Groundwater Availability Model for the Igneous and parts of the West Texas Bolsons (Wild Horse Flat, Michigan Flat, Ryan Flat and Lobo Flat) Aquifers

Prepared for:

Texas Water Development Board

By:

James A. Beach, John B. Ashworth, Steven T. Finch, Jr., Andrew Chastain-Howley, Kenny Calhoun, Kevin M. Urbanczyk, John M. Sharp, John Olson

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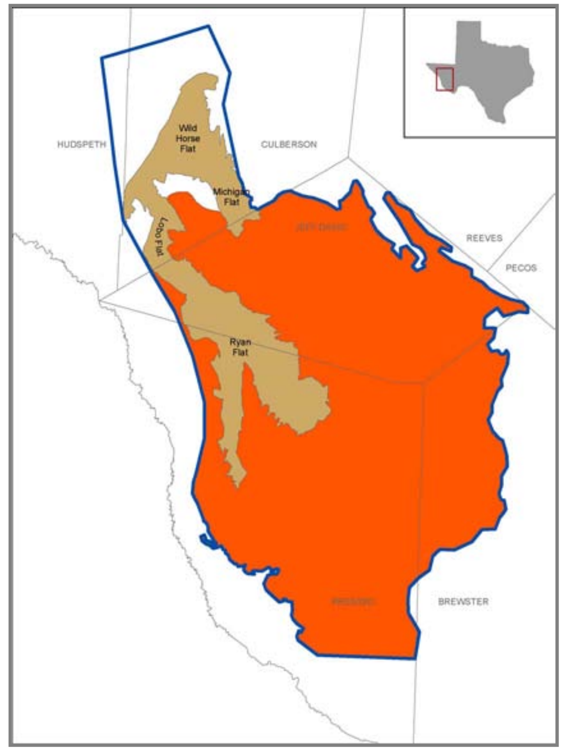

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ABSTRACT

The Igneous and West Texas Bolsons aquifer systems of the Trans-Pecos region of West Texas represent the primary source of water supply within their extent. The flow systems of the Igneous and Salt Basin Bolson aquifers are interconnected and complex. Because these aquifer systems represent an important resource for West Texas and because there is a renewed interest in developing these resources, it is important to understand them and to develop quantitative tools to support all stakeholders in planning the future of these resources.

A three-dimensional groundwater model was developed for the Igneous and Salt Basin Bolson aquifers as a tool to evaluate groundwater availability and water-level responses due to projected pumping under normal and drought conditions. The model is regional in scale, and was developed with the MODFLOW groundwater flow code. The conceptual model divides the aquifer system into three layers, the Salt Basin Bolson, Igneous aquifer, and the underlying Cretaceous and Permian water-bearing zones. The conceptual model was based on data compiled from many sources and included a detailed analysis of recharge for the model area. Available hydraulic conductivity, aquifer storage properties, and water level measurements were assimilated for use in developing a representative model. The model was successfully calibrated to steady-state conditions in 1950 and transient conditions between 1950 and 2000. The model simulates water level responses in the Bolson aquifer relatively well. However, due to the complexity of the Igneous aquifer, the model is considered an interpretive tool for that aquifer. The model was used to assess aquifer response from 2000 to 2050 based on water demand projections contained in the 2002 State Water Plan.

Model results indicate that some of the adopted water management strategies will cause water level declines in the Igneous and Bolson aquifers over the 50-year simulation period. In addition, the model indicates that because of limited hydraulic connection between the Salt Basin Bolson aquifer and the Igneous aquifer, there is limited impact on Igneous aquifer water levels due to pumping in the Salt Basin Bolson aquifer.

1.0 INTRODUCTION

The Igneous and West Texas Bolsons aquifer systems of the Trans-Pecos region of West Texas are classified as minor aquifers by the Texas Water Development Board (Ashworth and Hopkins, 1995) and generally represent the sole source of water supply within their extent. This report describes the hydrologic flow characteristics of the Igneous aquifer system that underlies the Davis Mountains and adjacent areas and the Salt Basin portion of the West Texas Bolsons aquifer system. Hydrologic data from these aquifers, as well as adjacent water-bearing formations, were evaluated to establish a conceptual model of the groundwater flow system that is the basis for a groundwater availability model (GAM).

The goal of the Texas Water Development Board (TWDB) GAM program is to provide reliable information on groundwater availability to the citizens of Texas to ensure adequate supplies or recognize inadequate supplies over a 50-year planning period. The Igneous Bolsons Groundwater Availability Model (IBGAM) conceptual model was developed by assimilating and assessing all pertinent scientific information about the aquifers in the study area. For the current study, existing data was assimilated in the model area to define:

- Physiography, climate, vegetation, and land use
- Geology, hydrostratigraphy and structure of the aquifers
- Groundwater quality
- Hydraulic properties of the aquifers
- Surface water and groundwater interaction
- Recharge rates for the aquifers
- Water levels
- Pumping rates

In addition, new field data was collected and analyzed to assess hydraulic properties of the aquifers and current water levels.

A model boundary encompassing contiguous Tertiary-age igneous rocks is portrayed in this report and is hereafter referred to as the Igneous aquifer. Also, the portion of the

Salt Basin graben which is 1) aerially defined by the geographic areas referred to as Wild Horse, Michigan, Lobo, and Ryan Flats; 2) vertically defined by saturated portions of bolson fill and underlying hydrologically connected Tertiary volcanic formations and Permian and Cretaceous limestones, and 3) defined by waters containing less than 3,000 total dissolved solids (TDS) is referred to in this report as the Salt Basin Bolson aquifer.

The IBGAM numerical computer model (created using the MODFLOW code) of the aquifers provides a scientific, quantitative tool to evaluate aquifer responses to current and projected pumping and to assist in regional water planning efforts and aquifer management decisions. The TWDB GAM program allowed stakeholders the opportunity to provide input and comments during the conceptual model development. The result is a standardized, thoroughly documented, and publicly available numerical groundwater flow model and support information.

The IBGAM can be used to evaluate regional water management strategies and groundwater availability in the Far West Texas regional water planning area. The IBGAM can also be used as a water management tool for the local groundwater conservation districts. Predictive simulations documented in this report were based on the most recent projections of groundwater demands, and provide much needed insight into the viability of current and potential groundwater management strategies, which is vital to those dependent on the aquifers for water supply.

2.0 STUDY AREA

2.1 Location

The Salt Basin Bolson aquifer and the Igneous aquifer of the Davis Mountains area occur in four West Texas counties; Brewster, Culberson, Jeff Davis and Presidio (Figure 2.1.1). The area is part of the Trans-Pecos region of Texas, and includes the mountain ranges and intervening valleys west of the Pecos River. Figure 2.1.2 shows the location of the West Texas Bolsons, Igneous aquifers, and other aquifers currently designated by the TWDB that are pertinent to the modeling process. The present study area (Figure 2.1.3) includes the Salt Basin portion of the West Texas Bolsons aquifer and an expanded area of the Igneous aquifer, and is based on a consideration of modeling objectives, geologic structure, hydrologic conditions, and regional groundwater flow directions necessary to develop appropriate boundary conditions for the numerical model.

The West Texas Bolsons include several deep basins filled with erosional sediments of Quaternary and Tertiary age that contain variable quantities of groundwater. These filled basins, or bolsons, include Red Light Draw, Eagle Flat, Green River Valley, Presidio-Redford, and Salt Basin (Ashworth and Hopkins, 1995). The easternmost basin is the Salt Basin, which can be further subdivided into four aquifer sub-basins; Wild Horse, Michigan, Lobo, and Ryan Flats (Figure 2.1.3). These four sub-basins are included in the study area and are referred to as the Salt Basin Bolson aquifer. Groundwater from the Salt Basin Bolson aquifer provides the water supply for the communities of Van Horn, Sierra Blanca (purchased from Van Horn), and Valentine. In addition, the four sub-basins provide irrigation water for agricultural areas in the flats and are the primary source of water supply for all other water users where the aquifer exists. The northern portion of the Salt Basin extending beyond the study area is referred to as the Salt Flats and contains significantly more brackish to saline groundwater.

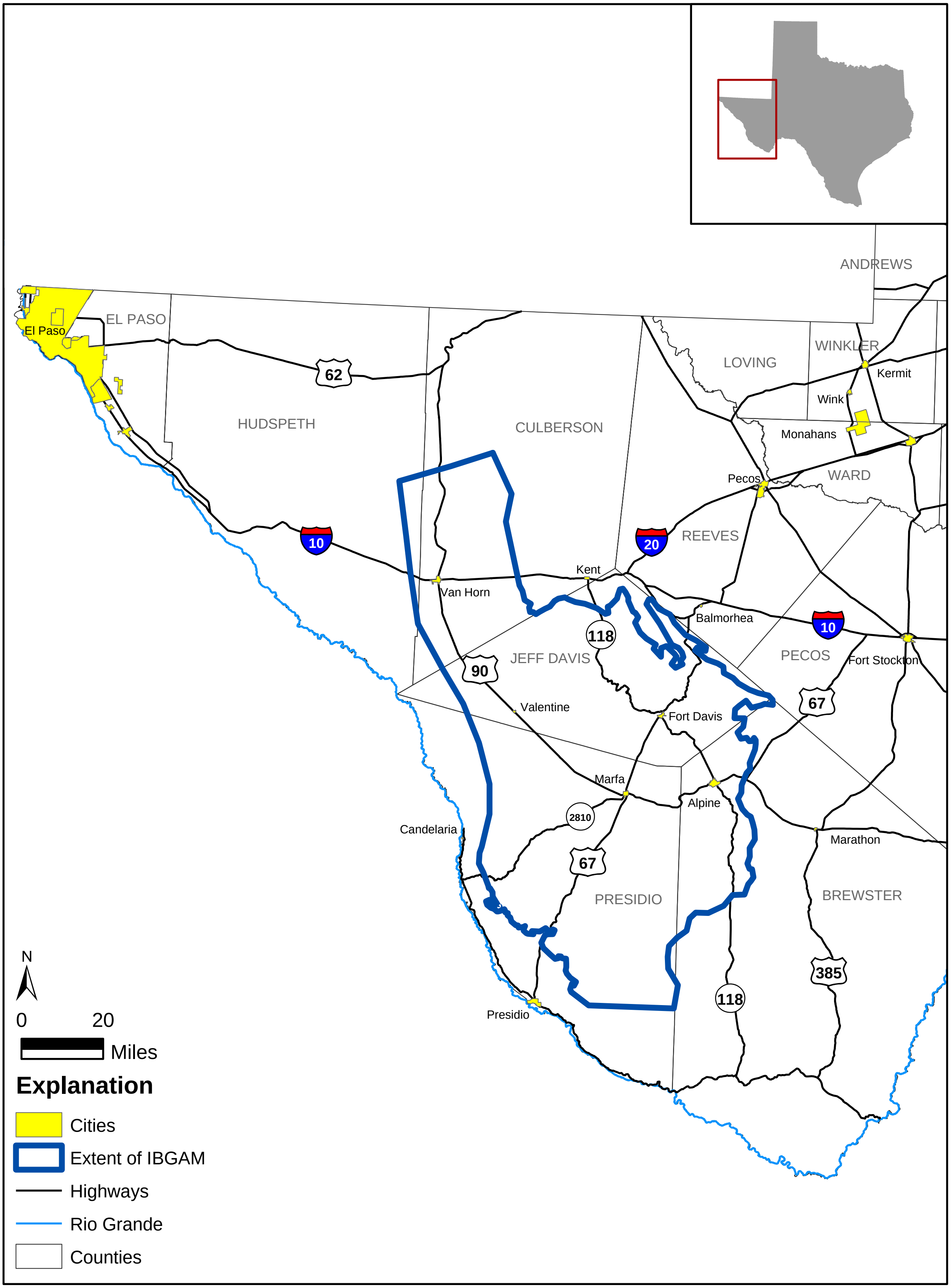


Figure 2.1.1 - Location of the Study Area

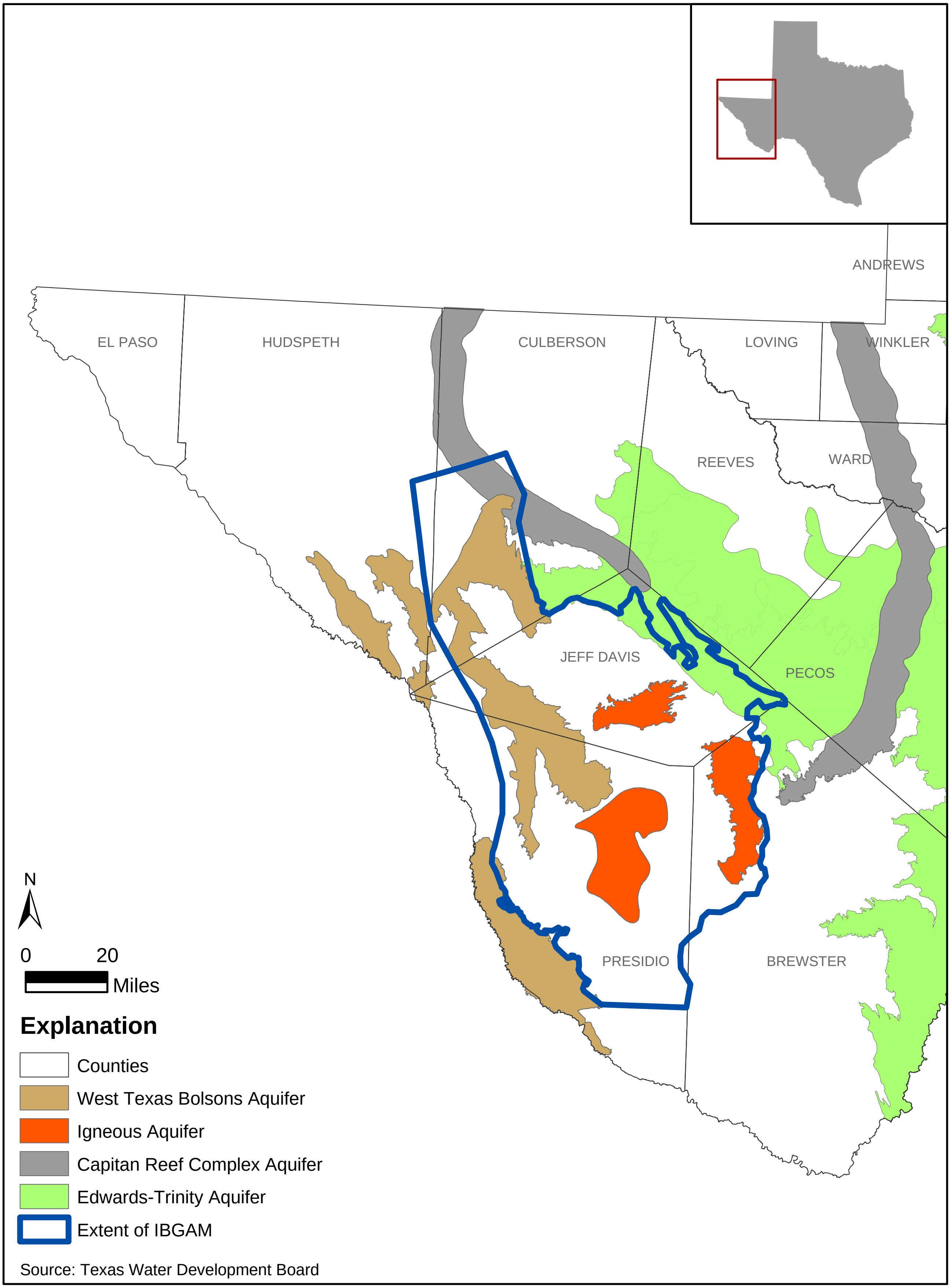


Figure 2.1.2 - Selected Aquifers Associated with the IBGAM as Designated by the TWDB

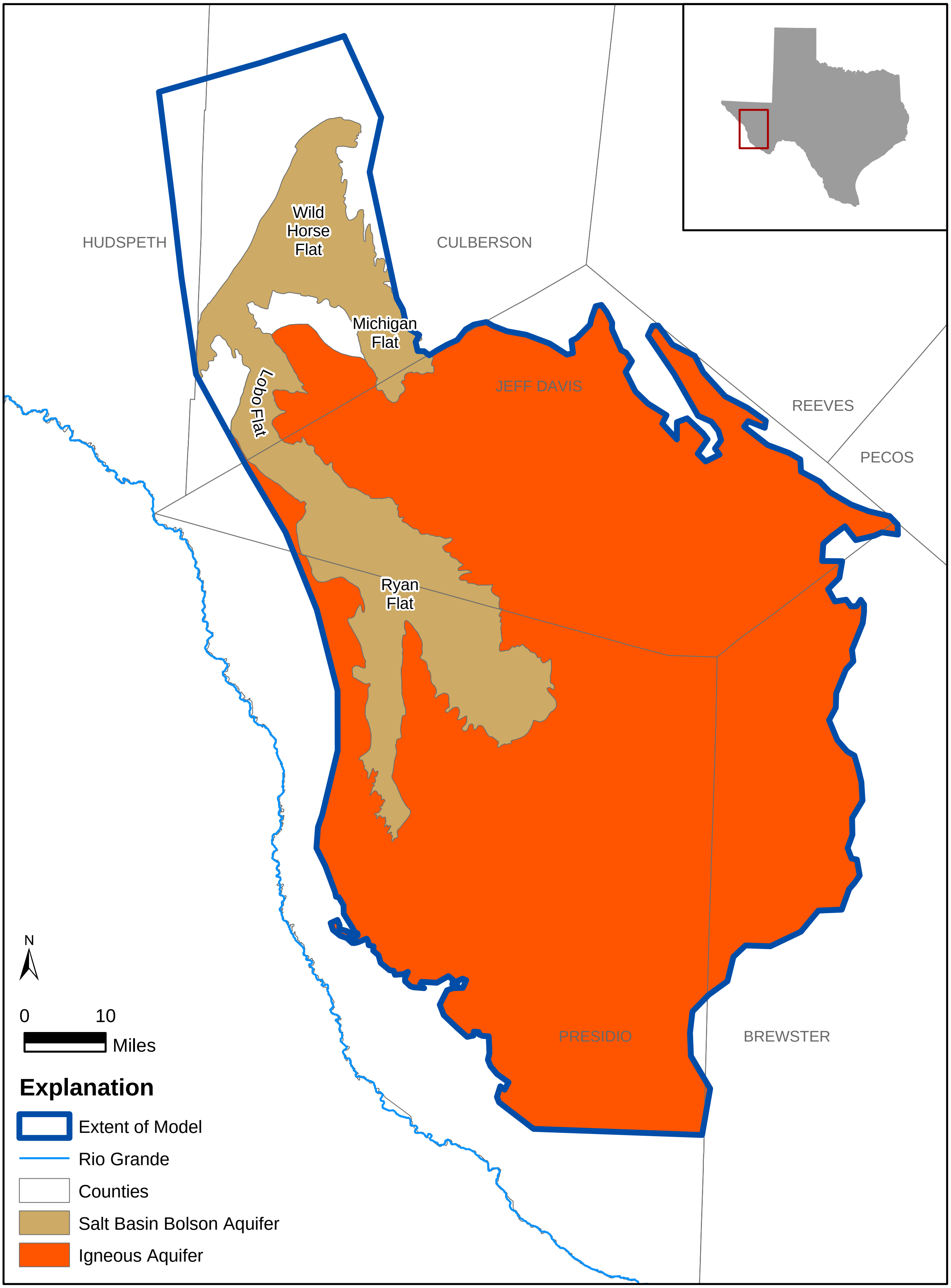


Figure 2.1.3 - Location of the Salt Basin Bolson and Igneous Aquifers

The Igneous aquifer, as currently designated by the TWDB, occurs in three separate areas within Brewster, Presidio, and Jeff Davis Counties (Ashworth and Hopkins, 1995) where it provides water to the local population centers (Figure 2.1.2). However, a recent study of the aquifer for the Far West Texas Regional Water Planning Group (Ashworth and others, 2001) reveals that the Igneous aquifer system is more extensive than previously recognized by the TWDB. This newly delineated area (Figure 2.1.3) retains the TWDB designation of Igneous aquifer; however, it is important to recognize that the reference to Igneous aquifer in this report refers to the igneous area within the model boundary and not the three smaller areas identified in the current TWDB Minor Aquifers Map. The Igneous aquifer is the sole source of water for three cities in the study area; Fort Davis, Marfa, and Alpine. In addition, it meets rural domestic, livestock and industrial demands throughout the extent of the aquifer.

The IBGAM study area, therefore, includes the full contiguous extent of the Igneous rocks and the four Salt Basin flats, as well as the basin-bordering mountain areas, as these areas serve as potential areas of recharge to the Salt Basin Bolson aquifer. The IBGAM model area is contained within the following approximate geographic/geologic boundaries:

North - Victorio Flexure

North-Northeast – Apache Mountains

Northeast and East – Eastern edge of igneous outcrop

South – East-west fault along Torneros Creek

West – Drainage divide along Sierra Diablo, Van Horn Mountains, Sierra Vieja, and Chinati Mountains

The study area is completely contained within the Far West Texas Water Planning Region (also known as Region E) as shown in Figure 2.1.4. Region F lies just east of the study area boundary. There are four groundwater conservation districts in the study area, as shown in Figure 2.1.5, with each district covering all or part of a single county. The study area is also completely contained within TWDB Groundwater Management Area 4, as shown in Figure 2.1.6.

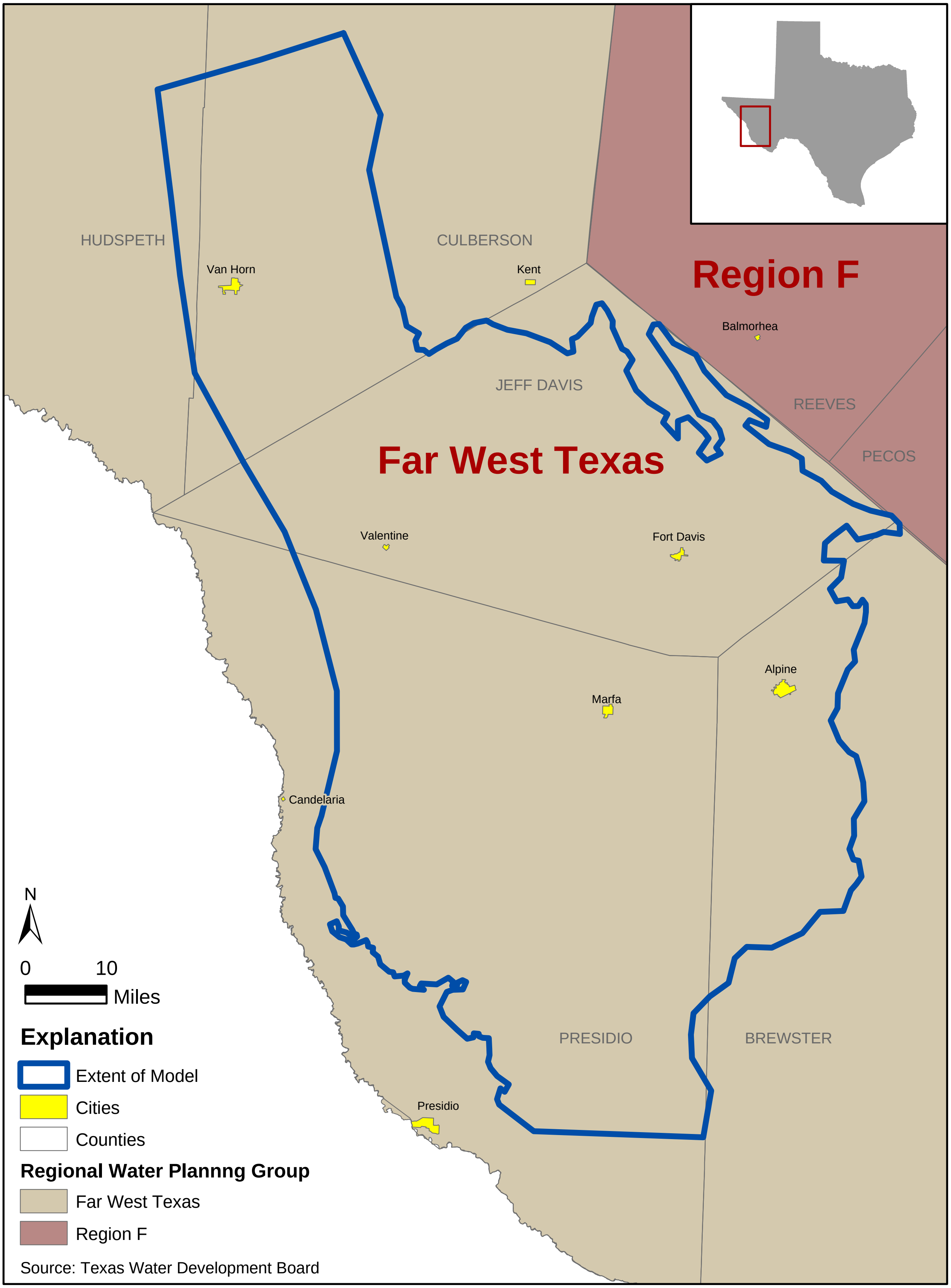


Figure 2.1.4 - Regional Water Planning Groups

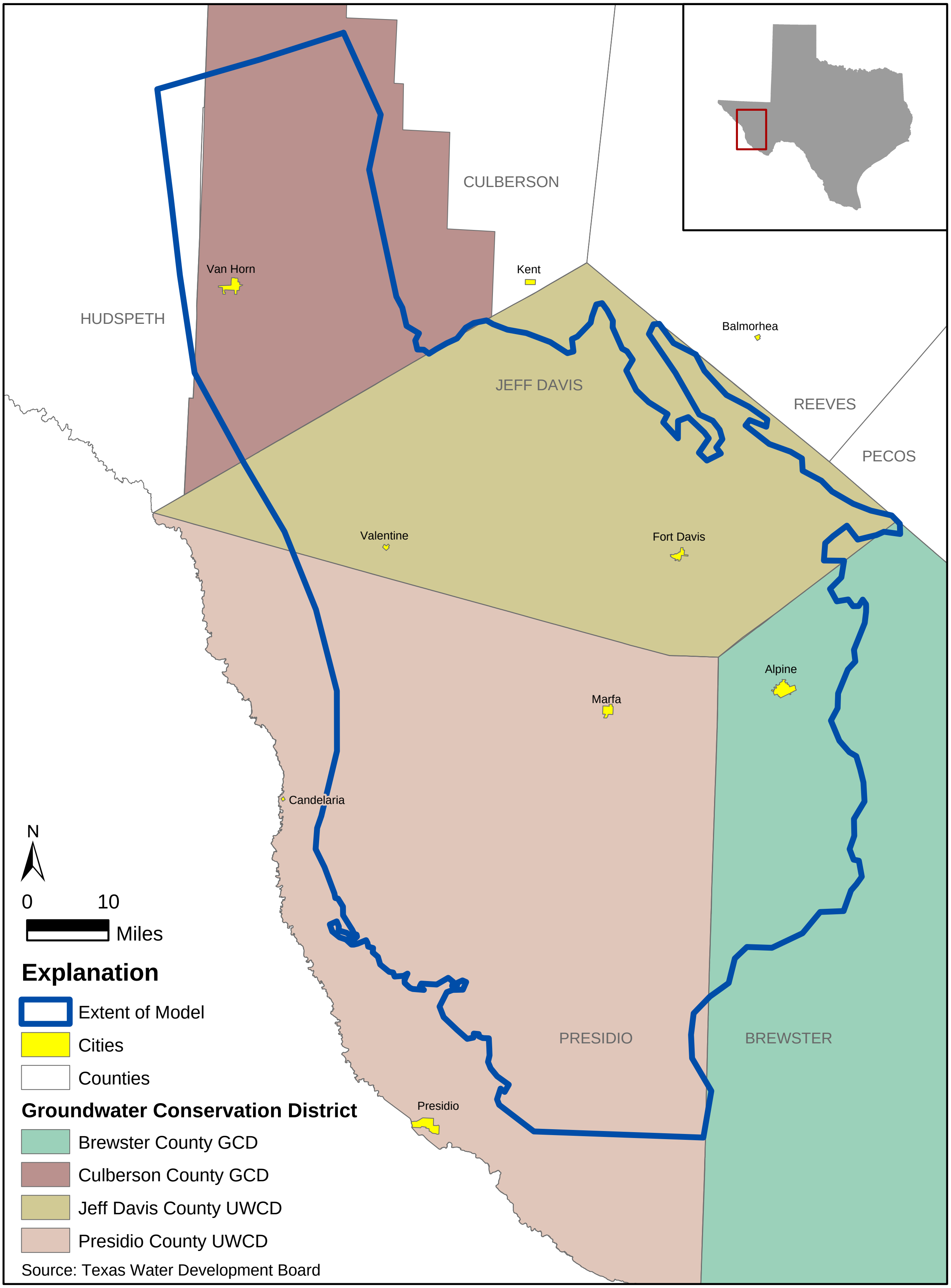


Figure 2.1.5 - Groundwater Conservation Districts

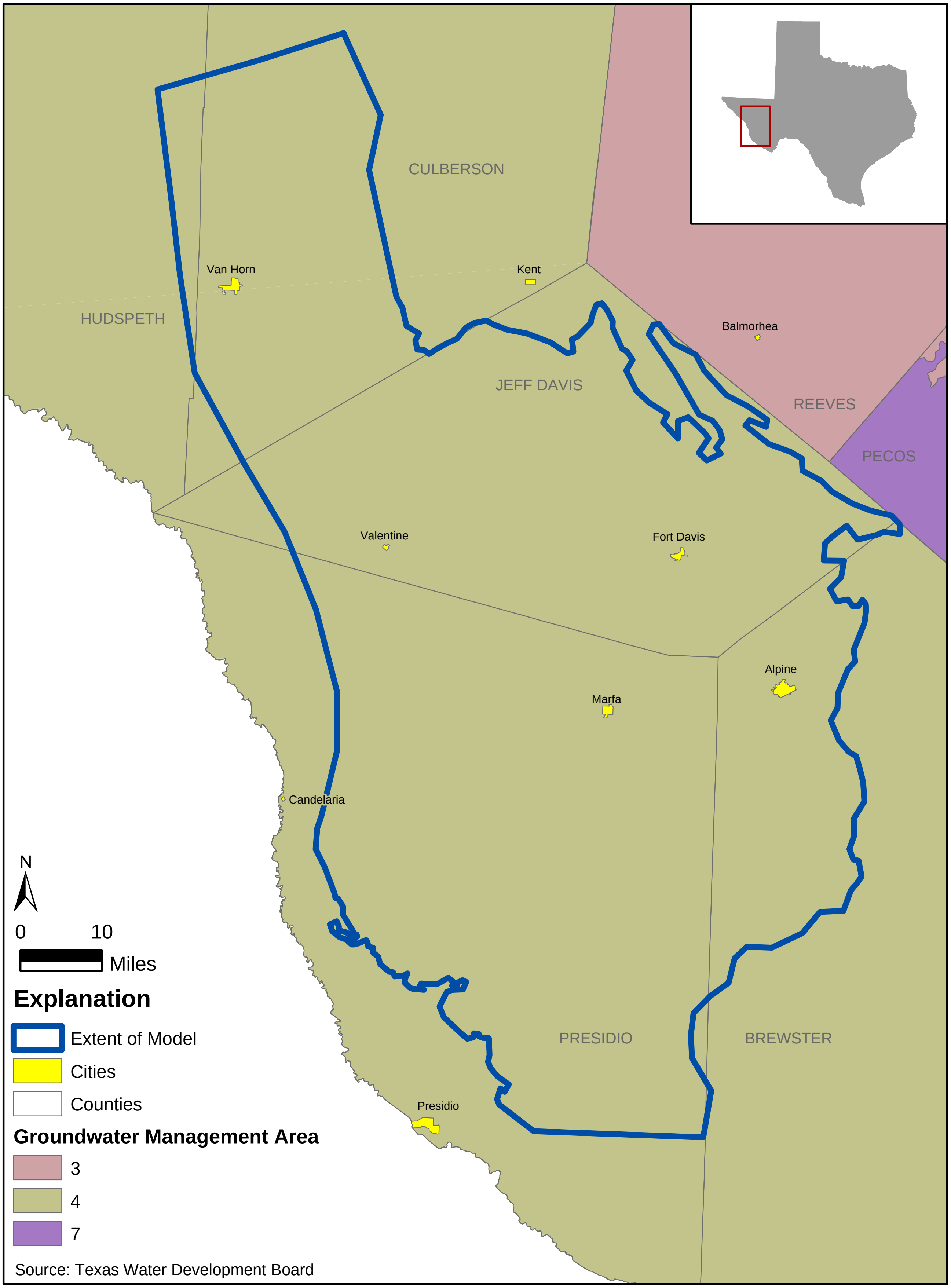


Figure 2.1.6 - Groundwater Management Areas

2.2 Physiography

The Davis Mountains igneous complex and adjoining Salt Basin are located within the Trans-Pecos region of Far West Texas and in a topographically distinct area of North America known as the Basin and Range Physiographic Province (Fenneman, 1931; Thornbury, 1965). Figure 2.2.1 shows the physiographic province and its two sub-sections, Sacramento and Mexican Highland. The Great Plains Province lies adjacent to the northeast. In Texas, the Trans-Pecos region is bounded on the north by New Mexico, on the south and west by the Rio Grande, and along the east by the Pecos River.

Traversed from north to south by an eastern range of the Rocky Mountains, the region contains all of Texas' true mountains with higher elevations and greater local relief than is characteristic of other areas of the state. Although the topography throughout most of Texas is generally flat and elevations are less than 2,500 feet above mean sea level (msl), the floors of most of the basins in West Texas are at elevations greater than 3,000 feet. Widely spaced mountain ranges rise from 1,000 to more than 3,000 feet above the lowlands. Fault-block basins separating the mountains are filled with sediments (bolson deposits) eroded from the surrounding highlands. Surface water in the study area primarily occurs as storm-water runoff, with the exception of springs and the perennial Limpia and Calamity Creeks.

The topography of the region is shown in Figure 2.2.2. The Davis Mountains, with a number of peaks with elevations greater than 6,000 feet, exist principally in Jeff Davis County. Mount Livermore, at 8,378 feet, is one of the highest peaks in Texas. These mountains intercept moisture-bearing winds and receive more precipitation than other locations in West Texas. The Davis Mountains are greener with more grass and forest trees than other mountains of the region.

Topographically, the study area is contained within the Rio Grande Basin, Pecos River Basin, and the Salt Basin. These three major river basins and the sub-basins of these three major basins are shown in Figure B.3 in Appendix B.

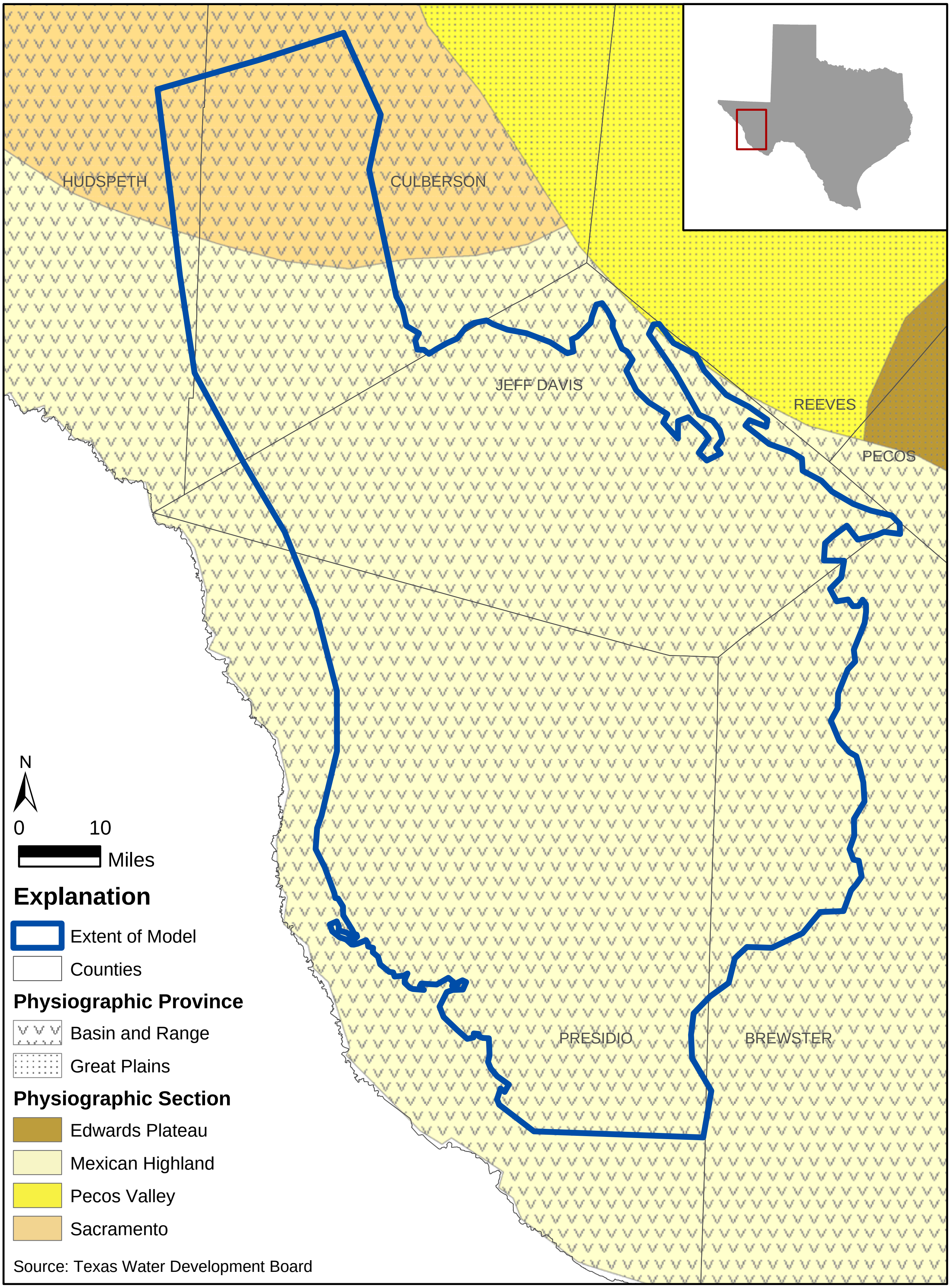


Figure 2.2.1 - Physiographic Provinces and Sections

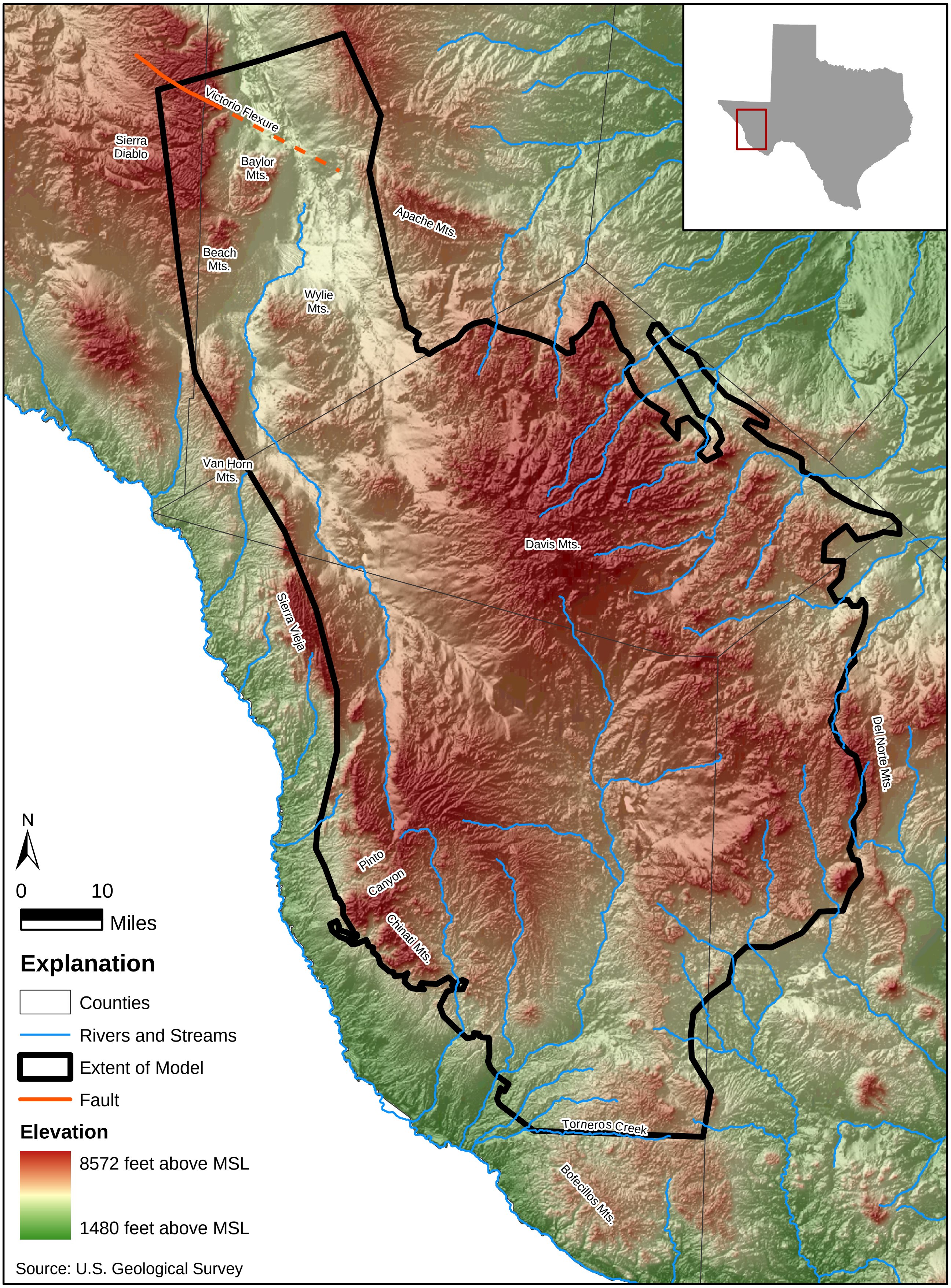


Figure 2.2.2 - Topography

Overlapping the Trans-Pecos region of Texas is the northern portion of the Chihuahuan Desert, a 1,200-mile long and 800-mile wide arid zone that extends southward into Mexico. Included in the Chihuahuan Desert region are parts of the states of Arizona, New Mexico and Texas in the United States, as well as parts of the states of Chihuahua, Coahuila, Nuevo Leon, Durango, Zacatecas, and San Luis Potosi in Mexico.

2.3 Climate

The Chihuahuan Desert is traversed by Mexico's two great mountain ranges - the Sierra Madre Oriental and the Sierra Madre Occidental. As warm moist air rises to move across these mountains, the air cools rapidly, and the cooling generates rainfall on the windward face of the mountains. This also creates a rain-shadow effect on the lee face of the mountain ranges and over the basins of the Chihuahuan Desert. While the other North American deserts have summer and winter rainy seasons (because of their location further to the west), rain typically comes to the Chihuahuan Desert between the months of June and October, during which as much as 90 percent of the annual rainfall takes place. This is often referred to as the monsoon season of the Southwest.

Within the Trans-Pecos region of the Chihuahuan Desert, only the highest altitudes receive sufficient precipitation to be considered semiarid, rather than true desert (Schmidt, 1995). For example, the climate of Jeff Davis County and adjoining areas of Brewster and Presidio Counties ranges from cool-temperate-humid at elevations above 4,000 ft to arid-subtropical at lower elevations (Bomar, 1995). At elevations above 6,800 ft, summer temperatures exceed 90ºF only 10 percent of the time. The mean annual temperature at Mount Locke (6,800 ft) is 57ºF; at Marfa (4,700 ft), 61ºF; at Alpine (4,500 ft), 64ºF; and at Balmorhea (3,256 ft), 65ºF. This represents an 8ºF difference in temperature over a horizontal distance of less than 30 miles, and a vertical elevation change of 3,544 ft (Hart, 1992).

Rainfall during the spring and summer months (June through October) is dominated by widely scattered thunderstorms (Larkin and Bomar, 1983; Nativ and Riggio, 1989 and 1990). Figure 2.3.1 shows the distribution of mean annual precipitation in the study area based on GIS interpretations of data from available weather statistics. Because of the convective nature of thunderstorms and the orographic lifting effect of mountainous areas, the amount of spring and summer precipitation increases with elevation. The influence of orographic lifting on average annual rainfall is illustrated by the higher median precipitation areas centered over the Davis Mountains in Jeff Davis County and along the mountain ridge that borders the western side of the Salt Basin (e.g. Sierra Diablo).

Evaporation is very high in the study area. Figure 2.3.2 shows the average annual lake evaporation from 1940 through 2000. The average monthly evaporation ranges from about 54 to over 70 inches per year. Figure 2.3.3 shows annual precipitation at selected weather stations. Average monthly evaporation is usually at least five times greater than average monthly precipitation, even during the rainy season in late summer and early fall.

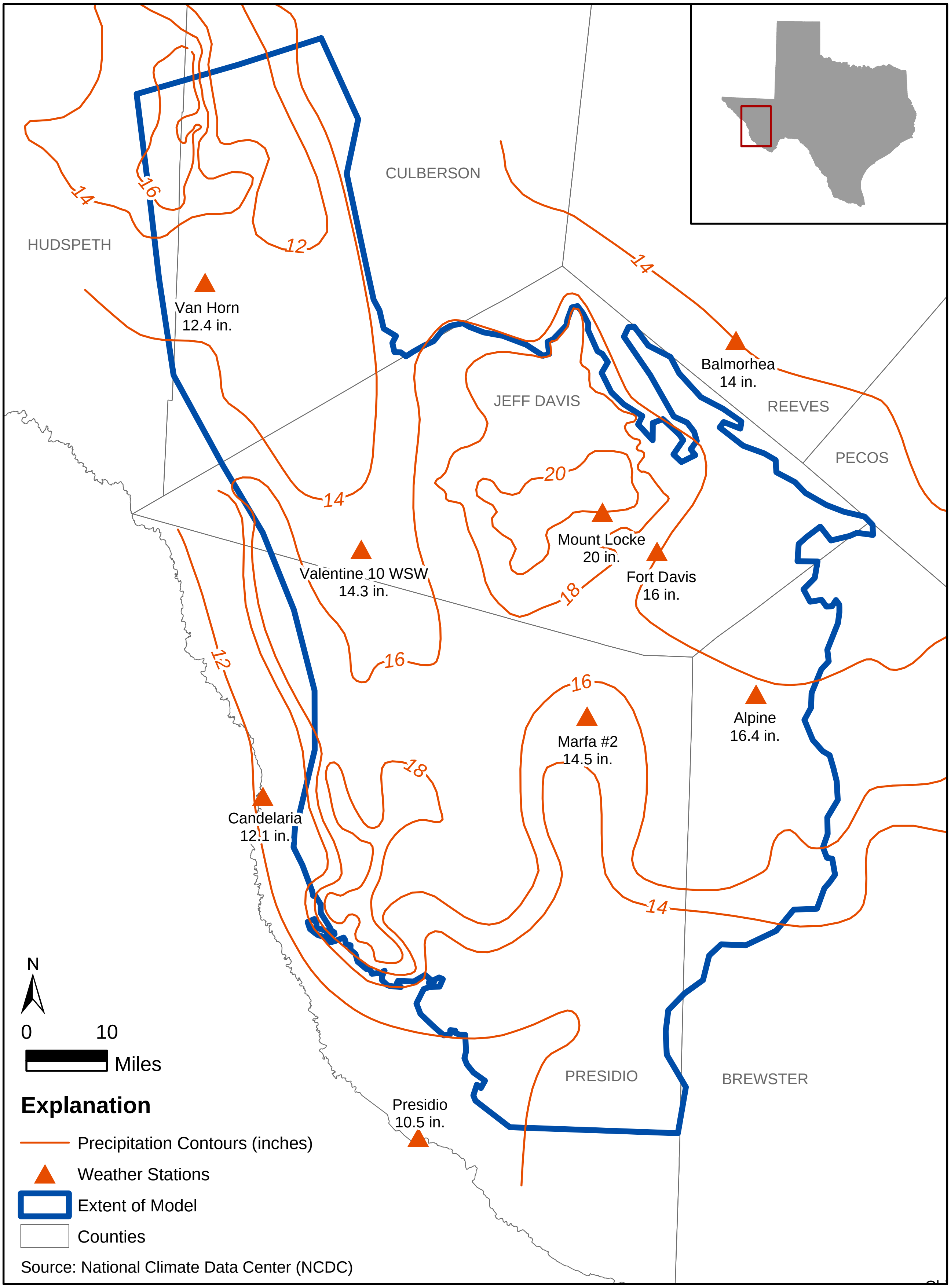


Figure 2.3.1 - Mean Annual Precipitation (1960-2000)

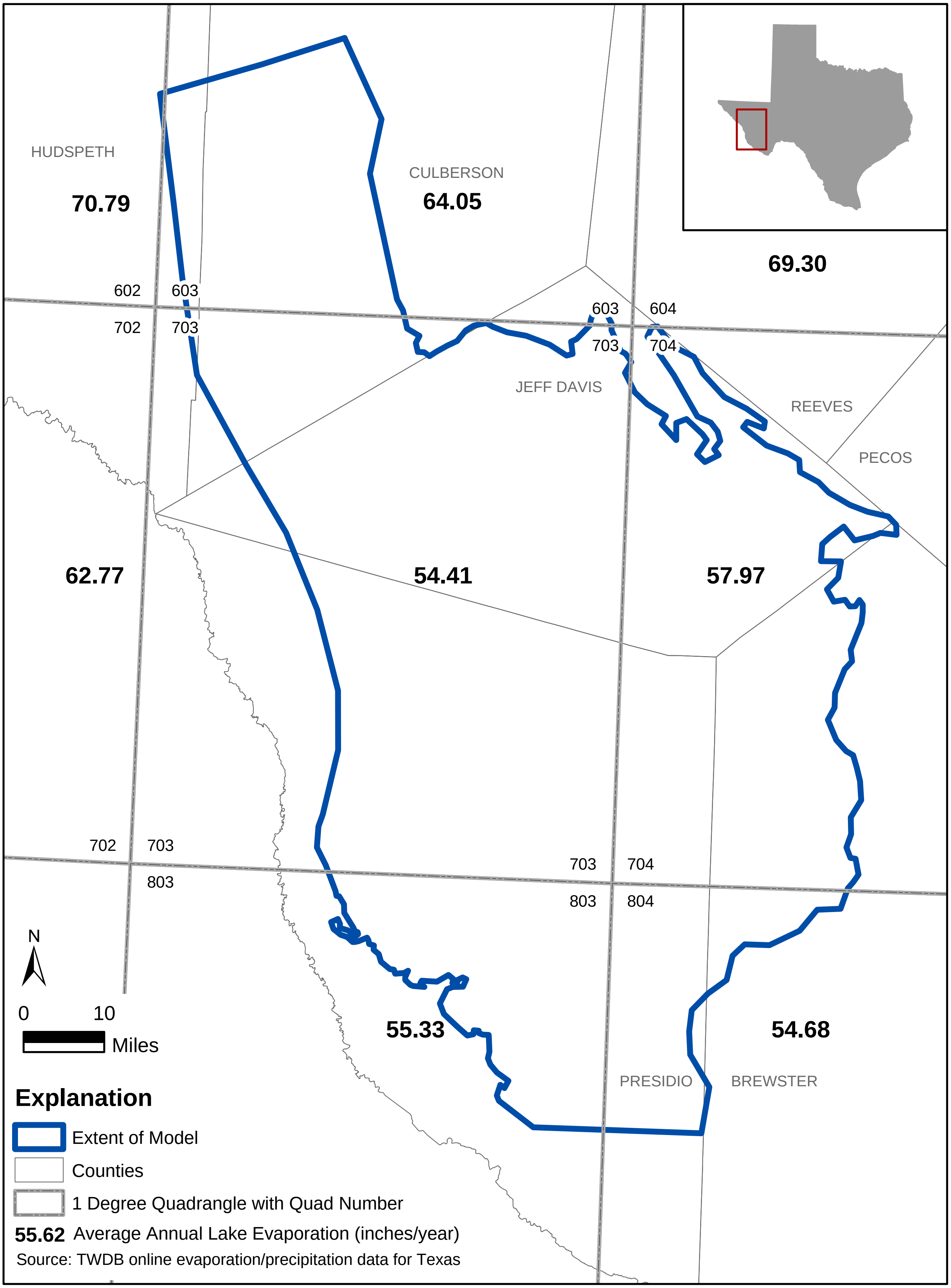
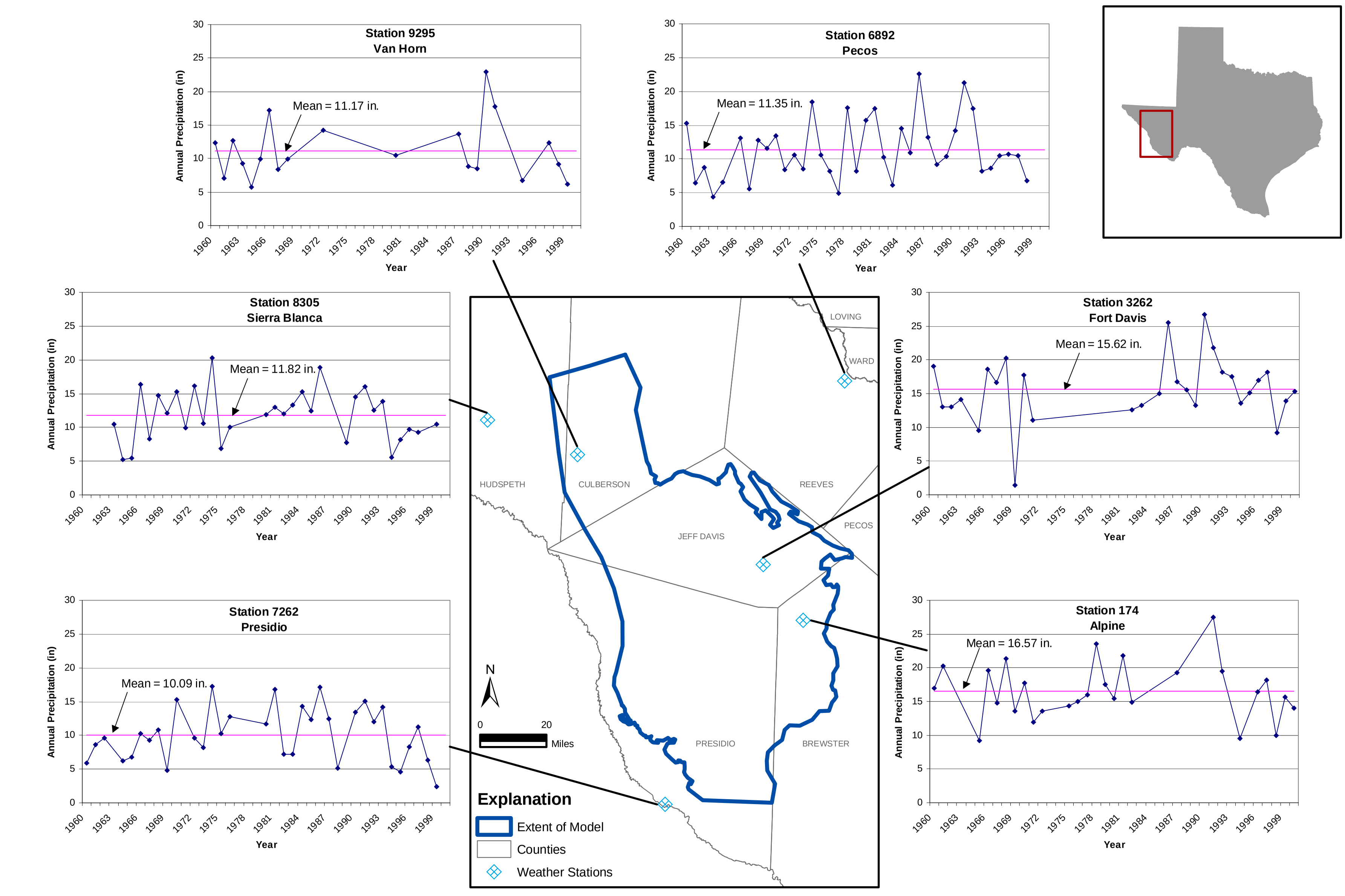


Figure 2.3.2 - Average Annual Lake Evaporation



Source: Texas Office of the State Climatologist

Figure 2.3.3 - Selected Weather Stations with Historic Precipitation Data

2.4 Vegetation and Land Use

Figure 2.4.1 shows the distribution of vegetation in the study area. The major climatic influence on natural vegetation in this region is the distribution of precipitation. Altitudinal differences, along with associated local temperature variations, are the major secondary controls. Desert shrub communities, particularly of creosote bush and mesquite, are most common in the region's western arid zones from the lowest altitudes to about 4,500 ft. The two plant indicators of the Chihuahuan Desert are lechuguilla (*Agave lechuguilla*) and sotol (*Dasylirion wheeleri*), which are generally found on the rough limestone slopes of the foothills. There are indications that xerophytic vegetation has been expanding upslope through the region for more than a century as a result of grassland disturbance from grazing, cultivation, introduction of non-native species, and drought (Schmidt, 1995).

The more semiarid eastern portion of the study area supports short grassland. At higher elevations, the desert grassland grades into open woodland consisting of juniper and various species of oak. Woodlands consisting of pine and fir are generally restricted to the higher elevations of the Davis Mountains above 6,900 ft. Scattered through the region are smaller areas of riparian, holophytic, and other vegetation adapted to specific site conditions (Schmidt, 1995).

Most vegetation in this arid region of the State has adapted to the drier climate by developing means of storing water within the body of the plant. Evapotranspiration (ET) is significantly less from desert plants than from vegetation in wetter climates. Table 2.1 summarizes the available evapotranspiration rates and mean maximum root depths for vegetation types in the model area.

Table 2.1 Evapotranspiration Rates and Mean Maximum Root Depths of Vegetation in the Model Area

Species[1]	Evapotranspiration Rate (inches/year)	Mean Maximum Root Depth (feet)
Mesquite	8.8 – 24.3	46.9
Creosote Bush	10.6 – 14.9	--
Temperate Grassland	--	8.5
Oak	30.2	13.1 – 31.8
Juniper	23.3 - 25	--
Deciduous Forest	--	9.5
Coniferous Forest	--	12.8

1 - Sources of data: ET Rate: *Mesquite*- Tromble (1977) and Duell (1990); *Creosote Bush*- Cable (1980); *Oak*- Dolman (1988); *Juniper*- Dugas and others (1998); *Root Depth*- Canadell and others (1996)

Figure 2.4.2 shows the land use and land cover distribution in the study area, with the vast majority of the land characterized as rangeland. The figure also shows the extent of forestland in the Davis Mountains as well as the agricultural areas within the Salt Basin. The extent of the urban areas associated with the cities of Alpine, Marfa, Fort Davis, Valentine and Van Horn are also shown.

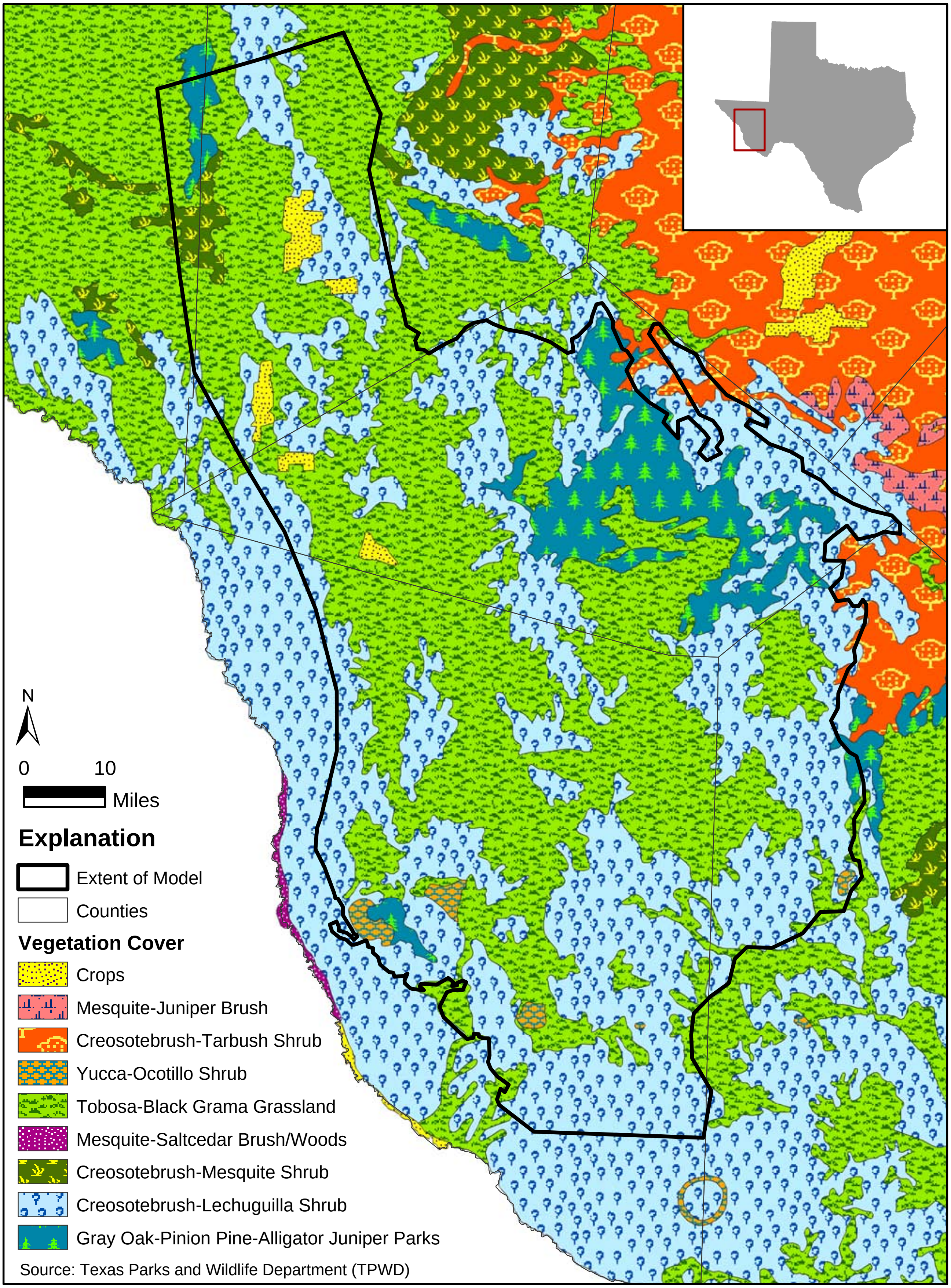


Figure 2.4.1 - Distribution of Vegetation

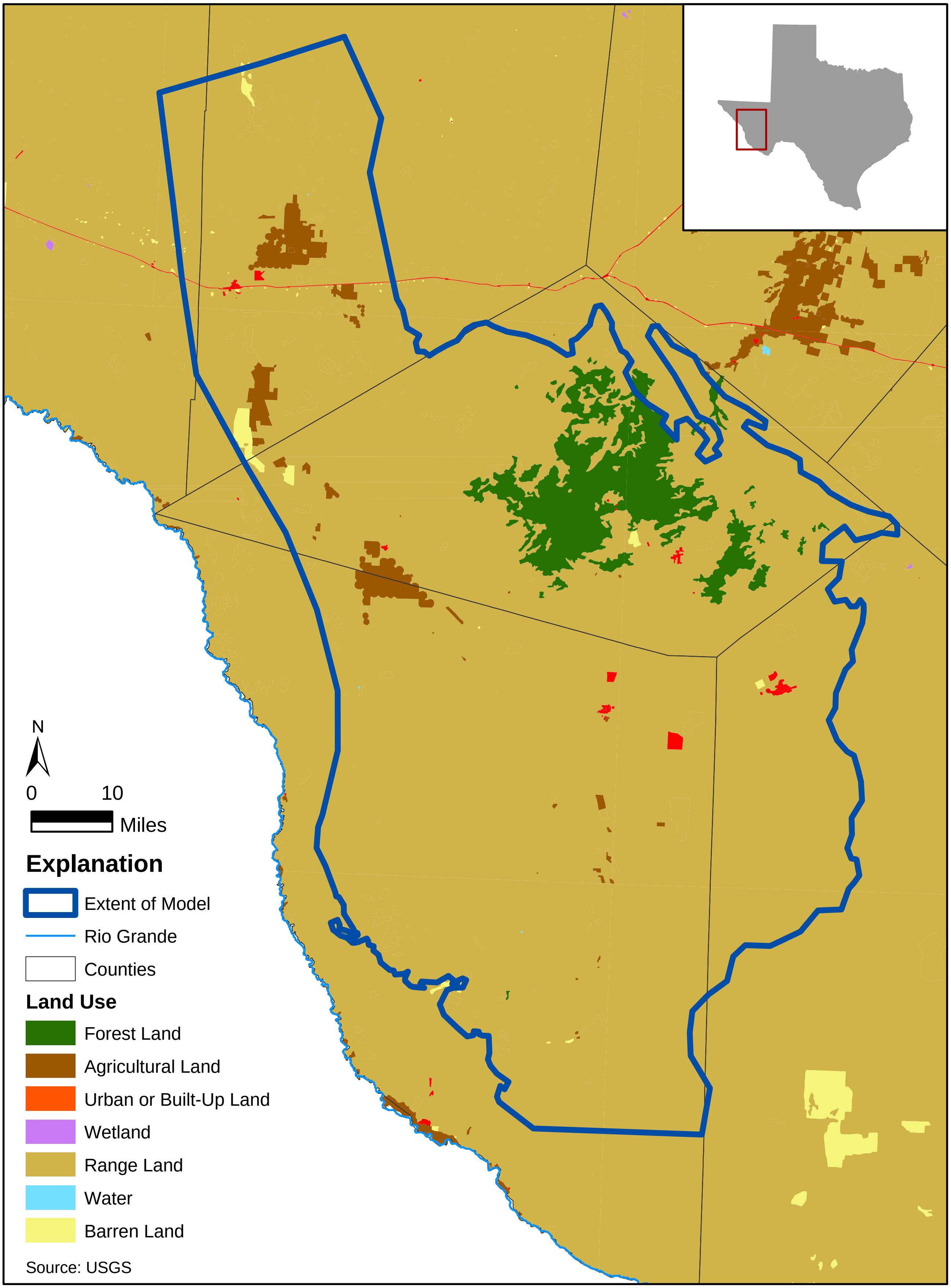


Figure 2.4.2 - Land Use

2.5 Geology

The geologic history of the Trans-Pecos region of Texas has given rise to the hydrogeologic complexities of this area and encompasses many aspects of North American geologic history (King, 1959, Urbanczyk and others, 2001). Precambrian-age crystalline metamorphic rocks are exposed in the Franklin Mountains, Van Horn Mountains, and Sierra Diablo Mountains. Xenoliths (fragments) of these rocks recovered from volcanic rocks in the Davis Mountains, Bofecillos Mountains, and Chisos Mountains provide strong evidence that almost all of Trans-Pecos Texas is underlain by Precambrian rocks similar to those that crop out at the surface. Cambrian-age to Pennsylvanian-age rocks crop out in the Franklin Mountains, Marathon Basin, Solitario, and at Persimmon Gap. These rocks represent a transgressive, then regressive marine depositional sequence that was later deformed during a mid- to late-Paleozoic tectonic event referred to as the Marathon-Ouachita Orogeny (King, 1978, Muehlburger and Dickerson, 1989). The foreland areas of these Paleozoic mountains became the Permian Basin, and the carbonate rocks associated with this intracratonic sea now crop out in the Guadalupe, Glass, Apache, Van Horn, Chinati and Sierra Diablo mountain ranges (King, 1959), and are present in the subsurface underlying volcanic sequences of the Davis Mountains. The complex sequence of lithologies produced during this episode varies from a discontinuous reef system to deep basinal sedimentary rocks.

There was a depositional hiatus from the Triassic to Mid-Cretaceous time. It was followed by the deposition of mid- to late-Cretaceous limestones that cover much of central and far west Texas and comprises important aquifers such as the Edwards aquifer.

Mesozoic clastic and carbonate sedimentation did not begin in the Trans-Pecos region until Middle Cretaceous time with the deposition of the Comanchean series rocks. These represent carbonate sedimentation associated with a widespread, intracontinental sea that inundated much of North America from Texas to Alaska. Late Cretaceous uplift related to the Laramide orogeny is responsible for Gulfian series rocks, a regressive sequence of limestone to terrigenous shale and sandstone that overlie the Comanchean series. The Laramide Orogeny continued from the late Cretaceous to the early Tertiary, causing local deformation, which can be seen in the Del Norte-Santiago Mountains, Mariscal Mountains, the Terlingua-Fresno Monocline, and in the Chihuahua Tectonic Belt, mostly residing outside of the IBGAM area.

Laramide compression was followed by a long period of large-scale ignimbritic volcanism in Trans-Pecos Texas (Henry and McDowell, 1986). This volcanic event produced a complex series of welded pyroclastic rocks, lavas, and volcaniclastic sediments throughout the model area. The igneous rocks are the most complex units in the geologic sequence within the model and include more than 40 different named units (see Table 2.2). There is a large variation of units from tuffs and breccias to basalts and trachytes. Each has a different geographic extent, and there are only a few units, such as the Petan Basalt and the Mitchell Mesa Rhyolite, which can be used as marker beds within the igneous units.

The chronology for the igneous formations in the model area is mainly from one period within the Tertiary. These volcanic rocks were formed between 48 and 27 million years ago (Ma). The approximate extent of these volcanic eruptive units and their respective chronology are discussed in Chastain-Howley (2001). The volcanic rocks consist of a complex layering of vents, flows, and interbedded volcanic-sedimentary units, which were deposited in numerous intervals between eruptions. This layering has led to the very complex interrelationships between the rock units. The most obvious trends are the main-center shifts from the south in the early phase of volcanic activity (48 to 39 Ma), to the north in the middle phase (39 to 35 Ma) and back to the south again in the late phase (35 to 27 Ma). Although Tertiary-age volcanic rocks occur elsewhere in Far West Texas, the contiguous Davis Mountains igneous rocks are only evident in Brewster, Jeff Davis and Presidio Counties. The Tertiary volcanics do not extend significantly into Culberson County and end approximately at Chispa Mountain at the northern entrance to Lobo Valley.

As Laramide compression continued to wane, ignimbritic volcanism yielded to smaller-scale effusive volcanism that was coupled with extensional tectonics, resulting in Basin and Range structures and related mountain ranges in the Trans-Pecos (Muehlberger and others, 1978, Henry and others, 1991). Between these ranges, which include the Franklin, Hueco, Guadalupe, Delaware, Sierra Diablo, Sierra Vieja, and Van Horn mountains, large basins formed, beginning in the Tertiary and continuing throughout the Quaternary, that filled with thick sequences of gravel and sand eroded from the adjacent mountains. These basins formed as the result of the extensional tectonics that produced a discontinuous series of north-northwest-trending pull-apart grabens that terminate at west-northwest-trending strike-slip faults.

The surface geology in the study area is shown in Figure 2.5.1. The stratigraphy of the study area is illustrated in a series of hydrostratigraphic cross sections, the locations of which are shown in Figure 2.5.2. Individual cross sections are shown in Figures 2.5.3 through Figure 2.5.6. Cross sections B-B’, C-C’ and D-D’ are adapted from a report prepared by Olson (2002); A-A’ is after Finch and Armour (2001) and Gates and others (1980).

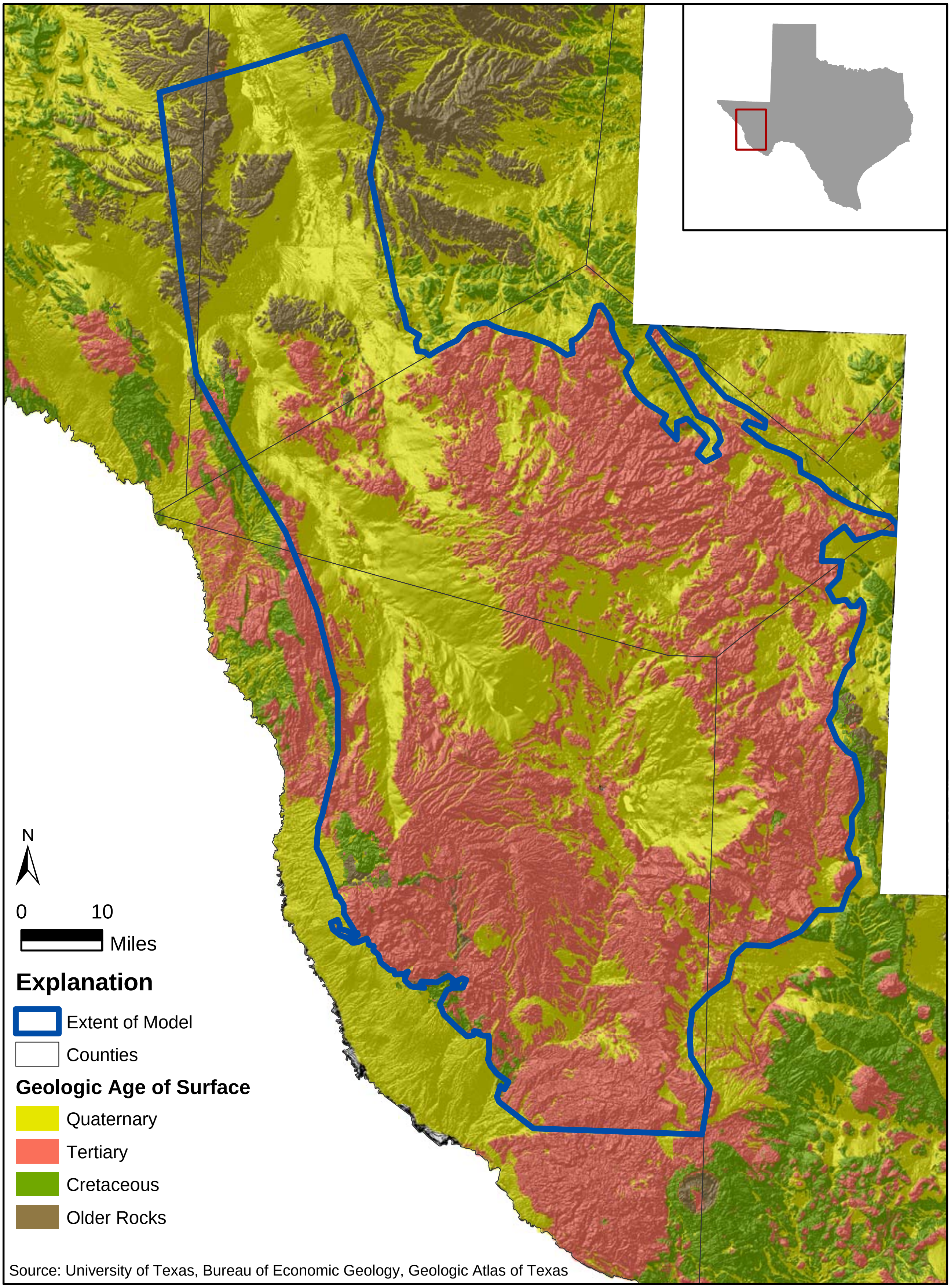


Figure 2.5.1 - Surface Geology

Table 2.2 Stratigraphic units

Era	System	Salt Basin	Davis Mountains	Model Hydrostratigraphic Layers
Cenozoic	Quaternary	Quaternary deposits Bolson deposits	Quaternary deposits	Salt Basin Bolson Aquifer
	Tertiary	Volcaniclastics undifferentiated Igneous rocks undifferentiated Perdiz Conglomerate	Igneous rocks undifferentiated Perdiz Conglomerate Tarantula Gravel Petan Basalt Tascotal Formation Mitchell Mesa Welded Tuff Brooks Mountain Formation Goat Canyon Formation Medley Formation Wild Cherry Formation Eppenauer Ranch Formation Mount Locke Formation Barrel Springs Formation Capote Mountain Tuff Merrill Formation Duff Formation / Decie Member Sheep Pasture Formation Sleeping Lion Formation Frazier Canyon Formation Cottonwood Spring Basalt Bracks Rhyolite Adobe Canyon Formation Chambers Tuff Limpia Formation Potato Hill Andesite Gomez Tuff Star Mountain Rhyolite Crossen Trachyte Sheep Canyon Basalt Pruett Formation Huelster Formation Buckshot Ignimbrite Colmena Tuff Gill Breccia	Igneous Aquifer
Mesozoic	Cretaceous	Cretaceous undifferentiated	Cretaceous undifferentiated Buda Limestone Boracho Formation San Martine Limestone Member Levinson Limestone Member Finlay Formation Cox Sandstone	Cretaceous and Permian Hydrogeologic Units
Paleozoic	Permian	Capitan Limestone Bone Spring - Victorio Peak	Permian undifferentiated	

Note: Stratigraphic names adopted from Fisher (1979, 1983, and 1995).

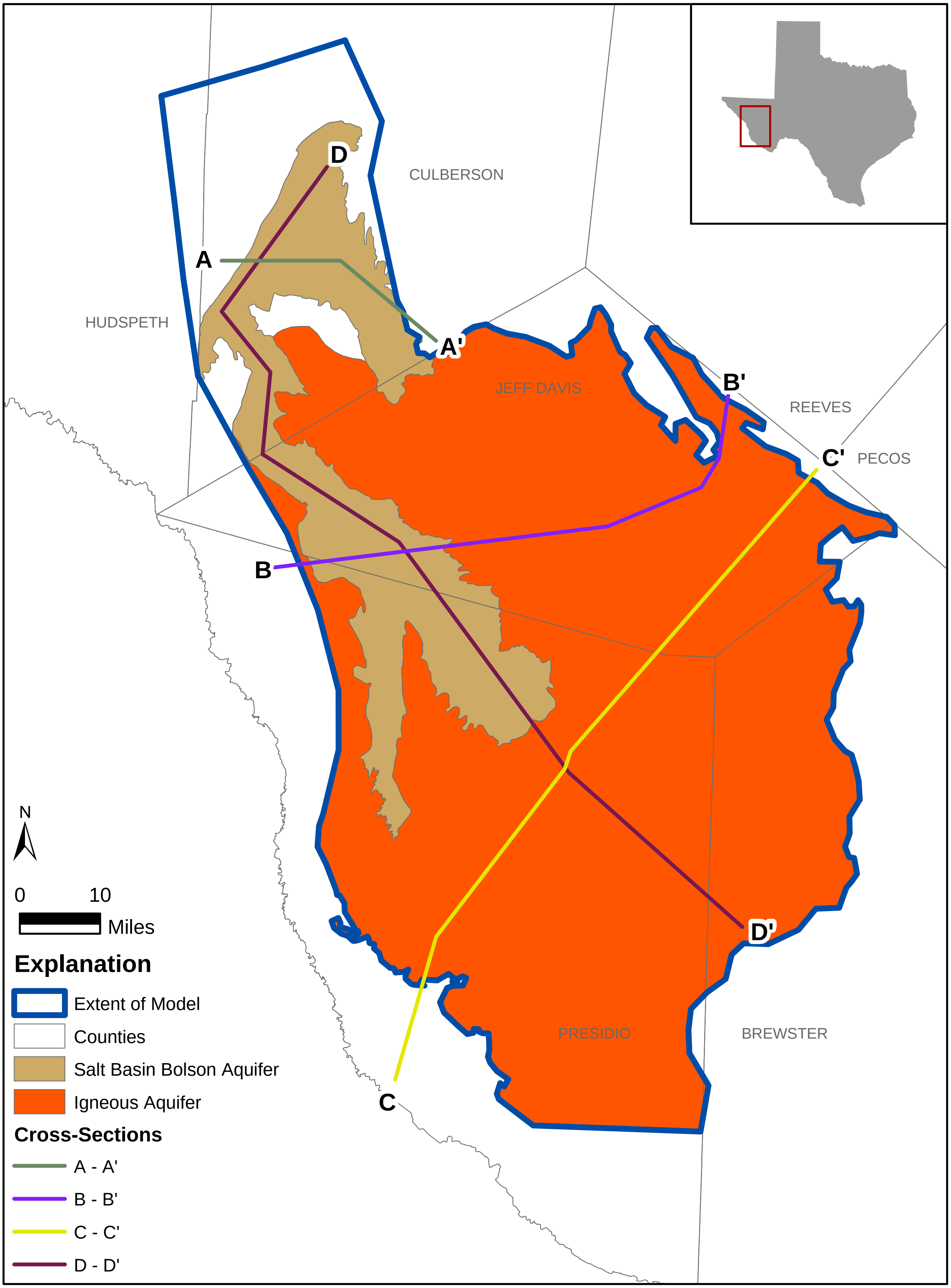


Figure 2.5.2 - Location of Cross-Sections

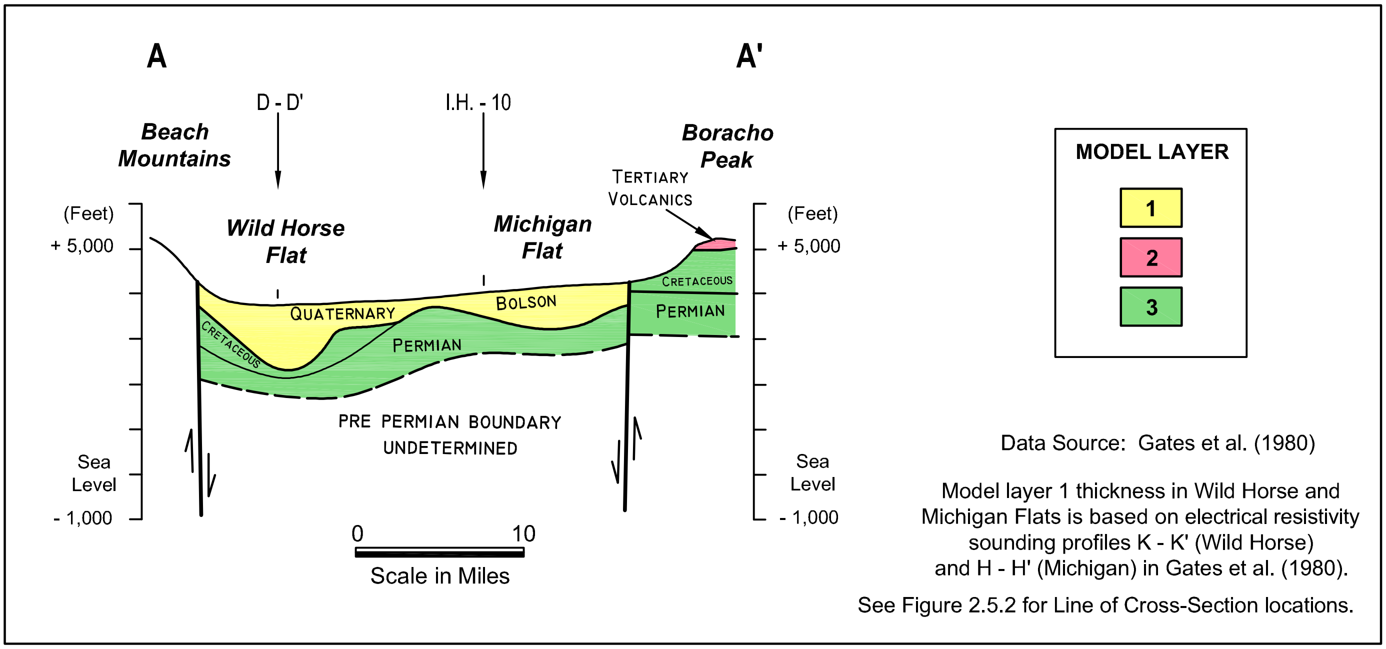


Figure 2.5.3 Geohydrologic Cross-Section A-A'

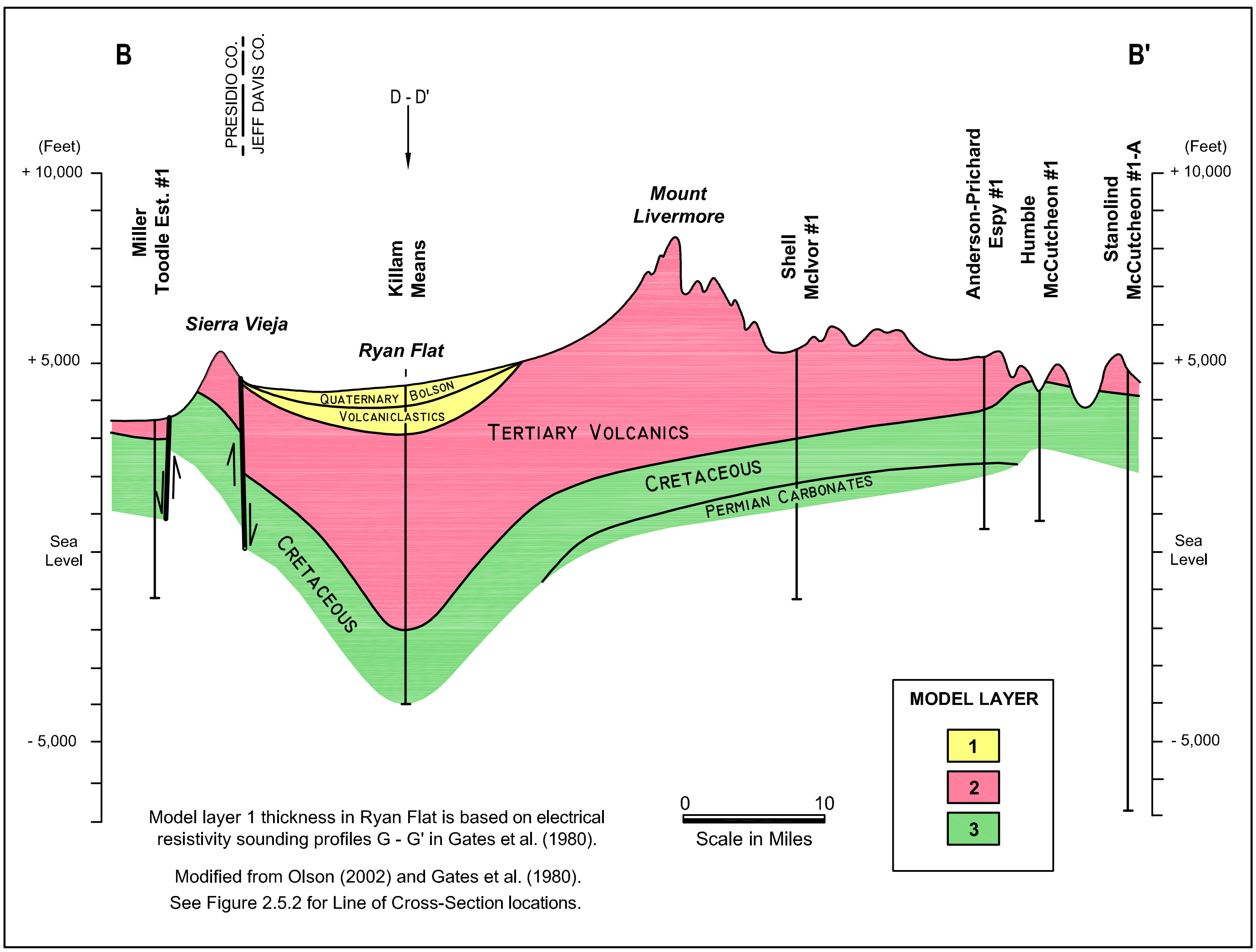
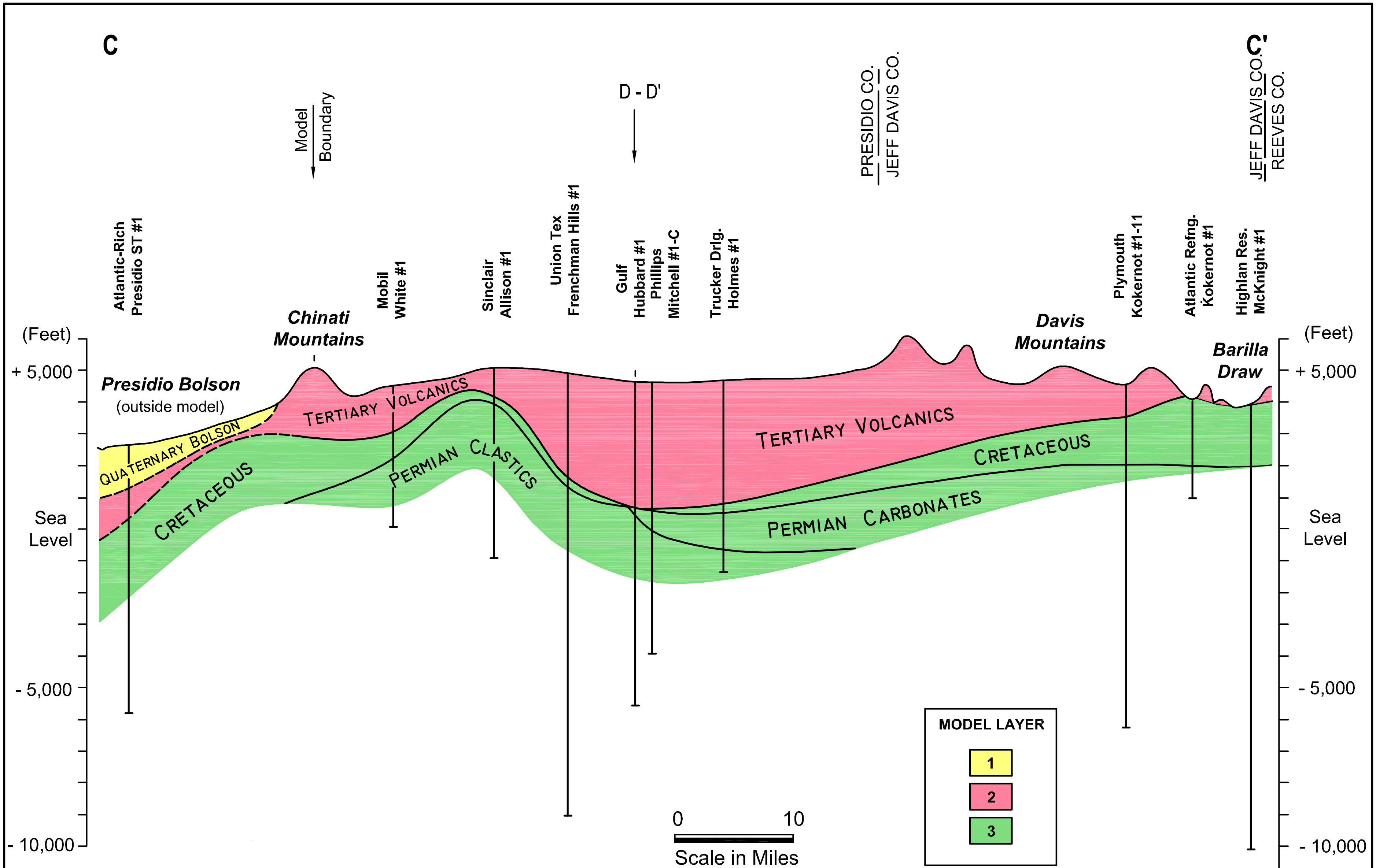


Figure 2.5.4 Geohydrologic Cross-Section B-B'



Modified from Olson (2002).
See Figure 2.5.2 for Line of Cross-Section locations.

Figure 2.5.5 Geohydrologic Cross-Section C-C'

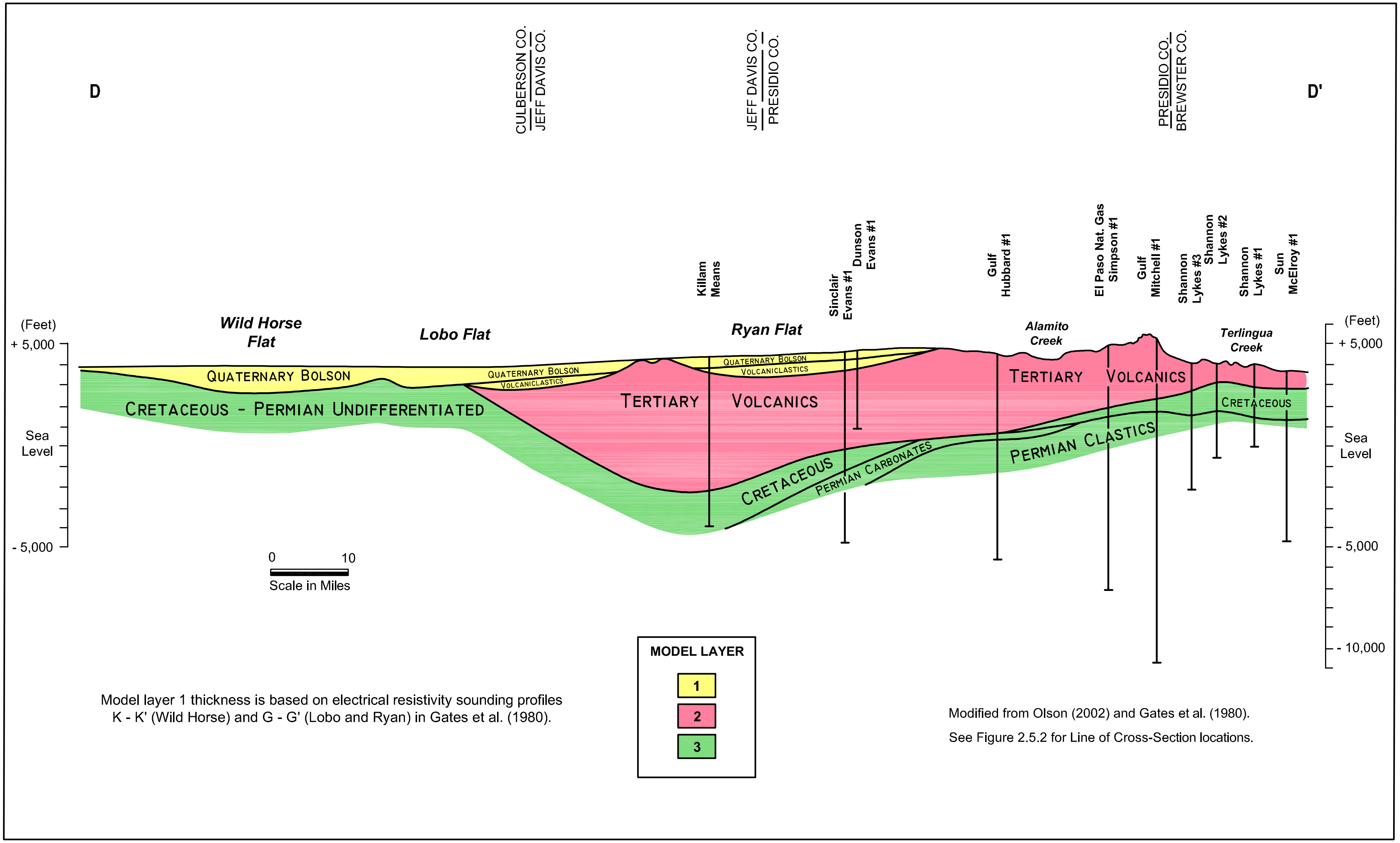


Figure 2.5.6 Geohydrologic Cross-Section D-D'

3.0 PREVIOUS WORK

Section 2.5 provides references to a number of studies that detail the region's geology. In addition, there have been several groundwater models developed within the study area. However, none of these models covered the Igneous aquifer or the entire extent of the Salt Basin Bolson aquifer.

3.1 Hydrogeologic Framework

The conceptual model and hydrogeologic framework of the study area is largely based on previous work performed by Gates and others (1980), Kreitler and Sharp (1989), and Mace and others (2001). The U. S. Geological Survey (USGS) performed the first comprehensive hydrogeologic study of the West Texas Bolsons in the late 1970s (Gates and others, 1980). The USGS study primarily focused on water availability from the bolsons and adjacent areas. More recently, a comprehensive report on the hydrogeologic framework of the Wild Horse, Michigan, Lobo, and Ryan Flat Bolsons was presented by Angle (2001). Ashworth and others (2001) and Chastain-Hawley (2001) document recent hydrogeologic studies of the Igneous aquifer. A number of specific studies on regional groundwater flow and hydrogeology of Trans-Pecos Texas are provided in Kreitler and Sharp (1989).

3.2 Groundwater Models

Within the study area, there have been four groundwater flow models developed over the last 13 years (Nielson and Sharp, 1989; Black, 1993; Brown and Caldwell, 2001; and Finch and Armour, 2001) primarily of the Wild Horse, Lobo, and Ryan Flats area where irrigation pumping has been concentrated. Brown and Caldwell (2001) completed a hydrologic study and numerical model of Ryan Flat. Finch and Armour (2001) completed a study and numerical model for Culberson County that covered Wild Horse and Lobo Flats. Figure 3.2.1 is a map showing the location of previous modeling studies, and a comparison of these models is provided in Table 3.1.

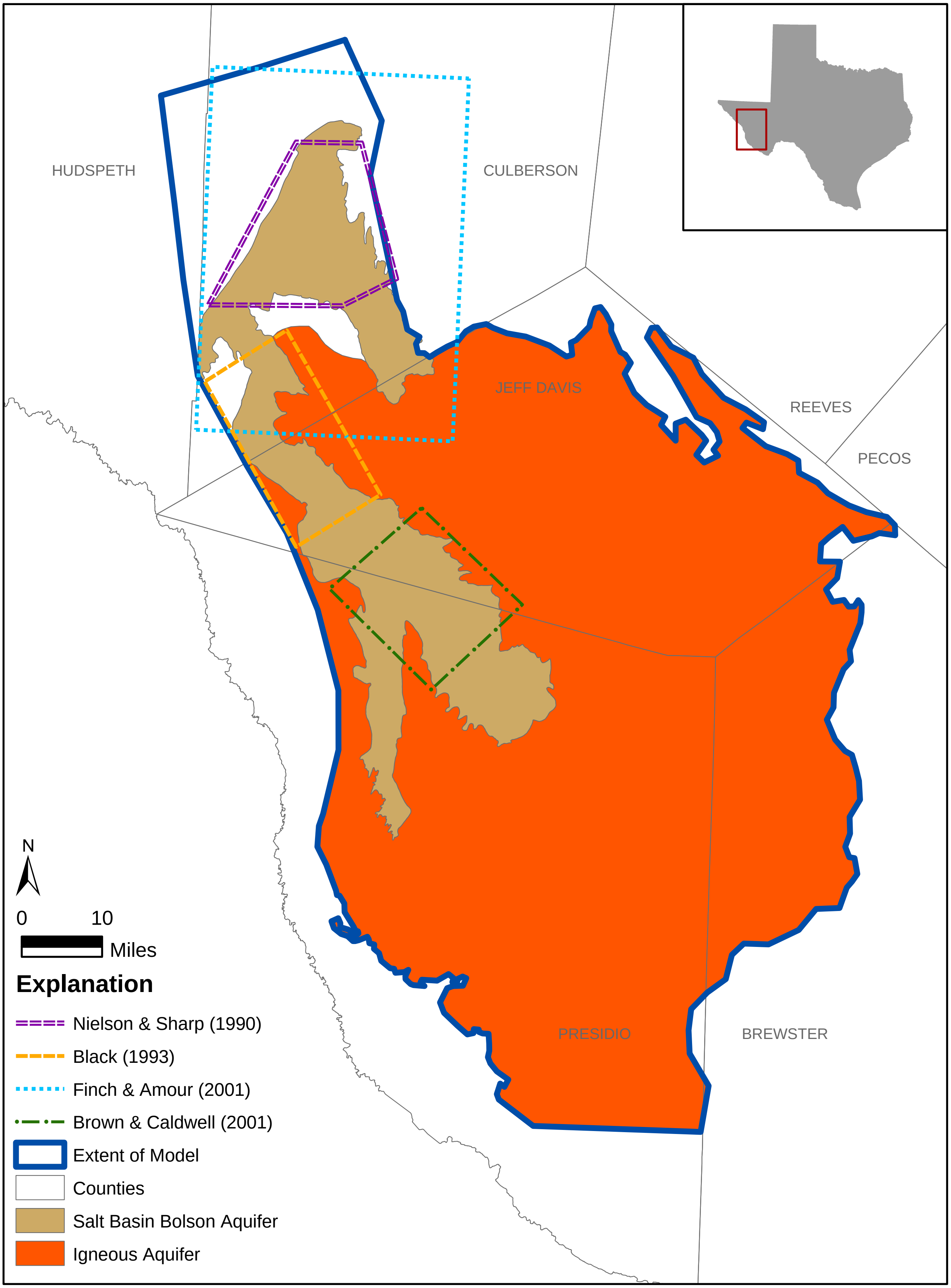


Figure 3.2.1 - Location of Areas Covered byPrevious Modeling Studies

Table 3.1 Comparison of previously developed groundwater flow models

Model	Code	Type model	Number of layers	Aquifer modeled	Type of calibration	Predictive simulations
Nielson and Sharp (1989)	Trescott and others (1976)	Two dimensional	1	Wild Horse Flat	Steady-state	No
Black (1993)	MODFLOW	Two dimensional	1	Lobo Flat	Steady-state	No
Brown and Caldwell (2001)	MODFLOW	Three dimensional	7	Ryan Flat	Steady-state and transient	Yes
Finch and Armour (2001)	MODFLOW	Three dimensional	4	Wild Horse, Michigan, and Lobo Flats	Transient	Yes

Earlier models developed by Nielson and Sharp (1989) and Black (1993) were research projects designed to evaluate primarily the recharge component of the conceptual models of the Salt Basin Bolson aquifer. Models developed by Brown and Caldwell (2001) and Finch and Armour (2001) were developed to evaluate the drawdown effects from irrigation and potential municipal pumping. The current IBGAM is the first groundwater flow model of the Igneous aquifer.

4.0 HYDROLOGIC SETTING

Groundwater of variable quantity and quality is contained in many of the rock formations that occur within the study area. Its occurrence and movement are associated with the porosity and permeability, elevation, and structural features of the various rock formations. For the purpose of the IBGAM project, these water-bearing formations are grouped as aquifers or aquifer systems and include the following:

- Salt Basin Bolson aquifer (which includes saturated bolson deposits and underlying, hydrologically connected volcaniclastic units),
- Igneous aquifer (which includes all igneous units other than the volcaniclastics included in the Salt Basin Bolson aquifer), and
- Cretaceous-Permian formations (undivided).

Older Paleozoic and Precambrian rocks are not considered hydrologically significant for this project, and are excluded from this discussion. Table 2.2 provides a listing of individual rock formations in each aquifer group. The vertical arrangement of igneous formations in the Davis Mountains column is uncertain and does not necessarily imply correlation.

The conceptualization of the hydrostratigraphy was developed for the purposes of this study in preparation for the development of the IBGAM. The cross-sections describe the major variations in the highly complex geology within the model area and how that complexity is simplified in the hydrostratigraphic representation, which is the foundation for the IBGAM model structure.

Figures 2.5.3 and 2.5.6 illustrate the subsurface hydrostratigraphic relationship of the three modeled layers. These relationships, in conjunction with the available data, suggest that an appropriate conceptualization of hydrostratigraphy to meet the objectives of the IBGAM can be generalized into three basic sequences. In descending order, is the Salt Basin Bolson aquifer (model layer 1), which consists of Quaternary sedimentary rocks and the volcaniclastic units, mostly related to the Basin and Range extensional tectonics.

Second is the Igneous aquifer (model layer 2), which consists of volcanic rocks associated with the Tertiary ignimbritic volcanism. Third is the Cretaceous and Permian formations (model layer 3), which consists of Cretaceous and older dominantly carbonate rocks that immediately underlie the Tertiary or Quaternary sequences.

4.1 Salt Basin Bolson Aquifer

4.1.1 Hydrostratigraphy

The Salt Basin Valley lies on the southeastern edge of the Southern Basin and Range - Rio Grande rift tectonic province (Collins and Raney, 1997) and extends from southern New Mexico into Texas. The Salt Basin Bolson aquifer consists of connected sub-basins underlying Wild Horse, Michigan, Lobo, and Ryan Flats, which occupy the middle and southern Salt Basin Valley in Texas (Angle, 2001) (Figure 2.1.3). Thick bolson sediments of the Salt Basin extend northward from Wild Horse Flat; however, groundwater contained in these sediments is more saline and is therefore not characterized as being a part of the Salt Basin aquifer.

Bolson deposits contain alluvial, lacustrine, and evaporite sediments that reflect the rocks from the surrounding mountains (King, 1965). Wild Horse and Michigan Flats consist primarily of erosional detritus from bordering Permian formations, while Lobo and Ryan Flats contain reddish sediments originating from the surrounding Tertiary igneous units.

Alluvial fan deposits of sand, gravel, silt, and clays are found along the margins of the basin and typically become finer grained away from the mountains. Coarser grained deposits along the mountain front readily infiltrate recharge from storm-water runoff (Scanlon and others, 2001). Salt flats north of the Baylor Mountains and on the northern model boundary represent areas of groundwater discharge by evaporation (Boyd and Kreitler, 1986).

The volcaniclastic units are the intermediate step between the igneous formations and the bolson deposits and have many hydrogeological characteristics similar to the bolson sediments. This is especially true of the hydraulic properties as noted in the wells underlying the Ryan Flat area. Brown and Caldwell (2001) indicate that the volcaniclastic units are a major water-producing unit in the three wells tested on Antelope Valley Farms in Ryan Flat. For the purposes of the IBGAM, the volcaniclastic unit is considered part of the Salt Basin Bolson aquifer unit.

The thickness of Salt Basin sediments was first mapped by Gates and others (1980), and was then modified using oil and gas exploration data reported by Veldhuis and Keller (1980). The Salt Basin sediments are reported by Collins and Raney (1997) to be up to 3,000 ft thick, but the thickness varies according to geologic structures within the bolson (Veldhuis and Keller, 1980). Figures 4.1.1, 4.1.2, and 4.1.3 show the thickness, elevation of the base of the bolson, and elevation of the top of the bolson, respectively. These maps were developed using estimates from previous studies and the hydrogeologic database developed for this study. The area from Lobo to Ryan Flat was modified from previous studies to represent the combined thickness of the bolson and volcaniclastic deposits, which are assumed to be a part of the same hydrostratigraphic unit for the purposes of this study.

4.1.2 Structure

The generally north-south trending Salt Basin is an asymmetrical down-faulted valley (graben) with the greatest thickness occurring along the western edge (Henry and Price, 1985). Cliffs are common on the western side of the bolson near Ryan and Lobo Flats where faulting has caused the topographic variation.

Figure 4.1.4 illustrates faults in the study area, which in this region form the major structural control. The major faults shown on this map are primarily controlled by the graben development associated with the extensional tectonics discussed in Section 2.5. These faults are summarized from Geologic Atlas of Texas maps (Emory Peak-Presidio, Fort Stockton, Marfa, and Van Horn-El Paso sheets). Basin-and-range movement remains seismically active within the area and has produced numerous small earthquakes.

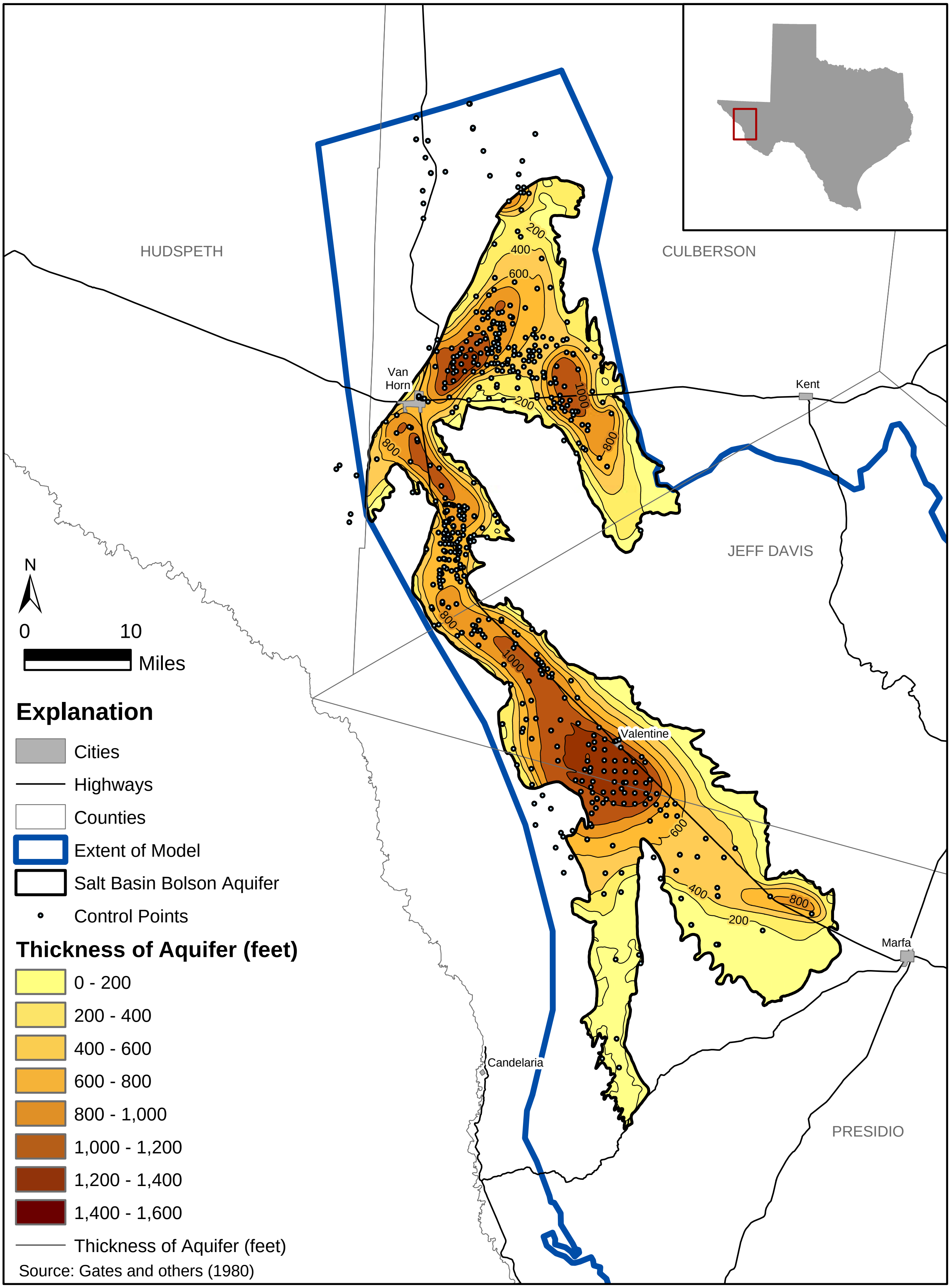


Figure 4.1.1 - Thickness of the Salt Basin Bolson Aquifer

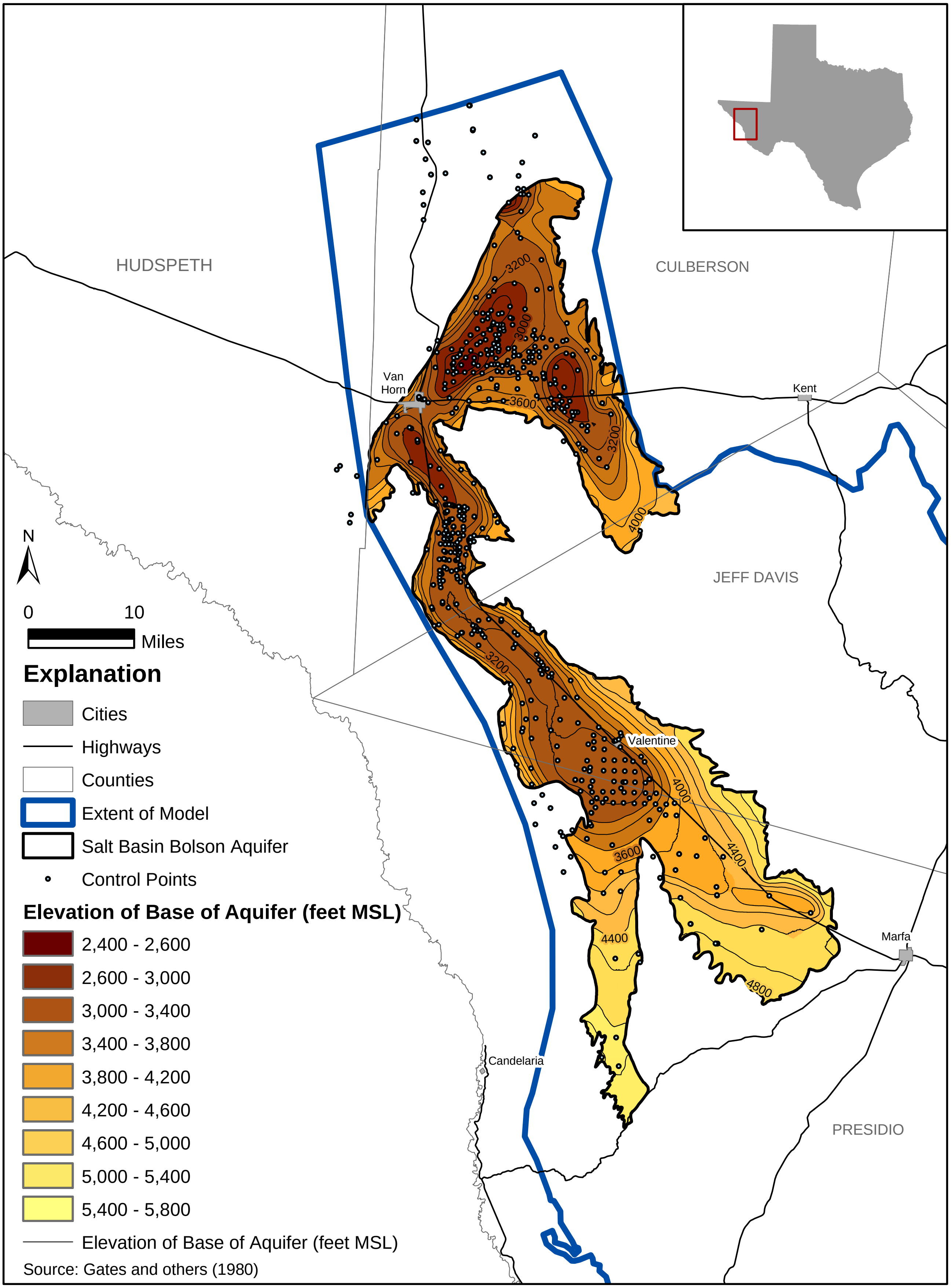


Figure 4.1.2 - Elevation of the Base of the Salt Basin Bolson Aquifer

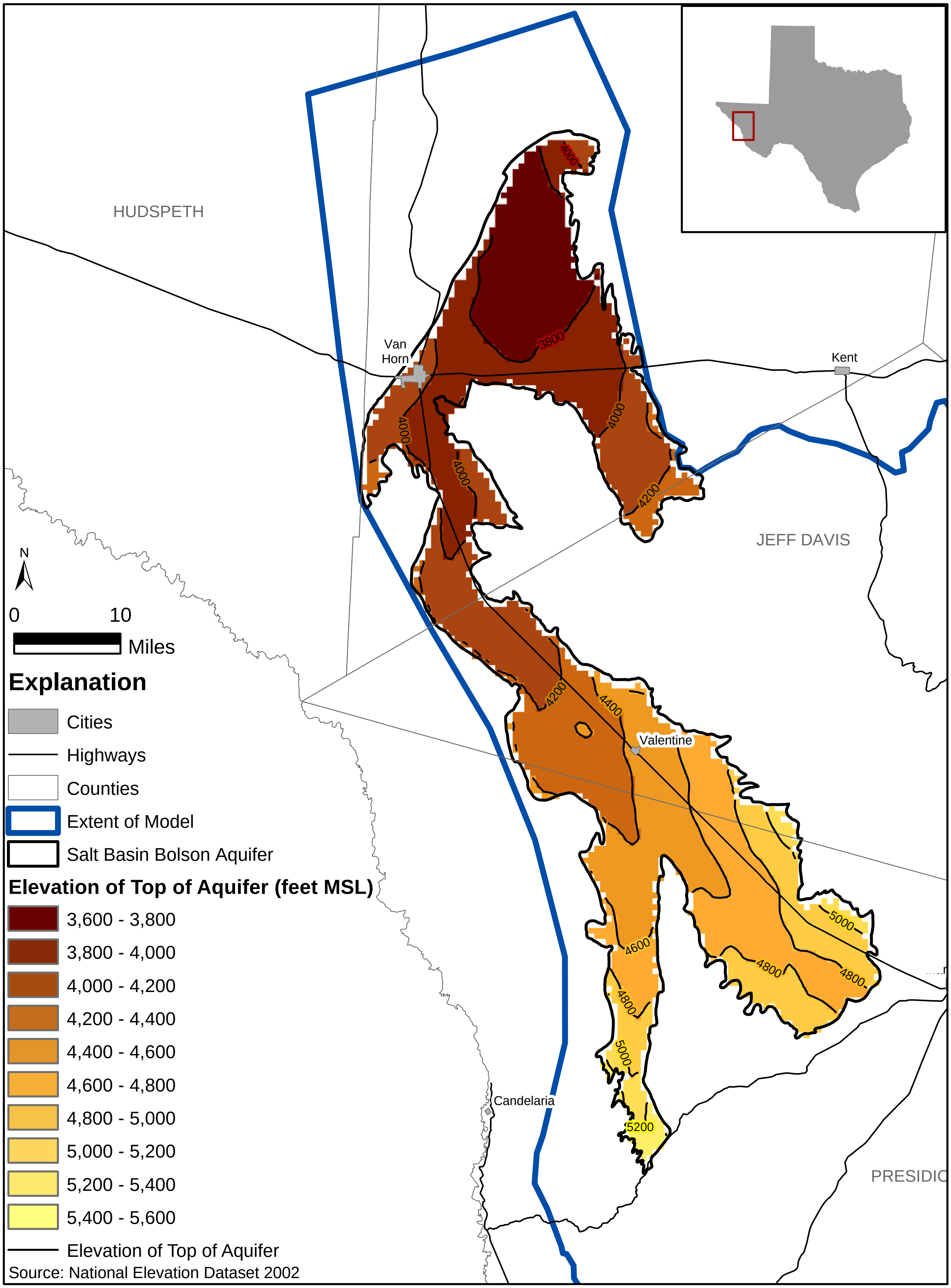


Figure 4.1.3 - Elevation of the Top of the Salt Basin Bolson Aquifer

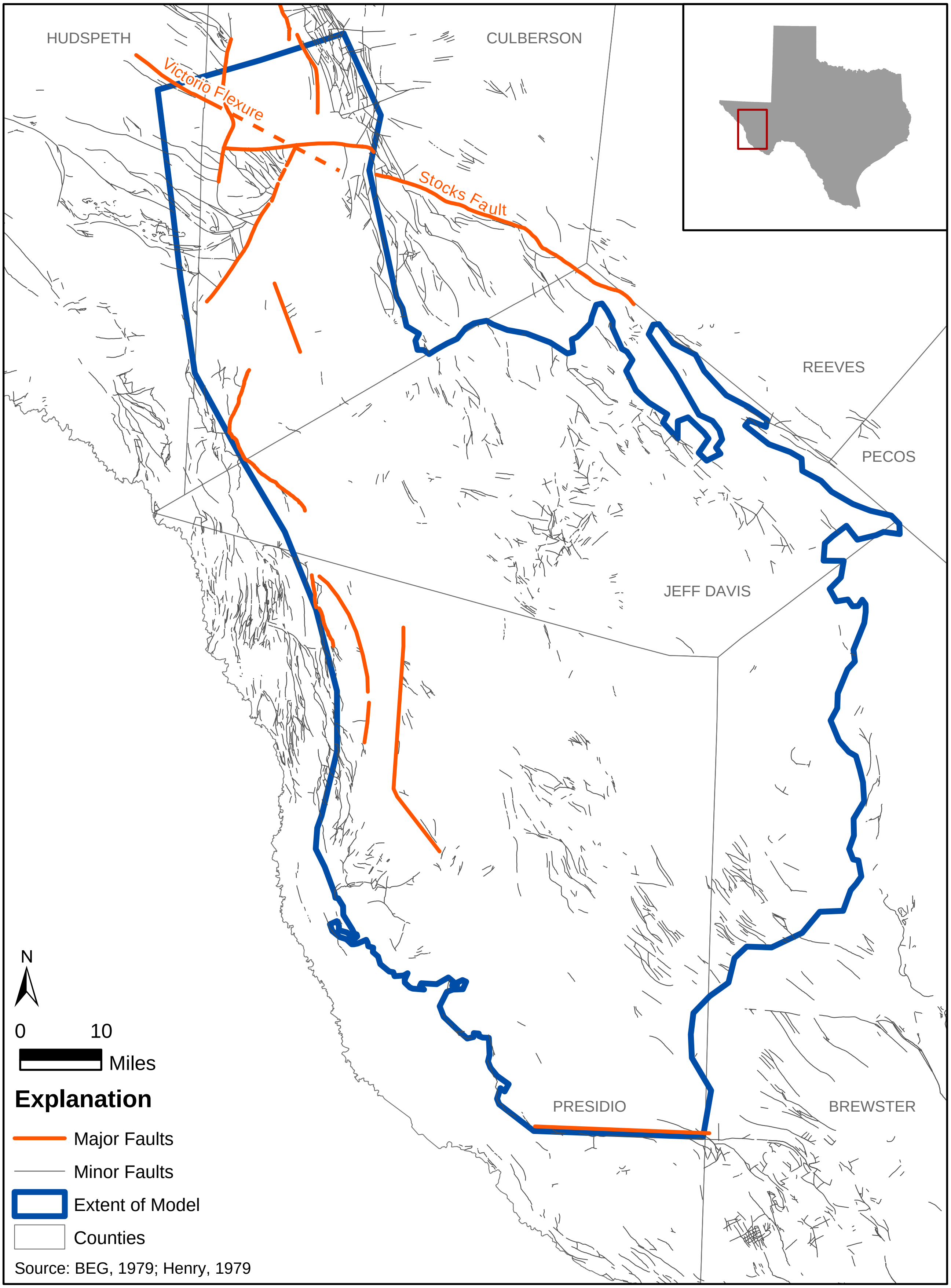


Figure 4.1.4 - Structural Faulting

Along the northern edge of the model area, the Victorio Flexure and Stocks Fault trend from northwest to southeast (Figure 4.1.4). The Victorio Flexure is a linear structural feature of Permian and early Mesozoic-age located from the Baylor Mountains to the Apache Mountains. The flexure represents a groundwater flow divide between Wild Horse Flat and the Salt Flats to the north. The Stocks Fault parallels the southern face of the Apache Mountains and is considered an area of high permeability preferential for groundwater outflow (Sharp, 2001).

