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.

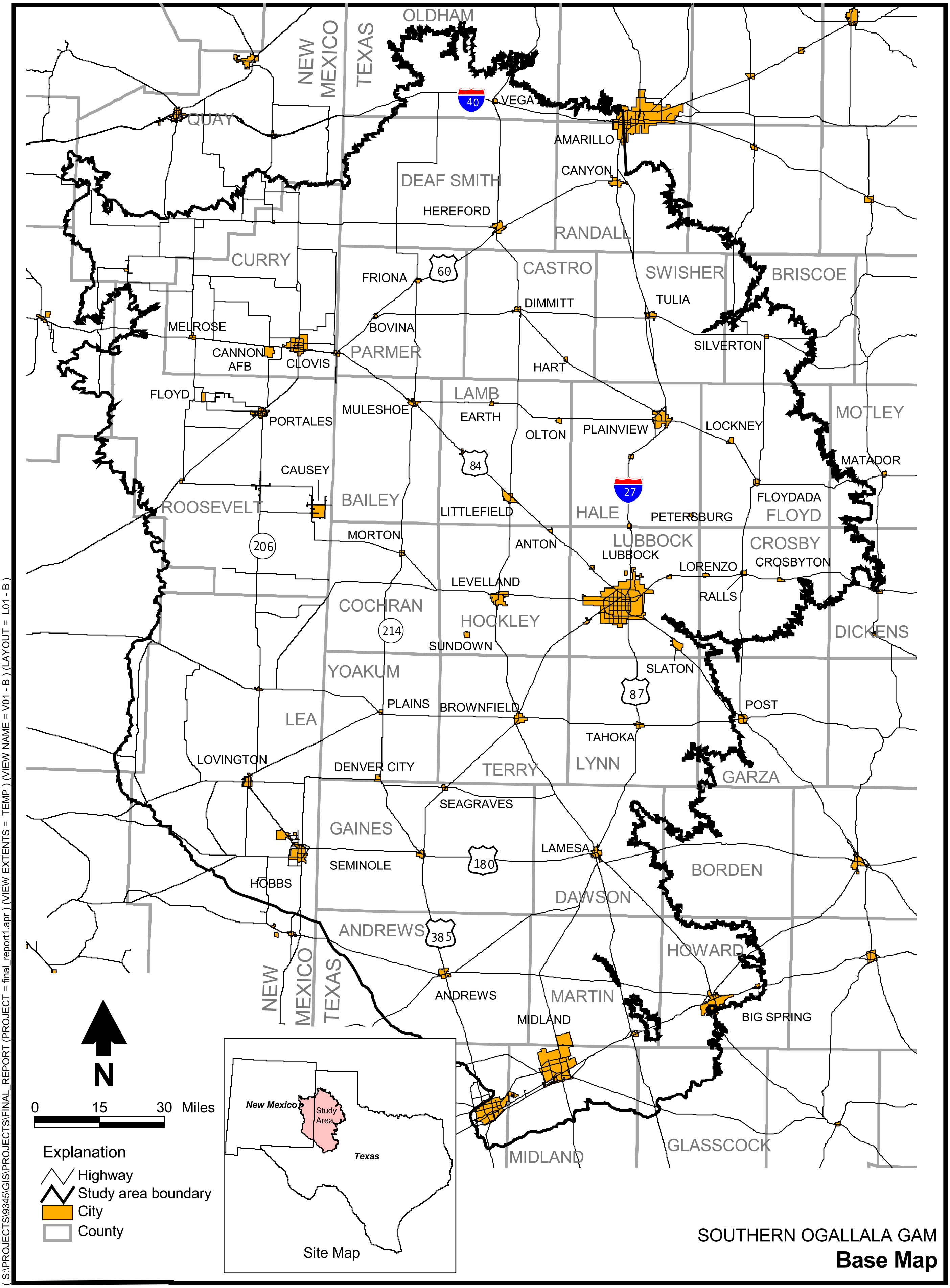
The first comprehensive hydrogeological studies and evaluations of the Southern Ogallala aquifer, including groundwater flow modeling, were published during the mid-1980s. These studies illustrated the likelihood that, should depletions of the aquifer continue at projected rates, substantial declines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

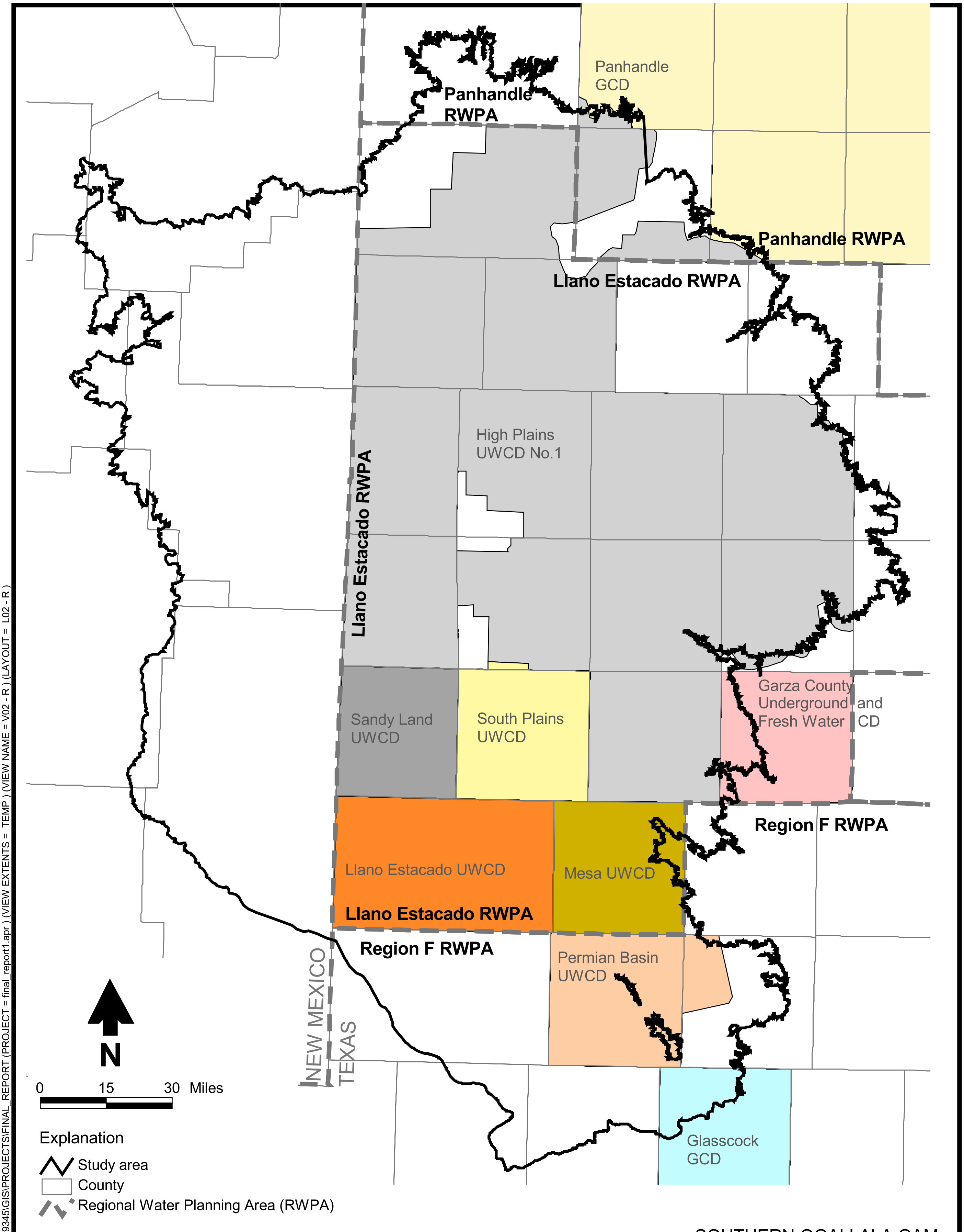
The Southern Ogallala aquifer underlies an area of about 29,000 square miles (mi^2) in western Texas and eastern New Mexico, encompassing all or part of 31 counties in Texas and 6 counties in New Mexico (fig. 1). The study area spans Regional Water Planning Area O (Llano Estacado) and extends into Areas 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

1-30-03

Figure 1



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Note: UWCD = Underground Water Conservation District
GCD = Groundwater Conservation District
CD = Conservation District

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)

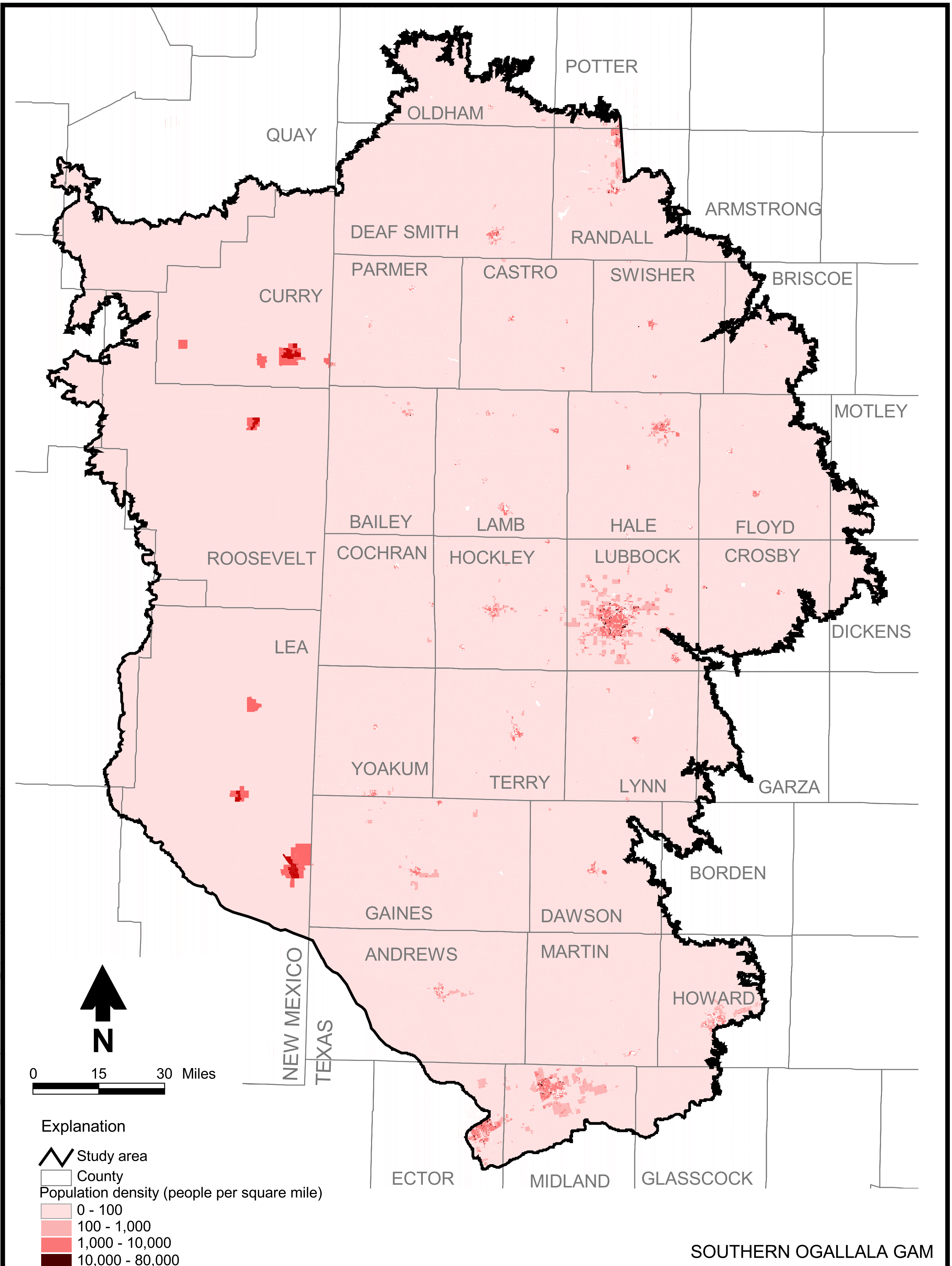
The Southern High Plains is bordered to the west by the Pecos River Valley and to the east by the Osage Plains (called the Rolling Plains on some physiographic maps). The erosional retreat of the High Plains Caprock Escarpment to the east and west and the incision of the Canadian and Pecos Rivers were 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).



Source: Population data from U.S. Census Bureau, Texas 2000 and New Mexico 1990.

SOUTHERN OGALLALA GAM

Population Density

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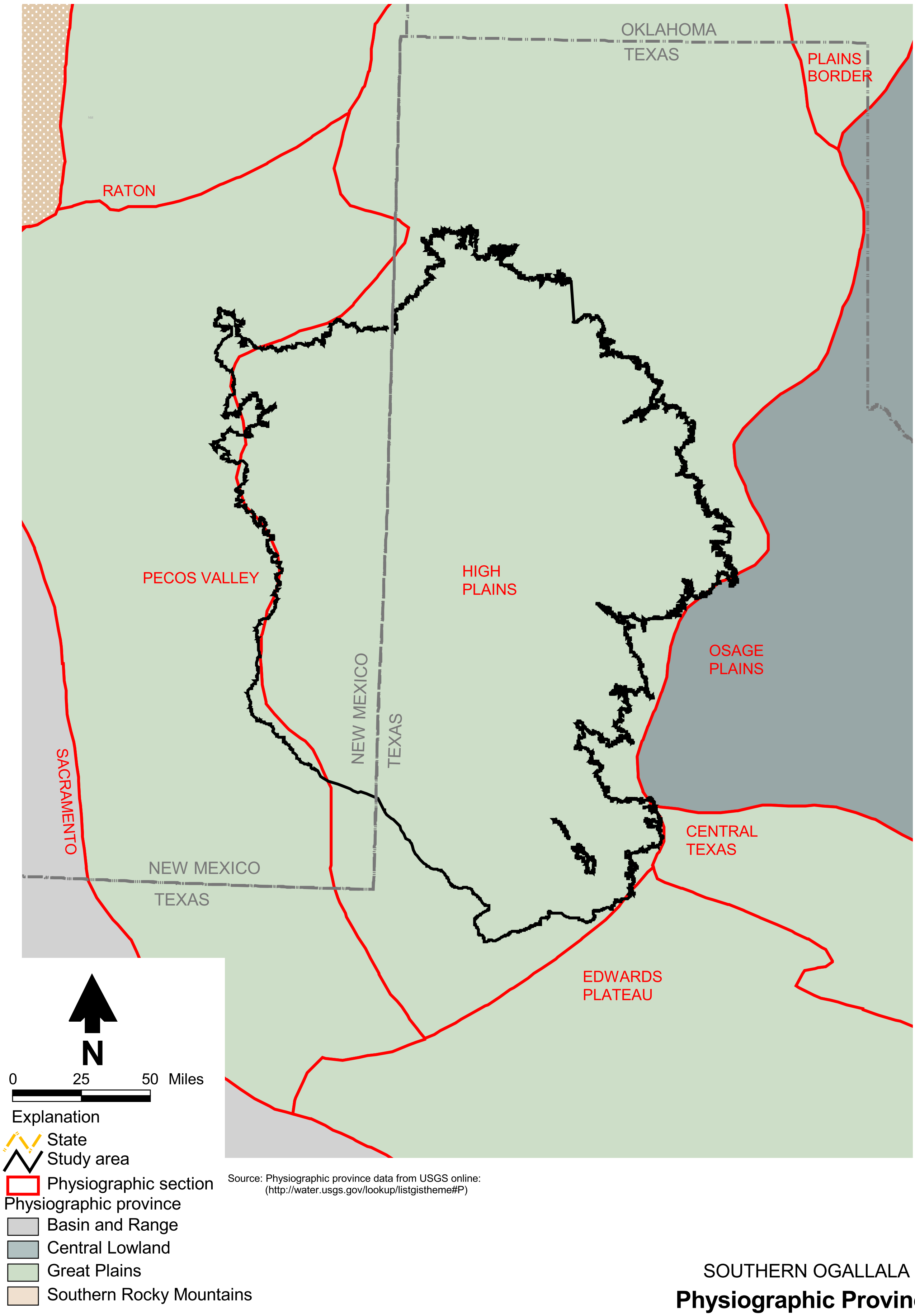
Figure 3



SOUTHERN OGALLALA GAM

Physiographic Provinces

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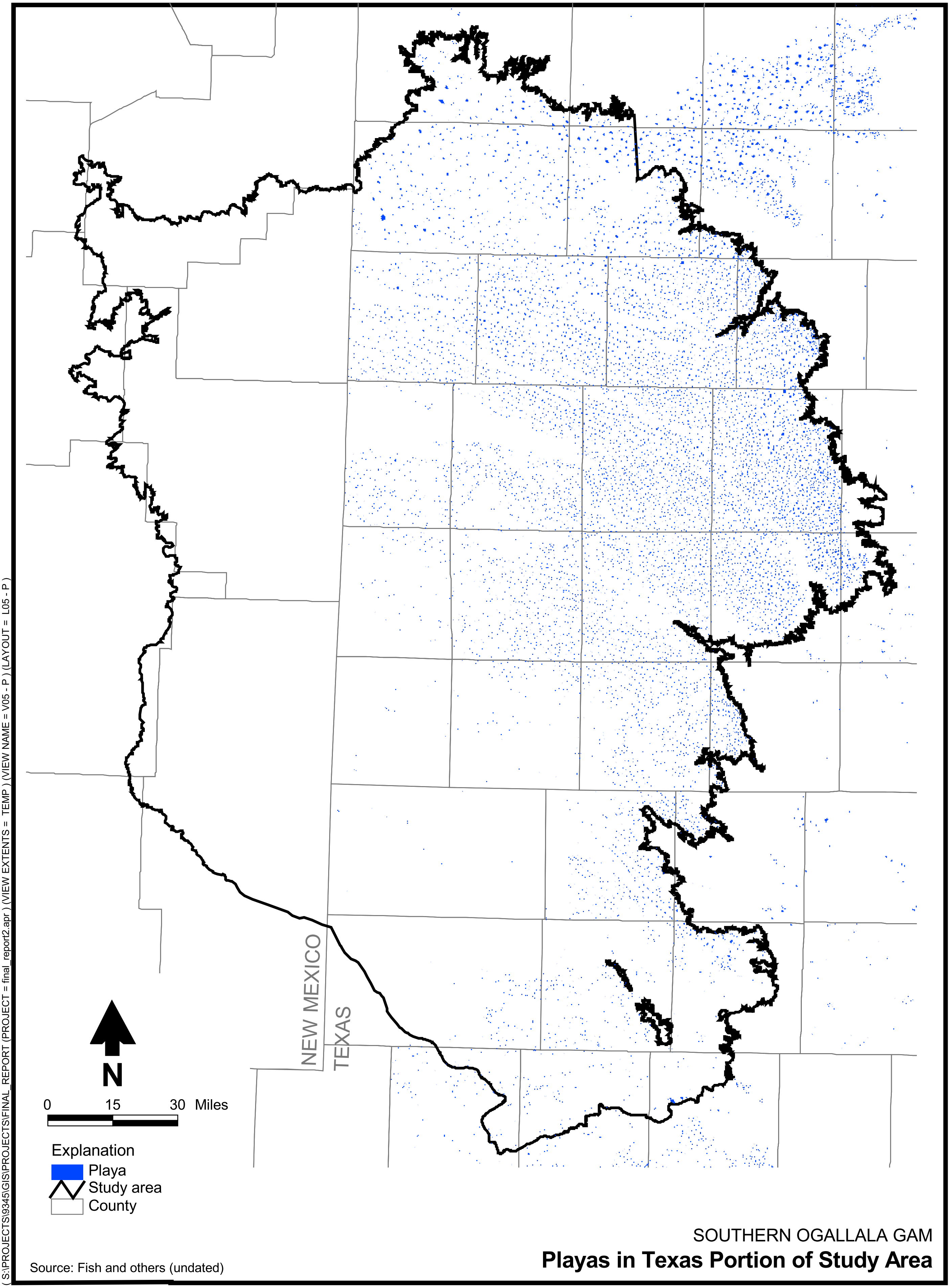
Figure 4



SOUTHERN OGALLALA GAM

Playas in Texas Portion of Study Area

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Figure 5

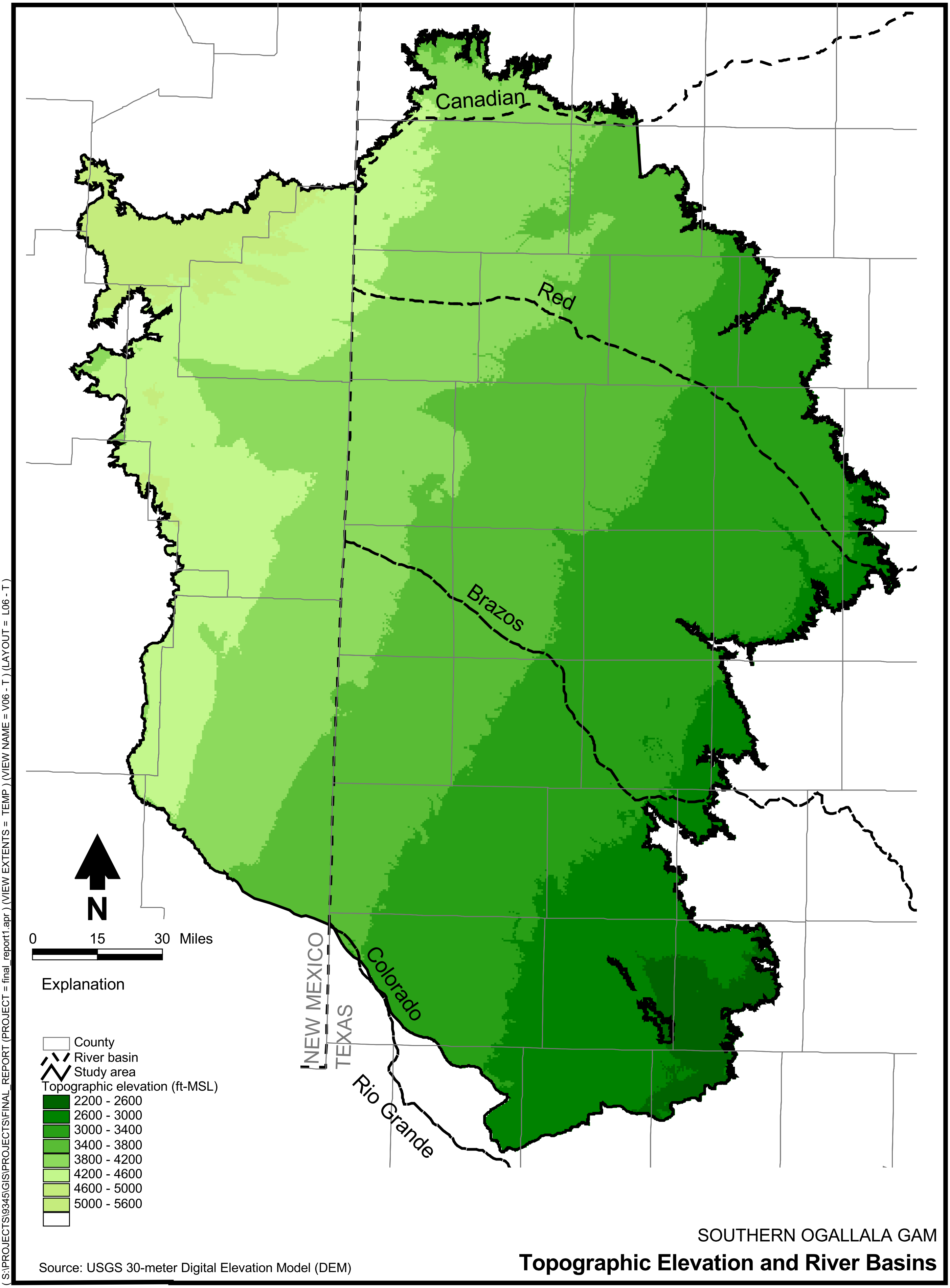

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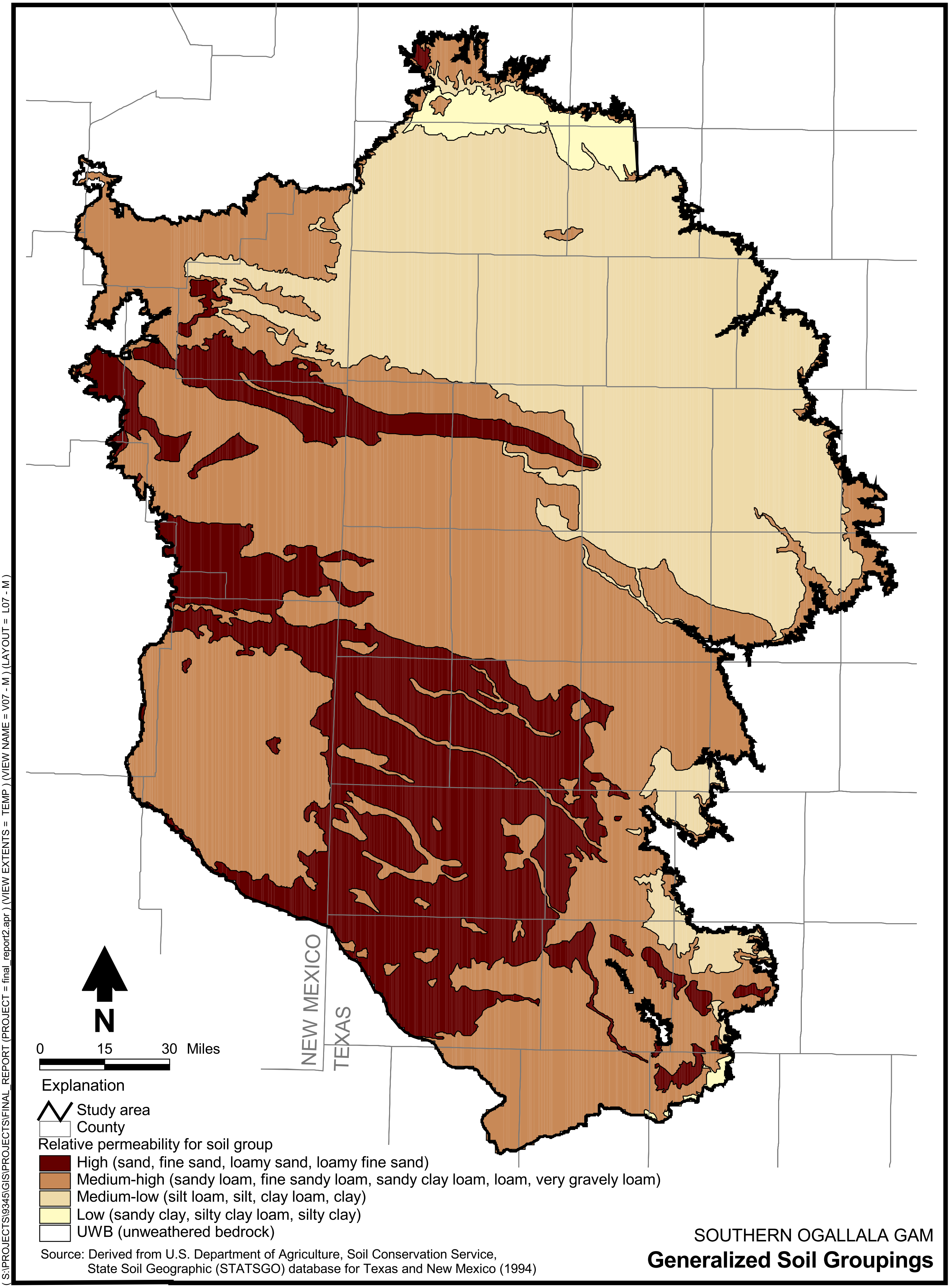
Figure 6



SOUTHERN OGALLALA GAM

Generalized Soil Groupings

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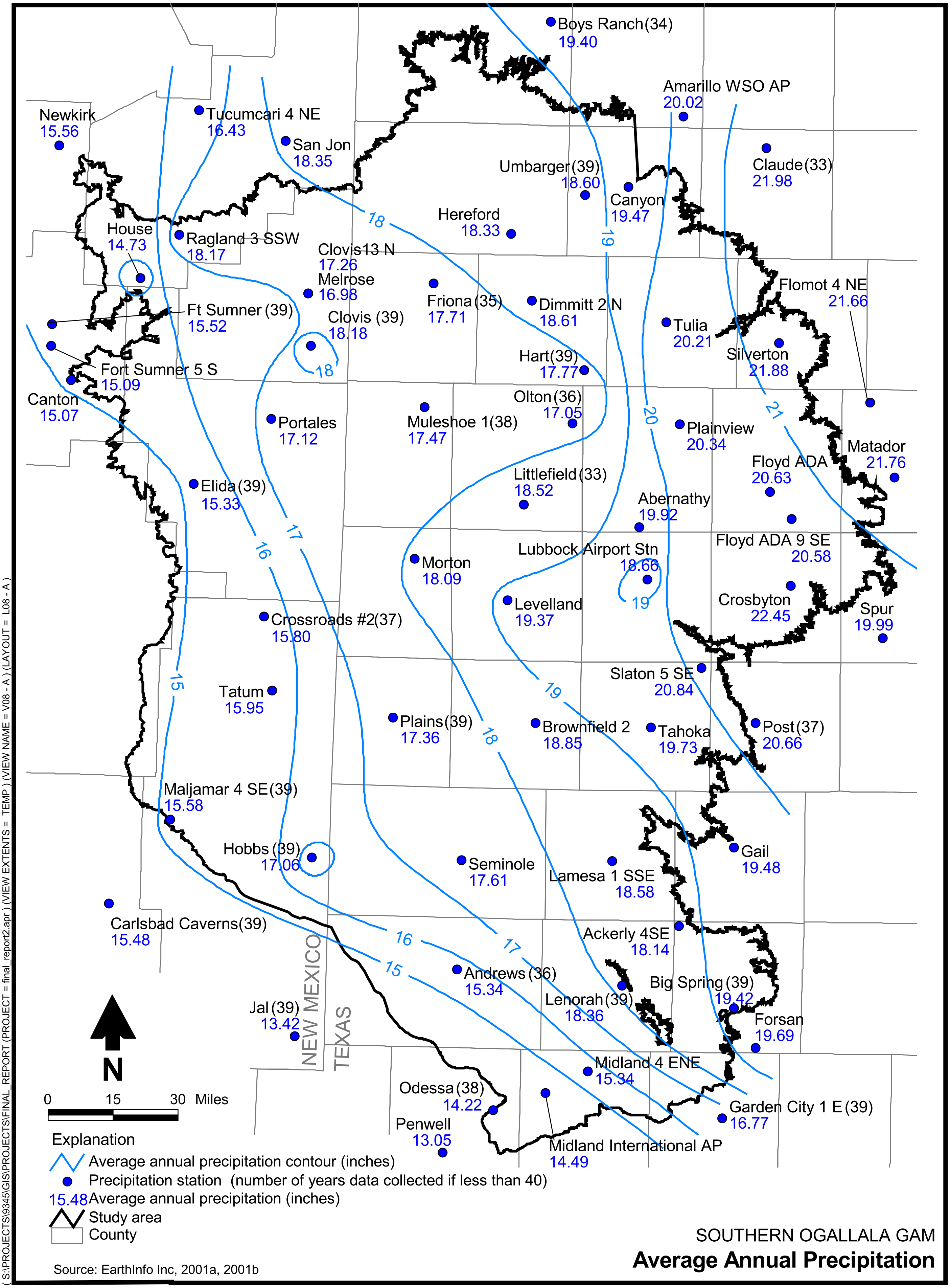
Figure 7



SOUTHERN OGALLALA GAM

Average Annual Precipitation

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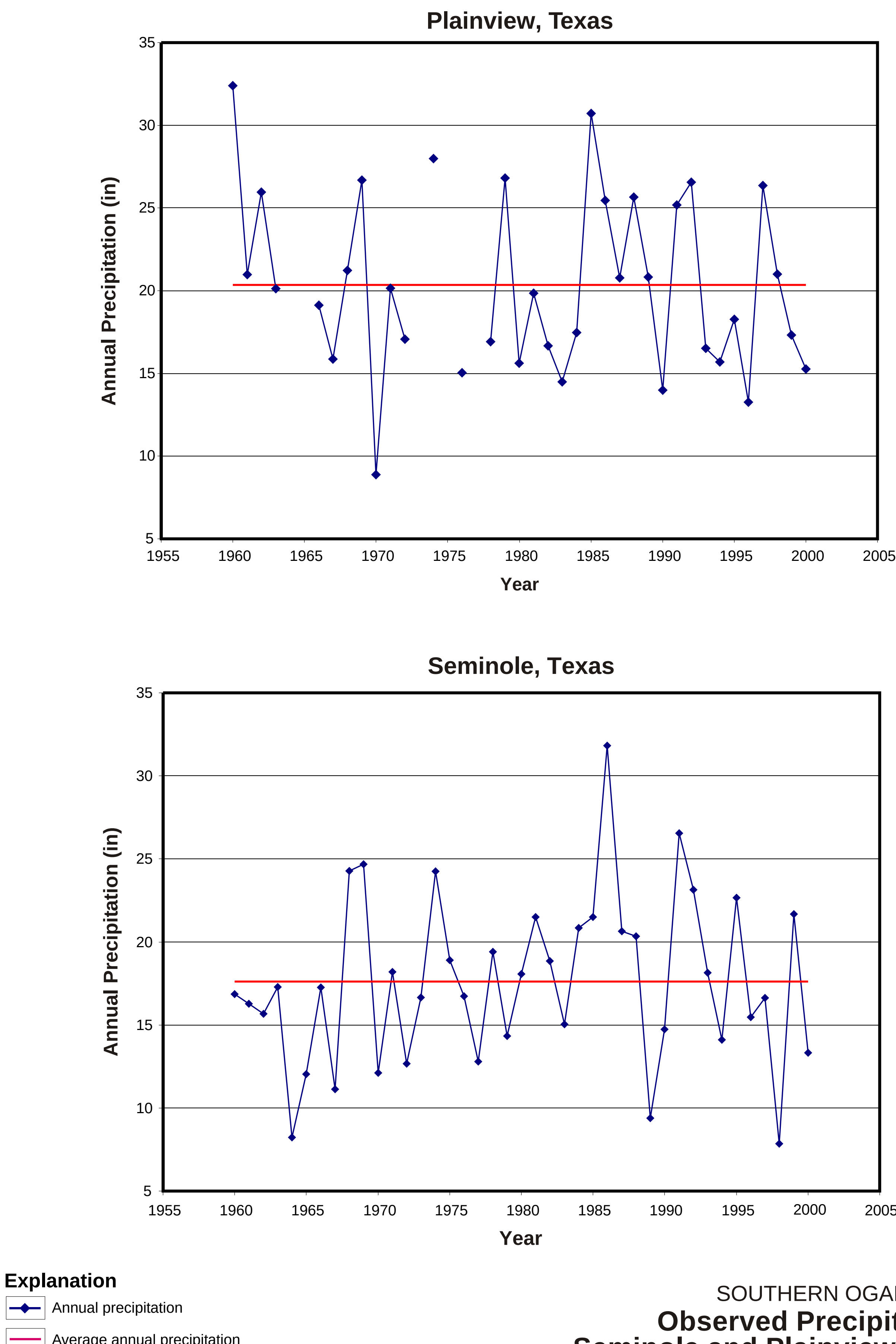
Figure 8



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SOUTHERN OGALLALA GAM

Observed Precipitation for Seminole and Plainview Stations

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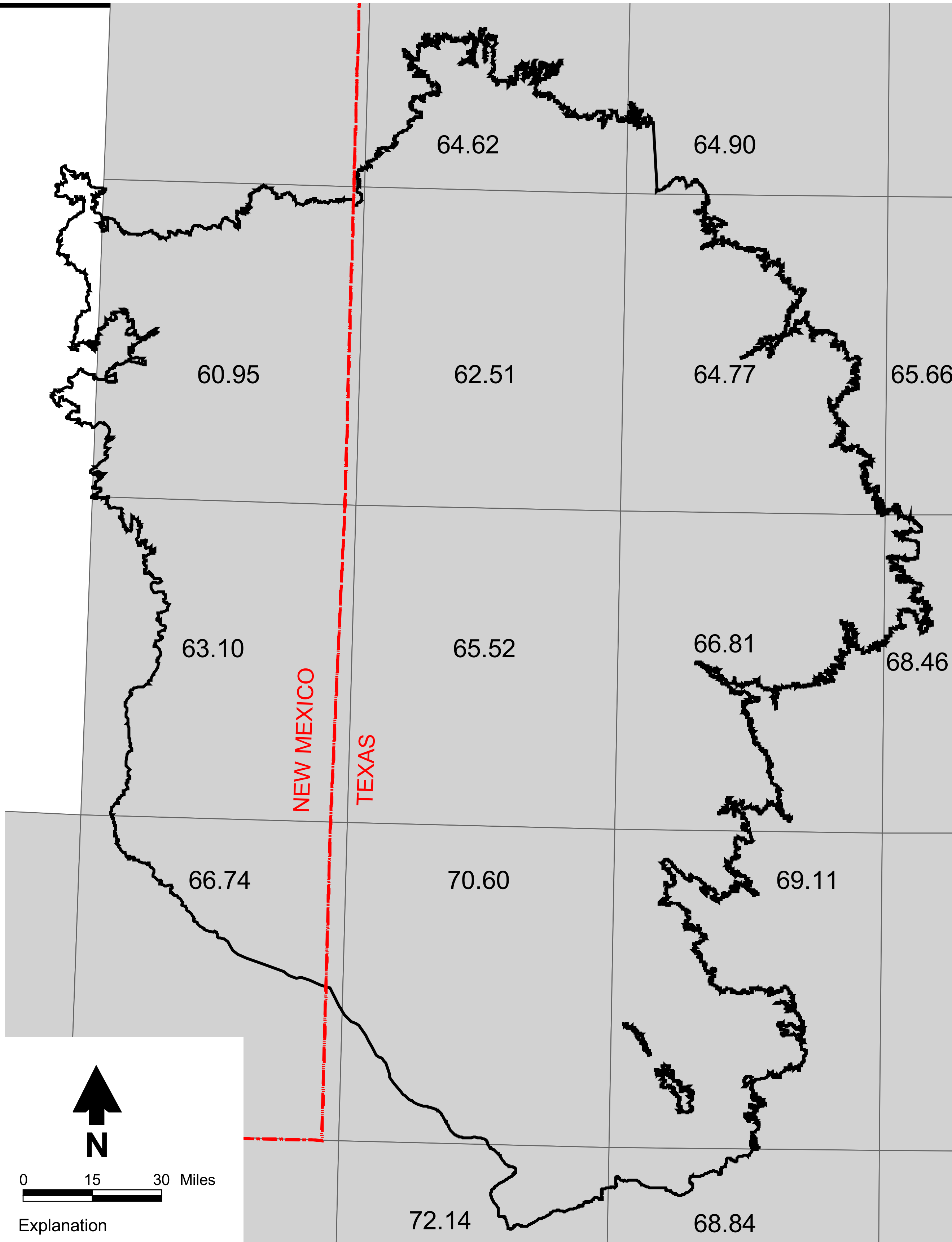
Figure 9



Explanation

State
Study area
1 degree quadrangle
65.52 Average annual lake evaporation (in/yr)

Source: TWDB online evaporation/precipitation data for Texas (http://hyper20.twdb.state.tx.us/Evaporation/evap.html)

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).

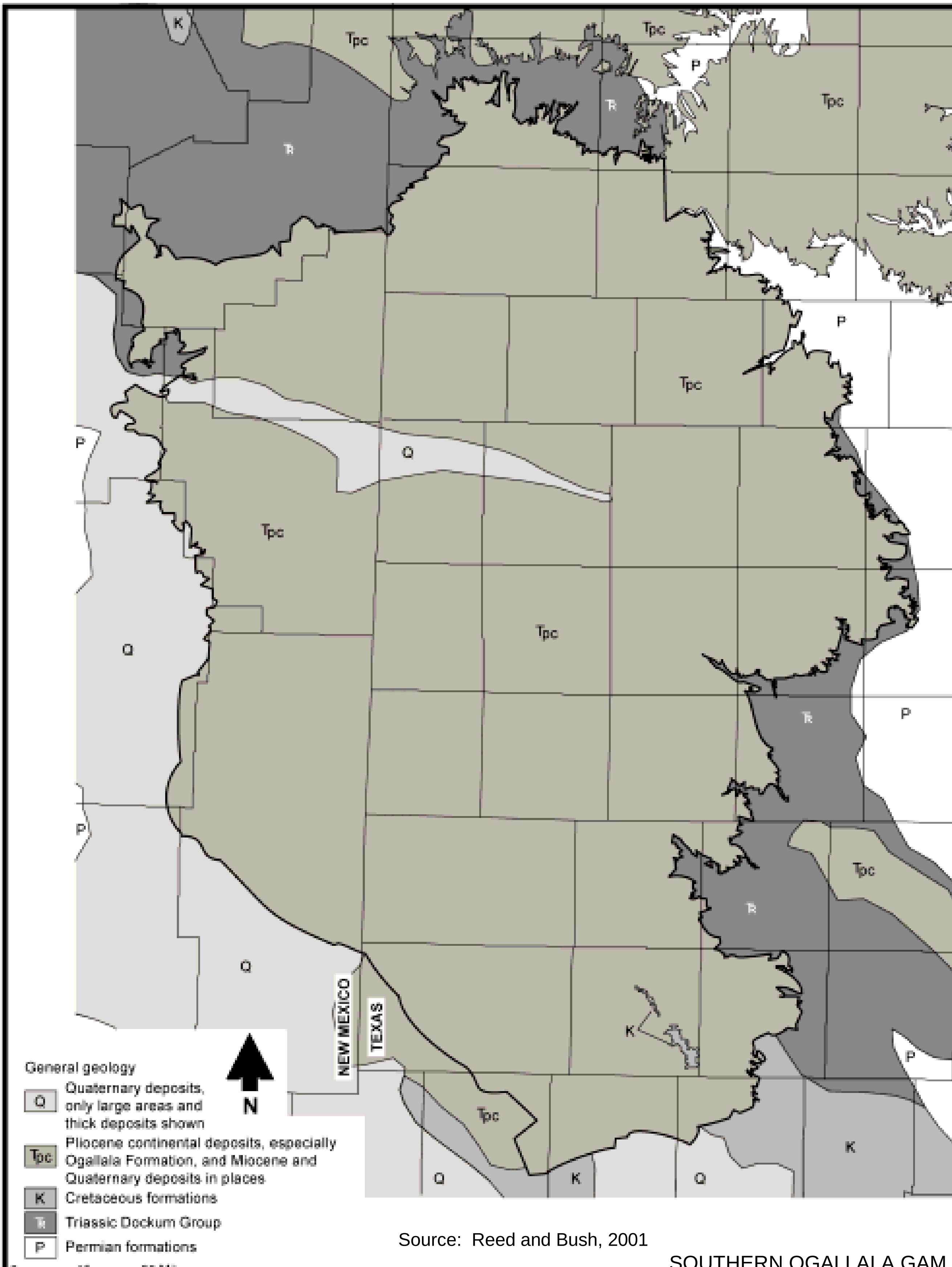
Throughout most of the Southern High Plains, the Ogallala Formation and Cretaceous rocks are underlain by Triassic-age rocks of the Dockum Group, which were deposited in fluvial, deltaic, and lacustrine environments (McGowen and others, 1977, 1979). The Triassic section can be as much as 2,000 ft thick, 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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Figure 11

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

* 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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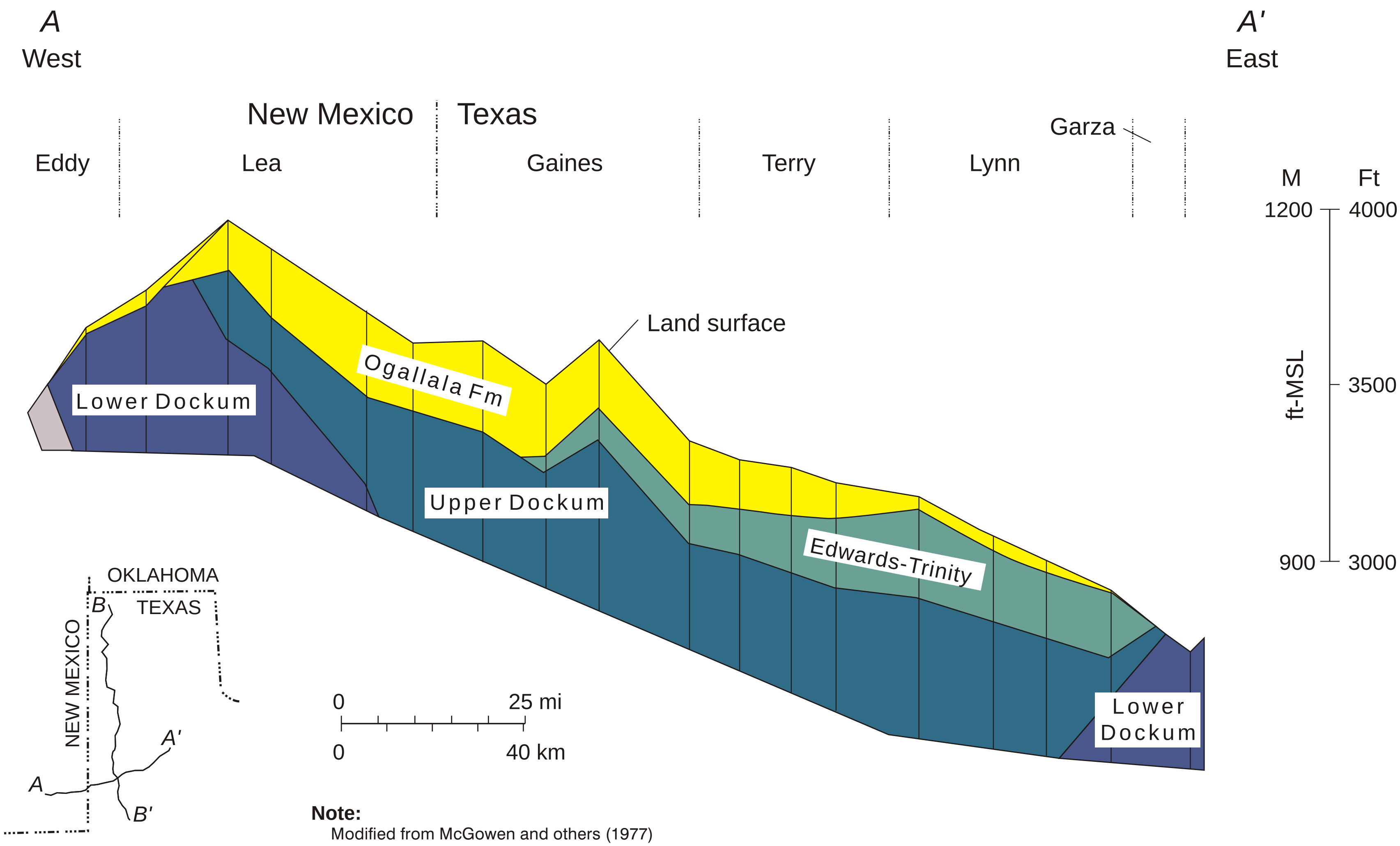
Figure 12



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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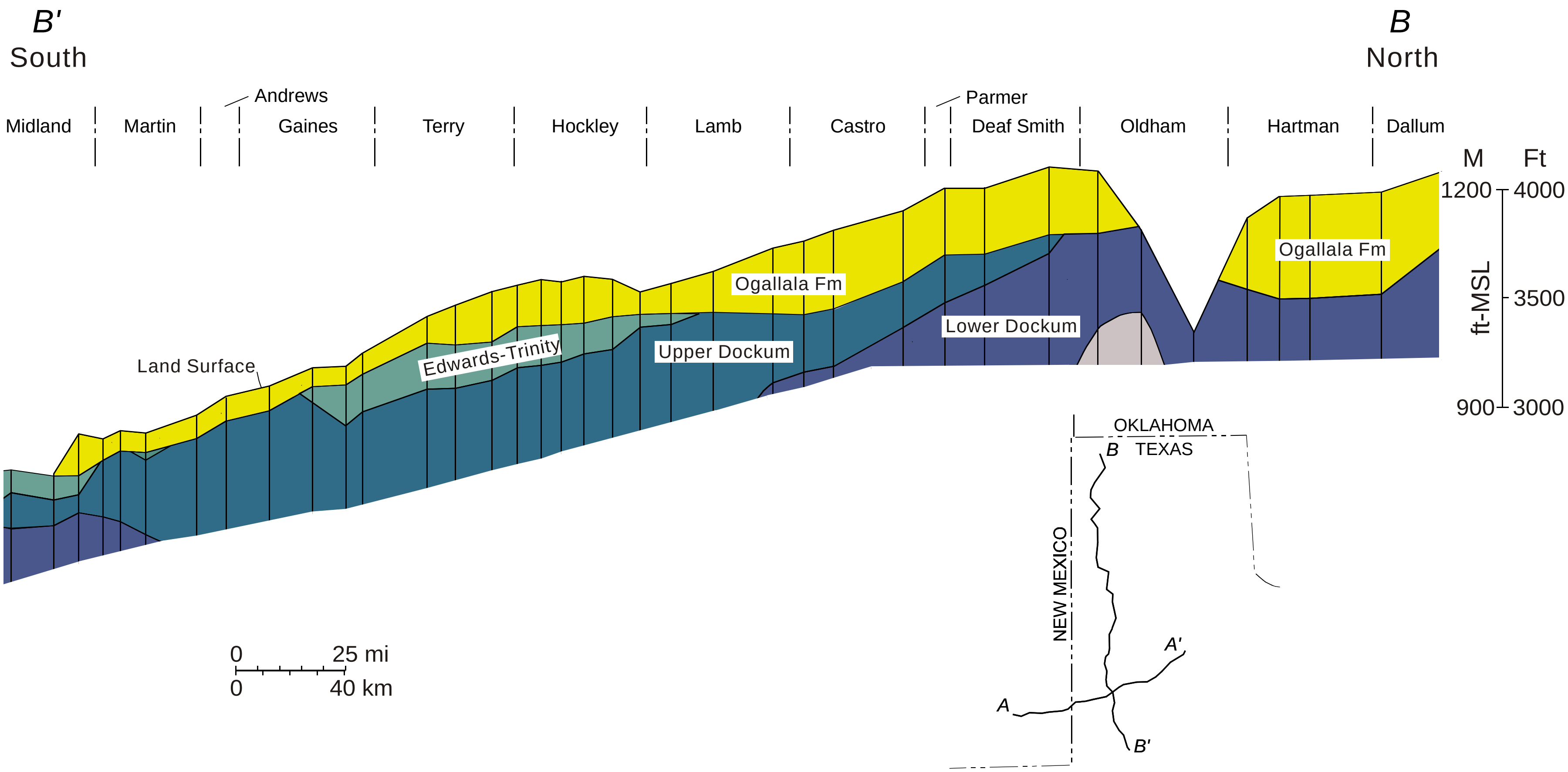

Note:
Modified from McGowen and others (1977)

Explanation

Tertiary-Quaternary

Cretaceous

Triassic

Permian

SOUTHERN OGALLALA GAM

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

Figure 14

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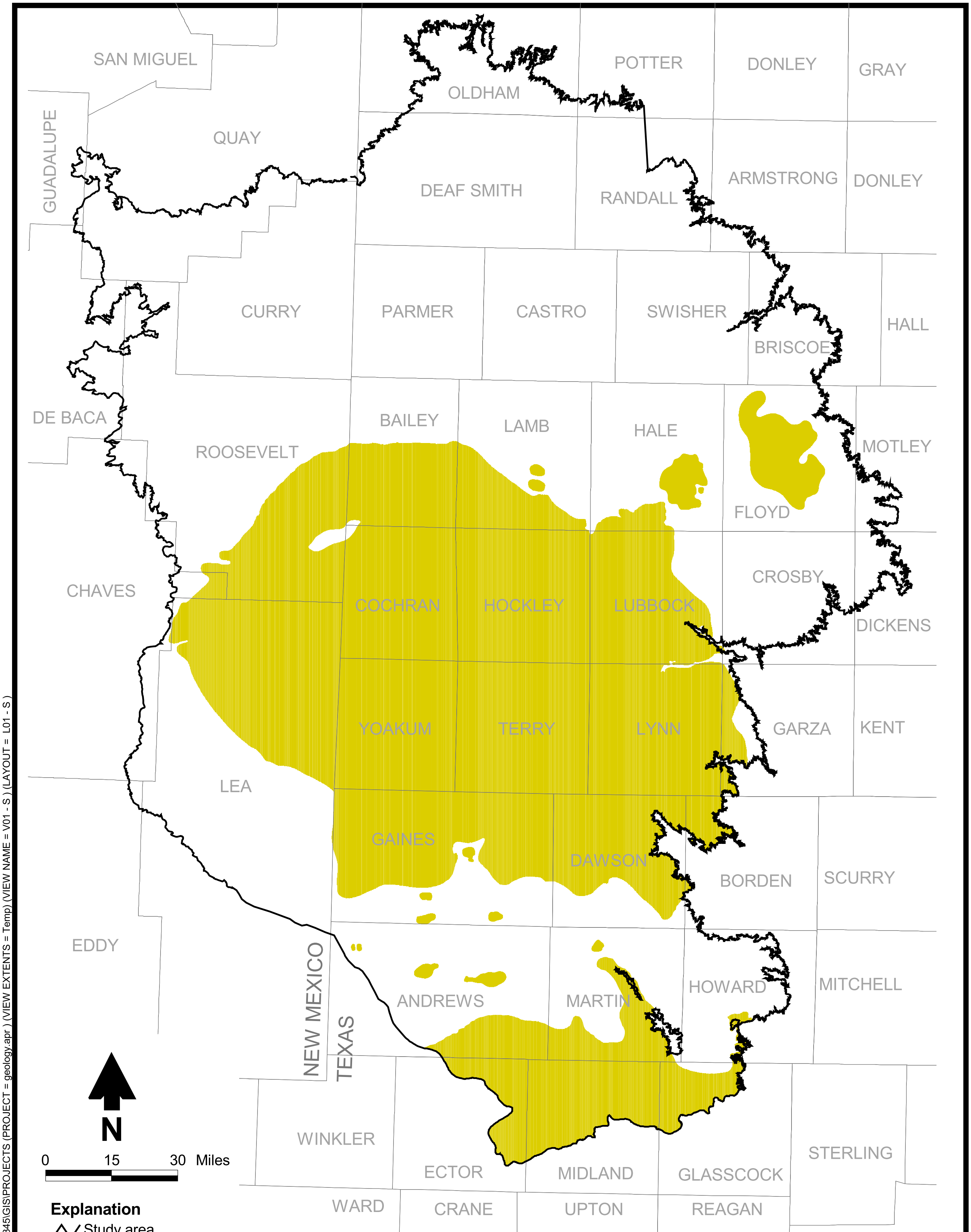

