Groundwater Availability of the Southern Ogallala Aquifer in Texas and New Mexico Numerical Simulations Through 2050

Report No. ________

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Groundwater Availability of the Southern Ogallala Aquifer in Texas and New Mexico: Numerical Simulations Through 2050

Abstract

A numerical groundwater flow model of the Southern Ogallala aquifer in Texas and New Mexico was developed to evaluate future changes in water levels and saturated thickness over a 50-year planning horizon. The model was developed to assist with regional water planning efforts, and it updates other availability models, which either date from the mid-1980s or are based largely on those previous efforts.

For this current modeling effort, new information was collected to determine hydraulic conductivity of the aquifer, agricultural pumping rates, and recharge beneath irrigated fields. Specifically:

- Previous geological models of the Ogallala Formation depositional system were extended to include the southern portion of the study area in Texas and the New Mexico portion of the study area.
- Hydraulic conductivity was estimated based on the extended geological model and more than 7,500 specific-capacity tests obtained from multiple sources.
- Detailed computations of agricultural pumping were derived for the 1980s and 1990s using climate data, information from producers on water application rates, and detailed water use observations for irrigated crops from instrumented research facilities.
- Groundwater recharge was investigated at three test sites. Two of the sites are adjacent to irrigated fields and one is in a natural setting never irrigated; none of the sites are near playas. Results of the field testing demonstrate that no recharge occurs in the natural inter-playa setting, and significant recharge can occur beneath irrigated agricultural fields.

A groundwater flow model representative of predevelopment (1940) hydrologic conditions was developed to determine predevelopment recharge rates and hydraulic conductivity of the aquifer in the absence of the complicating factors of specific yield, irrigation return flow, enhanced recharge, and pumping.

Using the calibrated predevelopment model as a starting point, a transient model calibration was conducted for the period 1940 through 2000. Model calibration was assessed through comparison of simulated and observed hydrographs for 80 wells distributed throughout the study area and through comparison of all available water level data for the winters of 1979-1980, 1989-1990, and 1999-2000. Validation of the model was conducted by comparing the simulated water levels and observed water levels at 10 locations not used during the model calibration process.

A series of predictive simulations were conducted for each decade through 2050 based on withdrawal estimates in the state water plan. A baseline scenario assumed average pumping and recharge conditions, and five drought-of-record scenarios assumed increased agricultural pumping and reduced recharge for the 5-year period preceding the end of each simulation. Results of the predictive simulations suggest that estimated withdrawals for a number of counties in the study area may not be sustainable over the 50-year planning horizon.

Introduction

The Southern Ogallala aquifer is one of the largest and most significant aquifers in Texas. The natural boundary of the aquifer includes a large portion of the Texas panhandle, as well as a large portion of eastern New Mexico. The availability of water is critical to the economy of this region, as approximately 95 percent of groundwater pumped is used for irrigated agriculture. Livestock production, oil and gas production and related services, manufacturing, and wholesale and retail trade are also significant contributors to the region's economy (LERWPG, 2001).

The groundwater resources of this region have been studied since the early 1900s, when development of groundwater on a limited scale first began. Significant groundwater development began in the 1940s, primarily for irrigated agriculture. Development continued rapidly through the 1950s, and groundwater has been used to sustain large regions of irrigated agriculture ever since.

The only significant external source of recharge to the aquifer is precipitation. Throughout much of the aquifer, groundwater withdrawals exceed the amount of recharge, and water levels have declined fairly consistently through time, indicating that the aquifer is being mined. In some regions of the aquifer, however, water levels have remained fairly stable over the past several decades or have even increased, indicating that overall recharge is approximately the same as or greater than groundwater pumping.

Irrigation return flow also recharges the aquifer; however, this water is not "new" water, but rather some portion of water that was previously pumped from the aquifer. While early farming practices were inefficient in the use of water, this region has been at the forefront of the development and implementation of efficient irrigation technologies and practices, and irrigation efficiency has increased significantly through time.

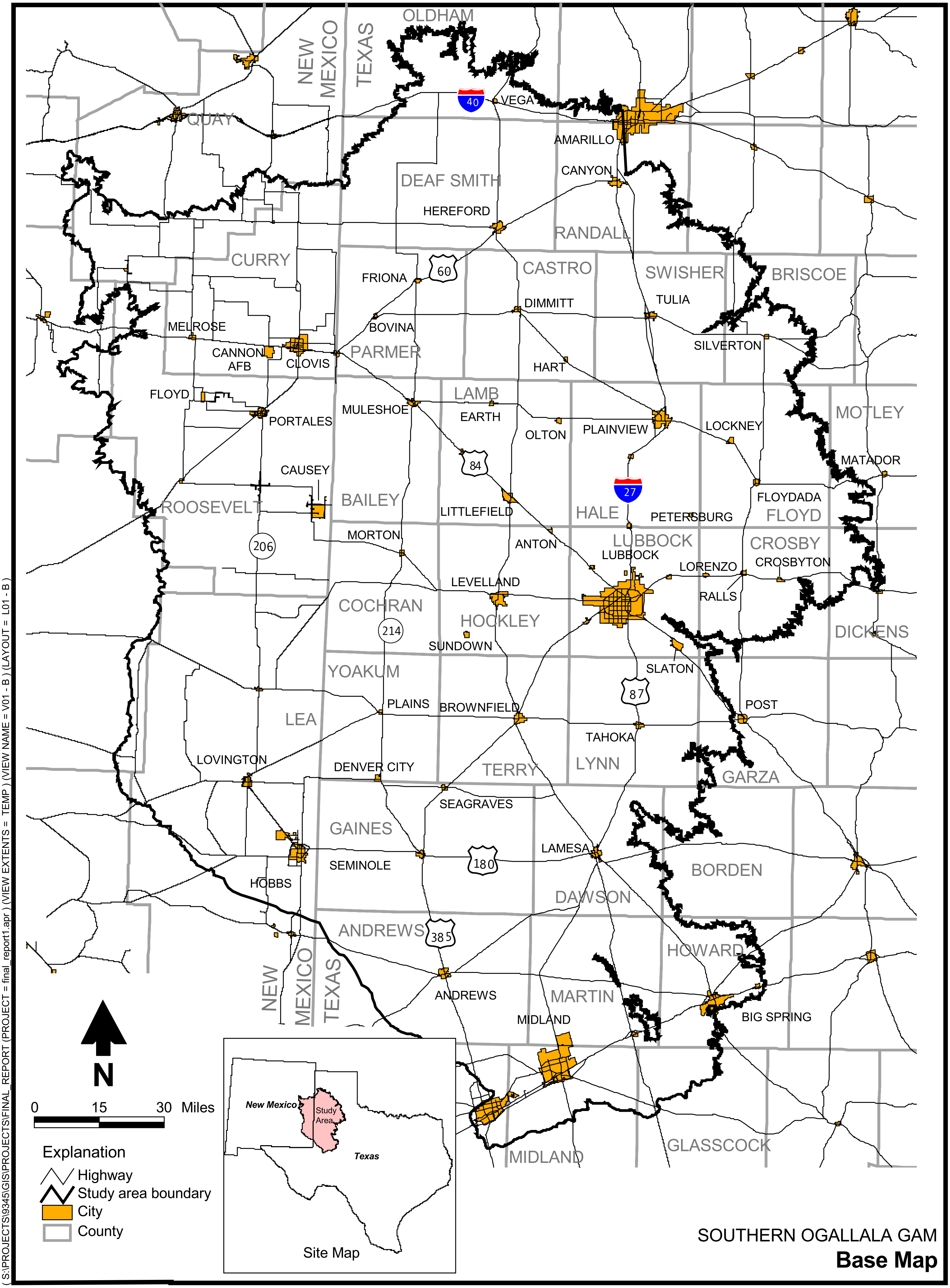
The first comprehensive hydrogeological studies and evaluations of the Southern Ogallala aquifer, including groundwater flow modeling, were published during the mid-1980s. These studies illustrated the likelihood that, should depletions of the aquifer continue at projected rates, substantial declines in water levels would continue.

Since that time, significant advancements have been made in the art and science of groundwater modeling, and substantial improvements have been made to computer software for groundwater modeling and spatial analysis. In addition, computational platforms are much more robust and powerful, to the extent that modeling analyses that could not be conducted 15 years ago can now be easily completed on a desktop computer. Many additional studies of groundwater recharge and other hydrogeological aspects of the aquifer have been completed, and an additional 15 years or so of observed water level data are available.

When developed appropriately in conjunction with observed data, a numerical groundwater flow model is a tool that can be used to estimate changes in water levels through time, subject to assumed groundwater demand. The numerical groundwater flow model described herein was developed for the Southern Ogallala aquifer as a tool to assist regional water planning efforts and planning activities of the Underground Water Conservation Districts (UWCDs). This model was used to evaluate groundwater availability for a series of predictive simulations for both average and drought-of-record conditions.

Study Area

The Southern Ogallala aquifer underlies an area of about 29,000 square miles (mi^2) in western Texas and eastern New Mexico, encompassing all or part of 31 counties in Texas and 6 counties in New Mexico (fig. 1). The study area spans Regional Water Planning Area O (Llano Estacado) and extends into Areas A (Panhandle) and F (fig. 2). The High Plains Underground Water Conservation District (HPUWCD) No. 1 covers all or portions of 15 counties in the study area. Seven other groundwater conservation districts cover individual counties in the southern half of the



SOUTHERN OGALLALA GAM

Base Map

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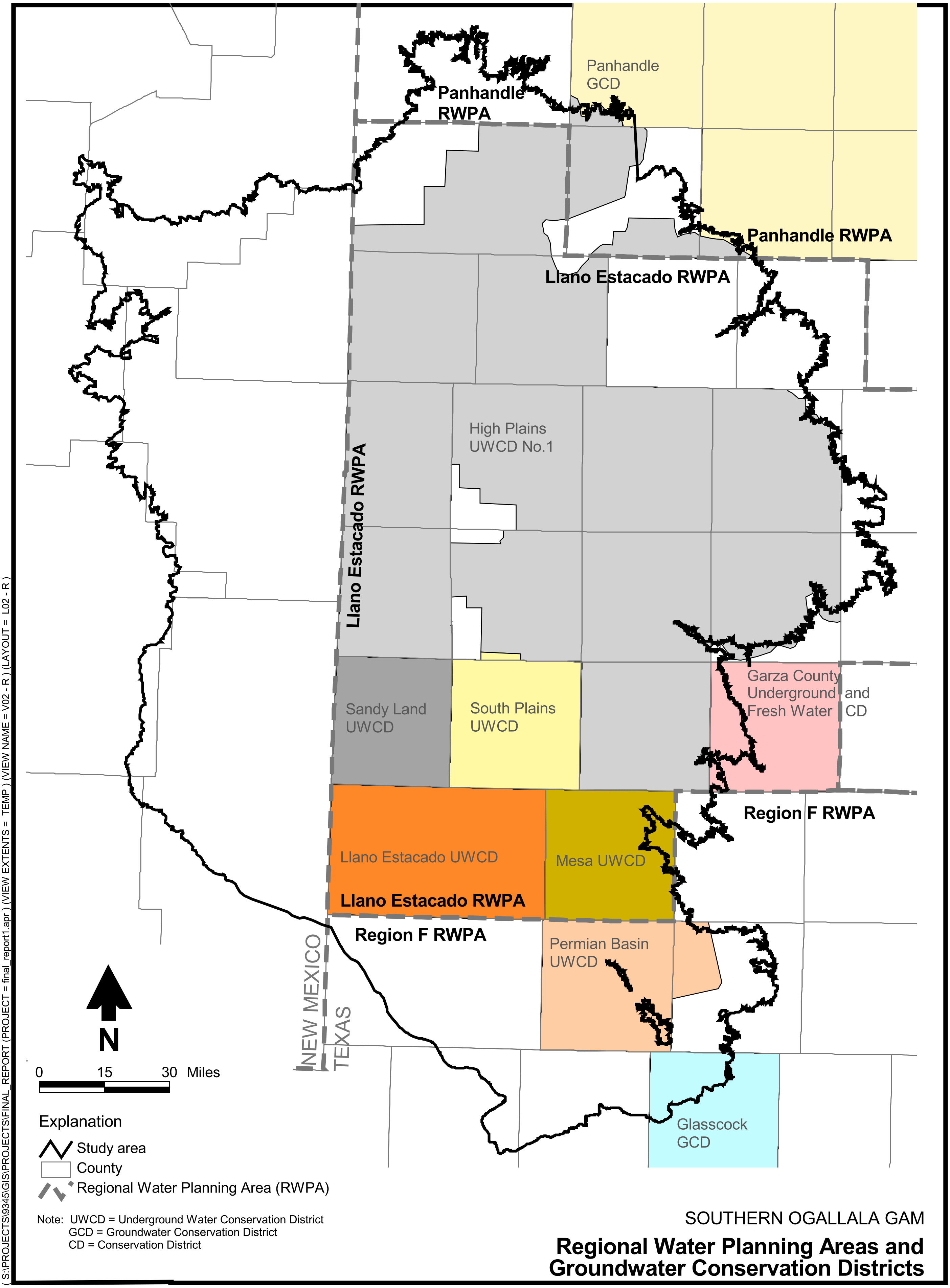
1-30-03

Figure 1



SOUTHERN OGALLALA GAM

Regional Water Planning Areas and Groundwater Conservation Districts

1-30-03

Figure 2

study area (the Permian Basin UWCD also covers part of a second county) (fig. 2).

The main population centers in the study area are Lubbock, Midland, and Odessa, Texas and Hobbs and Clovis, New Mexico. A small portion of the City of Amarillo falls inside the northeastern boundary of the study area in Randall County, but most of Amarillo lies outside the study area. Most of the study area is rural and sparsely populated (fig. 3).

Physiography and Climate

The study area lies in the Great Plains physiographic province, which is further subdivided into the High Plains, Pecos Valley, and Edwards Plateau Sections (fig. 4). The study area consists of that part of the High Plains south of the Canadian River and Palo Duro Canyon. The region is often referred to as the Llano Estacado, or "staked plains," as named by Spanish explorers.

Regional physiographic features in and adjacent to the Southern High Plains include:

- The broadly flat to slightly sloping High Plains surface, which is an extensive plain of minimal topographic relief
- Erosional escarpments to the west and east that border the High Plains
- Valleys of the Canadian River (Canadian River Breaks) and Prairie Dog Town Fork of the Red River (Palo Duro Canyon), which form the northern boundary of the study area, and of other smaller streams that cross the study area
- Tens of thousands of closed drainage depressions known locally as playa basins or lakes, which may pond water after rainfall (fig. 5)

The Southern High Plains is bordered to the west by the Pecos River Valley and to the east by the Osage Plains (called the Rolling Plains on some physiographic maps). The erosional retreat of the High Plains Caprock Escarpment to the east and west and the incision of the Canadian and Pecos Rivers were strongly influenced by dissolution of buried Permian salt beds (Gustavson and Finley, 1985). The eastern escarpment is more eroded and incised than the western escarpment, indicating the influence of greater sapping effects of groundwater (Reeves and Reeves, 1996, pp.164-165; Wood, 2002). The study area includes portions of the Canadian, Red, Brazos, and Colorado river basins.

Land surface elevations range from more than 5,000 feet above mean sea level (ft-MSL) in the far northwestern portion of the study area in Quay County, New Mexico to less than 2,500 ft-MSL in the far southeastern portion of the study area in eastern Howard County, Texas. The regional slope of the land surface is approximately 100 feet per mile in a southeasterly direction (fig. 6).

The general distribution of soils within the study area is provided in Figure 7. The lowest-permeability soils (those that contain significant proportions of clay and silt) occur in the northern third of the study area, while the higher permeability soils (primarily sand and silt loams) occur in the southern two thirds of the study area and throughout most of New Mexico.

Average annual precipitation ranges from more than 21 inches per year (in/yr) in eastern portions of the study area to less than 15 in/yr in the western and southwestern portions of the study area (fig. 8). Observed annual precipitation through time at a northeastern (Plainview) and southwestern (Seminole) climate station are provided in Figure 9. About 80 percent of the average annual precipitation occurs during May through October (LERWPG, 2001), during the growing season.

Mean annual temperatures in the study area range from 58 to 62 degrees Fahrenheit (LERWPG, 2001). Average annual lake evaporation ranges from approximately 61 in/yr in the northwestern portion of the study area to more than 72 in/yr in the far south-central portion of the study area (fig. 10).

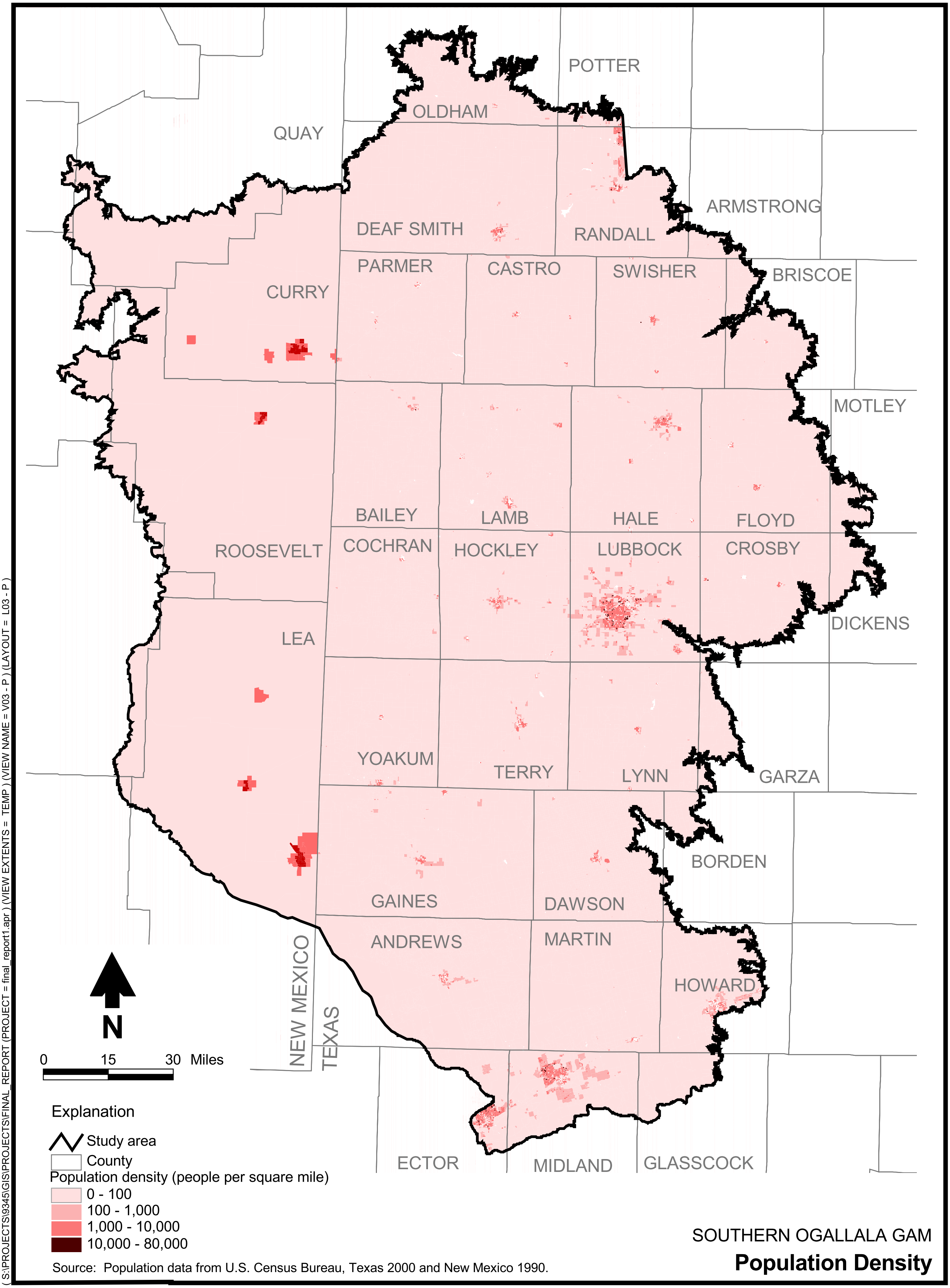


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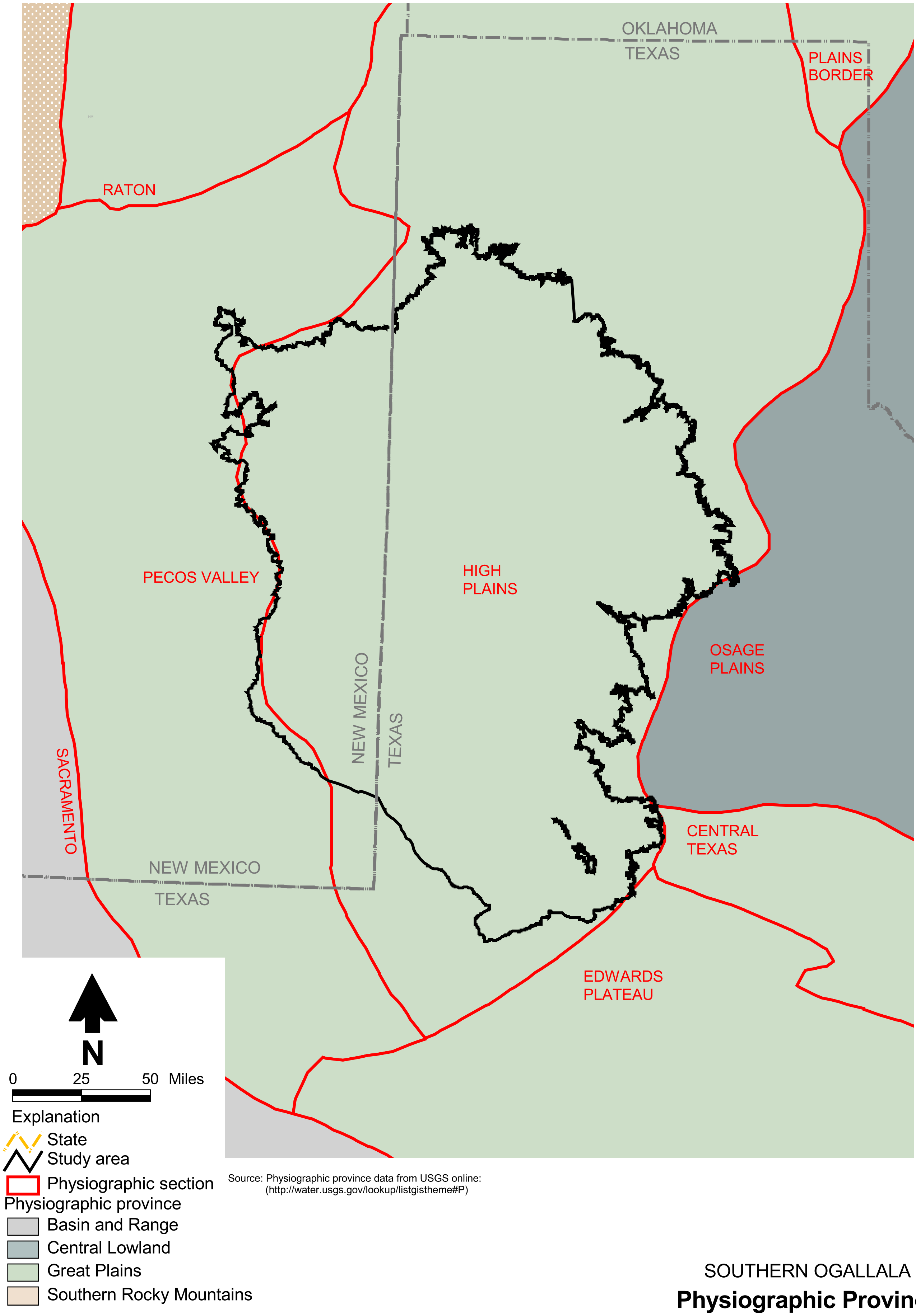
Figure 3



Source: Physiographic province data from USGS online:
(http://water.usgs.gov/lookup/listgistheme#P)

SOUTHERN OGALLALA GAM

Physiographic Provinces

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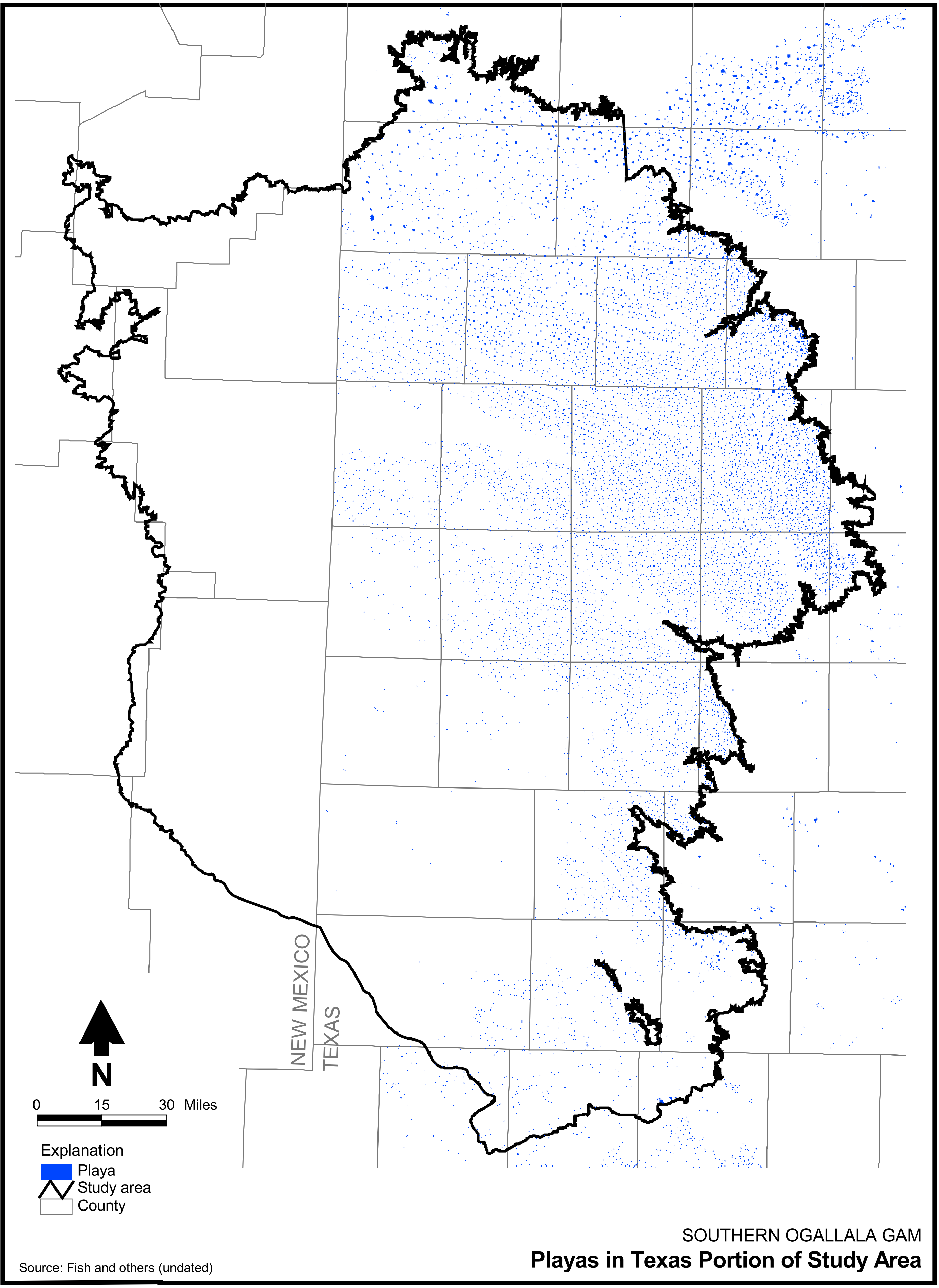
Figure 4



SOUTHERN OGALLALA GAM
Playas in Texas Portion of Study Area

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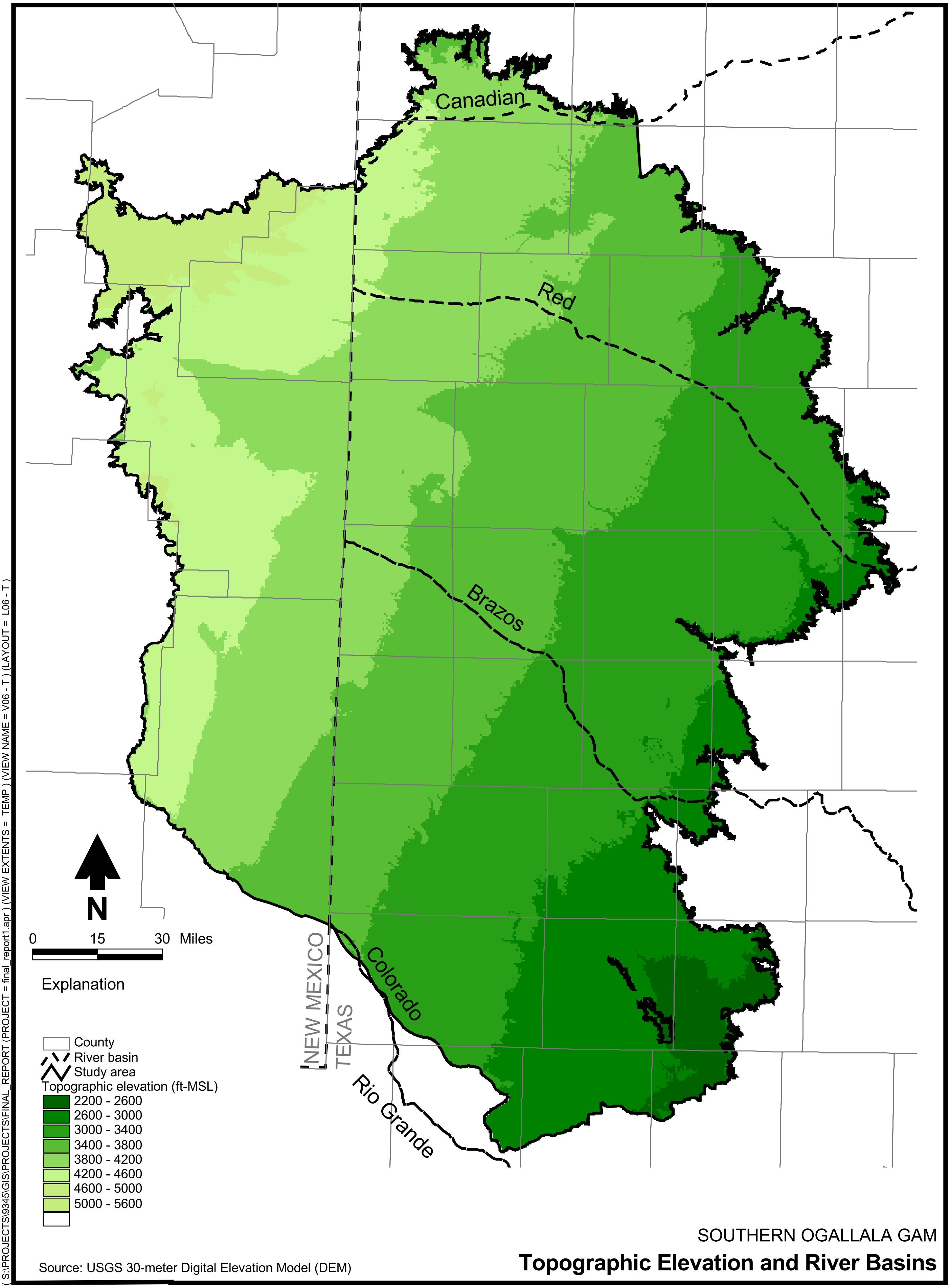
Figure 5



