is assumed to be zero. Section on groundwater pumping amended to discuss New Mexico.*
41	Suggest adding leakage symbol between Duck Creek/Kiamichi and Edwards/Comanche Peak/ Walnut formations. Needs a figure showing how the conceptual model is translated into the computer model. *Figure amended and figure added.*

Figures	Comments
Table 1	Please include New Mexico pumping data. *New Mexico Edwards-Trinity (High Plains) Aquifer pumping is assumed to be zero. Section on groundwater pumping amended to discuss New Mexico.*

Appendix F

Draft Completion Report Comments and Responses

Edwards-Trinity (High Plains) Aquifer groundwater availability model draft-final report and deliverables to the Texas Water Development Board

Contract number 0604830589

REQUIRED CHANGES

General Draft Final Report comments:

1. Please proofread the report before submitting, looking for spelling and grammatical errors per contract Exhibit B, Attachment 3, Section 5.0. Please remember to submit final report with separate text (MS Word), tables (MS Excel), and figures (vector/raster based file format).

Report has been proof read and requested files are being submitted.

2. The conceptual model and the groundwater flow model indicate a no-flow boundary between Ogallala and Edwards-Trinity (High Plains) aquifers and the underlying Dockum Aquifer. However, the sections on sensitivity analysis imply inter-aquifer flow involving the Dockum Aquifer (Figures 74, 75, 102, and 103). Please explicitly discuss this and revise the conceptual model, if necessary.

This issue was discussed in Section 4.4 (Recharge) and Section 4.7 (Discharge), and some additional discussion has been added to Section 5.0 (Conceptual Model). Figure 41 has been revised to illustrate the potential for exchange of water between the Edwards-Trinity (High Plains) and Dockum Aquifers. The approach followed during model development was that this component of flow, to the extent it exists, is considered small enough to be ignored. This assumption was evaluated in the model sensitivity analysis (hence the figures referenced above). Some additional discussion regarding the assumed Dockum leakage numbers used in the sensitivity analysis was added to Section 8.5 (Sensitivity Analysis) of the final report.

3. Per contract, Exhibit B, Attachment 1, Section 3.2.3, Model extents and boundaries: Please use a consistent definition of the study area covering the entire model area because Ogallala Aquifer portion of the model was updated. The figures should all reflect the full extent of the study area.

The definition of "study area" has been changed to refer to the entire model area in the figures and at numerous locations in the text. Some figure extents were changed, but most were not. Figure extents were selected based on the information being presented; many figures focus on the extent of the Edwards-Trinity (High Plains) Aquifer because information or simulation results relevant to that aquifer are the main point of the figure. This approach was approved by TWDB.

4. Per contract, Exhibit B, Attachment 3, please spell out all abbreviations, except TWDB.

Abbreviation and acronym definitions have been added or revised as appropriate.

5. Per contract, Exhibit B, Attachment 3, Section 2.2.2: the county boundaries in many of the figures are too faint to be seen easily. Please revise them.

The county boundaries in the figures have been made darker.

6. Please check the url's referenced in the text to make sure they open to the appropriate destination.

The url's referenced in the text have been checked and revised as appropriate.

7. The plots often have different intervals (scales) on the y-axis. Please keep consistent (y-axis) interval in the plots.

Consistent y-axis scales were used where appropriate.

8. Order of tables in report differs from the order listed after the Table of Contents. Please keep ordering system consistent throughout the report.

The table order was correct as provided. Regardless, the Table of Contents has been updated to account for table and figure number changes required to respond to other comments.

9. Page 1, Section 1.0 Abstract: Please remove additional period after last sentence of first paragraph.

Edit made.

10. Page 3: The Edwards-Trinity (High Plains) Aquifer underlies <u>13</u> counties in Texas and <u>2</u> counties in New Mexico, please revise the text to reflect this.

The number of counties is correct as listed in the draft report; this edit was not made.

11. Page 6, paragraph 1: Please delete space in sixth line of first paragraph.

Edit made.

12. Page 19, paragraph 5; Page 20, paragraph 8; and Page 21, paragraph 3: Please change "fig. 41" to "figure 42".

The correct figure number is now referenced, subject to updated figure numbering required by other comments below.

13. Page 23, paragraph 4: Please delete "…up to…".

Edit made.

14. Page 26, paragraph 2: Please change "occurred" to "occur".

Edit made.

Draft Final Report Comments:

15. Section 9.0: Please add justification of why the steady-state model run is divided into 18,982 time steps.

Additional explanation of the steady-state simulation approach was added to the first paragraph under Section 8.0.