SOUTHERN OGALLALA GAM
Approximate Extent of the Cretaceous Section Beneath the Southern High Plains

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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:

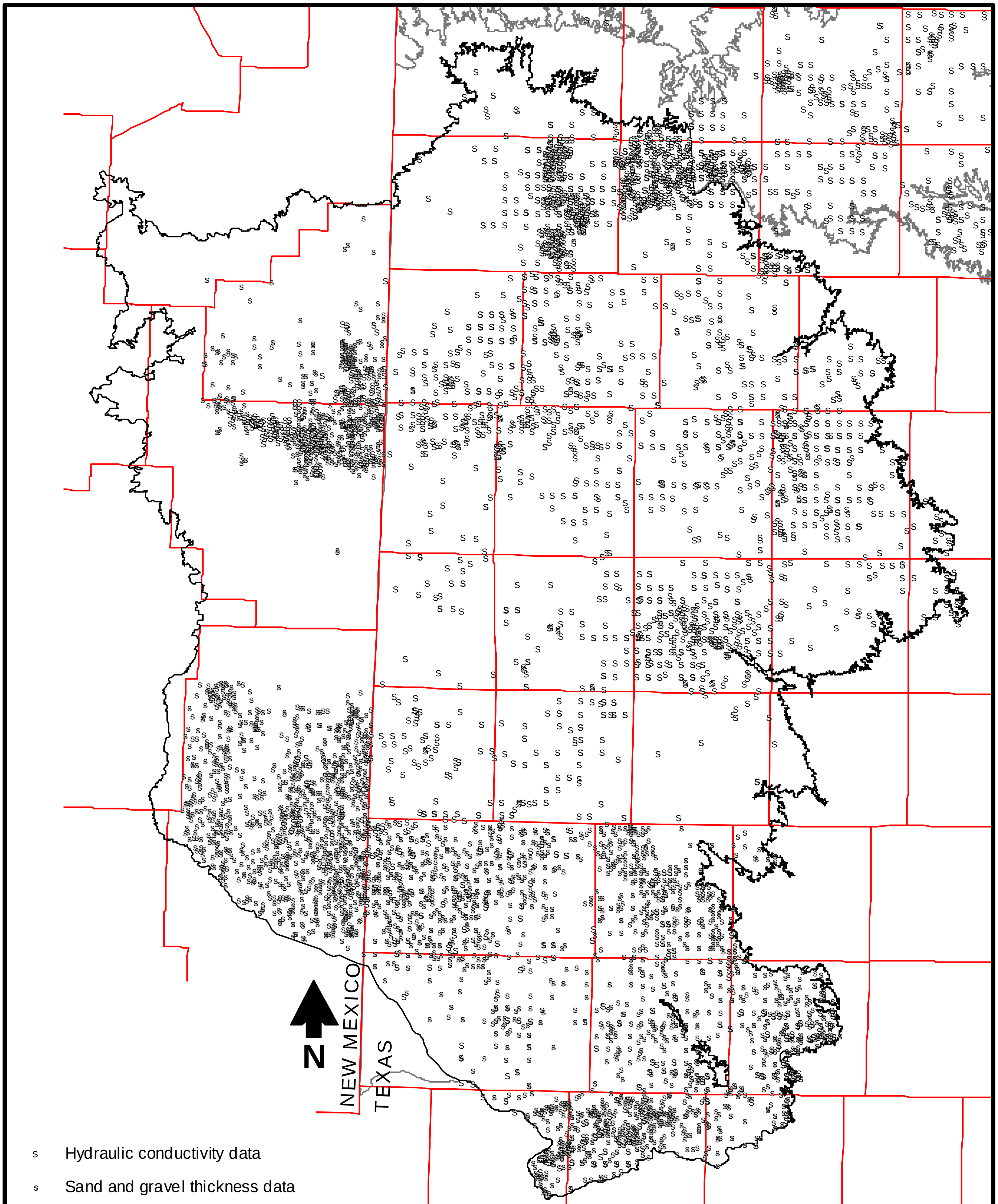
- Recharge throughout most of the model area for predevelopment (steady-state) conditions is 0.086 inch per year (in/yr), although higher recharge rates of up to 1.03 in/yr are applied to a limited area along Running Water draw. For the period 1960 through 1980, a recharge of 2 in/yr was applied to all 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.



s Hydraulic conductivity data

s Sand and gravel thickness data

Note: Some data points in Texas represent the center of 2.5-minute quadrangles with average data

SOUTHERN OGALLALA GAM

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

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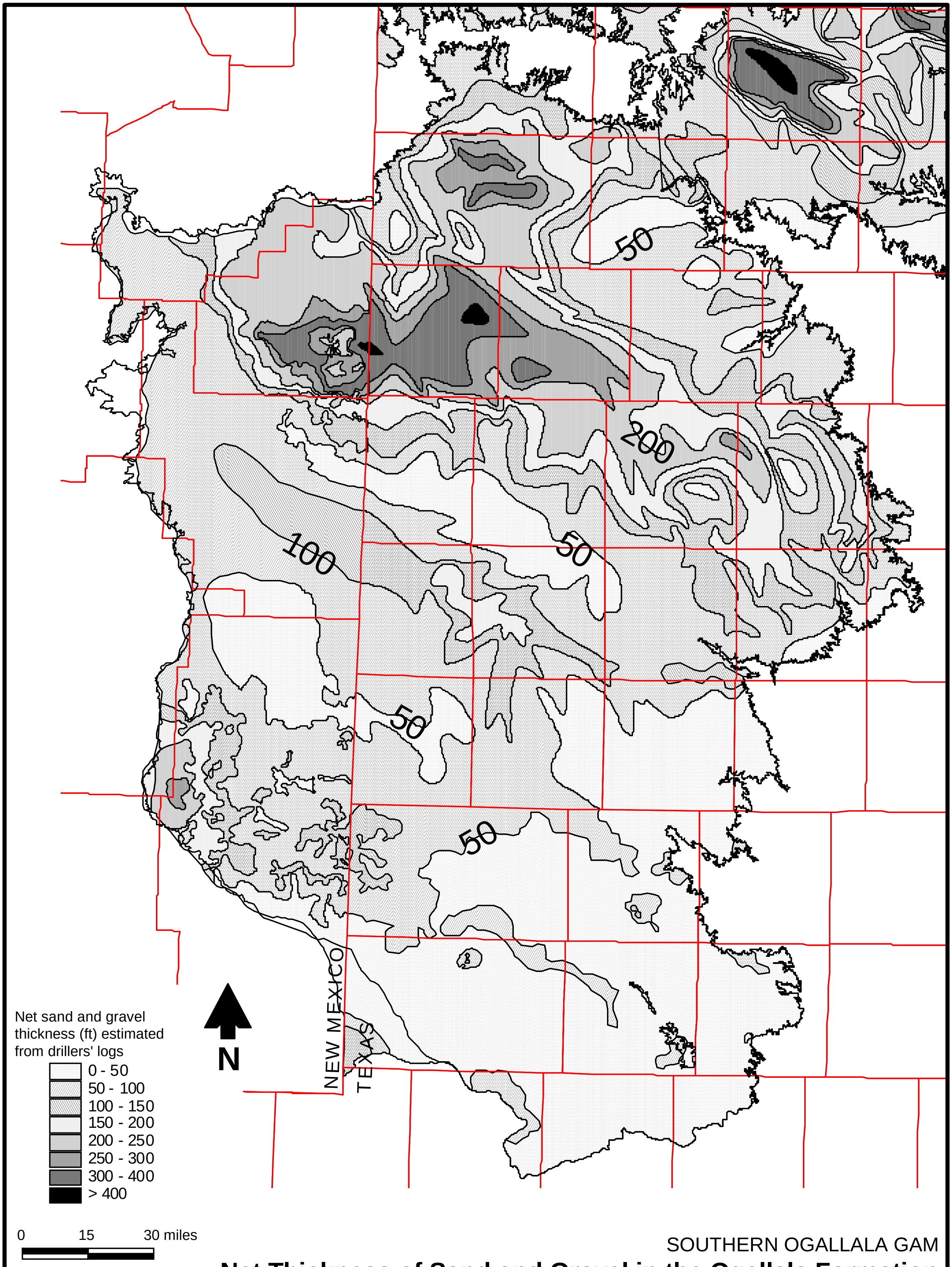
Figure 16



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SOUTHERN OGALLALA GAM

Net Thickness of Sand and Gravel in the Ogallala Formation

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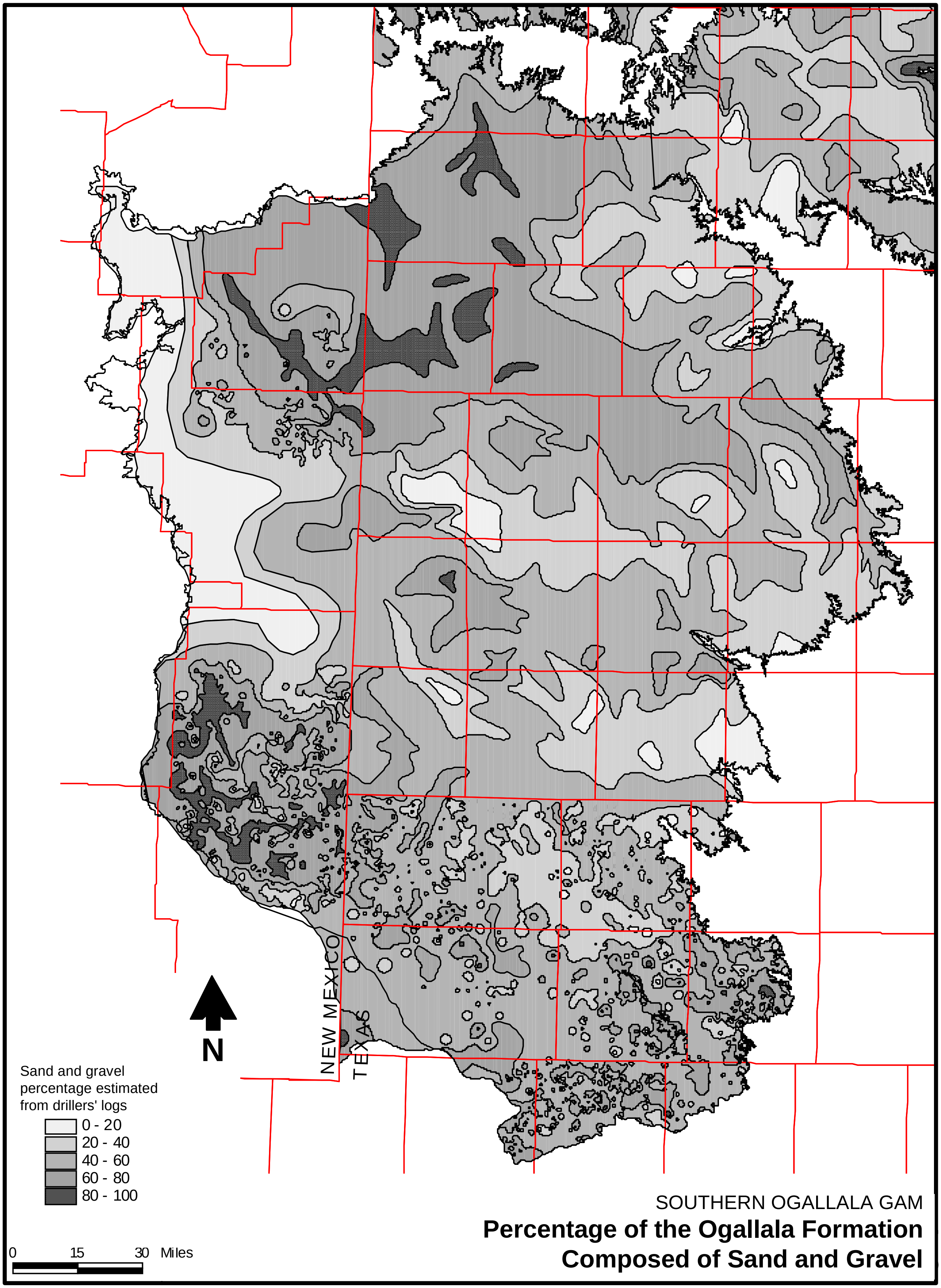
Figure 17



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SOUTHERN OGALLALA GAM

Percentage of the Ogallala Formation Composed of Sand and Gravel

10-4-02

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).

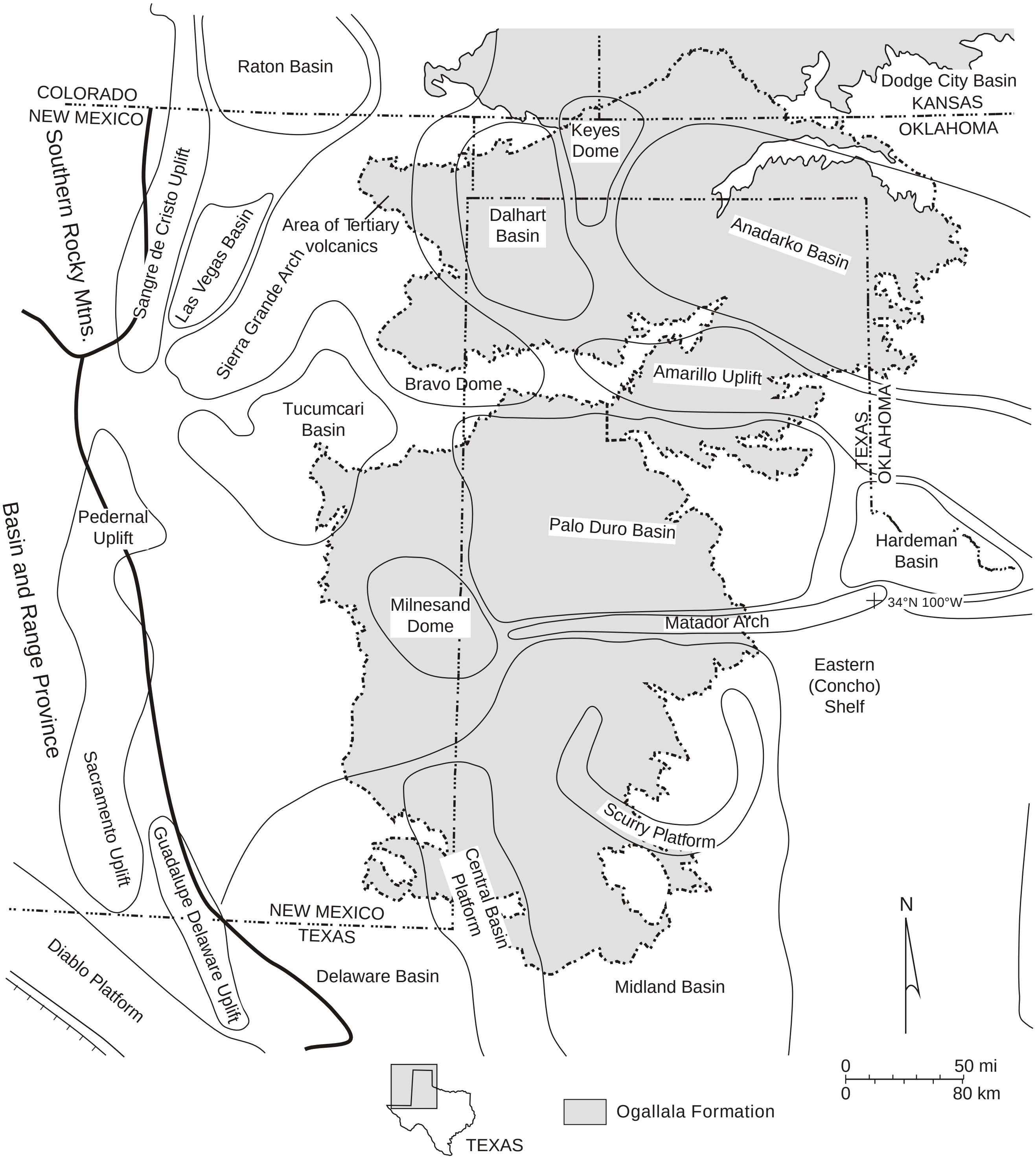
Since the regional uplift, groundwater circulation from the Ogallala sediments downward into the underlying Permian section has resulted in dissolution of Permian salt beds. Ground-surface subsidence and collapse into the salt caverns resulted in locally thick accumulations of Ogallala sediment. Salt-dissolution 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)

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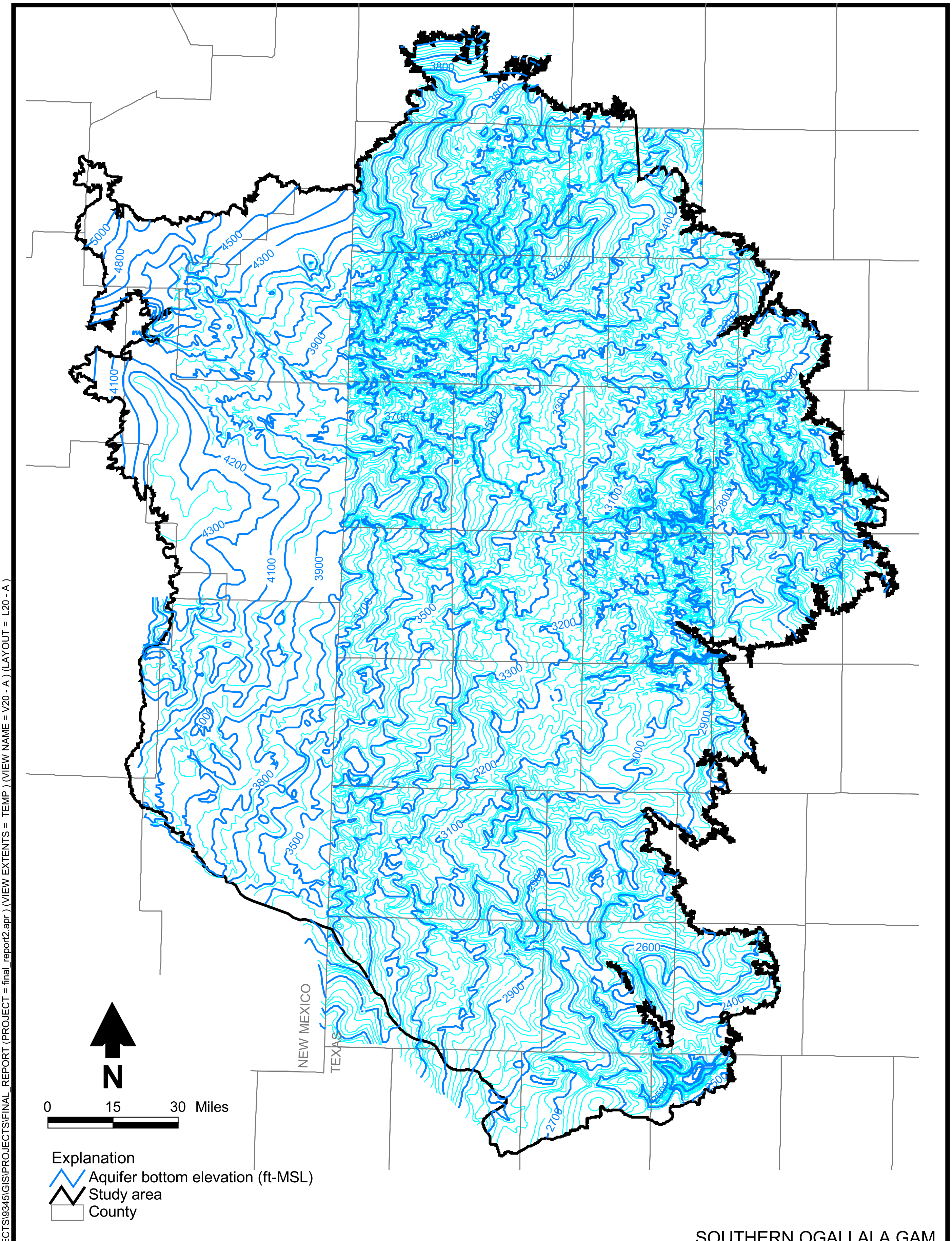
SOUTHERN OGALLALA GAM

Regional Geologic Structure in the Texas Panhandle and Eastern New Mexico

10-4-02 JN 9345

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.

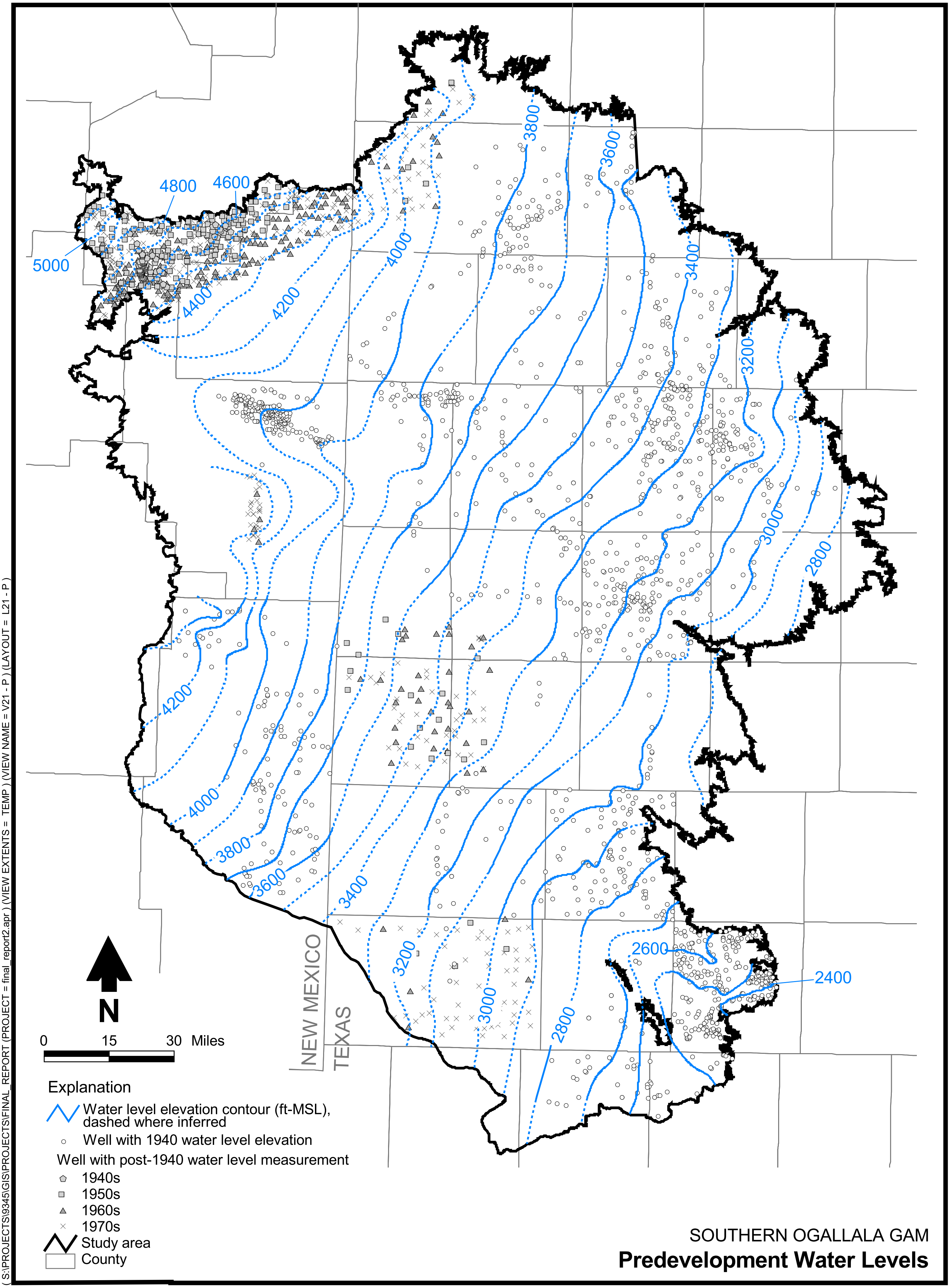
Figure 21 shows the water table within the study area representative of aquifer conditions prior to significant groundwater development. This figure was constructed based primarily on observed water levels for 1940 or earlier, but in some areas with limited groundwater withdrawals and relatively constant 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).



SOUTHERN OGALLALA GAM

Predevelopment Water Levels

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Figure 21

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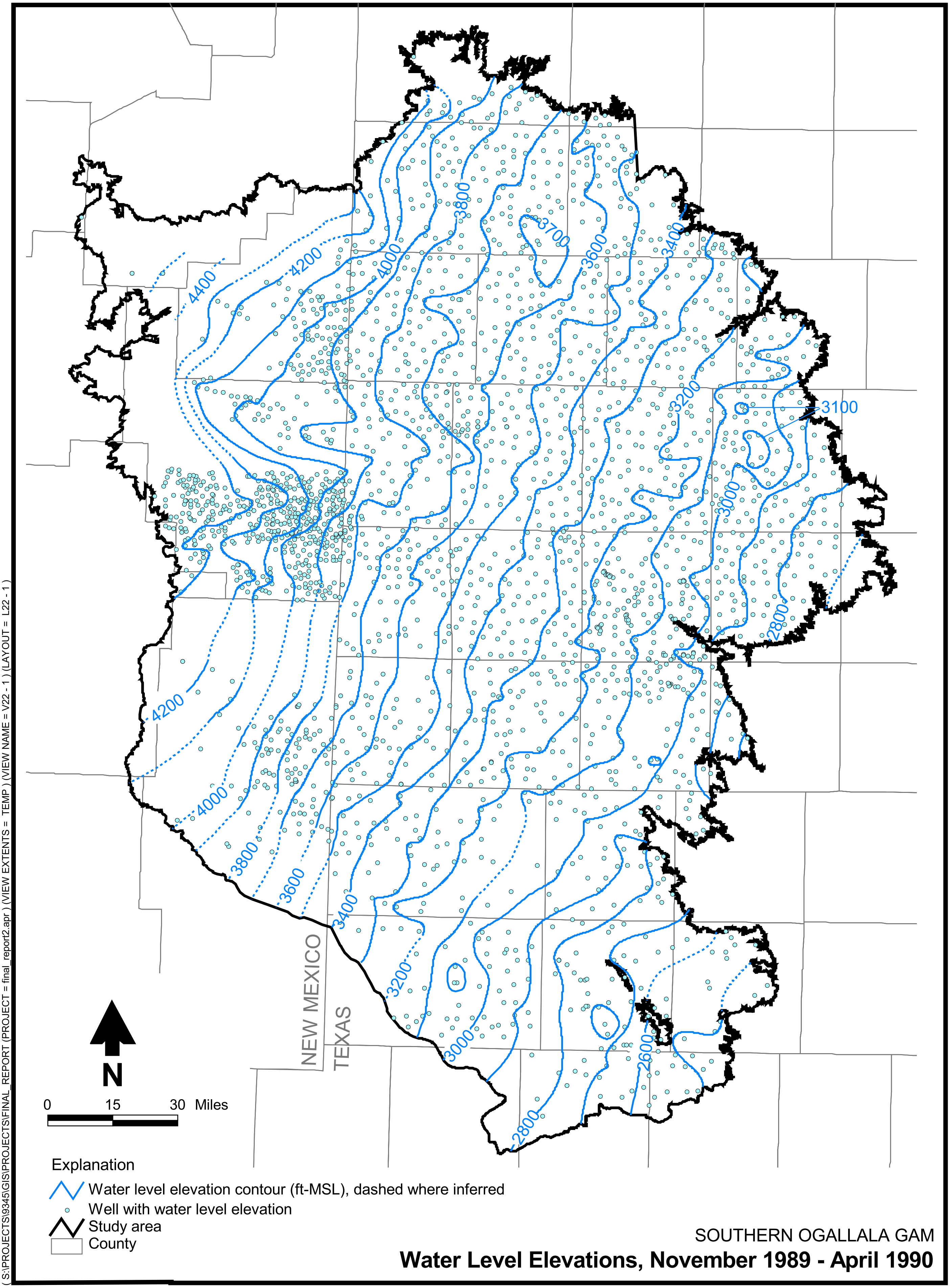

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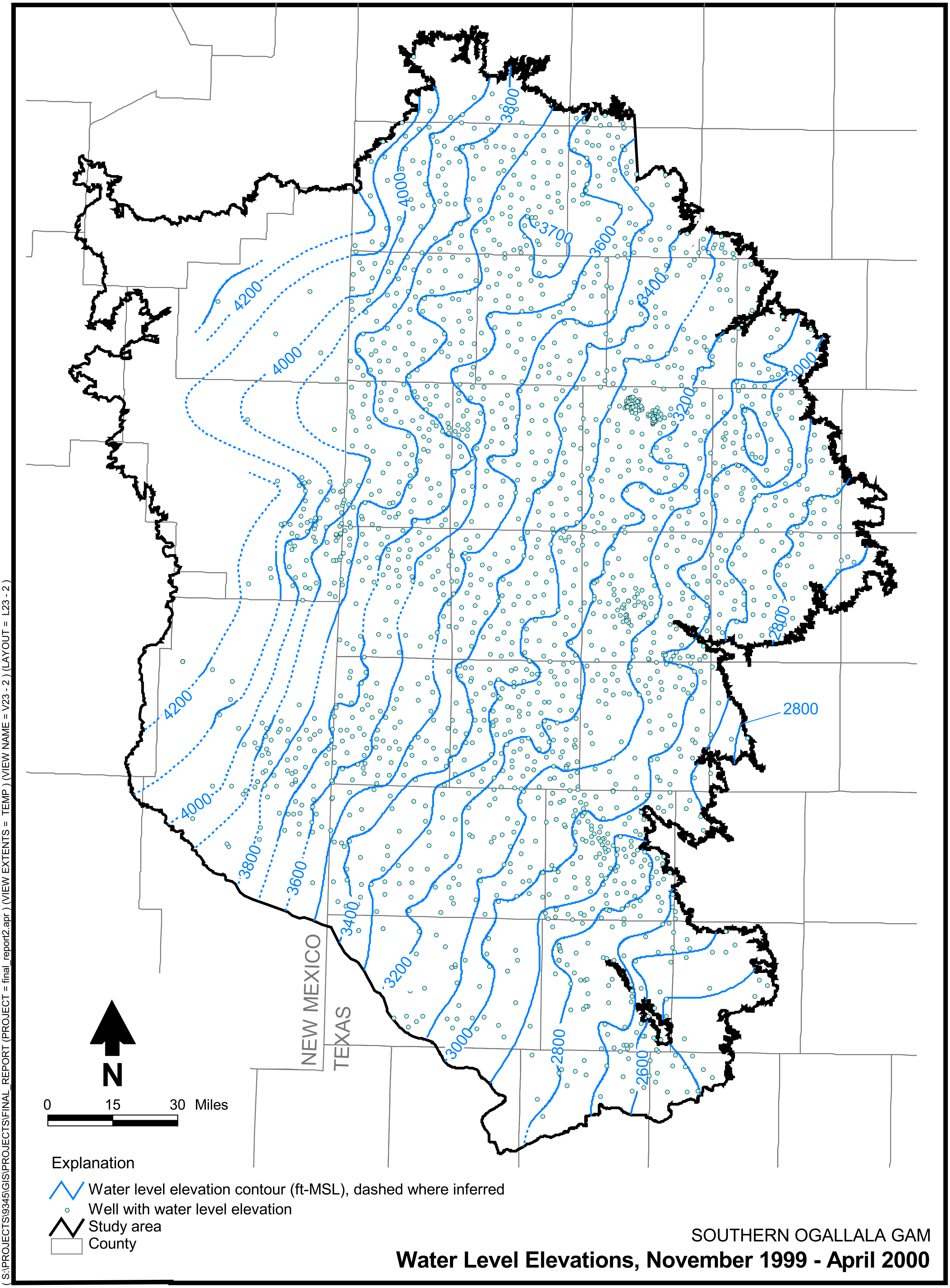
SOUTHERN OGALLALA GAM

Water Level Elevations, November 1989 - April 1990

1-30-03

Figure 22



SOUTHERN OGALLALA GAM

Water Level Elevations, November 1999 - April 2000

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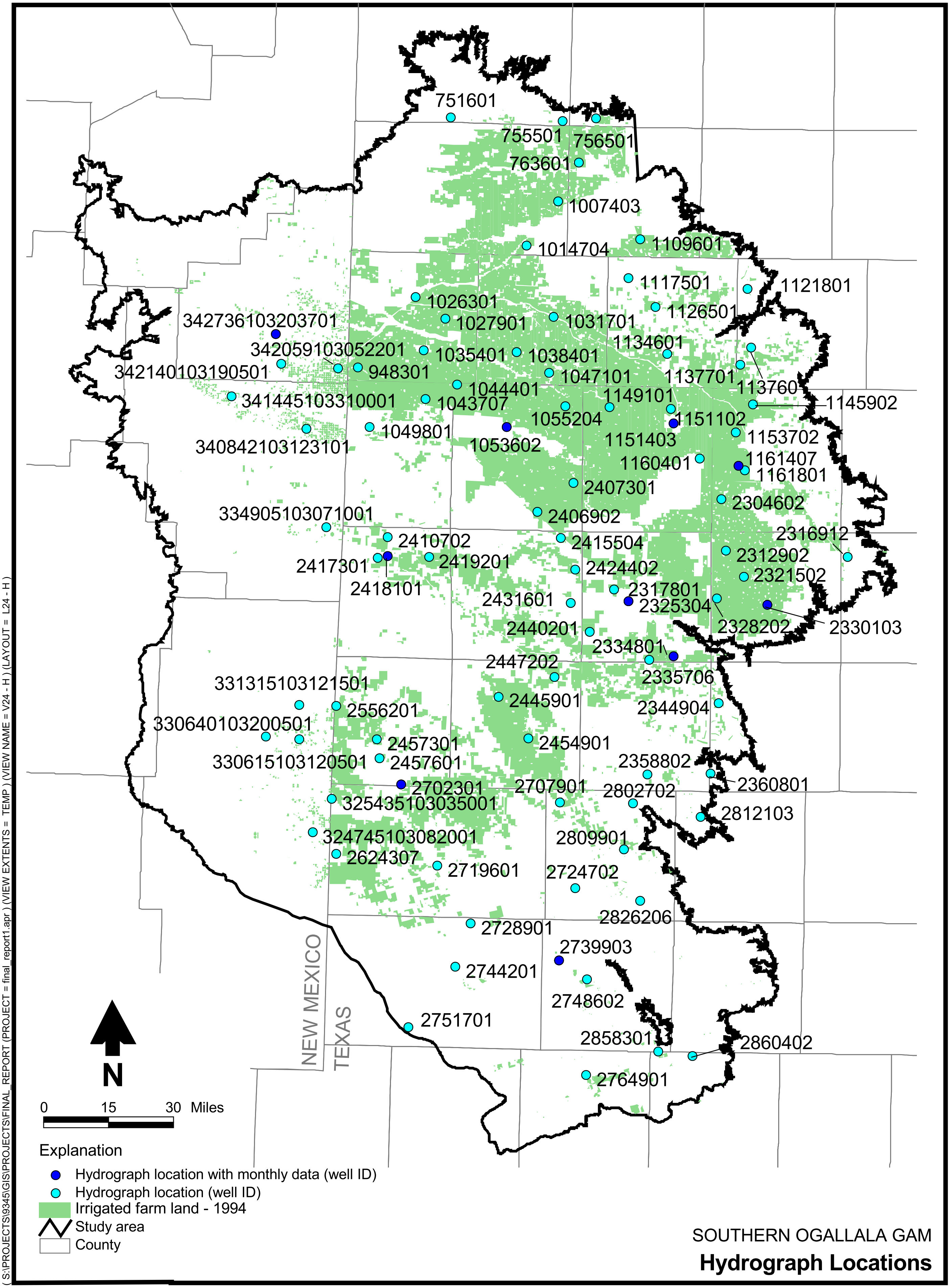

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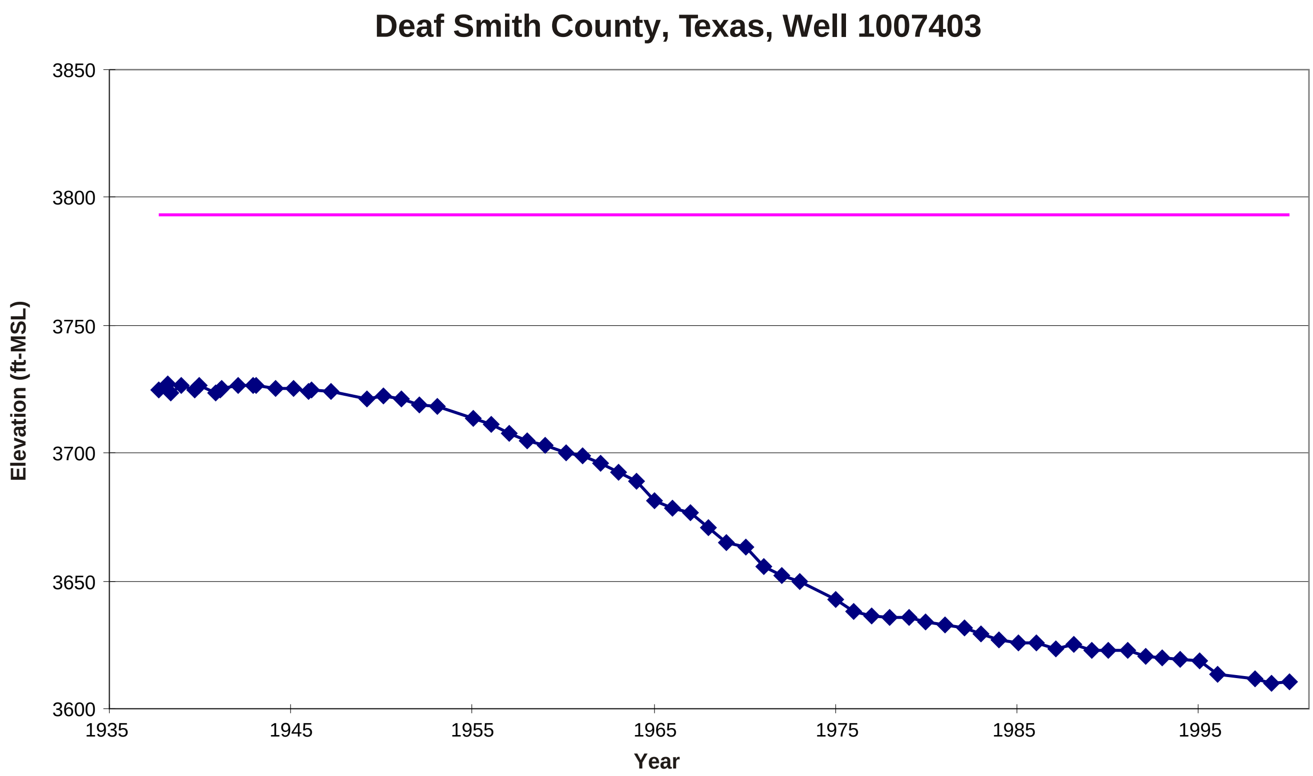
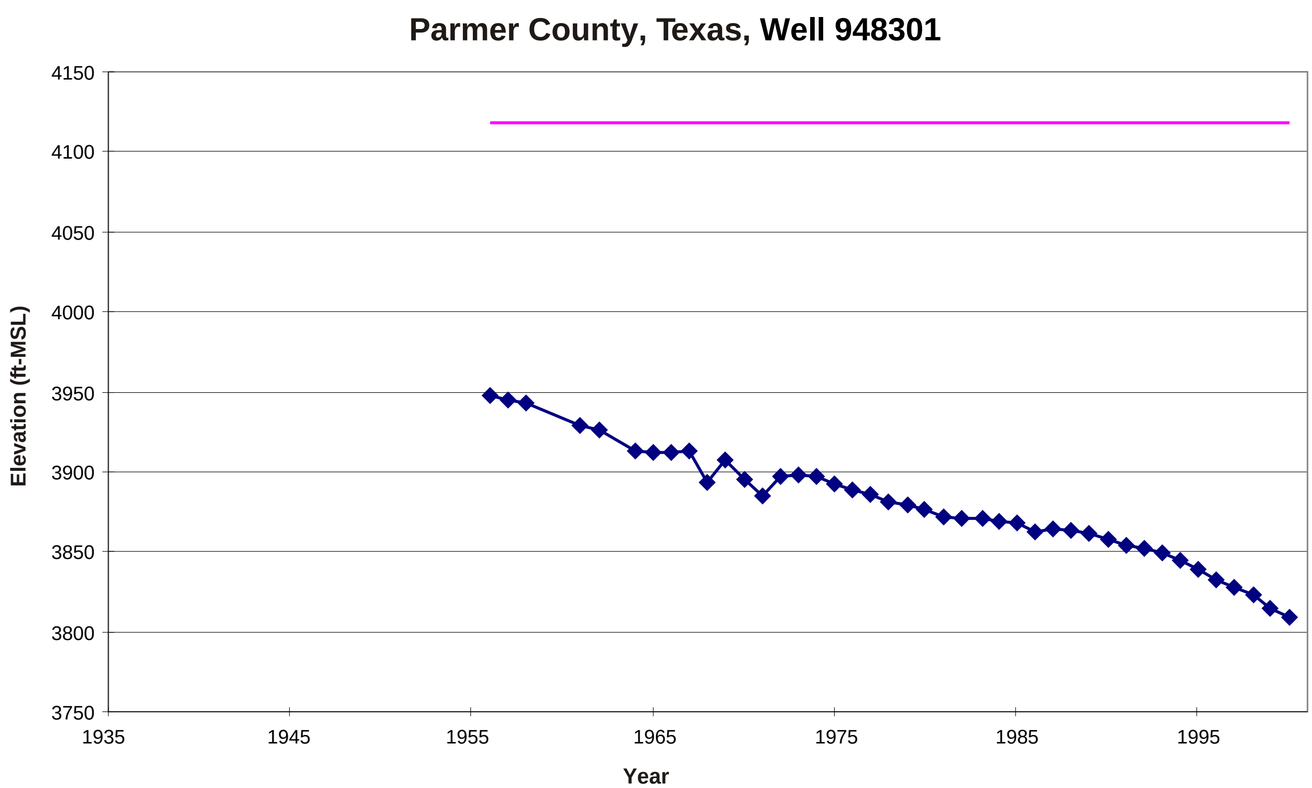
Figure 24





Explanation

Water level

Land surface

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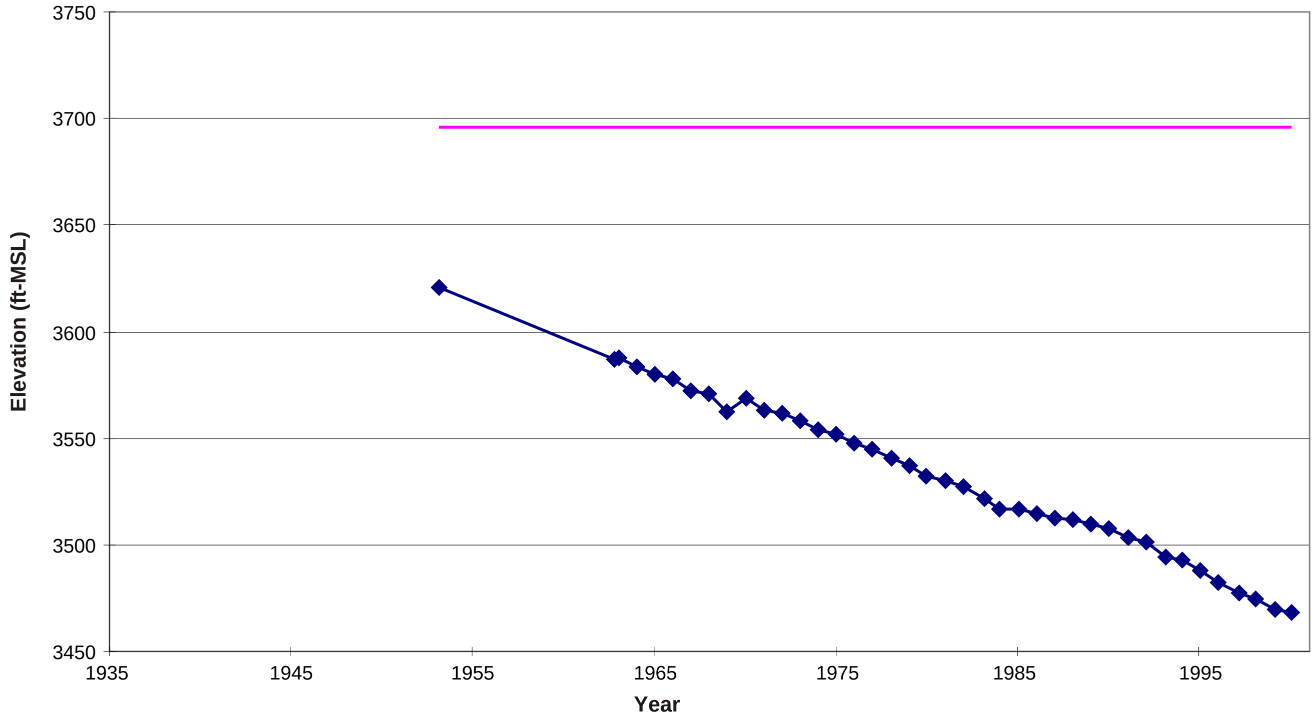
SOUTHERN OGALLALA GAM

Observed Water Levels in Deaf Smith and Parmer Counties

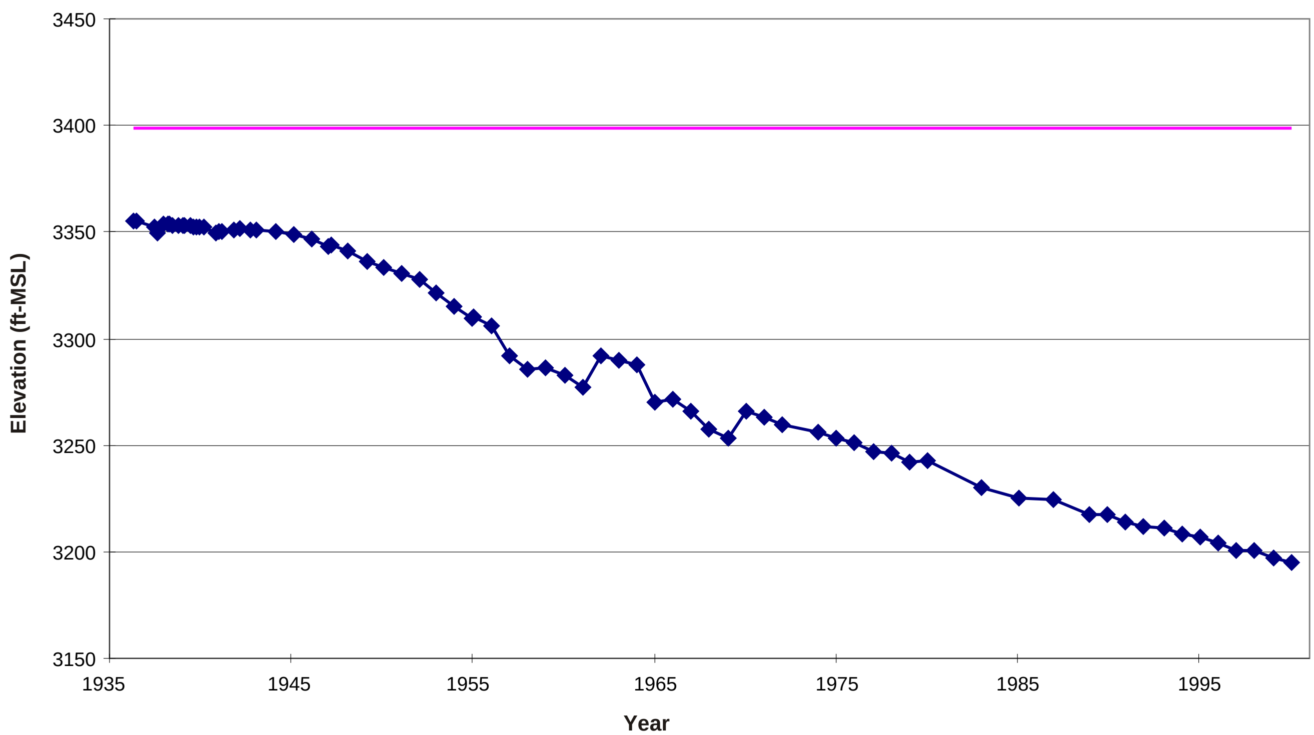
1-30-03

Figure 25

Castro County, Texas, Well 1047101



Hale County, Texas, Well 1151102



Explanation

Water level

Land surface

SOUTHERN OGALLALA GAM

Observed Water Levels in Castro and Hale Counties

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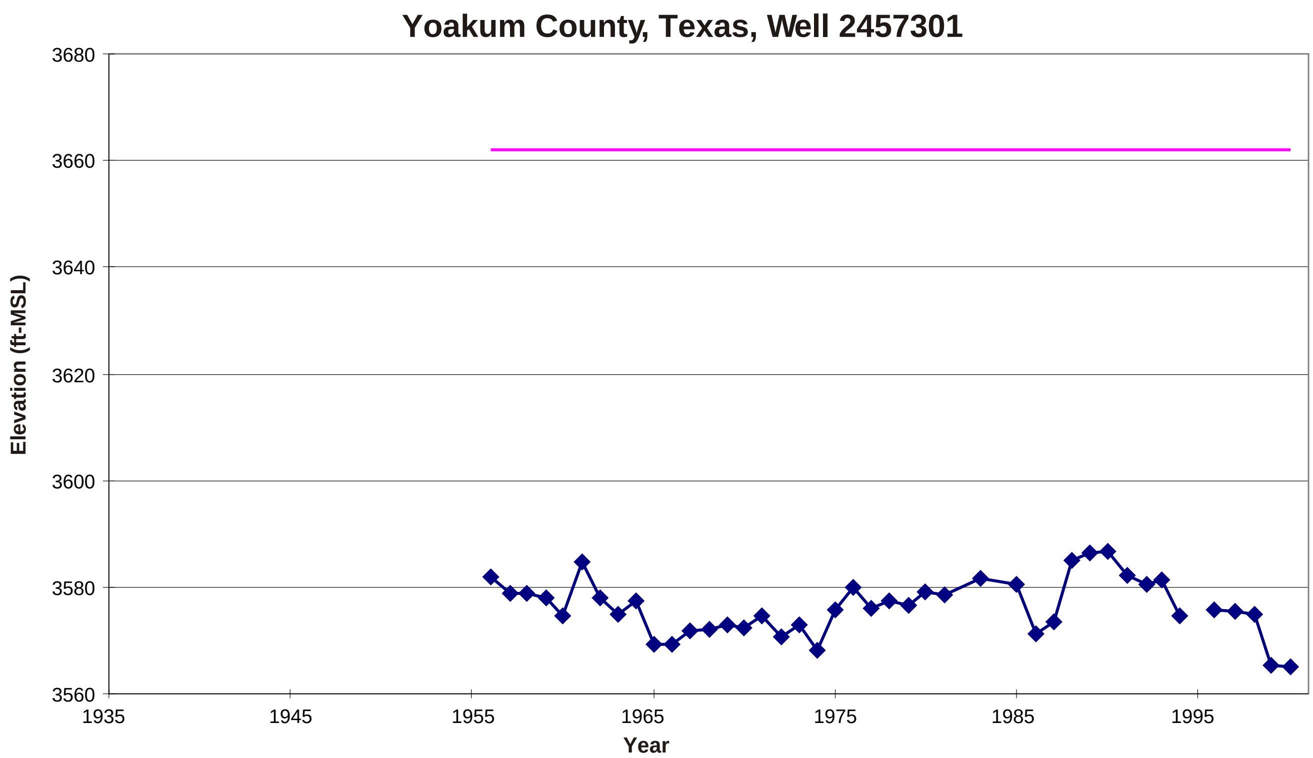
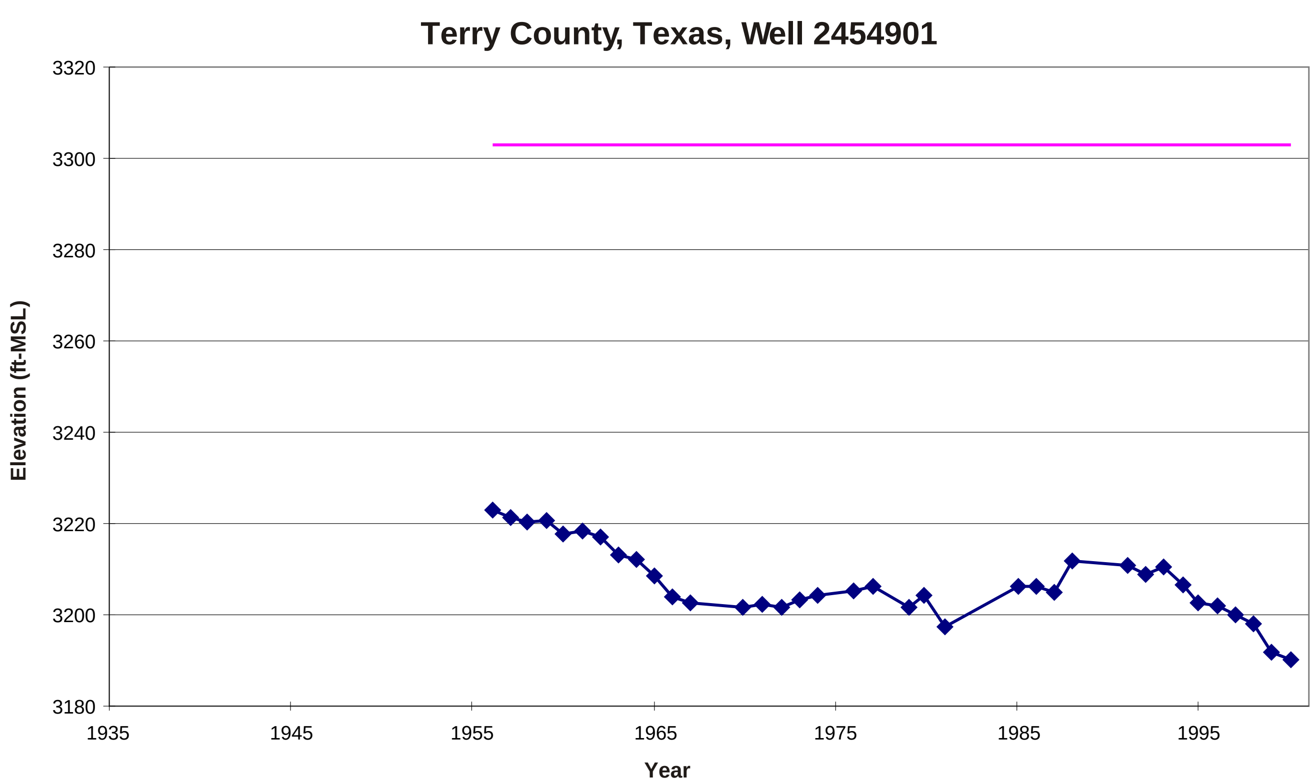
1-30-03