SOUTHERN OGALLALA GAM

Topographic Elevation and River Basins

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Figure 6

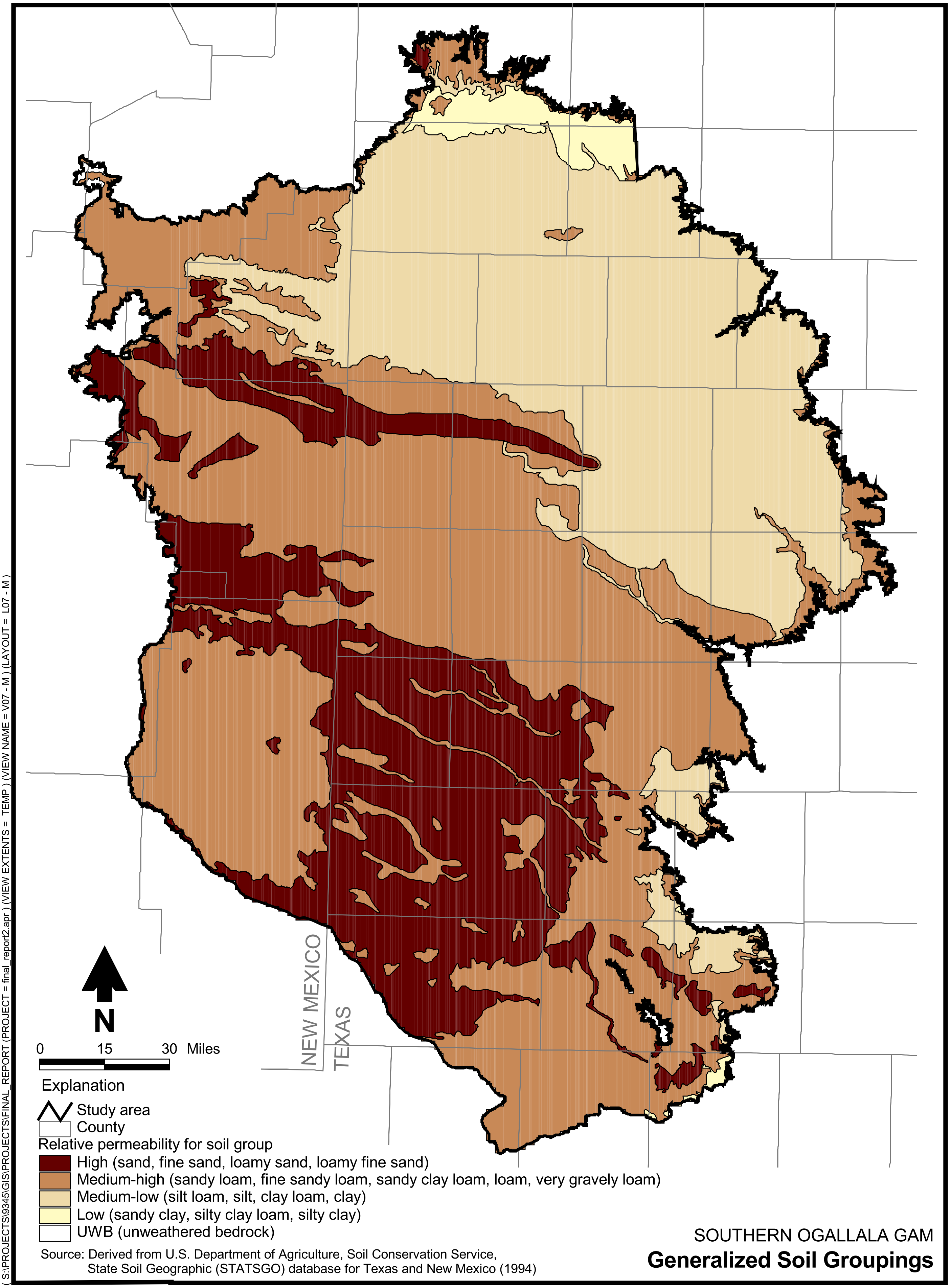

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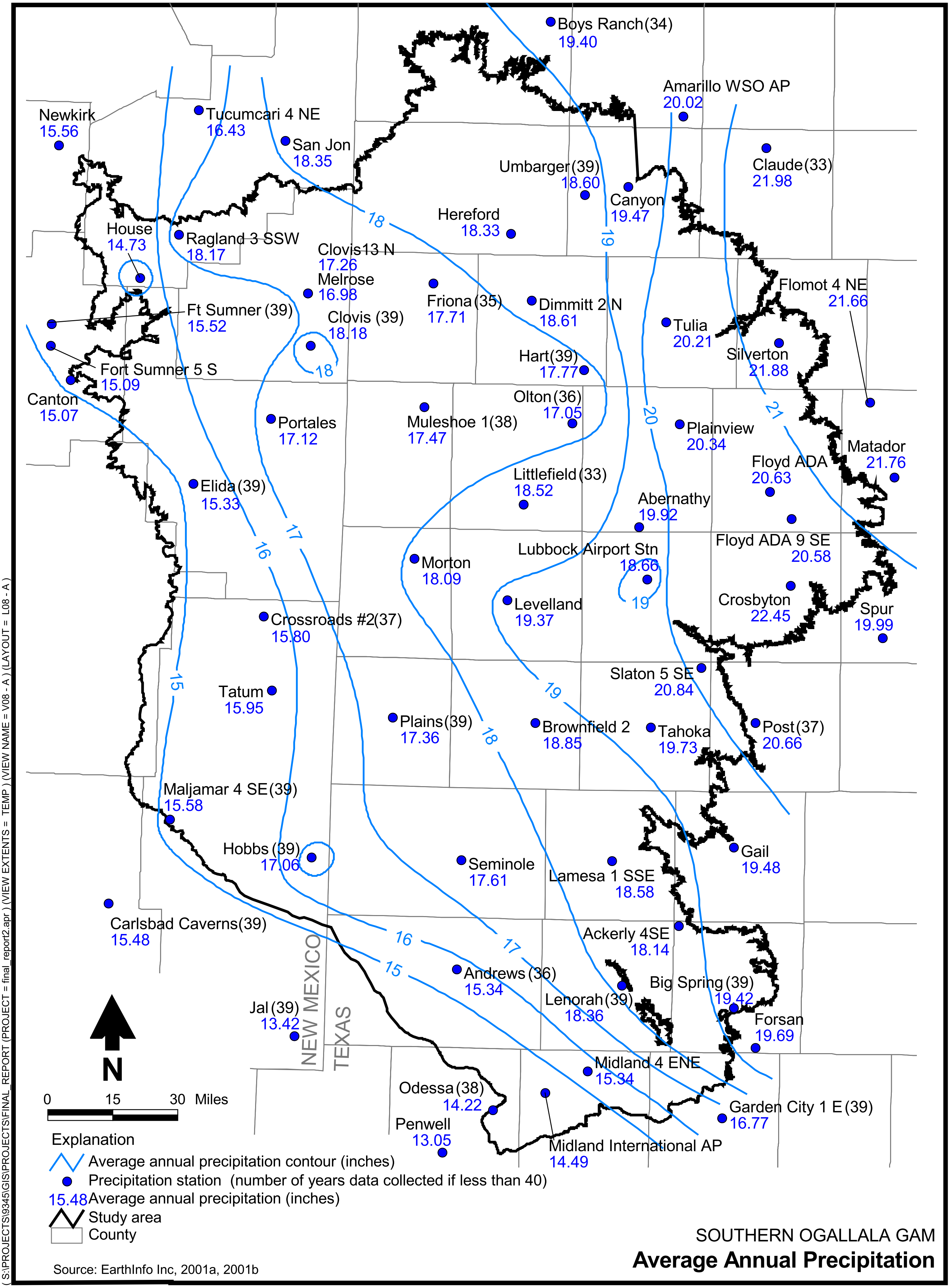
Figure 7



SOUTHERN OGALLALA GAM

Average Annual Precipitation

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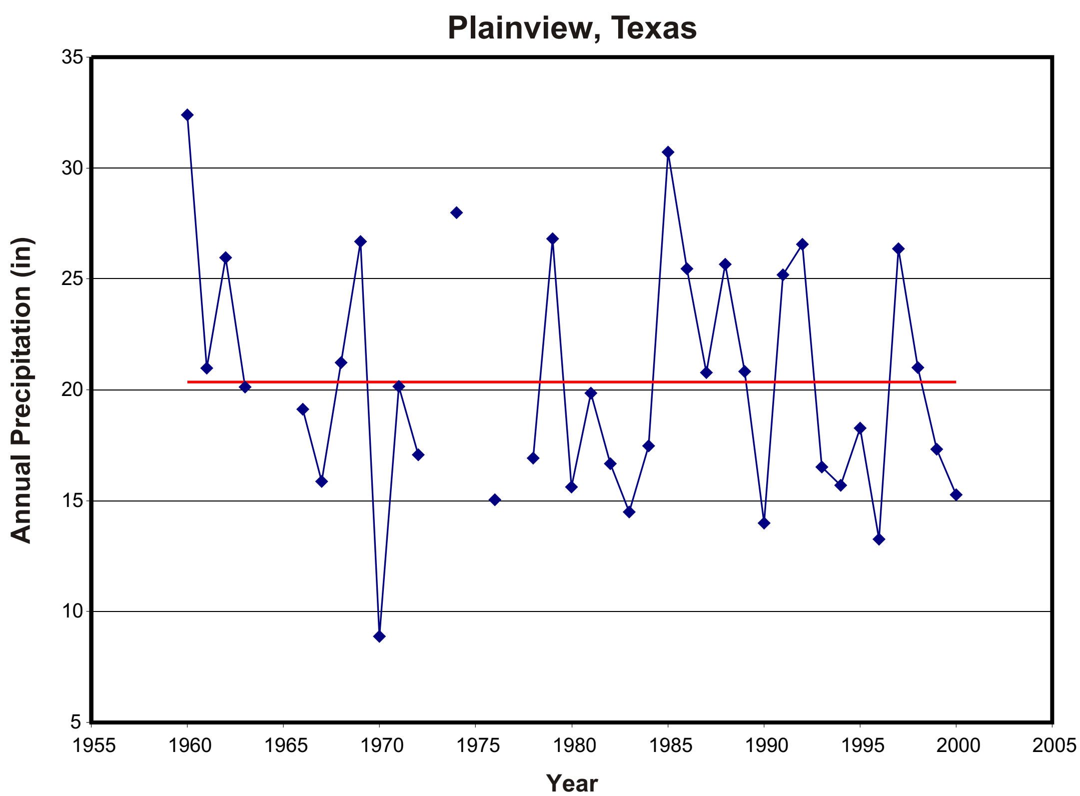
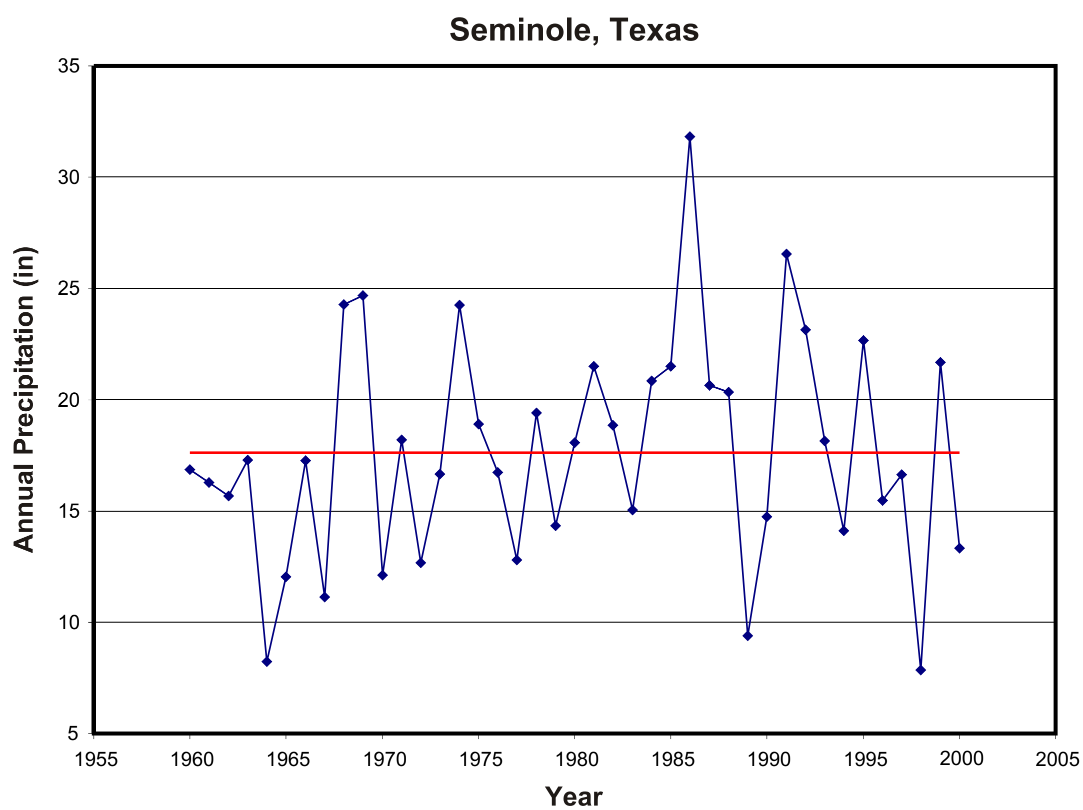
Figure 8





Explanation

Annual precipitation

Average annual precipitation

SOUTHERN OGALLALA GAM

Observed Precipitation for Seminole and Plainview Stations

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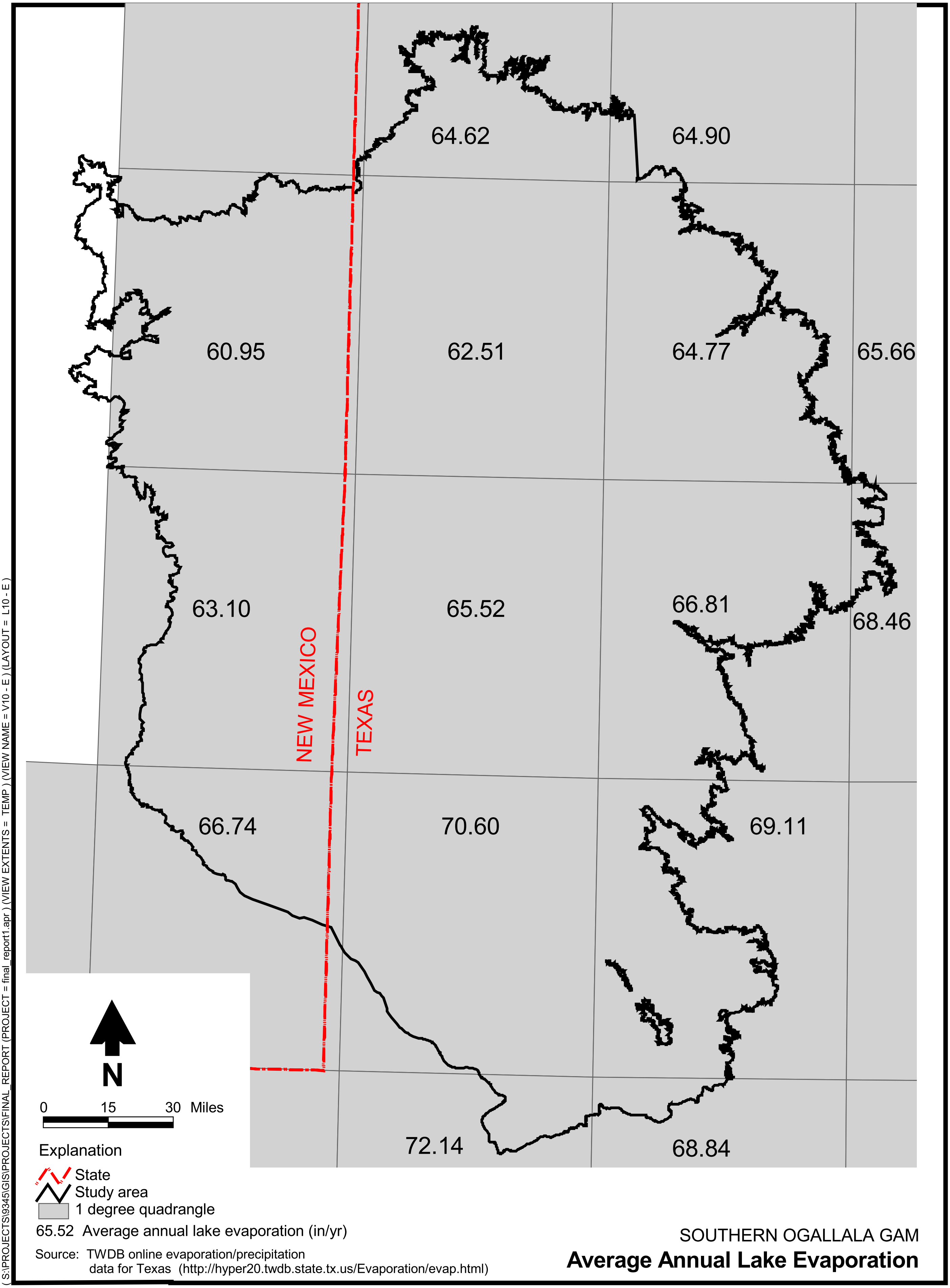
Figure 9



SOUTHERN OGALLALA GAM

Average Annual Lake Evaporation

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Figure 10

Geology

Figure 11 illustrates the general surficial geology in the vicinity of the Southern High Plains. The study area is underlain mainly by the Tertiary Ogallala Formation and the Quaternary Blackwater Draw and Tule Formations (fig. 12). The Ogallala Formation ranges in thickness from 0 to more than 800 ft and consists of fluvial gravel, sand, and silt, and eolian sand and silt. Although the Ogallala Formation in areas north of Texas is subdivided into several members, the Texas section is not formally divided. The uppermost section of the Ogallala Formation is marked by several widespread calcretes and local silcretes, which form an erosion-resistant caprock.

The Ogallala Formation in the study area unconformably overlies Permian, Triassic, and Cretaceous formations (Gutentag and others, 1984; Knowles and others, 1984). Cretaceous rocks underlie approximately 9,000 mi^2 of the Ogallala beneath the Southern High Plains (figs. 13 through 15). The Cretaceous rocks make up the Edwards-Trinity (High Plains) minor aquifer (Nativ and Gutierrez, 1988; Ashworth and Hopkins, 1996) (fig. 12). The Cretaceous section is as much as 300 ft thick (figs. 13 and 14).

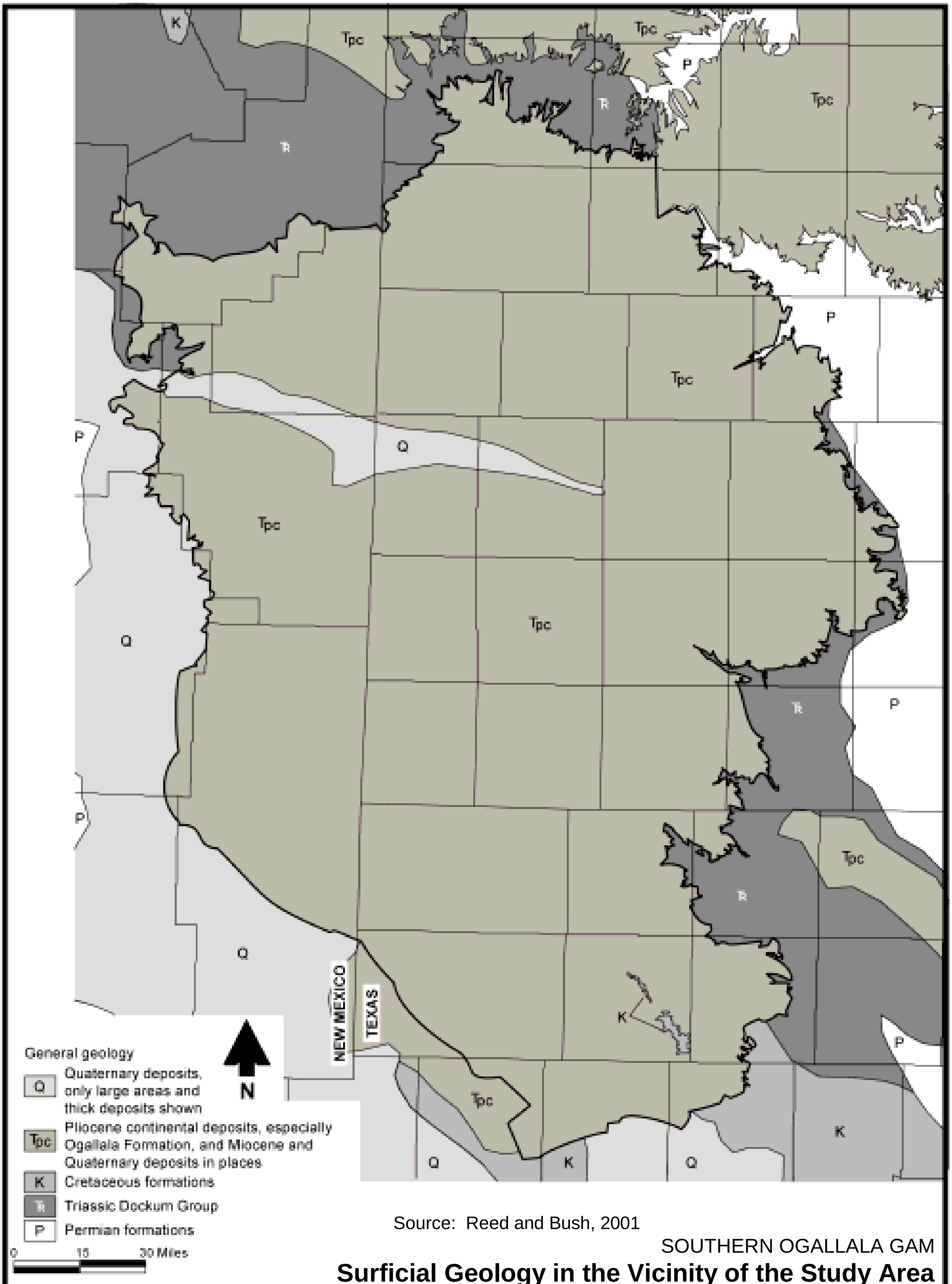
Throughout most of the Southern High Plains, the Ogallala Formation and Cretaceous rocks are underlain by Triassic-age rocks of the Dockum Group, which were deposited in fluvial, deltaic, and lacustrine environments (McGowen and others, 1977, 1979). The Triassic section can be as much as 2,000 ft thick, and its low-permeability sediments separate groundwater in the Ogallala and Edwards-Trinity aquifers (collectively called the High Plains aquifer) from groundwater in the deeper Permian section beneath most of the Southern High Plains.

The source of Ogallala sediment has been interpreted as the Rocky Mountains to the northwest (e.g., Seni, 1980). Depositional environments of the Ogallala Formation have been interpreted as including coalescing alluvial fans or alluvial aprons (Johnson, 1901; Frye and Leonard, 1964; Seni, 1980; Reeves, 1984), or fluvial-dominated valley fill sequences confined within paleovalleys (Gustavson, 1996). In Texas, there are three major paleovalley systems, named the Panhandle, Clovis, and Slaton channels (Gustavson, 1996). In the lower part of the Ogallala, coarse fluvial sediments are concentrated along the major paleovalleys and finer sediments are concentrated between channel axes.

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

Deposition of the Ogallala Formation in some areas was contemporaneous with dissolution of underlying Permian salt beds. While surface waters were carrying sediments across the ground surface, groundwater was also moving through the subsurface. Where the groundwater came into contact with the Permian beds of halite that underlay the Mesozoic section, it dissolved the halite, and the ground surface subsided and collapsed in some places. Additional Ogallala sediments were subsequently deposited into these subsidence and collapse basins, resulting in parts of the Ogallala having greater thickness than others, local variations in thickness, and perhaps disruption of the fabric of the sand and gravel packages. Salt dissolution was greater in the northern part of the Southern High Plains than in the south.