4.1.3 Water Levels and Regional Groundwater Flow

Regional groundwater flow in the Salt Basin Bolson aquifer and surrounding area was first evaluated by Gates and others (1980), and was revisited by Sharp (1989), Sharp (2001), and Angle (2001). Water-level data for the Salt Basin Bolson aquifer are generally focused in specific areas of the Salt Basin where irrigation has occurred. Due to the lack of water level measurements in the Igneous aquifer and portions of the Salt Basin, an interpretive method was used to estimate water level contours in the model area. The methodology is described in Appendix A. Analysis indicates that comparison of water level elevation and land surface elevation is reasonably linear - indicating that the potentiometric surface mimics topography in a subdued fashion. The available data and interpretive contours therefore suggest that groundwater flows from the surrounding highlands toward the central axes of the bolson and from Ryan Flat northward to Wild Horse Flat. A groundwater divide along the Victorio Flexure on the north side of Wild Horse Flat prevents groundwater in Wild Horse Flat from discharging to the playa lakes to the north.

Sharp (1989) demonstrates that historical (predevelopment) discharge or groundwater outflow from Wild Horse was to the east in the subsurface, potentially along the Capitan Reef and Stocks Fault in the Apache Mountains. Figure 4.1.5 shows the estimated water-level surface in 1950, prior to significant development of the aquifer.

The map also shows the location of water-level measurements used to develop the potentiometric surface contours. There are few data points to define the predevelopment potentiometric surfaces. By 1950, groundwater flow was already inward to Wild Horse Flat.

Figures 4.1.6, 4.1.7, and 4.1.8 show the estimated water-level surface in 1980, 1990, and 2000, respectively. The maps also include the location of water-level measurements from which the potentiometric surface was developed. The 1980 map indicates that there were significantly more water-level measurements taken during that time than in 1950, however most of the data are still concentrated in relatively small areas compared with the scale of the study area. An evaluation of water-level contours of the Salt Basin Bolson aquifer indicates that the trend in observed water-level data between 1950 and 2000 toward slightly lower water-level elevations over time is reproduced in the potentiometric surface maps throughout the study area. Two important observations can be made from the water-level contours shown on Figure 4.1.8. First, groundwater flows radially from the Davis Mountains, and groundwater flows from low permeability rocks of the Igneous aquifer to the Bolsons, confirming cross-formation groundwater flow between those aquifers. Springs were not implemented directly into the calculations but only indirectly by incorporating topography. Therefore, they are not shown on the map. The historical water level contours developed for the Igneous aquifer are considered semi-quantitative, and were intended only for general information and not to draw specific conclusions.

Transient water-level data assimilated for the IBGAM in the Salt Basin Bolson aquifer are illustrated and summarized in selected hydrographs provided in Figures 4.1.9 through 4.1.12. Hydrographs show water-level responses to pumping from irrigation centers, particularly in Wild Horse and Lobo Flats where pumping has been fairly consistent since the 1950s. Observed drawdown in Lobo Flat has ranged from 50 to near 100 ft, and in Wild Horse Flat drawdown has ranged from 20 to 50 ft over the last 50 years. Hydrographs from wells in Michigan and Ryan Flats show water-level responses to relatively short-term pumping events in the late 1970s and early 1980s.

Sharp (2001) illustrates regional flow patterns in the Igneous and Salt Basin Bolson aquifers as well as other aquifers around the study area (Figure 4.1.13). Groundwater in the Salt Basin Bolson aquifer generally flows in a similar path as described in the predevelopment discussion. However, significant pumping, especially in the Wild Horse Flat area, locally influences flow patterns.

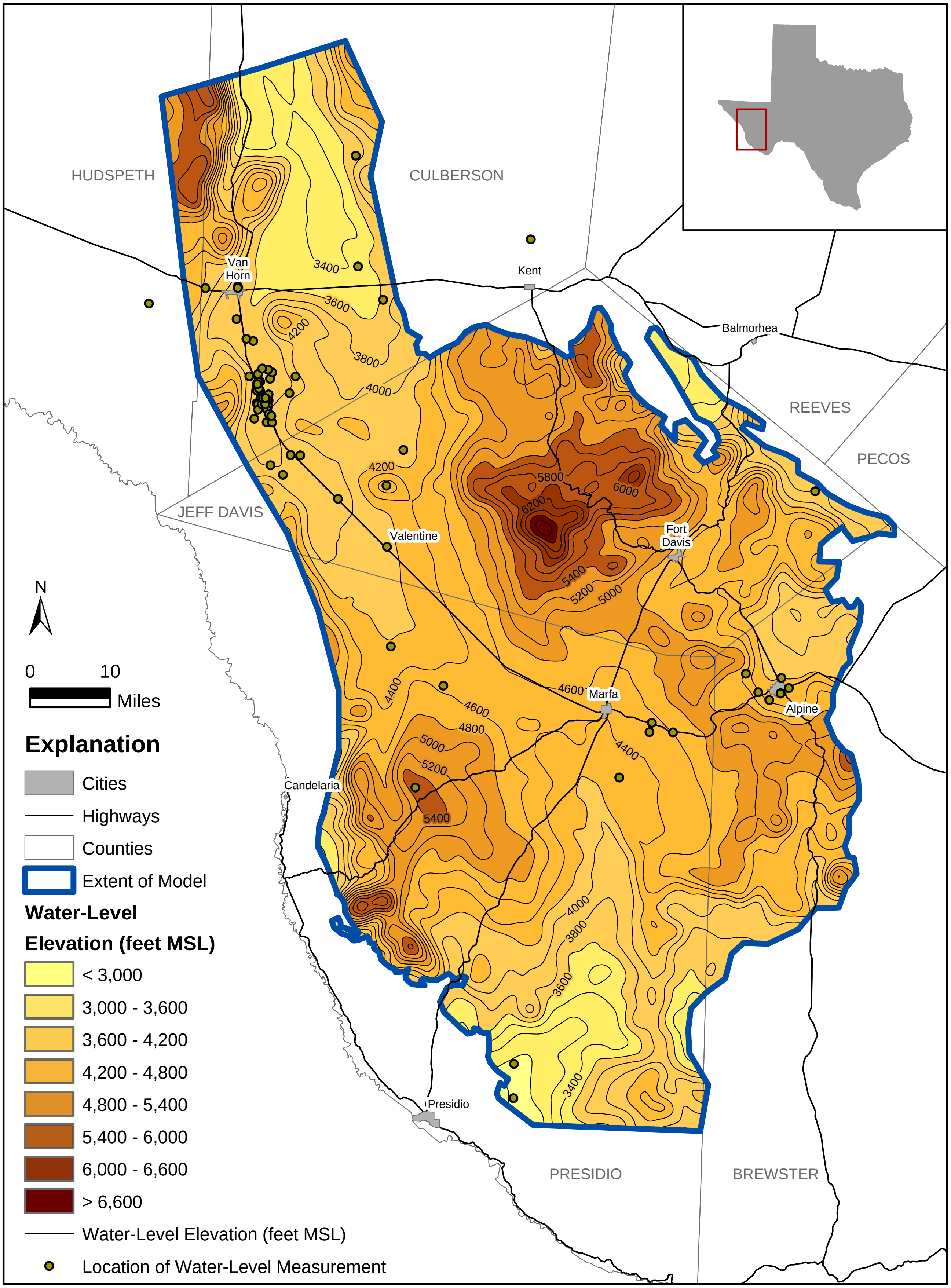


Figure 4.1.5 - 1950 Water-Level Elevations in the Salt Basin Bolson and Igneous Aquifers

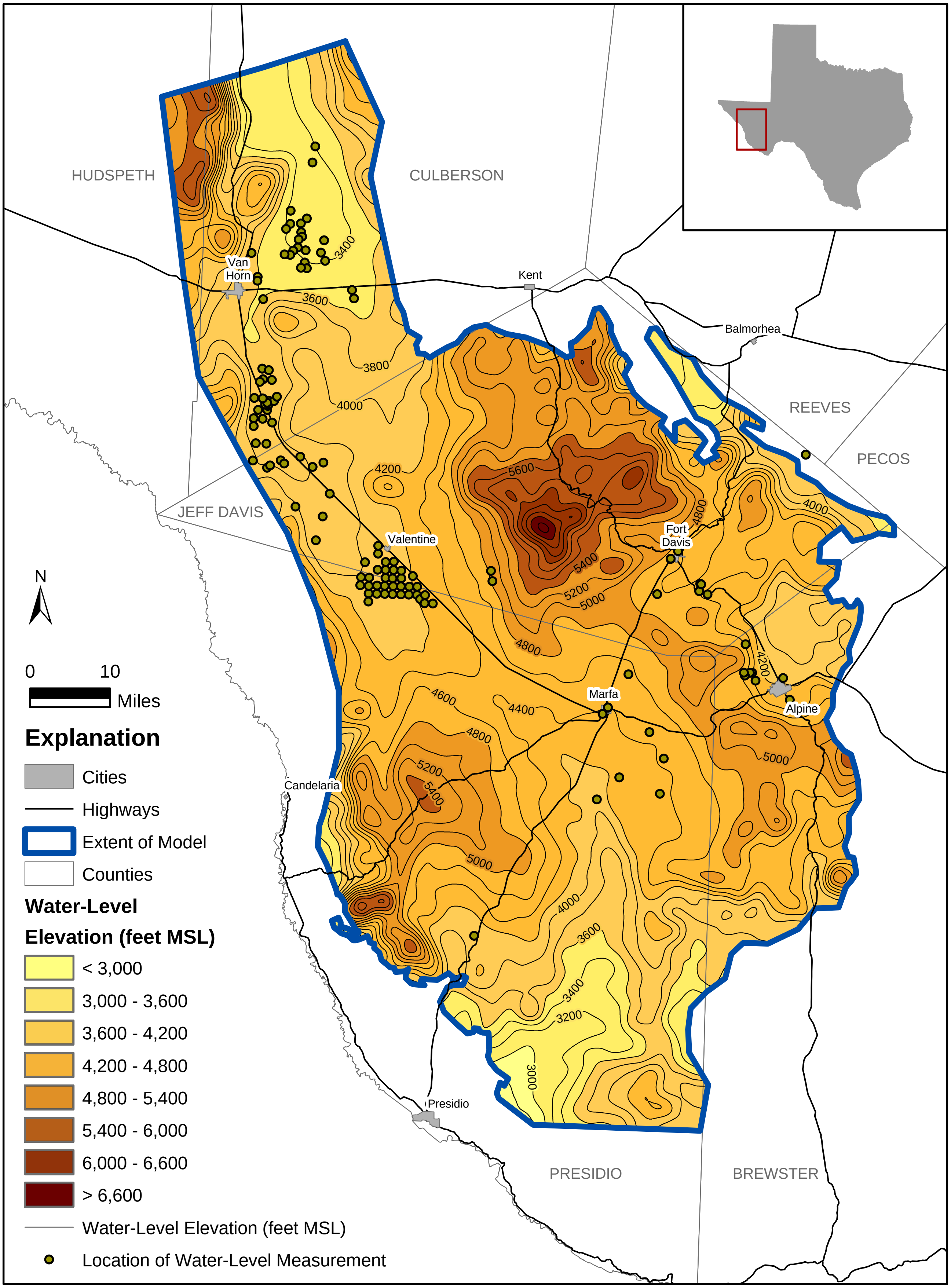


Figure 4.1.6 - 1980 Water-Level Elevations in the Salt Basin Bolson and Igneous Aquifers

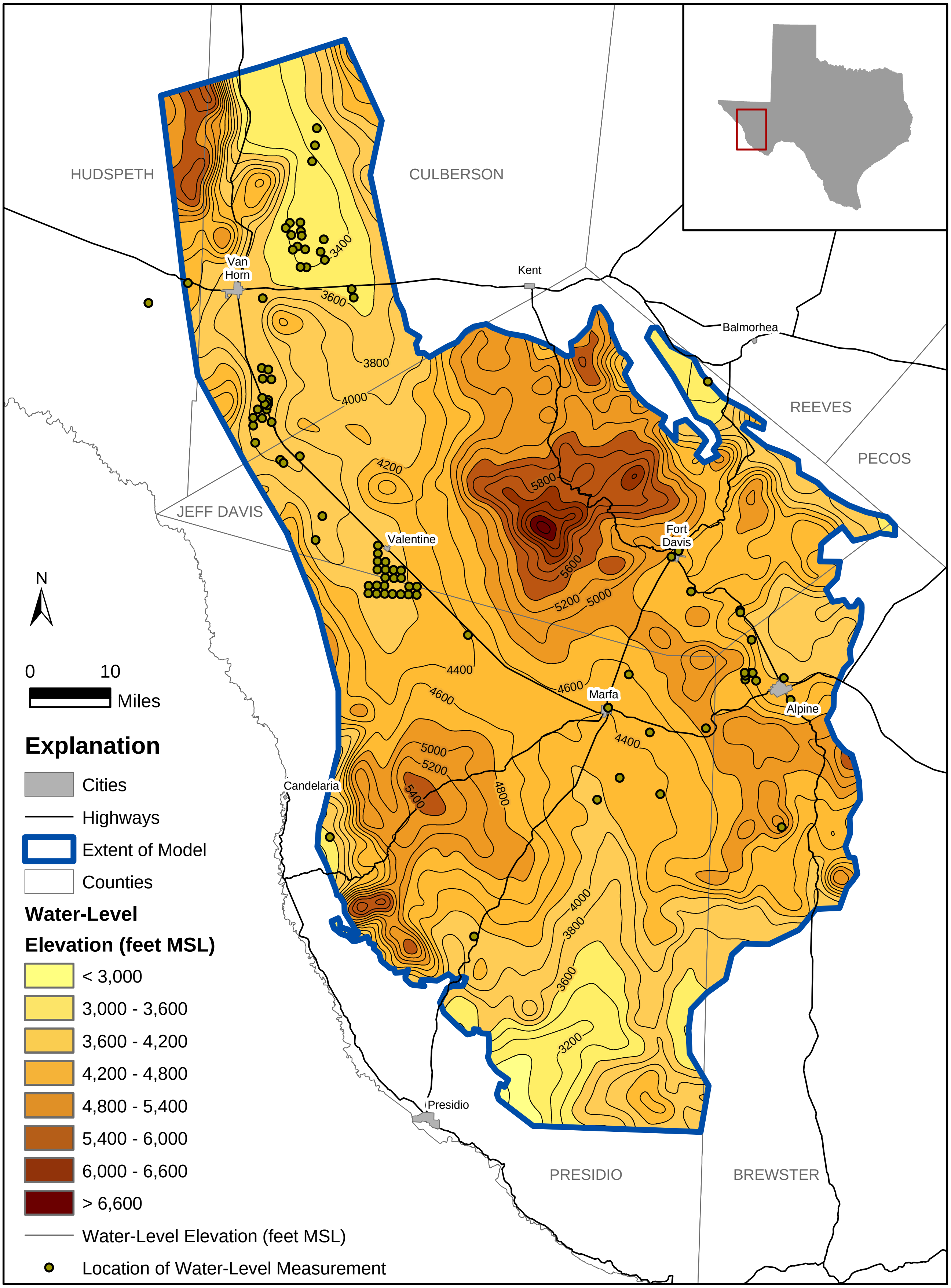


Figure 4.1.7 - 1990 Water-Level Elevations in the Salt Basin Bolson and Igneous Aquifers

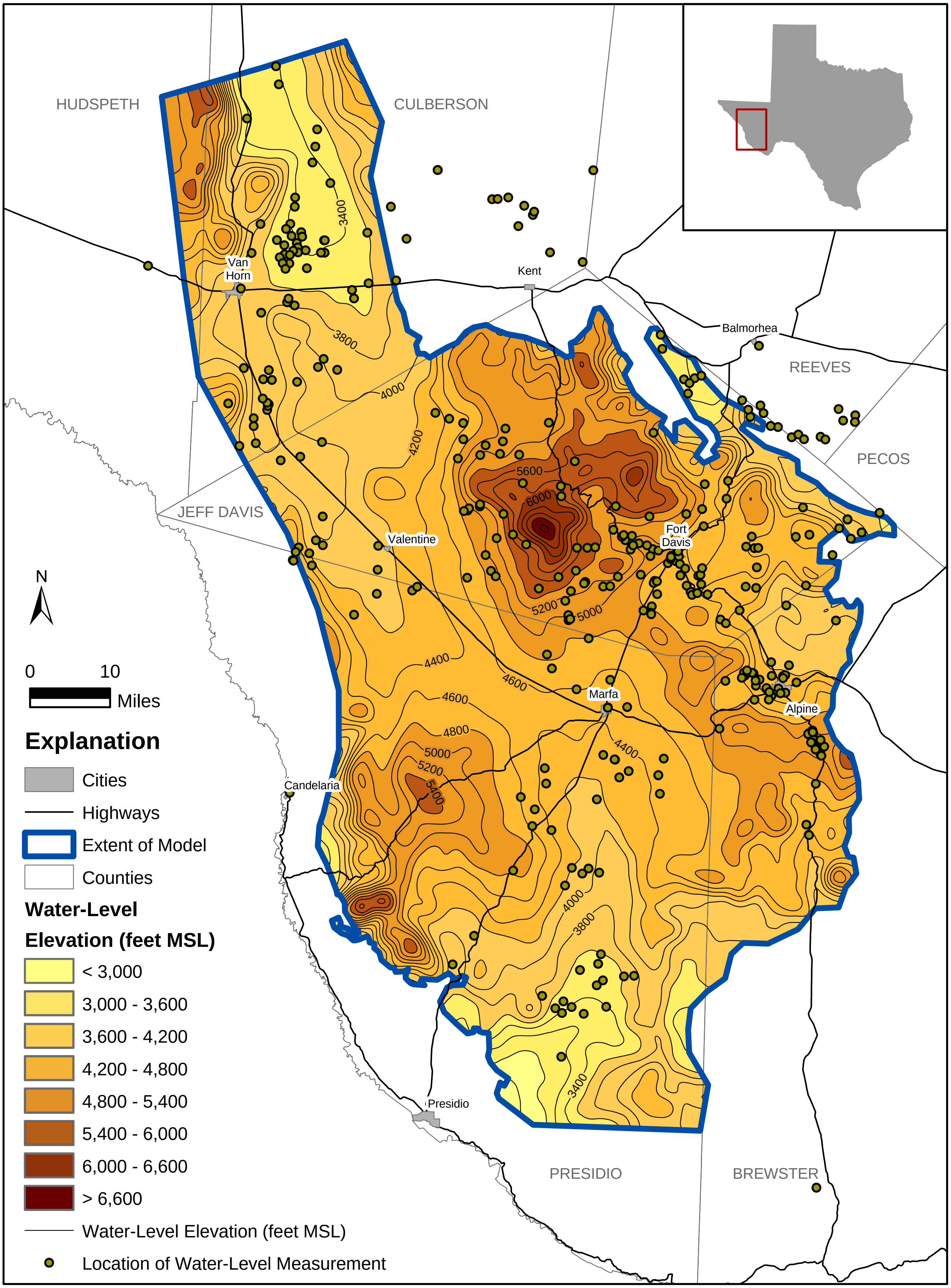


Figure 4.1.8 - 2000 Water-Level Elevations in the Salt Basin Bolson and Igneous Aquifers

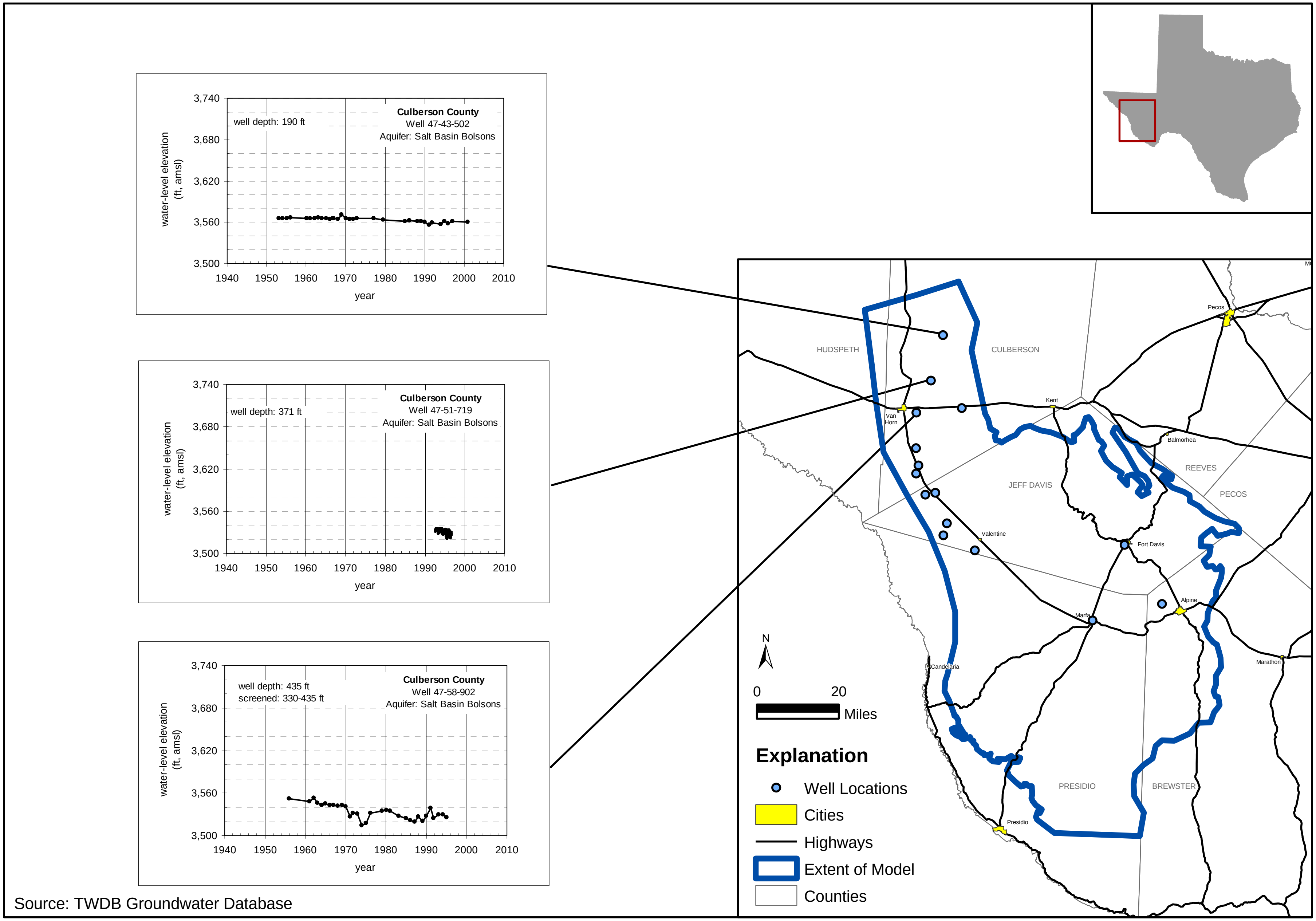


Figure 4.1.9 - Hydrographs for Wells in Wild Horse Flat

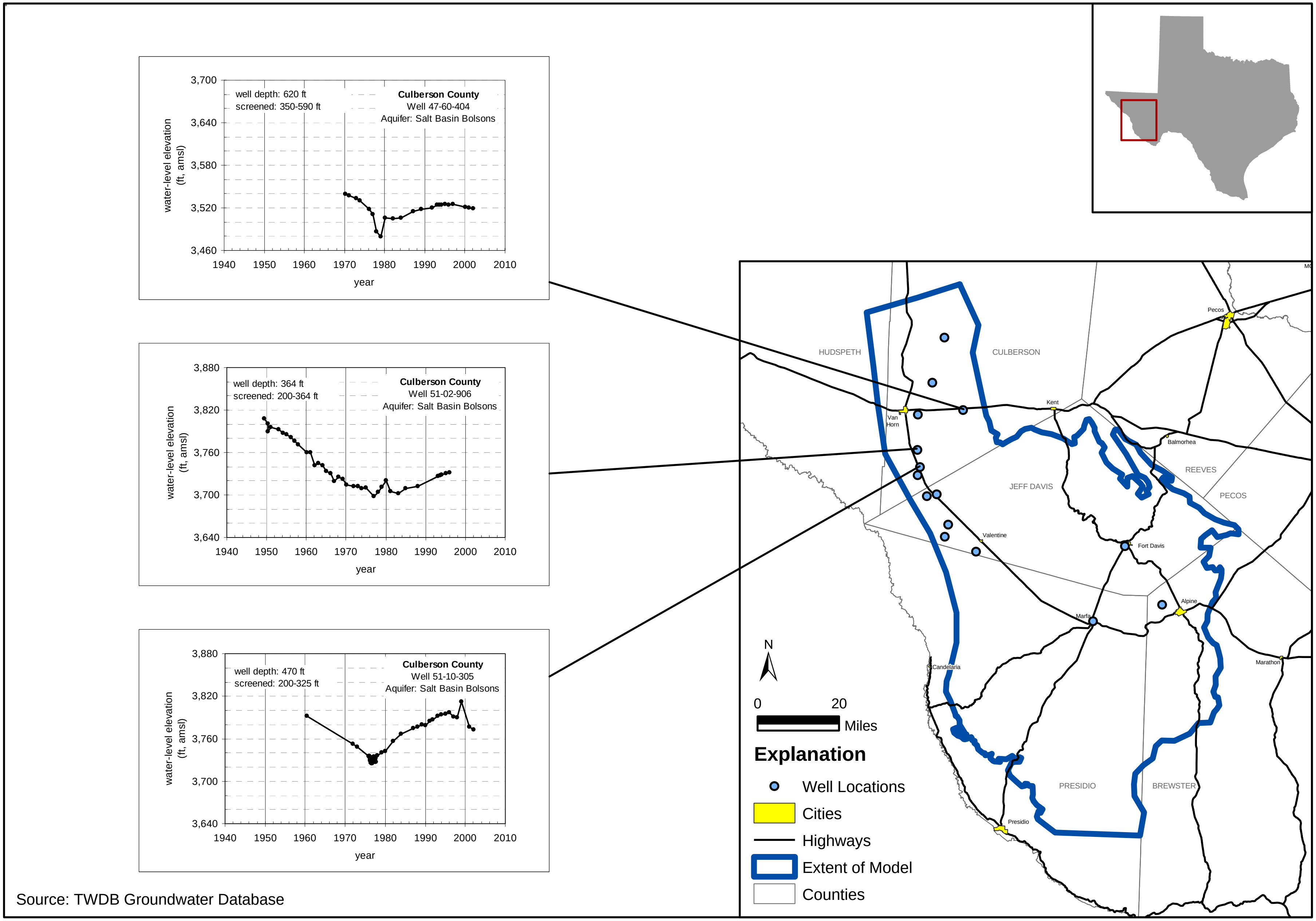
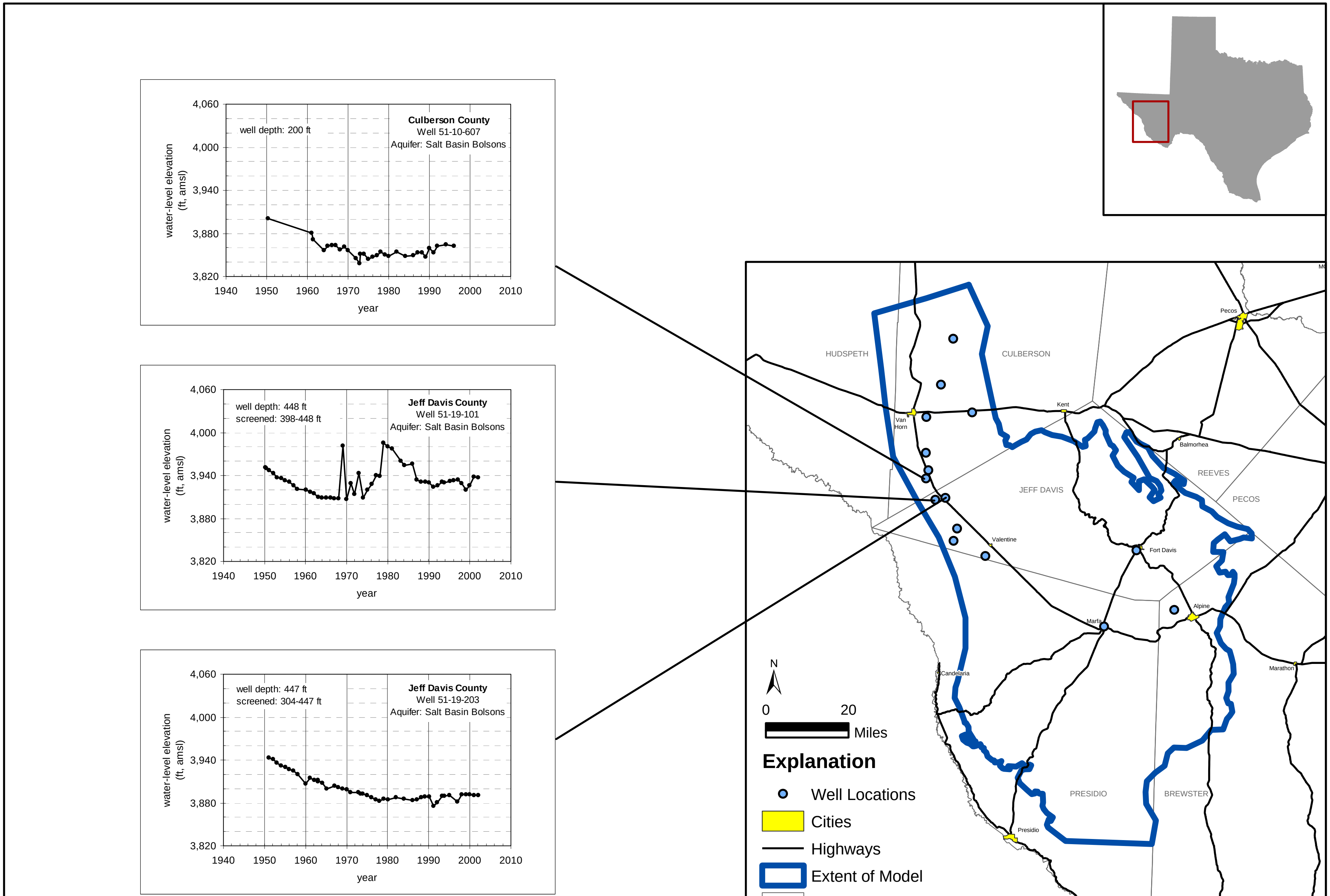
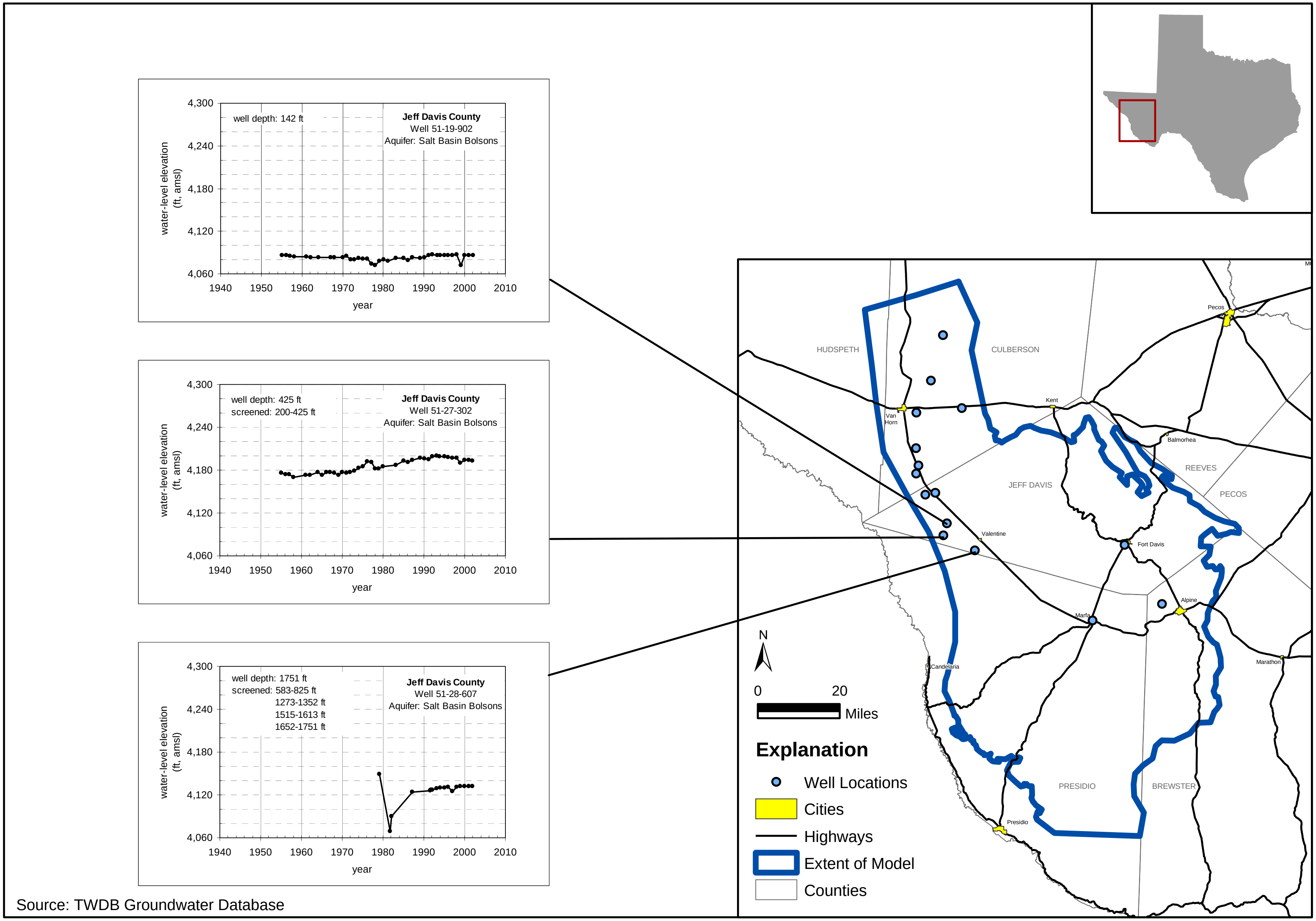


Figure 4.1.10 - Hydrographs for Wells in Michigan and Lobo Flats



Source: TWDB Groundwater Database

Figure 4.1.11 - Hydrographs for Wells in Lobo Flat



Source: TWDB Groundwater Database

Figure 4.1.12 - Hydrographs for Wells in Ryan Flat

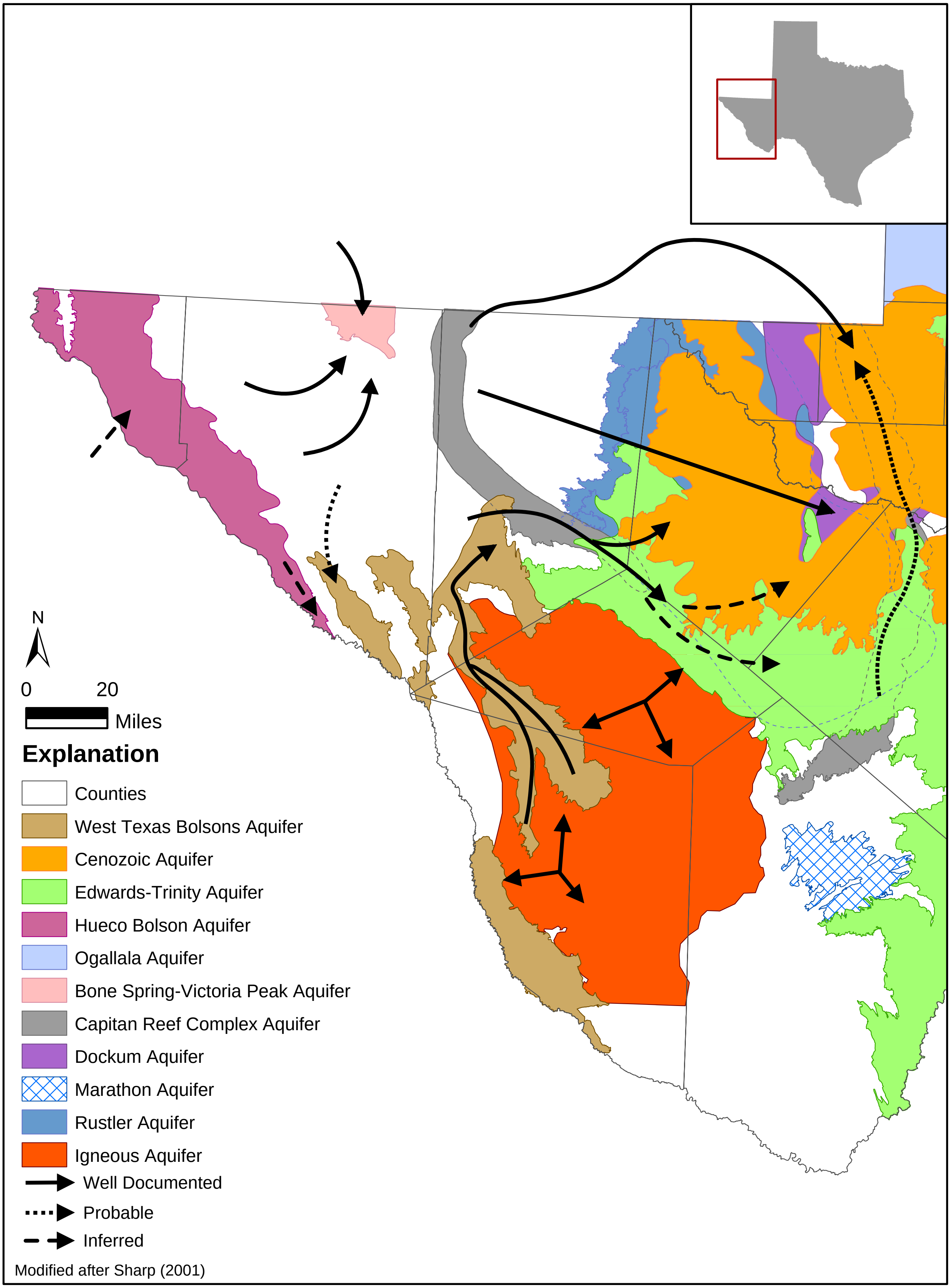


Figure 4.1.13 - Regional Groundwater Flow Patterns

4.1.4 Recharge

Groundwater recharge primarily occurs or originates from infiltration of precipitation in the higher elevations (i.e. Davis Mountains) and from infiltration of storm-water runoff on alluvial fans along the bolson perimeter (Scanlon and others, 2001; Finch and Armour, 2001).

Previous investigators have estimated recharge to West Texas bolsons based on a percentage of precipitation and calculations of groundwater inflow (Hood and Scalapino, 1951; Gates and others, 1980; and Cliett, 1994). At the time of the USGS study in the late 1970s, the basic rule of thumb for the Basin and Range province of the Trans-Pecos Region was to use one percent of the average annual precipitation as the rate of recharge (Gates and others, 1980). This method does not take into account watershed characteristics, rock type, and the feasibility of surface water to infiltrate into the groundwater system.

The method selected to calculate initial recharge for the IBGAM study area is based on those previous studies completed by Nichols (2000), Stone and others (2001), and Bennett and Finch (2002). This approach of determining recharge and distribution of recharge takes into account climate, watershed, and geologic characteristics for each sub-basin defined in the study area. The method includes the following analyses:

1. Delineating mountain, alluvial fan, and bolson sub-basins within the study area, and their hydrologic characteristics;
2. Calculating topographic statistics for each sub-basin;
3. Estimating potential recharge (corrected for elevation zones and potential evaporation) for each sub-basin;
4. Determining runoff from each sub-basin by analyzing the magnitude of precipitation events that result in runoff (scaled to elevation); and,
5. Determining which sub-basins receive runoff from up-gradient sub-basins and the amount of runoff that is lost from the area of recharge (redistribution).

Details regarding the recharge methodology and analysis are provided in Appendix B. The assumptions made for calculating recharge magnitude and distribution include the following:

1. Direct precipitation on the bolson aquifer does not infiltrate and become recharge;
2. Precipitation increases with elevation as defined by existing data;
3. There is no potential recharge for areas with less than 12 inches per year average precipitation;
4. Dry soil conditions are used for estimating the runoff curve number; and,
5. Approximately 30 percent of the runoff infiltrates at the alluvial fan and the remaining 70 percent evaporates or flows out of the model domain.

The first step in determining potential recharge is to develop a relationship between precipitation and elevation for weather stations within and surrounding the study area. Average annual and daily precipitation data for the period of record were collected for 21 weather stations (Figure 4.1.14) (Texas Office of the State Climatologist, 2003). For each weather station, the frequency of 24-hour precipitation events of specified magnitudes that could potentially generate storm-water runoff were determined. A linear relationship between elevation and frequency of precipitation events was used to calculate runoff from each sub-basin in the study area. Calculated runoff is subtracted from potential recharge in topographically up-gradient sub-basins and added to potential recharge in ‘receiving’ sub-basins at lower elevations.

To avoid overestimating potential recharge, evapotranspiration and other losses are considered. To do this, the potential recharge is estimated from empirical relationships (coefficients) described by Nichols (2000). The Nichols coefficients are based on a multiple linear regression model of data from similar basins in Nevada, and were modified to represent Trans-Pecos climate conditions (Bennett and Finch, 2002). The coefficients used to estimate potential recharge are summarized in Table 4.1. The percent of total precipitation becoming potential recharge, increasing with elevation ranges from 0 to 7 percent.

Table 4.1 Summary of coefficients used to estimate potential recharge, and corresponding elevation, average annual precipitation, and potential recharge

Average annual precipitation (in/yr)	Potential recharge coefficient	Potential recharge (in/yr)	Elevation (ft, msl)
12	0.000	0.00	3,000
14	0.018	0.25	3,870
16	0.035	0.56	4,740
18	0.052	0.94	5,600
20	0.070	1.40	6,475

The results of the recharge analysis are illustrated on Figures 4.1.15 and 4.1.16, and summarized in Table 4.2. Total potential recharge to the IBGAM study area is estimated at 68,977 ac-ft/yr, which is about 1.3 percent of the total precipitation. Most of the potential recharge to the bolson is from infiltration of storm-water runoff in the alluvial fan sub-basins where they adjoin the bolson, and from cross-formational groundwater flow between the Igneous aquifer and the Salt Basin Bolson aquifer.

Table 4.2 Summary of recharge estimates for Salt, Pecos, and Rio Grande Basins within the IBGAM study area

Parameter	Unit	Salt	Pecos	Rio Grande	Total
Area	Acres	1,625,355	1,135,324	1,370,137	4,130,816
Total precipitation	ac-ft/yr	2,111,077	1,512,759	1,798,709	5,422,545
Potential recharge	ac-ft/yr	51,665	55,964	60,787	168,416
Runoff	ac-ft/yr	35,548	29,262	47,027	111,653
Estimated recharge	ac-ft/yr	25,367	29,536	14,074	68,977
	in/yr	0.19	0.31	0.12	0.20
Total precipitation that becomes recharge	Percent	1.2	2.0	1.4	1.3

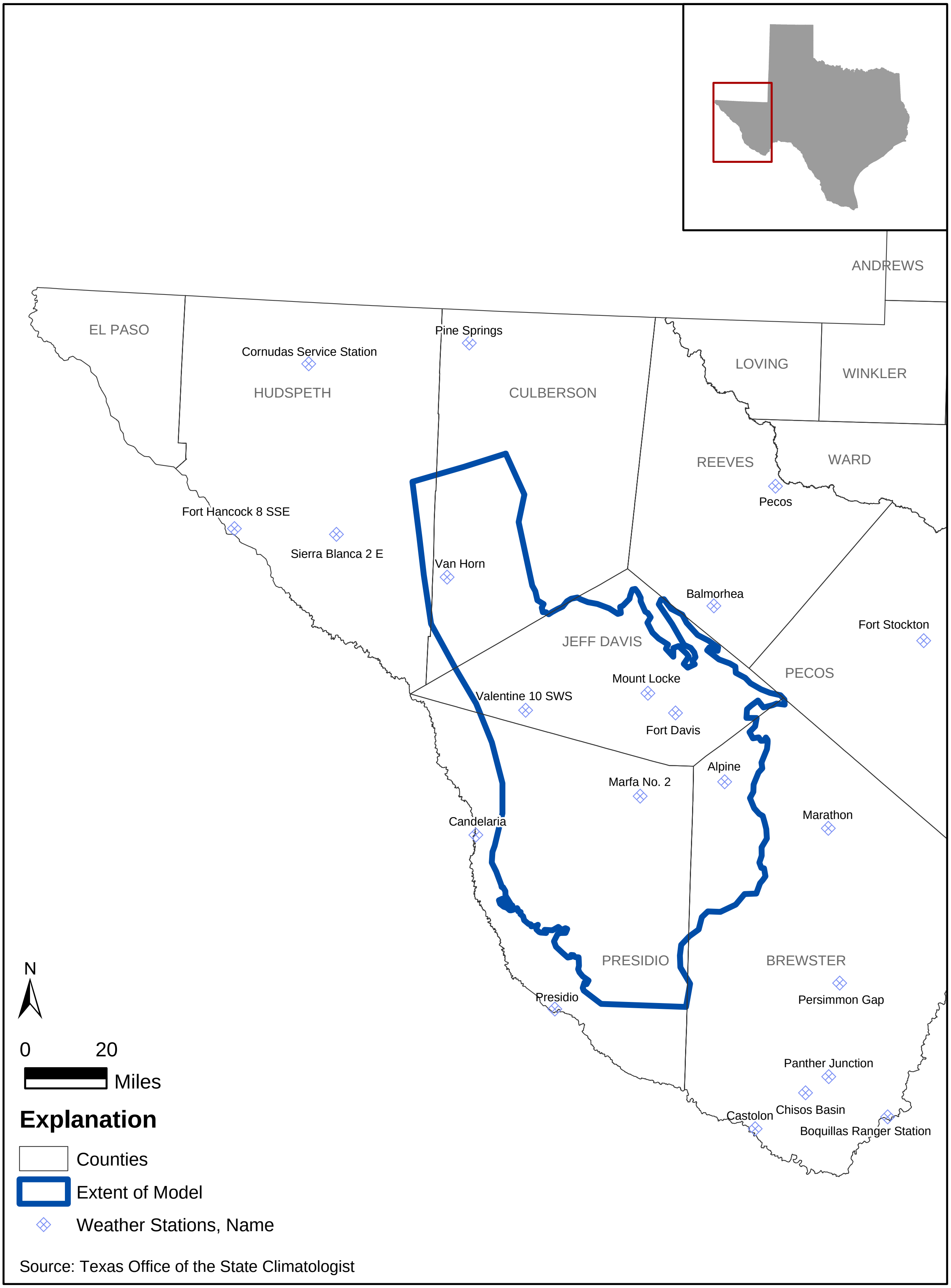


Figure 4.1.14 - Location of Rain Gages Used for Recharge Analysis

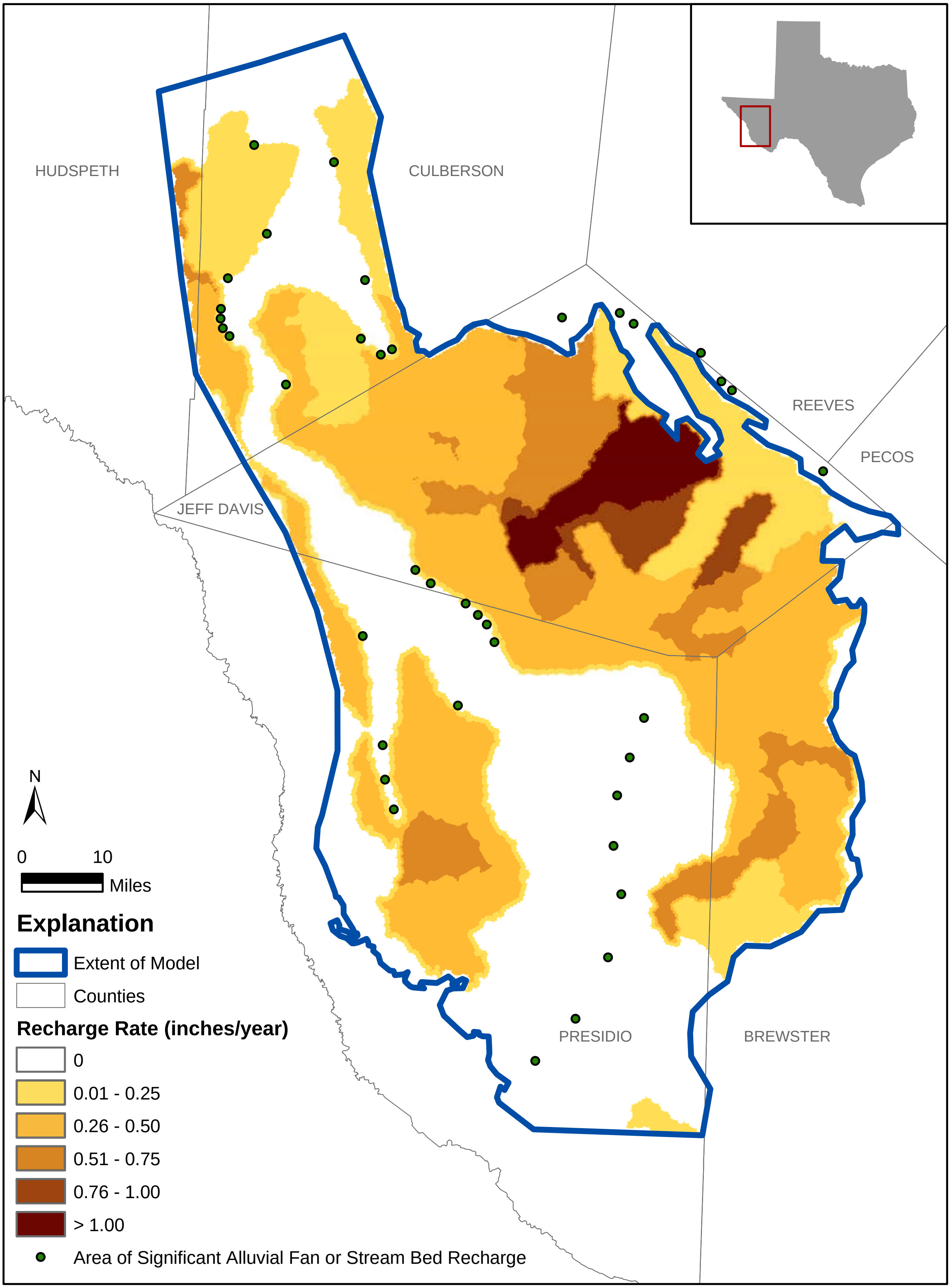


Figure 4.1.15 - Distribution of Average Recharge

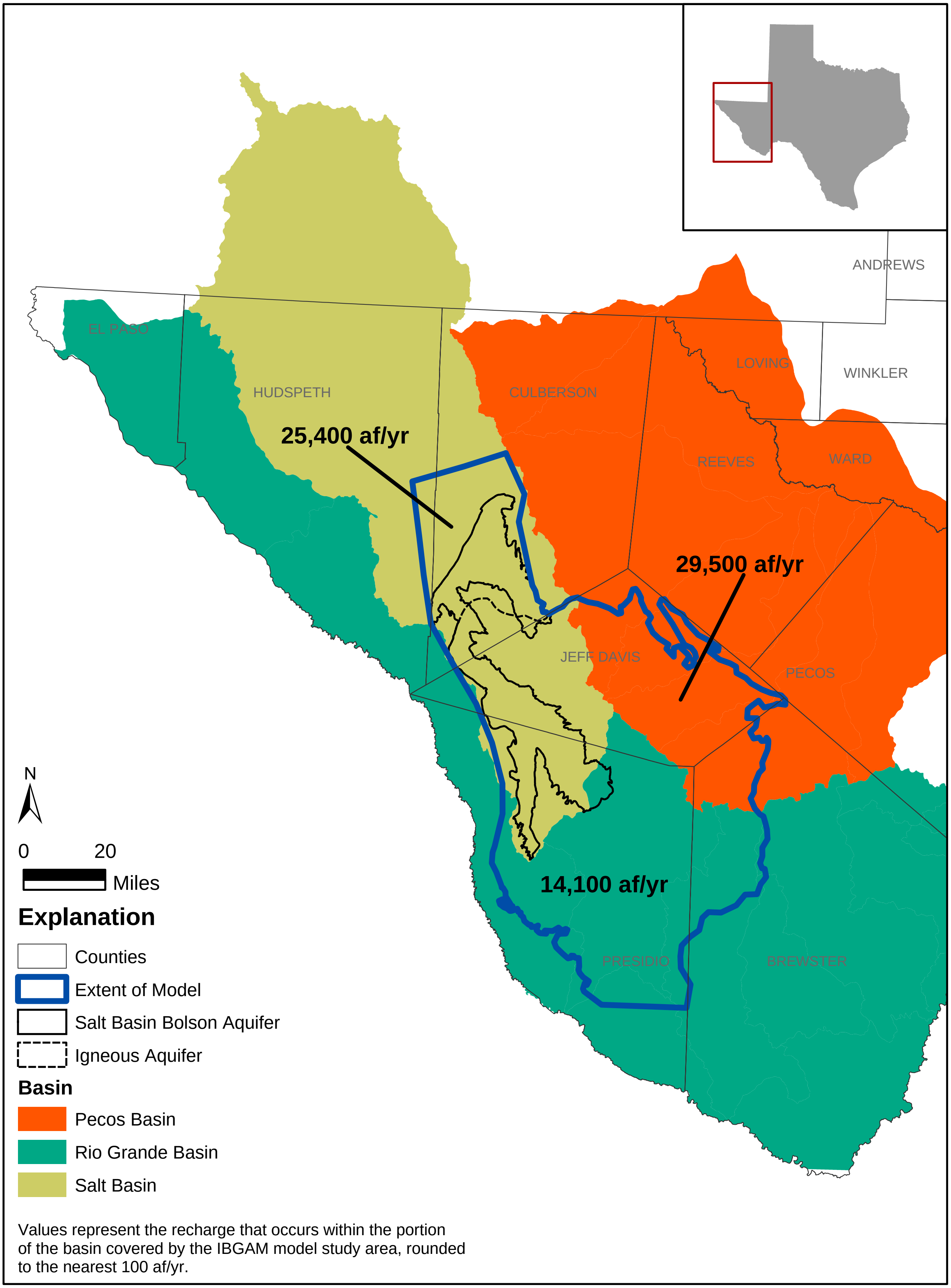


Figure 4.1.16 - Distribution of Recharge in the Major Basins

A comparison of other recharge methods with the re-distribution method is provided for the study area in Table 4.3. The runoff-redistribution method appears to be an appropriate method for the IBGAM because it considers the runoff characteristics of each sub-basin and the variable precipitation received by each sub-basin. Previous recharge estimates using a percentage of the precipitation (Gates and others, 1980; Mayer, 1995) does not consider components of the conceptual model, such as geologic characteristics for infiltration and areas on the bolsons where recharge does not likely occur. Therefore, the runoff-redistribution method provides constraints on a sensitive model parameter consistent with the conceptual model, and helps minimize the inherent non-uniqueness associated with parameterization in numerical models.

Table 4.3 Comparison of recharge methods for the IBGAM study area

Method	Unit	Salt	Pecos	Rio Grande	Total	Comments
Total precipitation	ac-ft/yr	2,111,077	1,512,759	1,798,709	5,422,545	
One-percent rule (Gates and others, 1980)	ac-ft/yr	21,111	15,128	17,987	54,225	Does not consider watershed or geologic variability
Modified Maxey Eakin (Mayer, 1995)	ac-ft/yr	135,543	172,641	205,256	513,440	Over estimates recharge at lower elevations
	in/yr	1.0	1.8	1.8		
Storm-runoff infiltration (Finch and Armour, 2001)	ac-ft/yr	10,664	9,810	10,263	30,737	Does not consider areal (direct) recharge at higher elevations or geology
Runoff redistribution (this study)	ac-ft/yr	25,367	29,536	14,074	68,977	Accounts for watershed characteristics and distribution of recharge from storm water runoff
	in/yr	0.19	0.31	0.12		

Groundwater flow models are sensitive to prescribed recharge and recharge distribution, and given the uncertainties in recharge estimates for the study area, the runoff-redistribution method provides an approximation to recharge distribution and quantity that would otherwise be difficult or impossible to obtain.

In general, recharge estimates (using methods similar to the runoff-redistribution) for regional modeling studies have resulted in recharge values slightly greater than those obtained from final model calibration. The USGS Espanola Basin model prepared by McAda and Wasiolek (1988) calibrated to 9,600 ac-ft/yr of recharge for selected drainages along the western side of the Sangre de Cristo Mountains. A very detailed recharge analysis of the same area by the USGS (Wasiolek, 1995) resulted in an average recharge of 14,700 ac-ft/yr; the model calibrated recharge resulted in approximately 66 percent of the estimated. Similar results have been realized from recent studies of the Tularosa Basin in southern New Mexico, where the estimated recharge (Waltemeyer, 2001) was approximately 60 percent of the model calibrated (Huff, 2004).

There is likely some rejected recharge that is not accounted for in the recharge estimates that causes the model-calibrated recharge to be less than the estimated recharge. One example of rejected recharge would be recharge to a perched ground-water system that is discharged to a spring or by evapotranspiration. Other possibilities for the recharge discrepancy may be related to the lack of long-term climate data (i.e. comparing 20 years of climate data to a regional hydrologic system that takes 1,000s of years for water to be recharged and ultimately discharged), and the lack of detail in the regional model to account for conveyance of all the estimated recharge through the groundwater system.

4.1.5 Rivers, Streams, Springs, and Lakes

Ephemeral surface-water drainage within the Salt Basin consists of the northward flowing Chispa Creek in Ryan and Lobo Flats, and Wild Horse Creek in Wild Horse Flat. Although all surface drainage is internal within the Salt Basin, water only accumulates in these drainages following significant precipitation events in which storm-water runoff exceeds the rate of infiltration into the alluvial fans along the perimeter of the basin. In general, streams originate at higher altitudes, gain water from storm-water runoff and springs, and then loose water in the streambeds as the streams traverse out of the mountains to alluvial fans. There are no stream gages on these creeks and there have been no studies to estimate the conductance of the streambed in the creeks. An accounting of this recharge into the alluvial fans was previously discussed in Section

4.1.4. North of Wild Horse Flat and outside of the model area, surface water occasionally accumulates in a number of salt lake depressions.

4.1.6 Hydraulic Properties

Hydraulic conductivity is an important input parameter in simulating the manner in which an aquifer operates. Hydraulic conductivity refers to the ability of a porous media (geologic formation) to transmit water and has units of length per time (e.g., feet/day).

Figure 4.1.17 shows the location of Salt Basin wells from which hydraulic conductivity estimates have been tabulated. Histograms of the hydraulic conductivity in Bolson wells completed in various underlying units are shown in Figure 4.1.18. The data suggest that the geometric mean of the hydraulic conductivity in wells completed only in the overlying bolson sediments is about 10 ft/day, but may be as high as 90 ft/day. Wells completed in both bolson sediments and underlying volcaniclastic units are more likely to encounter higher permeability rocks. The histogram of hydraulic conductivity data for wells completed in bolsons and underlying Cretaceous and Permian units indicate similar characteristics as bolson-only wells.

The average hydraulic conductivity of bolson sediments in Wild Horse Flat is approximately 15 ft/day, with values ranging from 5 to 33 ft/day (Finch and Armour, 2001). In Lobo and Michigan Flats, the average hydraulic conductivity is approximately 28 ft/day, but ranges from 2 to 79 ft/day. Analysis of data from Well 51-10-607, located in the southern part of Lobo Flat, indicates a hydraulic conductivity of over 600 ft/day in the volcaniclastic rocks, although this is likely a very localized phenomenon. Aquifer tests performed in Ryan Flat by Brown and Caldwell (2001) indicate the average hydraulic conductivity is 10 ft/day.

Values of estimated horizontal hydraulic conductivity for the bedrock units adjacent to the bolson vary dramatically. The range in hydraulic conductivity for the limestone

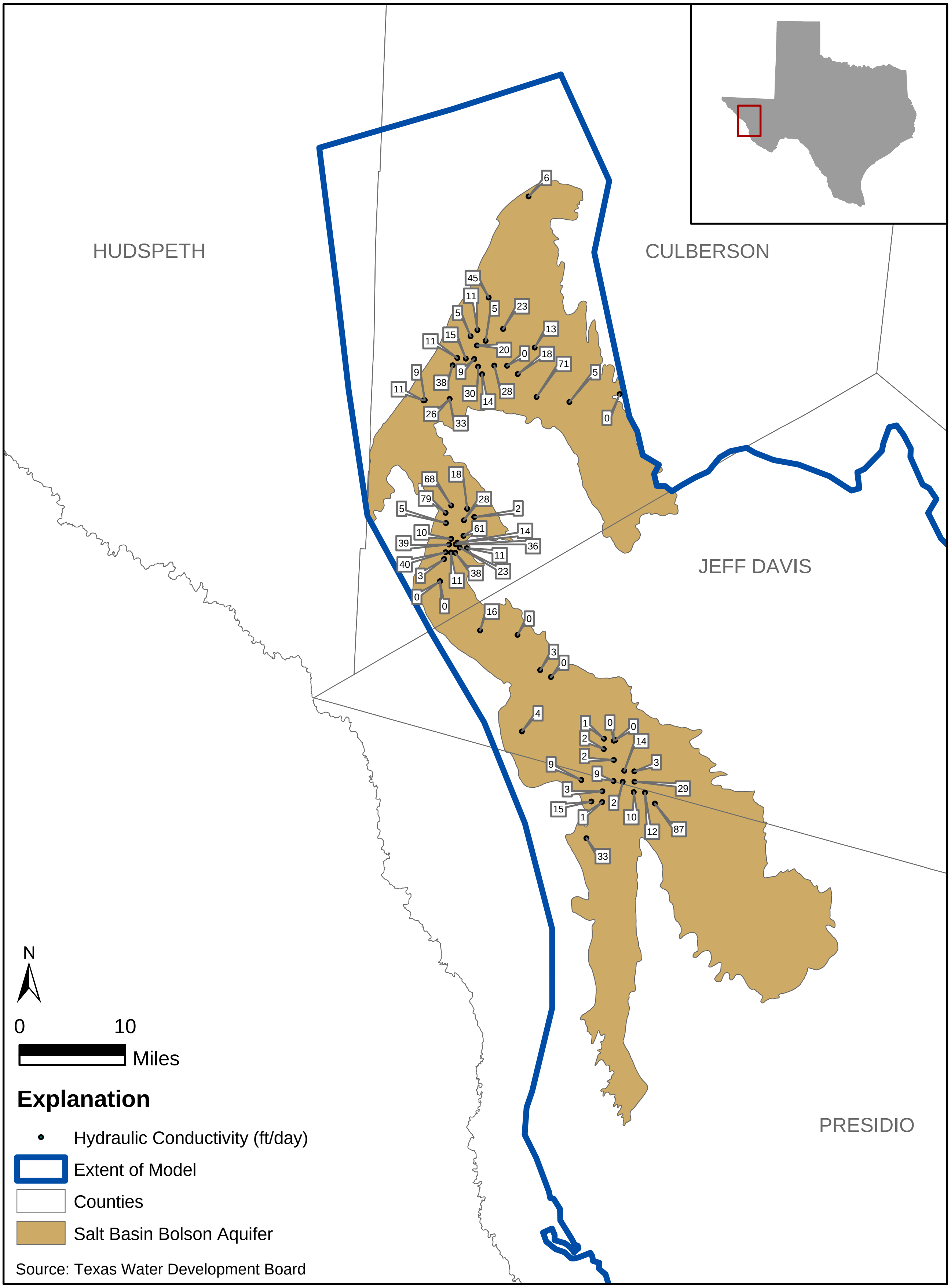


Figure 4.1.17 - Hydraulic Conductivity Data in the Salt Basin Bolson Aquifer

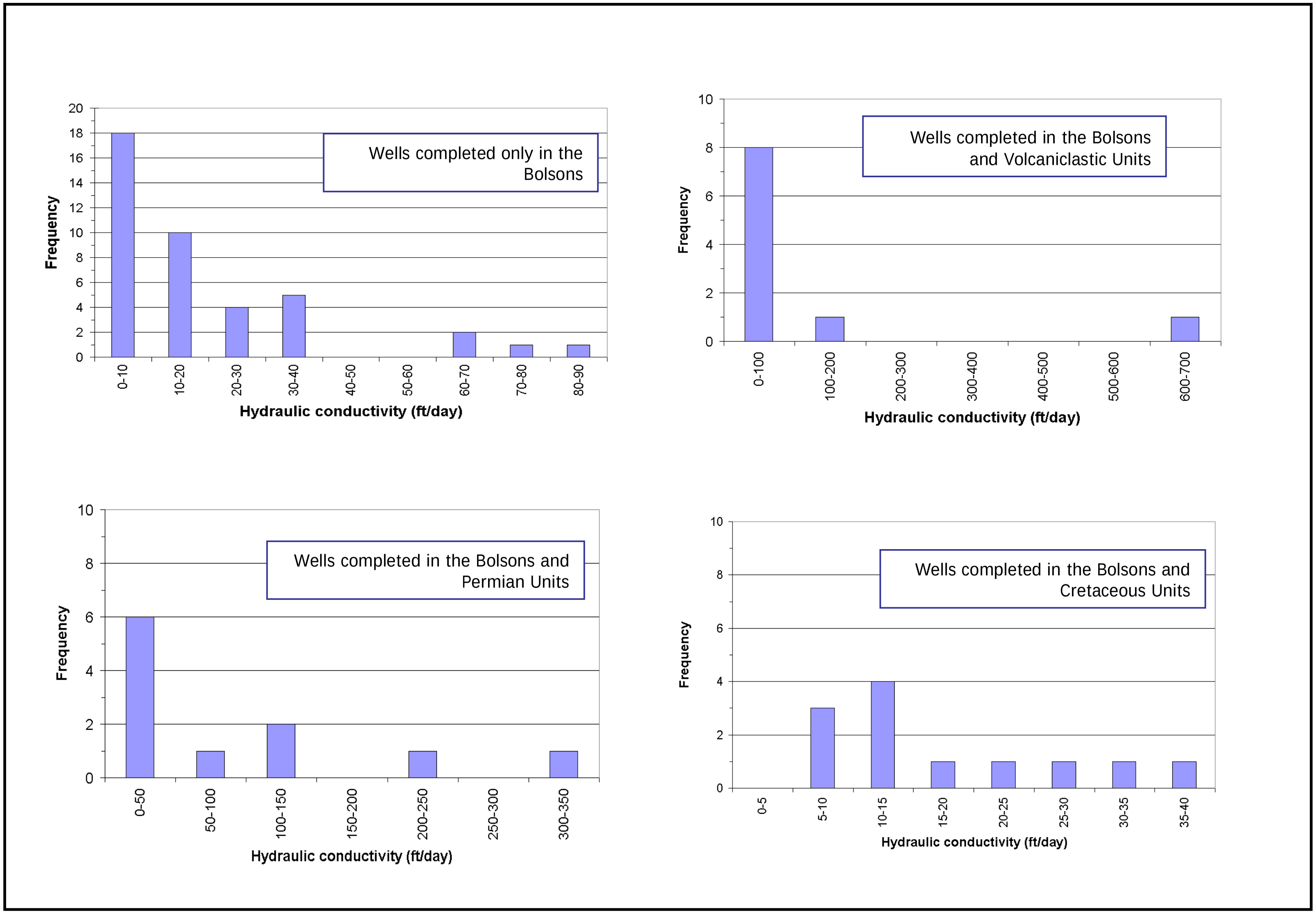


Figure 4.1.18 Histograms of hydraulic conductivity in the Bolsons

rocks in the Wild Horse Flat area is 0.5 to over 100 ft/day. The higher values of hydraulic conductivity are related to the Capitan Reef aquifer in the Apache Mountains northeast of Wild Horse Flat. Data from wells completed in the Cretaceous rocks (Cox Sandstone) show hydraulic properties similar to the basin fill deposits.

Nielson and Sharp (1989) performed a sensitivity analysis of hydraulic conductivity for a two-dimensional groundwater flow model of the Wild Horse Flat area, and found that the best matches were made using a hydraulic conductivity value between 10 and 20 ft/day. Finch and Armour (2001) calibrated a three-dimensional groundwater flow model of the Wild Horse-Michigan-Lobo Flats area using a hydraulic conductivity of 25 ft/day for the upper two thirds of the basin fill, and a hydraulic conductivity of 5 ft/day for the lower third of the fill (depths greater than 1,000 ft).

Transmissivity is the product of hydraulic conductivity and the thickness of a water bearing unit. Estimated transmissivity of the Salt Basin Bolson aquifer ranges from 10 feet squared per day (ft^2/day) to 9,900 ft^2/day (Angle, 2001). The Brown and Caldwell (2001) aquifer tests suggest an average transmissivity of 7,000 ft^2/day for the Ryan Flat area. Storage coefficients, determined from pumping tests, are essentially non-existent for the Salt Basin Bolson aquifer.

Specific yield is the ratio (percent) of the volume of water a rock will yield to the volume of the rock and is equivalent to effective porosity in an unconfined aquifer. Gates and others (1980) indicated the specific yield (unconfined storage coefficient) ranged from 0.10 to 0.15 and averaged 0.13 for the Salt Basin Bolson aquifer based on water budget and pumping estimates. Finch and Armour (2001) assumed for model development that values of specific yield varied according to rock type. They also assigned a specific yield value of 0.15 to the basin fill and consolidated rocks that have good porosity and permeability were assigned a specific yield of 0.10. Confined aquifer storage coefficients were assumed equal to the layer thickness multiplied by $1x10^{-6}$, except for rocks with fracture porosity, which were assigned a value of the layer thickness multiplied by $1x10^{-7}$. These data were used as a basis for estimating storage parameters in the model across the study area.

Regardless of aquifer hydraulic characteristics, yields in existing wells are often a factor of well construction. Wells with the highest yields are typically those with the longest screen interval in the area where aquifer saturated thickness is greatest.

Freeze and Cherry (1979) describe a hydraulic conductivity ellipsoid to define the variation in hydraulic conductivity along three major axes of flow. Horizontal hydraulic anisotropy refers to the difference in hydraulic conductivity in the horizontal plane and vertical hydraulic anisotropy refers to the difference in hydraulic conductivity in the vertical plane. There is no documentation of pumping tests in the Bolson aquifer that provide evidence of horizontal hydraulic anisotropy. However, due to the depositional environment of the Bolsons, it is likely that there are local horizontal hydraulic anisotropic bolson sediments. There is probably significant vertical hydraulic anisotropy due to the natural layering of sediments in the bolson. However, documentation of vertical hydraulic conductivity estimates was not discovered during this study. However, lithologic descriptions on drilling logs from wells completed in the Bolson aquifer indicate that there are significant lithologic variations with depth. These lithologic variations can cause significant vertical hydraulic anisotropy, which can impact vertical flow within the aquifer and between the bolson and underlying hydraulically connected units.

4.1.7 Discharge

Pumping for irrigated agriculture accounts for approximately 81 percent of the total groundwater withdrawal within the study area between 1980 and 2000. There is no significant discharge to springs, streams, or lakes from the Salt Bolson aquifer within the model area. Accordingly, accurate estimates of pumping for this use are important to understanding the groundwater flow system and estimating future aquifer responses based on historical pumping impacts. Pumping estimates for irrigated agriculture were determined from the historical water use inventories provided by the TWDB. Because of the importance of this water budget component, additional sources of information were also used in conjunction with the TWDB water use inventories to determine withdrawals for irrigated agriculture. Finch and Armour (2001) provide fairly detailed estimates of pumping for irrigated agriculture for the years 1947 through 2000 for Culberson County, which accounts for 70 percent of all agricultural pumping in the study area between 1980 and 2000. A detailed description of how pumping estimates were derived can be found in Appendix C.

Pumping for irrigated agriculture accounts for approximately 94 percent of the total groundwater withdrawal within Culberson County, 82 percent in Jeff Davis County, 57 percent in Presidio County and, 6 percent in Brewster County. In contrast to the heavy agricultural pumping in Culberson, Jeff Davis, and Presidio Counties, Brewster County produced only 50 acre-feet of groundwater for irrigation in 1964.

Agricultural pumping was assigned within the study area based on land use maps and the 1994 irrigated lands survey conducted for the TWDB. Irrigated lands are shown in Figure 4.1.19. Available information indicates that, on a regional scale, areas of irrigated acreage in Culberson County have been fairly constant through time since 1980. For example, the number of model cells with irrigation wells in the Wild Horse Flat Irrigation area of Culberson County was 57 in 1980, 1985, 1990, 1995 and 2000. The irrigated regions of Lobo Flat and Michigan Flat have also remained relatively constant as well during the same time period.

Non-agricultural pumping is divided into municipal, livestock, manufacturing, and rural domestic uses. Next to irrigated agriculture, municipalities are the largest users of groundwater, with Alpine, Marfa, Van Horn, and Fort Davis being the largest municipal users. A significant portion of the total pumpage in Brewster County is for Alpine's municipal use. The manufacturing category includes mining and power generation. Rural domestic use includes municipal type use that could not be associated with specific points of withdrawal. Pumping values for each of these uses were determined from compilations of the water use inventories provided by the TWDB.

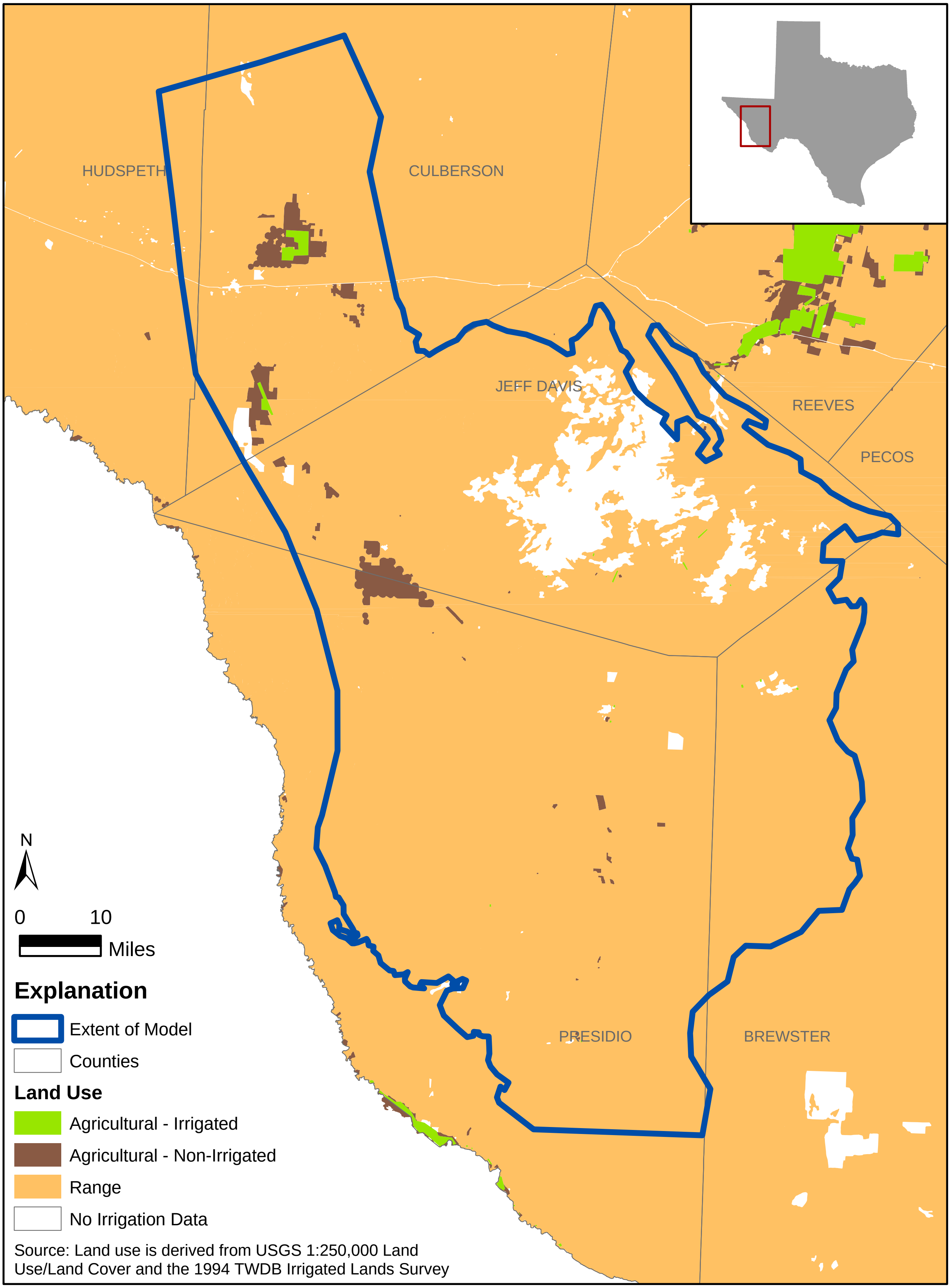


Figure 4.1.19 - Irrigated Land in 1994

Total historical pumping, groundwater withdrawals by aquifer, and groundwater withdrawals by county are illustrated in Figures 4.1.20 through 4.1.22, respectively. In Figure 4.1.22, elevated levels of pumping in Culberson County between 1973 and 1977and in Jeff Davis County between 1979 and 1984 are attributed to above average irrigation activity. Spatially distributed withdrawals within the study area in 1980 and 2000 are summarized in Figures 4.1.23 and 4.1.24, respectively. Rural domestic pumping was proportionally distributed by rural population density (Figure 4.1.25). A more detailed explanation of the procedures used to develop historical pumping estimates is provided in Appendix C.

4.1.8 Water Quality

The quality of groundwater in the Salt Basin Bolson aquifer was evaluated to help potential users of the model assess the quality of available groundwater. Water-quality data was compiled from the TWDB groundwater database and the Texas Commission on Environmental Quality (TCEQ) public water-supply well database. The main parameter of interest for this study is total dissolved solids (TDS). Several other parameters may be of interest from the standpoint of water quality for drinking-water supplies, including nitrate. A summary of the available data for these parameters is included below.

TDS is a measure of the salinity of groundwater, and is the sum of the concentrations of all of the dissolved ions, mainly sodium, calcium, magnesium, potassium, chloride, sulfate, and bicarbonate. The TWDB has defined aquifer water quality in terms of dissolved-solids concentrations expressed in milligrams per liter (mg/L) and has classified water into four broad categories:

- fresh (less than 1,000 mg/L);
- slightly saline (1,000 - 3,000 mg/L);
- moderately saline (3,000 - 10,000 mg/L); and
- very saline (10,000 - 35,000 mg/L).

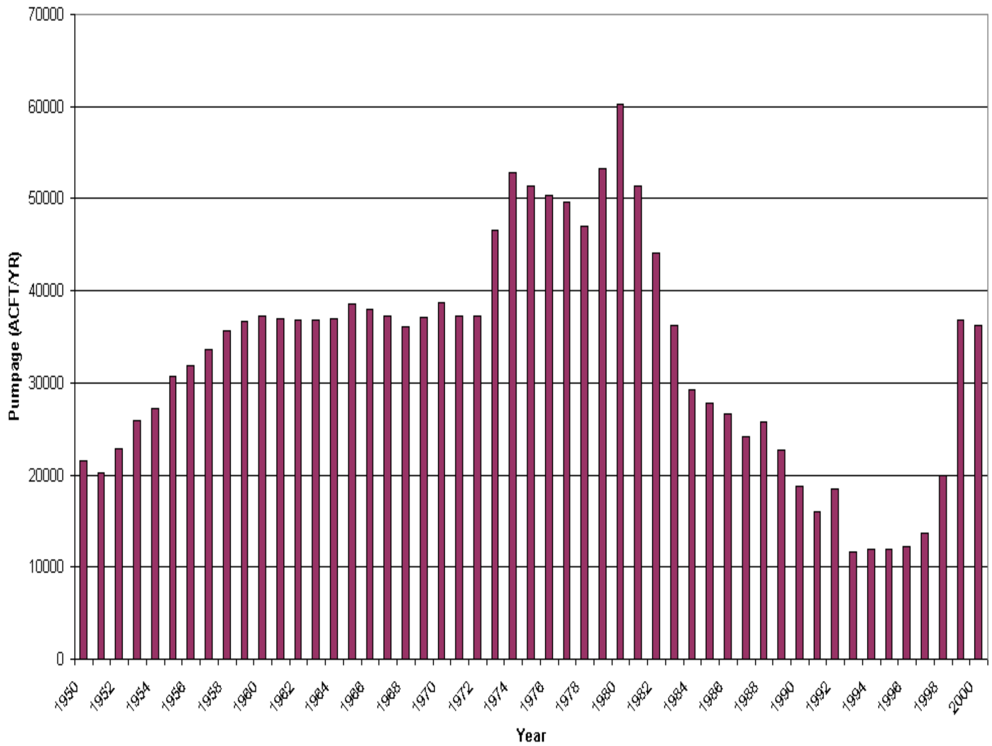


Figure 4.1.20 Total pumping in the study area

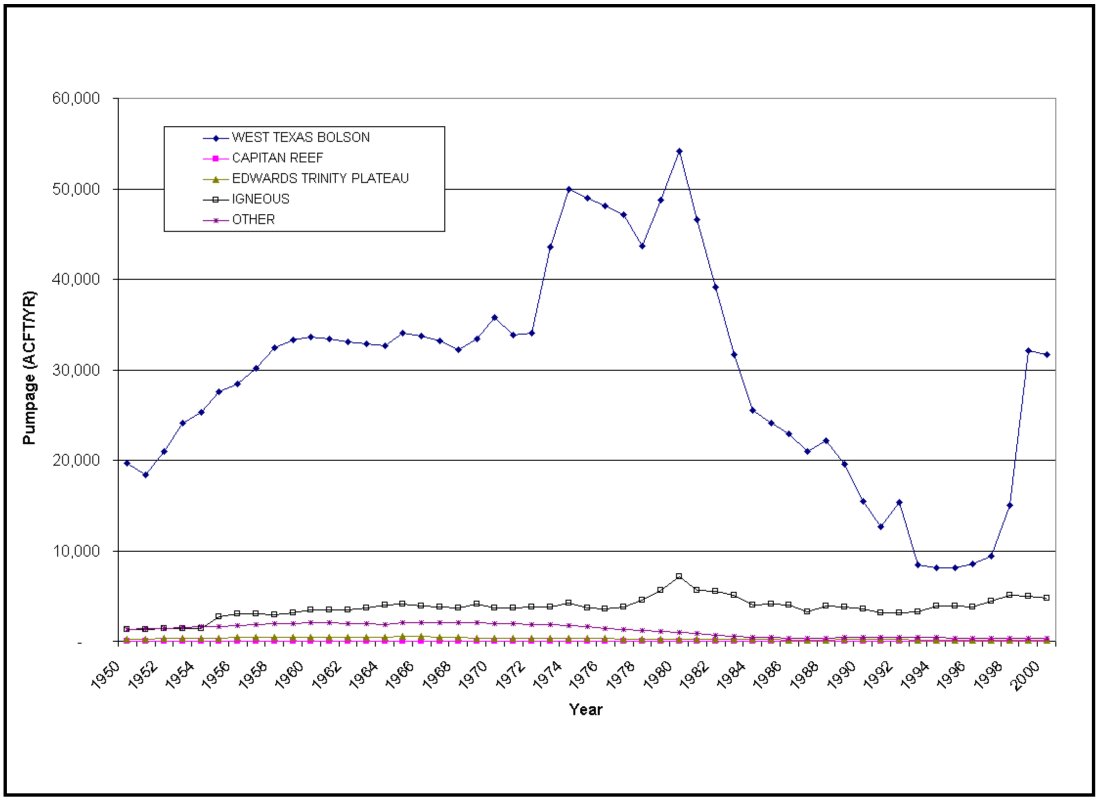


Figure 4.1.21 Total pumping by aquifer

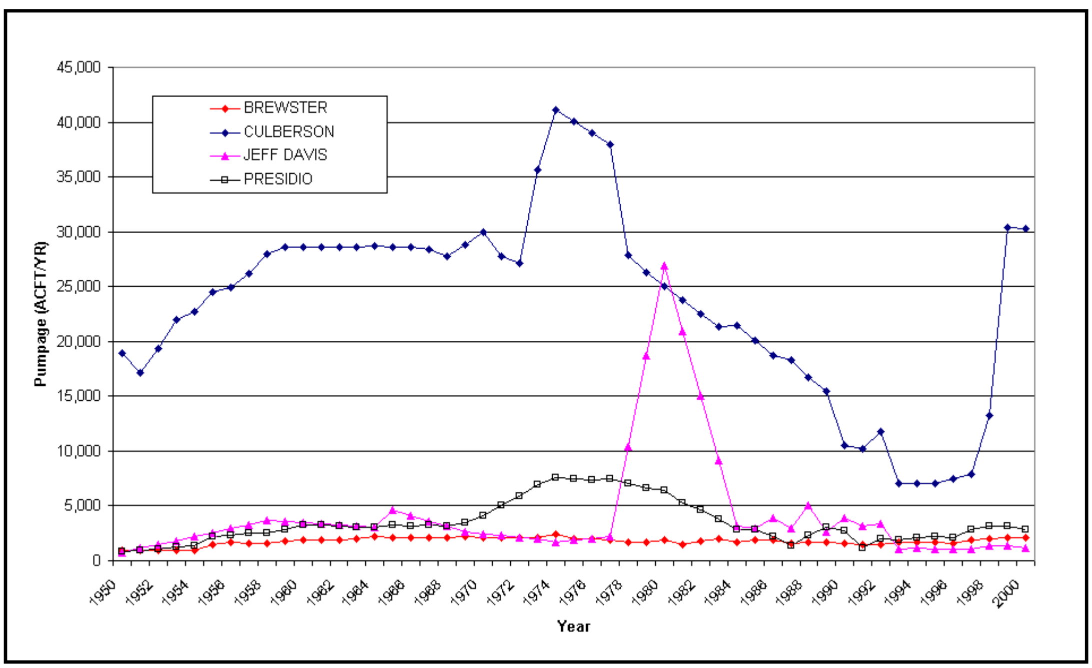


Figure 4.1.22 Total pumping by county

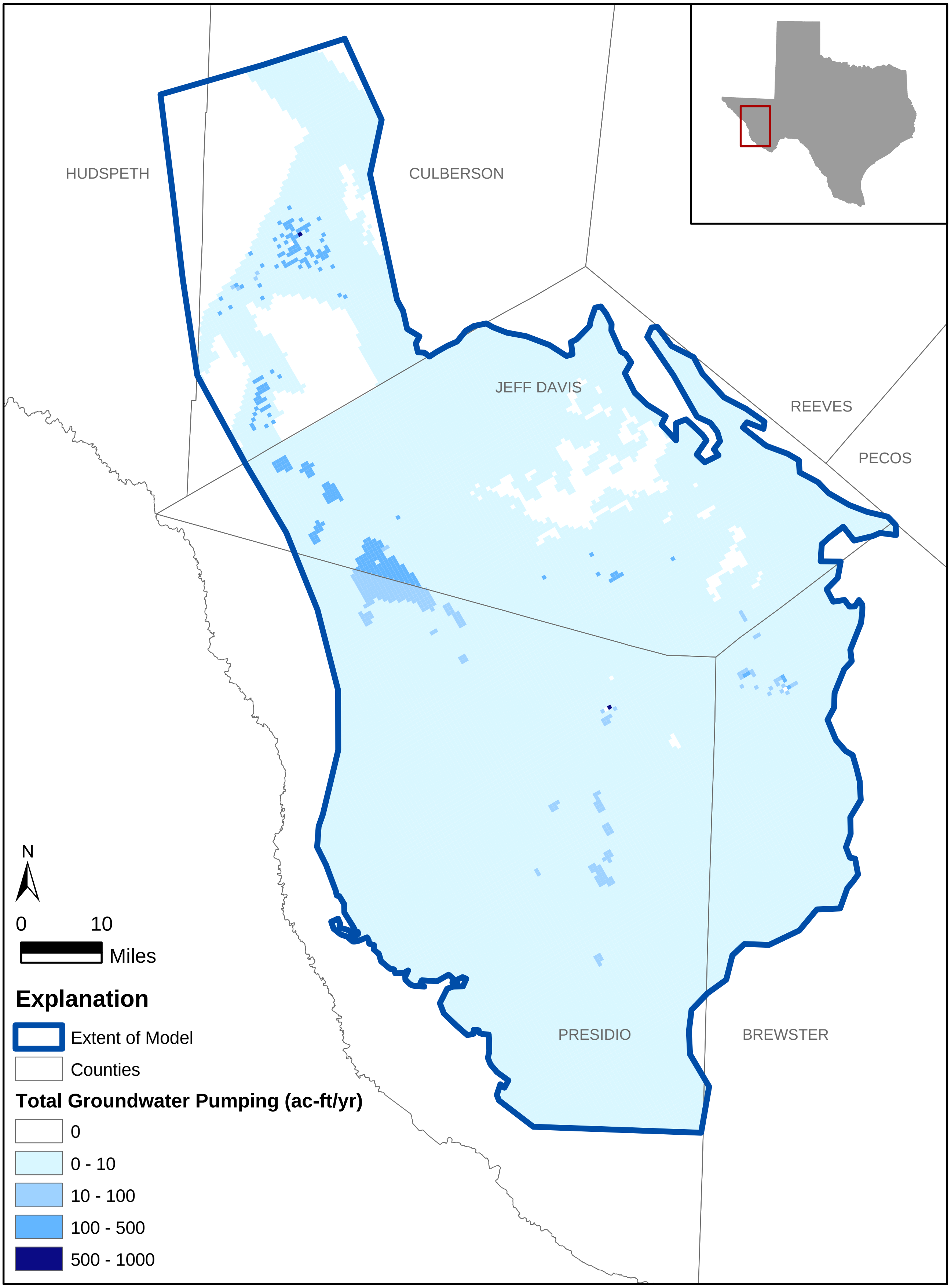


Figure 4.1.23 - Spatial Distribution of Groundwater Withdrawals in 1980

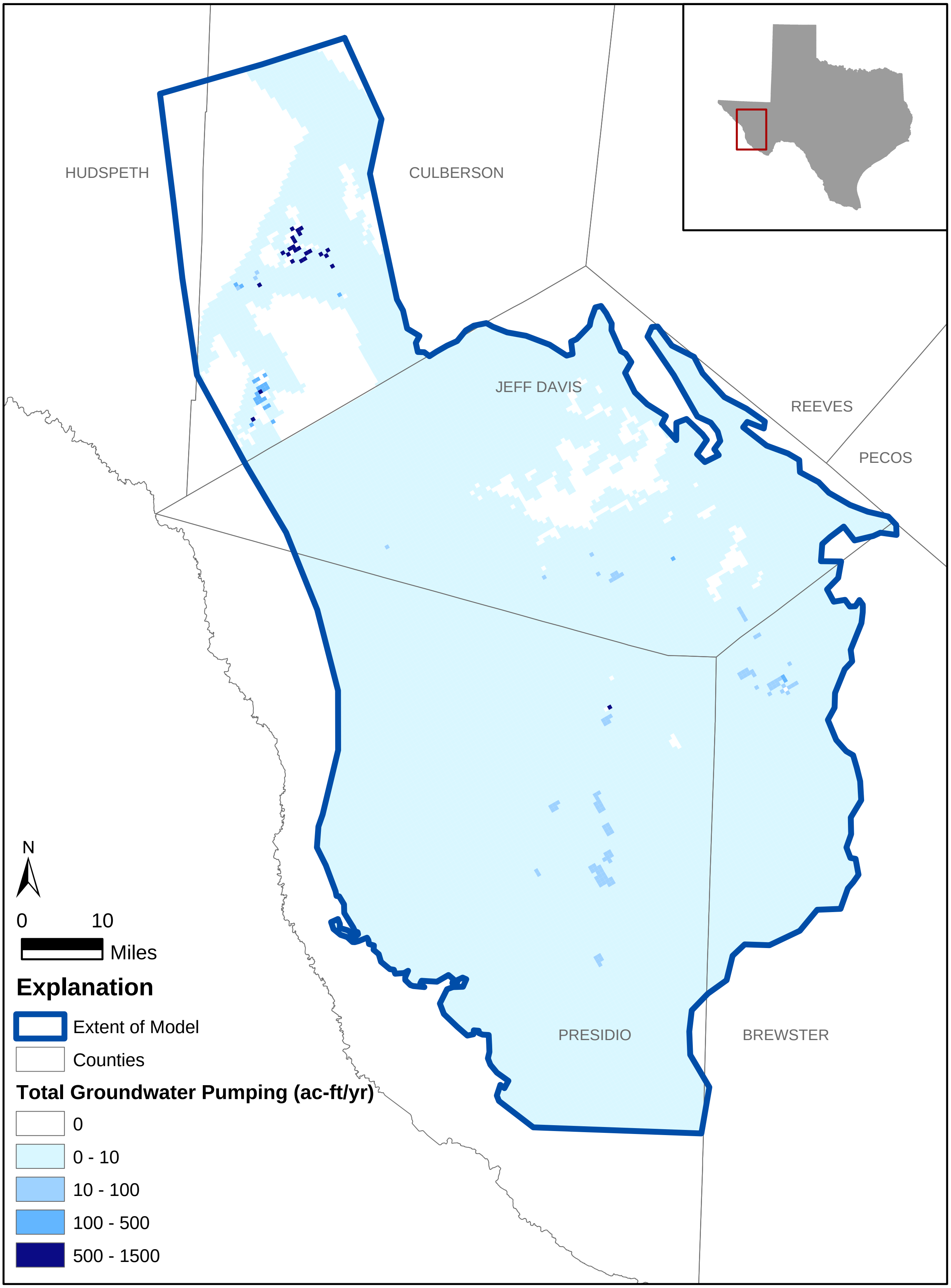


Figure 4.1.24 - Spatial Distribution of Groundwater Withdrawals in 2000

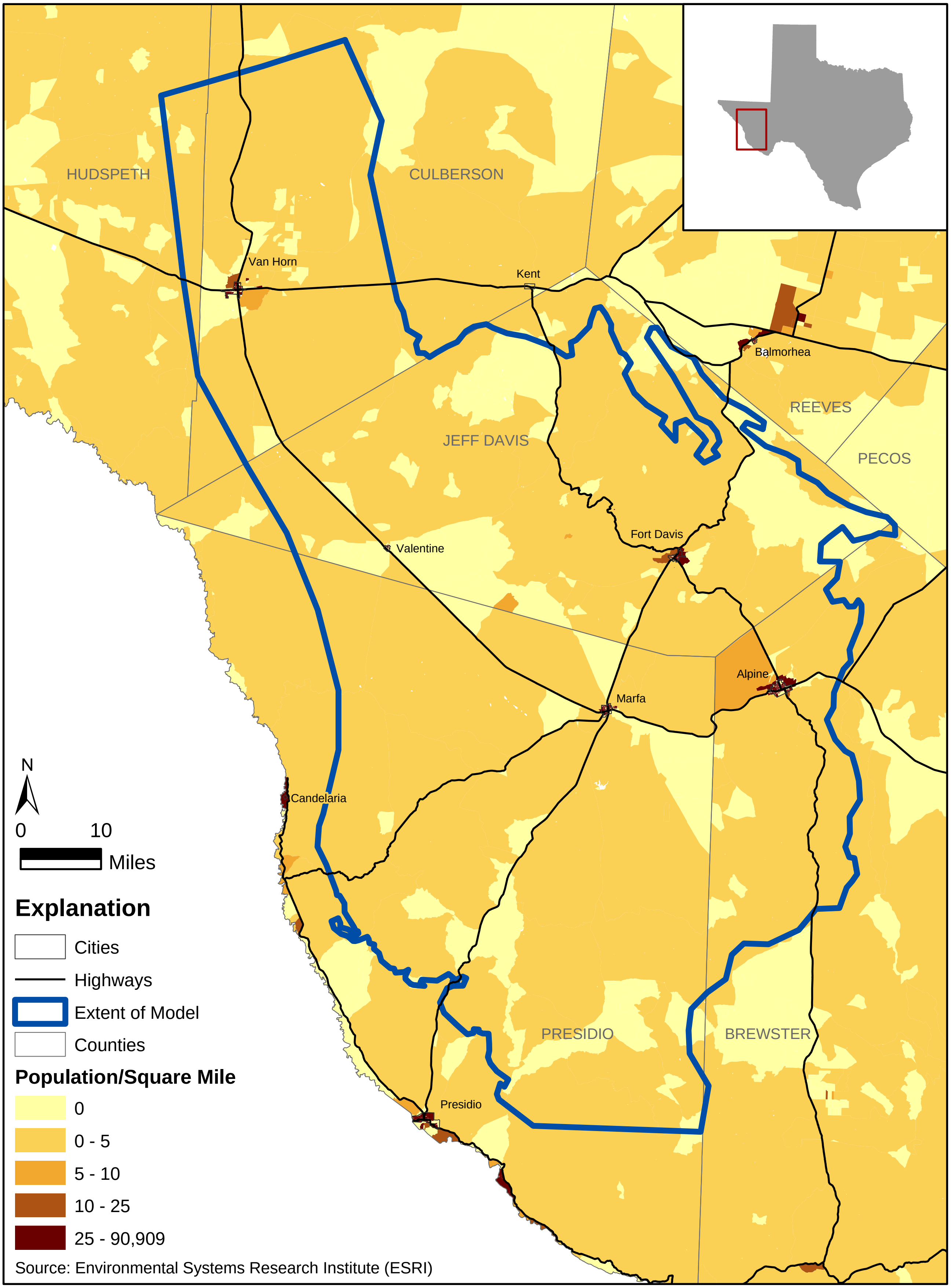


Figure 4.1.25 - Study Area Population Density in 1990

A total of 189 Bolson water-sample data points were used for the analysis of groundwater quality. Figure 4.1.26, illustrating TDS distribution, indicates that most Salt Basin Bolson aquifer water is fresh, with TDS less than 1,000 mg/L. The exception to this is in the central part of the Salt Basin, in Wild Horse and Michigan Flats, where slightly to moderately saline analyses are more common.

More than 25 percent of the water analyses had reported nitrate concentrations above the primary standard of 10 mg/L as nitrate-nitrogen (44mg/l as nitrate). In addition to nitrate, TDS exceeded the secondary standard in 20 percent of the available analyses, followed by sulfate (300 mg/l)(19 percent), chloride (200 mg/l)(13 percent), and fluoride (2 mg/l)(9 percent above the secondary standard and 2 percent above the primary standard, 4 mg/l).

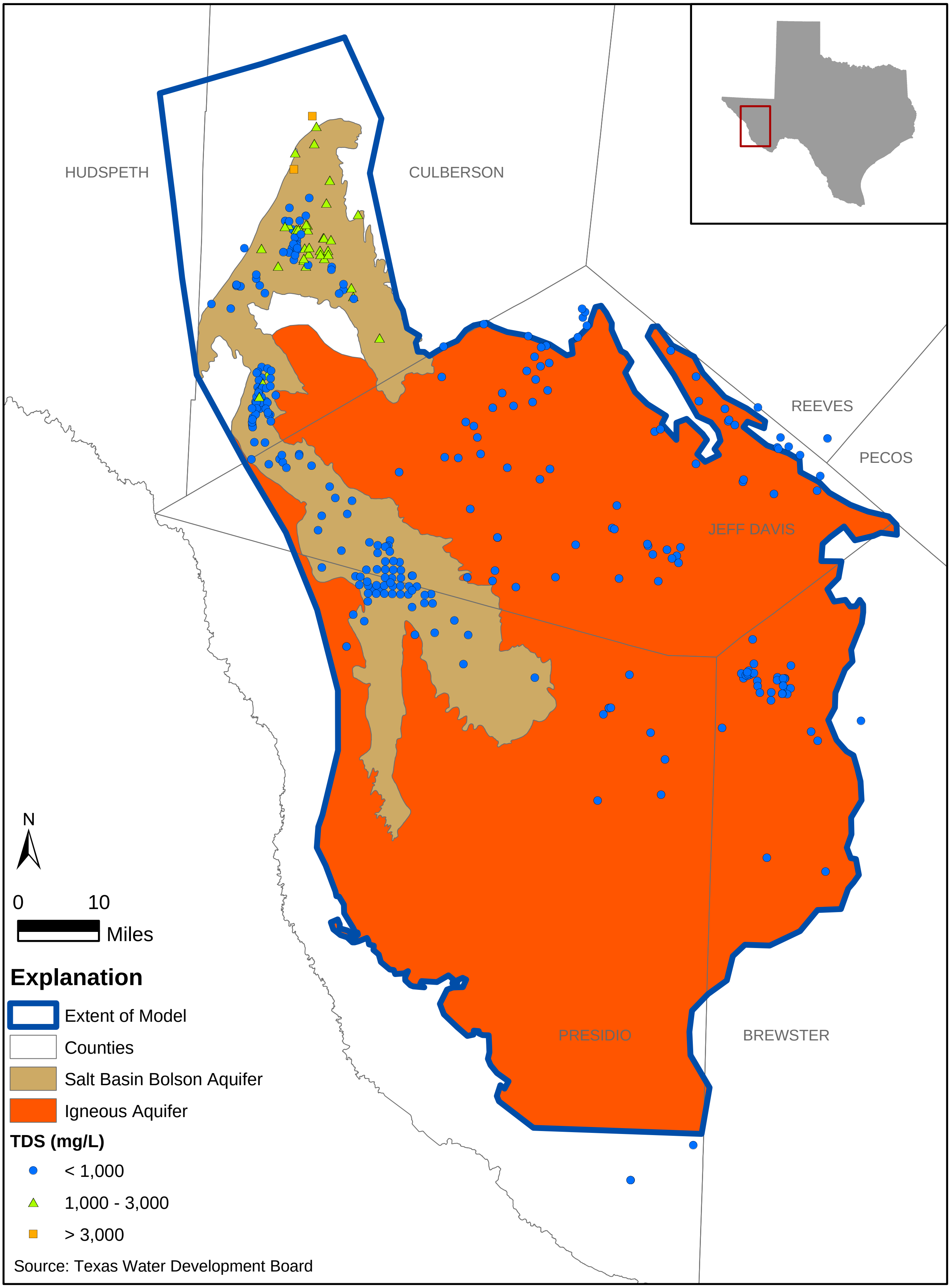


Figure 4.1.26 - Groundwater Quality in the Salt Basin Bolson and Igneous Aquifers

4.2 Igneous Aquifer System

4.2.1 Hydrostratigraphy

The Igneous aquifer system comprises all contiguous Tertiary igneous formations that underlie the Davis Mountains and adjacent areas. Centers of eruptive igneous activity within the West Texas volcanic field shifted over time and covered all of Presidio County, most of Jeff Davis County, and more than 25 percent of Brewster County. Today the Tertiary igneous rocks form the impressive highlands of the Davis Mountains as well as the Sierra Vieja and Chinati Mountains to the west and southwest.

The Fort Stockton, Marfa, Emory Peak-Presidio, and Van Horn-El Paso sheets of the Geologic Atlas of Texas show over 40 named volcanic units, many which have been subdivided by more detailed mapping (Table 2.2). Woodward (1954) also recorded over 40 different lava flow or tuff units within the 6,032 ft thickness of volcanics from the Killam oil test well near Valentine. Individual igneous formations are highly variable in nature and suggest varying forms of intrusive and extrusive volcanic activity interspersed with periods of low activity when erosional clastic sediments (volcaniclastics) accumulated.

The thickness of Tertiary igneous rocks (Figure 4.2.1) has been estimated from geophysical and sample logs of prospective oil wells. In areas where the igneous rocks were not overlain by bolson, the thickness was estimated by subtracting the elevation of the base of the Igneous aquifer (Figure 4.2.2) from the elevation of the topographic surface. Where bolson was present, the thickness of the igneous rocks was estimated by subtracting the elevation of the base of the Igneous aquifer from the elevation of the base of the bolson. The elevation of the top of the Igneous aquifer is shown in Figure 4.2.3. The thickness contours have been smoothed owing to the sparse control available for the aquifer base. The Killam oil test well near Valentine encountered the greatest recorded thickness of volcanic rock at 6,032 feet. Most of the aquifer's areal extent is underlain by thickness ranging from 1,000 to 4,000 feet. The aquifer thickness naturally thins around the outer edges due to erosion.

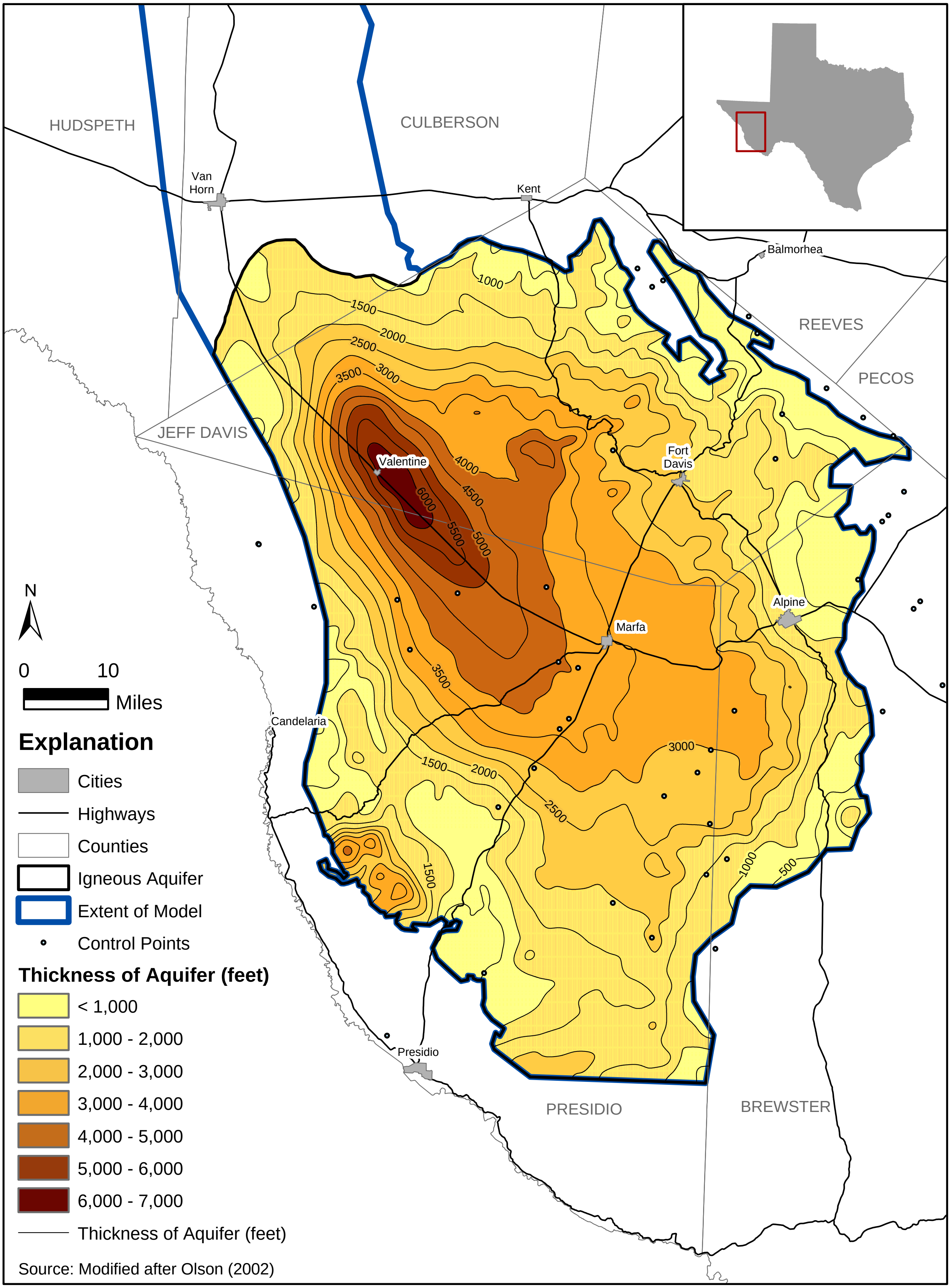


Figure 4.2.1- Thickness of the Igneous Aquifer

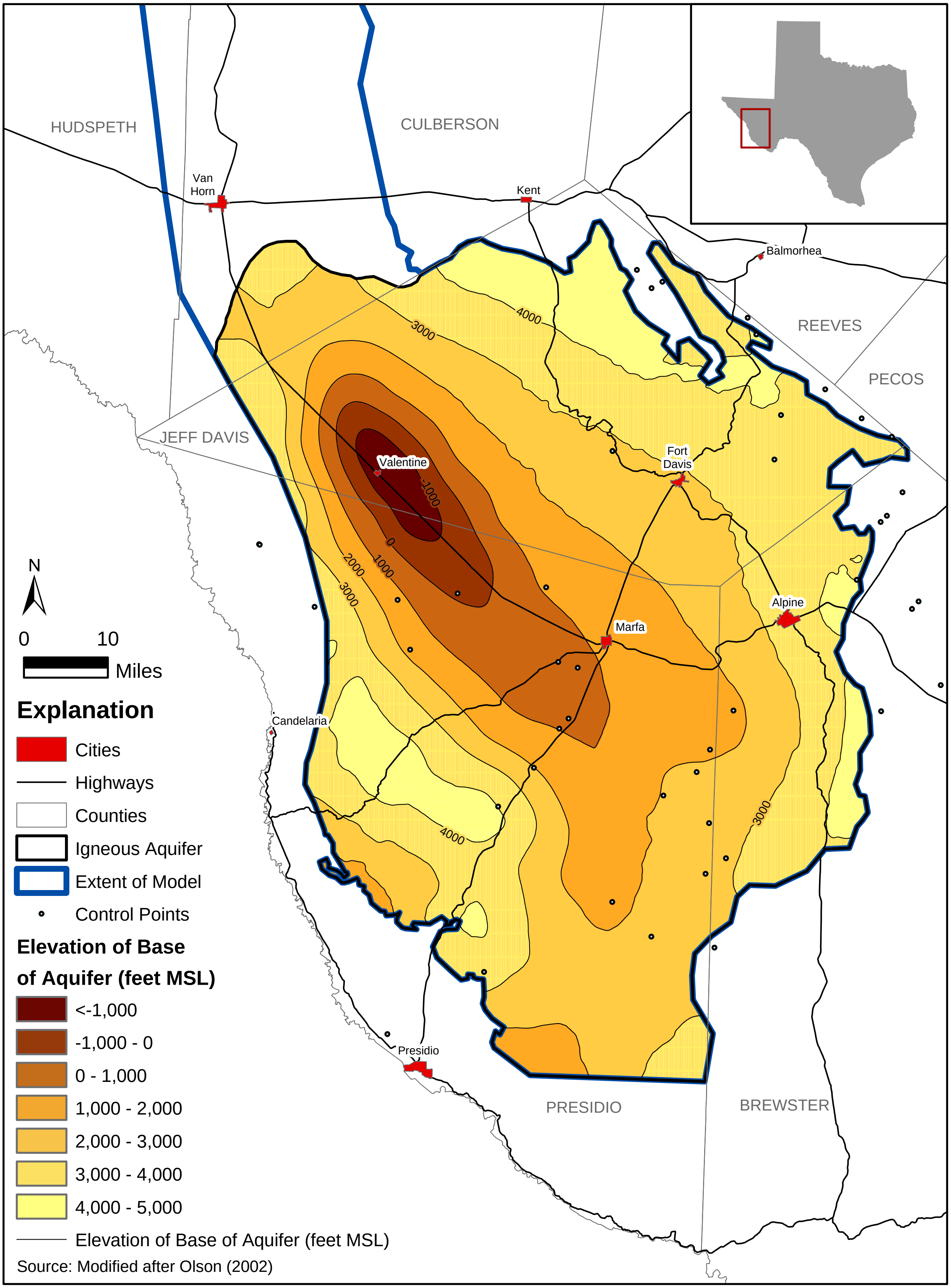


Figure 4.2.2 - Elevation of the Base of the Igneous Aquifer

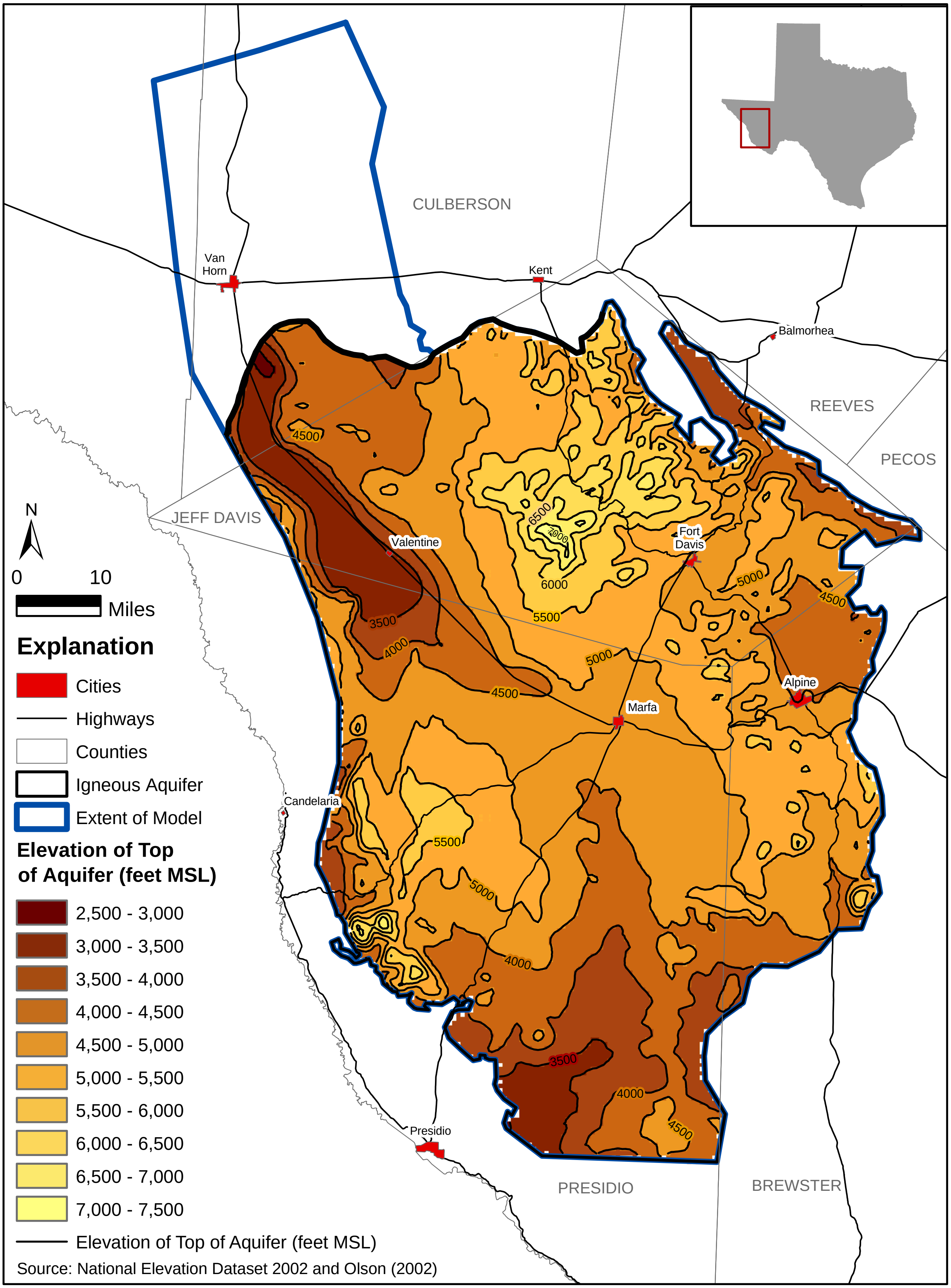


Figure 4.2.3 - Elevation of the Top of the Igneous Aquifer

The Igneous aquifer is not a single homogeneous aquifer but rather a system of complex water-bearing formations that are in varying degrees of hydrologic communication. In a study of the hydrogeology of the Davis Mountains, for example, Hart (1992) reported that groundwater in Jeff Davis County is found in 11 distinct water-bearing units. The individual aquifers occur in lava and pyroclastic flows (ignimbrites), in clastic sedimentary rocks deposited in an overall volcanic sequence, and possibly in ash falls (tuffs). Late Tertiary sedimentary deposits (volcaniclastics), such as the Perdiz Conglomerate and Tarantula Gravel, may be included in the Salt Basin Bolson aquifer if they occur beneath Quaternary bolson deposits. As mentioned in Section 4.1, volcaniclastic deposits were included in the bolsons in Lobo and Ryan Flat because they have similar hydraulic properties.