Figure 26





Explanation

Water level

Land surface

SOUTHERN OGALLALA GAM

Observed Water Levels in Yoakum and Terry Counties

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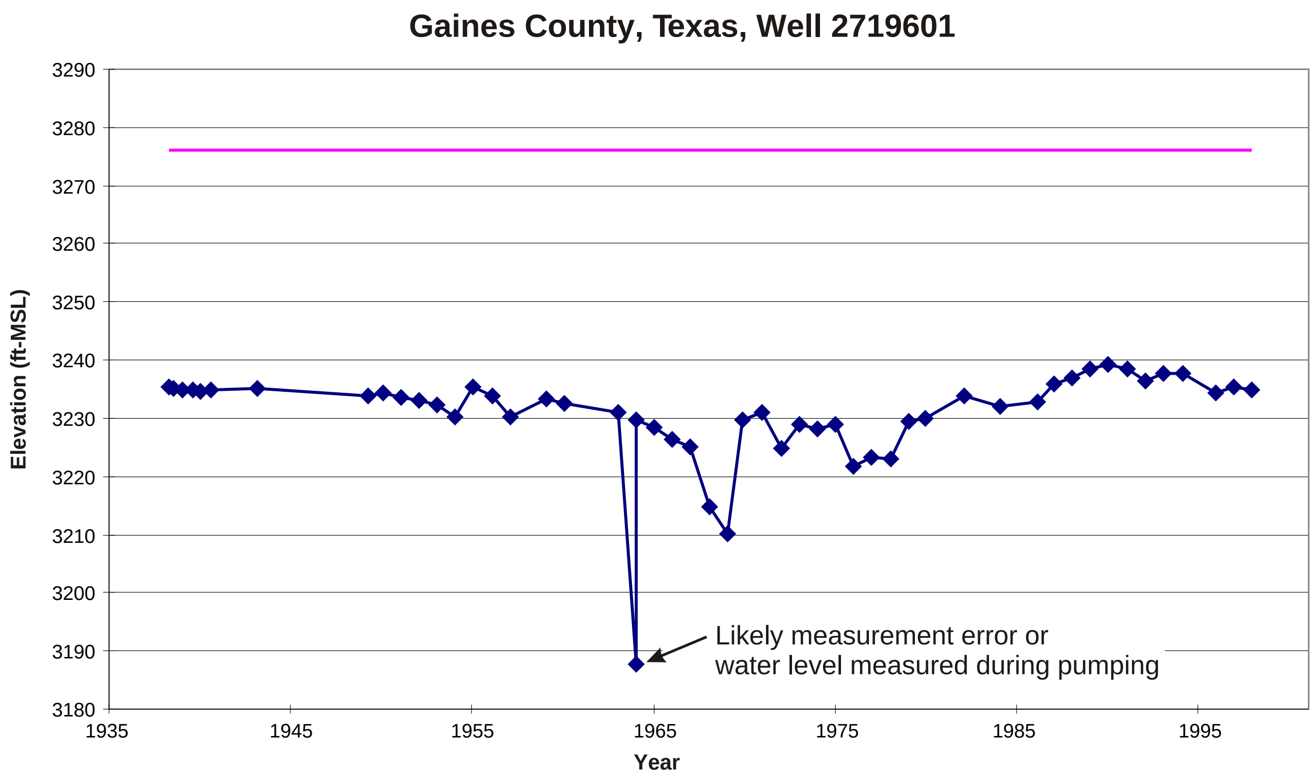

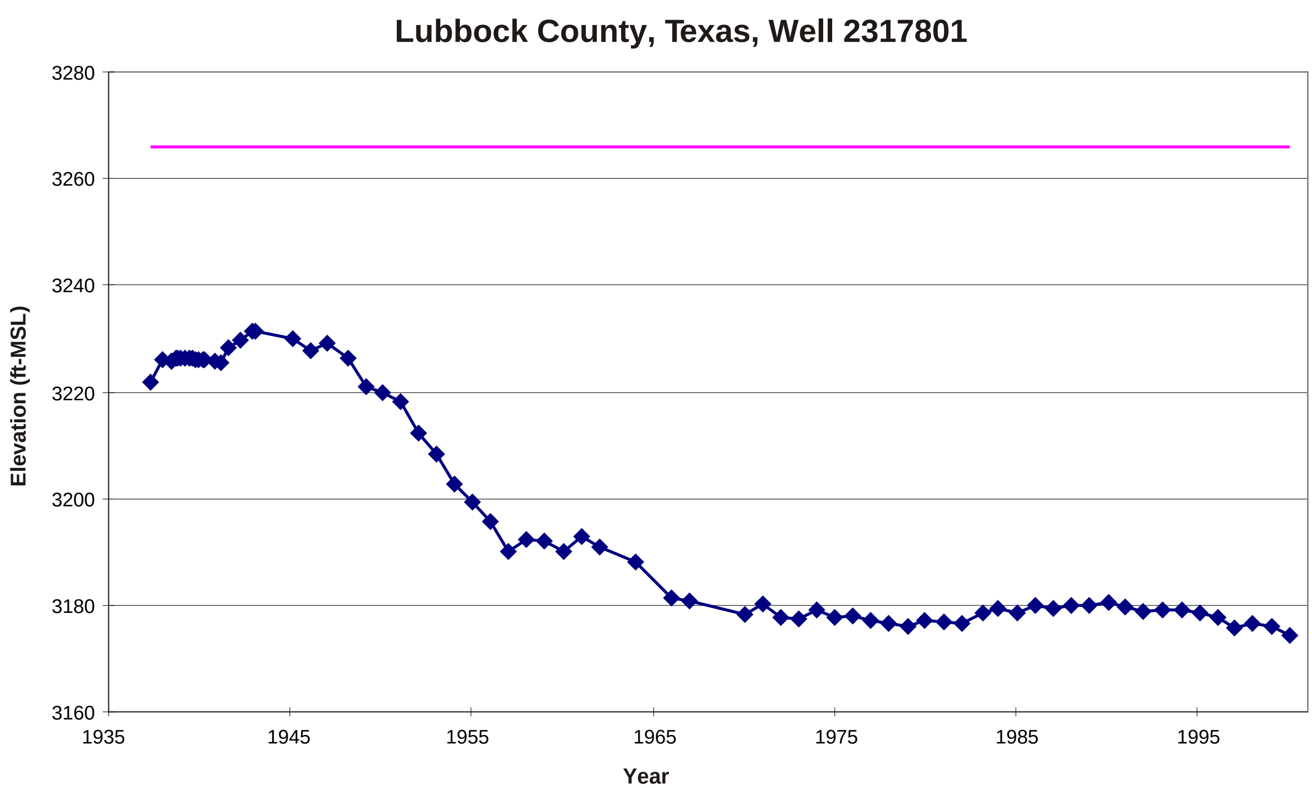

Explanation

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

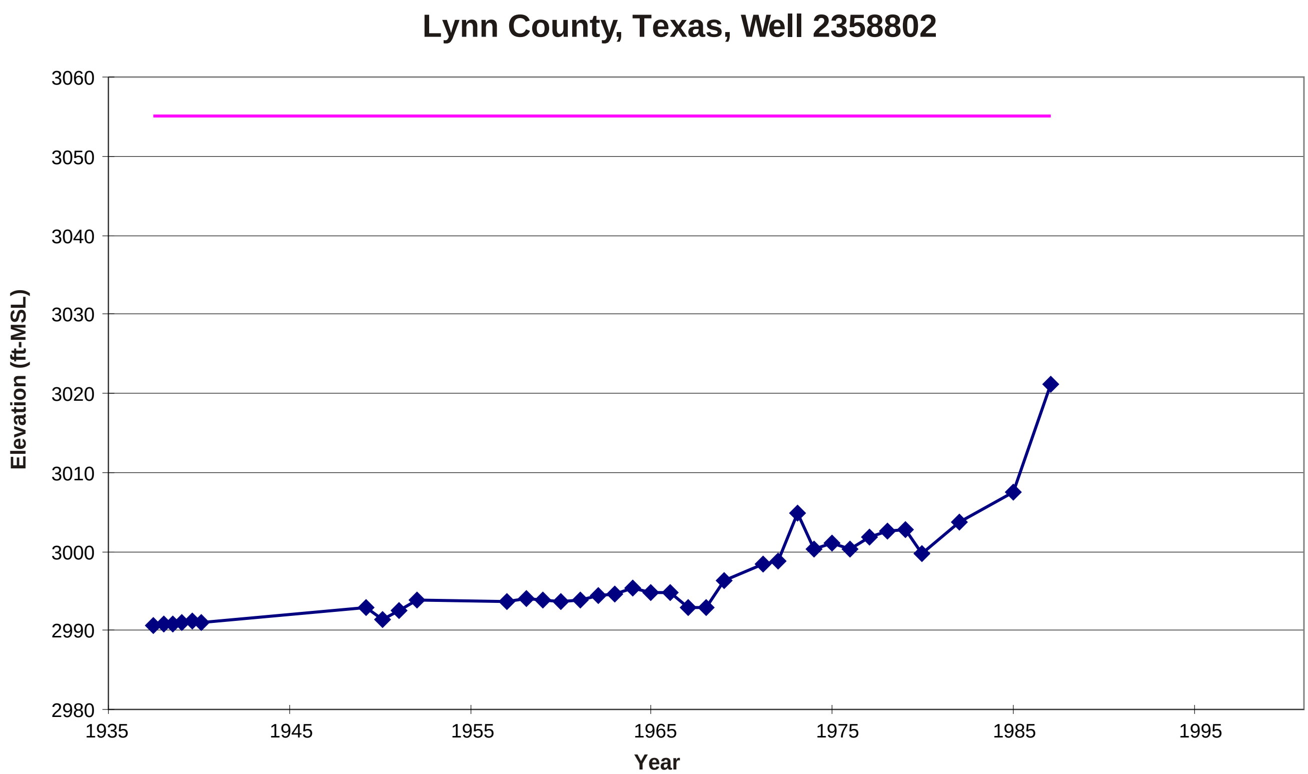
The primary sources of recharge to the Southern Ogallala aquifer are playas, headwater creeks, and irrigation return flow. The creeks (draws) are ephemeral and flow only after heavy rainfalls. Playas (also called wet-weather lakes) hold water for various lengths of time after rainfall events, but generally 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.

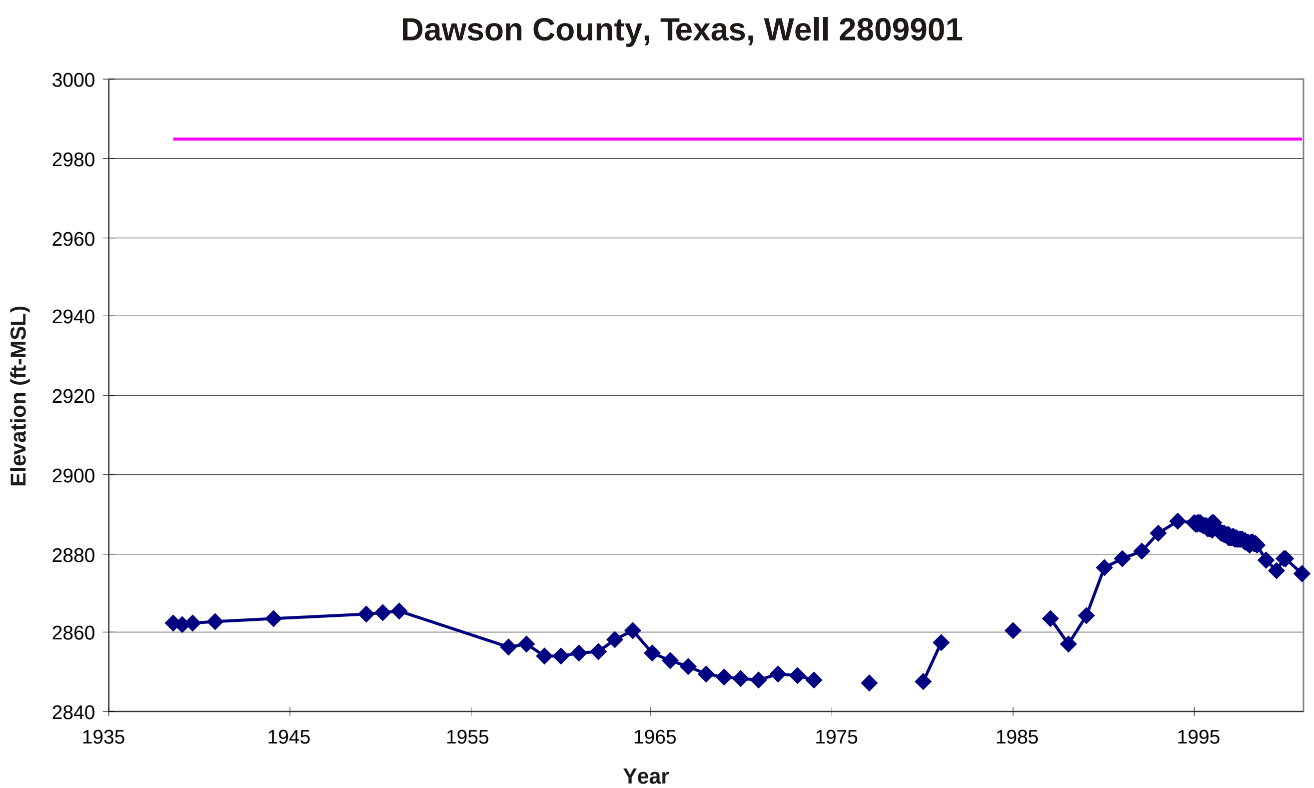
A number of fairly recent studies evaluated recharge at playas, but very few direct measurements have been made of recharge beneath agricultural fields, either from irrigation return flow or direct precipitation on fields that are dryland farmed.

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

SOUTHERN OGALLALA GAM

Observed Water Levels in Lynn and Dawson Counties

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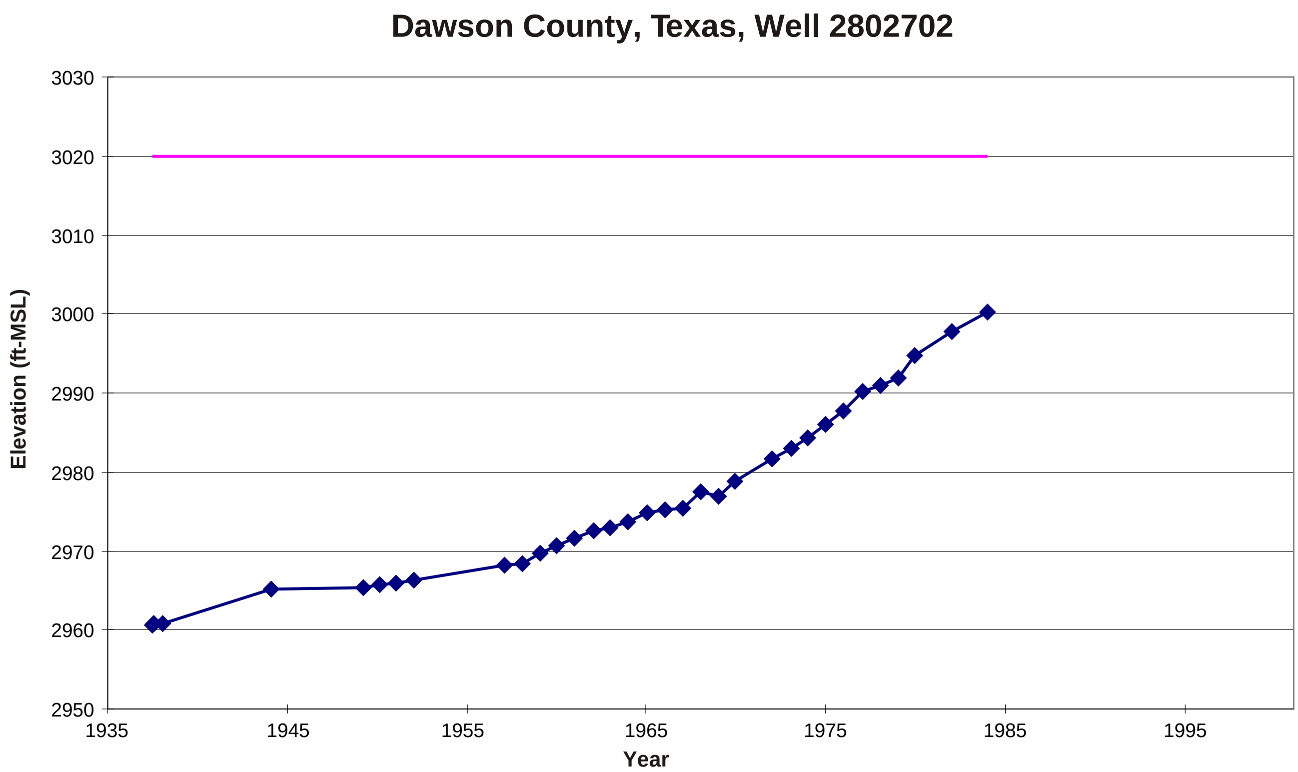
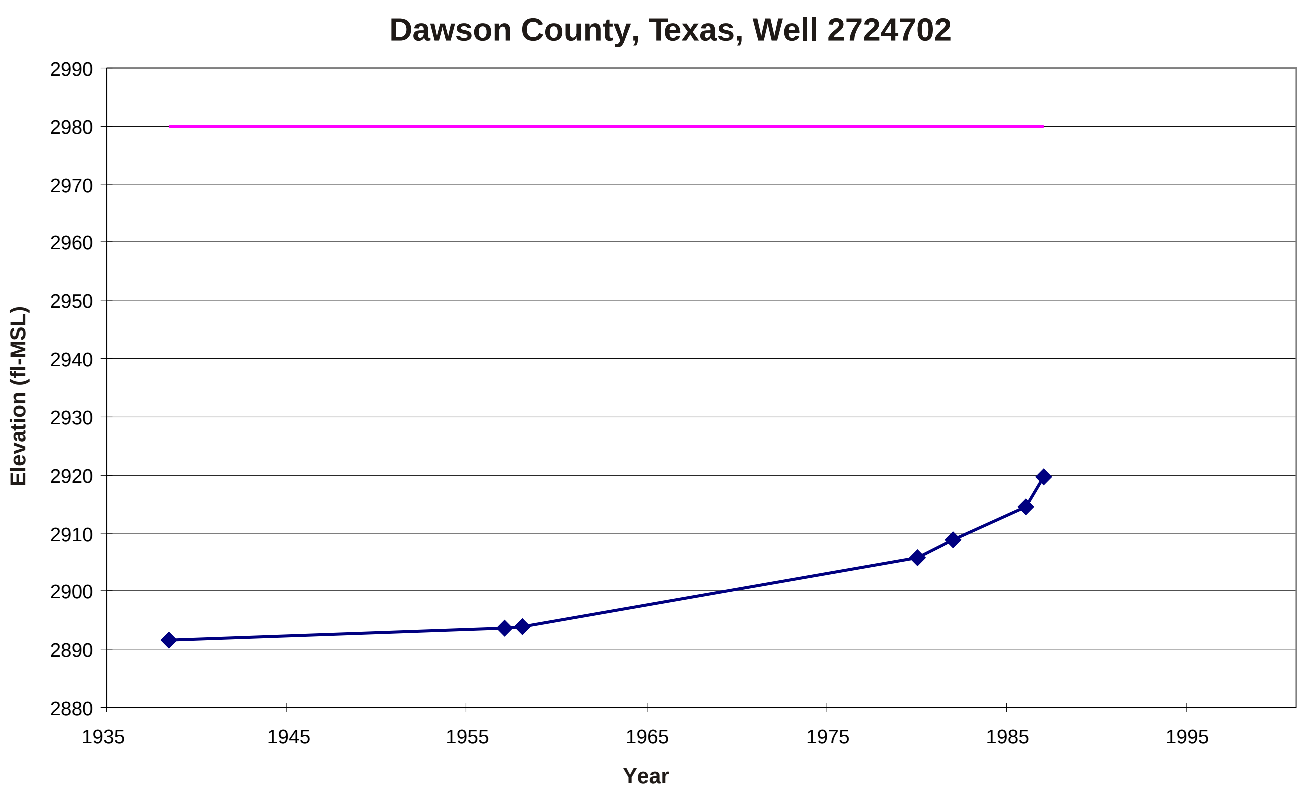
Figure 29





Explanation

Water level

Land surface

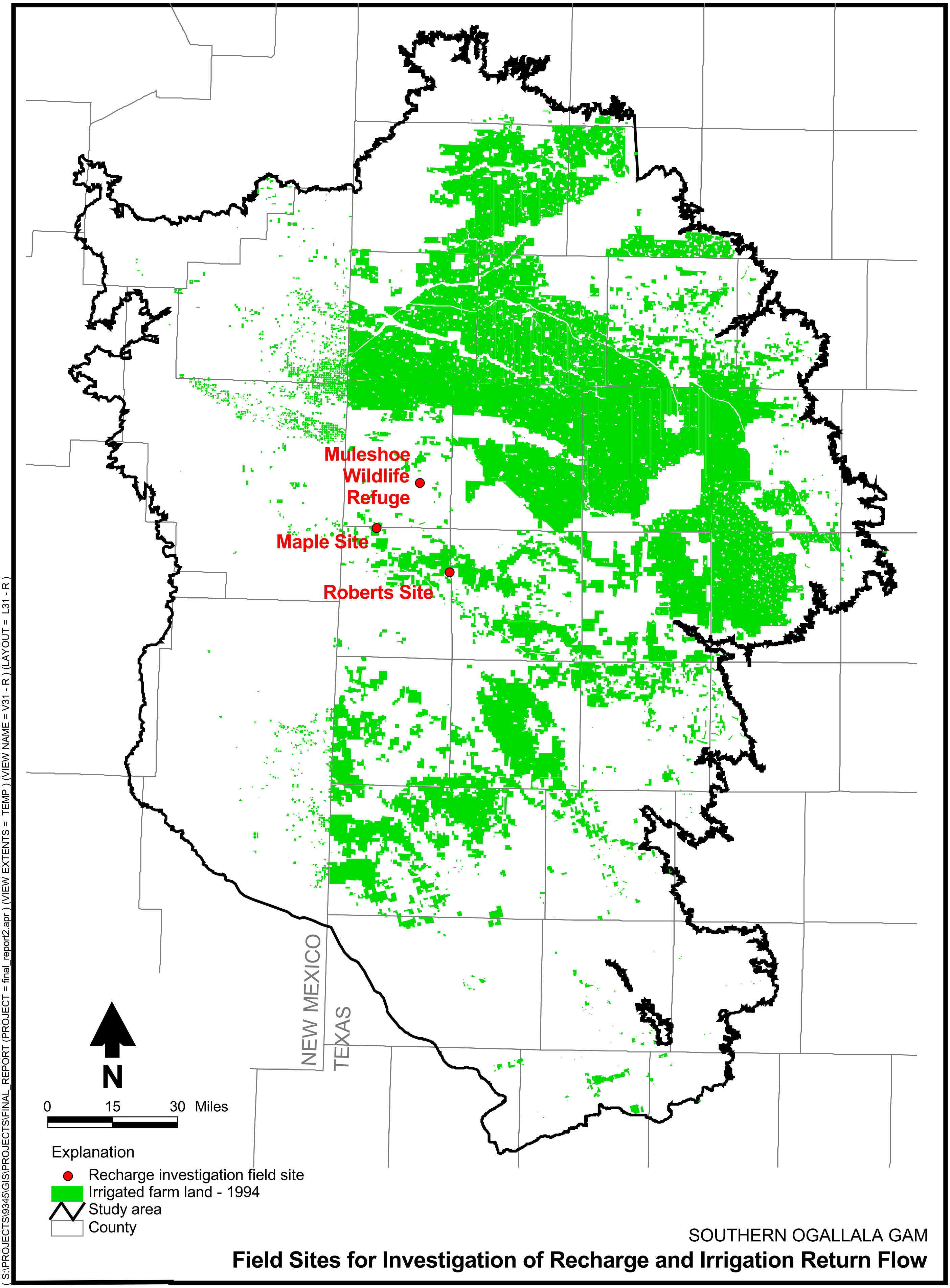
SOUTHERN OGALLALA GAM

Observed Water Levels in Dawson County

VDR\0-VDR-PROJECTS\9345\934555W.CDR

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

Figure 31

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.

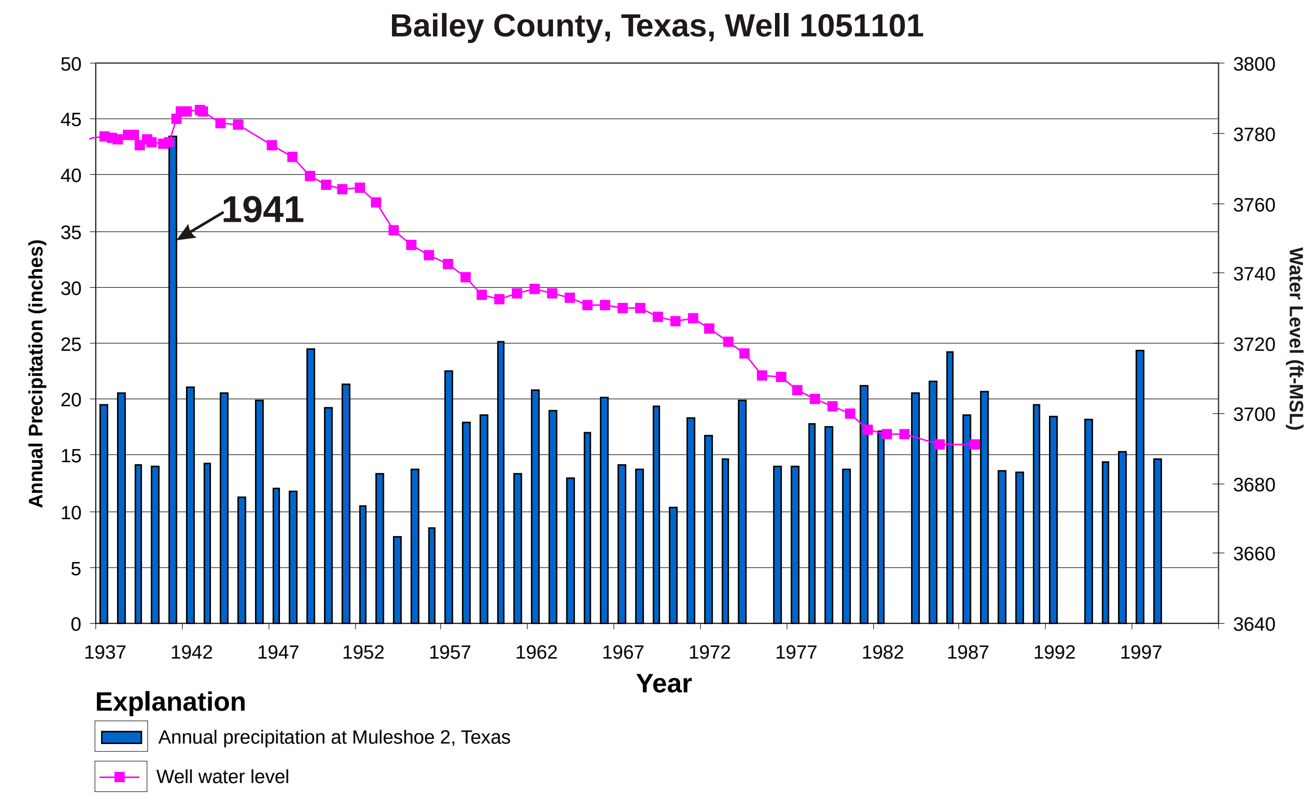
Increased recharge rates caused by clearing of native vegetation, and corresponding rises in aquifer water levels, have been documented for other semiarid regions. For example, Favreau and others (2002) determined that recharge rates in southwest Niger, Africa increased by an order of magnitude due to 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).

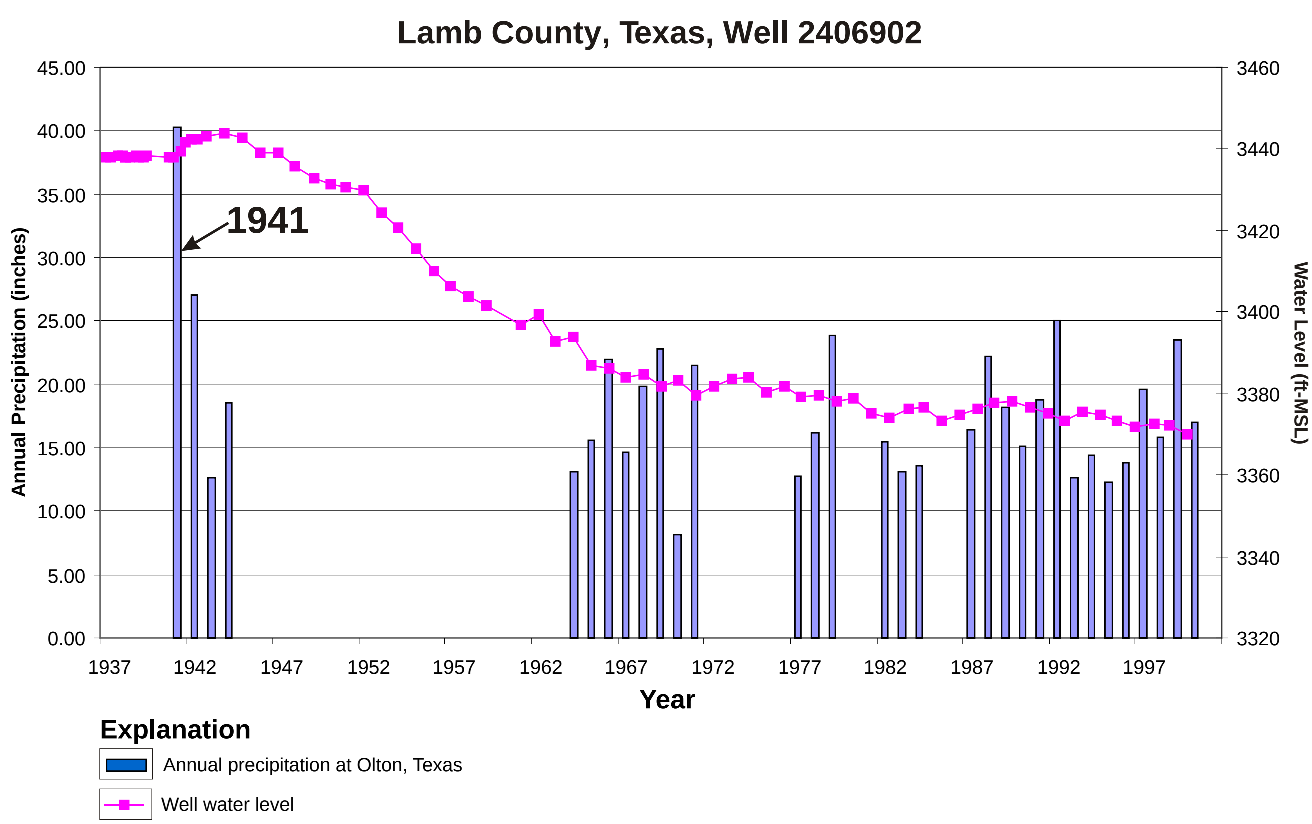
Knowles and others (1984, pp. 44-45) also state that the observed rises in water levels might be attributable to additional recharge from historical irrigation water, readjustment of water levels following decreases in pumping, and enhanced recharge caused by abnormally high precipitation. In fact, both 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.

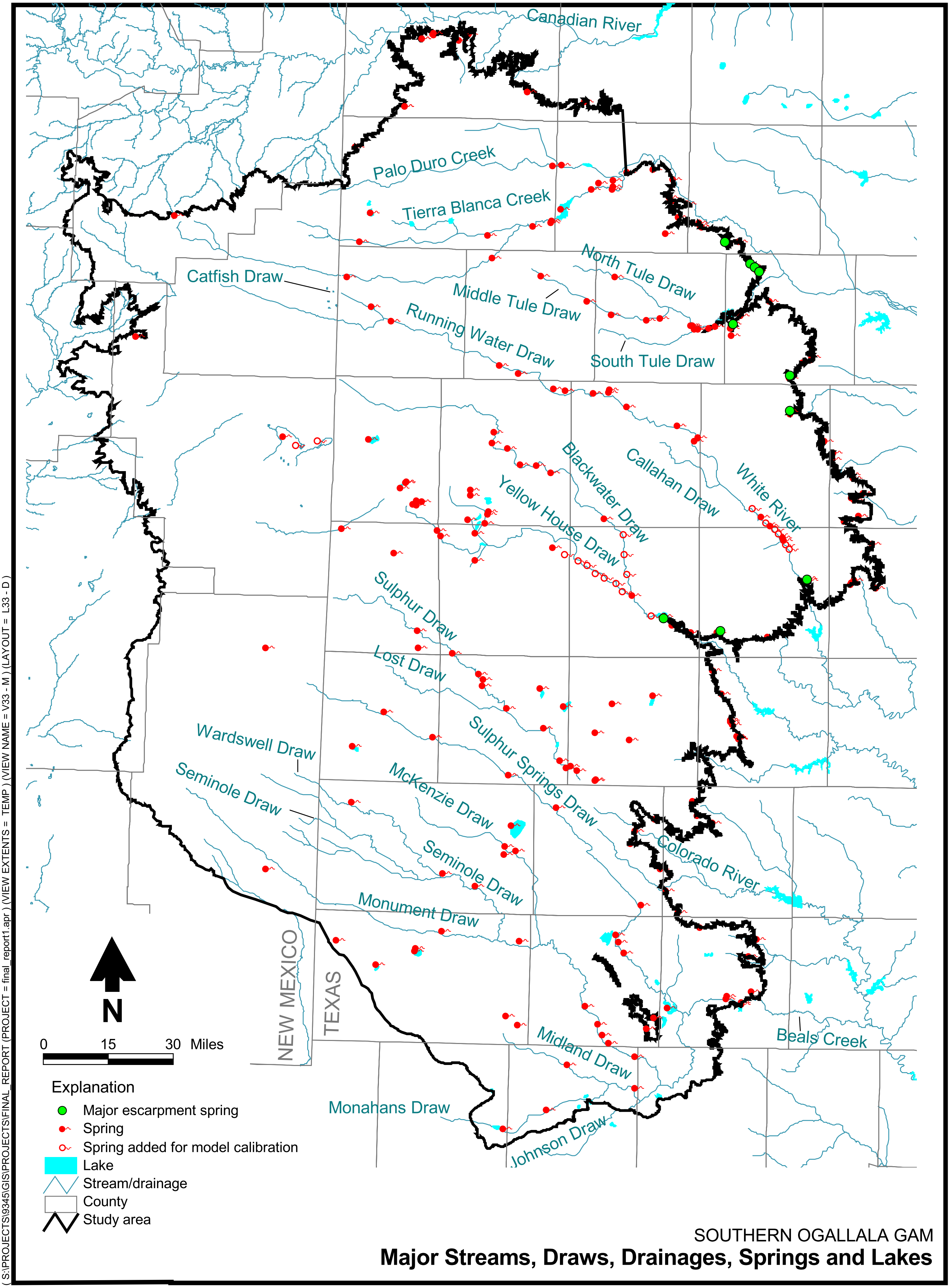
Rivers, Streams, Springs, and Lakes

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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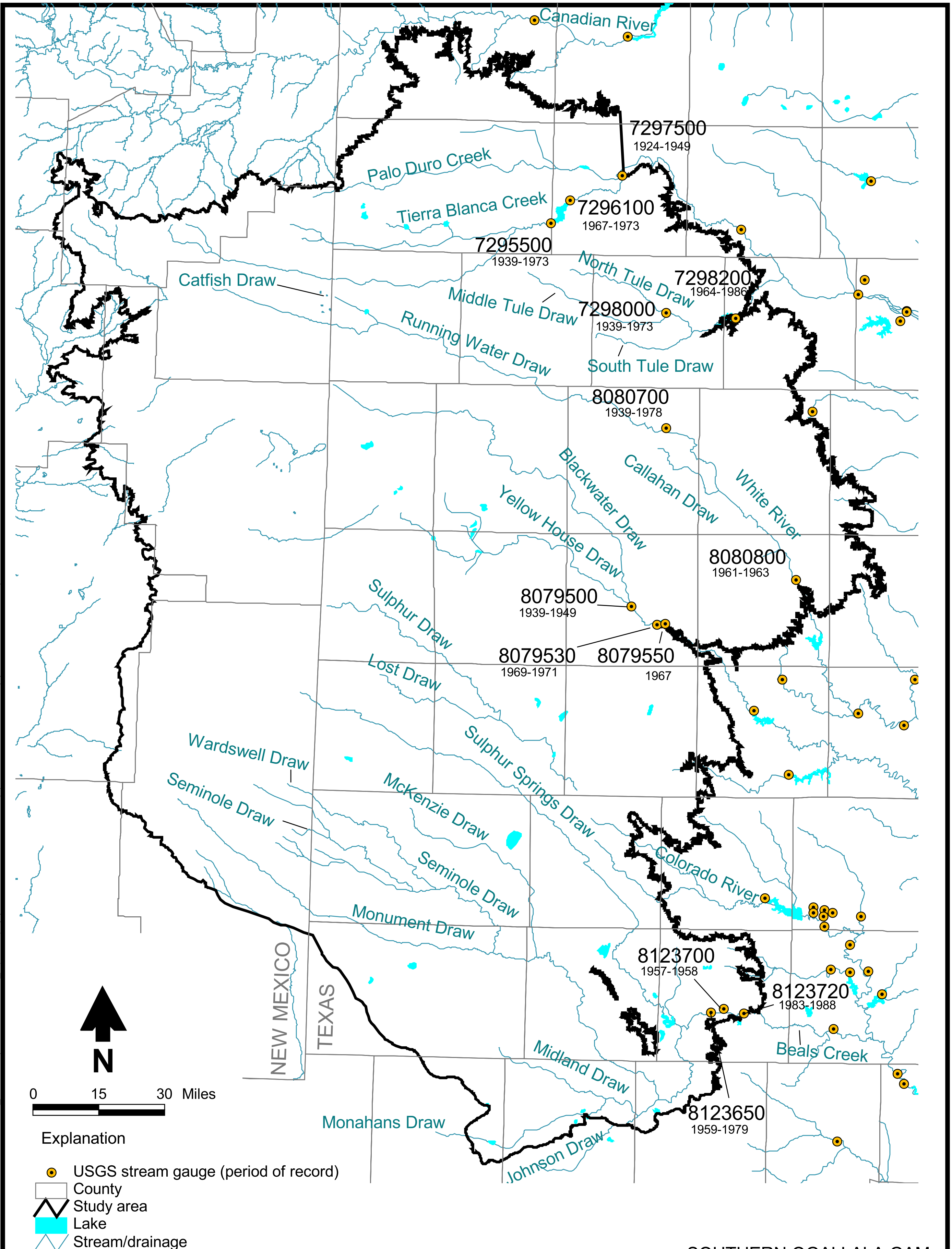
Figure 33



SOUTHERN OGALLALA GAM

USGS Stream Gauges and Periods of Record

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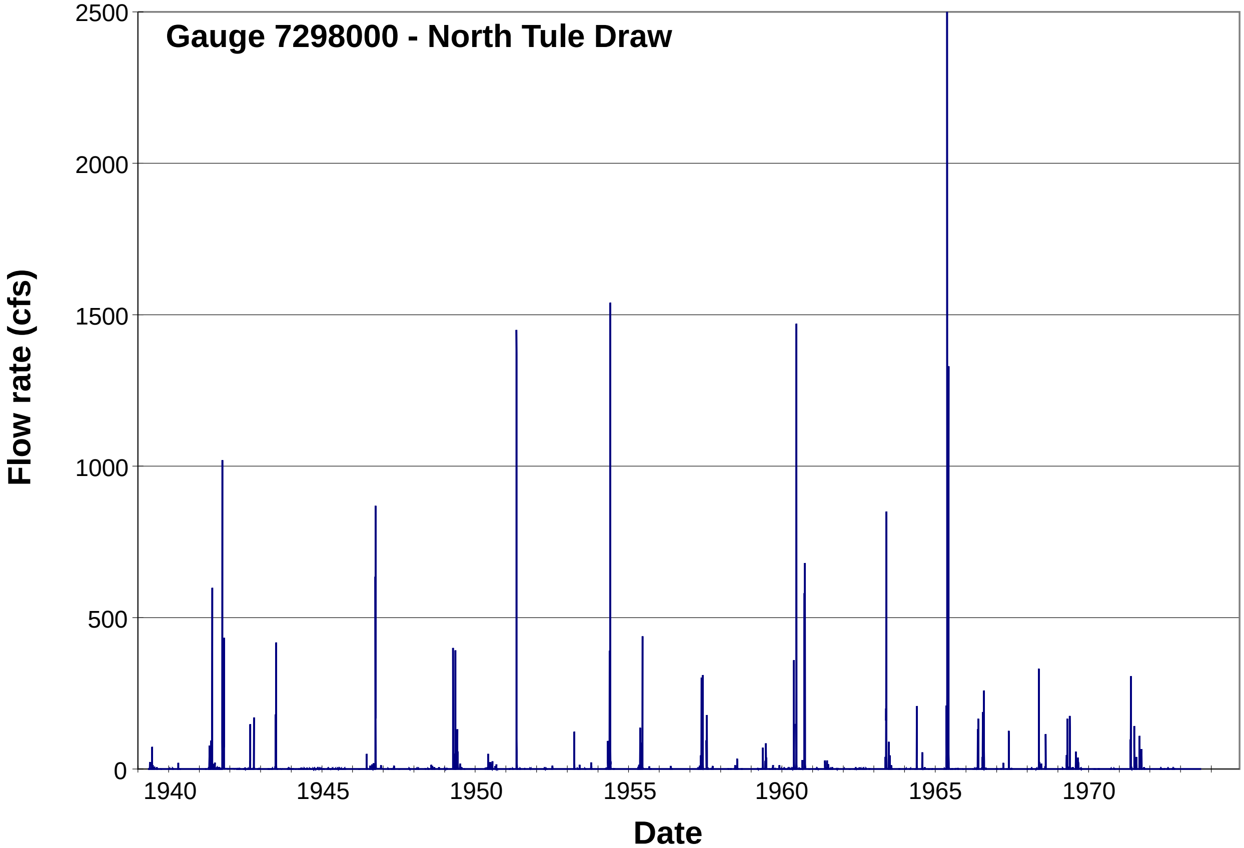
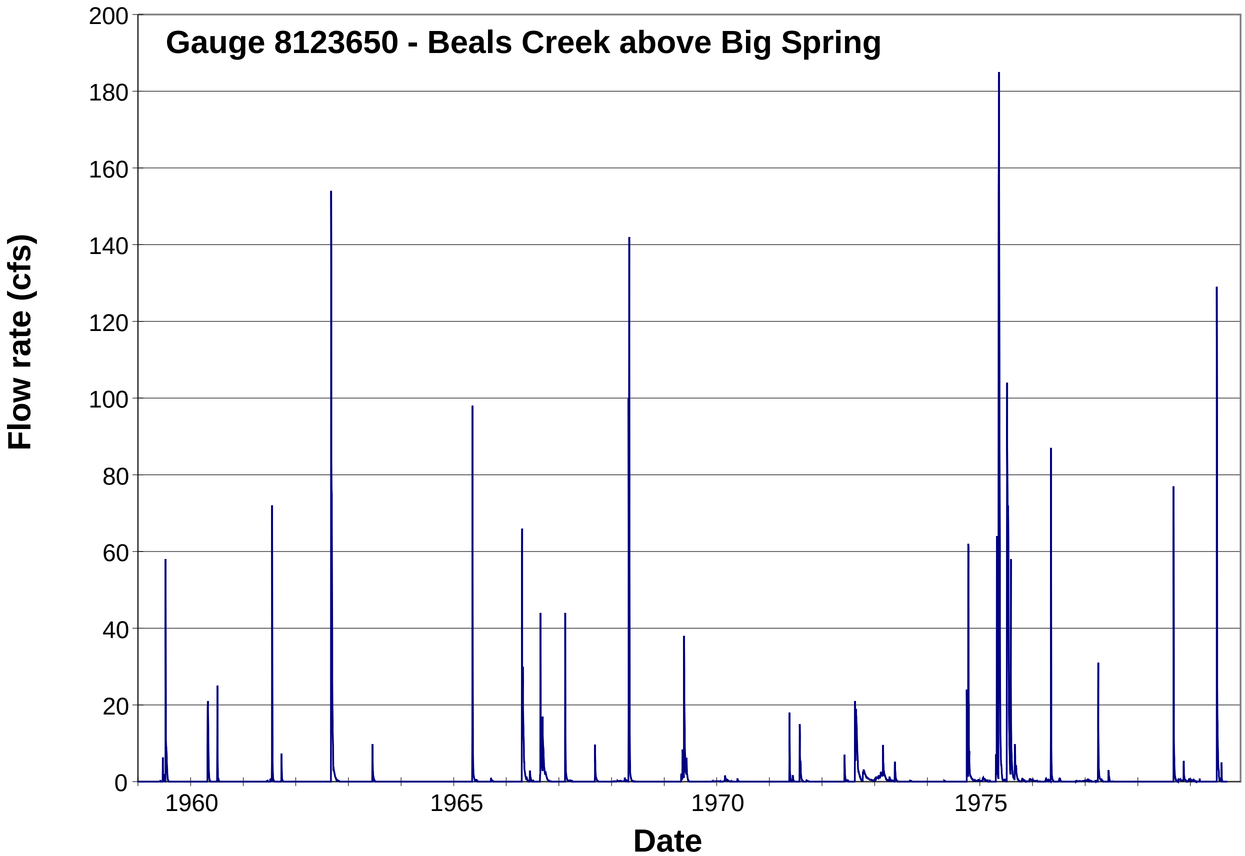
Figure 34





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SOUTHERN OGALLALA GAM

Stream Flow for USGS Stream Gauges 7298000 and 8123650

Figure 35

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/

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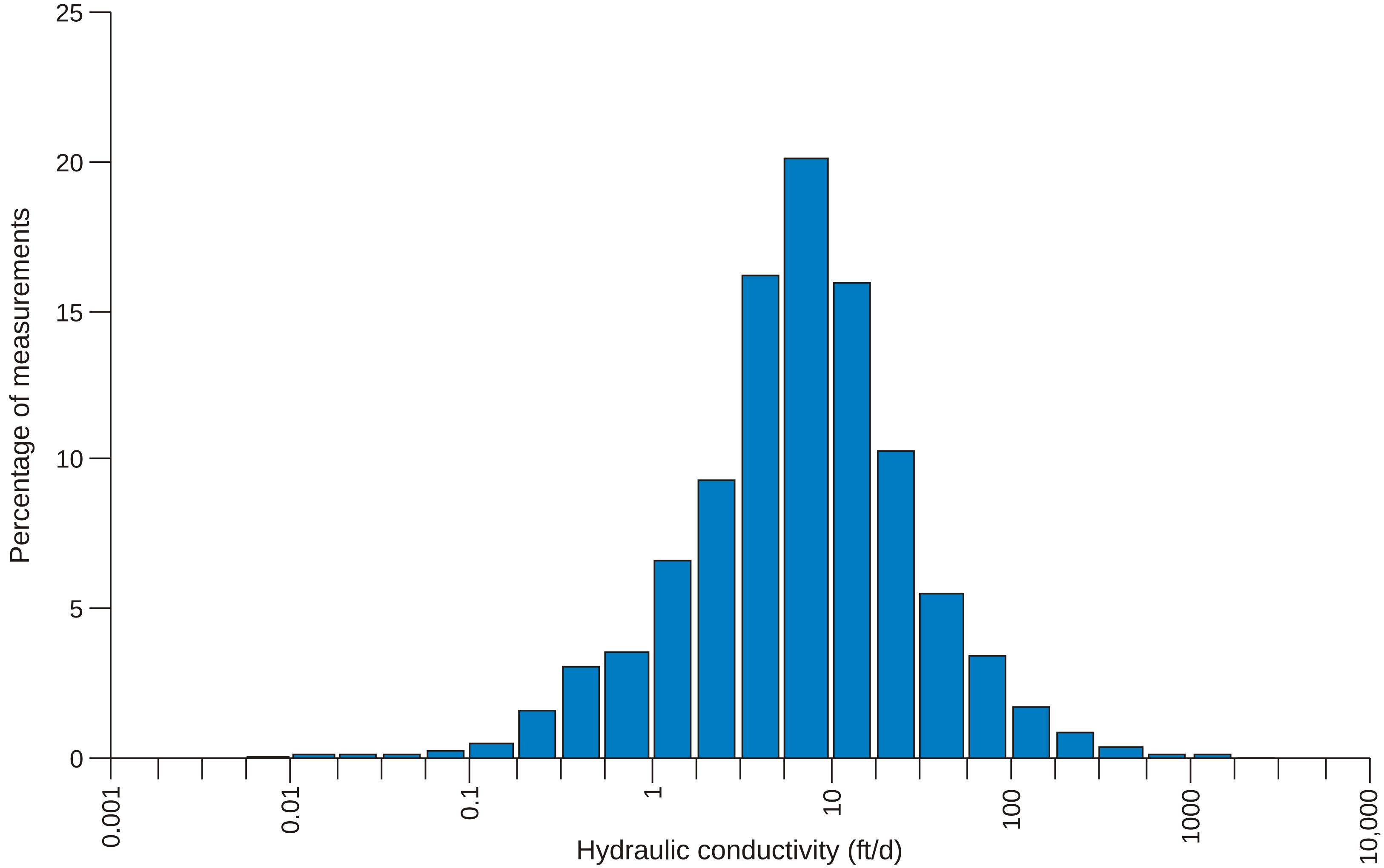

SOUTHERN OGALLALA GAM

Histogram of Hydraulic Conductivity Measurements

Figure 36

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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.