Seni (1980) mapped the distribution of sand and gravel in the Ogallala Formation for most of the Texas part of the study area (although he did not break out the lower and upper stratigraphy of the Ogallala). As part of this project, Seni's (1980) maps were extended to the southern part



Source: Reed and Bush, 2001

SOUTHERN OGALLALA GAM

Surficial Geology in the Vicinity of the Study Area

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1-16-03

Figure 11

ERA	System	Series	Group	Formation		General Lithology and Depositional Setting	Hydrostratigraphic Units	
CENOZOIC	Quaternary	Holocene				Playa deposits		Local zones of perched groundwater
		Pleistocene		Tule		Eolian and lacustrine clastics, freshwater limestones		
				Blackwater Draw				
	Tertiary	Pliocene		Blanco		Fluvial, eolian, and lacustrine clastics	High Plains Aquifer	
		Miocene		Ogallala				Ogallala aquifer
MESOZOIC	Cretaceous	Comanche	Washita	Duck Creek		Marine sandstones, limestones, and shales		Edwards-Trinity (High Plains) aquifer **
			Fredericks-burg	Kiamichi				
				Edwards				
				Walnut				
			Trinity	Paluxy		Transgressive sand and gravel		
	Jurassic*	Upper		Morrison		Marine sandstone and shale		
	Triassic	Upper (?)	Dockum	Trujillo	Chinle	Fluvial-deltaic and lacustrine clastics	Dockum aquifer**	
					Santa Rosa			
				Tecovas				
PALEOZOIC	Permian	Ochoa		Dewey Lake		Brine-pool salt, anhydrite, red beds, and carbonates	Evaporite aquitard	
				Alibates				
		Guadalupe	Artesia	Salado				

* Locally present

** Minor aquifer in Texas

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SOUTHERN OGALLALA GAM

Generalized Geologic and Hydrostratigraphic Column for the Study Area

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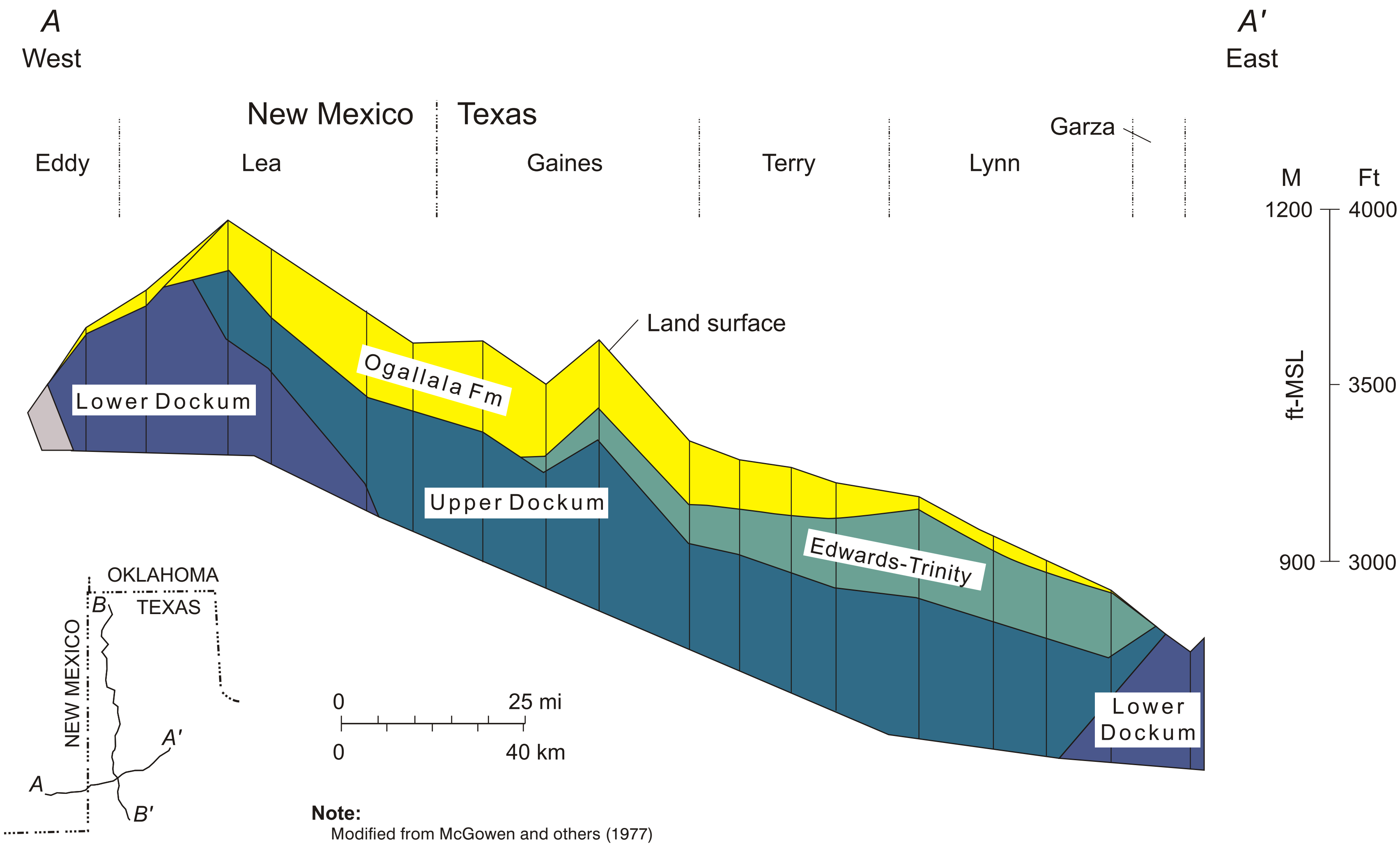
Figure 12



Note:
Modified from McGowen and others (1977)

Explanation

Tertiary-Quaternary

Cretaceous

Triassic

Permian

SOUTHERN OGALLALA GAM

West to East Geologic Cross Section Showing Relationship of Ogallala Formation to Underlying Strata

Figure 13

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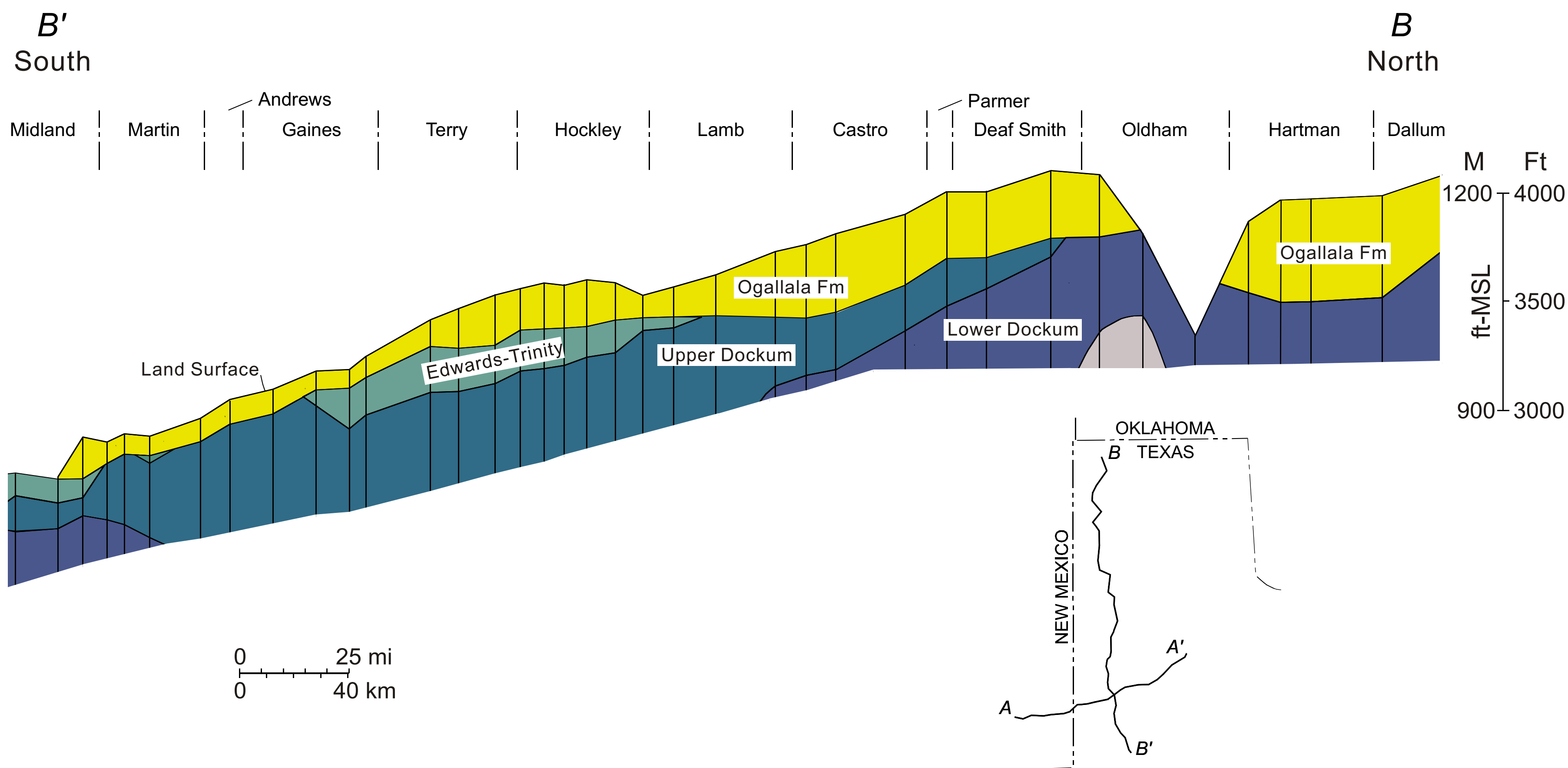

Note:
Modified from McGowen and others (1977)

Explanation

Tertiary-Quaternary	Triassic
Cretaceous	Permian

SOUTHERN OGALLALA GAM

North to South Geologic Cross Section Showing Relationship of Ogallala Formation to Underlying Strata

Figure 14

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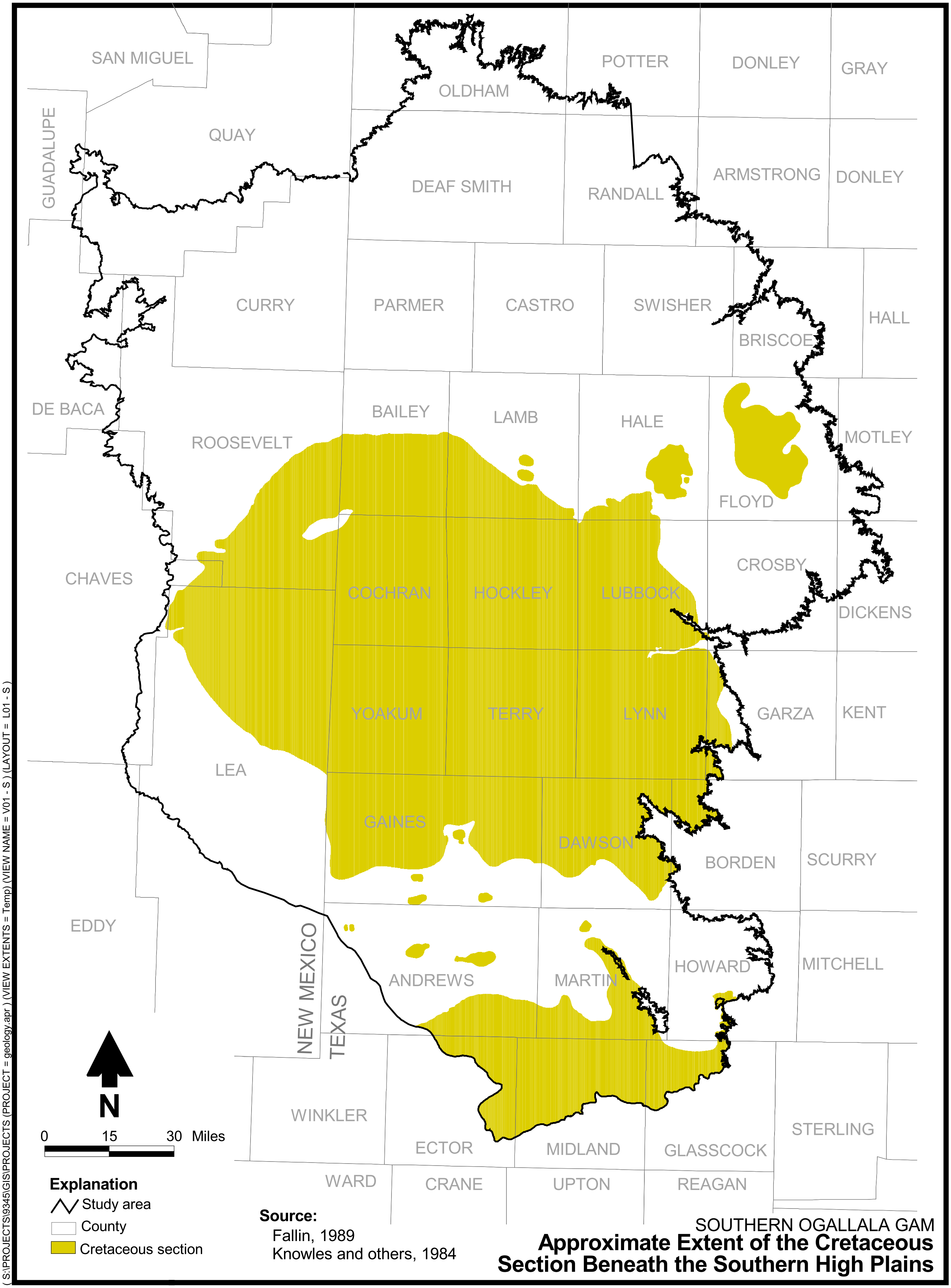

SOUTHERN OGALLALA GAM

Approximate Extent of the Cretaceous Section Beneath the Southern High Plains

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Figure 15

of the study area and into New Mexico using data on sand and gravel thicknesses compiled from drillers' logs on file at the Texas Commission on Environmental Quality (TCEQ) and from the New Mexico Office of the State Engineer (fig. 16). Seni's (1980, Table 2) criteria for conversion of drillers' descriptions to sand and gravel values were followed.

The resulting maps of net thickness of sand and gravel (fig. 17) and percentage of sand and gravel (fig. 18) illustrate the three major channels described by Seni (1980), which are related to the three paleovalley systems identified by Gustavson (1996). The maps of sand and gravel distribution also show where paleovalleys head into New Mexico. The presence of another significant channel of sand and gravel in the southern part of the study area, more narrow and thin than the three previously identified major channels, is also suggested.

Previous Work

This section provides a brief overview of previous modeling efforts and compares the current groundwater availability model (GAM) to those developed previously.

USGS RASA Model

The U.S. Geological Survey (USGS) model, developed as part of the Regional Aquifer Systems Analysis (RASA) program, and supporting studies are documented in USGS Professional Papers 1400-A through 1400-G. The model is documented in USGS Professional Paper 1400-D (Luckey and others, 1986), and predictive simulations are provided in Professional Paper 1400–E (Luckey and others, 1988). While the USGS model covers the entire Ogallala aquifer (called the High Plains aquifer by the USGS) in Texas, New Mexico, Oklahoma, Kansas, Colorado, Nebraska, Wyoming and South Dakota, the Southern Ogallala in Texas and New Mexico is analyzed and described separately.

The USGS model includes predevelopment (steady state) and post-development (transient) simulation periods. The model consists of a single grid layer, and model cells are 10 miles on a side, or 100 mi^2. Some key points of the model include:

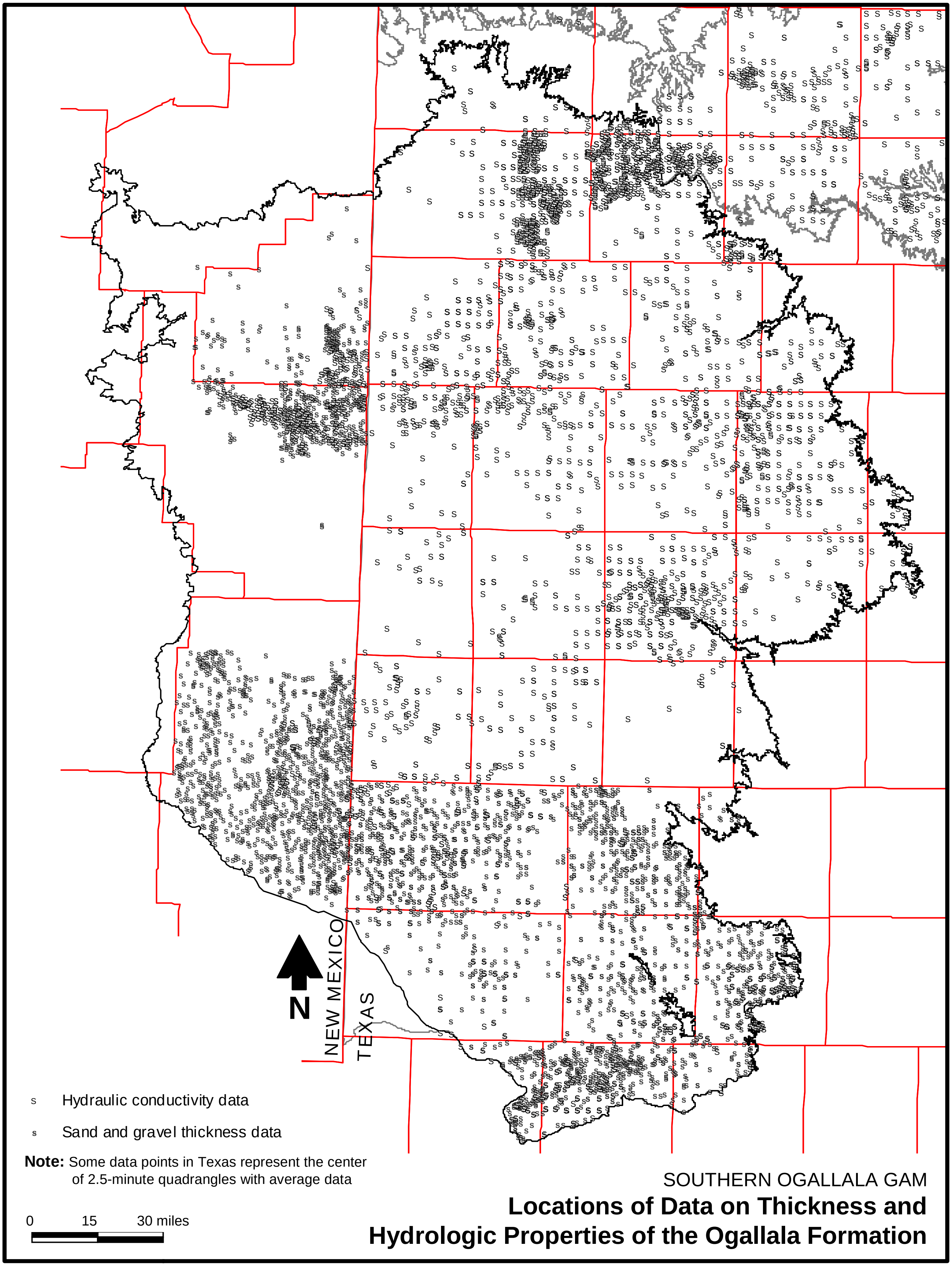
- Recharge throughout most of the model area for predevelopment (steady-state) conditions is 0.086 inch per year (in/yr), although higher recharge rates of up to 1.03 in/yr are applied to a limited area along Running Water draw. For the period 1960 through 1980, a recharge of 2 in/yr was applied to all agricultural lands (irrigated land and dryland) in the model.
- Return flow from irrigated agriculture is assumed to occur within the same 10-year period during which irrigation pumping for the area was calculated. Irrigation return flow is estimated to be 50 percent of applied irrigation water during the period from 1940 to 1960 and 46 to 37 percent of applied water during the period from 1960 to 1980.
- Hydraulic conductivity in the model ranges from 10 to 150 feet per day (ft/d).

Predictive simulations were conducted using the model for the period 1980 through 2020 (Luckey and others, 1988).

TWDB Model

The Texas Water Development Board (TWDB) published a regional groundwater flow model for the Ogallala aquifer in Texas (Knowles and others, 1984). The effort was partially funded by the USGS as part of their RASA program. A large amount of field work and basic analysis was conducted as part of this study, including development of a detailed set of base of aquifer maps, measurement of water levels for construction of water level maps, construction of maps of specific yield and hydraulic conductivity correlated to lithology, and development of a numerical model of the aquifer.

The model was divided into two pieces: the south model and the north model. The south model approximately coincides with that portion of the Southern Ogallala GAM model in Texas.



SOUTHERN OGALLALA GAM

Locations of Data on Thickness and Hydrologic Properties of the Ogallala Formation

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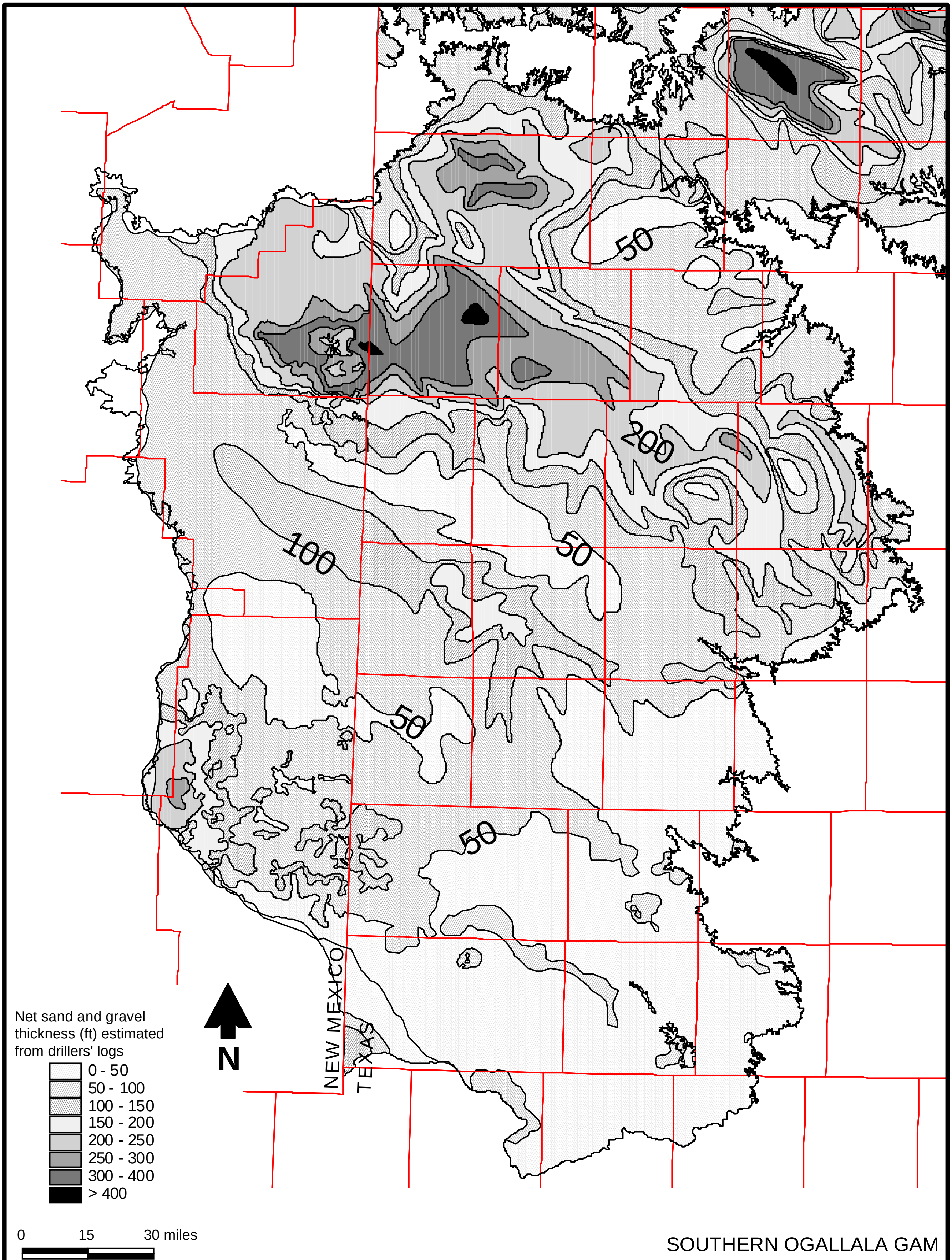

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SOUTHERN OGALLALA GAM

Net Thickness of Sand and Gravel in the Ogallala Formation

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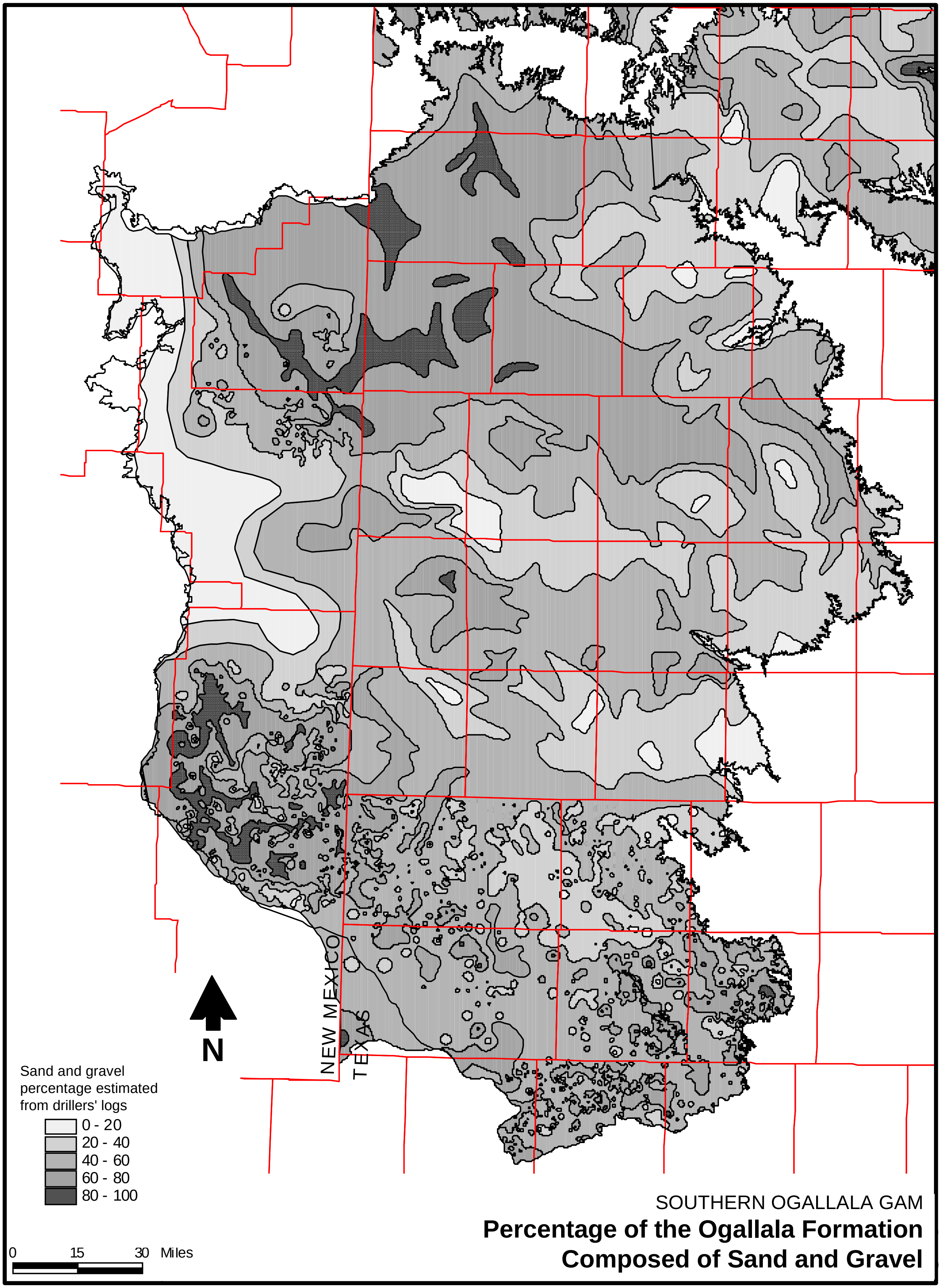
Figure 17



SOUTHERN OGALLALA GAM

Percentage of the Ogallala Formation Composed of Sand and Gravel

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Figure 18

The TWDB model, however, stops at the Texas-New Mexico state line.

Model cells are nearly 9 mi^2 (2.895 mi on a side). The model was calibrated to 1960 through 1979 hydrologic conditions. An overall recharge rate of 0.2 in/yr was applied, although it varied spatially. Enhanced recharge was used for specific calibration periods to simulate rising water levels in the central and southern counties of the Southern High Plains. Knowles and others (1984) had to reduce estimated pumping values in the TWDB irrigation use inventories significantly to achieve model calibration. Average specific yield and hydraulic conductivity used in the model are 15.6 percent and 68 ft/d, respectively (Knowles and others, 1984, p.60).

Peckham and Ashworth (1993) updated and revised the recharge values in the Knowles and others (1984) model based on results of the USGS modeling study (Luckey and others, 1986) and applied the updated model to predict future aquifer conditions. They documented the rise in water levels that occurred throughout much of the central and southern portions of the study area during 1980 to 1990 and attribute the rise to increased recharge and decreased pumping caused by increased precipitation during the study period and implementation of more efficient irrigation practices (Peckham and Ashworth, 1993, p.7).

Texas Tech Models

The original model of Knowles and others (1984), as updated by Peckham and Ashworth (1993), served as the basis for two modeling studies conducted by graduate students in the Engineering Department of Texas Tech University in Lubbock, Texas (Dorman, 1996; Harkins, 1998). Dorman (1996) converted the TWDB model, which had been constructed and run using the TWDB groundwater flow code GWSIM-III, to MODFLOW (McDonald and Harbaugh, 1988) format. Once the translation was verified, he conducted predictive simulations for 1990 through 2040. Harkins (1998) developed a customized version of MODFLOW that calculates pumping rate adjustments based on transmissivity and applied the model to estimate future aquifer conditions for 1990 through 2040 for several predictive scenarios.

SB1 Regional Water Planning Model

As part of the regional water planning process conducted under Senate Bill 1 (SB1), Texas Tech, under subcontract to HDR Engineering, Inc., developed a new regional groundwater flow model to evaluate groundwater availability over the period 2000 through 2050. The results of this model are summarized in the Region O Regional Water Plan (LERWPG, 2001), and the model is fully documented by Stovall and others (2001).

This model uses 1-mi^2 grid cells and includes the New Mexico portion of the aquifer, although model inputs for the New Mexico portion of the study area are based on Luckey and others' (1986) model. For the period 1985 through 1995, which is the calibration period, an automated calibration routine was used to estimate aquifer input parameters for the portion of the study area covered by the HPUWCD No.1. Initial conditions for 1985, the beginning of the calibration period, were based on observed data for that general time period. Initial conditions for the beginning of the predictive simulations for 1995 were updated based on observed water levels. Prescribed hydraulic head boundaries were applied along the eastern escarpment.

Average total recharge for Region O determined by Stovall and others is 2.75 in/yr. Predictive simulation results of this model indicate large regions of saturated thicknesses less than 20 ft throughout the Region O counties in the study area by 2050 (Stovall and others, 2001).

Comparison of GAM Model to Previous Models

The GAM model described in this report is significantly different from previous models for a number of reasons, including:

- A uniform grid of 1 mi^2 was used, and all aquifer boundary information and aquifer input parameters were developed for the finer discretization.

- Hydraulic conductivity used in the model was developed based on geologic interpretation of numerous well logs and specific-capacity tests in Texas and New Mexico.
- New detailed estimates of pumping for irrigated agriculture were developed for 1982 through 1997 using recent information on crop evapotranspiration and observations of metered pumping at selected locations.
- The model includes a predevelopment calibration and a subsequent transient calibration and verification for the full period of 1940 through 2000. Observed water levels at 80 locations distributed throughout the study area and all observed water levels for 1980, 1990, and 2000 were used to calibrate the model. Model verification was conducted using water levels at 10 additional locations.
- Data on base of aquifer, pumping locations and volumes, and other model inputs were collected and applied for the New Mexico portion of the study area.

Hydrogeologic Setting

This section describes the physical factors, either natural or man-made, that have a significant influence on groundwater flow in the aquifer. The hydrogeologic setting is based on (1) numerous previous studies, some conducted as early as the 1930s, as referenced in the text, and (2) additional studies conducted in support of this modeling effort. The additional studies include

- Monitoring of recharge at three field sites and associated modeling and analyses
- Estimation of irrigation pumping using modern techniques calibrated to and adjusted based on field data and observations
- Detailed geological and hydrogeological characterization of the aquifer using numerous well logs and aquifer tests available from records in state agencies
- Assemblage and analysis of a wide array of aquifer data such as water levels and spring flows

Hydrostratigraphy

Where Triassic units form the base of the Ogallala aquifer, the vast majority of water yielded to wells is from the Ogallala Formation. However, in some regions where Cretaceous units underlie the Ogallala Formation, significant volumes of groundwater are obtained from wells in the Edwards-Trinity (High Plains) minor aquifer in addition to, or in lieu of, water obtained from the Ogallala Formation.

Cretaceous units underlie all or significant portions of Bailey, Lamb, Hale, Floyd, Cochran, Hockley, Lubbock, Yoakum, Terry, Lynn, Gaines, Dawson, Borden, Martin, Andrews, Ector, Midland, and Glasscock Counties in Texas and southern Roosevelt and northern Lea Counties in New Mexico (fig. 15). Water levels in the Cretaceous units tend to be similar to those in the Ogallala Formation, but are generally less similar to those in the Triassic section (Dutton and Simpkins, 1986). Accordingly, the Ogallala and Cretaceous sections are considered to be interconnected as aquifer units and are grouped together as part of the High Plains aquifer (Gutentag and others, 1984) (fig. 12). In this report, the term Ogallala aquifer is used for consistency with TWDB terminology, but the term Ogallala aquifer is generally understood to be synonymous with the High Plains aquifer.