16. Page 28, paragraph 4: The goal of sensitivity analysis is to determine the uncertainties associated with calibration values for selected parameters. Insensitive parameters have high uncertainty, in other words, the model will remain calibrated over a wide range of values, while sensitive parameters have relatively low uncertainties. Please revise the text to reflect this.

Text not revised. Parameter sensitivity and certainty are not necessarily related.

17. Page 29. paragraph 5: Please include the Ogallala Aquifer calibration statistics from the previous version of the model.

The MAE and ME calibration statistics are the same between models, as now noted at the end of the third paragraph in Section 8.1 of the final report.

18. Please combine figures 54 and 55, figures 59 and 61, and figures 60 and 61. As a result of this, figures 55 and 61 will become redundant and can be deleted.

Draft report Figures 55 and 61 have been deleted. The information on Figure 61 was incorporated into Figures 59 and 60 (renumbered Figures 57 and 58 in final report). Figures 54 and 55 were combined, but the observed data points obscured large regions of the plotted contours. Therefore, the data points were removed to make the Ogallala predevelopment calibration figure (fig. 52 in final report) consistent with the other Ogallala calibration figures (figs. 73 and 76 in final report). The locations of the observed data points used to construct the observed contours in Figure 52 are provided in Figure 55. All required figure renumbering and changes to text have been made.

19. Please explicitly state that Layer 2 in the model was not calibrated.

Text added in first paragraph of Section 8.2 of final report.

20. Per contract, Exhibit B, Section 3.3 Calibration of the Model: Please add calibration figures (simulated and observed water-level map and graph, and difference map) for 1980.

Requested figures have been added to the final report as Figures 81, 82, 83 and 84, and text has been edited.

21. Please add figures similar to Figure 93 showing simulated flow for 1980 and 1990.

Requested figures have been added to the final report as Figures 94 and 95, and text has been edited.

22. Please discuss the inflows from wells that occur in the model including the mechanisms that produce these inflows.

Injection wells are used to simulate recharge from selected individual playas in the vicinity of Lubbock. Text has been added in final report (Sections 9.3.1 and 9.4) to explain the purpose of the recharge wells. See Comment No. 103.

23. Per Exhibit B, Section 3.2, "Length units . . . will be in feet and time units will be in days." Please specify units of length, they are presently undefined in the discretization file (LENUNI).

All units of length are in feet.

24. Per Exhibit B, Section 3.4 sensitivity analysis, "Sensitivity analysis shall be performed by globally adjusting . . . pumping, hydraulic head assigned at any constant head and general head boundaries . . ." Please include pumping (i.e. well and MNW packages) and constant head values in the sensitivity analysis for the transient model.

Pumping and prescribed boundary head values have been included in the transient model sensitivity analysis.

25. Per Exhibit B, Section 3.4, ". . . the mean error between calibrated water levels and the simulated water levels at the calibration points for the adjusted parameter shall be determined . . .". Please include the mean error in the sensitivity analysis.

The information is sufficient as provided based on discussion and clarification with the TWDB; no changes are required.

26. It seems that the water levels in Layers 3 and 4 are almost identical (Figures 59 and 60). Please add justification in the text for having these two geological units as separate hydrostratigraphic units and not combining them as was done with the Kiamichi and Duck Creek formations in Layer 2, especially considering the amount and distribution of calibration data.

Additional discussion was added at the end of the first paragraph of Section 8.2, Calibration Results of Edwards-Trinity (High Plains) Aquifer. These layers were not combined because:

a. Specific yield values are substantially different, which could affect predictive simulation results.

b. Maintaining separate layers will make model updates easier as more information on this aquifer becomes available.

c. The fact that simulated water levels in model layers 3 and 4 are nearly identical was not known prior to completion of the model calibration.

d. The approach of using separate model layers is consistent with the scope of work and contract requirements.

27. The distribution of recharge in Figure 94 does not appear realistic, especially in the southern counties (Andrews, Martin, Howard, Ector, Midland, and Glasscock counties) and in New Mexico. Please revise or discuss in detail in the text.

The recharge distribution is discussed in detail in Blandford and others (2003), and some additional explanation has been added to the final report under Section 9.3.1 (Recharge). The distribution is a function of the combined influences of soil type, land use, and some adjustments made by county lacking a better identified alternative. For the Texas counties mentioned, the apparent change in recharge occurs because (1) there are smaller amounts of irrigated acreage and (2) recharge was reduced because simulated water levels are generally high.

28. References Section: Please double check that the Walker (1979) and BEG (1967, 1974, 1976, and 1978) references are called out in the text or figures.