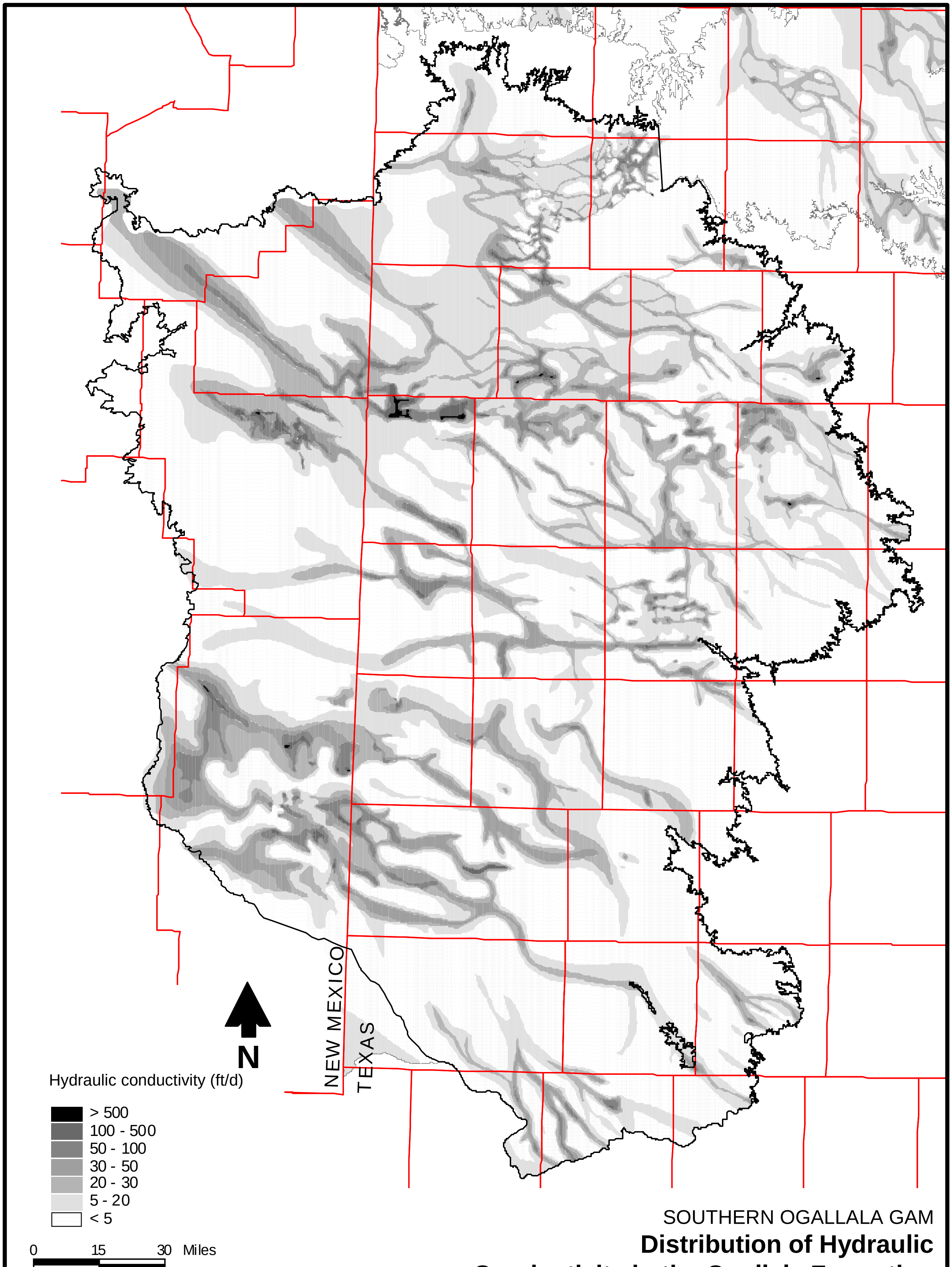
The quality and amount of information collected from drillers' logs are variable. Quality issues include completeness of information and transcription errors in recording pumping rate and time. For quality control purposes, only legible logs containing all required information (pumping rate, test duration, 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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Figure 37

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.

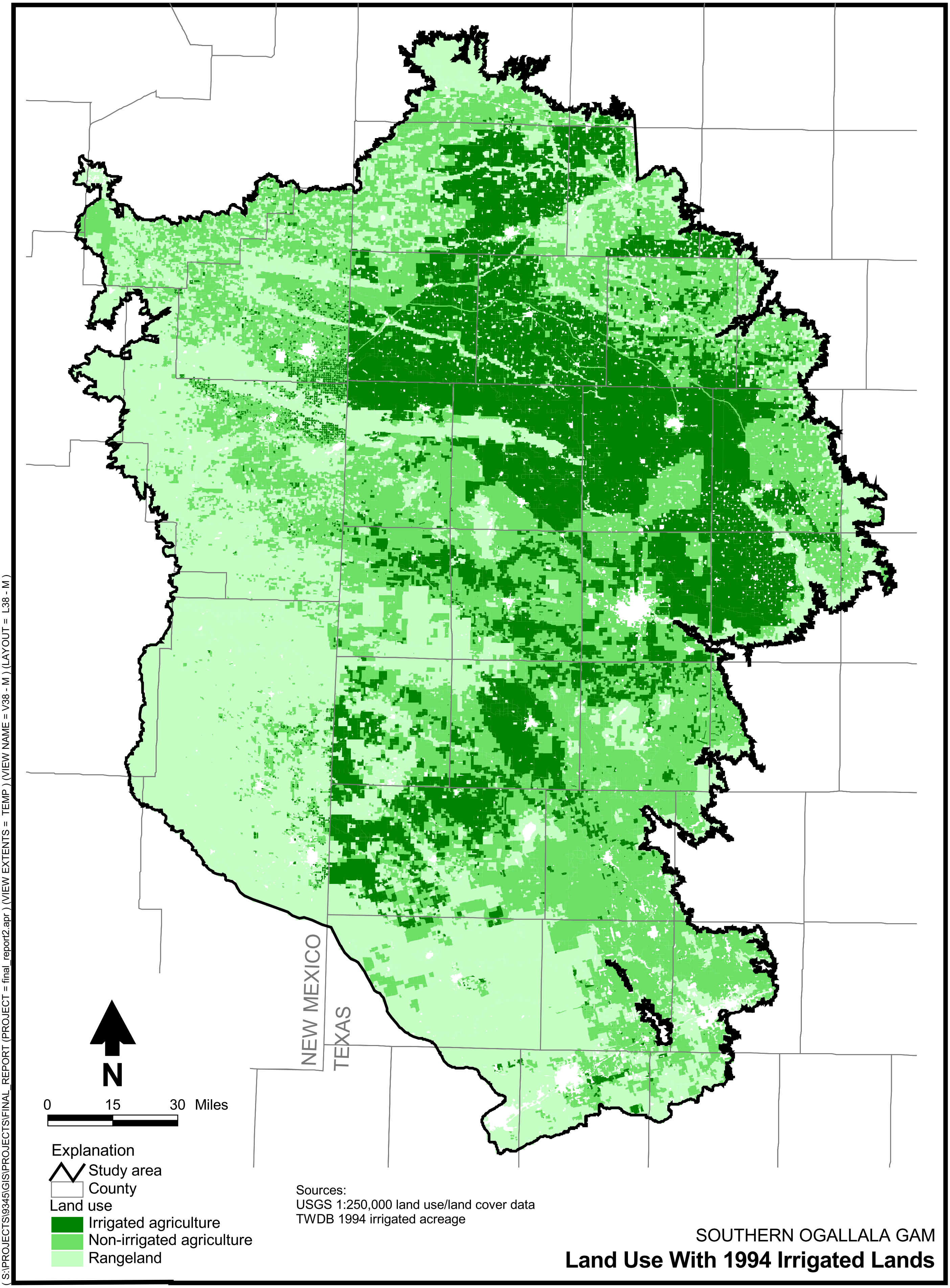
Prior to 1958 in Texas, irrigation pumping was assumed to increase linearly from zero to the 1958 estimated value, according to the estimated growth in irrigated acreage for the Southern High Plains provided by Luckey and others (1986, p.11). The periods 1940 through 1944, 1945 through 1949, 1950 through 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

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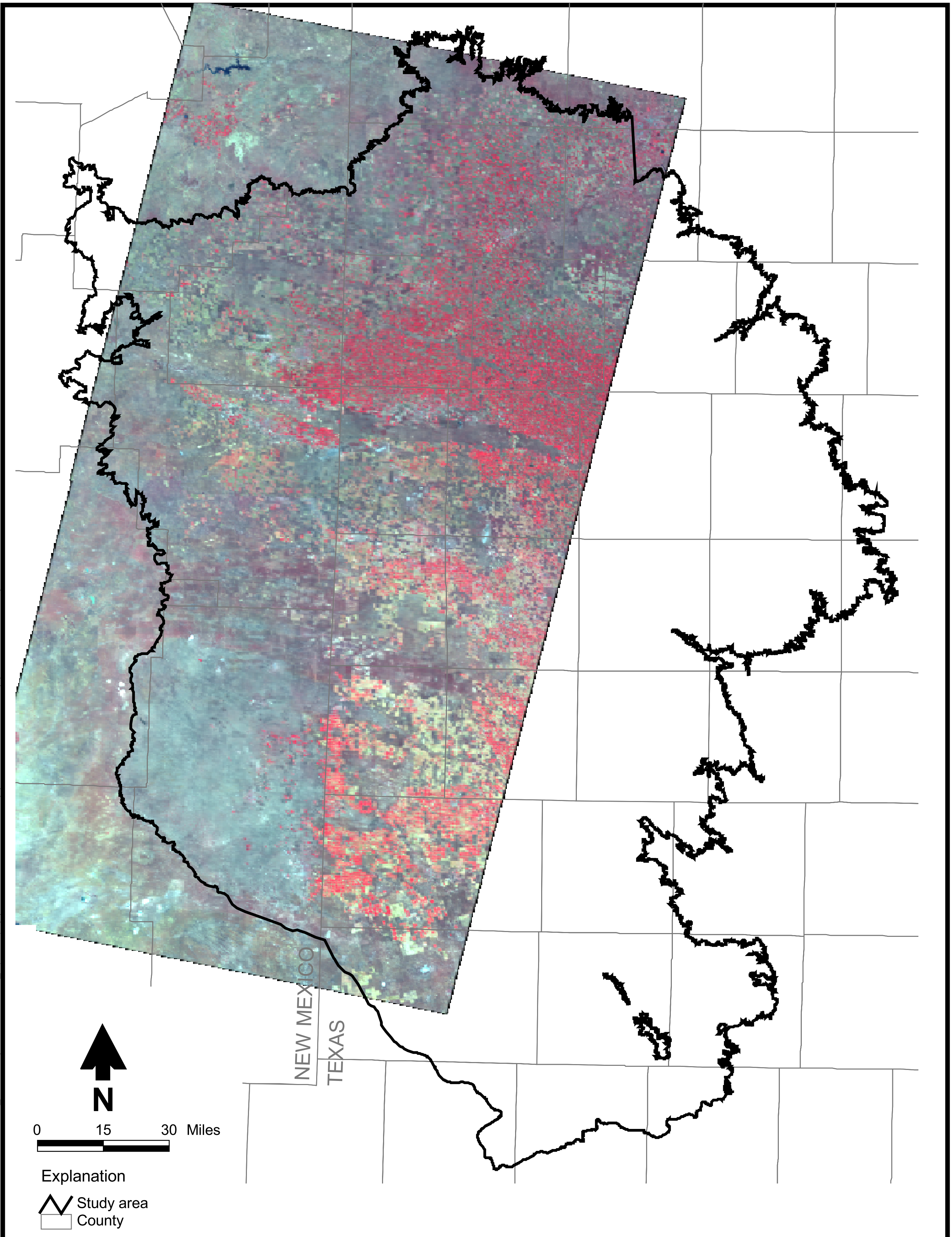
1-30-03

Figure 38



SOUTHERN OGALLALA GAM

1994 LandSat Image of Irrigated Lands

Figure 39

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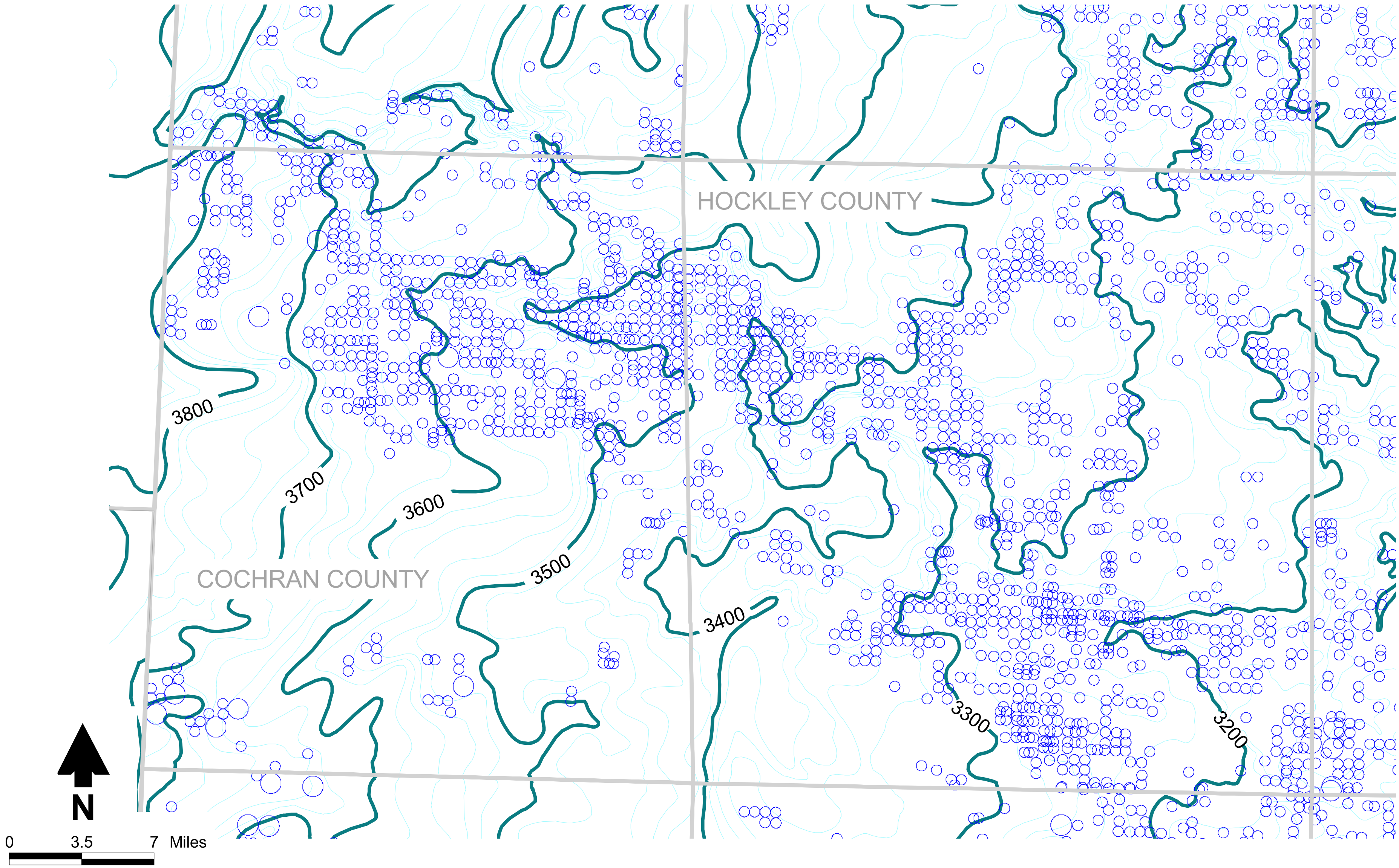
S:\PROJECTS\9345\GIS\PROJECTS (PROJECT=aquifer bottom.apr) (VIEW EXTENTS = temp) (VIEW NAME = 7) (LAYOUT = 7)



Explanation

- 1998 Center pivot locations from HPUWCD No. 1
- County
- Base-of-aquifer elevation contours (100-ft interval)
- Base-of-aquifer elevation contours (20-ft interval)

SOUTHERN OGALLALA GAM

Aquifer Bottom Elevation and 1998 Center Pivot Locations

Figure 40

2-04-03

the paleochannels in the aquifer. In the center of Cochran County, for example, no center pivot systems are identified between a fairly significant paleochannel to the north and a smaller paleochannel to the south, nor is there any irrigated acreage shown in this area in the 1994 TWDB coverage or the LandSat imagery (figs. 38 and 39).

Non-Agricultural Pumping

Non-agricultural pumping is divided into municipal, livestock, manufacturing, and county other uses. Next to irrigated agriculture, municipalities are the largest users of groundwater on the Southern High Plains (fig. 41). The manufacturing category includes mining and power generation, and the county other category includes rural domestic use and municipal use that could not be associated with specific points of withdrawal.

For the counties in Texas, values for these uses were determined from compilations of the water use inventories provided by the TWDB. For counties in New Mexico, estimates of municipal, livestock, and power generation (for Lea County only) use were compiled from Dinwiddie (1963), New Mexico of the 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 uses, combined with pumping for irrigated agriculture, generally account for more than 99 percent of the estimated groundwater use for counties in New Mexico. Estimated non-agricultural pumping for each county in the study area is provided in Appendix C. Also provided in Appendix C is a more detailed explanation of the procedures used to develop historical pumping estimates for the non-agricultural categories. Total pumping within the study area is summarized in Figure 42.

Discharge from Springs

The most complete documentation of discharge from springs in the Texas portion of the study area is provided by Brune (1981, 2002), who documents the discharge from numerous springs in the study area with flows ranging from seeps and trickles up to substantial flows on the order of hundreds of gallons per minute (gpm). Brune documents a number of measurements made during the 1970s and provides some historical estimates, measurements, or anecdotal evidence of earlier spring flows. The springs within the Texas portion of the study area documented by Brune (1981, 2002) and those within the New Mexico portion of the study area documented by White and Kues (1992) are illustrated in Figure 43 and listed in Table 2. The discharge values provided by Brune are, for the most part, viewed as general estimates of variable quality. Due to the lack of rigorous measurements conducted through time, as well as the general difficulty of accurately measuring flow at many springs in the study area, the magnitude of reported discharge values in Table 2 were viewed only as a general guideline of the magnitude of discharge for a given spring.

In addition to the springs specifically documented by Brune, many others likely exist or did exist as well. Although many documented springs exist along the eastern escarpment, many springs also exist west of the escarpment along the major draws and their tributaries that incise the plains (fig. 43). Results of the modeling presented herein indicate that, under predevelopment conditions, approximately 40 to 50 percent of the groundwater discharge from the Ogallala aquifer was from springs along the major draws and their tributaries and at salt lakes.

During 1938 and 1939, White and others (1946) conducted a detailed survey of groundwater discharge along a 75-mile stretch of the eastern escarpment, from Quitaque Creek to the Double Mountain Fork of the Brazos River across parts of Briscoe, Floyd, Motley, Dickens, and Crosby Counties. They also conducted a study of groundwater discharge within a 9,000-mi^2 area extending approximately 120 mi to the northwest of this portion of the eastern escarpment. As part of this study, White and others measured or estimated the discharge from all springs or seeps and estimated the amount of groundwater discharged through evapotranspiration along the escarpment and draw bottoms. For this portion of the study area,

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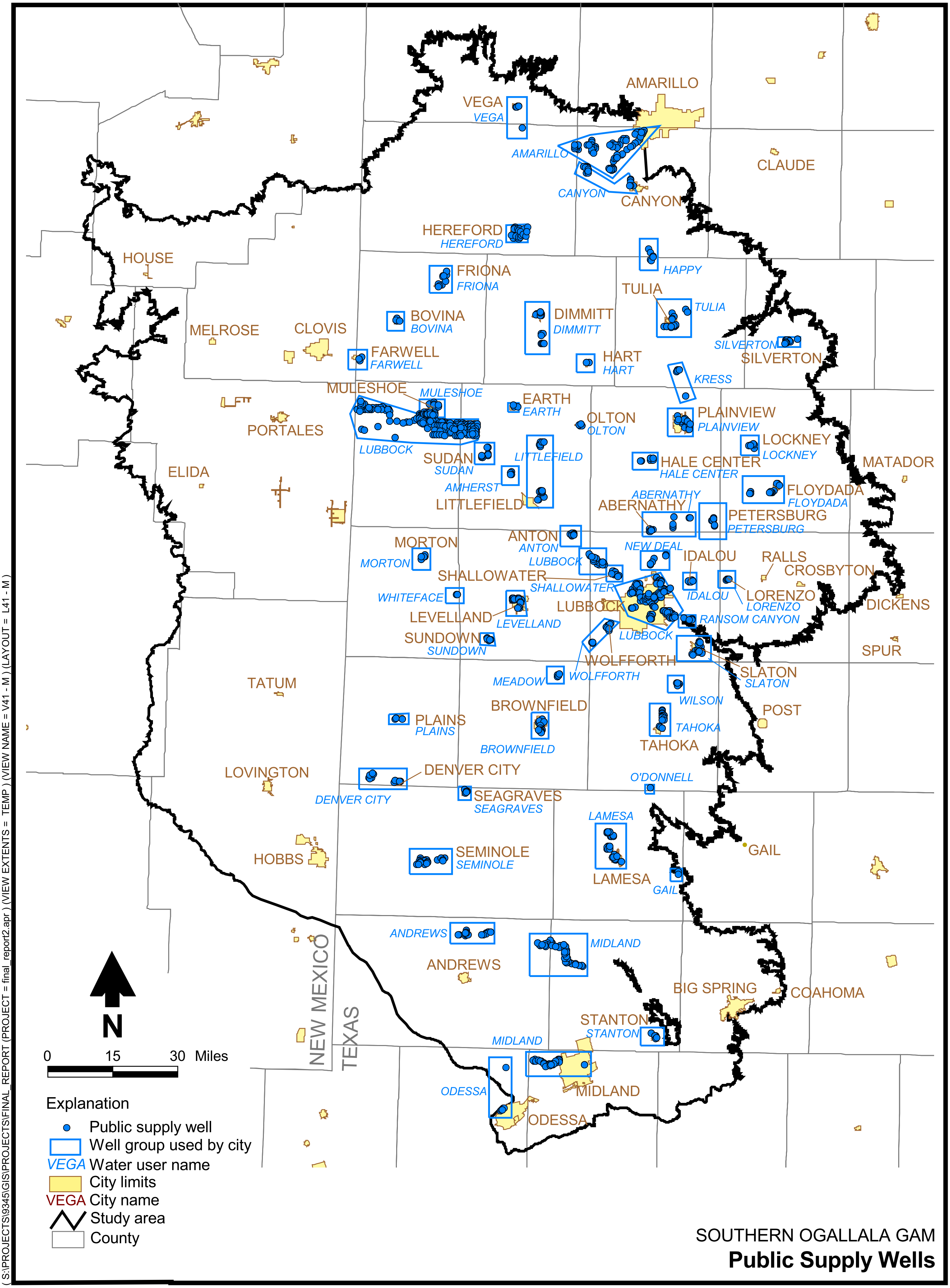

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Figure 41

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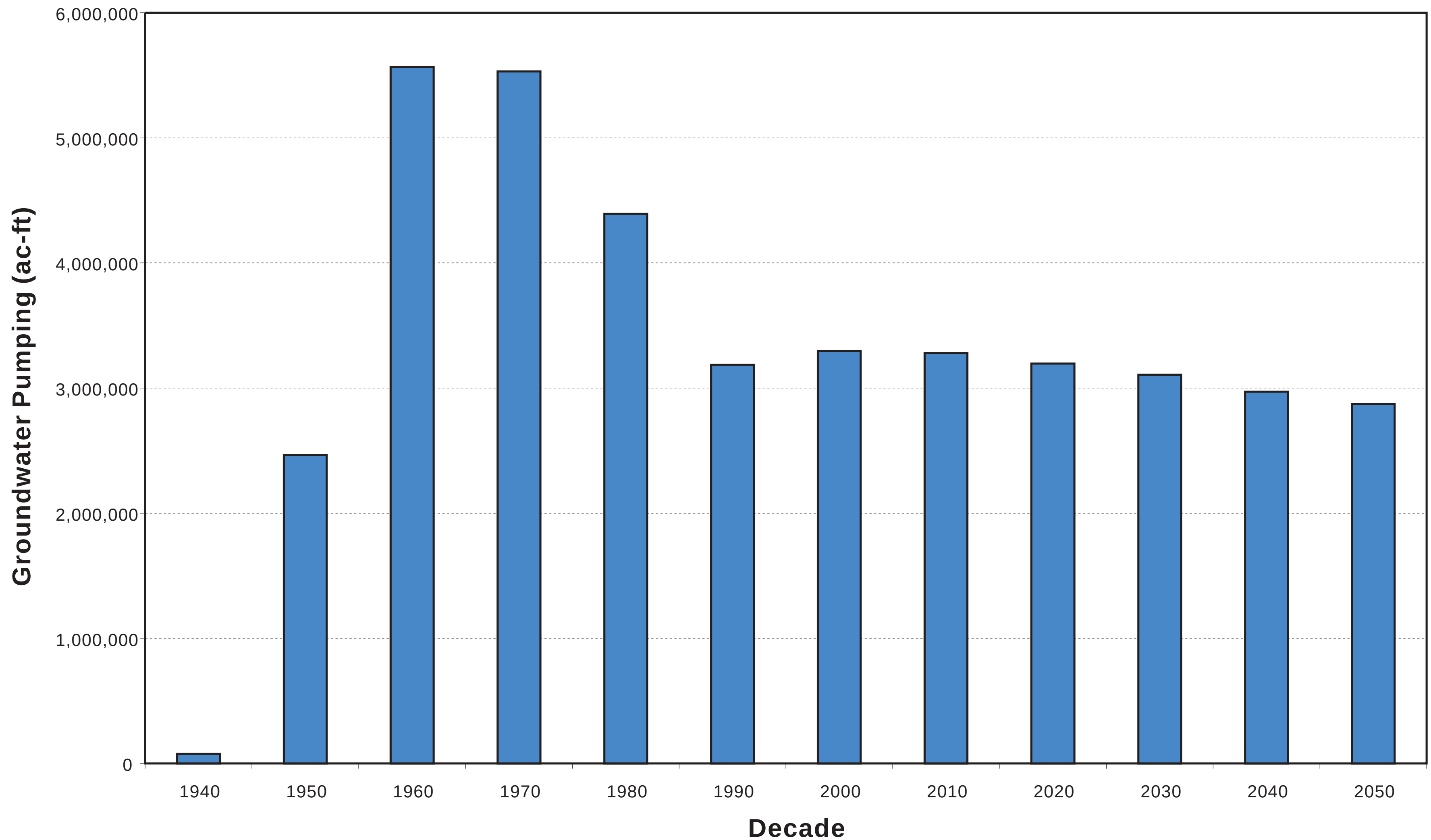
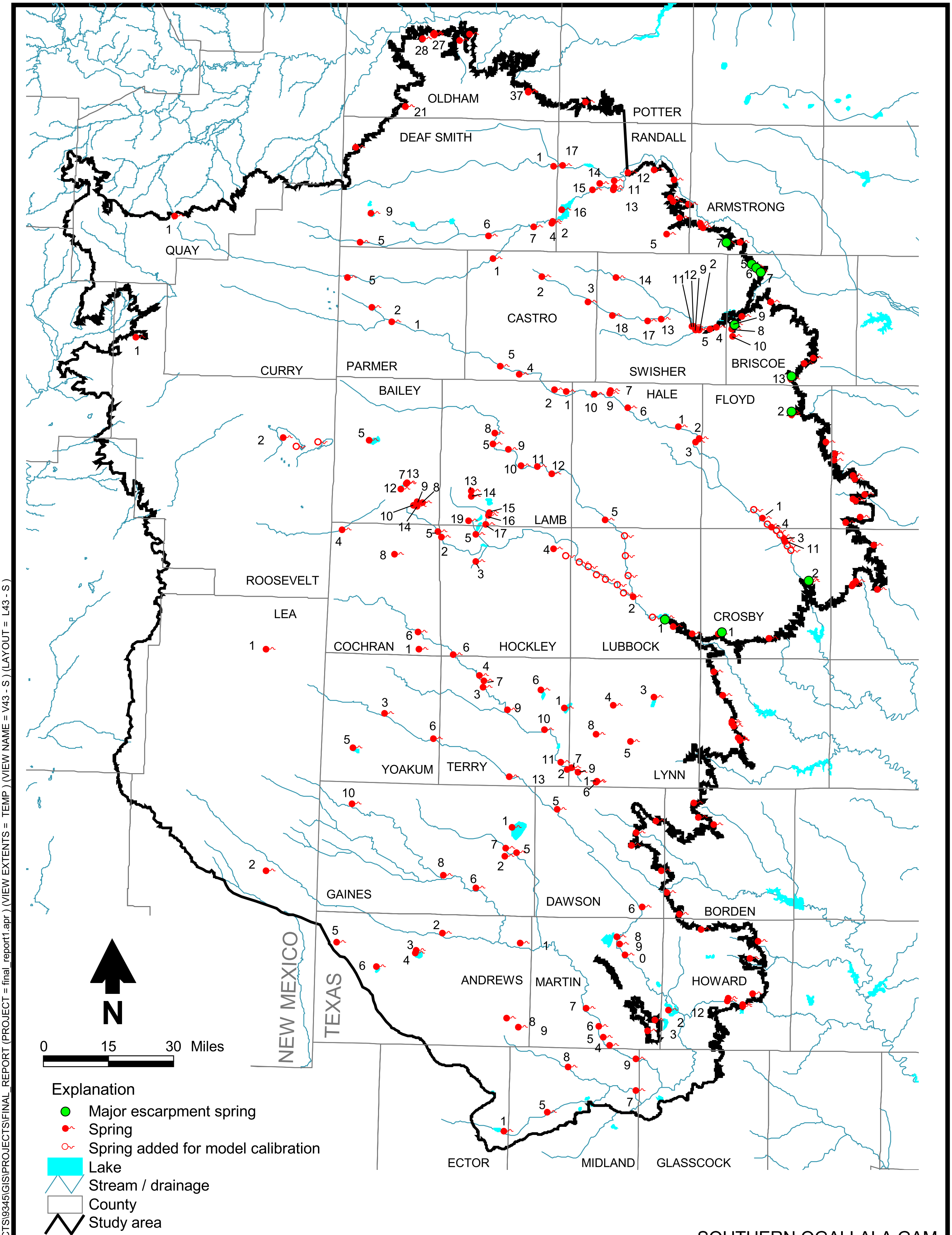


SOUTHERN OGALLALA GAM

Historical and Predictive Total Groundwater Withdrawals

Figure 42

3-17-03 JN 9345



SOUTHERN OGALLALA GAM
Spring Locations

Figure 43

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Table 2: Measured discharge for springs identified in the study area

County	Number	Name	Date Measured	Flow (L/s)	Flow (cfd)	Flow (gpm)
Andrews	1	no name	---	---	---	---
	2	no name	---	---	---	---
	3	no name	---	---	---	---
	4	no name	---	---	---	---
	5	no name	---	---	---	---
	6	Whalen Lake	---	---	---	---
	8	Baird Springs	03/21/77	0.06	183	1.0
	8	Baird Springs	04/19/79	0.10	305	1.6
Armstrong	7	Pleasant Springs	04/1/40	9.5	28,983	150.6
	7	Pleasant Springs	08/07/78	1.2	3,661	19.0
Bailey	7	Barnett Spring	---	---	---	---
	8	White Springs	1977	0.06	183	1.0
	9	no name	---	---	---	---
	10	no name	---	---	---	---
	12	no name	---	---	---	---
	13	Alkali Springs	1936	0.03	92	0.5
	14	no name	1936	0.03	92	0.5
Briscoe	5	Deer Springs	09/09/46	19	57,966	301.2
	5	Deer Springs	06/23/71	1.7	5,186	26.9
	5	Deer Springs	09/04/78	1.3	3,966	20.6
	6	Turkey Springs	09/09/46	25	76,271	396.3
	6	Turkey Springs	06/23/71	3.1	9,458	49.1
	6	Turkey Springs	09/04/78	2.5	7,627	39.6
	7	Cedar Springs	09/09/46	16	48,814	253.6
	7	Cedar Springs	06/23/71	1.4	4,271	22.2
	7	Cedar Springs	09/04/78	1	3,051	15.9
	8	no name	09/10/46	13.00	39,661	206.1
	9	no name	09/10/46	9.50	28,983	150.6
	10	Mayfield Spring	---	---	---	---
	13	Las Lenquas Springs	10/19/67	19	57,966	301.2
	13	Las Lenquas Springs	09/05/78	1.9	5,797	30.1
Castro	1	no name	---	---	---	---
	2	no name	---	---	---	---
	3	no name	---	---	---	---

Sources: Brune, 1981, 2002
White and Kues, 1992

L/s = Liters per second
gpm = Gallons per minute

cfd = Cubic feet per day
--- = Flow measurements not provided by Brune.

Table 2: Measured discharge for springs identified in the study area (continued)

County	Number	Name	Date Measured	Flow (L/s)	Flow (cfd)	Flow (gpm)
Castro (cont.)	4	no name	---	---	---	---
	5	Flagg Springs	---	---	---	---
Cochran	1	no name	---	---	---	---
	4	no name	---	---	---	---
	5	Silver Springs	04/13/77	0.63	1,922	10.0
	5	Silver Springs	10/21/78	0.05	153	0.8
	6	no name	---	---	---	---
	8	Morton Springs	---	---	---	---
Crosby	1	Cottonwood Springs	1938	13	39,661	206.1
	1	Cottonwood Springs	1975	0.32	976	5.1
	2	Couch Springs	11/02/38	54	164,746	855.9
	3	Rock House Springs	1938	14	42,712	221.9
	3	Rock House Springs	1975	0.62	1,892	9.8
	11	Ericson Springs	---	---	---	---
Dawson	5	no name	---	---	---	---
	6	no name	---	---	---	---
Deaf Smith	1	Fowler Springs	---	---	---	---
	2	Parker Springs	---	---	---	---
	4	Big Springs	1937	0.95	2,898	15.1
	4	Big Springs	05/77	0.32	976	5.1
	5	Escarbada	---	---	---	---
	6	Punta de Agua or Source of Water	---	---	---	---
	7	Sulphur Springs	---	---	---	---
	9	Ojita de Garcia or Little Garcia Springs	---	---	---	---
Ector	1	no name	---	---	---	---
Floyd	1	Massie Springs	---	---	---	---
	2	Blue Hole Springs	11/04/38	14.00	42,712	221.9
	2	Blue Hole Springs	12/10/68	13.00	39,661	206.1
	2	Blue Hole Springs	06/18/75	0.63	1,922	10.0
	2	Blue Hole Springs	07/16/78	0	0	0
	4	Montgomery Springs	---	---	---	---
Gaines	1	Buffalo Springs	1963	0.01	18	0.1
	2	no name	---	---	---	---
	5	Balch Springs	03/18/77	2.50	7,627	39.6

Sources: Brune, 1981, 2002
White and Kues, 1992

L/s = Liters per second
gpm = Gallons per minute

cfd = Cubic feet per day
--- = Flow measurements not provided by Brune.

Table 2: Measured discharge for springs identified in the study area (continued)

County	Number	Name	Date Measured	Flow (L/s)	Flow (cfd)	Flow (gpm)
Gaines (cont.)	6	no name	---	---	---	---
	7	no name	---	---	---	---
	8	Ward's Well	---	---	---	---
	10	Boar's Nest Springs	---	---	---	---
Hale	1	no name	---	---	---	---
	2	no name	---	---	---	---
	3	no name	---	---	---	---
	5	Eagle Springs	---	---	---	---
	6	Running Water Springs	---	---	---	---
	7	Jones Springs	---	---	---	---
	9	Morrison Springs	---	---	---	---
	10	Norfleet Springs	---	---	---	---
Hockley	2	Devil's Ink Well	---	---	---	---
	3	no name	---	---	---	---
	4	no name	---	---	---	---
	5	Yellow House Springs	---	---	---	---
	6	no name	---	---	---	---
	12	no name	---	---	---	---
Lamb	1	King Springs	---	---	---	---
	2	no name	---	---	---	---
	5	Sod House Spring	---	---	---	---
	8	no name	---	---	---	---
	9	Rocky Ford Springs	05/01/52	4.70	14,339	74.5
	9	Rocky Ford Springs	08/28/52	0	0	0
	9	Rocky Ford Springs	11/52	0	0	0
	10	no name	---	---	---	---
	11	Fieldton Springs	---	---	---	---
	12	Hart Springs	---	---	---	---
	13	Bull Springs	10/03/78	seeps		
	14	Roland Springs and Ponds	10/03/78	seeps		
	15	Illusion Springs	10/04/78	1.60	4,881	25.4
	16	Yellow Springs	10/04/78	0.14	427	2.2
	17	no name	10/04/78	0.71	2,166	11.3
	19	Green Springs	10/21/78	0.75	2,288	11.9

Sources: Brune, 1981, 2002
White and Kues, 1992

L/s = Liters per second
gpm = Gallons per minute

cfd = Cubic feet per day
--- = Flow measurements not provided by Brune.

Table 2: Measured discharge for springs identified in the study area (continued)

County	Number	Name	Date Measured	Flow (L/s)	Flow (cfd)	Flow (gpm)
Lea	1	no name	---	---	---	---
	2	Monument Spring	---	---	---	---
Lubbock	1	Buffalo Springs	1937	8.5	25,932	134.7
	1	Buffalo Springs	1939	19	57,966	301.2
	1	Buffalo Springs	1969	96	292,882	1521.6
	1	Buffalo Springs	1970	93	283,729	1474.1
	1	Buffalo Springs	1971	85	259,322	1347.3
	1	Buffalo Springs	1972	57	173,898	903.5
	1	Buffalo Springs	1973	42	128,136	665.7
	1	Buffalo Springs	1974	42	128,136	665.7
	1	Buffalo Springs	1975	62	189,153	982.7
	1	Buffalo Springs	1976	85	259,322	1347.3
	2	Lubbock Lake	---	---	---	---
Lynn	1	Saleh Lake and Seeps	---	---	---	---
	3	Tahoka Springs	12/13/74	6.00	18,305	95.1
	4	Double Lakes Springs	12/12/75	1.00	3,051	15.9
	4	Double Lakes Springs	09/09/78	seeps		
	5	Guthrie Springs	---	---	---	---
	6	Gooch Springs	10/26/78	0.78	2,380	12.4
	7	New Moore Springs	12/13/75	7.50	22,881	118.9
	7	New Moore Springs	10/25/78	5.70	17,390	90.3
	8	no name	---	---	---	---
	9	Frost Springs	10/26/78	4.20	12,814	66.6
Martin	2	no name	---	---	---	---
	3	Mulkey Springs	---	---	---	---
	4	Baldwin Springs	---	---	---	---
	5	Mustang Springs	---	---	---	---
	6	no name	---	---	---	---
	7	Kilpatrick Springs	---	---	---	---
	8	no name	---	---	---	---
	9	Soda Springs	04/20/79	3.80	11,593	60.2
	10	Sulpher Springs	1936	0.63	1,922	10.0
	10	Sulpher Springs	04/20/79	0.13	397	2.1

Sources: Brune, 1981, 2002
White and Kues, 1992

L/s = Liters per second
gpm = Gallons per minute

cfd = Cubic feet per day
--- = Flow measurements not provided by Brune.

Table 2: Measured discharge for springs identified in the study area (continued)

County	Number	Name	Date Measured	Flow (L/s)	Flow (cfd)	Flow (gpm)
Midland	5	no name	---	---	---	---
	7	no name	---	---	---	---
	8	no name	---	---	---	---
	9	Mustang Springs	---	---	---	---
Motley	4	Burleson Springs	1938	8.8	26,847	139.5
	4	Burleson Springs	1968	8.8	26,847	139.5
Oldham	21	Rocky Dell Springs	---	---	---	---
	27	Joaquin Spring	---	---	---	---
	28	George Springs	---	---	---	---
	37	Cheyenne	1938	0.03	92	0.5
Parmer	1	no name	---	---	---	---
	2	no name	---	---	---	---
	5	no name	---	---	---	---
Quay	1	no name	---	---	---	---
Randall	5	South Cita Springs	08/10/78	7.50	22,881	118.9
	11	T-Anchor Springs	---	---	---	---
	12	no name	---	---	---	---
	13	Thompson Springs	---	---	---	---
	14	Long Springs	---	---	---	---
	15	Carruth Springs	---	---	---	---
	16	no name	---	---	---	---
	17	Dean Springs	---	---	---	---
Roosevelt	1	Spring No. 56	---	---	---	---
	2	Portales Spring	---	---	---	---
Swisher	2	Hackberry Springs	---	---	---	---
	4	Rogers Springs	11/12/45	0.32	976	5.1
	4	Rogers Springs	09/07/78	seeps		
	5	Dead Horse Springs	---	---	---	---
	9	Dawson Springs	---	---	---	---
	11	no name	---	---	---	---
	12	Edwards Springs	---	---	---	---
	13	Poff Springs	---	---	---	---
	14	no name	---	---	---	---
	17	Maupin Springs	---	---	---	---
	18	Hardy Springs	---	---	---	---

Sources: Brune, 1981, 2002
White and Kues, 1992

L/s = Liters per second
gpm = Gallons per minute

cfd = Cubic feet per day
--- = Flow measurements not provided by Brune.

Table 2: Measured discharge for springs identified in the study area (continued)

County	Number	Name	Date Measured	Flow (L/s)	Flow (cfd)	Flow (gpm)
Terry	1	Mound Springs	12/13/75	4.00	12,203	63.4
	2	no name	---	---	---	---
	3	no name	---	---	---	---
	4	no name	---	---	---	---
	6	Rich Springs	1900	19.00	57,966	301.2
	6	Rich Springs	10/23/78	1.20	3,661	19.0
	6	Rich Springs	05/18/38	0.63	1,922	10.0
	7	no name	---	---	---	---
	9	no name	---	---	---	---
	10	no name	---	---	---	---
	11	no name	---	---	---	---
	13	no name	---	---	---	---
Yoakum	3	no name	---	---	---	---
	5	no name	---	---	---	---
	6	no name	---	---	---	---

Sources: Brune, 1981, 2002
White and Kues, 1992

L/s = Liters per second
gpm = Gallons per minute

cfd = Cubic feet per day
--- = Flow measurements not provided by Brune.

they estimated a total groundwater discharge of 25,000 to 30,000 ac-ft/yr (White and others, 1946, p. 391).

Discharge to Streams and Lakes

As discussed in the previous section, discharge to salt lakes and streams (draws) occurs through springs along the margins of the salt lake basins. Observed or estimated discharge rates for these and other springs are provided in Table 2. Along the eastern margin of the study area, spring discharge prior to large-scale groundwater pumping was sufficient to form small perennial streams, as discussed in the Rivers, Streams, Springs, and Lakes section. Quantitative estimates of the volumes of discharge to these streams are not available.

Evapotranspiration

Discharge by evapotranspiration directly from the water table is believed to be limited and is not considered in the model. Throughout most of the study area, observed water levels are generally several tens of feet or more below the land surface, and evapotranspiration is assumed to be negligible. Under predevelopment conditions, evapotranspiration did occur through marsh grass and sedges, salt grass, subirrigated alfalfa, and trees (cottonwoods and willows) along some regions of draw bottoms (White and others, 1946, p.391). However, as the regions of vegetation along the draws are not known, groundwater discharge along the draw bottoms was simulated as spring flow. Spring flow and evapotranspiration from plants along the draw bottoms has stopped or been greatly reduced due to water level declines caused by pumping.

Conceptual Model of Groundwater Flow

This section presents the overall interpretation of how groundwater flow occurs within the aquifer and how the flow is affected by various sources and mechanisms of groundwater recharge and discharge, as well as by the physical properties of the aquifer. The conceptual model of groundwater flow is presented graphically, in cross section form, in Figure 44a. Implementation of the conceptual model into the numerical model is illustrated schematically in Figure 44b.

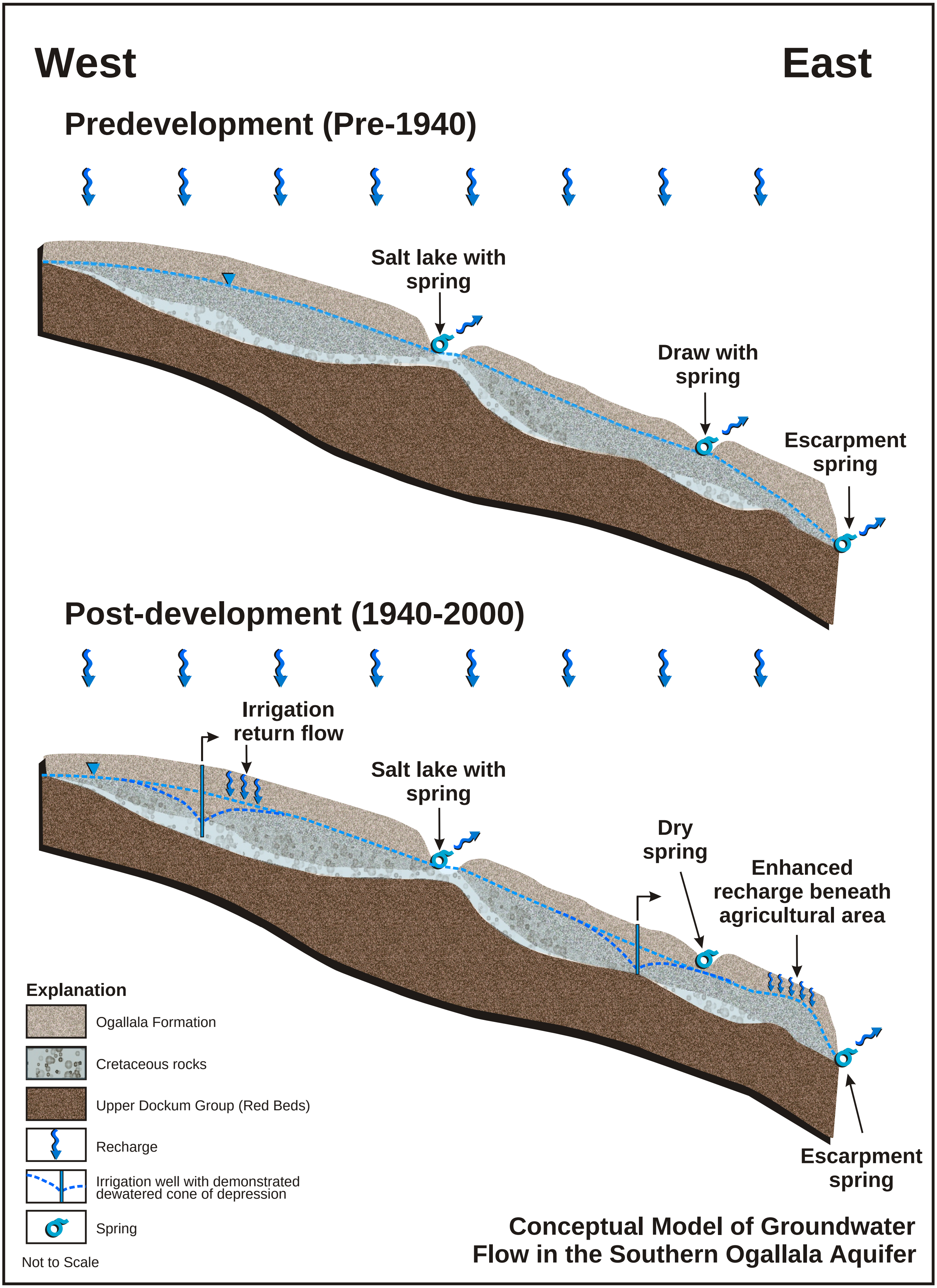
The Southern Ogallala aquifer is recharged by precipitation. Significant recharge occurs at playa lakes, beneath agricultural fields, and likely within the bottoms of ephemeral draws. Recharge in natural, inter-playa settings is negligible. Recharge also occurs from the return flow of a portion of irrigation water that has been applied to irrigated fields, although this water is not “new” water, but rather the return of water that was previously pumped from the aquifer.

The water table, as does the land surface, generally slopes toward the southeast, and hence the regional direction of groundwater flow is from northwest to southeast. The direction of groundwater flow is affected locally by points of discharge, such as springs and wells, and aquifer properties, such as thickness and hydraulic conductivity.

Under predevelopment conditions (approximately pre-1940), prior to significant regional groundwater pumping, discharge from the aquifer occurred at springs and seeps along the caprock escarpment, draws, and the margins of salt lakes. Discharge at the “interior” springs (those west of the eastern escarpment) was a significant percentage of the total discharge from the aquifer, as evidenced by the lack of an increasing hydraulic gradient near the eastern escarpment, as would be expected if most of the discharge occurred along the escarpment (fig. 21).

Some downward leakage probably occurs from the Southern Ogallala aquifer through the upper Dockum units into the Santa Rosa sandstone (fig. 12), but the amount of such discharge is believed to be relatively small. It is also likely that there is some leakage downward to or upward from Cretaceous rocks that underlie the Ogallala Formation sediments but are not in direct hydraulic communication with them. These potential components of recharge to or discharge from the Ogallala aquifer are also believed to be relatively small.

Significant groundwater withdrawals, primarily for irrigated agriculture, began during



Conceptual Model of Groundwater Flow in the Southern Ogallala Aquifer

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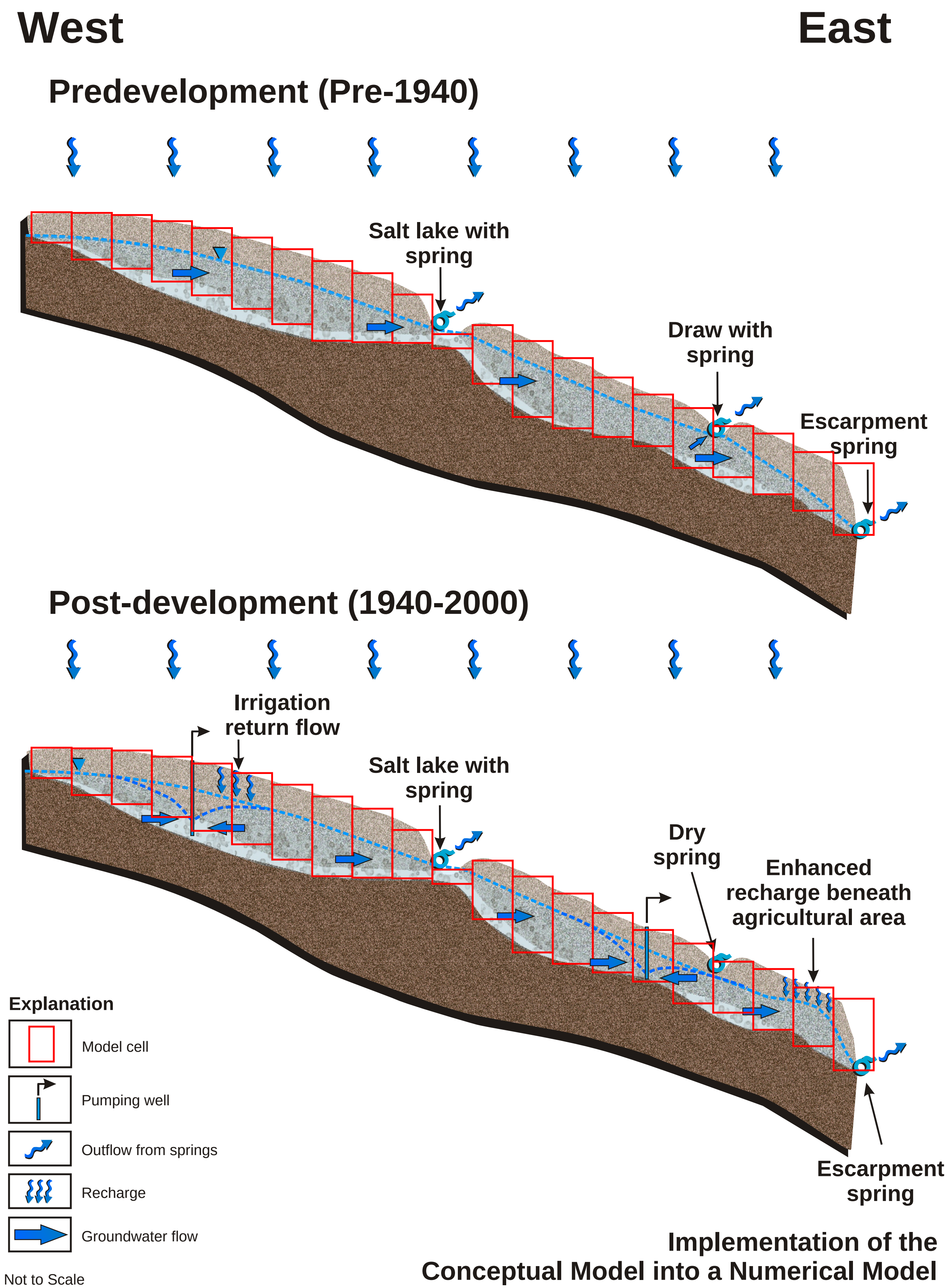
Figure 44a



Implementation of the Conceptual Model into a Numerical Model the 1940s and continued into the mid- to late 1950s, by which time much of the irrigated acreage observed today was in place. Pumping for irrigated agriculture became, and still is, the dominant use of water on the Southern High Plains. Early irrigation practices were very inefficient, but irrigation efficiencies have improved steadily over time, with the greatest advances realized from the mid-1980s up to the present day. As a result of more efficient irrigation practices, less water is available for irrigation return flow and less is lost to evaporation. Where large declines in the water table were caused by pumping for irrigated agriculture, flows at springs have either ceased or been reduced, often significantly.

Development of large portions of the land area for irrigated and dryland farming appears to have significantly increased the rate of recharge to the aquifer from precipitation. A number of counties in the east-central and southeastern portion of the study area have experienced significant rises in water levels over time, in some cases rising steadily over many decades. In other counties, generally those in the south-central portion of the study area, water levels have been relatively constant over the long term, even with significant withdrawals for irrigated agriculture and lesser withdrawals for other uses. Where water levels are steadily rising, recharge must exceed discharge, and where water levels are relatively steady, recharge approximately equals discharge. This "enhanced" recharge beneath agricultural fields is expected to be more pronounced beneath irrigated fields than beneath fields that are dryland farmed.