The uppermost unit of the Triassic Dockum Group, the Chinle Formation, is a massive shale with some interbedded sandstones that typically yields only very small quantities of water to wells. This is the “red bed” unit that forms the base of the Ogallala aquifer (figs. 13 and 14). Many of the water wells in the study area are drilled through the entire aquifer thickness until the Chinle Formation is reached.

Structure

The study area overlies much of what is known as the Permian Basin (fig. 19). The Permian Basin area includes several Paleozoic structural elements, basins that subsided and were filled in with sediment from 570 million to 245 million years ago (Dutton and others, 1982; Bassett and Bentley, 1983). Structural as well as stratigraphic traps in those basins form reservoirs that contain huge oil and gas deposits. The basins are separated by structurally positive areas, including arches and platforms, that did not subside as much as did the basins.

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

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

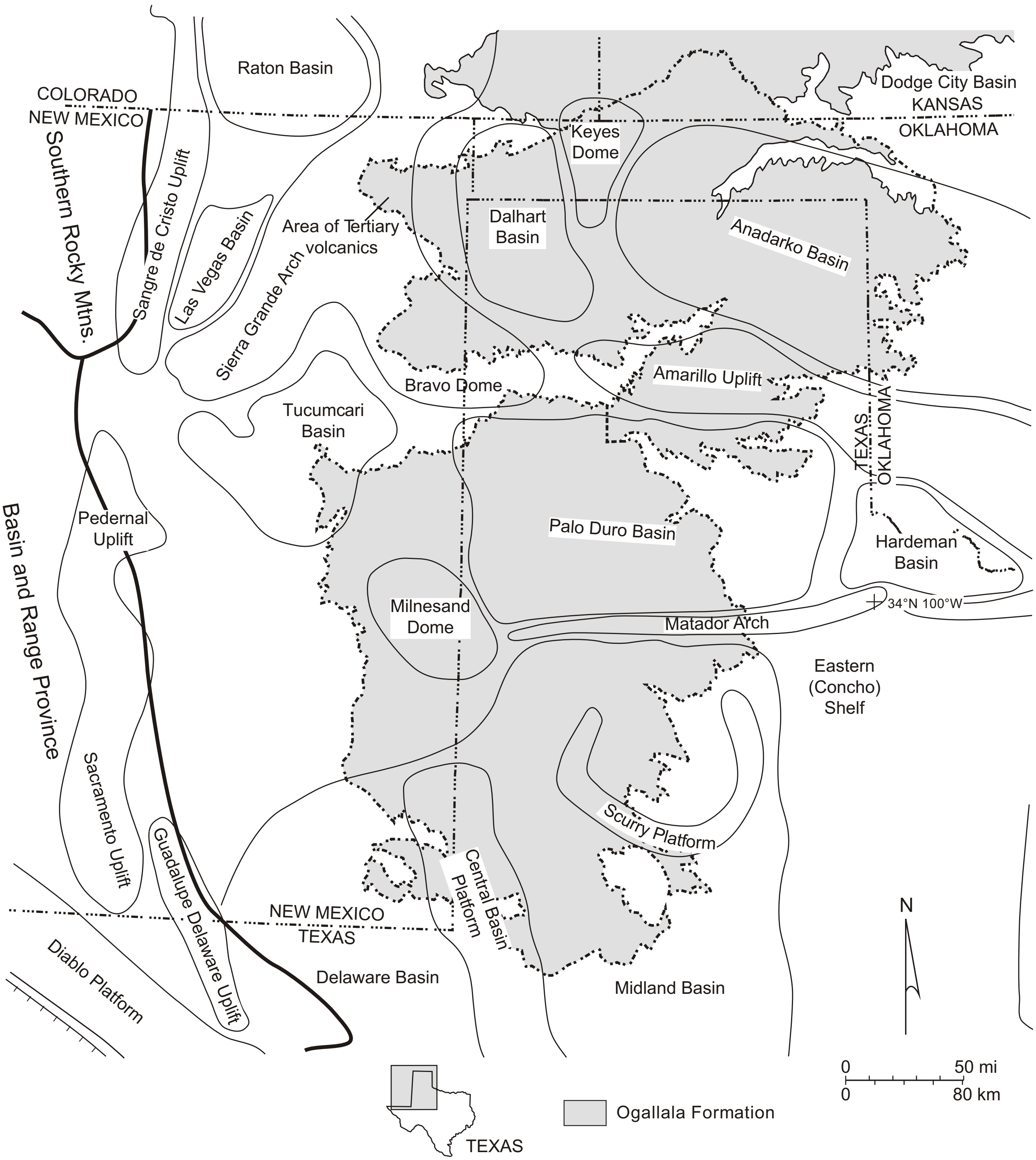
Since the regional uplift, groundwater circulation from the Ogallala sediments downward into the underlying Permian section has resulted in dissolution of Permian salt beds. Ground-surface subsidence and collapse into the salt caverns resulted in locally thick accumulations of Ogallala sediment. Salt-dissolution played a major role in the formation of the Pecos and Canadian River Basins and in the retreat of the High Plains Caprock Escarpment, and is an active geological process in Modern time (Gustavson and Finley, 1985; Osterkamp and Wood, 1987). The area of the Ogallala aquifer most affected by salt dissolution is around the periphery of the modeled area, lying in a narrow zone beneath the eastern and western High Plains escarpments and below and adjacent to the Canadian River valley.

The bottom elevation (aquifer bottom) for the GAM model was developed using the base of the Ogallala aquifer as mapped in several previous studies:

- For counties or portions of counties in Texas that are part of the HPUWCD No. 1, the base of aquifer maps by McReynolds (1996a through 1996o) were used.
- For counties or portions of counties in Texas not covered by the HPUWCD No. 1, the base of aquifer maps from Knowles and others (1984) were used.
- For much of New Mexico, the base of aquifer map provided by Cronin (1969) was used.
- For the far western extent of the aquifer in New Mexico and throughout much of central and western Roosevelt County, the base of aquifer map from Weeks and Gutentag (1981) was applied.

The base elevations from the various sources were digitized, checked and georeferenced using a geographic information system (GIS). However, no effort was made to “match” the contours from the various references at the Texas-New Mexico state line. At many locations the bottom elevations match up quite well, while at other locations there are significant differences. Because the observed elevations were averaged over 1-mi^2 grid cells, any significant changes in aquifer base elevation across the state line were averaged out so that abrupt changes would not occur. The averaging process is presented in the Model Parameters section.

The base elevation contours are presented in Figure 20. A number of paleochannels are evident in the base of aquifer contour plot. One of the largest paleochannels exists along the borders of Castro and Lamb and Parmer and Bailey Counties and extends into New Mexico. The withdrawals for irrigated agriculture in the region overlying this paleochannel are very large, mainly because of the large saturated



Note:
Modified from Ruppel (1983) and Howard and Williams (1972)

SOUTHERN OGALLALA GAM

Regional Geologic Structure in the Texas Panhandle and Eastern New Mexico

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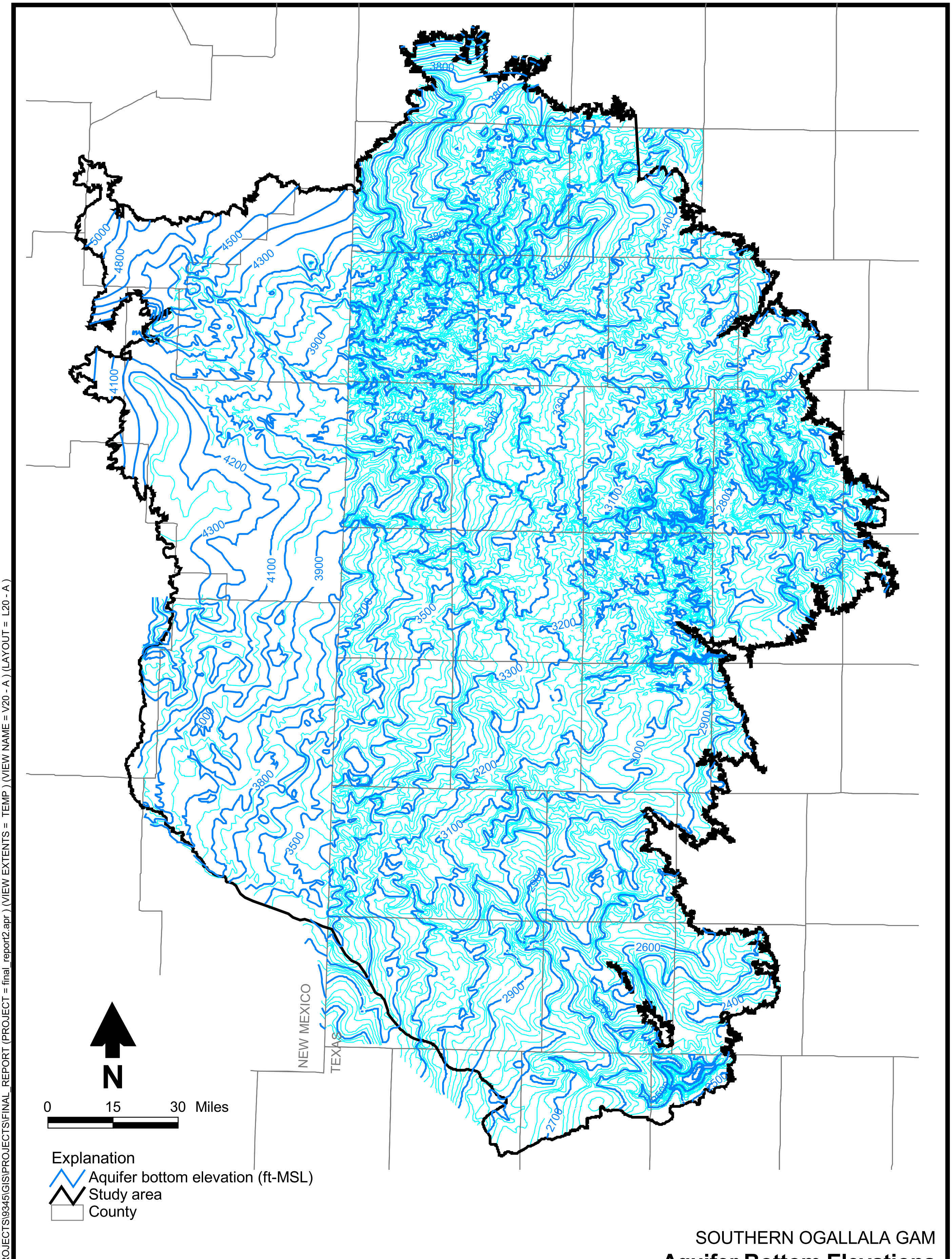
Figure 19



SOUTHERN OGALLALA GAM

Aquifer Bottom Elevations

1-30-03

Figure 20

thickness and high-permeability sediments that exist there.

At some Texas locations in the vicinity of salt lakes, aquifer bottom elevations were not available. In these cases, the base elevation contours adjacent to the lakes were interpolated across the lake basins and subsequently compared to land surface. At most of the salt lakes, the interpreted base of aquifer would be above or close to land surface. In part because of this result, the salt lake basins are treated as regions of no flow in the model, as discussed further in the Rivers, Streams, Springs, and Lakes section.

Water Levels and Regional Groundwater Flow

Regional groundwater flow in the Southern Ogallala aquifer generally follows the regional slope of the land surface, which is to the southeast. Locally, the direction of groundwater flow is influenced by the presence of paleochannels and springs, although the effects of these features are generally not discernable on regional-scale maps of the water table. Groundwater tends to flow toward each of these features because paleochannels are generally zones of higher transmissivity and springs are points of groundwater discharge.

Water level information for Texas was obtained from the TWDB database (at http://www.twdb.state.tx.us/data/waterwell/well_info.html) and from the Sandy Land, South Plains and Mesa UWCDs (annual measurements made by the HPUWCD No.1 are automatically incorporated into the TWDB database). For the New Mexico portion of the study area, water levels were obtained from the USGS Ground-Water Site Inventory (GWSI) at http://waterdata.usgs.gov/tx/nwis/gwsi.

Figure 21 shows the water table within the study area representative of aquifer conditions prior to significant groundwater development. This figure was constructed based primarily on observed water levels for 1940 or earlier, but in some areas with limited groundwater withdrawals and relatively constant water levels, later data were used. As shown in Figure 21, groundwater flow under predevelopment conditions was generally to the southeast at an average hydraulic gradient of about 0.002 ft/ft.

Figures 22 and 23 show the water table for 1990 and 2000, respectively. These maps illustrate that, for the most part, the direction of regional groundwater flow is similar to predevelopment conditions, although water levels have declined throughout much of the study area, particularly in the northern counties. On a regional scale, water levels in the central and southern counties are for the most part fairly similar to predevelopment conditions. Some of the differences between the predevelopment and 1990 and 2000 water level contour maps are due to the greater density of observed data points for the later periods.

Figure 24 illustrates the locations of some of the wells for which historical long-term hydrographs were prepared as part of this study. Representative hydrographs for several locations are presented in Figures 25 through 30.

Figures 25 and 26 illustrate fairly typical hydrographs of wells in the northern part of the study area in or near regions of heavy agricultural pumping. Significant drawdown has occurred through time (generally 150 ft or more) at each of these locations, and the drawdown continues today, although at a reduced rate in some locations (e.g., Deaf Smith County).

Figures 27 and 28 illustrate typical hydrographs for the central and southern counties in or near irrigated areas. These hydrographs show that water levels in these regions have been fairly constant through time, fluctuating generally about 20 ft or less, at least since the mid-1960s or so. Because the saturated thickness and in some cases the hydraulic conductivity of the aquifer are smaller in these areas as compared to the northern part of the study area, farmers in this area often cannot pump as much water as those to the north. In most of these counties, the Cretaceous section (Edwards-Trinity aquifer) can form a significant component of the Ogallala aquifer (figs. 13 through 15).

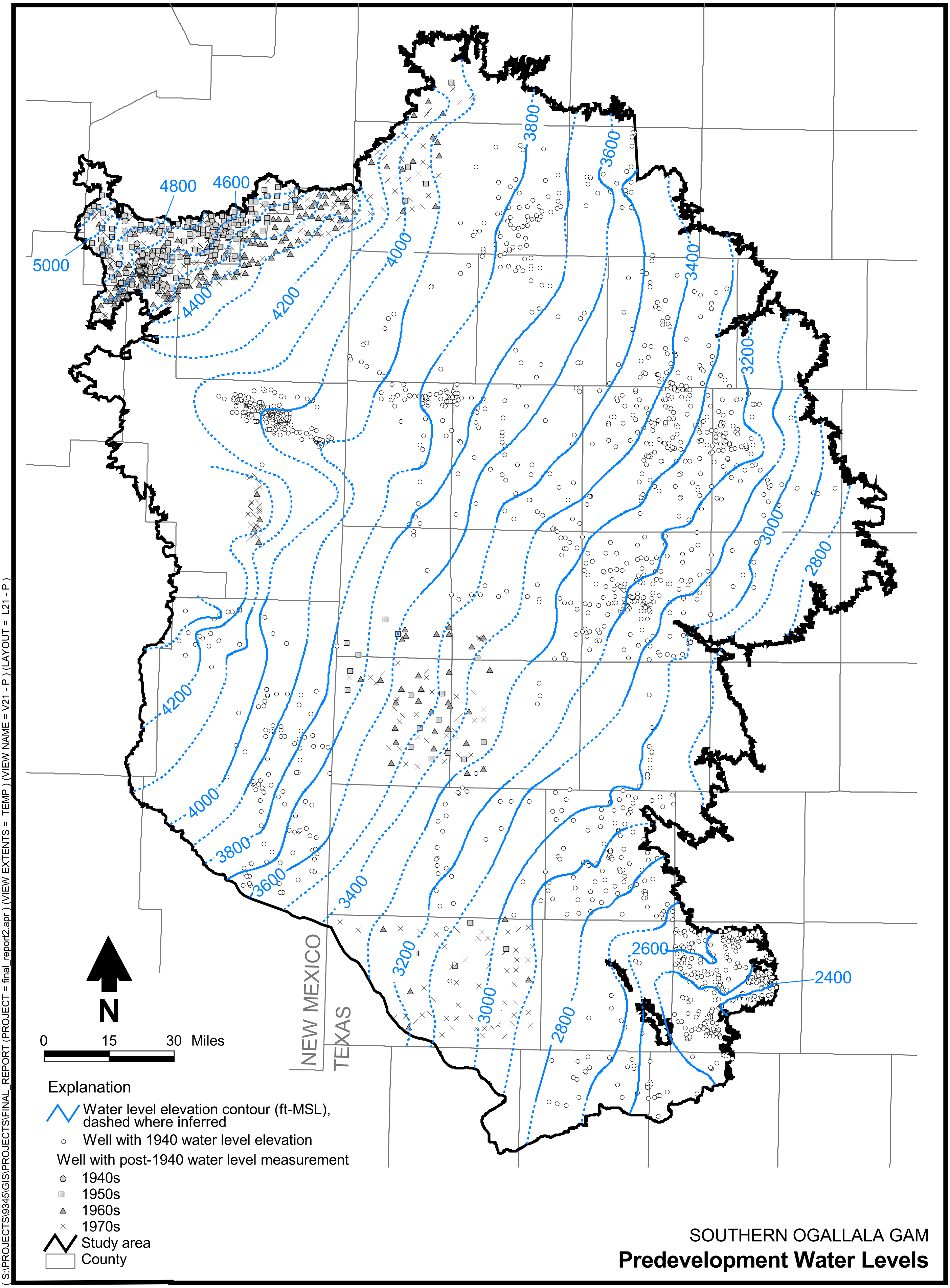


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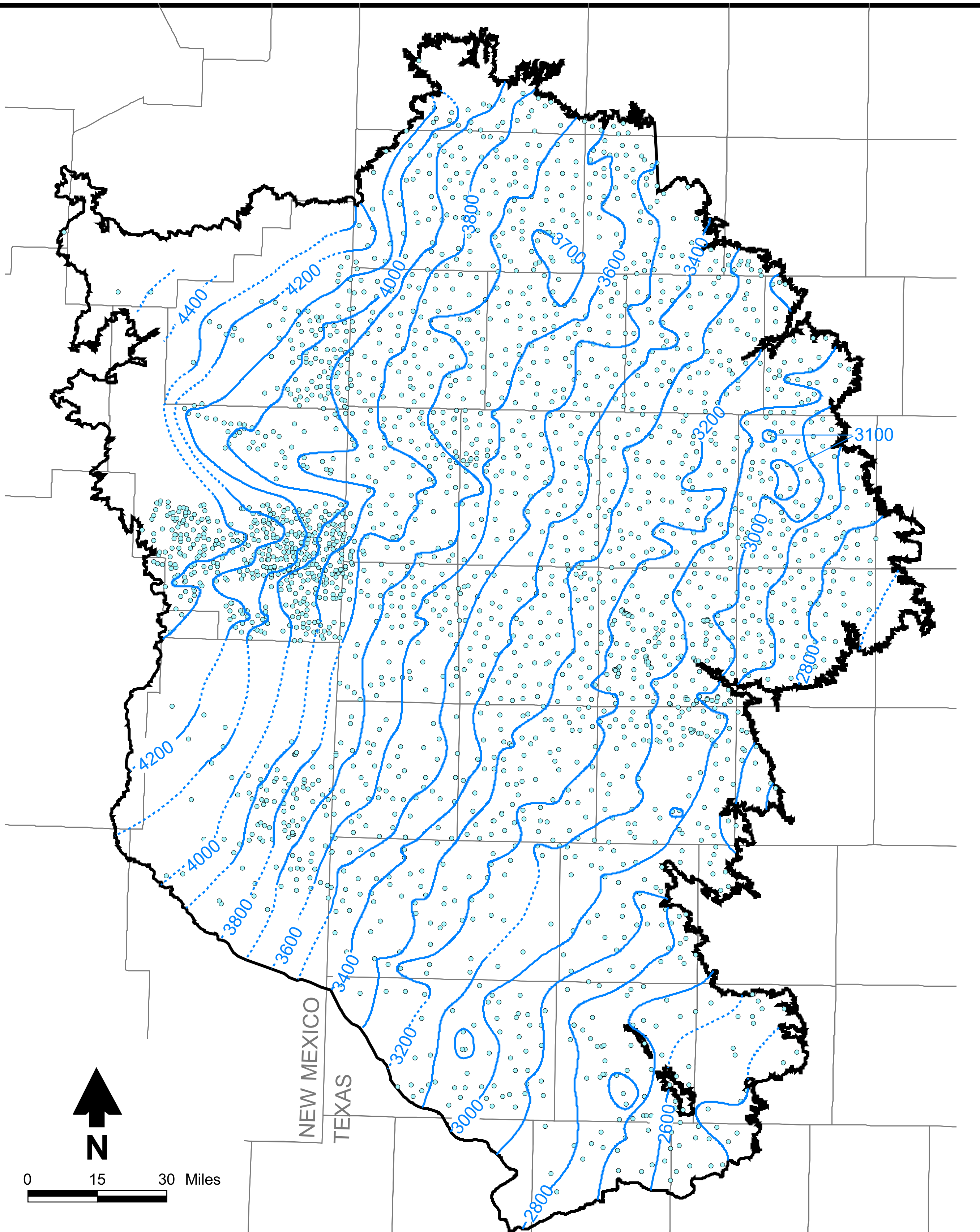
Figure 21



Explanation
Water level elevation contour (ft-MSL), dashed where inferred
Well with water level elevation
Study area
County

SOUTHERN OGALLALA GAM

Water Level Elevations, November 1989 - April 1990

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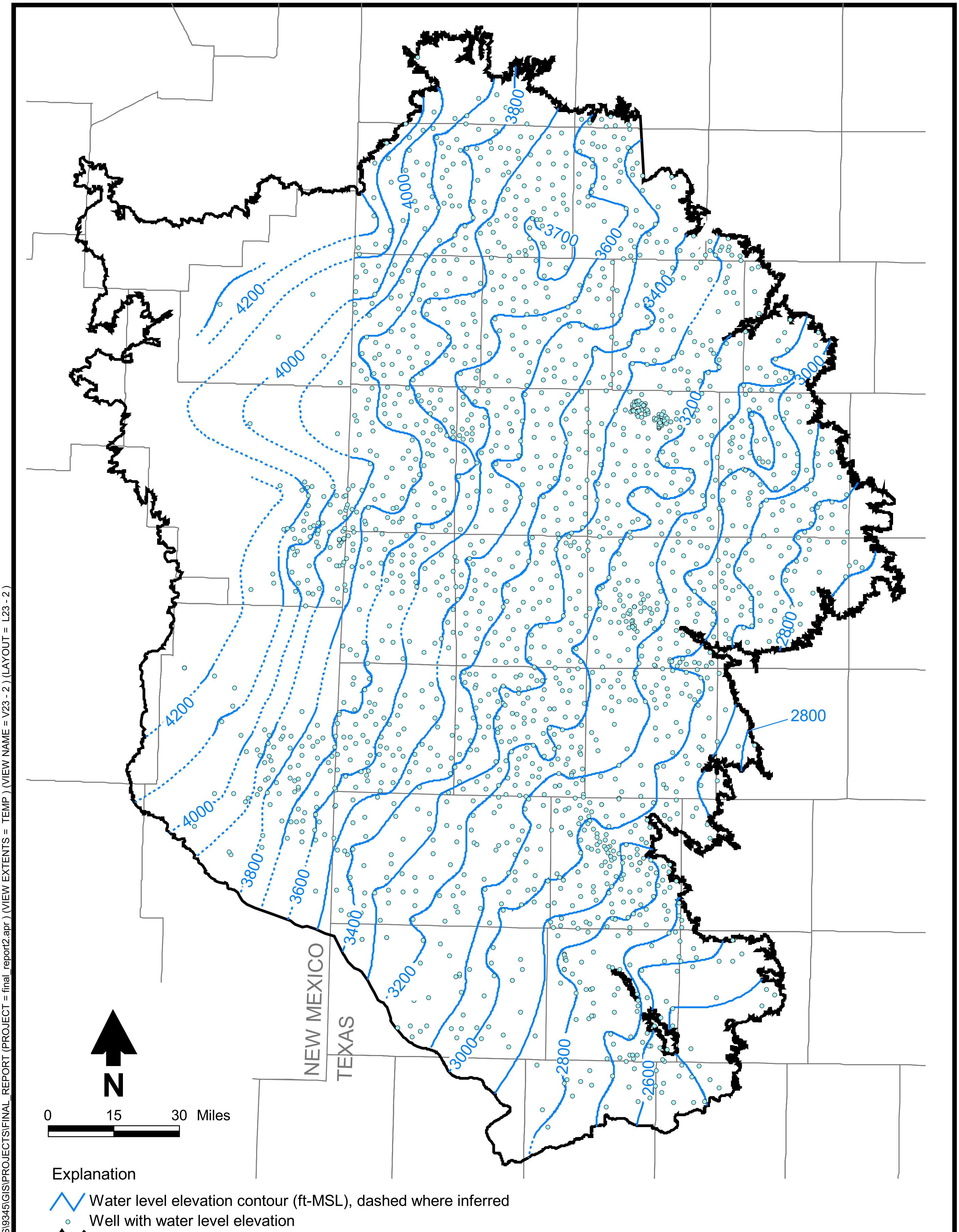
Figure 22



SOUTHERN OGALLALA GAM

Water Level Elevations, November 1999 - April 2000

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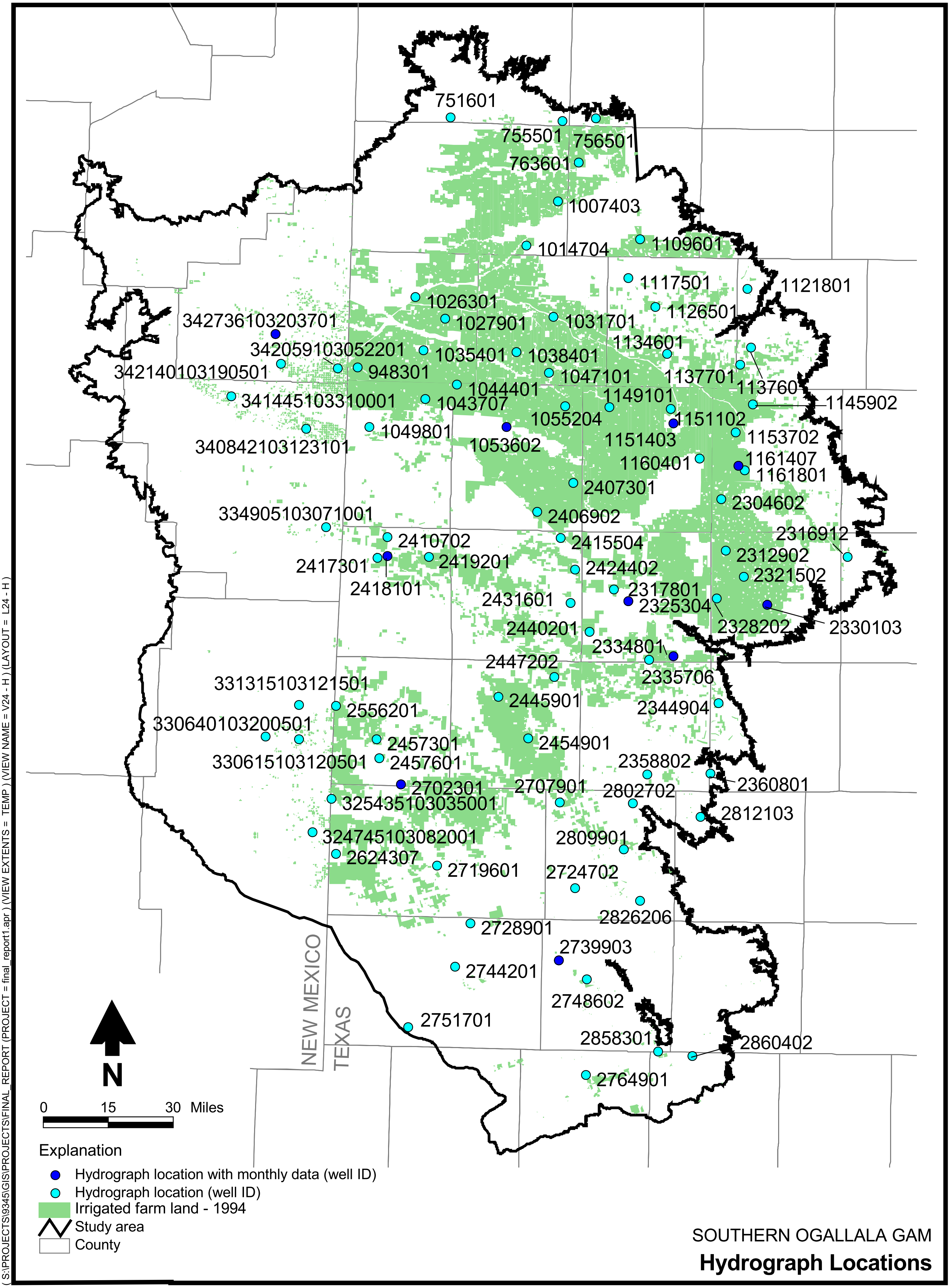
Figure 23