Walker (1979) is used in Table 1 (was fig. 16 in Draft report). Other references have been added to the text in the fifth paragraph under Section 2.2 (Geology).

Geodatabase and Figure Comments:

29. Please remove date and file location references from all figures.

Date and file location references removed from all figures.

30. Please revise county boundaries symbolization. On many maps it is hard to determine where counties begin and end in the north-south direction.

Line width for county boundaries increased in all figures.

31. There is a discrepancy in quality of vector features in figures between printed copies and electronic (pdf) copies. I suggest you increase the line weight so that the document can be printed on most printers. The printed copies you submitted suffer from missing vector lines or hardly visible ones.

Increased line widths and increased export resolutions for pdfs has resolved the discrepancy in the quality of vector features between the printed figures and pdf versions.

32. Figure 1: There is no supporting data for the counties in New Mexico. Please combine the Texas counties with the New Mexico counties into one feature class. There is also no supporting data for Edwards-Trinity (HP) aquifer or the Ogallala aquifer boundaries. Please add feature classes for these features. In subsequent figures you refer to the Edwards-Trinity (HP) feature as the "Study area" (e.g. Figure 3) and provide a different boundary for the aquifer in other figures (e.g. Figure 21). Please revise all figures to ensure consistent labeling of features.

Texas and New Mexico counties have been combined into a single feature class in the geodatabase. Added Ogallala and Edwards-Trinity (High Plains) Aquifer boundary to geodatabase. See response to Comment No. 3 regarding study area definition and usage.

33. Figure 2: The "GCDs' feature class does not match what is in this figure. Because this feature class is often updated please download a new copy and revise the figure.

Updated version of the GCDs feature class was added to the geodatabase.

34. Figure 3: There is no feature class that matches the lakes shown in this figure. Please add this feature class. Figure 3, please increase line thickness for stream/drainage symbol in legend.

Lakes feature class has been added to the geodatabase. Line thickness increased as requested.

35. Figure 5: Basin and Range, as symbolized in the legend, is not apparent in the map. Please revise either the legend or the map. Figure 5, please add the Canadian River and Palo Duro Canyon to Figure 5 as they are references in the text for this figure.

"Basin and Range" removed from legend of figure. Canadian River and Palo Duro Canyon added to figure.

36. Figure 6: Playas coverage extends well beyond the study area. Please revise the map or the caption.

Scale of figure changed to include entire study area.

37. Figure 7: The legend shows eight classes of elevation; however, we can only distinguish six on the map and it is hard to tell which shade is which elevation. Please add labeled contours and revise the legend. Please use thicker lines for the county boundaries.

Color ramp in the elevation layer has been updated and contour labels added.

38. Figure 8: The 'Low' and 'UWB' categories present in the legend are not apparent in the map. Please revise legend. Please use thicker lines for the county boundaries.

Updated legend and removed "UWB" to reflect map. "Low" is present in small area in the southwest corner of Borden County.

39. Figure 9: There is no climate region feature class to support this figure. Please add a climate region feature class.

Added Texas climate region feature class to geodatabase.

40. Figure 10: When we asked for an additional contour line in Lubbock County, we meant you need to derive it from data, not just draw it on the map. The contour line is missing from the feature class. Please revise data.

Added contour line to feature class.

41. Figure 11: Please include time series data to support the graphs in this figure. Ticks and grid lines are shown inconsistently throughout the four charts. Please revise this figure.

Edits made so that the inset figures are consistent.

42. Figure 12: The 58F contour should pass through the 58F point in the north-east island portion of the study area. Please revise.

Revision made.

43. Figure 13: Please indicate time frame (i.e. 1971 to 2000).

Time frame has been added to the figure (1971 to 2000).

44. Figure 16: This "figure" is more appropriate in the Tables section.

Figure 16 in the Draft report is now Table 1 in the final report.

45. Figure 17: Please make county lines thicker, also the nomenclature in the text is not consistent with the nomenclature used in the legend for Figure 17. Perhaps add Blackwater Draw and Tule Formations in parenthesis after Quaternary deposits? Also, may want to add Tertiary in front of Ogallala Formation as well since age of Blackwater Draw and Tule Formations are included. Please do same throughout the legend.

Lines thickened as requested. Geologic ages added to Dockum Group and Ogallala Formation in Figure 17 (now fig. 16 in final report). Text left unchanged.

46. Figure 18: "Geologic_control_points' feature class data does not match this figure. There is no attribute that provides the category distinction you claim in this figure (geophysical well log versus water well log). Please revise data and/or figure.

Updated Geologic Control Points by adding a "Type" field which distinguishes a geophysical well log from a water well log.