Groundwater flow in the aquifer is also significantly affected by aquifer properties. Aquifer saturated thickness is the difference between the elevation of the water table and the aquifer bottom. The saturated thickness is largest along paleochannels eroded into the Triassic and Cretaceous rocks on which the Ogallala Formation was deposited. Hydraulic conductivity also tends to be higher along these paleochannels than in the adjacent, inter-channel regions. Accordingly, most regions of irrigated agriculture are clustered above these zones of greater aquifer thickness and hydraulic conductivity.

Model Design

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

Code and Processor

In accordance with TWDB specifications for the GAMs, the USGS computer code commonly known as MODFLOW-96 (Harbaugh and McDonald, 1996) was applied to simulate groundwater flow in the Southern Ogallala aquifer. MODFLOW-96 has been applied extensively to simulate groundwater flow throughout the world for numerous hydrogeological settings and different types of aquifers. The code is extremely well tested, validated, and documented, and it is in the public domain. It also is versatile in that it has options to simulate a variety of boundary conditions (e.g., prescribed and general head, rivers, drains, and evapotranspiration) and aquifer types (e.g., confined or unconfined). The model was developed and run on a Compaq PC with 786 megabytes of RAM and a 1.7-gigahertz processor running Windows NT 4.0.

Layers and Grid

Discretization is the process of dividing the study area into a series of model blocks or cells, referred to as the model grid. The model grid for the Southern Ogallala aquifer consists of 78,300 cells (270 rows by 290 columns), of which 28,992 are active. (An active model cell is one where either a boundary condition is prescribed or hydraulic head is simulated.) The model grid is divided into 1-mi^2 cells in the horizontal dimension and consists of a single model layer in the vertical dimension. This single model layer is used to represent the entire saturated thickness of the Ogallala aquifer. Each of these attributes is consistent with TWDB specifications for the GAM model.

The areal extent of the model grid and pertinent specifications are illustrated in Figure 45. The western and eastern boundaries of the grid were extended beyond the boundaries of the Ogallala aquifer to include the outcrop and downdip areas of the Dockum minor aquifer in Texas and New Mexico. This was done in anticipation that the Southern Ogallala model grid would serve as a basis for the model grid of a Dockum aquifer GAM, if one is ever constructed.

The entire model grid is not plotted in Figure 45 because the individual cells would be indiscernible at the scale of the plot. However, the model grid for Lamb and Hale Counties is provided in Figure 46 as an illustration of the relative size of individual model cells.

Model Parameters

The primary model input parameters are bottom elevation, hydraulic conductivity, and specific yield. The methodologies used to prescribe each of these parameters in the model are presented in this section. Model input parameters related to boundary conditions are presented in the following section.

The bottom elevations used in the model were developed by creating a triangulated irregular network (TIN) based on the digitized points used to define the base-elevation contours. Next, an average aquifer base elevation was determined for each model cell by computing the elevation at the centroid of nine sub-cells of equal area and then averaging the nine values to get an average base elevation for each 1-mi^2 model cell.

Hydraulic conductivity was interpolated onto the model grid based on the contour plot presented in Figure 37. This initial hydraulic conductivity grid file was simplified into 15 zones of hydraulic conductivity by grouping values of similar magnitude. Some of the individual cells had very low interpolated hydraulic conductivity values. These cells were set to a minimum value of 2.5 ft/d, because it was not believed to be realistic that an entire model cell representing 1 mi^2 would have an average hydraulic conductivity significantly lower than this value.

Initially, the hydraulic conductivity for each of the 15 zones was set to the geometric mean for that zone. After a number of early model calibration runs, however, the hydraulic conductivity of each zone was increased by 20 percent. This zonation of hydraulic conductivity is considered to be the initial input for modeling purposes and is presented in Figure 47.

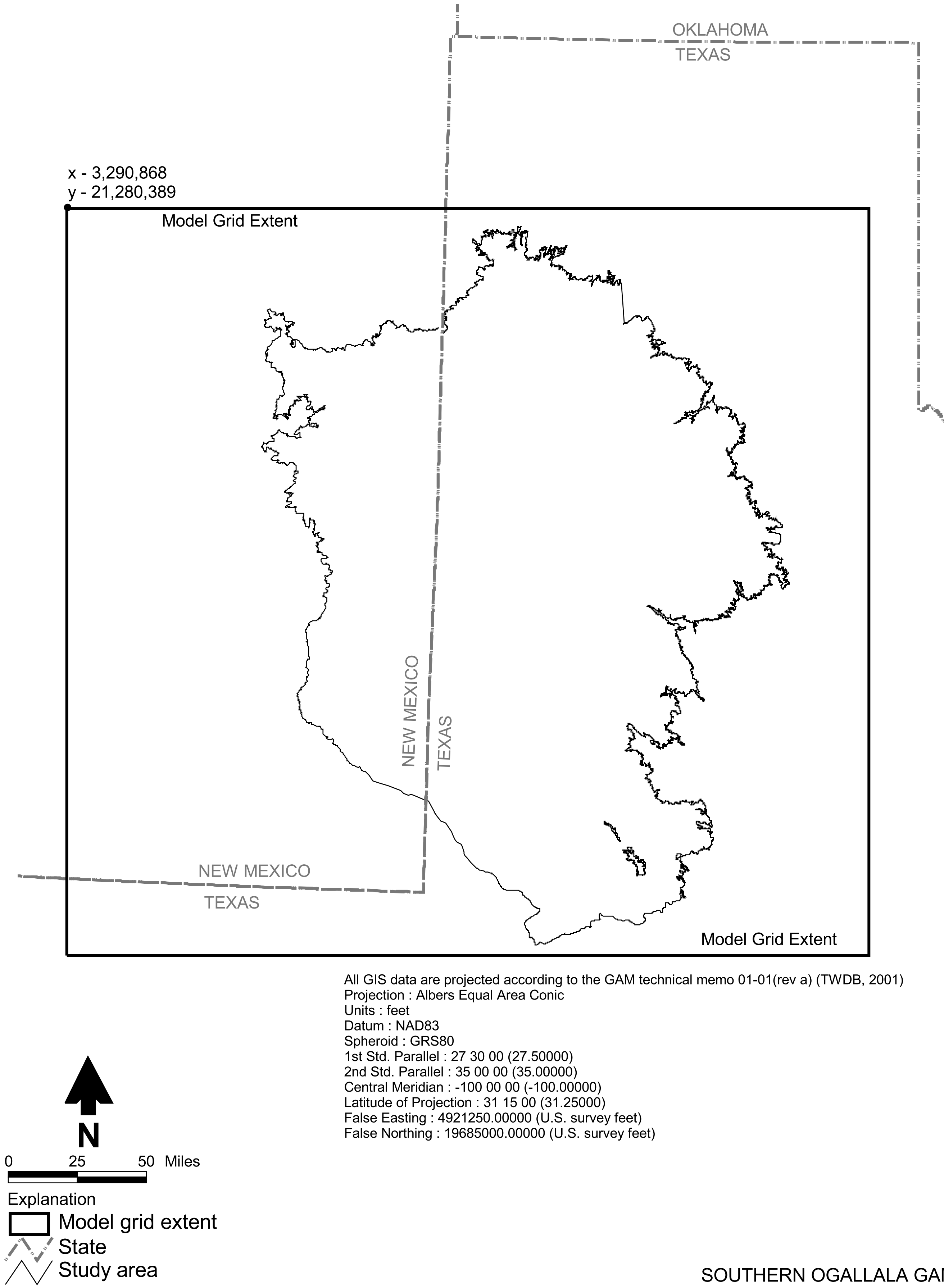
Specific yield in the model ranges from 15 to 22 percent and was applied in conjunction with the hydraulic conductivity zones; that is, higher values of specific yield were applied to higher zones of hydraulic conductivity (fig. 48). The average specific yield in the GAM model is 16 percent.

Pumping was assigned in the model as described in the Discharge section. Initially, pumping for irrigated agriculture was assigned according to the proportion of a given model cell that had irrigated acreage. Proportions were done on a county by county basis because the available or derived pumping estimates were by county. However, after several model runs, agricultural pumping was adjusted based on the transmissivity (calculated from the results of the predevelopment simulation) of the model cells within a given county. This procedure was designed to reduce pumping in low-transmissivity model cells (small saturated thickness and/or small hydraulic conductivity), to be consistent with actual conditions.

Several procedures for making this adjustment were tested, but the approach described below yielded the best overall model calibration results and was therefore the one used.

1. The computed transmissivity values for each model cell that had irrigated acreage in a given county were ranked from low to high.

2. The lowest 5 percent of the cells were assigned zero pumping.



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SOUTHERN OGALLALA GAM

Extent of Model Grid

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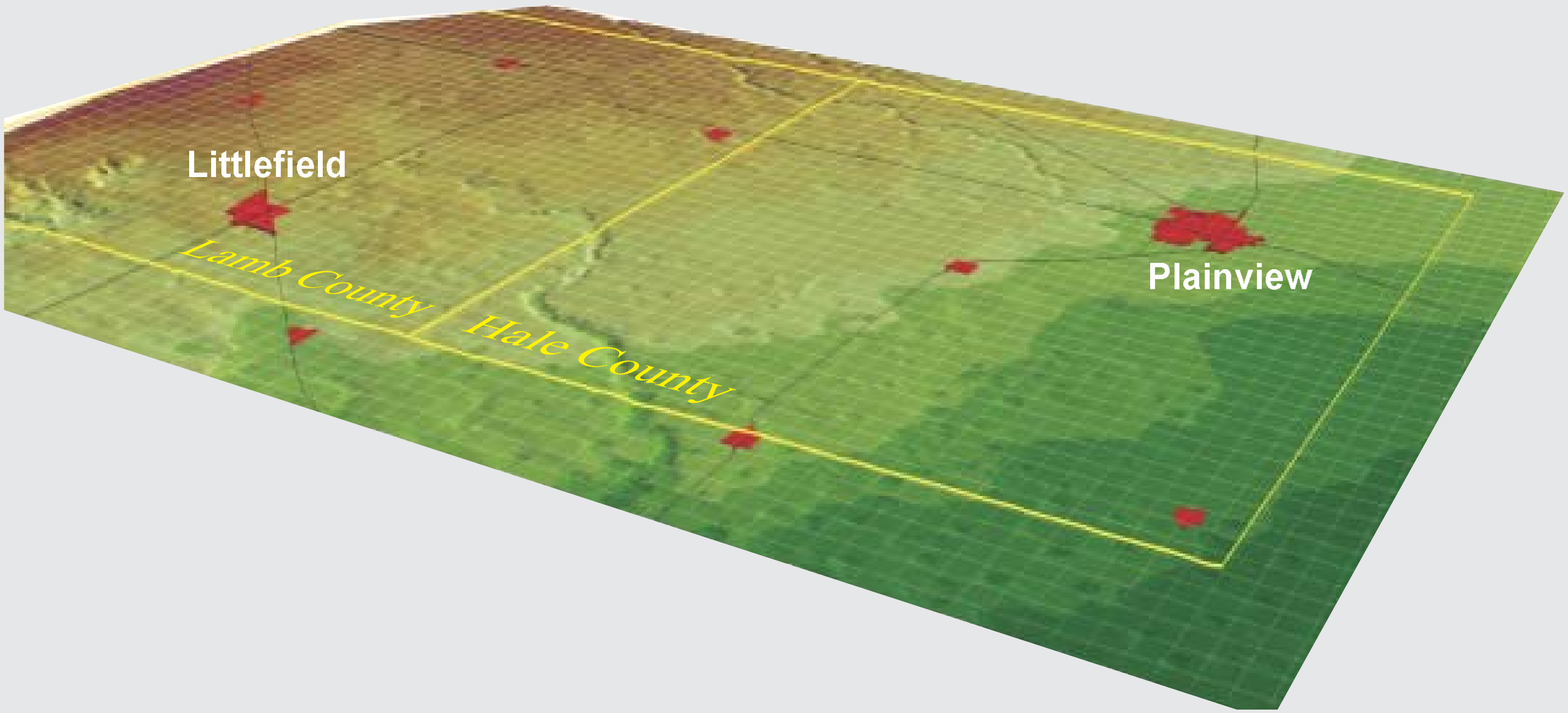
Figure 45



SOUTHERN OGALLALA GAM

Lamb and Hale Counties with Model Grid

Figure 46

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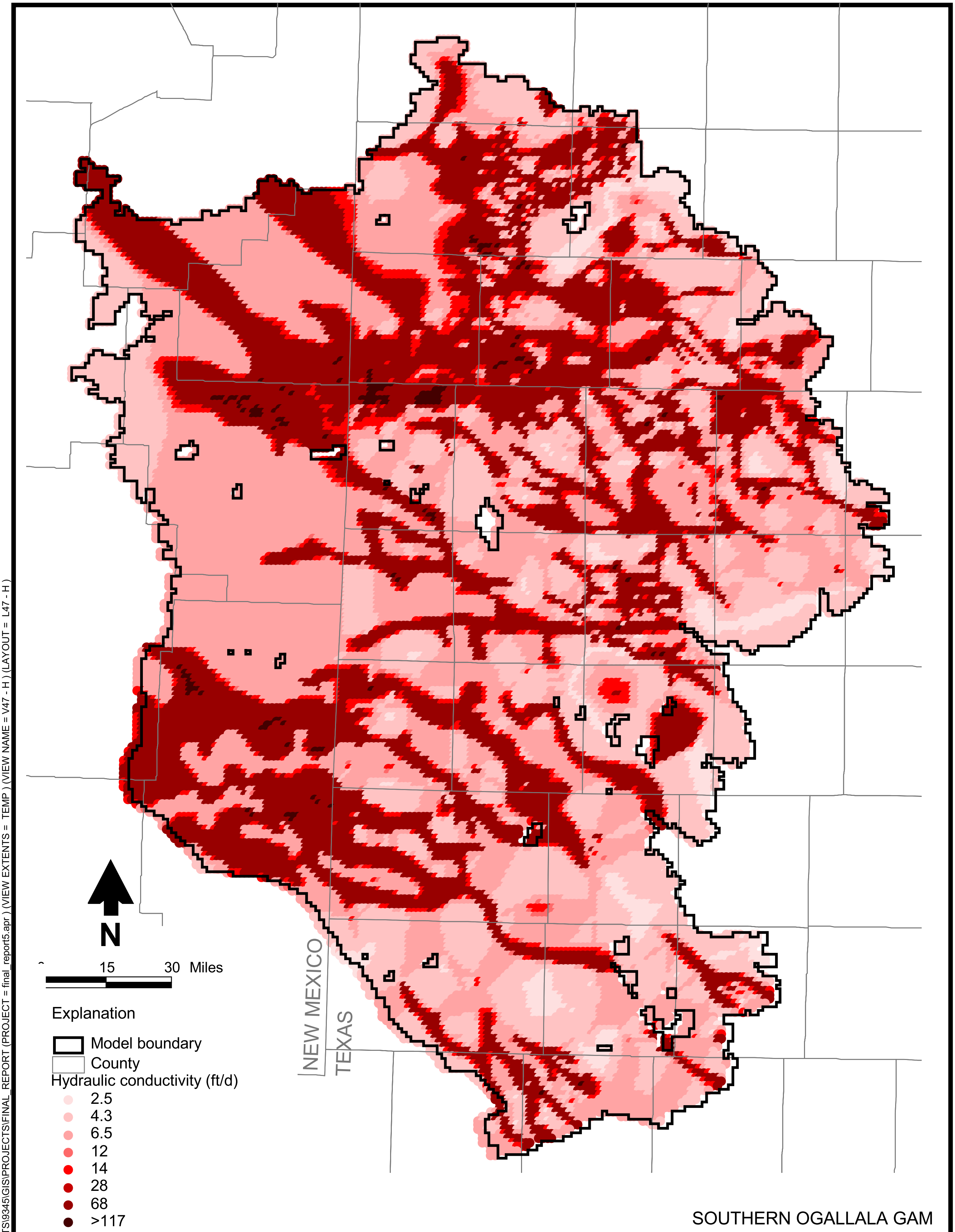

SOUTHERN OGALLALA GAM

Hydraulic Conductivity Used at Beginning of Model Calibration

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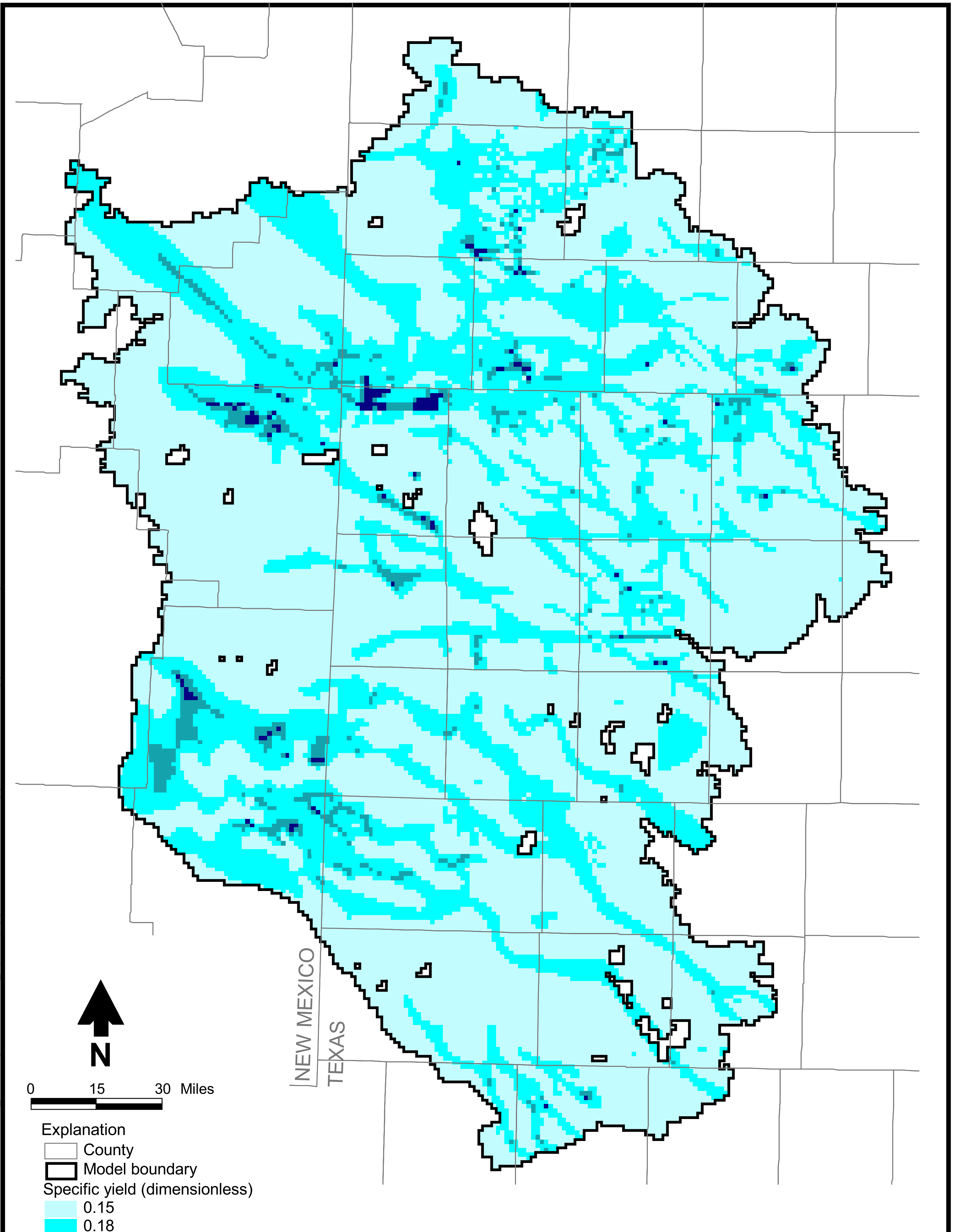
Figure 47



SOUTHERN OGALLALA GAM

Specific Yield

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Figure 48

3. Cells between 5 percent and 50 percent in the ranking were assigned 75 percent of their initially estimated pumping.
4. The amount of pumping removed from cells during steps 2 and 3 was redistributed among the model cells that had transmissivity values in the upper 50th percentile. The amount of redistributed pumping assigned to these cells was added to the original rate of pumping assigned to each of these cells based on their irrigated area, thereby preserving the entire volume of estimated pumping on a county by county basis.

Model Boundaries

The model boundaries are illustrated in Figure 49. The active region of the model, within which computations of hydraulic head are made, generally follows the outline of the study area.

The western, northern, and southern boundaries of the model are no-flow, except in parts of the northern boundary where several springs are documented (Brune, 1981, 2002). A no-flow boundary is one where there is no exchange of groundwater across the model boundary.

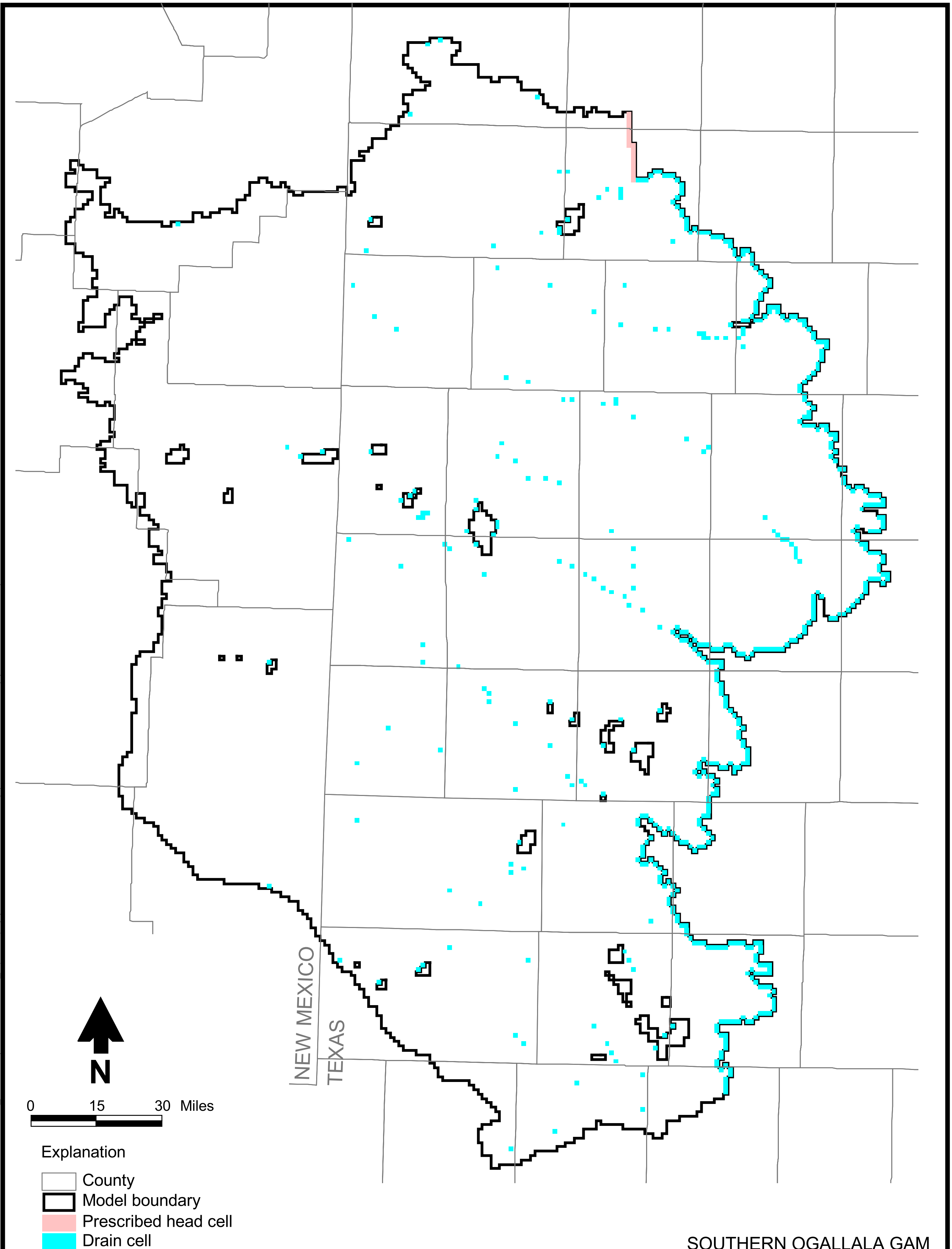
For the model cells along the eastern caprock escarpment, outflow boundaries were used. In the predevelopment model, hydraulic head was prescribed for these cells based on the predevelopment water level contour map (fig. 21). For the transient calibration and predictive simulations, these boundary cells were converted to drain cells where the drain conductance was back-calculated from the predevelopment groundwater efflux value for each cell. Drain cells represent a boundary condition where the flux of water from the cell is a function of the simulated hydraulic head within the model cell and prescribed physical parameters such as the conductance and base elevation (McDonald and Harbaugh, 1988). Drain elevations for the escarpment boundary cells were set to 1 ft above the base of aquifer for each cell.

Along the far northeastern model boundary, west of Amarillo, prescribed hydraulic head cells were used during the predevelopment and transient calibrations. The prescribed hydraulic head values were based on observed data in the TWDB water level database for wells near the boundary. Groundwater flow across this boundary represents the only connection between the Southern and Central Ogallala aquifers (the Central Ogallala aquifer is sometimes called the Northern Ogallala aquifer in Texas).

In addition to the boundary conditions along the circumference of the model described above, a number of interior boundary conditions were applied to represent springs, salt lakes, and regions where the aquifer is not present. These boundary conditions are also illustrated in Figure 49.

Drain cells were used to represent documented springs along draws and the margins of salt lake basins (Brune, 1981, 2002; White and Kues, 1992). Additional springs were added along selected reaches of some draws in the eastern part of the study area to allow for more evenly distributed outflow. Drain cell elevations were determined from the digital elevation map (DEM) developed for the study area. All internal drain conductances were set to 7,440 ft^2/d, similar to the value used by Dutton and others (2000). Sensitivity analysis indicated that outflow at the drains was not very sensitive to the conductance and was primarily controlled by the difference in simulated hydraulic head and prescribed base elevation of the drain cell.

Salt lakes and their associated topographic basins were treated as regions of no flow, as these are typically areas of thin or zero aquifer thickness. The region of no-flow cells used in the model to represent the lakes was determined through examination of geologic maps (BEG, 1967, 1974, 1976, 1978; Eifler and others, 1968, 1974), the DEM, spring locations, and the interpolated aquifer base elevation relative to the land surface. All of the internal no-flow cells in Figure 49 represent salt lakes and their topographic basins, except for the northwest-southeast trending linear feature in eastern Martin County. This feature is a topographic



SOUTHERN OGALLALA GAM

Model Boundary and Cell Types

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Figure 49

low where the Ogallala aquifer does not exist, but no salt lake exists at that location. Along the margins of each of the salt lakes, drain cells are used to represent outflow from springs at the edges of the lakes (see the Rivers, Streams, Springs, and Lakes section).

Consistency with Ogallala North Model

The Southern Ogallala GAM was also constructed to provide reasonable continuity with the Ogallala North model developed as part of the SB-1 regional water planning process (Dutton and others, 2000). Because the Ogallala North model was constructed using a different coordinate projection than that required by the GAM modeling protocol, the model grids could not be precisely aligned along the common boundary of the two models west of Amarillo in Randall County. However, the aquifer hydraulic conductivity field and the aquifer bottom elevation maps are continuous across the boundary. In addition, the simulated and prescribed hydraulic heads in the Southern Ogallala model at and near the common boundary are in reasonable agreement with the hydraulic heads used in the general head boundary conditions applied along this boundary in the Ogallala North model.

Modeling Approach

The overall modeling approach consisted of (1) calibrating a steady-state, predevelopment model, (2) calibrating and verifying a transient, post-development model, and (3) applying the calibrated transient model to predict future aquifer conditions subject to assumed future pumping rates.

The predevelopment model is useful to determine average aquifer hydraulic conductivity and recharge under natural conditions without the added complexity of significant groundwater pumping, recharge from return flow and changes in land use, and effects of specific yield. The simulated hydraulic heads from the predevelopment model serve as the initial (starting) condition for the transient post-development simulation. Accordingly, the predevelopment model was calibrated to average hydrogeologic conditions at or about 1940, prior to significant groundwater development of the aquifer (Luckey and others, 1986, p.11). Specifically, the predevelopment model was calibrated to observed hydraulic head and outflows at the 10 largest springs along the eastern escarpment.

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

The transient model was calibrated to observed changes in water levels at 80 locations distributed throughout the study area in irrigated and non-irrigated regions, and to observed water levels for all available points in the study area for the winters of 1979-1980, 1989-1990, and 1999-2000. Changes in simulated spring flows were also examined, but insufficient historical information is available to conduct detailed comparisons of model output with observed values through the transient simulation period. Model verification was conducted through comparison of simulated water levels to 10 additional hydrographs for wells distributed throughout the study area, 8 of which have monthly water level observations.

Finally, the calibrated transient model was applied to conduct predictive simulations for a variety of scenarios and time periods as specified by the TWDB.

This sequence of simulation and model parameter estimation was selected to minimize, to the extent possible, the problem of non-unique simulation results. Model results are non-unique when changes in multiple aquifer parameters, all within reasonable limits, lead to the same or similar simulation results. For example, suppose that the simulated drawdowns in water levels over time for a certain region are high. One could decrease the simulated drawdown by reducing pumping, increasing recharge, increasing specific yield, increasing hydraulic conductivity, or by applying some combination of all the above. However, the solution would be highly non-unique due to the number of parameters involved.

This issue is important due to the effects that various input parameters may have on predictive simulations. Say, for the situation outlined above, that in reality the pumping rates put into the model were too high, but unknowingly the modeler increased hydraulic conductivity to solve the problem of too much simulated drawdown. When the model is used for predictive purposes, the erroneous historical pumping will be replaced by estimated future pumping, but the erroneously high hydraulic conductivity will still be applied. The final result will be one where future drawdown is underestimated due to the erroneously high hydraulic conductivity identified during the historical model calibration process.

Steady-State Model

The steady-state (predevelopment) model represents average hydrogeologic conditions at or about 1940. The model calibration, water budget, and sensitivity analysis are presented in the following three sections.

Calibration

The steady-state model was calibrated to (1) observed hydraulic heads for 1940, (2) the estimated predevelopment water level contours (fig. 21), and (3) observed spring flow for the 10 largest springs along the eastern caprock escarpment. Following the testing of numerous adjustments to various model parameters during the calibration process, model calibration was eventually achieved through (1) adjustment of recharge rates according to soil types within the study area, (2) adjustment of the hydraulic conductivity field in selected regions in the central and southern parts of the model, and (3) implementation of drain outflow conditions to simulate springs in the interior of the model.

The simulated and observed water level contours for the predevelopment period are illustrated in Figure 50. For the most part, simulated groundwater flow directions and hydraulic gradients are similar.

A plot of observed versus simulated 1940 water levels (often called a 45-degree plot) is provided in Figure 51. If the model were capable of simulating observed water levels with perfect accuracy, all of the points in Figure 51 would fall on the solid line (the 45-degree line). The fact that all of the points fall close to the line, both for high and low water levels, indicates that the model is well calibrated to observed water levels. In addition, for the most part the plotted points tend to fall equally distributed on either side of the 45-degree line, which indicates that there is no significant bias in the simulation.

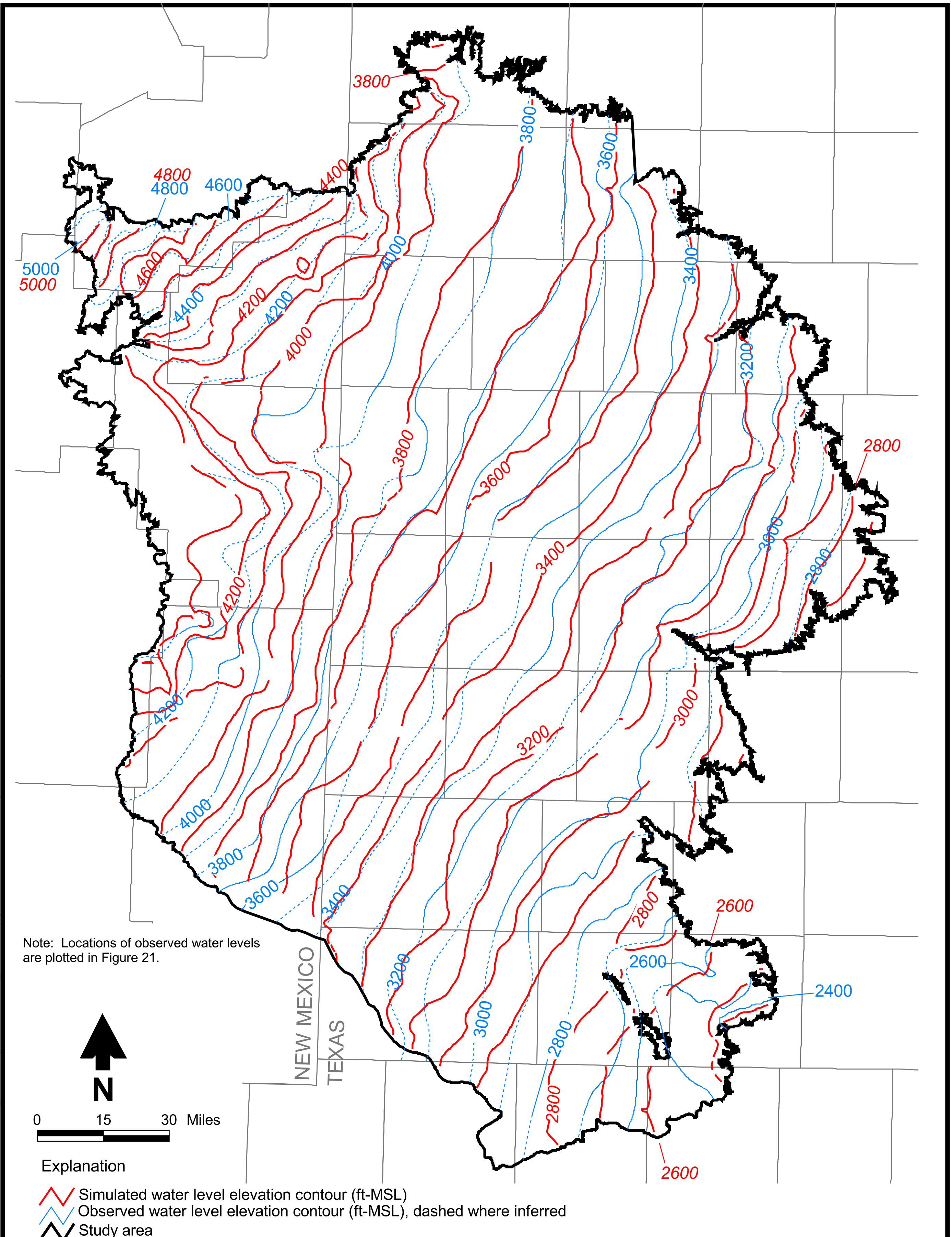
Figure 51 also provides the calibration statistics for the steady-state model for the match between simulated and observed 1940 hydraulic heads. Calibration statistics are presented in terms of root-mean-squared error (RMSE), mean-absolute error (MAE), and residual mean error (RME). These terms are defined as follows:

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

where n = number of water level observations
h_{obs} = observed water level
h_{sim} = simulated water level
Abs = absolute value

The RMSE of the Southern Ogallala model calibration is 34 ft, which is 1.5 percent of the range in observed hydraulic heads of 2,320 ft (fig. 51). The maximum allowable value for this statistic set by the TWDB is 10 percent.

The MAE, also provided on Figure 51, is a measure of the average difference between



SOUTHERN OGALLALA GAM

Simulated and Observed Predevelopment Water Levels

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Figure 50

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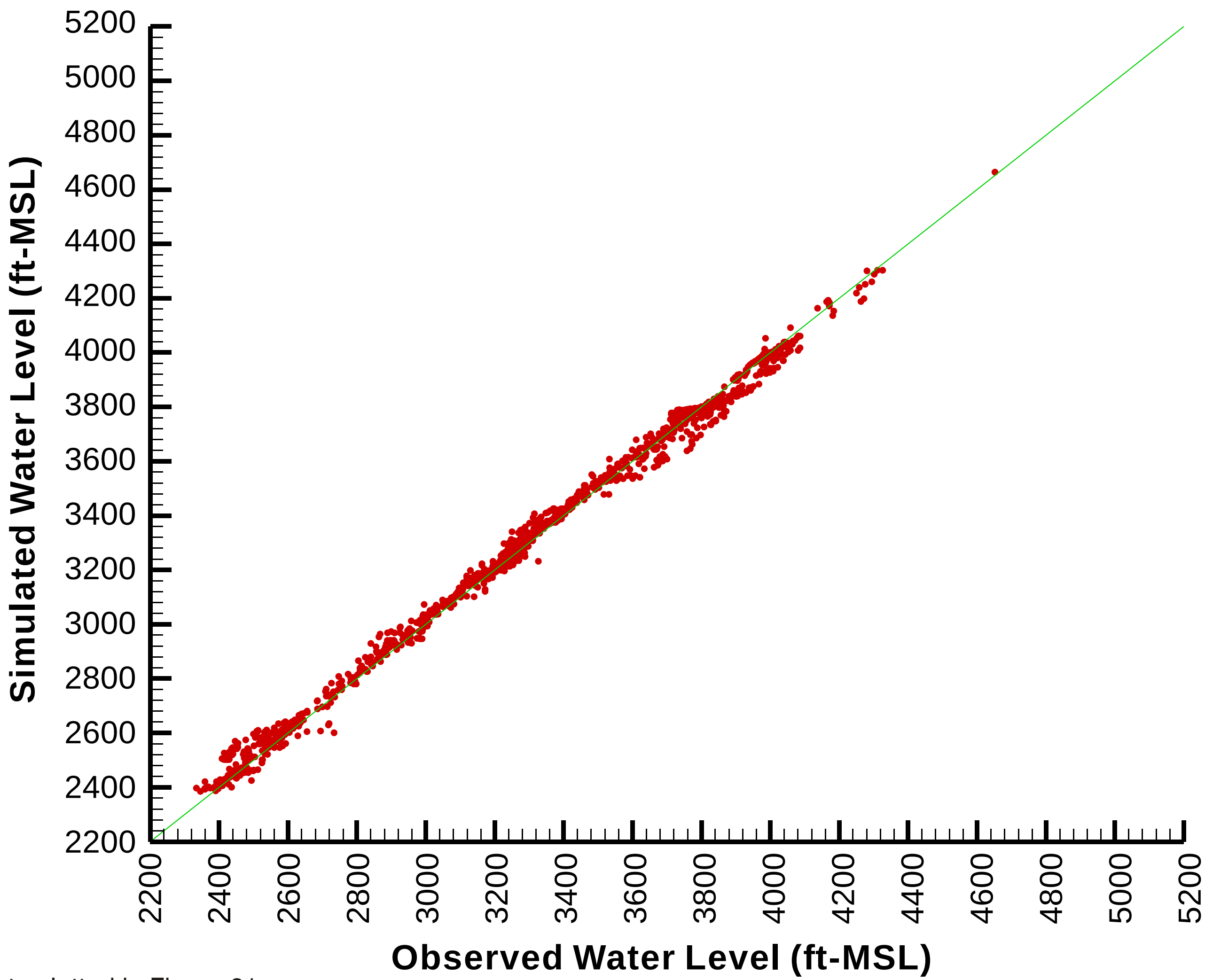

Note:
Observed data points plotted in Figure 21

Calibration Statistics

RMSE: 34 ft
MAE: 26 ft
RME: -8 ft
RMSE/Range: 1.5%
High: 123 ft
Low: 133 ft

SOUTHERN OGALLALA GAM

Simulated vs Observed Hydraulic Heads for Predevelopment Model Calibration

Figure 51

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observed and simulated water levels. For the predevelopment simulation, this value is 26 ft.

The RME is –8 ft, indicating that, on average, the simulated hydraulic head values are slightly greater than the observed values.

Figure 52 illustrates the magnitude of the difference between simulated and observed water levels, as well as whether they were higher or lower than observed values. As shown in Figure 52, simulated hydraulic heads in the predevelopment model tend to be uniformly over- or under-estimated in three regions:

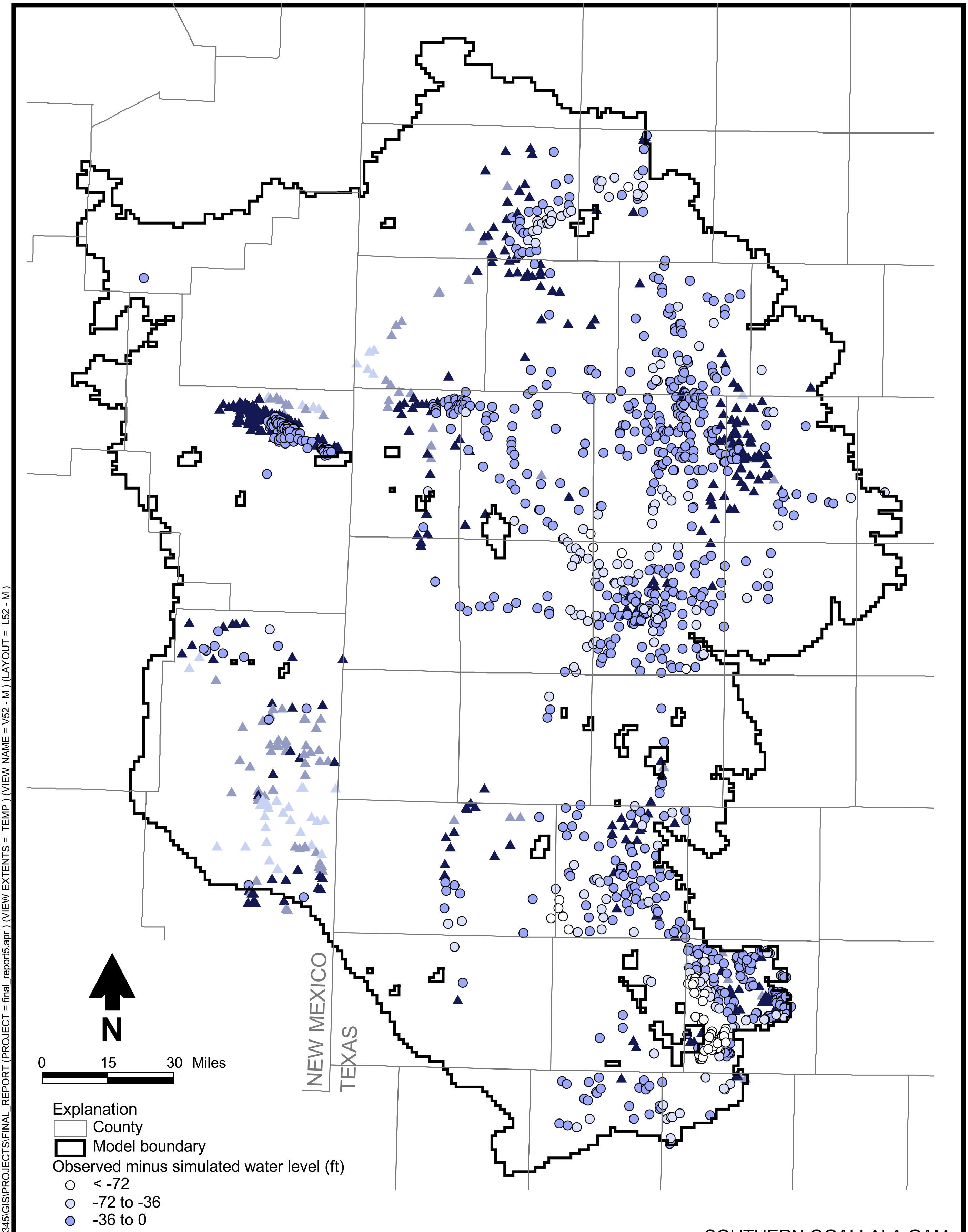
- In Lea County, New Mexico and western Gaines County, Texas, simulated water levels are consistently lower than observed water levels. The simulated water levels in this area can be observed at about the 3,500- to 4,000-ft levels in Figure 51.
- In southwestern Parmer County, Texas and southeastern Curry County, New Mexico, the model simulates water levels significantly lower than those that have been observed or interpolated (although early water level observations are limited in this area).
- In the far southeastern portion of the model in parts of eastern Martin County and western Howard County, simulated water levels higher than those observed can be seen at about the 2,500- to 2,600-ft levels (fig. 51).

Attempts to improve the simulated water levels in Lea County were not successful without sacrificing the good match between simulated and observed water levels in central and eastern Gaines County and Dawson County. Simulated water levels in southwestern Parmer County and southeastern Curry County could not be improved without losing the reasonably good match between simulated and observed water levels in the Portales Valley of New Mexico in northern Roosevelt County. The high water levels in eastern Martin and western Howard Counties are likely due to local hydrogeologic factors, such as the nature of the hydraulic communication of water in the Ogallala Formation with the underlying and adjacent Edwards-Trinity aquifer. Conducting additional model calibration runs for this region was determined not to be an efficient use of resources because (1) it is a relatively small and isolated area of the model that has no significant (in terms of volume) groundwater uses, and (2) it is far removed from regions of significant groundwater use and historical drawdown.

The final calibrated recharge rates for predevelopment conditions range from 0.007 to 0.085 in/yr (fig. 53). The simulated recharge rates are highest in the northern part of the model, where the soil types are the least permeable. Initial attempts at model calibration using higher recharge rates where the soils were the most permeable (i.e., the central and southern portions of the model) did not yield as good a match to observed water levels as the final calibrated model.

If the conceptual model that most of the recharge to the aquifer occurs through playas is valid for predevelopment conditions, then it is reasonable that more recharge would occur in regions of lower-permeability soils because there would be more runoff to playas after precipitation events. This hypothesis is suggested by Wood and Sanford (1995, p. 461), but they acknowledge the lack of actual field data to demonstrate this possibility. They do note, however, that playas in the northern part of the study area tend to be larger, deeper, and occur more frequently. Comparison of Figures 5 and 7 illustrates that playas do occur more frequently (the coverage is more dense) in the northern portion of the study area, in conjunction with the lower-permeability soil types. Gustavson and others (1995, p.13, Table 4) illustrated quantitatively that playa basins formed in more permeable sandy soils are smaller and shallower than those that developed in less permeable clayey soils. They also determined that more runoff occurs to playa basins formed in clayey soils than to those formed in loamy soils (Gustavson and others, 1995, p.18).

Under predevelopment conditions, the largest recorded springs along the eastern escarpment were all in the vicinity of or north of Lubbock. One possible explanation for this phenomenon is



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SOUTHERN OGALLALA GAM

Difference Between Observed and Simulated Water Levels for Predevelopment Calibration

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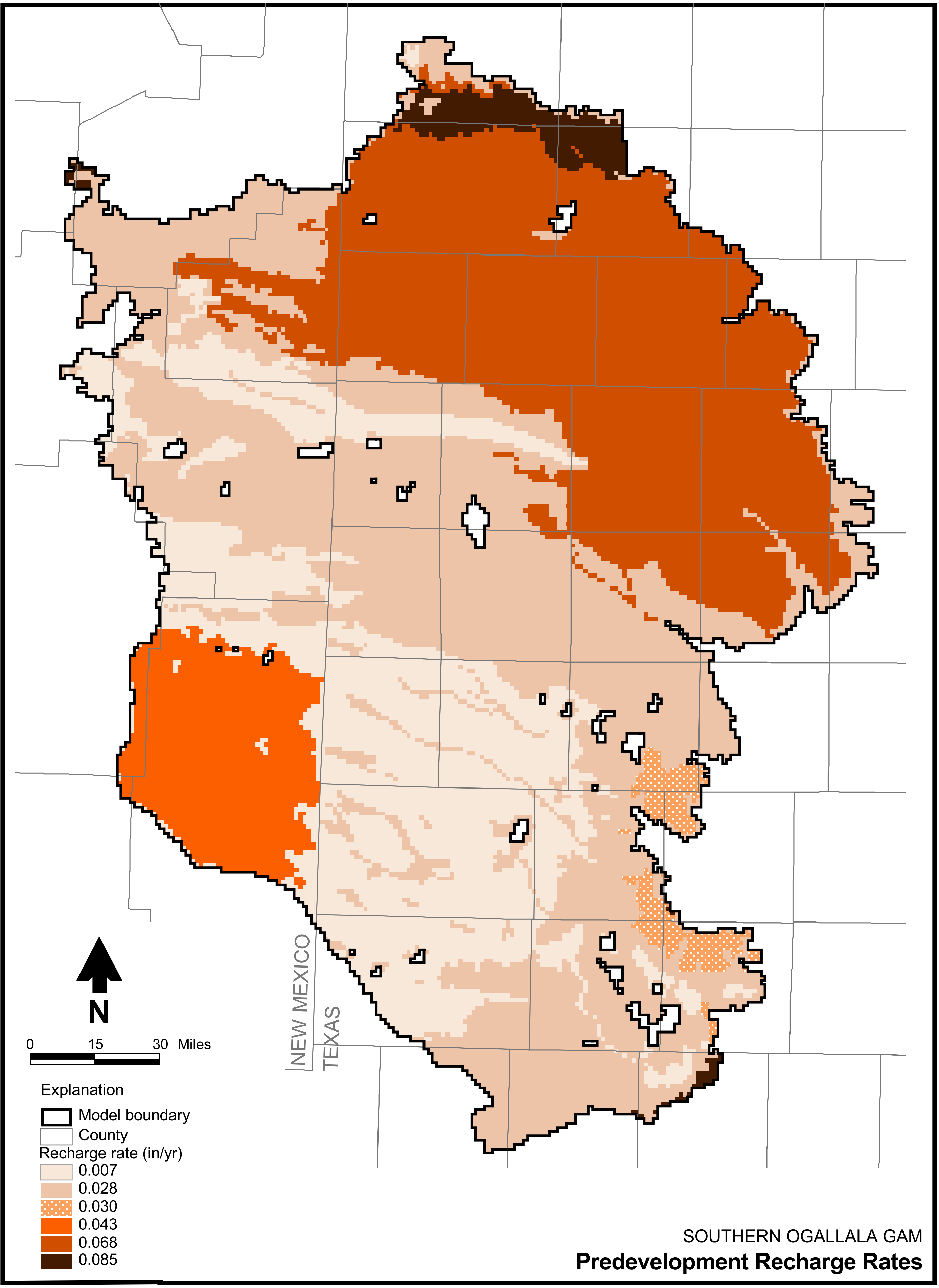
Figure 52



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SOUTHERN OGALLALA GAM

Predevelopment Recharge Rates

3-17-03

Figure 53

that recharge upgradient of these springs may have also been greater relative to other regions of the aquifer. Simulated total outflow at these 10 springs (fig. 43) is 2,582 gpm, while the observed or estimated discharge from Brune (1981, 2002) is 3,112 gpm, a difference of about 17 percent.

The simulated recharge rate for much of the northern third of the model domain is 0.07 in/yr (fig. 53). This value is nearly identical to the rates of 0.05 to 0.0625 in/yr back-calculated from groundwater discharge estimates made by White and others (1946) for the same approximate area.