The best aquifers are found in igneous rocks with primary porosity and permeability such as vesicular basalts, interflow zones in lava successions, sandstones, conglomerates, and breccias. Faulting and fracturing can enhance aquifer productivity in poorly permeable rock units.

4.2.2 Structure

The major structural elements that influence the occurrence and movement of groundwater within the Igneous aquifer system are faulting, fracturing, and topography. Faulting of igneous rocks is the combined result of regional basin and range faulting and local pressure equalization of the variable thickness of new strata generated by the extrusive flows over the previous land surface. Generally, vertical displacement is relatively minor. Areas with the greatest density of faults exposed at land surface are in the middle to higher elevations of the watersheds of the Davis Mountains in Jeff Davis County (McCutcheon fault zone) and in the igneous rocks that border the Alamito Valley (drained by Alamito Creek) in Presidio County. Faulting in the lowlands is masked by alluvial cover and is quite possibly of similar density to that seen where the bedrock is exposed. Elsewhere, graben faulting has downwardly displaced igneous units underlying the Salt Basin. Figure 4.1.4 shows the regional trends of the mapped fault and fracture systems within the Igneous aquifers area.

Fracturing of the igneous rocks mostly occurred as the molten lava flows cooled. The vertically oriented columnar jointing of some formations, such as the Sleeping Lion formation that crops out around Fort Davis, forms spectacular cliffs. Fractures and joints in rocks at the land surface serve to capture precipitation and create avenues of preferential recharge. There are a number of springs associated with faults and fractures, suggesting that there is hydraulic connection between the units through faults.

Topography is highly variable, especially in the mountainous sections including the Davis Mountains and Sierra Vieja. In these areas there can be more than 1,000 feet of elevation change in less than half a mile. Rainfall rates increase in the higher elevations of the Davis Mountains.

4.2.3 Water Levels and Regional Groundwater Flow

Regional Igneous aquifer water-level contours display a radial pattern emanating outward from areas of higher land elevation (Figures 4.1.5 through 4.1.8). This radial pattern suggests that topography is an important factor in estimating water-level elevation. Bedrock geology, faulting and regional structures also influence water-level elevation. The lack of water level measurements in the Cretaceous units precludes gaining insight into the vertical flow between the Igneous and Cretaceous units. While the water level estimation methodology presented in Appendix A was used to produce the potentiometric maps to better visualize general groundwater flow patterns in the Igneous and Bolson aquifers, the accuracy of these maps is limited due to the sparse water level measurements. Therefore, these potentiometric maps were used only as a guide for boundary and initial head conditions during the model calibration. As discussed in Section 4.1.3, springs were not implemented directly into the calculations but only indirectly by topography. Therefore, they are not shown on the map.

Very little water-level data for the Igneous aquifer exists prior to 2001. To increase regional water-level accuracy, water levels in 85 additional wells were measured and added to the database (Ashworth and others, 2001). Also, an interpretive method of water level analysis was used to develop potentiometric surfaces for the entire study area. The methodology for this interpretative scheme is outlined in Appendix D. Although the methodology does not account for all the possible factors affecting water levels in this complex aquifer system, the method does attempt to account for variations in topography, surface geology, and water-level measurements that were identified within the near-surface water-bearing units.

Hydrographs displayed in Figure 4.2.4 are from municipal wells at Marfa, Fort Davis, and Alpine, and provide information on localized water-level changes over time in these areas. Unfortunately, there are no time-series water-level data available that are representative of the undeveloped areas of the Igneous aquifer. Because there are relatively few heavy pumping demands in remote areas of the Igneous aquifer, it is assumed that water-level variations in these areas are caused by changes in natural conditions, mainly the recharge that occurs from precipitation. Therefore, the potentiometric surface map developed from water-level measurements collected around 2000 was a valuable guide in assessing historical water-levels throughout much of the Igneous aquifer.

4.2.4 Recharge

Recharge to the Igneous aquifer originates as precipitation that infiltrates through soil and rock to reach the saturated zone of the aquifer. Four significant factors that control recharge in the study area are: 1) amount of precipitation, 2) location of drainages which concentrate surface-water runoff, 3) location and density of exposed fractured rock, and 4) soil infiltration potential. Based on these factors, recharge is most favorable in areas of higher elevation where precipitation rates are at their greatest and fractured rock is exposed, and in lower elevation valleys containing porous soils (Ashworth and others, 2001). The freshness of Igneous aquifer system water quality, as exhibited by its typically low total dissolved solids content, indicates water is transmitted (recharged) relatively rapidly from the surface to the aquifer.

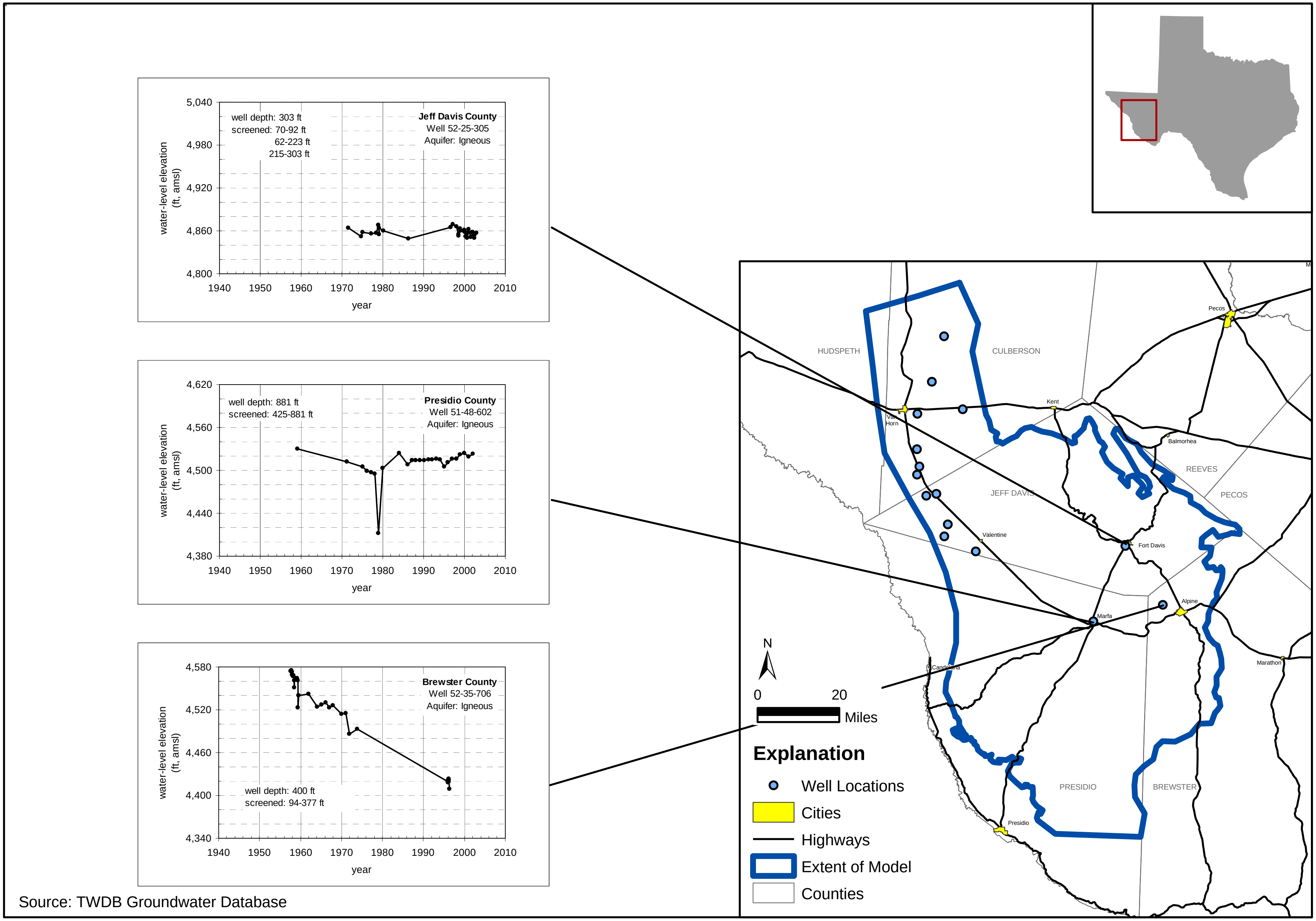


Figure 4.2.4 - Hydrographs for Wells in the Igneous Aquifer

A method for estimating potential recharge to the IBGAM study area was discussed in detail in Section 4.1.4 and in Appendix B. Using this methodology, the majority of the Igneous aquifer receives direct recharge estimated at 0.35 inch per year.

Hart (1992) observed that fault zones that intersect stream courses are channels for the direct infiltration of water. In these areas, streams carrying water from higher elevations of mountain watersheds lose a portion of their flow to the fractures. These "losing" streams can be identified on the basis of reductions in flow downstream of known fractures and fault zones (see following discussion in Section 4.2.5).

4.2.5 Rivers, Streams, Springs, and Lakes

Surface water in the Igneous aquifer portion of the IBGAM study area is in the form of springs, spring-fed creeks, and ephemeral runoff. Springs in this area, as in all arid lands, played an important role in the pre-settlement and settlement history of the area, particularly at Alpine and Fort Davis. Figure 4.2.5 shows the location of springs as well as estimated flow rate as documented by the USGS (Heitmuller and Reece, 2003). Springs issuing from the Igneous aquifer system provide water for domestic use and the watering of livestock and game. It is also important to note that surface water (springs and streams) in the study area are likely influenced by long-term and short-term cyclic climate patterns causing the disappearance and re-emergence of springs and perennial streams. Long periods of drought reduce the amount of recharge in the watersheds that provide the source water for springs. Pumpage from nearby wells also affects springflow by lowering the water level below the orifice of a spring. Local groundwater pumping has likely impacted springs around Alpine and Fort Davis.

In a survey of the springs of Texas, Brune (1981) counted more than 150 springs in Brewster, Jeff Davis and Presidio Counties. The discharge of many of the springs is highly variable, and Brune noted that many springs in this area were not flowing at the time of his survey. Brune reported that discharge of springs in this area ranges from less than 0.5 gallons per minute (gpm) to as much as 200 gpm. Most springs, however, were

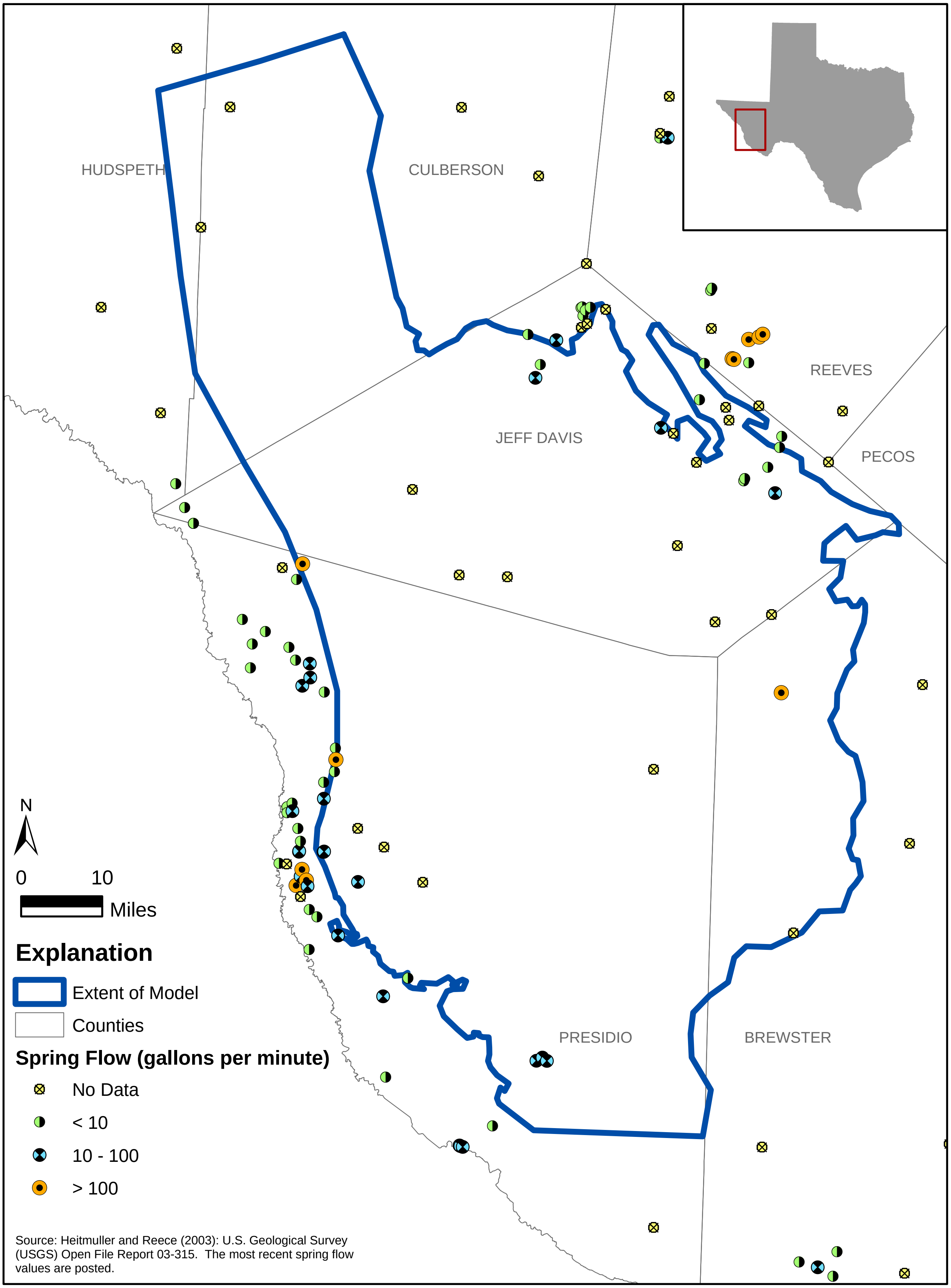


Figure 4.2.5 - Location and Approximate Flow of Springs

listed in the “small” to “very small” categories with discharges of less than 5 gpm. Hart (1992) estimated that total daily discharge from springs in Jeff Davis County is 1.1 million gallons per day.

The Balmorhea spring system includes Phantom Lake, Saragosa, Sandia, Giffin, and San Solomon (Figure 4.2.5). Historically, the combined discharge of these springs was approximately 100 cfs or 72,450 ac-ft/yr, but now discharge is about half that amount. The source of the springs is complicated, but research by LaFave and Sharp (1987), Sharp (2001), and recent unpublished research by the TWDB indicate local recharge from the Davis Mountains accounts for about half the spring flow, and regional flow from the fault systems and Capitan Reef aquifer contribute the base flow of the springs. The springs at Balmorhea are located outside of the IBGAM boundary; however, because of their hydrologic complexity, these springs are accounted for in the IBGAM by simulating northward groundwater outflow from the model boundary located near the Jeff Davis and Reeves County boundary and eastward from the Wild Horse - Michigan Flats area.

The occurrence of surface water primarily occurs as storm-water runoff during summer storms, and to lesser degrees from springs and groundwater discharge to major drainages in the area of the Igneous aquifer. Perennial streams in the study area (Figure 4.2.6) include Limpia Creek, Calamity Creek, and Torneros Creek. Torneros Creek forms the southern boundary of the study area.

The only two stream gages in the study area are located on Limpia Creek, which originates in Jeff Davis County. Figure 4.2.6 shows the location of two stream flow gages located on Limpia Creek. Each gage shows the same pattern of higher flow that correlates to the summer time thunderstorm season in the Trans-Pecos region (Figure 4.2.7). Flow in the stream is substantially less during other times of the year.

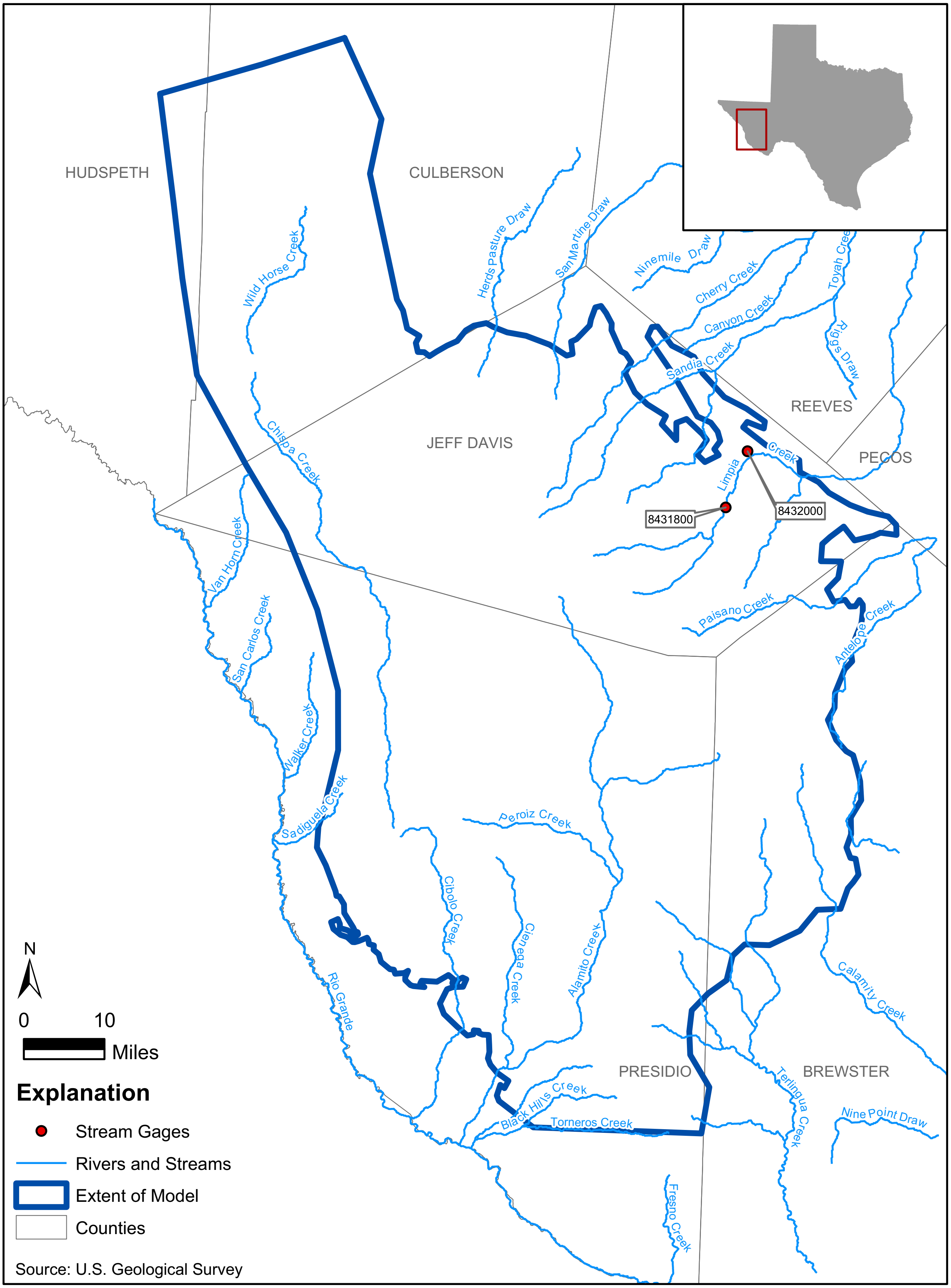


Figure 4.2.6 - Location of Streams and Stream-Gage Stations on Limpia Creek

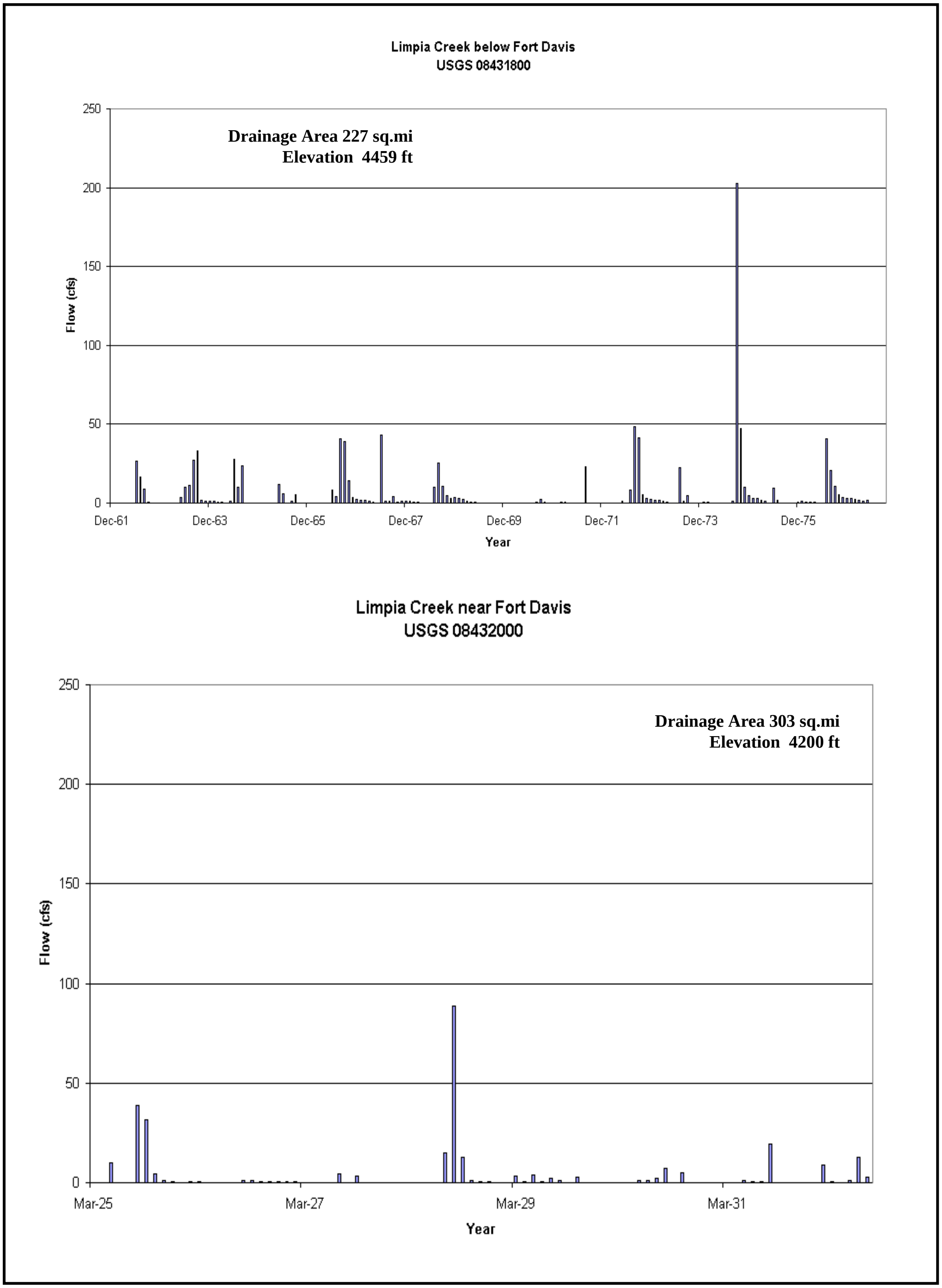


Figure 4.2.7 Mean monthly streamflow for gages on Limpia Creek near Fort Davis

Storm-water runoff accounts for the majority of surface water in the study area. The recharge analysis in Section 4.2.4 indicates the study area receives an average of 111,653 ac-ft/yr of runoff. A qualitative comparison of runoff measured by the U. S. Geological Survey to the average annual runoff estimates from the recharge analysis is shown in Table 4.4. There are likely not enough data to calculate a representative average measured streamflow, so the comparison between measured and calculated runoff can qualitatively be made by determining if the calculated runoff is within the minimum and maximum measured streamflow and approximate the average measured streamflow. Given the limited data, there appears to be good correlation between the measured and calculated annual average runoff, which tends to verify the recharge calculation method.

Table 4.4 Comparison of measured and calculated runoff (streamflow) for selected streams in the study area

Watershed	Minimum measured stream flow	Maximum measured stream flow	Average measured streamflow	Calculated annual runoff
	acre-feet/yr	**acre-feet/yr**	**acre-feet/yr**	**acre-feet/yr**
Upper Alpine Creek	129	6,658	1,514	1,123
Limpia Creek	196	16,011	3,692	9,500
Madera Canyon	35	14,800	3,847	3,335

Five streamflow gain-loss studies have been completed along different stretches of Limpia Creek near Fort Davis. These studies indicate that Limpia Creek is generally a gaining stream in the reaches above Fort Davis, becoming a losing stream as it flows east into Barrilla Draw and into Pecos County. This observation is consistent with those from other areas where mountain streams collect water from springs that issue at higher elevations and then lose the water to aquifers at lower elevations.

4.2.6 Hydraulic Properties

The multi-layered and fractured complexity of the Igneous aquifer system results in significant hydraulic property heterogeneity. This property variation provides a challenge when developing a regional-scale groundwater model, as it is difficult to account for local variations in properties that are responsible for flow system dynamics. The limited hydraulic properties as determined from literature and recent pumping tests (Ashworth and Chastain-Howley, 2003) show a wide variation even over very small distances. The geometric mean of transmissivity determined from 24 available pumping tests is 138 ft^2/day.

The location and spatial variation of hydraulic conductivity data (Figure 4.2.8) illustrates the complexity of this aquifer system. Because there is little hydraulic conductivity data for the Igneous aquifer, an empirical methodology was used to estimate transmissivity from existing specific capacity data. This methodology is outlined in Appendix D. Transmissivity was then converted to hydraulic conductivity by dividing the calculated transmissivity values by estimated saturated thickness at each location. The histogram of all the hydraulic conductivity values in the Igneous aquifer is shown in Figure 4.2.9. The values range over six orders of magnitude and the median value is about 0.75 ft/day.

Available hydraulic property data are generally derived from wells less than 1,000 feet in depth. The average well depth of the data set used for the calculation of hydraulic conductivity is 305 feet. Hydraulic conductivity likely decreases significantly with depth as overburden pressures increase and the pore spaces and fault related porosity decreases.

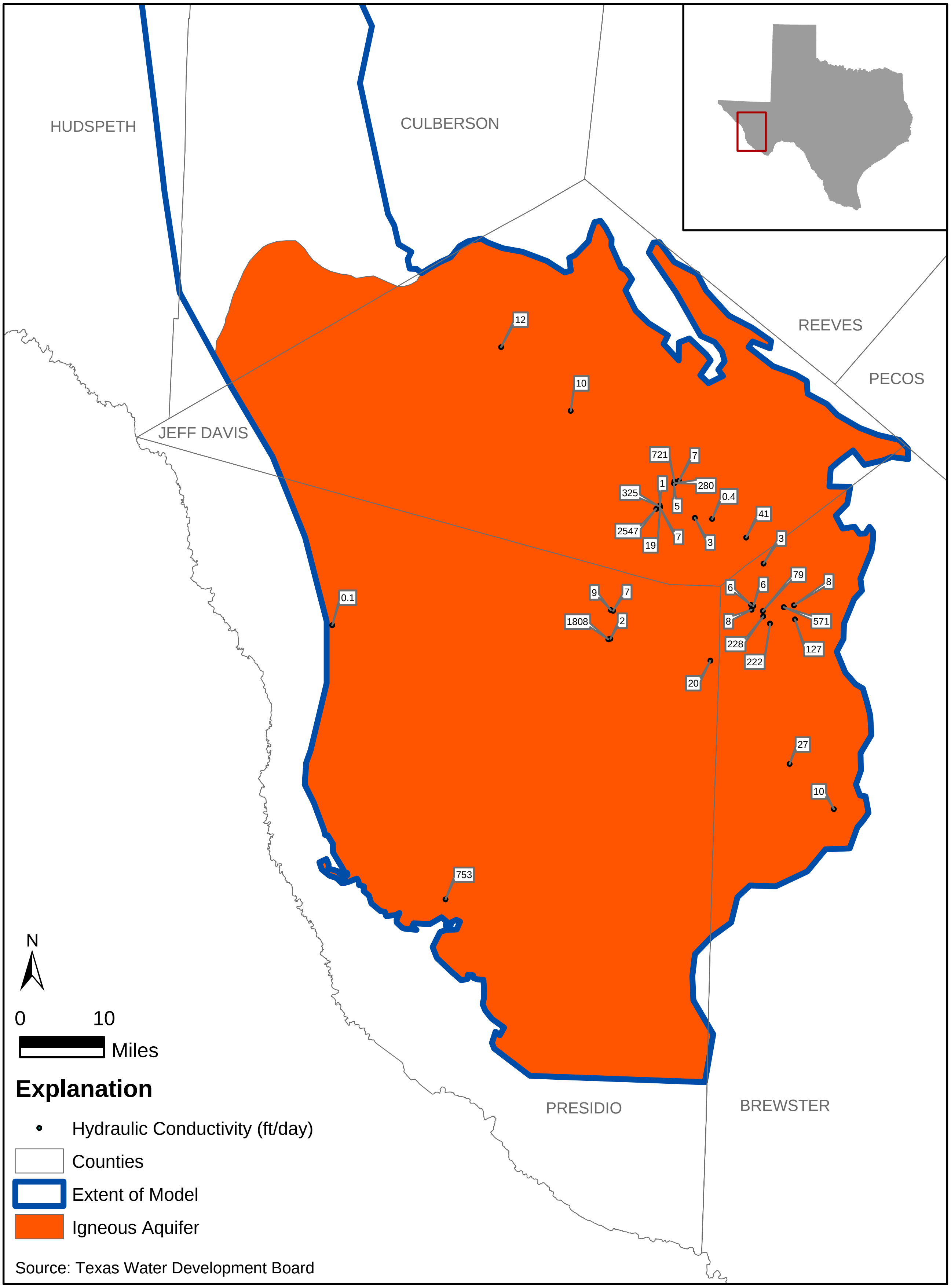


Figure 4.2.8 - Hydraulic Conductivity Data for the Igneous Aquifer

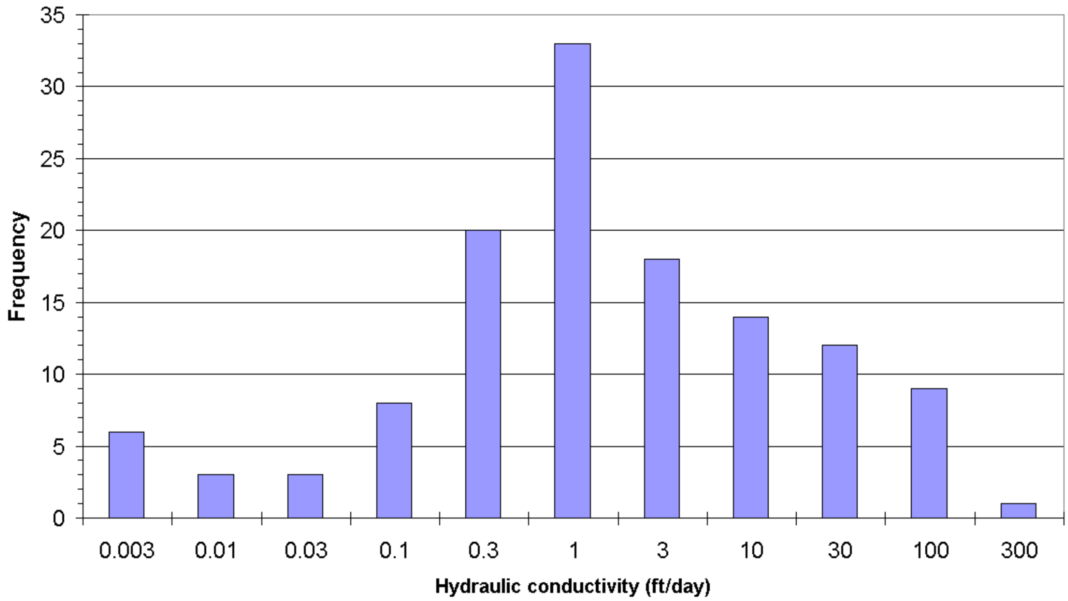


Figure 4.2.9 Histogram of hydraulic conductivity in the Igneous aquifer

Brown and Caldwell (2001) analyzed the flow dynamics of three wells, in Ryan Flat, completed through the bolson deposits and into the Igneous units. The study results suggest that there is significant flow within the bolson and the upper portion of the Igneous units (volcaniclastics), but very little flow within the deeper volcanic units. Figure 4.2.10 illustrates the four available storativity values in the Igneous aquifer. The storativity values, estimated from pumping tests in wells located northwest of Alpine, range from $3x10^{-5}$ to $2x10^{-4}$. Porosity in fractured crystalline rocks may vary from 0.0 to 0.10 (Freeze and Cherry, 1979).

4.2.7 Discharge

Discharge from the Igneous aquifer system occurs naturally by flow to springs and by municipal, domestic and livestock wells. Water naturally discharges through springs along the slopes of the Davis Mountains. However, most of this water reenters the aquifer downstream. There are no significant impoundments of surface water within the modeled boundary. Except for local stream segments, there is no major stream in the area to which groundwater discharges continually from shallow saturated sediments. A more detailed discussion on springs and streams is provided in Section 4.2.5. The major centers of discharge from the aquifer system are the municipal wellfields of Alpine, Fort Davis and Marfa; agricultural use by Village Farms and Powell Plant Farm; and from relatively closely spaced domestic wells.

4.2.8 Water Quality

A total of 124 water sample data points were used for the analysis of groundwater quality in the Igneous aquifer. Figure 4.1.26 shows the distribution of TDS in groundwater samples in the Igneous and Salt Basin Bolson aquifers. As indicated in this figure, all water analyses for the Igneous aquifer are fresh (less than 1,000 mg/L TDS). This is typical for the Igneous aquifer, where groundwater flows in fractures, and the aquifer material is relatively insoluble, resulting in low dissolved solids in the groundwater.

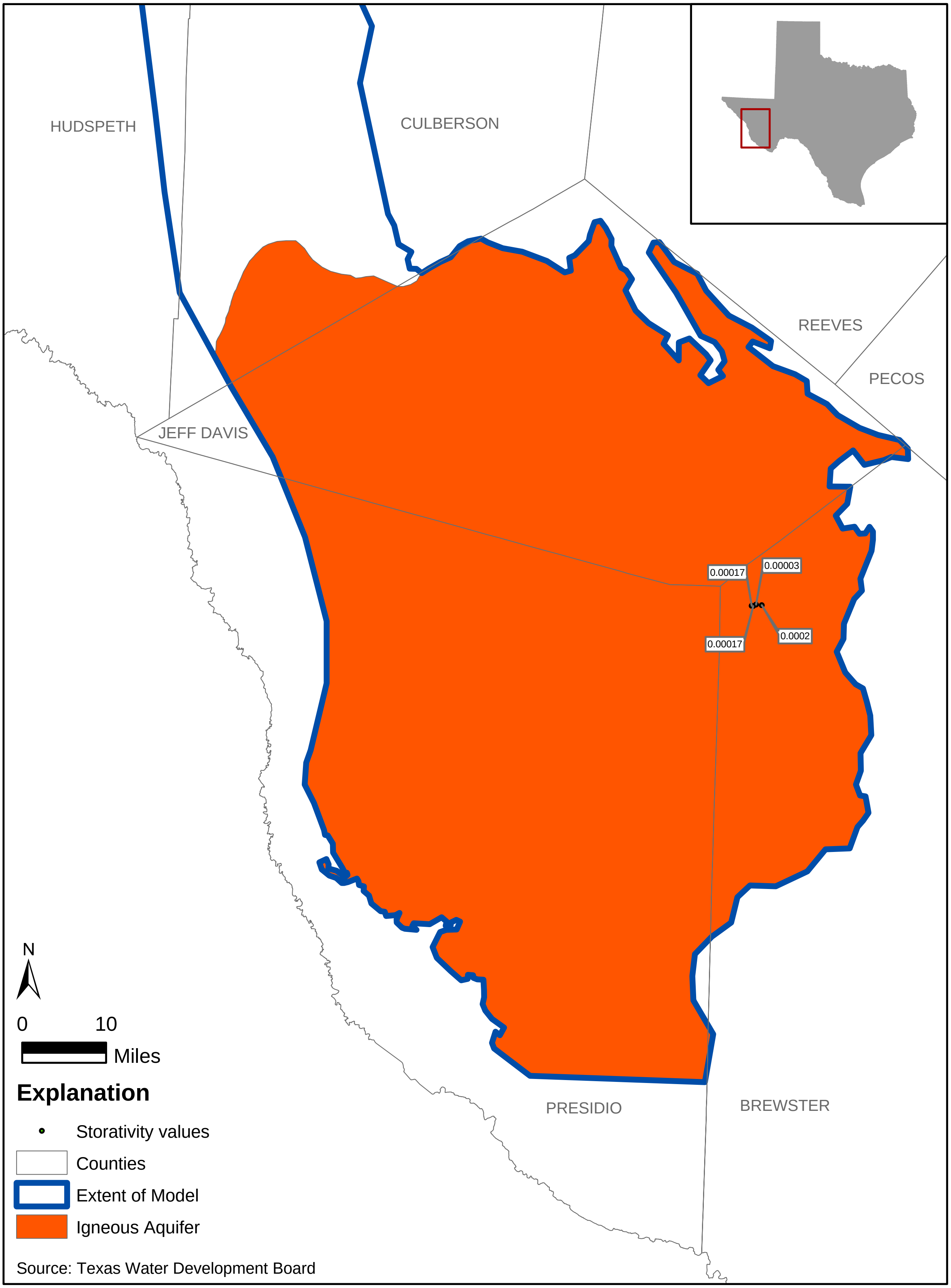


Figure 4.2.10 - Storativity Data for the Igneous Aquifer

Nitrate was evaluated with respect to the primary drinking water standard of 10 mg/L (as nitrogen). Nearly 20 percent of the samples contained nitrate concentrations above this standard. However, it is important to note that reported nitrate values are difficult to evaluate without reviewing individual lab results to determine the form in which the nitrate analyses are reported. Based on the nature of the Igneous aquifer and the types of land uses in the area, it is unlikely that nitrate concentrations are a significant problem in this area. Parameters evaluated with respect to secondary drinking water standards include chloride (300 mg/L), sulfate (300 mg/L), fluoride (with a primary standard of 4 mg/L and a secondary standard of 2 mg/L), and TDS (1,000 mg/L). None of these parameters exceeded the secondary drinking water standards given above, although fluoride exceeds the secondary standard of 2 mg/L in 16 percent of the analyses.

4.3 Cretaceous and Permian Formations

Model layer 3 represents Cretaceous and Permian age formations and is used in the IBGAM as a vertical boundary layer for the Igneous aquifer. These formations are not in themselves being investigated for their groundwater potential. Data on the lithology comes almost entirely from cutting descriptions and geophysical logs of oil tests (Olson, 2002), Geologic cross sections shown in Figures 2.5.3 through 2.5.6 depict the stratigraphic relationship of the Cretaceous and Permian formations with the overlying Tertiary igneous units. For purposes of this model, this layer is assumed to be 2,000 feet thick and contain three lithologic units (Figures 2.5.3 through 2.5.6).

The Cretaceous unit comprises all Cretaceous rocks up to 2,000 feet below the base of the Tertiary igneous rocks (model layer 2). In places the Cretaceous is less than 2,000 feet thick, and appears to be absent from a small area in northern Presidio County. The lithology is primarily limestone with varying amounts of sandstone and shale. The porosity and permeability vary considerably, but the Cretaceous rocks are not believed to contain significant aquifers within the model boundary.

The Permian carbonates are a subsurface continuation of the reef and platform carbonates exposed in the Apache Mountains. Restricted to the northeastern portion of the model area, the carbonates are mainly dolomites with good to excellent porosity and permeability.

The Permian clastics are mainly sandstones and shales, with minor amounts of limestone and represent basin fill of the Marfa Basin. They occur south of and extend northward under the Permian Carbonates. The Permian Clastics are not believed to contain significant aquifers.

5.0 CONCEPTUAL MODEL OF FLOW IN THE IGNEOUS AND SALT BASIN BOLSON AQUIFERS

Chapters 2 through 4 document and summarize available hydrologic and hydrogeologic data for the study area. While it is evident that there is still much to learn about the aquifer system, the assimilated data provide a foundation for developing a more quantitative understanding of the aquifers and a numerical model that can be improved as more data become available.

A groundwater conceptual model of an aquifer represents the foundation for the numerical model. The conceptual model describes the basic structure of the flow system, the hydrologic processes that are important to the water budget of the system, the occurrence and movement of groundwater, and the inflow and outflow components. Anderson and Woessner (1992) describe a conceptual model as a pictorial representation of the groundwater flow system, frequently in the form of a block diagram or a cross section. The conceptual model for the Igneous and Salt Basin Bolson aquifers provides a regional perspective of the aquifer system dynamics, which is consistent with the objectives of the IBGAM.

Figure 5.1 shows two different depictions of the conceptual model for the IBGAM. The top diagram shows the relationship between the three major hydrostratigraphic units in the aquifer system in a block-form schematic and the lower diagram shows the relationships in cross-section form. Both diagrams show the three aquifers that are a part of the flow system: the Bolson aquifer, the Igneous aquifer, and Cretaceous-Permian hydrogeologic units. In some parts of the study area, the Bolsons lie on top of the Igneous aquifer and in other areas, they lie on the Cretaceous and Permian aquifers. All of the hydrostratigraphic units are connected and under natural conditions, the combination of the driving force caused by higher heads in recharge areas, variable hydraulic properties, and the location of discharge areas determines groundwater movement. Aquifer pumping may also influence flow direction.

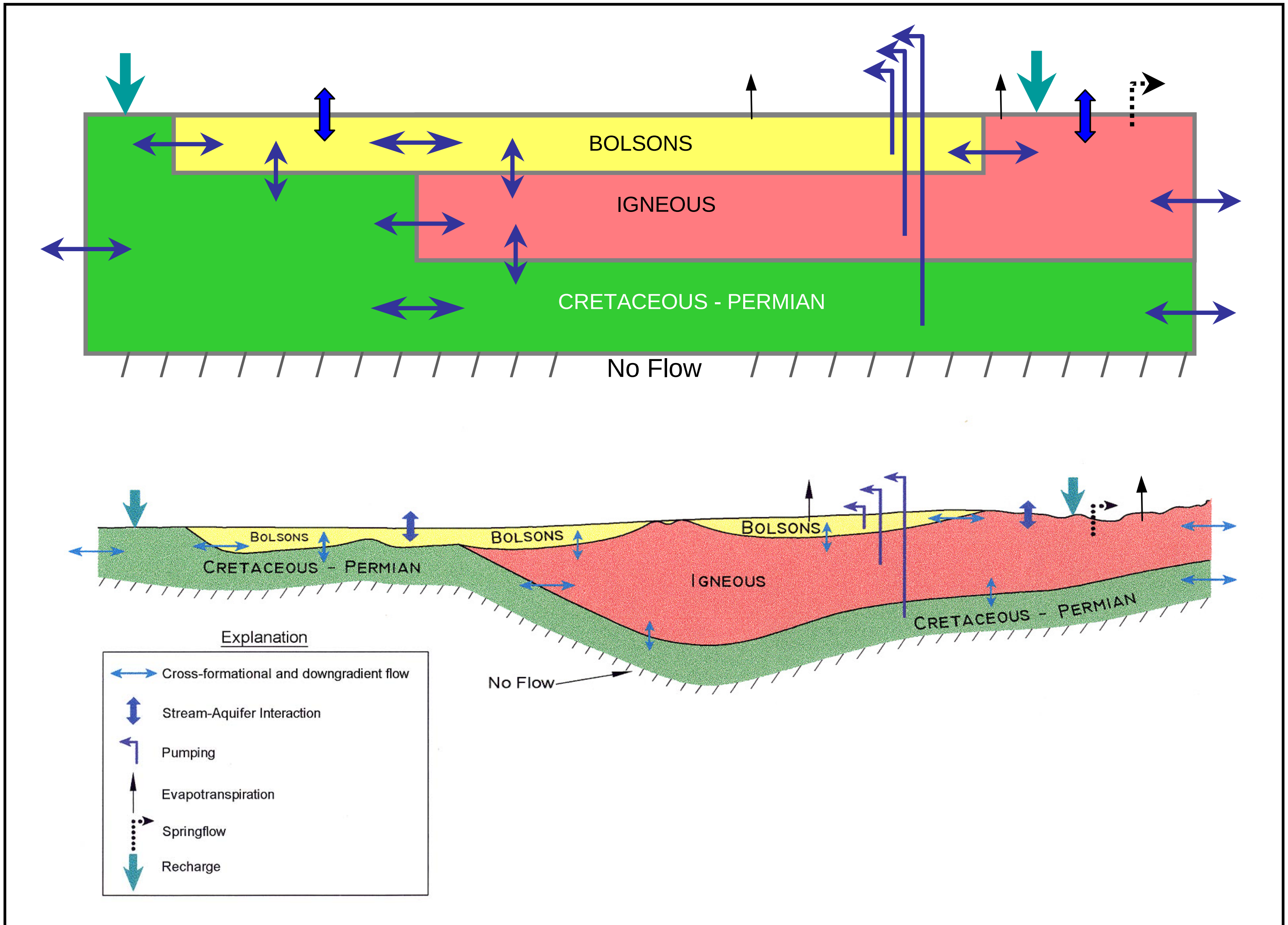


Figure 5.1 Schematic conceptual model for the IBGAM

The assessment of recharge in the study area is based on the distribution of recharge and the understanding of groundwater flow between the various hydrostratigraphic units. Direct recharge to the Igneous aquifer moves downward through volcaniclastics and fractured rocks until it reaches a lower permeability layer. The combination of lower permeability units and perennial recharge is evidenced by the higher water levels in the Davis Mountains and other areas. Some of the water that recharges the Igneous aquifer is lost from the aquifer system as evapotranspiration, streamflow, and pumping. A portion of the recharge moves laterally, and some of it discharges as groundwater underflow to the Salt Basin Bolson aquifer, to other rocks of higher permeability, or as spring flow outside the model area.

Direct recharge to the Igneous, Cretaceous and Permian aquifers may constitute a significant portion of the recharge to the study area, and likely accounts for base flow in the perennial streams and deep circulation of groundwater through regional Cretaceous and Permian aquifers; similar to those discussed by Sharp (2001). Infiltration of storm-water runoff occurs in streambed alluvium and on alluvial fans along the perimeter of the bolson. The infiltration of runoff accounts for the majority of recharge to the bolson and shallow alluvial systems adjacent to the Igneous aquifer.

The hydraulic properties and the variability of these properties throughout the system also play a role in determining the movement of groundwater. In addition, the hydrogeologic structural controls in the system help determine both regional and local flow components and natural discharge locations (springs and streams). Evapotranspiration is also a force in the hydrologic system and mainly impacts the water budget of the unsaturated zone (above the water table) and functions to limit recharge to a small percentage of precipitation. In a few areas where the water table is close to land surface, direct evapotranspiration from the water table may be a factor in the saturated zone water budget on a local level. Significant pumping, which began around 1950, and the associated hydraulic head response provides some insight into how the aquifer system will respond to future pumping.

6.0 MODEL DESIGN

A numerical groundwater flow model uses a computer code to simulate groundwater flow based on data developed for the conceptual model. Design of the numerical model consists of choosing a computer modeling code, developing a model grid (horizontal extent and vertical layers), assigning model parameters and stresses, and determining boundary conditions, types and values in the model grid. Each of these components of model design and their implementation are described in this section.

6.1 Code and Processor

The TWDB selected the MODFLOW-96 (Harbaugh and McDonald, 1996) to be used for the Igneous and Salt Basin Bolson GAM. MODFLOW-96 is a multi-dimensional, finite-difference, block-centered, saturated groundwater flow code which is supported by a variety of boundary condition packages to handle recharge, drainage, ET, and wells, as well as other packages which were not employed in the Igneous and Salt Basin Bolson GAM streams (Prudic, 1988), and reservoirs (Fenske and others, 1996). Some of the benefits of using MODFLOW are (1) MODFLOW is the most widely accepted groundwater flow code in use today, (2) MODFLOW was written and is supported by the United States Geological Survey (USGS) and is public domain, (3) MODFLOW is well documented (McDonald and Harbaugh, 1988; Harbaugh and McDonald, 1996), (4) there are a several graphical user interface programs written for use with MODFLOW, and (5) MODFLOW has a large user group.

As required by the TWDB, LBG-Guyton Associates has developed the MODFLOW data sets to be compatible with Processing MODFLOW for Windows (PMWIN) Version 5.3 (Chiang and Kinzelbach, 1998). The model was developed and executed on x86 compatible (i.e. Pentium class) computers equipped with the Windows 2000 or XP operating system. The type of computer and memory required to use the model will vary depending on the type of pre- and post-processing software used.

6.2 Model Layers and Grid

Based on the conceptual hydrostratigraphy described in Section 4 and the conceptual flow model detailed in Section 5, three model layers were used in the Igneous and Salt Basin Bolson GAM model. Each of the model layers is described below in the order in which MODFLOW-96 numbers the model layers, which is from top (nearest to ground surface) to bottom.

Layer 1 represents the Salt Basin Bolson aquifer, layer 2 represents the Igneous aquifer, and layer 3 represents the underlying Cretaceous and Permian units. The model layers are shown with the model hydrostratigraphy in Figures 2.5.3 through 2.5.6 and in Figure 5.1. In the area north of the extent of the Igneous aquifer (mainly in Culberson County), the model assumes that the Igneous aquifer is one foot thick to allow vertical communication between the Salt Basin Bolson aquifer (layer 1) and the underlying Cretaceous and Permian units (layer 3).

As shown in Figure 6.2.1, a rectangular grid covers the model area. The model area is bounded laterally on the north by the Victorio flexure and the associated groundwater divide that has developed due to pumping in the Wild Horse Basin east of Van Horn. The southern boundary of the model is defined by a groundwater divide associated with the East-West fault and the associated Torneros Creek north of the Rio Grande in Presidio County.

MODFLOW-96 requires a rectilinear grid and also requires an equal number of rows for all columns. One axis of the model grid is typically aligned parallel to the primary direction of flow. Because of the radial flow from the highest elevations in the Davis Mountains and the variations in the orientation of the Salt Basin Bolson aquifers, this was difficult to do for this model. However, the model was rotated and aligned with the primary direction of flow in Ryan Flat and along some of the major structural features in the model area. The grid was also oriented to minimize the number of model grid cells. The model grid origin (the lower left-hand corner of the grid) is located at GAM coordinates (3593650, 18997700), and rotated 30 degrees counterclockwise.

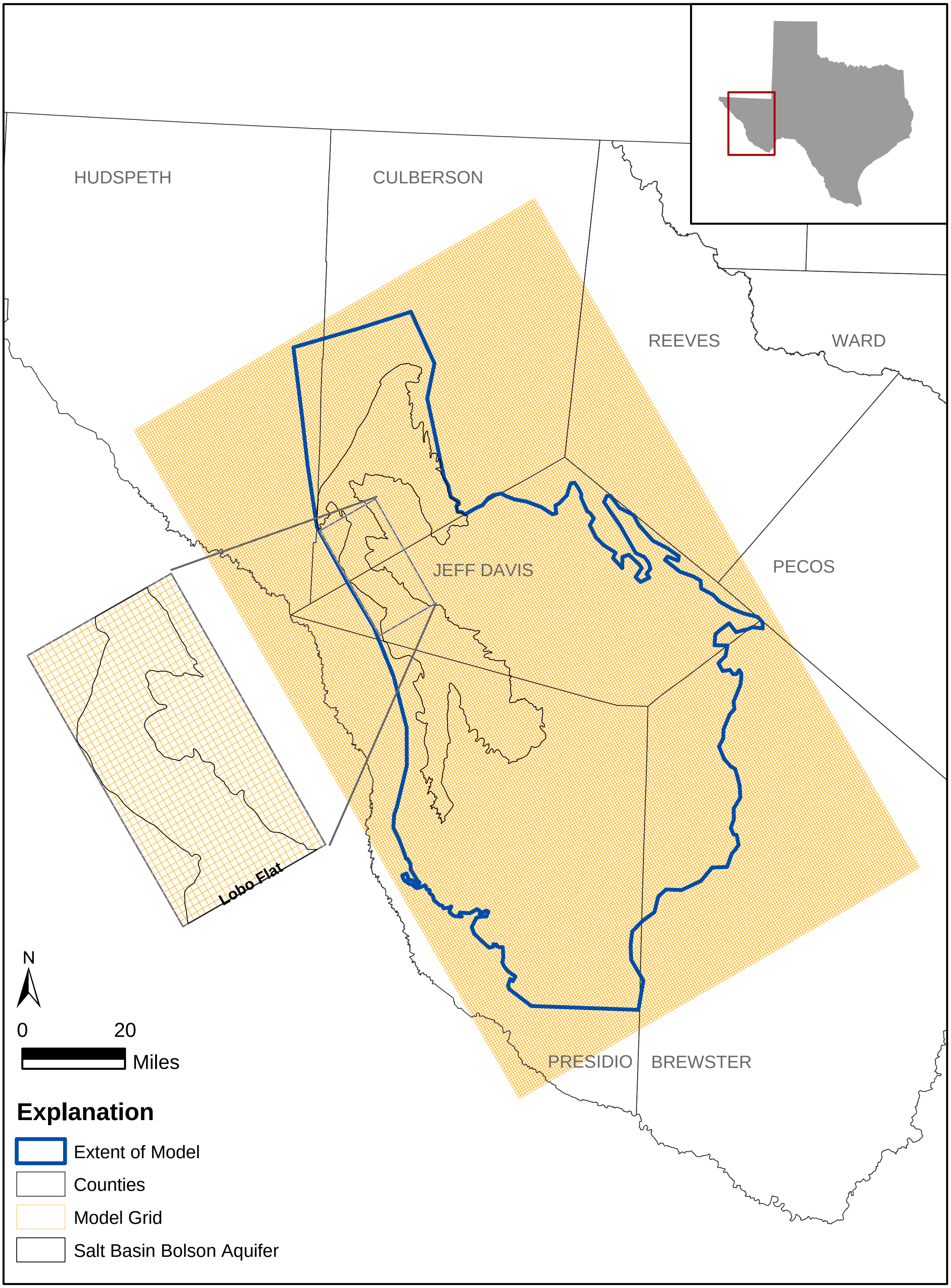


Figure 6.2.1 - Model Grid

The grid cells are square with a uniform dimension of ½-mile on each side and contain ¼ square miles or 160 acres. The model has 300 rows and 180 columns, totaling 54,000 grid cells per layer. Only those cells overlaying part of the aquifer that the layer represents have to be active cells. Figures 6.2.2, 6.2.3, and 6.2.4 show the active cells in layers 1, 2, and 3, respectively. Layers 1, 2, and 3 contain 3,127, 25,512, and 25,190 active cells, respectively, totaling 53,829 active cells for the entire model.

Active cells in layer 1 do not extend to the full extent of the Bolson aquifer in some areas because some of the cells on the southern extent have a relatively small saturated thickness (generally less than 50 feet). These cells continually caused problems during model calibration because they would cause instabilities for the MODFLOW solvers. Therefore, to avoid this problem, many of the cells with small saturated thickness were inactivated. Recharge from stormwater runoff in these areas was automatically applied (by MODFLOW) to the highest active layer, which was layer 2.

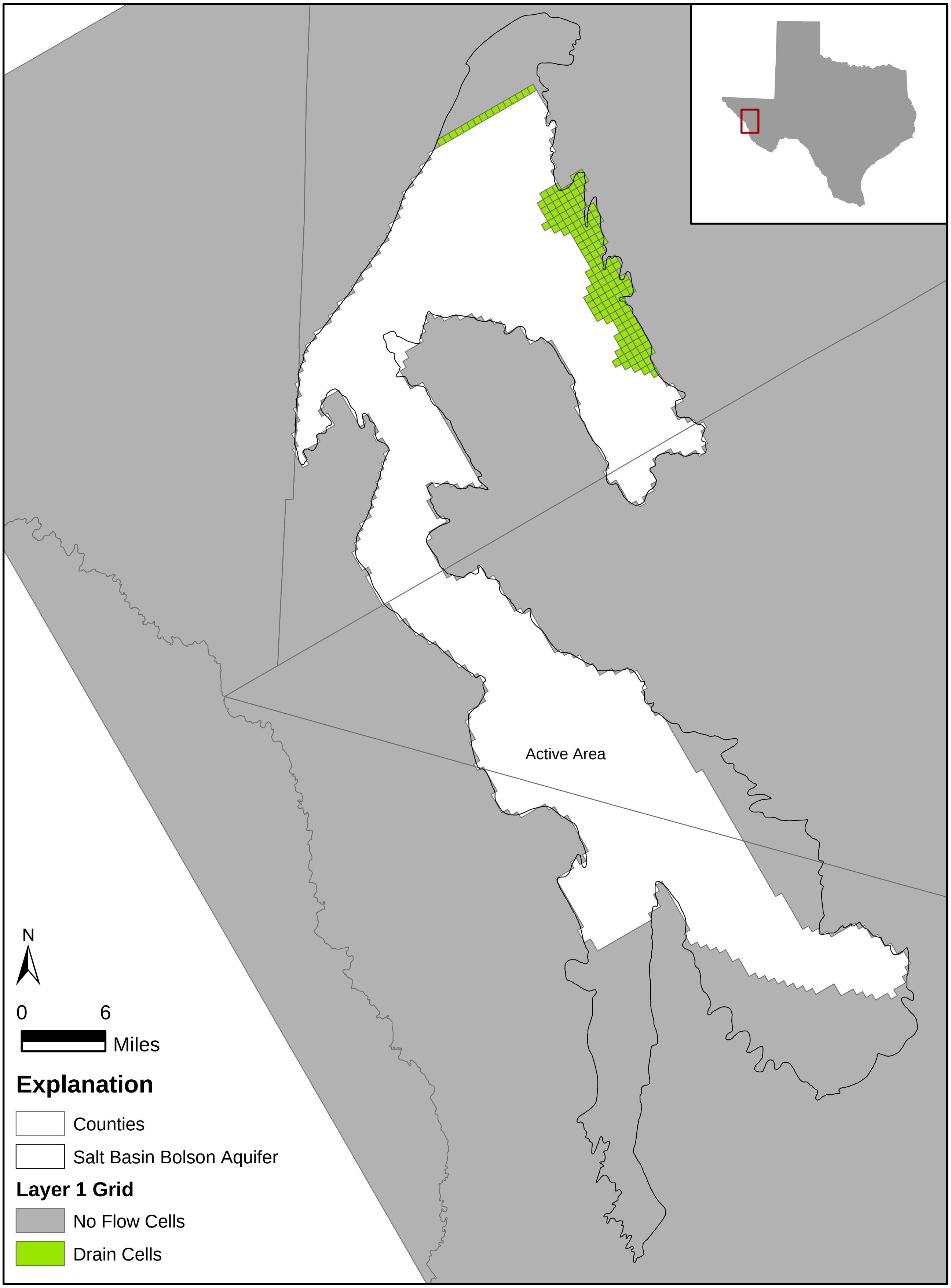


Figure 6.2.2 - Active Cells and Boundary Conditions in Layer 1

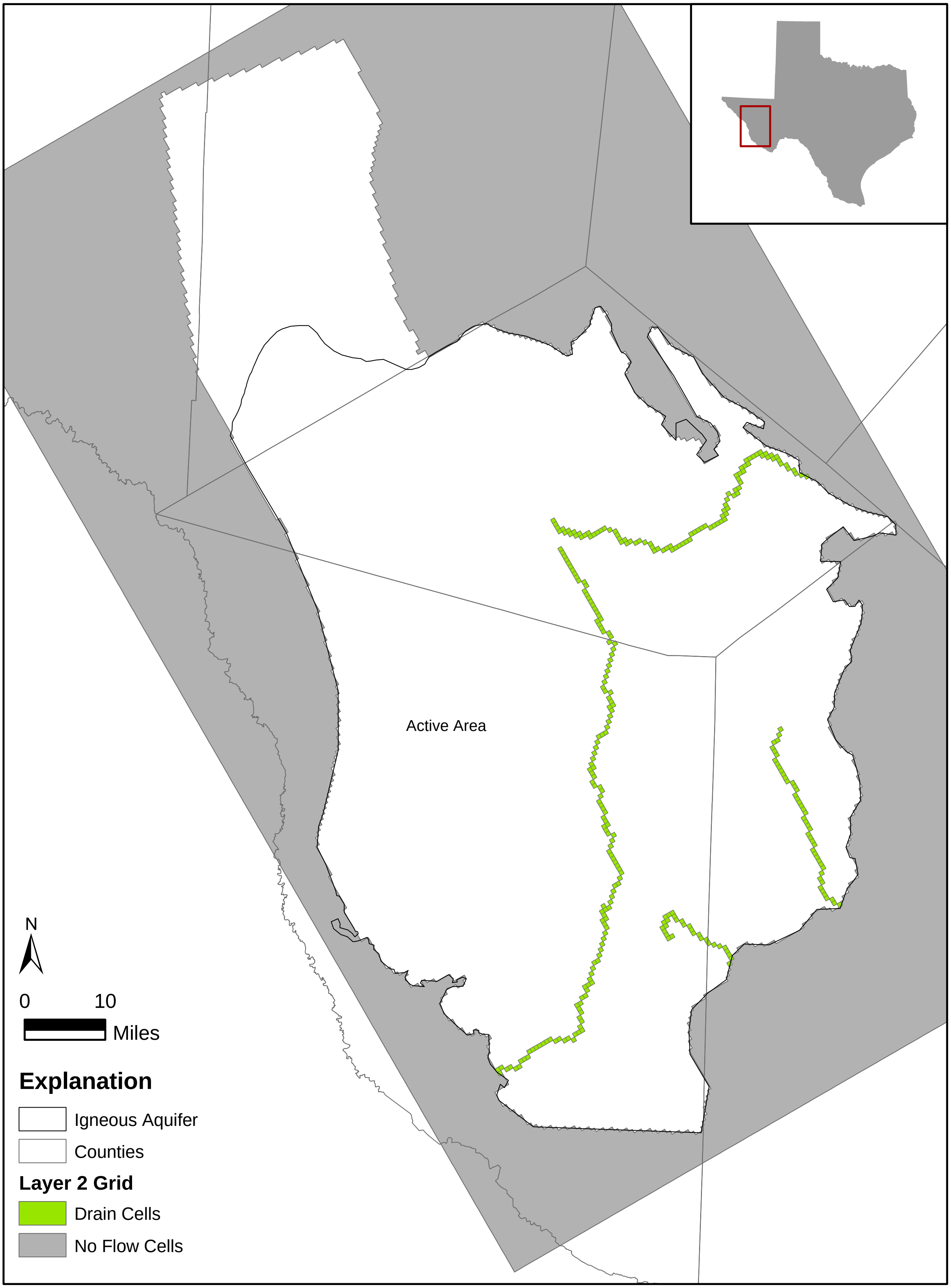


Figure 6.2.3 - Active Cells and Boundary Conditions in Layer 2

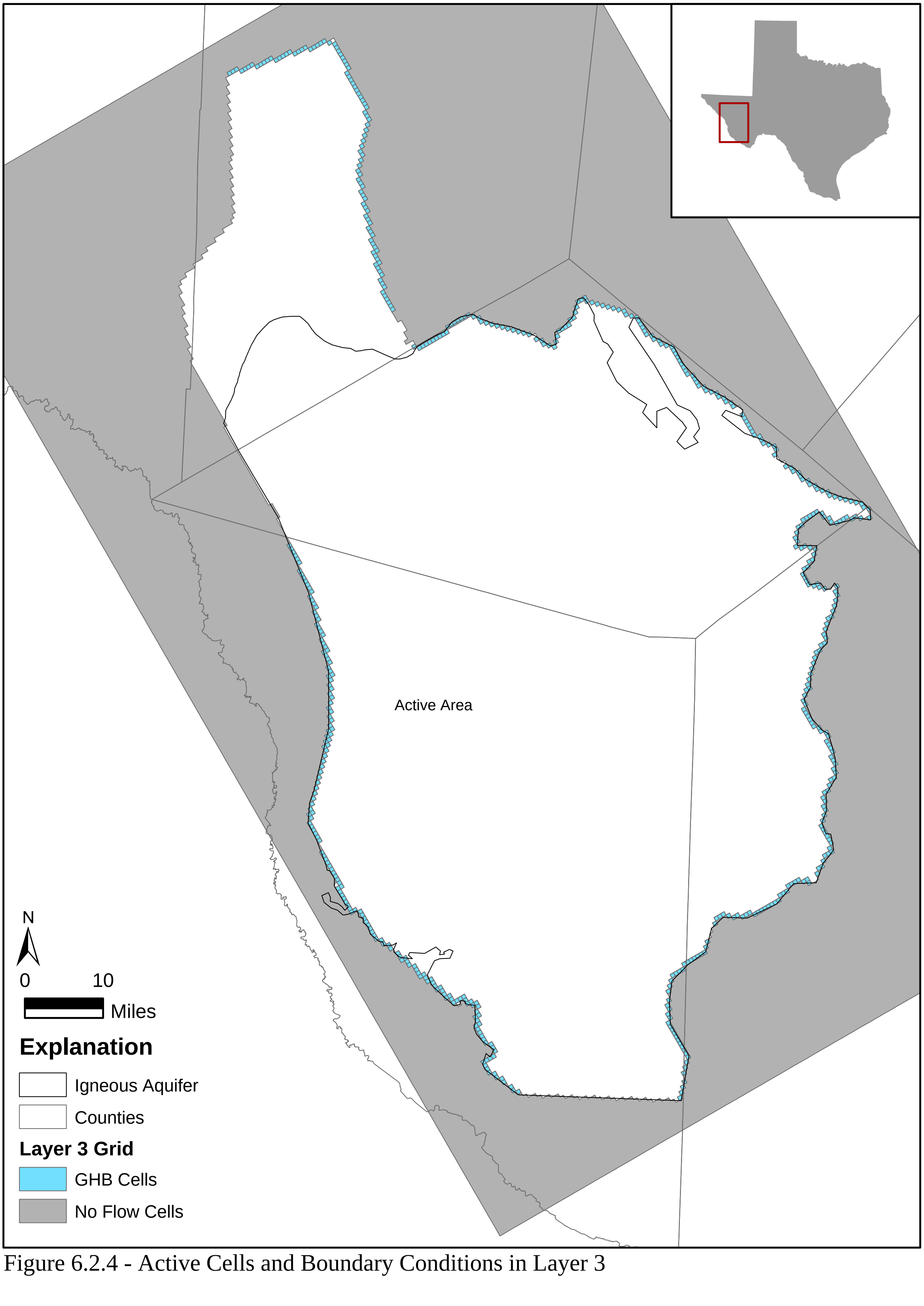


Figure 6.2.4 - Active Cells and Boundary Conditions in Layer 3

6.3 Boundary Condition Implementation

Boundary conditions constrain a model by representing physical components in the system such as wells, evapotranspiration, or cross-formational flow. Boundary conditions are also used to permit the interaction between the active simulation grid domain (modeled area) and the hydrologically connected system surrounding the model area. Anderson and Woessner (1992) identify three general types of boundary conditions; specified flow, specified head, and head-dependent flow. Boundaries can be steady (does not change with time) or transient (does change with time). In MODFLOW, a stress period of time over which it is assumed that boundary conditions in the model are steady and do not change appreciably. Within a given stress period, there may be many computational time steps. Based on the level of data available in the model area regarding pumping rates, precipitation, measured water levels, and other hydrologic conditions, the stress period was set equal to one year.

6.3.1 Lateral Boundaries

Based on the conceptual model developed for the Igneous and Salt Basin Bolson aquifers, it was necessary to define lateral boundary conditions which allow hydrologic communication with the other aquifers in the area. The Cretaceous and Permian units represented by layer 3 were connected to areas outside the model area by head-dependent boundary conditions. The lateral connection between the Igneous and the Salt Basin Bolson aquifers were simulated by allowing flow to pass through the active grid blocks in layer 1 and 2. This does not require any specified boundary condition. In this case, the amount of lateral flow between the aquifers is governed by hydraulic properties assigned to the active grid blocks that connect the two aquifers. The same applies to layers 2 and 3.

6.3.2 Vertical Boundaries

A no-flow boundary is assumed for the base of layer 3. This is consistent with the conceptual model, which assumes that the amount of flow across the bottom the Cretaceous and Permian aquifers is insignificant in relation to water planning scenarios at this time.

6.3.3 Streams and Springs

Although it is relatively dry in the model area, there are some streams and springs which have been incorporated into the model in the Igneous aquifer. Head-dependent drain boundary conditions were used to incorporate the loss of groundwater to streams and springs. Drain boundaries are a simplified approach to simulating the interaction between groundwater and surface water because drains allow water to be removed from the groundwater system, but they don't allow water in a stream to flow downstream to locations where the stream naturally adds water to the aquifer. This limitation does not significantly impact the model because the flow to streams and springs is a relatively small portion of the overall water budget.

6.3.4 Recharge

As discussed in Chapter 4, initial estimates of recharge were based on the results of a recharge-redistribution analysis that is detailed in Appendix B. In general, recharge estimates (using methods similar to the runoff-redistribution) for regional modeling studies have resulted in recharge values slightly greater than those obtained from final model calibration. As discussed in Chapter 4, similar applications of this methodology to arid settings have resulted in over-predicting model recharge. Based on the published work discussed in Chapter 4, the recharge estimates from the recharge-redistribution method were scaled by a factor of 0.60 to get an estimate of initial recharge. The spatial distribution of the recharge was not modified from the original assessment.

Normally, recharge in a regional system is a very sensitive parameter. However, because of the limited connection between the Igneous and Bolson aquifers in the model and because the Bolsons do not receive any direct recharge from precipitation, the sensitivity of the Bolson layer is somewhat muted because most of the recharge is received by the Igneous layer. Because there was very little historic water level data in the Igneous, it was difficult to calibrate the model based to recharge because most of the recharge to the Igneous is lost to evapotranspiration and streams. Therefore, changes in recharge are inversely offset by changes in evapotranspiration and streamflow.

6.3.5 Pumping Discharge

Estimation and implementation of pumping is important in model development because it represents a stress similar in nature and magnitude to the stresses the model is being developed to simulate. Historical pumping and the observed changes in the aquifer due to that pumping offers some of the best available historical data from which to develop a useful model. For this reason, we assumed that the predevelopment period was prior to 1950 because that is about the time that pumping began and some corresponding water level measurements were collected.

The methodology and data used to estimate and allocate pumping are summarized in Section 4.1.7 and 4.2.7, and are described in detail in Appendix C. Because the stress period length used in the transient simulations was one year, all pumping was averaged throughout the year, and seasonal impacts were not accounted for in the model.

6.4 Hydraulic Properties

Hydraulic conductivity is one of the most important parameters to be estimated and distributed across the model because in part, it determines how fast water will flow in the system. The storage coefficient is important in determining the rate of water level change when the aquifer is pumped.

6.4.1 Hydraulic Conductivity

The first step in estimating hydraulic conductivity is to compile the existing estimates. As discussed in Sections 4.1.6 and 4.2.6, there is a small number of hydraulic conductivity estimates for the Bolson and Igneous aquifers. In determining the utility of locally determined hydraulic conductivity estimates (generally, from pump and specific capacity tests), it is important to consider the nature of the aquifer and the type of rocks which make up the aquifer. Although a pumping test can be used to estimate local scale hydraulic conductivity, it is still small in scale by comparison regional flow systems. The effective hydraulic conductivity which is incorporated into the model depends on the geometry, hydraulic conductivity, and the scale at which variations in hydraulic conductivity occurs.

In the model development process, it was assumed that the available Bolson hydraulic conductivity and transmissivity data, or interpreted hydraulic conductivity data, typically represent the highest permeability porous media tested and that these estimates could be used as a guide for estimating effective model hydraulic conductivity. However, direct estimates of vertical hydraulic conductivity meaningful to the general modeling process are almost never available, and that is true for this study. The distribution and estimated values of vertical hydraulic conductivity for the model, while guided by available data, are usually determined mainly through the model calibration process. This can lead to non-unique parameterization and may introduce potentially a large degree of uncertainty into the model's results. The type and amount of available calibration data (water level measurements and discharges) and the degree to which it is implemented usually determine the degree of success in reducing this uncertainty. For this study, there was very little information regarding vertical head differences in the different aquifers being simulated. This lack of data is not uncommon, but it does hinder the model calibration process.

The Igneous aquifer is a complex fractured and layered system. Hydraulic conductivity estimates from short duration pumping tests are very helpful in estimating local scale hydraulic conductivity, but the estimates are likely to be biased toward high values for several reasons. First, pumping tests are not performed in "dry boreholes". Second, pumping tests are usually not performed in wells which don't produce much water. These biases are enough to skew the estimates of hydraulic conductivity. In addition, the connection of the fracture network on a regional basis is unknown, and many surface water and groundwater interactions are controlled by local faults and fractures. These local structures are not represented in the data or the conceptual model, nor can they be incorporated into the numerical model at the regional scale. Therefore, estimates of hydraulic conductivity in the Igneous aquifer are biased toward high values and were decreased in the model.

There are portions of the aquifers that exhibit horizontal anisotropy in the hydraulic conductivity tensor. For the IBGAM project, these considerations were not necessary to achieve relatively good calibration and reasonable results. In addition, because the fracture density in the Igneous is assumed to be higher in the upper portion of the aquifer, anisotropy may be overestimated if it applied to the current single-layer representation of the Igneous aquifer. It would be more appropriate to incorporate anisotropy in a model that uses more than one layer to represent the Igneous aquifer.

6.4.2 Storativity

As discussed in Section 4.2.6, several estimates of storativity are based on pumping tests in the Igneous aquifer. These data are probably reasonable estimates of confined storage properties and are used as a guide in calibrating the model. Specific yield estimates in the Salt Basin Bolson aquifer are based on pumping tests and modeling studies and are considered as relatively reliable information that can be used in model calibration.

7.0 MODELING APPROACH

Calibration of a groundwater flow model is the process of adjusting model parameters until the model reproduces field-measured values of water levels (heads) and flow rates. Successful calibration of a flow model to observed heads and flow conditions is usually a prerequisite to using the model for prediction of future groundwater availability. Parameters that are typically adjusted during model calibration are hydraulic conductivity, storativity, and recharge. Model calibration typically includes completion of a sensitivity analysis and a verification analysis. Sensitivity analysis entails running the model with a systematic variation of the parameters and stresses in order to determine which parameter variations produce the most change in the model results. Those parameters which change the simulated aquifer heads and discharges the most are considered important parameters to the calibration. The sensitivity analysis guides the process of model calibration by identifying potentially important parameters but does not in itself produce a calibrated model. Model verification is another approach used to determine if the model is suitable for use as a predictive tool. Verification is using the model to predict aquifer conditions during a time period that contains different observed data than was used for the model calibration.

7.1 Calibration and Verification

7.1.1 Approach

Groundwater models are inherently non-unique. Non-uniqueness refers to the characteristic of a model that allows many combinations of hydraulic parameters and aquifer stresses to reproduce measured aquifer water levels. To reduce the impact of non-uniqueness on model results, several approaches were used. Where possible, the model incorporated parameter values (i.e., hydraulic conductivity, storativity, recharge) that were consistent with measured values. In addition, a relatively long calibration period was selected to incorporate a wide range of hydrologic conditions and the verification period entailed simulation of different time periods. Finally, to the degree possible, two different calibration performance measures, hydraulic heads, and aquifer flowrate, were used to reduce non-uniqueness in the model.

Initially, hydraulic conductivity and storativity values in each layer of the model were assumed to be a homogeneous and were based on representative values from the data presented in Chapter 4. Initial hydraulic conductivity estimates for layers 1, 2, and 3 were 10, 1, and 5 ft/day, respectively. As mentioned in Chapter 6, there are no available measurements of vertical hydraulic conductivity. Therefore, vertical hydraulic conductivity was estimated based on professional judgment. The initial specific yield value for the Bolson aquifer was 0.10. The initial storativity value for layers 2 and 3 was $3x10^{-5}$. Modifications to initial estimates of the hydraulic properties during the calibration process, to the degree possible, were based on measured data where it was available. Initial estimates of recharge were based on the redistribution method as discussed in Section 6.3.

Initial heads in each model layer were based on the estimated potentiometric surfaces presented in Chapter 4. A few changes were made around the eastern side of Wild Horse Flat and the perimeter of the Igneous aquifer. The model contained a long transient stress period to represent the predevelopment period, which allows the model to come to equilibrium (steady-state) based on hydraulic properties and model boundary conditions. Therefore, these initial heads do not have an impact on the simulated steady-state heads.

Model parameters were held to within reasonable ranges during calibration based on available data and relevant literature. Adjustments to parameters from initial estimates were minimized to the extent possible to meet the calibration criteria. As a general rule, parameters that have few measurements were adjusted preferentially as compared to parameters that have a good supporting database.

The model was calibrated for two hydrologic conditions, one representing steady-state conditions (i.e., prior to major pumping) and the other representing transient conditions after pumping started. There is very little, if any water-level data available prior to development of the Igneous and Salt Basin Bolson aquifers. However, there are a few water-level measurements around 1950, which is about the time that significant pumping began to occur in the Salt Basin, specifically in Lobo Flat. Therefore, 1950 was selected as a time representative of "predevelopment" conditions and the water-level measurements from that time period were used to calibrate the steady-state model. Historical records indicate that significant pumping started in the late 1940's; therefore no pumping stresses were applied to the predevelopment model. The final predevelopment water levels from the steady-state model were then used as the initial water levels for the calibration period, which was from 1950 to 1990. The transient verification period ran from 1991 through 2000. All stress periods during the calibration and verification period were one year long because that was the resolution of most of the pumping estimates. Table 7.1 summarizes the stress periods used in the model.

Table 7.1 Summary of calibration and verification stress periods

Date	Model Period	Number of Stress Periods	Length of each Stress Period (years)
Pre-1950	Steady-state	1	27378
1950-1990	Transient Calibration	41	1
1991-2000	Transient Verification	10	1

The advantage of calibrating the model to 41 years of historical data is that this period incorporates a wide range of hydrological and pumping conditions. The goal of the steady-state predevelopment model was to simulate a period of equilibrium where aquifer recharge and discharge are equal. The goal of the transient calibration was to adjust the model to appropriately simulate the water-level changes that were occurring in the aquifers due to pumping. The steady-state and transient model periods may show sensitivity to different parameters.

7.1.2 Calibration Targets and Measures

In order to calibrate a model, targets and calibration measures must be developed. The primary type of calibration target is hydraulic head (water level). Table 7.2

summarizes the available water level measurements for the steady-state and transient model periods.

Table 7.2 Summary of the number of calibration and verification head targets

Layer	Steady-state	Calibration & Verification	Total
Bolson	53	1193	1246
Igneous	1	423 *	424
Cretaceous	54	1616	1670

* - Includes 245 geographically distributed measurements from 2000-2001

To address the issue of non-uniqueness, it is best to use as many types of calibration targets as possible. Therefore, to the degree possible, average stream-flow measurements and gain-loss estimates along Limpia Creek near Fort Davis were also used. Simulated heads were compared to measured water levels in wells through time (hydrographs) and head distribution maps.

Model calibration is judged by quantitatively analyzing the difference (or residual) between observed and model computed (i.e., simulated) values. Several graphical and statistical methods are used to assess the model calibration. These statistics and methods are described in detail in Anderson and Woessner (1992). The mean error is defined as:

$$ME = \frac{1}{n}\sum_{i=1}^{n} (h_m - h_s)_i \qquad 7.1$$

where:

h_m is measured hydraulic head, and

h_s is simulated hydraulic head, and

$(h_m - h_s)$ is known as the head error or residual.

A positive mean error (ME) indicates that the model has systematically underestimated heads, and a negative error, the reverse. It is possible to have a mean error near zero and still have considerable errors in the model (i.e., errors of +50 and -50 give the same mean residual as +1 and -1). Thus two additional measures, the mean absolute error and the root mean square of the errors, are also used to quantify model goodness of fit. The mean absolute error is defined as:

$$MAE = \frac{1}{n}\sum_{i=1}^{n} \left|(h_m - h_s)_i\right| \qquad 7.2$$

and is the mean of the absolute value of the errors. The standard deviation (SD) of errors or root mean squared (RMS) error is defined as:

$$RMS = \left[\frac{1}{n}\sum_{i=1}^{n} (h_m - h_s)_i^2 \right]^{0.5} \qquad 7.3$$

A large SD means that there is wide scattering of errors around the mean error.

These statistics were calculated for the calibration and verification period. In addition, the distribution of residuals was evaluated to determine if they are randomly distributed over the model grid and not spatially biased. Head residuals were plotted on the simulated water-level maps to check for spatial bias. Scatter plots were used to determine if the head residuals are biased as compared to the observed head surface.

7.1.3 Calibration Target Uncertainty

Groundwater elevation measurements have an inherent error component due to several factors, including measurement error, instrument error, sampling scale limitations, and recording errors. In order to know when the model calibration is acceptable, a level of reasonable uncertainty in the observed head data should be recognized and estimated. This uncertainty in observed data provides some guidance regarding setting calibration goals to avoid over-calibrating the model. Over-calibration of a model occurs when parameters are modified too much in order to match observed conditions.

The TWDB GAM standard for calibration criteria for head is an RMS less than or equal to 10% of head variation within the aquifer being modeled. Head differences across the Salt Basin Bolson aquifer are about 900 feet. Head differences across the Igneous aquifer are about 3000 feet. This leads to an acceptable RMS of about 300 feet for the entire model, and about 90 feet for the Bolsons. This RMS can be compared to an estimate of the head target errors to consider what level of calibration the underlying head targets can support.

Although they can vary significantly, measurement errors in water levels are usually tenths of feet, and are considered insignificant at the scale of the Igneous and Bolsons aquifers model. However, estimates of measuring point elevation can be significant because these data are sometimes estimated from topographic maps based on the estimated location of the well. These data can easily be 5 to 20 feet in error, and sometimes more in mountainous areas.

Converting highly variable ground-surface elevations into a single value in each model gridblock can also cause significant errors. The digital elevation data for the model area are available on a 30-meter grid and are averaged to a model grid block that is a half-mile wide, resulting in averaging errors that can range from 10 feet in relatively flat areas to more than 100 feet in areas with higher topographic relief, such as the Davis Mountains.

Another conceptual translation error arises when complex lithology is assumed to be adequately represented by a single grid block. This type of simplification may occur for the Igneous and the Salt Basin Bolson aquifer units and therefore, the simulated head for those layers contain some potential error because the simulated water level is “vertically averaged” as opposed to the water level in individual zones in which the wells are screened and the water levels are measured. The magnitude of this error is difficult to quantify, but could range from a relatively small value in areas that have good vertical connection to a significantly larger error in areas that have poor vertical connection.

Accumulation of all these potential errors provides an estimate of the error in the simulated heads, and ranges from about 15 to more than 120 feet. Because of the simplification of the Igneous aquifer into a single model layer, it is expected that the largest potential errors in simulated heads are in layer 2. Because the Salt Basin Bolson aquifer generally has a relatively flat land surface and less vertical variation in hydraulic properties, errors in simulated heads in layer 1 should be smaller. Therefore, the minimum ratio of the RMS error to the range in heads was considered separately for each model layer. Based on this analysis, a minimum calibration RMS value of 15 and 120 feet was used for the Bolson and Igneous aquifers, respectively. Calibrating the model to RMS values less than 15 feet in layer 1 and 120 feet in layer 2 would potentially result in an over parameterized model. That level of parameterization was not justified by the available data and model architecture.

7.2 Sensitivity Analyses

A sensitivity analysis was performed on the steady-state and transient calibrated models to determine how changes in a calibrated parameter affect the results of the calibrated model. The sensitivity analysis was completed such that each of the hydraulic parameters or stresses was adjusted from its calibrated value by a small factor while all other hydraulic parameters were held at their calibrated values. The results of each sensitivity simulation were evaluated by calculating the average head change in the model and also by assessing the change in the hydrographs for selected wells.

7.3 Predictions

After the model was satisfactorily calibrated (i.e., the criteria for calibration and verification periods met predetermined objectives), the model was used to make predictive simulations to assess future conditions. Six predictive simulations were completed. Pumping stresses for the predictive simulations were based on predicted groundwater demands between 2000 and 2050 developed for the 2001 Far West Texas

Regional Water Plan and documented in the 2002 State Water Plan. The first predictive simulation incorporated average hydrologic conditions (i.e., recharge) from 2000 through 2050. The other predictive simulations were run from 2001 to 2010, 2020, 2030, 2040, and 2050 and incorporated the regional drought-of-record estimated recharge during the last seven years of each simulation.

8.0 STEADY-STATE MODEL

The calibration of the steady-state model involved adjusting some of the model input parameters in order to get a good fit to the observed target data. The process of calibrating the IBGAM was iterative and involved both trial-and-error approach and automated parameter estimation techniques. Because the steady-state and transient periods are contained in the same model, the parameter adjustments for the steady-state model are used in the transient model as well. This section describes the final steady-state calibration results.

8.1 Calibration

8.1.1 Calibration Targets

Very few water level measurements were collected prior to development of the Igneous and Bolson aquifers because wells were typically installed and immediately pumped. However, it was assumed that water level measurements collected prior to 1950 were useful in steady-state model calibration. Figure 8.1.1 shows the locations of the wells with water levels that were used for the steady-state calibration. As discussed in Chapter 7 and shown in Table 7.2, a total of 53 water level measurements were available in the Bolson aquifer for steady-state calibration and only one measurement was available in the Igneous aquifer.

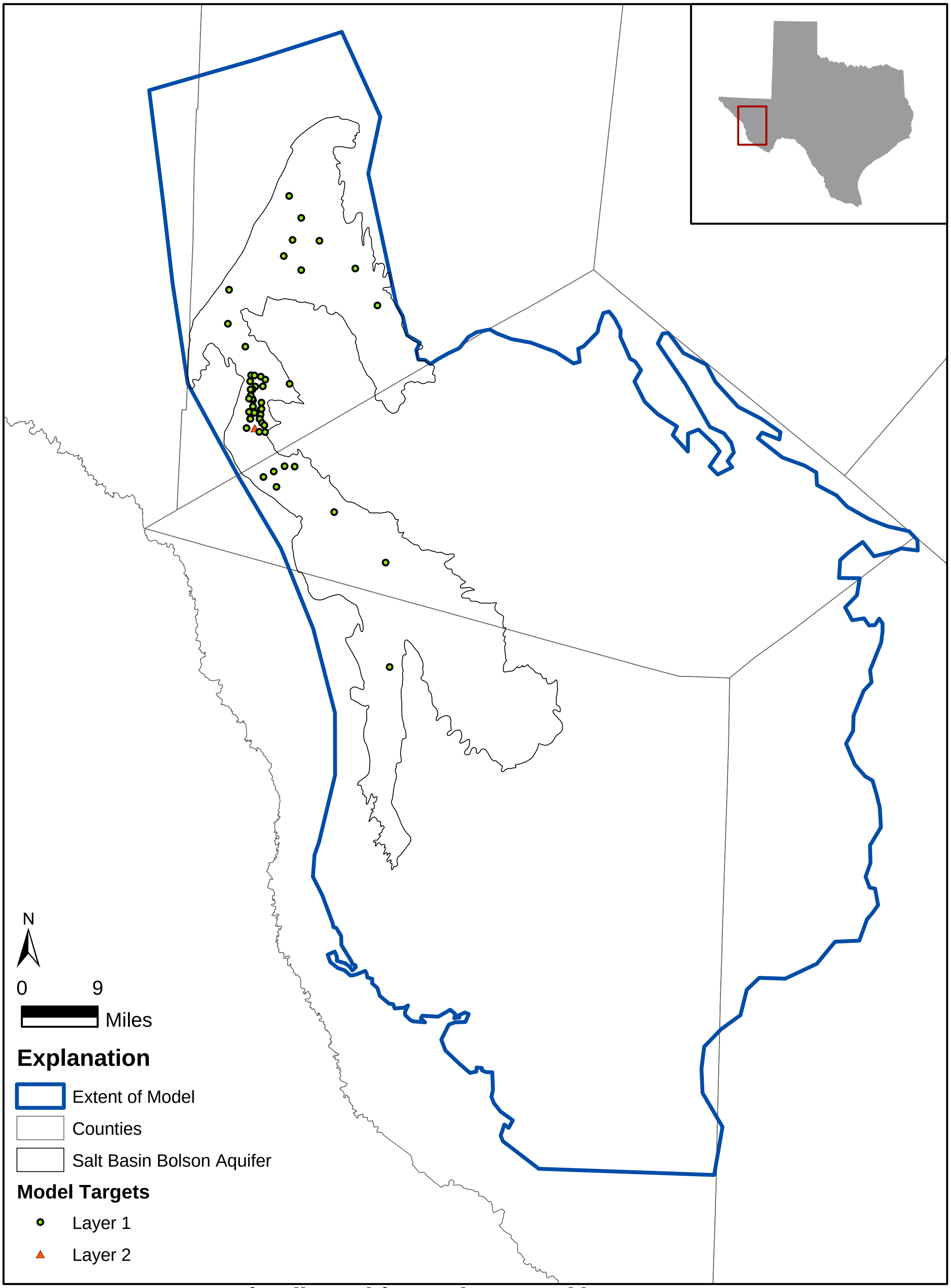


Figure 8.1.1 - Location of Wells Used for Steady-State Calibration Targets (Including Layer Designation)

8.1.2 Horizontal and Vertical Hydraulic Conductivities

The initial homogeneous distribution of hydraulic conductivity was based on the measured data as discussed in Chapter 6. During calibration, the hydraulic conductivity estimates were distributed by zones which were generally consistent with the major water producing areas of the Bolson (i.e., Ryan Flat, Lobo Flat, Wild Horse Flat, and Michigan Flat). The zoned hydraulic conductivity estimates were adjusted during the calibration period of the steady-state and transient model. Table 8.1 summarizes the range of calibrated hydraulic conductivity values used in each layer. The final distribution of hydraulic conductivity values for layer 1, 2, and 3 are shown in Figures 8.1.2, 8.1.3, and 8.1.4, respectively. Also shown on each figure is the ratio of horizontal to vertical hydraulic conductivity for each zone.

There are many reasons why the hydraulic conductivity in the calibrated model may not match measured hydraulic conductivity. First, the hydraulic conductivity estimates come from many different pumping tests and from wells that are completed differently. Second, the conceptual model and model architecture assumptions are different than the physical system, and therefore, the hydraulic conductivity used in the model may need to be different than some of the measured data. Third, most pumping tests only test a relatively small portion of the aquifer around the well, while the hydraulic conductivity in the model is usually more representative of regional conditions. Although the data from pumping tests does allow us to better understand the heterogeneity of the aquifer, it is not always advantageous (from a calibration perspective) to incorporate all the heterogeneity into regional models.

Table 8.1 Summary of hydraulic properties used in model

Layer	Horizontal Hydraulic Conductivity (ft/day)	Vertical Hydraulic Conductivity (ft/day)	Specific yield (-)	Storativity (-)
1	4 - 50	0.0001 - 0.35	0.06	---
2	0.2 - 1	0.00008 - 0.1	0.01	$3x10^{-5}$
3	0.1 - 1	0.0001 - 0.1	0.01	$3x10^{-5}$

Hydraulic conductivity in the Salt Basin Bolson aquifer varies from 4 to 50 ft/day. The Ryan Flat area was assigned a hydraulic conductivity of 5 ft/day based on compiled estimates, previous modeling studies, sensitivity analysis, and the calibration process.

The horizontal to vertical hydraulic conductivity anisotropy ratio is relatively high in Ryan Flat and the zone between Ryan Flat and Lobo Flat. The primary cause of vertical hydraulic anisotropy on a small scale is the orientation of clay minerals in sedimentary rocks and unconsolidated sediments. In the field, it is not uncommon for layered heterogeneity to lead to regional anisotropy values on the order of 100:1 or even larger (Freeze and Cherry, 1979). The high anisotropy in these areas are caused mainly by the relatively low vertical hydraulic conductivity that was necessary to prevent too much water from moving to the Bolsons from the Igneous aquifer. In other words, the steady-state calibration of heads in layer 1 and 2 was achieved by lowering the vertical hydraulic conductivity in both aquifers to "hold up" the heads in the Davis Mountains.

The area between Lobo Flat and the Van Horn area was assigned a relatively low horizontal hydraulic conductivity. This is the area where the Igneous aquifer pinches out and there are no measured hydraulic conductivity data or water level measurements.

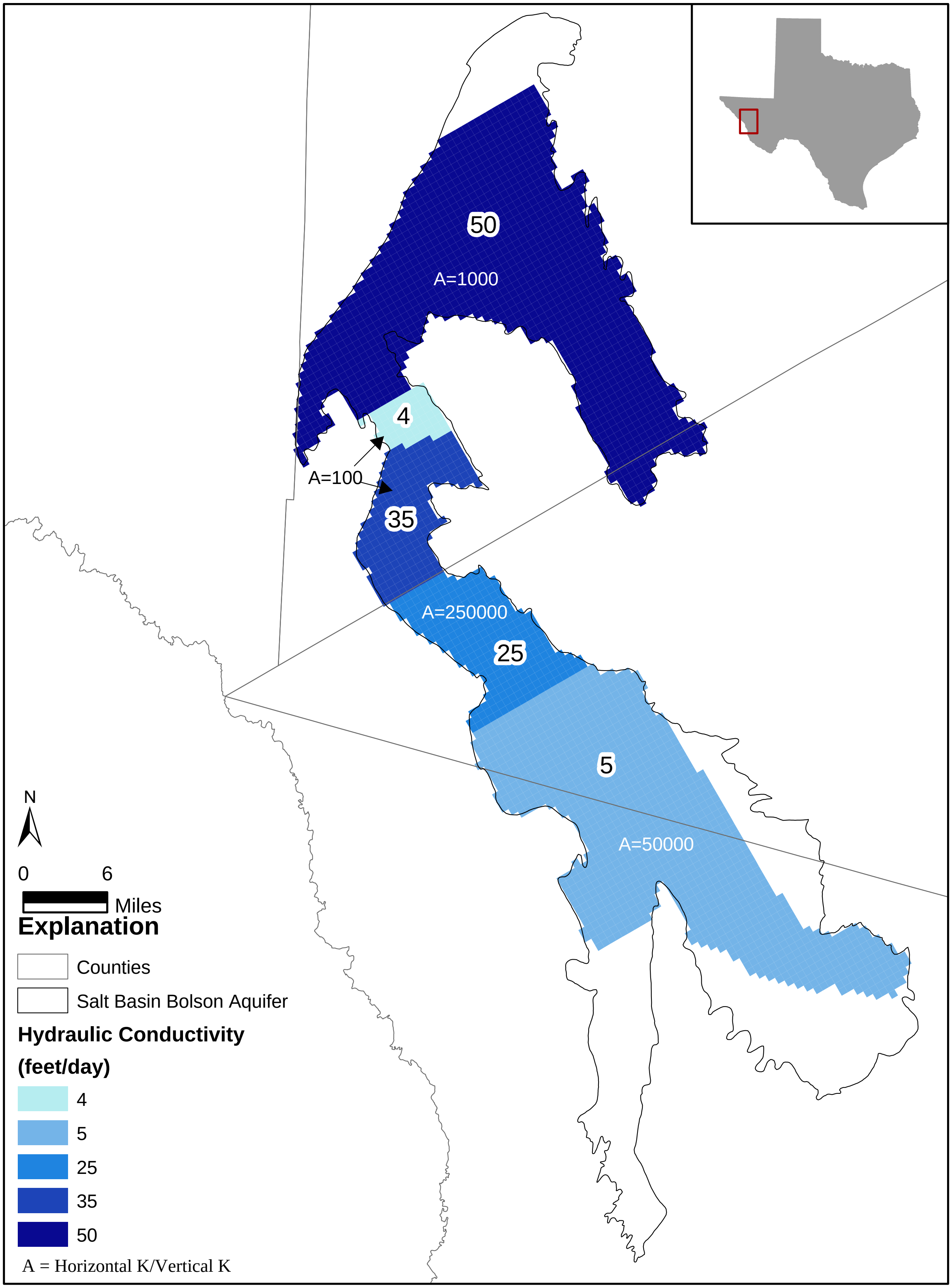


Figure 8.1.2 - Final Distribution of Hydraulic Conductivity in Layer 1

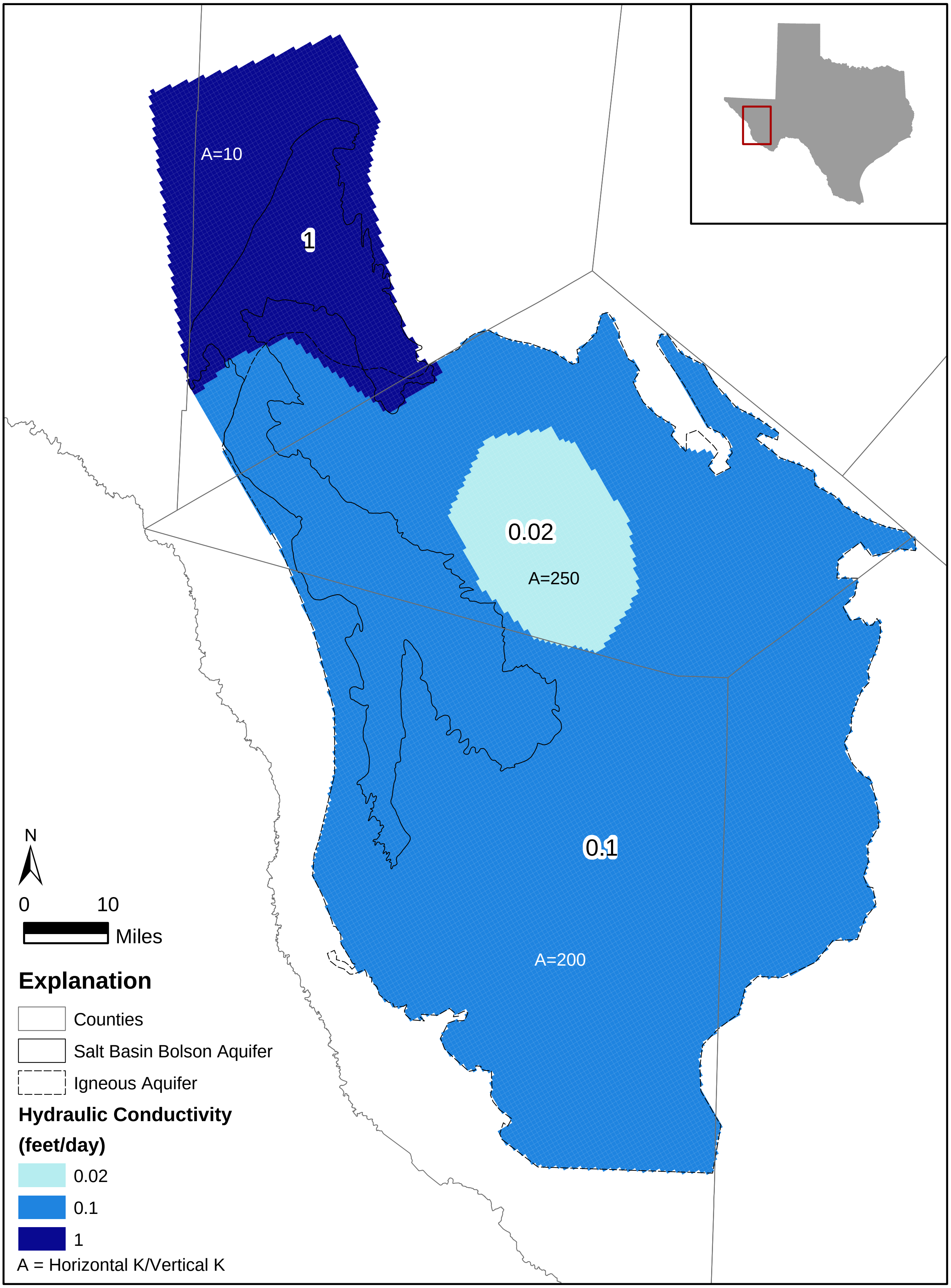


Figure 8.1.3 - Final Distribution of Hydraulic Conductivity in Layer 2

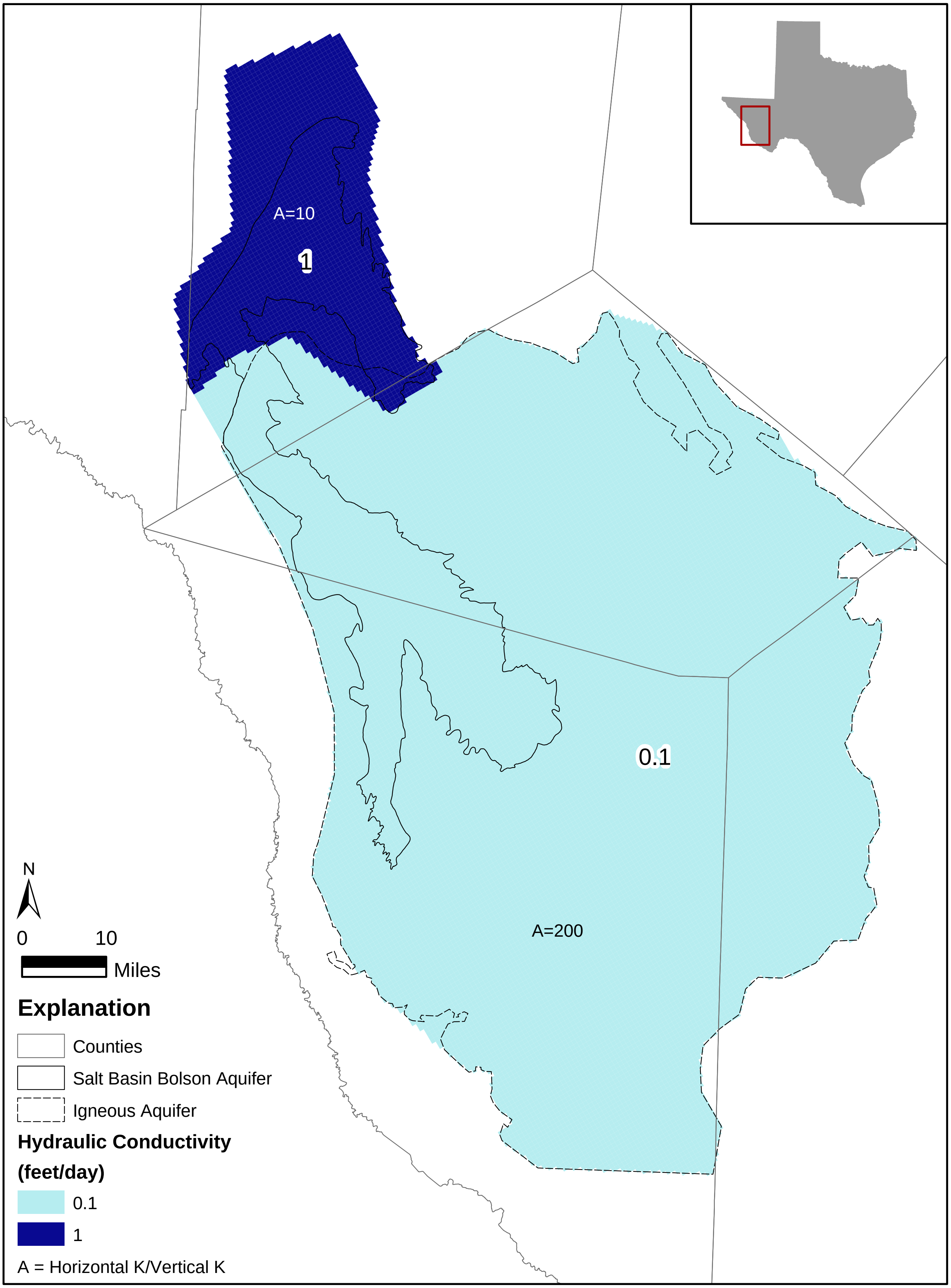


Figure 8.1.4 - Final Distribution of Hydraulic Conductivity in Layer 3

There is a significant water level drop across this area, which indicates some change in hydraulic properties or other change in the flow system. To account for this relatively steep slope of the water table in this area, a horizontal hydraulic conductivity of 4 ft/day was assigned. However, it should be recognized that there may be other hydrogeologic complexities in this area that are not accounted for in the conceptual model. Most of the other areas in the Salt Basin Bolson aquifer were assigned hydraulic conductivity values ranging from 25 to 50 ft/day, based on compiled estimates and the model calibration.

The spatial pattern of vertical hydraulic conductivity zones was consistent with the pattern used for the horizontal hydraulic conductivity. The vertical hydraulic conductivity estimates are used to estimate a vertical conductance between model layers. The model is relatively sensitive to vertical hydraulic conductivity estimates in two areas, Ryan and Wild Horse Flats. In Ryan Flat, there is a significant upward head gradient from the underlying Igneous into the Salt Basin Bolson aquifer due to the elevations and water levels in the Davis Mountains. Under steady-state conditions, the model simulated head difference in Ryan Flat between the Igneous and Salt Basin Bolson aquifers is up to 300 feet, resulting in an upward gradient that provides upward "cross-formational" flow from the Igneous to the Salt Basin Bolson aquifer. The calibrated model estimates this cross-formational flow to be about 2000-3000 acre-feet per year, depending on the geographical area considered. In Wild Horse Flat, there is a significant downward movement of water from the Bolson to the underlying Cretaceous and Permian aquifer system. Therefore, the model is relatively sensitive to the vertical hydraulic conductivity estimates in these two areas. The ratio of the horizontal to vertical hydraulic conductivity (referred to as anisotropy) is about 50000 in Ryan Flat, 100 in Lobo Flat, and a 1000 in Wild Horse Flat.

Figure 8.1.3 illustrates the distribution of hydraulic conductivity in layer 2. The circular pattern of lower hydraulic conductivity and corresponding lower vertical hydraulic conductivity was necessary to maintain heads at levels close to those observed in recent years. Without this low hydraulic conductivity zone, simulated heads were significantly lower than observed heads. This indicates that the Igneous aquifer in the Davis Mountains areas may be somewhat hydraulically isolated from the Salt Basin Bolson aquifer system. As shown in Figure 8.1.4, the hydraulic conductivity for layer 3 was assumed to be constant under the Igneous aquifer, but was assumed to be higher under Wild Horse Flat because there are wells in that area completed into the Cretaceous and Permian units that have relatively high yields.

8.1.3 Recharge

As discussed in Sections 4.1.4 and 6.3.4, initial estimates of recharge were based on the results of a runoff-redistribution analysis that is detailed in Appendix B. Those sections address the assumptions regarding recharge estimates and the application of the results to the model. See Section 6.3.4 for a discussion of the assumptions regarding the initial estimate of recharge.

For the steady-state calibration, recharge was varied by a factor of 0.5 to 1.5 times the initial value. However, the initial estimate was determined to provide reasonable model results. The spatial distribution of calibrated recharge in the steady-state model is shown in Figure 8.1.5. Direct recharge from precipitation is not assigned to the Bolsons, and assumed to be zero. The recharge estimates range from 0 to about 0.7 inches/yr where the Igneous aquifer outcrops across the model area. Figure 8.1.5 also shows the location of recharge associated with runoff from mountain front watersheds that drain to the alluvial valleys. The average recharge associated with each of these watershed discharge points is indicated in the figure.

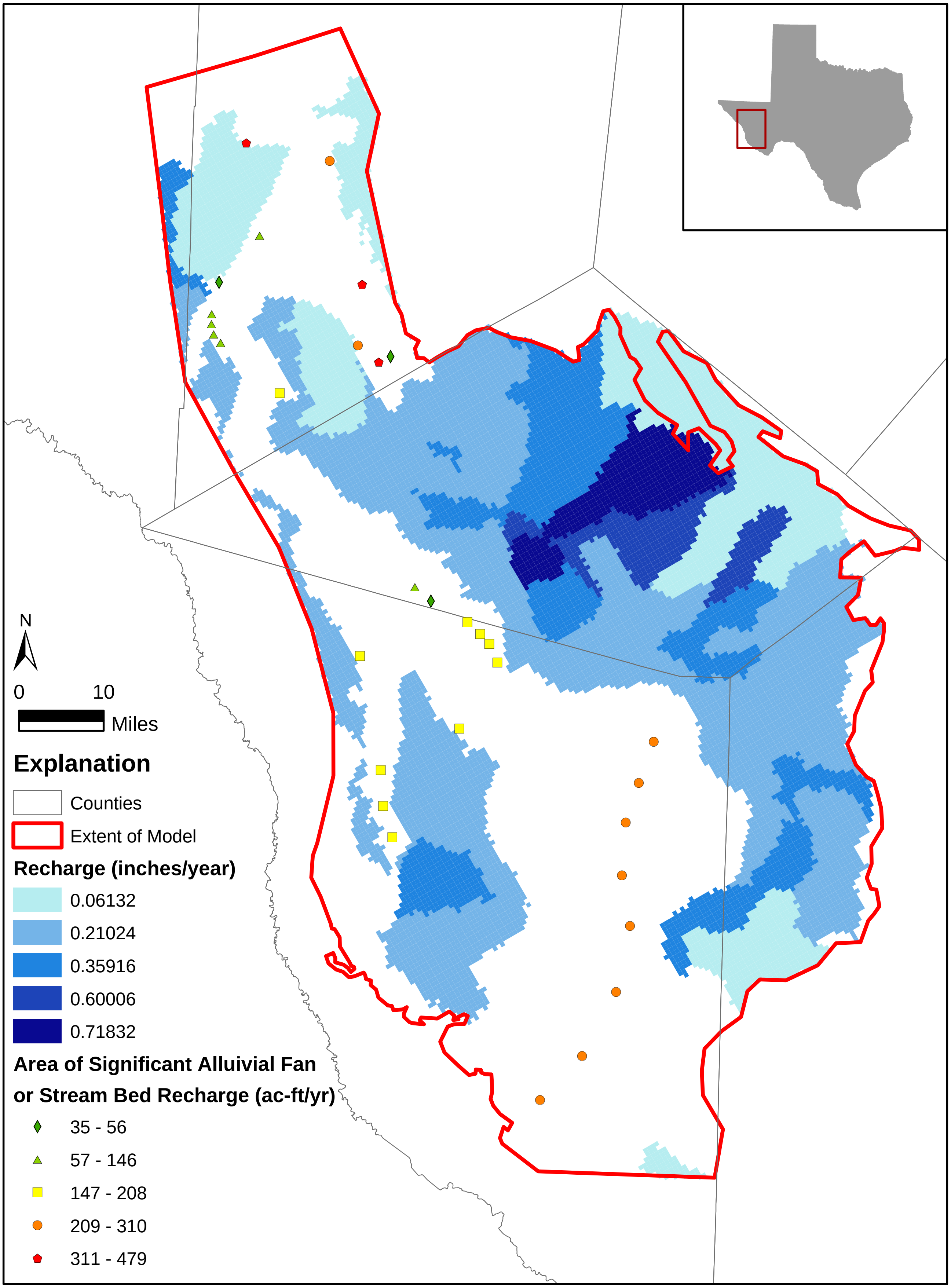


Figure 8.1.5 - Final Distribution of Recharge Rate in the Steady-State Model

8.1.4 Groundwater Evapotranspiration

It was assumed that the evapotranspiration extinction depths applied to the steady-state model remained the same across the model area. This estimate was based on reported maximum rooting depths of grasses similar to those found in the model area and was set equal to 10 feet. The final extinction depth and rate implemented in the calibrated model are shown in Figure 8.1.6. Simulated evapotranspiration rates in the steady-state calibrated model are shown in Figure 8.1.7. There are only a few areas where the water levels are relatively close to land surface, and therefore, evapotranspiration directly from the water table is not active over most of the model area. It is assumed that some of the shallow groundwater that would be lost to evapotranspiration near streams and springs is simulated by loss to drains, which represent streams in the model. This is discussed further is Section 8.4.2.

8.1.5 General Head Boundaries

General head boundaries (GHBs) were used to simulate cross-formational flow into and out of layer 3, which represents the Cretaceous and Permian units. The location of the GHB cells in layer 3 is shown in Figure 6.2.4. Originally, GHB cells were included in the layer 2 to simulate the cross-formational flow of the Igneous. However, because the Igneous typically pinches out at the edges of the model, some of the GHB cells would go dry, forcing all the flow downward to layer 3 in order to exit. Therefore, to simplify the model and try to reduce the difficulty caused by this condition, all GHB cells were moved to the boundary edge of layer 3. Heads for the GHBs were based on estimated heads from the Igneous aquifer and then adjusted downward based on the conceptual model that assumes that flow generally moves downward from the Igneous to the lower units. Conductance estimates for the GHBs in layer 3 were based on the layer thickness of 2000 feet, and an assumed hydraulic conductivity of 0.1 ft/day. Some of the conductance and heads were modified during calibration to better simulate regional flow patterns discussed in Chapter 4.

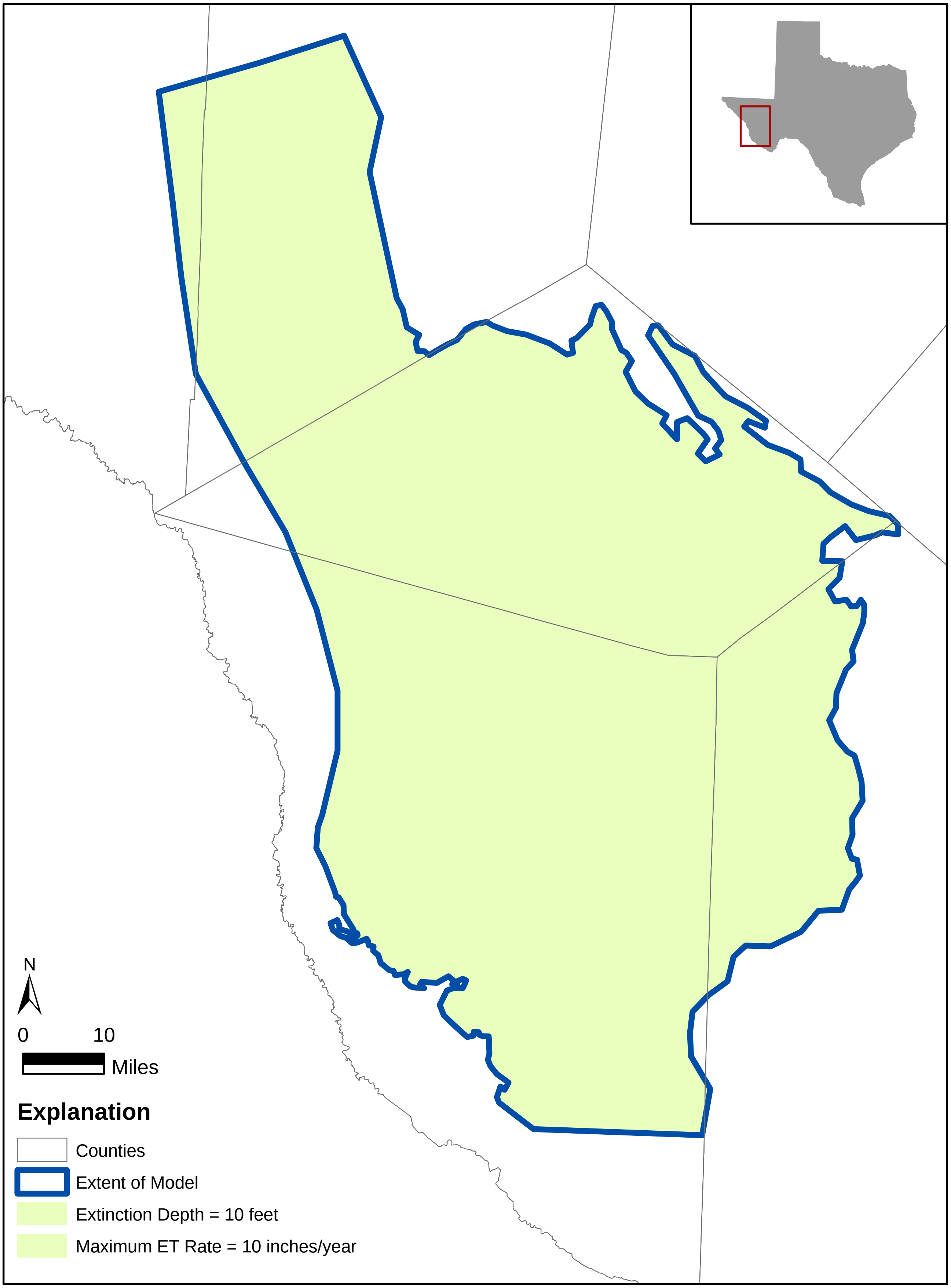


Figure 8.1.6 - Final Distribution of Evapotranspiration Extinction Depths and Rates

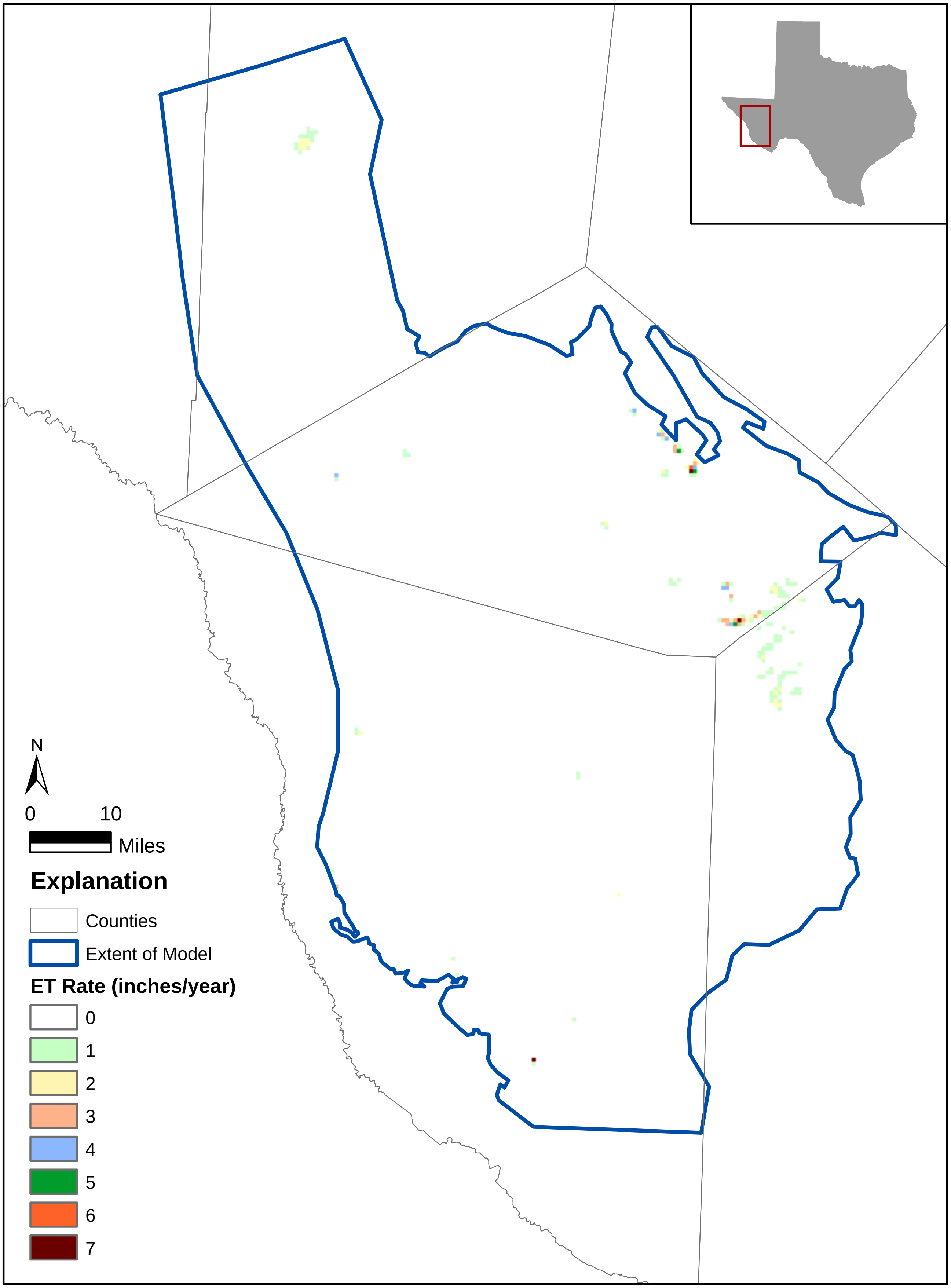


Figure 8.1.7 - Simulated Evapotranspiration Rates in the Steady-State Model

8.1.6 Streams

Surface water occurs primarily as storm-water runoff during summer storms, and to lesser degrees from springs and groundwater discharge to major drainages in the area of the Igneous aquifer. Therefore, streams were simulated by incorporating the MODFLOW drain package. As shown in Figure 6.2.3, layer 2 contained drain cells along the major creeks, including Limpia Creek and Calamity Creek.