47. Figures 19 and 20: The cross section lines are missing from the 'Cross_Section_lines' feature class. Please revise the data. In Figure 20 also correct the elevation scale label.

Added cross sections "C" and "D" to Cross sections feature class.

48. Figures 21 through 31: You need to provide the raster data that the contours (present in these figures) were derived from. Use the appropriate raster catalogs to include the data in the geodatabase.

Raster data provided where possible (original fig. nos. 21, 22, 23, 25, 26 and 27, which now correspond to fig. nos. 20, 21, 22, 24, 25 and 26). Some figure contours were drawn by hand or obtained from other sources and are noted as such.

49. Figure 21: Contour lines in this figure do not match the data. Please revise. Also, contour lines should not extend in areas where the aquifer is absent. Please revise.

Contour lines have been updated.

50. Figures 21 to 24: Please make county lines thicker. Also, according to the text on page 10 the caption on Figure 21 should be the base for the Antlers Sand.

County lines adjusted on all figures as noted previously. The caption for Figure 21 is as requested by TWDB comments on the draft Conceptual Model report, so it was not changed. Text added in first sentence of Section 4.2 (Structure) to clarify that the base of the Antlers Sand is the base of the Edwards-Trinity (High Plains) Aquifer.

51. Figures 25 to 27: Please make county lines thicker. Also, the range for thickness provided in the text (10-30 ft) does not agree with Figure 25 (20-40 ft). The same is true for Figure 26, (10-90 ft) in the text versus (20-100 ft) in Figure 26.

Text amended to better describe approximate thickness ranges.

52. Figure 22: Contours in the north-east island portion of the study area are not labeled. Please revise.

Contours labels have been added.

53. Figure 24: Please limit the extent of contour lines to the extent of the study area and fix labeling as you have two adjacent contour lines at 3400 feet.

Contours have been clipped to the study area. Contour label has been corrected.

54. Figure 25: This figure and the supporting data need to be revised. There are unfinished contour lines and they are very rough. If necessary, smooth out the data.

Requested edits have been made.

55. Figures 28 through 31: Please explain why you used a mix of solid and dotted contour lines; otherwise please make all lines solid. Also, there are no clear criteria on how control points were selected from the 'Water_level_control_points' feature class. I

selected wells by period, but I couldn't match what you displayed in these figures. Please revise data and/or figures.

Contours have been changed to be solid lines only. Water level control points were updated to include the field "Notes," which distinguishes the relevant time period.

56. Figure 31: Please remove labels with no associated contours.

Labels removed.

57. Figure 32: Please include time series data to support the graphs in this figure.

Graphs updated to correspond to the Edwards-Trinity (High Plains) Aquifer calibration wells and time series data provided. Final report figure number is 31.

58. Figure 33: Please include the raster dataset for the Duck Creek/Kiamichi Formations and the feature class for the Ogallala directly on limestone. If the Ogallala layer extends into the Kiamichi formation please use appropriate symbology to make it apparent.

The raster dataset for the Duck Creek/Kiamichi Formations was already present in the geodatabase under the geology grids as "Layer2_thick." Added feature class of Ogallala directly on Limestone to geodatabase.

59. Figure 34: Please include a feature class for stream gauges. Please revise line weights for streams and change the background of call-out boxes so they don't seem lost on a white background.

Added Stream Gauges to geodatabase. Figure edits made.

60. Figure 35: Please include time series data to support the graphs in this figure. Please keep the interval for flows (y-axis) consistent among the graphs shown in Figure 35. Also, please label the name of the gauge for site 8079500 as was done for the graph of gauge 8080700.

Time series data provided.

61. Figure 36: Please include a field in the 'Springs' feature class attribute table that identifies springs in the major escarpment category. Please revise line weights for streams.

Added major escarpment note to Comment field in Springs feature class.

62. Figure 37: Please include a feature class for the hydraulic conductivity points.

Added Hydraulic conductivity points to geodatabase.

63. Figure 40: Please add data to support this figure. Please adjust font color for county labels so they are legible.

Added images to image catalog.

64. Figure 41: Please include the contour feature class.

Added TDS contours to geodatabase.

65. Figure 42: There are six stratigraphic layers in your graphic; however, only five appear in your legend/explanation. Please revise.

Shading of saturated Ogallala Formation removed to avoid confusion. Five stratigraphic layers were illustrated.

66. Figure 45: Please include north arrow and scale bar on Figure 45. Please make county lines thicker in Figures 46-50.

Edits made.

67. Figure 46 through 53: Please provide feature classes with data to support these figures.

Added feature class data to geodatabase for Figures 46, 47, 48, 49, 50, 51, and 52. Figure 53 (recharge) was already in geodatabase.