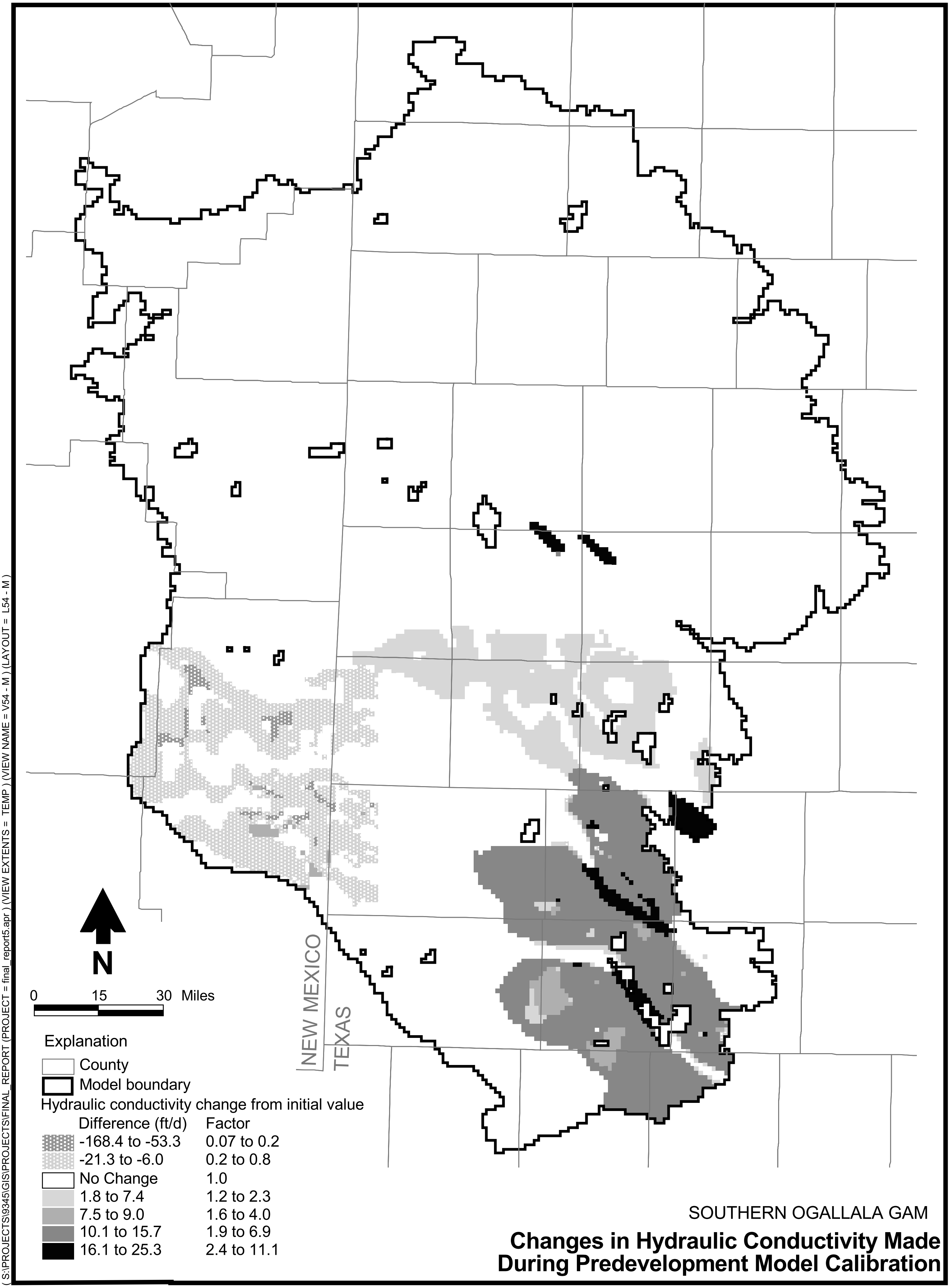
Hydraulic conductivity was adjusted in the central and southern portion of the model to better match the observed hydraulic heads in Lea, Gaines, Terry, and Dawson Counties (fig. 54). The initial estimates of hydraulic conductivity were reduced in portions of Lea County and increased in eastern Gaines County and a significant portion of Dawson County. A region in eastern Gaines County where Cretaceous sediments form the primary aquifer (Rettman and Leggat, 1966) was assigned a hydraulic conductivity of 20 ft/d. In addition, some channels of higher permeability that trended southeast from Dawson County into Howard County, but ended abruptly in the initial assignment of hydraulic conductivity to the model grid, were continued to the southeast. The same concept was applied to two small areas in northern Hockley and Lubbock Counties (fig. 54). For the most part, in order to maintain the geological basis of the hydraulic conductivity field, hydraulic conductivity for the various zones was not adjusted beyond the maximum or minimum values that occurred within that zone based on the initial estimates.

For two hydraulic conductivity zones in the central portion of the study area, however, hydraulic conductivity was approximately doubled from the initial estimate, which corresponds to an increase in the hydraulic conductivity value of 30 to 40 percent above the maximum value for each of these zones. The first of these zones covers portions of north-central Yoakum County, south-central Cochran County, north-central Terry County, and south-central Hockley County, as well as much of the western half of Lynn County. The hydraulic conductivity for this zone was initially 4.3 ft/d (fig. 47), but was increased to 8.5 ft/d (fig. 54). The second zone envelops the first zone throughout much of Terry and Yoakum Counties and extends to the southeast through Terry County. The hydraulic conductivity for this zone was initially 6.5 ft/d (fig. 47), but was increased to 12 ft/d (fig. 54). The average hydraulic conductivity in the final model is 15.7 ft/d.

Water Budget

The water budget for the predevelopment model is provided in Table 3. Total simulated inflows to the model are 57,776 ac-ft/yr, and total outflows from the model are 57,579 ac-ft/yr, a difference of less than 1 percent. Most of the inflow is from recharge, although there is a small component (about 1 percent of the total) from several isolated prescribed hydraulic head cells along the eastern escarpment. This inflow is an artifact of prescribing the boundary heads based on an estimated predevelopment water table map and has no impact on the model because the inflow exits the model in the same local area where it occurs. Approximately 53 percent of the simulated discharge occurs at the eastern caprock escarpment and along the northeastern prescribed head boundary, and 47 percent of the simulated discharge occurs at interior springs along the draws and margins of salt lakes.

Due to convergence problems encountered while running the model in steady-state mode, transient simulations were used to simulate steady-state conditions by running the model for a very long time period. For this purpose, the length of time that the model was run has no physical meaning; the simulation approach is simply a mechanism to obtain a converged steady-state solution. The steady-state simulation was run until simulated changes in storage for inflow and outflow were less than 1 percent of the total simulated values.



SOUTHERN OGALLALA GAM

Changes in Hydraulic Conductivity Made During Predevelopment Model Calibration

1-30-03

Figure 54

Table 3: Simulated Water Balance for Predevelopment Simulation

Component	Amount (ac-ft/yr)
Inflows	
Prescribed head boundary	860
Recharge	56,916
Total inflows	57,776
Outflows	
Prescribed head boundary [a]	30,775
Springs and seeps [b]	26,804
Total outflows	57,579
Percent error [c]	0.34
Number of dry cells	31

ac-ft/yr = Acre-feet per year
[a] Includes prescribed head cells used to simulate springs and seeps along eastern escarpment.
[b] Interior springs and seeps along draws and margins of salt lake basins only.
[c] Calculated as:
[(Total inflow – Total outflow) / Total inflow] x 100.

Sensitivity Analysis

Sensitivity analyses for the predevelopment model were conducted for hydraulic conductivity, recharge, drain conductance, and prescribed hydraulic head along the eastern escarpment. Each of these input parameters, except for prescribed hydraulic head, were increased uniformly by 10 percent and 20 percent above the calibrated value and decreased 10 percent and 20 percent below the calibrated value. Prescribed hydraulic head along the eastern escarpment was increased by 50 ft, which is half the contour interval of the predevelopment hydraulic head map (fig. 21) and decreased by half of the initial saturated thickness.

The sensitivity analysis results for hydraulic conductivity, recharge, and drain conductance are presented in terms of (1) average difference between calibrated water levels and sensitivity run water levels at the calibration points (fig. 55a), (2) flux through the northern prescribed head boundary that separates the Southern Ogallala aquifer from the Central Ogallala aquifer (fig. 55b), (3) discharge at interior springs (fig. 56a), and (4) discharge at the eastern escarpment (fig. 56b).

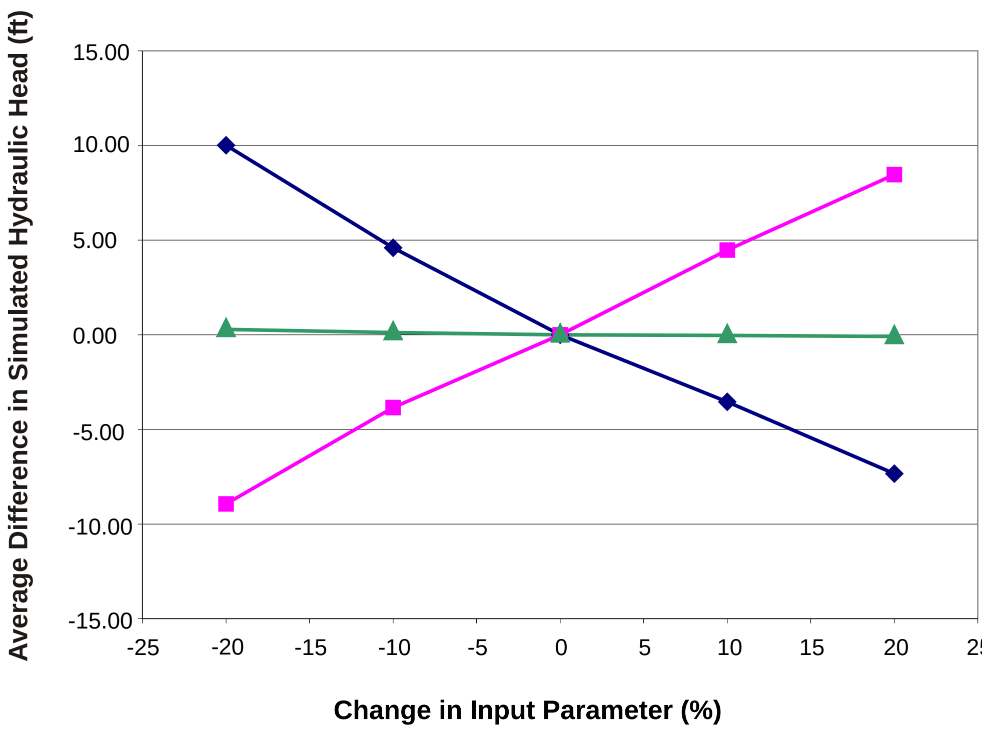
The sensitivity analysis results indicate that, as expected, the simulation results are most sensitive to recharge and hydraulic conductivity, which generally have equal but opposite effects (i.e., the effects of increasing hydraulic conductivity are similar to those of reducing recharge and visa versa). For the most part, the simulation results are insensitive to (not affected by) changes in drain conductance, as indicated by the horizontal or nearly horizontal lines in Figures 55 and 56. The simulated discharge from interior springs is most sensitive to the applied recharge rate (fig. 56a).

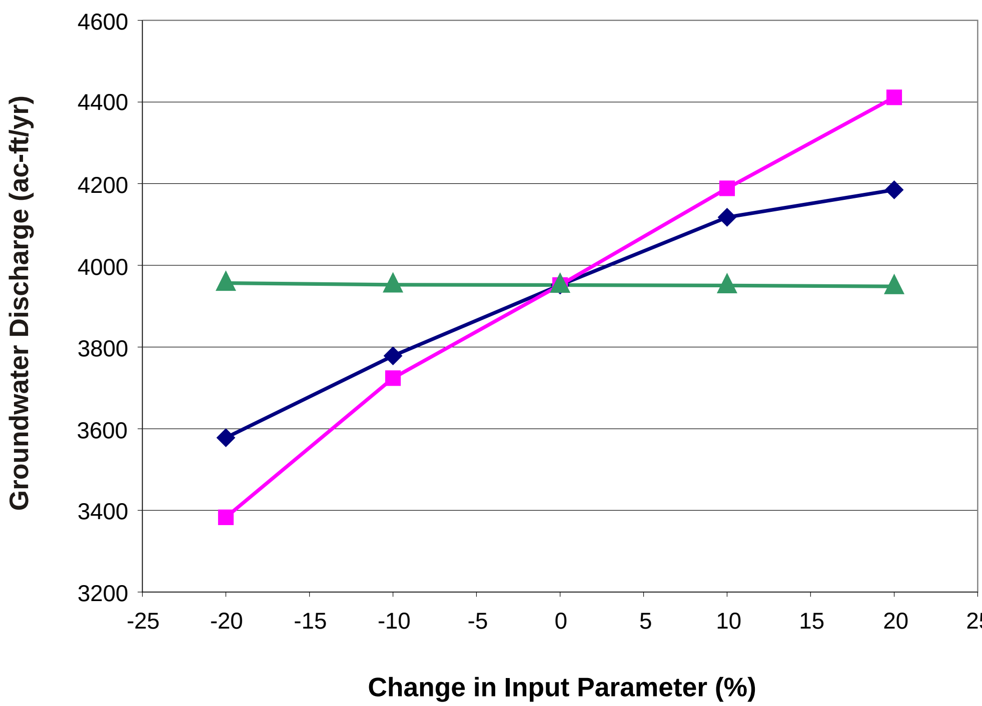
Changes of 10 percent to both hydraulic conductivity and recharge produced similar calibration statistics to those of the calibrated model. Changes of 20 percent caused the RMSE to increase by a foot or more.

Adding 50 ft to the prescribed hydraulic heads along the eastern escarpment decreased outflow along this boundary by about 19 percent and increased outflow at interior springs by about 16 percent (Table 4). Reducing the prescribed hydraulic heads along the eastern escarpment had only a small effect on outflows along the escarpment (increase of 3 percent), but decreased outflows at interior springs by about 7 percent.

Transient Model

The transient model simulates water levels in the aquifer for the period 1940 through 2000. Initially, the period 1991 through 2000 was reserved to be used as a model verification period, but in the process of trying to minimize the number of dry cells that occurred during the transient calibration, water level observations from the longer period were used during model calibration. Model verification was still conducted by comparing the simulated water levels to observed values for the entire period of record. Again, hydrographs for ten wells distributed throughout the study area (eight of which have monthly observations) but not used for model calibration were used for the model verification.





Explanation

- Hydraulic conductivity
- Recharge
- Drain conductance

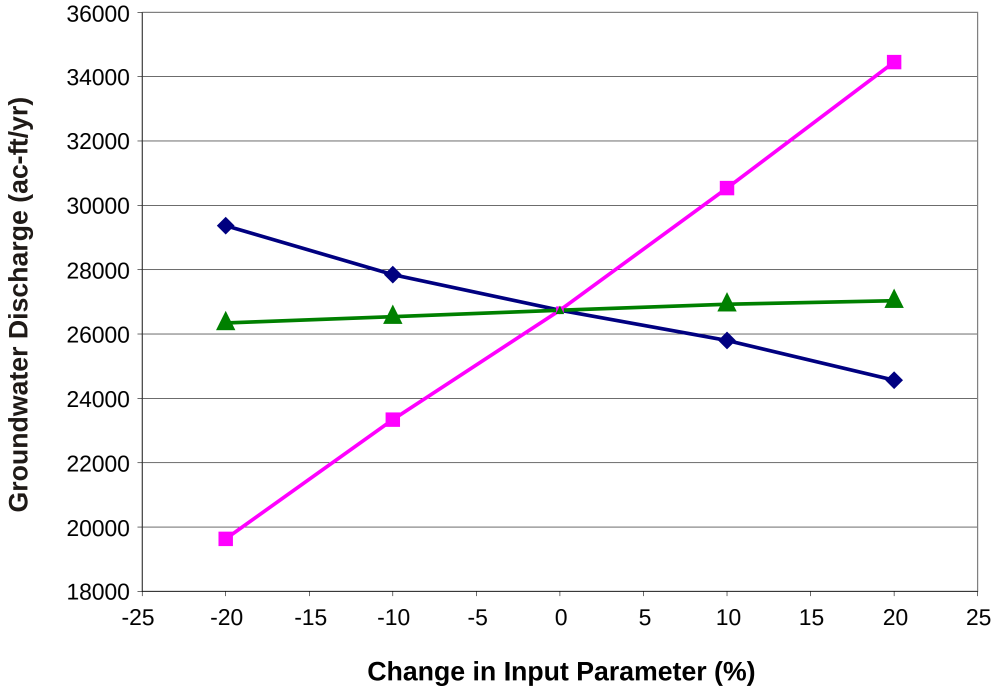
SOUTHERN OGALLALA GAM

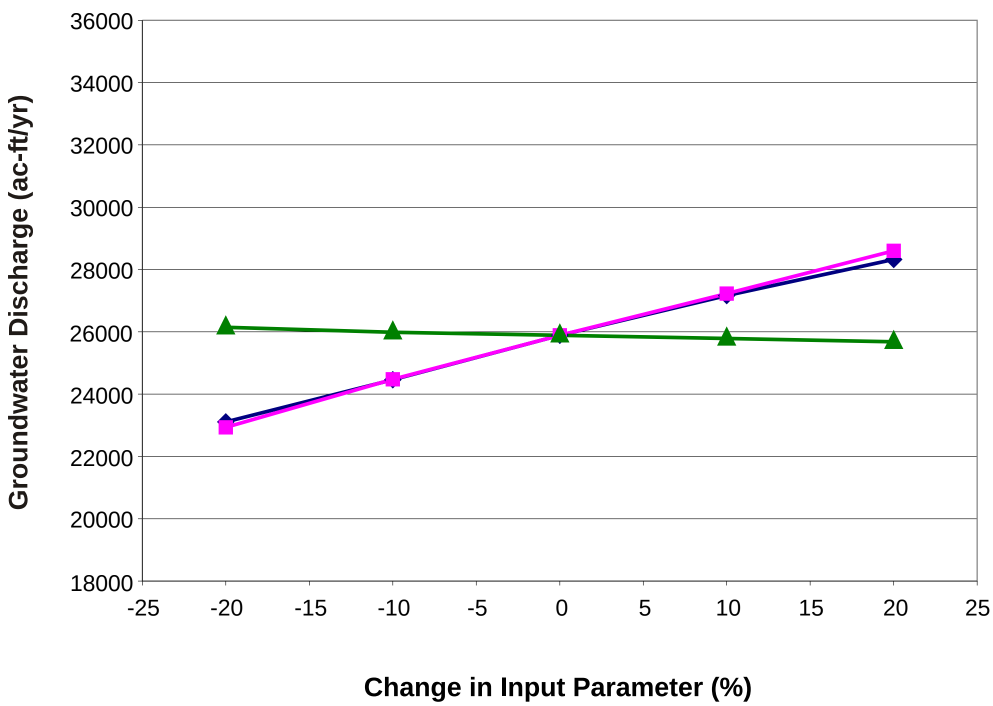
Average Head Difference at Calibration Points and Groundwater Discharge Out of the Northern Prescribed Head Boundary for Predevelopment Model Sensitivity Runs

VDR\0-VDR-PROJECTS\93451\934589b.CDR

2-03-03

Figure 55





Explanation

- Hydraulic conductivity
- Recharge
- Drain conductance

VDR10-VDR-PROJECTS\93451\934591b.CDR

SOUTHERN OGALLALA GAM

Total Discharge from Interior Springs and Groundwater Discharge at Eastern Escarpment for Predevelopment Model Sensitivity Runs

2-03-03

Table 4: Results of Boundary Head Sensitivity Analysis

Measure	Discharge (ac-ft/yr) BH Increased	Calibration Run	BH Reduced
Northeastern boundary	3,494	3,952	4,104
Eastern escarpment	21,646	25,889	27,732
Interior springs	31,176	26,804	24,860
Average difference in hydraulic head (ft)	7.1	0	–1.6

BH = Boundary head

Simulation results from the steady-state model were used as initial conditions for the transient model. Boundary conditions in the transient model were the same as those in the steady-state model except on the eastern and northern boundaries:

- The prescribed head cells along the eastern escarpment were changed to drain cells to allow changes in simulated outflow as simulated hydraulic head in the aquifer changed through time. The conductance for the drain cells was back-calculated from the simulated outflow at each cell obtained from the steady-state model, and the drain elevation was set to 1 ft above the base of aquifer for the model cell.

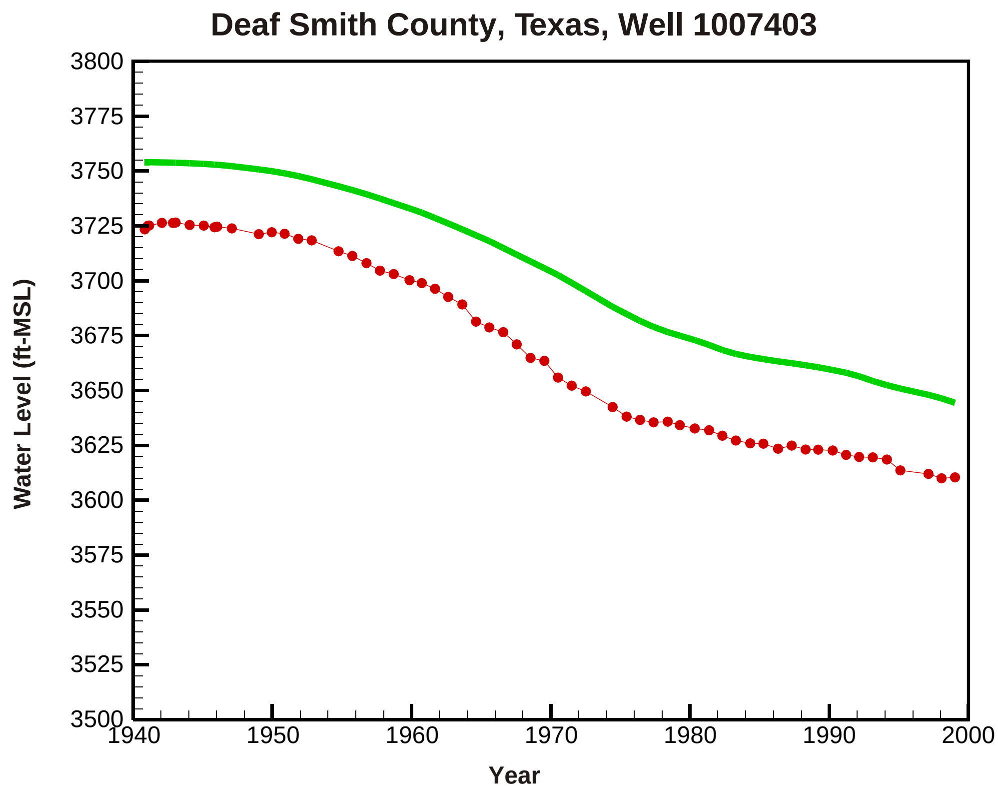
- The prescribed hydraulic heads along the northern model boundary west of Amarillo were changed through time to represent observed changes in water levels in that area.

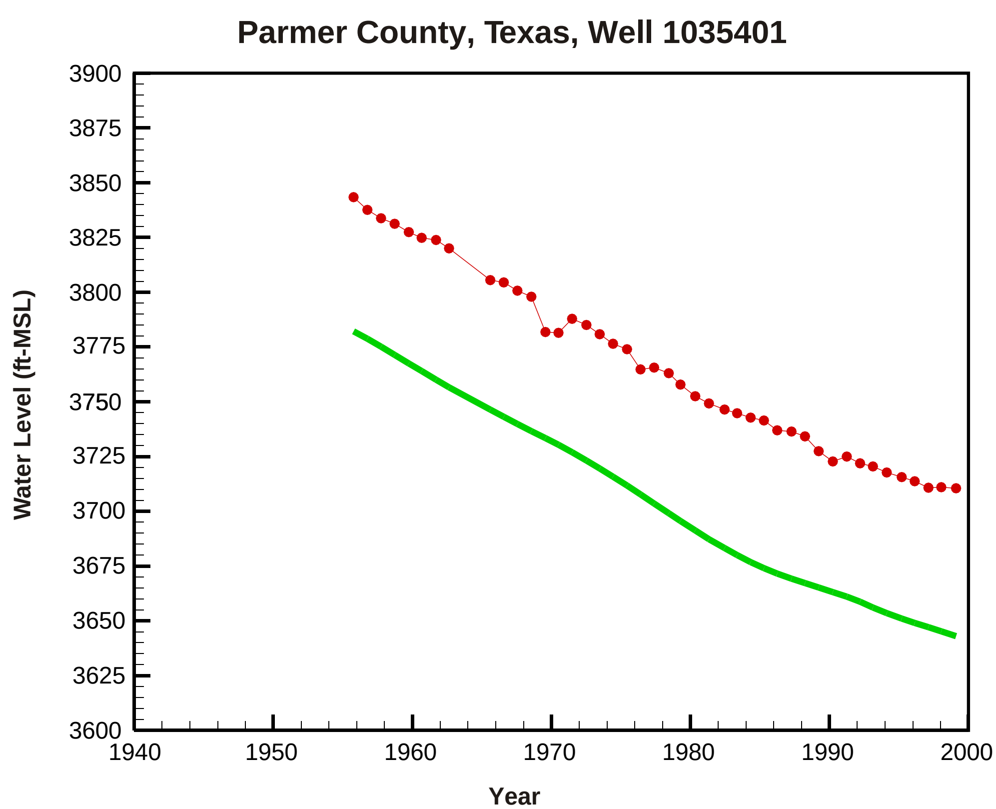
Pumping was applied in the model as presented in previous sections. Annual pumping for each pumping category is provided in Appendix C.

Calibration Results

Calibration of the transient model was completed by adjusting model input parameters to obtain a reasonable match between simulated and observed water levels at 80 wells (each with substantial periods of record) distributed throughout the study area (fig. 24). Once the calibration to the 80 hydrographs was essentially complete, the calibration was checked using scatter plots of simulated and all observed water levels for the winters of 1979-1980, 1989-1990, and 1999-2000, referred to as 1980, 1990, and 2000, respectively. The simulated and observed water levels of each of the 80 hydrographs used in the transient calibration are provided in Appendix D.

Several examples of simulated hydrographs from throughout the study area, along with observed water levels, are provided in Figures 57 through 60. The location for each of these hydrographs is provided in Figure 24. As illustrated in the figures, a good match between simulated and observed water levels was obtained for regions of significant drawdown (e.g., Deaf Smith, Parmer, Castro, and Hale Counties), regions of fairly stable water levels (e.g., Terry and Gaines Counties), and in regions of rising water levels (e.g., Dawson and Garza Counties). The goal of the transient simulation was to match the trends in observed water levels through time. The starting points for the simulated water levels are generally different from the observed data because they were taken from the predevelopment modeling results.





Explanation

Observed water level

Simulated water level

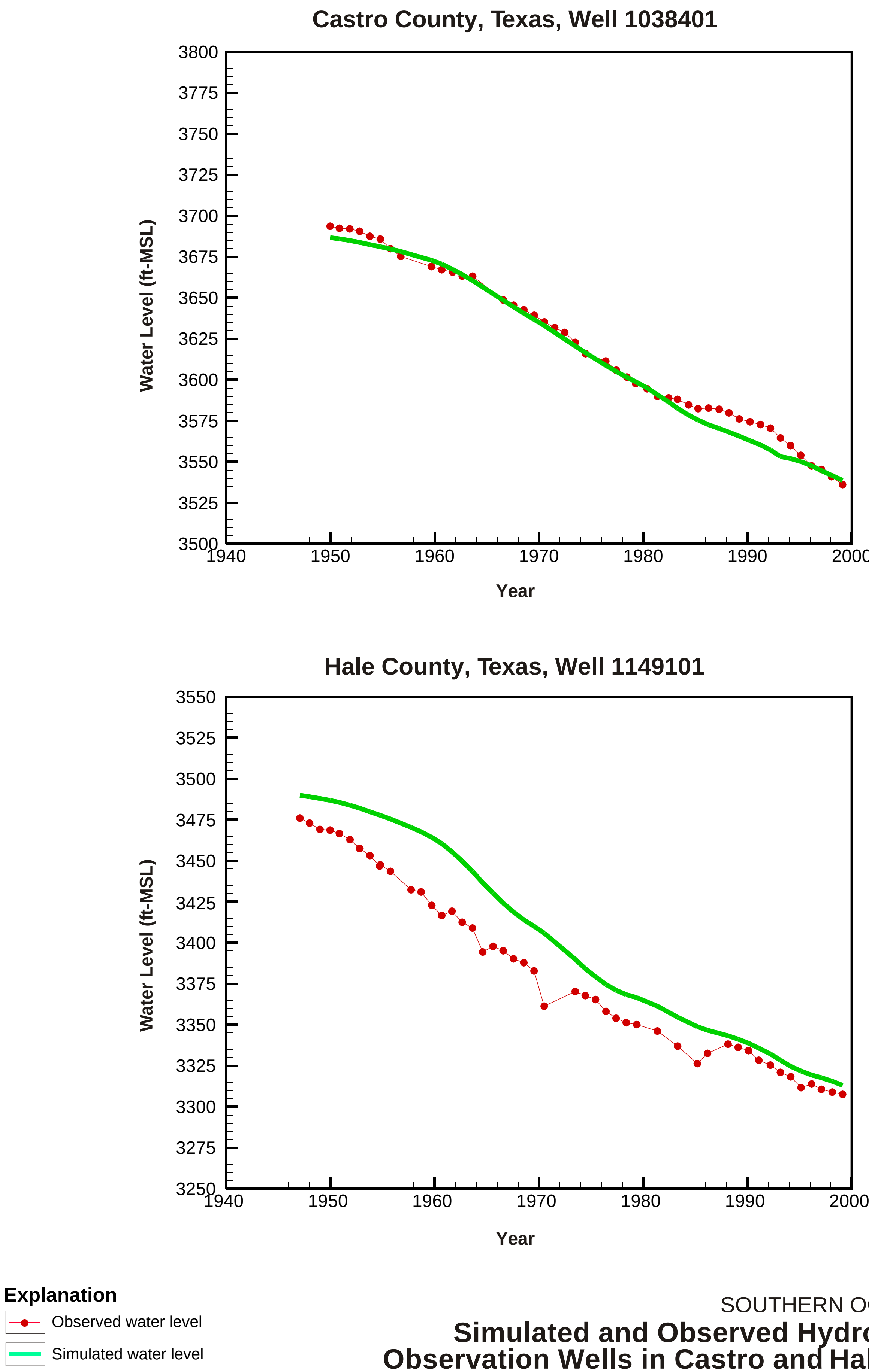
SOUTHERN OGALLALA GAM

Simulated and Observed Hydrographs for Observation Wells in Deaf Smith and Parmer Counties

VDR\0-VDR-PROJECTS\9345\934580b.CDR

1-30-03

Figure 57



SOUTHERN OGALLALA GAM

Simulated and Observed Hydrographs for Observation Wells in Castro and Hale Counties

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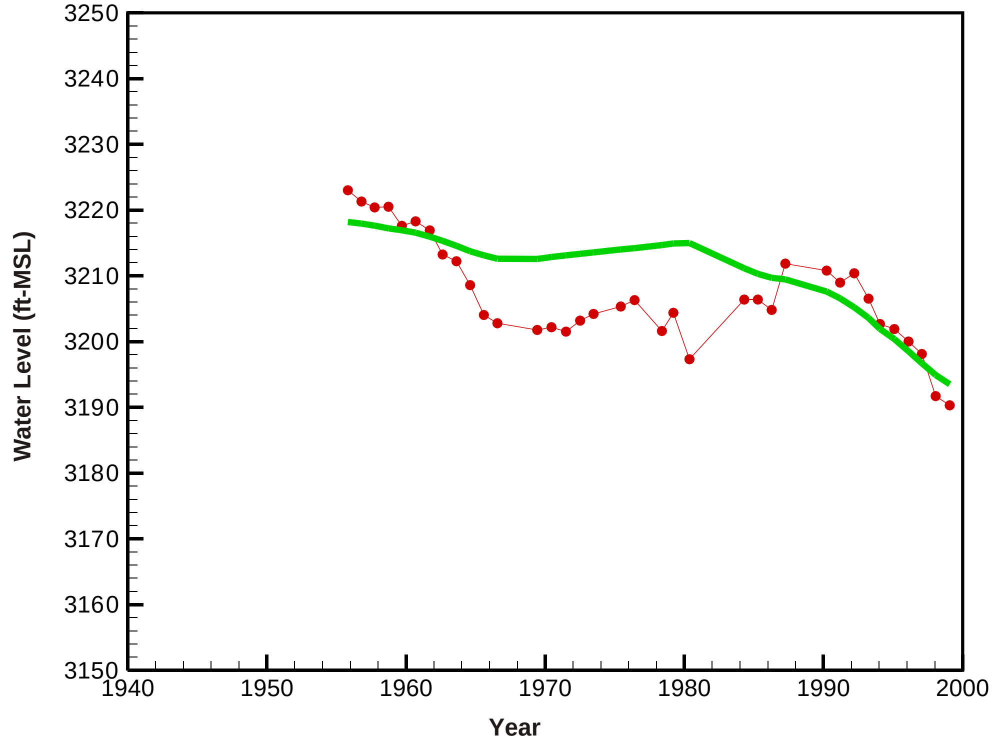
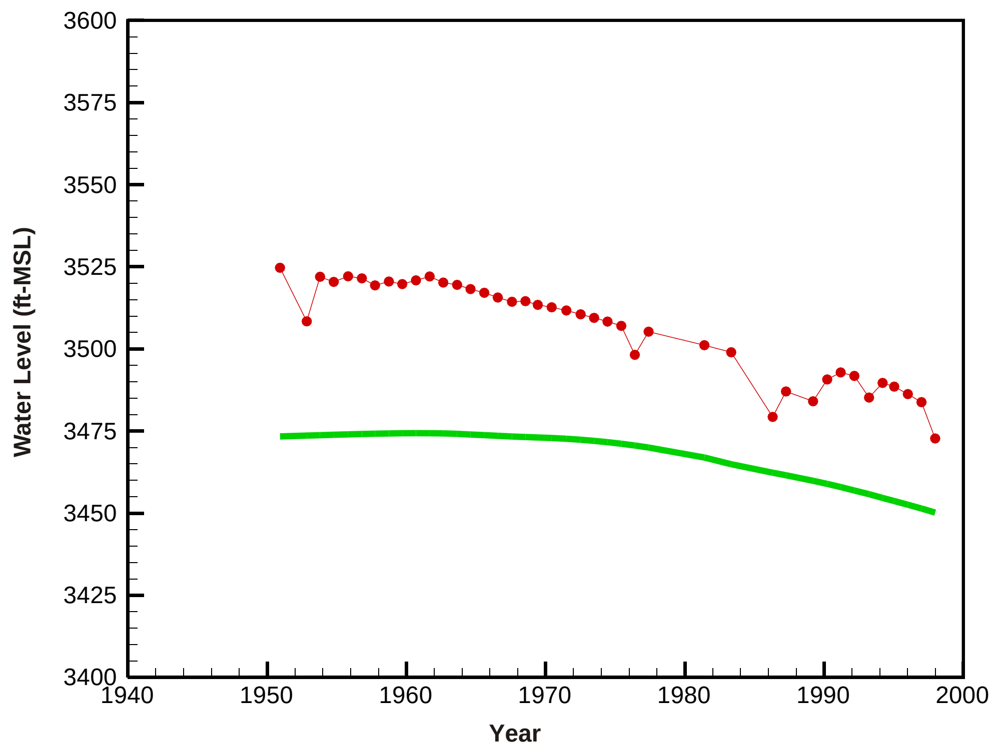
1-30-03

Figure 58

Terry County, Texas, Well 2454901



Gaines County, Texas, Well 2624307



Explanation

Observed water level

Simulated water level

VDR10-VDR-PROJECTS\9345\934583b.CDR

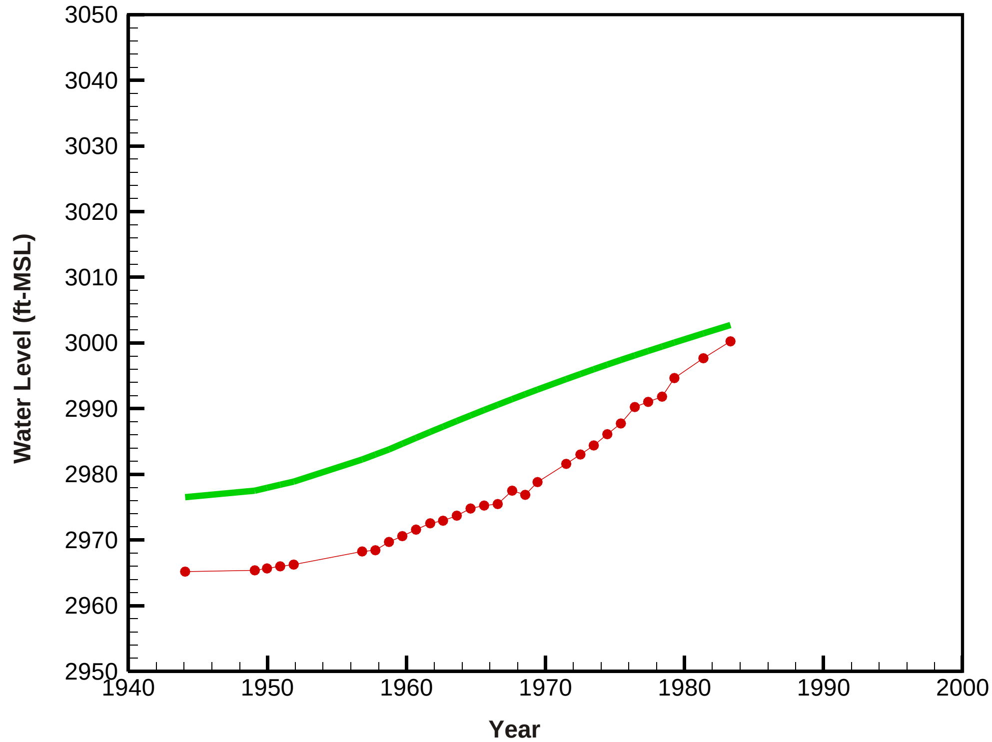
SOUTHERN OGALLALA GAM

Simulated and Observed Hydrographs for Observation Wells in Terry and Gaines Counties

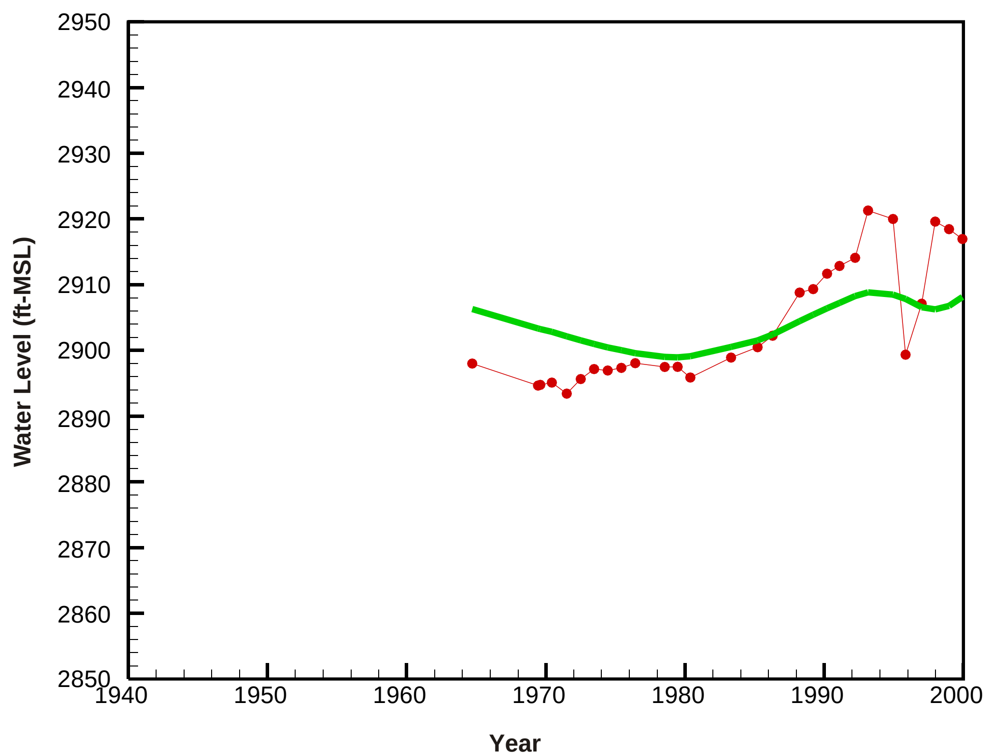
1-30-03

Figure 59

Dawson County, Texas, Well 2802702



Garza County, Texas, Well 2344904



Explanation

- Observed water level
- Simulated water level

SOUTHERN OGALLALA GAM

Simulated and Observed Hydrographs for Observation Wells in Dawson and Garza Counties

VDR10-VDR-PROJECTS\93451\934582b.CDR

1-30-03

Figures 61 and 62 illustrate the calibration scatter plots and associated calibration statistics for 1990 and 2000, respectively. The RMSE is 47 ft and 44 ft for 1990 and 2000, respectively, and the RMSE divided by the range in observed hydraulic head values is about 2 percent for both years. These values are greater than the equivalent calibration statistics obtained for the predevelopment model calibration, probably due to (1) the increased variability in observed water levels due to pumping and (2) the greater number of observed water levels available for later times. The RME is –5 ft for 1990 and –9 ft for 2000, indicating that overall, simulated hydraulic heads are slightly greater than observed values. Although not presented, the scatter plot and calibration statistics for 1980 are similar to those for 1990 and 2000.

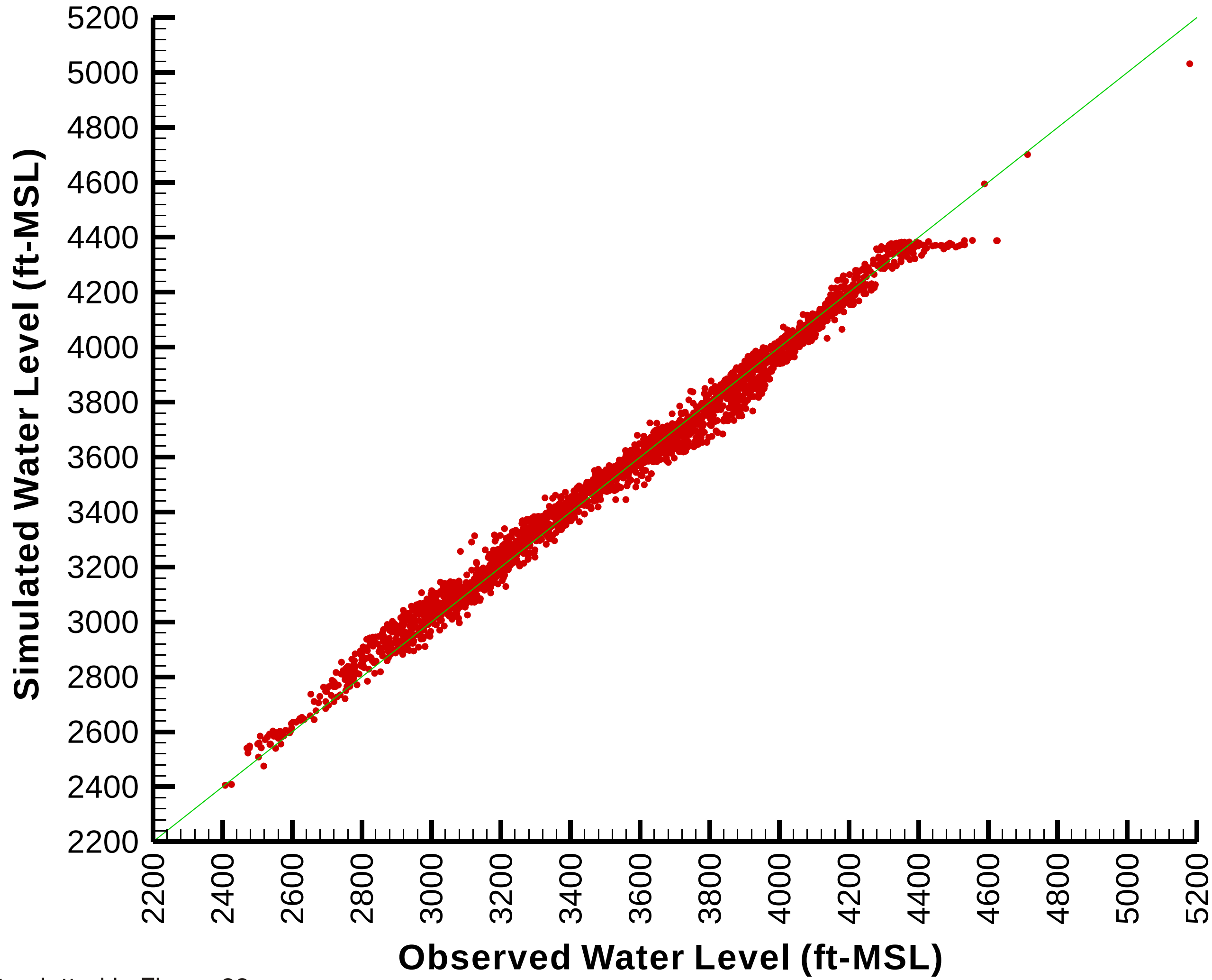
To evaluate the match between observed and simulated water levels, calibration statistics were also determined for each hydrograph. The RMSE of the hydrographs ($RMSE_{hyd}$) was determined in the same manner as the RMSE, except that (1) the observed values change with time for a given location and (2) the simulated values were adjusted at each location to remove inherent bias caused by the starting water level obtained from the predevelopment simulation. The latter point is illustrated by the simulated and observed hydrograph for well 1035401 in Parmer County (bottom graph in fig. 57). At this location, the starting head at the beginning of the observation record is about 50 ft low. In order to obtain a measure of how well the trends in the observed water levels are replicated by the model, approximately 50 ft was added to each simulated water level during the period of record shown, and the $RMSE_{hyd}$ was calculated using the adjusted simulation results. The resulting $RMSE_{hyd}$ is 3.8 ft for this well, indicating a very good match to the observed trend in water levels at this location. The $RMSE_{hyd}$ for the unadjusted simulated hydrograph would be much greater.

The combined $RMSE_{hyd}$ for all of the hydrographs is 30.5 ft, which is less than the RMSE calculated for 1990 and 2000 (figs. 61 and 62) because the simulated water levels were adjusted as described above. The $RMSE_{hyd}$ varies from a low of 2 ft to a high of 96 ft for individual wells, although 84 percent of the wells have an $RMSE_{hyd}$ less than 30 ft. The largest $RMSE_{hyd}$ values occur for observation wells in Floyd and Crosby Counties, where the initial water level is simulated reasonably well but historical drawdowns are significantly underestimated. A complete listing of the $RMSE_{hyd}$ calculated for each observation well hydrograph is provided in Appendix D.

Simulated directions of groundwater flow and hydraulic gradients are similar to the observed 2000 values for most of the study area (fig. 63). Figure 63 also illustrates model cells that are “dry,” where the simulated water level fell below the bottom of the aquifer at some point during the simulation, and model cells that are “flooded,” where the simulated water level is above the land surface elevation for the cell. Relatively small (with respect to the size of the entire model) areas of dry cells occur in southern Parmer and northern Bailey Counties in Texas and in southeastern Curry and northeastern Roosevelt Counties in New Mexico, which are regions of significant agricultural pumping (fig. 24). Numerous attempts were made to eliminate these regions of dry cells in the model, but they persisted unless unreasonable cutbacks in irrigation pumping or increases in recharge were made. Other occurrences of dry cells are very localized. Overall, slightly less than 3 percent of the total number of active model cells become dry by the year 2000.

Simulation results in the regions of dry cells were investigated in detail using the simulated hydrographs provided in Appendix D. Hydrographs Curry 3, Parmer 4, Potter 1, and Yoakum 4 occur in model cells that go dry prior to the end of the simulation. For the most part, the simulated regions of dry cells occur where starting hydraulic heads in the model are lower than the observed water levels, due to the results of the steady-state simulation. At other areas where dry cells occur yet the starting heads are not low, the saturated thickness of the aquifer is relatively thin.

In all cases, the difference between the simulated water level and the base of the aquifer (i.e., the simulated saturated thickness), and in



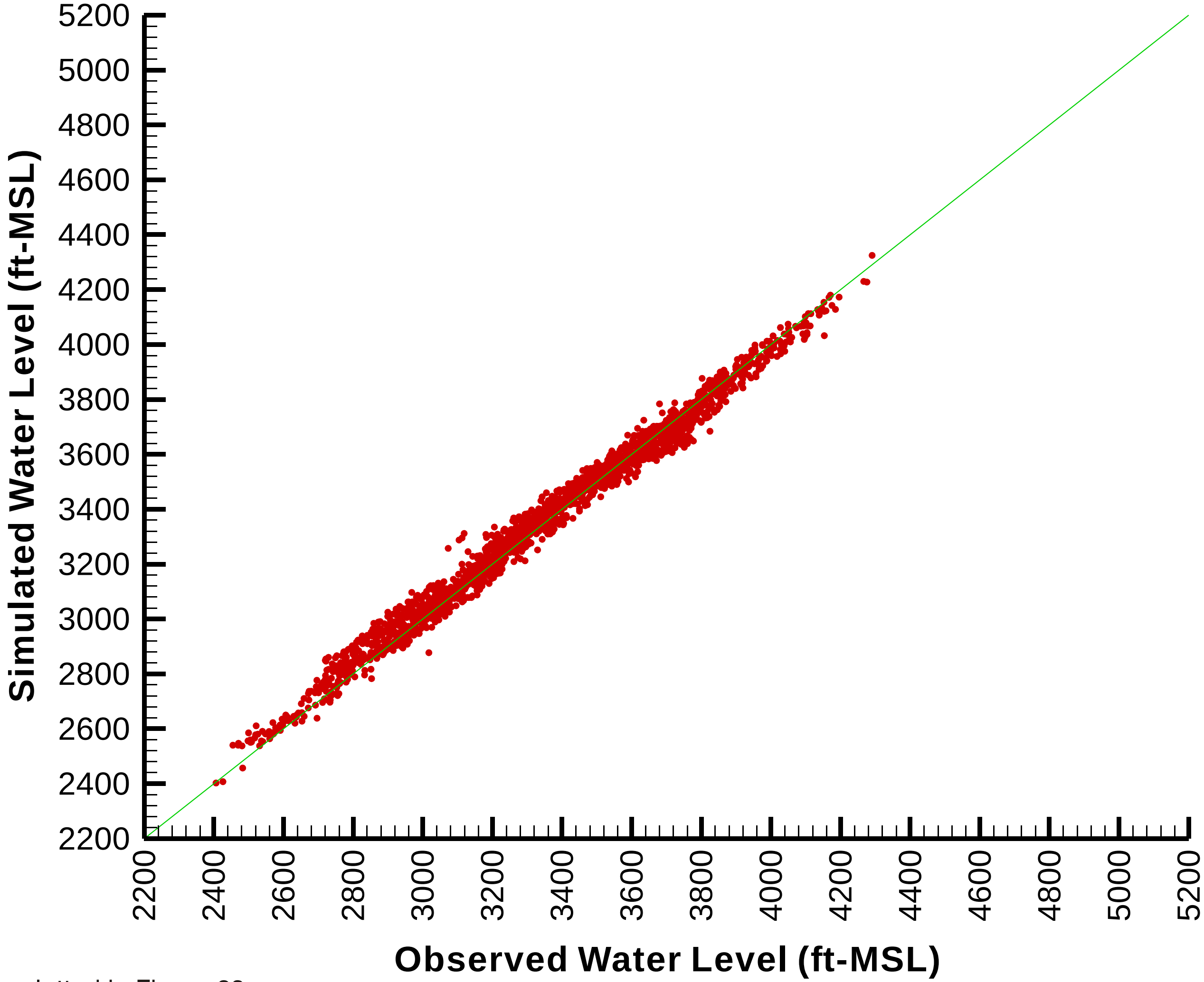
Note:
Observed data points plotted in Figure 22

Calibration Statistics
RMSE: 47 ft
MAE: 36 ft
RME: -5 ft
RMSE/Range: 1.7%
High: 189 ft
Low: 239 ft

SOUTHERN OGALLALA GAM

Simulated vs Observed Hydraulic Heads for 1990

Figure 61



Note:

Observed data points plotted in Figure 23

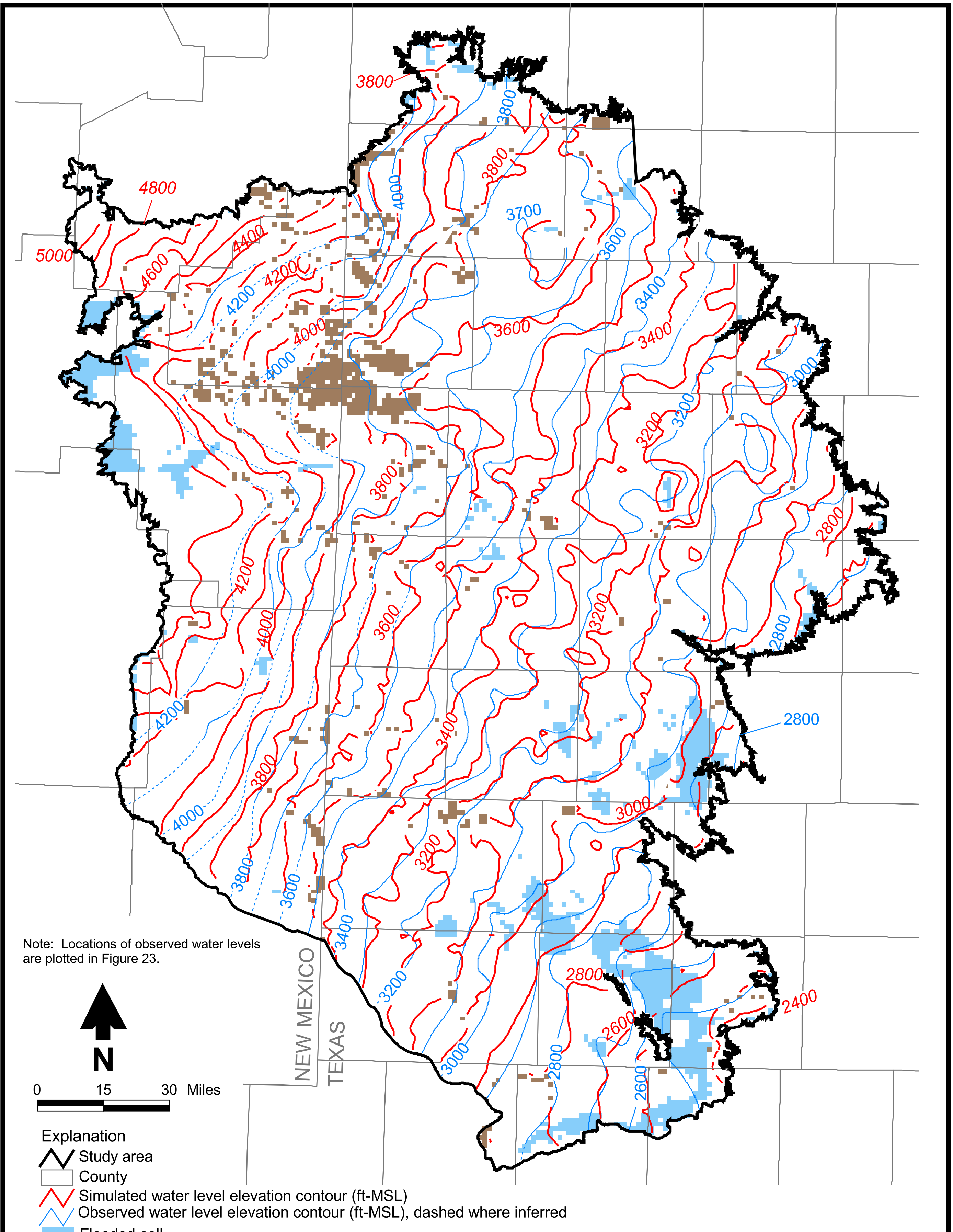
Calibration Statistics

RMSE: 44 ft
MAE: 34 ft
RME: -9 ft
RMSE/Range: 2.3%
High: 193 ft
Low: 141 ft

SOUTHERN OGALLALA GAM

Simulated vs Observed Hydraulic Heads for 2000

Figure 62



SOUTHERN OGALLALA GAM

Simulated and Observed Year 2000 Water Levels

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1-30-03

Figure 63

many cases the difference between the observed water level and aquifer base elevation (i.e., the actual saturated thickness), is less than the RMSE of the simulation results (i.e., 44 to 47 ft). For example, the model cell that contains the Parmer 4 observation well (well 948301 in Figures 24 and 25 and Appendix D) goes dry at about 1995. At that point in time, the actual saturated thickness (the difference between the base of the aquifer and the observed water level) is about 85 ft. However, at the beginning of the simulation, the simulated water level at this well is about 85 ft below the observed water level. Therefore, even though the simulated decline in water level at this location is quite accurate, the model cell goes dry because the starting hydraulic head was low. There is no way to avoid this problem without making numerous local adjustments to the predevelopment model, which would lead to substantial "over-calibration" of the model due to the lack of observed data for model input parameters.