8.2 Results

The steady-state model was calibrated to water levels in 1950, which were assumed to represent predevelopment conditions. This section describes some of the observations that were made during the calibration of the model and presents results of the calibration of the steady-state portion of the model.

The TWDB GAM protocol requires that a long stress period be added to the beginning of the calibration model to simulate steady-state conditions prior to the transient calibration. For the IBGAM, a 10,000,000-day “steady-state” stress period was incorporated to simulate predevelopment conditions prior to 1950. During the transient run, steady-state (pre-1950) and transient (1950-2000) water level measurements were used to calibrate both steady-state and transient models. Therefore, calibration occurred in a coupled fashion.

Early in the calibration process, it became apparent that the steady-state heads in the Igneous and Bolson aquifers were very dependent on the distribution of hydraulic conductivity. Therefore, to achieve steady-state calibration, steady-state data was weighted significantly higher in the coupled runs until the simulated steady-state heads were similar to the observed 1950 water level measurements. Then, the focus shifted to the transient calibration in which the hydraulic conductivity was a less sensitive parameter, and therefore was not modified significantly.

Normally, recharge in a regional system is a very sensitive parameter. However, in order to simulate the observed heads in the Igneous aquifer that were measured around 2000, it was necessary to reduce the horizontal and vertical hydraulic conductivity of the Igneous aquifer below the values discussed in Section 4.2. This modification limited the connection between the Igneous and Bolson aquifers in the model and caused more of the recharge to the Igneous aquifer to be lost to streamflow and evapotranspiration because it could not move downward. Because the Bolsons do not receive any direct recharge from precipitation except the recharge from stormwater runoff, the sensitivity of the Bolson layer to changes in recharge is somewhat muted because most of the recharge is received by the Igneous layer, and is lost to streams and evapotranspiration.

Because there was very little historic water level data in the Igneous, it was difficult to calibrate the model based to recharge because most of the recharge to the Igneous is lost to evapotranspiration and streams. Therefore, changes in recharge are inversely offset by changes in evapotranspiration and streamflow from the Igneous aquifer.

For the steady-state calibration of water levels in the Bolson, the hydraulic conductivity (horizontal and vertical) was first adjusted in Ryan Flat and then successively downgradient through Lobo, Michigan and Wild Horse Flats. Boundary heads associated with the general head boundaries in layer 3 were initially based on estimated water levels discussed in Section 4.1. The water levels were modified slightly during calibration because layer 3 general head boundary conditions are very influential in determining the steady-state heads in the entire system.

8.2.1 Calibration Statistics

Table 8.2 shows a summary of the calibration statistics for the calibrated steady-state model. The RMS of the steady-state calibration targets for the Salt Basin Bolson aquifer is 21 feet over a range of 690 feet, resulting in a RMS/range ratio of about 3%. Because there was only one water level measurement in layer 2, statistics could not be calculated. However, the one water level measurement was matched within 6 feet.

Calibration statistics were not calculated for layer 3 because there were no available water level measurements.

Table 8.2 Summary of steady-state head calibration statistics

Layer	Count	ME (feet)	MAE (feet)	RMSE (feet)	Range (feet)	RMSE / Range
Bolson	53	6	17	21	690	0.03
Igneous	1	7	7	-	-	-
Cretaceous	0	-	-	-	-	-
All Layers	54	6	17	21	690	0.03

8.2.2 Hydraulic Heads

Figure 8.2.1 shows a crossplot of the observed heads versus the simulated heads for the steady state model. The figure indicates that there is relatively good agreement in all areas of the model. Figure 8.2.2 shows a map of the simulated hydraulic head results from the calibrated steady-state model as well as the head residuals. Residuals greater than zero indicate that the simulated head is higher than the measured head, and residuals less than zero indicates that the simulated head is lower than the measured head. As indicated in Figure 8.2.2, the flow direction and gradients are very similar to those shown in Figure 4.1.5 in the Salt Basin Bolson aquifer.

Some cells near the edge of the Bolson and Igneous aquifers went dry in the steady-state simulation. The rewetting option was not used in the steady-state period because it was unstable. Dry cells in MODFLOW can be indicative of model instability during solver iterations or may indicate that the layer has a small saturated thickness or is dry. The simulated water table in both aquifers is relatively smooth near the dry zones, therefore the dry cells are probably indicative of actual dry zones or areas where the

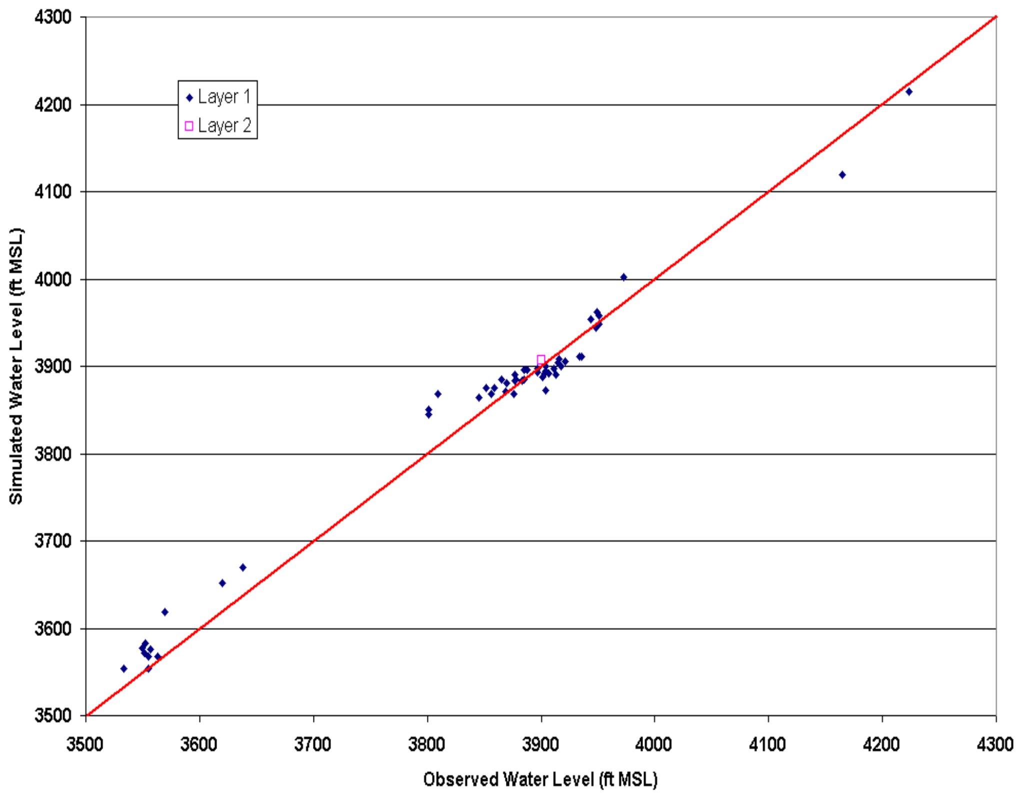


Figure 8.2.1 Simulated versus observed heads in the steady-state model

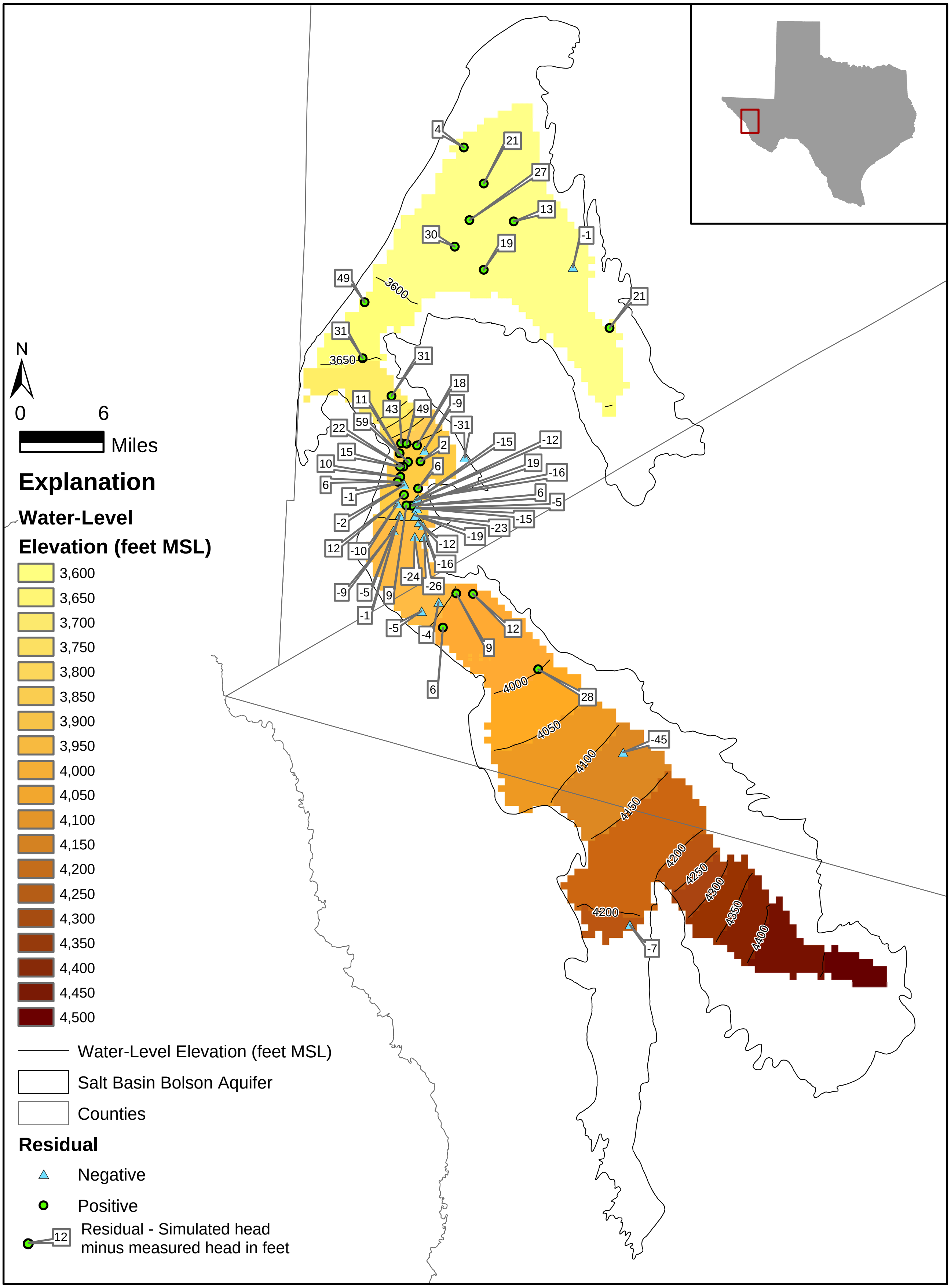


Figure 8.2.2 - Simulated Steady-State Hydraulic Heads and Residuals in Layer 1 in 1950

saturated thickness is so small that the flow in the cells is relatively insignificant to the overall flow dynamics. Therefore, it is assumed the dry cells do not have a significant impact on model results.

Figure 8.2.3 illustrates the simulated steady-state heads in the Igneous aquifer in 1950. Although there are no water level measurements available for layer 2 in 1950, it was assumed that the water level measurements available from more recent years was representative of conditions in the Igneous aquifer under predevelopment conditions. Therefore, these water levels from recent years were used to guide the calibration of layer 2 with respect to overall flow direction and water levels. Figure 8.2.4 shows the simulated water levels in layer 3. There are no calibration data available for layer 3, but the general flow directions in the aquifer mimic the regional flow patterns that were discussed in Section 4.2.3.

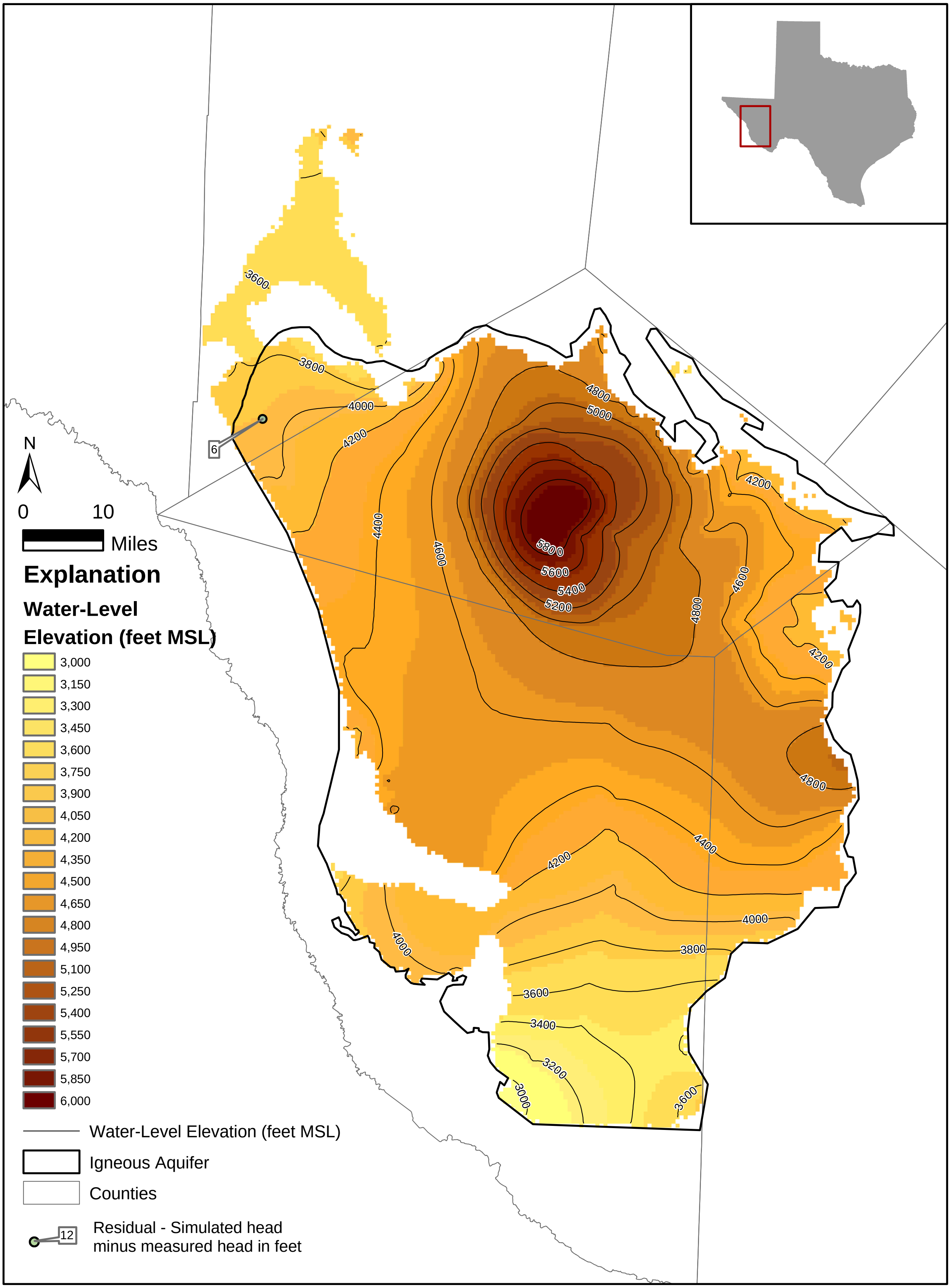


Figure 8.2.3 - Simulated Steady-State Hydraulic Heads and Residuals in Layer 2 in 1950

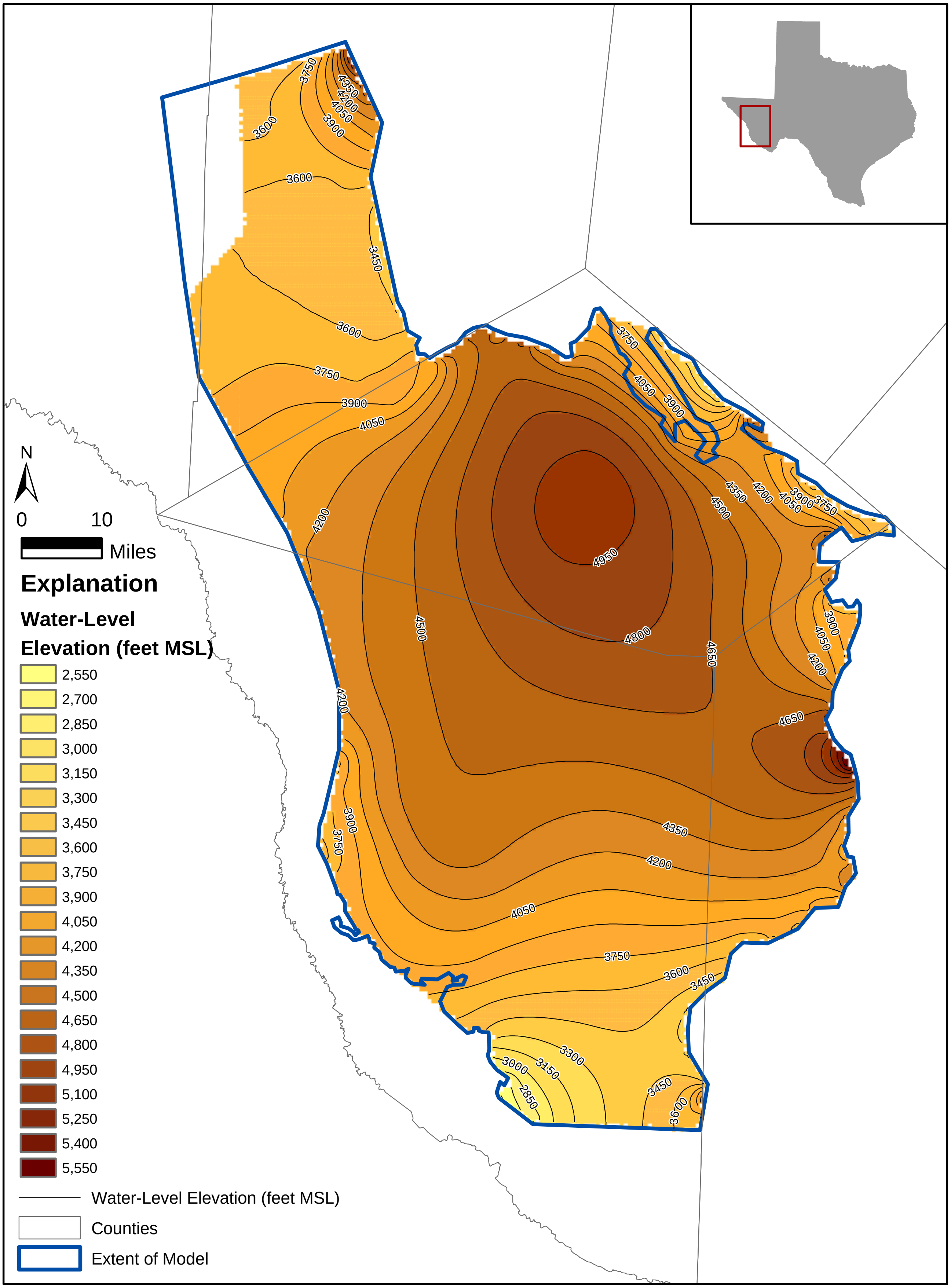


Figure 8.2.4 - Simulated Steady-State Hydraulic Heads in Layer 3 in 1950

8.2.3 Water Budget

Table 8.3 provides a summary of the water budget for the steady-state model in terms of volume. As indicated in this table, the bottom flow components in Bolsons have a balance of about 15000 acre-feet per year coming into layer 1. About 30,000 acre-feet per year of the 50,000 acre-feet per year of recharge is lost to ET and drains (streams and springs). A significant amount of water is moving through layer 3 by cross-formational flow. On average about 3700 acre-feet per year of recharge occurs in the alluvial channels of the Bolsons from stormwater runoff. Figure 8.2.5 illustrates the steady-state budget components for each layer in graphical form.

As indicated in Table 8.3, groundwater flows into and out of the bottom of Bolson aquifer. The net flow through the base of the Bolsons (the sum of all gridblocks) is about 5,000 acre-feet per year into layer 1 from layer 2. More detailed assessment of model results indicates that most of the upward movement is in Ryan and Lobo Flats and the area between them.

About 31,000 acre-feet per year of the 50,000 acre-feet per year of recharge is lost to evapotranspiration and drains (streams, springs and flow out of Wild Horse Flat). A significant amount of water is moving through layer 3 as cross-formational flow. On average about 3700 acre-feet per year of recharge occurs in the alluvial channels of the Bolsons from stormwater runoff. Figure 8.2.5 illustrates the steady-state budget components for each layer in graphical form. Figure 8.2.5 provides a graphical illustration of the flow in and out of the bottom and top of each model layer.

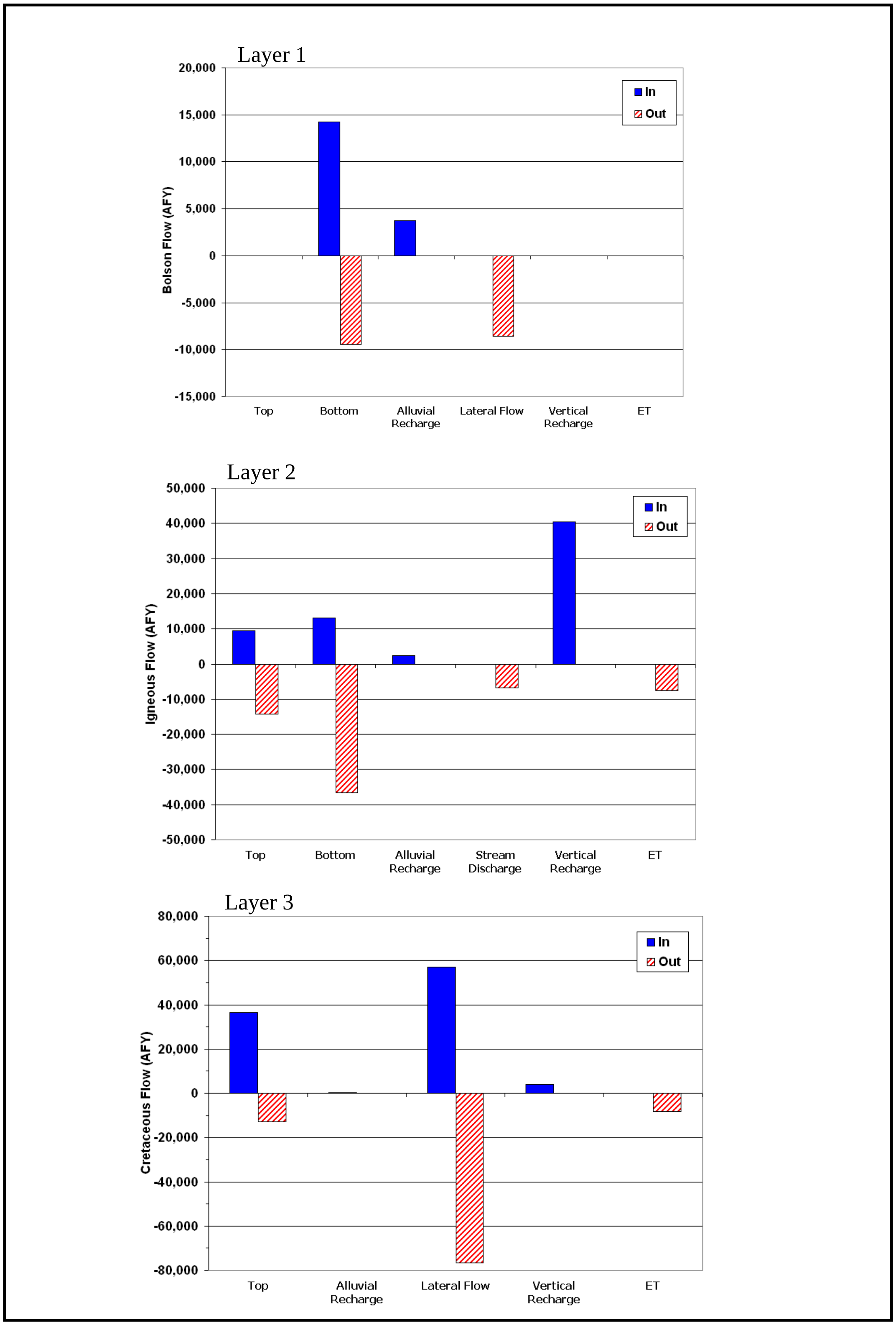


Figure 8.2.5 Water budget components in the steady-state model

Table 8.3 Summary of steady-state water budget components

IN	Layer	Top	Bottom	ET	Drain	GHBs	Recharge
	1	0	14296	0	0	0	3712
	2	9495	13029	0	0	0	42722
	3	36605	0	0	0	57028	4248
	Sum			0	0	57028	50682
OUT	1	0	9495	0	8588	0	0
	2	14296	36605	7558	6791	0	0
	3	13029	0	8234	0	76621	0
	Sum			15792	15379	76621	0
All units in acre-feet per year							

8.3 Sensitivity Analysis

A sensitivity analysis was completed for the calibrated steady-state model. One purpose of a sensitivity analysis is to quantify the impact on the model results when input parameters are varied. For this evaluation, hydraulic parameters were systematically increased and decreased from their calibrated values while the average change in head was calculated for the individual layers. For each parameter that was varied, four simulations were completed. The sensitivity factors were 0.8, 0.9, 1.1, and 1.2.

For the steady-state analysis, the sensitivity of five parameters was evaluated. The five parameters are:

1. Horizontal hydraulic conductivity
2. Vertical hydraulic conductivity
3. Recharge
4. GHB head
5. GHB conductance

Figure 8.3.1 indicates that when hydraulic conductivity is decreased, average head in layer 1 increases, showing a negative correlation. The most sensitive positively correlated parameter is GHB head. Parameters that are positively correlated to a lesser degree are recharge and vertical hydraulic conductivity. The least sensitive parameter is GHB conductance.

Figures 8.3.2 and 8.3.3, which illustrate sensitivity in layers 2 and 3, indicate the same type of correlation as layer 1 except that the positive correlation of the GHB head is even more significant. Figures 8.3.4 and 8.3.5 compare the change in head in each layer based on global changes in horizontal hydraulic conductivity and recharge, respectively. The sensitivity of head in each layer is very similar given global changes in horizontal hydraulic conductivity. Figure 8.3.5 indicates that the most sensitive layer to changes in recharge is layer 2 because that is where most of the direct recharge occurs. Layer 1 is the least sensitive because no direct recharge from precipitation occurs in layer 1. The relative sensitivity of recharge is significant as compared to hydraulic conductivity because the measure of sensitivity is average head change in the model for all the gridblocks. Because the estimated recharge has the most impact on the Igneous aquifer and because the Igneous aquifer covers such a large area, the sensitivity is relatively high. However, because there are so few water level measurements in the Igneous aquifer, and changes to recharge have very little effect on the Bolsons, it is difficult to use existing data to reduce the non-uniqueness of the recharge estimate.

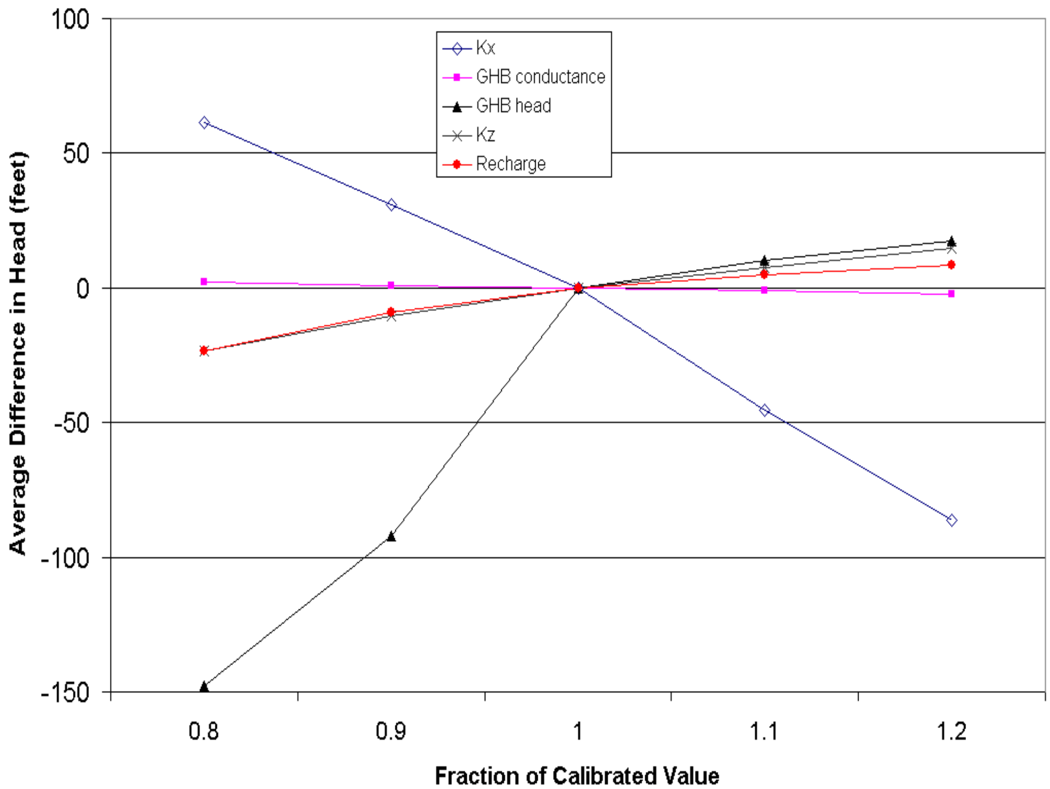


Figure 8.3.1 Steady-state sensitivity results for Layer 1 using all active gridblocks

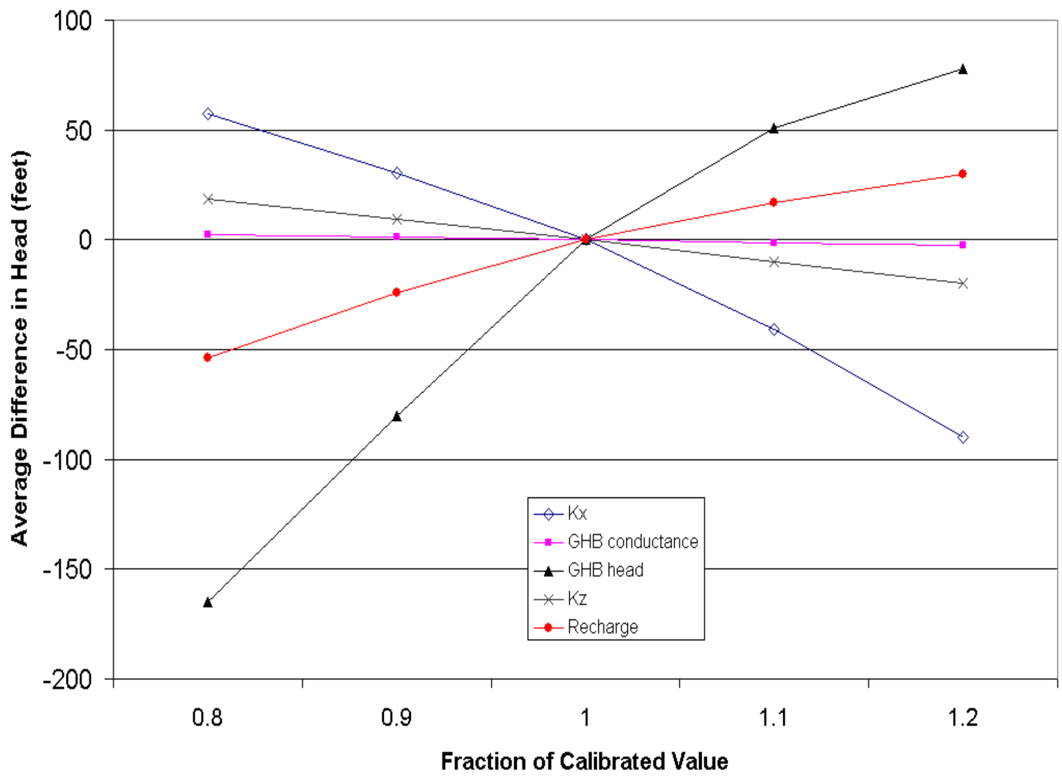


Figure 8.3.2 Steady-state sensitivity results for Layer 2 using all active gridblocks

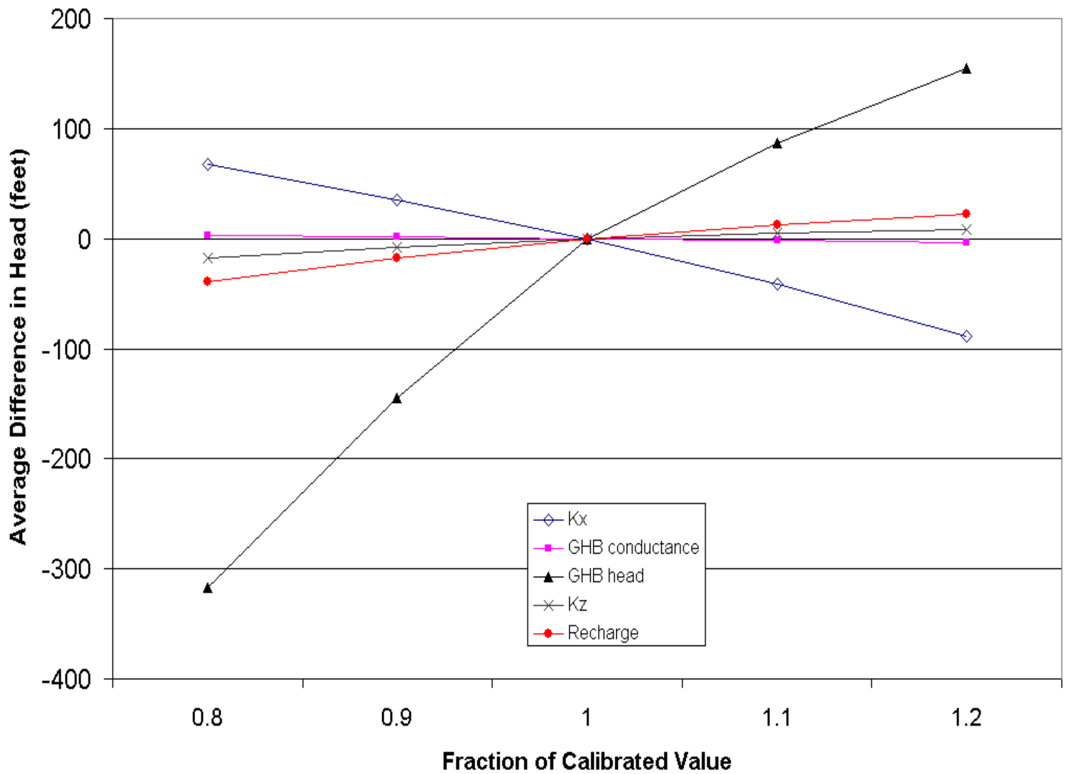


Figure 8.3.3 Steady-state sensitivity results for Layer 3 using all active gridblocks

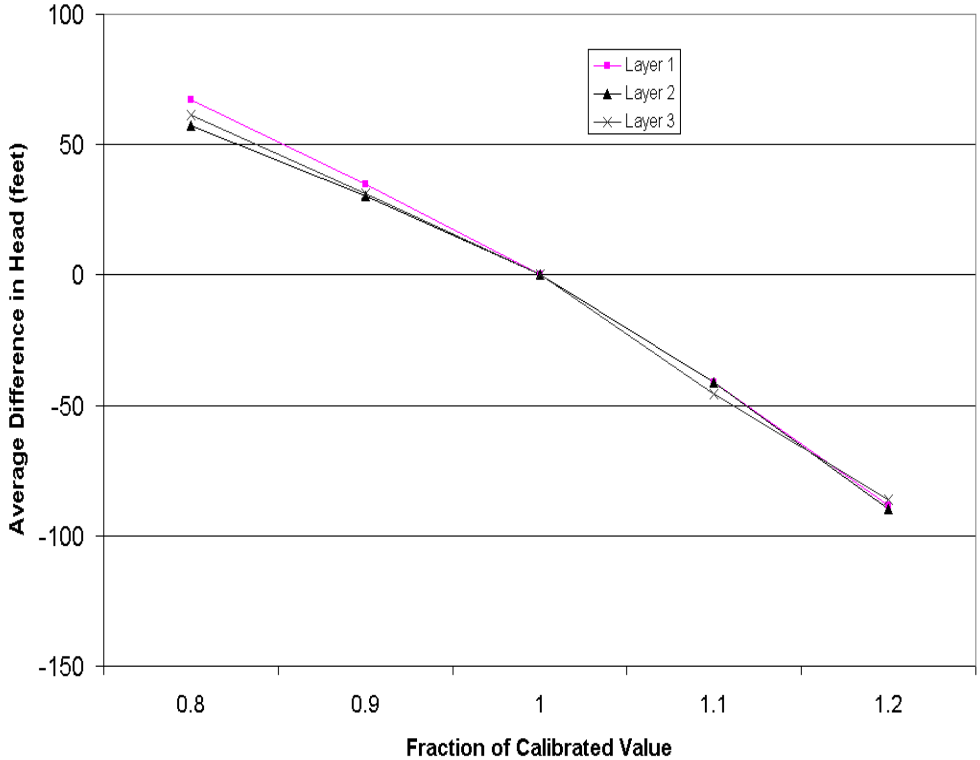


Figure 8.3.4 Steady-state sensitivity where horizontal conductivity is varied

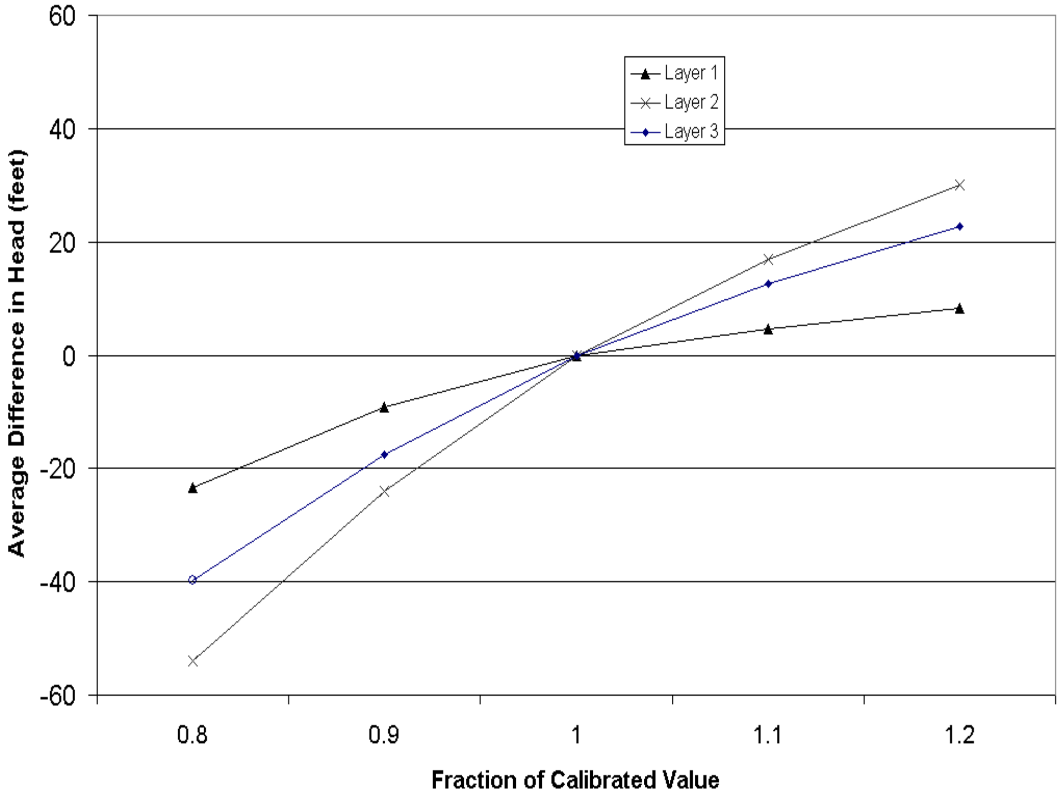


Figure 8.3.5 Steady-state sensitivity where recharge is varied

9.0 TRANSIENT MODEL

This section documents the calibration and verification of the transient model and presents the transient model results. This section also details the sensitivity analysis completed for the transient model.

9.1 Calibration

As described in Section 8.2, the transient model was developed with a very long stress period at the beginning of the simulation to represent steady-state conditions prior to simulating transient conditions between 1950 and 2000. Some of the aquifer storage properties that were less sensitive during the long steady-state stress period were more sensitive during the transient calibration and were adjusted to improve calibration. Because the calibration of the steady-state and transient models were coupled, the transient calibration also resulted in adjustment of hydraulic conductivity values and zonation as well as adjustment in the specific yield estimates. The initial value of specific yield was assumed to be 0.10, but was lowered during the transient calibration to 0.06. The hydraulic conductivity estimates within each zone were also adjusted to better calibrate the simulated response to the measured water level response between 1950 and 2000. In addition, recharge and pumpage are varied each year in the transient model. A discussion of these stresses and parameters is included below.

The long stress period at the beginning of the transient run was required by the GAM protocol. During the transient run, steady-state (1950) and transient (1951-2000) water level measurements were used to calibrate the model and the transient and steady-state calibration did occur in a coupled fashion. Early in the calibration process, it became apparent that the steady-state heads in the Bolson aquifer were very dependent on the distribution of hydraulic conductivity in the Bolson. Therefore, the steady-state calibration data was weighted significantly higher in the coupled runs until the simulated steady-state heads were similar to the observed 1950 water level measurements. Then, the focus shifted to the transient calibration in which the hydraulic conductivity was a less sensitive parameter, and therefore was not modified significantly.

9.1.1 Calibration and Verification Targets

As summarized in Table 7.2, water level measurements collected between 1950 and 2000 were used to calibrate and verify the model. Figure 9.1.1 shows the locations of the wells containing water level measurements that were used for the transient calibration and verification. Many of the wells shown in Ryan Flat are from one-time monitoring events that occurred in 1974 and 1991. There are only two monitoring wells where water level measurements have been collected on an ongoing basis. Many of the wells shown in the Igneous aquifer are also from recent years and most of those wells contain only one water level measurement. However, these data were very important in developing a better understanding of the water level surface in the Davis Mountains.

9.1.2 Storativity

MODFLOW requires estimates of confined and unconfined aquifer storage properties, also referred to as storativity and specific yield, or primary and secondary storage coefficients. There are very few estimates of storativity and specific yield in the model area. Sections 4.1.6 and 4.2.6 discuss the available information. Based on the relative lack of data, storativity and specific yield values were assumed to be constant throughout each layer. The distribution of storage coefficients for each layer of the model is shown in Figures 9.1.2, 9.1.3, and 9.1.4. The calibrated value of specific yield for layer 1 was 0.06. The selection of this value was based on a combination of previous estimates and the calibration results. Figures 9.1.3 and 9.1.4 show the confined storage coefficient for layers 2 and 3, respectively. These layers were also assumed to have a specific yield of 0.01, which is the storage coefficient used in areas where the aquifer is unconfined.

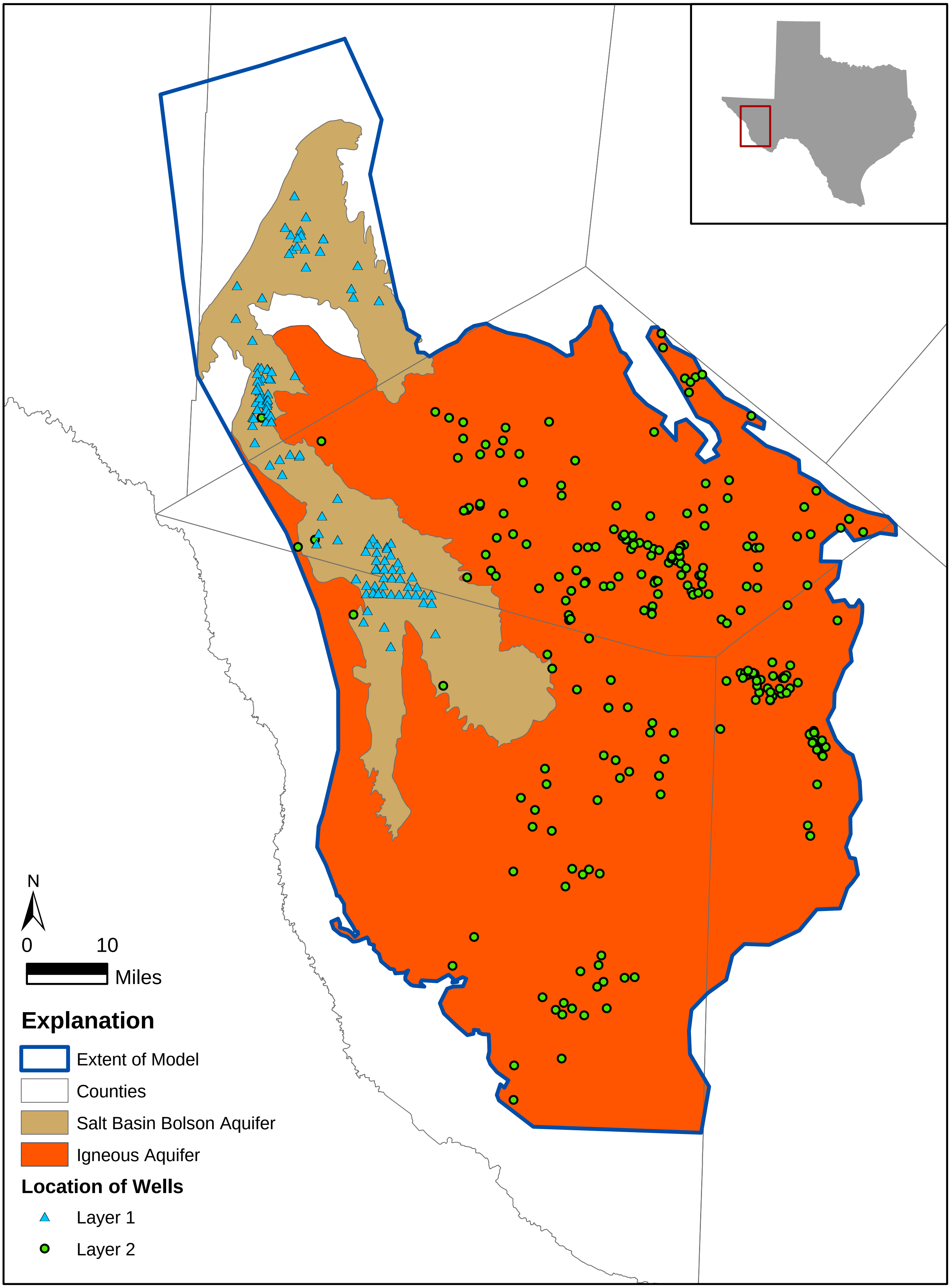


Figure 9.1.1 - Location of Wells Used for Transient Calibration Targets

9.1.3 Recharge and Pumpage

Figures 4.1.20 through 4.1.22 illustrate the estimated pumping that has occurred in the model area between 1950 and 2000. The magnitude and location of the heaviest pumping has changed through time. In the 1950s, pumping began in Lobo Flat in Culberson County. In the late 1970s, pumping began in Ryan Flat, which straddles the Jeff Davis and Presidio Counties. This pumping and the associated water level declines provide important insight into how the aquifer will respond to future pumping. The details of how historical pumping was distributed in the model are discussed in Appendix C.

For the transient calibration and verification periods, it was assumed that the recharge was variable and was directly correlated to yearly precipitation. Because the Davis Mountains receive the highest precipitation and recharge, the variability in recharge was based on the variability in precipitation at the Mount Locke precipitation gage. The yearly factor applied to the average recharge that was determined from the recharge-redistribution analysis is shown in Figure 9.1.5.

This simplified approach to varying recharge was based on the broad assumption that recharge is directly proportional to total yearly rainfall. In some cases, a relatively dry year may have a couple of relatively wet periods when recharge was significant and perhaps even higher than a relatively wetter year. On the other hand, large storm events may occur in some years that increase the total yearly precipitation above average, but most of the rainfall may run off. In this case, there may be a larger percentage of the rainfall that contributes to Bolson recharge through stormwater runoff. Further research may help identify what types of precipitation events provide the greatest recharge and how that recharge is distributed. Then, it might be possible to estimate historical recharge based on the frequency of these types of events.

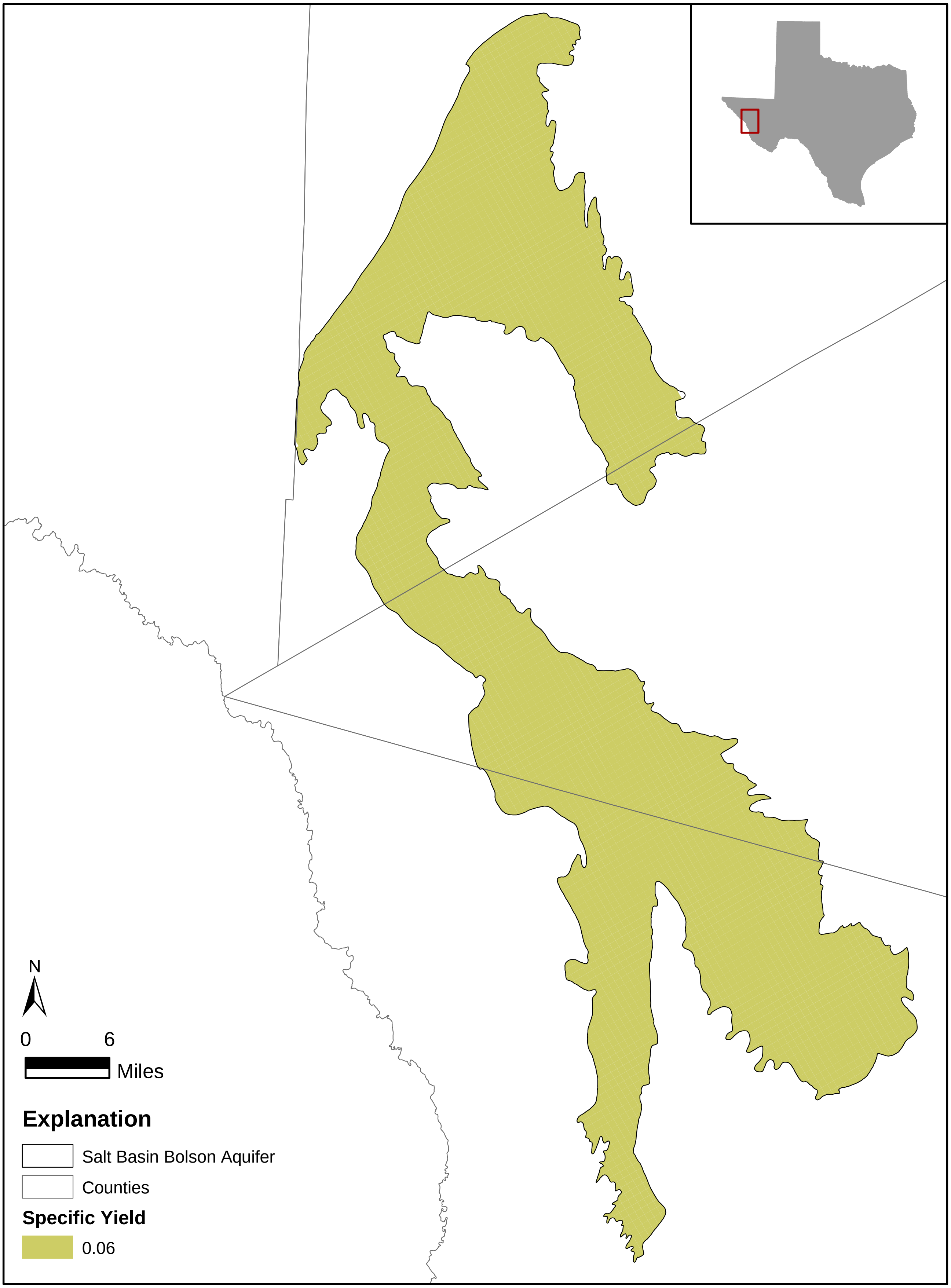


Figure 9.1.2 - Final Distribution of Specific Yield in Layer 1

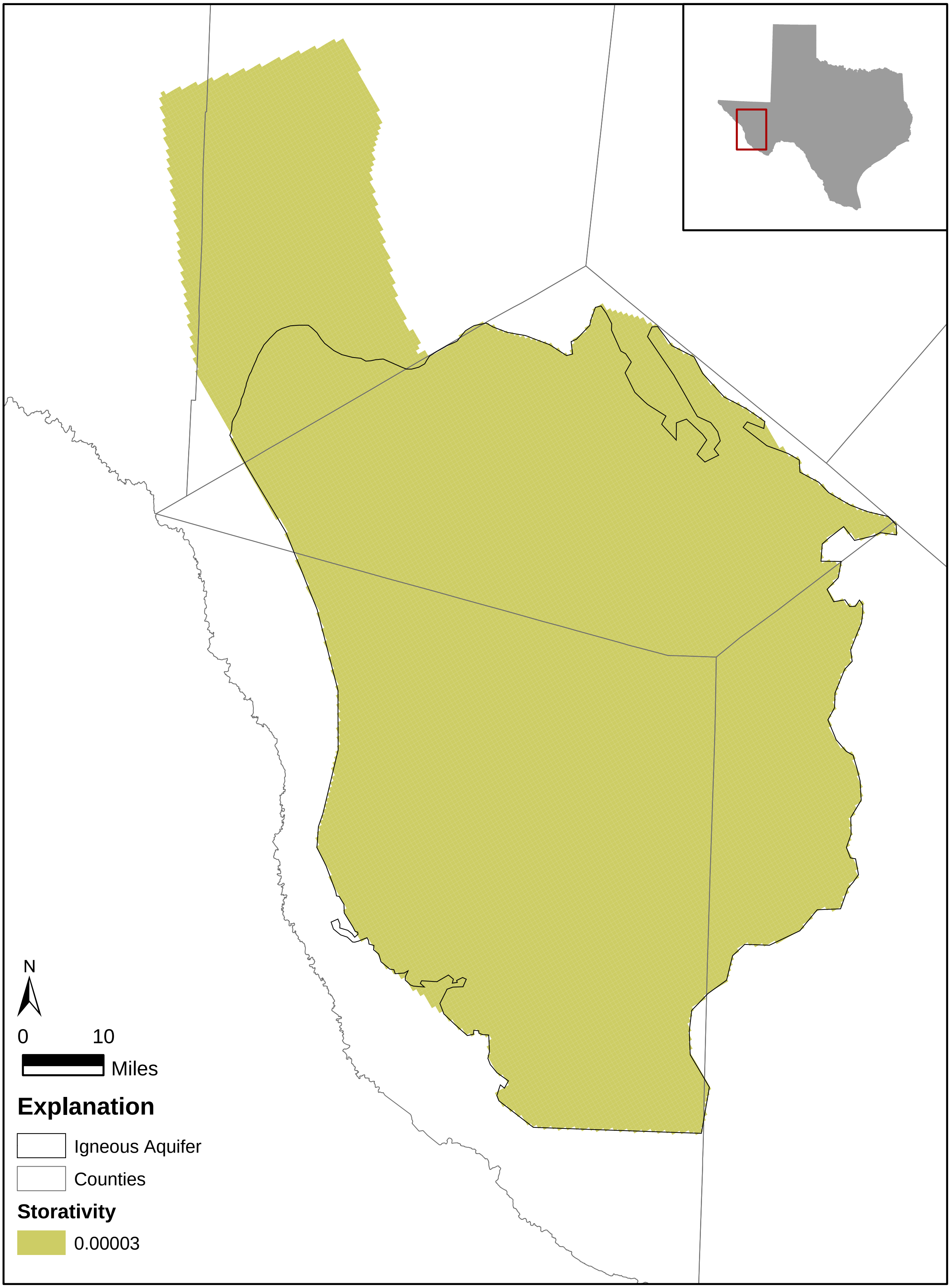


Figure 9.1.3 - Final Distribution of Storativity in Layer 2

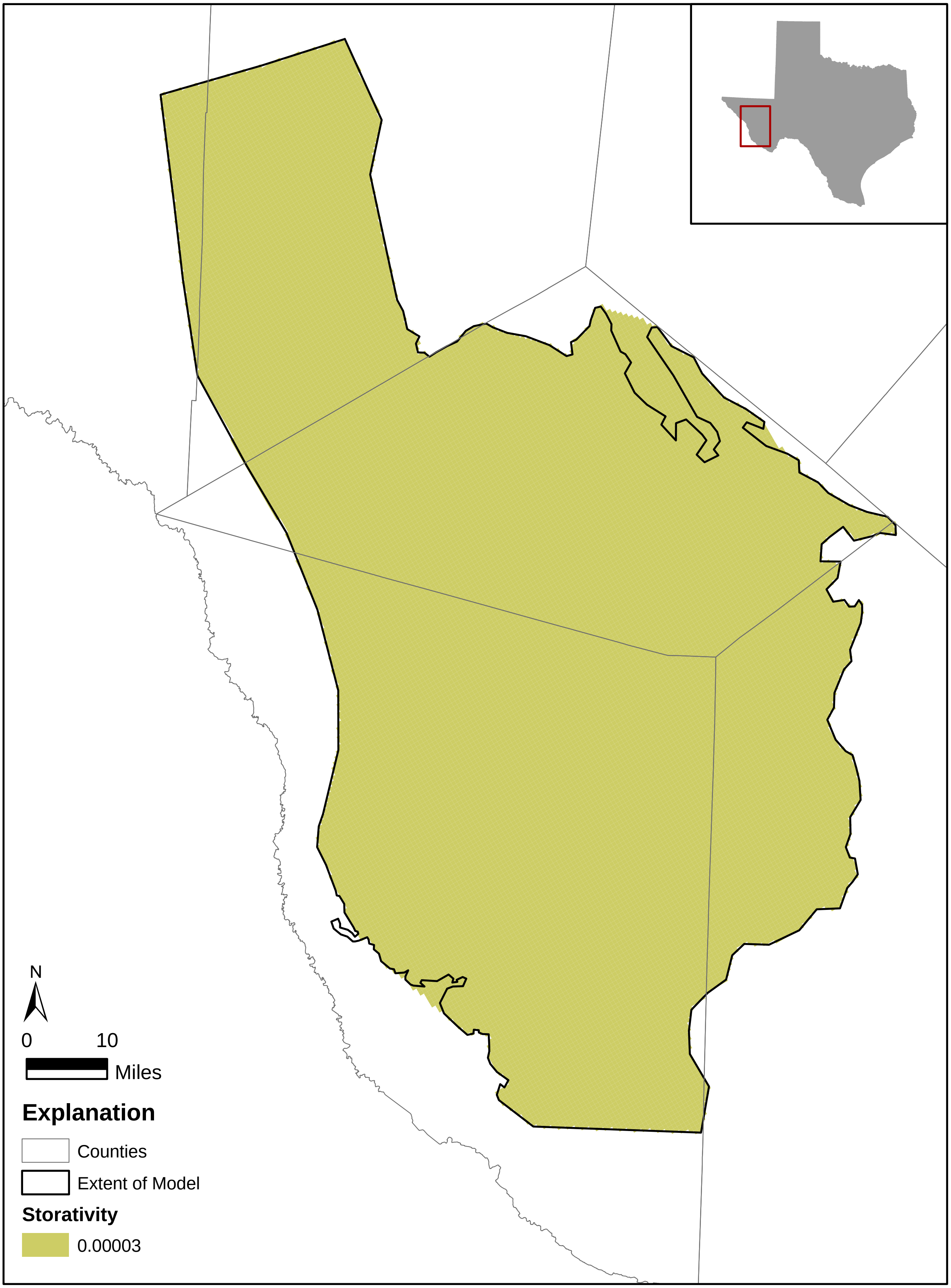


Figure 9.1.4 - Final Distribution of Storativity in Layer 3

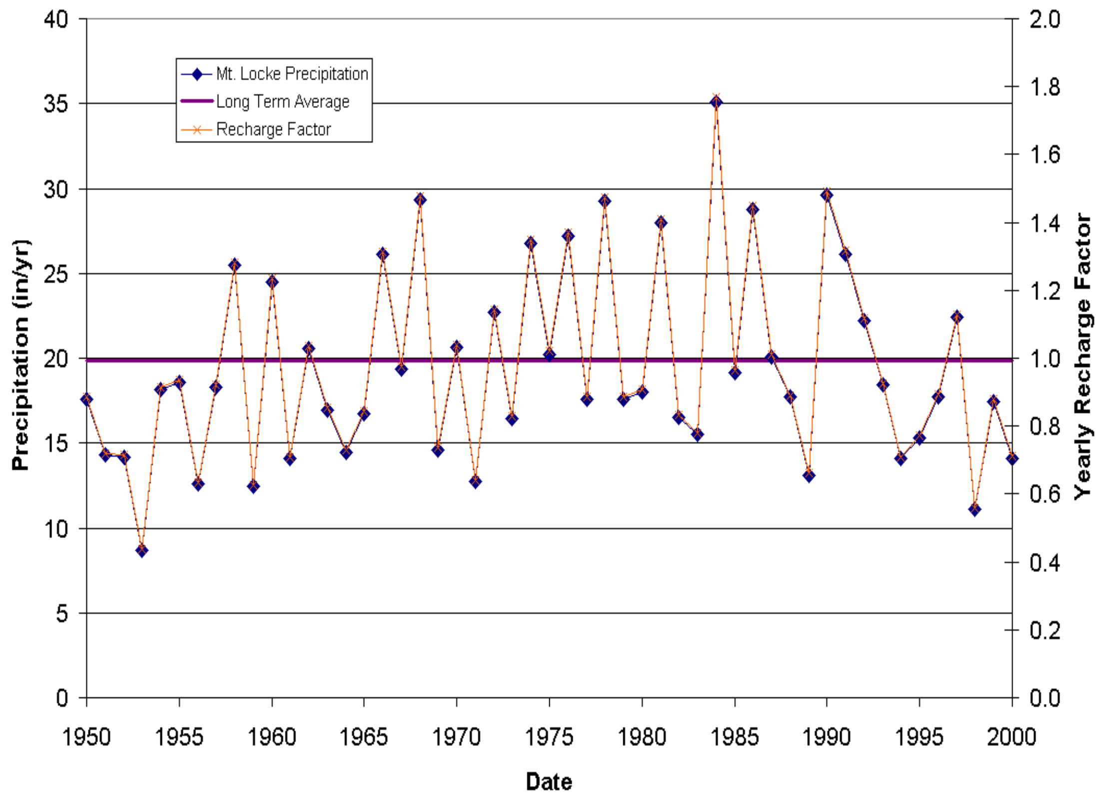


Figure 9.1.5 Factor applied to recharge between 1950 and 2000

9.2 Results

As described in Section 8, the calibration of the transient model was iterative, and was coupled with the calibration of the steady-state model. The calibration was divided up into two periods, a calibration phase (1950-1990), and a verification phase (1991-2000). This section will describe the results of the calibration phase of the model and then detail how the model performed in the verification phase.

9.2.1 Calibration Statistics

Table 9.1 summarizes the statistics for the available head targets during the calibration and verification periods of the transient model. The statistics for both periods show that the model is capable of simulating heads and the change in head through time relatively well. The ratio of RMS to range for layers 1 and 2 vary from 2 to 5 percent during the calibration and the verification periods. The RMS for layers 1 and 2 during the calibration phase is about 35 feet. During the verification phase, the RMS in layer 2 increases to 150 feet because there are 245 geographically distributed water level measurements available during this period as opposed to the calibration period when there were water level measurements from a few wells. Therefore, the larger residuals in the verification period are normal due to the underlying data differences. Other than that difference, the model appears to simulate aquifer responses well in both periods.

Figures 9.2.1 and 9.2.2 show the crossplot of the observed and simulated heads during the calibration and verification periods, respectively. In both figures, it is evident that the trends in the observed water level hydrographs in the Salt Basin Bolson aquifer are simulated well because the data points track mostly parallel to the red line (match line) on the graphs. Although points on the plot are not identified by individual wells, it is apparent that some points that lie above the match line and track parallel to it are water levels from wells where the steady-state heads in 1950 are higher than observed while those points starting and tracking below the match line are those which start low in 1950. This indicates that the model does a good job of simulating drawdown. That will be illustrated further in the next section. Figure 9.2.3 shows the average residuals for all water level measurements in each calibration well for the calibration and verification periods. In general, the average residual at each well is biased in the same fashion as the steady-state residuals because the model simulates head changes relatively well. In other words, if the steady-state simulated water level is high, water levels simulated during the calibration and verification periods will likely remain high and vice-versa for low water levels.

Table 9.1 Head calibration statistics for the calibration and verification periods

Calibration period (1950 - 1990)

Layer	Count	ME (feet)	MAE (feet)	RMSE (feet)	Range (feet)	RMSE / Range
1	895	-10	27	35	819	0.04
2	122	17	35	35	1142	0.03
3	0	-	-	-	-	-
All	1017	7	28	34	1501	0.02

Verification period (1991 - 2000)

Layer	Count	ME (feet)	MAE (feet)	RMSE (feet)	Range (feet)	RMSE / Range
1	298	-15	28	35	745	0.05
2	301	-15	105	150	2833	0.05
3	0	-	-	-	-	-
All	599	-15	64	109	2833	0.04

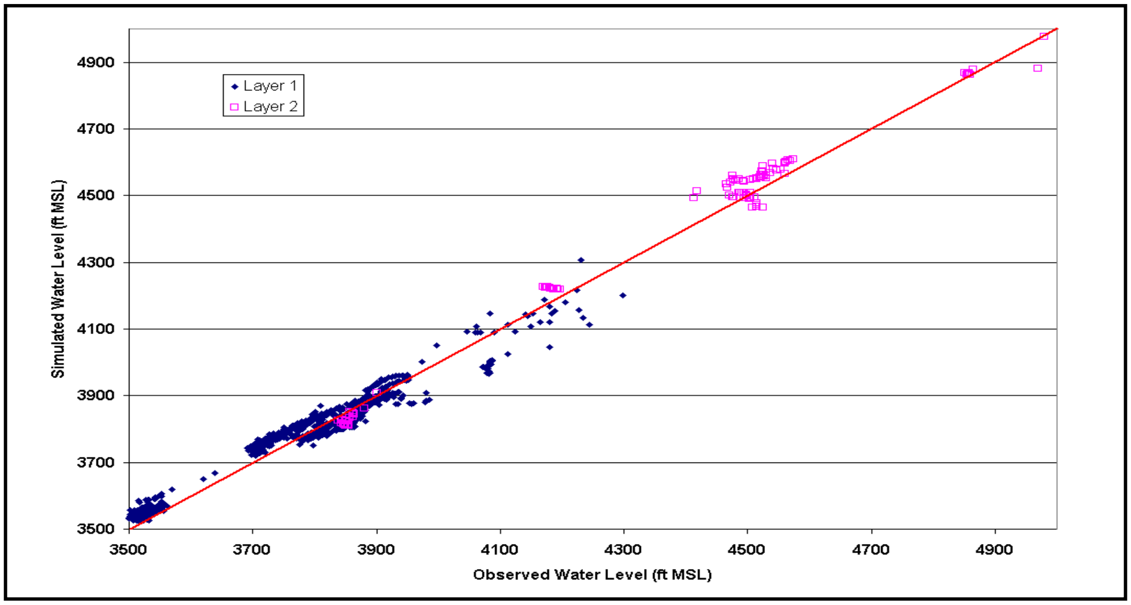


Figure 9.2.1 Simulated versus observed heads during the calibration period

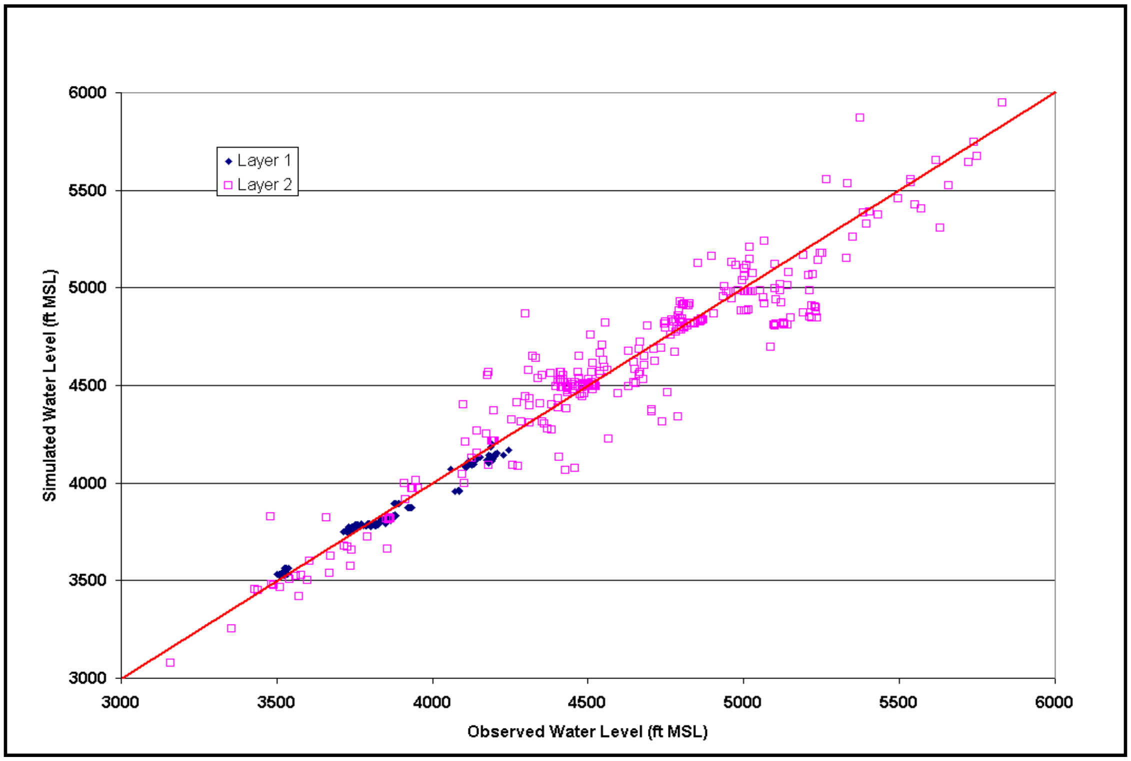


Figure 9.2.2 Simulated versus observed heads during the verification period

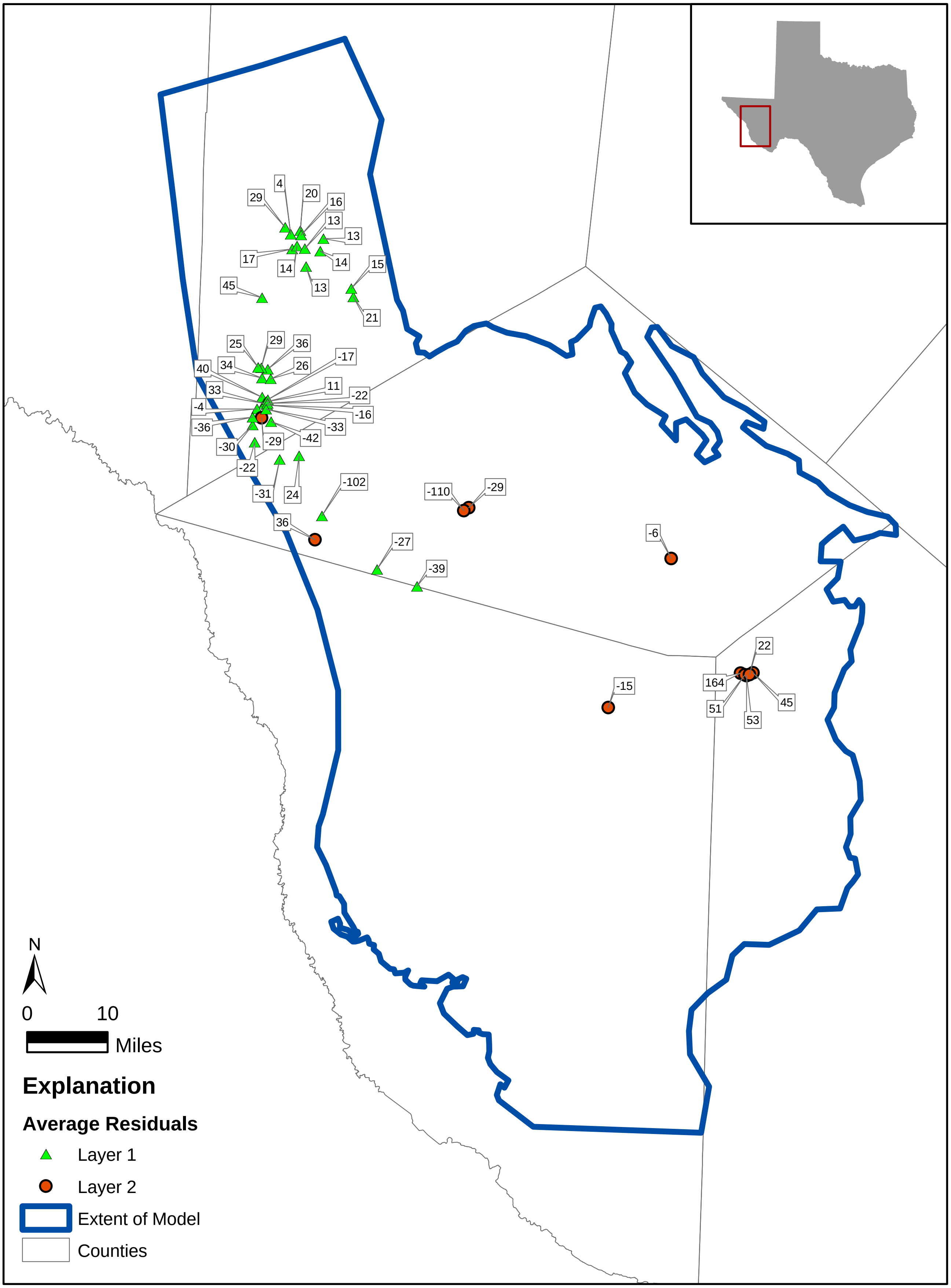


Figure 9.2.3 - Average Residuals for the Calibrated Model in Layer 1 and Layer 2

9.2.2 Hydraulic Heads

Figure 9.2.4 shows the simulated hydraulic heads and available residuals in layer 1 between 1950-2000. Figure 9.2.5 shows the simulated hydraulic heads and available residuals in layer 2 between 1950-2000. Figure 9.2.6 shows the simulated hydraulic heads in layer 3 between 1950-2000, but there are no available water level measurements for layer 3, so residuals could not be calculated. In general, the hydraulic head maps show very similar trends to the steady-state maps shown in Section 8.2. Flow directions are consistent with those discussed in Chapter 4.

Figures 9.2.7 through 9.2.10 show simulated and observed hydrographs for selected wells in different area of the model and include wells for the Igneous and Salt Basin Bolson aquifers. In general, there is good agreement between the observed and simulated water levels, but more importantly, the simulated trends are usually very similar to observed trends.

Figure 9.2.11 shows the simulated water level declines in layer 1 in 1990 and 2000. The declines in the Bolson are very consistent with the observed regional declines in water levels seen since the 1950s. Declines are largest in Lobo and Wild Horse Flats. Figure 9.2.12 shows the simulated water level declines in layer 2 in 1990 and 2000. The three “bulls-eyes” on the east side of the model reflect the drawdown associated with pumping for the cities of Fort Davis, Alpine, and Marfa. In addition, Bolson pumping in Lobo Flat has resulted in local declines in the Igneous in the Lobo Flat area. Figure 9.2.13 shows the simulated water level declines in layer 3 in 1990 and 2000. Like layer 2, the model indicates that water levels in layer 3 have also decreased due to historical pumping in Lobo and Wild Horse Flat. Because the Igneous is thinner or non-existent in this area, the impact to the underlying Cretaceous is more significant than in other areas of the model. The decline in the southwest corner of Presidio County is related to a small change in the extent of the overlying dry zone in the Igneous during the calibration and verification periods.

The twenty-four wells used as head calibration targets were selected to evaluate drawdown because these wells had the longest period of record. Twenty-one wells were located in the Bolson (Lobo and Wild Horse Flat) and three wells were located in the Igneous aquifer near the city of Alpine. For comparison purposes, simulated drawdowns were adjusted to account for the difference in the drawdown between 1950 (the beginning of the simulation) and the first water level measurement in each well. Figure 9.2.14 shows the crossplot of the simulated drawdowns and observed drawdowns for the 24 selected wells during the calibration and verification periods. The figure indicates that there is very good agreement between the simulated and observed drawdowns, which indicates that the model is suitable for predicting future drawdowns. Figure 9.2.15 shows the drawdown hydrographs for six of the twenty-four wells used in the analysis. The six wells are located in the Igneous aquifer (near Alpine) and in bolson aquifer in Lobo and Ryan Flats and indicate that the model simulates drawdown relatively well in these areas.

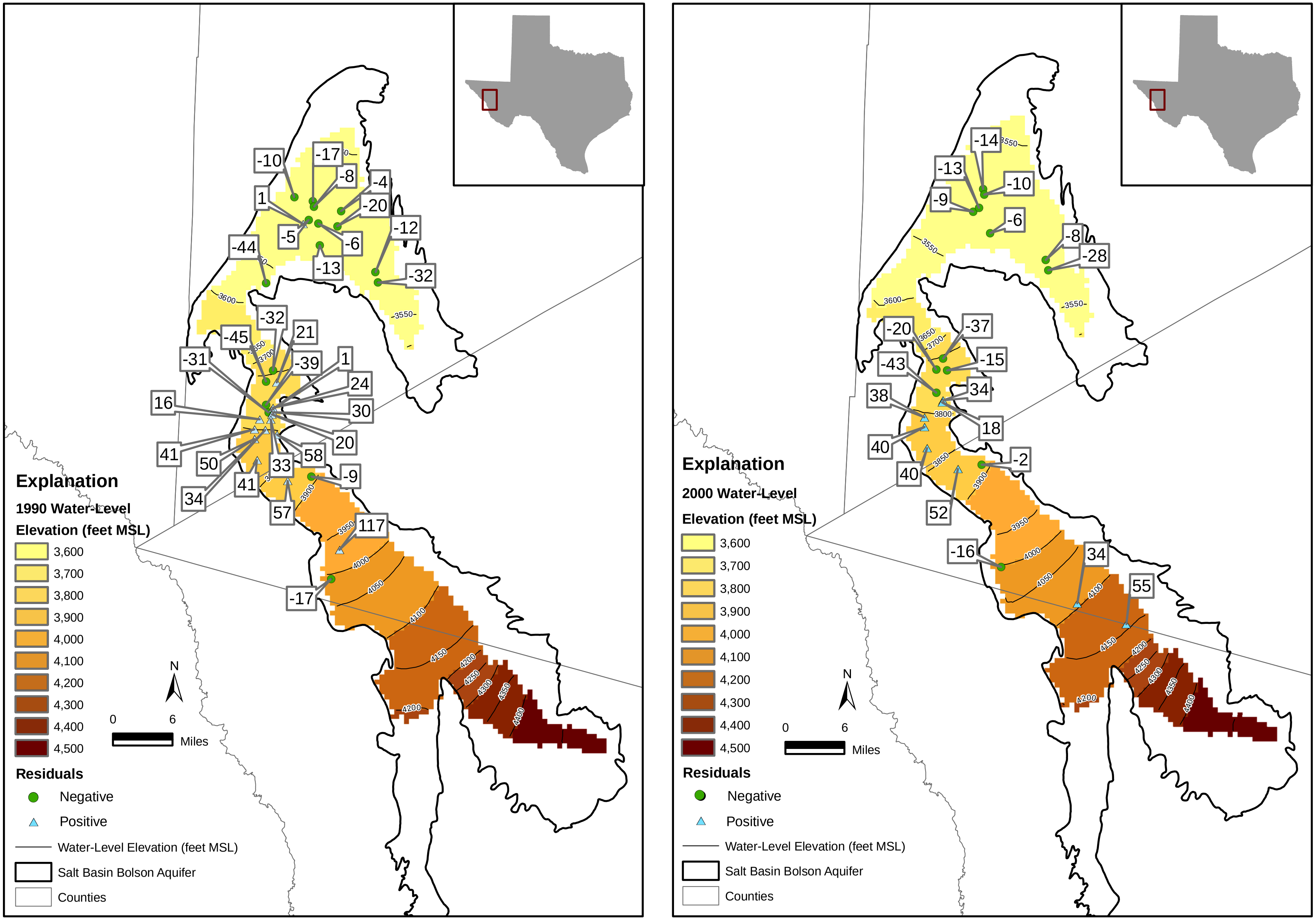


Figure 9.2.4 - Simulated Hydraulic Heads and Residuals in Layer 1 in 1990 and 2000

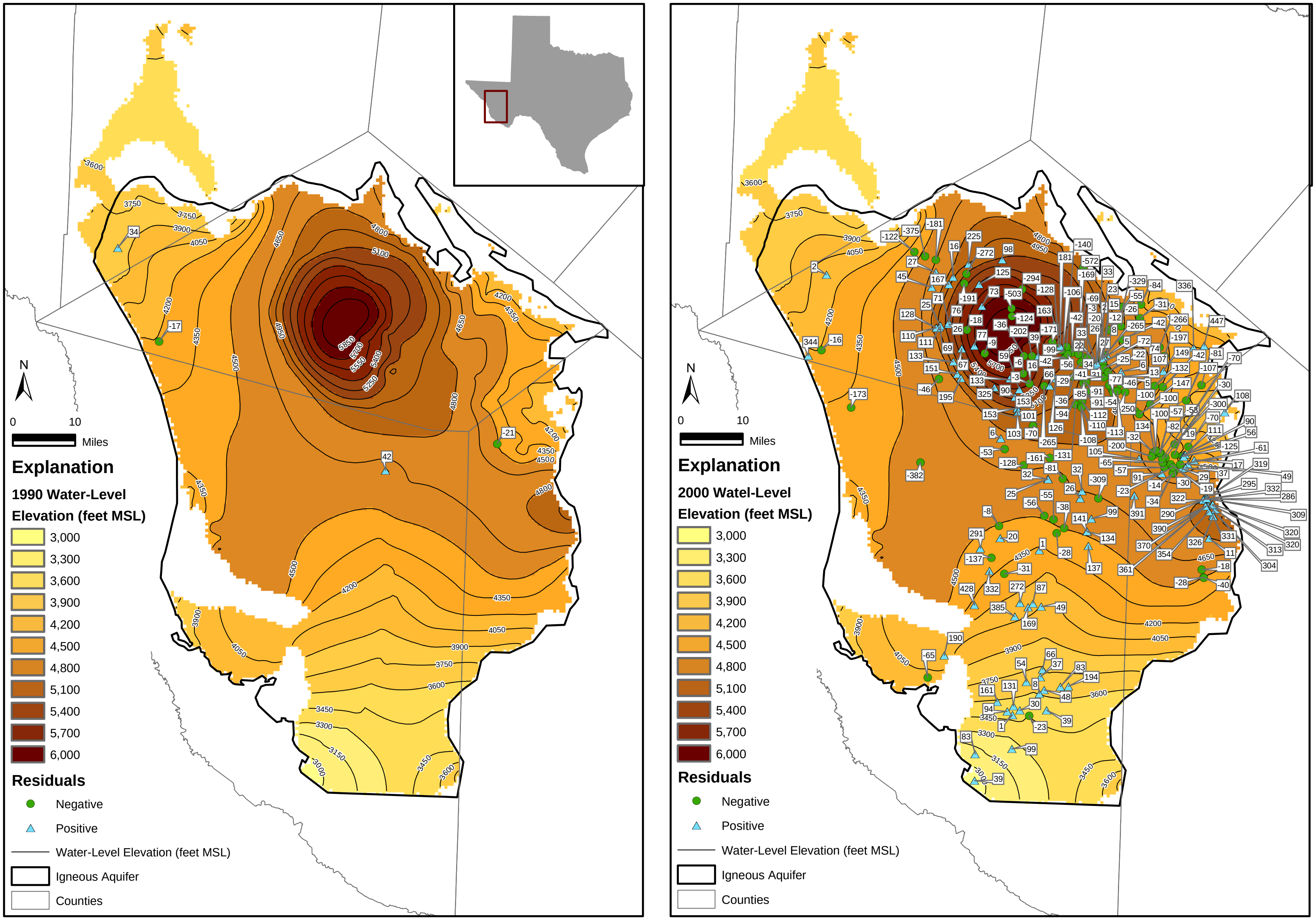


Figure 9.2.5 - Simulated Hydraulic Heads and Residuals in Layer 2 in 1990 and 2000

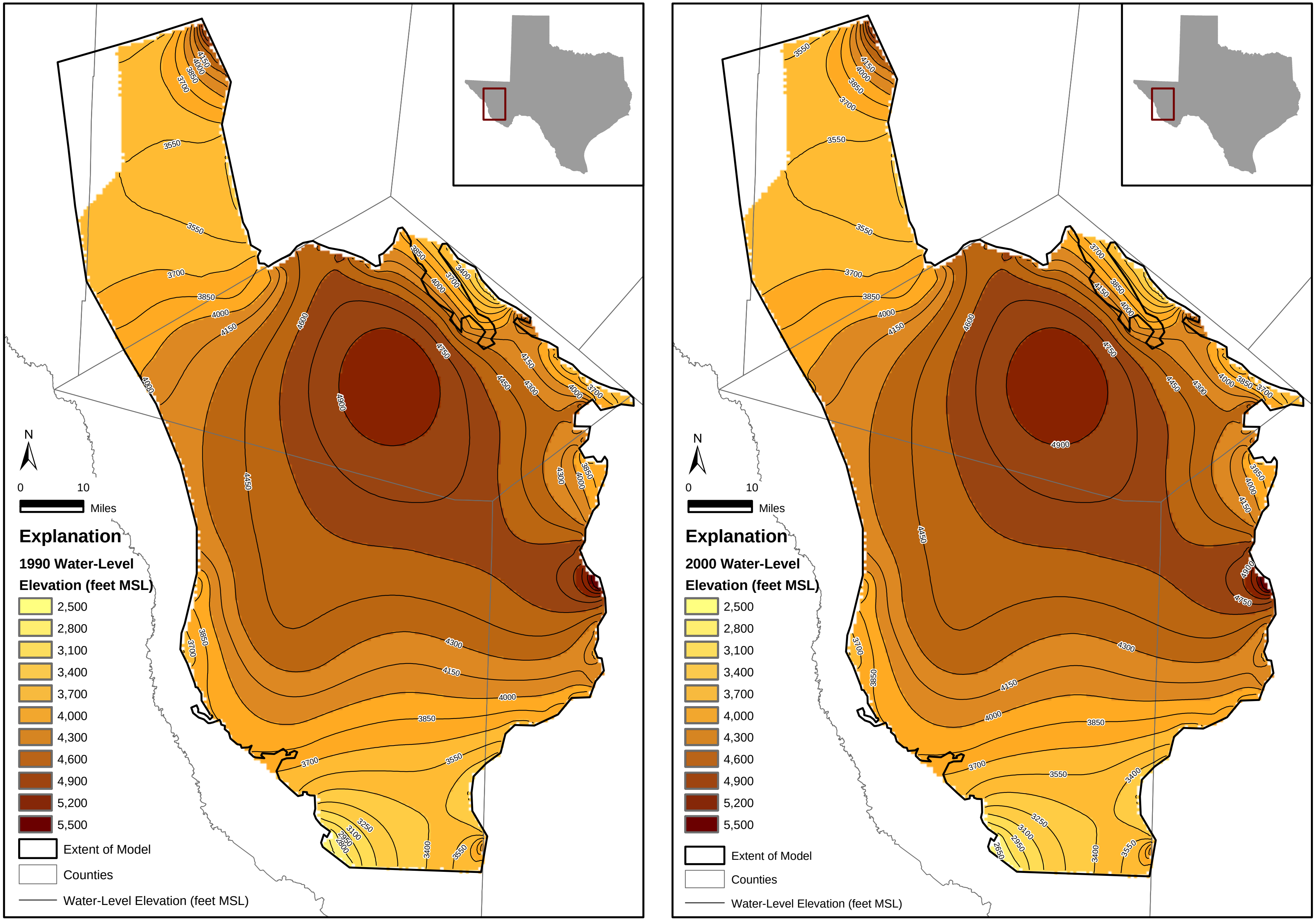


Figure 9.2.6 - Simulated Hydraulic Heads in Layer 3 in 1990 and 2000

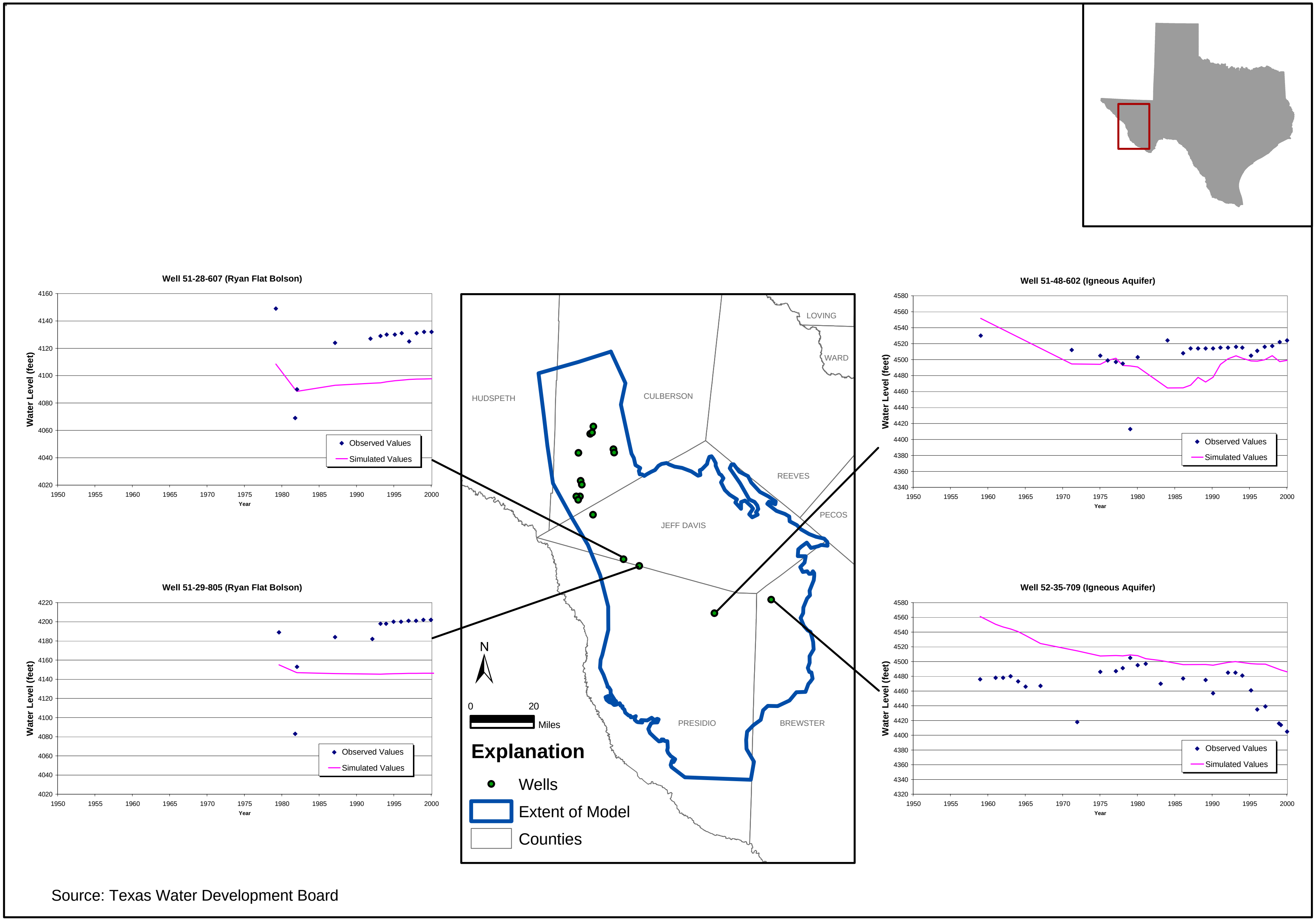
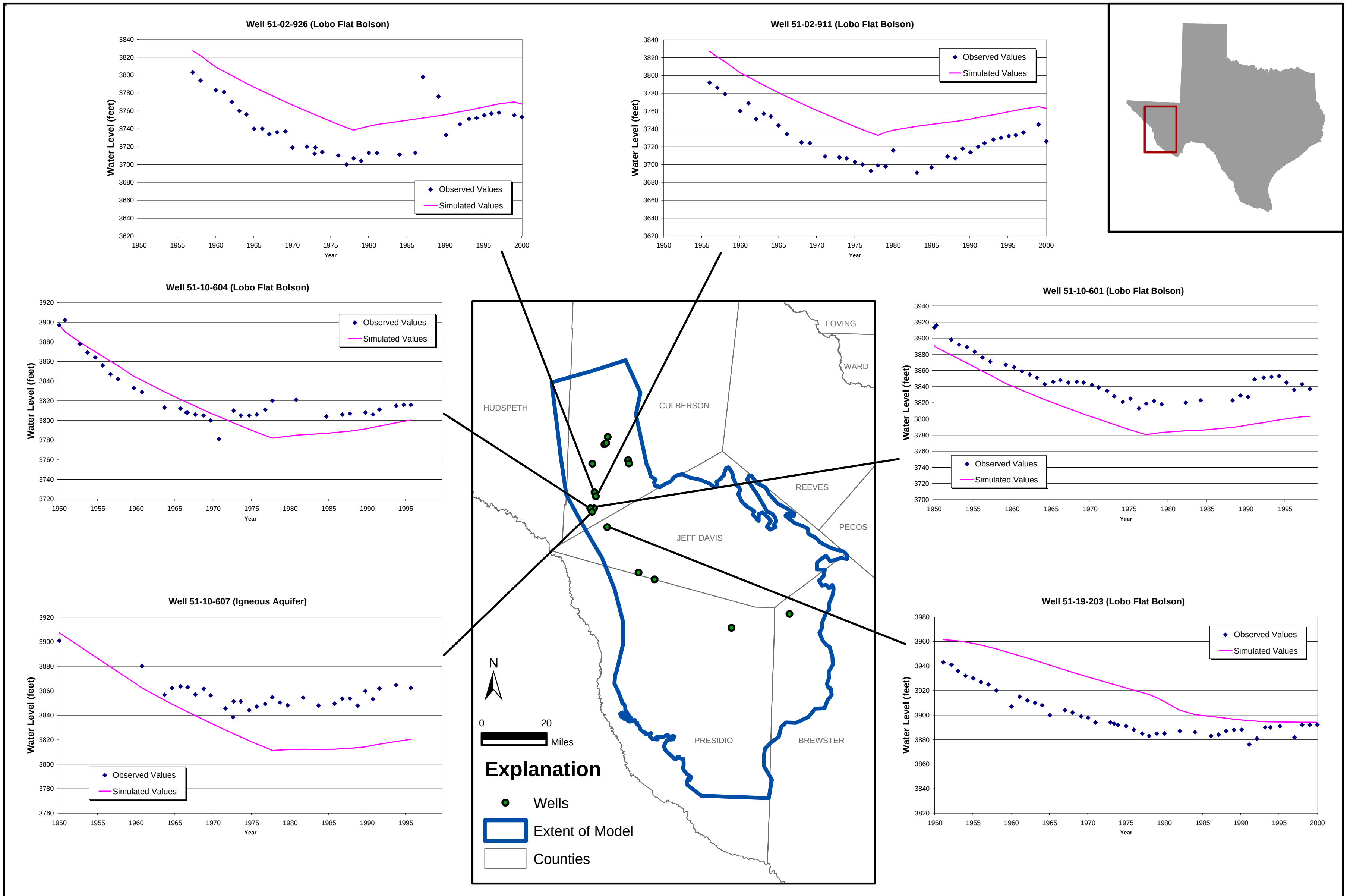
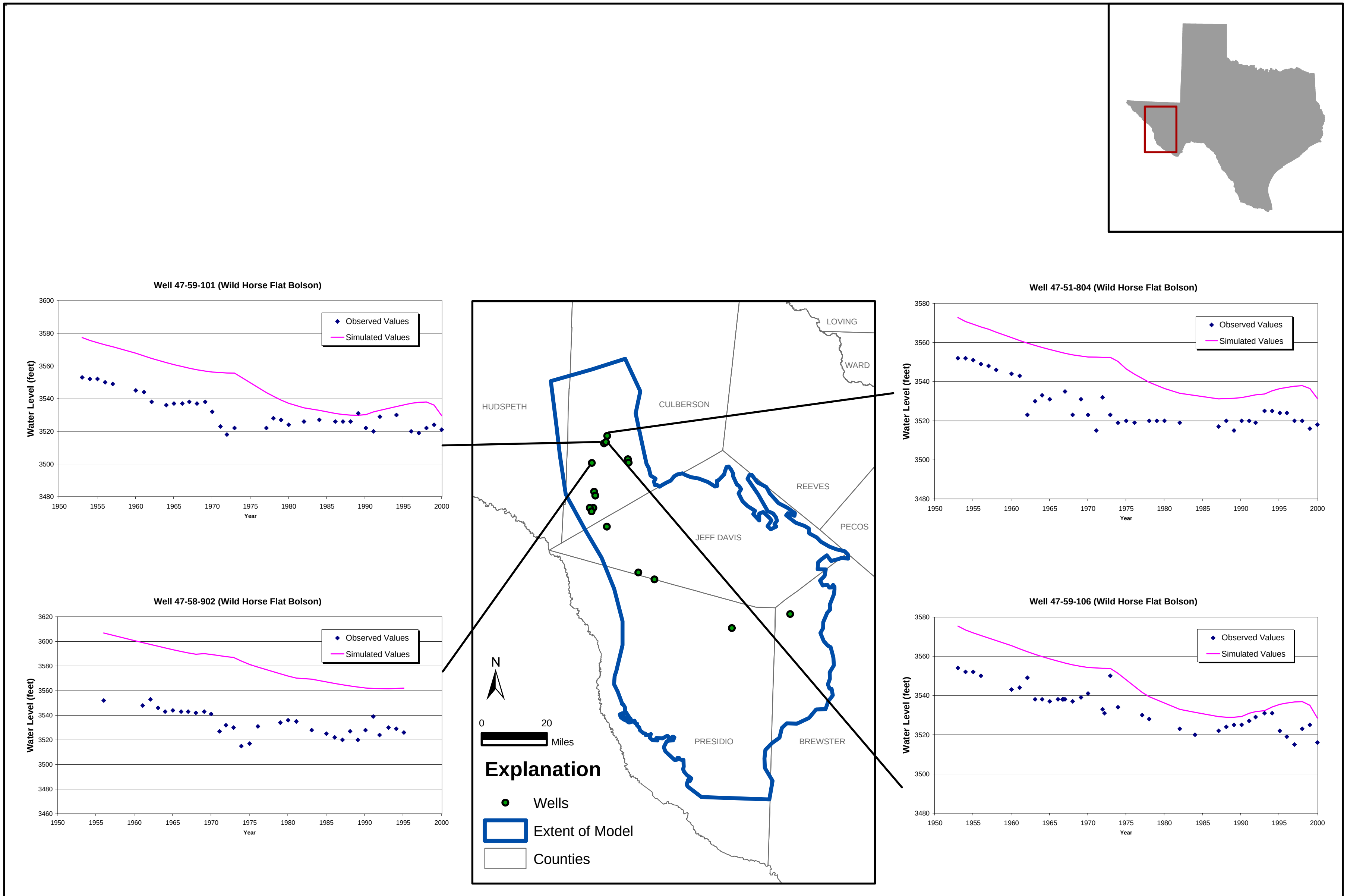


Figure 9.2.7 - Simulated and Observed Hydrographs Between 1950 to 2000 (Ryan Flat and Igneous Aquifer)



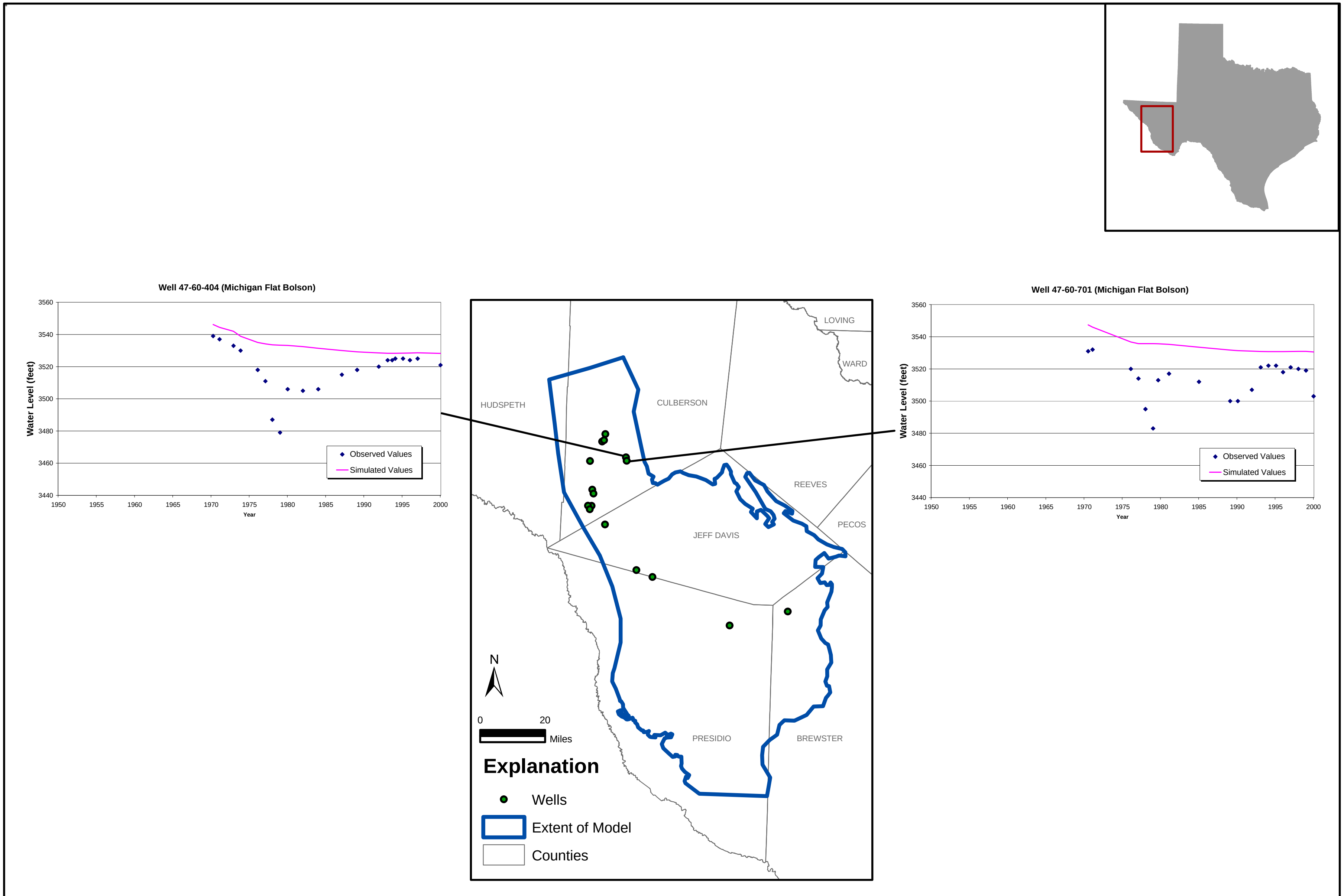
Source: Texas Water Development Board

Figure 9.2.8 - Simulated and Observed Hydrographs Between 1950 to 2000 (Lobo Flat)



Source: Texas Water Development Board

Figure 9.2.9 - Simulated and Observed Hydrographs Between 1950 to 2000 (Wild Horse Flat)



Source: Texas Water Development Board

Figure 9.2.10 - Simulated and Observed Hydrographs Between 1950 to 2000 (Michigan Flat)

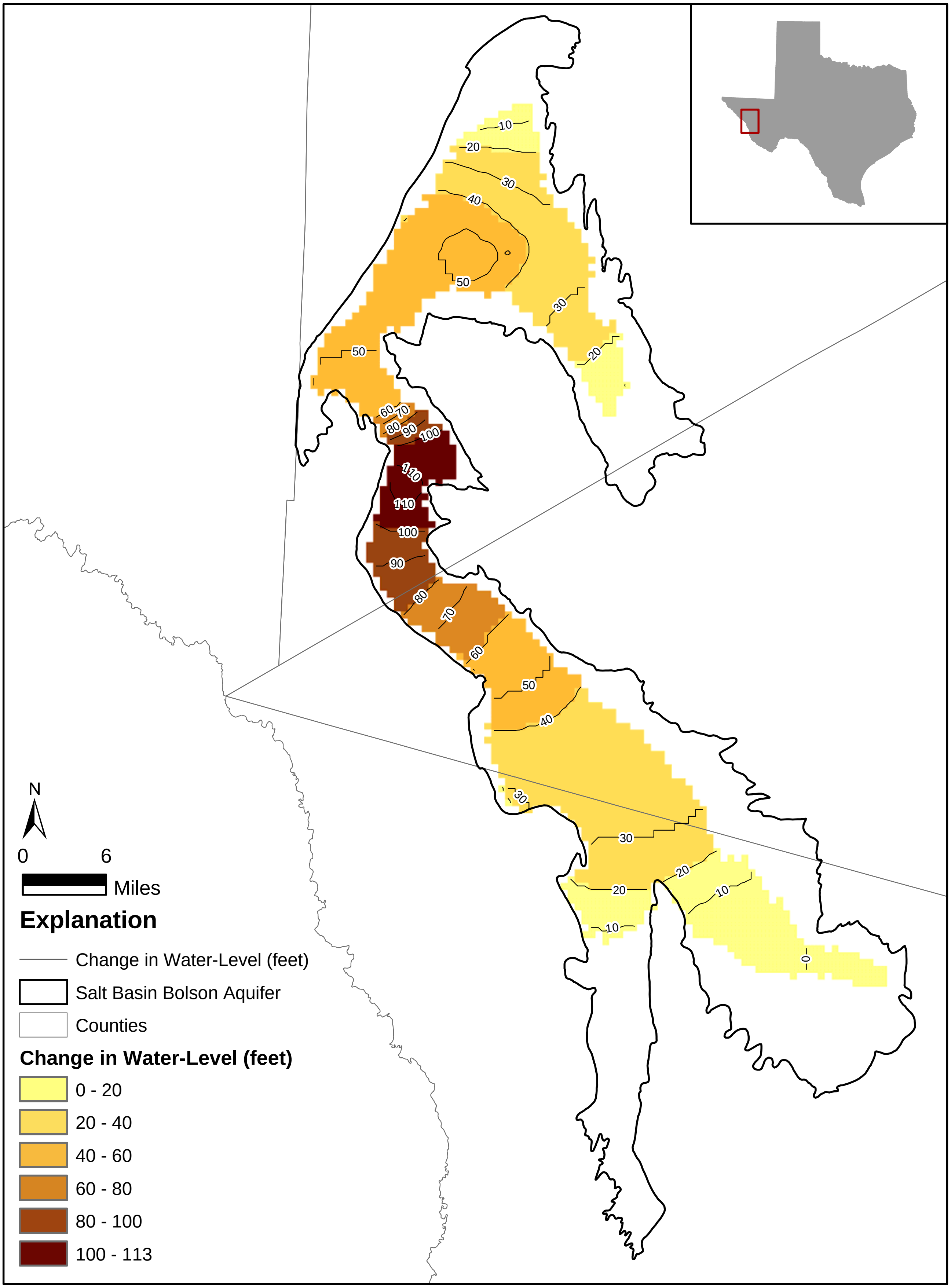


Figure 9.2.11 - Change in Water-Levels Between 1950 and 2000 in Layer 1

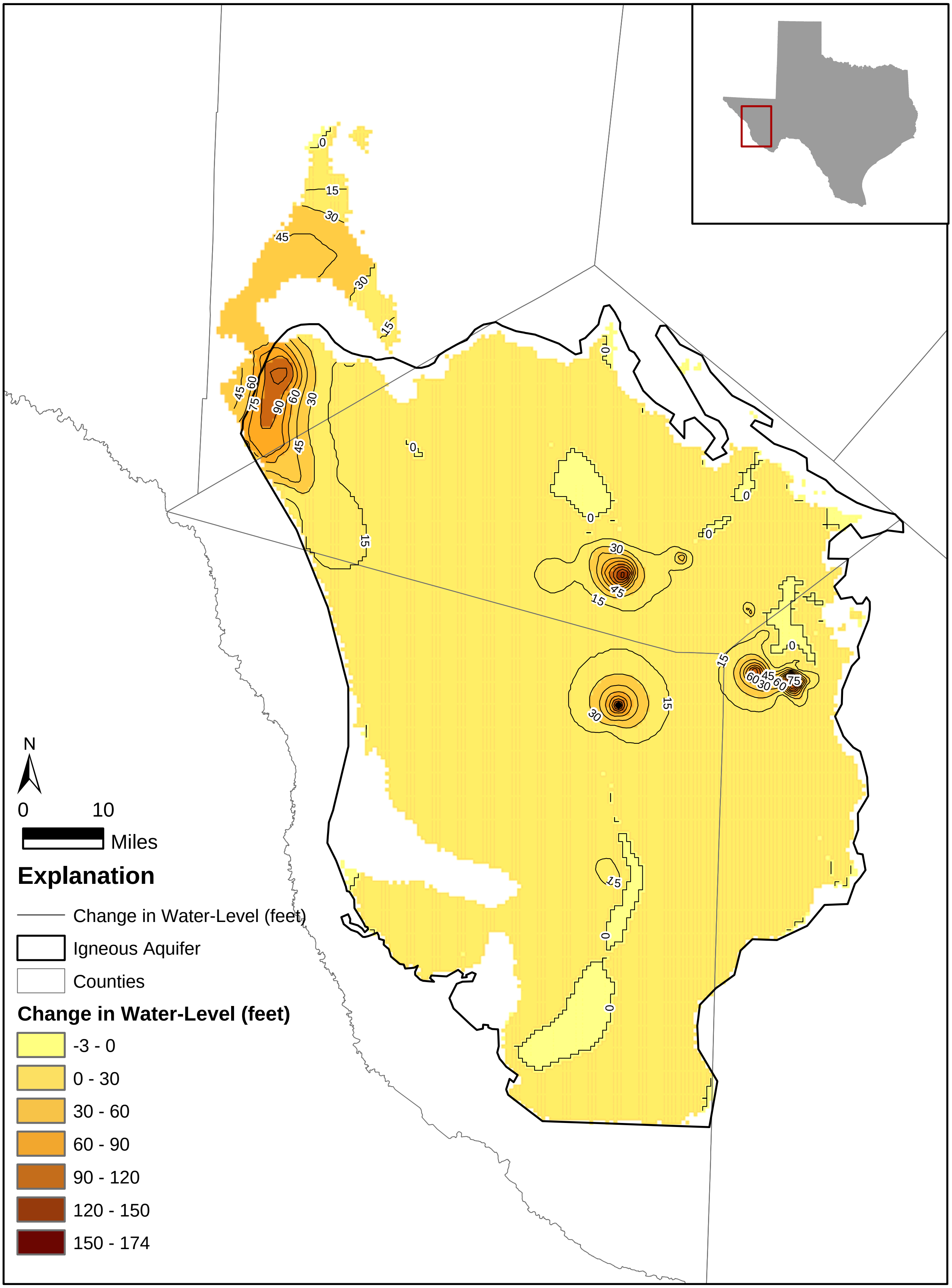


Figure 9.2.12 - Change in Water-Levels Between 1950 and 2000 in Layer 2

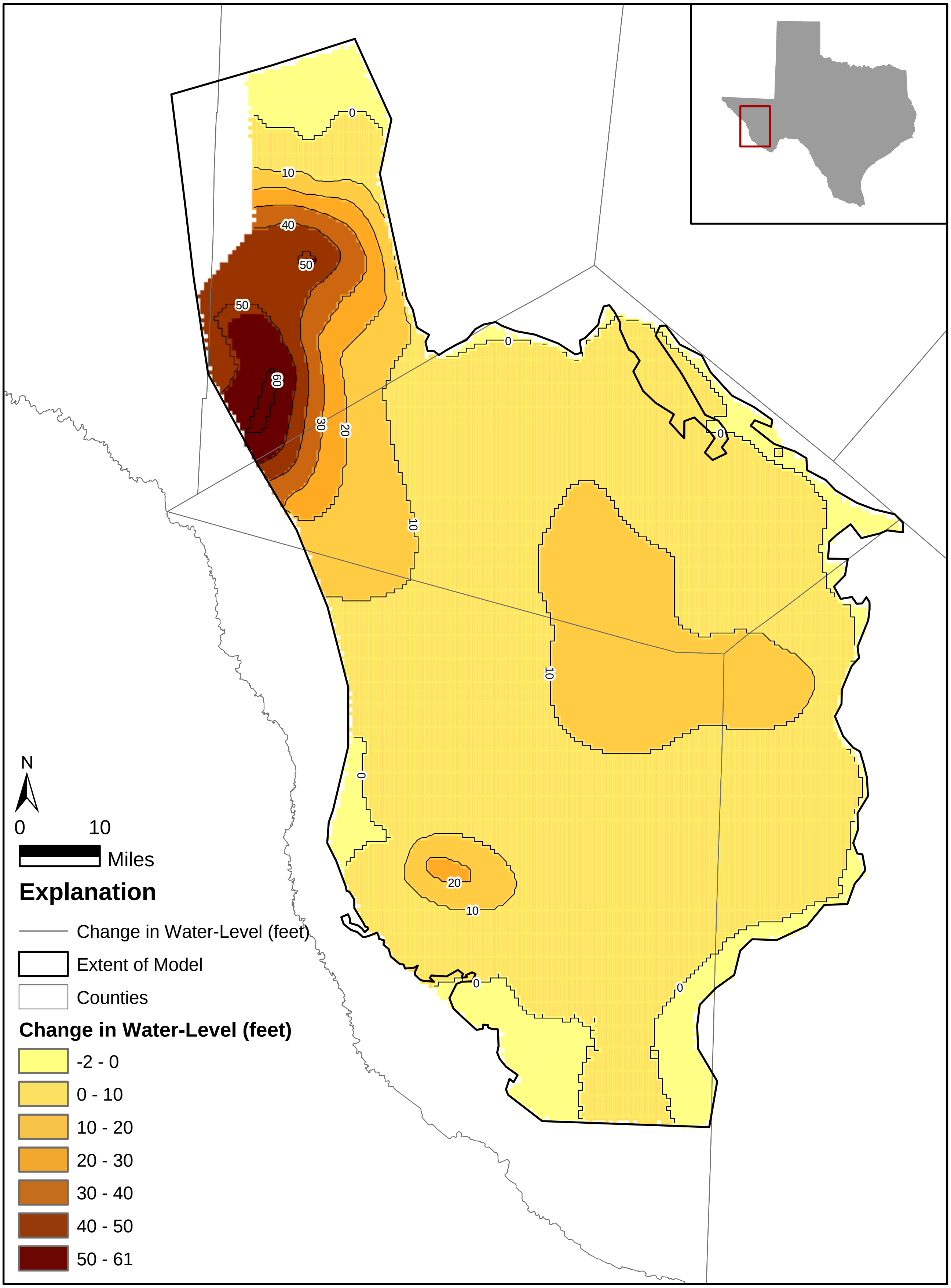


Figure 9.2.13 - Change in Water-Levels Between 1950 and 2000 in Layer 3

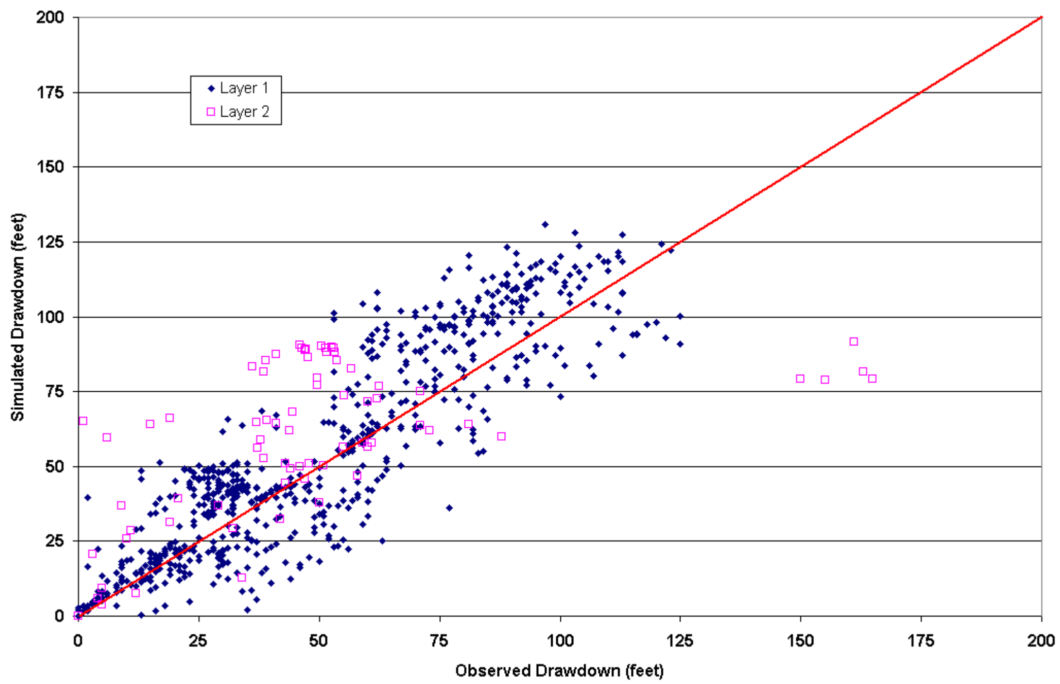


Figure 9.2.14 Crossplot of simulated versus observed drawdowns during the calibration and verification periods

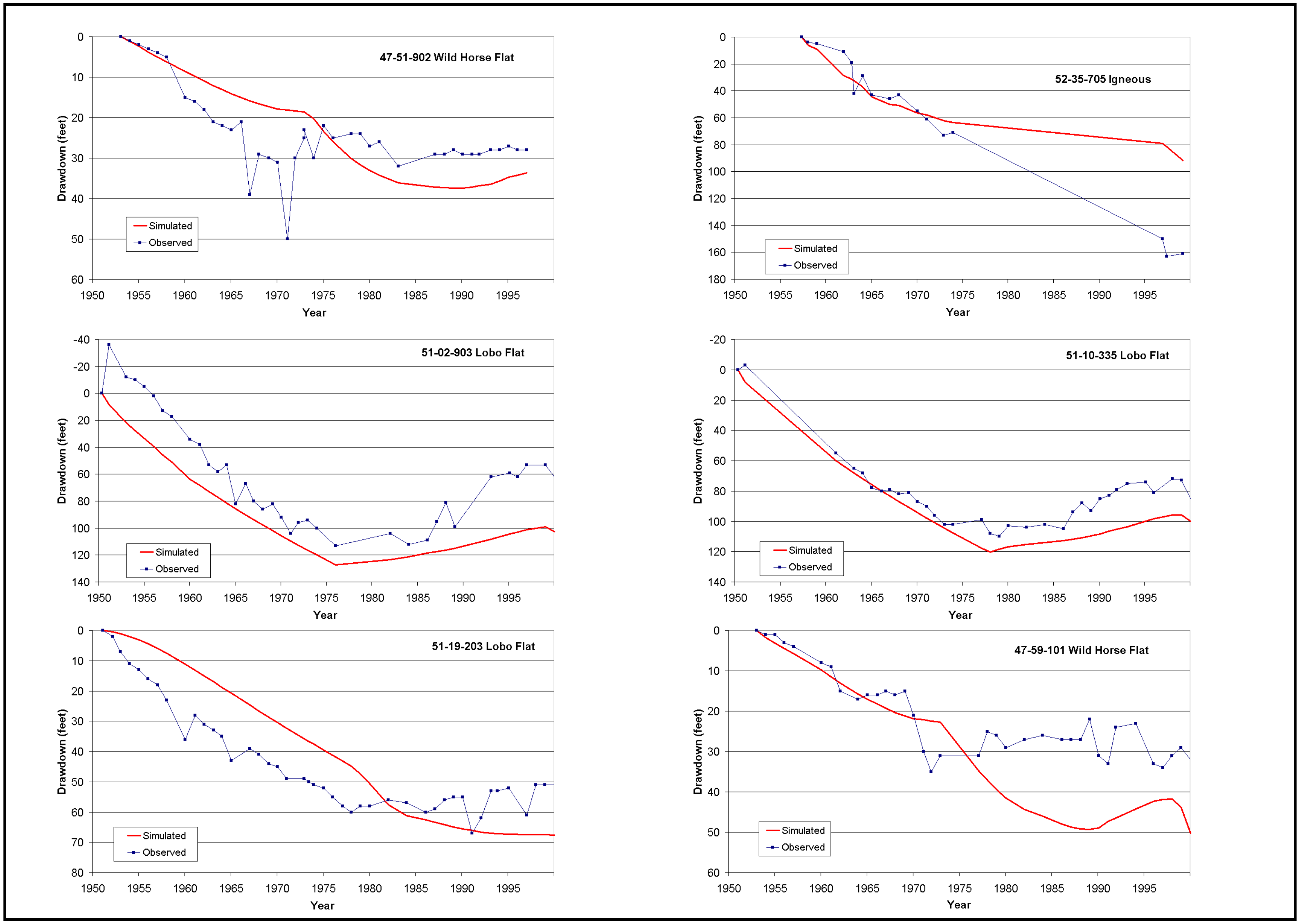


Figure 9.2.15 Drawdown hydrographs for selected wells

9.2.3 Water Budget

Figures 9.2.16, 9.2.17, and 9.2.18 provide a graphical summary of the water budget components for layers 1, 2 and 3 respectively during the transient calibration and verification periods. The major changes in the layer 1 flow components are pumping and associated changes in aquifer storage. Another component that changes is the outflow from drains located in Wild Horse Flat that represent flow out of the Bolson to the southeast toward Balmorhea. The flow out of this boundary drops from about 2100 acre-feet per year in 1950 to zero by the mid 1970s.