68. Figures 54 through 63:

- Please revise your data. Figures suffer from numerous interrupted contours and contours where the aquifer is absent. Use solid lines for all contours.

  Interrupted contours in the simulated water levels were due to zones of no-flow cells which had not been posted on the figures. No-flow cells were added to final report Figures53, 73, and 76. Observed contours were edited to reflect the no-flow areas. No-flow feature class was added to the geodatabase. Used solid lines for all contours.

- Please include feature classes with dry cell spatial distribution per layer.

  Added dry cell feature classes to geodatabase.

- Please include feature classes for hydraulic head locations and residuals for figures where they appear.

  Hydraulic_Head_Locations_Layer1 and Hydraulic_Head_Locations_Layers3_and_4 feature classes were added to the geodatabase. File includes attribute for residuals; the same feature class is used for Layer 1 and for Layers 3 and 4.

- Please clarify which feature classes in 'SubSurfaceHydro' feature dataset represent the observed predevelopment water levels for model layers 3 and 4.

Observed pre-development water levels for layers 3 and 4 were added to the geodatabase.

- Please rename all feature classes in the 'SubSurfaceHydro' feature dataset with a consistent naming format and a consistent temporal format.

Naming format in the 'SubSurfaceHydro' feature dataset was updated for consistency.

- Please choose consistent category breaks for residuals.

All category breaks on model calibration difference plots were set up to have two 25-foot intervals in the positive and negative directions. The third and final interval in each direction contains all additional points, with the largest number equivalent to the largest negative or positive difference for the time period considered. This approach leads to a total of 6 categories for most difference figures; more categories would be very difficult to illustrate in a meaningful way.

69. Figure 64: According to the feature class attribute table, there are six value categories for recharge. Please revise the figure to include all categories.

Figure 64 is correct as is; 4 values for recharge were applied in the steady-state model. The feature class attribute table was updated.

70. Figures 65 through 69: Please include feature classes/raster datasets for these figures.

Added vertical flow and calibrated hydraulic conductivity feature classes to geodatabase.

71. Figures 76, 79, 84, 85, 88, and 89:

- Please revise your data. Figures suffer from numerous interrupted contours and contours where the aquifer is absent. Use solid lines for all contours.

- Please include feature classes with dry cell spatial distribution per layer.

Interrupted contours in the simulated water levels were due to no-flow cells which had not been posted on the figures. No-flow cells were added to the figure, and contours have been made solid. Dry cells feature class was added to the geodatabase.

72. Figure 78: Please include the point feature class used for this figure.

Added 1990 residuals point feature class to the geodatabase.

73. Please recheck the model statistics on Figures 77, 80, 86, and 90 and update the figures and appropriate text. There are far fewer targets for some of the stress periods and layers than are shown in these figures.

Figure 77 (final report fig. 74) (1990, Layer1):- Max Residual changed to 233 ft; the 133 ft was a typographical error. There are 2,514 data points used to calculate these statistics and all of the locations are indicated in Figure 78 (final report Figure 75).

Figure 80 (final report fig. 77) (2000, Layer 1): There are 2,061 data points used to calculate these statistics and all the locations are indicated in Figure 81(final report Figure 78).

Figure 86 (final report fig. 87) (1990, Layer 4): There are 288 data points used to calculate these statistics and all the locations are indicated in Figure 87(final report fig. 88).

Figure 90 (final report fig. 91) (2000, Layer 4): All 89 data points are indicated in Figure 91(final report fig. 92). Calibrated statistics were checked and changed slightly as follows: RMSE = 32 ft, MAE = 25 ft, ME = 9 ft, MAE/Range as % = 3.0.

74. Figure 81: Please include the point feature class used for this figure.

Added 2000 residuals point feature class to the geodatabase.

75. Figures 82 and 83: Please include the hydrograph feature classes and time series data for charts.

Added hydrograph locations point feature class to the geodatabase. A table was added to the geodatabase called Water_levels_used_in_hydrographs.

76. Figure 87: Please include the point feature class used for this figure.

Added 1990 residuals point feature class to the geodatabase.

77. Figure 91: Please include the point feature class used for this figure.

Added 1997 residuals point feature class to the geodatabase.

78. Figure 92: Please include the hydrograph feature classes and time series data for charts.

Added hydrograph locations point feature class to the geodatabase. A table was added to the geodatabase called Water_levels_used_in_hydrographs.

79. Figure 93: Please include a feature class/raster dataset for 1997 simulated flow.

Added vertical flow feature class to geodatabase.