SOUTHERN OGALLALA GAM

Hydrograph Locations

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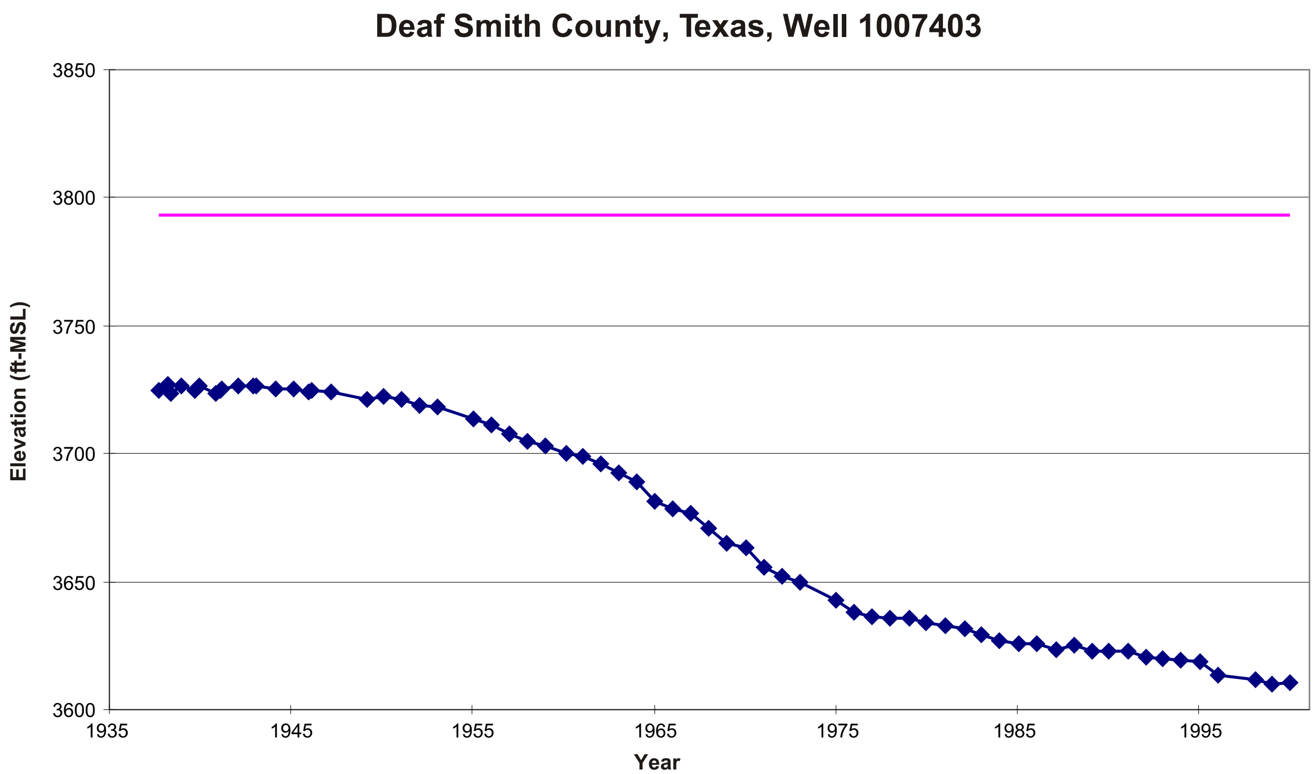
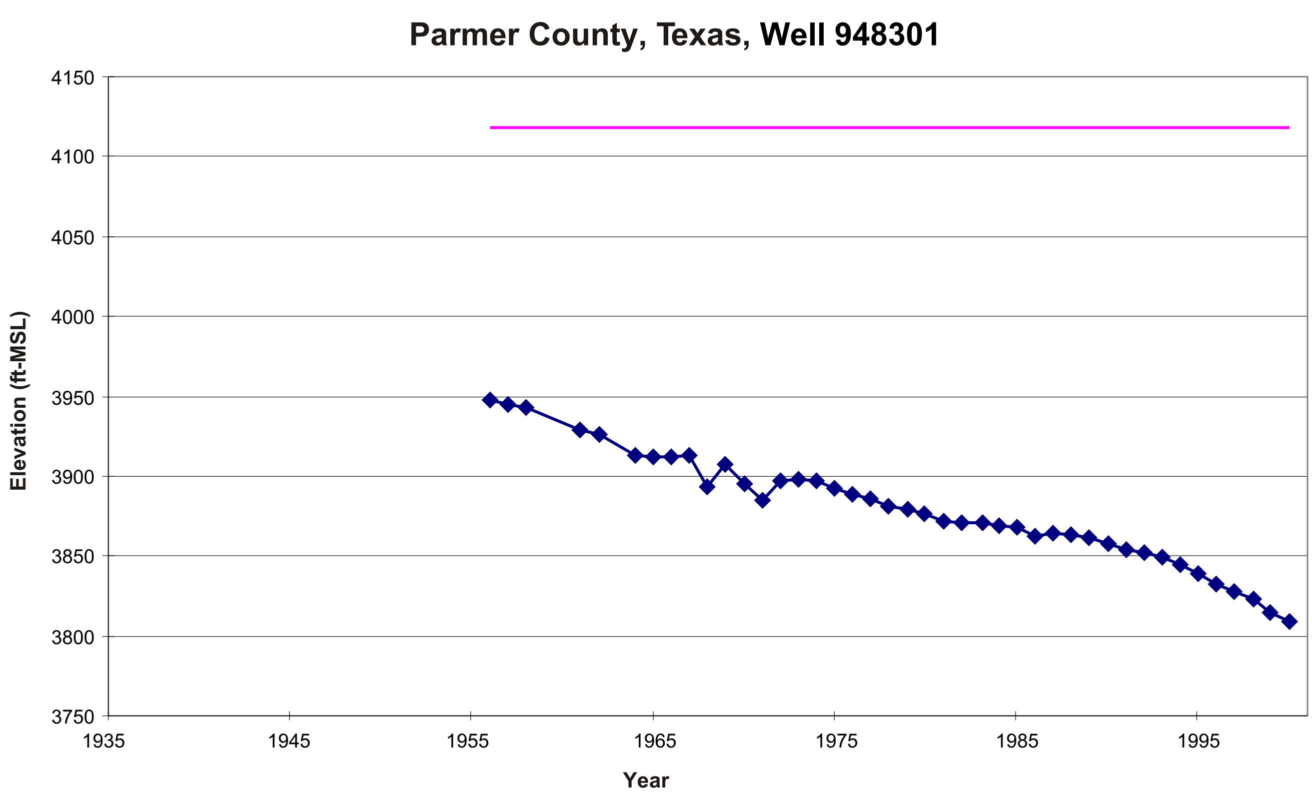
Figure 24





Explanation

Water level

Land surface

SOUTHERN OGALLALA GAM

Observed Water Levels in Deaf Smith and Parmer Counties

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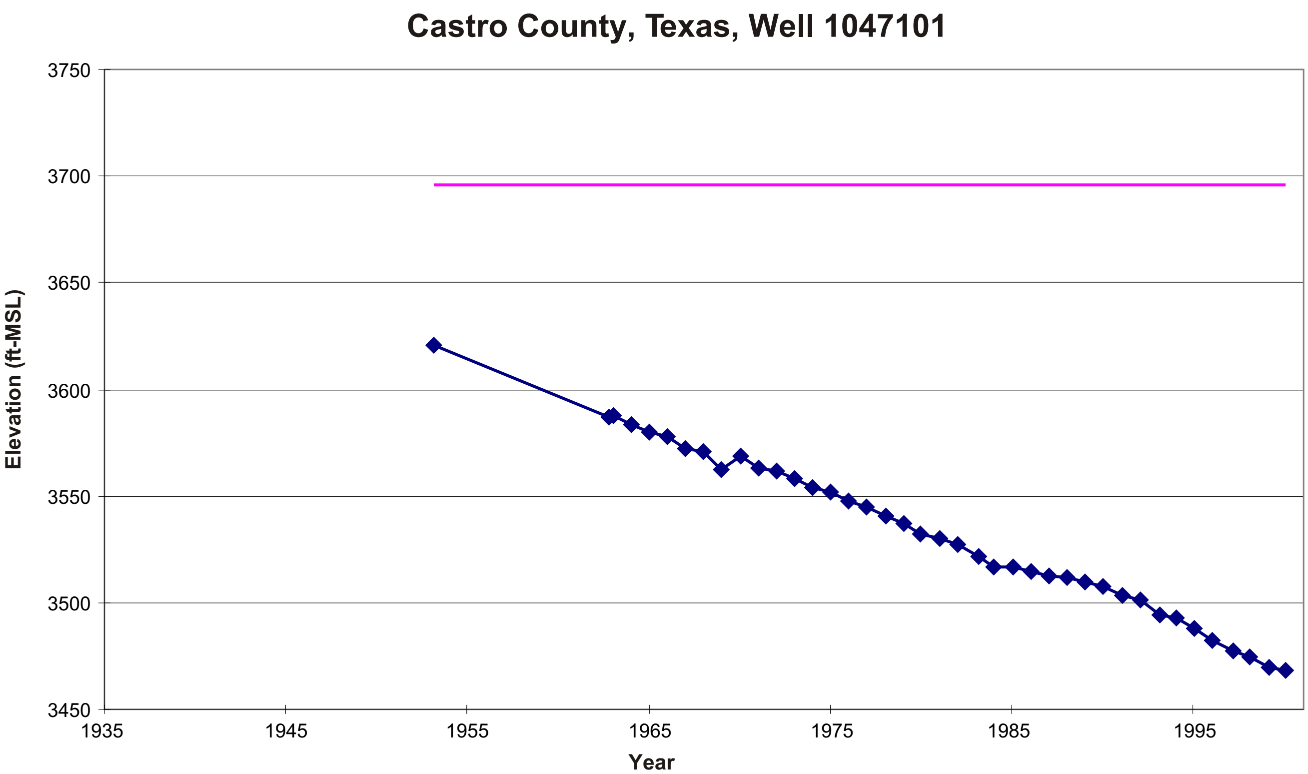
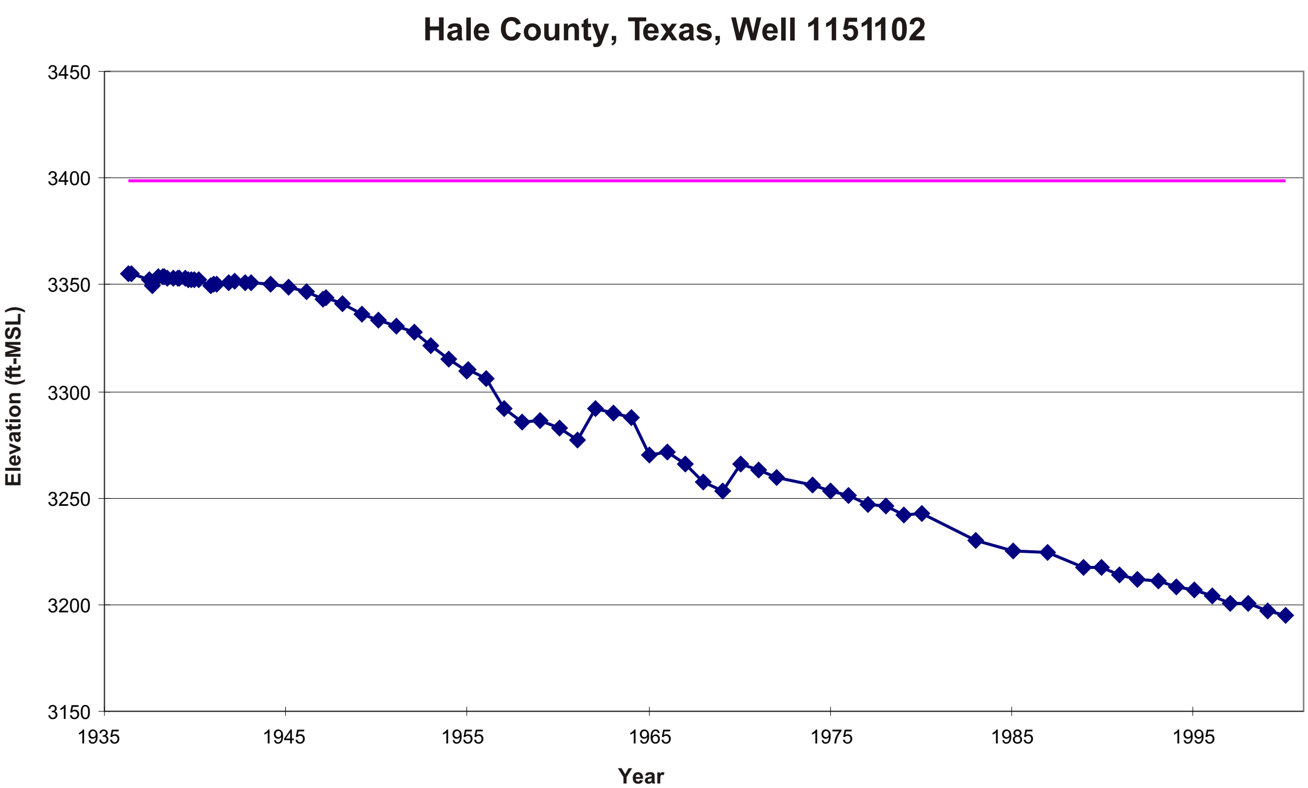
Figure 25





Explanation

Water level

Land surface

SOUTHERN OGALLALA GAM

Observed Water Levels in Castro and Hale Counties

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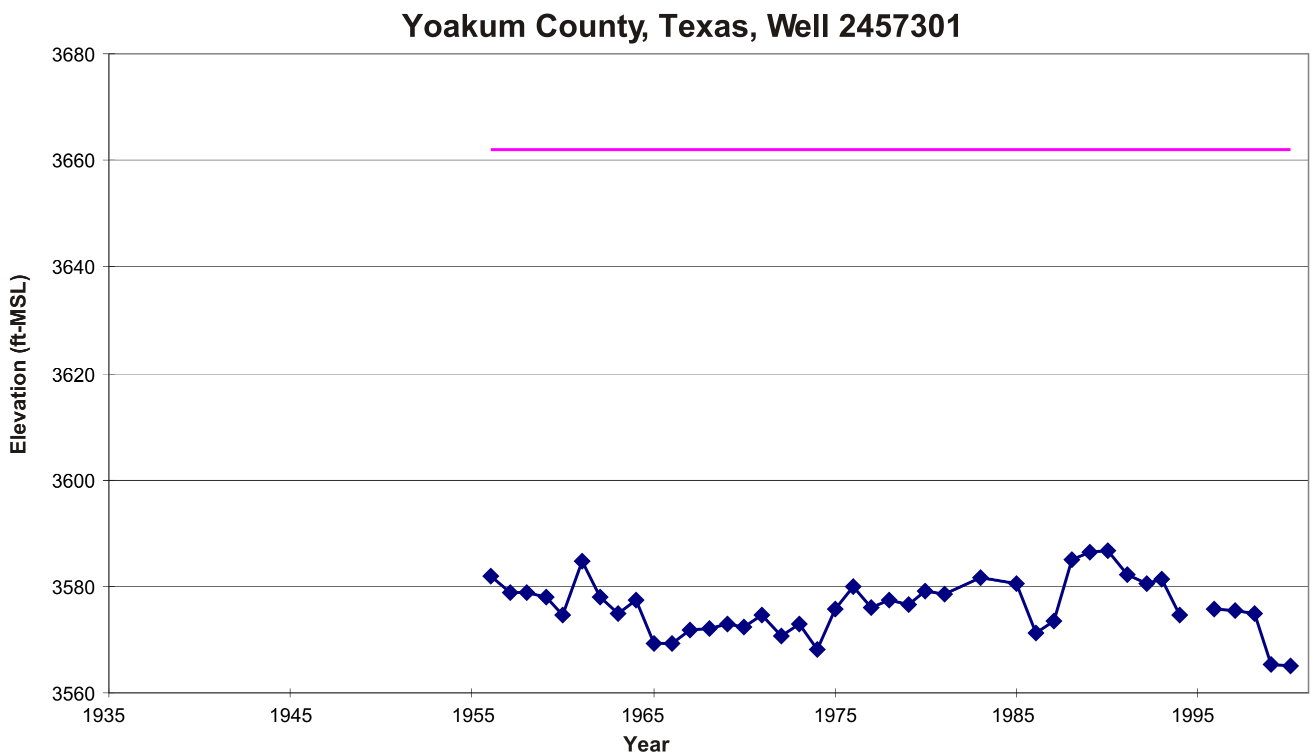
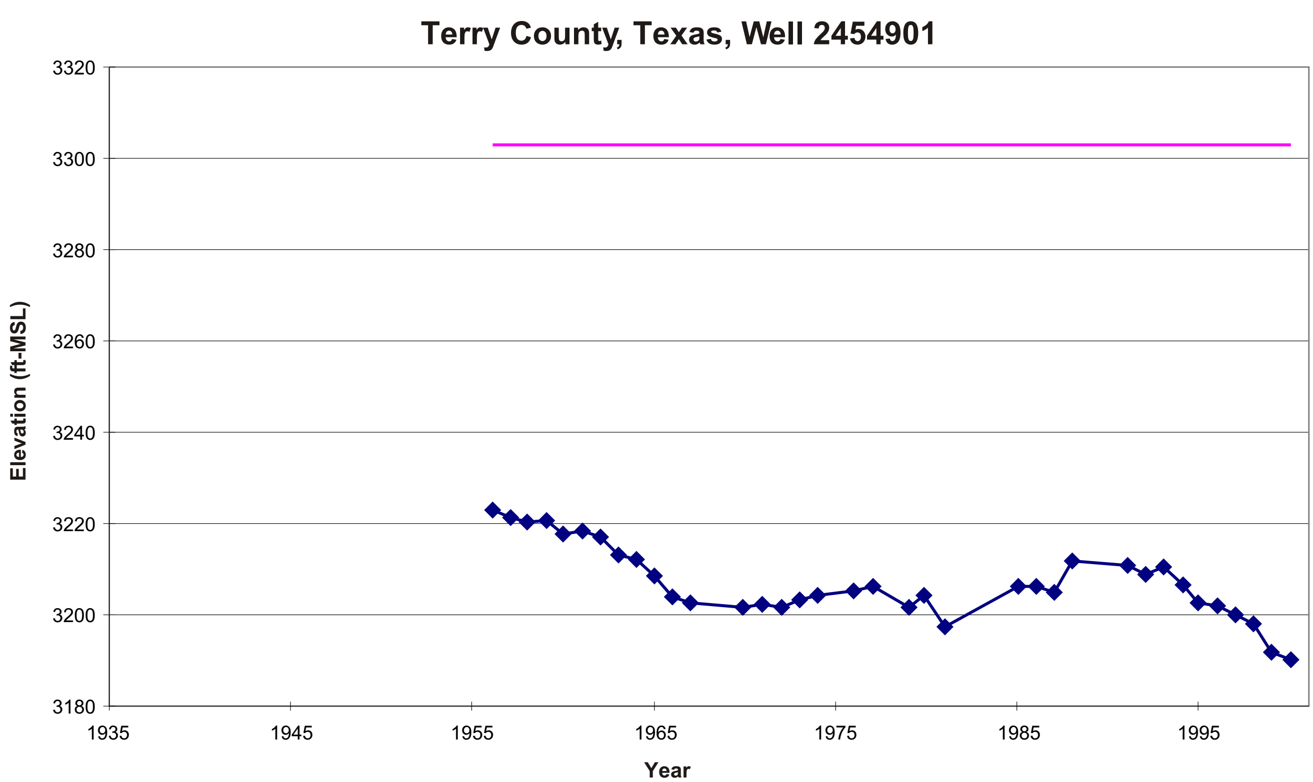
Figure 26





Explanation

Water level

Land surface

SOUTHERN OGALLALA GAM

Observed Water Levels in Yoakum and Terry Counties

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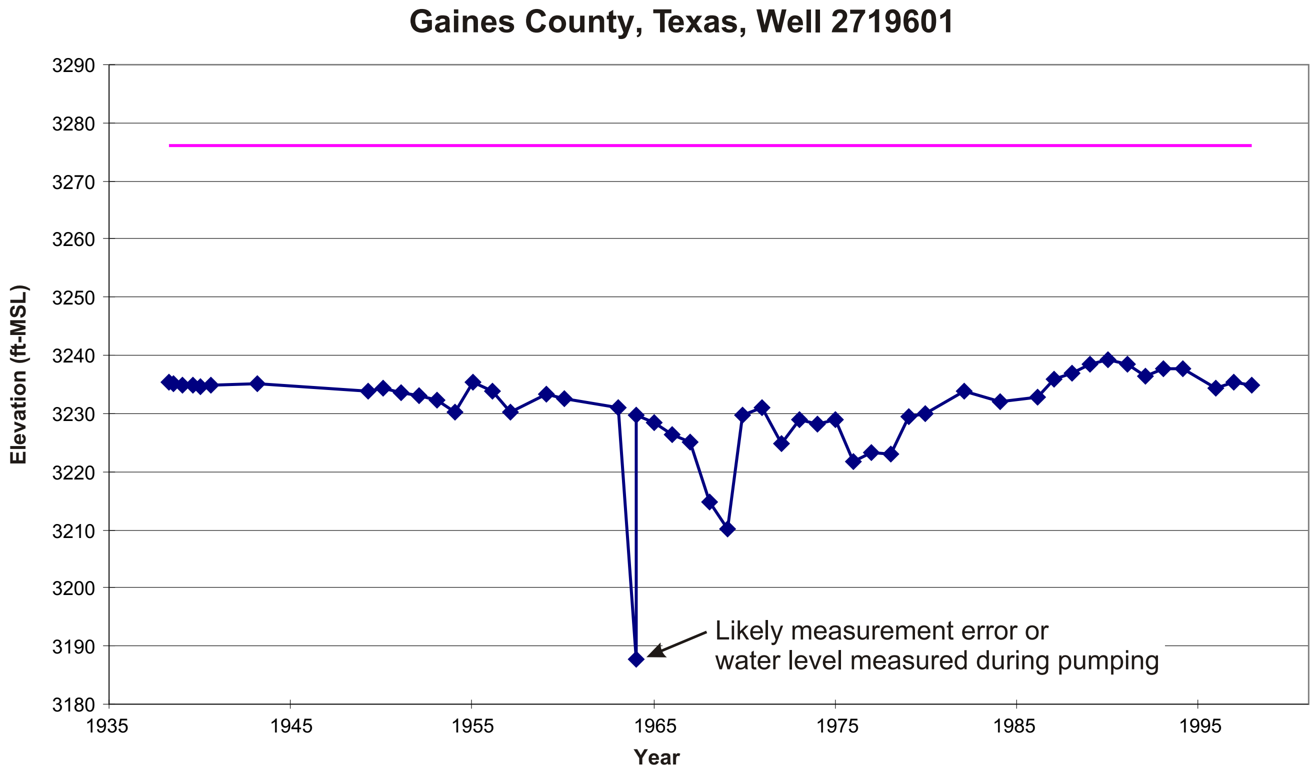
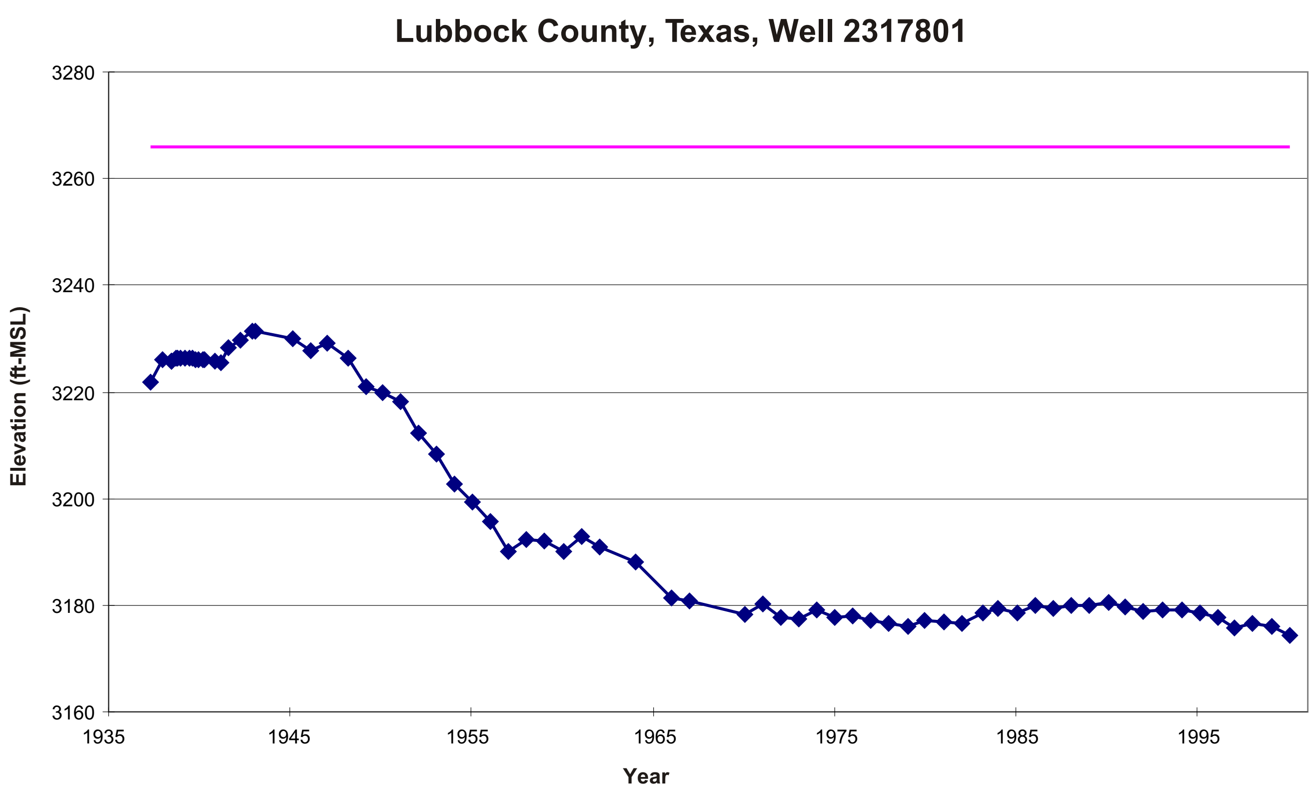
Figure 27





Explanation

Water level

Land surface

SOUTHERN OGALLALA GAM

Observed Water Levels in Gaines and Lubbock Counties

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1-30-03

Figure 28

It appears that in many of these areas an approximate equilibrium has developed over the past 30 to 40 years between recharge and groundwater pumping. Recharge occurs from precipitation and irrigation return flow, and groundwater pumping is a function of irrigated acreage, crop type, irrigation methods, and physical limitations of the aquifer.

Relatively stable water levels (fluctuations on the order of about 20 ft or less) are also observed in a number of northern counties that include the eastern or northern escarpments, and where extensive irrigated agriculture has not been practiced. Some examples of these areas include Oldham County, northern Briscoe County, and Dickens County.

Figures 29 and 30 illustrate several hydrographs for the central and southern counties in non-irrigated areas where water levels have risen consistently through time. Although these figures contain hydrographs for only Lynn and Dawson Counties, some hydrographs in Gaines, Terry, Garza, Borden, Midland, and Glasscock Counties also show increasing water levels through time on the order of 15 to 30 ft or more. Water level rises in these areas are believed to be a result of enhanced recharge due to changes in land use (i.e., farming), although no direct information other than the observed hydrographs is available to support this conclusion.

Nevertheless, enhanced recharge beneath agricultural fields has likely occurred across much of the study area, particularly in the central and southern counties, where the soils are more permeable than in the north. In the irrigated areas, the effects of the enhanced recharge are offset by agricultural pumping, resulting in the fairly steady behavior evident in the hydrographs.

The three hydrographs provided for Dawson County illustrate this point. Figure 30 shows two hydrographs for portions of Dawson County that are far removed from areas of significant irrigated acreage, while Figure 29 shows a hydrograph for a well in Dawson County adjacent to an irrigated region (see Figure 24 for well locations). It is evident that the well in the irrigated region has a fairly steady water level, while the wells in the dryland farming regions have rising water levels. There is no apparent reason why recharge from precipitation would be substantially different among these three regions, as the soil types and average annual rainfall for all three locations are similar. Recharge is discussed in more detail in the following section.

Recharge

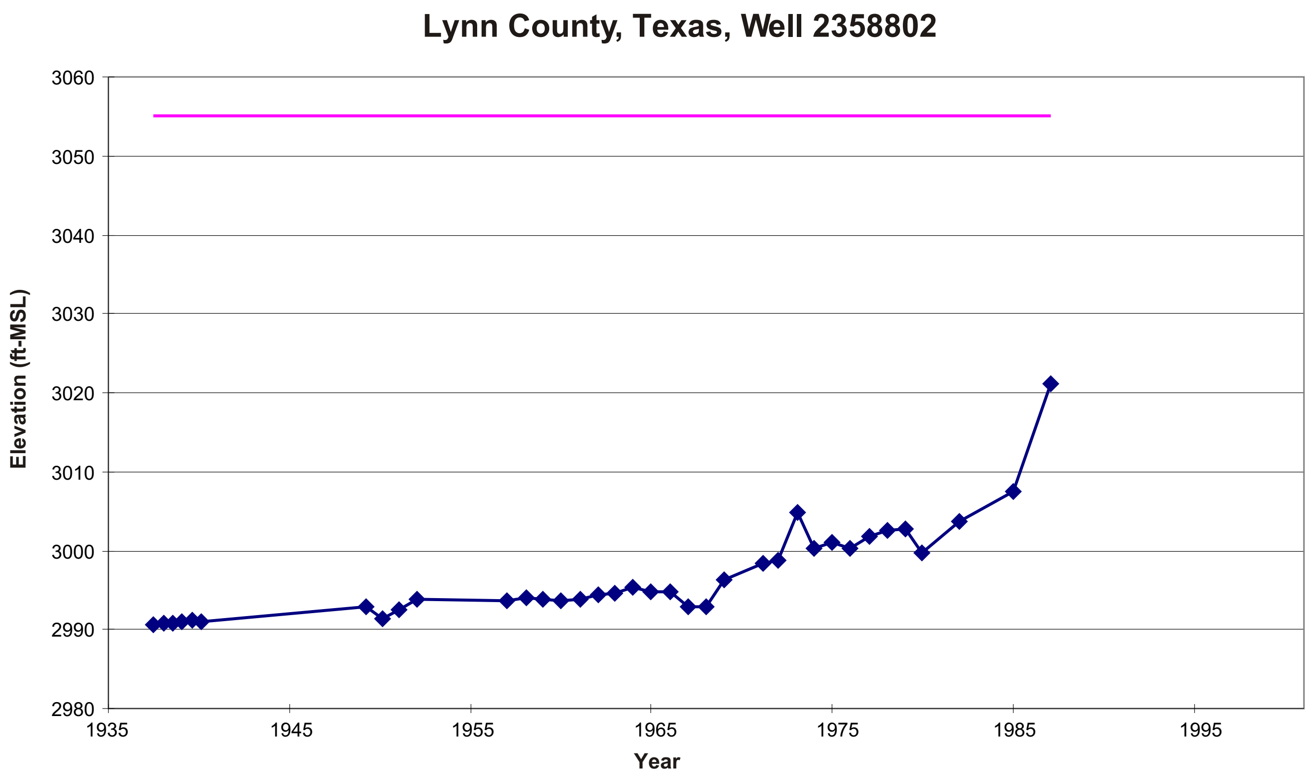
The primary sources of recharge to the Southern Ogallala aquifer are playas, headwater creeks, and irrigation return flow. The creeks (draws) are ephemeral and flow only after heavy rainfalls. Playas (also called wet-weather lakes) hold water for various lengths of time after rainfall events, but generally do not contain water year-round. Recharge in inter-playa settings under natural conditions is negligible, as evidenced by high chloride concentrations in the unsaturated zone (Aronovici and Schneider, 1972; Scanlon and others, 1997). The vast majority of recharge on the Southern High Plains, therefore, occurs from playas or beneath agricultural fields.