Layer 2 flow components show some temporal variation due to changes in the recharge. The change in the recharge on a yearly basis is mimicked by a corresponding change in the aquifer storage due to increasing water levels. During years when recharge increases from the previous year, there is a corresponding increase in storage (shown on the graph as a decrease in storage outflow). This response is consistent with the conceptual model for the Igneous aquifer in regard to the relative stability of water levels in the past except in areas where municipal pumping has caused some persistent water level declines. Layer 3 flow components show almost no change through time, which is expected because in most cases, it is not heavily pumped and generally does not receive direct recharge in the model area.

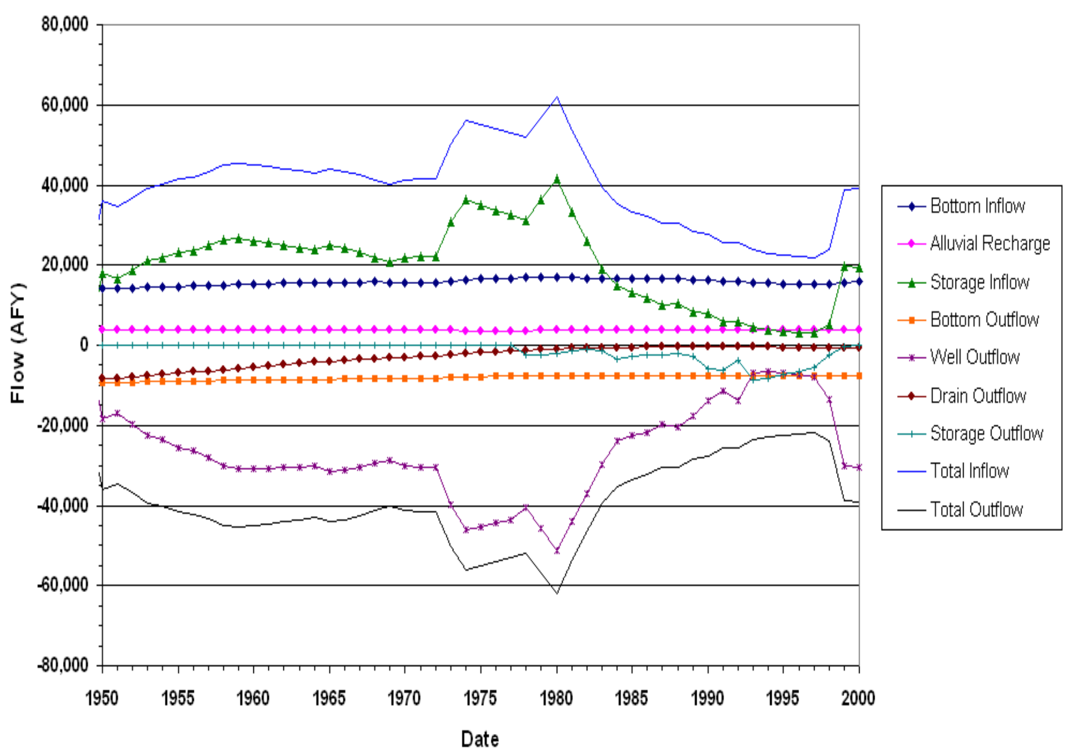


Figure 9.2.16 Water budget components between 1950 and 2000 for Layer 1

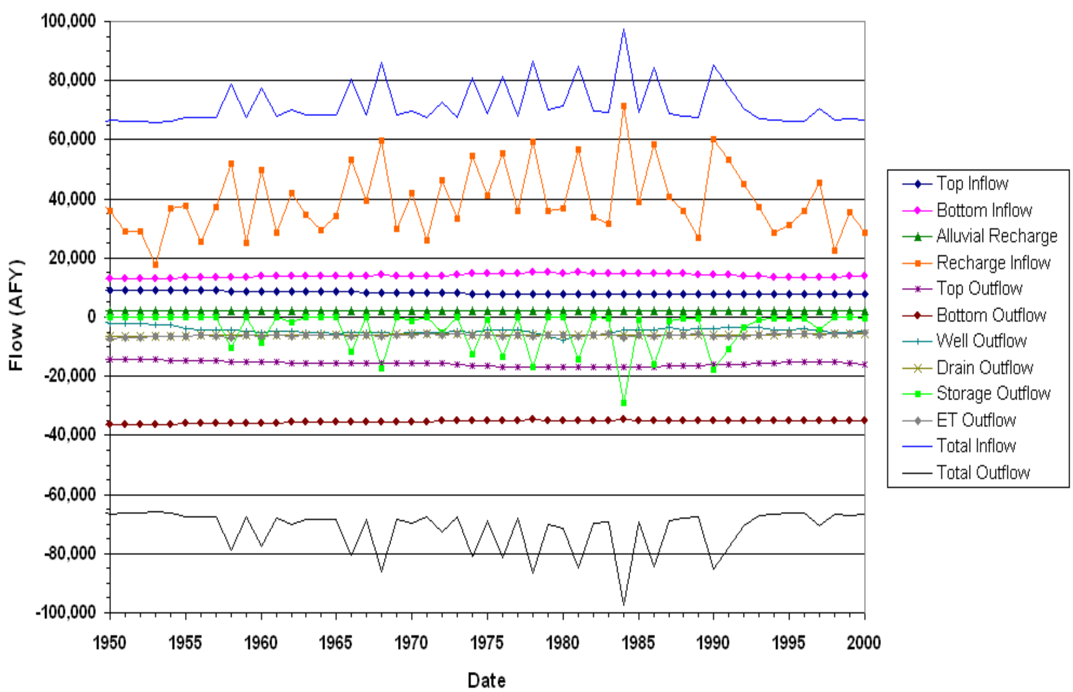


Figure 9.2.17 Water budget components between 1950 and 2000 for Layer 2

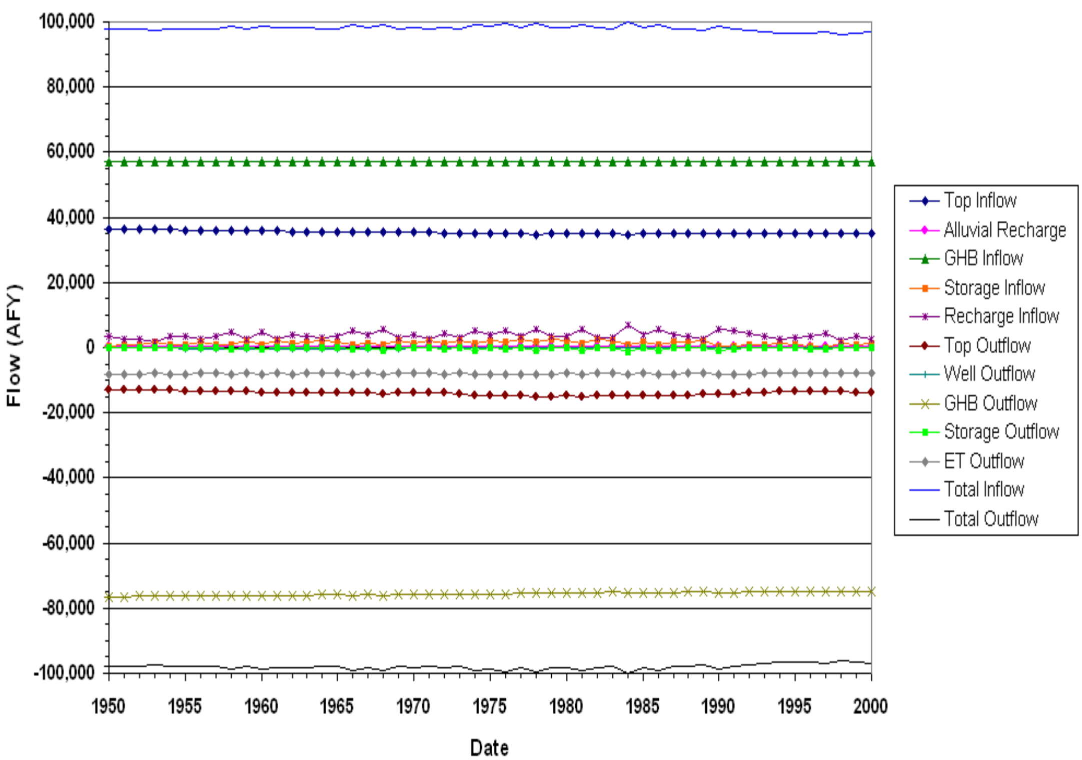


Figure 9.2.18 Water budget components between 1950 and 2000 for Layer 3

9.3 Sensitivity Analysis

A sensitivity analysis was performed on the calibrated transient model to provide a summary of the sensitivity of the model to changes in individual input parameters. For this analysis, model parameters were globally adjusted from their calibrated values and the results of average head change in each layer were calculated. As in the steady-state sensitivity evaluation, the model parameters were adjusted +/- 10% and +/- 20% from their calibrated value, and, where appropriate, order-of-magnitude changes where made to the lognormal parameter values. This sensitivity analysis helps to identify the hydrologic parameters which have the most influence on the hydrologic system being modeled and can help assess which parameters should be better determined in future field studies in order to lower the model uncertainty. A summary of the transient sensitivity analysis is provided below.

For the transient analysis, the sensitivity of seven parameters was evaluated. The seven parameters are:

1. Horizontal hydraulic conductivity,
2. Vertical hydraulic conductivity,
3. Recharge,
4. GHB Head,
5. GHB Conductance,
6. Specific yield (unconfined), and
7. Storativity (confined).

In general, there are many similarities between the results of the steady-state and the transient sensitivity analysis. As shown in Figure 9.3.1, horizontal hydraulic conductivity is still negatively correlated to heads in layer 1. As with the steady-state analysis, the most sensitive positively correlated parameter is GHB head. Parameters which are positively correlated to a lesser degree are recharge and vertical hydraulic conductivity. Of the two storage properties assessed herein, specific yield has more influence on average head than does storativity. This makes sense because there is very little stress in layers 2 and 3, where the storativity would have an impact. The least sensitive parameter is GHB conductance.

Figures 9.3.2 and 9.3.3, which illustrate sensitivity in layers 2 and 3, indicate the same type of correlation as layer 1 except that the positive correlation of the GHB head is even more significant. As was the case in layer 1, the storage properties have little impact on heads in layers 2 and 3 because there is very little water level change in those layers. Figure 9.3.4 compares the change in head in each layer based on global changes in horizontal hydraulic conductivity. The sensitivity of head in each layer is very similar given global changes in horizontal hydraulic conductivity. Figure 9.3.5 shows the sensitivity of hydrographs to global changes in horizontal hydraulic conductivity. The three hydrographs selected are in the Salt Basin Bolson aquifer and are located in Ryan Flat, Wild Horse Flat, and Lobo Flat. These hydrographs indicate that the heads in Ryan Flat are most sensitive to global changes of horizontal hydraulic conductivity, followed by Lobo and Wild Horse Flats. This relationship exists because Wild Horse Flat is located in the lowest part of the hydraulically connected Bolson, and next highest is Lobo, followed by Ryan Flat, which is at the highest elevations. If the simulated Bolson hydraulic conductivity is too high during the steady state calibration period, water simply drains from the highest elevation (Ryan Flat) to the lowest elevation (Wild Horse), and this has more of an impact at the highest elevations than at the lowest. Therefore, there is a larger sensitivity to horizontal hydraulic conductivity changes in Ryan Flat than in the lower flats of the aquifer.

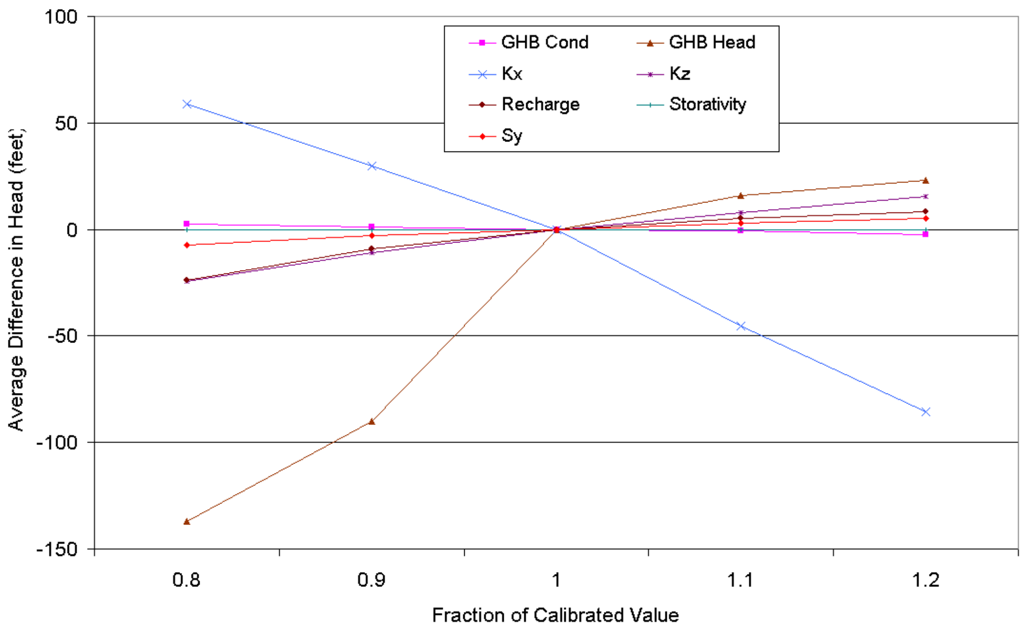


Figure 9.3.1 Transient sensitivity results for Layer 1

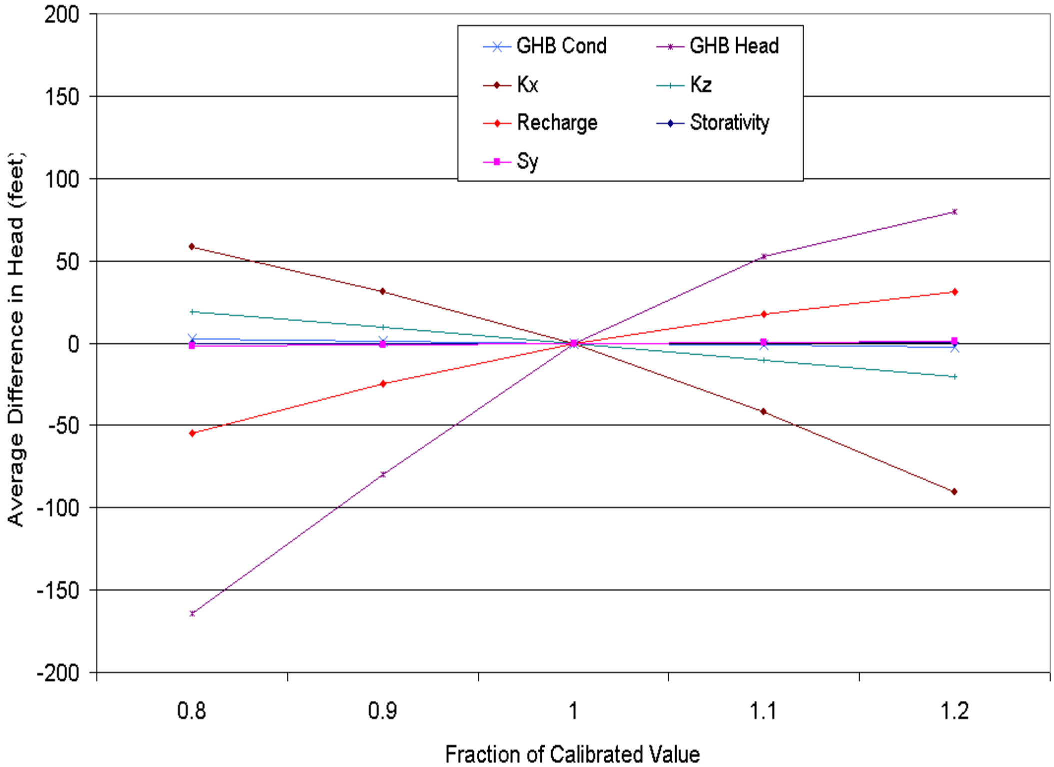


Figure 9.3.2 Transient sensitivity results for Layer 2

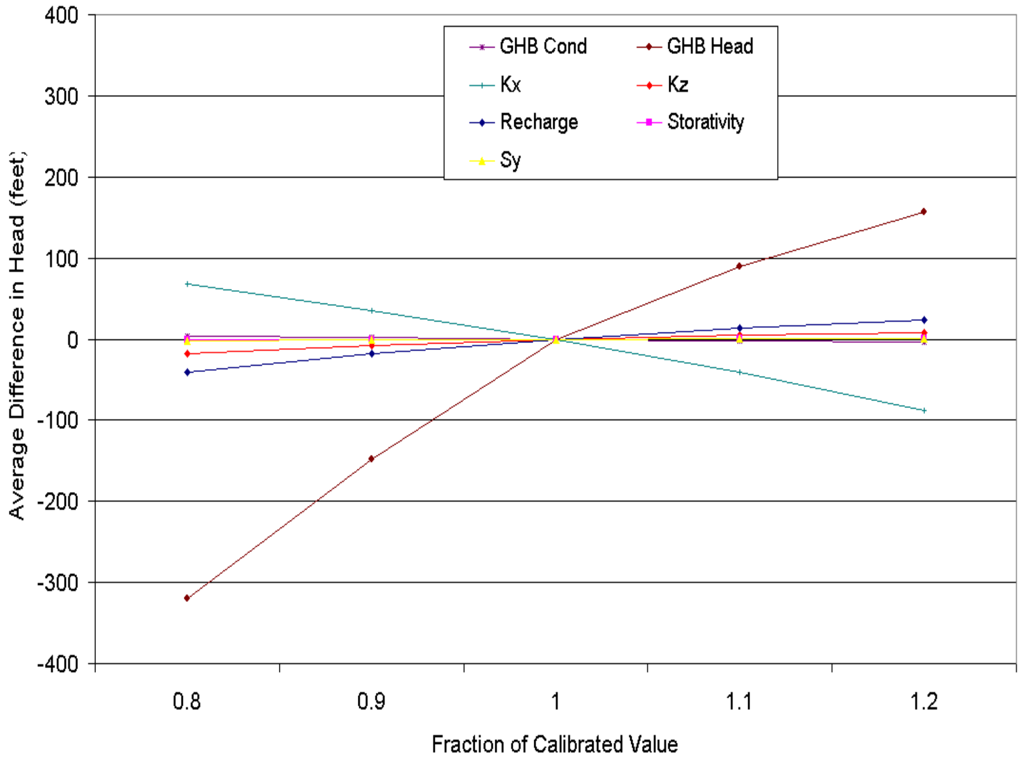


Figure 9.3.3 Transient sensitivity results for Layer 3

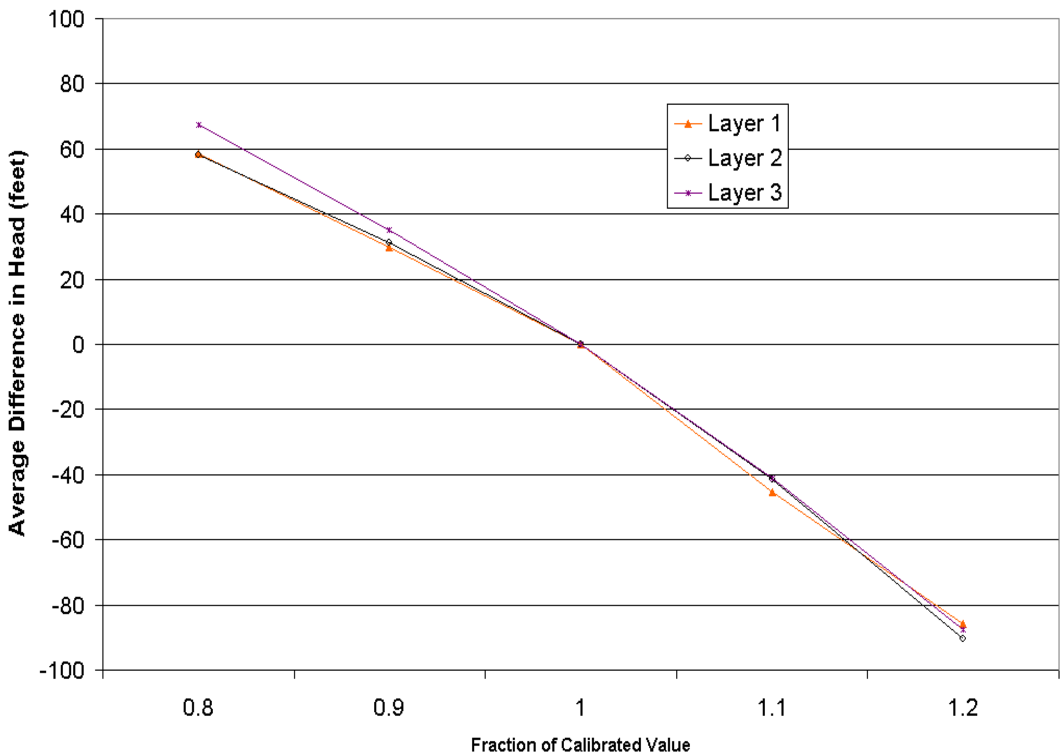


Figure 9.3.4 Transient sensitivity results where horizontal hydraulic conductivity is varied

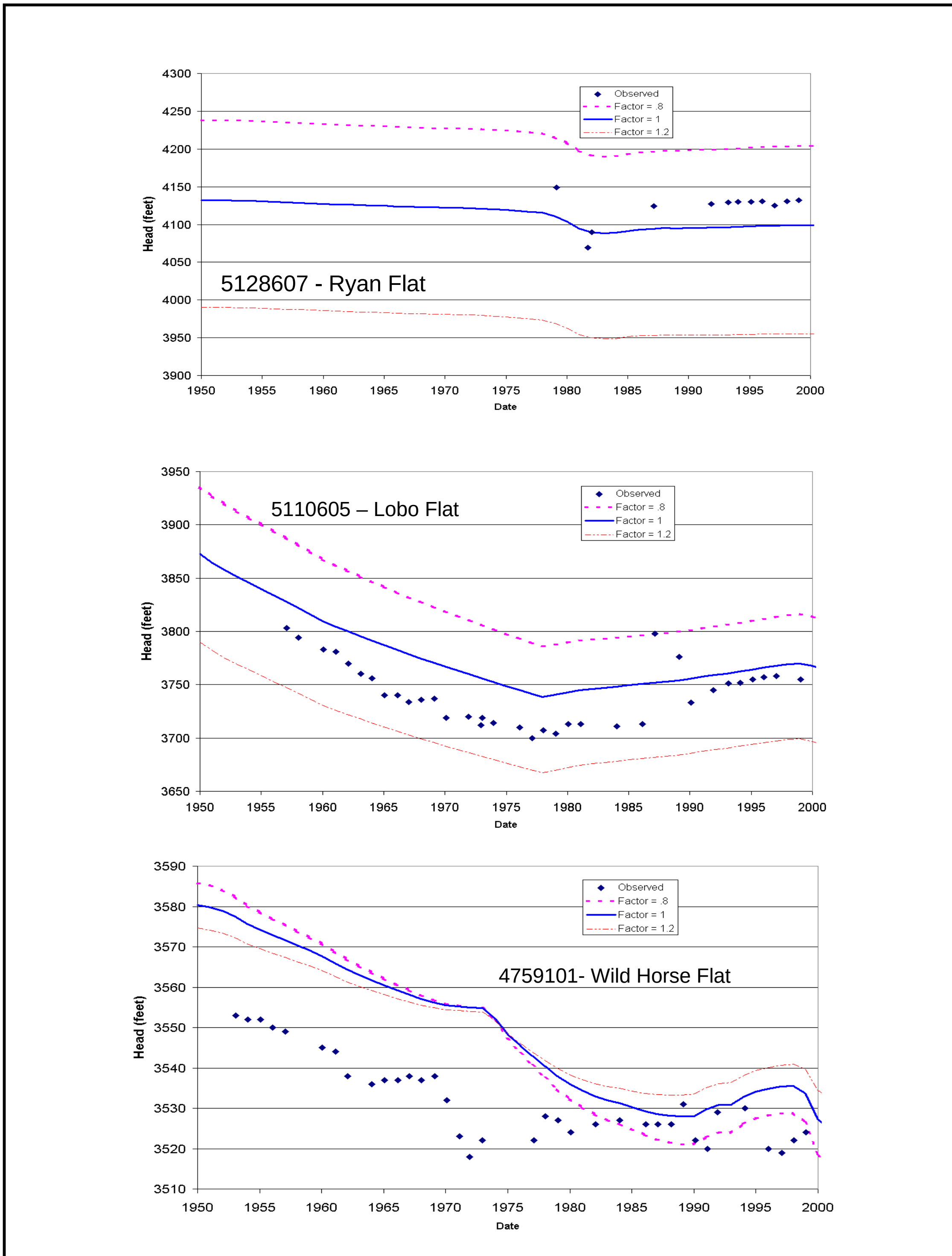


Figure 9.3.5 Transient sensitivity hydrographs for Layer 1 where horizontal hydraulic conductivity is varied

10.0 PREDICTIONS

The IBGAM was used to model the change in water levels and fluxes in the aquifer over a 50-year planning period (2001-2050) using water demand projections developed by the Region E (Far West Texas) regional water-planning group (RWPG) under average and drought-of-record (DOR) conditions. This section details the results of the predictive simulations.

Six predictive simulations were completed: (1) average recharge through 2050, (2) average recharge ending with the DOR in 2010, (3) average recharge ending with the DOR in 2020, (4) average recharge ending with the DOR in 2030, (5) average recharge ending with the DOR in 2040, and (6) average recharge ending with the DOR in 2050. During the predictive simulations, estimates of pumping (quantity and location) were based on projections developed by the Region E RWPG and documented in the 2002 State Water Plan for Texas (TWDB, 2002). With the exception of recharge, all other hydrologic conditions including groundwater evapotranspiration (ET), spring and streamflow (represented by drains), and lateral flow boundary conditions (general head boundaries) were held at conditions identical to 2000 during the predictive simulation.

10.1 Drought of Record and Projected Pumping

Drought is a normal, recurring climatic event. It is conceptually defined by the National Drought Mitigation Center as a protracted period of deficient precipitation, usually over a season or more, resulting in a water shortage for some activity, group, or environmental sector. The TWDB GAM protocol specifies that the drought-of-record should be based on the past 100 years (or longest period of record) and should consider severity and duration. Drought is related directly to precipitation, which is the primary variable controlling recharge in the model region. Therefore, precipitation data were used to define the drought-of-record in the study area.

Drought indices are quantitative measures, which assimilate climatic data into a single value, which defines how precipitation has varied from the “average” or normal condition. Several drought indices are typically used to measure the degree of drought that a region experiences. A common measure is “percent of normal” precipitation, which is calculated by dividing the measured annual precipitation by the average annual precipitation and multiplying by 100. Many precipitation gages in the model area only have consistent records since 1950. Evaluation of dry periods documented by TWDB (1966) indicated that droughts prior to the 1950s were less severe than the drought of the 1950s. Therefore, precipitation records from four gages containing data from 1950 to 2000 were evaluated to assess the DOR for the model area.

Figure 10.1.1 shows the precipitation records for the Candelaria, Alpine, Mt. Locke, and Valentine gages, and the average for all four gages. These graphs indicate that the drought of the 1950s was the longest and most severe drought period in the area between 1950 and 2000. The graphs show that precipitation was significantly lower than normal for several gages in the model area. Some locations have other periods which may be nearly as severe as the 1950s drought, for example the 1960s drought in Candelaria (nearly an extension of the 1950s drought), or the 1990s drought in many locations. However, none of these are as severe or consistent across the region as the 1950s drought.

From a precipitation perspective, the drought started in the 1951, was most severe in 1954 and continued through 1957 for a total of seven years. The severe drought conditions in the 1950s were consistently recorded by the precipitation gages in the model region. The average precipitation, as measured in percent of normal averaged across the four gages, is less than 80 percent of normal for every year from 1951 through 1957, and averages only 67 percent of normal from 1950 to 1957. The driest years during the drought in the study area were 1953 and 1956, with 47 percent and 42 percent of normal precipitation, respectively. Therefore, the drought-of-record was defined for this model as the seven-year period inclusive of 1951 through 1957, when the precipitation ranged from 42 to 80 percent of normal and averaged 65 percent of normal.

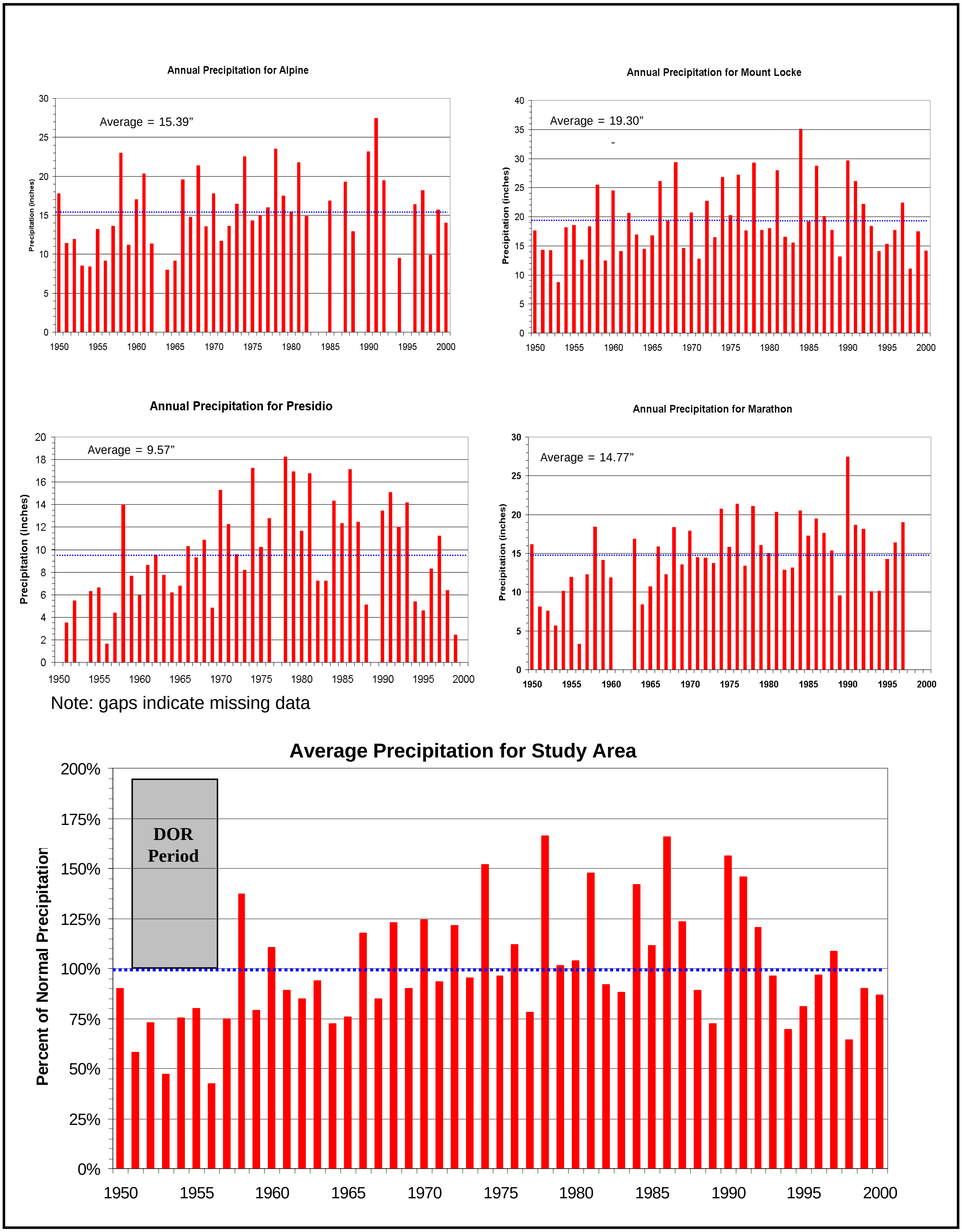


Figure 10.1.1 Annual precipitation for four precipitation gages in the study area, and average for all four gages

The other factor that was modified during the predictive simulations was pumping. Figure 10.1.2 shows the total projected pumping in the study area between 2001 and 2050. As stated above, estimates of pumping (quantity and location) were based on projections developed by the Region E (Far West Texas) RWPG. Appendix C contains a detailed description of how predictive pumping was allocated throughout the model.

As shown in Figure 10.1.2, total pumping is projected to increase in the model area from about 20,000 to over 60,000 acre-feet per year based on anticipated demands. As shown in Figure 10.1.3, most of the increased pumping is projected to come from Jeff Davis and Presidio Counties. In 2020, a regional water strategy is projected to begin pumping groundwater from Antelope Valley Farm in Ryan Flat. Antelope Valley Farm straddles the Presidio and Jeff Davis county line, and therefore, there is a corresponding increase in pumping from both those counties based on the estimated production from the well field between 2020 and 2050. Details of this strategy are discussed in Appendix C.

The total projected groundwater use in Culberson County decreases slightly over the 50-year prediction period and Brewster County pumping increases slightly. The projected pumping estimates for Culberson County after 2000 are significantly less than some historical estimates. Figure 4.1.22 indicates that estimated historical pumping in Culberson County is over 30,000 acre-feet per year in 1999 and 2000. However, the projected pumping for Culberson County in (Figure 10.1.3) is less than 10,000 acre-feet per year. The impact that the difference between the historical and future pumping have on the model results are discussed more in Section 10.2.

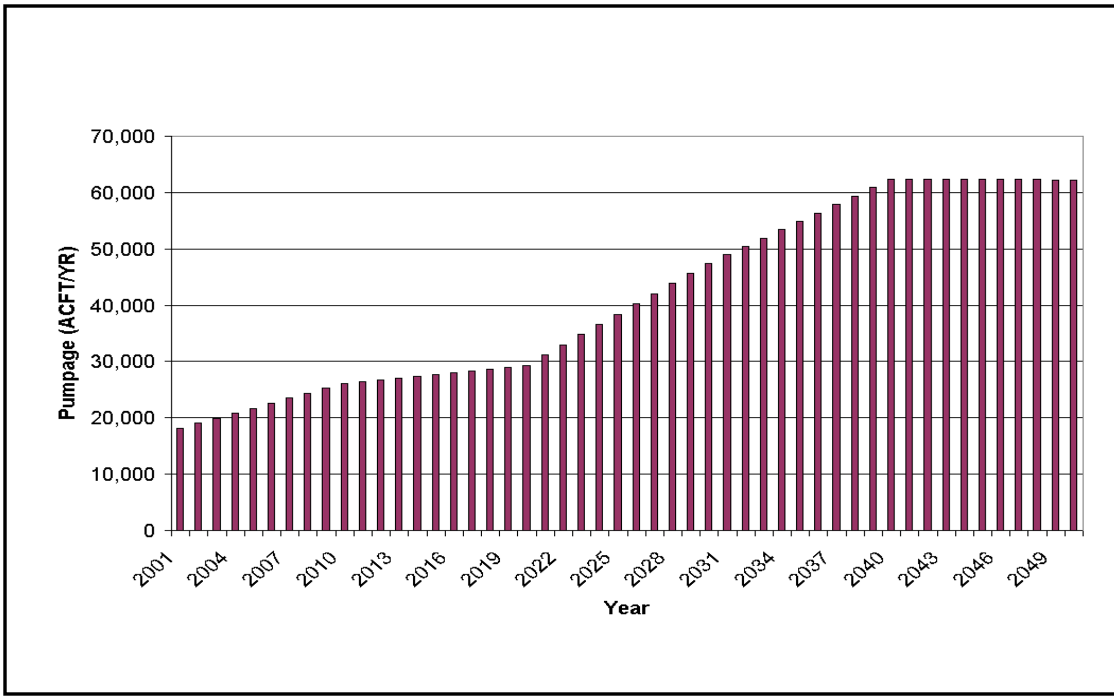


Figure 10.1.2 Total projected pumping in the study area between 2001 and 2050

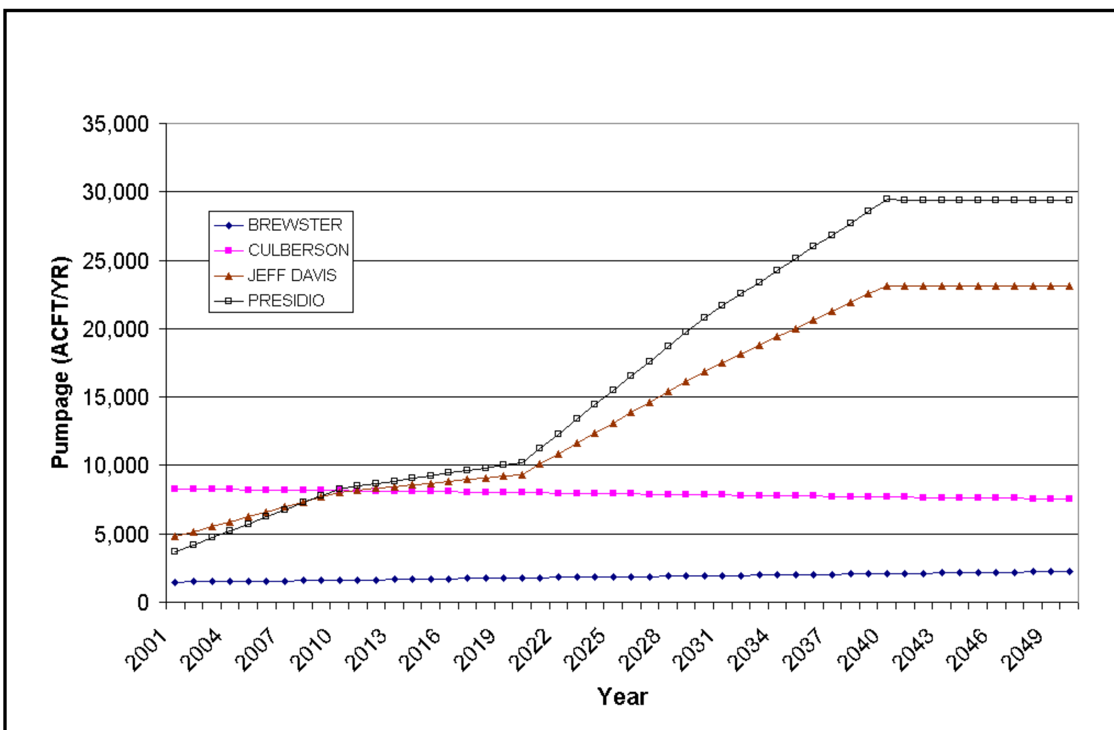


Figure 10.1.3 Projected pumping by county between 2001 and 2050

10.2 Predictive Simulation Results

Each of the predictive simulations is described below. It should be noted that there are a few gridblocks in some of the predictive simulations that go dry, which means that pumping from those gridblocks ceases after that time in the model. The reduction in pumping from dry cells is less than 5 percent of the overall pumping from the Bolson aquifer.

10.2.1 Hydraulic Heads

The first 50-year predictive simulation assumed average recharge conditions. Figures 10.2.1 to 10.2.15 show the simulated water levels, saturated thickness, and water level declines in the model layers in 2010, 2020, 2030, 2040, and 2050, under average recharge conditions. Figures 10.2.17 to 10.2.31 likewise, show the simulated water levels, saturated thickness, and water level declines in the model layers over the 50-year period, under DOR conditions. The difference in simulated water-level declines in 2050 for the three model layers between average and DOR conditions is illustrated in Figure 10.2.33. A major component of pumping in layer 1 (Salt Basin Bolson aquifer) is that the strategy involving withdrawals from the El Paso water farm in Ryan Flat will occur. However, it is recognized that this strategy was adopted by the Regional Planning Group with special conditions.

Under the average recharge scenario, water-level declines are most prominent in Ryan Flat (layer 1), beginning with a decline of 20 feet in 2010 (Figure 10.2.1). The water-level decline increases to over 330 feet by 2050 (Figure 10.2.13). During the simulation, there are a few gridblocks which go dry on the east side of the Antelope Valley Farm wellfield in Ryan Flat. The cells go dry because the simulated water level in the area reaches the base of the aquifer in year 2040. After 2040, cells continue to go dry as the water levels continue to decline. When a MODFLOW cell goes dry, the pumping assigned to that well is removed from the model. By 2050, the pumping from the wellfield decreases by a total of about 2500 acre-feet per year due to the dry cells.

Water levels actually rebound by as much as 20 feet through the first three decades in Wild Horse Flat (Figures 10.2.1, 10.2.4, and 10.2.7) before leveling out during the final two decades (Figures 10.2.10 and 10.2.13). The rebound is the result of reduced pumping after 2000 as compared to recent historical pumping levels, as discussed in Section 10.1.

Only small water-level declines are observed over time in the Igneous aquifer (layer 2), with the largest declines occurring primarily around the cities of Fort Davis and Marfa. By 2030, water-level declines are evident around Alpine (Figures 10.2.2, 10.2.5, 10.2.8, 10.2.11, and 10.2.14).

An area of Igneous aquifer water-level decline underlying Ryan Flat which appears in 2040 (Figure 10.2.11) and 2050 (Figure 10.2.14) is a result of the reduction in artesian pressure caused by the lowering of heads in the overlying Salt Basin Bolson aquifer (layer 1). A similar condition resulting from the reduced overlying aquifer heads in the Ryan Flat area and the Marfa area occurs in layer 3 (Figure 10.2.15). However, layer 3 water levels rebound by as much as 20 feet in Wild Horse Flat (similar to layer 1) and in the southwestern part of the model area. Figure 10.2.16 presents hydrographs showing historical water level observations and future predicted water-level trends in selected wells from Wild Horse Flat and Ryan Flat. The hydrographs show that under the projected pumping demands evaluated in this study, different portions of the Salt Basin Bolson aquifer respond oppositely.

DOR conditions were assumed for the second prediction scenario. As discussed above, five predictive simulations were completed. The results of the final timestep of each simulation are shown in Figures 10.2.17 through 10.2.31. Because the Salt Basin Bolson aquifer (layer 1) naturally receives very little recharge except through cross-formational flow and stormwater runoff, the DOR condition results in very similar water-level declines as simulated under the average recharge condition (Figures 10.2.17, 10.2.20, 10.2.23, 10.2.26 and 10.2.29). Drought has a greater affect on the Igneous aquifer (layer 2), as shown in the simulated 50-year water-level declines, which differ slightly from those simulated under average recharge conditions (Figures 10.2.18, 10.2.21, 10.2.24, 10.2.27, and 10.2.30). Layer 3 water-level declines are also similar in trend to levels simulated under average recharge conditions, with greatest declines in the Ryan Flat area and the Marfa area (Figures 10.2.19, 10.2.22, 10.2.25, 10.2.28, 10.2.31). However, layer 3 water levels rebound only in Wild Horse Flat (similar to layer 1) and not in the southwestern part of the model area. The water-level declines in the southwest portion of layer 3 are associated mainly with dry cells in layer 2 which occur during the predictive simulation. Figure 10.2.32 presents hydrographs showing historical water level measurements and simulated water-level trends in selected wells under the DOR condition. Comparison of these hydrographs to the hydrographs simulated under average conditions in Figure 10.2.16 indicates no significant difference between the hydrographs because the DOR has very little impact on the Salt Basin Bolson aquifer since it receives very little recharge.

Figure 10.2.33 indicates that the DOR would have some impact on the water levels in layers 2 and 3 as compared to the average recharge condition. As observed in these comparisons, virtually no difference is observed in the Salt Basin Bolson aquifer (layer 1). The approximately 10 feet of difference in the Igneous aquifer (layer 2) occurs primarily in the area of higher elevations in the Davis Mountains where the reduced recharge has the greatest impact. In layer 3, the greatest difference occurs in the southwestern part of the model area where, under DOR conditions, water levels decline in the area where layer 3 receives direct recharge because layer 2 is dry.

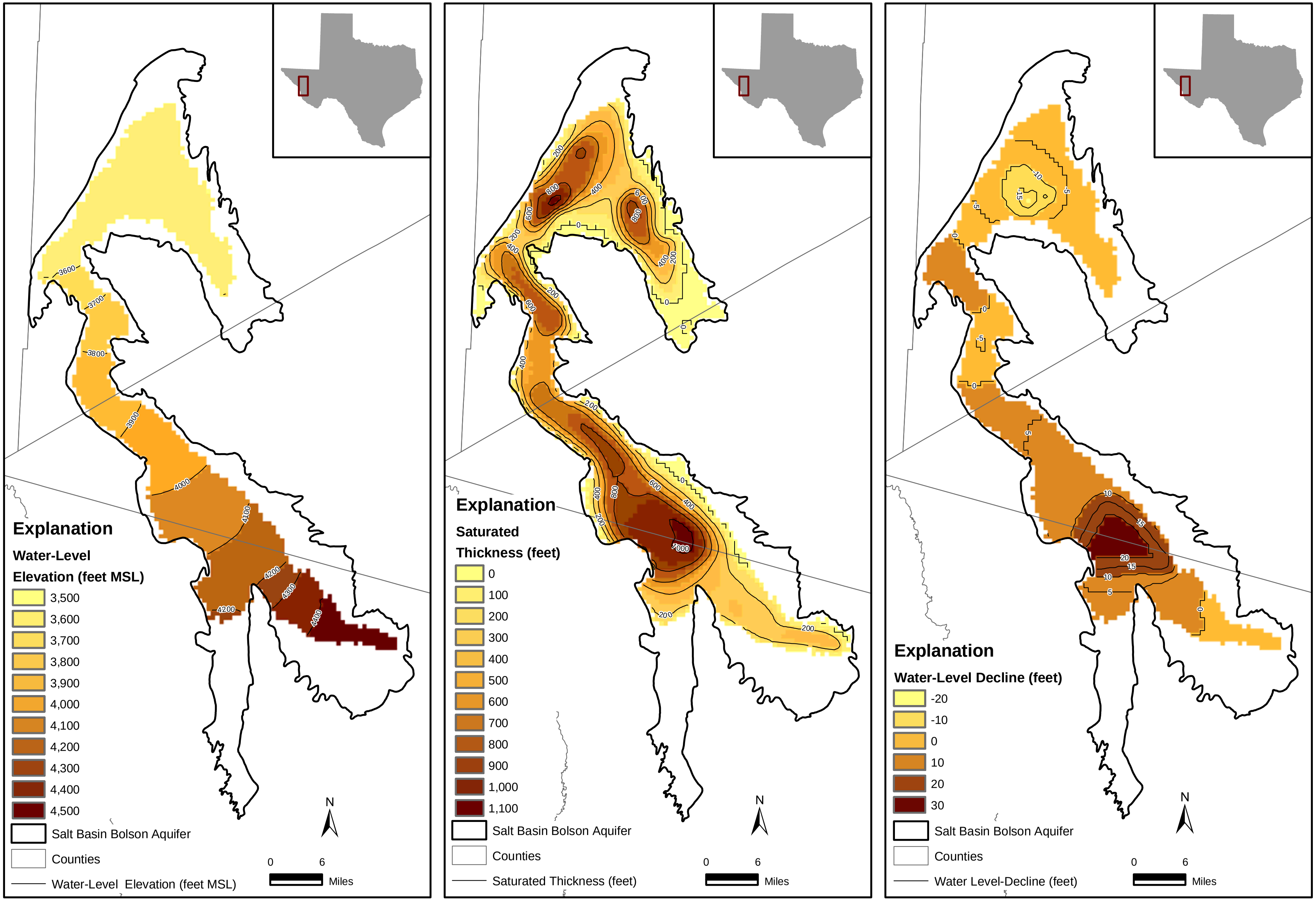


Figure 10.2.1 - Simulated Water-Levels, Saturated Thickness, and Water-Level Declines in 2010 Under Average Conditions (Layer 1)

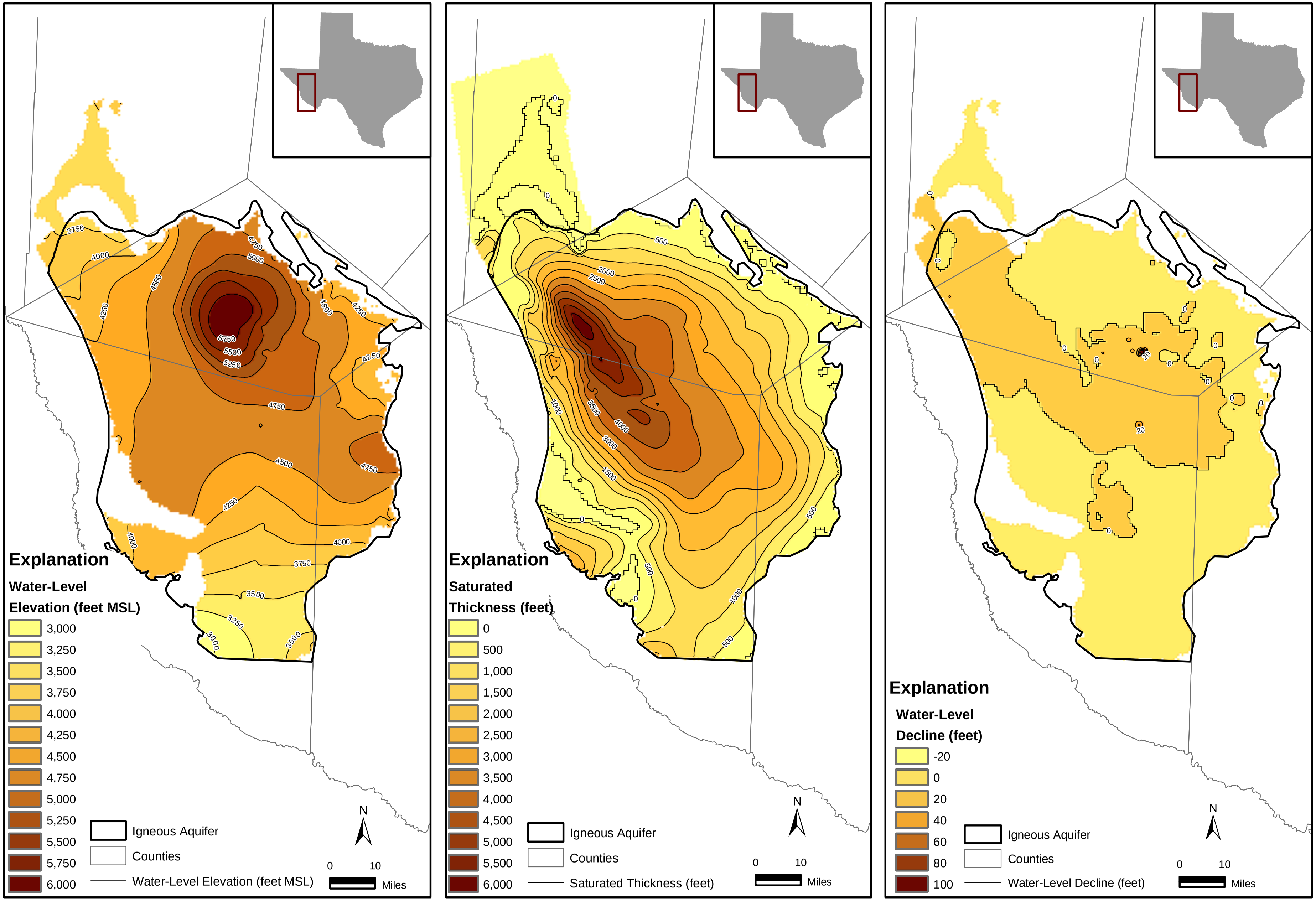


Figure 10.2.2 - Simulated Water-Levels, Saturated Thickness, and Water-Level Declines in 2010 Under Average Conditions (Layer 2)

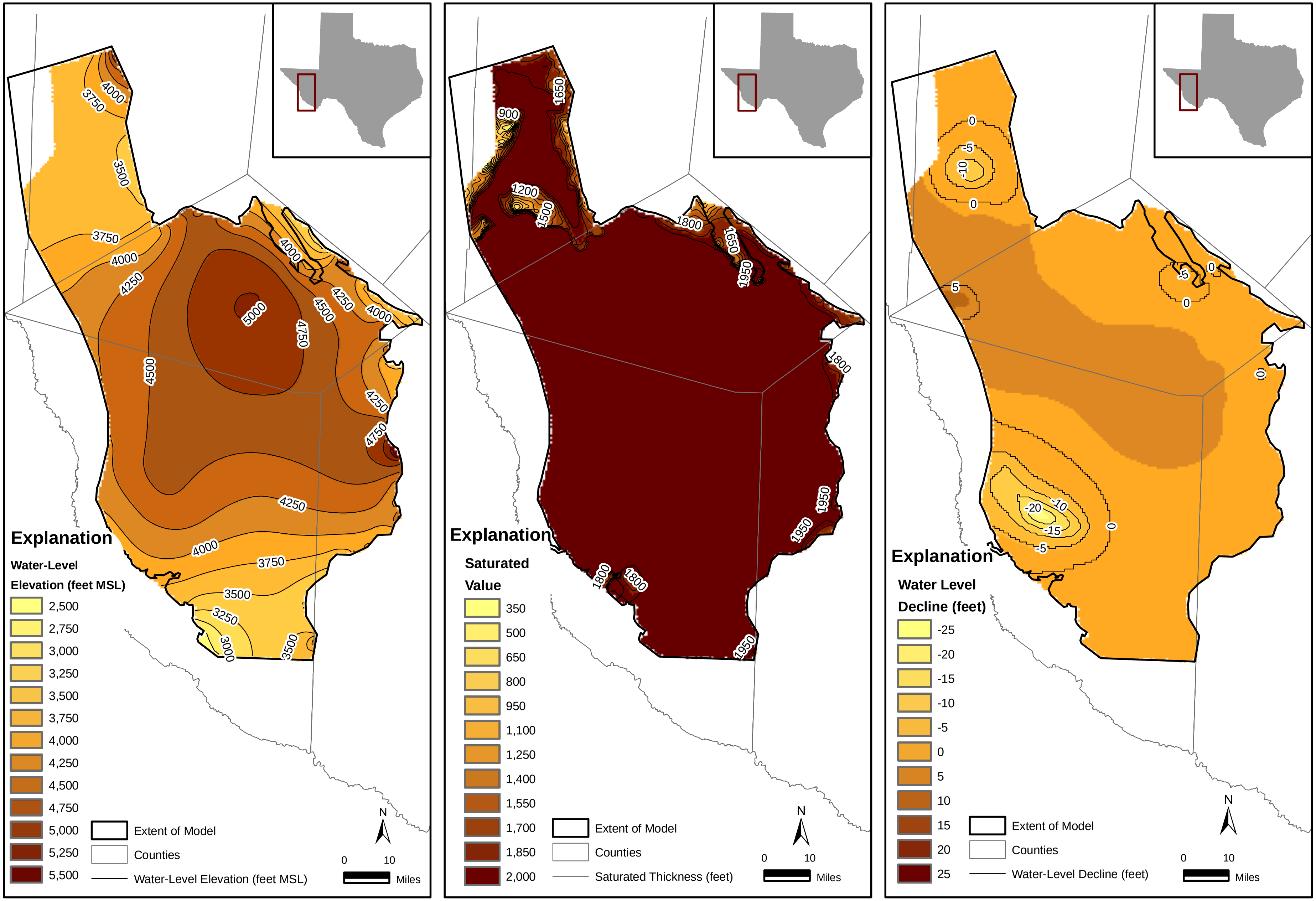


Figure 10.2.3 - Simulated Water-Levels, Saturated Thickness, and Water-Level Declines in 2010 Under Average Conditions (Layer 3)

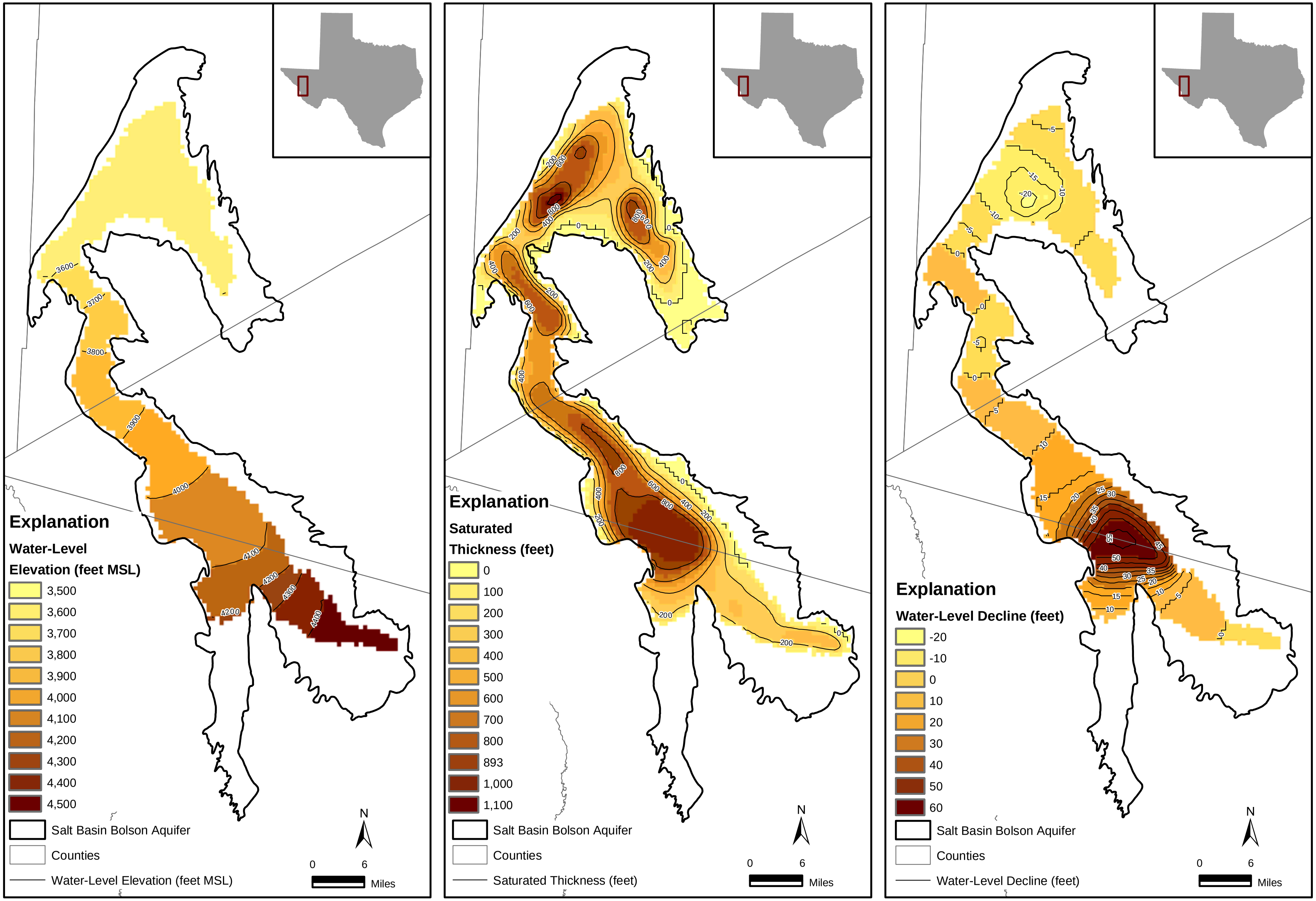


Figure 10.2.4 - Simulated Water-Levels, Saturated Thickness, and Water-Level Declines in 2020 Under Average Conditions (Layer 1)

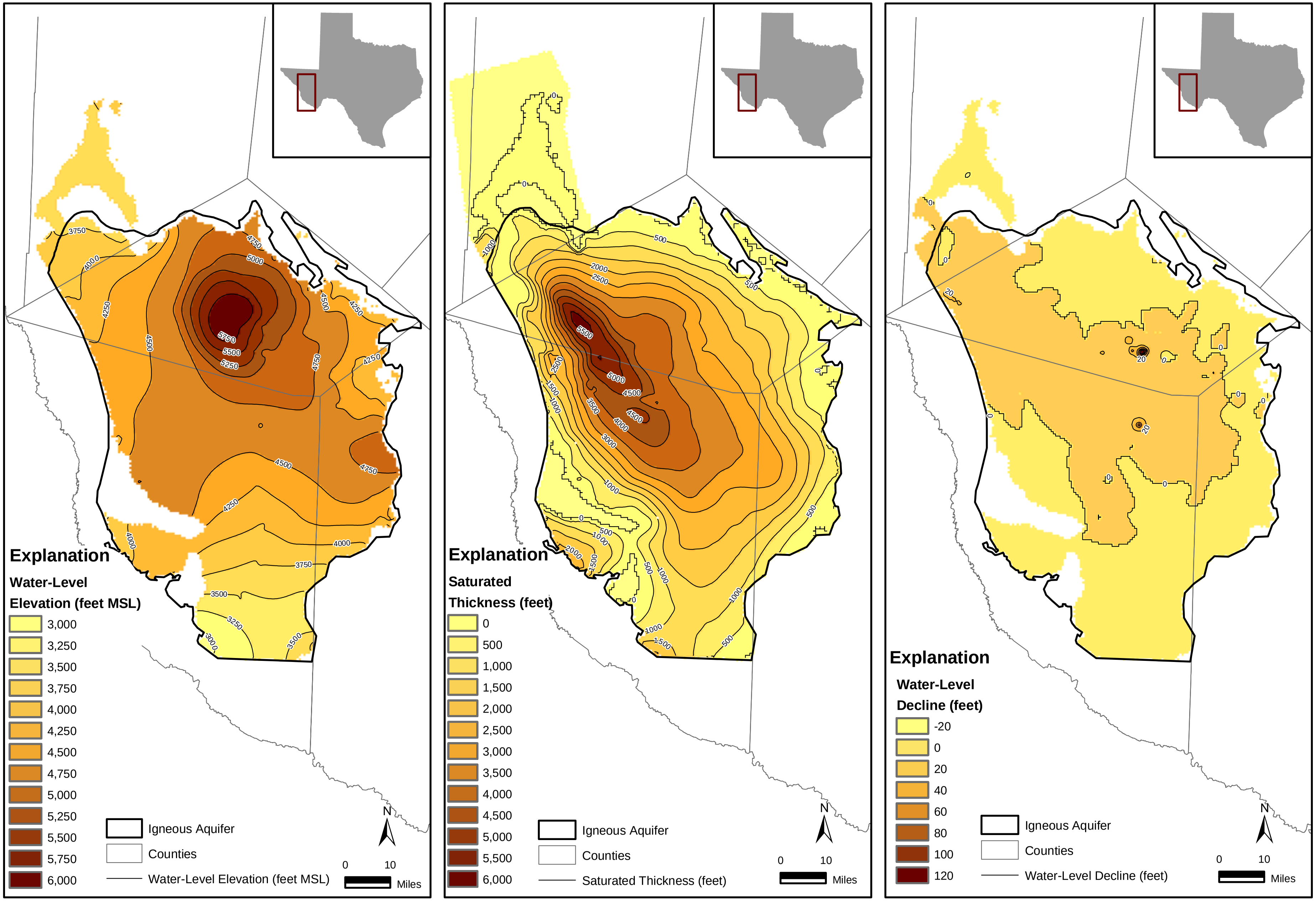


Figure 10.2.5 - Simulated Water-Levels, Saturated Thickness, and Water-Level Declines in 2020 Under Average Conditions (Layer 2)

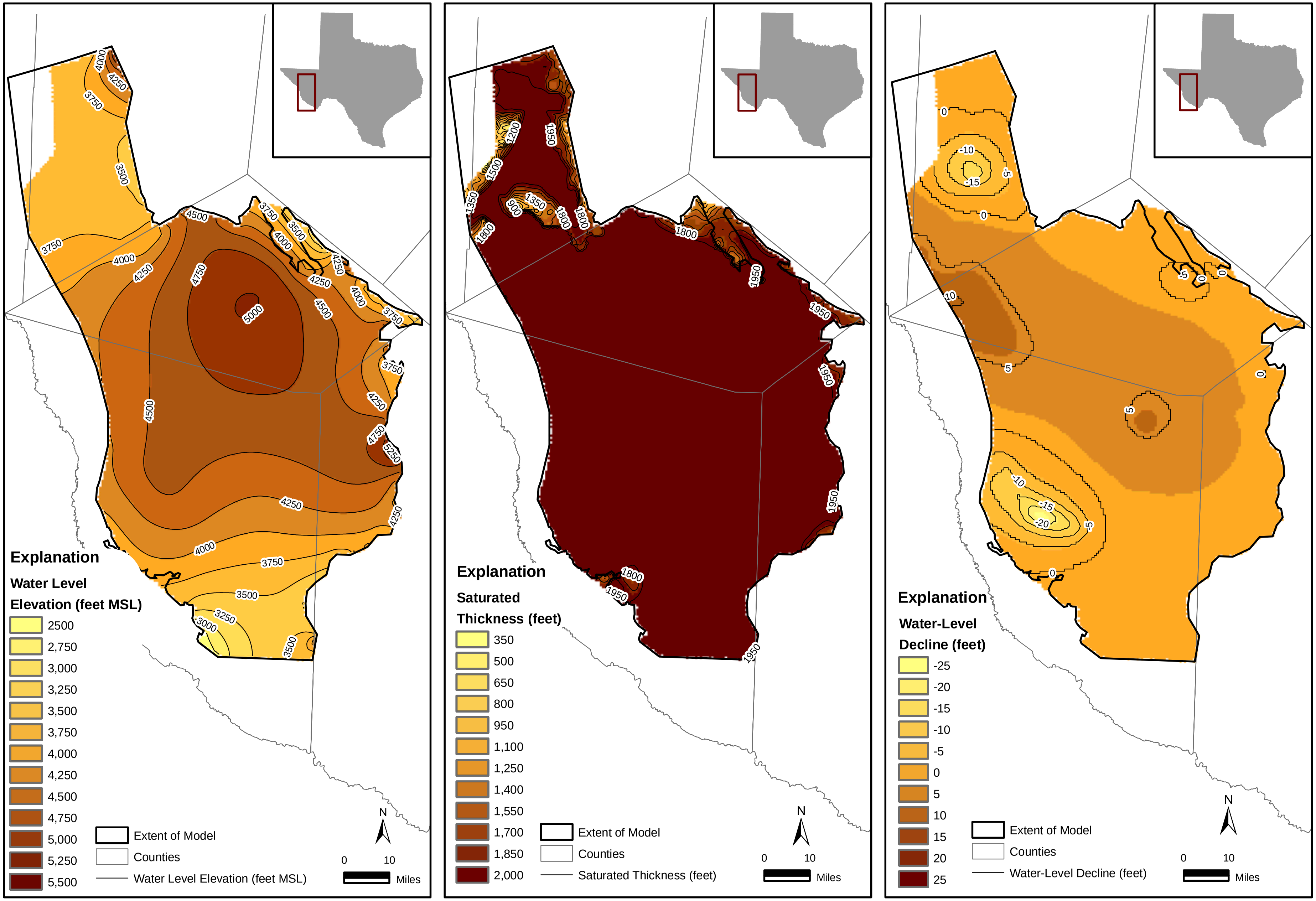


Figure 10.2.6 - Simulated Water-Levels, Saturated Thickness, and Water-Level Declines in 2010 Under Average Conditions (Layer 3)

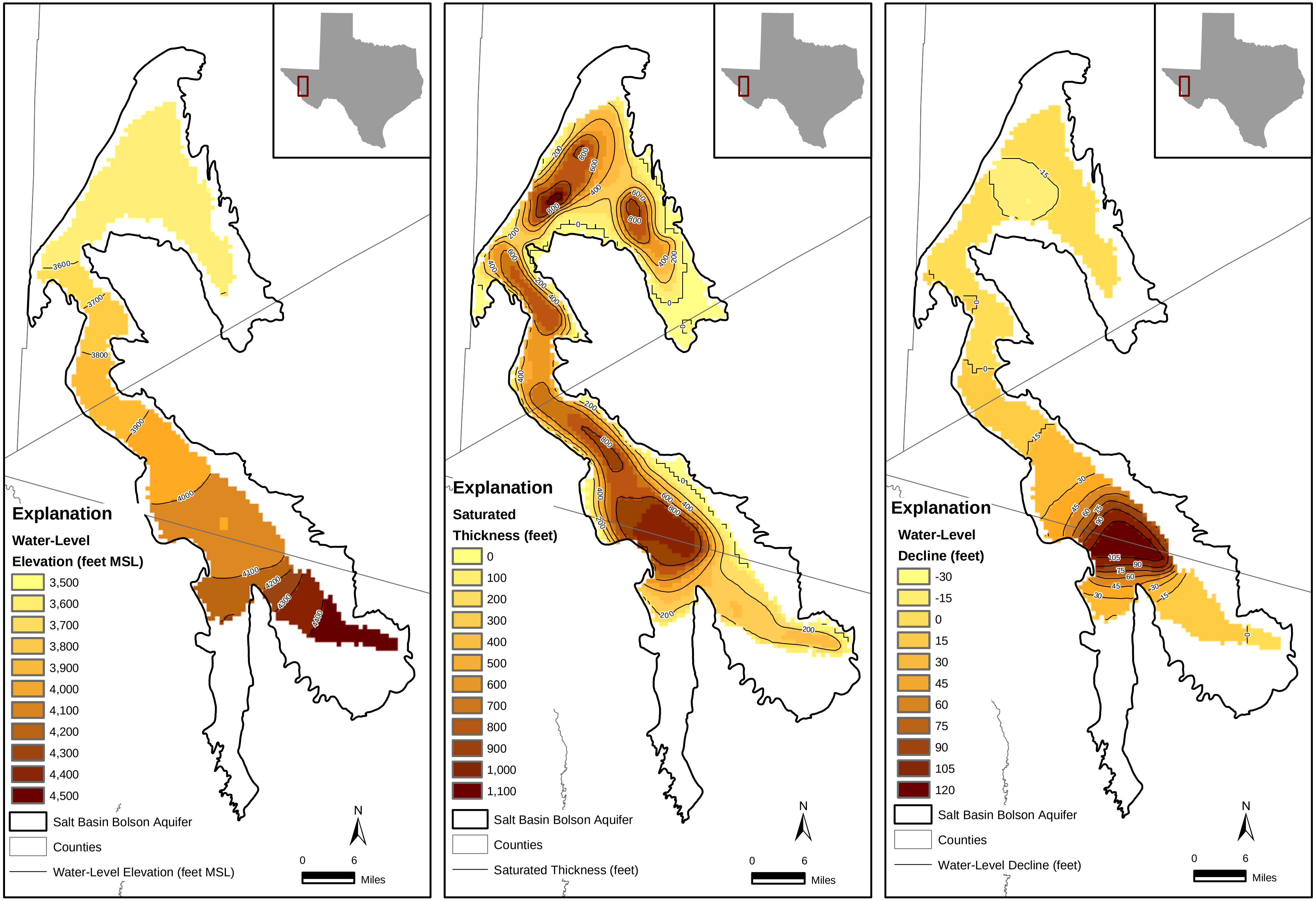


Figure 10.2.7 - Simulated Water-Levels, Saturated Thickness, and Water-Level Declines in 2030 Under Average Conditions (Layer 1)

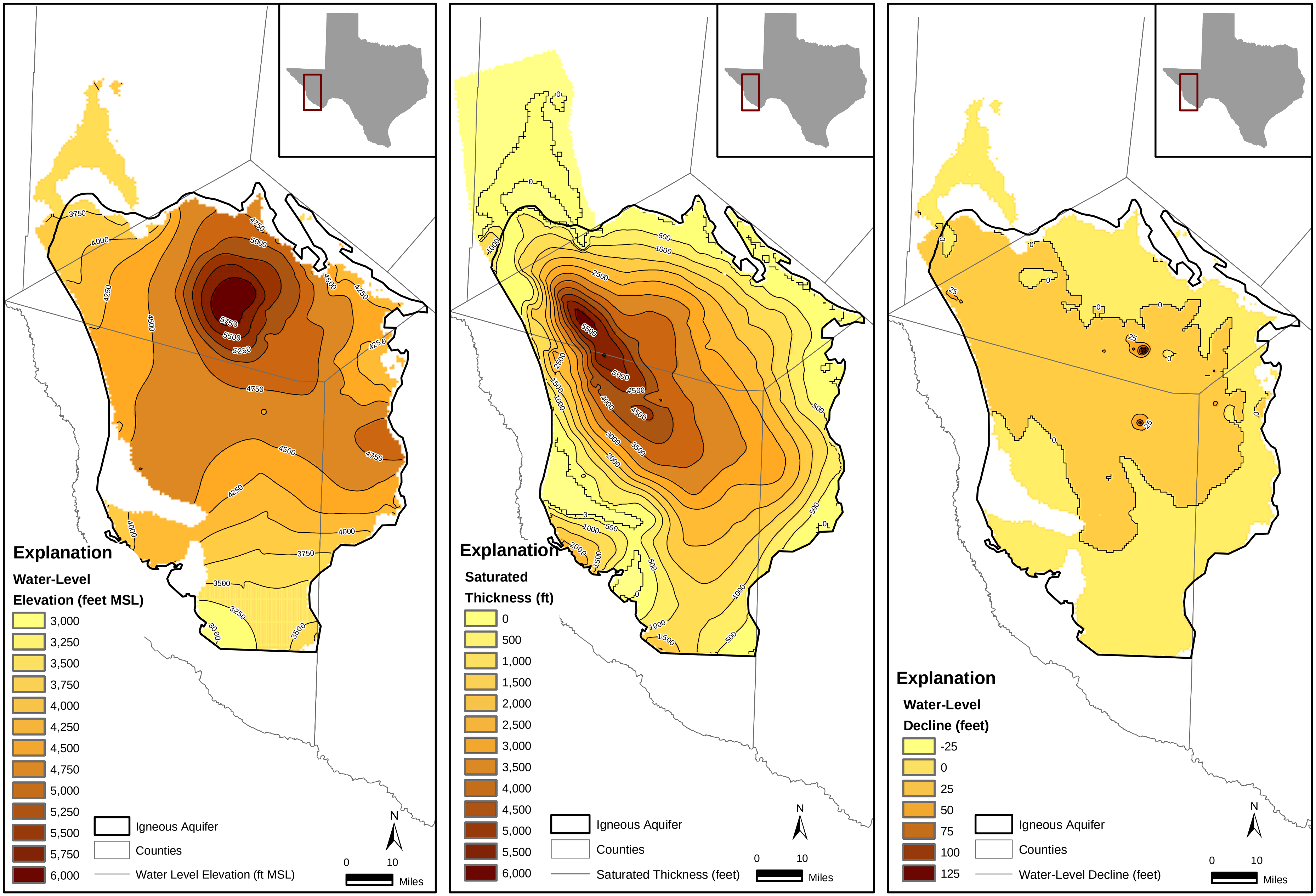


Figure 10.2.8 - Simulated Water-Levels, Saturated Thickness, and Water-Level Declines in 2030 Under Average Conditions (Layer 2)

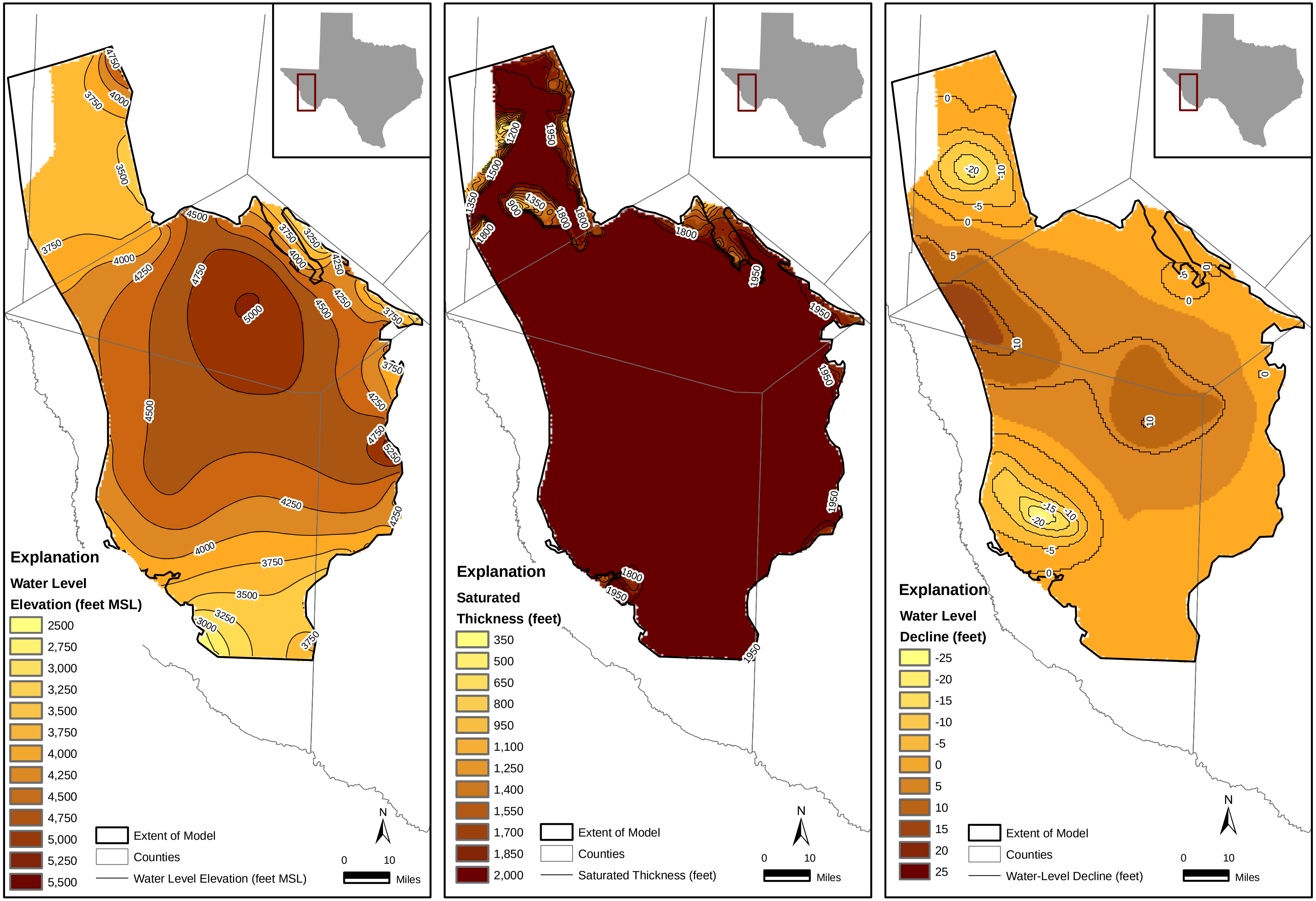


Figure 10.2.9 - Simulated Water-Levels, Saturated Thickness, and Water-Level Declines in 2030 Under Average Conditions (Layer 3)

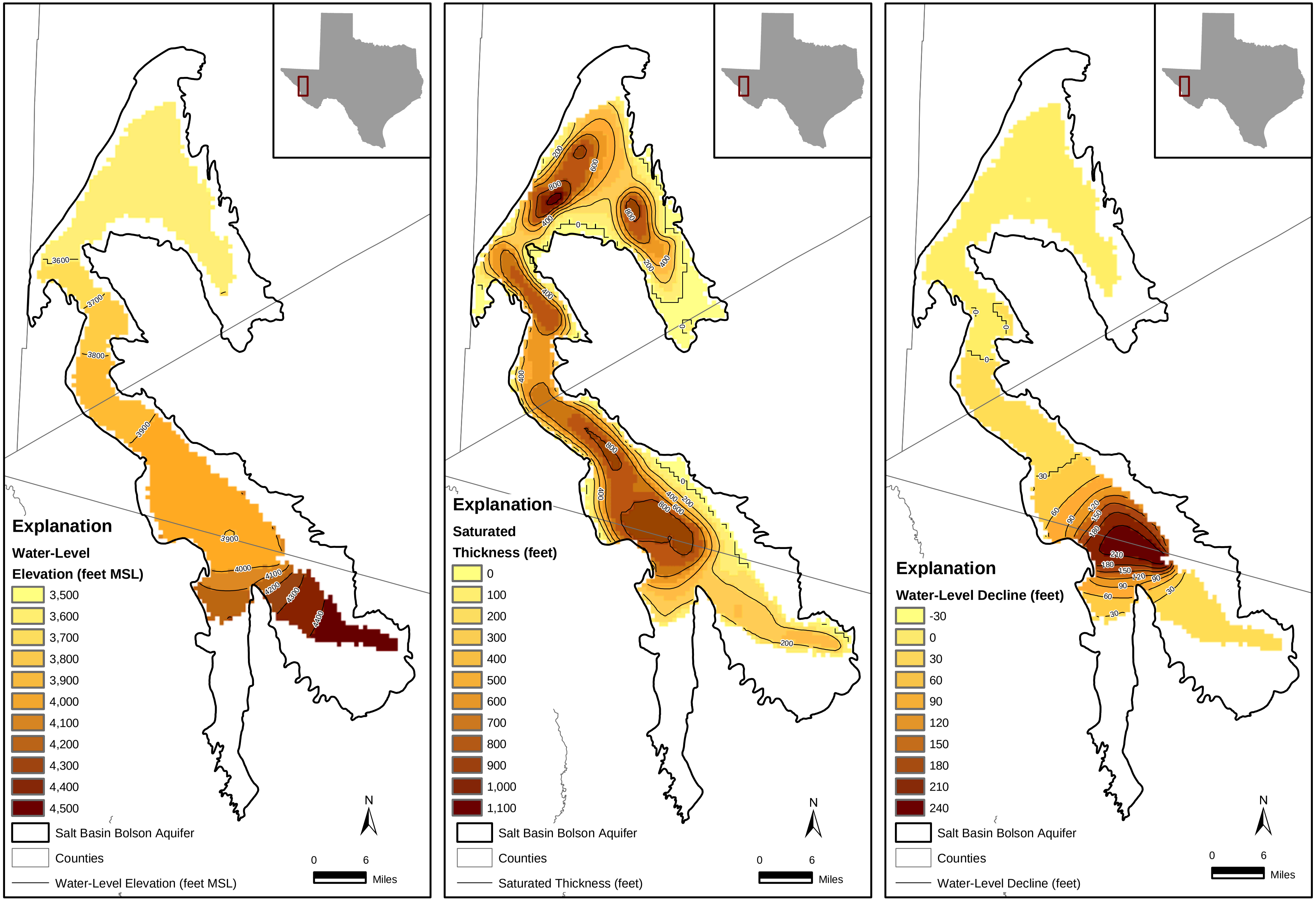


Figure 10.2.10 - Simulated Water-Levels, Saturated Thickness, and Water-Level Declines in 2040 Under Average Conditions (Layer 1)

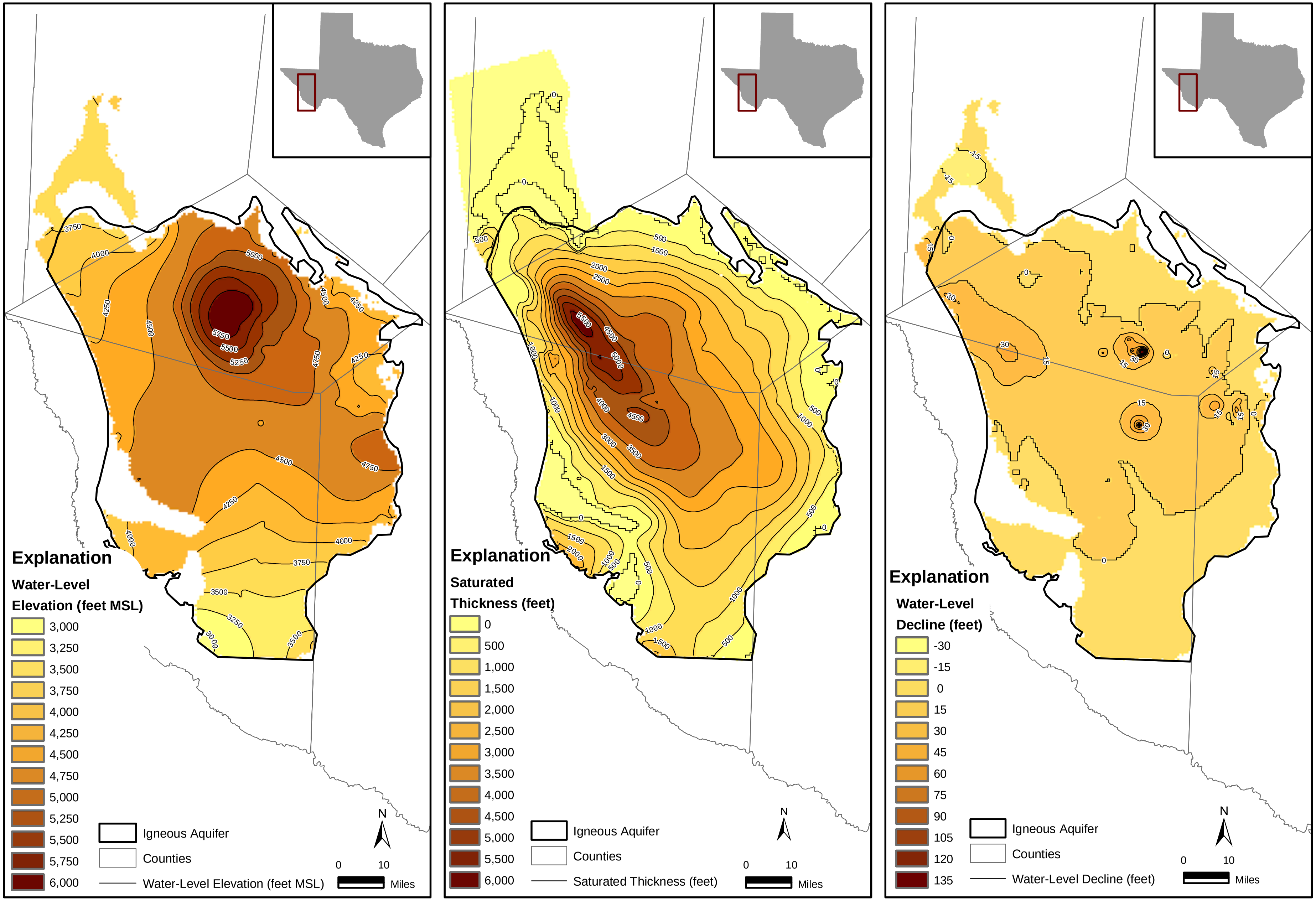


Figure 10.2.11 - Simulated Water-Levels, Saturated Thickness, and Water-Level Declines in 2040 Under Average Conditions (Layer 2)

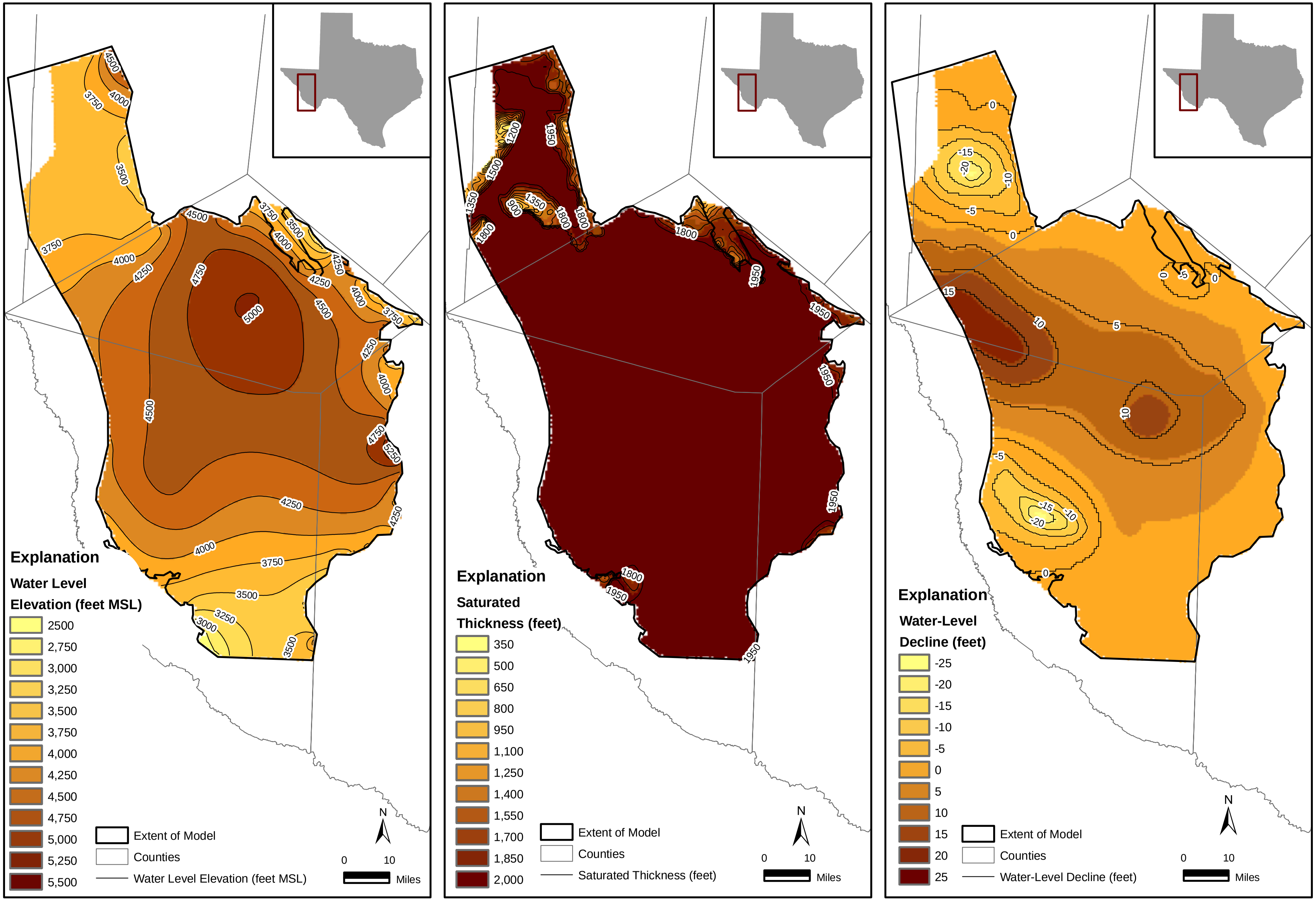


Figure 10.2.12 - Simulated Water-Levels, Saturated Thickness, and Water-Level Declines in 2040 Under Average Conditions (Layer 3)

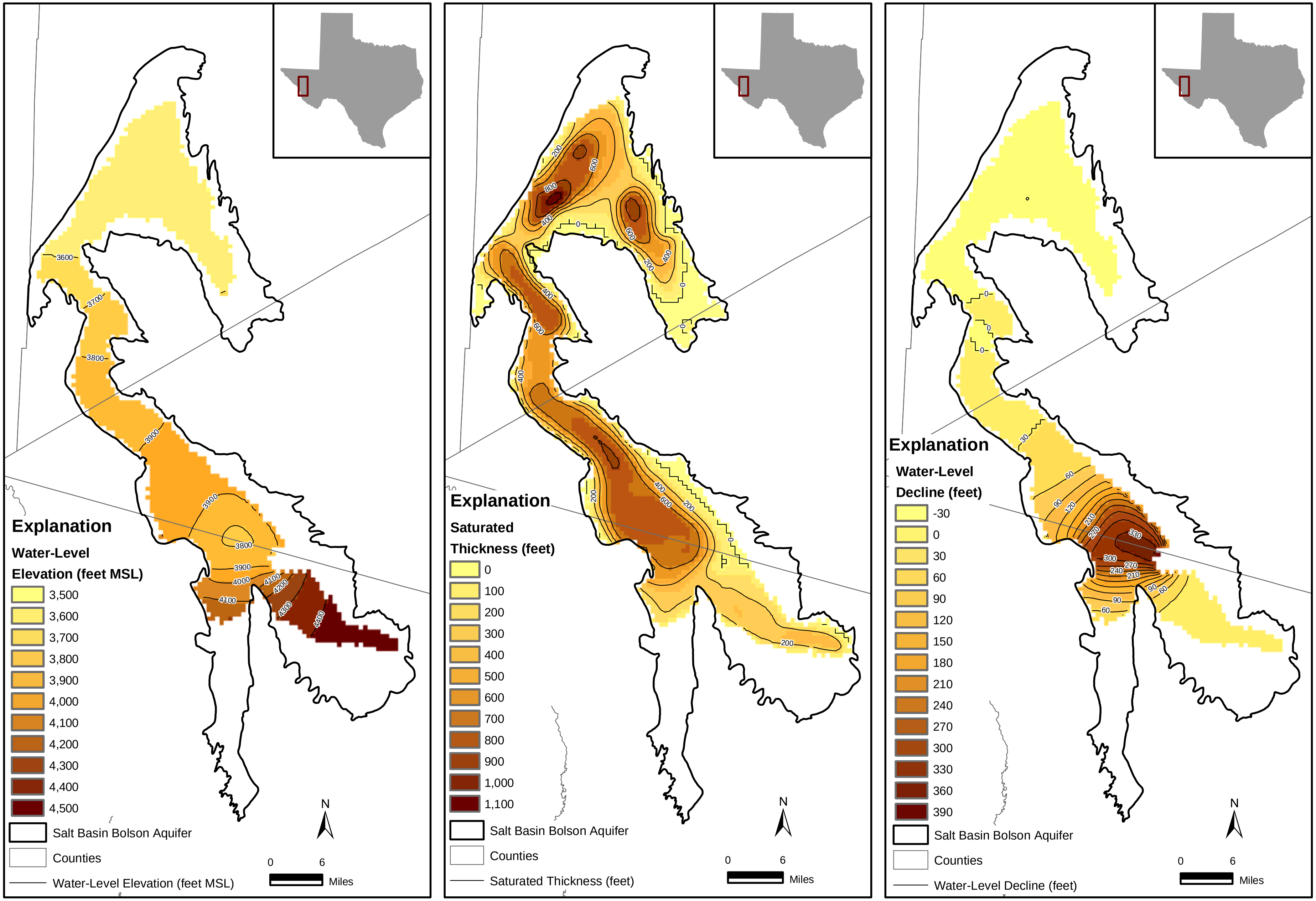


Figure 10.2.13 - Simulated Water-Levels, Saturated Thickness, and Water-Level Declines in 2050 Under Average Conditions (Layer 1)

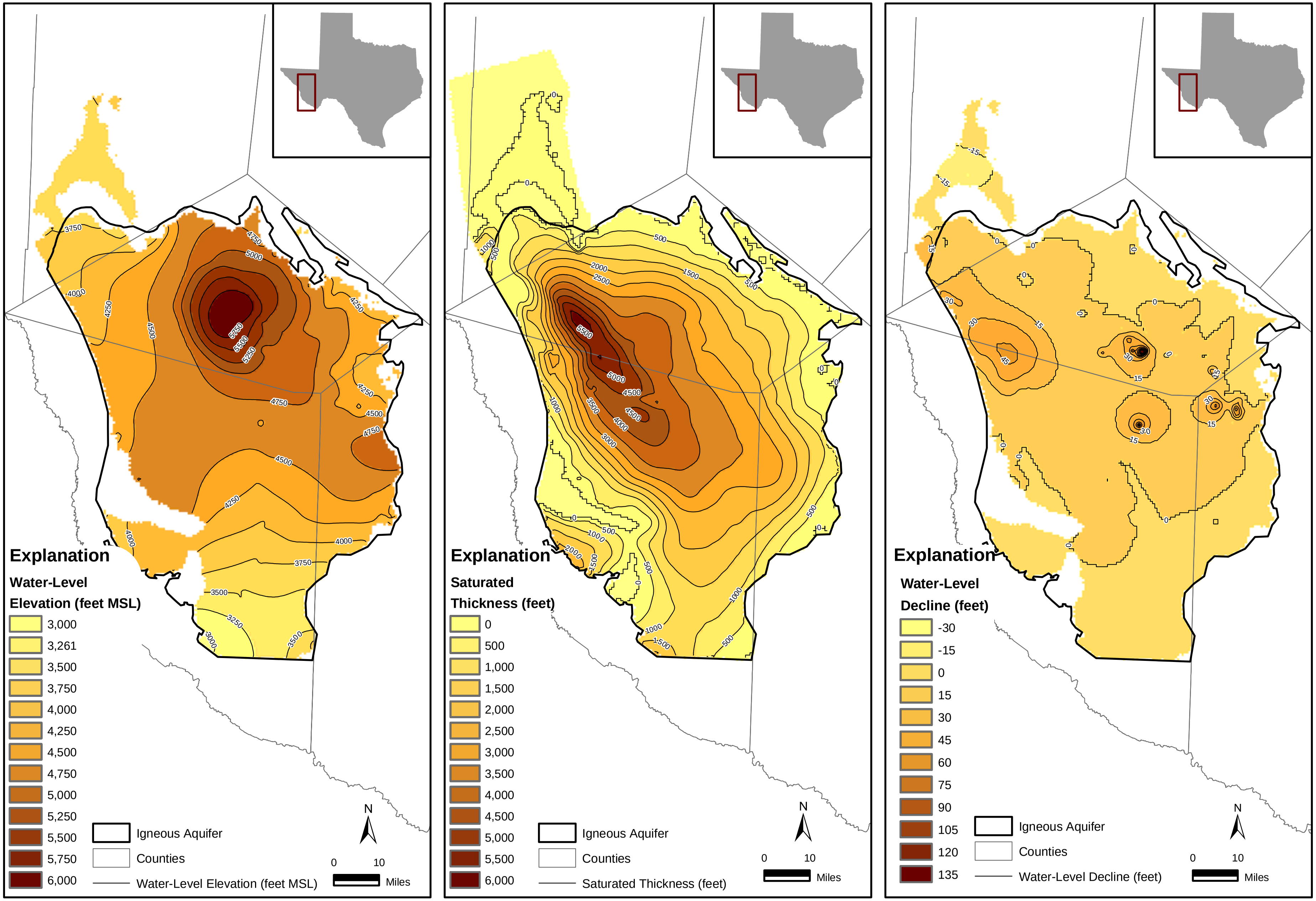


Figure 10.2.14 - Simulated Water-Levels, Saturated Thickness, and Water-Level Declines in 2050 Under Average Conditions (Layer 2)

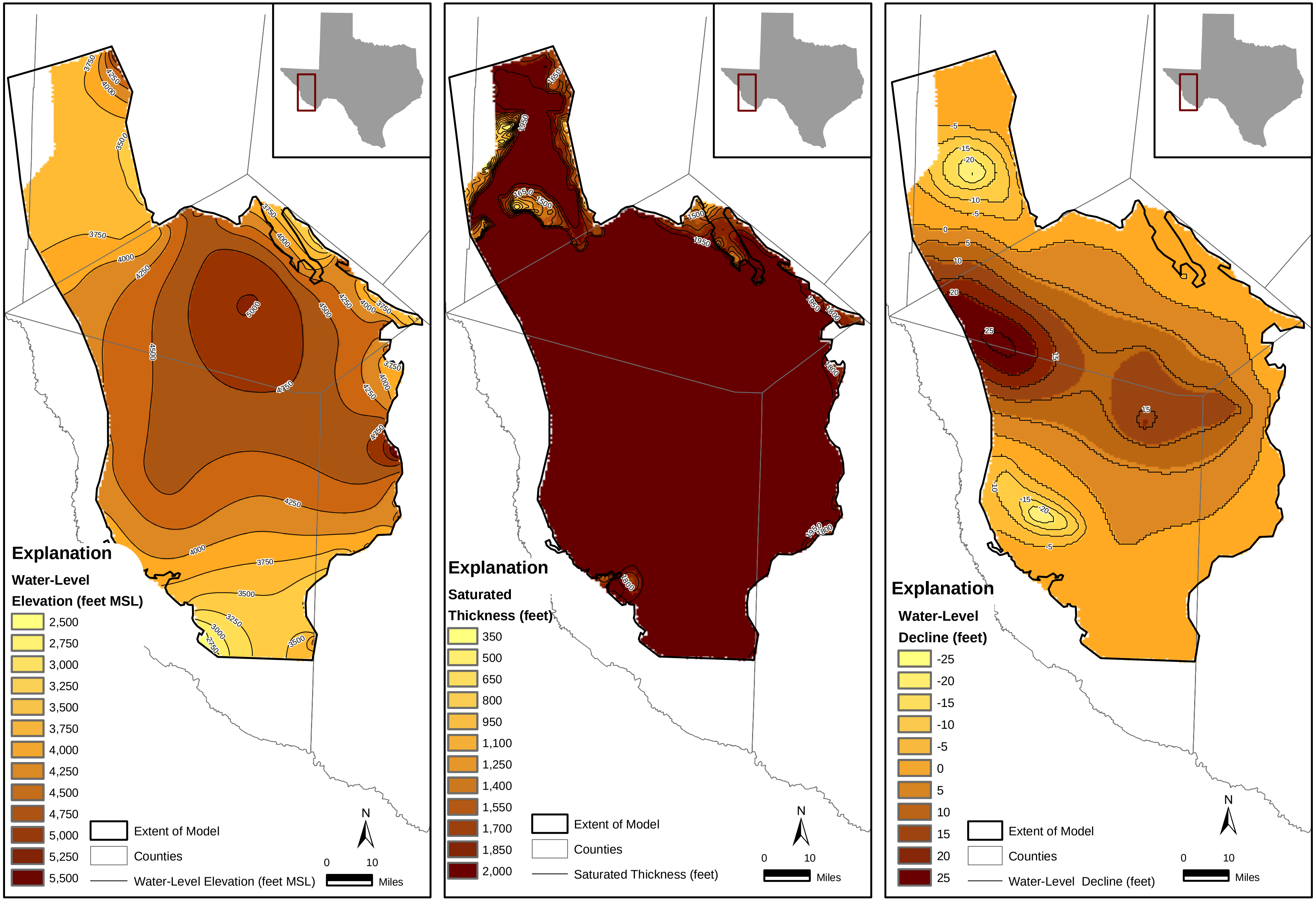


Figure 10.2.15 - Simulated Water-Levels, Saturated Thickness, and Water-Level Declines in 2050 Under Average Conditions (Layer 3)

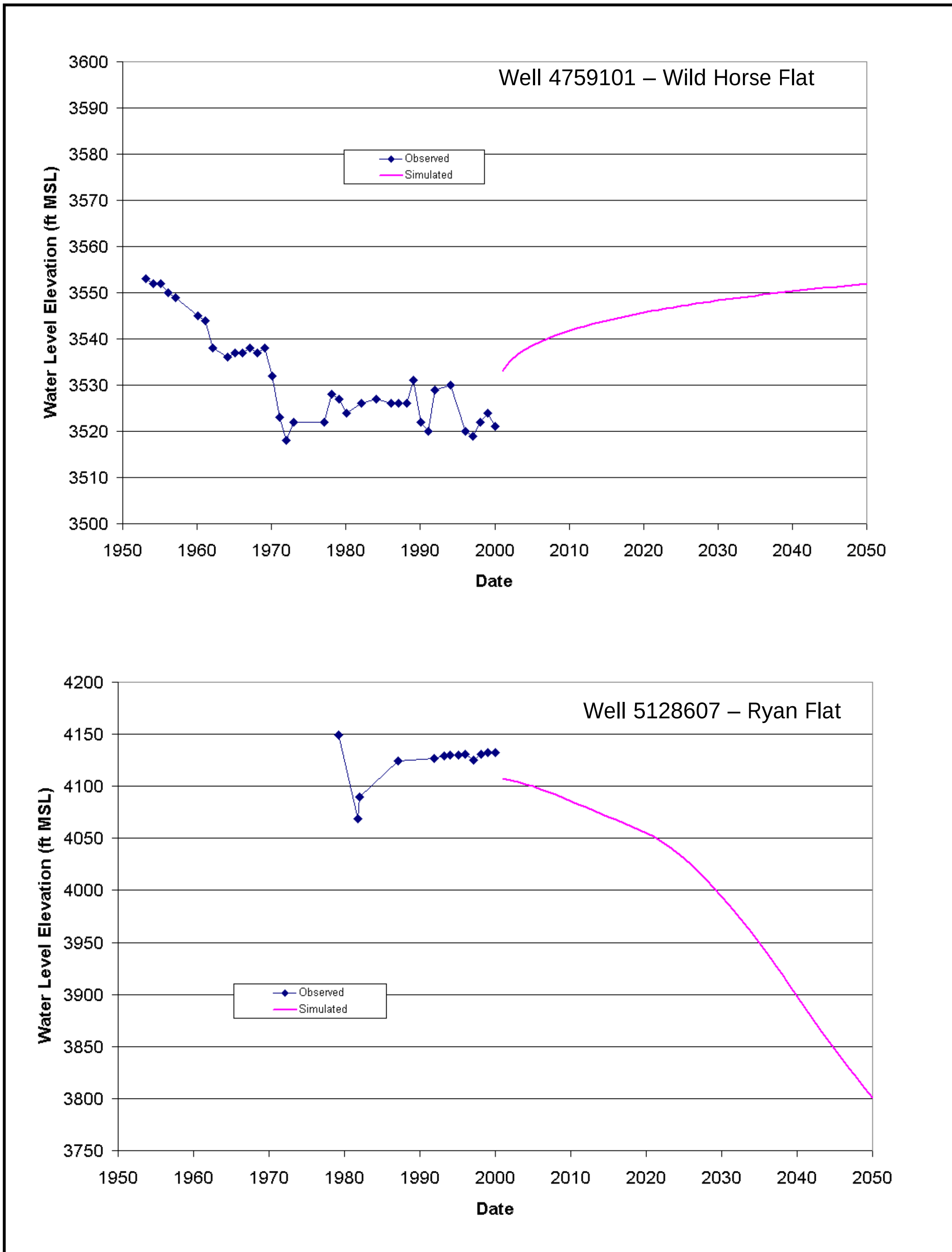


Figure 10.2.16 Hydrographs for selected wells from 1950 to 2050 under average conditions

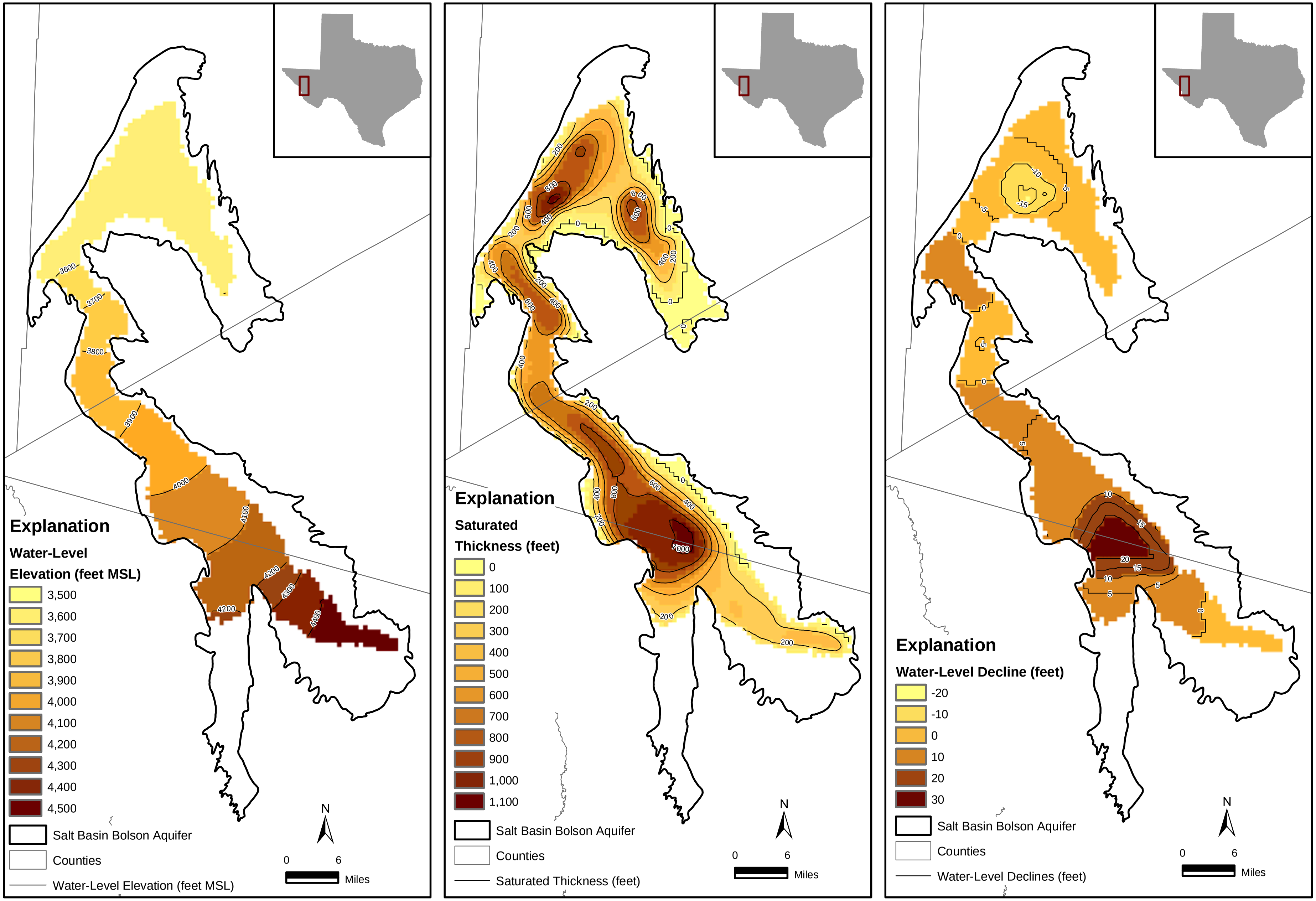


Figure 10.2.17 - Simulated Water-Levels, Saturated Thickness, and Water-Level Declines in 2010 Under DOR Conditions (Layer 1)

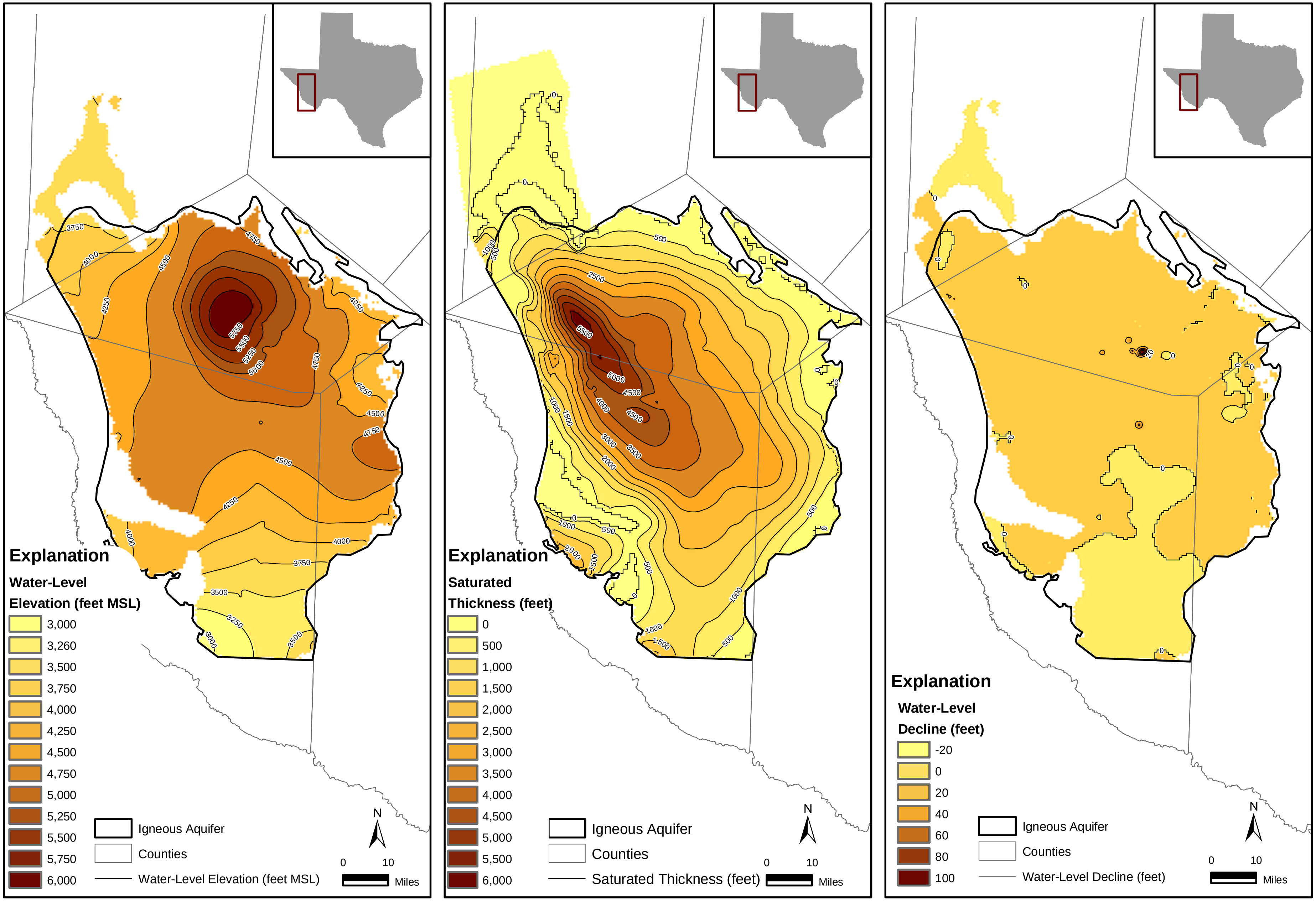


Figure 10.2.18 - Simulated Water-Levels, Saturated Thickness, and Water-Level Declines in 2010 Under DOR Conditions (Layer 2)