80. Figure 94: Please include a feature class/raster dataset for 2000 simulated recharge.

A 2000 simulated recharge feature class was already present in the geodatabase.

81. Figure 95: Please include a feature class/raster dataset for 2000 pumping distribution.

Added 2000 pumping distribution point feature class to the geodatabase.

82. Figure 96: Please include a point feature class for pumping wells with the two defined categories and remove contour labels since there are no contours.

Edwards-Trinity (High Plains) Aquifer pumping wells and multi-aquifer pumping wells added to geodatabase. Removed contour labels from figure.

83. Figure B-1: Please provide appoint feature class for hydrograph locations.

Added hydrograph locations point feature class to the geodatabase (see Comment No. 75).

84. Figure C-1: Please provide a point feature class for hydrograph locations. What's with the unexplained chicken pox phenomenon?

Added hydrograph locations point feature class to the geodatabase (comment 78). Plotting is correct as is.

Geodatabase Metadata:

85. Generally, many feature classes are missing keywords and purpose in the metadata. Please revise.

Metadata updated to include keywords and purpose.

86. 'Physiographic_provinces' feature class: Please add metadata.

Metadata added.

87. 'Raster_catalog' was added to the geodatabase; however, it is empty. Please remove it and do not alter the schema unless you have specific reasons and data to contribute.

Deleted "Raster Catalog" from geodatabase.

88. 'Recharge' raster: Please add metadata.

File was a duplicate of the Duck Creek/Kiamichi thickness. File deleted. Correct recharge file has been added.

89. Water level feature classes are referenced either by name (e.g. Ogallala) or by layer number (e.g. Layer 1). Please choose a consistent naming format. Someone not familiar with the naming conventions can be easily confused.

Naming format in the 'SubSurfaceHydro' feature dataset was updated for consistency.

Model Comments:

90. Per Exhibit B, Section 4.3, please include all MODFLOW input files in ASCII format. The drain package was missing from the steady-state MODFLOW input files.

Drain package has been provided.

91. Please recheck the model statistics for the steady-state calibration. The ME is -8.54 (or -9 ft). Please update caption in Figure 56 and reference to the value in the text on page 29 (third paragraph down from the top of page). Also, please include the number of targets in the figure caption.

The statistics were rechecked and the ME is –8.45ft, hence the original rounded value of –8 ft. Because the statistics were calculated using 1,471 data points, a variation of 0.09 ft (i.e., 8.54 – 8.45 = 0.09) may be possible depending on the software applied, etc. The value was not changed because it is consistent with the software and methodology used to calculate all model statistics. The number of targets (1,471) was added to the figure, not the figure caption.

92. Please consider caveating the limitations of the model in these problem areas of the Ogallala Aquifer (extreme lows -138 ft and extreme highs 203 ft) illustrated in Figure 57 and discussed on page 29 (bullet items). The section 11.0 model limitations may be the most appropriate place to insert a comment.

The bulleted items in the referenced section do not necessarily correspond to the most extreme low or high value. The last paragraph of the "Limitations of the Model" Section addresses the issue noted, both in the draft and final report.

93. Please recheck the statistics for the ME provided on Figure 62 and update the figure caption and text on page 30 as appropriate (third paragraph under section 9.2). Also, please include the number of targets.

The statistics were rechecked and are correct as is. The number of targets is 53 and was added to the figure (Figure 59 in final report), not the figure caption.

94. Please check the number of dry cells for layer 1 listed in Table 4. A total of 214 dry cells are reported, but I am getting 212. A total of 98 are reported for layer 2, but I am getting 97 and 25 are reported for layer 3, but I am getting 18.

The number of dry cells for each layer was updated in the table; the values in the comments are correct.

95. Please keep the same range (y-axis) for the sensitivity plots shown in Figures 70 to 75.

Y-axis scale has been made consistent between figures, except for Figure 75b (changed to Figure 72b for the final report) where the scale is larger in order to show all values. This change in scale was agreed to by TWDB.

96. Page 33, last sentence of third paragraph from the top: Please clarify if you are referring to figure 71b, and update text accordingly.

Comparison to Figure 71 deleted from text.

97. Page 32, first paragraph under sensitivity analyses indicates that certain parameters were increased and decreased uniformly by a factor of 5 and 10. However, horizontal hydraulic conductivity was increased and decreased by 5 and 10 percent. However, the plots on Figures 70 and 71 indicate that horizontal hydraulic conductivity was varied by a multiplier of 5 and 10. Please adjust so text and figures agree.

Text and figures are correct as is. Figures 70 and 71 in the Draft report indicate adjustments to horizontal hydraulic conductivity of 10 and 50 percent, as indicated in the text.