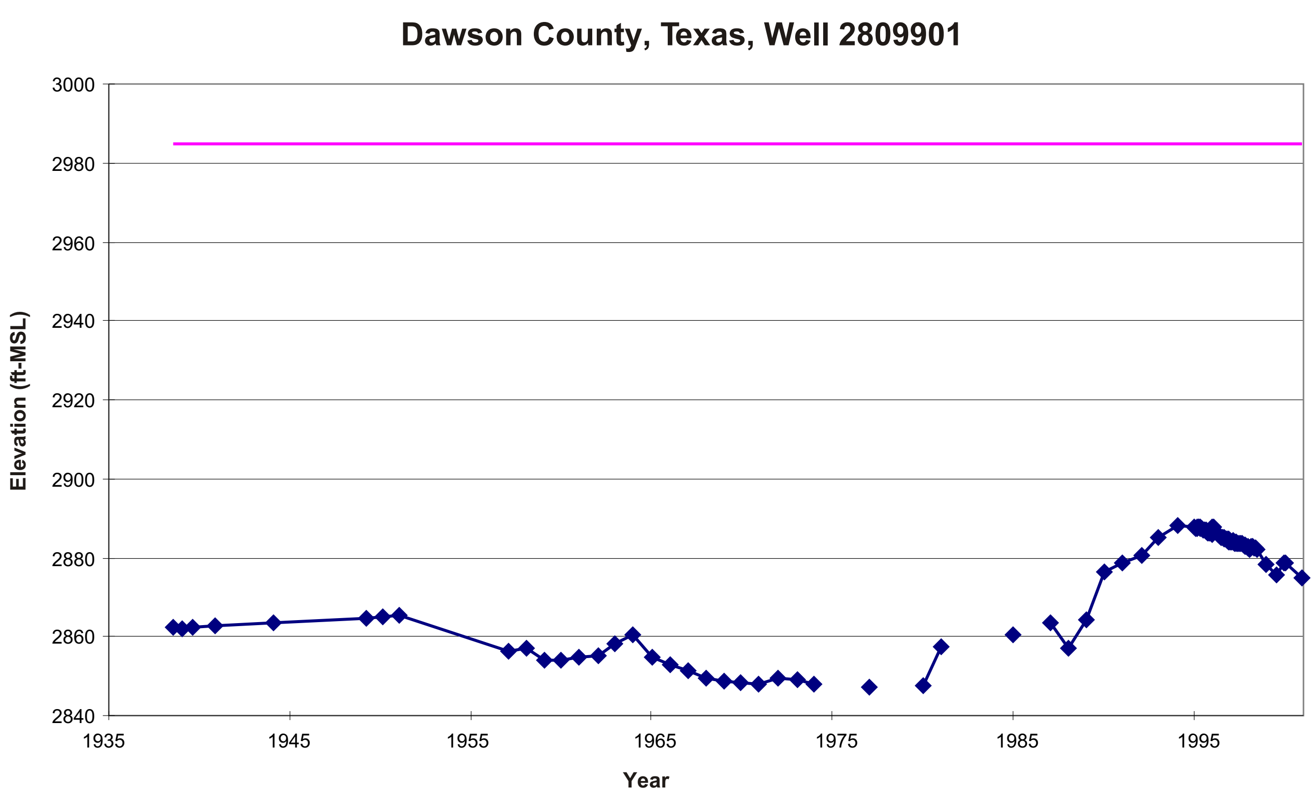
A number of fairly recent studies evaluated recharge at playas, but very few direct measurements have been made of recharge beneath agricultural fields, either from irrigation return flow or direct precipitation on fields that are dryland farmed.

As part of this study, the Bureau of Economic Geology (BEG) in cooperation with the USGS equipped three test wells with instruments to evaluate recharge. Two of the wells were located adjacent to irrigated farmland, and one well was at a site that had never been farmed (fig. 31). None of the test wells are in or near a playa. This section summarizes the results of the field recharge study, as well as those of some other recharge studies. Further detail regarding some of these studies is provided in Appendix A.

Previous Studies

Recharge rates estimated from tritium concentrations in the unsaturated zone beneath individual playas range from 3 to 4.7 inches per year (in/yr) (Scanlon and others, 1997; Wood





Explanation

Water level

Land surface

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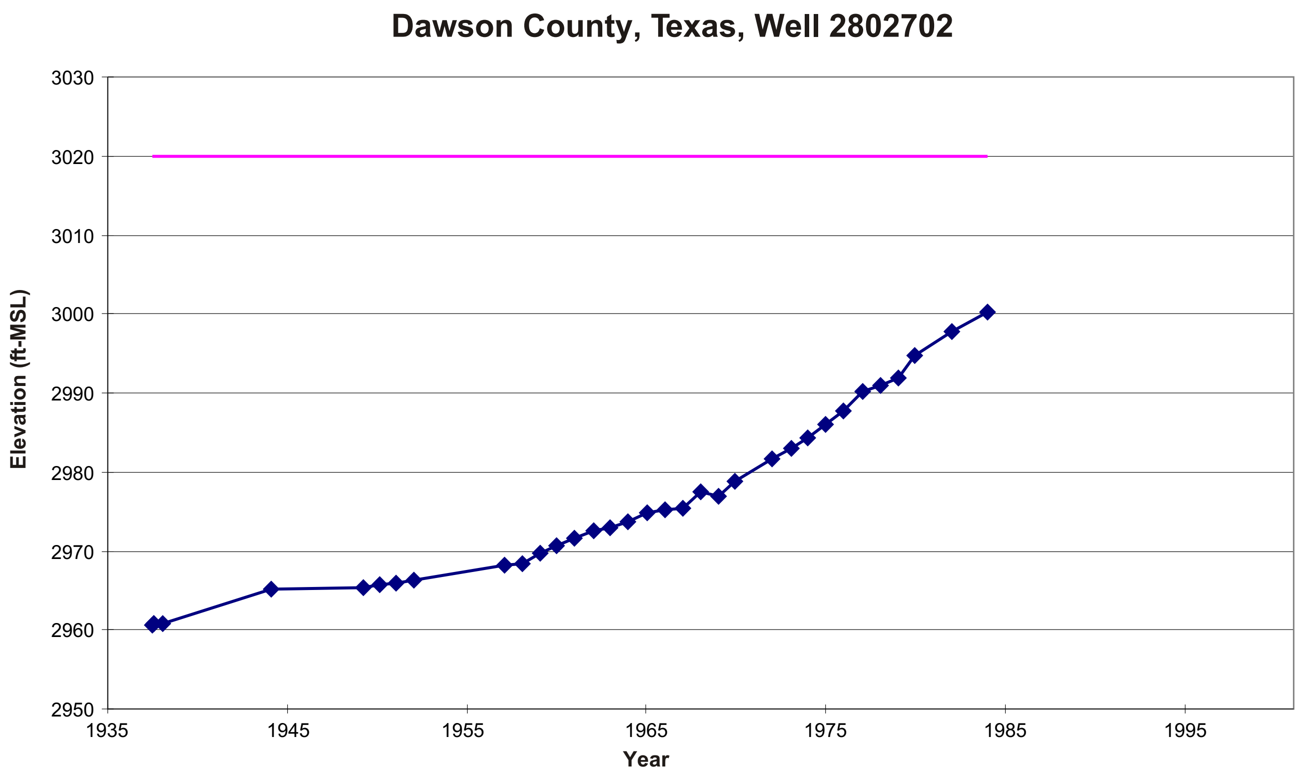
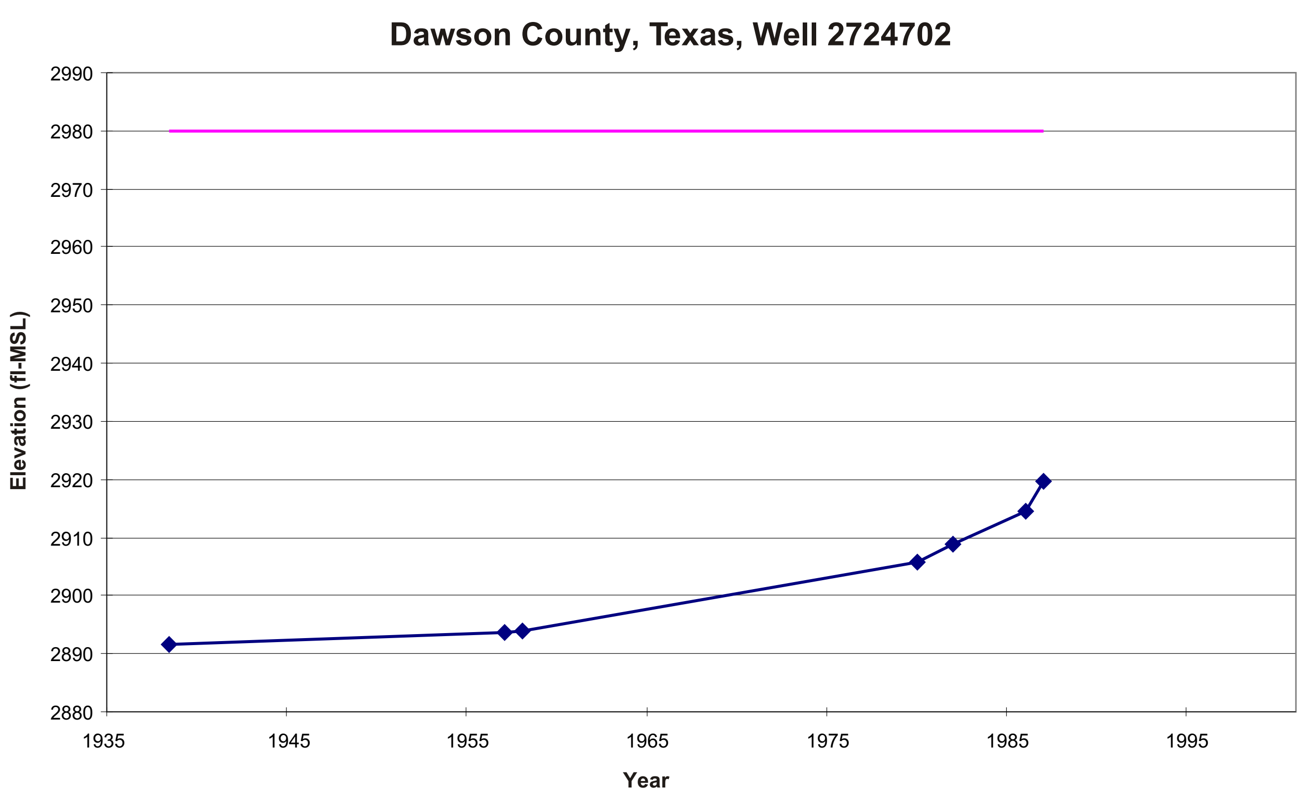
SOUTHERN OGALLALA GAM

Observed Water Levels in Lynn and Dawson Counties

1-30-03

Figure 29





Explanation

Water level

Land surface

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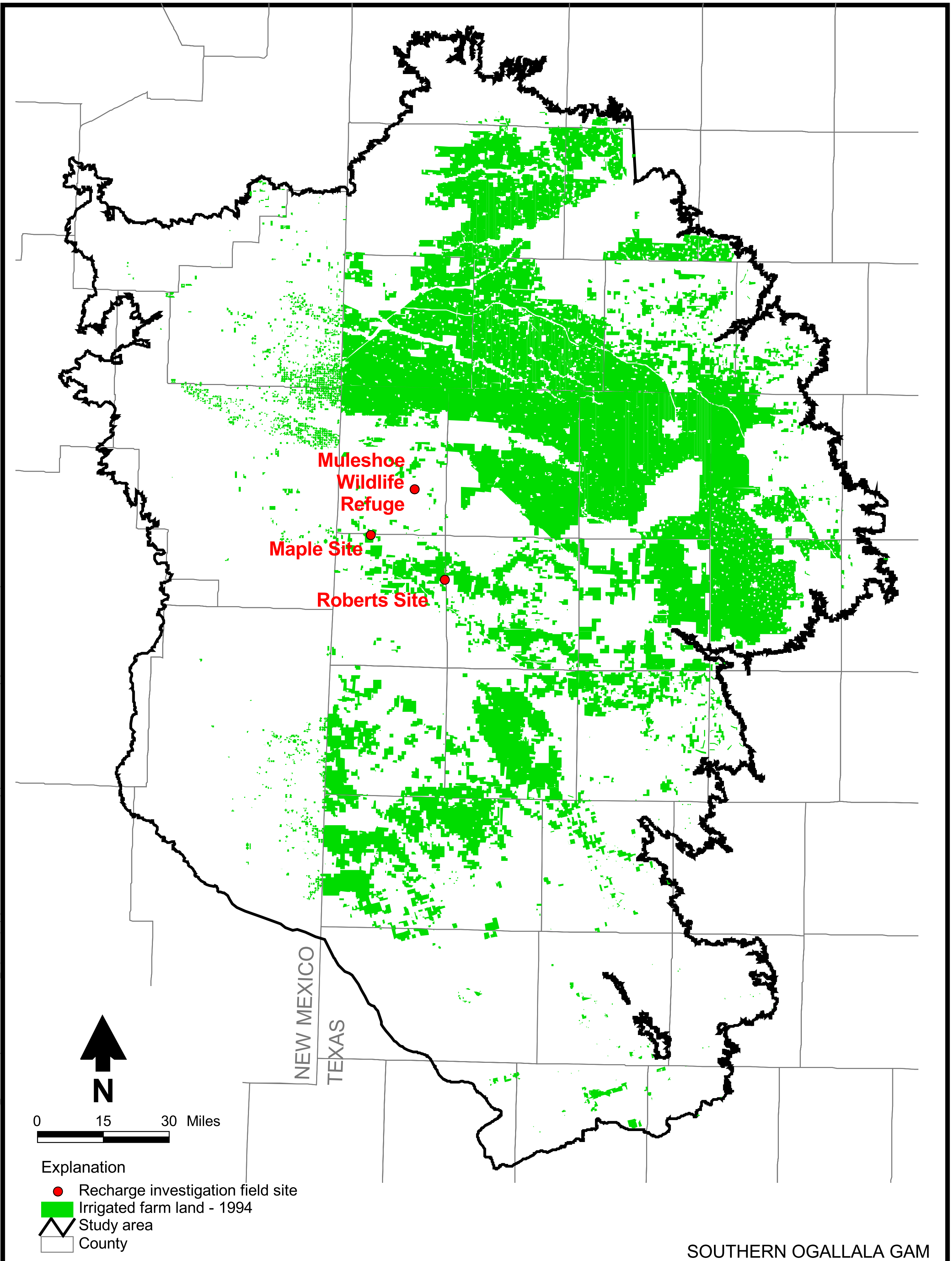
SOUTHERN OGALLALA GAM

Observed Water Levels in Dawson County

1-30-03

Figure 30



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SOUTHERN OGALLALA GAM

Field Sites for Investigation of Recharge and Irrigation Return Flow

1-30-03

and others, 1997). As would be expected, regional rates that incorporate the effects of playas and inter-playa areas are significantly lower. Using the chloride mass balance method, Wood and Sanford (1995) calculated an average regional recharge rate for the northern half of the Southern High Plains of 0.4 in/yr. Additional analysis using the same technique conducted as part of this study yielded a slightly lower value of 0.31 in/yr (Appendix A). Nativ (1988) estimated regional recharge rates of 0.5 to 3.2 in/yr (mean value of 1.6 in/yr) in the south-eastern part of the Ogallala aquifer in the vicinity of Lubbock, Lynn, and Dawson Counties based on high tritium concentrations in groundwater. White and others (1946, p.391) estimated a total groundwater discharge of 25,000 to 30,000 ac-ft/yr for a 9,000-mi^2 area covering much of the northern one-third of the study area. If the groundwater discharge observed in this region is equal to the recharge, the average regional recharge would be about 0.05 to 0.0625 in/yr.

Recharge rates applied in previous ground-water modeling studies of the Southern Ogallala aquifer are variable. Those estimated by Knowles and others (1984) range from 0.06 to 0.83 in/yr. These estimates were based on a study of water content in the unsaturated zone at irrigated and non-irrigated sites in each county (Klemt, 1981). Luckey and others (1986) applied an average recharge rate of 0.13 in/yr in the Southern Ogallala aquifer during the predevelopment period. In addition to irrigation return flow applied during aquifer development, Luckey and others (1986) applied an additional 2 in/yr of recharge to irrigated and dryland farming areas during the 1960 to 1980 period. A more recent modeling study conducted by Stovall and others (2001) applied an average recharge rate of 2.75 in/yr based on automated inverse modeling.

Irrigation Return Flow

Irrigation-return flow also contributes significant amounts of recharge to the aquifer, but is believed to have declined through time. Large-scale irrigation using groundwater began during the 1940s and continued to grow through the mid- to late 1950s. The efficiency of irrigation methods has increased significantly over time, particularly since the early 1980s. A general overview of the change in irrigation methods in the study area is provided by the LERWPG (2001, pp. 1-41 and 1-42).

The earliest form of irrigation was furrow irrigation with the water supplied by open, unlined ditches. This method could have losses through percolation of up to 60 percent, yielding an irrigation efficiency of only 40 percent. An early study conducted by the staff at the HPUWCD No. 1 on a farm in northwestern Lynn County determined that about 16 percent of the total water pumped was lost to infiltration along the open ditch, prior to the water reaching the field (Broadhurst, 1954).

In addition to direct losses beneath fields or along unlined ditches, during the first decades of irrigation significant volumes of tailwater ponded in low areas or drained to playa lakes, particularly in areas of lower-permeability soils (generally the northern half of the study area). A number of examples of ponded water and flowing tailwater are provided by HPUWCD No. 1 (1955). In one case, irrigation water filled a county road bar-ditch and continued to run for 4 miles into a playa. In another case, several acres of farmland were flooded with irrigation water from adjacent areas, some from as far away as 7 miles. As the LERWPG (2001, p. 153) states, “In earlier days irrigation tailwater kept many playa basins full for all or part of the year.”

Where water is ponded, losses to infiltration generally far exceed losses to evaporation. Calculations conducted by the HPUWCD No. 1 indicate that, even for low-permeability soils such as Pullman clay, more than 90 percent of the water loss in a ditch is due to infiltration rather than evaporation. For high-permeability soils such as fine sands or sandy loams, the percentage exceeds 98 percent (HPUWCD No. 1, Undated, p.7).

Irrigation efficiency improved by about 10 to 20 percent during the 1960s and 1970s through replacement of unlined ditches with buried pipe, implementation of tailwater pits (particularly in regions with lower-permeability soils), and use of sprinkler irrigation, especially in regions with sandy soils. Although the early over-crop sprinkler systems were more efficient than furrow irrigation, they still had losses of approximately 50 percent due to greater evaporation (LERWPG, 2001). Consequently, less water would be available to infiltrate and recharge the aquifer where sprinklers were used.

During the early 1980s and continuing through the present day, a variety of new or modified irrigation techniques, all designed to conserve water, have been developed and implemented across the Southern High Plains. These techniques include furrow irrigation with surge valves, furrow irrigation with surge valves combined with tailwater pits, low-energy precision application (LEPA) and a variety of derivatives of this technique, and drip irrigation. The most efficient techniques, such as LEPA, center pivot, and drip irrigation, can provide irrigation efficiencies of 95 percent or more (LERWPG, 2001, p.1-41).

Field Study of Irrigation Return Flow. The BEG and USGS recharge investigation conducted during this project studied recharge at three field sites: the Roberts, Maple, and Muleshoe sites (fig. 31). The Roberts and Maple sites are at irrigated fields, whereas the Muleshoe site has never been irrigated or farmed. None of the sites are near a playa. Irrigation began in 1958 at both of the irrigated sites, with cotton as the main crop. The fields were initially irrigated using furrow irrigation, but sprinkler irrigation has been implemented in more recent years. The efficiency of the irrigation systems has improved over time, and consequently the amount of "excess" water available for irrigation return flow at these sites has probably decreased substantially with time.

All data at the Muleshoe site indicate that no recharge occurs in the natural inter-playa setting. Matric potential monitoring conducted over the past irrigation season indicates that, when irrigation occurs in conjunction with larger precipitation events (greater than about 1.0 inch), infiltration and redistribution of water beneath the Roberts and Maple sites occur to depths between 6.6 and 9.8 ft. In addition, the monitoring data indicate that the soil profile is much wetter beneath the irrigated fields than at the non-irrigated site.

Recharge rates were calculated using tritium data collected from test wells constructed adjacent to the fields at the irrigated sites. Recharge rates calculated using the center of mass approach ranged from 0.7 to 1.3 in/yr. Recharge rates calculated based on the deepest occurrence approach ranged from 4.6 to 5.0 in/yr. These recharge rates are approximately 2 to 3 times greater than rates calculated by removing the tails of the tritium distributions at depth, which were 2.4 and 1.7 in/yr, respectively (Appendix A).

These estimates could be considered bounding values for recharge at these sites. The tritium data provide average recharge estimates for the time period considered (38 to 48 years). However, as stated previously, recharge rates from irrigation return flow probably changed over time as more efficient irrigation practices were introduced.

Time Lag of Irrigation Return Flow. The tritium profiles and related recharge calculations presented above cannot provide any information regarding the variability of irrigation return flow through time. However, the time that it takes for irrigation return flow to reach the water table from the time it is applied at the land surface (the lag time) could be important for simulating groundwater flow in the aquifer, particularly if it is more than about 10 years. To evaluate potential irrigation return flow lag times, some analytical computations and vertical one-dimensional numerical modeling were conducted (Appendix A). The modeling results indicate that lag times can range from less than 1 year to several decades, depending on the amount of applied irrigation water, sediment texture, and profile depth. Because of the simplifying assumptions used for the lag time computations, this term was evaluated using sensitivity analyses in the model.

Irrigation Return Flow Applied in the Model. The percentage of water pumped for irrigation that was assumed to be irrigation return flow in the groundwater flow model is provided in Table 1. The assumed reduction in irrigation return flow with time generally corresponds with the implementation of more efficient irrigation practices as discussed in LERWPG (2001) and a variety of other references.

Table 1: Return Flow Estimates for Texas and New Mexico

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

[a] Assumed to occur in same year as pumping.

For example, as part of their RASA study, the USGS estimated historical pumping for agriculture (Heimes and Luckey, 1982, 1983; Thelin and Heimes, 1987). As part of this work, application of irrigation water to selected fields in Hockley, Lamb, and Parmer Counties for the 1980 growing season was measured (Heimes and Luckey, 1982, Table 2). In Lamb and Parmer Counties, approximately 80 percent of the acreage evaluated was flood irrigated, with the remaining 20 percent irrigated with sprinklers. Assuming that return flow beneath the flood and sprinkler irrigated acreage is 35 percent and 15 percent, respectively, an average return flow of about 30 percent would be expected. The equivalent calculation for Hockley County yields a return flow of 24 percent. In the model, return flow for the 1976 through 1980 and 1981 through 1985 periods was assumed to be 35 percent and 25 percent, respectively (Table 1).

In 1998 in the Texas portion of the study area, about 75 percent of the irrigated acreage was irrigated with center pivot systems, 75 percent of which had full or partial drops. About 20 percent of the remaining acreage was furrow irrigated using underground pipe and surge valves, and the remaining 5 percent of the acreage was irrigated using a variety of older techniques (LERWPG, 2001, p.1-42). Assuming that 10 percent of the total amount of water applied from the center pivot systems is available for return flow, and possibly more from the furrow irrigation with surge valves and the older systems, an irrigation return flow of about 10 percent for 1998 is reasonable, and this value was applied in the model for the 1996 through 2000 period.

In New Mexico the decline in the assumed amounts of irrigation return flow lag behind those in Texas. This approach was taken because implementation of the more efficient irrigation techniques may have been slower in New Mexico than in Texas. For example, in Lea County, New Mexico, furrow irrigation was being used almost exclusively, with some side roll sprinklers, during the late 1970s. During the 1980s more center pivot systems were implemented, and during the mid-1990s to the present more efficient center pivot systems have become more common (Pers. comm. with Johnny Hernandez, Lea Basin Supervisor, New Mexico Office of the State Engineer Roswell Office, August 14, 2002).

Irrigation return flow is assumed to occur during the same year that the water is pumped. In reality, however, it is likely that the timing of return flows is variable based on complex site-specific conditions. So long as return flows reach the water table within about 10 years or less from the time of application of the irrigation water, the effects on the model results are small. The effects of using a longer lag time for irrigation return flow (20 years) on the model were evaluated in the sensitivity analysis discussed later in this report.

Enhanced Recharge Beneath Agricultural Lands

As discussed in the Water Levels and Regional Groundwater Flow section, water levels in a number of regions in the study area, particularly Lubbock, Hockley, and Cochran Counties and counties to the south of these, have been relatively stable since the mid-1960s or so or, in some cases, have been rising throughout the period of record. In order for water levels to be stable, recharge must approximately equal discharge over the long term. In order for water levels to rise, recharge to the water table must exceed discharge.

It has been hypothesized in previous studies (e.g., Knowles and others, 1984, p.45; Luckey and others, 1986, p.18) that the observed rises in water levels might be caused by an increase in recharge due to farming practices. Wyatt and others (1976) also hypothesize that recharge in Crosby County may be greater than under natural conditions due to changes associated with large-scale irrigation development. They state that “Some of the farming practices which are believed to have altered the recharge rate are: clearing the land of deep rooted native vegetation; deep plowing of fields, which eliminates hard pans, and the plowing of playa lake bottoms and sides; bench leveling, contour farming and terracing; maintaining a generally higher soil moisture condition by application of irrigation water prior to large rains; and increasing the humus level in the root zone by plowing under a large amount of foliage from crops grown under irrigation.” (Wyatt and others, 1976, p. 4). This reasoning can be extended to other counties within the study area. Rettman and Leggat (1966) cite the removal of mesquite, and to a lesser extent grasses, as the likely cause of rising water levels in eastern Gaines County.

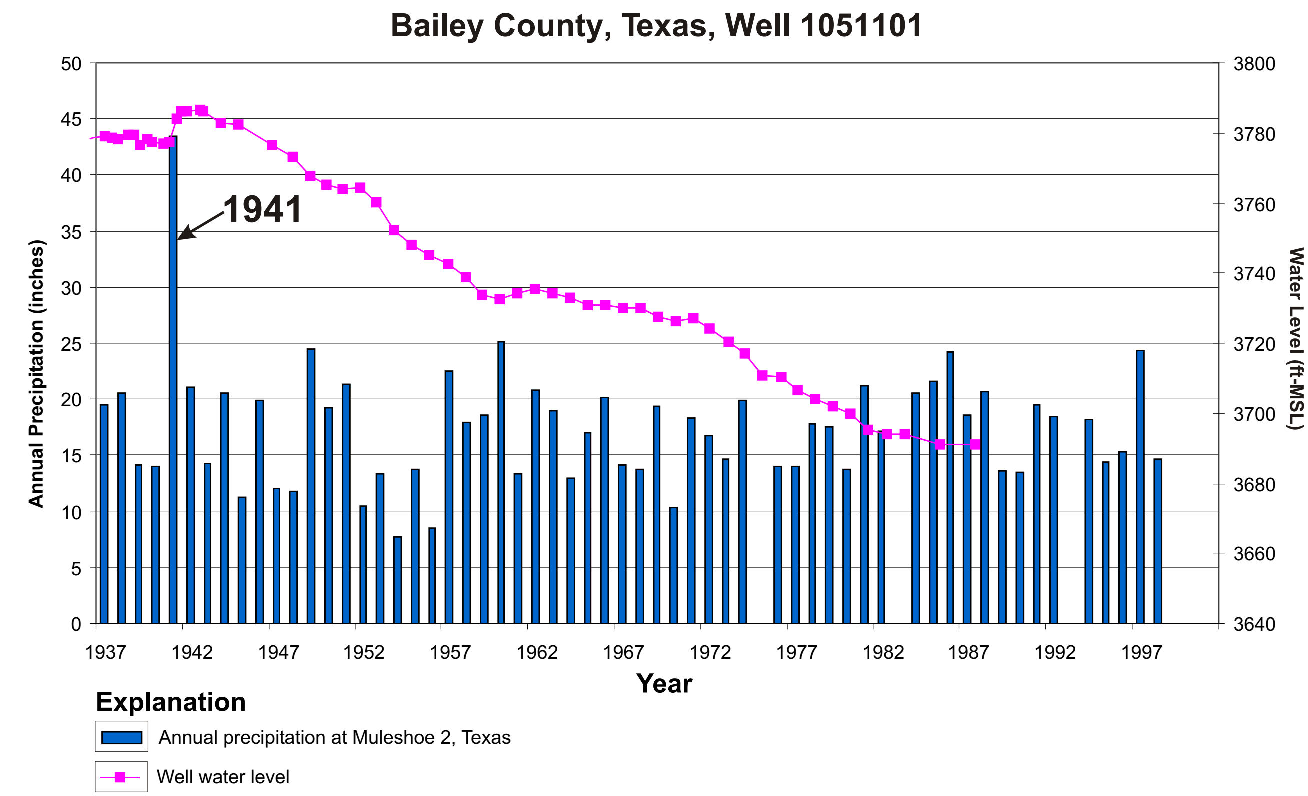
Increased recharge rates caused by clearing of native vegetation, and corresponding rises in aquifer water levels, have been documented for other semiarid regions. For example, Favreau and others (2002) determined that recharge rates in southwest Niger, Africa increased by an order of magnitude due to clearing of native vegetation. In Australia, replacement of deep-rooted native eucalyptus trees with shallow-rooted crops resulted in recharge increases of about two orders of magnitude (Allison and others, 1990).