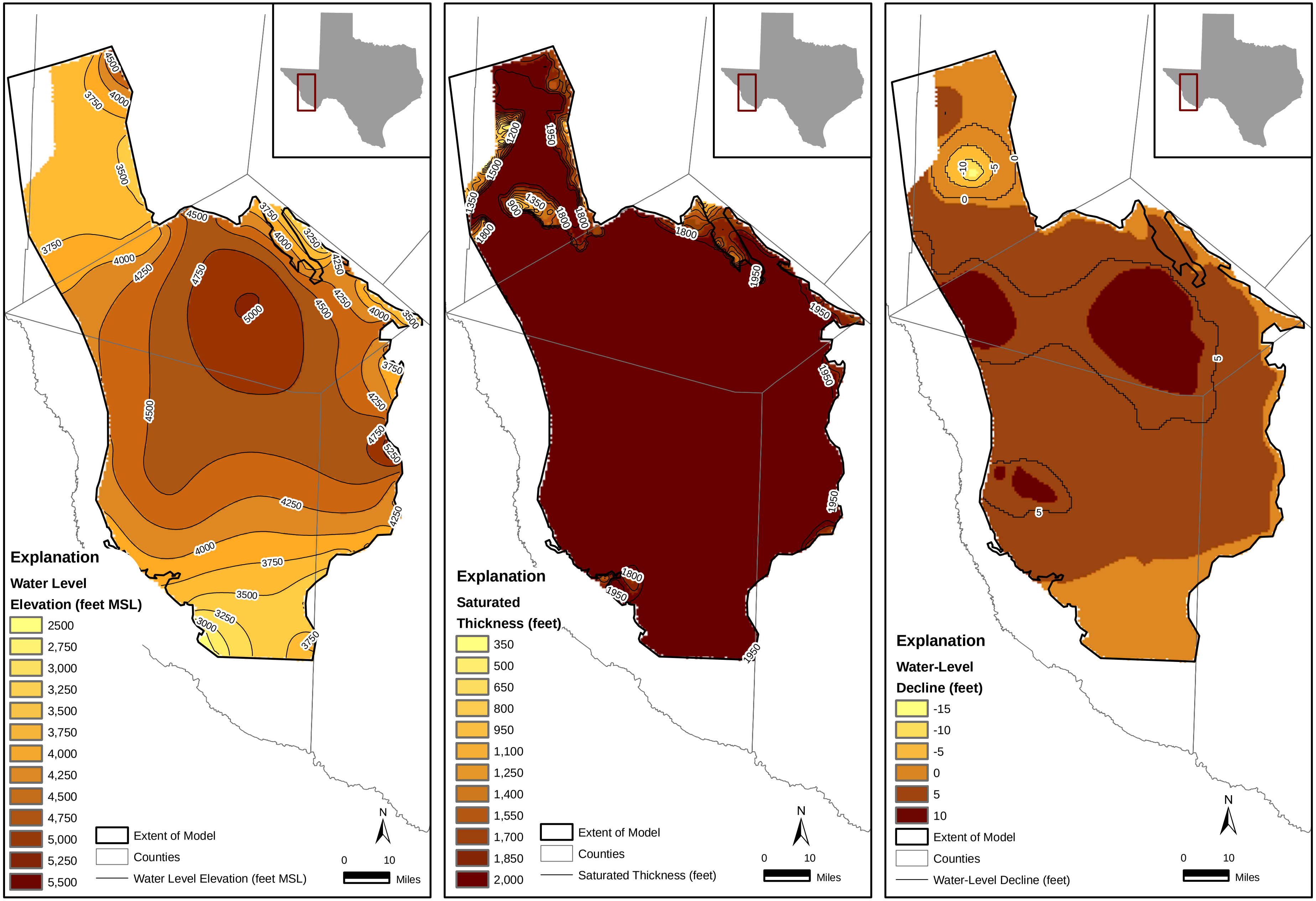


Figure 10.2.19 - Simulated Water-Levels, Saturated Thickness, and Water-Level Declines in 2010 Under DOR Conditions (Layer 3)

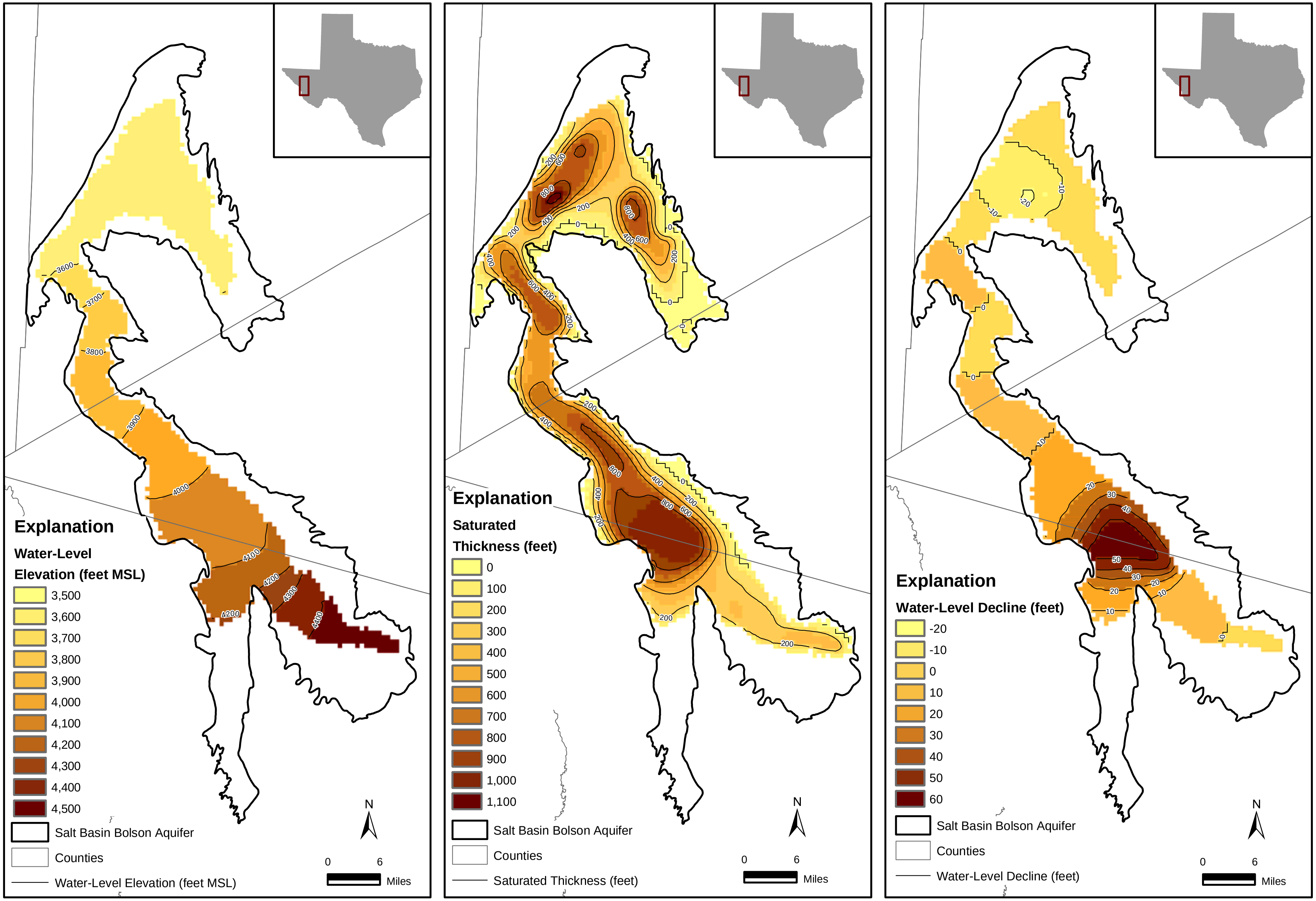


Figure 10.2.20 - Simulated Water-Levels, Saturated Thickness, and Water-Level Declines in 2020 Under DOR Conditions (Layer 1)

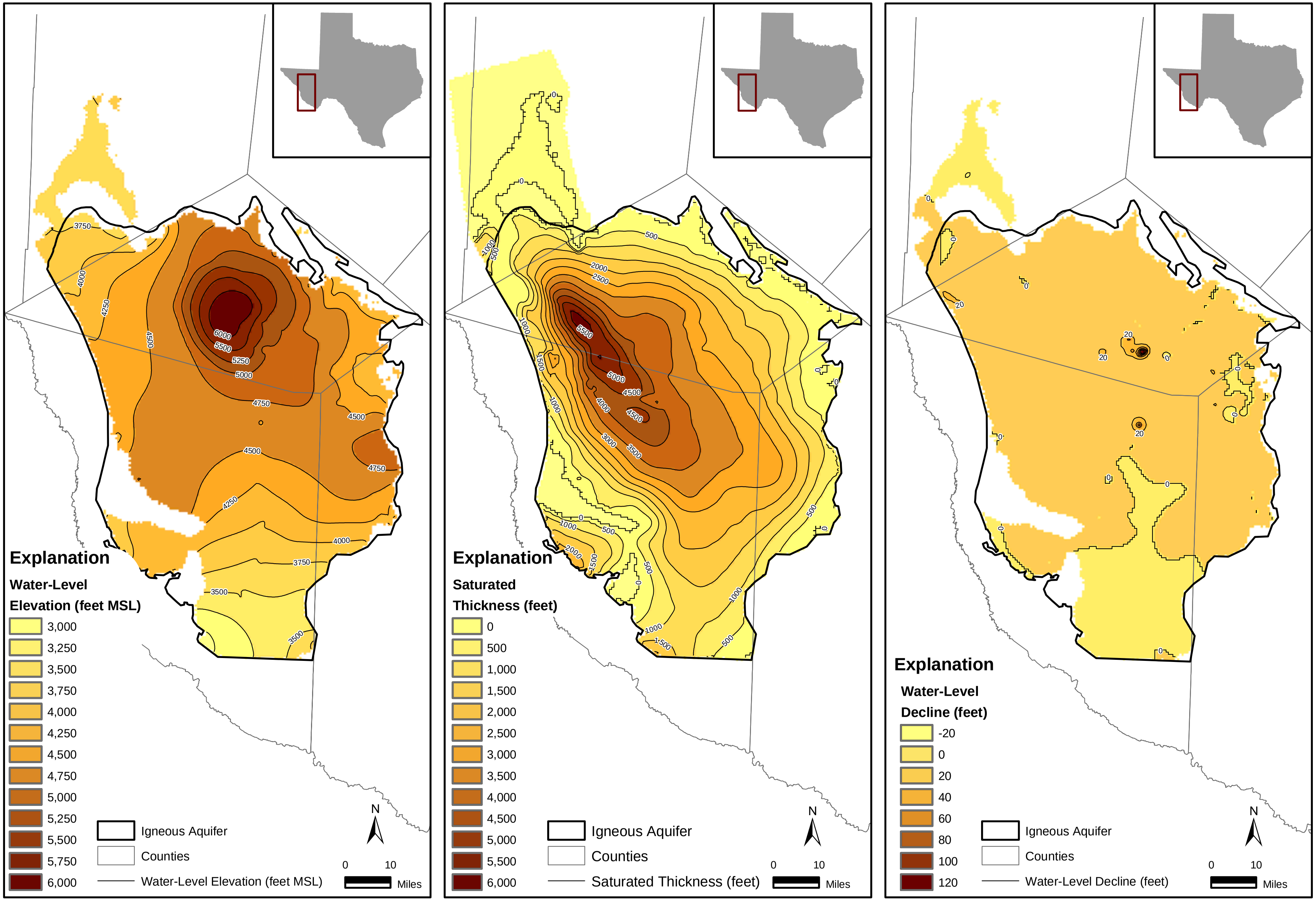


Figure 10.2.21 - Simulated Water-Levels, Saturated Thickness, and Water-Level Declines in 2020 Under DOR Conditions (Layer 2)

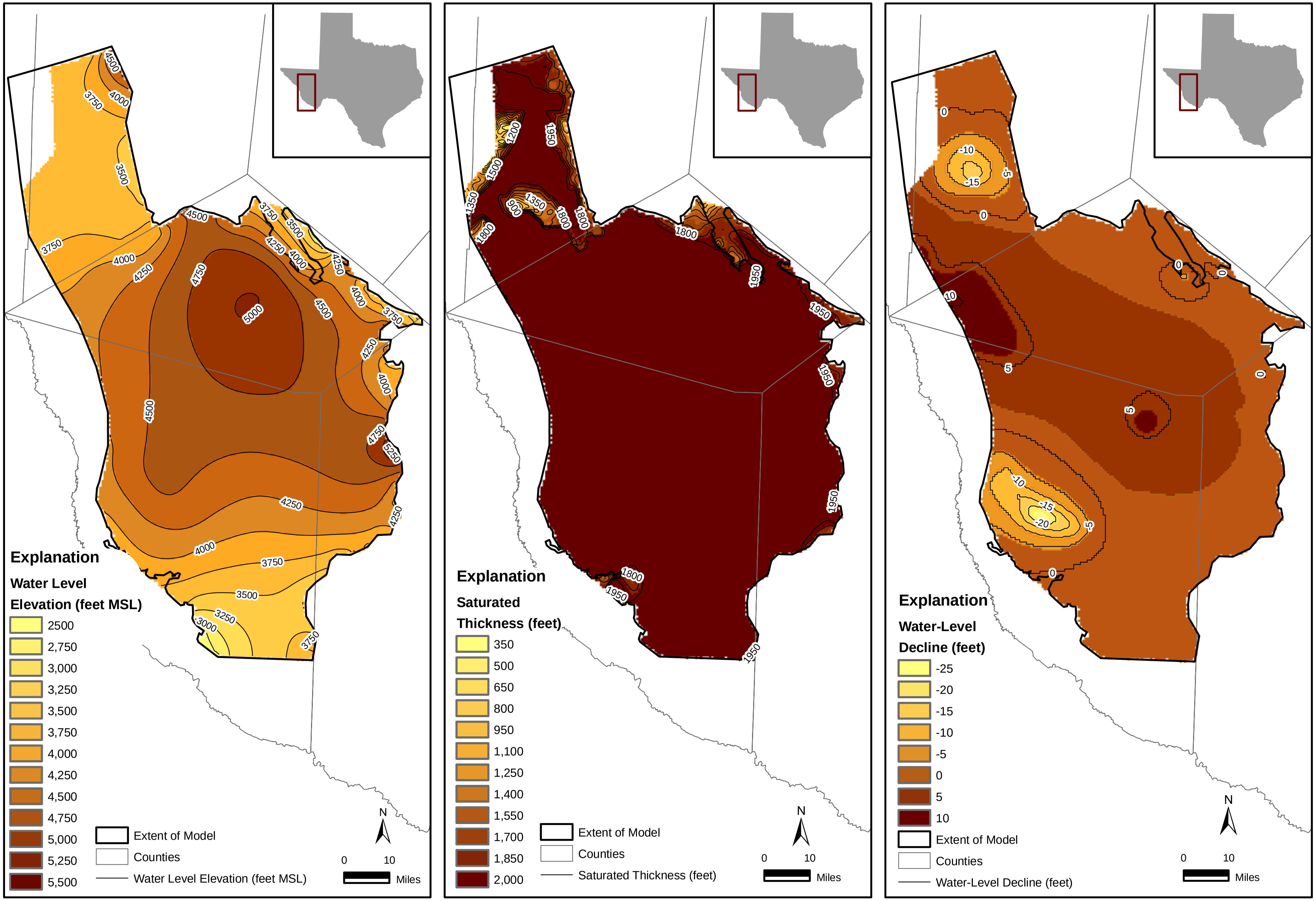


Figure 10.2.22 - Simulated Water-Levels, Saturated Thickness, and Water-Level Declines in 2020 Under DOR Conditions (Layer 3)

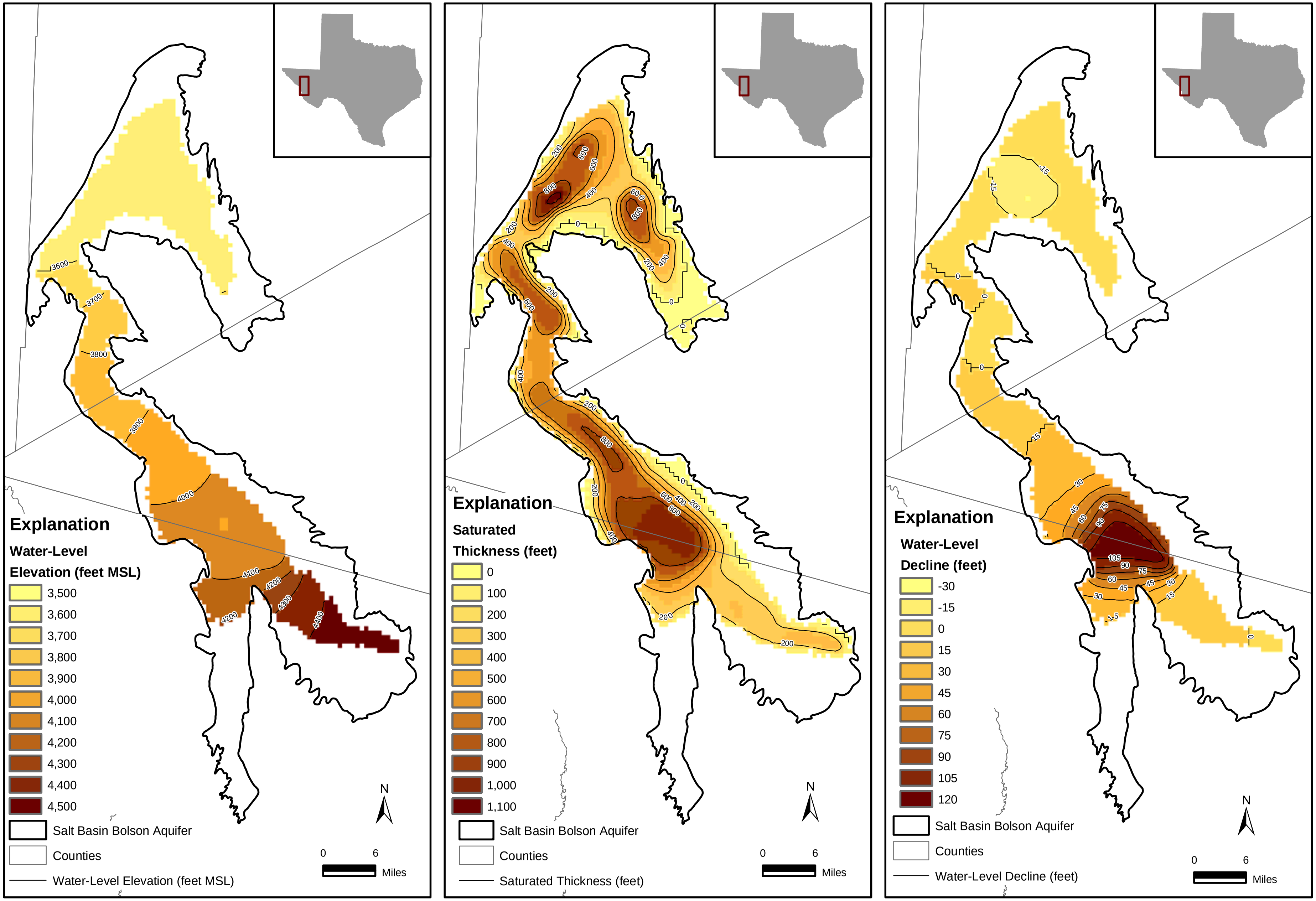


Figure 10.2.23 - Simulated Water-Levels, Saturated Thickness, and Water-Level Declines in 2030 Under DOR Conditions (Layer 1)

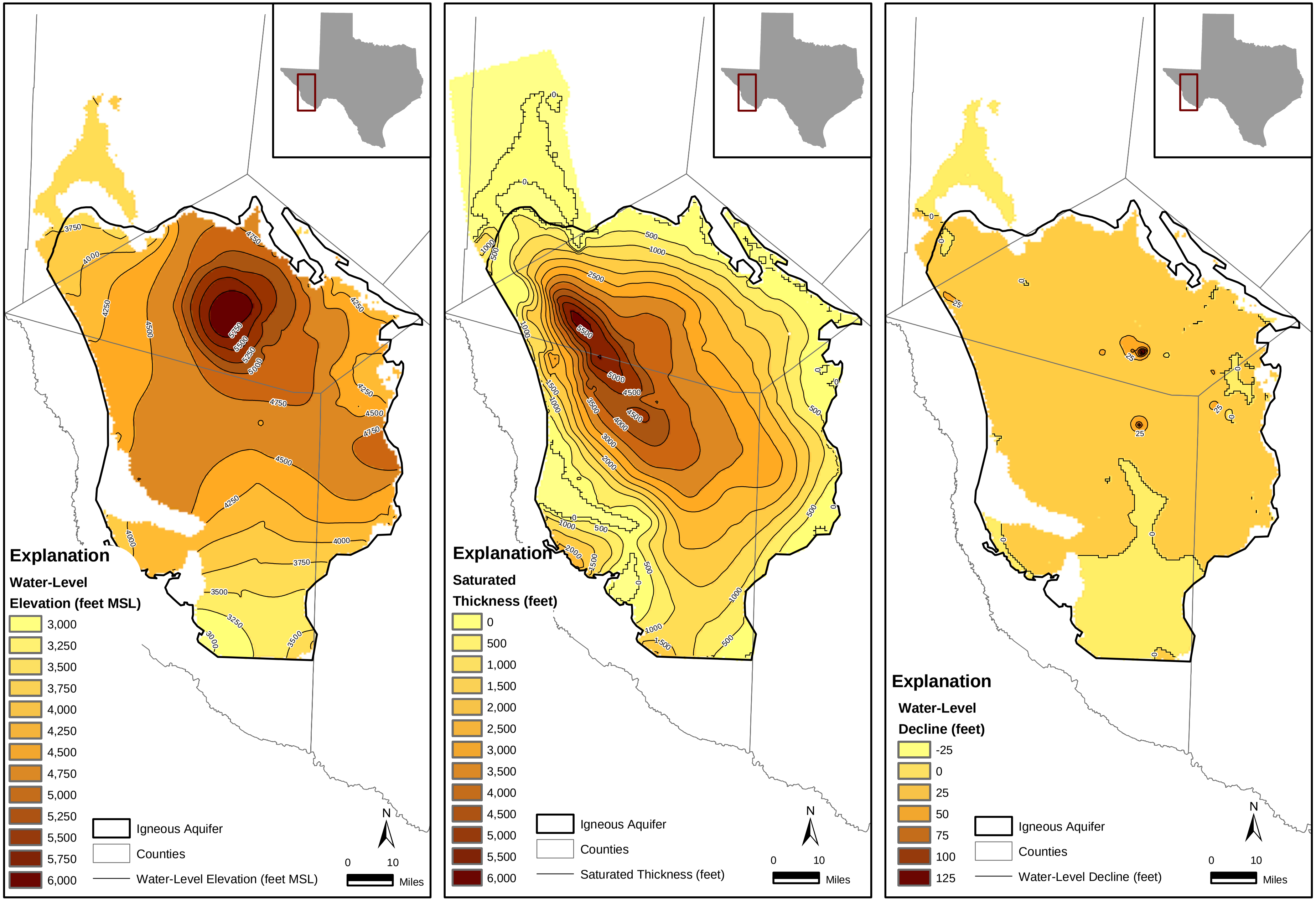


Figure 10.2.24 - Simulated Water-Levels, Saturated Thickness, and Water-Level Declines in 2030 Under DOR Conditions (Layer 2)

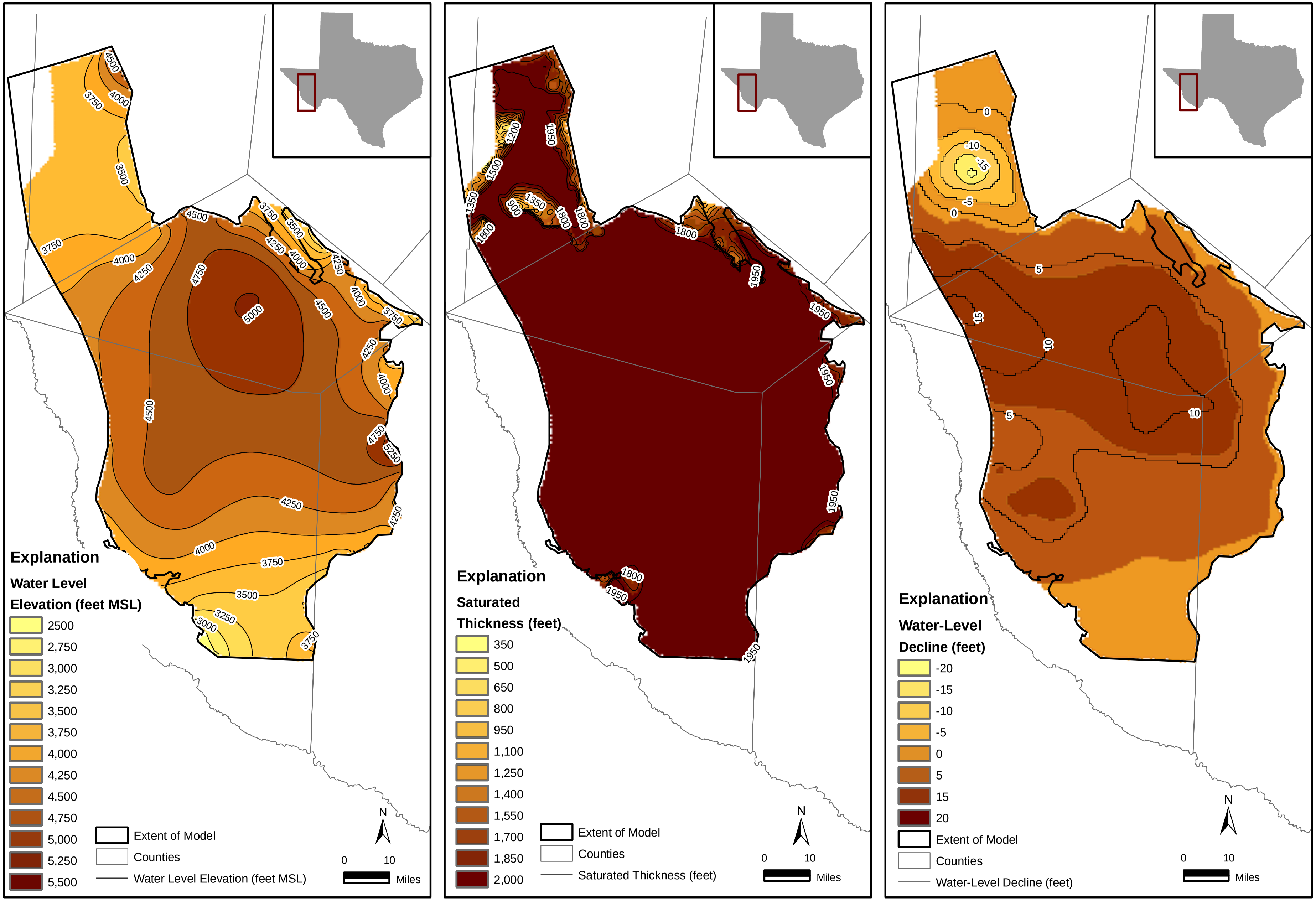


Figure 10.2.25 - Simulated Water-Levels, Saturated Thickness, and Water-Level Declines in 2030 Under DOR Conditions (Layer 3)

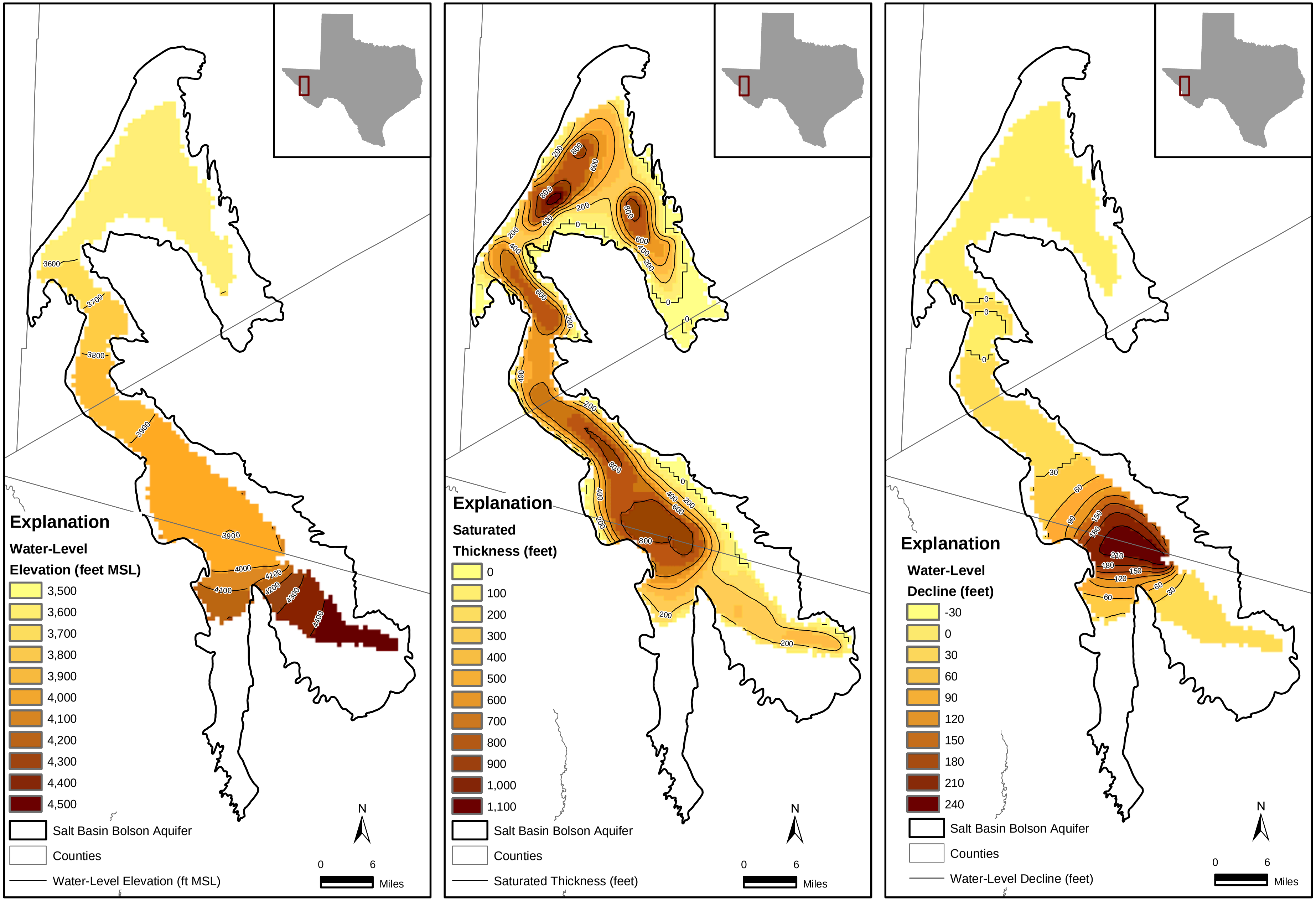


Figure 10.2.26 - Simulated Water-Levels, Saturated Thickness, and Water-Level Declines in 2040 Under DOR Conditions (Layer 1)

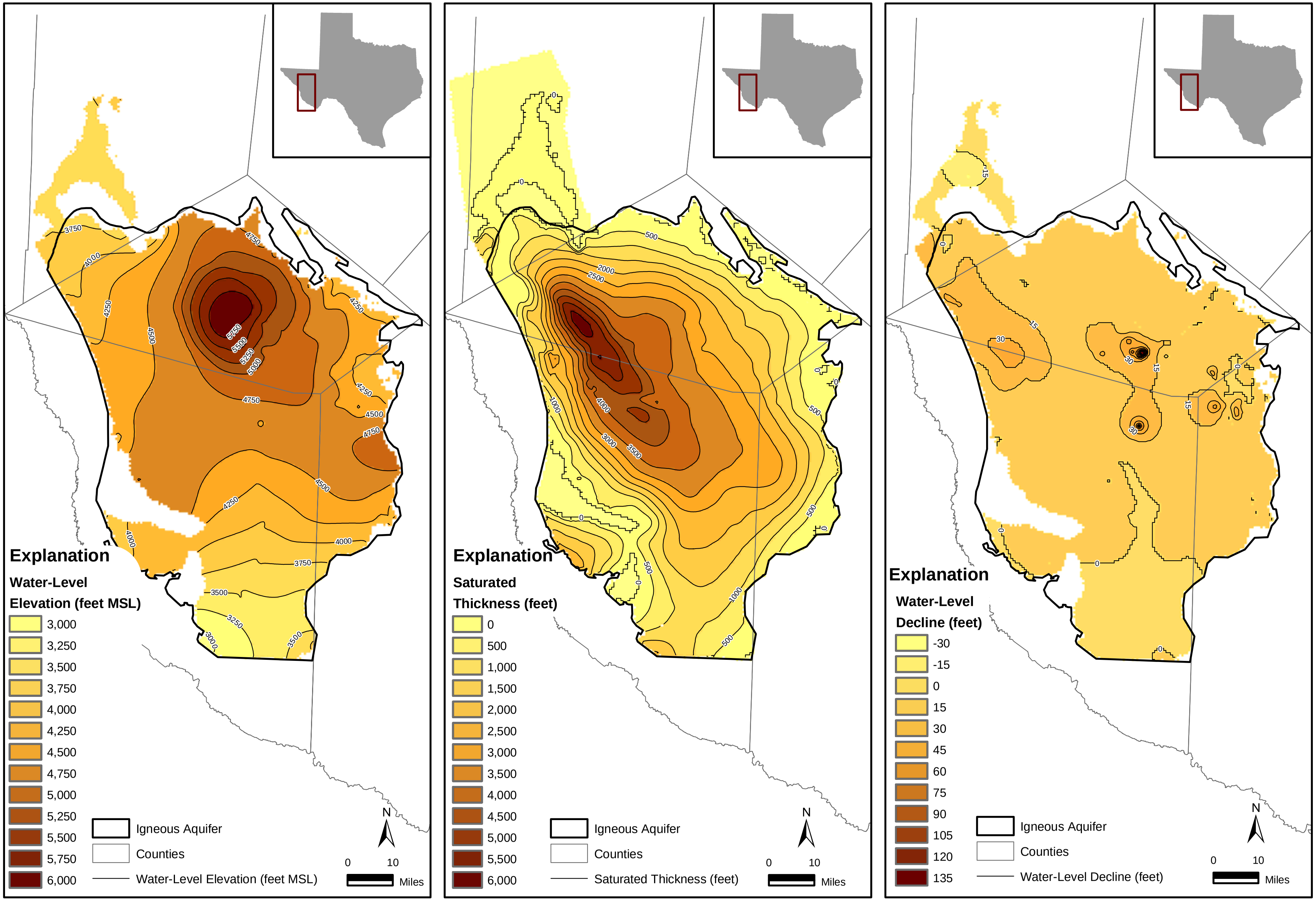


Figure 10.2.27 - Simulated Water-Levels, Saturated Thickness, and Water-Level Declines in 2040 Under DOR Conditions (Layer 2)

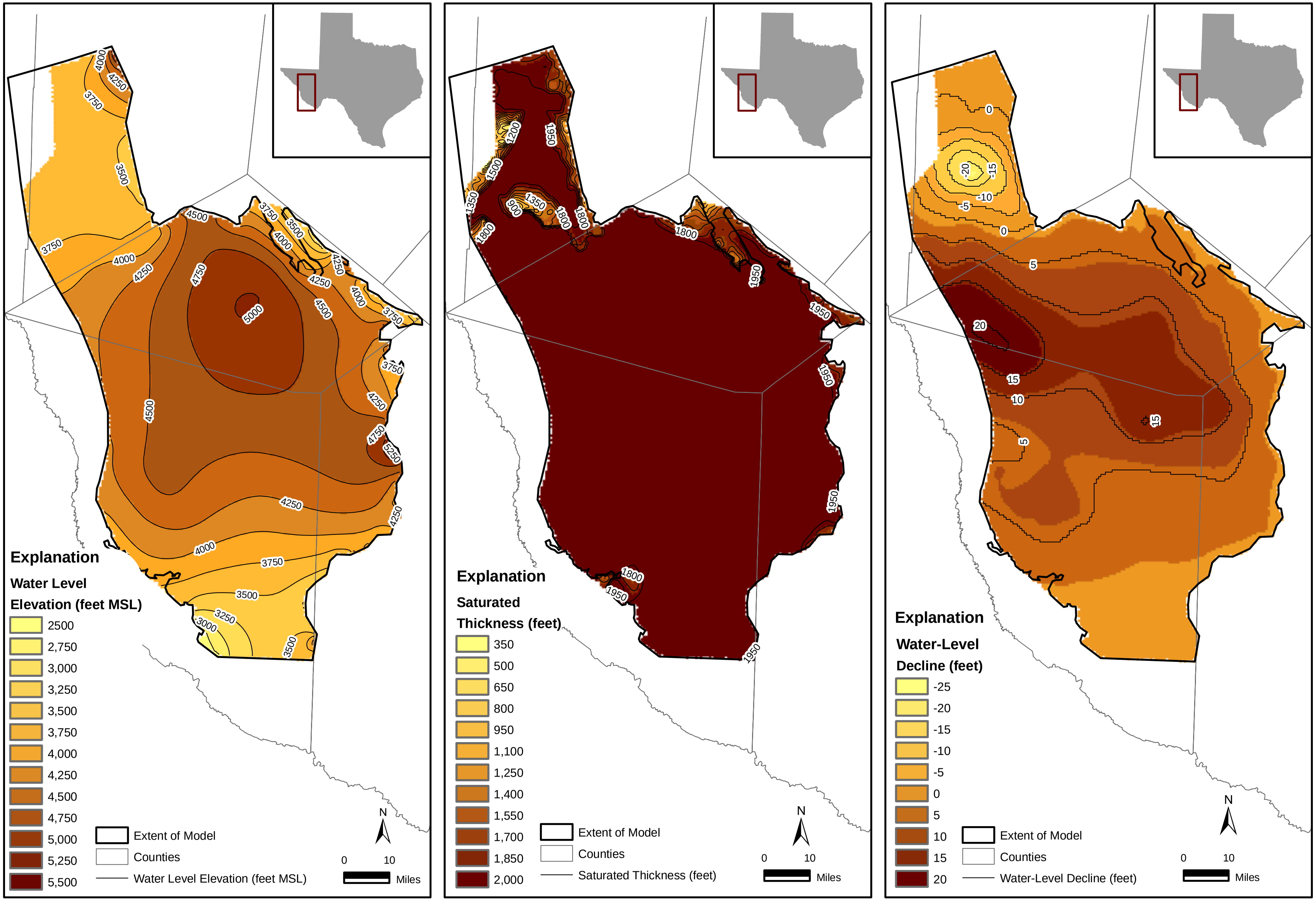


Figure 10.2.28 - Simulated Water-Levels, Saturated Thickness, and Water-Level Declines in 2040 Under DOR Conditions (Layer 3)

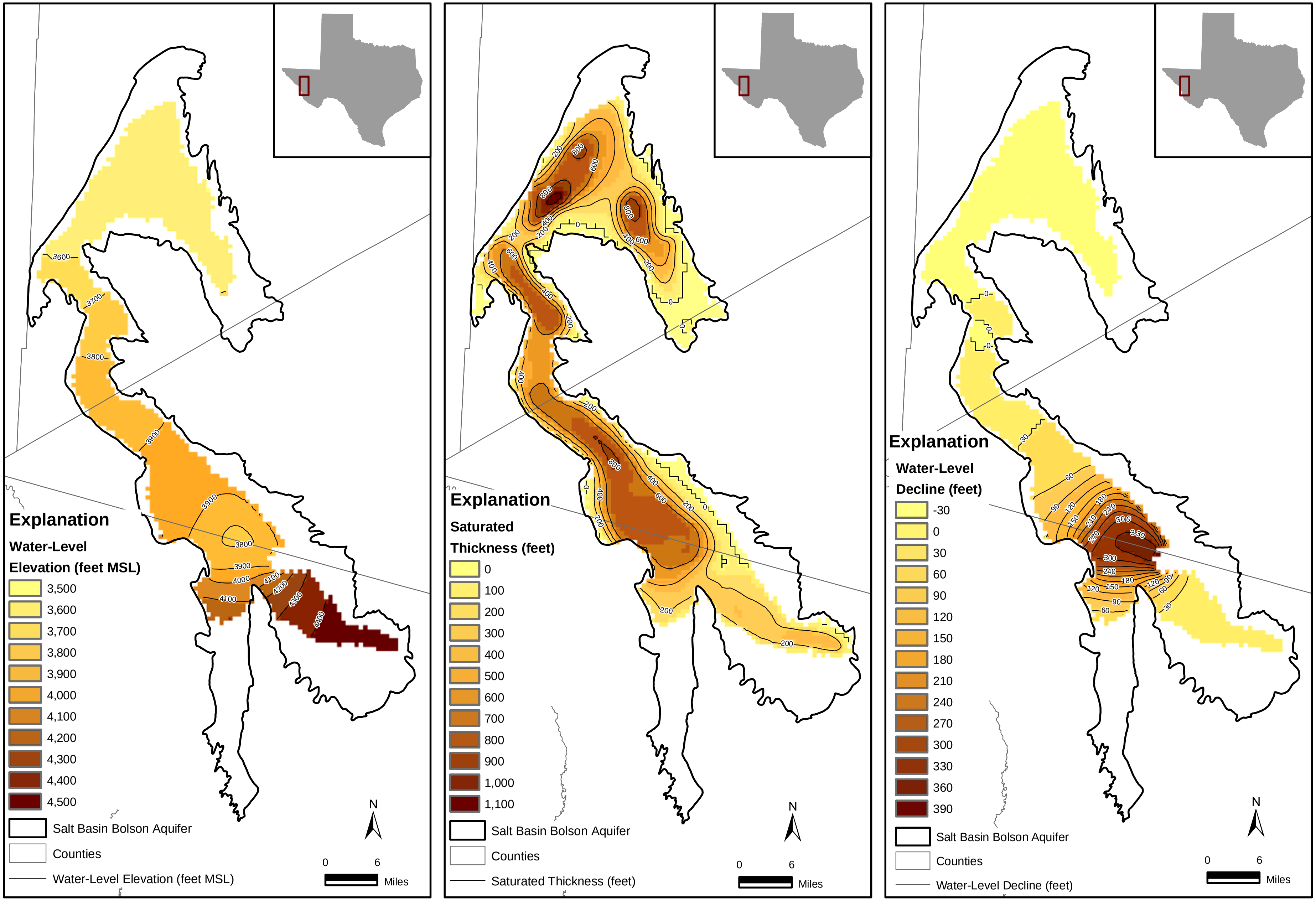


Figure 10.2.29 - Simulated Water-Levels, Saturated Thickness, and Water-Level Declines in 2050 Under DOR Conditions (Layer 1)

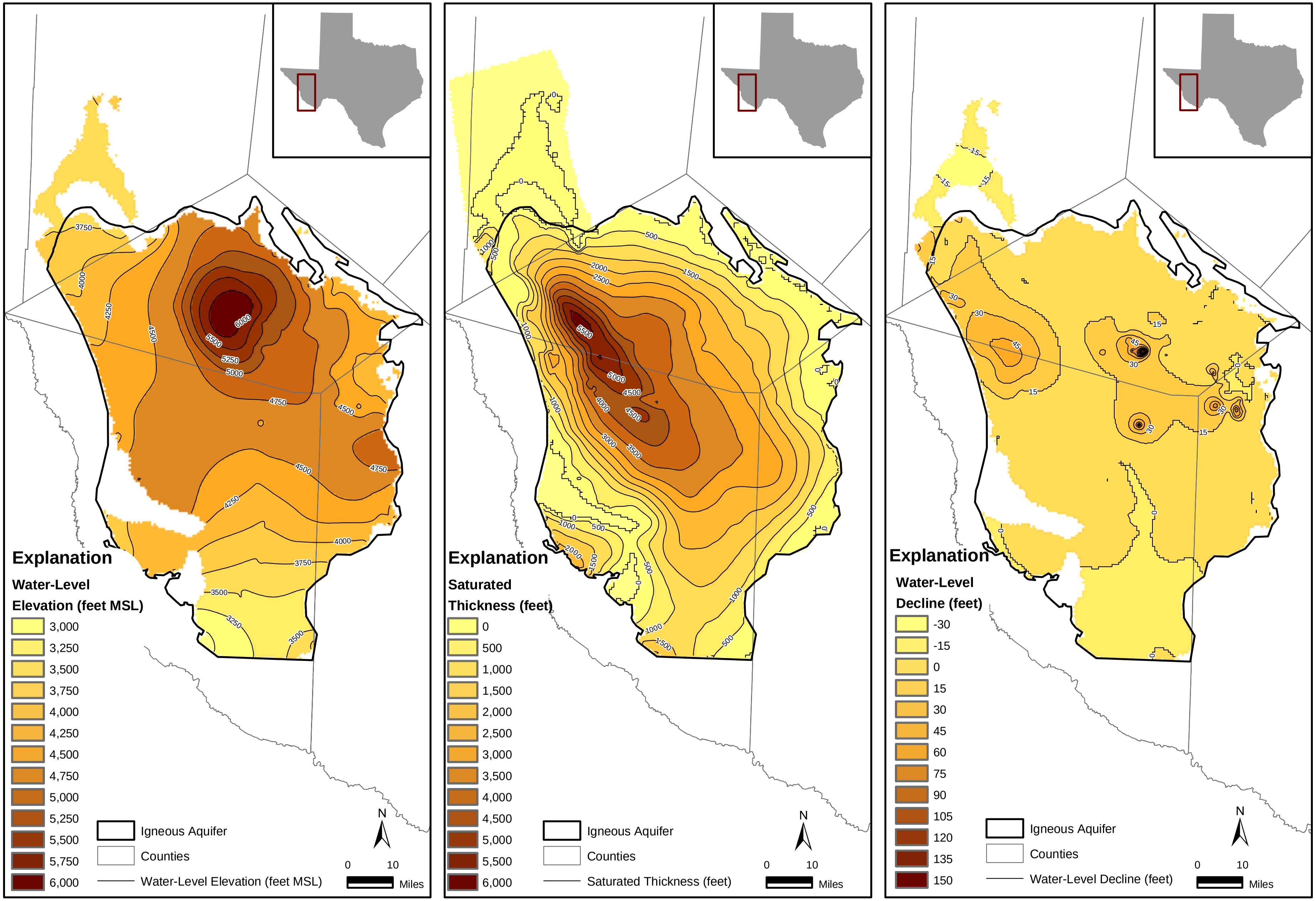


Figure 10.2.30 - Simulated Water-Levels, Saturated Thickness, and Water-Level Declines in 2050 Under DOR Conditions (Layer 2)

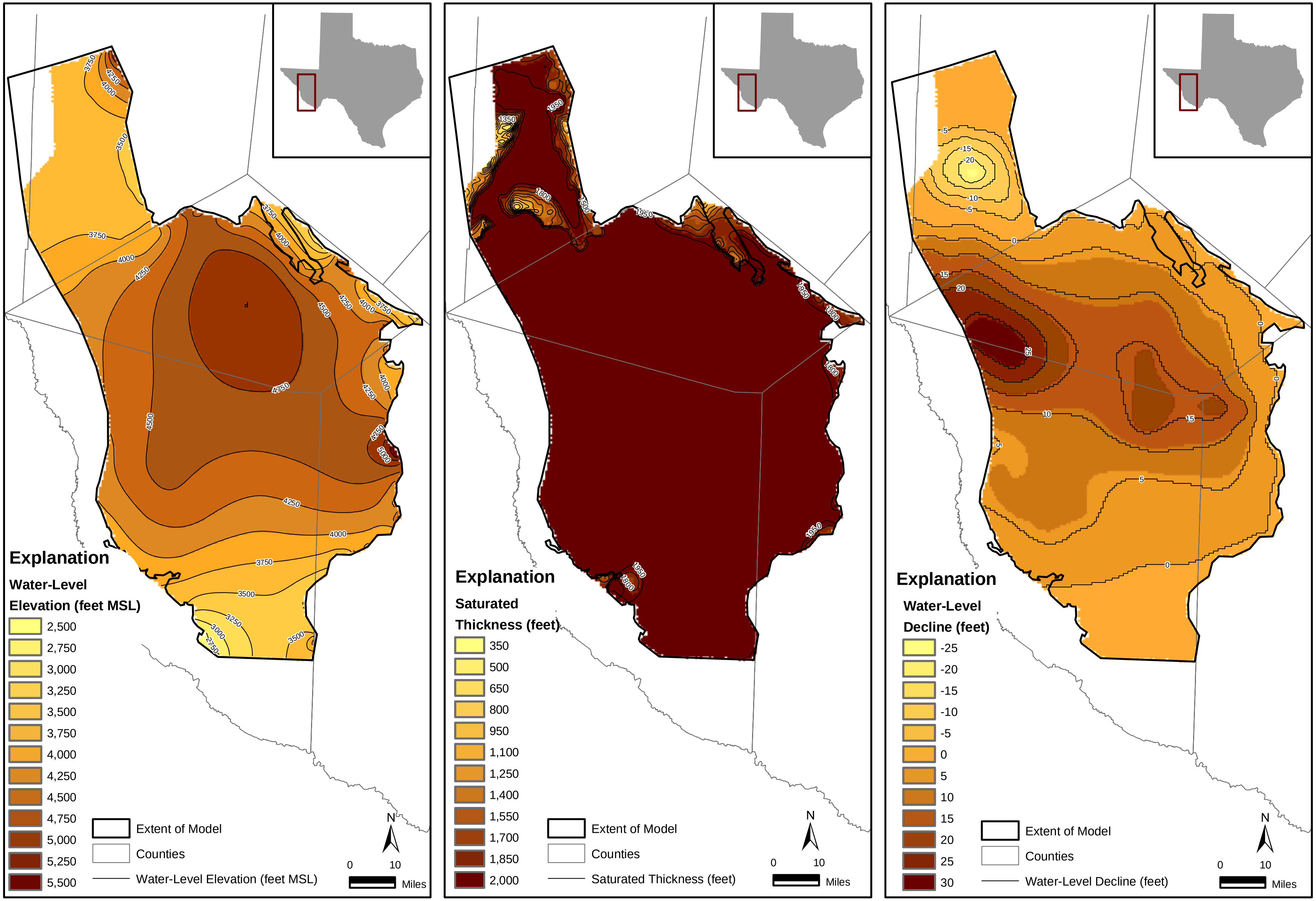


Figure 10.2.31 - Simulated Water-Levels, Saturated Thickness, and Water-Level Declines in 2050 Under DOR Conditions (Layer 3)

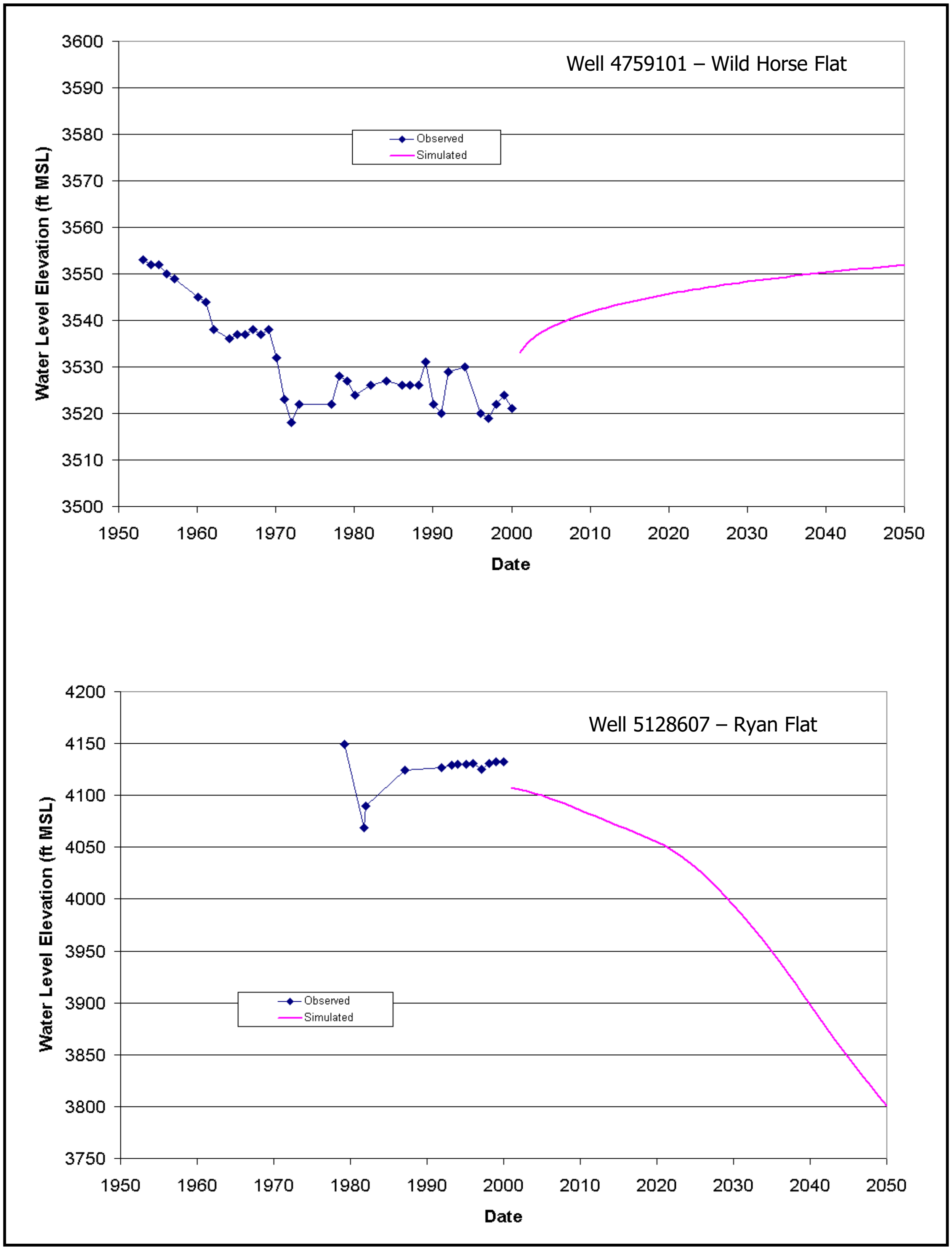


Figure 10.2.32 Hydrographs for selected wells from 1950 to 2050 under DOR conditions

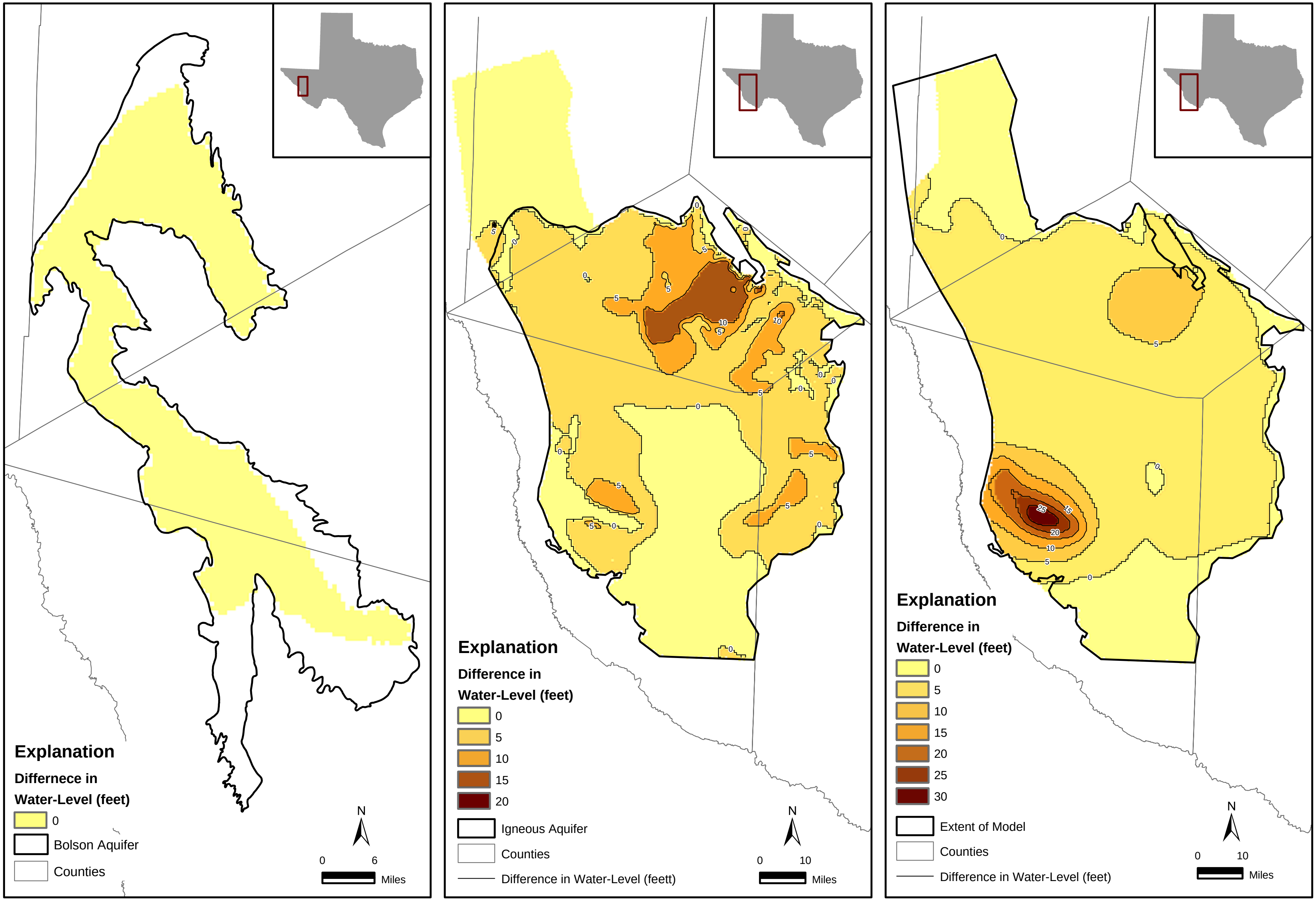


Figure 10.2.33 - Difference in Simulated Water-Level Declines in 2050 Between Average and DOR Conditions (Layer 1, 2, and 3)

10.2.2 Water Budget

Figure 10.2.34 shows the water budget for the predictive model (all layers) under average and DOR conditions. The mass balance plot indicates that almost all of the water pumped from the model is coming from storage as indicated by the opposite trends of the "well outflow" and "storage inflow" volumes. Although the plot considers all layers of the model, the majority of pumping comes from the Salt Basin Bolson, and likewise, the reduction in storage volume is also from that aquifer.

Figure 10.2.34 indicates that the only significant difference between the results for the two simulations is that the loss of recharge in the DOR simulation is offset by a change in storage in the model. As indicated in Figure 10.2.34, changes in storage in the Igneous aquifer are closely related to changes in recharge because the Igneous aquifer receives most of the recharge in the model area.

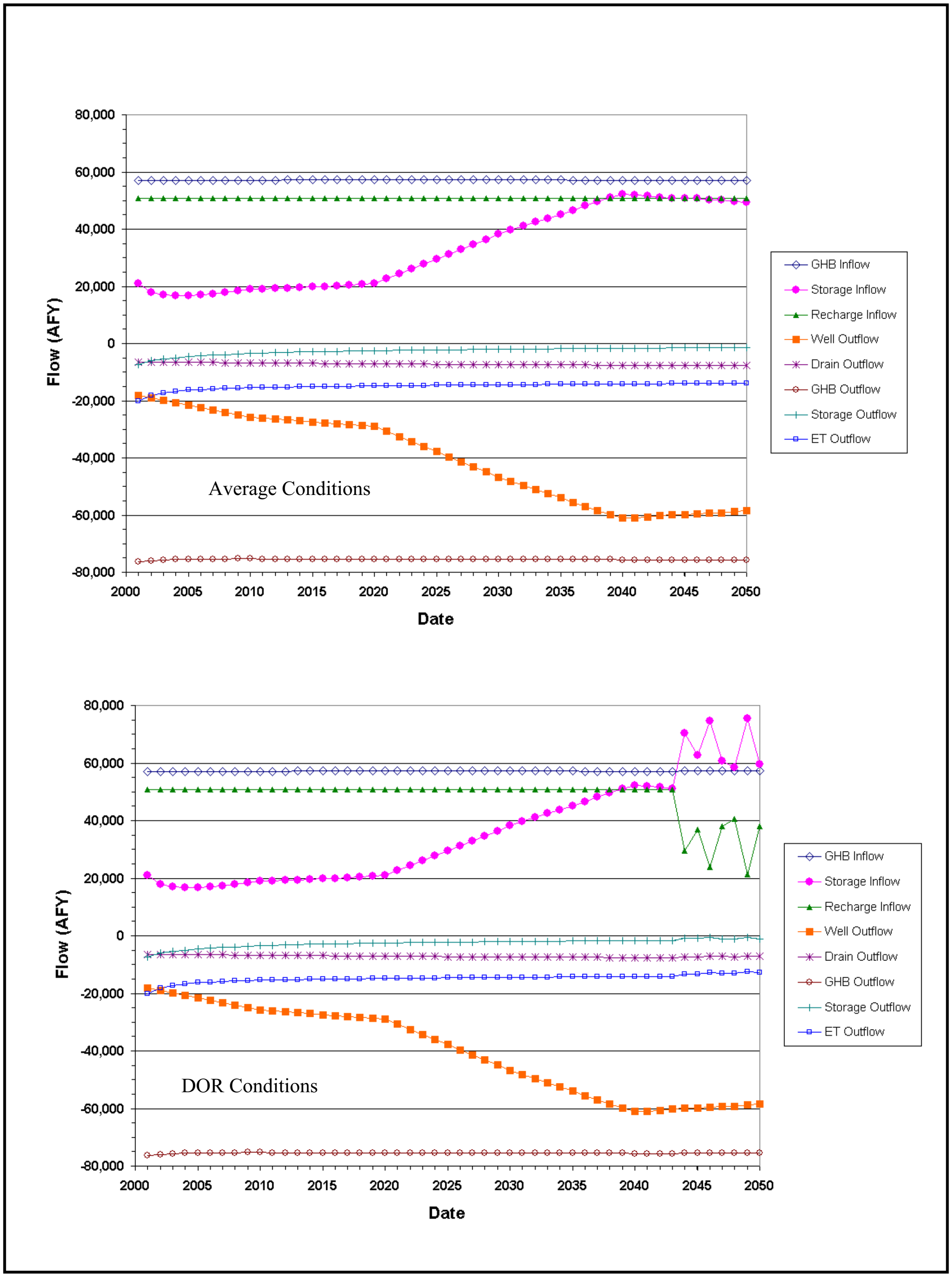


Figure 10.2.34 Water budget for the predictive model under average and DOR conditions

11.0 LIMITATIONS OF THE MODEL

11.1 Limitations of Supporting Data

A groundwater model is an attempt to simulate aquifer dynamics and responses to hydrologic stresses such as groundwater withdrawals and change in recharge conditions. The accuracy to which a model can make these predictions is directly related to the reliability of aquifer data which are input into the model. The IBGAM attempts to simulate groundwater flow in two adjacent but hydrogeologically distinct aquifers which are partially connected. Although the model adequately simulates the observed regional radial flow pattern, it should be recognized that the model assumes a single, although heterogeneous, hydrologic unit.

Because of recent studies of the Igneous aquifer, there is more information on which to develop a model than before. However, because the Igneous aquifer is a complex and heterogeneous system, the lack of available data is still a limitation when developing a groundwater flow model, even at the regional scale. Some examples of data shortages include the lack of:

- sufficient well data for depths > 1,000 ft,
- sufficient long-term water-level trends,
- aquifer transmissivity and saturated thickness data,
- location and extent of fracture zones and associated hydraulic characteristics,
- definition and characterization of distinct water bearing zones within the Igneous units, and
- structural controls and other factors which impact stream-aquifer interaction.

11.2 Limiting Assumptions

The flow system in the study area contains several complexities which have been simplified for modeling purposes. Each of the major aquifer units in the model area is represented by a single model layer in the conceptual and numerical models. In reality, each aquifer consists of many different zones which are hydraulically connected in varying degrees. The Igneous aquifer contains many potential water-bearing zones which transmit groundwater, but because there is a lack of data to characterize these units, the Igneous aquifer has been lumped together into a single layer in the model. The same is true for the Bolson as well as the Cretaceous and Permian units. While this conceptualization is consistent with the current understanding of the aquifer, it should be recognized that it is a great simplification of a very complex hydrogeologic system.

Cross-formational flow from the Igneous aquifer to the Salt Basin Bolson aquifer is controlled by several factors which have not been fully characterized, including the hydraulic conductivity and connection between the aquifers. The significance of any interaction with underlying units has not been established.

MODFLOW is formulated to simulate flow in continuous porous media like sand and gravel aquifers. Flow in the Igneous aquifer occurs in fractures, fissures, and through the porous matrix. Simulating flow in such a complex system with MODFLOW offers significant limitations under some conditions. MODFLOW has been used in other studies to simulate flow in fractured flow systems. However, there are limits to the applications for the model.

11.3 Limits for Model Applicability

The Igneous aquifer was included in the IBGAM mainly because of the recognition that it is a part of the regional flow system in the study area and is connected to the Salt Basin Bolson aquifer. In general the model does a reasonable job simulating steady-state conditions in the Igneous aquifer and is helpful for gaining insight into the regional conditions in the aquifer and the regional impact of proposed strategies. However, the model is probably not a reasonable tool to assess spring flow in the Davis Mountains, stream-aquifer interaction, or assessment of localized water level conditions or aquifer dynamics in the Igneous aquifer. These types of aquifer dynamics and interactions are controlled by many complex and local factors which were not and could not have been incorporated into the simplified conceptual, data, or numerical model developed for this study. In addition, the Igneous portion of this model should be used with caution when attempting to simulate individual well dynamics, and possibly even wellfield conditions because the model was not developed with that goal in mind nor were the data available on a regional basis to construct such a model for the entire Igneous aquifer.

Based on the available calibration and verification data, the model simulates groundwater movement within the individual flats comprising the Salt Basin Bolson aquifer relatively well. However, the simulation of lateral movement between the flats is less defendable due to limited hydraulic property data and historic water level information.

12.0 FUTURE IMPROVEMENTS

12.1 Supporting Data

Groundwater data characterizing the Salt Basin Bolson aquifer are relatively abundant within the individual flats; however, the horizontal movement of groundwater between the flats is expected but not substantiated with physical data. Also, the vertical interaction with underlying geologic units (Cretaceous and Permian underlying Wild Horse and Michigan Flats, and Tertiary Igneous underlying Lobo and Ryan Flats) is not understood. Lateral eastward flow out of the Salt Basin Bolson aquifer through Cretaceous and Permian formations has been studied (LaFave and Sharp (1987), Sharp (2001)); however, westward movement toward the Rio Grande has yet to be evaluated.

Continued collection of basic groundwater data (water levels, water chemistry and pumping tests) in the Igneous aquifer would help refine the model. However, the greatest need is to better understand the complexity and hydrologic connection between the individual water-bearing layers (flows) within the framework of the total Tertiary igneous package and their lateral and vertical interaction with the Salt Basin Bolson aquifer. Because of the heterogeneity of the Igneous aquifer, it would take many investigations to adequately characterize the distinct aquifer units so that a more detailed conceptualization could be implemented for a flow model. These detailed studies are more likely to occur in localized areas as the need arises for water resources.

A significant amount of subsurface information is available and awaits evaluation from numerous oil-test geophysical logs, cuttings, and drilling reports. It is possible that in the future primary water-bearing units might be aerially mapped and characterized such that expected well yields might be more readily predicted. More characterization of the hydraulic properties of the volcaniclastics that underlie Ryan Flat would be helpful in understanding the role this unit plays in that area and to reduce the uncertainty in the model results. However, the results of the sensitivity analysis should be interpreted carefully because the sensitivity is based on changes in simulated heads for each gridblock in the model. The ±10% “uncertainty” in the boundary heads that was simulated during the sensitivity analysis (as per TWDB requirements) is a relatively large change in head at the boundaries in Layer 3. By comparison, ±10% uncertainty in the recharge value may be small when comparing the sensitivity to heads in every cell of the model.

12.2 Model Improvements

The model could be enhanced by better defining the distinct water bearing units within the Igneous aquifer represented by layer 2. Incorporating these layers would allow a more realistic representation of the flow in this complex system. In addition, better refinement of drains along streams and on the east side of the Davis Mountains may improve model calibration. GHB heads in layer 3 were based on estimated heads in the Igneous aquifer and were adjusted during calibration. The sensitivity analyses indicated that average model heads are sensitive to this boundary and therefore, more water level information in the Cretaceous and Permian units would help justify the head values selected for layer 3.

Yearly estimates of recharge were based on yearly rainfall. This simplified approach to varying recharge was based on the broad assumption that recharge is directly proportional to total yearly rainfall. In some cases, a relatively dry year may have a couple of relatively wet periods when recharge is significant and perhaps even higher than a relatively wetter year. On the other hand, large storm events may occur in some years that increase the total yearly precipitation above average, but most of the rainfall may run off. In this case, there may be a larger percentage of the rainfall that contributes to Bolson recharge through stormwater runoff. Further research may help identify what types of precipitation events provide the greatest recharge and how that recharge is distributed. Then, it might be possible to estimate historical recharge based on the frequency of these types of events.

The distribution of historical pumping has a significant impact on model calibration and the estimates of future pumping volumes and distribution is important to predicting areas where water level declines are likely to occur. There may be better ways to distribute pumping (especially irrigation pumping) that would improve the model calibration.

13.0 CONCLUSIONS

A three-dimensional groundwater model was developed for the Igneous and Salt Basin Bolson aquifers according to a methodology prescribed by the TWDB. This modeling approach was consistent with TWDB GAM protocol and includes: (1) the development of a conceptual model of groundwater flow in the aquifer, (2) model design, (3) model calibration and verification, (4) sensitivity analysis, (5) model prediction, and (6) documentation of the model.

The model is regional in scale, and was developed with the MODFLOW flow code. The conceptual model developed for the flow model divides the aquifer system into three layers, the Salt Basin Bolson, Igneous aquifer, and the underlying Cretaceous and Permian water-bearing zones. The conceptual model was based on data compiled from many sources and included a detailed analysis of recharge for the model area. Available hydraulic conductivity, aquifer storage properties, and water level measurements were assimilated for use in developing a representative and defendable model.

One purpose of this IBGAM is to provide predictions of groundwater availability through the year 2050 based on current groundwater demand projections during average and drought-of-record hydrologic conditions. The IBGAM integrates all of the available hydrogeologic data for the study area into the flow model which can be used as a tool for the assessment of water management strategies. Because the model is publicly available, it can be used by planners, Regional Water Planning Groups (RWPGs), Groundwater Conservation Districts (GCDs), and other entities to assess groundwater conditions under various scenarios.

The calibrated steady-state model reproduces the available water level measurements and flow directions well. The model also simulates the observed radial flow pattern in the Davis Mountains. Sensitivity analysis indicates that the most sensitive parameters in the model are boundary heads, hydraulic conductivity, and recharge. Calibration of the transient model from 1950 through 2000 incorporated historical pumping and variable recharge. The model is capable of reproducing aquifer heads which follow the same trends as observed hydrographs. Simulated drawdown hydrographs in the Salt Basin Bolson aquifer match the observed drawdowns very well. On a regional basis, the model reproduces model heads to within estimated head target errors.

The calibrated model was used to predict water level declines between 2000 and 2050 by incorporating projected groundwater demands developed by the Region E RWPG. Average and drought-of-record recharge conditions were simulated in the predictive simulations. Results from the predictive simulations indicate that currently proposed groundwater demands from the Salt Basin Bolson aquifer in Ryan Flat may cause almost 400 feet of drawdown in that area by 2050. Simulated water levels rebound in Wild Horse Flat due to slight decreases in projected demands. Water levels in the Igneous aquifer remain relatively stable in most areas but show some decline near Fort Davis, Marfa and Alpine over the 50-year simulation.

The model is a valuable tool for evaluating proposed pumping in the Salt Basin Bolson aquifer. Drawdown estimates from the model in the Salt Basin Bolson aquifer compare well to historical observed drawdowns. Therefore, the IBGAM model can be used to simulate drawdown under proposed pumping in the Salt Basin Bolson aquifer. In addition, the ½-mile grid spacing allows relatively refined assessments of proposed wellfields in the Salt Basin Bolson aquifer. This is not necessarily true for the Igneous aquifer because the potential for local hydrogeologic complexity is not incorporated into the model. Although the model can be used to simulate regional groundwater flow in the Igneous aquifer, it has limitations and is not applicable for some problems. However, the IBGAM does provide a well-documented tool for evaluating regional groundwater availability in the model area.

14.0 ACKNOWLEDGEMENTS

The successful completion of a major modeling project, such as this IBGAM, requires the cumulative knowledge, assistance, and backing of many individuals and groups outside the modeling team itself. Throughout the project, the Far West Texas Regional Water Planning Group remained keenly interested and supportive. The Group recognized that, upon completion, the IBGAM would likely be a major tool in evaluating regional water management strategies.

A significant limitation to the development of the IBGAM was the lack of basic hydrologic data, especially for the Igneous aquifer portion of the model. Prior to initiating the IBGAM project, the TWDB provided supplemental funding to the Far West Texas Regional Planning Group to study the Igneous aquifer system. The results of that study (Ashworth and others, 2001) formed the cornerstone of the Igneous portion of the conceptual model. Also early in the project, the El Paso Water Utilities provided funding through the auspices of the Regional Planning Group for the development of additional data in the form of pumping tests and water-level measurements.

We would also like to thank the IBGAM Stakeholder Group for their interest and vital input to the project. Comments provided by this group were critical in attaining a historical perspective on the groundwater response to the long-term use of the local aquifers. Specific thanks go to Bill Hutchison (El Paso Water Utilities) and Zhuping Sheng (Texas Agricultural Experiment Station) and Van Robinson for their technical insight on modeling issues.

Thanks are extended to the four groundwater conservation districts located within the study area (Brewster, Culberson, Jeff Davis, and Presidio) for their support and assistance in providing needed local well information and landowner contacts. In particular, Janet Adams is deserving of special appreciation for her personal interest in this project. Local landowners who allowed access to their wells for pumping tests and water-level measurements provided an invaluable service to the furthering of hydrologic knowledge in the region.

And finally, we wish to thank the Texas Water Development Board for its forward thinking in developing and funding the statewide aquifer GAM program and its staff for their guidance and assistance in completing this major project. Ted Angle (contract manager), Cindy Ridgeway, and Robert Mace are deserving of special thanks for their direct involvement.

Comments received from the TWDB and stakeholders on the Draft Conceptual Model Report and the Draft Final Report can be found in Appendix E. Responses to each comment are also included in Appendix E.

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APPENDIX A

METHODOLOGY FOR DEVELOPING INTERPRETIVE WATER LEVEL MAPS

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1.0 Introduction

The West Texas Bolson and Igneous Aquifers Groundwater Availability Model is an interpretive model. The data for this model are very sparse in many areas, and specifically with respect to the water level data within the Igneous portions of the model area. Two recent studies, Ashworth and others (2001) and Ashworth and Chastain-Howley (2003), increase the amount of data available. These data have been used in the development of interpretive water level contour maps to gain a better understanding of regional flow in the model area. The TWDB GAM protocol requires that water level contour maps be developed for the predevelopment period and during the calibration and verification period; therefore maps were developed for 1950, 1980, 1990 and 2000. These maps were not used directly in the modeling process but only as a guide to understanding regional water level trends.

In all but the most recent period (2000), there were less than 100 data points available for contouring within the Igneous Aquifers area. This caused significant errors when these data were contoured, and meant that water levels across the mapped area varied between 1400 feet below surface to 800 feet above surface based on a standard kriging approach over the model area. This was not suitable, and so the following methodology was developed to estimate the water levels more appropriately and in a manner consistent with the conceptual model.

2.0 Methodology

In order to create water level surfaces over a large area based on the sparse data points a methodology was developed that used surface geology as a proxy for data points. “Before” and “after” graphics (Figures A.1 and A.2) are presented below to outline the differences between the water level contours prior to implementing this methodology and those after.

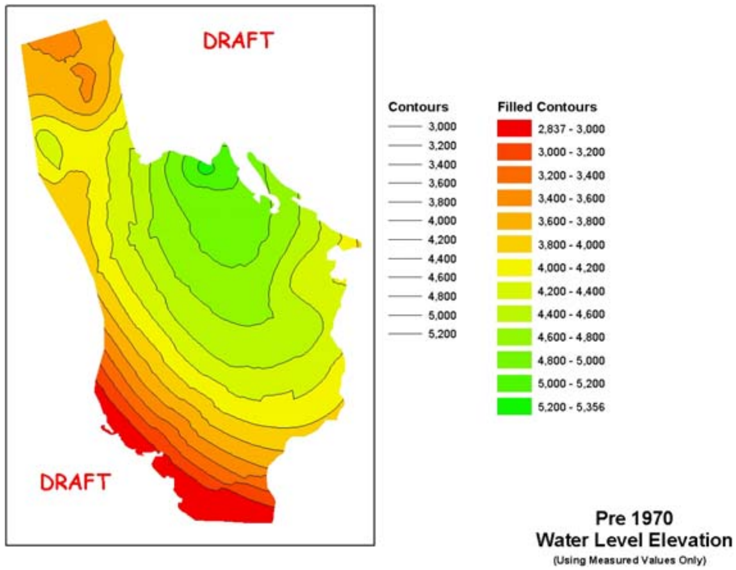

Figure A.1   Contours from all water level data pre-1970

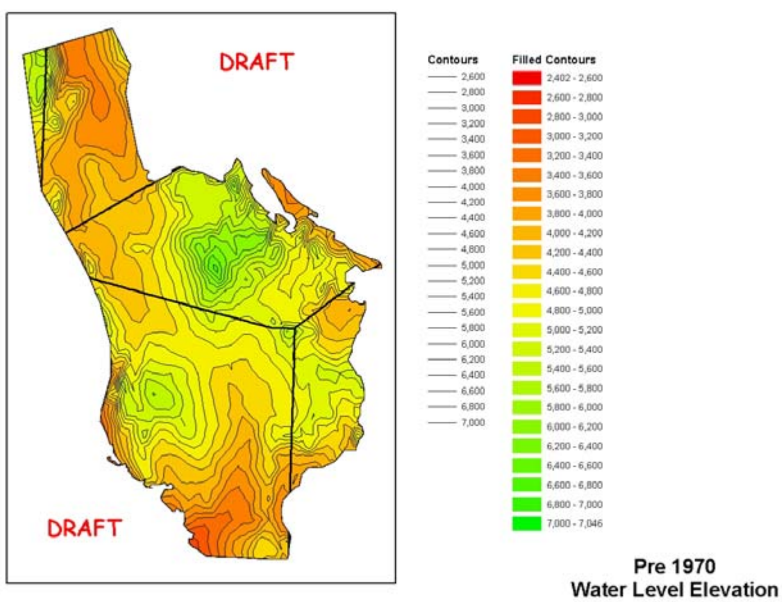

Figure A.2   Calculated contours from interpretive data pre-1970

All available water levels from one year either side of each year were recorded (i.e. for 1980, data from 1979 to 1981 was analyzed and assigned to a specific geologic unit). Table A.1 details the average values developed from this analysis. It should be noted that this table does not show all the geological units, although the full data set is available in the associated data files. It should also be noted that not all of the geological units have a water level measurement in each of the time periods.

Table A.1 Average water level data for each of the geological units for specific time periods.

Sum of FORM_MEAN	FORM									
YEAR	Psr	Qal	Qao	Qb	Qf	Ql	Qtb	Qws	Tac	Tbs
1950	550	115.63			189.83			320.00		
1970	550	132.83	345.12	194.89	162.54	91.05		241.65	62.00	127.59
1980		188.61		238.47	188.66			252.19		
1990		165.83		245.24	138.09		188.82			
2003		117.87	124.73	235.90	142.04			241.56		8.00
Grand Total	1100	720.78	469.86	914.50	821.15	91.05	188.82	1055.39	62.00	135.59

In addition to the average water levels for each geological unit, an overall average for all the data was calculated for each time period. This data was used for all the geological units that did not have any specific water level data.

The model grid system (0.5 mile square cells) was placed over the surface geologic coverage of the study area and specific geologic units were thus assigned to each cell. Associated average water levels for each geologic unit were then given to each corresponding cell. Once all the cells had been assigned a value, the individual water level data points were re-entered, along with the topographic elevation of known springs at their location.

The springs are included on the DEM elevation at that location and they are not averaged. These are separate data points, as are the actual well water levels. Spring locations were incorporated and given surface elevation values. These data points were adjusted for elevation by subtracting depth to water from elevation values taken from the National Elevation Dataset (NED). The resulting data points were then used to create a water level surface using ArcGIS Geostatistical Analyst. A water level proxy map was created using ordinary kriging and a second order detrending function (50% Global 50% Local). The resultant surface was then contoured.

The above method allowed creation of more realistic water level surface data than would have been possible using only the existing measured data points. This methodology also uses the geometric mean of the data points within specific lithologies, in order to reduce the averaging errors associated with the relatively small datasets.

Due to the small amount of data, the water level maps still have significant errors. More data in the future will lead to better refinement of the mapped water level.

3.0 References

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APPENDIX B

RECHARGE ESTIMATION METHODOLOGY

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RECHARGE ESTIMATION METHODOLOGY

1.0 INTRODUCTION

Groundwater recharge primarily occurs or originates from infiltration of precipitation in the higher elevations (i.e., Davis Mountains) and from infiltration of storm-water runoff on alluvial fans along the bolson perimeter (Scanlon et al., 2001; Finch and Armour, 2001). This recharge concept is depicted in Figure B.1.

Previous investigators have made estimates of recharge to the bolsons based on a percentage of precipitation and calculations of groundwater inflow (Hood and Scalapino, 1951; Gates et al., 1978; and Cliett, 1994). At the time of the USGS study in the late 1970s (Gates et al., 1978; Gates et al., 1980), the basic rule of thumb for the Basin and Range province of the Trans-Pecos Region was to use one percent of the average annual precipitation as the rate of recharge (Gates et al., 1978). This method did not take into account watershed characteristics, rock type, and the feasibility of surface water to enter the groundwater system.

In the current study, the method selected to calculate initial recharge estimates for the study area was based on previous studies completed by Nichols (2000), Stone et al. (2000), and Bennett and Finch (2002). This approach to determining recharge and distribution of recharge takes into account climate, watershed, and geologic characteristics for each sub-basin defined in the study area. The method includes the following analyses:

1. Delineating mountain, alluvial fan, and bolson sub-basins within the study area, and their hydrologic characteristics;
2. Calculating topographic statistics for each sub-basin;
3. Estimating potential recharge (corrected for elevation zones and evaporation) for each sub-basin;
4. Determining runoff from each sub-basin by analyzing the magnitude of precipitation events that result in runoff (scaled to elevation); and,
5. Determining which sub-basins receive runoff from up-gradient sub-basins and the amount of runoff that is lost from the area of recharge (redistribution).

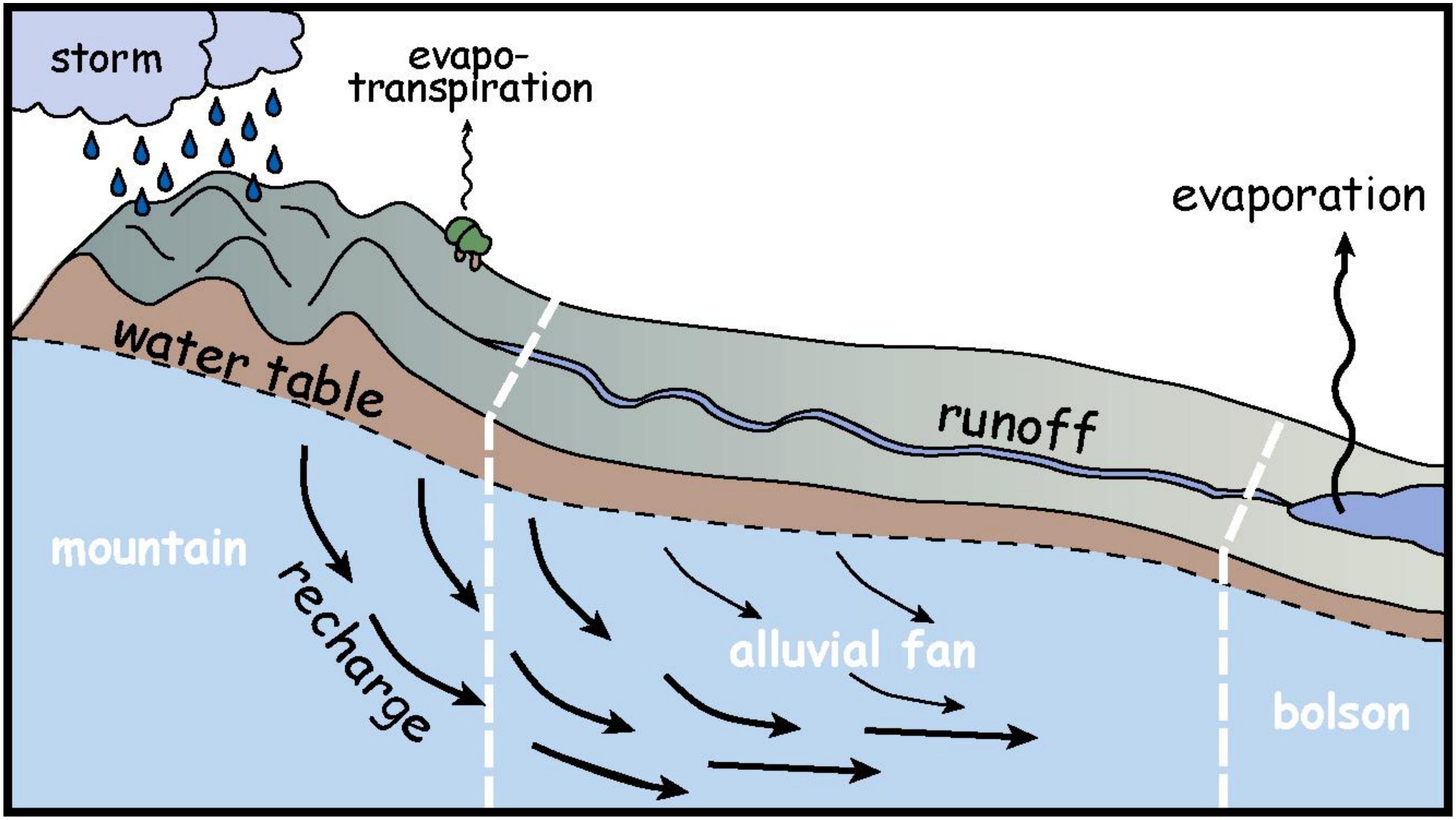

Figure B.1. Schematic of recharge processes and methods used to estimate recharge.

The assumptions made for calculating recharge and recharge distribution include the following:

1. Direct precipitation on the bolson does not infiltrate and become recharge;
2. Precipitation increases with elevation as defined by existing data;
3. There is no potential recharge for areas with less than 12 inches per year average precipitation;
4. Dry soil conditions are used for estimating the runoff curve number; and,
5. Approximately 30 percent of the runoff infiltrates at the alluvial fan and the remaining 70 percent evaporates or flows out of the model domain.

Average annual and daily precipitation data for the period of record were collected for 21 weather stations (Figure B.2) in and around the study area (Texas Office of the State Climatologist, 2003). The relationship between precipitation and elevation for these weather stations was used to determine potential recharge in each sub-basin in the study area. For each weather station, the frequency of 24-hour precipitation events of specified magnitudes that could potentially generate storm-water runoff were determined. A linear relationship between elevation and frequency of runoff events at the weather stations was used to calculate runoff for each sub-basin in the study area. Calculated runoff was subtracted from potential recharge in topographically up-gradient sub-basins and added to potential recharge in 'receiving' sub-basins at lower elevations.

The effects of evapotranspiration and other losses need to be considered when estimating potential recharge; otherwise the potential recharge values for the sub-basins are overestimated. To do this, the potential recharge is estimated from empirical relationships (coefficients; Nichols, 2000) modified to represent Trans-Pecos climate conditions (Bennett and Finch, 2002).

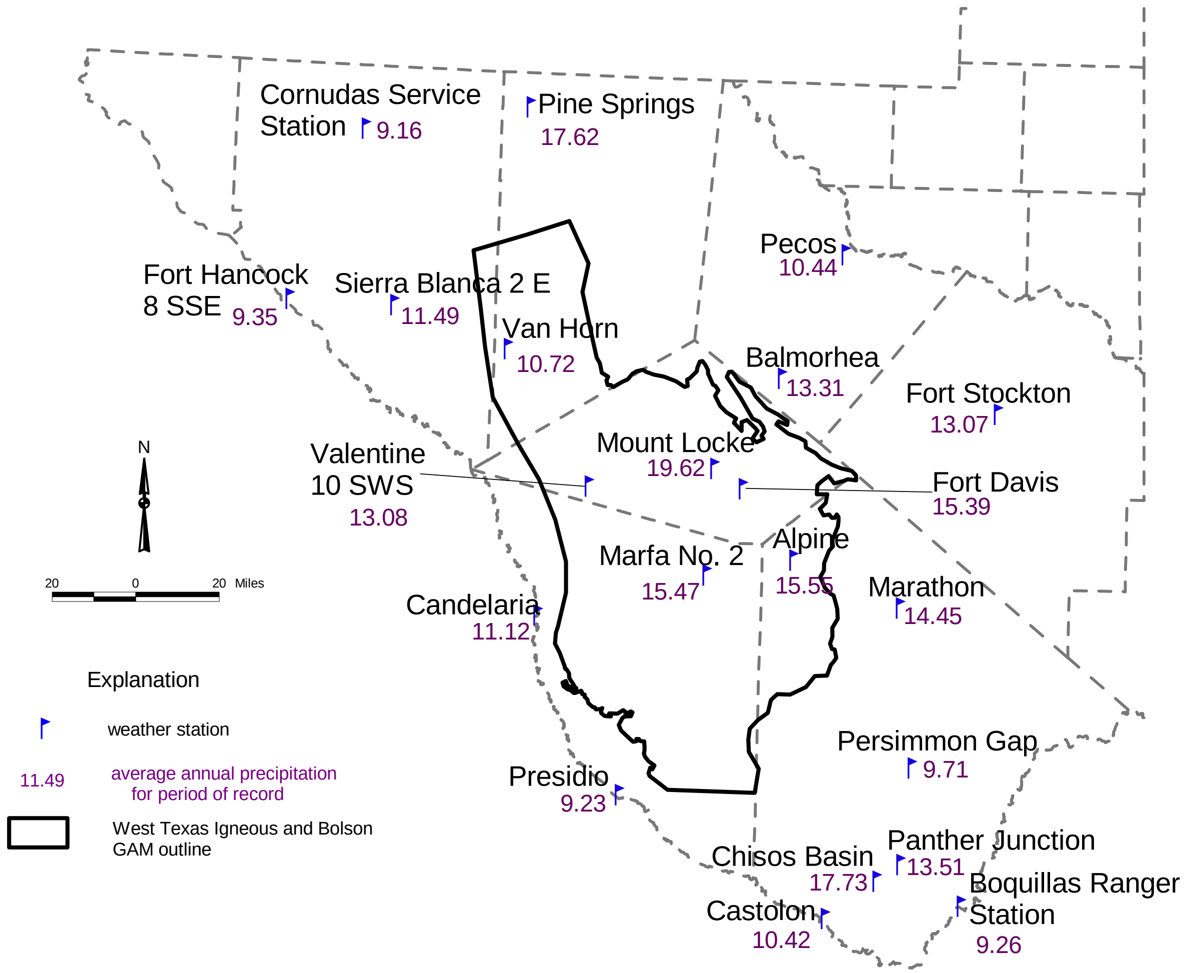

Figure B.2. Location of weather stations used for recharge analysis.

2.0 METHODS

2.1 Delineating Sub-Basins

The three major basins that encompass the study area are the Wild Horse Basin, the Pecos River Basin, and the Rio Grande Basin (Figure B.3). Smaller sub-basins within these major basins (Table B.1; Figure B.3) were delineated. Dominant soil types and topographic statistics, such as areas within given elevation intervals, were determined for each sub-basin based on soil surveys (USDA, 1972; USDA, 1974; USDA, 1977; USDA, 2003) and 1:100,000 scale U.S. Geological Survey topographic maps for the region. Soil type, geology, and land cover information were used to classify each sub-basin in terms of hydrologic soil group and curve number (CN, a measure of the ability of a soil to retain precipitation; USDA, 1986), and determined which weather stations give representative precipitation data for each sub-basin (Table B.1).

2.2 Analysis of Precipitation Data

Daily precipitation data for the period of record for 21 weather stations in and around the study area was obtained (Texas Office of the State Climatologist, 2003) and used to develop a relationship between precipitation and elevation (Table B.2; Figure B.4).

In Figure B.4, standard deviations associated with average annual precipitation values overlap with the trend line, except for Cornudas. The Cornudas, Fort Hancock, and Sierra Blanca weather stations, located northwest of the study area, show lower precipitation than expected based on their elevations. These weather stations show little variation in annual precipitation over an elevation range of 635 feet. They cast doubt on the precept that the data for the study region have a simple linear relationship. If the Fort Hancock, Sierra Blanca, and Cornudas weather stations are not included in the graph, a better linear fit is achieved (Figure B.5; R-squared value of 0.87 instead of 0.65). The Van Horn weather station remains on the graph because it is within the boundaries of the study area.

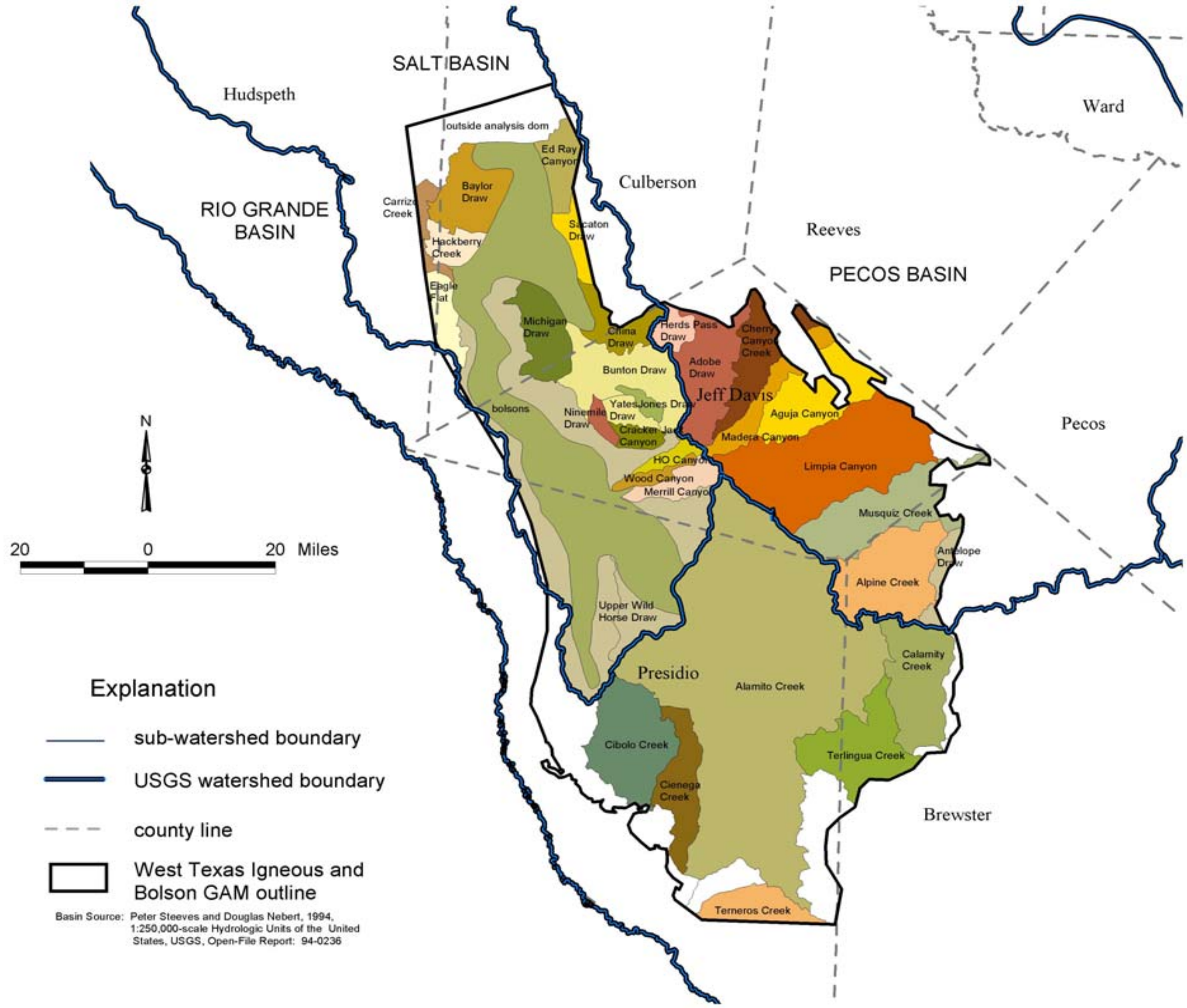

Figure B.3Basins and sub-basins in the study area.

Table B.1 Basins and sub-basins of the Igneous-Bolson aquifer groundwater availability model study area, Trans-Pecos Texas

basin	sub-basin	sub-basin type	geology	hydrologic soil group[1]	CN[2]	CN[2], dry conditions	weather station	Ia,[3] dry conditions, inches
Wild Horse	Baylor Draw	mountain	limestone	D	88	74.8	Van Horn	0.67
	Ed Ray Canyon	mountain	limestone	D	88	74.8	Van Horn	0.67
	Hackberry Creek	mountain	limestone	D	88	74.8	Van Horn	0.67
	Upper Carrizo Creek	mountain	limestone	B	74	55.8	Van Horn	1.58
	Lower Carrizo Creek	bolson	limestone under fan	D	91	79.8	Van Horn	0.51
	Sacaton Draw	mountain	limestone	D	88	74.8	Van Horn	0.67
	Michigan Draw	bolson	trachyte under fan	D	88	74.8	Van Horn	0.67
	China Draw	mountain	trachyte	B	74	55.8	Van Horn	1.58
	Bolsons of Wild Horse Draw and Michigan Draw	bolson	alluvium and fan	B	82	65.8	Van Horn	1.04
	Upper Wild Horse Draw	mountain		D		74.8	Van Horn	0.67
	Upper Eagle Flat Draw	mountain	sandstone under fan	D	88	74.8	Van Horn	0.67
	Lower Eagle Flat Draw	bolson	sandstone	D	88	74.8	Van Horn	0.67
	Bunton Draw	mountain	trachyte under fan	D	88	74.8	Van Horn	0.67
	Upper Jones Draw	mountain	trachyte	D	88	74.8	Van Horn	0.67
	Lower Jones Draw	bolson	trachyte under fan	D	91	79.8	Van Horn	0.51
	Upper Yates Draw	mountain	intrusive rocks	D	88	74.8	Van Horn	0.67
	Lower Yates Draw	bolson	intrusive rocks	C	88	74.8	Van Horn	0.67
	Upper Ninemile Draw	mountain	intrusive rocks	D	88	74.8	Van Horn	0.67
	Lower Ninemile Draw	bolson	basalt under fan	D	88	74.8	Van Horn	0.67
	Upper Cracker Jack Draw	mountain	rhyolite	D	88	74.8	Van Horn	0.67
	Lower Cracker Jack Draw	bolson	intrusive rocks under fan	C	88	74.8	Van Horn	0.67
	Upper HO Canyon	mountain	rhyolite	D	88	74.8	Van Horn	0.67
	Lower HO Canyon	bolson	rhyolite under fan	C	88	74.8	Van Horn	0.67
	Upper Wood Canyon	mountain	intrusive rocks	C	77	59.4	Van Horn	1.37
	Lower Wood Canyon	bolson	rhyolite under fan	D	88	74.8	Van Horn	0.67
	Upper Merrill Canyon	mountain	rhyolite	C	77	59.4	Van Horn	1.37
	Lower Merrill Canyon	bolson	rhyolite under fan	C	88	74.8	Van Horn	0.67

[1]Hydrologic soil group D represents clay loam, silty clay loam, sandy clay, silty clay, or clay with highest runoff rates and lowest infiltration rates; C represents sandy clay loam with low infiltration rates; B represents silt loam or loam with moderate infiltration rates. Hydrologic soil groups identified in the Soil Survey of Jeff Davis County (U.S. Department of Agriculture, 1977).
[2]CN is the Curve Number, as defined by U.S. Department of Agriculture (1986). CN for dry conditions from Wanielista et al. (1997).
[3]Ia is the initial abstraction for a 24-hour storm event; it is assumed that precipitation events with magnitudes below the Ia do not generate runoff. The Ia was calculated based on the CN for dry conditions.

Table B.1. Basins and sub-basins of the Igneous-Bolson aquifer groundwater availability model study area, Trans-Pecos Texas (continued)

basin	sub-basin	sub-basin type	geology	hydrologic soil group[1]	CN[2]	CN[2], dry conditions	weather station	Ia,[3] dry conditions, inches
Pecos River	Upper Herds Pass Draw	mountain	rhyolite	D	88	74.8	Mount Locke	0.67
	Lower Herds Pass Draw	bolson	limestone	D	91	79.8	Mount Locke	0.51
	Upper Adobe Draw	mountain	rhyolite	D	88	74.8	Mount Locke	0.67
	Lower Adobe Draw	bolson	rhyolite	C	88	74.8	Mount Locke	0.67
	Upper Cherry Canyon Creek	mountain	rhyolite	D	88	74.8	Mount Locke	0.67
	Lower Cherry Canyon Creek	bolson	limestone	C	88	74.8	Mount Locke	0.67
	Upper Madera Canyon	mountain	trachyte	C	77	59.4	Mount Locke	1.37
	Lower Madera Canyon	bolson	rhyolite	C	88	74.8	Mount Locke	0.67
	Upper Aguja Canyon	mountain	rhyolite	C	77	59.4	Mount Locke	1.37
	Lower Aguja Canyon	bolson	rhyolite	C	88	74.8	Mount Locke	0.67
	Upper Limpia Canyon	mountain	rhyolite	C	77	59.4	Fort Davis	1.37
	Lower Limpia Canyon	bolson	rhyolite under fan	D	91	79.8	Fort Davis	0.51
	Upper Musquiz Creek	mountain	trachyte	C	77	59.4	Fort Davis	1.37
	Lower Musquiz Creek	bolson	rhyolite under fan	C	88	74.8	Fort Davis	0.67
	Upper Alpine Creek	mountain	trachyte	D	88	74.8	Alpine	0.67
	Lower Alpine Creek	bolson	trachyte under fan	C	88	74.8	Alpine	0.67
	Upper Antelope Draw	mountain	trachyte	D	88	74.8	Alpine	0.67
	Lower Antelope Draw	bolson	limestone under fan	D	91	79.8	Alpine	0.51

[1]Hydrologic soil group D represents clay loam, silty clay loam, sandy clay, silty clay, or clay with highest runoff rates and lowest infiltration rates; C represents sandy clay loam with low infiltration rates; B represents silt loam or loam with moderate infiltration rates. Hydrologic soil groups identified in the Soil Survey of Jeff Davis County (U.S. Department of Agriculture, 1977).
[2]CN is the Curve Number, as defined by U.S. Department of Agriculture (1986). CN for dry conditions from Wanielista et al. (1997).
[3]Ia is the initial abstraction for a 24-hour storm event; it is assumed that precipitation events with magnitudes below the Ia do not generate runoff. The Ia was calculated based on the CN for dry conditions.

Table B.1. Basins and sub-basins of the Igneous-Bolson aquifer groundwater availability model study area, Trans-Pecos Texas (concluded)

basin	sub-basin	sub-basin type	geology	hydrologic soil group[1]	CN[2]	CN[2], dry conditions	weather station	Ia,[3] dry conditions, inches
Rio Grande	Upper Cibolo Creek	mountain	rhyolite	C	77	59.4	Presidio	1.37
	Lower Cibolo Creek	bolson	trachyte under fan	C	88	74.8	Presidio	0.67
	Upper Cienega Creek	mountain	rhyolite	C	77	59.4	Presidio	1.37
	Lower Cienega Creek	bolson	basalt under fan	C	88	74.8	Presidio	0.67
	Upper Alamito Creek	mountain	rhyolite	C	77	59.4	Presidio	1.37
	Lower Alamito Creek	bolson	basalt under fan	D	91	79.8	Presidio	0.51
	Upper Terneros Creek	mountain	conglomerate	D	88	74.8	Presidio	0.67
	Lower Terneros Creek	bolson	conglomerate	D	91	79.8	Presidio	0.51
	Upper Terlingua Creek headwaters	mountain	rhyolite	C	77	59.4	Presidio	1.37
	Upper Terlingua Creek	bolson	rhyolite	C	88	74.8	Presidio	0.67
	Upper Calamity Creek	mountain	rhyolite	C	77	59.4	Presidio	1.37
	Lower Calamity Creek	bolson	basalt	C	88	74.8	Presidio	0.67

[1]Hydrologic soil group D represents clay loam, silty clay loam, sandy clay, silty clay, or clay with highest runoff rates and lowest infiltration rates; C represents sandy clay loam with low infiltration rates; B represents silt loam or loam with moderate infiltration rates. Hydrologic soil groups identified in the Soil Survey of Jeff Davis County (U.S. Department of Agriculture, 1977).
[2]CN is the Curve Number, as defined by U.S. Department of Agriculture (1986). CN for dry conditions from Wanielista et al. (1997).
[3]Ia is the initial abstraction for a 24-hour storm event; it is assumed that precipitation events with magnitudes below the Ia do not generate runoff. The Ia was calculated based on the CN for dry conditions.

Table B.2 Weather stations in and around Igneous-Bolson aquifer groundwater availability model study area, Trans-Pecos Texas

weather station	county	period of record	number of years	elevation, feet
Alpine	Brewster	1900-2002	73.56	4,530
Boquillas Ranger Station	Brewster	1910-2002	49.2	1,880
Castolon	Brewster	1947-2002	26.29	2,168
Chisos Basin	Brewster	1947-2002	53.42	5,299
Marathon	Brewster	1897-2002	62.40	4,055
Panther Junction	Brewster	1955-2002	46.60	3,740
Persimmon Gap	Brewster	1952-2002	19.66	2,865
Pine Springs	Culberson	1939-2002	21.45	5,600
Van Horn	Culberson	1939-2002	55.40	3,955
Cornudas Service Station	Hudspeth	1948-2002	50.24	4,480
Fort Hancock 8 SSE	Hudspeth	1966-2002	32.65	3,905
Sierra Blanca 2 E	Hudspeth	1950-2002	38.81	4,535
Fort Davis	Jeff Davis	1902-2002	84.57	4,880
Mount Locke	Jeff Davis	1935-2002	66.71	6,790
Fort Stockton	Pecos	1940-2002	58.26	2,979
Candelaria	Presidio	1948-2002	52.67	2,875
Marfa	Presidio	1907-2002	52.20	4,760
Presidio	Presidio	1927-2002	71.80	2,560
Valentine 10 SWS	Presidio	1978-2002	23.26	4,430
Balmorhea	Reeves	1923-2002	73.83	3,220
Pecos	Reeves	1904-2002	69.60	2,610

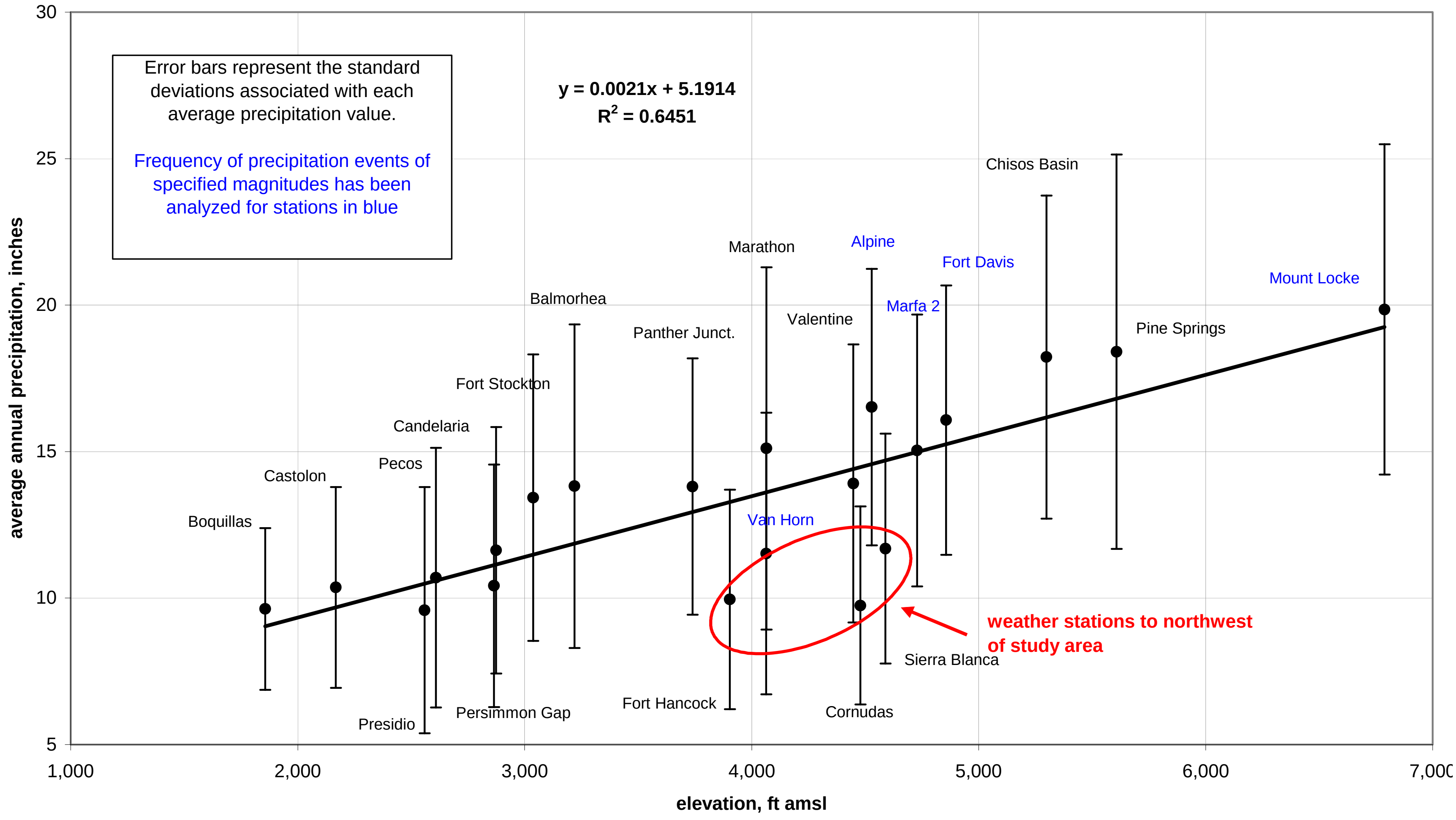

Figure B.4. Elevation and average annual precipitation for the period of record at 21 weather stations in the IBGAM study area, Trans-Pecos Texas.

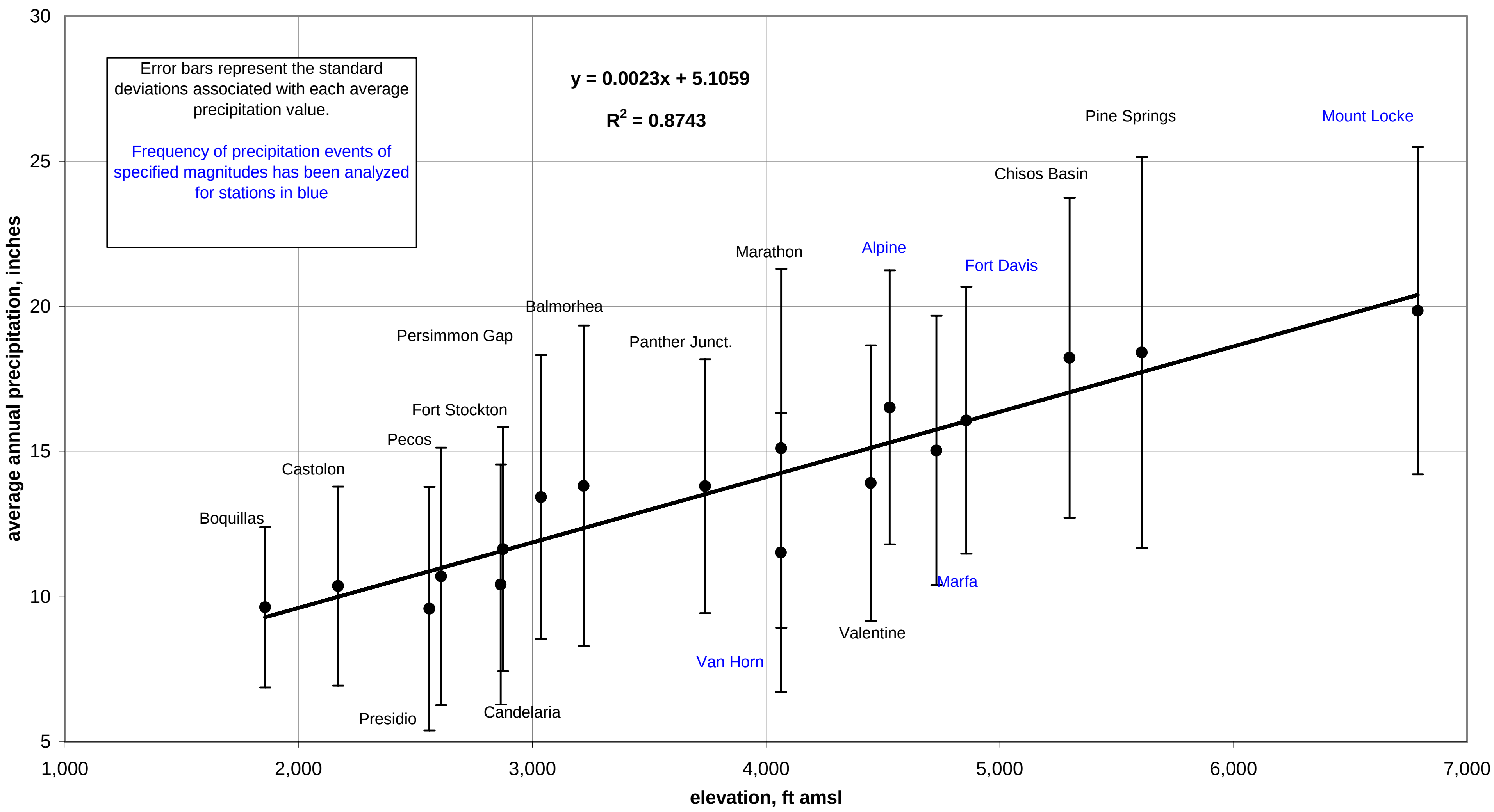

Figure B.5. Elevation and average annual precipitation for the period of record at 18 weather stations in the IBGAM study area, Trans-Pecos Texas.

Daily precipitation data for the period of record for five weather stations within the study area were analyzed, including the Van Horn, Alpine, Mount Locke, Fort Davis, and Presidio weather stations. The daily data were used to determine the frequency of 24-hour storm events of specified magnitudes (for example, precipitation events of 0.01 to 0.10 inch magnitudes, 0.11 to 0.50 inch magnitudes, and so on) that could potentially generate storm-water runoff. The results of this analysis are presented in Table B.3.

2.3 Estimating Potential Recharge

The effects of evapotranspiration and other losses need to be considered with estimating potential recharge; otherwise the potential recharge values for the sub-basins are overestimated. To do this, the potential recharge is estimated from empirical relationships (coefficients) described by Nichols (2000). The coefficients from Nichols (2000) were adjusted to reflect Trans-Pecos climate conditions (see Figure B.6). The adjustment included setting the x-intercept to 12-inches per year; an average annual precipitation value equivalent to the bolsons and lower elevations in Trans-Pecos region where recharge does not occur as suggested by studies performed by Finch and Armour (2001) and Scanlon et al. (2001). The coefficients used to estimate potential recharge, summarized in Table B.4, result in a range of 0 to 7 percent of total precipitation becoming potential recharge, with the percentage increasing with increasing elevation.

The Nichols coefficients are based on a multiple linear regression model of data from basins in Nevada, and were modified to represent Trans-Pecos climate conditions (Bennett and Finch, 2002). The potential recharge rate is equal to the average precipitation multiplied by the modified coefficient, using the following relationship:

$$\text{POTENTIAL RECHARGE} = C * \text{PPTN}$$

where,

PPTN is equal to average annual precipitation (inches/year) and C is equal to (0.00874) * (PPTN) – (0.10488).