98. Table 5 lists the steady-state stress period as "Pre-1930", but the text on page 28, in the first sentence under section 9.0 steady-state model, describes the steady-state model as, "average hydrogeologic conditions at or about 1930." Please keep Table 5 and descriptions in the text consistent.

No changes made. Table 5 documents how the steady-state simulation period is considered in the groundwater flow model regarding stress periods; the model requires a precise delineation of time increments. The referenced text describes the reality of how 1930 conditions were determined and are conceptualized given the available data. Early available data were used to determine estimated steady-state conditions, but not all data were specifically from the year 1930 or earlier years; in some places where data were limited and early pumping was minimal or non-existent, water levels later than 1930 were used to develop the steady-state potentiometric surface maps, as discussed in Section 4.3 (Water Levels and Regional Groundwater Flow). The assumption is that in the absence of significant groundwater pumping, there would have been only relatively small changes in water levels through time.

99. Page 40, first paragraph under sensitivity analyses indicates that certain parameters were increased and decreased uniformly by a factor of 5 and 10. However, horizontal hydraulic conductivity was increased and decreased by 5 and 10 percent. However, the plots on Figures 98 and 99 indicate that horizontal hydraulic conductivity was varied by a multiplier of 5 and 10. Please adjust so text and figures agree.

Text and figures are correct as is. Figures 98 and 99 in the Draft report indicate adjustments to horizontal hydraulic conductivity of 10 and 50 percent, as indicated in the text.

100. Please keep the interval for water levels consistent among the sensitivity analysis plots (Figures 98 to 103).

Y-axis scale made consistent between figures to the extent reasonable. Final report figs. 101 through 104 have the same y-axis scale in the final report, and figures 105 and 106 *(which present larger numbers) have the same scale. This approach was agreed to by TWDB.*

101. Please change the Tr designation in the discretization file to Ss for the steady-state model. The model is transient and storage inflows and outflows are showing up in the water budget (storage values are also listed in the bcf file for the steady-state solution). Please revise the water budget for the steady-state model in Appendix A as appropriate.

See response to Comment No. 15 and added text in Section 9.0. Because transient simulation is used to determine steady-state conditions, a small amount of groundwater inflow to, or outflow from, storage will be simulated. There is no need to revise the water budget in Appendix A.

102. Please revisit the drain conductances, some values of zero were detected.

The drain files and boundary condition figures were updated to be consistent. At several locations, drains were inadvertently added with a zero conductance where the aquifers are likely to be dry along the eastern escarpment.

103. Injection wells are showing up in the well and multinode well packages and are presented in the water table budgets provided in Appendix A. Please include a brief, clear explanation for the source of these injection wells. If these wells should not be injecting, the sensitivity analysis should also be re-performed.

Injection wells are used to simulate recharge from specific individual playas in the vicinity of Lubbock. Text has been added (final report Sections 9.3.1 and 9.4) to explain the purpose of the recharge wells. See Comment No. 22. Recharge attributed to the MNW package is negligible and is discussed at the end of Section 9.3.4.

104. Please consider using a time-step multiplier other than 1.

There is no need to apply a time-step multiplier other than one. Although such an approach can be useful for some situations (e.g., simulating aquifer test analyses where changes in water levels are large at the beginning of the test and much smaller at later times), there is no need to implement a multiplier other than 1 for the GAM.

SUGGESTED CHANGES

Draft Final Report Comments:

105. Page 1, paragraph 4: Please clarify the definition of "groundwater system".

Edit made to referenced paragraph to remove the phrase "groundwater system."

106. Page 2: last sentence, second paragraph, "Even so, the transient model replicates the observed data quite well at most locations." Please quantify this statement.

No edit made. A detailed description of the calibration is provided in the report.

107. Page 3, paragraph 4: "... .9,000 square miles (mi2). Please use the (mi2) notation when it is first called out after the first reference listed in the first paragraph (first sentence of 2.0 Introduction).

Edit made.

108. Page 5, paragraph 3: Please add a reference(s).

No edit made. The appropriate references are provided on the referenced figures.

109. Page 17, paragraph 3: Please insert (1960) after Cooper at the start of the third sentence in the last paragraph of section 5.7.

Edit made.

110. Page 17, paragraph 4: Please cite the year after Brune reference that occurs at the start of the second sentence under the first paragraph in section 5.7.1. Please do the same for the reference to Brune on the fourth sentence of section 5.7.1

Edits made.