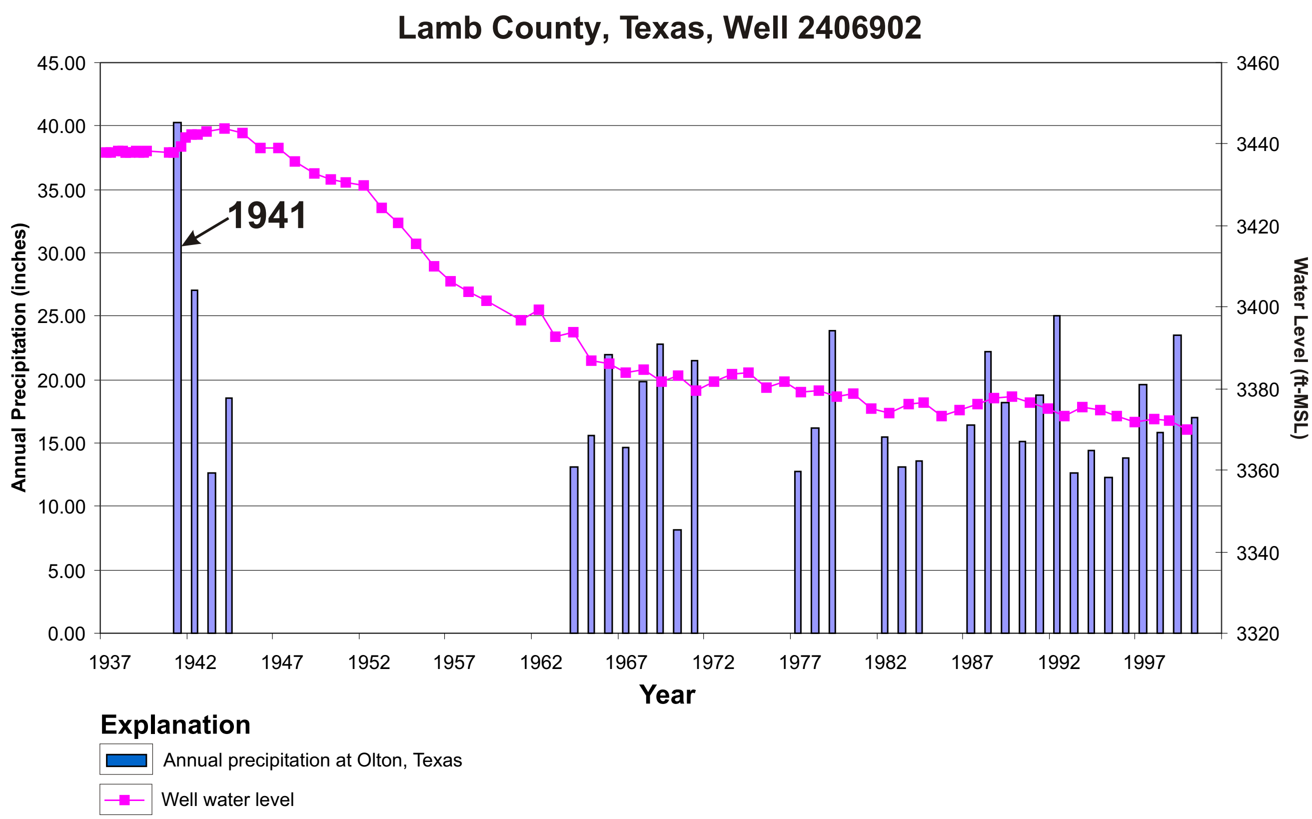
Knowles and others (1984, pp. 44-45) also state that the observed rises in water levels might be attributable to additional recharge from historical irrigation water, readjustment of water levels following decreases in pumping, and enhanced recharge caused by abnormally high precipitation. In fact, both Knowles and others (1984) and Luckey and others (1986) assumed that the enhanced recharge was most likely caused by a large precipitation event during the early 1970s (in conjunction with changes in land use) and consequently either reduced or eliminated the enhanced recharge in their models when conducting their predictive simulations.

Based on an additional 20 years of water level observations and other data, the possibilities presented by Knowles and others other than continued enhanced recharge do not adequately explain the rises in water levels or the continuation of relatively stable water levels over the long term. In some areas water levels have risen continuously for the entire period of record (e.g., parts of Dawson, Lynn, and Garza Counties). A continuous rise in water levels over decades cannot be explained by irrigation return flow because (1) some of these areas are not near areas of irrigated land and (2) irrigation return flow alone cannot cause a rise in water levels greater than those observed before pumping began. Recharge from large, discrete precipitation events or abnormally wet years is also unlikely to cause continuously rising or stable water levels over time periods of decades.

During 1941, for example, record precipitation occurred across much of the Southern High Plains. The effects of this year of extremely high precipitation (many stations recorded 40 inches of rain or more, more than double the mean annual precipitation) is observable in hydrographs for that year (fig. 32). However, as indicated in Figure 32, the effects on water levels of this one year of very high precipitation are not observed in water levels measured after several years of more normal climatic conditions. Furthermore, the early 1940s were a period when significant agricultural pumping was just beginning, and overall pumping was much less than in the 1950s and subsequent decades.

Given the above observations, it is believed that recharge rates beneath agricultural lands have increased significantly from predevelopment conditions due to farming. In addition, it is hypothesized that the increase in recharge from precipitation is greater beneath irrigated regions





SOUTHERN OGALLALA GAM

Annual Precipitation and Observed Water Level Rise During the Early 1940s in Bailey and Lamb Counties

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Figure 32

than beneath non-irrigated regions. This is due to the fact that the soil profile beneath irrigated areas is wetter, and less rainfall that infiltrates into the subsurface beneath the root zone will be lost to storage in the soil profile.

Another way that recharge could be increased due to land use changes is if more runoff occurs to playas than under natural conditions. Whether this has occurred on a large scale over the past several decades is unknown. Early on, straight row furrow irrigation was common (LERWPG, 2001, p. 1-54), and runoff to playas from precipitation was likely higher during these early days of farming.

Rejected Recharge

One of the TWDB requirements for development of the GAMs is that the modeling approach account for rejected recharge. Because the water table throughout the study area is generally several tens of feet or more below the land surface, even under predevelopment conditions, regions where recharge might be rejected are very limited. Under predevelopment conditions, regions of rejected recharge were probably limited to discharge zones which, as described in the following two sections, were concentrated along the bottoms of draws. As the water table declined due to pumping, such regions that were once discharge zones would have become zones of potential recharge.

This process is accounted for in the model because discharge from springs is simulated using drain nodes (see the Model Boundaries section). Therefore, when the simulated water level falls below the drain elevation (which is set to be the land-surface elevation), flow from the drain ceases and applied recharge at that location will enter the aquifer.

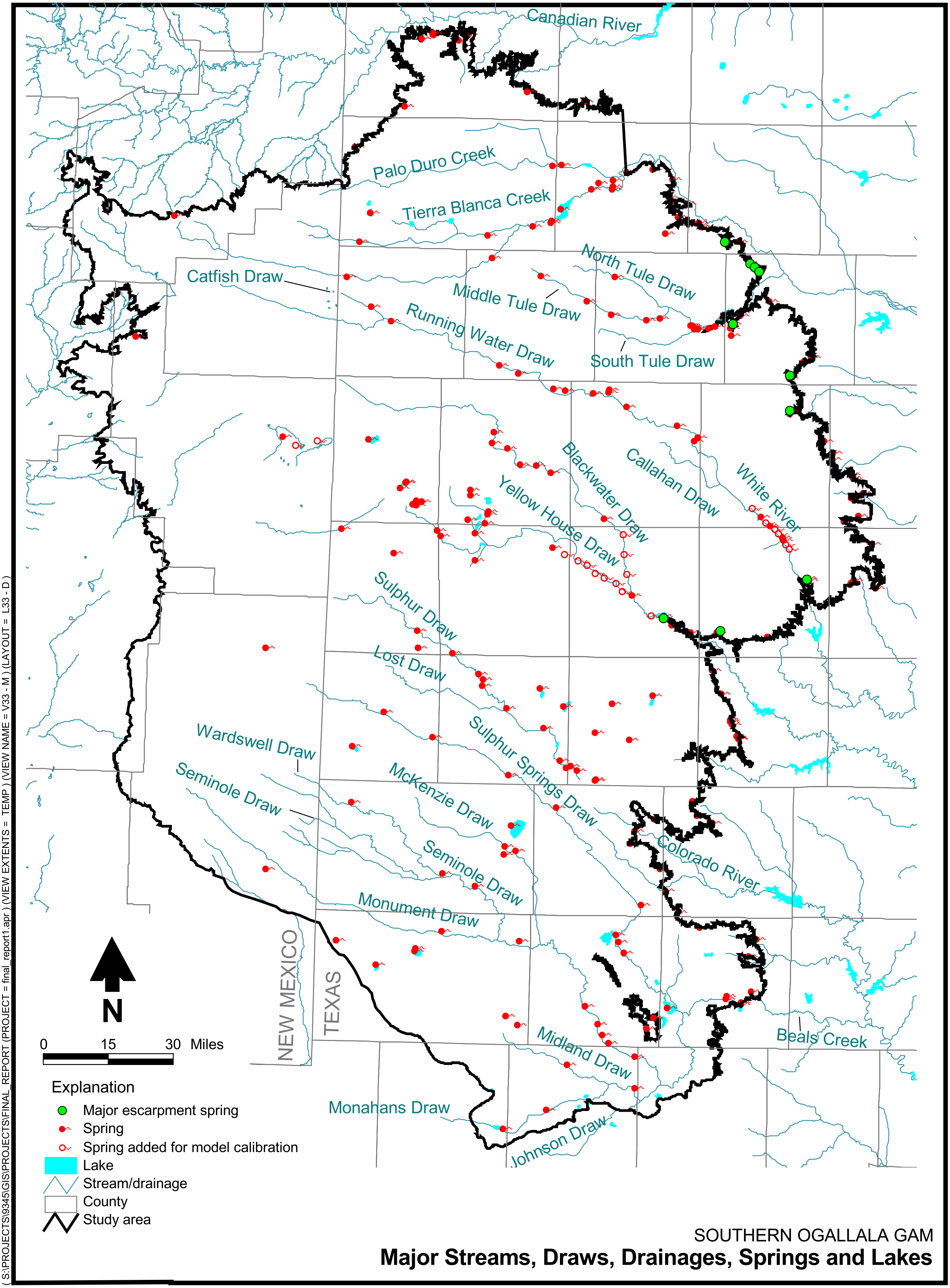
Rivers, Streams, Springs, and Lakes

Figure 33 illustrates the major streams, recorded springs, and salt lakes in the study area. No perennial rivers or streams are located within the study area. Prior to significant groundwater development, however, small perennial streams fed by Ogallala springs did exist near the eastern Caprock escarpment where the stream drainages are deeply incised (Baker, 1915, p.50; White and others, 1946, p. 391). The locations of the major streams (called draws) on the Southern High Plains indicate where springs occur; all of the recorded springs that are not located along the western, eastern, or northern escarpments or the margins of salt lakes are located along major draws or their tributaries.

The draws on the Southern High Plains are very long and narrow with limited drainage areas. The locations of some of the draws are apparently controlled by geologic structure, as they tend to be linear for large distances and are punctuated by sharp angular changes in direction. Reeves (1970) and Reeves and Reeves (1996) discuss the development of the major draws and illustrate that the principal lineament trends on the Southern High Plains are northwest-southeast, southwest-northeast, and north-south. Fallin (1989, p. 30) states that major fracture trends in the Cretaceous section are oriented northwest-southeast and, to a lesser extent, northeast-southwest, and that the fractures trends are "especially well developed in Bordon, Dawson, Hale, Hockley, Lubbock and Terry Counties." Sulphur Springs Draw, located between Natural Dam Lake in western Howard County and the town of Lamesa in central Dawson County, is an excellent example of this (fig. 33).

Some USGS stream gauges have been operated along several of the major draws at various times (fig. 34). Observed flows for two of these gauges (Gauge 7298000 on North Tule Draw and Gauge 8123650 on Beals Creek west of Big Spring) are illustrated in Figure 35. These streamflow hydrographs illustrate that flow volumes are generally small and the draws are dry except after significant storm events. In addition, the duration of flows is on the order of several days or less. Calhoun and others (2002) calculated an average storm flow duration of about 3 days for a gauge on the Prairie Dog Town Fork of the Red River near Canyon, in the northern part of the study area.

Most of the playa lakes in the study area (fig. 5) lie above the water table and only hold water for some period of time after precipitation events (LERWPG, 2001, p. 1-53). It has been estimated that playa lakes and salt lakes drain



SOUTHERN OGALLALA GAM

Major Streams, Draws, Drainages, Springs and Lakes

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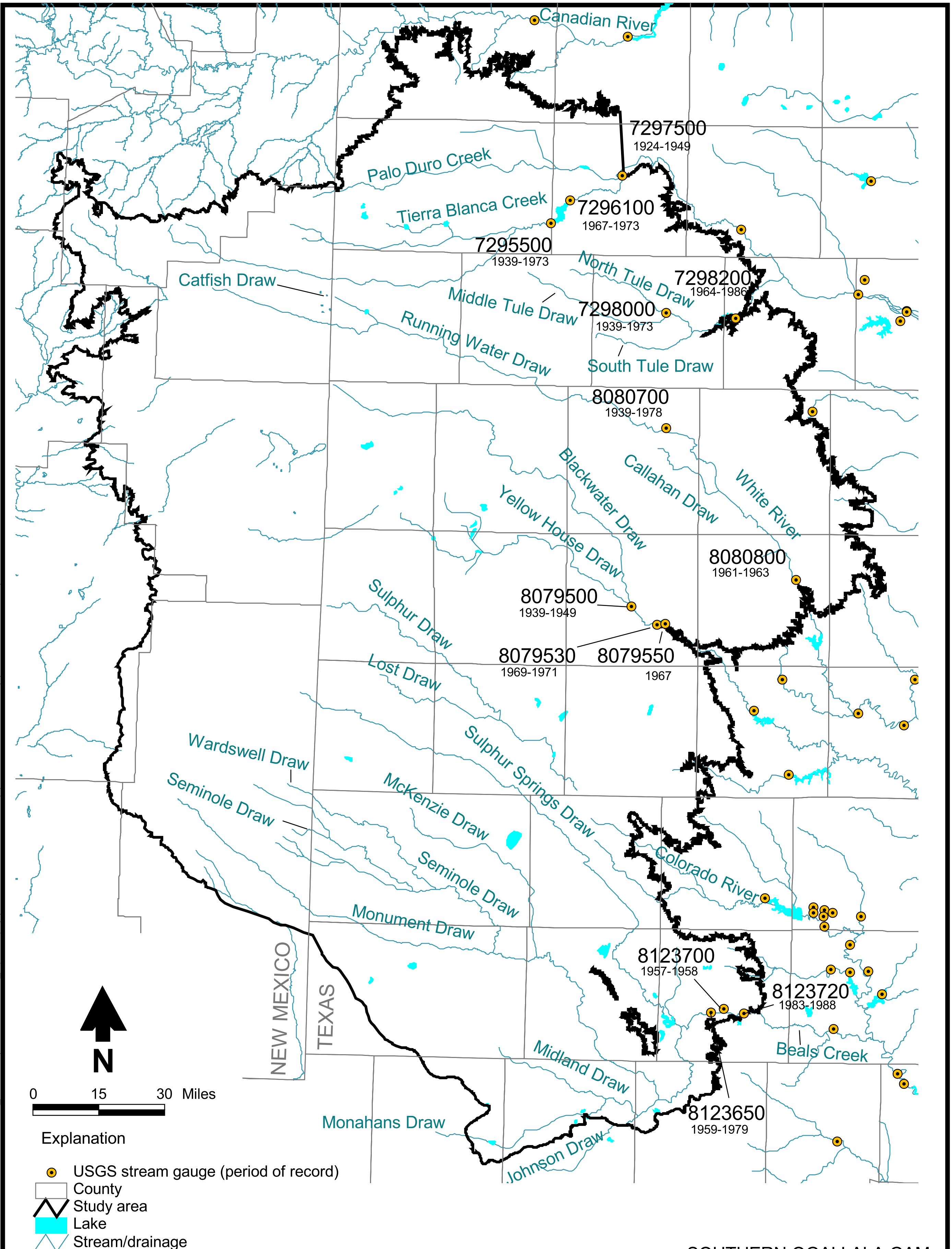
Figure 33



SOUTHERN OGALLALA GAM

USGS Stream Gauges and Periods of Record

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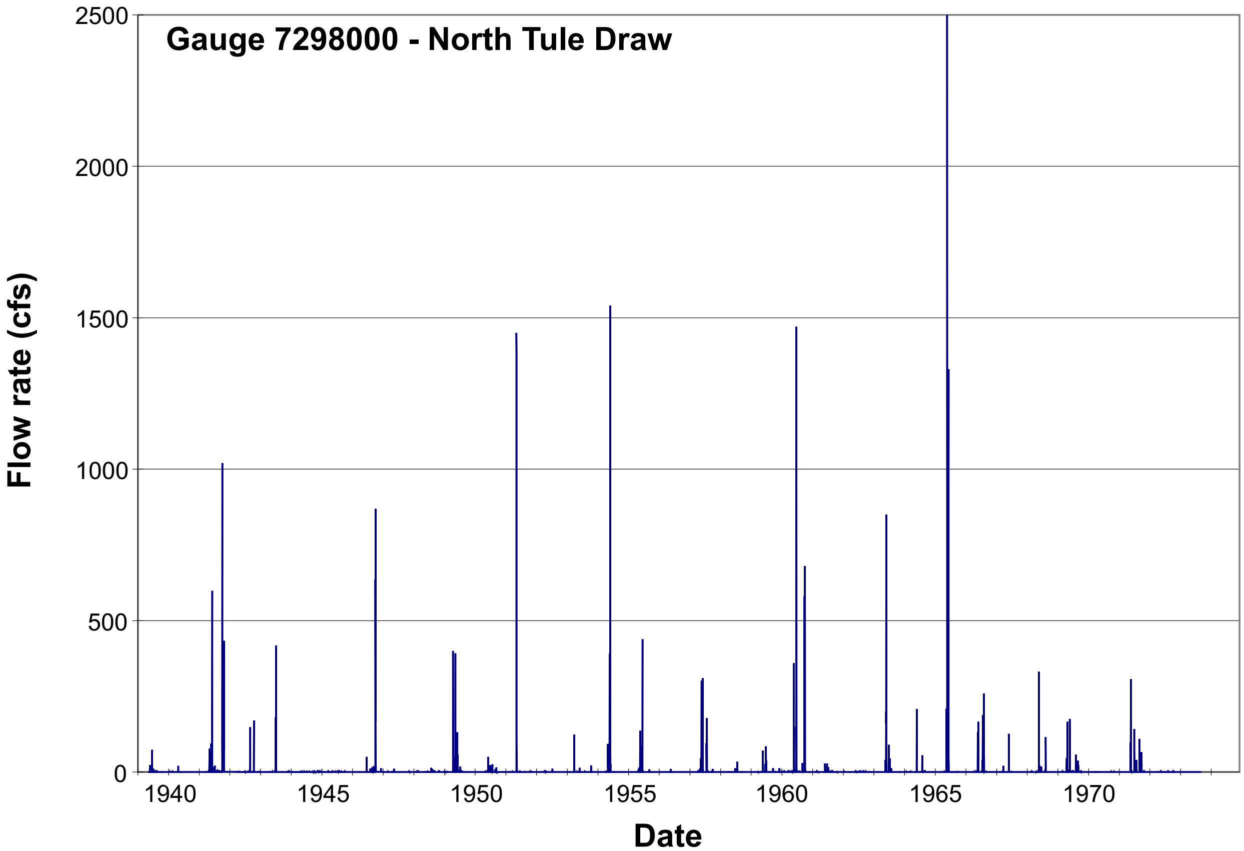
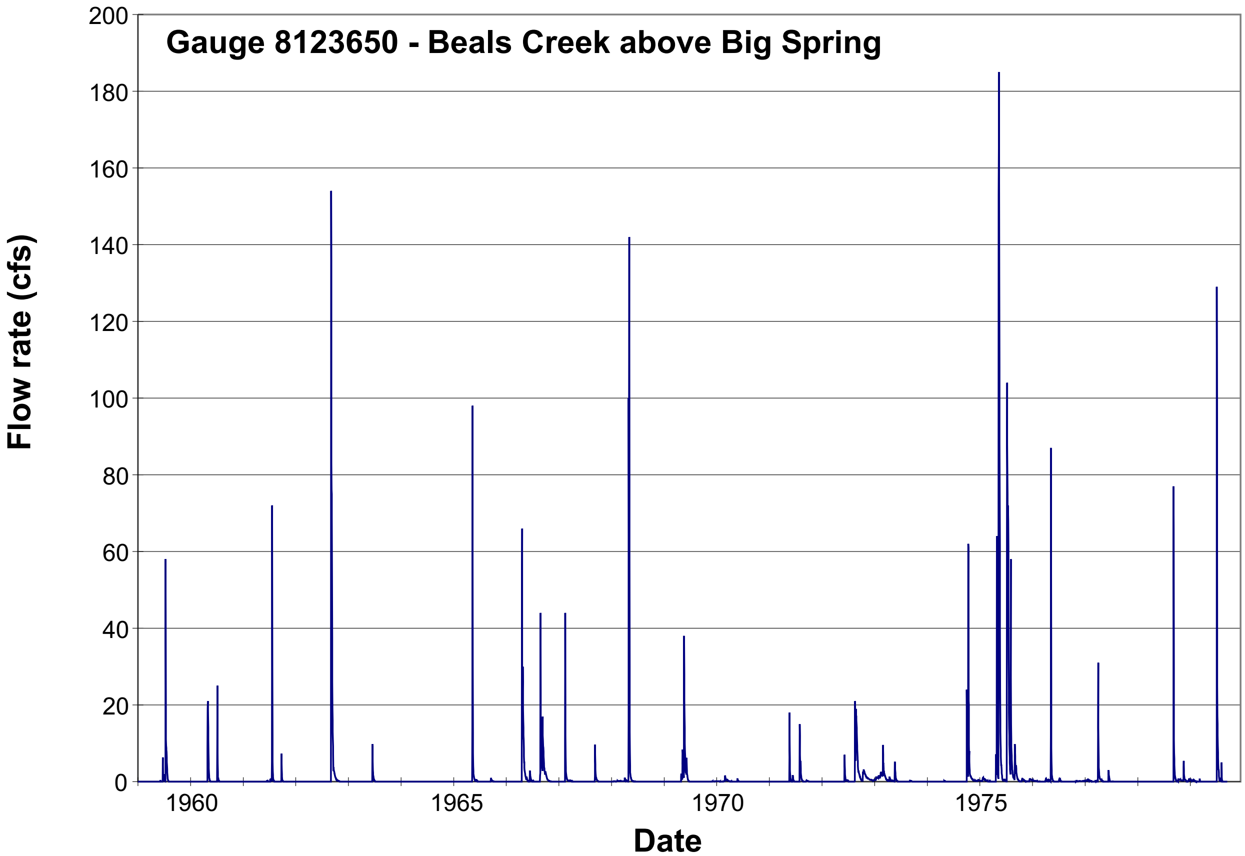
Figure 34





SOUTHERN OGALLALA GAM

Stream Flow for USGS Stream Gauges 7298000 and 8123650

Figure 35

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more than 90 percent of the land surface within the Southern High Plains (Wood and Jones, 1990, p. 198). As discussed in the Recharge section, previous studies have found substantially higher recharge rates beneath playa lakes as compared to inter-playa settings, at least under natural conditions.

In addition to the many thousands of playa lakes that cover the High Plains, there are approximately 40 substantially larger salt lakes within the study area (Wood and Jones, 1990, p. 193; Reeves and Reeves, 1996, p.211). These lakes are significantly different from playa lakes hydrologically in that they are regions of groundwater discharge and typically lie within relatively large topographic depressions, some on the order of several tens of square miles. These lakes tend to occur in association with regional topographic highs on the Cretaceous section and where the Ogallala section is less than 200 ft thick (Reeves and Reeves, 1996, p.210). At most lake basins, a significant topographic depression occurs where the Ogallala Formation has been eroded away and Cretaceous rocks crop out along the west and northwest margins of the lake basins. Although information is limited, most of the lakes may hold standing water only intermittently, and when they do have water, it is shallow (Wood and Jones, 1990, p.199; Baker, 1915, p.46). Leggat (1957, p.27), however, reported that Bull and Illusion Lakes in southwestern Lamb County usually contained water except during prolonged periods of drought.

Water in the lakes is a combination of runoff from precipitation and seepage from Ogallala aquifer springs that occur along the lake basin margins, commonly on the west or northwest sides (fig. 33). Lake water is highly saline, with concentrations of total dissolved solids (TDS) ranging from several thousand to more than 400,000 milligrams per liter (mg/L), substantially higher than Ogallala aquifer water (Wood and Jones, 1990, p.196). Wood and Jones (1990) show that the TDS concentrations in the lake water are high due to concentration of salts in the closed lake basins caused by evaporation, and the TDS concentrations of many of the springs along the lake basin margins are elevated due to mixing of fresh aquifer water with saline lake water that has saturated portions of the aquifer beneath and immediately adjacent to lakes.

Hydraulic Properties

This section presents an overview of the hydraulic properties of the Southern Ogallala aquifer. As very few aquifer tests have been conducted within the study area, most estimates of aquifer parameters have been determined based on lithology (type of aquifer material) and groundwater flow model calibration. A significant portion of the time and effort spent as part of this study involved the estimation of a hydraulic conductivity field based on thousands of well logs and specific-capacity tests collected for both Texas and New Mexico.

Hydraulic Conductivity

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

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

Because hydraulic conductivity inputs for the Southern Ogallala GAM were interpreted based on test data for wells that for the most part fully or almost fully penetrated the entire saturated thickness of the aquifer, the resulting hydraulic conductivity is an average affected by all of the sediment types beneath the water table at a given location at the time of the test. The average is probably influenced most by the thickest layer of the material with the highest hydraulic conductivity.

At the scale of measurement, the hydraulic conductivity is likely to be the same in all horizontal directions. If it exists, horizontal anisotropy in the Ogallala aquifer is likely small and was therefore not considered during development of the model. Conversely, the degree of vertical anisotropy can be high due to sediment layering. However, since the aquifer was modeled as a single hydrogeologic unit (one layer), vertical anisotropy is not a required model input parameter.

The geometric mean of Ogallala aquifer hydraulic conductivity determined from aquifer tests is approximately 6.8 ft/d (fig. 36). Measured or estimated hydraulic conductivity ranges from a minimum of 0.01 ft/d to a maximum of 2,600 ft/d. The measurements and estimates of hydraulic conductivity appear to be log-normally distributed (fig. 36), which is common for this parameter. The mean value of hydraulic conductivity from long-term pumping tests is not significantly different from that derived from specific-capacity tests.

Data used to calculate transmissivity and hydraulic conductivity of the Ogallala aquifer were collected from various published reports and open-file records available for Texas and New Mexico (Naing, 2002). Results of long-term pumping tests or core analyses provided 115 measurements of hydraulic conductivity. In addition, approximately 7,500 data points representing 4,120 locations in the study area were collected (fig. 16), most of which were from specific-capacity tests. Use of specific-capacity data greatly extends the amount of available information on hydraulic conductivity (Mace, 2001). Evenly spaced data in Texas reflect averaged values assigned to 2.5-minute quadrangle centers (fig. 16).