Table B.3 24-hour storm events recorded at weather stations in the Igneous-Bolson aquifer groundwater availability model study area, Trans-Pecos

24-hour storm event, inches	percent of total precipitation events at Van Horn weather station	percent of total precipitation events at Alpine weather station	percent of total precipitation events at Presidio weather station	percent of total precipitation events at Mount Locke weather station	percent of total precipitation events at Fort Davis weather station
0.01 to 0.10	48 percent, occurring once every three weeks	46 percent, occurring once every two weeks	47 percent, occurring once every three weeks	46 percent, occurring once every two weeks	37 percent, occurring once every three weeks
0.11 to 0.50	39 percent, occurring once every three weeks	37 percent, occurring once every three weeks	38 percent, occurring once a month	38 percent, occurring once every two weeks	44 percent, occurring once every three weeks
0.51 to 1.00	9 percent, occurring once every three months	11 percent, occurring once every two months	10 percent, occurring once every six months	11 percent, occurring once every two months	14 percent, occurring once every two months
1.01 to 1.50	3 percent, occurring once a year	3 percent, occurring once a year	3 percent, occurring once a year	3 percent, occurring once every six months	4 percent, occurring once a year
> 1.50	1 percent, occurring once every two years	2 percent, occurring once a year	2 percent, occurring once every two years	2 percent, occurring once a year	1 percent, occurring once every two years

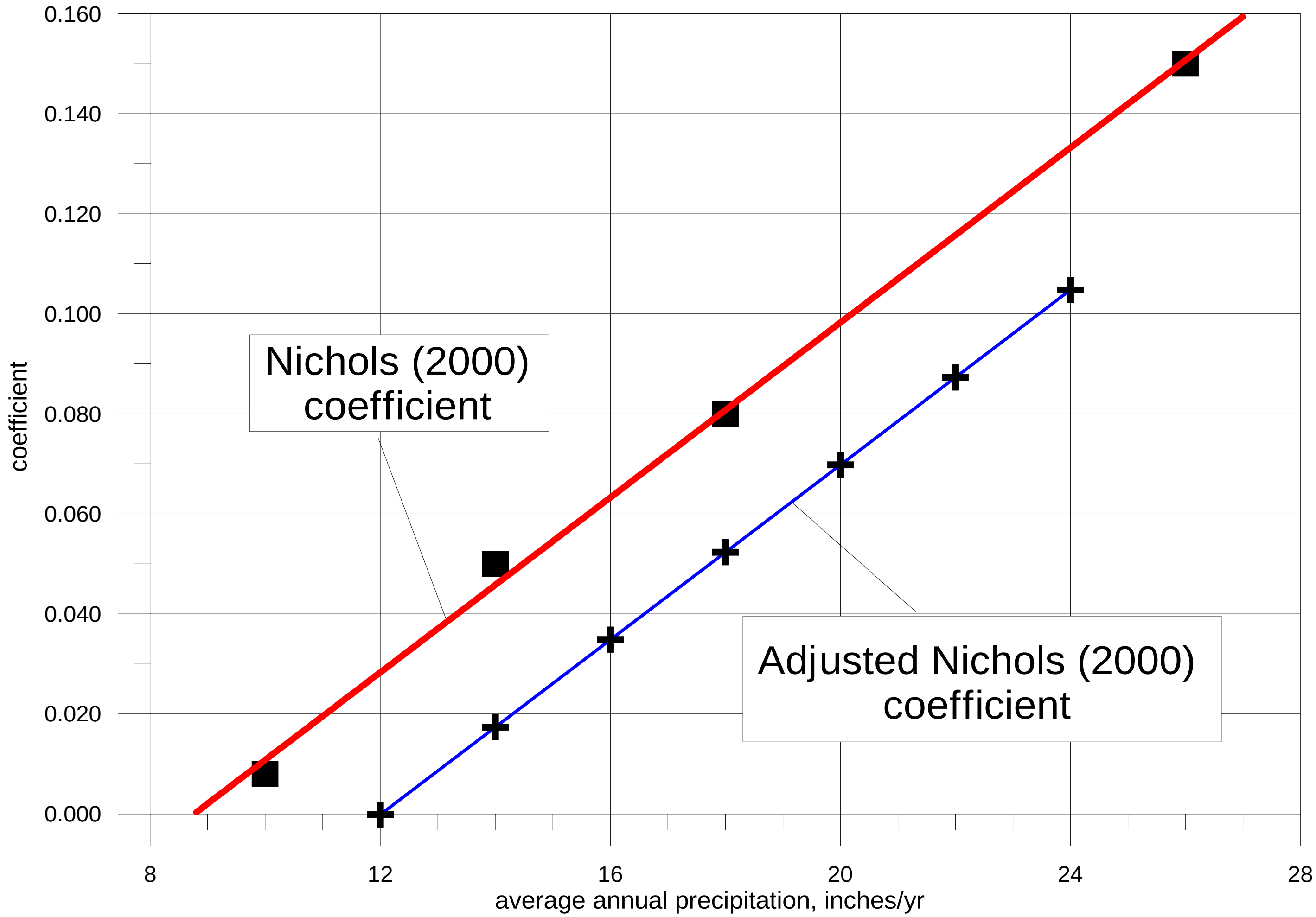

Figure B.6. Graph showing potential recharge coefficient versus average annual precipitation.

Table B.4 Summary of coefficients used to estimate potential recharge, and corresponding elevation, average annual precipitation, and potential recharge

average annual precipitation, inches per year	potential recharge coefficient	potential recharge, inches per year	elevation feet, above mean sea level
12	0.000	0.00	3,000
14	0.018	0.25	3,870
16	0.035	0.56	4,740
18	0.052	0.94	5,600
20	0.070	1.40	6,475

2.4 Determining Runoff

To calculate the average amount of runoff based on average precipitation, the magnitude that must be reached by a precipitation event in order for runoff to occur was determined. Runoff does not occur in a 24-hour precipitation event until the amount of precipitation has exceeded an initial abstraction (I_a), which is influenced by vegetative cover, vegetation density, permeability of the soil surface, and the condition of the soil prior to the precipitation event (Stone et al., 2001; Wanielista et al., 1997; USDA, 1973). I_a is equal to S (the amount of water retained in a drainage basin in a long precipitation event) multiplied by 0.2. S is related to soil and cover conditions according to:

$$S = (1{,}000 / CN) - 10$$

where,

CN is the curve number, which represents the effect of the hydrologic soil-cover complex on the amount of rainfall that runs off (USDA, 1986).

Soils in hydrologic group ‘A’ have low run-off potential. These soils have high infiltration rates when thoroughly wet. The depth to any restrictive layer is greater than 40 inches and the depth to a permanent water table is deeper than 6 feet (USDA, 1986). There are no soils in hydrologic group A in the study area, but areas with exposed fractured rock may have hydrologic group 'A' characteristics. Therefore, the dominant rock types for each sub-basin were defined (Table B.5).

Soils in hydrologic group ‘B’ have moderate infiltration rates when thoroughly wet. The depth to any restrictive layer is greater than 20 inches and the depth to a permanent water table is deeper than 2 feet (USDA, 1986). Soils in hydrologic group B occur in Wild Horse Draw, China Draw, and Upper Carrizo Creek, in the Salt Basin, and in Upper Antelope Draw in the Pecos Basin (Table B.5).

Soils in hydrologic group ‘C’ have low infiltration rates when thoroughly wet. The depth to any restrictive layer is greater than 20 inches and the depth to a permanent water table is deeper than 2 feet (USDA, 1986). Soils in hydrologic group C occur in the Salt, Pecos, and Rio Grande Basins (Table B.5).

Soils in hydrologic group ‘D’ have high runoff potential. These soils have very low infiltration rates when thoroughly wet, and water movement through the soil is slow to very slow. The depth to a restrictive layer is 20 inches or less and the depth to a permanent water table is shallower than 2 feet (USDA, 1986). Soils in hydrologic group D occur in the Salt, Pecos, and Rio Grande Basins (Table B.5).

CN values were determined for each sub-basin based on the hydrologic soil group associated with the dominant soil type, cover type and density, and soil moisture conditions prior to precipitation events. A cover density of 40 percent was assumed for juniper-grass cover in the mountain sub-basins and a cover density of 25 percent was assumed for desert brush cover in the alluvial fan and bolson sub-basins. In most watersheds of the southwestern U.S., the cover density for juniper-grass cover ranges from zero to 80 percent and the cover density for desert brush cover ranges from zero to 50 percent. The cover densities assumed in the current study are ‘middle-of-the-road’ assumptions. CN values were determined for each sub-basin based on curves constructed for each hydrologic soil group on plots of cover density versus curve number for each cover type (USDA, 1973). The CN values were then adjusted based on the assumptions that dry conditions, in which soils are dry but not to the wilting point, exist prior to each precipitation event (Wanielista et al., 1997).

Table B.5 Geology of sub-basins in the Igneous-Bolson aquifer groundwater availability model study area, Trans-Pecos Texas

basin	sub-basin	dominant rock types	secondary porosity	hydrologic soil group[1]	CN[2]
Salt Basin	Baylor Draw	Quaternary fan and fluviatile deposits, Permian limestone	NE-trending faults cut Permian rocks	D	74.8
	Ed Ray Canyon	Quaternary fan deposits, Permian sandstone and limestone	NW-trending faults cut Permian rocks	D	74.8
	Hackberry Creek	Quaternary fan deposits, Ordovician limestone, Precambrian sandstone	faults with three orientations cut pC rocks	D	74.8
	Upper Carrizo Creek	Precambrian limestone and sandstone	a	B	55.8
	Lower Carrizo Creek	Quaternary fan deposits, Permian limestone, Precambrian sandstone	faults with two orientations cut P and pC rocks	D	79.8
	Sacaton Draw	Quaternary windblown sand deposits, Cretaceous limestone and sandstone, Permian limestone	NW-trending faults cut K and P rocks	D	74.8
	Michigan Draw	Quaternary fan, alluvial, and windblown sand deposits, Tertiary trachyte[1], Permian limestone	na	D	74.8
	China Draw	Quaternary alluvial and windblown deposits, Tertiary trachyte[1] and rhyolite[2]	NW-trending faults cut T rocks in southern part	B	55.8
	Wild Horse Draw	Quaternary alluvial and fan deposits	na	B	65.8
	Upper Eagle Flat Draw	Quaternary alluvial and fan deposits, Cretaceous sandstone, Precambrian sandstone and limestone	a	D	74.8
	Lower Eagle Flat Draw	Quaternary alluvial and fan deposits, Tertiary trachyte[1]	a	D	74.8
	Bunton Draw	Tertiary trachyte[1] and rhyolite[2]	a	D	74.8
	Upper Jones Draw	Tertiary trachyte[1] and rhyolite[2]	a	D	74.8
	Lower Jones Draw	Quaternary alluvial and fan deposits, Tertiary trachyte[1], rhyolite[2], and intrusive igneous rocks[4]	a	D	79.8

[a] from USDA (1986)
[b] from USDA (1972; 1973;1974; 1977; and 2003) and adjusted for dry conditions according to Wanielista et al. (1997)
[1] Trachyte is a fine-grained, gray or red-colored volcanic rock with no quartz and abundant alkali feldspars and feldspathoids
[2] Rhyolite is a fine-grained, light gray-colored volcanic rock with abundant quartz
[3] Basalt is a fine-grained, dark-colored volcanic rock with abundant magnesium- and iron-rich minerals
[4] Intrusive rocks form from magmas that cooled slowly beneath Earth's surface, unlike volcanic rocks, which form from eruption of magmas at Earth's surface.
[5] consolidated volcanic ash deposit
a only a few faults mapped in watershed na no faults mapped in watershed

Table B.5. Geology of sub-basins in the Igneous-Bolson aquifer groundwater availability model study area, Trans-Pecos Texas (continued)

basin	sub-basin	dominant rock types	secondary porosity	hydrologic soil group[1]	CN[2]
Salt Basin	Upper Yates Draw	Tertiary intrusive igneous rocks[4]	a	D	74.8
	Lower Yates Draw	Tertiary intrusive igneous rocks[4]	a	C	74.8
	Upper Ninemile Draw	Tertiary intrusive igneous rocks[4]	a	D	74.8
	Lower Ninemile Draw	Quaternary alluvial and fan deposits, Tertiary basalt[3]	na	D	74.8
	Upper Cracker Jack Draw	Tertiary rhyolite[2]	a	D	74.8
	Lower Cracker Jack Draw	Tertiary intrusive igneous rocks[4]	na	C	74.8
	Upper HO Canyon	Tertiary rhyolite[2] and intrusive igneous rocks[4]	a	D	74.8
	Lower HO Canyon	Quaternary alluvial deposits, Tertiary rhyolite[2] and basalt[3]	na	C	74.8
	Upper Wood Canyon	Tertiary intrusive igneous rocks[4]	a	C	59.4
	Lower Wood Canyon	Quaternary alluvial deposits, Tertiary rhyolite[2] and basalt[3]	na	D	74.8
	Upper Merrill Canyon	Tertiary rhyolite[2] and basalt[3]	faults with two orientations cut T rocks	C	59.4
	Lower Merrill Canyon	Quaternary alluvial deposits, Tertiary rhyolite[2] and basalt[3]	na	C	74.8
	Upper Ryan Flat	Tertiary rhyolite[2] and intrusive igneous rocks[4]	na	C	59.4
	Lower Ryan Flat	Quaternary alluvial deposits, Tertiary rhyolite[2], basalt[3], and fanglomerate of mixed composition	na	C	74.8

[a] from USDA (1986)
[b] from USDA (1972; 1973;1974; 1977; and 2003) and adjusted for dry conditions according to Wanielista et al. (1997)
[1] Trachyte is a fine-grained, gray or red-colored volcanic rock with no quartz and abundant alkali feldspars and feldspathoids
[2] Rhyolite is a fine-grained, light gray-colored volcanic rock with abundant quartz
[3] Basalt is a fine-grained, dark-colored volcanic rock with abundant magnesium- and iron-rich minerals
[4] Intrusive rocks form from magmas that cooled slowly beneath Earth's surface, unlike volcanic rocks, which form from eruption of magmas at Earth's surface.
[5] consolidated volcanic ash deposit
a only a few faults mapped in watershed   na no faults mapped in watershed

Table B.5. Geology of sub-basins in the Igneous-Bolson aquifer groundwater availability model study area, Trans-Pecos Texas (continued)

basin	sub-basin	dominant rock types	secondary porosity	hydrologic soil group[1]	CN[2]
Pecos River	Upper Herds Pass Draw	Tertiary rhyolite[2]	a	D	74.8
	Lower Herds Pass Draw	Quaternary alluvial and old deposits, Cretaceous and Permian limestones	a	D	79.8
	Upper Adobe Draw	Tertiary rhyolite[2]	a	D	74.8
	Lower Adobe Draw	Quaternary alluvial and old deposits, Tertiary rhyolite[2], Cretaceous limestone	na	C	74.8
	Upper Cherry Canyon Creek	Tertiary rhyolite[2] and ash-flow tuff[5]	na	D	74.8
	Lower Cherry Canyon Creek	Quaternary alluvial, landslide, and old deposits, Cretaceous limestone	NW-trending faults cut K rocks	C	74.8
	Upper Madera Canyon	Tertiary trachyte[1]	NW-trending faults cut T rocks	C	59.4
	Lower Madera Canyon	Quaternary alluvial and landslide deposits, Tertiary rhyolite[2]	na	C	74.8
	Upper Aguja Canyon	Tertiary rhyolite[2]	na	C	59.4
	Lower Aguja Canyon	Quaternary alluvial and landslide deposits, Tertiary rhyolite[2] and intrusive igneous rocks[4]	faults with two orientations cut T rocks, which have columnar joints	C	74.8
	Upper Limpia Canyon	Tertiary rhyolite[2]	na	C	59.4
	Lower Limpia Canyon	Quaternary fan deposits, Tertiary rhyolite[2] and ash-flow tuff[5]	faults with two orientations cut T rocks	D	79.8
	Upper Musquiz Creek	Tertiary trachyte[1] and rhyolite[2]	T rocks have well-developed columnar joints	C	59.4
	Lower Musquiz Creek	Quaternary alluvial and fan deposits, Quaternary- to Tertiary gravel deposits, Tertiary ash-flow tuff[5]	na	C	74.8
	Upper Alpine Creek	Tertiary trachyte[1] and rhyolite[2]	na	D	74.8

[a] from USDA (1986)
[b] from USDA (1972; 1973;1974; 1977; and 2003) and adjusted for dry conditions according to Wanielista et al. (1997)
[1] Trachyte is a fine-grained, gray or red-colored volcanic rock with no quartz and abundant alkali feldspars and feldspathoids
[2] Rhyolite is a fine-grained, light gray-colored volcanic rock with abundant quartz
[3] Basalt is a fine-grained, dark-colored volcanic rock with abundant magnesium- and iron-rich minerals
[4] Intrusive rocks form from magmas that cooled slowly beneath Earth's surface, unlike volcanic rocks, which form from eruption of magmas at Earth's surface.
[5] consolidated volcanic ash deposit
a only a few faults mapped in watershed na no faults mapped in watershed

Table B.5. Geology of sub-basins in the Igneous-Bolson aquifer groundwater availability model study area, Trans-Pecos Texas (concluded)

basin	sub-basin	dominant rock types	secondary porosity	hydrologic soil group[1]	CN[2]
Pecos River	Lower Alpine Creek	Quaternary alluvial and fan deposits, Tertiary trachyte[1]	na	C	74.8
	Upper Antelope Draw	Tertiary trachyte[1] and sandstone, Permian limestone	na	B	74.8
	Lower Antelope Draw	Quaternary alluvial and fan deposits, Cretaceous limestone	na	D	79.8
Rio Grande	Upper Cibolo Creek	Tertiary rhyolite[2] and ash-flow tuff[5]	na	C	59.4
	Lower Cibolo Creek	Tertiary trachyte[1], fanglomerate, and intrusive igneous rocks[4]	na	C	74.8
	Upper Cienega Creek	Tertiary rhyolite[2], sandstone, and fanglomerate	na	C	59.4
	Lower Cienega Creek	Tertiary fanglomerate and basalt[3]	na	C	74.8
	Upper Alamito Creek	Tertiary rhyolite[2]	na	C	59.4
	Lower Alamito Creek	Quaternary alluvial deposits, Tertiary fanglomerate and basalt[3]	na	D	79.8
	Upper Terneros Creek	Tertiary conglomerate	na	D	74.8
	Lower Terneros Creek	Tertiary conglomerate	na	D	79.8
	Upper Terlingua Creek headwaters	Quaternary alluvial deposits, Tertiary rhyolite[2] and basalt	NW-trending faults cut T rocks	C	59.4
	Upper Terlingua Creek	Quaternary old deposits, Tertiary rhyolite[2], ash-flow tuff[5]	NW-trending faults cut T rocks	C	74.8
	Upper Calamity Creek	Tertiary rhyolite[2], trachyte[1], basalt[3], intrusive igneous rocks[4]	a	C	59.4
	Lower Calamity Creek	Tertiary basalt[3] and ash-flow tuff[5]	na	C	74.8

[a] from USDA (1986)
[b] from USDA (1972; 1973;1974; 1977; and 2003) and adjusted for dry conditions according to Wanielista et al. (1997)
[1] Trachyte is a fine-grained, gray or red-colored volcanic rock with no quartz and abundant alkali feldspars and feldspathoids
[2] Rhyolite is a fine-grained, light gray-colored volcanic rock with abundant quartz
[3] Basalt is a fine-grained, dark-colored volcanic rock with abundant magnesium- and iron-rich minerals
[4] Intrusive rocks form from magmas that cooled slowly beneath Earth's surface, unlike volcanic rocks, which form from eruption of magmas at Earth's surface.
[5] consolidated volcanic ash deposit
a only a few faults mapped in watershed na no faults mapped in watershed

The total amount of precipitation that occurred during events that exceeded I_a (in the period of record for each weather station) was divided by the number of events that exceeded I_a. The resulting value (denoted as P) represents the average precipitation event that exceeds I_a, was used to calculate runoff (Q) in the following equation:

$$Q = (P - I_a)^2 / (P - I_a) + S$$

An analysis of 24-hour storm events that exceed 0.67 inches in magnitude (for many of the sub-basins, the I_a was calculated to be 0.67 inches), which represent storm events that generate runoff, shows that the average magnitude of runoff events does not show linear variation with respect to elevation (Figure B.7). Thus, the average magnitude of runoff events (as recorded at the weather stations) cannot be adjusted according to elevation. However, the frequency of runoff events does increase linearly with increasing elevation (Figure B.8), and we use this linear relationship to determine the annual number of runoff events for each sub-basin.

Annual precipitation and runoff vary considerably from year to year and from weather station to weather station (Figures B.9 through B.18). Several of the weather stations had a few years with missing or incomplete data (Figs.9, 11, 15, and 17). Years with complete and incomplete data were used for the graphs showing runoff events (Figs. 10, 12, 14, 16, and 18). Years with less than 75 percent of the daily precipitation records were not used in the calculation of the average number of annual runoff events.

The mid-1940s to the late-1960s was a period of lower-than-average precipitation and runoff at the five weather stations analyzed in the recharge study. From about 1993 to 2002 was also a period of lower-than-average precipitation. From the late-1960s to 1993 was a period of greater-than-average precipitation and runoff. Precipitation trends do not necessarily correspond with runoff trends. For example, lower-than-average precipitation occurred between 1993 and 2002 and greater-than-average runoff occurred between 1990 and 1997. Table B.6 and Figure B.19 summarize the periods of lower-than-average and greater-than-average precipitation and runoff for the periods of record at the Van Horn, Fort Davis, Mount Locke, Alpine, and Presidio weather stations.

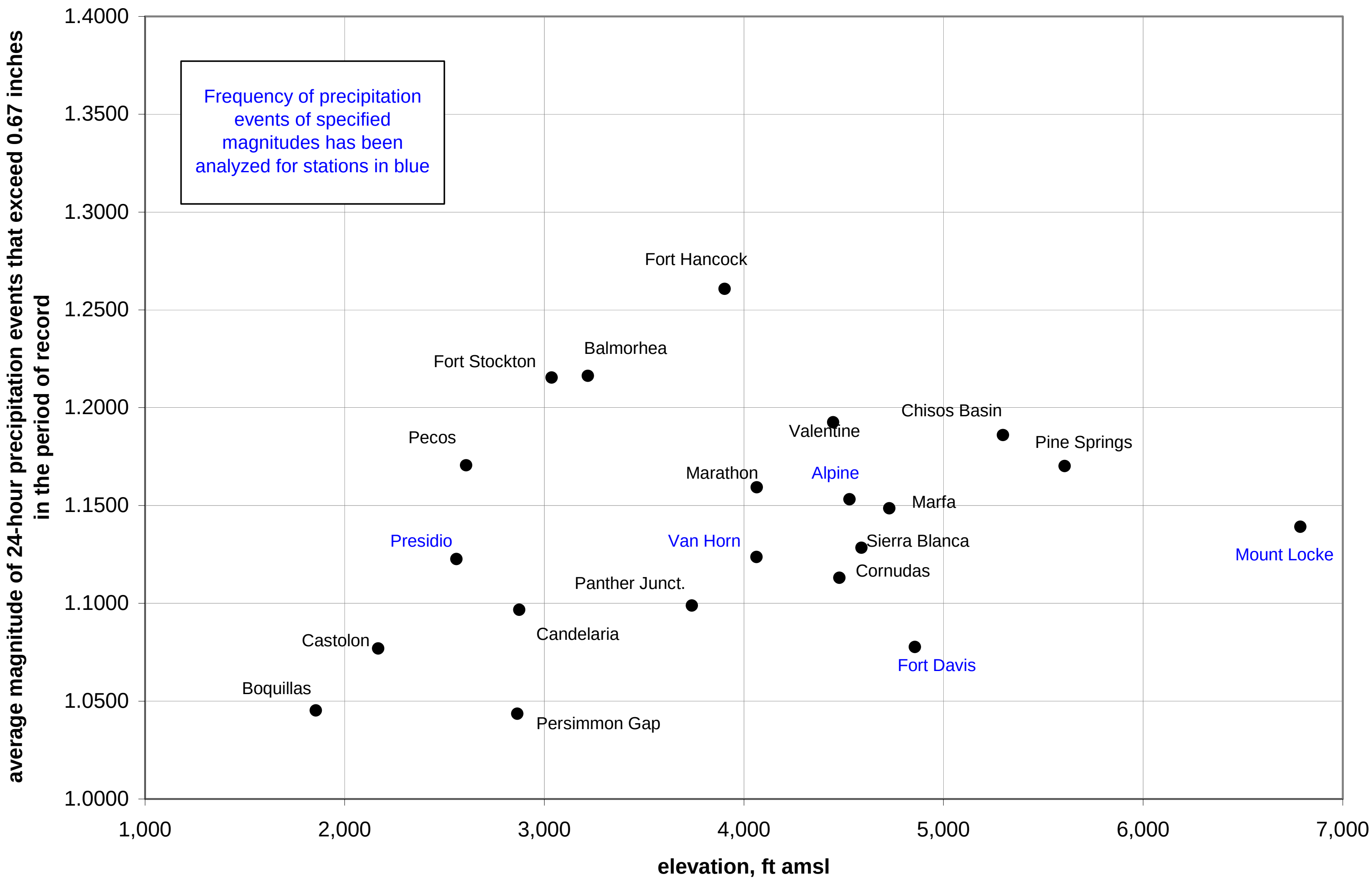

Figure B.7. Average magnitude of 24-hour precipitation events that exceed 0.67 inches (runoff-producing events) for the period of record at weather stations in and around the IBGAM study area.

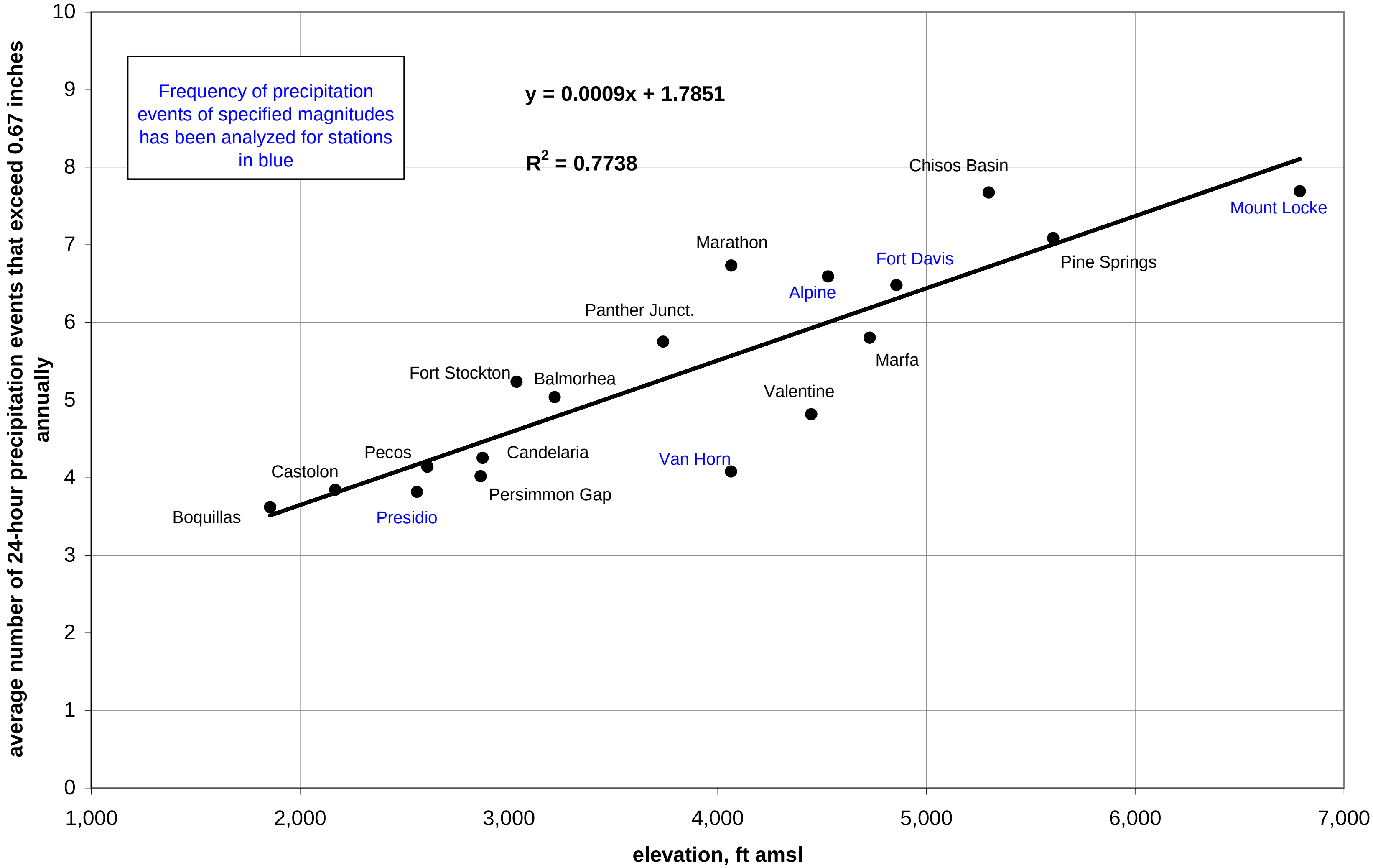

Figure B.8. Average number of 24-hour precipitation events that exceed 0.67 inches (runoff-producing events) annually at weather stations in and around the IBGAM study area.

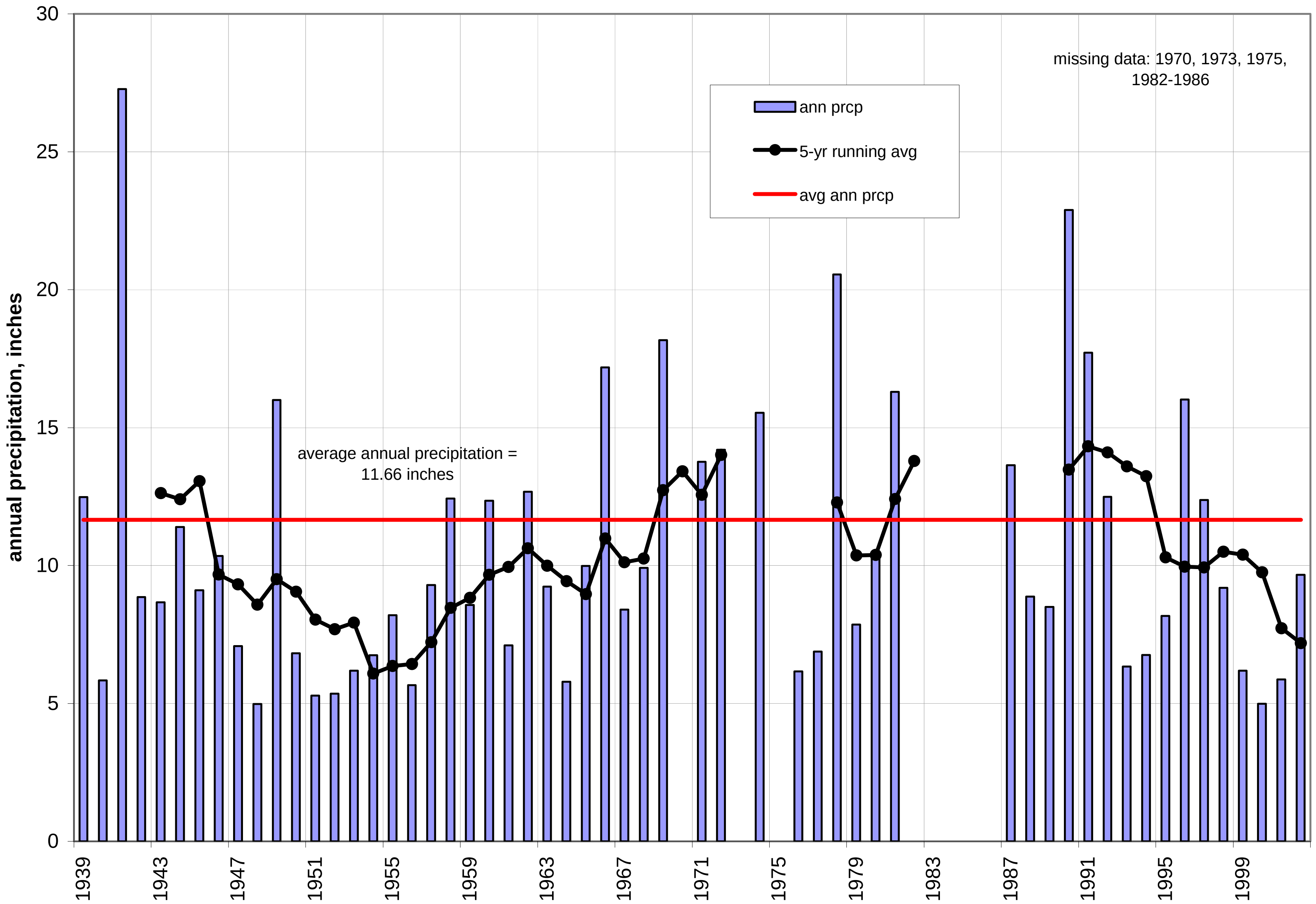

Figure B.9. Average annual precipitation at the Van Horn weather station for the period of record 1939 to 2002.

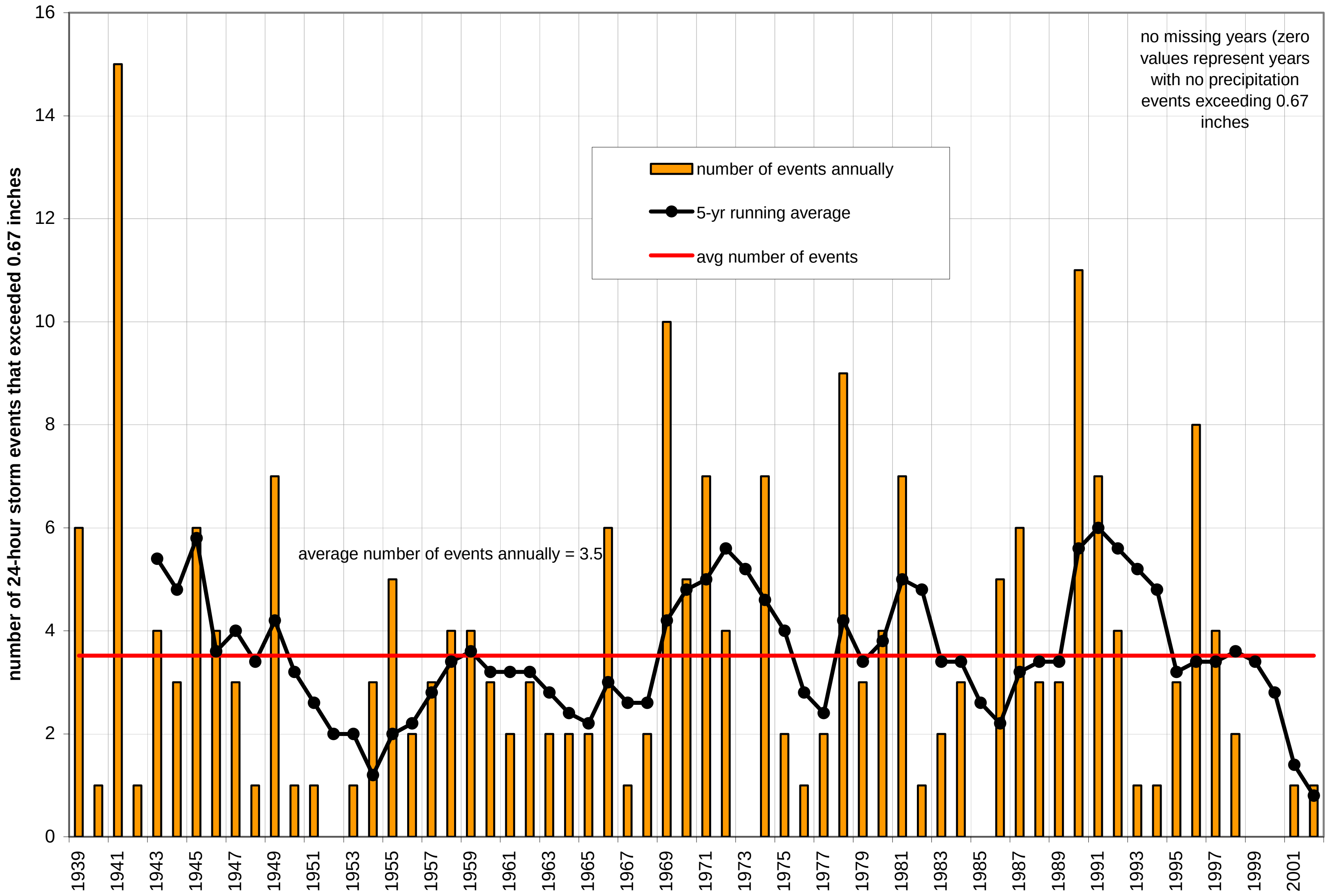

Figure B.10. Average number of runoff-producing storm events annually at the Van Horn weather station for the period of record 1939 to 2002.

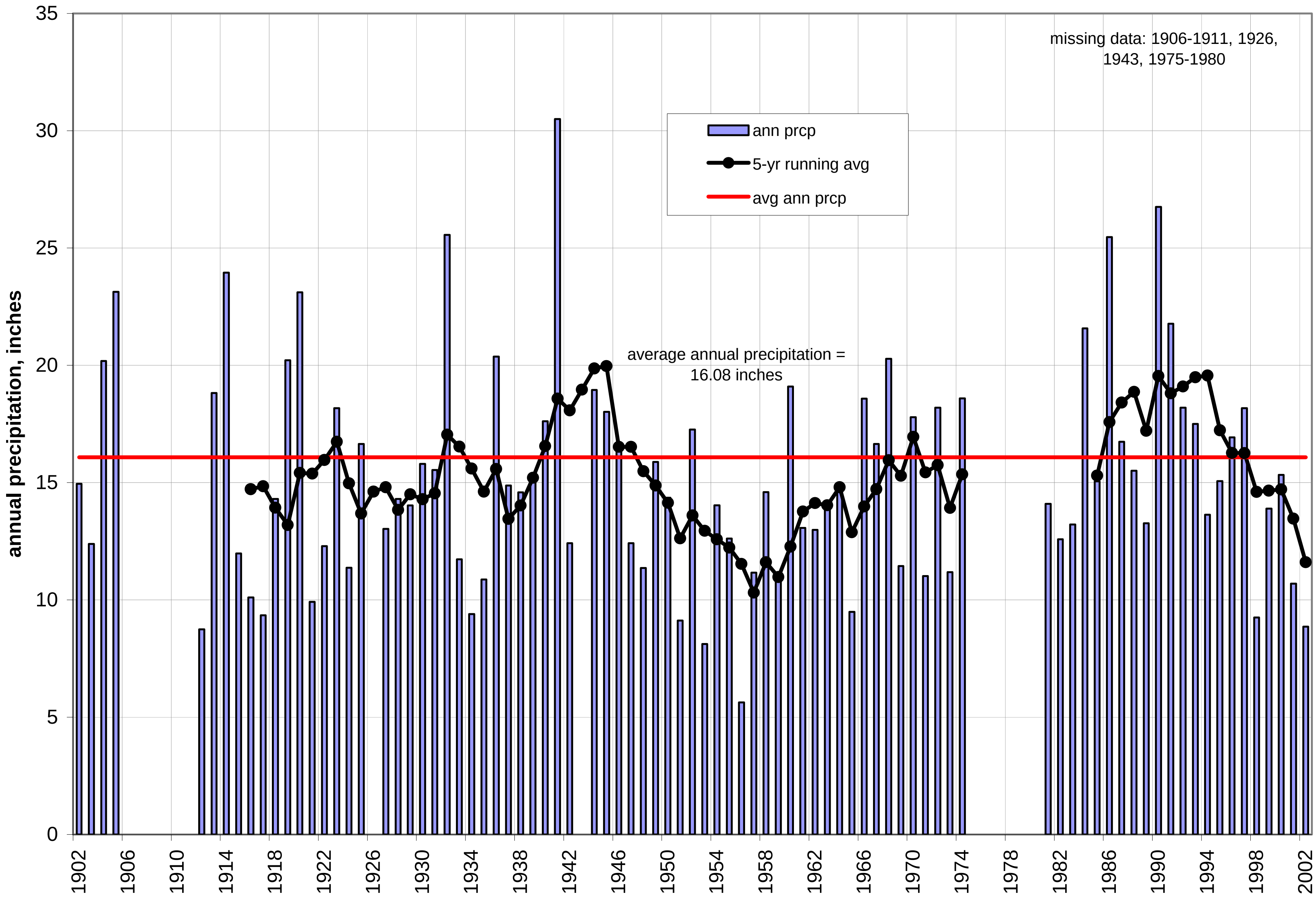

Figure B.11. Average annual precipitation at the Fort Davis weather station for the period of record 1902 to 2002.

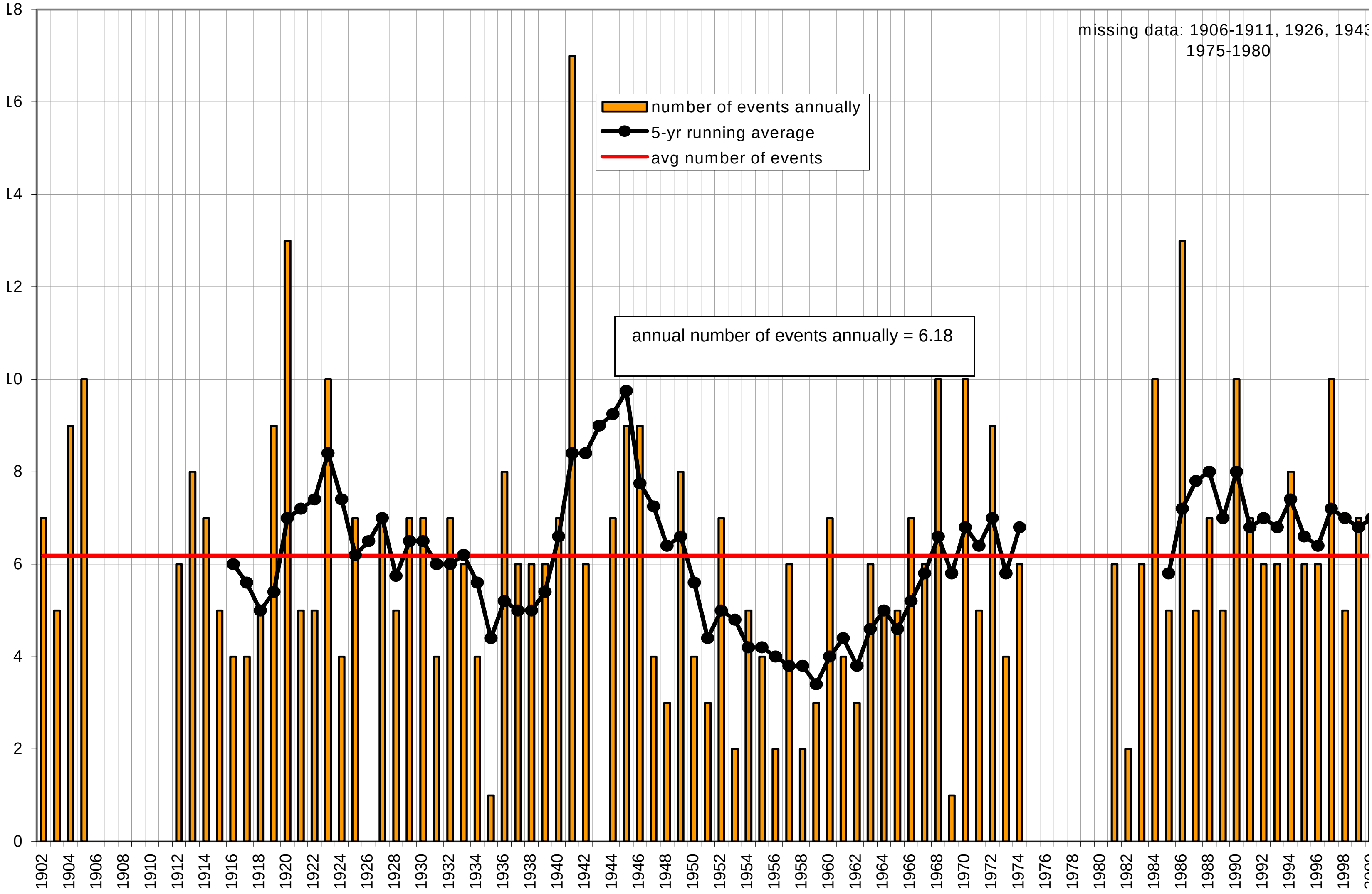

Figure B.12. Average number of runoff-producing storm events annually at the Fort Davis weather station for the period of record 1902 to 2002.

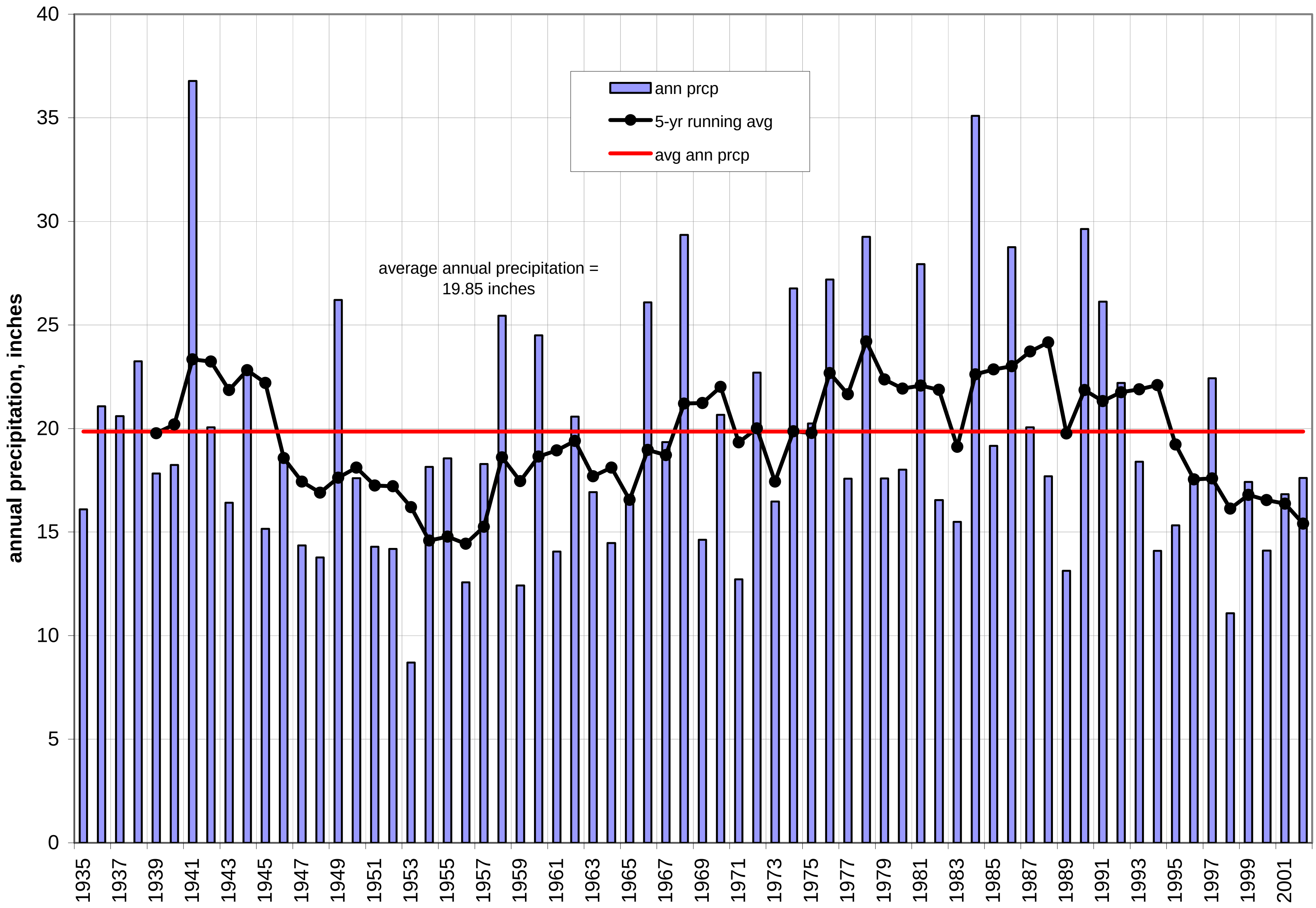

Figure B.13. Average annual precipitation at the Mount Locke weather station for the period of record 1935 to 2002.

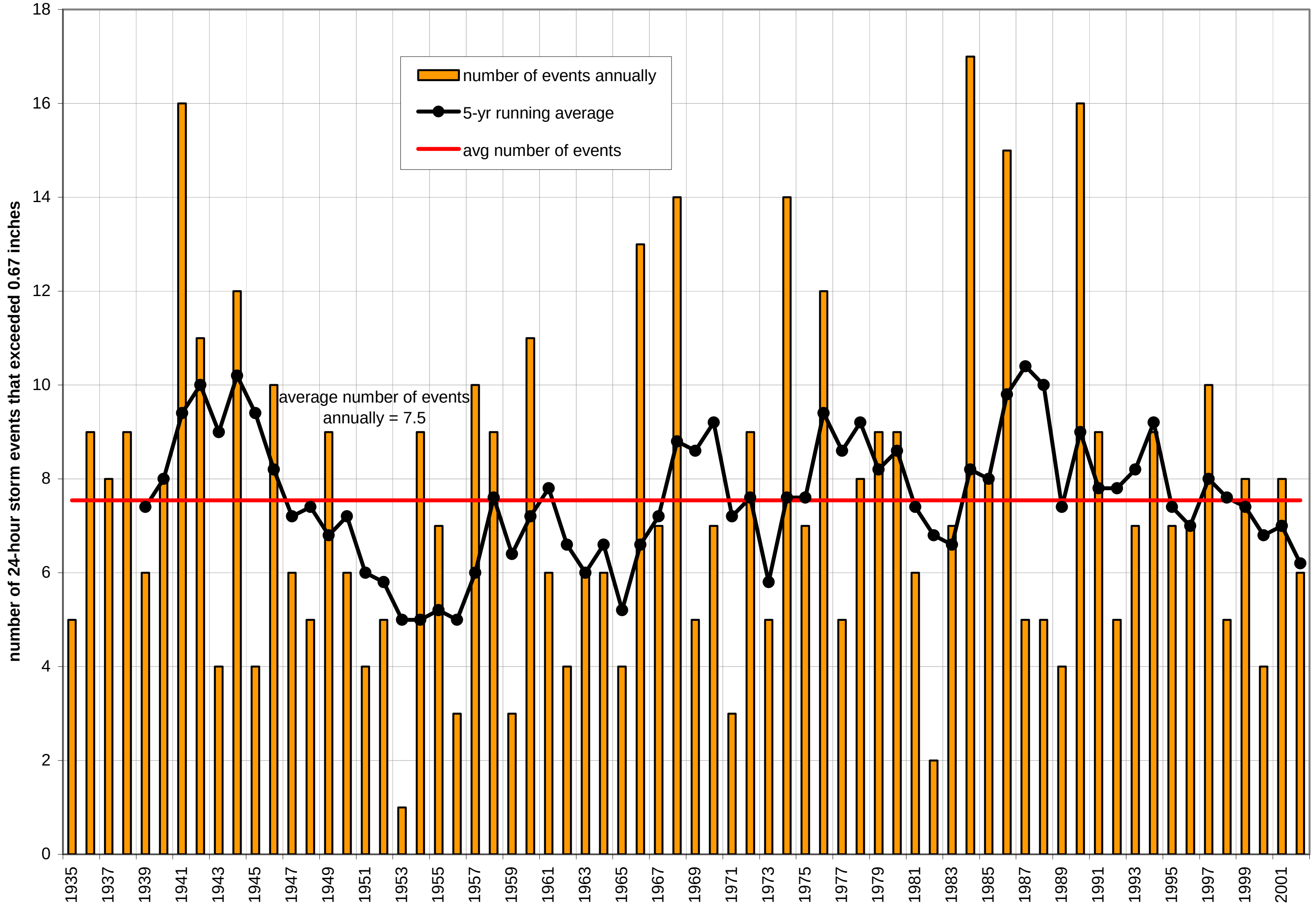

Figure B.14. Average number of runoff-producing storm events annually at the Mount Locke weather station for the period of record 1935 to 2002.

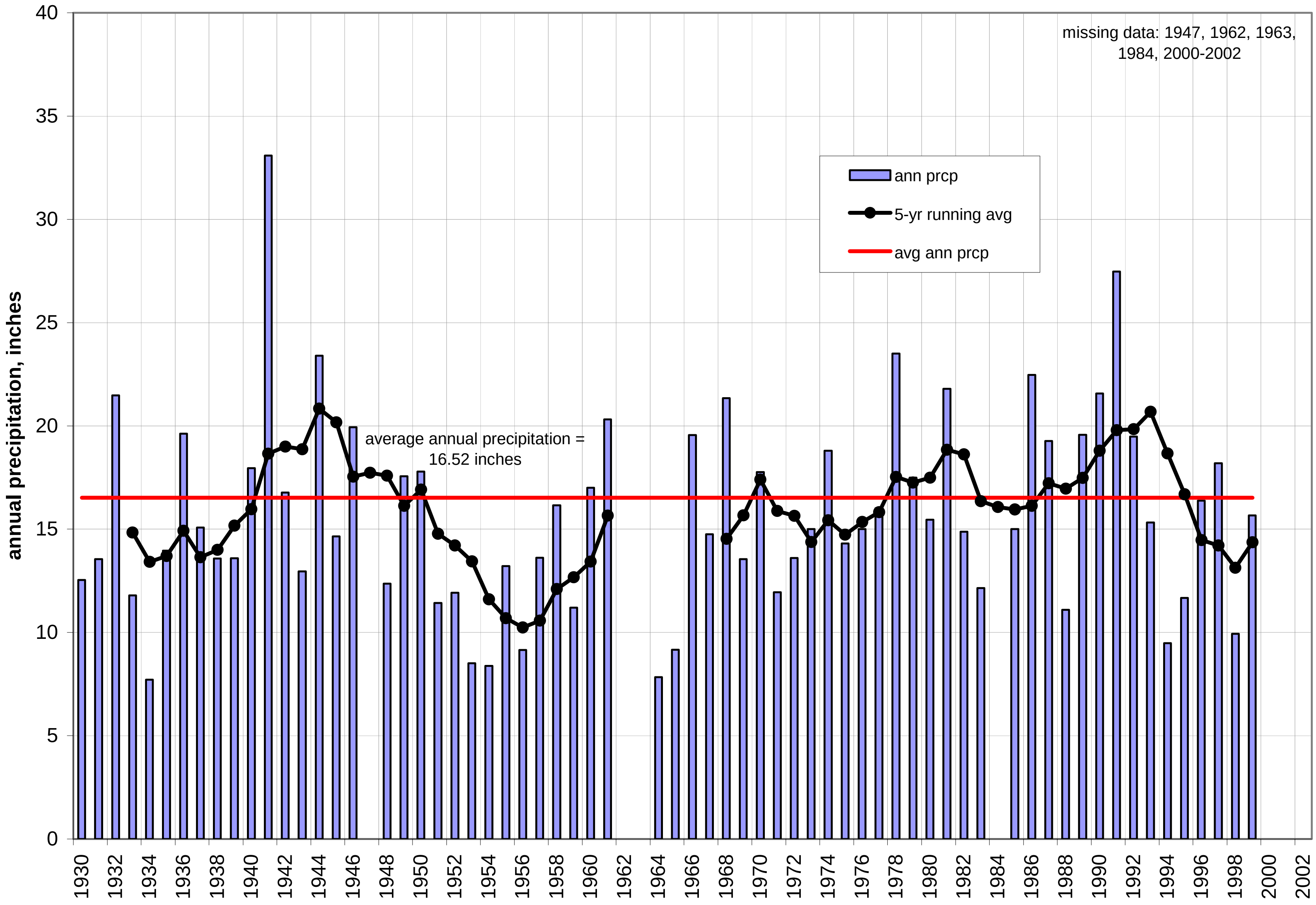

Figure B.15. Average annual precipitation at the Alpine weather station for the period of record 1930 to 2000.

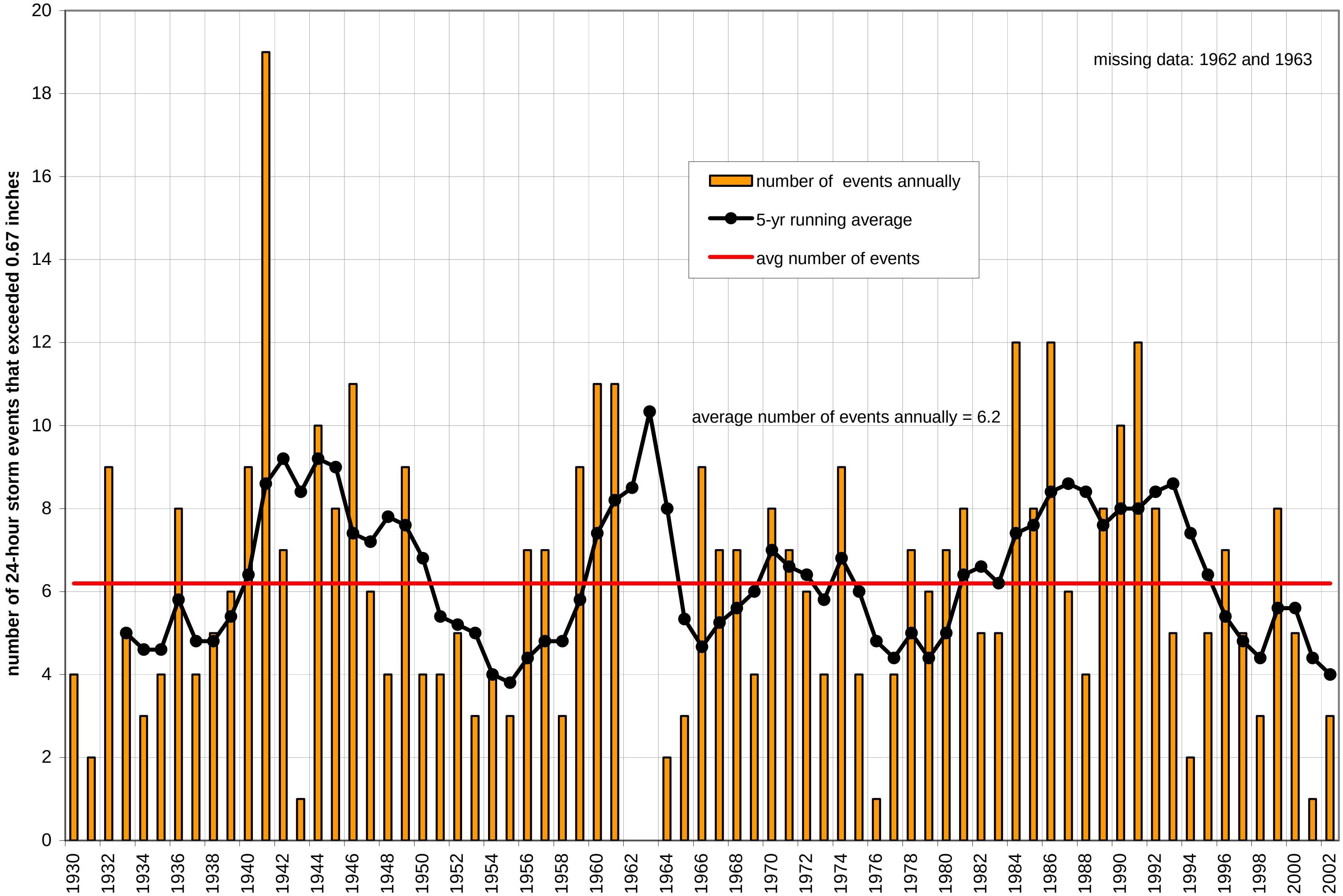

Figure B.16. Average number of runoff-producing storm events annually at the Alpine weather station for the period of record 1930 to 2000.

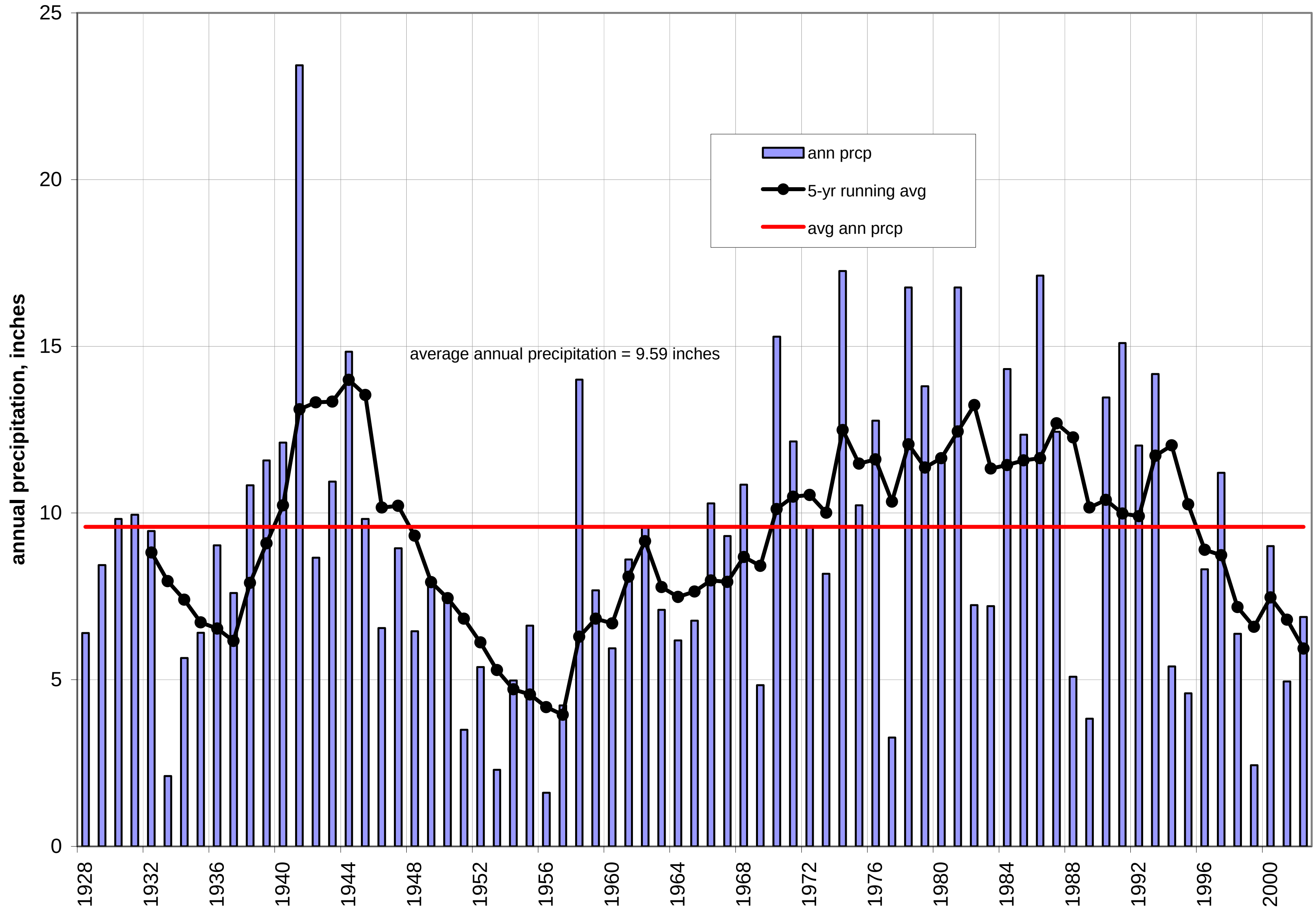

Figure B.17. Average annual precipitation at the Presidio weather station for the period of record 1928 to 2002.

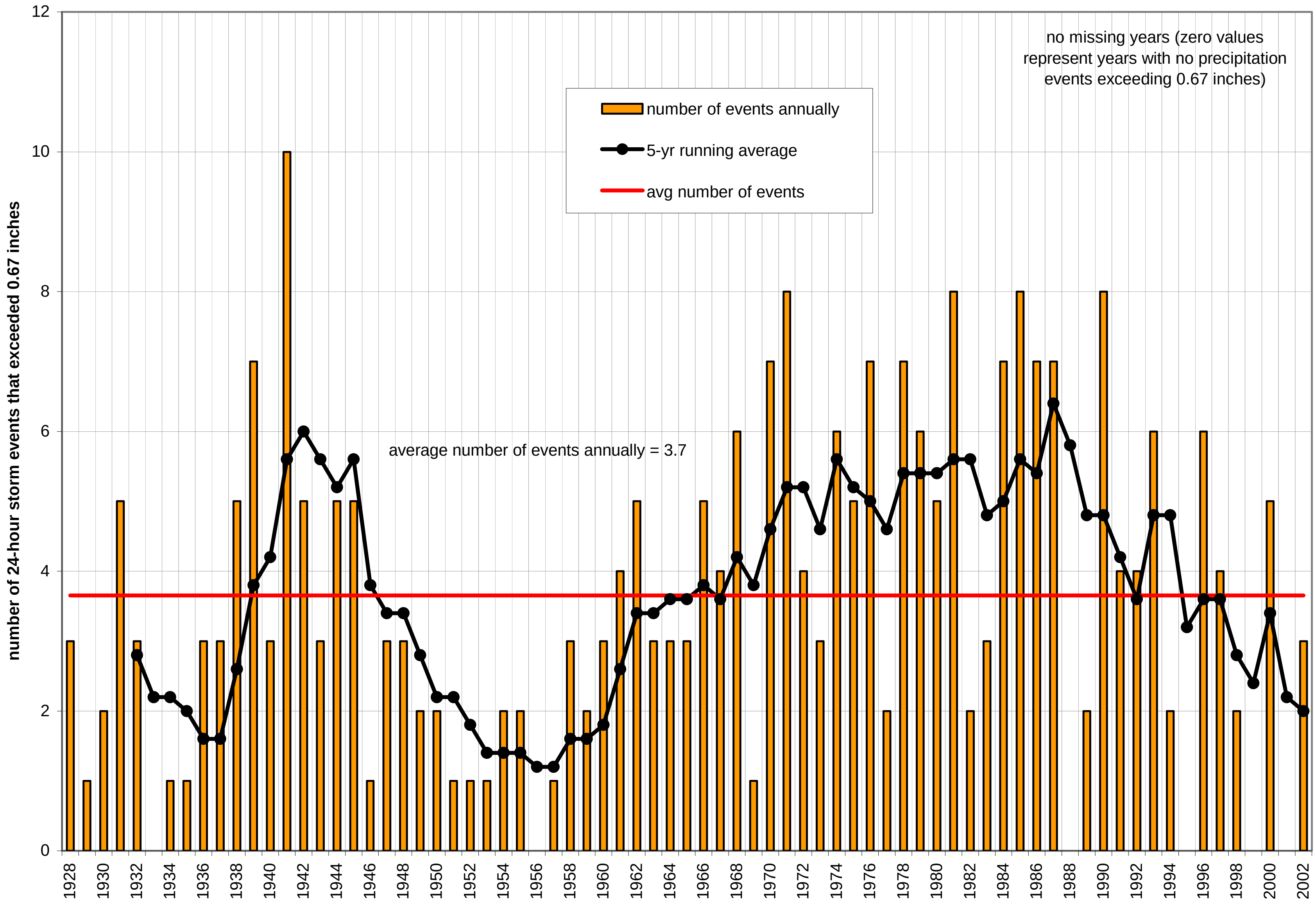

Figure B.18. Average number of runoff-producing storm events annually at the Presidio weather station for the period of record 1928 to 2002.

Table B.6 Summary of lower-than-average and greater-than-average precipitation and runoff events at the Van Horn, Fort Davis, Mount Locke, Alpine, and Presidio weather stations

weather station	period of lower-than-average precipitation	period of greater-than-average precipitation	period of lower-than-average runoff	period of greater-than-average runoff
Van Horn[1]	1942 to 1968 1993 to 2002	1969 to 1992	1950 to 1968 1982 to 1989 1997 to 2002	1969 to 1981 1990 to 1997
Fort Davis[2]	1915 to 1939 1947 to 1965 1998 to 2002	1940 to 1946 1966 to 1997	1933 to 1939 1950 to 1967 2001 to 2002	1920 to 1932 1940 to 1949 1968 to 2000
Mount Locke	1943 to 1967 1993 to 2002	1968 to 1992	1946 to 1967 1998 to 2002	1940 to 1946 1968 to 1997
Alpine[3]	1933 to 1940 1951 to 1977 1992 to 1999	1941 to 1950 1978 to 1992	1933 to 1939 1950 to 1958 1975 to 1979 1993 to 2002	1940 to 1949 1959 to 1974 1980 to 1992
Presidio	1932 to 1937 1946 to 1969 1994 to 2002	1938 to 1945 1970 to 1993	1932 to 1937 1946 to 1965 1998 to 2002	1938 to 1945 1966 to 1997

[1] missing or incomplete data for years 1970, 1973, 1975, and 1982-1986
[2] missing or incomplete data for years 1906 to 1911, 1926, 1943, and 1975 to 1980
[3] missing or incomplete data for years 1947, 1962, 1963, 1984, and 2000-2002

In 5 out of the 56 sub-basins, the calculated runoff value exceeded potential recharge. These sub-basins are Lower Carrizo Creek in the Salt Basin (runoff of 215 ac-ft/yr and potential recharge of 121 ac-ft/yr), Lower Cherry Canyon Creek in the Pecos Basin (runoff of 2,400 ac-ft/yr and potential recharge of 634 ac-ft/yr), Lower Antelope Draw in the Pecos Basin (runoff of 4,069 ac-ft/yr and potential recharge of 2,397 ac-ft/yr), Lower Alamito Creek in the Rio Grande Basin (runoff of 37,849 ac-ft/yr and potential recharge of 36,518 ac-ft/yr), and Lower Terneros Creek in the Rio Grande Basin (runoff of 2,627 ac-ft/yr and potential recharge of 1,199 ac-ft/yr). In these cases, runoff was set equal to potential recharge, assuming that all rainfall that falls within the sub-basin leaves the basin as runoff.

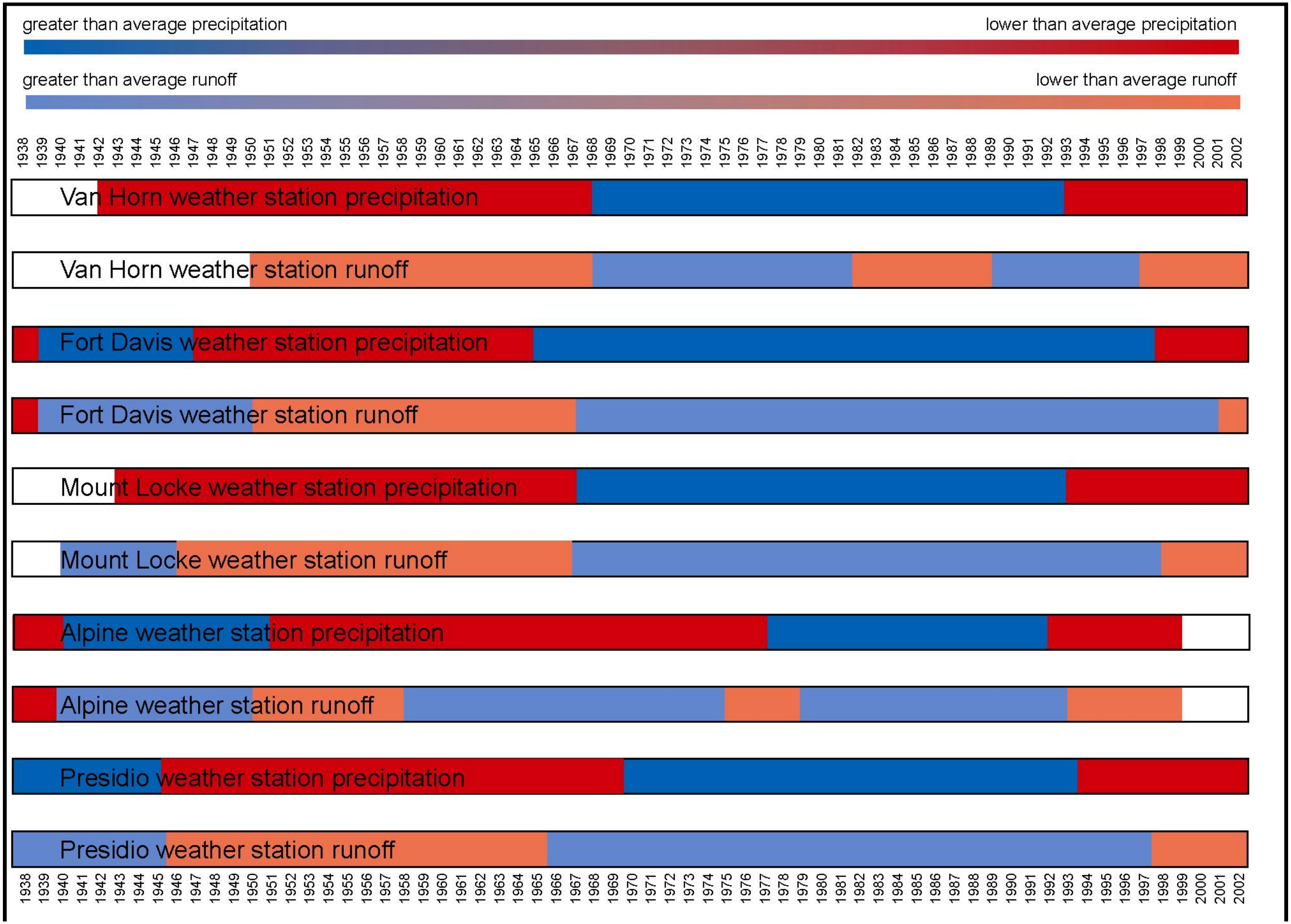

Figure B.19. Summary of lower-than-average and greater-than-average precipitation and runoff events at the Van Horn, Fort Davis, Mount Locke, Alpine, and Presidio weather stations.

The Lower Carrizo Creek sub-basin has a very low I_a value, which means that relatively small precipitation events result in runoff and infiltration is minimal. Lower Cherry Canyon Creek is the lowest elevation sub-basin in the Pecos Basin and the second lowest elevation sub-basin in the entire IBGAM study area. Because most of the sub-basin area is at low elevation, the potential recharge value is low. Precipitation data used to determine the frequency of runoff-producing storm events, and thus, total annual runoff in the Pecos Basin sub-basins, come from the Mount Locke weather station. The Mount Locke weather station is at a relatively high elevation in the Pecos Basin part of the study area, and the Lower Cherry Canyon Creek sub-basin is considerably lower than any other sub-basin in the Pecos Basin part of the study area. Thus, the Mount Locke weather station data does not adequately represent the Lower Cherry Canyon Creek sub-basin. Like Lower Carrizo Creek, Lower Antelope draw has a very low I_a value. The Lower Terneros Creek and Lower Alamito Creek sub-basins have very low I_a values and are the first and fourth lowest elevation sub-basins in the study area.

The next step (for each sub-basin) is to subtract the average runoff produced by an average storm (using the equation above) from the potential recharge. The runoff from a topographically high mountain sub-basin will be subtracted from the potential recharge for that basin and then 30 percent of that runoff is added to the respective receiving alluvial fan sub-basin. The remaining precipitation represents estimated recharge to the mountain sub-basin. The distribution of mountain and alluvial fan sub-basins is presented in Table B.7.

The runoff from an alluvial fan sub-basin is subtracted from that sub-basin and 30 percent of that runoff is added to the receiving bolson (in the case of the Salt Basin) or main drainage (in the case of the Pecos River and Rio Grande Basins). The precipitation that remains in the alluvial fan sub-basin, combined with the runoff from the up-gradient mountain sub-basin, represents the estimated recharge for the alluvial fan sub-basin.

In the case of the Salt Basin, all precipitation that falls in the bolsons of Wild Horse Flat and Michigan Flat evaporates or flows out of the model area. As noted above, the estimated recharge for the bolsons is equal to 30 percent of the runoff entering the bolsons from surrounding alluvial fan sub-basins (Finch and Armour, 2001).

Table B.7 Distribution of up-gradient mountain sub-basins, receiving alluvial fan sub-basins, and receiving bolsons and main drainages in the Igneous-Bolson aquifer groundwater availability model study area, Trans-Pecos Texas

<table>
<tr><th>mountain sub-basin</th><th colspan="3">alluvial fan sub-basin(s)</th><th>main drainage</th></tr>
<tr><td colspan="4">Baylor Draw ⇒</td><td rowspan="16">Wild Horse Flat and Michigan Flat Bolsons</td></tr>
<tr><td colspan="4">Ed Ray Canyon ⇒</td></tr>
<tr><td colspan="4">Hackberry Creek ⇒</td></tr>
<tr><td colspan="4">Sacaton Draw ⇒</td></tr>
<tr><td colspan="4">Upper Wild Horse Flat ⇒</td></tr>
<tr><td colspan="4">Upper Michigan Flat ⇒</td></tr>
<tr><td colspan="2">Upper Jones Draw ⇒</td><td>Lower Jones Draw ⇒</td><td rowspan="4">Bunton Draw ⇒</td></tr>
<tr><td colspan="2">Upper Yates Draw ⇒</td><td>Lower Yates Draw ⇒</td></tr>
<tr><td colspan="2">Upper Ninemile Draw ⇒</td><td rowspan="2">Lower Ninemile Draw ⇒</td></tr>
<tr><td>Upper Cracker Jack Draw ⇒</td><td>Lower Cracker Jack Draw ⇒</td></tr>
<tr><td colspan="4">China Draw ⇒</td></tr>
<tr><td colspan="2">Upper Carrizo Creek ⇒</td><td colspan="2">Lower Carrizo Creek ⇒</td></tr>
<tr><td colspan="2">Upper Eagle Flat ⇒</td><td colspan="2">Lower Eagle Flat ⇒</td></tr>
<tr><td colspan="2">Upper HO Canyon ⇒</td><td colspan="2">Lower HO Canyon ⇒</td></tr>
<tr><td colspan="2">Upper Wood Canyon ⇒</td><td colspan="2">Lower Wood Canyon ⇒</td></tr>
<tr><td colspan="2">Upper Merrill Canyon ⇒</td><td colspan="2">Lower Merrill Canyon ⇒</td></tr>
<tr><td>Upper Herds Pass Draw ⇒</td><td colspan="3">Lower Herds Pass Draw ⇒</td><td rowspan="9">Pecos</td></tr>
<tr><td>Upper Adobe Draw ⇒</td><td colspan="3">Lower Adobe Draw ⇒</td></tr>
<tr><td>Upper Cherry Canyon Creek ⇒</td><td colspan="3">Lower Cherry Canyon Creek ⇒</td></tr>
<tr><td>Upper Madera Canyon ⇒</td><td>Lower Madera Canyon ⇒</td><td colspan="2" rowspan="2">Lower Aguja Canyon ⇒</td></tr>
<tr><td colspan="2">Upper Aguja Canyon ⇒</td></tr>
<tr><td>Upper Limpia Canyon ⇒</td><td colspan="3">Lower Limpia Canyon ⇒</td></tr>
<tr><td colspan="2">Upper Musquiz Creek ⇒</td><td colspan="2" rowspan="2">Lower Musquiz Creek ⇒</td></tr>
<tr><td>Upper Alpine Creek ⇒</td><td>Lower Alpine Creek ⇒</td></tr>
<tr><td>Upper Antelope Draw ⇒</td><td colspan="3">Lower Antelope Draw ⇒</td></tr>
<tr><td>Upper Cibolo Creek ⇒</td><td colspan="3">Lower Cibolo Creek ⇒</td><td rowspan="6">Rio Grande</td></tr>
<tr><td>Upper Cienega Creek ⇒</td><td colspan="3">Lower Cienega Creek ⇒</td></tr>
<tr><td>Upper Alamito Creek ⇒</td><td colspan="3">Lower Alamito Creek ⇒</td></tr>
<tr><td>Upper Terneros Creek ⇒</td><td colspan="3">Lower Terneros Creek ⇒</td></tr>
<tr><td>Upper Terlingua Creek headwaters ⇒</td><td colspan="3">Lower Terlingua Creek ⇒</td></tr>
<tr><td>Upper Calamity Creek ⇒</td><td colspan="3">Lower Calamity Creek ⇒</td></tr>
</table>

3.0 RESULTS

The results of the recharge analysis are summarized in Table B.8. Recharge values for individual sub-basins of the Salt, Pecos, and Rio Grande Basins are presented in Tables B.9, B.10, and B.11. Total recharge to the IBGAM study area is estimated at 68,977 ac-ft/yr, which is about 1.3 percent of the total precipitation. Most of the recharge to the bolson is from infiltration of storm-water runoff in the alluvial fan sub-basins where they adjoin the bolsons. The majority of the igneous aquifer receives direct recharge at a typical rate of 0.35 inch per year.

Table B.8 Summary of recharge estimates for Salt, Pecos, and Rio Grande Basins within the Igneous Bolson GAM study area

<table>
<tr><th>parameter</th><th>unit</th><th>Salt</th><th>Pecos</th><th>Rio Grande</th><th>total</th></tr>
<tr><td>Area</td><td>acres</td><td>1,625,355</td><td>1,135,324</td><td>1,370,137</td><td>4,130,816</td></tr>
<tr><td>Total precipitation</td><td>ac-ft/yr</td><td>2,111,077</td><td>1,512,759</td><td>1,798,709</td><td>5,422,545</td></tr>
<tr><td>Potential recharge</td><td>ac-ft/yr</td><td>51,664</td><td>55,964</td><td>60,718</td><td>168,346</td></tr>
<tr><td>Runoff</td><td>ac-ft/yr</td><td>35,364</td><td>29,262</td><td>47,027</td><td>111,653</td></tr>
<tr><td rowspan="2">Estimated recharge</td><td>ac-ft/yr</td><td>25,389</td><td>28,741</td><td>13,810</td><td>68,977</td></tr>
<tr><td>in./yr</td><td>0.19</td><td>0.31</td><td>0.12</td><td>0.21
(average)</td></tr>
<tr><td>Total precipitation that becomes recharge</td><td>percent</td><td>1.2</td><td>2.0</td><td>0.8</td><td>1.3
(average)</td></tr>
</table>

ac-ft/yr acre-feet per year
in./year inches per year

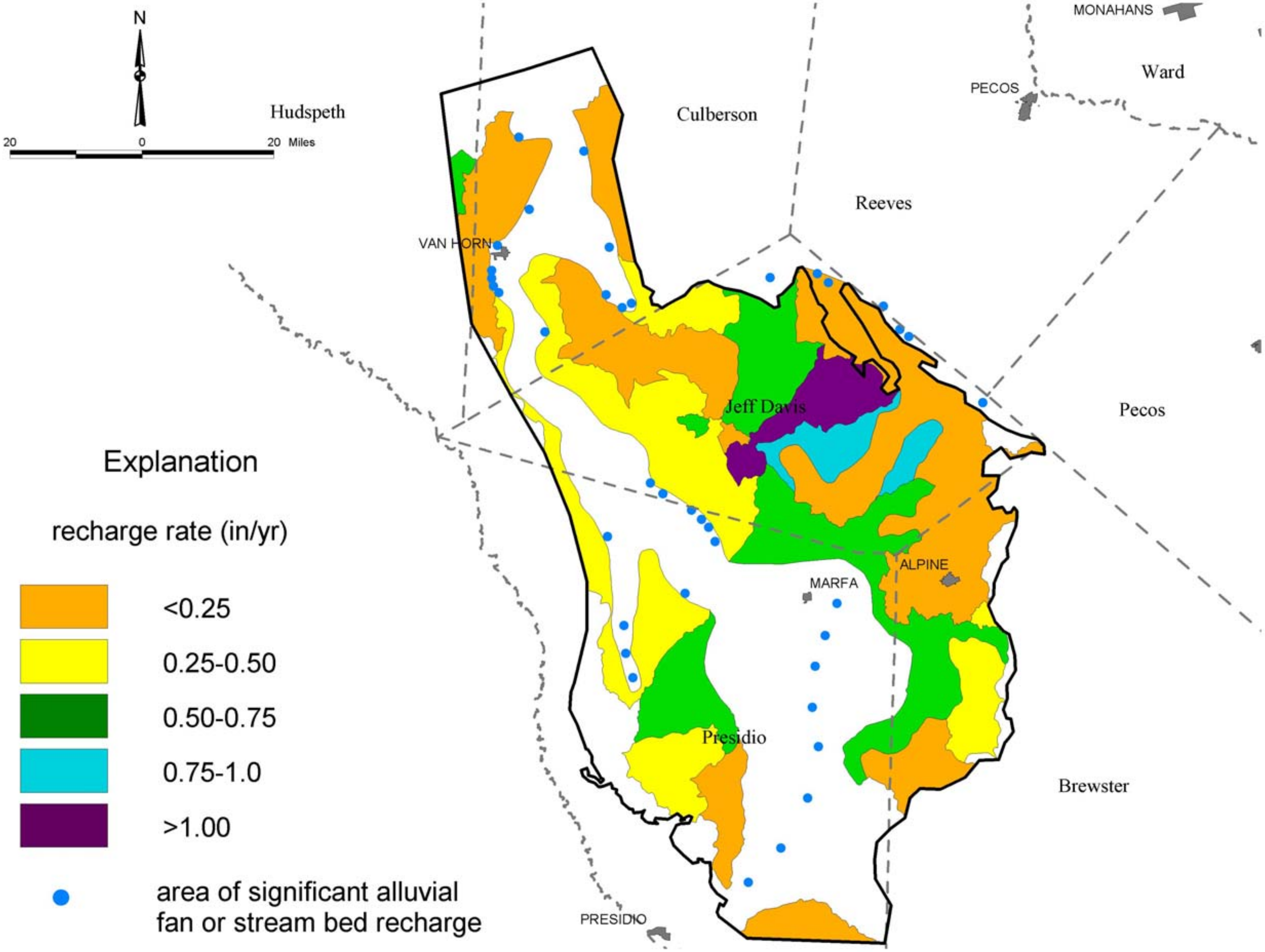

Figure B.20. Distribution of average recharge in the study area.

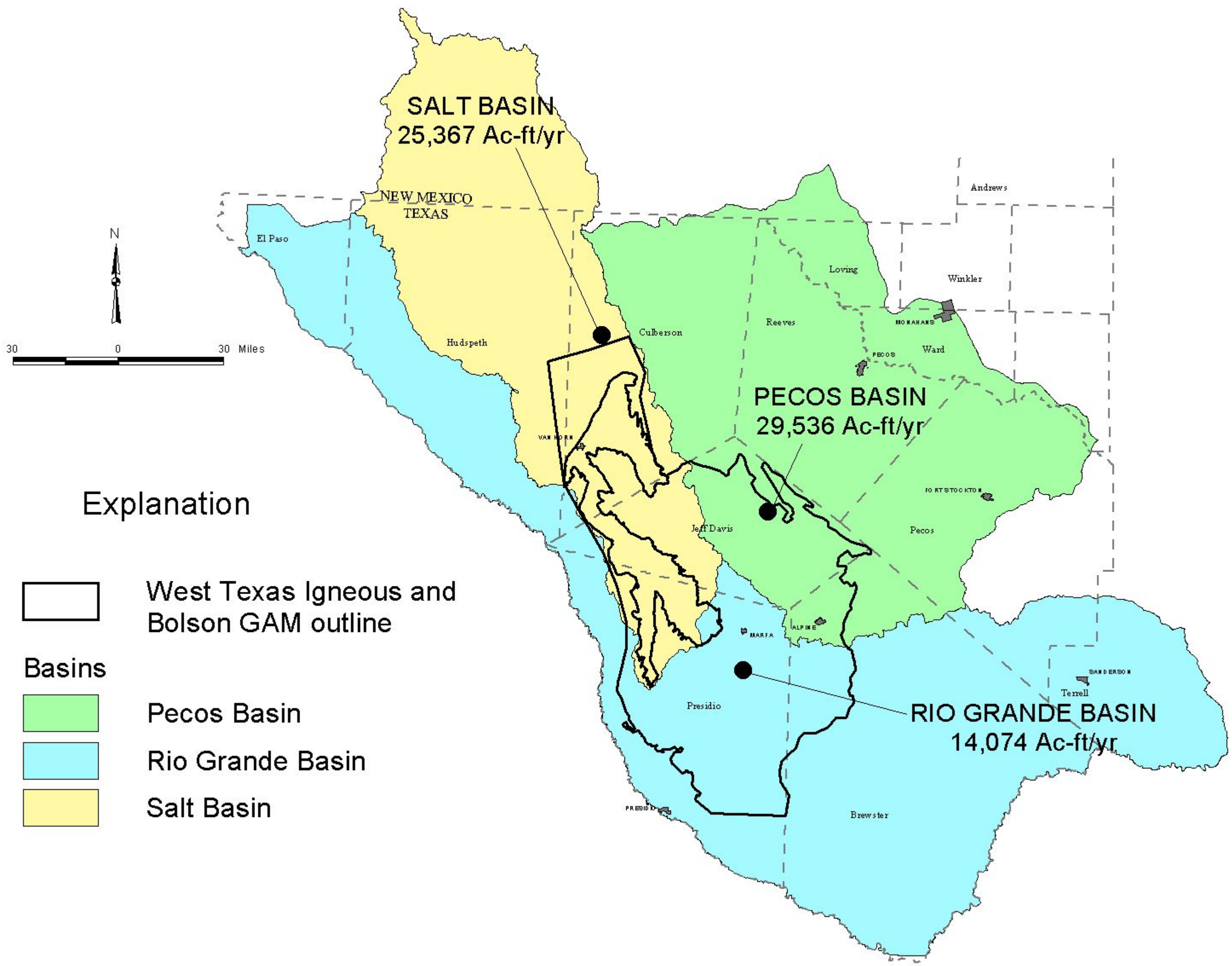

Figure B.21. Distribution of recharge in the major basins.

Table B.9 Recharge for Salt Basin

sub-basin	sub-basin area, acres	Ia[1], inches	precipitation, ac-ft/yr	potential recharge, ac-ft/yr	runoff generated within sub-basin that leaves sub-basin, ac-ft/yr	runoff that enters sub-basin from up-gradient sub-basins, ac-ft/yr	estimated recharge, ac-ft/yr[a]
Baylor Draw	73,576	0.67	94,375	2,851	2,068	0	783
Ed Ray Canyon	62,435	0.67	78,289	2,116	1,640	0	476
Hackberry Creek	29,872	0.67	38,905	1,257	812	0	445
Lower Carrizo Creek	4,528	0.51	5,485	121	121	20	6
Upper Carrizo Creek	4,623	1.58	6,473	271	20	0	251
Sacaton Draw	83,380	0.67	104,333	2,789	2,180	0	609
Upper Michigan Draw	65,511	0.67	79,584	1,788	1,723	0	65
China Draw	56,096	1.58	71,714	2,133	241	0	1,892
Bolsons of Wild Horse Draw and Michigan Draw	520,909	1.04	651,902	0	5,143[b]	27,648	3,152
Upper Wild Horse Draw	358,001	0.67	488,906	19,171	11,553	0	7,618
Lower Eagle Flat Draw	108,240	0.67	141,953	4,783	2,780	678	2,206
Upper Eagle Flat Draw	20,825	0.67	30,539	1,508	678	0	830
Bunton Draw	116,363	0.67	153,016	5,144	3,464	806	1,922
Lower Jones Draw	3,389	0.51	4,659	184	170	208	76
Upper Jones Draw	6,801	0.67	9,899	477	208	0	270
Lower Yates Draw	13,456	0.67	17,841	620	356	158	311
Upper Yates Draw	5,088	0.67	7,412	358	158	0	200
Lower Ninemile Draw	10,604	0.67	13,745	435	279	344	259
Upper Ninemile Draw	545	0.67	764	32	16	0	16
Lower Cracker Jack Draw	11,990	0.67	16,788	703	329	149	419
Upper Cracker Jack Draw	4,683	0.67	6,920	350	149	0	202
Lower HO Canyon	8,920	0.67	12,490	523	255	54	284
Upper HO Canyon	6,876	1.37	2,340	193	54	0	139
Lower Wood Canyon	12,834	0.67	17,957	750	360	17	395
Upper Wood Canyon	2,198	1.37	3,583	238	17	0	220
Lower Merrill Canyon	16,209	0.67	22,696	950	450	141	542
Upper Merrill Canyon	17,403	1.37	28,509	1,920	141	0	1,779
TOTAL	1,625,355		2,111,077	51,664	35,364		**25,367[d]**
leaves model area							26,284[c]

[a] only 30 percent of the runoff that is redistributed from mountain sub-basins to alluvial fan sub-basins, and from alluvial fan sub-basins to bolsons contributes to recharge
[b] runoff generated within the Bolsons of Wild Horse Draw and Michigan Draw leaves the model area through evaporation
[c] 70 percent of all redistributed runoff and all runoff generated in Bolsons of Wild Horse Draw and Michigan Draw leaves the model area through evaporation
[d] negative sub-basin recharge values are treated as zero in the summation of basin-wide recharge
[1] Ia is the initial abstraction for a 24-hour storm event; it is assumed that precipitation events with magnitudes below the Ia do not generate runoff

Table B.10 Recharge for Pecos Basin

sub-basin	sub-basin area, acres	Ia[1], inches	precipitation, ac-ft/yr	potential recharge, ac-ft/yr	runoff generated within sub-basin that leaves sub-basin, ac-ft/yr	runoff that enters sub-basin from up-gradient sub-basins, ac-ft/yr	estimated recharge, ac-ft/yr[a]
Lower Herds Pass Draw	2,978	0.51	4,170	175	144	688	237
Upper Herds Pass Draw	21,996	0.67	31,133	1,359	688	0	670
Lower Adobe Draw	75,874	0.67	106,029	4,451	2,208	995	2,541
Upper Adobe Draw	26,747	0.67	42,836	2,704	995	0	1,709
Lower Cherry Canyon Creek	100,229	0.67	105,614	634	634	1,898	569
Upper Cherry Canyon Creek	56,751	0.67	85,538	4,596	1,898	0	2,698
Lower Madera Canyon	15,290	0.67	18,315	382	388	3,559	61
Upper Madera Canyon	38,038	1.37	59,462	3,559	224	0	3,335
Lower Aguja Canyon	99,173	0.67	118,152	2,517	2,597	628	108
Upper Aguja Canyon	41,378	1.37	64,095	3,721	241	0	3,480
Lower Limpia Canyon	207,236	0.51	279,456	10,334	9,499	296	924
Upper Limpia Canyon	72,276	1.37	110,224	6,153	296	0	5,857
Lower Musquiz Creek	104,447	0.67	129,741	3,375	2,339	2,841	1,889
Upper Musquiz Creek	48,549	1.37	67,921	2,848	176	0	2,672
Lower Alpine Creek	86,189	0.67	110,374	3,310	2,665	1,123	981
Upper Alpine Creek	33,829	0.67	47,882	2,090	1,123	0	967
Lower Antelope Draw	82,529	0.51	100,868	2,397	2,397	751	225
Upper Antelope Draw	21,815	0.67	30,950	1,363	751	0	612
TOTAL	1,135,324		1,512,759	55,964	29,262		**29,536**[c]
Pecos Basin (outside model area)							21,333 evaporates, 5,945 recharge[b]

[a] only 30 percent of the runoff that is redistributed from mountain sub-basins to alluvial fan sub-basins, and from alluvial fan sub-basins to the Pecos Basin (outside the model area) contributes to recharge
[b] 70 percent of all redistributed runoff leaves the model area through evaporation and 30 percent of runoff redistributed to the Pecos Basin (outside the model area) contributes to recharge in the Pecos Basin (outside the model area)
[c] negative sub-basin recharge values are treated as zero in the summation of basin-wide recharge
[1] Ia is the initial abstraction for a 24-hour storm event; it is assumed that precipitation events with magnitudes below the Ia do not generate runoff

Table B.11 Recharge for Rio Grande Basin

sub-basin	sub-basin area, acres	Ia[1], inches	precipitation, ac-ft/yr	potential recharge, ac-ft/yr	runoff generated within sub-basin that leaves sub-basin, ac-ft/yr	runoff that enters sub-basin from up-gradient sub-basins, ac-ft/yr	estimated recharge, ac-ft/yr[a]
Lower Cibolo Creek	88,715	0.67	117,207	4,014	2,206	98	1,838
Upper Cibolo Creek	30,841	1.37	43,912	1,959	98	0	1,861
Lower Cienega Creek	44,683	0.67	53,284	1,084	1,027	66	78
Upper Cienega Creek	22,092	1.37	30,932	1,295	66	0	1,228
Lower Alamito Creek	785,789	0.51	1,041,863	36,518	36,518	145	-1,288
Upper Alamito Creek	40,557	1.37	55,208	2,206	145	0	2,061
Lower Terneros Creek	58,821		68,373	1,199	1,199	735	-1,208
Upper Terneros Creek	27,990	0.51	34,614	867	735	0	132
Upper Terlingua Creek	121,482	0.67	146,777	3,196	2,866	126	367
Upper Terlingua Creek headwaters	42,751	0.67	59,994	2,533	126	0	2,407
Lower Calamity Creek	75,263	1.37	102,453	3,923	1,935	126	2,020
Upper Calamity Creek	31,152	0.67	44,093	1,925	106	0	1,818
TOTAL	1,370,137		1,798,709	60,718	47,027		**14,074**[c]
Rio Grande Basin (leaves model area)							32,919 evaporates, 13,725 recharge[b]

[a] only 30 percent of the runoff that is redistributed from mountain sub-basins to alluvial fan sub-basins, and from alluvial fan sub-basins to the Pecos Basin (outside the model area) contributes to recharge

[b] 70 percent of all redistributed runoff leaves the model area through evaporation and 30 percent of runoff redistributed to the Pecos Basin (outside the model area) contributes to recharge in the Rio Grande Basin (outside the model area)

[c]negative sub-basin recharge values are treated as zero in the summation of basin-wide recharge

[1]Ia is the initial abstraction for a 24-hour storm event; it is assumed that precipitation events with magnitudes below the Ia do not generate runoff

4.0 DISCUSSION

The runoff-redistribution method appears to be more realistic than whole-basin recharge estimates because it considers the runoff characteristics of each sub-basin and the varying amount of precipitation received by each sub-basin. Previous recharge estimates using a percentage of the precipitation (Gates et al, 1978; Mayer, 1995) did not consider components of the conceptual model, such as geologic characteristics for infiltration and areas on the bolsons where recharge does not likely occur. Therefore, the runoff-redistribution method provides constraints on a sensitive model parameter consistent with the conceptual model, and helps minimize the inherent non-uniqueness associated with parameterization in numerical models.

Groundwater flow models are sensitive to prescribed recharge and recharge distribution, and given the uncertainties in recharge estimates for the study area, the runoff-redistribution method hopefully provides a better approximation to recharge distribution and quantity that would otherwise be difficult or impossible to obtain.

There is likely a component of rejected recharge that is not accounted for in the recharge estimates that causes the under-prediction of model-calibrated recharge to estimate recharge. One example of rejected recharge would be recharge to a perched groundwater system that is discharged to a spring or by evapotranspiration. Other possibilities for the recharge discrepancy maybe related to the lack of long-term climate data (i.e., comparing 20 years of climate data to a regional hydrologic system that represents 1,000's of year), and the lack of detail in the regional model to account for conveyance of all the estimated recharge through the groundwater system.

A comparison of other recharge methods used for the study area, and the re-distribution method used in the current study, is provided as Table B.12. The runoff-redistribution method appears to be an appropriate method for the IBGAM because it considers the runoff characteristics of each sub-basin and the variable precipitation received by each sub-basin.

Table B.12 Comparison of recharge methods for the IBGAM study area

method	unit	Salt	Pecos	Rio Grande	total	comments
total precipitation	ac-ft/yr	2,111,077	1,512,759	1,798,709	5,422,545	
one-percent rule (Gates et al., 1978)	ac-ft/yr	21,111	15,128	17,987	54,225	does not consider watershed or geologic variability
modified Maxey Eakin (Mayer, 1995)	ac-ft/yr	135,543	172,641	205,256	513,440	overestimates recharge at lower elevations
	in./yr	1.0	1.8	1.8		
storm-runoff infiltration (Finch and Armour, 2000)	ac-ft/yr	10,664	9,810	10,263	30,737	does not consider aerial (direct) recharge at higher elevations or geology
runoff redistribution (this study)	ac-ft/yr	25,389	28,741	13,810	67,940	accounts for watershed characteristics and distribution of recharge from storm-water runoff
	in./yr	0.19	0.30	0.12		

ac-ft/yr acre-feet per year
in./year inches per year

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APPENDIX C

METHODOLOGY FOR DISTRIBUTION OF PUMPING

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1.0 Pumping Data

Water-use inventories provided by the TWDB were totaled by county and aquifer designation based on the following categories: agricultural, municipal point, municipal non-point, manufacturing point, manufacturing non-point, and livestock. The files provided by the TWDB are broken into three temporal sets: pre-1980, post-1980, and predictive. Point data were distributed to the model at the point of withdrawal. If a location of pumping could be identified with a precision as good as the ½-mile grid cell size, the pumping was assigned to that cell. For instance, if a mobile home park reports a value and an x-y coordinate could be obtained, then the pumping for that location was assigned to the underlying grid cell. When available, dates that indicate when wells or well fields begin or cease operations were used. If a municipal well field went off-line during a particular year and a new well field was used the following year, the pumping values used in the model were assigned to the appropriate location for the appropriate year. Non-point pumping data were distributed throughout the model based on land use and, in the case of the rural domestic pumping, census data.

2.0 Land Use

USGS land use and land cover data, organized by 1:250,000 quadrangle, were obtained for the study area. These quadrangles were merged together and then projected from the Geographic decimal degrees coordinate system to the Texas Centric projection required by the TWDB. One problem with this file was that it does not break apart irrigated agriculture from non-irrigated agriculture; however, non-irrigated agriculture is minimal in the study area. Pumping for non-irrigated agriculture accounts for approximately 1 percent of the total groundwater withdrawal within Culberson County, 5 percent in Jeff Davis County, 5 percent in Presidio County, and 10 percent in Brewster County. The 1:250,000 USGS land use file was merged with the TWDB 1994 irrigated lands coverage to obtain irrigated acreage coverage. The 1994 irrigated farmlands cover has accurate attribute information, although the spatial extents of the polygons are not very accurate. The 1994 irrigated agriculture file was used to identify the irrigated lands within the agricultural lands designated in the USGS coverage. The remaining lands were classified non-irrigated agriculture.

3.0 Non-point Data Spatial Distribution

Pumping data in the TWDB databases are reported at the county level. These values are distributed to grid cells using GIS. To distribute the rural domestic pumping, the ArcView function *Intersect* was used to combine the census data polygons with the model grid cell ID designations. The resulting shapefile contains polygons based on population, distributed into model grid cells. For livestock pumping, grid cells were used whose centroid intersected the non-irrigated agriculture or rangeland land use classifications. Next, the total areas covered in each county by these two land uses were calculated. The area value for each polygon was divided by the total county area value to get a percentage, creating the percentage field in the attribute table. This percentage was used to weigh how much pumping the polygon's cell ID should receive. Each grid cell then had a value that is the percentage or factor of a pumping type in the county within which the grid cell's centroid lies. The county pumping totals in the database were then multiplied by these factors to calculate how much pumping to assign to each grid cell. A QA/QC procedure was performed at this point that adds up the values of each cell within a county for a particular pumping type. This value should equal the county pumping total reported by the TWDB.

4.0 Irrigated Agriculture

Irrigated agricultural pumping was compiled from a combination of the water use inventories provided by the TWDB and supplemental data calculated from additional studies by Finch and Armour (2001), TWDB Report 347, Gillett and Janca (1965, as cited in TWDB Report 16, 1966), Davis (1961), and Hood and Scalapino (1951). The study by Finch and Armour (2001) was used entirely in place of the water use inventories provided by the TWDB for Culberson County because the report gives point data information and provides pumping data back to 1947. These records were treated as point data so that the grid cell that a well lies within was assigned the pumping for that well. Because the TWDB pre-1980 historical summary table only dates back to 1974, the supplemental data were used to calculate pumping for years before 1974 in Brewster, Jeff Davis, and Presidio Counties. The values were linearly interpolated back in time from the 1974 TWDB data to the dates calculated from the supplemental data. These non-point pumping values were spatially distributed based on land use/land cover.

The USGS land use/land cover data were combined with the TWDB 1994 irrigated lands coverage. Spatial extents of agricultural lands were identified from the USGS land use/land cover, except for areas around Alpine and Fort Davis where the USGS coverage failed to identify small areas of agricultural lands that were identified in the TWDB 1994 coverage. For these small areas, the grid cells that intersect the 1994 irrigated lands coverage were assigned pumping.

5.0 Rural Domestic (County Other)

Rural domestic data were derived from the water use inventories provided by the TWDB for the post-1980 data. Because the pre-1980 data give only total municipal amounts, the point data totals were subtracted from the county totals to determine the county other values within a county for the pre-1980 data. 1990 and 2000 U.S. Census block GIS coverages were used to distribute the county other data. Each census block has a persons/area designation. All census blocks that were outside of a city boundary, as determined by the Texas Natural Resources Information System (TNRIS) city coverage, were intersected with the model grid polygon GIS coverage. Census Bureau rural area GIS files do not include boundaries for the cities that are pumping water for municipal use in the region; therefore, the TNRIS city coverage was used as a base for city boundaries. By calculating the area of each new polygon using the population distribution of the census blocks within the model grid cell, a population of each polygon was then calculated within the grid cell.

The county other data were then distributed throughout each county based on the populations of each cell within that county. The 2000 census blocks were used for 1991 through 2000 data. The 1990 census blocks were used for the post-1980 data, as well as the 1974 and 1977 pre-1980 files. Linear interpolations were used to fill in the gaps between 1974 and 1977 and between 1977 and 1980. Decade-based census data by county, as supplied by the TWDB, were used to linearly interpolate data back to 1940.

6.0 Livestock

Livestock data were derived from the historical summary table in the pre-1980 and post-1980 pumpage databases. Post-1980 data are divided by county and aquifer and pre-1980 data are broken out only by the county designation. The USGS land use was used to determine areas where livestock pumping is likely to have occurred. A query performed from the TWDB groundwater database indicated that 85 percent of livestock wells fell within the agricultural non-irrigated land and rangeland use classes. Any model grid cell with a centroid that landed within these two land use classes was used to distribute the pumpage for that county or county/basin value. Because historical data from before 1974 were not available, the 1974 value was applied to all years prior to 1974.

7.0 Point Data Spatial Distribution

The entire statewide groundwater database was downloaded from the TWDB website. This download provided well information such as state well number, latitude and longitude (lat/long) coordinates, well owner, drill date, aquifer, and water use.

Well locations were identified for each point-pumpage record using the following three methods (in order of preferred use):

1. Lat/long values were directly incorporated from the state groundwater database when the *alphanum* field in the TWDB water use inventory's pumpage table linked to the *user_code_econ* field in the state groundwater database.

2. Some well records in the state groundwater database had null values in the *user_code_econ* field. In these cases, the *user_code_econ* value was entered into the well table when the corresponding *alphanum* was found by matching owner name, supplier information, and address line values through historical research using internet resources.

3. When no lat/long coordinates could be established through the state groundwater database, the geographical location of the water user was located by using internet resources and deriving the lat/long coordinates for the location in the GIS. For these non-well locations, the value “Bus. Search” was entered in the well table’s *source* field.

8.0 Municipal Point

Municipal point data were obtained from the provided city municipal pre-1980 and post-1980 data. Initially, all records that included a latitude and longitude were included. Those records were then limited based on the study area. If a well fell geographically outside of the clipped study area, the record was excluded from further consideration. Additional queries were constructed to verify that the raw tables provided did not contain unlinked information. A lat/long is given for each state well number. Each unique state well number, along with its given lat/long, was exported to a dbf file and brought into ArcView. Using ArcView, the lat/long was converted to decimal degrees and then Texas Centric coordinates. Once the state well numbers were displayed in the Texas Centric projection, they were spatially joined with the model grid to obtain cell IDs for each well. The resulting table contained identified state wells within the study area and their cell ID numbers.

Municipal pumping was distributed within a city by dividing the annual pumping for a city by the number of wells in that city for which actual coordinates were available. The pumpage numbers for each model grid cell and each year were then summed to derive pumping for a cell in a particular year. Wherever available, the well’s drilling date was used to screen out wells that were not in use for a particular year.

Decade-based census data by county, as supplied by the TWDB, were used to interpolate data back to 1950. Only wells that had a pumpage value in 1955 were interpolated back in time to 1950. Gaps in annual data were not linearly interpolated for point data.

9.0 Manufacturing Point

The manufacturing category includes mining. The manufacturing point data presented are a combination of innate point data and those that had to be researched. The innate point data are those records in the water use inventories provided by the TWDB that contained a state well number (which comes with lat/long). These coordinates (for both the innate and researched point data) were then projected to the Texas Centric projection. Next, these points were spatially joined in ArcView with the model grid to obtain cell IDs for each location. This process allowed each entity to be assigned to a model cell ID.

Decade-based census data by county, as supplied by the TWDB, were used to interpolate data back to 1950. Only wells that had a pumpage value in 1955 were interpolated back in time. Gaps in annual data were not linearly interpolated for point data. All power data fell outside of the model area and were therefore eliminated from the dataset.

10.0 Predictive Calculations

TWDB annual predictive values were used to interpolate annual values to 2050. All cells that were designated as pumping in the 2000 historical pumping calculations were used to spatially distribute the predictive pumping values.

Predictive pumpage to accommodate Far West Texas planning strategy 71-6A was evenly distributed between Jeff Davis and Presidio Counties. This potential area of future municipal pumpage is on property referred to as "Antelope Valley Farm", which is evenly spaced on either side of the boundary between the two counties (see letter attached to the end of this appendix).

11.0 Vertical Data Distribution

Data were distributed vertically throughout the three layers of the model based on which aquifer the data were associated with (Table C.1). Most of the water use inventories provided by the TWDB had aquifer designations assigned to the pumping values. These values were distributed to the appropriate layer in the database. For data that did not have an aquifer designated in the water use inventories, rural domestic and pre-1980 historical summary data, the geographic positioning of the grid cell over the aquifer boundaries was used to assign pumping to a particular layer. In the case of the rural domestic pumping data, the recommended method from the GAM technical memo 02-02, was used by distributing the vertical distribution of rural domestic pumping by statistically correlating to nearby and similar pumping. Each grid cell was assigned the same aquifer and layer designation that it was assigned in the livestock pumping. This method was used because livestock data has a designated aquifer in the water use inventories provided by the TWDB; in most cases, livestock pumping is the only other pumping that occurs in these rural areas of the model area. There were 5,486 of 19,885 rural domestic grid cells, 28 percent, where rural domestic pumping did not overlay livestock land use. In these instances, nearby cells with livestock pumping were used to statistically correlate the aquifer designation.

Table C.1 Vertical Distribution of Pumping to the Model by Aquifer Designation

Aquifer	Model Layer
WEST TEXAS BOLSON	1
IGNEOUS	2
OTHER	2
CAPITAN REEF	3
EDWARDS TRINITY PLATEAU	3

12.0 Pumping Database

Two databases are used to distribute pumping throughout the horizontal and vertical portions of the model. The Historical_Pumping.mdb and the Predictive_Pumping.mdb files are Microsoft Access 97 database files. Figures C.1 through C.10 are tree diagrams that describe the relationships between the various tables and queries within the database.

Each tree diagram begins with the source files and steps through the appropriate queries, culminating in a final pumping table that is distributed by model grid cell, layer, and county.

13.0 Historical Pumping Database

Figures C.1 through C.4 refer to the relationships between the various tables and queries within the historical pumping database. The historical pumping database is used to associate the various GIS analysis with the pumping data to derive the spatially distributed historical pumping data. The final output tables within the historical pumping database are not linear interpolated. The final step in preparing the historical pumping data is to export the tables into Microsoft Excel and perform a linear interpolation to fill in the data gaps that exist between 1974 and 1978, as well as 1978 and 1980. The TWDB source files for historical pumping end in 1997. These numbers are carried forward from 1997 to 2000. WUG values were manually assigned for non-point data in the Excel file.

14.0 Predictive Pumping Database

The 2000 pumping data from the final historical pumping database files are used as the initial value for distributing the predictive pumping within the predictive pumping database. A factor is derived from the pumping value for each model grid cell and layer. This factor represents the record's percentage of county pumping and particular pumping type. Predictive pumping values for subsequent years are calculated by multiplying the factor by the annual predictive pumping data supplied by the TWDB. Figures C.5 through C.10 refer to the relationships between the various tables and queries within the predictive pumping database.

Any future changes to the predictive pumping values can be implemented within the predictive pumping database source files. Once changes are made to the appropriate tables, the changes will be reflected within the various queries. For instance, if a county reports a new predictive value for the year 2020, the value will need to be changed in the appropriate source table within the predictive pumping database. Once the queries are run, the new final tables will reflect the changed value.