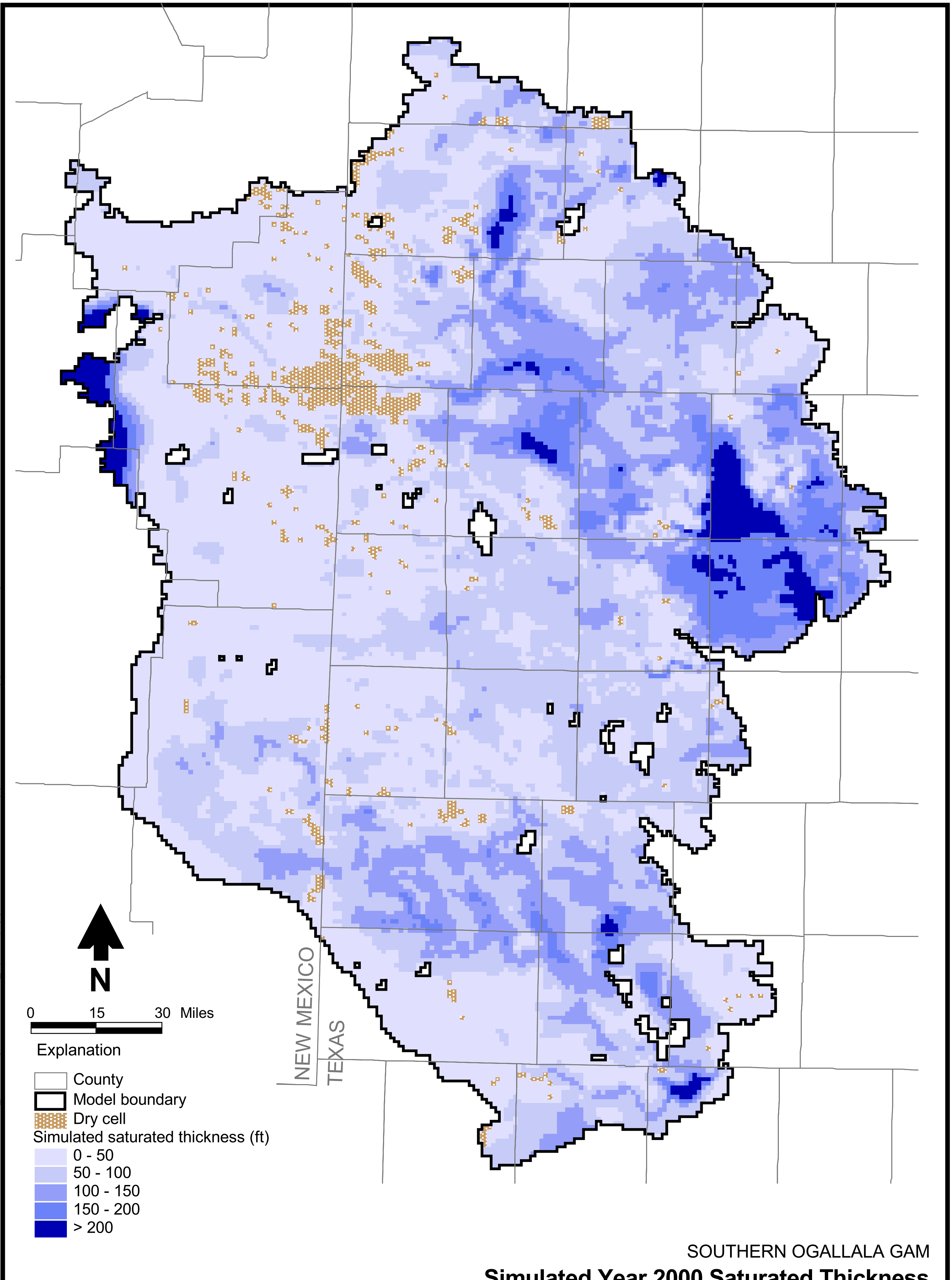
Isolated areas of flooded cells in the central and northern portion of the study area generally occur near salt lakes, draws, and the eastern escarpment, where land surface elevations change significantly over short distances. Flooded cells in these areas are, for the most part, artifacts caused by averaging the land surface elevation to get an average value for the model cell. The flooded cells in New Mexico along the far western model boundary occur in regions where the bottom elevation of the aquifer and other aquifer properties are virtually unknown, and are thus likely caused by inaccuracies in the model input parameters in these areas. For much of the southern regions where flooded cells occur, such as in southern Dawson County and northern Martin County (fig. 63), depths to water are again generally similar to or less than the RMSE of the model calibration. For example, depths to groundwater in the regions where flooded cells exist in the model are reported to be 40 ft or less (Calhoun and others, 2002, Figure 5). Therefore, even though simulated hydraulic head values are within the overall accuracy of the model, simulated heads can occur above land surface.

These anomalies do not mean that the model is any less accurate in these areas; it is still appropriate for simulation of relative changes in water levels through time. For example, simulated trends in water levels match the observed trends very well for two observation wells in Martin County, although the simulated values are higher than observed values by about 50 to 60 ft.

The largest region of flooded cells occurs in northeastern Martin and western Howard Counties. In this area, simulated water levels are significantly greater than land surface. This is a low topographic region that contains Sulphur Springs Draw and a series of salt lakes and is adjacent to two elongated regions where the aquifer does not exist (fig. 33). Although data for this area are limited, observed water levels appear to be relatively close to land surface. For example, well 2852702 in southwestern Howard County is within the region of flooded cells illustrated in Figure 63. The observed water level in this well was 9 ft below land surface in 1936, and was reported to be at land surface in the late 1980s. However, only two water level observations are available for this well, so it is not known if the 1980s value is a measurement or data entry error.

Water levels have risen through time to within about 40 ft below land surface (within the RMSE of the model) in well 2860402 in Glasscock County, due south of well 2852702 along the Howard-Glasscock county line. It is likely that the local hydrogeology of this particular area is not well understood and may not be well represented in the model. Simulated water levels on either side of this region, however, are reasonable (i.e., central and western Martin County and eastern Howard County). Because this region is far removed from major areas of pumping and has limited observed data and no significant groundwater withdrawals (in terms of volume), further analyses and model refinements were not warranted.

The simulated saturated thickness for the year 2000 is less than 100 ft through much of the study area (fig. 64). The greatest saturated thicknesses generally occur in the northern portion of the study area in portions of Deaf



SOUTHERN OGALLALA GAM

Simulated Year 2000 Saturated Thickness

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Figure 64

Smith, Castro, Lamb, Swisher, Hale, Floyd, and Crosby Counties. The simulated saturated thickness is overestimated in Floyd and Crosby Counties because historical drawdown is underestimated in this area (although simulated trends at later times agree well with observed data).

The simulated drawdown from predevelopment conditions (fig. 65) matches general observed trends of large water-level declines in the northern counties, smaller declines or stable water levels throughout many of the central and southern counties, and water level rises in some of the southeastern counties.

Model Parameters

The transient model calibration was accomplished by adjusting specific yield, irrigation return flow percentage, agricultural pumping volume, and enhanced recharge beneath agricultural lands. Some adjustments to hydraulic conductivity were investigated but not applied in the final transient model.

Adjustments to specific yield and irrigation return flow were very limited, and their final values were set (in accordance with available field data and other studies) very early in the calibration process. Specific yield is illustrated in Figure 48, and applied irrigation return flow, as a percent of water pumped, is provided in Table 1.

Adjustments to estimated pumping for irrigated agriculture were also limited. Estimated agricultural pumping for 1969, 1975, and 1980 for Roosevelt, Curry, and Quay Counties in New Mexico was decreased by 25 percent from published values (see Pumping for Irrigated Agriculture section). This was done because estimates of pumping for these years, as determined by the New Mexico Office of the State Engineer using climatic data and crop irrigation requirements, were substantially higher than estimated pumping for both earlier years, as derived by the USGS using power records and well efficiency data, and later years, as derived by Amosson and others (Appendix B), who used a similar but updated approach.

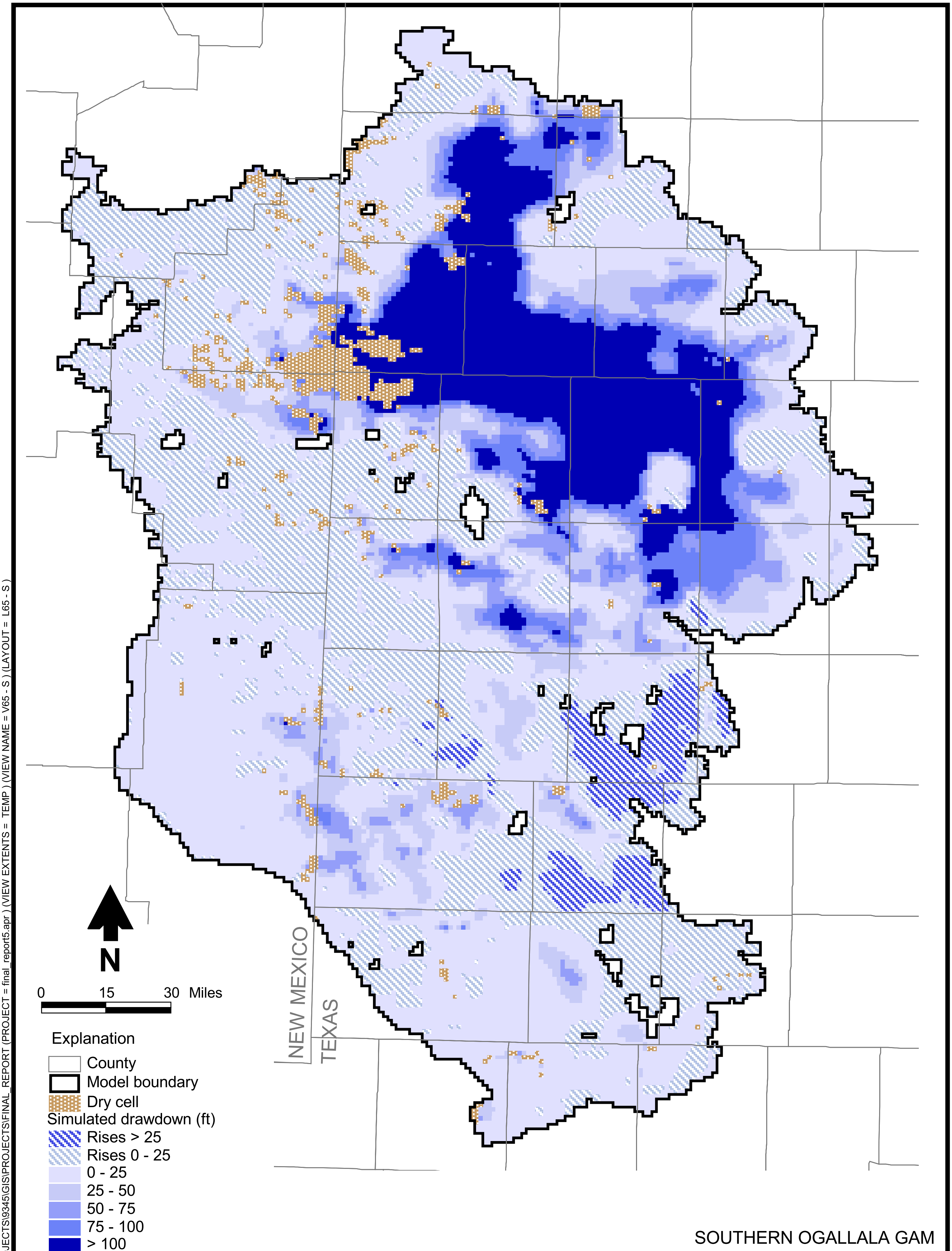
In Texas, estimated pumping for 1974 in Yoakum and Terry Counties was reduced because it was substantially greater than estimated values for the adjacent 5-year periods in the agricultural surveys, although annual rainfall was similar between periods for each respective county. Adjustments were made by determining an average application of water per acre, based on the adjoining survey periods, and using the factor to calculate use in the year in which pumping was reduced. The 1974 irrigated acreage for Yoakum County was multiplied by 0.9 acre-feet per acre (ac-ft/ac) to obtain 92,106 ac-ft of pumping (down from 138,651 ac-ft), and the acreage for Terry County was multiplied by 0.38 ac-ft/ac to obtain 65,827 ac-ft of pumping (down from 145,570 ac-ft). In addition, based on Rettman and Leggat (1966), the 0.7 factor was still applied to estimated historical pumping in Yoakum and Gaines Counties as described in the Discharge section.

Similar adjustments were made to estimated agricultural pumping for Cochran County for 1958 and 1964. Estimated acreage for Cochran County for these years was multiplied by the factor 0.8 ac-ft/acre to obtain 52,480 ac-ft for 1958 (down from 108,784 ac-ft) and 70,880 ac-ft for 1964 (down from 125,266 ac-ft).

All of the Texas counties where agricultural pumping adjustments were made are in the south-central portion of the study area, where pumping is often limited due to aquifer characteristics.

In addition to the above changes, the estimated agricultural pumping determined by Amosson and others (Appendix B) was reduced by 10 percent for the 1980s and 1990s in the west-central counties of Bailey, Lamb, Cochran, Hockley, Yoakum, Terry, and Gaines because simulated water level declines in these areas tended to be greater than observed values. The 10 percent reduction in pumping was the maximum amount that was considered reasonable for these areas.

Although all of the adjustments described above assisted with calibration of the transient model, the major calibration parameter for the transient simulation was enhanced recharge beneath irrigated and non-irrigated agricultural lands. Recharge applied to other land uses (primarily rangeland) was maintained at predevelopment rates. The term enhanced



SOUTHERN OGALLALA GAM

Simulated Drawdown from Predevelopment to Year 2000

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1-30-03

Figure 65

recharge refers to an increase in recharge from precipitation from predevelopment to post-development conditions. This recharge component is separate and distinct from irrigation return flow.

Numerous combinations of recharge rates and application methodology (based on soil type and land use) were applied. The final recharge distribution for the transient simulation is provided in Figure 66. It was assumed that enhanced recharge was (1) greater beneath regions of higher-permeability soils than regions with lower-permeability soils and (2) greater beneath irrigated fields than beneath non-irrigated fields.

As illustrated in Figure 66, applied recharge in the transient model ranges from 2.25 in/yr under irrigated agricultural lands with high-permeability soils down to 0.25 in/yr for non-irrigated agricultural lands in regions with low-permeability soils, lesser amounts of average annual precipitation, or fairly steady observed water levels through time. The distribution of recharge in Figure 66 is a combination of land use and soil factors (figs. 38 and 7, respectively) and calibrated recharge rates based on observed water levels. A summary of how the transient model recharge was applied is provided in Table 5.

For the most part, the recharge distribution provided in Figure 66 and Table 5 is a function of land use and soil type. However, some values were assigned on a regional basis, such as increased recharge under non-irrigated agricultural lands in Lynn, Dawson, Garza, and Borden counties. Applied recharge was greater in these counties to simulate observed rises in water levels, but it is unknown why recharge in these counties is apparently larger than recharge in adjacent areas with similar average annual precipitation and soils. Consequently, although changes in recharge will obviously not occur precisely along county boundaries, a suitable alternative for prescribing changes in recharge in this area could not be identified.

Water Budget

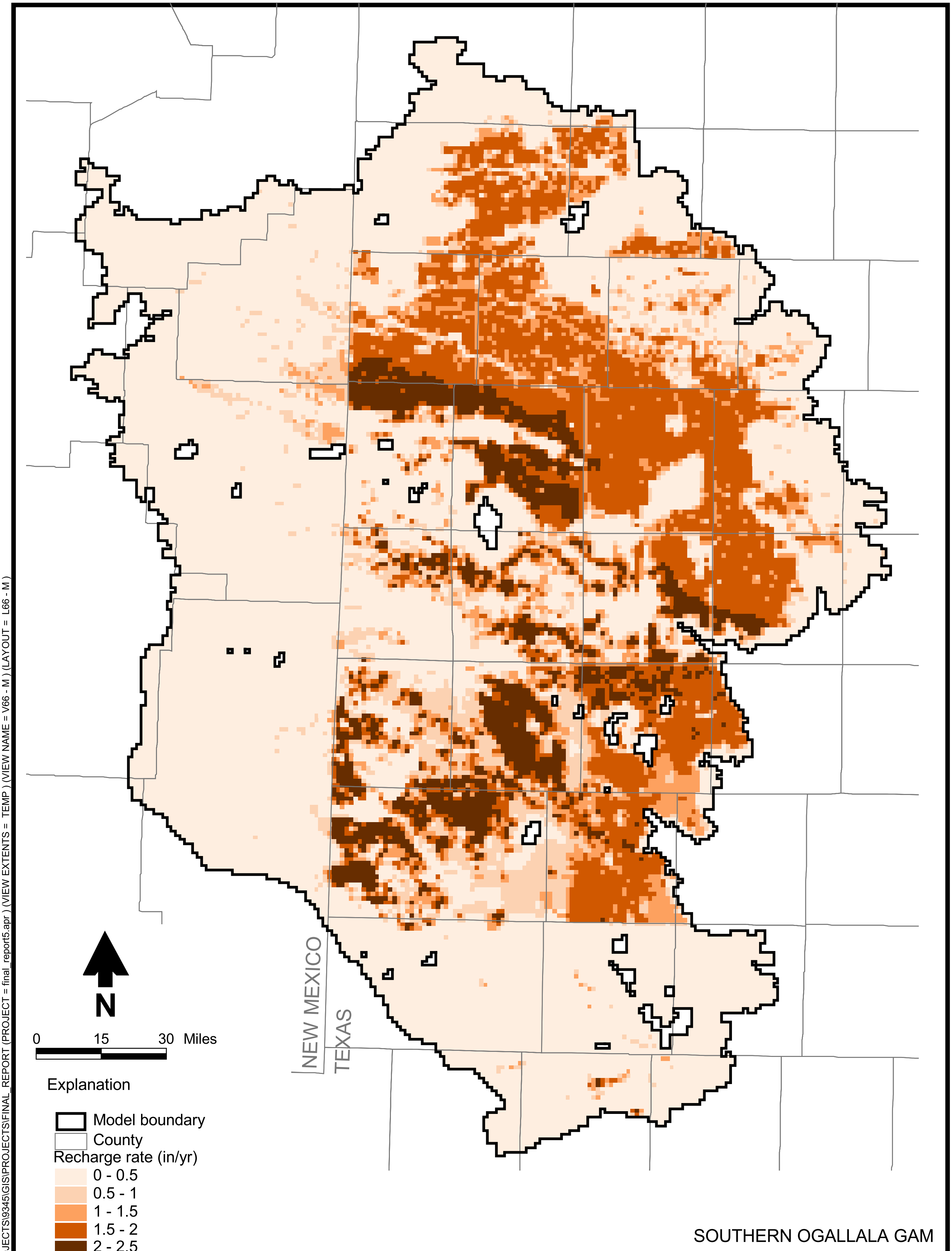
The simulated water budgets for 1980, 1984, 1990, and 2000 are provided in Table 6. According to the GAM protocol, 1980 is the beginning of the transient calibration period, 1990 is the beginning of the model verification period, and 2000 is the end of the transient simulation and the verification periods. The year 1984 is included in Table 6 because it is the last year in the three-year period of drought that occurred during the 1980s (Appendix B).

Table 5: Recharge Applied in Transient Model

	Applied Recharge (in/yr) / Location [b]	
Soil Permeability [a]	**Irrigated Agriculture [c]**	**Non-Irrigated Agriculture [c]**
High	2.50 / TX	1.0 / TX [d]
	1.75 / NM	0.5 / NM
		2.0 / TX [e]
Medium-high	2.25 / TX	0.5 / TX [d]
	1.25 / NM	0.25 / TX [f]
		1.75 / TX [e]
		0.25 / NM
Medium low and low	1.75	0.25
		1.5 [e]

[a] Soil types illustrated in Figure 7
[b] TX = Texas
NM = New Mexico
[c] Land uses illustrated in Figure 38
[d] All Texas counties except as otherwise noted
[e] Lynn, Garza, Dawson, and Borden Counties
[f] In Andrews, Martin, Howard, Ector, Midland, and Glasscock Counties

The significant differences between the transient and predevelopment simulations are illustrated by examining the water balance for the year 2000. Total simulated inflows to the model for 2000 (the last stress period of the model) are 2,822,969 ac-ft/yr, and total outflows from the model are 2,822,927 ac-ft/yr, a difference of a small fraction of 1 percent. The majority of inflow, 63 percent, is from storage in areas where water levels are declining. The remainder of the inflow (37 percent) is from recharge. The recharge value, however, does not include irrigation return flow, as this was



SOUTHERN OGALLALA GAM

Post-Development Recharge Rates

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Figure 66

subtracted from the pumping values before they were input to the model. Irrigation return flow for 2000 is about 245,263 ac-ft/yr, or about 25 percent of the recharge actually prescribed in the model.

Table 6: Simulated Water Balance for Selected Years of Transient Simulation

Component	Amount (ac-ft/yr) 1980	1984	1990	2000
Inflows				
Prescribed head boundary	260	518	838	770
Recharge	1,065,498	1,059,798	1,055,432	1,032,905
Storage	1,731,157	2,698,587	1,405,128	1,789,293
Total inflows	2,796,915	3,758,903	2,461,398	2,822,969
Outflows				
Prescribed head boundary	1,361	1,179	1,064	913
Pumping	2,475,964	2,991,219	2,271,383	2,652,179
Springs and seeps	43,753	43,045	42,588	41,583
Storage	275,943	724,803	146,328	128,253
Total outflows	2,797,020	3,760,246	2,461,364	2,822,927
Percent error [a]	0.004	–0.036	0.001	0.001
Number of dry cells	357	431	511	842

ac-ft/yr = Acre-feet per year
[a] Calculated as: [(Total inflow – Total outflow) / Total inflow] x 100.

Table 6 also illustrates two additional important aspects of the simulation results:

- Simulated inflow from recharge decreases by about 3 percent from 1980 to 2000. This occurs due to the number of cells that go dry during the simulation. When a model cells goes dry (i.e., the simulated water level drops below the bottom elevation of the aquifer), all groundwater fluxes associated with that cell are removed from the simulation.

- Groundwater pumping and the corresponding depletion of aquifer storage are significantly larger during drought periods (e.g., 1984) than during other years.

The overwhelming majority of discharge, 94 percent, is from groundwater pumping, and most of the pumping is for irrigated agriculture. Approximately 1.5 percent of the discharge is to springs under post-development conditions, and about another 4.5 percent of discharge is water that goes into storage where water levels are increasing. Total simulated discharge from springs within the study area decreased about 28 percent from predevelopment conditions to 2000. Reductions in simulated spring flow are greater in the northern portion of the study area, where larger declines in water levels occur, and less in the southern portion of the study area, where water levels in many locations are relatively constant or increasing.

Average recharge over the entire study area (excluding irrigation return flow) is 0.65 in/yr. Average recharge over the northern part of the Texas portion of the study area, which is heavily irrigated (i.e., Deaf Smith, Randall, Parmer, Castro, Swisher, Lamb, Hale, Floyd, Lubbock and Crosby Counties), is about 1.0 in/yr. Although somewhat higher, these values are the same order of magnitude as the average recharge estimates for the northern part of the study area provided by Wood and Sanford (1995) (0.4 in/yr) and presented in Appendix A (0.31 in/yr).

Monthly Simulations and Model Verification

Monthly simulations, using monthly stress periods with four time steps per stress period, were conducted for the periods 1982 through 1984 and 1992 through 1994. Monthly values for irrigation pumping for these years are provided by Amosson and others (Appendix B). Estimates of monthly pumping for municipal and other uses during these years were obtained from average monthly pumping values available in observed data for each county basin. Livestock pumping was assumed to be evenly distributed throughout the year. Simulated water levels were compared to observed water levels at ten wells within the study area for which monthly water level observations were available (fig. 24). Two of the wells with monthly observations (well 342736103203701 in Curry County, New Mexico [Curry 1] and well 2739903 in Martin County, Texas [Martin 2]) were actually used during the model calibration process.

In addition to providing an indication of the model's ability to simulate monthly fluctuations in water levels, this comparison also serves as a model verification, because water level observations at eight of these ten locations were not used during the model calibration phase of the study. Simulated and observed water level plots for these eight locations (wells Cochran 4, Crosby 4, Floyd 5, Hale 4, Lamb 5, Lubbock 4 and Lubbock 5, and Yoakum 4) are provided in Appendix D along with the rest of the transient simulation results.

Figure 67 illustrates monthly simulation results at wells 2335706 and 1161407 in Lubbock and Floyd Counties, respectively. These hydrographs indicate that fluctuations in monthly water levels simulated by the model are reasonable, although the magnitude of the simulated changes is generally less than observed values. This result is to be expected, given the regional scale and relatively large cell size (1 mi^2) used in the model.

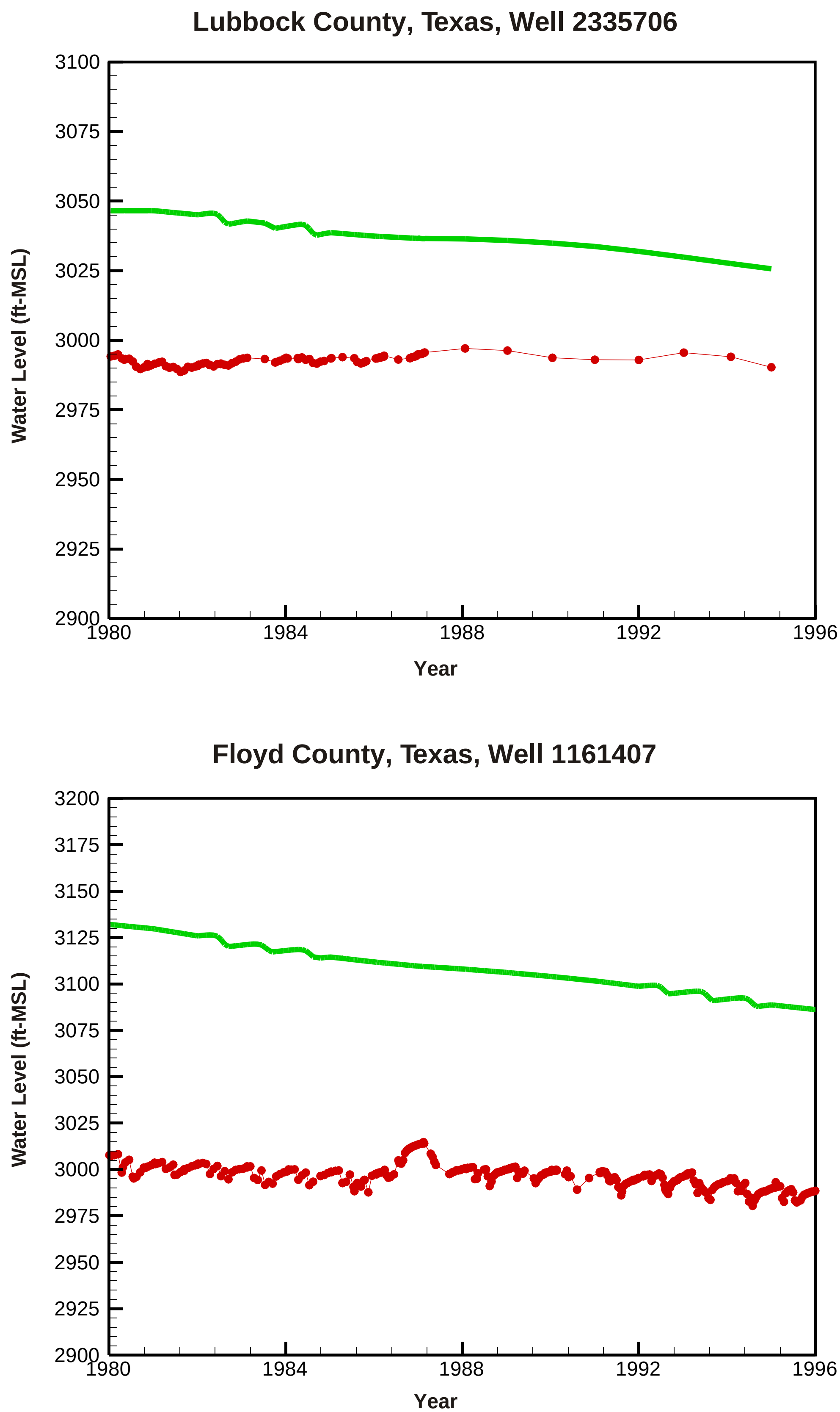
Sensitivity Analysis

Transient model sensitivity analyses were conducted for specific yield and timing of irrigation return flow. For specific yield, two sensitivity runs were conducted in which the calibrated model values were increased and decreased by 20 percent, respectively. As expected, lower specific yield generally caused larger drawdown and more dry cells as compared to the final transient calibration, and the higher specific yield had opposite effects. Figure 68 illustrates the effect of varying specific yield on simulation results at two observation wells, one in Briscoe County and one in Lamb County, Texas. For the Briscoe County well, changes in specific yield cause changes in simulated water levels of about 15 ft by the year 2000. For the Lamb County well, simulated differences are about 30 to 45 ft, probably due to larger amounts of agricultural pumping in the vicinity of this well.

The RMSE for each of the specific yield sensitivity runs was the same or slightly larger than that of the calibration run. The RMSE of the calibration run for 2000 is 44 ft, whereas the RMSE for the reduced and increased specific yield runs are 44 ft and 47 ft, respectively.

The RME for the calibration run is –9 ft, indicating that, on average, simulated hydraulic heads are higher than observed values for 2000. The RMEs for the reduced and increased specific yield runs are 0 ft and –16 ft, respectively. The reduced specific yield run yields simulated water levels that are, overall, lower than those in the calibrated model, while the increased specific yield run has the opposite effect. Although the reduced specific yield run provides similar calibration statistics to the calibrated model, a greater number of dry cells occur in the sensitivity run and a direct comparison of the calibration statistics is somewhat misleading.

The second sensitivity run conducted using the transient model was for irrigation return flow. In the calibrated model, irrigation return flow is assumed to reach the aquifer during the



Explanation

- Observed water level
- Simulated water level

SOUTHERN OGALLALA GAM

Simulated and Observed Hydrographs for Observation Wells in Lubbock and Floyd Counties

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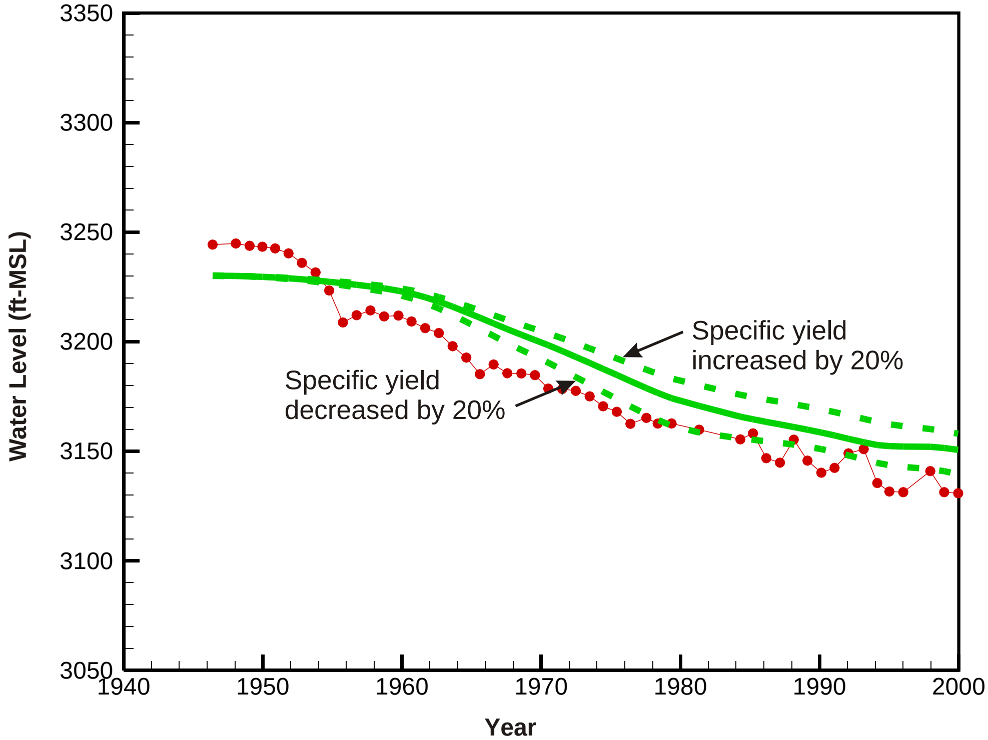
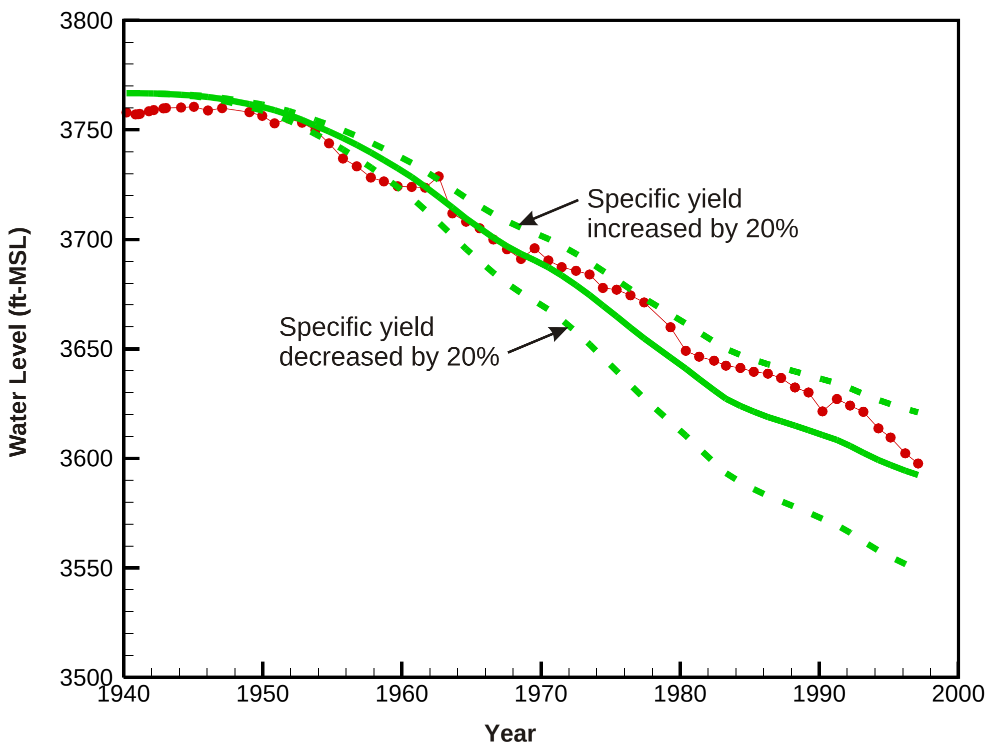
Figure 67

Briscoe County, Texas, Well 1137701



Lamb County, Texas, Well 1044401



Explanation

- Observed water level
- Simulated water level from calibrated model
- Simulated water level from model sensitivity run

SOUTHERN OGALLALA GAM

Simulated and Observed Hydrographs for Observation Wells in Briscoe and Lamb Counties for Specific Yield Sensitivity Analysis

same year that pumping occurs. Simulations conducted during model calibration indicated that if irrigation return flow occurs within about 10 years of the application of irrigation water, changes in simulated water levels are fairly small. However, relatively simplified computations conducted by BEG (Appendix A) indicate that potential lag times for irrigation return flow could range from less than a year to several decades. A sensitivity run was conducted to evaluate the effects of a longer lag time in irrigation return flow; a lag time of 20 years was selected for the analysis.

The simulation statistics for this run are similar to those of the calibration run. For 2000, the RMSE is 45 ft (the calibration run is 44 ft) and the RME is –11 ft, whereas the RME for the calibration run is –9 ft. Comparison of the simulated hydrographs indicates a worse match between simulated and observed water levels in Bailey, Castro, Dawson, Deaf Smith, Parmer, and Roosevelt Counties using a 20-year lag time for irrigation return flow. In Hale, Lubbock, Martin, and Potter Counties, however, the match between simulated and observed water levels was improved somewhat, in some cases significantly. For example, the observed water levels for wells 1149101 and 1151102 in Hale County are better replicated in the model using a lag in return flow of 20 years as opposed to assuming that return flow occurs quickly (fig. 69). For the counties not mentioned above, the effects of increasing the lag time were small.

Overall, the calibrated transient model yields the best simulation results when compared to observed data. Additional adjustments could have been made to reduce the RMSE by changing return flow lag time and specific yield on a site-by-site basis. However, such changes could not be justified based on observed data and the overall modeling approach, and would simply amount to "turning the knobs" in the model to improve the match between observed and simulated values. For example, there appears to be no physical basis for longer irrigation return flow lag times in Hale County than in other counties. Hale County does have soils of low overall permeability (fig. 7), but so do Parmer, Castro and Deaf Smith Counties, where the match between observed and simulated water levels became significantly worse when the 20-year lag time was applied.

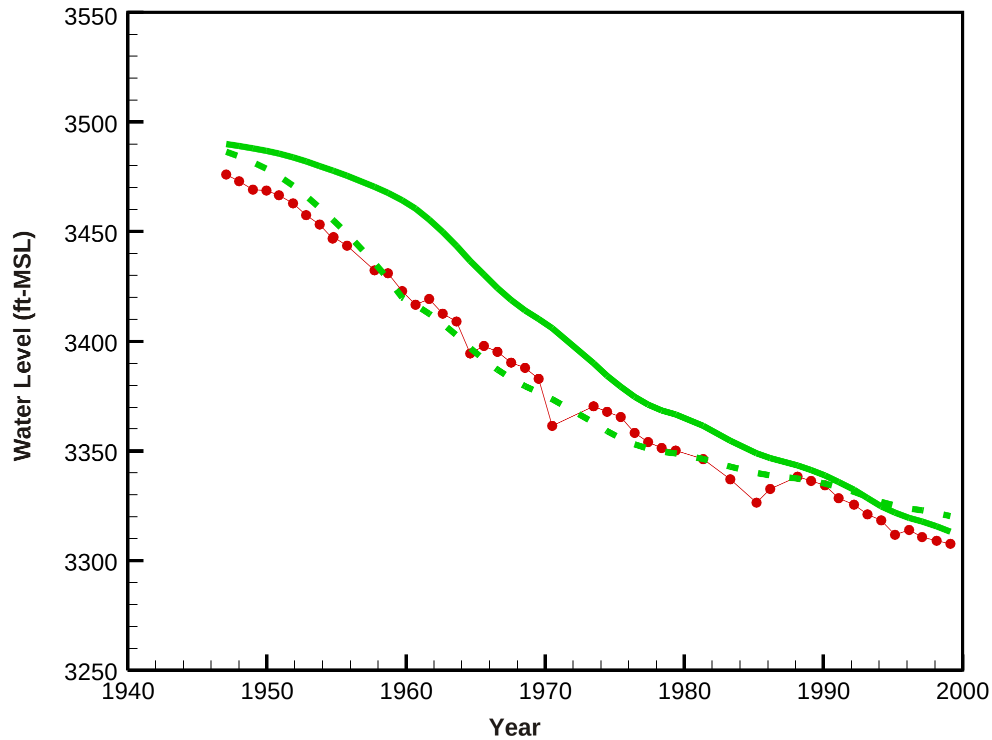
Predictions

The transient model was used to conduct simulations for the following seven predictive scenarios:

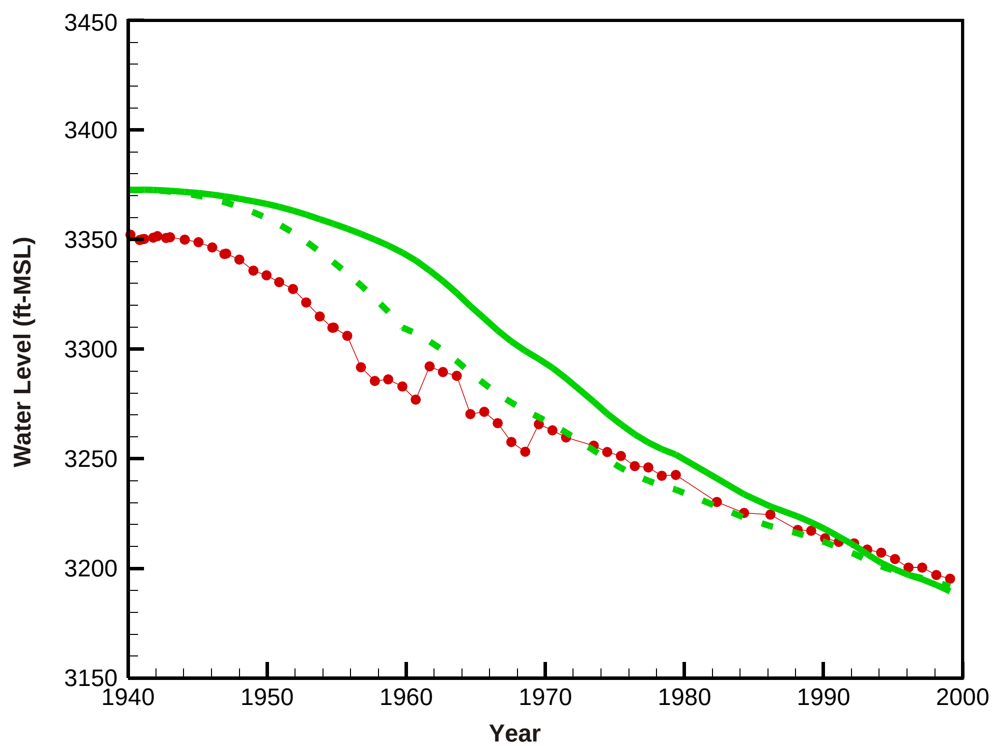
- Baseline Run: Average recharge and pumping through 2050
- 2010 Run: Average recharge and pumping through 2005 and drought-of-record pumping and recharge for 2006 through 2010
- 2020 Run: Average recharge and pumping through 2015 and drought-of-record pumping and recharge for 2016 through 2020
- 2030 Run: Average recharge and pumping through 2025 and drought-of-record pumping and recharge for 2026 through 2030
- 2040 Run: Average recharge and pumping through 2035 and drought-of-record pumping and recharge for 2036 through 2040
- 2050 Run: Average recharge and pumping through 2045 and drought-of-record pumping and recharge for 2046 through 2050
- 2050 Reduced Pumping Run: Average recharge and reduced pumping by 45 to 55 percent through 2050

The first 6 scenarios are standard model runs called for in the GAM modeling protocol. The seventh model run was an additional run in which agricultural pumping was reduced to avoid the simulation of dry cells in the predictive runs. Monthly stress periods were used for the final 10-year period of each simulation, and annual stress periods were used for earlier times.

Hale County, Texas, Well 1149101



Hale County, Texas, Well 1151102



Explanation

- Observed water level
- Simulated water level calibrated model
- Simulated water level 20 year return flow lag

SOUTHERN OGALLALA GAM

Simulated and Observed Hydrographs for Observation Wells in Hale County for Return Flow Sensitivity Run

Results from each of the predictive runs are provided as contour plots of hydraulic head (these figures also show dry and flooded cells) and color flood plots of saturated thickness and drawdown from 2000 conditions. All pumping in the predictive simulations was applied using the same spatial distribution applied for the last year of the transient calibration period (2000).

The drought of record for the Southern Ogallala aquifer was determined to be the 5-year period from 1952 through 1956 based on 1940 through 1998 climatic data (Appendix B). Recharge for the drought of record was assumed to be 30 percent less than the enhanced recharge rates applied in the model (Table 5, Figure 66); predevelopment recharge rates were not changed. The factor of 30 percent is the approximate difference between the average annual rainfall during the drought of record and the average annual rainfall for the period 1940 through 1998 (Appendix B, Table 4).

Pumping for irrigated agriculture during the drought of record in each simulation was determined by increasing the predictive agricultural numbers obtained from the TWDB spreadsheets by an annual factor to represent drought conditions. The factor was derived from the difference between the estimated pumping demands for long-term average conditions and the estimated pumping demands for drought-of-record conditions (Appendix B). On average, estimated pumping was increased by 27 percent to represent drought conditions, but the factor changes by county and year. Return flow from agricultural pumping was assumed to be 5 percent for all predictive simulations. No adjustments were made to other categories of pumping to represent drought conditions.

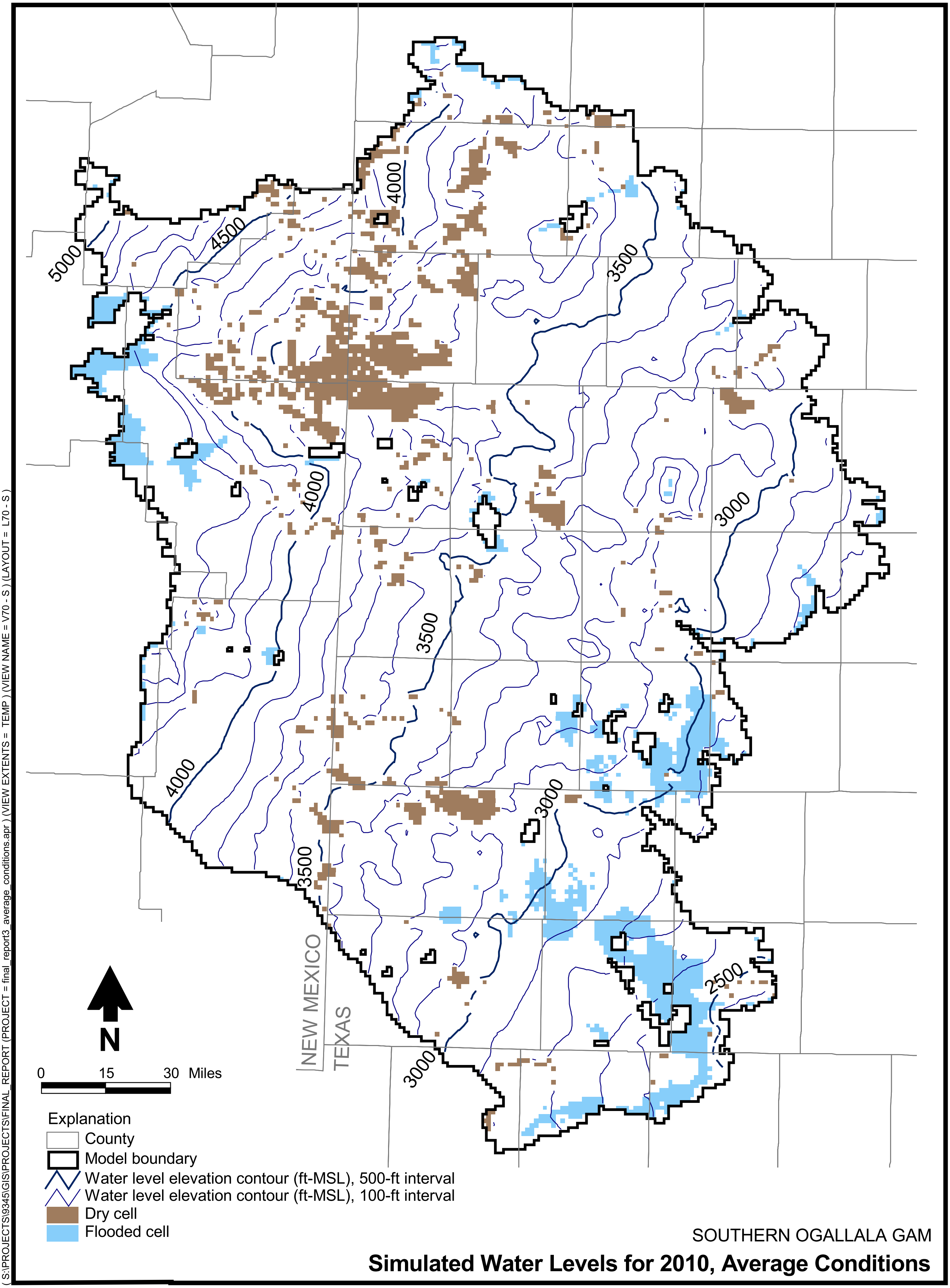
Predictive simulation results for the baseline scenario are provided in Figures 70 through 84. Figures 70 through 74 illustrate simulated water levels and dry and flooded cells for 2010, 2020, 2030, 2040 and 2050. Figures 75 through 79 and 80 through 84 follow the same time sequence, but show simulated drawdown and saturated thickness, respectively.

Figures 70 through 74 illustrate regions of the aquifer that are progressively dewatered through time, although the progression is more clearly illustrated in Figures 75 through 79. For example, Figure 75 illustrates that the largest simulated drawdown (25 to 50 ft) occurs in Deaf Smith, Parmer, Castro, Hale, and northern Bailey and Lamb Counties in the north, and in Gaines County in the south. In addition, comparison of the extent of the dry cells illustrated in Figure 75 with those illustrated in Figure 63 (2000 conditions) shows that the simulated extent of dry cells has increased over the 10-year simulation period. There are also regions of fairly small water level rises that correspond to regions of significant non-irrigated agriculture (fig. 38). Figure 76 illustrates that simulated declines continue in the same areas and, in some local areas (e.g., northwestern Castro County), exceed 75 ft by 2020. The extent of simulated dry cells has also increased.

Figures 77 through 79 illustrate continued progression of water level declines in regions with significant irrigated agriculture for 2030, 2040 and 2050, respectively. By 2050, significant portions of the irrigated regions of most counties with substantial agricultural pumping have gone dry, and simulated drawdown in adjacent areas is generally 50 to 75 ft or more. In portions of Lynn, Garza, and Dawson Counties, simulated water level rises are projected to exceed 25 ft in some areas due to enhanced recharge.

Simulated saturated thickness (figs. 80 through 84) follows the same trends as illustrated in the previous figures. By 2050, the simulated saturated thickness for much of the aquifer is 50 ft or less (fig. 84).