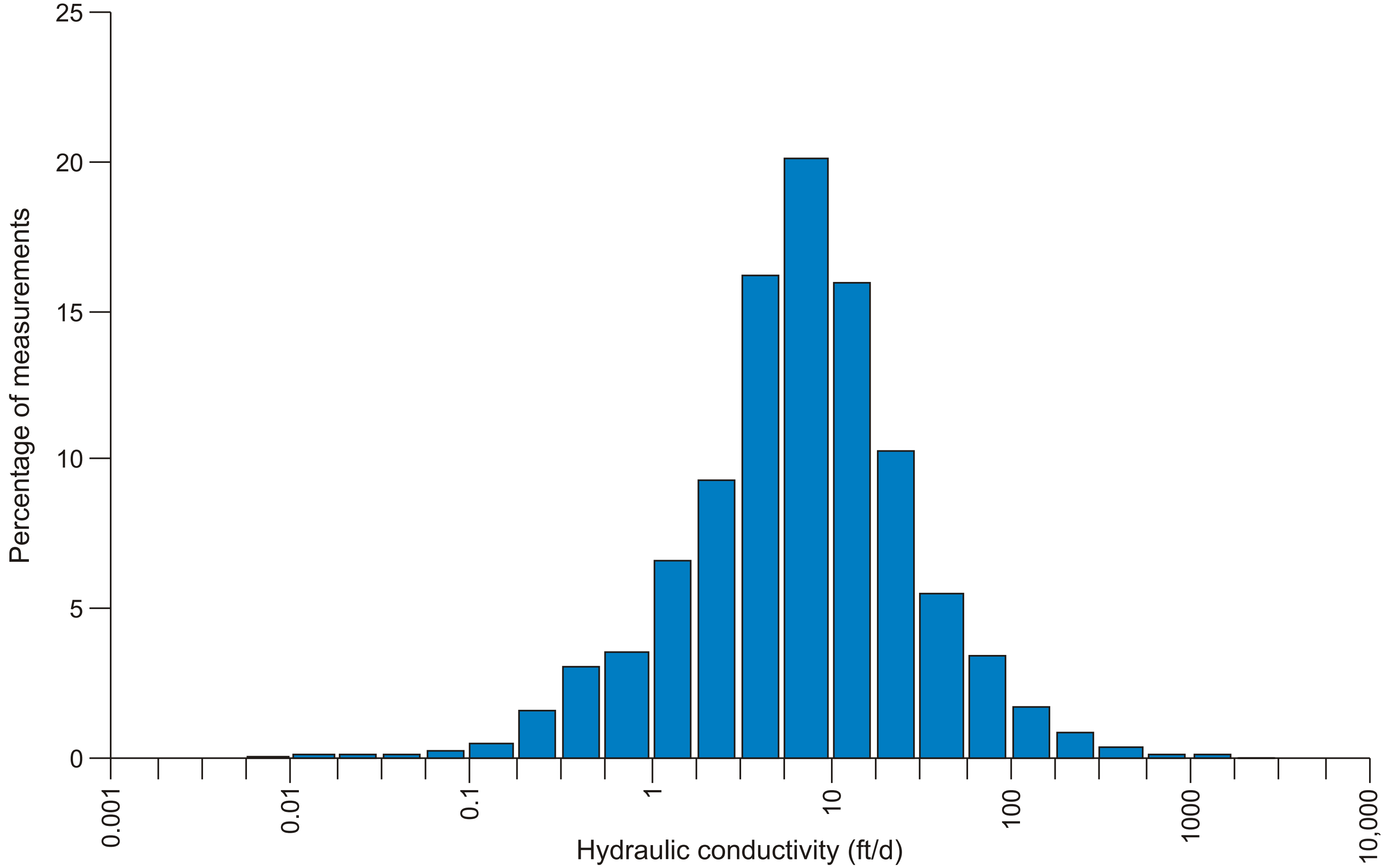
Several studies have collected field or laboratory data on hydrologic properties of the Ogallala aquifer. Hydraulic conductivity has been estimated using long-duration (8- to 24-hr) pumping tests at water wells, geophysical logs of wells, and laboratory analyses of aquifer materials obtained from drilled cores.

Hydraulic conductivity data from long-term pumping tests in 33 wells and specific-capacity tests in 723 wells in the Ogallala aquifer in the study area in Texas were obtained from Myers (1969). Available information on locations of wells used in these tests included either section and block coordinates or distance from the nearest town. Spatial coordinates for the 33 long-term pumping tests and 226 of the specific capacity tests were assigned using well maps published in various Texas Board of Water Engineers (TBWE) reports and cross-referencing well numbers in the TWDB's online groundwater database. Estimates of hydraulic conductivity from the 756 Ogallala aquifer records collated by Myers (1969) for the study area were included in statistical summaries, but only the 259 located well tests were included in the map of hydraulic conductivity.

Other data used in this study include:

- Ashworth (1980) provides 34 estimates of transmissivity or hydraulic conductivity from laboratory analyses of core and geophysical logging of test holes drilled through the Ogallala Formation.
- Data on hydraulic conductivity for Curry County, New Mexico were taken from Howard (1954).
- The TBWE published a number of groundwater reports for Texas counties in the study area from which the results of 204 specific-capacity tests were obtained.
- Results from 48 long-time pumping tests, primarily for the upper part of the Ogallala aquifer, collected at Superfund and petroleum contaminated sites throughout the study area were also obtained.

The vast majority of the data, however (about 98 percent), came from specific-capacity tests compiled from driller's well completion reports filed at State agencies in Texas and New Mexico, and from the TWDB groundwater database (http://www.twdb.state.tx.us/publications/reports/GroundWaterReports/



SOUTHERN OGALLALA GAM

Histogram of Hydraulic Conductivity Measurements

Figure 36

GWDatabaseReports/GWdatabaserpt.htm). TCEQ records contain 2,732 specific-capacity tests representing 1,316 locations, 349 tests were collected from New Mexico State Engineer files for Lea and Roosevelt Counties, and 1,492 specific-capacity tests for 47 Texas counties in and adjacent to the study area were obtained from the TWDB database.

Documentation for a specific-capacity test generally includes single values for pumping rate, static depth to water, and depth to water after pumping the well for a given amount of time. This information represents a single point on the long-time pumping test curve.

Well locations on drillers' logs in Texas are generally reported only to within a 2.5-minute quadrangle area, which leaves an accuracy of plus or minus 5 miles. Some reports, however, include a simple map with the well location shown. Where possible, data from multiple drillers' logs were compiled for 2.5-minute quadrangle areas, and the geometric mean of available hydraulic conductivity estimates was assigned to the center of the 2.5-minute area. In New Mexico, well locations are generally reported to within a quarter-mile accuracy or better and were therefore treated as point data.

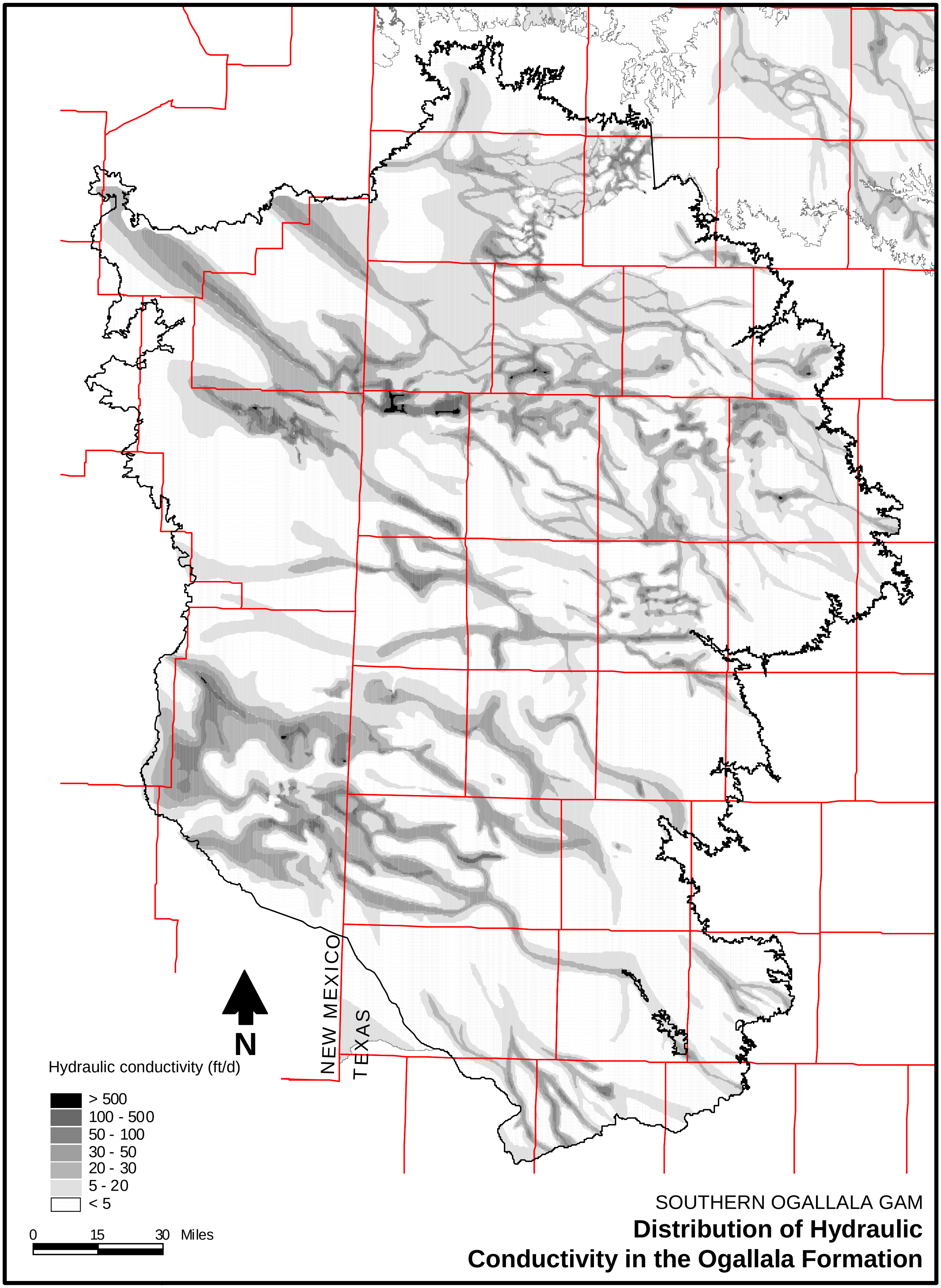
The quality and amount of information collected from drillers' logs are variable. Quality issues include completeness of information and transcription errors in recording pumping rate and time. For quality control purposes, only legible logs containing all required information (pumping rate, test duration, drawdown during pumping, static water level, well diameter, and well depth) were used. Analyses were limited to wells completed only in the Ogallala aquifer. Marker-bed characteristics defined by Seni (1980) were used to identify the base of the Ogallala Formation.

Transmissivity was estimated from specific-capacity data using the solution based on Theis's non-equilibrium equation (Theis and others, 1963; Mace, 2001). In the calculation, storativity is assumed to be 0.15, which is a representative specific yield value for the Ogallala aquifer (Mullican and others, 1997, p.28). Hydraulic conductivity was calculated by dividing transmissivity by saturated thickness, estimated as the height between the reported static water level in the unconfined aquifer and the total depth of the well.

Once a database of hydraulic conductivity was developed, values were posted on a base map and overlain on maps of percentage and net thickness of sand and gravel. Hydraulic conductivity was then contoured by hand (fig. 37). All data values were honored during construction of the hydraulic conductivity map. In areas of abundant data, detailed variation in hydraulic conductivity could be determined. The interpreted contouring pattern uses Seni's (1980) model of an alluvial fan with braided rivers as the depositional system in which Ogallala sediments were deposited. These interpreted contouring patterns were continued in areas where data were less abundant.

The resulting contours show that hydraulic conductivity is not uniformly distributed but varies in a generally predictable pattern that matches the major trends in sand and gravel content. The observed data show major changes in hydraulic conductivity within and between the major axes of sand and gravel deposition across distances of less than 5 miles. The interpreted distribution of hydraulic conductivity (fig. 37), where the high-conductivity zones are relatively narrow on a regional scale and are surrounded by large regions of lower conductivity, has important implications for the groundwater flow model. As discussed in Steady-State Model section, the average hydraulic conductivity of the GAM is lower than that used in previous models, which leads to lower predevelopment recharge rates. This lower average hydraulic conductivity is due primarily to the large inter-channel regions of low hydraulic conductivity.

Hydraulic conductivity of the Cretaceous section was not accounted for explicitly in the initial inputs to the model, although some wells in the study area do obtain a portion of their yield from Cretaceous sediments. A study by the TWDB for developing a GAM of the Edwards-Trinity Plateau aquifer (stratigraphically equivalent to the Cretaceous section beneath the Southern High Plains) determined that average hydraulic conductivity is 5.2 ft/d (Robert Mace, written communication,



SOUTHERN OGALLALA GAM

Distribution of Hydraulic Conductivity in the Ogallala Formation

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May 2002), which is similar to the mean hydraulic conductivity of the Ogallala aquifer of 6.8 ft/d. The 16th and 84th percentile values of the Edwards-Trinity Plateau aquifer hydraulic conductivity are 0.7 and 54 ft/d, respectively.

The base-of-aquifer maps obtained from Weeks and Gutentag (1981), Knowles and others (1984), and the HPUWCD No.1 (McReynolds 1996a through 1996o) include the thickness of the Cretaceous section believed or known to be in direct hydraulic communication with saturated Ogallala Formation sediments when the maps were constructed. However, comparison of these maps with the elevation of the top of the Cretaceous section as presented by Fallin (1989) indicates that, for the most part, the difference between the base of the Ogallala aquifer and the top of the Cretaceous sediments was only several tens of feet or less. It appears, therefore, that large thicknesses of the Cretaceous section are not included in the base-of-aquifer maps and are therefore not included in the model.

Specific Yield

The average specific yield of the Southern Ogallala aquifer is generally considered to be about 0.15, or 15 percent. Knowles and others (1984) applied specific yield values of less than 4 to more than 20 percent, although most of the values range from 12 to 20 percent. Luckey and others (1986) applied an average value of 15 percent. Mullican and others (1997, p.28) also selected 15 percent as an average specific yield for the Ogallala aquifer. In modeling studies that focused on portions of the aquifer in New Mexico, Musharrafieh and Logan (1999) applied specific yields of 18 to 25 percent, with most of the area between 23 and 25 percent. Musharrafieh and Chudnoff (1999) applied values of 12 to 24 percent, with most of the area between 20 and 23 percent. In various calculations and articles published by the HPUWCD No. 1 (such as their monthly newsletter, the *Cross Section*), a specific yield of 15 percent is always used.

Discharge

Groundwater discharge from the aquifer occurs through pumping and at numerous springs and seeps along the eastern escarpment, within the draws, and along the margins of salt lake basins. Under predevelopment conditions (generally prior to 1940), the vast majority of discharge was from springs, while under post-development conditions, groundwater discharge from pumping far exceeds that of discharge from springs. It is also possible that discharge occurs or has occurred through evapotranspiration or direct evaporation of water where the water table is or was relatively close to the land surface (i.e., within several tens of feet) or through downward leakage to lower aquifer units, such as the Dockum Group. However, relative to other components in the regional water balance, these potential discharge volumes are believed to be relatively small and were not considered in this study. This approach is consistent with previous studies, such as those of Knowles and others (1984) and Luckey and others (1986).

Pumping for Irrigated Agriculture

Pumping for irrigated agriculture accounts for approximately 95 percent or more of the total groundwater withdrawal within the study area. Accordingly, accurate estimates of pumping for this use are critical to understanding the groundwater flow system and estimating future aquifer conditions. Because of the importance of this water budget component, a separate study was conducted as part of this project to determine withdrawals for irrigated agriculture for all of the counties in the study area, with an emphasis on the 1980 through 2000 period. The results of this study are documented in a report by Amosson and others, which is included with this report as Appendix B. Amosson and others provide estimates of pumping for irrigated agriculture for the years 1982, 1983, 1984, 1987, 1992, 1993, 1994 and 1997. They also provide estimates of pumping for irrigated agriculture that would be required for 1997 agricultural practices and crop acreages, but based on (1) drought of record (1952-1956) climatic conditions and (2) long-term average (LTA) climatic conditions.

Prior to 1982, estimates of pumping for irrigated agriculture collected for the TWDB at 5-year intervals beginning in 1958 were used for the counties in Texas. These estimates were modified for Gaines and Yoakum Counties. For Gaines County, annual agricultural pumping estimates for the period 1940 through 1963 were obtained from Rettman and Leggat (1966). In addition, since the estimates of Rettman and Leggat (1966) were about 70 percent of those reported in the TWDB surveys as of the early 1960s, the TWDB survey numbers for Gaines County beginning in 1964 and for Yoakum County beginning in 1958 were multiplied by a factor of 0.7. The 70 percent factor was applied to Yoakum County because it lies immediately north of the most heavily irrigated portions of Gaines County and was assumed to have experienced a similar development history.

Estimates of irrigation pumping for the counties in New Mexico were obtained from Reeder and others (1959, 1960a, 1960b, 1961, 1962), New Mexico State Engineer Office (1967), U.S. Bureau of Reclamation and New Mexico Interstate Stream Commission (1976), Sorenson (1977, 1982), Wilson (1986, 1992), and Wilson and Lucero (1997). These references provide estimated pumping numbers for the New Mexico counties for 1940 through 1960, 1969, 1975, and 1980. Linear interpolation was used to estimate pumping for years for which no data were available for Texas and New Mexico.

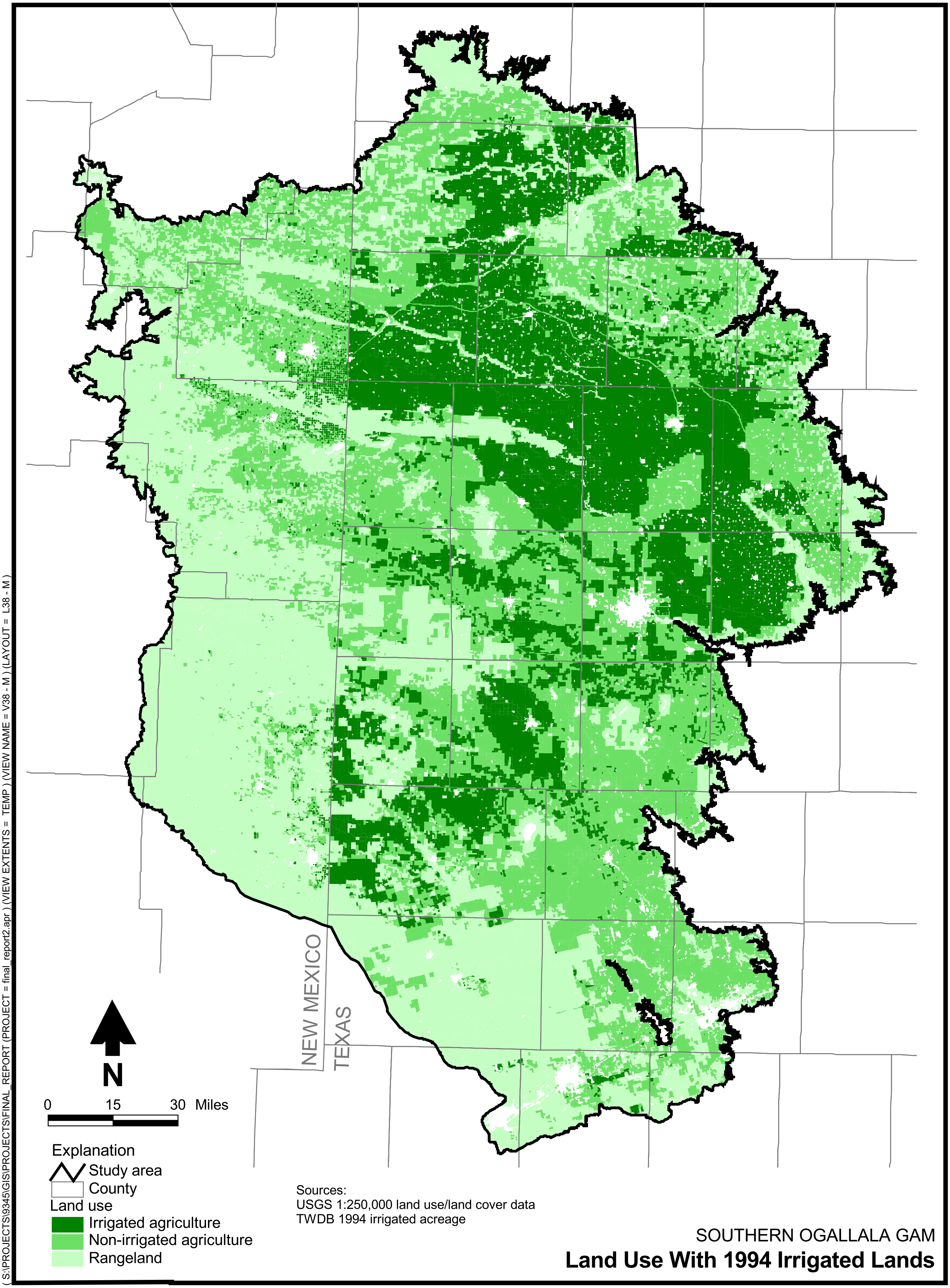
Prior to 1958 in Texas, irrigation pumping was assumed to increase linearly from zero to the 1958 estimated value, according to the estimated growth in irrigated acreage for the Southern High Plains provided by Luckey and others (1986, p.11). The periods 1940 through 1944, 1945 through 1949, 1950 through 1954, and 1954 through 1959 were 8, 33, 73, and 100 percent, respectively, of the 1958 estimated pumping number. Estimated pumping for irrigated agriculture is provided by county in Appendix C.

Agricultural pumping was assigned to model cells in Texas based on land use maps and the 1994 irrigation survey conducted for the TWDB. Irrigated lands are shown in Figure 38. Irrigated lands in New Mexico were determined from LandSat images obtained for 1994 (fig. 39). These images were also used to cross-check the delineation of irrigated lands in Texas for those counties or portions of counties covered by the images, and they were found to be quite accurate on a regional scale.

Available information indicates that, on a regional scale, areas of irrigated acreage have been fairly constant through time. For example, the 1994 irrigated acreage coverage is similar to, but more detailed than the 1980 irrigated acreage delineation (Thelin and Heimes, 1987). The irrigated acreage coverage was also compared to a series of digital center pivot maps provided by the HPUWCD No. 1 for 1995 and 1998, as well as to hard copies of irrigated acreage maps for Yoakum and Garza Counties for recent conditions. The regional patterns of irrigation indicated by all of these maps were very similar to the 1994 TWDB coverage. Current areas of irrigation in the Portales Valley of New Mexico in northern Roosevelt County are very similar to those shown in Galloway and Wright (1968) for 1967 conditions

A comparison of Figures 15 and 38 illustrates that regions of irrigated agriculture can be correlated in some areas with the extent of the Cretaceous subcrop. For example, in Lamb County very little irrigated acreage exists in the southwestern corner of the county, where the Cretaceous rocks exist. Likewise, in Hale County no irrigated agriculture occurs where an isolated remnant of the Cretaceous section exists in the southeastern quarter of the county. Apparently, the Cretaceous rocks have a low hydraulic conductivity in these areas, and the saturated thickness of the aquifer is limited.

One reason that the location of irrigated acreage is fairly constant through time is that irrigated fields tend to lie above paleochannels within the aquifer, which tend to have greater saturated thickness and higher hydraulic conductivities. Figure 40 shows the base of aquifer contours for Cochran and Hockley counties and some adjoining regions, with a portion of the HPUWCD No. 1 center pivot map overlain on them. As shown in this figure, the center pivot irrigation systems tend to lie above



SOUTHERN OGALLALA GAM

Land Use With 1994 Irrigated Lands

1-30-03

Figure 38

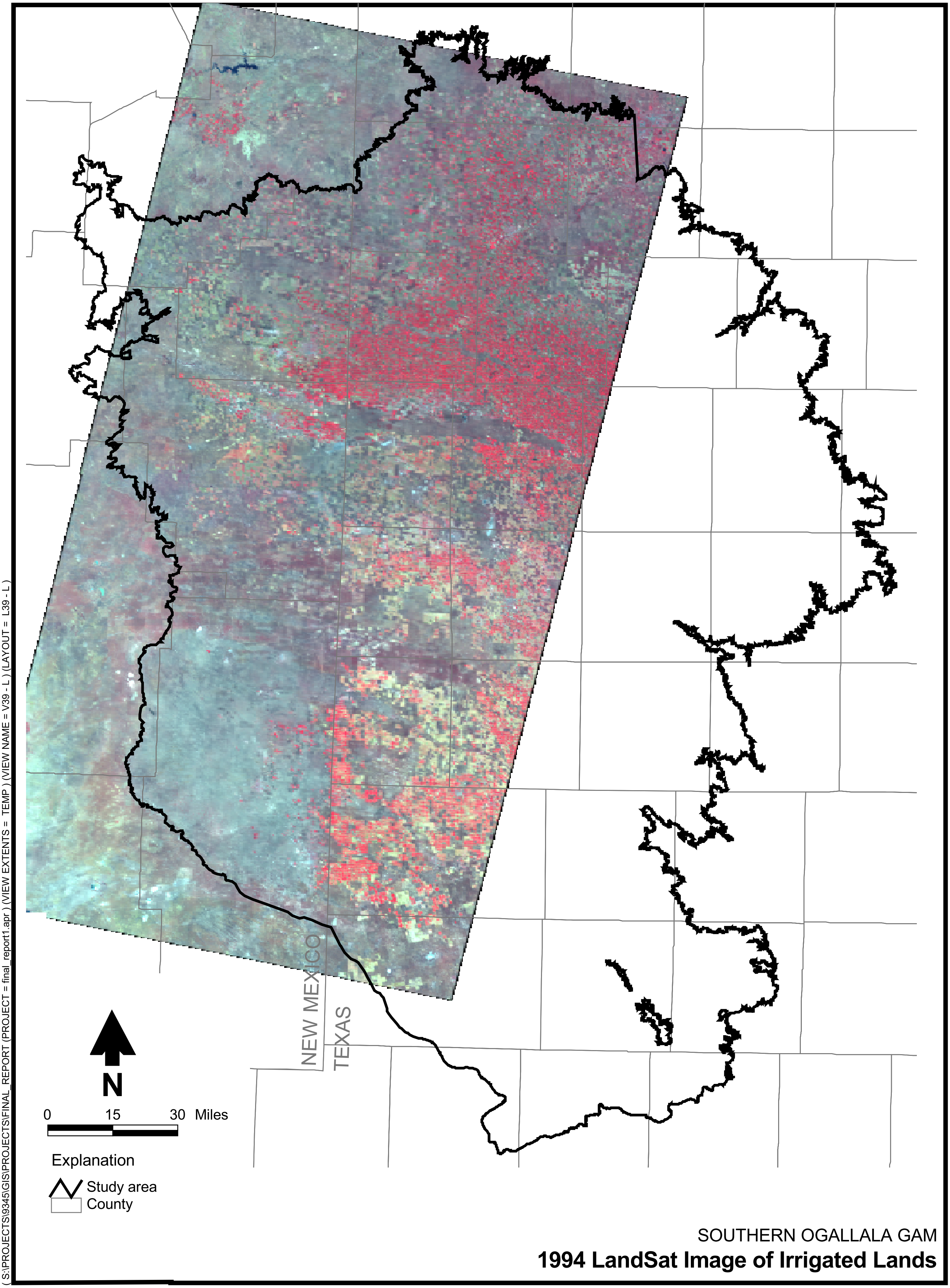


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Figure 39

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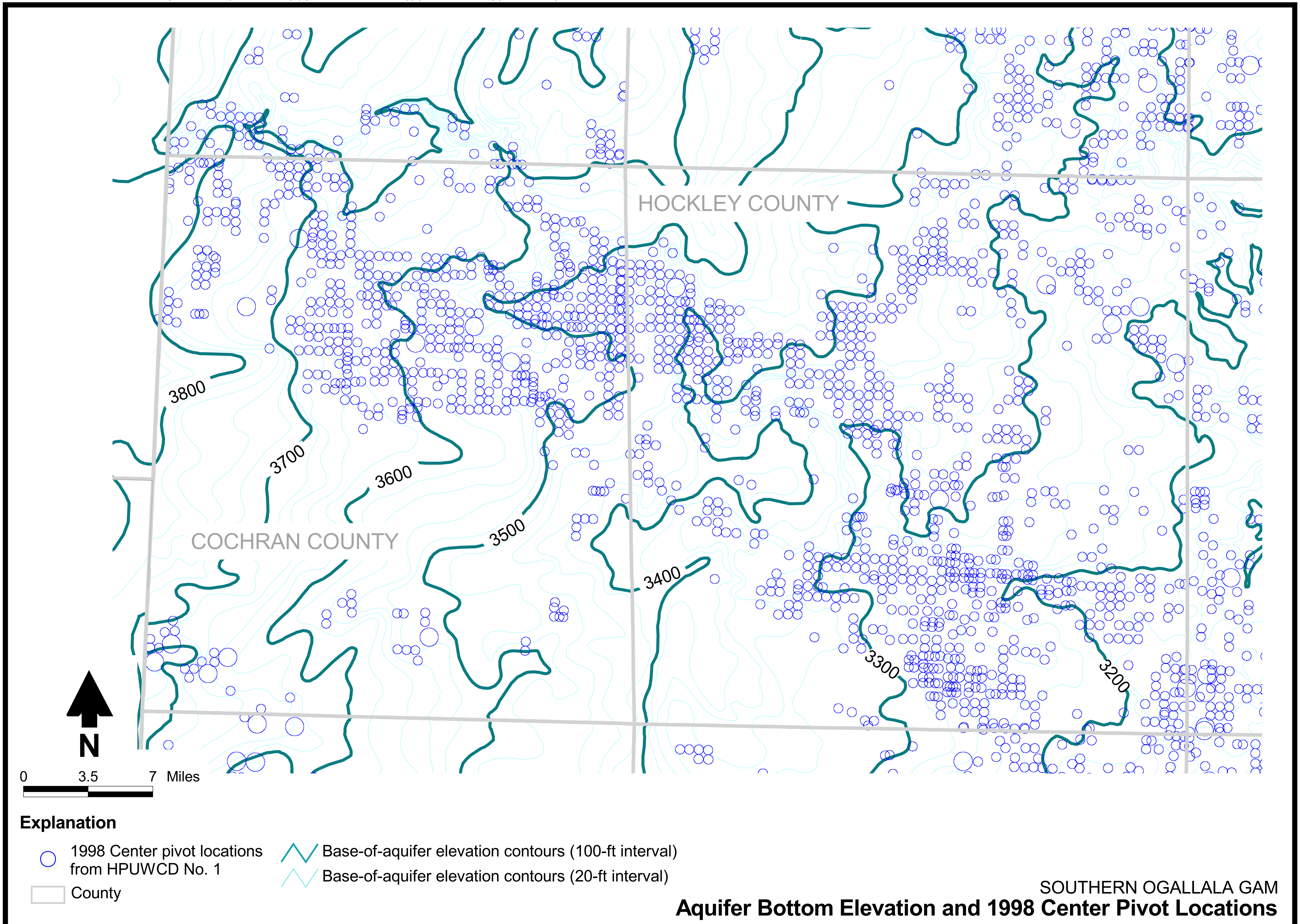

SOUTHERN OGALLALA GAM

Aquifer Bottom Elevation and 1998 Center Pivot Locations

Figure 40

2-04-03