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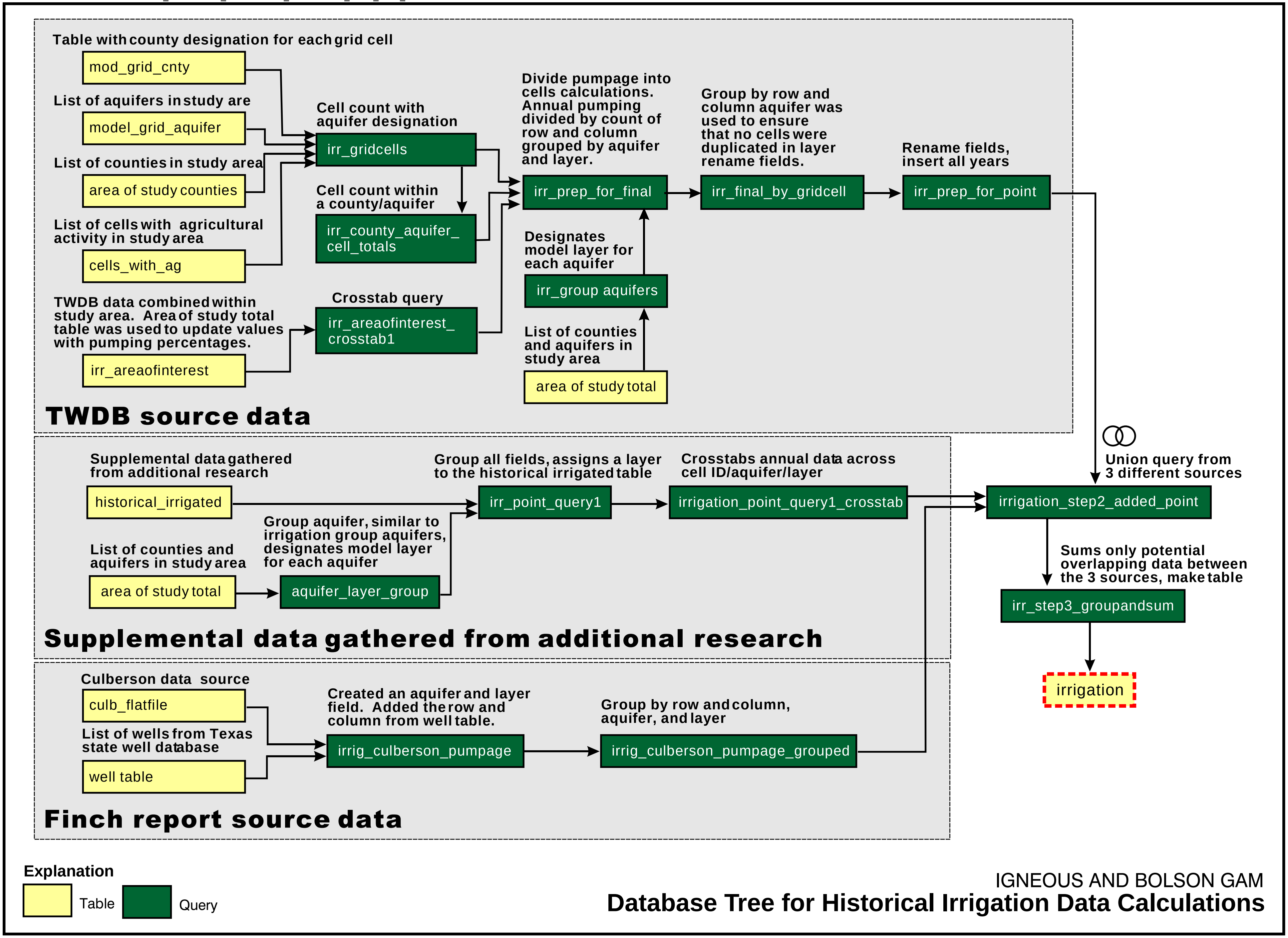
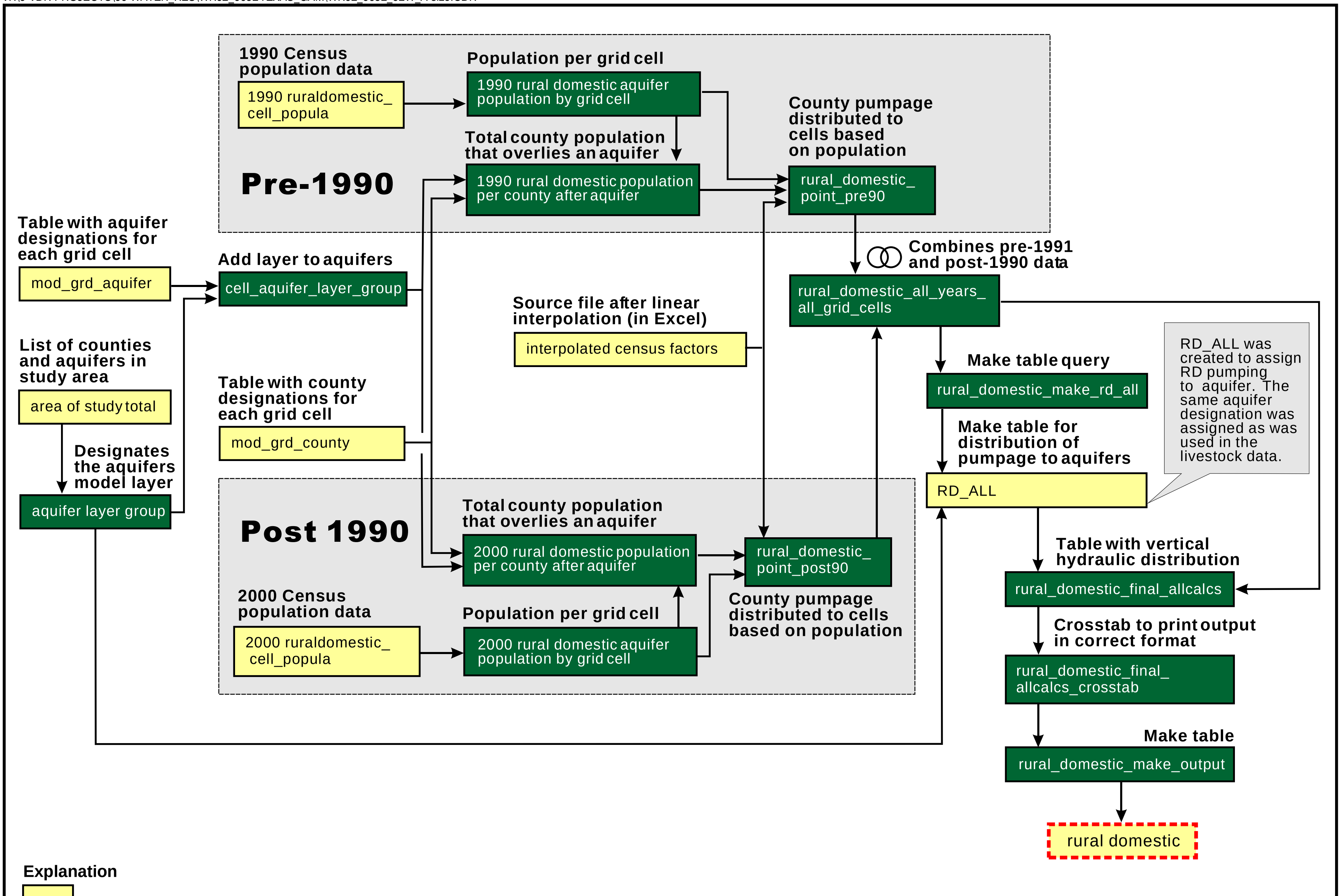


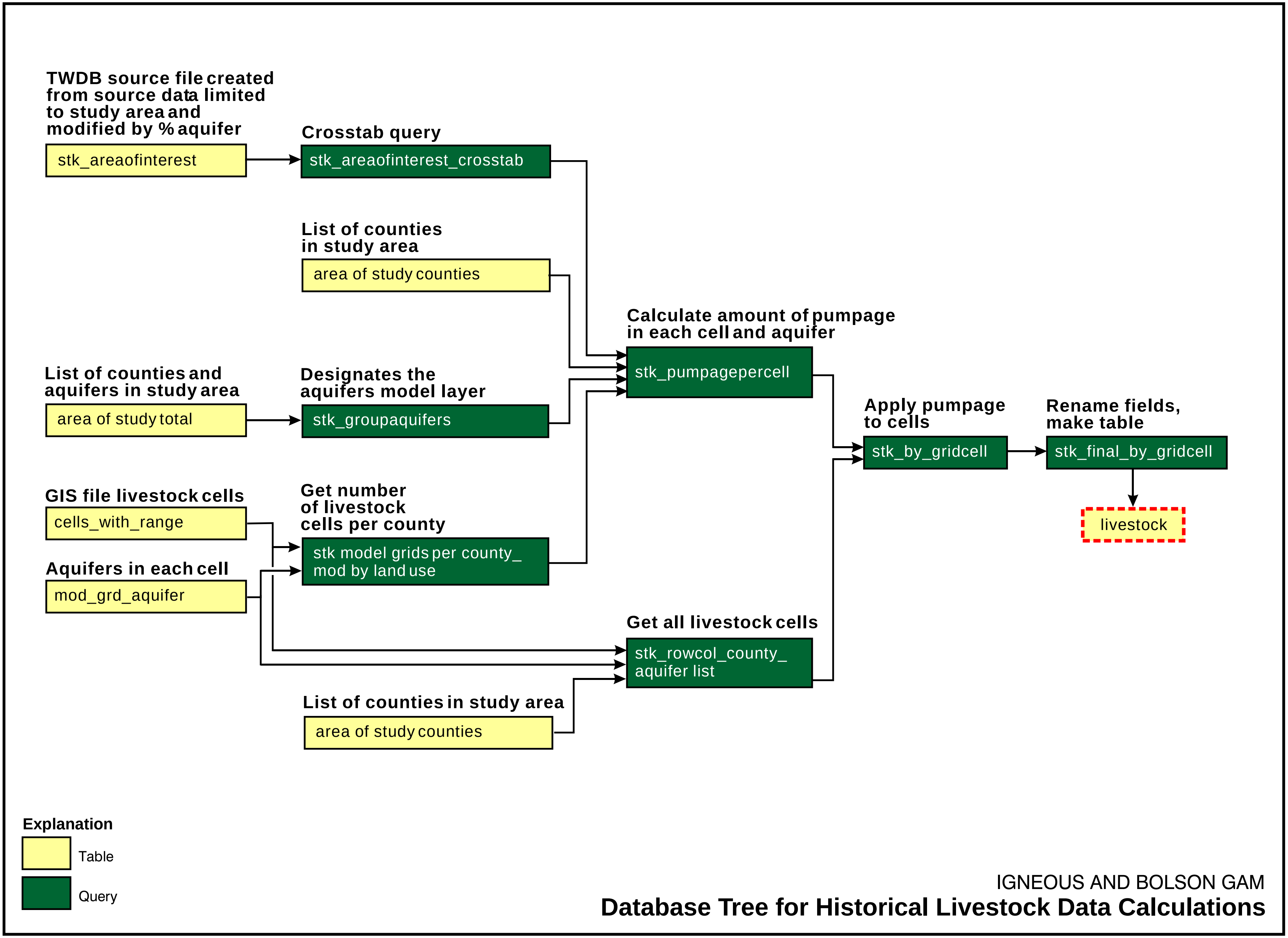
Figure C.1



IGNEOUS AND BOLSON GAM

Database Tree for Historical Rural Domestic Data Calculations

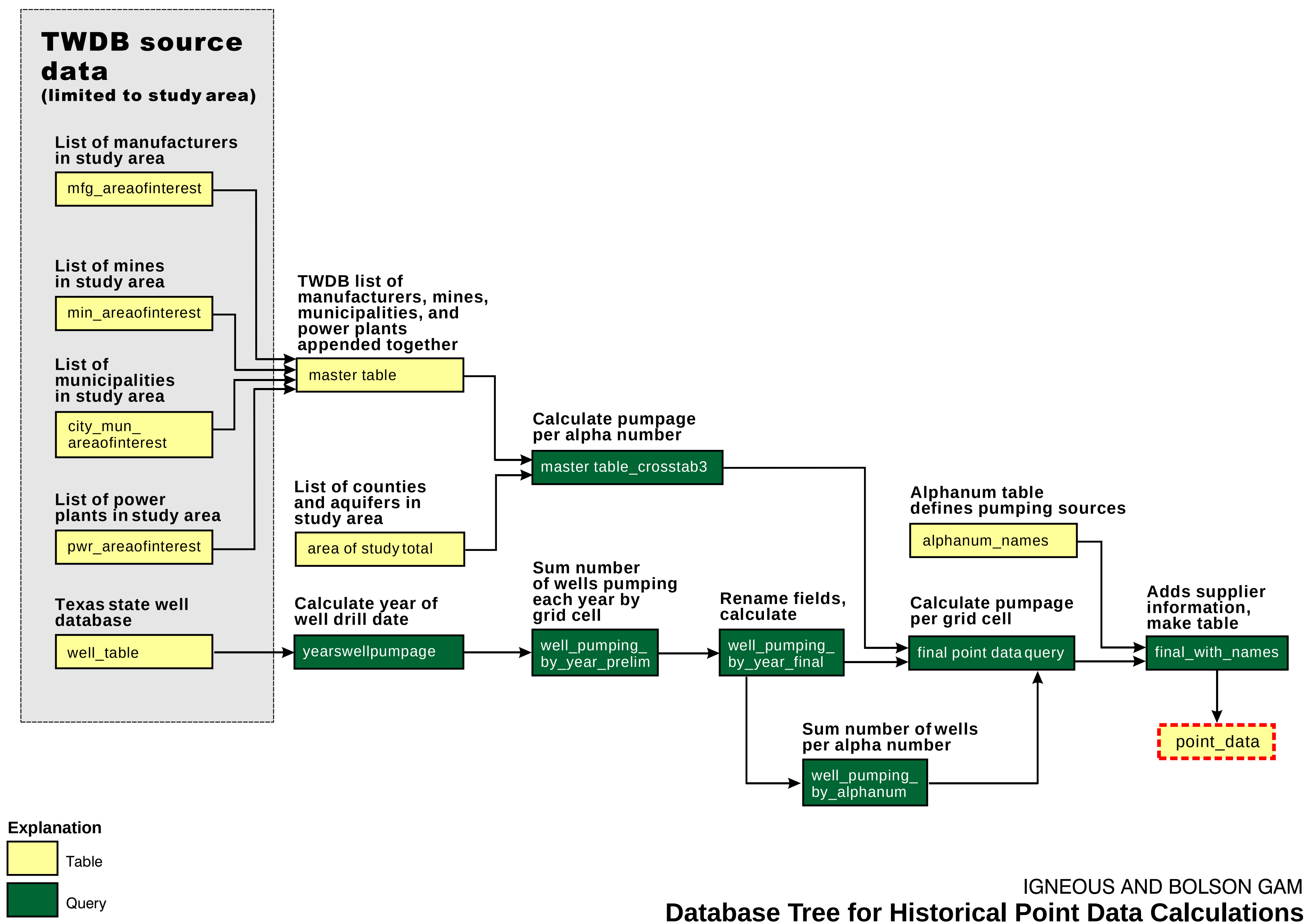
Figure C.2



IGNEOUS AND BOLSON GAM

Database Tree for Historical Livestock Data Calculations

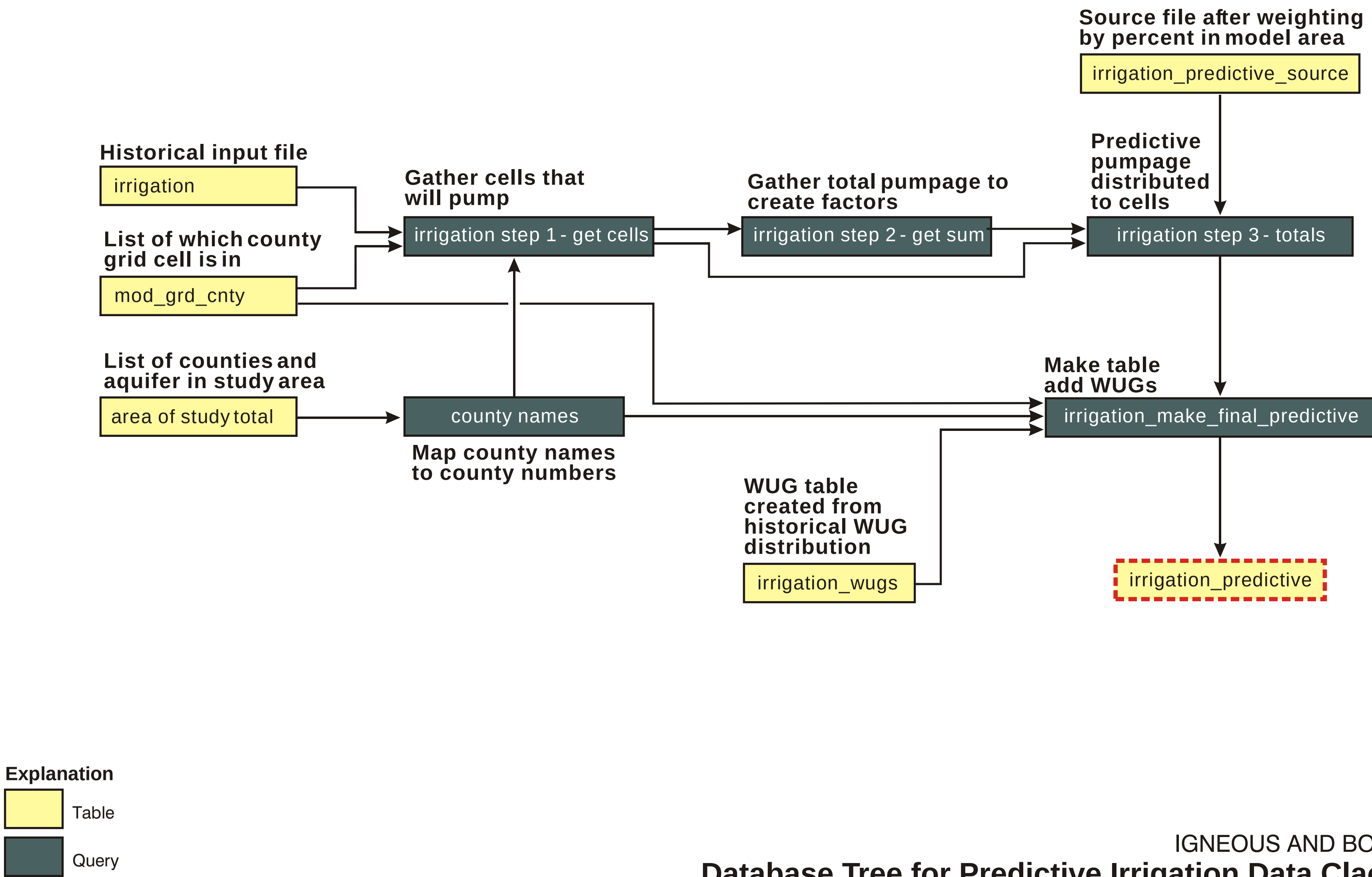
Figure C.3



IGNEOUS AND BOLSON GAM

Database Tree for Historical Point Data Calculations

Figure C.4



IGNEOUS AND BOLSON GAM

Database Tree for Predictive Irrigation Data Claculations

Figure C.5

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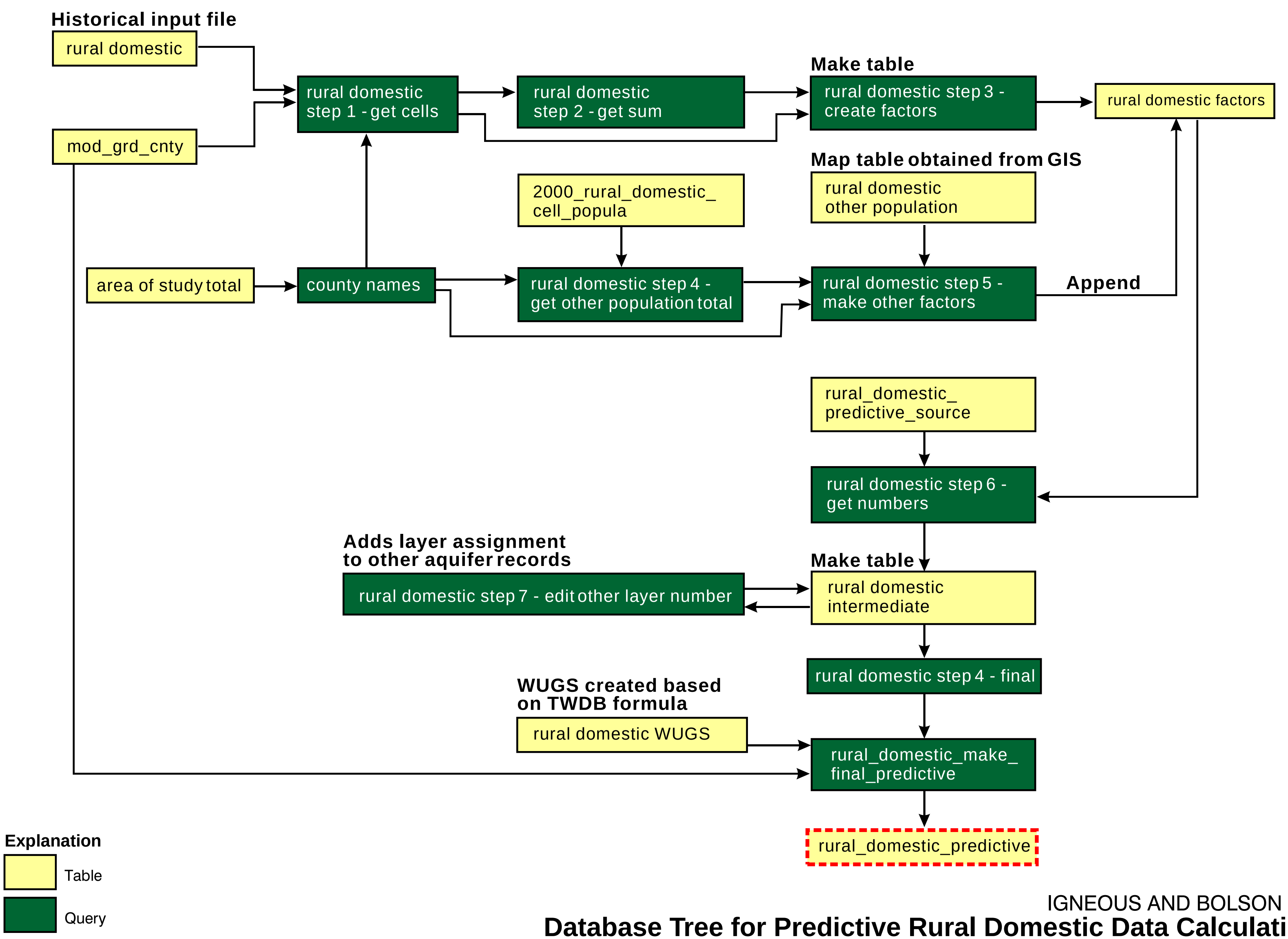

IGNEOUS AND BOLSON GAM

Database Tree for Predictive Rural Domestic Data Calculations

Figure C.6

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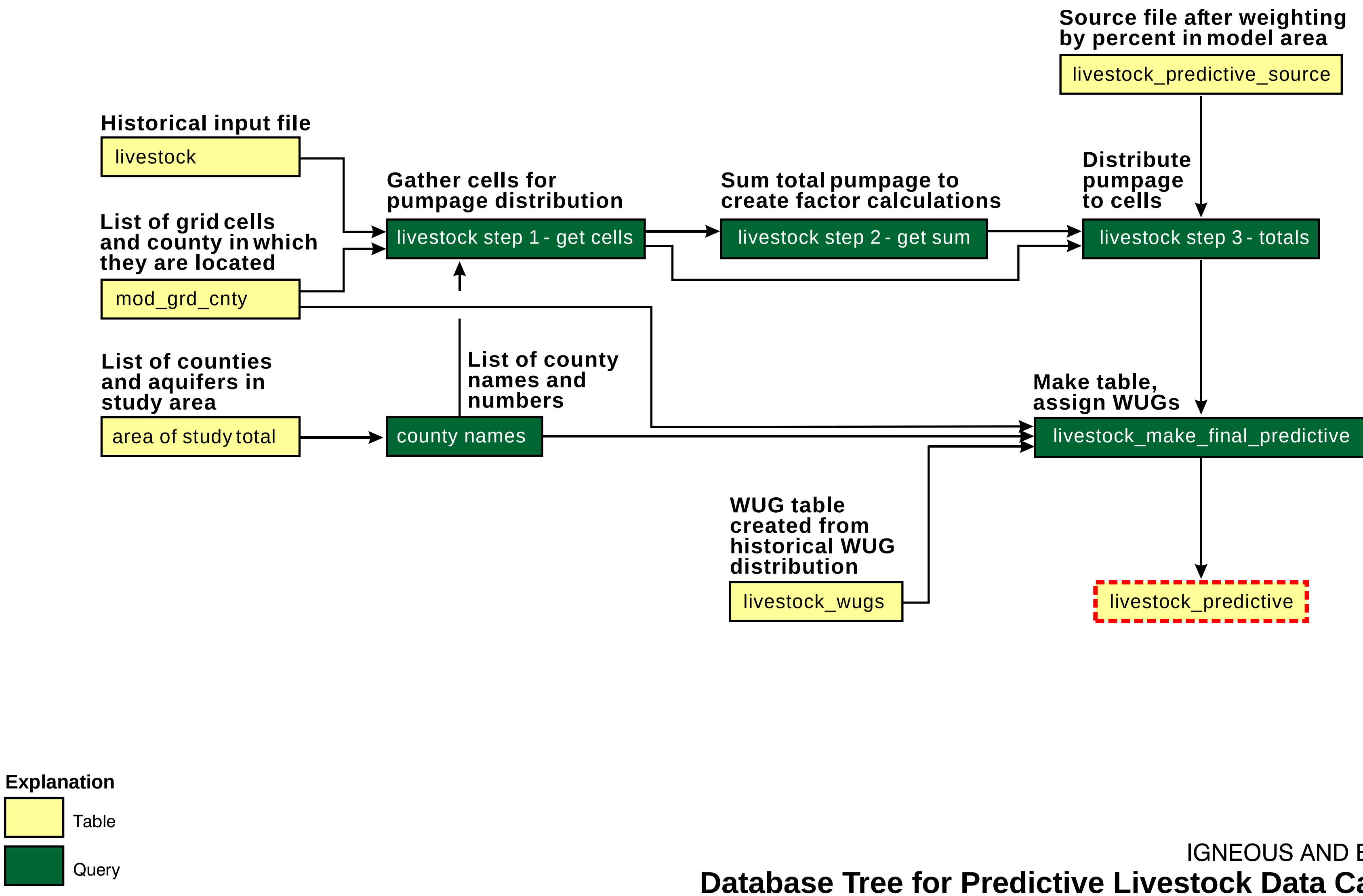
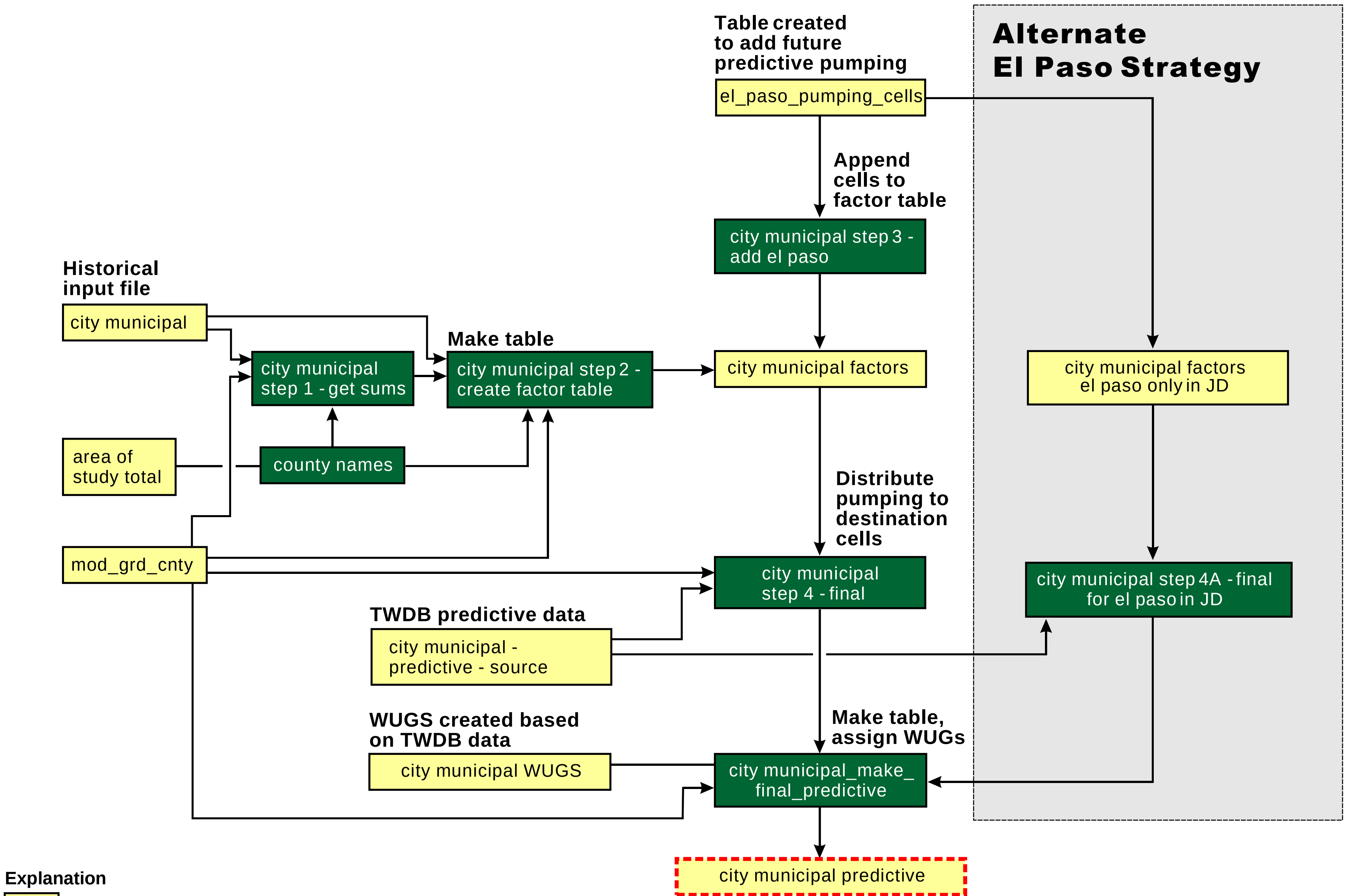


IGNEOUS AND BOLSON GAM

Database Tree for Predictive Livestock Data Calculations

Figure C.7

VR\0-VDR-PROJECTS\00-WATER_RES\WR02_0092-TEXAS_GAM\WR02_0092_10K_A-size.CDR

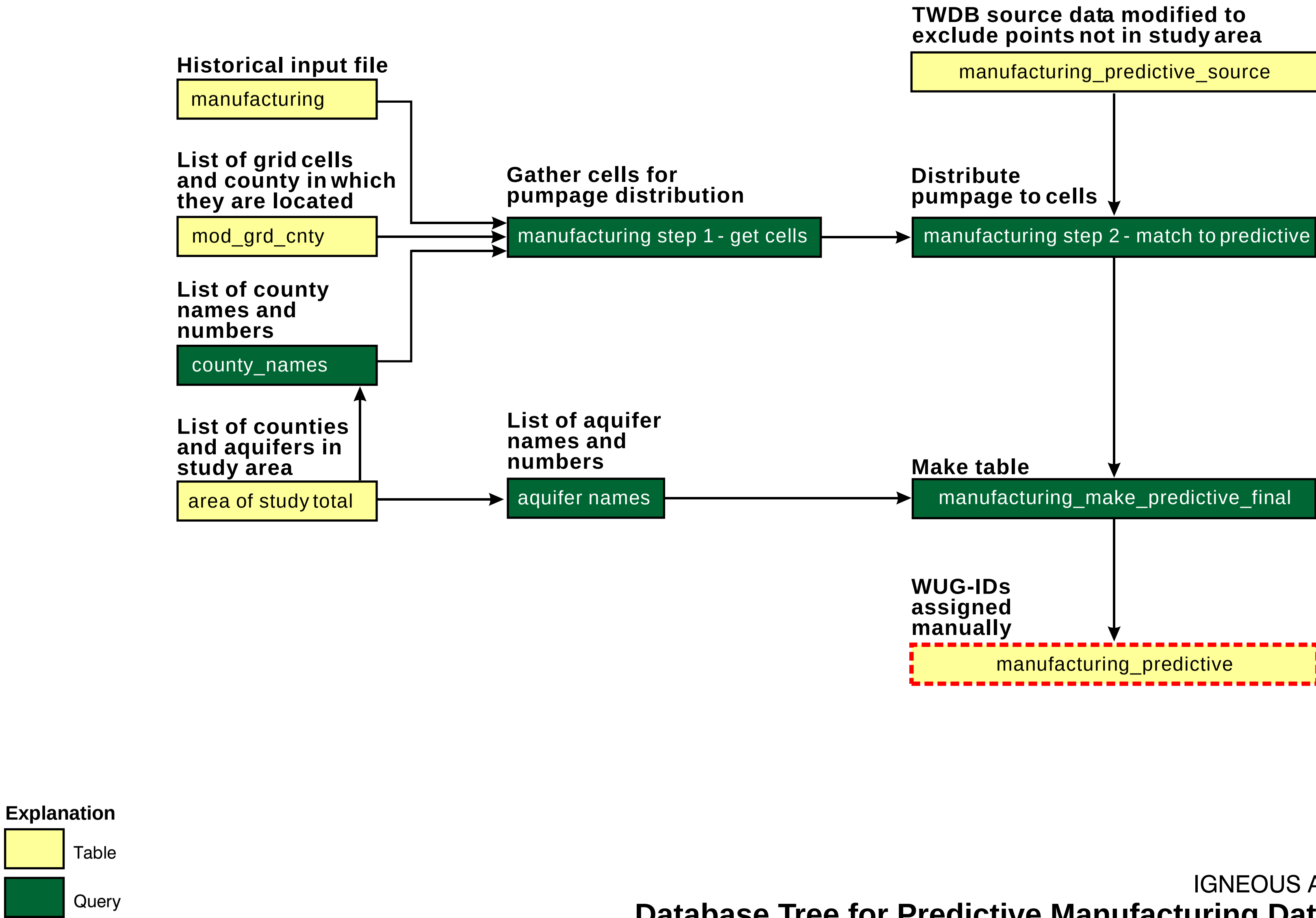


IGNEOUS AND BOLSON GAM

Database Tree for Predictive City Municipal Data Calculations

Figure C.8

VR\0-VDR-PROJECTS\00-WATER_RES\WR02_0092-TEXAS_GAM\WR02_0092_07W.CDR



IGNEOUS AND BOLSON GAM

Database Tree for Predictive Manufacturing Data Calculations

Figure C.9

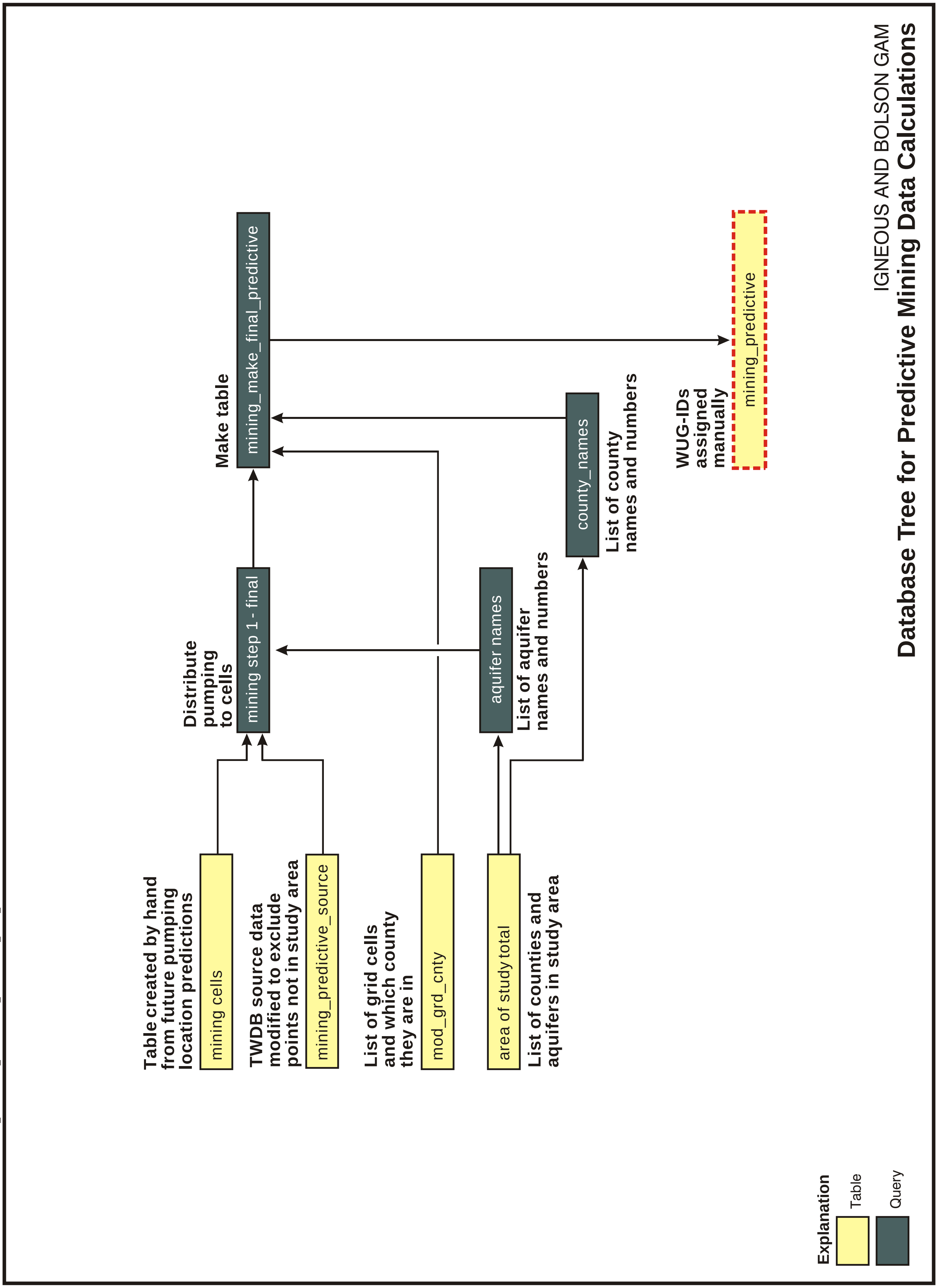

VR\0-VDR-PROJECTS\00-WATER_RES\WR02_0092-TEXAS_GAM\WR02_0092_09K.CDR
Table created by hand from future pumping location predictions
mining cells
TWDB source data modified to exclude points not in study area
mining_predictive_source
List of grid cells and which county they are in
mod_grd_cnty
area of study total
List of counties and aquifers in study area
Distribute pumping to cells
mining step 1 - final
aquifer names
List of aquifer names and numbers
Make table
mining_make_final_predictive
county_names
List of county names and numbers
WUG-IDs assigned manually
mining_predictive
Explanation
Table
Query
IGNEOUS AND BOLSON GAM
Database Tree for Predictive Mining Data Calculations

Figure C.10

References

Davis, M.1961. *Ground-water reconnaissance of the Marfa area, Presidio County, Texas*. U.S. Geological Survey Report.

Finch, S. and J. Armour. 2001. *Hydrogeologic analysis and groundwater flow model of the Wild Horse Flat area, Culberson County, Texas*.

Hood, J.W. and R.A. Scalapino. 1951. *Summary of the development of groundwater for irrigation in the Lobo Flats area, Culberson and Jeff Davis Counties, Texas*. U.S. Geological Survey Report.

Texas Water Development Board. 1966. *Water-level data from observation wells in Culberson, Jeff Davis, Presidio, and Brewster Counties*, *Texas*. Report 16.

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FAR WEST TEXAS WATER PLANNING GROUP

1100 North Stanton, Suite 610
El Paso, Texas 79902

915/533-0998 *915/532-9385 (FAX)*

March 15, 2004

FROM: Tom Beard, Chairman - Far West Texas Water Planning Group

TO: Ted Angle, IBGAM Contract Mgr.

SUBJECT: Assignment of future pumpage in the IBGAM

Dear Mr. Angle:

John Ashworth (LBG-Guyton Associates) has asked me to respond to your request for clarification of the location of potential future pumping withdrawals from the El Paso Water Utilities property in Ryan Flat as expressed in Strategy 71-6A of the 2001 Far West Texas Regional Water Plan. It is my understanding that the TWDB is providing the IBGAM consultants with potential future water demands by county, and have placed all potential withdrawals from Antelope Valley Farms (El Paso property) into Jeff Davis County based on your interpretation of Strategy 71-6A (EPWU groundwater transport) rather than splitting it with Presidio County, as the property and well field currently exists. Strategy 71-6A states that Antelope Valley Farms is in Ryan Flat near Valentine, but does not give a location by county. This letter is to acknowledge that the Far West Texas Water Planning Group fully recognizes that the El Paso Water Utilities (AVF) property exists in both Jeff Davis and Presidio Counties and, if Strategy 71-6A should someday come into being, withdrawals are expected to occur from the property in both counties. Also, the Planning Group wants to make it clear that the Group accepted this strategy conditionally on further study and feasibility analysis.

Sincerely,

Mr. Tom Beard, Chairman
Far West Texas Water Planning Group

APPENDIX D

METHODOLOGY FOR DEVELOPING TRANSMISSIVITY FOR THE IGNEOUS AQUIFER

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List of Figures

Figure No. **Title**

List of Tables

Table No. **Title**

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Pumping test data and calculated transmissivity values were relatively scarce in the area encompassed by the Igneous aquifer model area. Therefore, a methodology was developed to estimate transmissivity (T) from the much more common specific capacity (Sc) values, which are often recorded on drilling logs by local drillers. The specific capacity of a well is its pumping rate divided by the water-level drawdown. This approach provides an improved understanding of the transmissivity distribution by increasing the number of transmissivity estimates.

An empirical technique was used to give a more direct analysis of the relationship between Sc and T for the Igneous aquifer. Data from 24 available aquifer tests that reported both Sc and T were analyzed and graphed in Figure D.1.

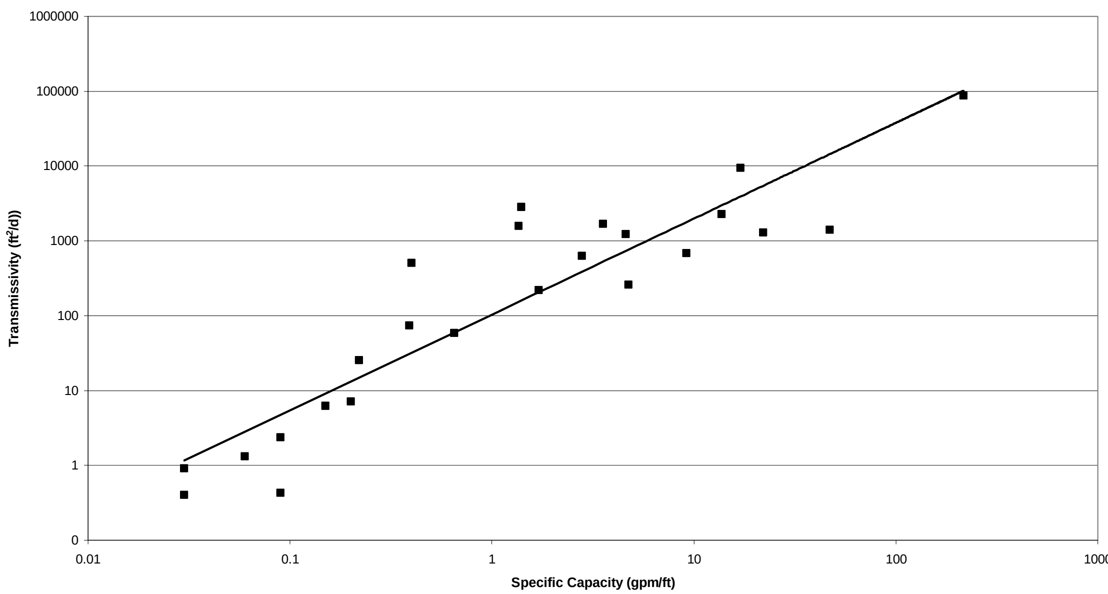

Figure D.1 Empirical Specific Capacity versus Transmissivity Relationships for the Igneous Aquifer

The data points on Figure D.1 allow a trend line to be fitted such that Sc can be directly related to T for the Igneous aquifer. The variation of data was less than one order of magnitude and appeared to relate reasonably well with other published datasets. Numerous T values were then estimated from available Sc values based on this empirical relationship. In turn, each of the T values was converted to hydraulic conductivity by dividing the T value of each well by the wells estimated saturated thickness or screened interval (Table D-1).

Table D.1 Summary of transmissivity and hydraulic conductivity values

TWDB Well Location	Diameter (inches)	Depth (ft)	Screen (ft)	Flowrate (gpm)	Drawdown (feet)	Time (hour)	Specific Capacity (gpm/foot)	Depth to Water (feet)	Transmissivity (ft^2/day)	Hydraulic Conductivity (feet/day)
52-25-5	6	232	100	232	2.47	24	93.93	129.15	32928.51	329.31
51-48-6	11	1100	414	1000	4.6	6	217.39	202.40	96937.79	234.16
74-14-2		220	120	278	6.7	48	41.49	18.20	11657.84	97.16
52-25-3	10	300	40	200	12	24	16.67	72.00	3721.65	93.05
52-25-3	6.625	50	23	30	3	5	10.00	13.00	1981.06	86.14
52-43-2	5.5625	345	9	46	10	24	4.60	140.00	769.86	85.55
52-35-8	6	252	20	220	28	36	7.86	119.00	1474.52	73.73
73-01	6.625	420	9	100	31	4	3.23	125.00	502.63	55.85
52-43-6	8	100	13	45	12	1	3.75		602.04	46.31
52-25-5	6	245	100	220	12	24	18.33	121.30	4189.36	41.90
52-25-3	6	90	30	85.5	14	24	6.11	68.50	1084.90	36.17
52-26-1	5.5	74	15	22	7	2.25	3.14	64.00	487.21	32.48
52-35-7	7	390	186	145	6	24	24.17	126.10	5911.69	31.79
52-43-1	8	540	12	120	50	4	2.40	86.47	353.30	29.44
52-43-2	10	219	119	155	10		15.50		3401.38	28.58
52-52-2	6	25	6	7	6	1	1.17	11.00	151.11	25.19
52-25-2	5.5	72	10	30	21	4	1.43	19.00	191.51	19.15
52-25-3	5	95	12	15	10	1	1.50	28.00	202.80	16.90
52-26-1	6	73	25	30	11	6	2.73	19.00	411.33	16.45
52-43-2	4.5	102	42	42	10	2	4.20	45.00	689.92	16.43
52-43-3	7	320	109	122			9.20	75.30	1788.46	16.41
52-35-7	6.625	162	40	120	30		4.00	84.00	650.58	16.27
52-25-6	6.625	110	35	30	10		3.00	50.00	460.87	13.17
52-43-2	4.5	350	100	165	27	2	6.11	120.00	1085.76	10.86
52-43-2	6.625	90	43	30	10	1	3.00	39.00	460.87	10.72
52-43-1	8	592	285	240	18	36	13.70	144.40	2919.53	10.24
52-25-3	6.625	91	11	15	19	12	0.79	47.00	96.01	8.73
73-04-5	8	75	20	25	20	1	1.25	25.00	163.79	8.19
52-60-8	6.625	367	18	12	15	2	0.80	23.00	97.49	5.42
52-25-2	4.5	206	50	19	10	4	1.90	154.00	267.90	5.36
52-34-3	11	400	160	225	45	2	5.00	131.70	851.42	5.32
52-43-3	6.625	180	70	20	8	1	2.50	77.00	370.86	5.30
52-43-2	4.5	300	40	40	30	2	1.33	144.00	176.63	4.42
52-25-3	6.625	72	13	20	41	4	0.49	19.00	55.21	4.25
52-33-5	5.5625	450	9	15	44	3.5	0.34	334.00	36.73	4.08

Table D.1 Summary of transmissivity and hydraulic conductivity values

TWDB Well Location	Diameter (inches)	Depth (ft)	Screen (ft)	Flowrate (gpm)	Drawdown (feet)	Time (hour)	Specific Capacity (gpm/foot)	Depth to Water (feet)	Transmissivity (ft^2/day)	Hydraulic Conductivity (feet/day)
52-43-3	6	100	36	18	17	1	1.06	36.00	134.95	3.75
52-35-7	8	345	155	96	27		3.56	143.80	564.78	3.64
52-60-4	4.5	150	40	22	20	1	1.10	46.00	141.09	3.53
52-34-7	4.5	590	120	25	10	7	2.50	445.00	370.86	3.09
52-43-6	6.625	181	150	30	10	1	3.00	30.00	460.87	3.07
52-43-3	6.625	300	216	100	27	1	3.70	120.00	593.13	2.75
52-42-8	7.625	43	24	15	27	1	0.56	16.00	64.07	2.67
52-43-3	7	160	110	20	10	1	2.00	30.00	284.64	2.59
52-25-5	6	250	100	200	116	24	1.72	117.95	238.89	2.39
52-26-1	6.625	60	23	20	42		0.48	8.00	53.71	2.34
52-25-3	6.625	118	57	90	110	3	0.82	32.00	100.05	1.76
52-26-1	6.625	55	35	20	40	12	0.50	10.00	56.79	1.62
51-14-5	6	185	40	16	30	12	0.53	113.18	61.14	1.53
52-43-6	6.625	120	60	22	30	1	0.73	33.00	88.17	1.47
52-43-5	7	102	62	15	20	1	0.75	39.00	90.48	1.46
52-44-7	4.5	100	30	20	52	2	0.38	48.00	42.12	1.40
52-60-8	7	118	68	15	20		0.75	48.00	90.48	1.33
51-24-4	4.5	805	20	6	24	2	0.25	690.00	25.89	1.29
52-17-7	4.5	365	20	25	100	2	0.25	215.00	25.89	1.29
52-44-8	4.5	480	160	15	10	3	1.50	300.00	202.80	1.27
52-44-8	4.5	200	50	32	59	2	0.54	67.00	62.33	1.25
52-43-5	8	107	54	20	35	0.5	0.57	45.00	66.17	1.23
51-48-3	10.75	655	285	300	126.75	24	2.37	261.72	347.51	1.22
51-48-6	10.75	655	285	300	126.75	24	2.37	261.72	347.51	1.22
52-43-3	8	101	36	20	52	1	0.38	38.40	42.12	1.17
52-43-3	7	152	152	20	15	1	1.33	21.00	176.63	1.16
74-39-7	6	405	80	70	100	36	0.70	200.00	83.56	1.04
52-43-2	6	120	35	15	45	1	0.33	33.00	35.81	1.02
52-43-3	6	120	35	15	45	1	0.33	33.00	35.81	1.02
52-35-8	4.5	270	30	15	52	1	0.29	175.00	30.41	1.01
52-35-9	4.5	220	40	25	68.042	4	0.37	21.70	39.99	1.00
51-31-8	4.5	150	21	8	40	1	0.20	20.00	20.16	0.96
52-52-5	8	184	144	43	40	0.5	1.08	80.00	137.36	0.95
52-25-3	5	200	88	105	150	48	0.70	10.76	83.56	0.95
52-43-2	7	150	60	20	40	1	0.50	53.00	56.79	0.95
51-48-3	10.75	655	325	250	121	24	2.07	273.50	295.80	0.91
51-48-6	10.75	655	325	250	121	24	2.07	273.50	295.80	0.91

Table D.1 Summary of transmissivity and hydraulic conductivity values

TWDB Well Location	Diameter (inches)	Depth (ft)	Screen (ft)	Flowrate (gpm)	Drawdown (feet)	Time (hour)	Specific Capacity (gpm/foot)	Depth to Water (feet)	Transmissivity (ft^2/day)	Hydraulic Conductivity (feet/day)
52-25-2	4.5	287	20	9	50	1	0.18	223.00	17.92	0.90
52-43-4	8	149	144	15	15	1	1.00	120.00	126.27	0.88
52-25-5	10	251	100	60	83	24	0.72	153.60	86.72	0.87
52-26-1	6.625	226	36	21	73	2	0.29	67.00	30.32	0.84
52-60-5	6	69	69	10	20	1	0.50	42.00	56.79	0.82
52-43-1	10	377	303	37	23.07		1.60	86.72	219.39	0.72
52-35-7	10	352	332	162	95	30	1.71	244.00	235.81	0.71
52-25-3	7	303	241	190	154	48	1.23	53.16	161.30	0.67
51-40-5	10	1100	400	650	400	12	1.63	210.00	222.80	0.56
52-43-3	8	150	90	20	45	1	0.44	59.00	49.65	0.55
52-43-3	6	160	100	35	75	0.5	0.47	45.00	52.49	0.52
52-43-5	8	172	124	22.5	40	1	0.56	43.00	64.99	0.52
52-52-2	4.5	230	80	20	60	2	0.33	40.00	35.81	0.45
52-34-2	8	541	496	180	112	288	1.61	100.00	219.92	0.44
51-31-8	4.5	130	30	8	60	1	0.13	38.00	12.83	0.43
52-26-1	6	O82	84	25	75	1.5	0.33	20.00	35.81	0.43
52-26-1	5.5	245	120	90	203	48	0.44		49.51	0.41
52-43-5	5	220	35	15	110	1	0.14	26.00	13.16	0.38
52-26-7	5	450	60	23	105	36	0.22	205.74	22.32	0.37
51-48-6	10	1120	400	450	400	24	1.13	210.00	144.83	0.36
52-26-1	5.5	245	120	90	235	48	0.38	32.00	41.92	0.35
52-35-4	16	435	305	80	97	4	0.82	129.00	100.98	0.33
52-60-2	8	100	85	10	40	1	0.25	21.00	25.89	0.30
51-56-7	7	371	63	21	125	10	0.17	225.00	16.59	0.26
52-35-7	10	435	176	80	200	11	0.40	129.00	44.04	0.25
51-48-6	18	882	642	180	151		1.19	194.50	154.95	0.24
52-43-3	5	166	76	25	136		0.18	30.00	18.34	0.24
52-60-6	6.625	140	90	20	100	1	0.20	26.00	20.16	0.22
52-35-7	10.75	850	750	112	98	24	1.14	381.00	147.52	0.20
52-26-1	6.625	111	78	12	78		0.15	26.00	15.04	0.19
52-43-5	8	200	100	18	100	1	0.18	54.00	17.92	0.18
52-43-3		241.5	173	17	59	24	0.29	35.50	30.38	0.18
52-52-2	4.5	222	60	15	139	1	0.11	50.00	10.16	0.17
52-25-5	6	270	100	13	86	5	0.15	112.78	14.75	0.15
52-44-1	4.5	350	100	15	100	2	0.15	110.00	14.63	0.15
52-43-2	4.5	240	60	9	100	4	0.09	60.00	8.32	0.14
52-43-5	8	300	35	10	182	1	0.05	118.00	4.85	0.14

Table D.1 Summary of transmissivity and hydraulic conductivity values

TWDB Well Location	Diameter (inches)	Depth (ft)	Screen (ft)	Flowrate (gpm)	Drawdown (feet)	Time (hour)	Specific Capacity (gpm/foot)	Depth to Water (feet)	Transmissivity (ft^2/day)	Hydraulic Conductivity (feet/day)
51-48-7	8	420	420	15	30		0.50	345.00	56.79	0.14
52-43-5	8	121	121	10	65	0.75	0.15	46.00	15.04	0.12
73-01-4	6	452	336	30	85		0.35	78.00	38.21	0.11
52-35-7	10	798	715	103	159		0.65	316.00	76.43	0.11
51-15-9	4.5	525	40	6	192	1	0.03	315.00	2.63	0.07
73-01-4	6	405	295	20	110		0.18	56.00	18.12	0.06
52-26-8	6	215	92	10	185	24	0.05	16.00	4.76	0.05
52-43-5	8	151	91	5	100	0.5	0.05	43.00	4.38	0.05
52-44-9	4.5	500	60	10	300	3	0.03	15.00	2.82	0.05
52-35-8	7	500	375	10	70	1	0.14	240.00	13.86	0.04
51-44-5	5	643	343	5	82	5	0.06	543.00	5.43	0.02
52-43-2	6	320	320	8	144	1.5	0.06	56.00	4.91	0.02
52-35-5	4.5	521	330	8	240	3	0.03	160.00	2.82	0.01
52-52-2	8	400	389	5	215	1	0.02	135.00	1.92	0.00
73-04-5	6	200	160	1.5	160	1	0.01	35.00	0.73	0.00
52-52-2	6.625	400	351	6	360	2	0.02	90.00	1.34	0.00
51-53-7	7	800	790	7	330	12	0.02	110.00	1.74	0.00
51-31-3	5	460	460	4	420	1	0.01	87.00	0.74	0.00
51-31-3	5	465	465	2.5	410	1	0.01	40.00	0.46	0.00

APPENDIX E

RESPONSE TO TWDB AND STAKEHOLDER COMMENTS

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Appendix E

Response To TWDB And Stakeholder Comments

During the IBGAM development, there were two opportunities for the TWDB and stakeholders to comment in writing regarding the model. The first opportunity was after the completion of the conceptual model report and the second was after the completion of the draft final report. This appendix contains responses to all the comments received from both of those comment periods.

1.0 RESPONSE TO CONCEPTUAL MODEL COMMENTS

1.1 TWDB Comments

Comment: Figure 2.1.12/page 2-16: Legend lists "creosote-mesquite" twice, please clarify or combine.

Response: *Legend has been refined.*

Comment: Figure 2.1.19/page 2-13:RFQ Attachment 1 (page 16) states average precipitation should be based on data from 1960 to present. Please clarify if this approach was used.

Response: *Data from 1960 to 2000 was used.*

Comment: Per RFQ Attachment 1 (page 16), Several plots of historical precipitation measured at rain gages in the study area shall be included. Please update the report with this information.

Response: *Figure 2.3.3 contains plots for several weather stations.*

Comment: Figure 4.1.1/page 4-2: Please correct spelling of "Cheryy Canyon Formation" to "Cherry Canyon Formation".

Response: *Corrected as requested.*

Comment: Per RFQ Attachment 1, Section 5.4, minimum requirements for figures states that drafted figures shall include a north arrow and scale. Please update the following figures with this information: Figure 4.1.2 (pg 4-4), Figure 4.1.3 (pg 4-5), Figure 4.1.4 (pg 4-6), Figure 4.1.5 (pg 4-7), Figure 4.1.6 (pg 4-8), Figure 4.1.8 (pg 4-10), Figure 4.1.9 (pg 4-13), Figure 4.1.10 (pg 4-14), Figure 4.3.1 (pg 4-19), Figure 4.3.2 (pg 4-21), Figure 4.3.3 (pg 4-22), Figure 4.3.4 (pg 4-23), Figure 4.4.1.(pg 4-32), and Figure 4.4.6 (pg 4-39).

Response: *Corrected as requested.*

Comment: Figure 4.1.6/page 4-8: Please clarify and confirm direction of arrows showing relative movement on faults.

Response: *Cross-sections have been updated.*

Comment: Figures 4.1.7 and 4.1.9/ pages 4-9 and 4-13: Per RFQ Attachment 1 (page 17) states maps of layer thickness for each of the model layers including control points shall be included. Please update Figures 4.1.7 and 4.1.9 with control points used.

Response: *Control points have been added.*

Comment: Figures 4.1.8 and 4.1.10/pages 4-10 and 4-14: Per RFQ Attachment 1 (page 17) states maps of bottom elevations for each of the model layers including control points shall be included. Please update Figures 4.1.8 and 4.1.10 with control points used.

Response: *Control points have been added.*

Comment: Figures 4.3.1, 4.3.2, 4.3.3, 4.3.4/ pages 4-19, 4-22, 4-23: Salt Bolson modeling area color scheme does not appear in legend. Please update legend explaining the color scheme used.

Response: *Figures have been updated.*

Comment: Section 4.5/pages 4-40 to 4-47: Per RFQ Attachment 1, Section 3.1.6 states that where appropriate conceptual and numerical models must include the concept and effect of 'rejected recharge'. Please research and clarify if this occurs in the study area. If applicable, please include a discussion of 'rejected recharge' in this section.

Response: *Discussion of rejected recharge has been added.*

Comment : Section 4.4/page 4-30, Figure 4.3.10. Reference is incorrect. Include Mace (2001) along with Sharp (2001).

Response : *Reference is correct. No change.*

Comment: Section 4.6/pages 4-48 to 4-52. T and P Railroad Lake is a major source of surface water for City of Balmorhea. Located downstream from Aguja Spring in Jeff Davis County (see White, W.N., Gale, H.S., and Nye, S.S., 1941. Geology and ground-water resources of the Balmorhea area, western Texas: U.S.

Geological Survey Water-Supply Paper 949-C, p. 83-146 for stream gain-loss study).

Response: *Study was reviewed and section was expanded.*

Comment: Figure 4.6.1/page 4-49: Per RFQ Attachment 1 (page 17) states the report will include a figure with representative stream-flow hydrographs for the major streams in the study area with a map indicating gage locations. Please update with map indicating gage locations.

Response: *Figure has been added.*

Comment: Table 4.4/page 4-52: Comparison between average measured streamflow and calculated annual runoff appear reasonable for Upper Alpine and Madera Canyon, however Limpia Creek average measured streamflow lists 3,692 acft/yr compared to 9,500 acft/yr for the calculated annual runoff. This appears as an anomaly.

Response: *The calculated value is a based on the methodology selected for the study, which is only an estimate.*

Comment: Section 4.7/pages 4-52 to 4-55: Per RFQ Attachment 1 (page 17) report shall include bar chart of yearly total historical and predicted groundwater usage. Please update this section with a bar chart showing historical and predictive pumpage for the study area.

Response: *Figures have been added.*

Comment: Section 4.7/pages 4-52 to 4-55: Per RFQ Attachment 1 (page 17), report shall include a map of rural population density. Please update the report with this map.

Response: *Figure has been added.*

Comment: Missing the following references in this section: Woodward, 1954 (page 4-11); Wightman, 1953 (page 4-11); Henry, 1998 (page 4-17); Nichols, 2000 (pages 4-40 and 4-44); Stone et al, 2000 (page 4-40); White et al, 1941 (pages 4-48 and 4-50); LaFave and Sharp, 1986 (page 4-48); Sharp, 2000 (page 4-48); Gillett and Janca , 1965 (page 4-53); Theis, 1963 (page B-1); Razack and Huntley, 1991 (page B-1); Mace, 2001 (page B-1 and B-2); Huntley, Nommensen, and Steffey, 1992 (page B-1); Custer and Dixon, 2002 (page B-1); Mott and MacDonald (page B-2)

Response: *References have been added.*

Comment: Introduction/page B-1: Third paragraph states TWDB central records data sets do not have specific latitude and longitude values. Please clarify if this is referencing TCEQ instead of TWDB and update accordingly.

Response: *Corrected as suggested.*

Comment: Introduction/page B-1: Please clarify last sentence, " Four methods were evaluated and used to calculate the respective T value using its specific calculation [capacity?].

Response: *Clarified and corrected.*

Comment: Introduction/page B-2: Missing figure B2 referenced in first paragraph on page B-2. Please update report with this figure.

Response: *Corrected as suggested.*

Comment: Delineating Sub-basins/page C-1: Missing figure C-1 referenced in first sentence. Please update report with this figure.

Response: *Figure has been added.*

Comment: Delineating Sub-basins/page C-1: Please provide reference for "JSAI".

Response: *Reference corrected.*

Comment: Irrigated Agriculture/page D-3: An alternative method for determining irrigation pre-1974 is to review TWDB report 347 (http://www.twdb.state.tx.us/publications/reports/GroundWaterReports/GWReports/R347.pdf) which lists acre feet of groundwater for agricultural use with estimates for 1958, 1964, and 1969.

Response: *Report 347 was used in the calculation.*

Comment: Section 2.0/page 2-4: Please reword sentence in third paragraph," Each district covers in a single county".

Response: *Correct as requested.*

Comment: Section 4.1.1.2/page 4-11: Please reword second paragraph, fifth sentence, from "Theses often include vesicular zones…" to "These often include vesicular zones…".

Response: *Corrected as requested.*

Comment: Section 4.6/page 4-52: Please reword last sentence from, “This finding is consistent with the observations from other areas where mountain streams collect water from springs that issue at higher elevations and than loose…” to “, “This finding is consistent with the observations from other areas where mountain streams collect water from springs that issue at higher elevations and then lose…

Response: *Corrected as requested.*

Comment: Section 4.7.1/page 4-53: Please restructure first sentence from “ …Davis County include Gillett and Janca (1965) (as cited in TWDB Report 16, 1966),…” to “ …Davis County include Gillett and Janca (1965, as cited in TWDB Report 16, 1966),…”. Please restructure same reference in first full paragraph on the same page.

Response: *Sentence reorganized.*

Comment: All figures in this section are very pixelated, and therefore difficult to interpret. Please review these figures and adjust the image quality accordingly.

Response: *All figures have been updated.*

Comment: Figures C2 and C3/pages C-4 and C-5: X-axis truncated, please adjust elevations so they appear on page.

Response: *All figures have been updated.*

Comment: Readme files and files that list the contents of each folder are missing

Response: *Readme files have been included.*

Comment: Are the "holes" in census1990_modgrd.shp and census2000_modgrd.shp real?

Response: *The census1990_modgrd.shp and census2000_modgrd.shp files represent the population distribution that was used for rural domestic pumping. Therefore, the cities have been clipped out since the municipal data is distributed throughout the cities. This is described in the metadata file.*

Comment: There is no population data in census2000_modgrd.shp. Where did the data in census2000_modgrd.shp come from?

Response: *Shapefiles have been checked and updated.*

Comment: City boundaries <u>may</u> change 1990-2000, so it may be a good idea to use TIGER data rather than the TNRIS shapefiles.

Response: *TIGER coverages were consulted.*

Comment: Is monthly evaporation data available?

Response: *Yes.*

Comment: It is not clear what the 1950_complete_gam.shp, 1980_complete_gam.shp, 1990_complete_gam.shp, and 2000_complete_gam.shp files are?

Response: *Metadata is now included to describe all files.*

Comment: The recharge.shp file does not contain any recharge data in the attributes table.

Response: *File has been updated.*

Comment: In regards to the gain_loss.shp file,

a) who conducted the study, and

b) there is no streamflow data in the attribute table.

Response: *Metadata and shapefile have been updated.*

1.2 Stakeholder Comments

<u>Comments from Stakeholder #1</u>

Comment: I have studied the Interim IBGAM Report on the Website. I am concerned about using recharge for Pecos (Davis Mountains) area of 0.35 in/yr. I agree that Potential recharge coefficient of 0.000 for 12" per year of rain is prudent. I do not believe 0.35 for 16" rain has sufficient data to justify it, particularly in the Davis Mountains where the porosity is in the fractures in the bedrock. This gives a huge recharge of 32,708 ac-ft/yr, versus usage for Fort Davis of about 240 ac-ft/yr.

Response: *Comment acknowledged. Some recharge is lost to evapotranspiration, streams, and springs.*

Comment: In the salt flat bolson area the porosity is about 15% versus to 4% in the fractures in the igneous bedrock in the Davis Mountains. The permeabilities are probably the same order of magnitude greater in the salt flat bolson, also. This would result in less recharge in the mountains in the rhyolite.

Response: *Comment acknowledged. Porosity is only one of many factors that affect recharge.*

Comment: Dan B. Stone, 2001 believes that there is very little recharge in bedrock with fracture porosity.

Response: *Comment acknowledged.*

Comment: There needs to be evaluation of recharge by measuring Tritium (3H), 36CL/36 ratio, and Carbon 14 as stated by Bridget R. Scanlon in "Evaluation of Groundwater Recharge in Basins in Trans-Pecos Texas" before stating that such a large volume of recharge occurs.

Response: *Age dating of the groundwater would be beneficial for gaining a better understanding of recharge processes.*

Comment: I think that to state such a large volume of recharge without sufficient proof is to possibly give false confidence of the water availability to the residents' of the Davis Mountains. A larger volume could be included later after farther testing is done.

Response: *Some recharge is lost to evapotranspiration, streams, and springs, and therefore is not available for municipal or other uses.*

Comment: The original location of Fort Davis was predicated upon that of the spring. The spring stopped flowing in the 1930's. This was possibly because of pumping in the town of about 240 ac-ft per year, and/or lack of recharge. The residents of Fort Davis are vitally concerned about the recharge of the Davis Mountain aquifer. Could you please address this specifically in the current study?

Response: *The IBGAM is a regional study and model. While the model can be used to look at groundwater availability in the general area, it would not be appropriate to use the model to determine specific availability for Fort Davis. Recharge and groundwater availability for municipal use in Fort Davis is determined by local factors that could not be accounted for in detail in the IBGAM.*

Comments from Stakeholder #2

Comment: *Page 2-1, Second Paragraph, Last Sentence*: "In addition, these bolson aquifers provide irrigation water for several agricultural areas in the flats and are the sole source of water for all other water users where the aquifers exist." This sentence needs to be reconsidered in light of the several wells that are completed in both the bolson and the underlying igneous aquifer.

Response: *Sentenced modified to: In addition, the four sub-basins provide irrigation water for agricultural areas in the flats and are the primary source of water supply for all other water users where the aquifer exists.*

Comment: *Page 2-4, Third Paragraph:* Jeff Davis County UWCD includes all of Jeff Davis County and small parts of Presidio and Brewster County. Culberson County GCD does not include the entire county.

Response: *Sentenced modified to: There are four groundwater conservation districts in the study area, as shown in Figure 2.1.5, with each district covering all or part of a single county.*

Comment: *Page 2-11, First Full Paragraph and Figure 2-19:* Please include a table or some other summary that summarizes the period of record for each station.

Response: *Table not included. All data from 1960 to 2000.*

Comment: *Page 4-11, First Paragraph:* Please explain the reasoning for inclusion of the volcaniclastic units as part of the bolson (i.e. similarity of hydraulic conductivity, the fact that is unconsolidated like the bolson deposits, etc.).

Response: *Change made in Section 4.1.*

Comment: *Page 4-15, Section 4.1.2:* I agree with the proposed layering. However, it is unclear whether there will be further subdivision of each layer through zonation of various areas based on specific capacity data, water level response, or geologic data.

Response: *Further subdivision will not occur.*

Comment: *Page 4-20 and Water level maps:* These maps need some more explanation:

- In the 1950 (pre-development) map, there are several areas with no data points, especially in mountain areas of Jeff Davis County. It appears that some of the data from 2000 were used to more-or-less anchor some of the pre-development water levels. If so, it should be stated.
- There appears to be a significant drop (almost 1000 ft) between 1950 and 1980 in some areas of northern Jeff Davis County where no data exist. This needs to be explained.
- The term "interpretive method" is not explained.

Response: *Further explanation is provided in Sections 4.1.3 and 4.2.3 as well as Appendix A. The 2000 data was used to anchor some of the pre-1950 data points within the model. Appendix A goes into more detail regarding the development of all the* *water level data used in the figures. The apparent drop in water levels observed between 1950 and 1980 is really just due to differences in the methods of contouring the data. The water levels maps were used only to help illustrate estimated water levels and general flow directions and were not used only as a guide in developing boundary and initial conditions for the model.*

Comment: *Figures 4.3.5 to 4.3.9:* The hydrographs need to have consistent x-axes. Ideally, the y-axes should also be the same.

Response: *Hydrographs have consistent x-axes and where appropriate, the same y-axes.*

Comment: *Figure 4-29, Section 4.4.1:* Hydraulic conductivity needs to be defined for the lay reader, not just as a "necessary parameter for groundwater models". Also, the "extreme variation" needs to be dealt with through zonation or some other method that should be described in this section.

Response: *Hydraulic conductivity has been defined as: Hydraulic conductivity refers to the ability of a porous media (geologic formation) to transmit water and has units of length per time (e.g., feet/day). Discussion of zonation is provided in Chapter 8.*

Comment: *Page 4-31, Section 4.4.1.1:* Section 4.4.1 is entitled "Hydraulic Conductivity", yet the discussion here is on transmissivity. The term should be defined at a minimum, or better yet, make the discussion more internally consistent.

Response: *Discussion has been modified.*

Comment: *Page 4-34, Second full paragraph:* Conceptualizing the upper portion of the igneous aquifer with a higher hydraulic conductivity than the lower is troublesome given the proposed layering. This could lead one to conclude it may be better to have two igneous aquifer layers to account for this observation. On the other hand, there is no discussion of lateral changes that would result in zonation.

Response: *Based on drilling logs, there is evidence of layering in the Igneous aquifer. However, for the purposes of this study and the objectives of the model, it is appropriate to conceptualize the Igneous as one layer, especially given the lack of characterization and hydraulic conductivity estimates in the individual layers.*

Comment: *Page 4-37, last sentence:* Unfortunately, our offices are being remodeled and I do not have ready access to Finch and Armour (2001). It is my recollection, however, that this model was not calibrated, but was more of a interpretive model.

Response: *The model was transiently calibrated.*

Comment: *Page 4-40, second paragraph in Section 4.5:* This is a good opportunity to discuss the differences in a lumped parameter vs. distributed parameter modeling approach, and how the estimates have evolved over time.

Response: *Discussion has been modified.*

Comment: *Page 4-44, middle of first paragraph:* How were the coefficients modified? This needs more explanation.

Response: *Appendix B contains detailed explanation of recharge methodology and results. The potential recharge coefficients from Nichols (2000) were based on the following slope formula*

*potential recharge coefficient = 0.00874 * pptn (in/yr) – 0.105*

where,

potential recharge coefficient (y intercept)

slope (m) = 0.00874

pptn (x-intercept) = 8.8 (in/yr) for a corresponding y-intercept of 0.0

The formula was modified by adjusting the y-intercept of zero for a corresponding value of 12 inches/yr (x-intercept) to represent no direct recharge to the lower elevations (bolson). The slope remained the same. This discussion will be added to Appendix B.

Comment: *Page 4-44, Table 4.1:* Is the coefficient dependent on rock type, or just precipitation? The table shows a summary of potential recharge, yet the discussion is on "total recharge". This discussion needs some editing to make the points clear.

Response: *The coefficient is not dependent on rock type, just climatic factors (precipitation, temperature, evaporation, etc). Appendix B contains detailed explanation of recharge methodology and results.*

Comment: *Page 4-47, text in between tables:* "The runoff-redistribution method appears to be an appropriate method for the IBGAM because it considers the runoff characteristics of each sub-basin and the variable precipitation received by each sub-basin" (emphasis added). I agree that runoff redistribution is an appropriate method. However, this statement proclaiming it be appropriate does not answer basic questions of how this method will be used in the model: Is it the general method that is appropriate, or the specific numbers that were used? If it is the general method, and some of the parameters are to be adjusted during calibration, then some sort of reasonable bounds should be discussed. If the specific numbers are considered appropriate, then it needs to be stated that no further adjustments will be made during model calibration.

Response: *This was discussed in more detail Section 4.1.4. Appendix B contains detailed explanation of recharge methodology.*

Comment: *Page 4-50, first full paragraph:* Are the springs "suspected" due to the geologic setting? Also, the difference between springs and baseflow needs to be better developed.

Response: *Section has been rewritten.*

Comment: *Page 4-50, last paragraph and Table 4.4:* It appears that 2 of the 3 flows are close, yet the text claims "good correlation". This needs to be better qualified.

Response: *Full discussion of the results is provided in Appendix B. The calculated value is a based on the methodology selected for the study, which is only an estimate.*

Comment: *Page 4-52, Section 4.7.1:* What is the basis for the statement that 86% of the pumping is for irrigation?

Response: *Statement has been clarified as follows: "Pumping for irrigated agriculture accounts for approximately 81 percent of the total groundwater withdrawal within the study area between 1980 and 2000."*

Comment: *Page 4-53, second full paragraph:* The maps and graphs do not coincide with the statement that areas of irrigation have been constant since 1980.

Response: *Text has been modified.*

Comment: *Page 5-1, second full paragraph:* This definition of a conceptual model is too limiting. Consider this as an alternative: The conceptual model of groundwater flow in the aquifer represents the foundation of the numerical model. The conceptual model describes the domain of the flow system, groundwater occurrence, groundwater movement, the inflow components and the outflow components. As part of the conceptual model development, areas of uncertainty and limitations are identified and discussed in the context of model calibration.

Response: *Conceptual model text has been modified and expanded.*

Comment: *Page 5-1 (bottom) and page 5-3 (top):* If I understand this discussion, 65% of the total recharge to the study area is direct recharge to the Igneous, Cretaceous and Permian aquifers, and 35% if the total recharge to the study area is infiltration of runoff in the bolson aquifer. If that is the starting point, it needs to be stated more clearly since there is some confusion as to the recharge to the bolson aquifer based on newspaper articles and the most recent update to the Jeff Davis County UWCD management plan.

Response: *Chapter 5 has been modified and expanded. The final report contains estimated locations of recharge to the bolsons from stormwater runoff. Appendix B contains detailed explanation of recharge methodology and results.*

Comment: *Page 5-3, second full paragraph:* The use of the word "anomaly" is odd. Regional models deal with regional flow systems and do not deal well with local flow conditions. Any model is objective based (e.g. regional flow or local transport as extremes), and to cast a shadow on the effort by discussing the limitations of computer technology is excessively negative.

Response: *Discussion has been modified and moved to Chapter 11.*

<u>Comments from Stakeholder #3</u>

Comment: Both this report and the igneous aquifers section of "Aquifers of West Texas" state that the igneous aquifers are not a single aquifer and that the aquifers are poorly connected. In fact, many of the aquifers are probably not connected at all. Treating the "Igneous Aquifer" as a single layer does not seem practical, and will almost surely result in groundwater availability numbers which are unreliable and of no practical value. I suspect that this approach is being taken because the Water Development Board wants the same data reported from every aquifer for consistency. The intent may be laudable but the quality of the results will be very inconsistent. Perhaps the most serious consequence of the current investigation is that it takes resources that could better be utilized in studying and improving our understanding of the geology of the igneous aquifers. There are over 50 oil-test wells in Presidio and Jeff Davis counties and several more in western Brewster county that have penetrated the entire volcanic section. It appears that no effort has been made to acquire information on these wells from the oil companies. Drill cuttings are probably still available on most of the wells, and many of them have been logged and the well logs available commercially; also, several oil companies have proprietary well logs which might be made available, especially the volcanic section. Geophysical logs ("electric logs") are available on most of the wells. Drilling records will contain information on water occurrences while drilling. Shallow seismic data may be available for groundwater studies and would help in locating fault zones. Much of this information may be already lost, and what remains is in imminent danger of being thrown out.

Response: *We agree that more fundamental geologic and geophysical research is needed in the area.*

Comment: The Davis report on the Marfa area is listed in the list of references but the similar report by Littleton & Audsley on the Alpine area is not (also the 1950 report by McAnulty might be included)

Response: *References have been updated.*

Comment: A map showing the location of the wells used in Appendix B would be helpful; from the well numbers it appears that most of the wells are in the same general vicinity— probably around Alpine and Marfa

Response: *Cross-sections have been modified.*

Comment: Chinati is misspelled (Chinate) on Figure 2.1.3

Response: *Spelling has been corrected.*

2.0 RESPONSE TO DRAFT FINAL REPORT

2.1 TWDB Comments

Comment: In your final report please include the review comments from the conceptual draft review with your responses, as well as your responses to the comments listed below.

Response: *Both sets of comments are included herein.*

Comment: Exhibit B, Attachment 1, Section 5.4, last paragraph states each report shall have an authorship list of persons responsible for the studies: firm or agency names as authors will not be acceptable. Please provide this information with the final report. In addition, with the new rules concerning geoscientists operating in the State of Texas working on state-related projects, please have the appropriate person or persons seal the final report using the guidance provided by the Texas Board of Professional Geoscientists (www.tbpg.state.tx.us).

Response: *Final report contains author list and seals.*

Comment: Include a cover page with an authorship list and contract title and number.

Response: *Cover page included.*

Comment: Replace all references to the "Bolson" aquifer with "Salt Basin Bolson" aquifer for consistency.

Response: *All references have been changed.*

Comment: Page 2-5, paragraph 1, line 8, "newly designated boundary" needs to be changed. TWDB has not changed the boundary of the Igneous aquifer yet. You may include a personal communication from Robert Mace that TWDB plans to expand limits of the Igneous aquifer boundary.

Response: *Changed to "igneous areas within the model boundary."*

Comment: Page 2-15, Figure 2.3.2, the grid numbers are not consistent with TWDB online evaporation/precipitation data.

Review http://hyper20.twdb.state.tx.us/Evaporation/evap.html and correct the grid numbers accordingly. A spot check of the evaporation data listed in Figure 2.3.2 reveals the data in the grid marked 45 is listed as '32.24 in/yr' it should be '64.05 in/yr'. The data in the grid marked 58 should is listed as being '54.67 in/yr, it should be '54.42 in/yr'. Please review all evaporation data in Figure 2.3.2 and ensure it is correct.

Response: *Data reviewed and corrected.*

Comment: Page 2-17, please include a discussion of ET in section 2.4

Response: *Paragraph on ET added to Section 2.4.*

Comment: Page 3-3, Table 3- please clarify what "super position" means in this context.

Response: *The model was calibrated to historical transient pumping and observed drawdown.*

Comment: Page 4-2, provide a correct reference for Table 4.1.

Response: *References corrected on Table 4-1.*

Comment: Page 4-7, Figure 4.1.3 is referenced incorrectly. It should be (BEG, 1979; Henry, 1979).

Response: *Reference corrected on Figure 4.1.3.*

Comment: Page 4-8 and 4-48, Section 4.1.3 and 4.2.3, include a discussion on water level differences between each layer, vertical connection between layers and features that affect flow.

Response: *Discussion on water levels has been expanded.*

Comment: Page 4-27, Section 4.1.5, discuss the absence/presence of stream gauges and the conductance of streambed.

Response: *Discussion has been expanded.*

Comment: Page 4-28, Section 4.1.6, K should be reported in as the geometric mean, not the average.

Response: *Reported hydraulic conductivity is the geometric mean.*

Comment: Page 4-29, Figure 4.1.16, Are the hydraulic conductivity values really average or are they actual values?

Response: *Actual, figure has been modified.*

Comment: Page 4-31, paragraph 3, line 9, the specific yield for fractured rocks is reported at 0.05, this seems very high.

Response: *This discussion is reporting the values used in Finch and Armour (2001) and is not intended to imply that these values are representative. The discussion has been reworded and expanded to include a range of potential specific yield values from 0.0001 to 0.05.*

Comment: Page 4-31, paragraph 3, remove the last sentence.

Response: *Last sentence removed.*

Comment: Section 4.1.6 Hydraulic Properties does not include a discussion about anisotropy or vertical K. Please add this material to this section.

Response: *Section has been expanded.*

Comment: Section 4.1.7, does not include any discussion of discharge to streams, springs or lakes. Please correct this.

Response: *Paragraph on natural discharge added to Section 4.1.7.*

Comment: Page 4-55, Figure 4.2.7, Are the Hydraulic Conductivity values really average or are they actual values?

Response: *Actual, figure has been modified.*

Comment: Page 4-54, Section 4.2.6, Change all units to ft^2/d.

Response: *Change completed.*

Comment: Include a figure that shows the conceptual model relative to the formations and their normal association (Example: see Report 353, page 69, Figure 50).

Response: *Figure 5.1 revised.*

Comment: Page 6-2, paragraph 4, further develop the discussion on the orientation of the model grid. Explain why the current orientation was chosen.

Response: *Discussion expanded.*

Comment: Page 6-11, paragraph 2, line 2, add the word “values” after “high”.

Response: *The word "values" was added.*

Comment: Equation 7.2 is missing. It needs to be included in the final report.

Response: *Equation has been included.*

Comment: Section 8.2.3 needs to be expanded to include a discussion about how the water budget compares to the conceptual model and the hydrogeologic setting.

Response: *Section expanded.*

Comment: Page 9-10, Section 9.1.2, specific yield values in this section do not agree with values in the conceptual model. Please review and correct as necessary.

Response: *Changes in the conceptual model discussion of specific yield provide a wider range of values and therefore, better agreement.*

Comment: Page 10-1, change the first paragraph to read, “The IBGAM was used to model the change in water levels and fluxes in the aquifer over a 50 year planning period (2001-2050) using state-approved water demand projections under average and drought-of-record (DOR) conditions. This section details the results of the predictive simulations.”

Response: *First paragraph changed.*

Comment: Page 10-4, Figure 10.1.1, resize the figure to fit the page or extend it over multiple pages. Explain the missing years in the figure.

Response: *Figure has been resized and discussion expanded.*

Comment: Figures for layer 3 (Simulated Water Levels, Saturated Thickness, and Water Level Declines), for 2010, 2020, 2030 and 2040 need to be included.

Response: *Figures have been added.*

Comment: Figure 10.2.22, water level contour marked “3500” should be “3750”

Response: *Contour has been relabeled.*

Comment: Page 11-1, paragraph 1, line 1, remove “actual” from this sentence.

Response: *"actual" has been removed from sentence.*

Comment: Page 11-3, paragraph 2, last line, this sentence is not clear. Please rewrite it so that the reader understands your communication.

Response: *Sentence has been rewritten.*

Comment: Page 13-1, paragraph 3, line 1.change “provide predictions of groundwater availability” to provide predictions of groundwater levels” or “assess groundwater availability” or “evaluate groundwater availability” Remember, groundwater availability is defined by GCDs, RWPGs, or local entities other than the TWDB.

Response: *Sentence has been reworded.*

Comment: The BEG GAT sheets are referenced incorrectly. Reference each sheet separately. Example:

Brown, L. F., Jr., Goodson, J. L., Harwood, P., and Barnes, V. E., 1972, Abilene sheet: The University of Texas at Austin, Bureau of Economic Geology, scale 1:250,000.

Response: *References revised in Section 15.*

Comment: Page 15-11, include all university theses in the reference section.

Response: *Reference section has been reorganized.*

Comment: Page 15-13, include all unpublished reports in the reference section. Reference to them as unpublished reports.

Response: *Reference section has been reorganized.*

Comment: The Appendices should stand alone in their content. Include a reference page at the end of each Appendix that has references in the text.

Response: *References added where appropriate.*

Comment: Include a reference section in Appendix A.

Response: *References added to Appendix A and all appendices.*

Comment: Page B-1, paragraph 3, line 1, there is no reference listed for (Theis, 1963, Racazk and Huntley, 1991, Mace 2001). Do not italicize the callouts. You have a reference for Mace, 2001 in the reference section, but I question if it is correct.

Response: *Appendix has been rewritten. It is now Appendix D of the report.*

Comment: Page B-1, bottom of page, the reference list 2, 3 and 4 are not in the reference section. Please add them.

Response: *Appendix has been rewritten. It is now Appendix D of the report.*

Comment: Appendix D: Include a discussion about Strategy 71-6A and distribution of pumpage between Jeff Davis and Presidio counties.

Response: *Paragraph discussing Strategy 71-6A predictive pumpage is added to "Predictive Calculations" section in Appendix B and the letter from the Region E Water Planning Group clarifying the location of the wellfield is also included.*

Comment: Change the title of the report to 'Groundwater Availability Model for the Igneous and parts of the West Texas Bolsons (Wildhorse Flat, Michigan Flat, Ryan Flat and Lobo Flat) aquifers'. This change should be reflected throughout the report.

Response: *Title has been changed.*

Comment: Change all figure pages to include a page number.

Response: *All figure pages include a page number.*

Comment: Left justify all figure and table captions.

Response: *Change has been made.*

Comment: Change font style on all figure captions to be the same as the text font style.

Response: *Change has been made.*

Comment: Change all "et al" "to and others".

Response: *"et al" changed to "and others".*

Comment: Use a 1” margin top, bottom and sides of all pages and insure that the figure and the figure caption remain inside the margins.

Response: *Change has been made.*

Comment: Change title (see *General* section above).

Response: *Title has been changed.*

Comment: In the List of Figures, add a tab to align the figure title text.

Response: *Change has been made.*

Comment: Page iii, Figure 2.1.3, “Location f the”, correct to read “Location of the”.

Response: *Correction has been made.*

Comment: There is no abstract, please add one.

Response: *Abstract has been added.*

Comment: Page 1-1, Paragraph 2, first line “IBGAM”. Change to ‘Igneous Bolsons Groundwater Availability Model (IBGAM)’.

Response: *Change has been made.*

Comment: Page 1-2, Top paragraph, line 2 and 3, remove ‘chemical quality’.

Response: *"chemical quality" has been removed.*

Comment: Page 1-2, Top paragraph, line 3, change ‘designated’ to ‘referred to’.

Response: *Change has been made.*

Comment: Page 2-1, paragraph 1, line 3, change “is commonly referred to as the” to ‘is part of the’.

Response: *Change has been made.*

Comment: Page 2-1, paragraph 2, line 7, change ‘designated’ to ‘referred to’.

Response: *Change has been made.*

Comment: Page 2-3, either add all aquifers in the Trans-Pecos region or remove all but the Igneous and West Texas Bolsons Aquifer and change the caption to reflect "selected aquifers".

Response: *Figure 2.1.2 title changed to reflect aquifers of interest in the modeling project.*

Comment: Page 2-14, Figure 2.3.1, Change "Balmorea" to "Balmorhea".

Response: *Change has been made.*

Comment: Page 2.15, Figure 2.3.2, Change 'evaopration' in the Source for the figure to 'evaporation'.

Response: *Change has been made.*

Comment: Page 2.22, paragraph 2, line 2, remove parenthesis from "(Figure 2.5.2)".

Response: *Parentheses have been removed.*

Comment: Page 2-23, Figure 2.5.1, change "Geoligic" to "Geologic" in the Explanation.

Response: *Change has been made.*

Comment: Page 2-25, Figure 2.5.4 change "et all" in the second reference to "et al".

Response: *Change has been made.*

Comment: Page 3-1, Paragraph 3, line 3, "LBG Guyton (2001)". Use the authors name in place of the company name.

Response: *Reference changed to Ashworth and others (2001). Also changed in Reference Section.*

Comment: Page 4-2, the table caption should be in the same font style as the text in the report.

Response: *Change has been made.*

Comment: Page 4-7, Figure 4.1.3, change "Victorio Flexture" to "Victorio Flexure".

Response: *Change has been made.*

Comment: Page 4-9, there is a format bust. Reformat the document so that 4-9 is a full page of text or figure and does not have just two sentences at the top.

Response: *The report has been formatted to avoid excess blank space.*

Comment: Page 4-16, Figure 4.1.9, in the caption, "Michgan" should be "Michigan".

Response: *Change has been made.*

Comment: Page 4-19, Figure 4.1.12 in the Explanation, change "Salt Basin Bolson Aquifer" to "West Texas Bolson Aquifer", and "Captian Reef" should be "Capitan Reef".

Response: *Change has been made.*

Comment: Page 4-20, paragraph 1, line 3, change "onto" to "into".

Response: *Change made as requested.*

Comment: Page 4-20, paragraph 3, line one, there is a problem with Appendix C call out. See Draft Report Appendices in this document.

Response: *Appendices have been reorganized.*

Comment: Page 4-23, bad break, please fix it.

Response: *Bad breaks have been fixed to the degree possible.*

Comment: Page 2-25, Figure 4.1.15, change "Vaules" to "Values".

Response: *Change has been made.*

Comment: Page 4-26, paragraph 1, line 5, "(Gates et al, 1978)" should be "(Gates and others, 1978)".

Response: *Change made to text.*

Comment: Page 4-26, Table 4.4, change "(Gates and others (1978)" to "(Gates and others, 1978)".

Response: *Change made to Table 4.4.*

Comment: Page 4-33, Figure 4.1.18, change "derrived" to "derived".

Response: *Change has been made.*

Comment: Page 4-37, 4-38, Figures 4.1.22, 4.1.23, change "Withdrawls" to "Withdrawals" in the caption.

Response: *Change has been made.*

Comment: Page 4-54, paragraph 1, last sentence, change "loose" to "lose".

Response: *Change made to text.*

Comment: Page 4-58, change "storativivty" to "storativity".

Response: *Change made to text.*

Comment: Page 6-1, paragraph 3, line 1, remove "(to the extent possible)".

Response: *Change made to text.*

Comment: Page 6-4, bad break.

Response: *Bad breaks have been fixed to the degree possible.*

Comment: The pagination for Section 9 is incorrect. The first page of the section starts as 9-8. Renumber this section correctly.

Response: *Section numbered correctly.*

Comment: Page 9-3, Paragraph 1, first sentence, add the word "to" between "selected evaluate".

Response: *Change made to text.*

Comment: Page 13-2, Paragraph 3, first sentence, add "a" between "is valuable".

Response: *Change made to text.*

Comment: The Appendices should be presented in the order they are called out. The first call out for an Appendix is on page 4-20, but the call out is for Appendix C. It should be for Appendix A. Please reorder the Appendices appropriately.

Response: *Change has been made.*

Comment: The page numbering in the Appendices is not consistent. Since the appendices are part of the report, all the pages in the appendices should be numbered including the title page.

Response: *Appendices will have Table of Contents, List of Figures and Tables, and page numbers.*

Comment: Make all the appendices consistent; if there are figures in the appendix, then add a figure list and make sure that the page number the figure shows up on is listed also. Same for tables.

Response: *Appendices will have Table of Contents, List of Figures and Tables, and page numbers.*

Comment: The model runs and reproduces water level maps in the report for steady-state calibrations. [requested action=none]

Response: *No action taken.*

Comment: The model runs and reproduces water level maps in the report for transient calibrations. [requested action=none]

Response: *No action taken.*

Comment: The model runs and reproduces water level maps in the report for predictive DOR simulations for Layers 1 and 2 (2010, 2020, 2030, 2040, 2050). Unable to check water levels for Layer 3 predictive DOR runs because they were not found in the report (except for 2050 DOR run which does match). Report does mention that Layer 3 has little change in water levels due to zero pumpage and zero recharge to Layer 3. [requested action=unknown]

Response: *Missing figures are included in the final report.*

Comment: The model reproduces water budget components for recharge, wells, ET, and drains in the report for steady-state calibration. [requested action=none]

Response: *No action taken.*

Comment: The model reproduces water budget components for recharge, wells, ET, and drains in the report for transient calibration. [requested action=none]

Response: *No action taken.*

Comment: The model reproduces water budgets components for recharge, wells, and drains in the report for predictive DOR runs… but not for the ET component. Report lists about 12,000 AF for ET and output.dat file lists 0.0 AF. [requested action=fix or explain]

Response: *Model files for 2050-DOR simulation were in error. The model files have been fixed.*

Comment: Generally, the model appears to have zero thickness' for both active and inactive cells for all 3 layers and drain elevations below cell bottoms for layers 1 and 2. Although these problems do not appear to affect the model runs, they should be cleaned up prior to final submission to TWDB. A text file attachment is provided to help contractor identify problems with model data. [requested action-fix]

Response: *Minimum thickness is now 1 foot.*

2.2 Stakeholder Comments

<u>Comments From Stakeholder #1</u>

The comments presented here address the Draft Final Report GAM for the Igneous and Salt Basin Bolson Aquifers (IG-Bol) of the Davis Mountains region of Texas. It is intended that these comments will be constructive and used to inform future data collection and GAM efforts as well as GAM runs. One of the expectations of the model is to assess availability of groundwater in the study area. One specific expectation is to provide an evaluation of the effects of pumping in the bolson on water availability in the igneous aquifer system. Meeting these expectations has proved difficult for the lack of data and inability to incorporate complexity into the model due to funding and time constraints

Comment: Section 4.1.3 - Water Levels and Regional Ground Water Flow (Bolson) - Readers should be directed to Appendix A for a discussion on how water level maps were produced.

Response: *Appendix A is now referenced in Section 4.1.3.*

Comment: If springs were used to define water level elevations, shouldn't they be on the maps (Figure 4.1.4)? If spring and surface water data were used in the water level contours, there could be a larger component of evapotranspiration in the model, particularly in the area of Calamity, Musque, and Limpia creeks.

Response: *Springs were not implemented directly into the calculations but only indirectly by topography. Therefore, they are not shown on the map. The historical water level maps developed for the Igneous aquifer were developed because it was a* *contract requirement, and were intended only for general information and not to draw specific conclusions.*

Comment: Figure 4.1.16 Hydraulic conductivity data does not match final distribution of hydraulic conductivity (Figure 8.1.2).

Response: *There are many reasons why the hydraulic conductivity in the calibrated model may not match measured hydraulic conductivity. First, the hydraulic conductivity estimates come from many different pumping tests and from wells that are completed differently. Second, the conceptual model and model architecture assumptions are different than the physical system, and therefore, the hydraulic conductivity used in the model may need to be different than some of the measured data.*

Comment: Figure 4.1.21 - The pumping number listed for Culberson County does not match the amount given in Figure 10.1.3. A discussion is needed to explain this discrepancy and its impact on the model.

Response: *The discussion in Section 10.1 and 10.2 has been expanded.*

Comment: The first paragraph points out the radial pattern to groundwater flow, with water levels closely approximating topography. The assertion is made that this correlation indicates that topography is the primary control on water level elevation. However, Appendix A explains that topography was used to calculate water levels. Bedrock geology, faulting and regional structures cannot be eliminated as lending controls to water levels. Additionally, Figure 4.2.4 indicates that publicly available spring data (i.e. Brune and USGS topo maps) has been left out of water level calculations. More discussion is needed to explain why so little relevance is given to spring data.

Response: *Text modified to reflect comment.*

Comment: Section 4.2.5 - Paragraph three mentions Brune's list of 150 springs in Brewster, Jeff Davis, and Presidio counties. Yet this information is not utilized in the construction of water level maps, if spring data is used, it is not clear how. It is reasonable to assign, for the construction of initial water level maps, water level elevations equal to ground surface elevations at spring locations.

Response: *Springs were not implemented directly into the calculations but only indirectly by topography. Therefore, they are not shown on the map. The historical water level maps developed for the Igneous aquifer were developed because it was a contract requirement, and were intended only for general information and not to draw specific conclusions.*

Comment: Lipan should be replaced with Bolson.

Response: *Text has been modified.*

Comment: Figure 8.1.2 Final distribution of Hydraulic Conductivity in Layer 1. The distribution of K values does not represent actual conditions (Figure 4.1.16). Why collect data if the real numbers will not inform the model?

Response: *There are many reasons why the hydraulic conductivity in the calibrated model may not match measured hydraulic conductivity. First, the hydraulic conductivity estimates come from many different pumping tests and from wells that are completed differently. Second, the conceptual model and model architecture assumptions are different than the physical system, and therefore, the hydraulic conductivity used in the model may need to be different than some of the measured data. Third, most pumping tests only test a relatively small portion of the aquifer around the well, while the hydraulic conductivity in the model is usually more representative of regional conditions.*

Collecting more data from pumping tests does allow us to better understand the heterogeneity in the model, even if it is not always reflected in regional models.

Comment: Section 8.2.3 Water Budget - As the water budget is a very important component of any modeling effort, and can be used to assess success, this section needs to be expanded. The text is not clear and does not explain the importance of the water budget. More detail (in layman's terms) needs to be added to explain how water transfers between layers and where the water comes from to offset pumping (aquifer storage, ET, GHB). It should also be noted that the only numbers in this budget that can be attributed to data collection and analysis are the recharge numbers. The outflow numbers (i.e. pumping) arise from conflicting data (see figures 4.1.21 and 10.1.3) and the ET estimations are made without the benefit of spring and surface water data.

Response: *The water budget section has been expanded.*

Comment: Figure 10.1.3 - The pumping numbers listed for Culberson County in 2001 (8000 acft/yr) do not match those reported in Figure 4.1.21 (30,000 acft/yr). The predictive results of this model differ dramatically in the Van Horn area from the Finch model. A discussion is needed to explain; why there are discrepancies in pumping data, why one set of numbers is used over another, and how the predictive runs might change by simply changing input numbers.

Response: *Text modified to reflect comment.*

Comment: Figure 10.2.4 indicates that draw down in the Ryan Flat area will be as much as 55 feet by the year 2020. All the lines of equal head of -35 feet or less are truncated by the edge of Layer 1, yet the corresponding Figure 10.2.5 indicates that draw down in the Layer 2 will only be 20 feet or less. One would not expect a wall of ground water at the convergence of Layers 1 and 2. Figure 10.2.19 shows truncated lines of equal head of 150 feet, yet the corresponding draw down in Layer 2 is only 30 feet. All the predictive run figures indicate a completely vertical gradient of groundwater at the boundary of the two layers. Some cells dry up due to pumping in Ryan Flat; do any of these cells include pumping wells? Will the wells for City of Valentine dry up?

Response: *The difference in head decline between layer 1 and 2 is caused by the relatively low vertical hydraulic conductivity between layer 1 and 2. It is a function of the MODFLOW leakance factor between the layers. The "completely vertical gradient" referred to is a result of the architecture limitation in MODFLOW that does not allow layer 2 to connect to layer 1 except from below, which is not exactly how the connection occurs in the physical system. Some of the cells that dry up during the simulation do contain pumping, and due to limitations within MODFLOW-96, this pumping is eliminated from the model after the cell goes dry. Wells for the City of Valentine do not go dry.*

Comment: Figures 10.2.12. The simulated hydrograph for well Ryan flat well 51-28-607 indicates a water level rise of 20 feet through 2050, though the simulated water level maps predict water level declines throughout the Ryan Flat area.

Response: *The identifying text on the figures was inadvertently switched. Text has been corrected.*

Comment: Figures 10.2.13 through 10.2.20. Since recharge inputs for DOR predictive runs do not figure in until the last seven years, shouldn't these figures should look like figures 10.2.1-10.2.10. They do not; note the expanded extent of the 20 foot decline contour in layer 2.

Response: *The figures should look slightly different because each DOR predictive run is a different simulation encompassing 10, 20, 30, 40, and 50 years, respectively. The 7-year DOR is implemented in the MODFLOW recharge package at the end of each of these runs. Therefore, the 2010 heads under average conditions should be different than the 2010 heads under DOR conditions.*

Comment: Appendix A - Methodology for Developing Interpretive Water Level Maps of the West Texas Bolson and Igneous Aquifer GAM. Several assumptions used in this method are not discussed.

Were water level elevations assumed to be below a minimum depth in areas where no data existed?

Response: *The depths in geological units without any water levels, were given the average value for all the water levels values.*

Comment: Water level depths are assumed to be normally distributed and more than likely they are not. If the determination of an average water level for a particular geologic formation is made by averaging water levels in wells completed in that formation, the elevations of springs, within that formation, should be included (see USGS topographic maps and Brune).

Response: *The springs are included as the DEM elevation at that location and they are not averaged. These are separate data points, as are the actual well water levels.*

Comment: One should not determine that average of something and ignore available data. The value of springs in assigning elevations to water levels seems to be underestimated. According to the text, spring data was incorporated into the data set after a manipulation of topographic and GIS data. However there is no discussion of how the data is used. Water level elevations represented by spring data should have been figured in before using topographic data to force water levels. What would the first iteration of the water level surface in 1950 look like if spring data had been used? Spring data, if used should be included on the water level maps.

Response: *Spring locations were incorporated and given surface elevation values. These data points were adjusted for elevation by subtracting depth to water from elevation values taken from the National Elevation Dataset (NED). The resulting data points were then used to create a water level surface using ArcGIS Geostatistical Analyst.*

Comment: Why weren't the previously developed water level contour maps (Sharp) used in developing these maps?

Response: *The ones for the bolson were put in. The same data points were used within the methodology, but since the methodology was different and the area was greater, the water level contours from Sharp were not used directly.*

Comment: Statistical error values should be provided concerning "average" water levels.

Response: *Given the methodology, typical statistical errors from kriging the data would only represent part of the potential error, and so they were not presented.*

Comment: Appendix B - Methodology for Developing Transmissivity Values From Specific Capacity Data for the Igneous Aquifer.

1. Should the last word in paragraph four be "capacity"?
2. The text indicates that four different methods were used to calculate Ts using specific capacity and refers to Figure B2 for an assessment of each method, yet there is no Figure B2. The text also refers to average, maximum, and minimum values were recorded for the four different methods. Where are those numbers and how were they used?
3. Statistics (equation of the line and an error value) should be provided for Figure B1.

Response: *This section in Appendix D has now been rewritten.*

<u>Comments From Stakeholder #2</u>

Comment: The LBG-Guyton team should be commended for putting together a comprehensive report with graphics that are much improved over the conceptual model report. The overall impression after my review is that this is a good piece of work on a model that was difficult to develop given the geologic complexities and data availability.

Some of the specific comments are specific and somewhat direct, but are not intended to be critical of the overall utility of the model. Indeed, I expect this model will be highly useful in the near future, especially in the evaluation of supply strategies in the current round of regional water planning. Rather, they are intended to gain a better understanding of what decisions were made in the development of this model with an eye towards full documentation. Specifically, I have specific comments about:

- The decision to choose a recharge factor of 0.60 and not vary it during steady state calibration

Response: *Normally, recharge in a regional system is a very sensitive parameter. However, because of the limited connection between the Igneous and Bolson aquifers in the model and because the Bolsons do not receive any direct recharge from precipitation, the sensitivity of the Bolson layer is somewhat muted because most of the recharge is received by the Igneous layer. Because there was very little historic water level data in the Igneous, it was difficult to calibrate the model based to recharge because most of the recharge to the Igneous is lost to evapotranspiration and streams. Therefore, changes in recharge are inversely offset by changes in evapotranspiration and streamflow.*

- The decision to assume horizontally isotropic hydraulic conductivity

Response: *Certainly, there are portions of the aquifers that exhibit horizontal anisotropy in the hydraulic conductivity tensor. Calibration may also be improved by incorporating anisotropy along major structural features. For the IBGAM project, these considerations were not necessary to achieve relatively good calibration and reasonable results. In addition, it might be inconsistent to assume a single-layer representation of the Igneous aquifer and also include significant anisotropy that is applied to the entire thickness of the aquifer. Future refinements of the model should reassess the importance of horizontal hydraulic anisotropy.*

Comment: Some modelers may have added those to the calibration parameters, and fully documenting those decisions will assist modelers who, in the future, take this model as a starting point to enhance and improve it.

Response: *The calibration section has been expanded to try to include some of these issues.*

Comment: Page 1-1, Second Paragraph - IBGAM is used but not defined until the next page.

Response: *Text modified to define IBGAM*

Comment: Figure 2.1.2 - Add model boundary to figure (similar to Figure 2.1.1)

Response: *Model boundary added to Figure 2.1.2*

Comment: Page 2-5, Second Paragraph - At least one of the figures should depict the 5 boundaries listed here (mountain ranges, creeks flexures etc).

Response: *Five boundaries are labeled or depicted on Figure 2.2.2.*

Comment: Page 4-3, Third Paragraph - AGI defines "bajada" as a continuous alluvial slope formed by the lateral coalescence of a series of separate but confluent alluvial fans. I am not sure that definition applies to this area, which (I think) is more of a series of alluvial fan deposits that have not really "coalesced".

Response: *"bajada" deleted.*

Comment: Page 4-3, Fourth Paragraph - I am not sure "paleo-bolson" is a good term here. The key characteristic on which you included the volcaniclastic units with the bolson deposits is that they are unconsolidated to moderately consolidated (just like the deeper bolson deposits).

Response: *Reference to "paleo-bolson" deleted.*

Comment: Figure 4.1.1 - The northern part of the bolson is somewhat confusing, and it may be due to the aquifer designation used by TWDB. You show several wells north of the Bolson area proper that presumably are in alluvium, but outside the designated bolson. Somehow, the fact that there is alluvium of considerable thickness outside the TWDB designated bolson aquifer needs to be shown.

Response: *An explanation of the northern part of the Salt Basin is added to the first paragraph of Section 4.1.1. No change is made to Figure 4.1.1.*

Comment: Page 4-14, Fourth and Fifth Line - Should be "were used" instead of "will be used"

Response: *Correction made.*

Comment: Figure 4.1.14 - The lowest category should be 0. The second category should be 0.01 to 0.25.

Response: *Index corrected.*

Comment: Page 4-27, First Paragraph - The four references cited (McAda and Wasiolek, 1988; Wasiolek, 1995; Waltmeyer, 2001; and Huff et al., 2004) are not listed in the References section. I would have liked the opportunity to review these reports.

Response: *References are cited in Appendix B.*

Comment: Page 4-28, First Paragraph - This is not a true definition of hydraulic conductivity. It could be said like this: "An aquifer's hydraulic conductivity is an expression of how easily water can move through an aquifer and is expressed in terms of feet per day." Either use something like this or provide a precise definition.

Response: *Sentence has been modified.*

Comment: Page 4-31, Second Paragraph - Please define transmissivity here (hydraulic conductivity times thickness).

Response: *Definition has been provided.*

Comment: Page 4-31, Last Paragraph - Hydraulic characteristics, not hydrologic characteristics.

Response: *Sentence has been modified.*

Comment: Figures 6.2.2, 6.2.3 and 6.2.4 (and other similar sets of figures) - The fact that the Layer 1 figures are at a different scale than Layers 2 and 3 figures makes it difficult to get a sense of vertical changes in the model. I am not sure that there are any features on any of the Layer 1 figures that require a smaller scale.

Response: *Layer 1 figures were expanded to the approximate extent of the Bolson aquifer so that model results would be more visible in the report figures.*

Comment: Figure 6.2.2 - Why don't the active cells in Layer 1 extend into the full area of the "bolson aquifer"?

Response: *Active cells in Layer 1 do not extend to the full extent of the Bolson aquifer because some of the cells on the southern extent have a relatively small saturated thickness (generally less than 50 feet). These cells continually caused problems during model calibration because they would cause instabilities for the solvers (SIP, PCG, etc.). Therefore, to avoid this problem, many of the cells with small saturated thickness were inactivated. Recharge from stormwater runoff in these areas was automatically applied (in MODFLOW) to layer 2.*

Comment: *Page 6-9, Section 6.3.4* - It unclear why the 0.60 factor was not varied in any calibration run. I understand that there are studies that suggest that this is an appropriate number, and that there is no justification to vary the spatial distribution. But I can see no reason to pick a number based on a couple of studies and not investigate it during calibration. This was discussed in the SAF meetings and I was under the impression that there would be some attempt to at least vary factor parameter during calibration. Based on a review of the sensitivity analyses in Sections 8 and 9, recharge exhibits moderate sensitivity (certainly not as much as the boundary heads, but more than hydraulic conductivity in many cases and certainly more than enough to warrant some sort of variation during calibration).

Response: *The recharge is a relatively sensitive parameter when calculating sensitivity as it was done for this study (i.e., change in model heads over the entire model). However, because there was very little historic water level data in the Igneous, it was difficult to calibrate the model based to recharge because there is very little sensitivity to the observed water level measurements (i.e., calibration data) in the Bolson aquifer because most of the recharge to the Igneous is lost to evapotranspiration and streams. Therefore, changes in recharge are inversely offset by changes in evapotranspiration and streamflow.*

Comment: Page 6-10, Section 6.4.1, First Paragraph - There is a consistent reference to "pump tests". In reality, the pump isn't being tested. It would be better to say single-well tests or pumping tests in this context.

Response: *Text modified to "pumping tests".*

Comment: Page 6-10, Section 6.4.1, Second Paragraph, Fifth Line - This sentence is confusing: "However, direct estimates of vertical hydraulic conductivity meaningful to the modeling process are almost not available, and that is true for this study." I think you are saying ".. are almost never available". It may be better to focus on what you did use instead of trying to defend the use of an estimate when there are no estimates available. Express the estimates as ratios of horizontal to vertical K that are based on either literature values or other studies.

Response: *Text modified to clarify the sentence.*

Comment: Page 7-3, Section 7.1.3 - The section opens with a rather elaborate discussion of measurement error, and over-calibration. Then in the third paragraph, it is noted that these measurement errors are usually in the tenths of feet. This is placing way too much emphasis on something that is truly irrelevant in the context of a regional model, especially this one. The discussion of errors resulting from topographic maps and digital elevation data is appropriate, but it could get lost.

Response: *The first two paragraphs discuss uncertainty and TWDB GAM calibration criteria in general. Only the third paragraph is discussing measurement error specifically.*

Comment: Page 7-4, Second Paragraph, Last Two Sentences - I have never seen a discussion of this nature. This is essentially saying that if the model fit is less than some RMS/Range value then there is a problem due to “over calibration”. I have seen literature discussions of “over parameterization” (e.g. PEST manual), but that is a different issue, as the improved fit would be due to adding more parameters in an inappropriate manner. This discussion seems to focus entirely on the supposed inappropriateness of lowering the RMS value below some predetermined value. Please offer some reference to support this assertion.

Response: *Over parameterization is a more appropriate term. The text has been modified.*

Comment: Page 8-1, Section 8.1.1 - Change to Igneous

Response: *Change made.*

Comment: Page 8-3, Table 8.1 - Somewhere (maybe not in this table), there needs to be some summary of the ratio of horizontal to vertical K. With this table, it is unclear whether the low horizontal is associated with the low vertical or not. If it is, there needs to be some discussion of a 4 to 5 order of magnitude difference in horizontal and vertical K. This seems a bit out of range for alluvial or fractured volcanic materials. Recognizing that there are no local data to support or refute these parameters, it would seem appropriate to at least quote similar studies as was done with the recharge factor.

Response: *A discussion has been added to the paragraph.*

Comment: Page 8-3, Section 8.1.2 - At one of the SAF meetings, the issue of horizontal anisotropy came up. However, it appears that horizontal anisotropy was not considered at all in the model. Please explain the decision to treat the aquifer as isotropic in the report, and please discuss it in the context of other modeling studies that assumed isotropic or anisotropic hydraulic conductivity.

Response: *Certainly, there are portions of the aquifers that exhibit anisotropy in the hydraulic conductivity tensor. Calibration may also be improved by incorporating anisotropy along major structural features. For the IBGAM project, these considerations were not necessary to achieve relatively good calibration and reasonable results. However, future refinements of the model should reassess the importance of horizontal hydraulic anisotropy.*

Comment: Figures 8.1.2, 8.1.3, and 8.1.4 - Same comments as Figures 6.22, 6.23, and 6.24 regarding scale. Also, it would be helpful to include the data points that you had for K on this graph. At the SAF meeting it was helpful for interpretation when you were able to switch slides and see that the area of low K in Layer 1 was the area with no data.

Response: *No changes made to figures.*

Comment: Page 8-8, Section 8.1.3 - Same comment as for Section 6.3.4

Response: *The recharge is a relatively sensitive parameter when calculating sensitivity as it was done for this study (i.e., change in model heads over the entire model). However, because there was very little historic water level data in the Igneous, it was difficult to calibrate the model based to recharge because there is very little sensitivity to the observed water level measurements (i.e., calibration data) in the Bolson aquifer because most of the recharge to the Igneous is lost to evapotranspiration and streams. Therefore, changes in recharge are inversely offset by changes in evapotranspiration and streamflow.*

Comment: Figure 8.1.5 - The distribution of recharge rate extends to outside the model boundary. Also, it is unclear how the "Area of Significant Alluvial Fan of Stream Bed Recharge" was used in the model. Were these specified fluxes at these specific points?

Response: *Recharge outside the model area is not included in the model. Stream bed recharge was assigned as a specified flux in the MODFLOW recharge package.*

Comment: Page 8-13, Section 8.2 - Normally, I have seen at least a summary of what specific parameters were varied, what the general starting points were, what the range of variation of the parameters were, and at least a general discussion of at what point hydraulic conductivity zones were added or their boundaries modified. In short, some sort of run record to fully document what was done and how it was done.

Response: *This section has been expanded.*

Comment: Page 8-7, Section 8.2.3, Table 8.2.3 - The top and bottom fluxes should not be summed in this manner. Given the potential for abuse, it would be better to provide an overall water budget, and a water budget for each layer on separate tables.

Response: *Top and bottom flux sums were accidentally included and have been removed.*

Comment: Page 8-2, Section 8.3 - Note the relative sensitivity of the recharge factor compared to hydraulic conductivity (See comments on Section 6.3.4 and Section 8.1.3)

Response: *The relative sensitivity of recharge is significant as compared to hydraulic conductivity because the measure of sensitivity is average head change in the model for all the gridblocks. Because the estimated recharge has the most impact on the Igneous aquifer and because the Igneous aquifer covers such a large area, the sensitivity is relatively high. However, because there are so few water level measurements in the Igneous aquifer, and changes to recharge have very little* *effect on the Bolsons, it is difficult to use existing data to reduce the non-uniqueness of the recharge estimate.*

Comment: Page 9-8, Section 9.1 - The approach to simulate a long stress period at the beginning of the transient run makes no sense at all. You spent a lot of time calibrating a steady state model and reporting on it. Wouldn't be better to couple the models and calibrate them together with separate targets for steady state and transient? If I am reading this literally, hydraulic conductivity was not changed at all during the transient calibration where there are more data points on which to base the calibration. A run record summary might yield that after some attempts to calibrate the model under transient conditions, some modifications were made to the steady state model, and then more calibration was completed on the transient model (see the language used in Section 9.2 of the report).

Response: *The long stress period at the beginning of the transient run was a contract requirement. During the transient run, steady-state (1950) and transient (1951-2000) water level measurements were used to calibrate the model and the transient and steady-state calibration did occur in a coupled fashion. Early in the calibration process, it became apparent that the steady-state heads in the Bolson aquifer were very dependent on the distribution of hydraulic conductivity in the Bolsons. Therefore, the steady-state calibration data was weighted significantly higher in the coupled runs until the simulated steady-state heads were similar to the observed 1950 water level measurements. Then, the focus shifted to the transient calibration in which the hydraulic conductivity was a less sensitive parameter, and therefore was not modified significantly.*

Comment: Figure 9.1.5 - The approach to vary recharge on an annual basis linearly with the precipitation is good. However, please comment on the effect of dampening the high ends or including a lower threshold. Recognizing that in very wet years, it is likely that a higher percentage of rainfall would runoff than in normal years, thus dampening the upper end of the recharge. Similarly, in very dry years, there would be more ET or water going into the soil moisture bank than normal, thus reducing the effective recharge. It is not suggested that these be included in a recalibration, but a comment on these mechanisms may assist future enhancements and improvements to the model. The discussion in Section 12.2 regarding model improvements simply says:

> "This is a simple approach that should be evaluated further to determine if there are better approaches for estimating annual variations in the recharge"

A short discussion from the people who put this method together would be of great benefit in the future to better understand their understanding and experience in working with these estimates in the context of this model.

Response: *This simplified approach to varying recharge was based on the broad assumption that recharge is directly proportional to total yearly rainfall. In some cases, a* *relatively dry year may have a couple of relatively wet periods when recharge was significant and perhaps even higher than a relatively wetter year. On the other hand, large storm events may occur in some years that increase the total yearly precipitation above average, but most of the rainfall may run off. In this case, there may be a larger percentage of the rainfall that contributes to Bolson recharge through stormwater runoff. Further research may help identify what type of precipitation events provide the greatest recharge and how that recharge is distributed. Then, it might be possible to estimate historical recharge based on the frequency of these types of events.*

Comment: Page 9-15, Section 9.2 - See comment on Section 8.2 regarding the need for a run record summary.

Response: *This section has been expanded.*

Comment: Page 9-15, Section 9.2.1 - This shows the limitations of running a calibration and verification period independently. Data were available during the verification period in areas that had no data in the calibration period. All things being equal, use of the independent calibration and verification period is good. However, where data availability changes significantly between the periods, where there is a significant hydrologic difference between the two periods, or when stresses are significantly different, this method imposes limitations that are unnecessary.

Response: *Calibration and verification periods were required by TWDB in the GAM contract.*

Comment: Figure 9.2.15 - Since these are drawdown plots, it would be better to reverse the order of the values on the y-axis so that water levels are going down rather than up.

Response: *The graph is labeled correctly to ensure clarity.*

Comment: Figure 9.2.16, Figure 9.2.17 and Figure 9.2.18

1. These are very difficult to interpret. I recommend that they be replaced with the following individual graphs:
    - Stacked bar chart showing net storage change (each stack is a layer). The net storage change is calculated by subtracting storage inflow and storage outflow).
    - Bar chart showing alluvial recharge
    - Stacked bar chart showing pumping (each stack is a layer)
    - Bar chart showing drain outflow
    - Bar chart showing net inflow (or outflow) from Layer 1 to Layer 2

- Bar chart showing net inflow (or outflow) from Layer 2 to Layer 3

2. All water budget data should be summarized in tabular form for other future analyses.

Response: *Some changes have been made to budget section, but all the suggested graphics have not been added.*

Comment: Page 10-1, First Paragraph - Instead of "state-approved", would it be more accurate to say "state-mandated" or "demand projections developed by the state"?

Response: *Sentence modified to "The IBGAM was used to model the change in water levels and fluxes in the aquifer over a 50-year planning period (2001-2050) using water demand projections developed by the Region E (Far West Texas) regional water-planning group (RWPG) under average and drought-of-record (DOR) conditions."*

Comment: Page 10-3 and Figure 10.1.3

1. More detail on the pumping needs to be included. Also, the Region E plan (Strategy 71-6A, Groundwater Transfers – Long Distance Pipeline from Antelope Valley Ranch) states on page 5-73:

   > "EPWU needs to preserve the option of importing a minimum of 15,000 acre-feet per year from one or both of two Far West Texas Aquifers – Ryan Flat (Antelope Valley Ranch) and Bone Springs-Victorio Peak (Dell Valley) – with a possible eventual total peak importation of 50,000 acre-feet per year from both sources combined."

2. On page 5-74 the following is stated: As previously outlined, "EPWU proposes to export 15,000 acre-feet per year initially".

3. On page 5-74 in the Cost Estimate section, the following is stated:

   > "The following preliminary cost estimate for this strategy was developed using the assumed transport of water from Antelope Valley Ranch to El Paso, and is based on blending 1 part imported water with approximately 2 part Hueco Bolson brackish ground water. The following table outlines the cost of blending approximately 30,000 acre-feet per year of Hueco Bolson brackish water at an average TDS of 1,300 mg/l with 15,000 acre-feet per year of imported Antelope Valley water at not more than 400 mg/l TDS to result in blended water with an average TDS of just under 1,000."

4. On TWDB summary table, the following is listed for this strategy and the same for a Dell City strategy:

- Year 2000 – NI
- Year 2010 – 15,000 AF/yr
- Year 2020 – 20,000 AF/yr
- Year 2030 – 30,000 AF/yr
- Year 2040 – 45,000 AF/yr
- Year 2050 – 45,000 AF/yr

5. In summary, the language says that the initial pumping from Antelope would be 15,000 AFY (which is shown in the summary table. However, the language says that the "total peak importation" for both Antelope and Dell City would be 50,000 AFY, yet the summary table shows a total peak of 90,000 AFY from the both sources.

6. The values in Figure 10.1.3 do not appear to correspond to the values listed in the summary table in the earlier years.

7. In summary, it appears that there may be a discrepancy between the language of the Strategy and the Summary Table. When I first looked at this and discussed the values with LBG-Guyton, I was relying on the language of the Strategy. When I reviewed the Summary Table, it appears that none of the three match.

8. A clarification is needed on exactly what the estimated pumping from Antelope was in the Regional Plan, and then simulate that.

Response: *The current strategy description in the State Water Plan can be interpreted several ways. It needs to be clarified in the next round of planning prior to being incorporated in the next State Water Plan.*

Appendix C contains an expanded description of the pumping allocation and distribution methodology, as well as a letter from the Region E (Far West Texas) regional water-planning group (RWPG) regarding the location of the EPWU well field located in Ryan Flats.

Comment: Figures 10.2.12 and 10.2.24 - It appears that these wells are mislabeled. Ryan Flat should be decreasing and Wild Horse Flat should be increasing.

Response: *The wells were mislabeled, but have been corrected.*

Comment: Figure 10.2.26 - Similar to the comment on 9.2.16, 9.2.17 and 9.2.18, these are difficult to interpret and should be replaced with a companion set of figures and summary tables as recommended above.

Response: *Some changes have been made to budget graphs.*

Comment: Page 12-1, Section 12.0

A discussion that ties "supporting data" to the sensitivity analysis is needed. The sensitivity analysis clearly shows that the boundary heads are the most sensitive parameter. Efforts should be made to obtain better groundwater elevation in these areas, and this should be emphasized in this section.

Response: *More data should be obtained in these areas to reduce the uncertainty in the model results. However, the results of the sensitivity analysis should be interpreted carefully because the sensitivity is based on changes in simulated heads for each gridblock in the model. The ±10% "uncertainty" in the boundary heads that was simulated during the sensitivity analysis (as per TWDB requirements) is a relatively large change in head at the boundaries. On the other hand, ±10% uncertainty in the recharge value may be small by comparison when comparing the sensitivity to heads in every cell of the model.*

Comment: Page 13-1, First Paragraph

I think calling the modeling approach "standard for the industry" should be replaced with something like "consistent with GAM requirements and guidelines".

Response: *Sentence modified.*

<u>Comments From Stakeholder # 3</u>

Comment: I have briefly reviewed the draft results of the IBGAM available on the Internet. It appears that parameters have been adjusted in the IBGAM to successfully match historical performance particularly in the Salt Basin Bolson in layer 1. The biggest revisions in the data appear to be in layer 2 (igneous layer). However, these adjustments in layer 2 may require conflicting assumptions.

Horizontal permeability in layer 2 is reduced an order of magnitude from the 24 actual well tests reported in the conceptual model in August, 2003. Vertical permeability is reduced to about one-thousandth of the horizontal permeability in layer 2. This was of course necessary because the huge volume of water in the model in layer 2 (about 18,000,000,000,000 gallons) does not prevent a drop in water levels due to production in layer 1.

Recharge of about 0.35 inch per year is assumed for layer 2 using conventional practices derived primarily for sedimentary rocks. This requires vertical fractures in the dense igneous rocks in layer 2. Fractures typically have vertical and horizontal permeability which are the same order of magnitude.

The assumptions that vertical permeability is one-thousandth of horizontal and that recharge occurs in layer 2, required to make layer 1 match historical performance; appear to be mutually exclusive.

There are several possible explanations why the huge volume of water used in the model in layer 2 does not support withdrawals from layer 1 using the original data presented in August, 2003:

1. There may be very little recharge currently in layer 2 under current climatic conditions.
2. The complex igneous deposition of 40 or more layers is not in hydraulic communication horizontally over distances of miles.
3. The net fractured water saturated thickness is an order of magnitude less than the gross thickness of several thousand feet used in the model. A preliminary analysis of well records and completion reports in the Limpia Crossing area seem to support this conclusion.
4. The forty or more layers may have little vertical movement of water because the fractured zones may be separated by dense non-permeable layers.
5. Would you please discuss how valid you think the model results are for layer 2 at the Fifth Stakeholder Advisory Forum on March 25, 2004?

Response: *Certainly the complex geology of the Igneous aquifer has the ability to hinder hydraulic connection over distance, both horizontally and especially vertically. The fracture porosity of the Igneous aquifer is unknown. Model results show that the vertical movement of water in the Igneous is significantly hindered as indicated by the relatively low vertical hydraulic conductivity required in the Igneous aquifer to maintain water levels in the Davis Mountains. These results were discussed at the 5th SAF on March 25, 2004.*