111. Page 17, paragraph 4: Please consider rephrasing the comment within the first sentence under section 5.7.1, "with flows ranging from seeps and trickles up to substantial flows . . .", perhaps consider rephrasing, "with maximum discharges equivalent to a third magnitude spring" (see Meinzer, 1927).

No change made.

112. Page 18, paragraphs 1 and 2: Please cite the Brune reference in the first sentence on page 18. Please cite the Brune reference in the first sentence on the second paragraph of page 18.

Edits made.

113. Page 18, paragraph 3: Please cite the reference to White and others provided in the third sentence of the third paragraph from the top of the page.

Edits made.

114. Page 22, paragraph 1: Please add discussion of the boundaries used in the model including why a no-flow boundary is used instead of a general-head boundary to simulate flow between the modeled aquifers and the Dockum Aquifer previously discussed on Page 19.

Text has been added earlier in the section that clarifies the reasoning and assumptions behind this approach (see response to Comment No. 2).

115. Page 23, paragraph 2: Please delete"…and consists of up to 4 active model layer in the vertical dimension." This is a repeat of information provided earlier in the paragraph.

Edit made.

116. Page 23, paragraph 2: Please explicitly state that the model grid also includes the southern portion of the Ogallala Aquifer.

Edit made to first paragraph of Section 7.2.

117. Page 26, paragraph 2: Please change "occurred" to "occur".

Edit made (same as Comment No. 14).

118. Page 26, paragraph 2: The last sentence of this paragraph is contradicted by the last sentence on Page 28, paragraph 2. Please revise for consistency.

The sentence on page 26 states that flow from the 10 largest springs occurs primarily from the Southern Ogallala Aquifer (actually 9 of 10 are exclusively from the Ogallala Aquifer), while the statement on page 28 refers to springs that emanate from the Edwards-Trinity (High Plains) Aquifer. Some text was added to page 26, paragraph 2, to clarify this point.

119. Page 27, paragraph 1: Please change "other values" to "other parameters".

Edit made.

120. Page 27, paragraph 2 and paragraph 4: Please change "residual" to "difference".

Edits made.

121. Page 31, paragraph 4: Please change "…at the base…" to "…through the base…"

Edit made.

122. Section 9.3: Please move this section to the beginning of the chapter.

Edit not made. The format of the report is consistent with the required report format provided as Exhibit B to the contract.

123. Page 34, paragraph 3: Please discuss whether the dry cells are realistic considering the uncertainties of the model.

Some discussion added to the referenced paragraph.

124. Page 36, paragraph 6: Please discuss why calibration points for the northwestern portion of the Edwards-Trinity (High Plains) Aquifer used to calibrate the 1990 time period were not used for 1997.

No edits made to the report. The 1990 points were not used because data at those locations are not available for 1997.

125. Section 10.3: Please move this section to the beginning of the chapter.

Edit not made. The format of the report is consistent with the required report format provided as Exhibit B to the contract.

126. Page 42, paragraph 2: Please add including interaction with the underlying Dockum Aquifer to future improvements because as water levels in the Ogallala and Edwards-Trinity (High Plains) aquifers are drawdown over time, the potential for upwelling from the Dockum Aquifer will increase. The sensitivity analysis conducted indicates that the Edwards-Trinity (High Plains) Aquifer portion of the model is sensitive to this.

Confirmation of Dockum Aquifer leakage could be a useful improvement to the model if the estimates can be made based on observed data. As noted in the updated sensitivity analysis text in the final report (Section 8.5), there are substantial data limitations that would have to be addressed in order to improve assessments of leakage beneath the Edwards-Trinity (High Plains) Aquifer. Namely, for most counties that overlie the Edwards-Trinity (High Plains) Aquifer, there are (1) no observations of underlying Dockum Aquifer water levels, and (2) the Dockum Aquifer is highly saline and consideration of density-dependent groundwater flow would be required to estimate appropriate inter-aquifer leakage rates. Finally, the sensitivity analysis conducted assumed an increase in leakage between the Edwards-Trinity (High Plains) Aquifer and the Dockum Aquifer, regardless of the direction of leakage (i.e., assumed leakage taken from the Dockum GAM is both into, and out of, the Edwards-Trinity (High Plains) Aquifer). Future declines in water levels, therefore, will not only increase the potential for inflow to the Edwards-Trinity (High Plains) Aquifer, but will also decrease outflow from the Edwards-Trinity (High Plains) Aquifer, which will have an offsetting effect.

Compared to other uncertainties in the model, we do not regard leakage to or from the Dockum Aquifer as one of the major issues that should be targeted for improvement. Some additional text discussing this issue has been added to Section 11 (Recommended Future Improvements) in the final report.