When a dry cell occurs in the model, the pumping assigned to that cell is removed. As regions of dry cells propagate, therefore, increasing amounts of the assigned pumping are eliminated from the simulation. In the baseline simulation, approximately 10 percent of the total prescribed future pumping is removed from the



SOUTHERN OGALLALA GAM

Simulated Water Levels for 2010, Average Conditions

3-14-03

Figure 70

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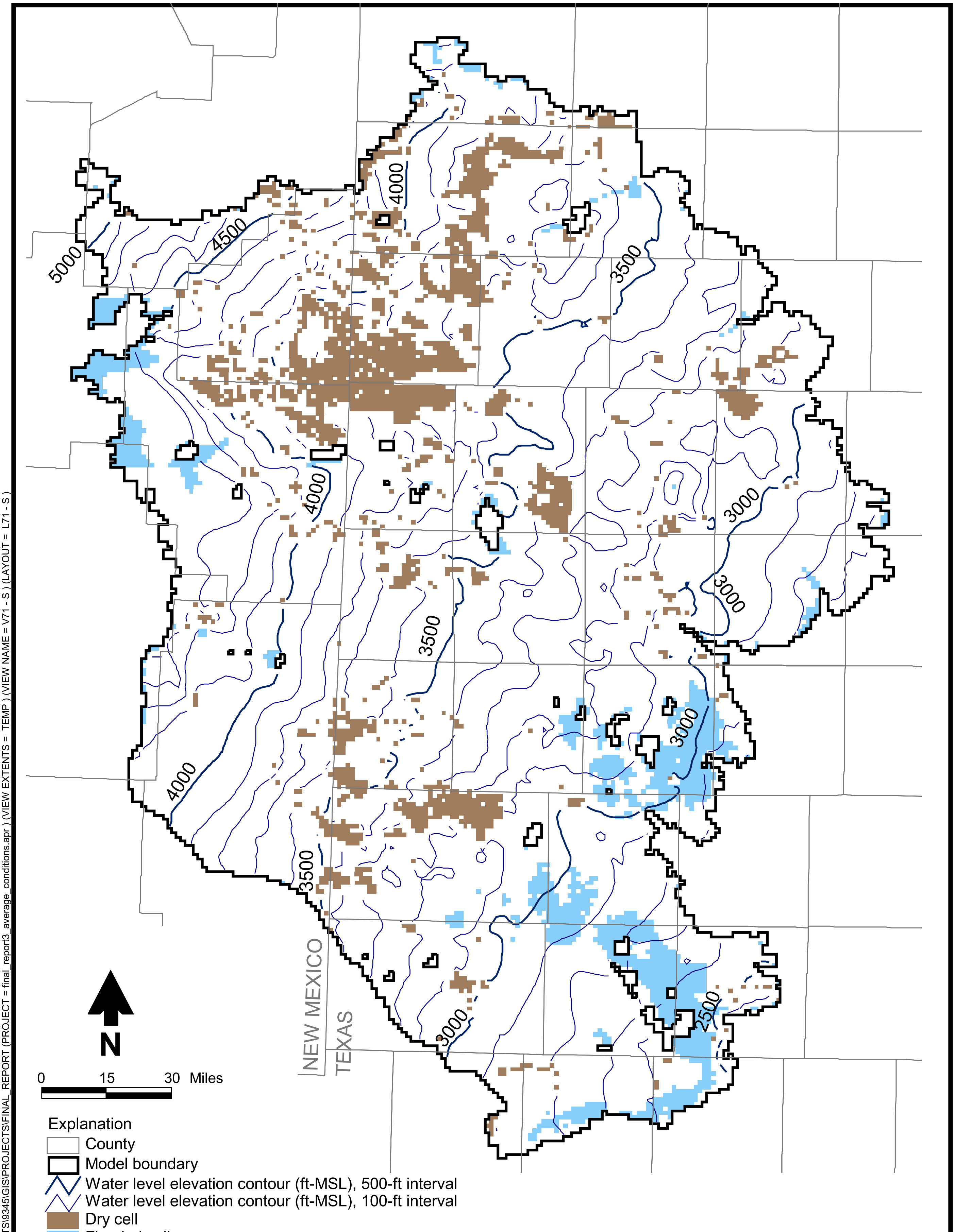
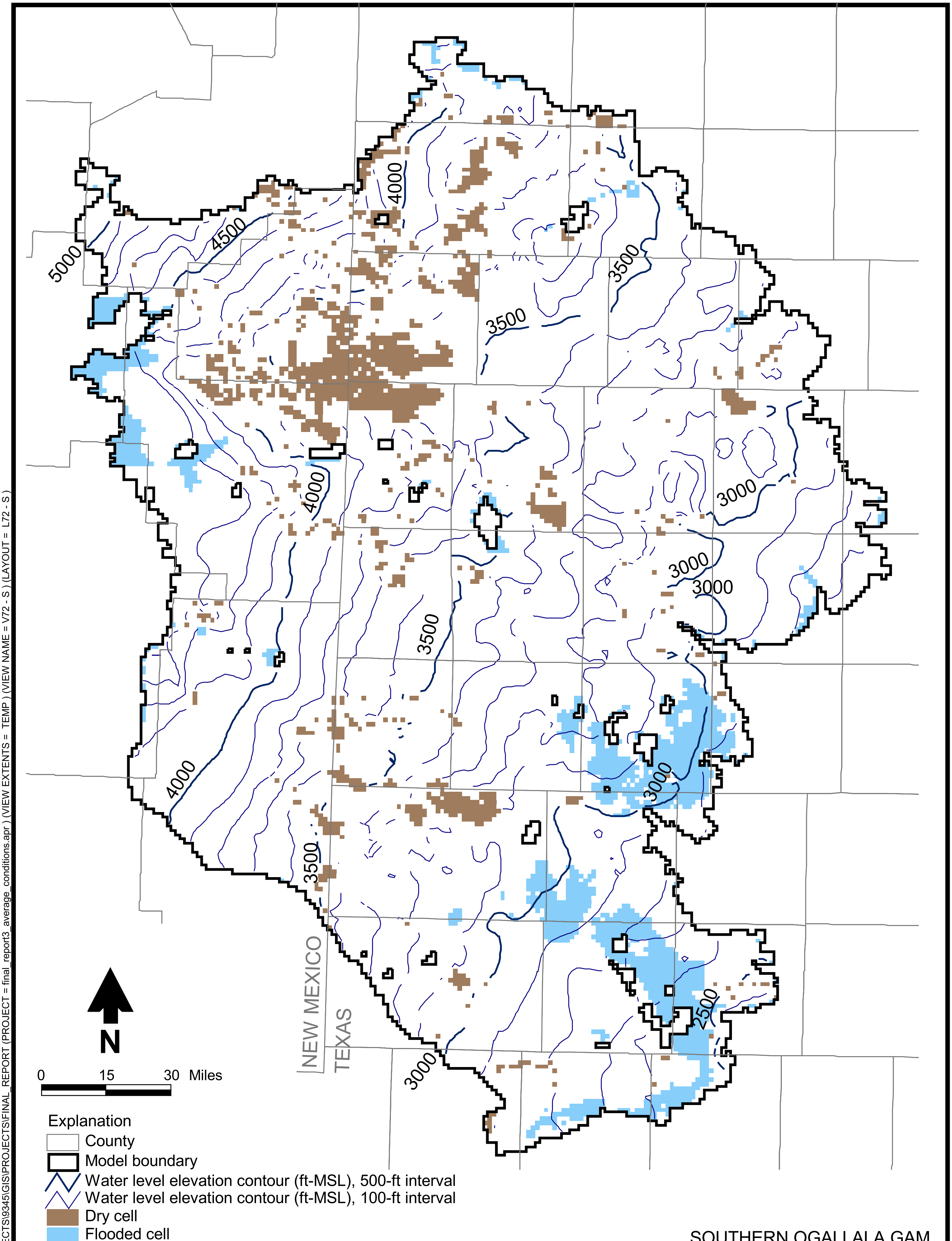


SOUTHERN OGALLALA GAM

Simulated Water Levels for 2020, Average Conditions

3-14-03

Figure 71



SOUTHERN OGALLALA GAM

Simulated Water Levels for 2030, Average Conditions

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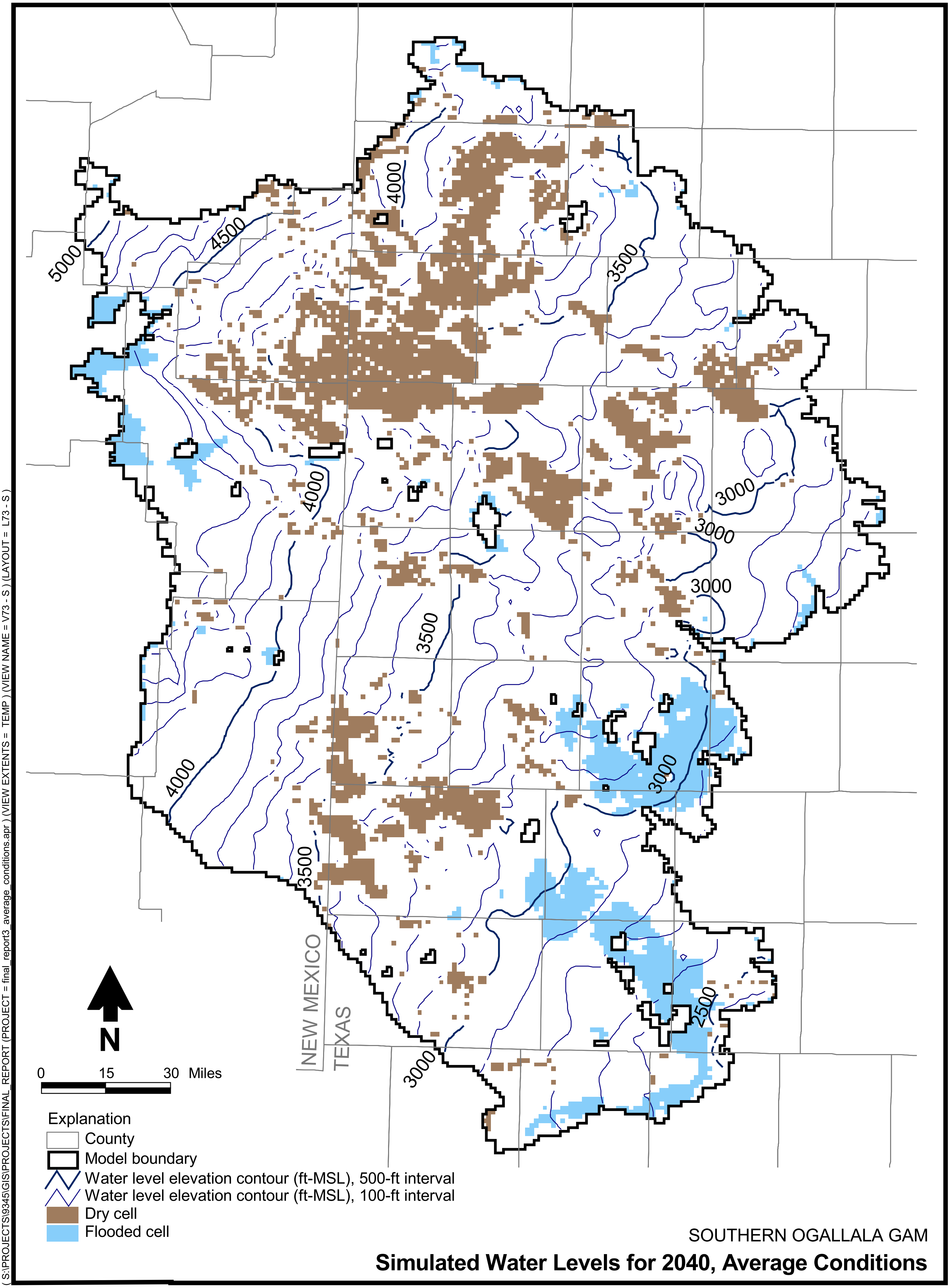
Figure 72

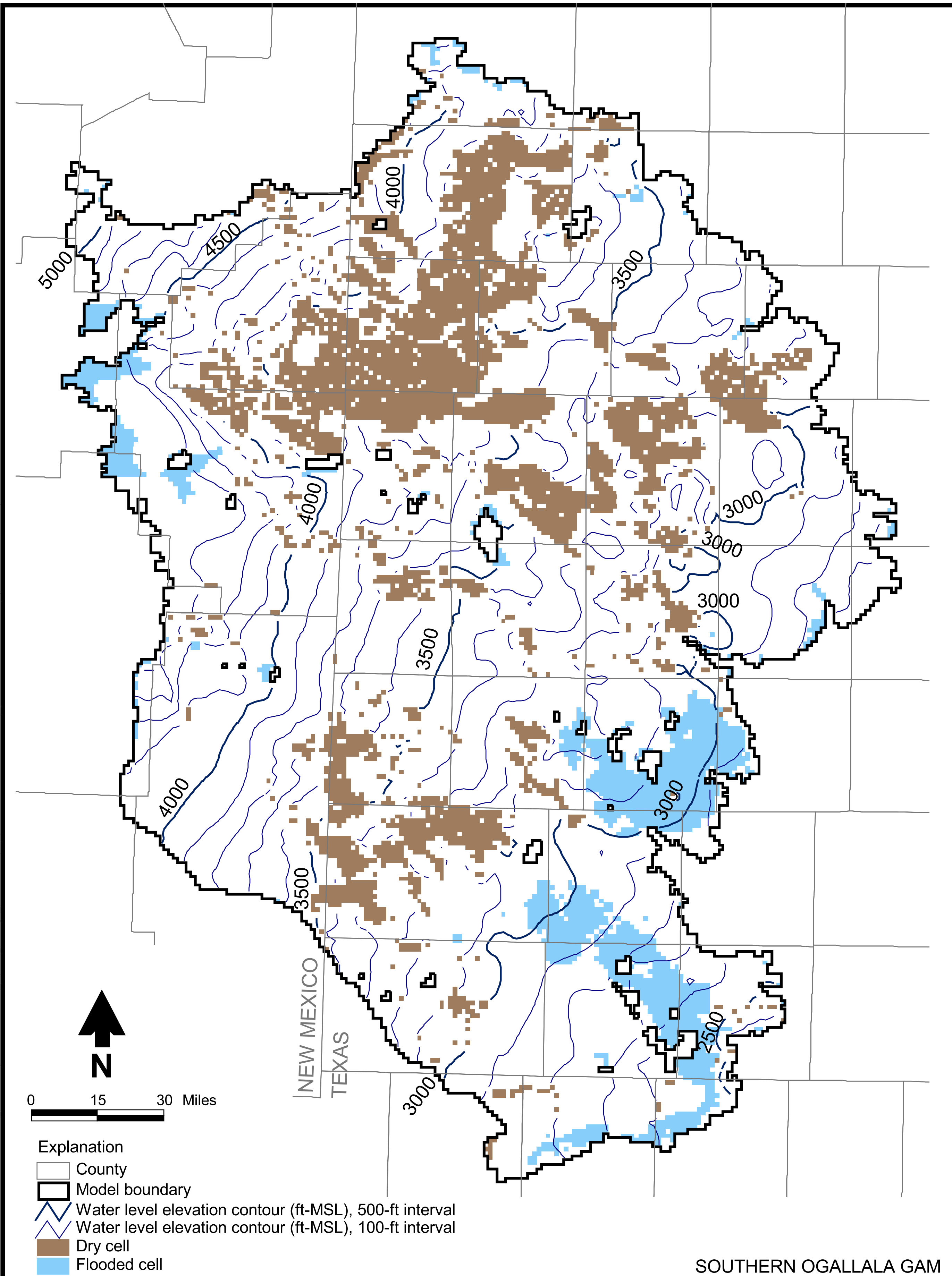


SOUTHERN OGALLALA GAM

Simulated Water Levels for 2040, Average Conditions

3-14-03

Figure 73



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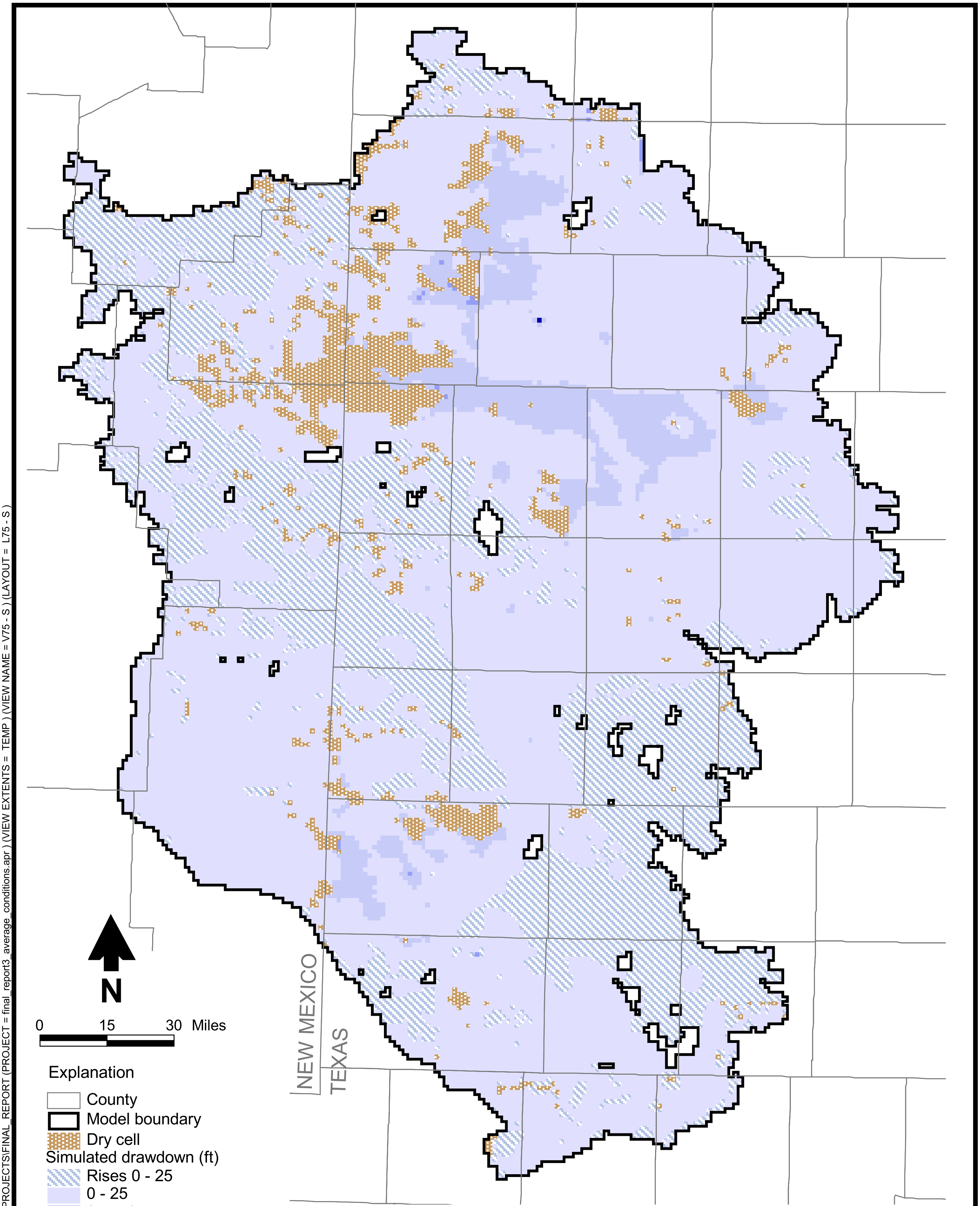
SOUTHERN OGALLALA GAM

Simulated Water Levels for 2050, Average Conditions

3-14-03

Figure 74



SOUTHERN OGALLALA GAM

Simulated Drawdown for 2010, Average Conditions

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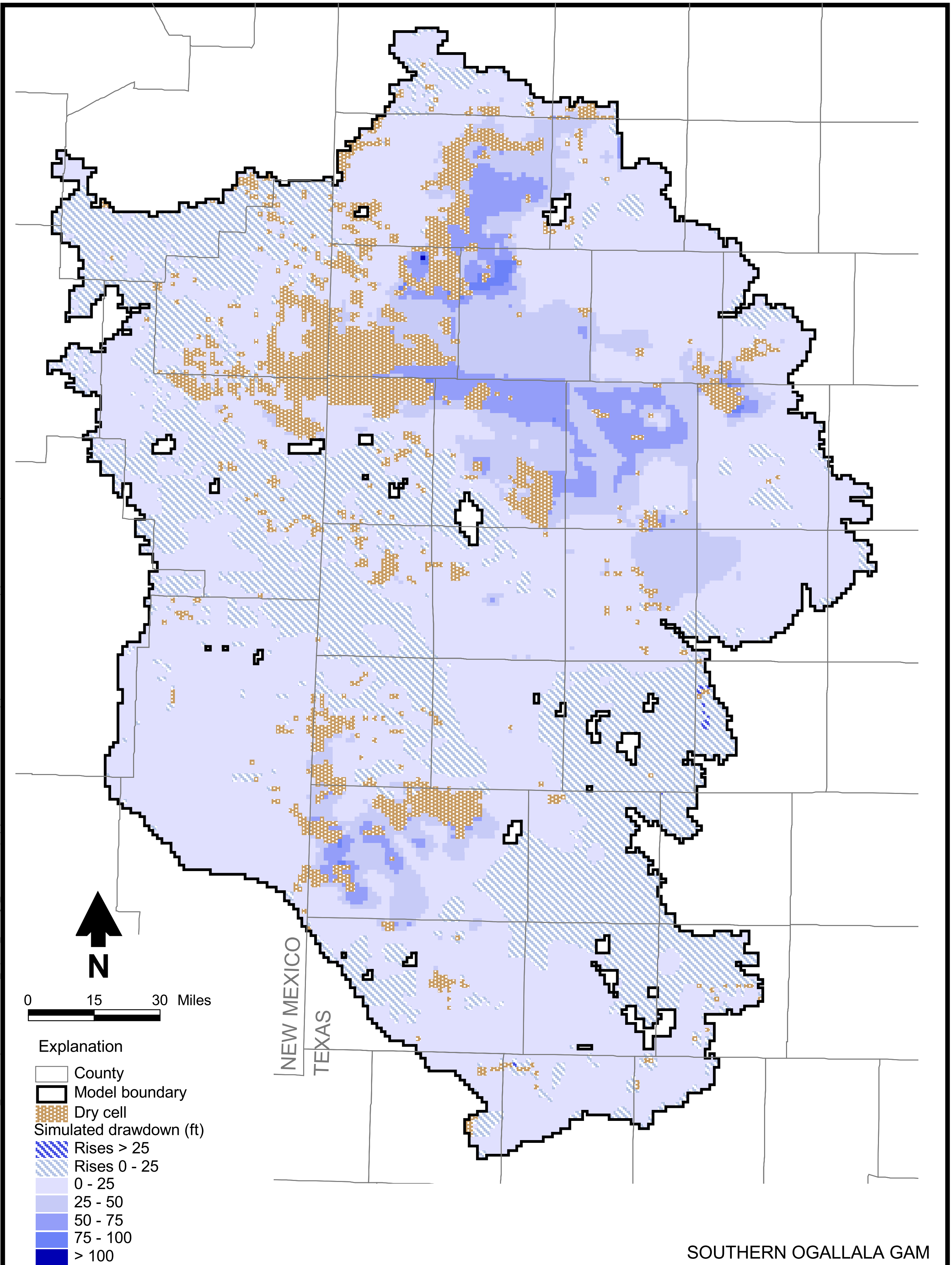
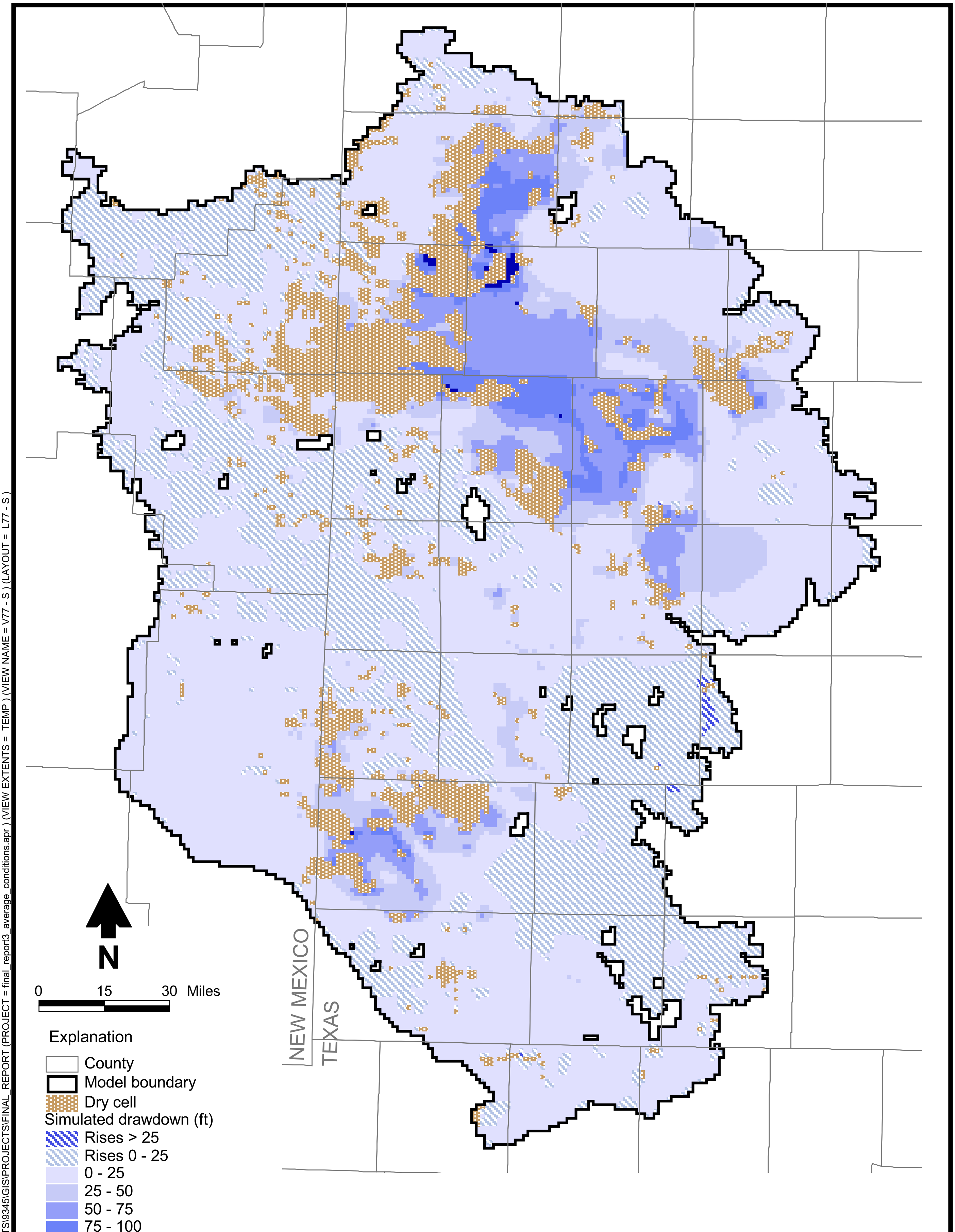
Figure 75



SOUTHERN OGALLALA GAM

Simulated Drawdown for 2020, Average Conditions



SOUTHERN OGALLALA GAM

Simulated Drawdown for 2030, Average Conditions

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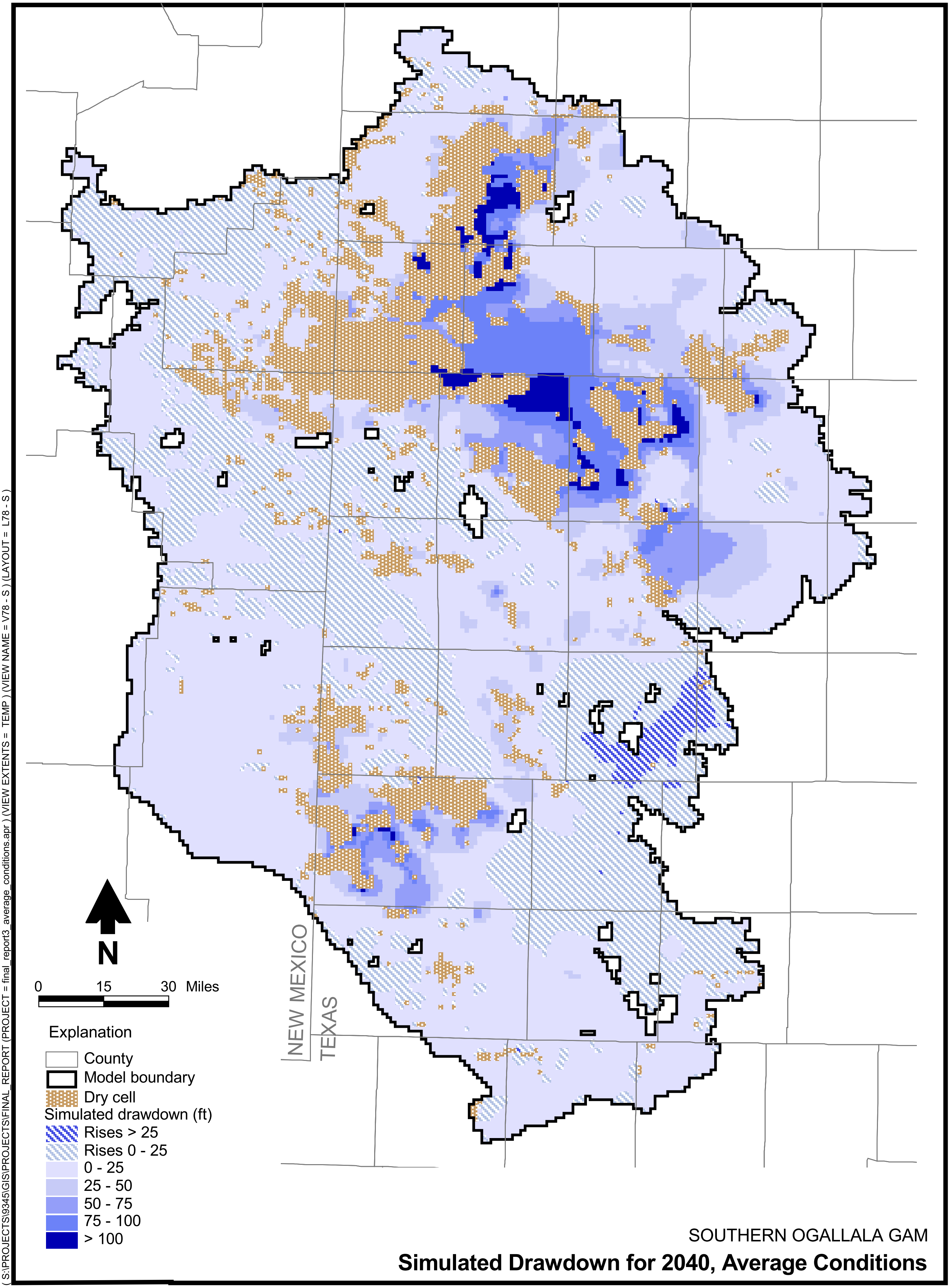
Figure 77

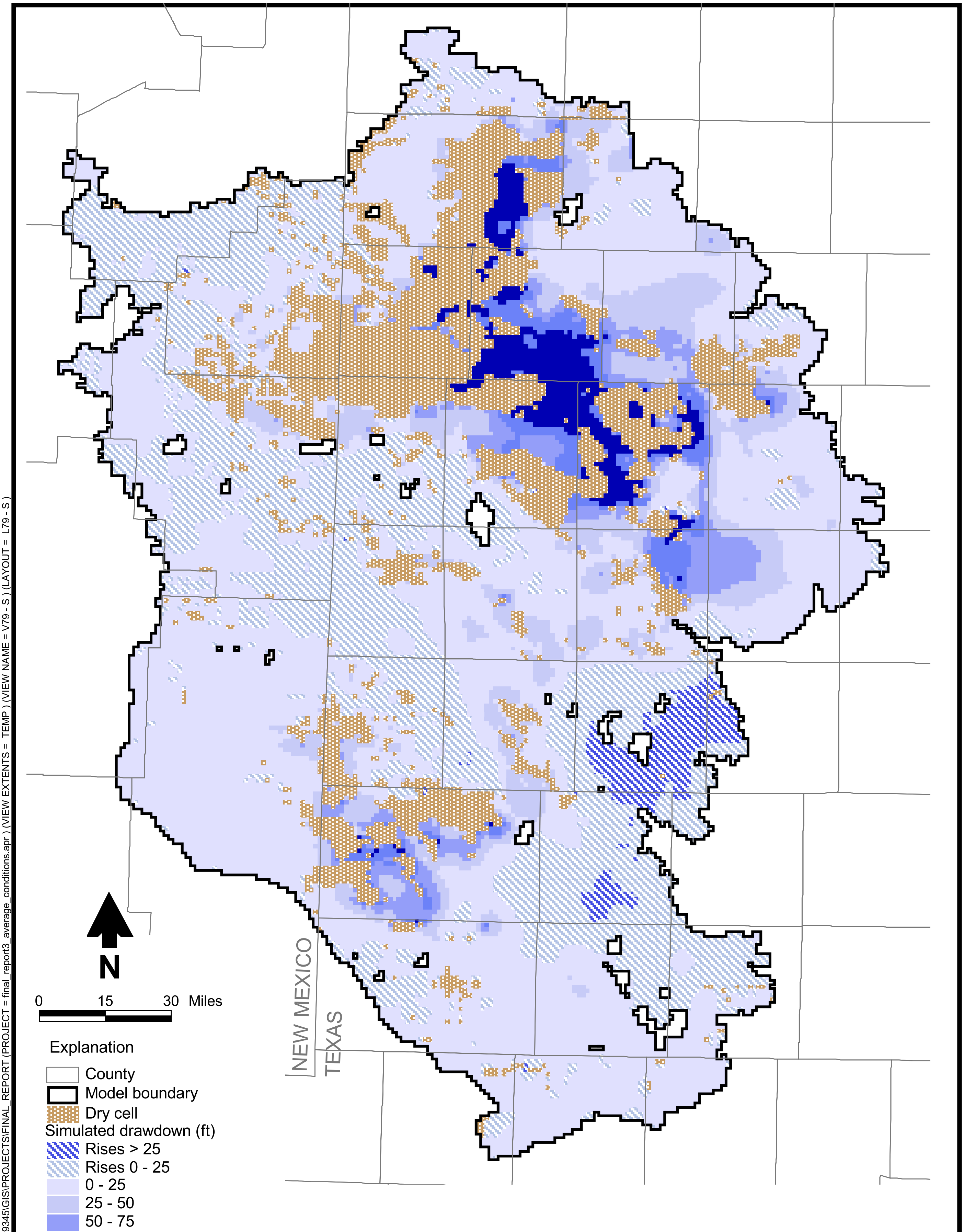


SOUTHERN OGALLALA GAM

Simulated Drawdown for 2040, Average Conditions

3-14-03

Figure 78



SOUTHERN OGALLALA GAM

Simulated Drawdown for 2050, Average Conditions

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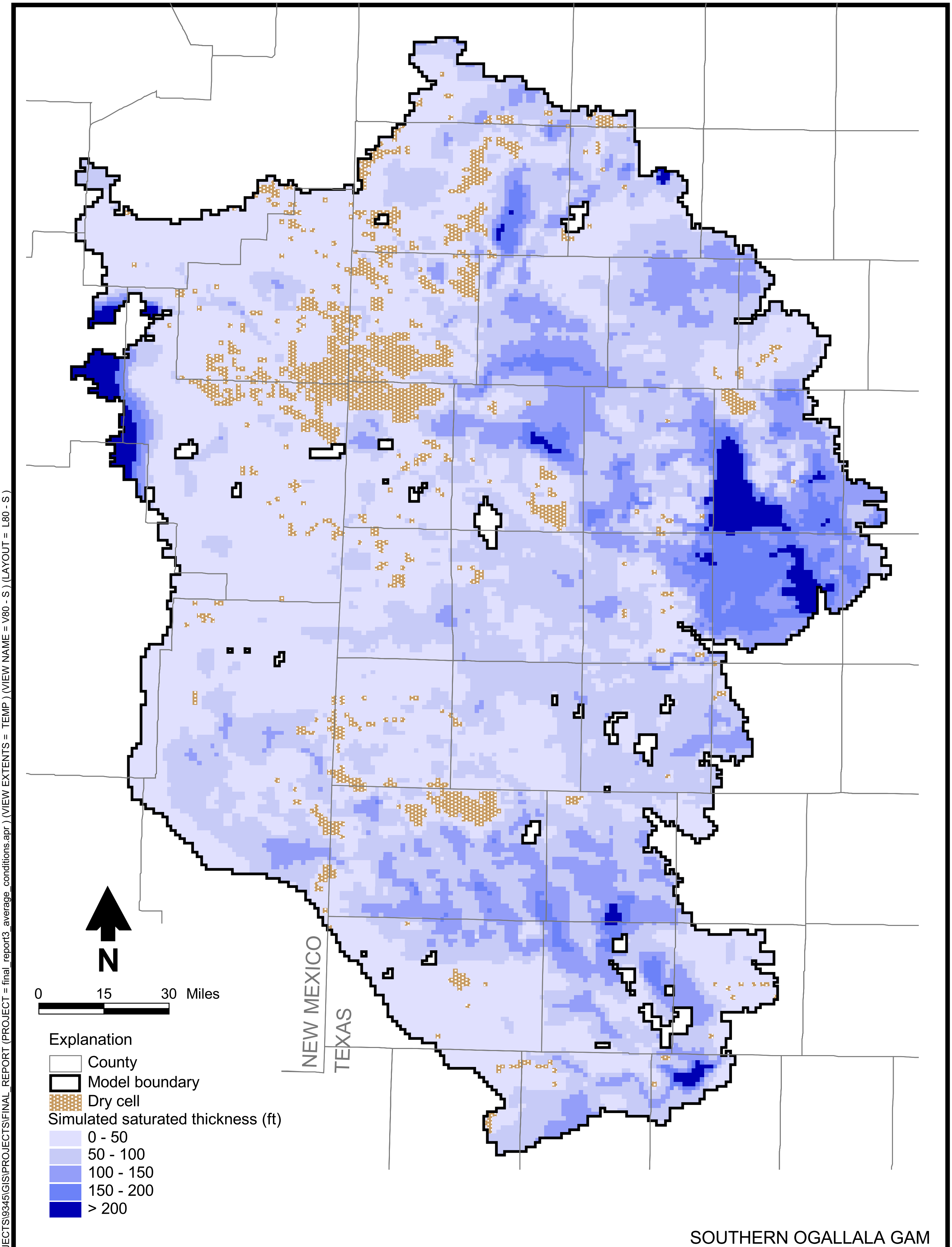
Figure 79



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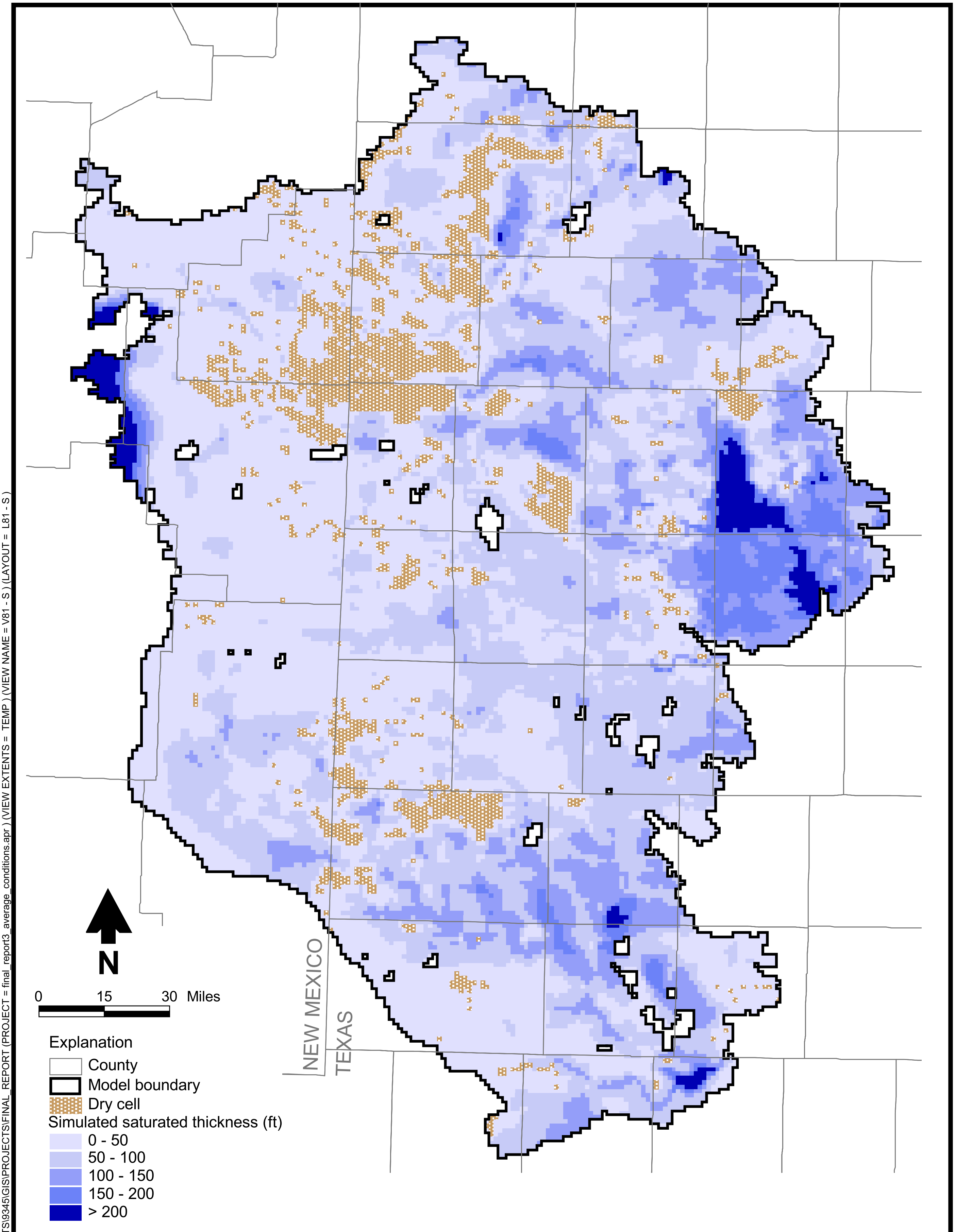
SOUTHERN OGALLALA GAM

Simulated Saturated Thickness for 2010, Average Conditions

3-14-03



SOUTHERN OGALLALA GAM

Simulated Saturated Thickness for 2020, Average Conditions

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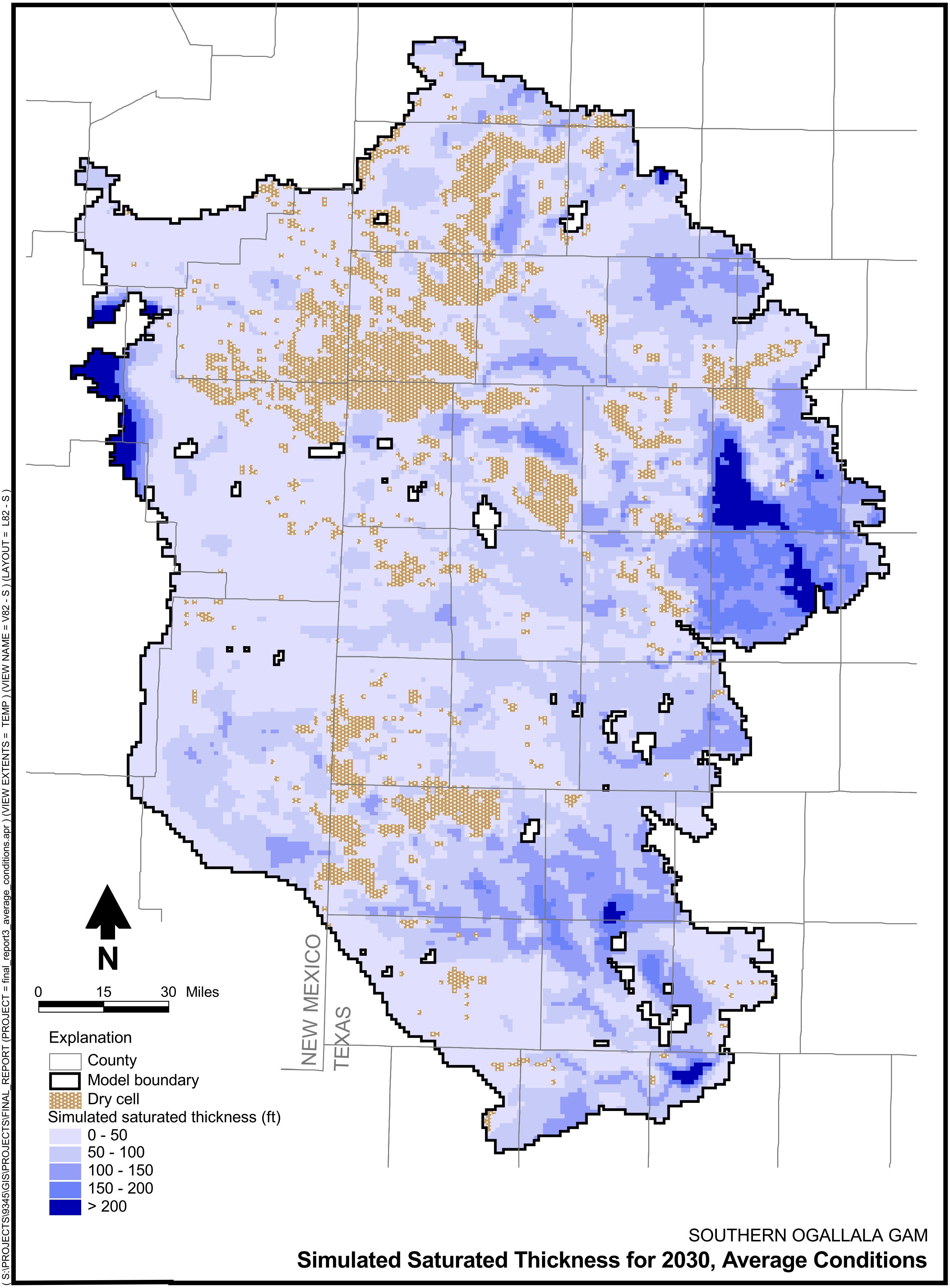
Figure 81

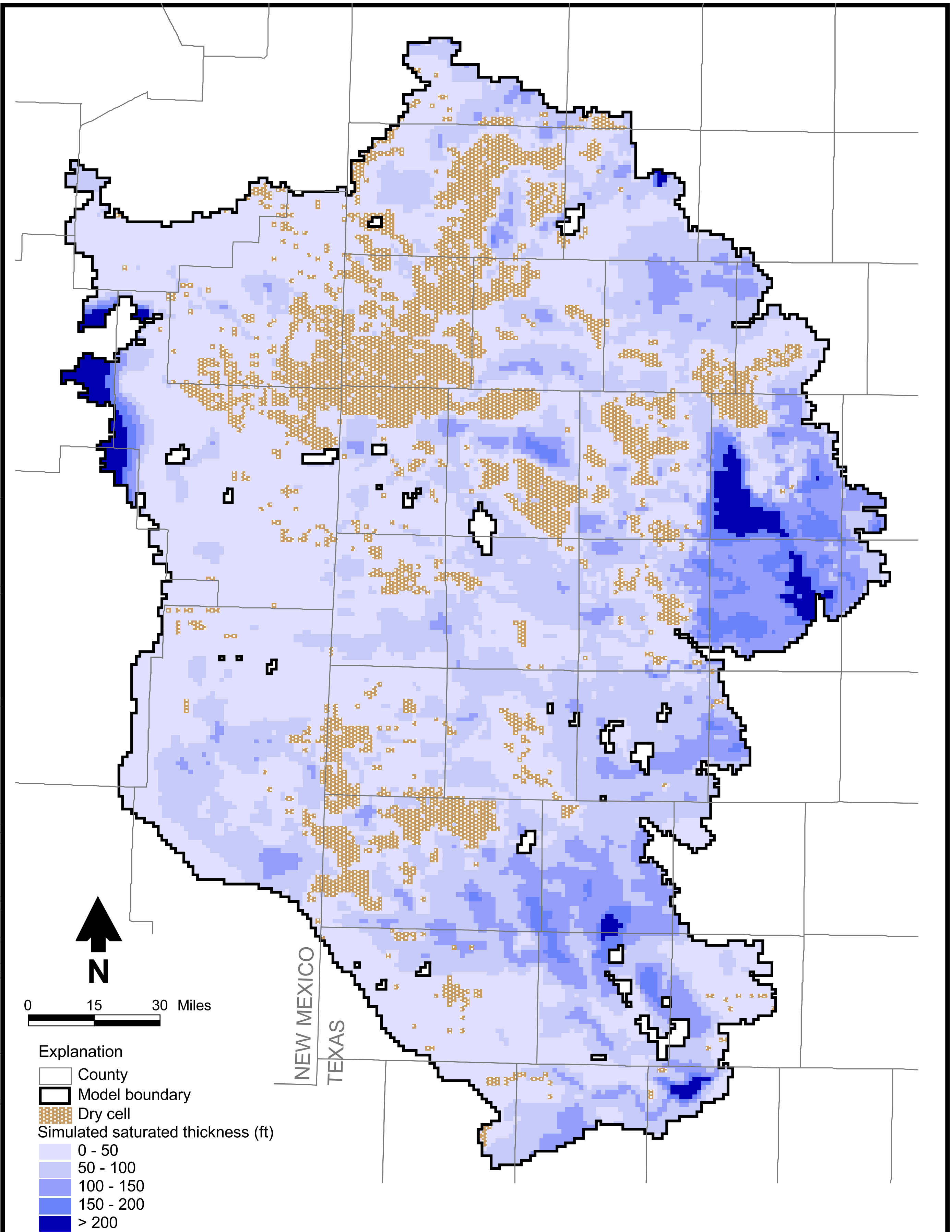


SOUTHERN OGALLALA GAM

Simulated Saturated Thickness for 2030, Average Conditions

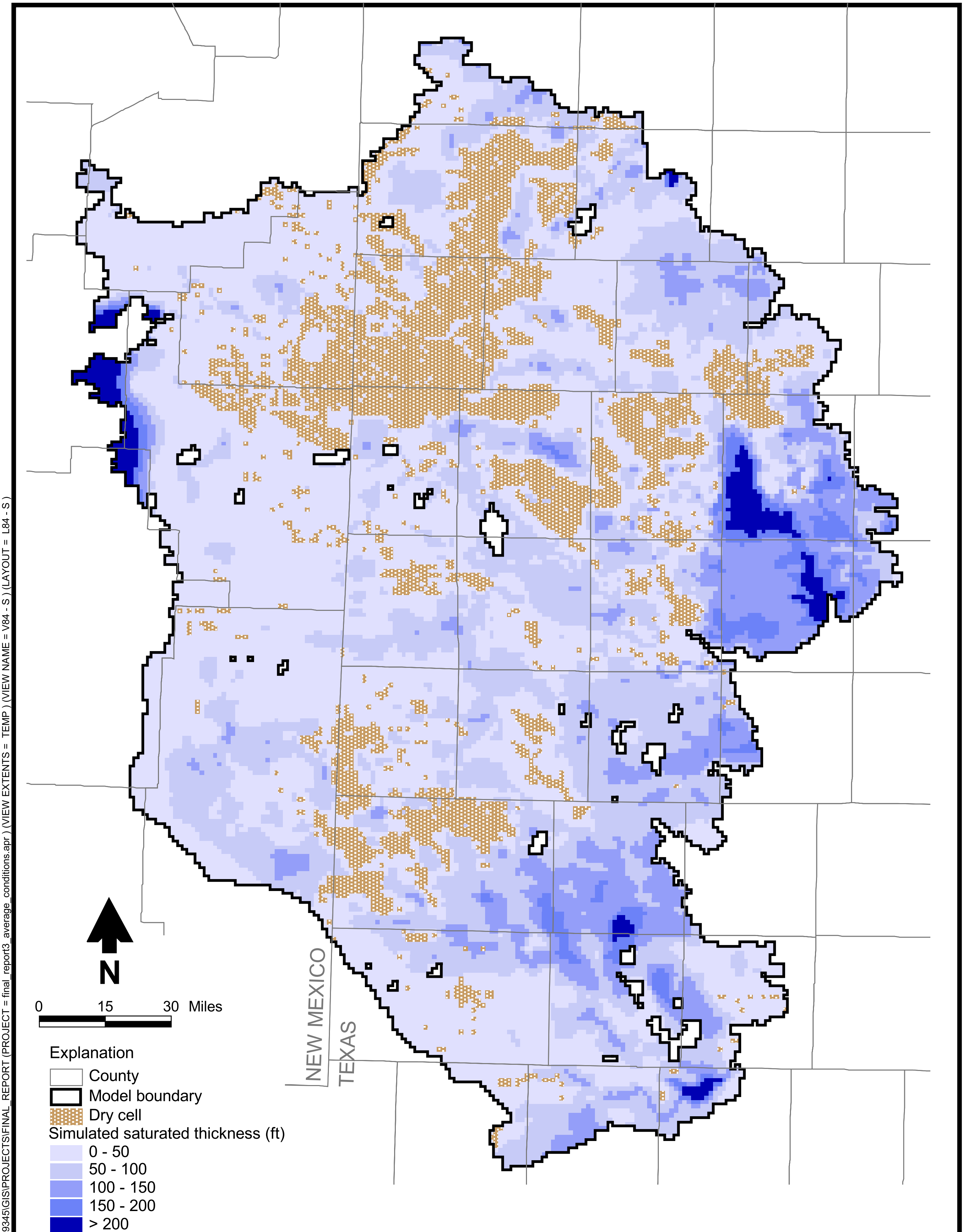
3-14-03

Figure 82



SOUTHERN OGALLALA GAM

Simulated Saturated Thickness for 2040, Average Conditions



SOUTHERN OGALLALA GAM

Simulated Saturated Thickness for 2050, Average Conditions

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simulation each decade due to dry cells. In 2010, approximately 22 percent of the prescribed pumping is lost to dry cells, but this includes about 7 percent lost to dry cells that exist at the beginning of the predictive simulation from the last year of the transient model calibration. Subsequently, in 2020, 2030, 2040, and 2050, about 32 percent, 42 percent, 51 percent, and 56 percent of the total prescribed pumping is removed from the simulation.

Results from the drought-of-record predictive runs are presented in Figures 85 through 87 for the 2010 run, Figures 88 through 90 for the 2020 run, Figures 91 through 93 for the 2030 run, Figures 94 through 96 for the 2040 run, and Figures 97 through 99 for the 2050 run. For the most part, the simulation results for the various drought-of-record runs are remarkably similar to those of the baseline run. For the 2010 run, the region of simulated drawdown between 25 and 50 ft in the northern counties is substantially larger than that simulated in the baseline run (compare Figures 86 and 75). However, simulated drawdown and extent of dry cells are similar for 2020 and later years (compare Figures 76 and 89).

The simulation results between the drought and baseline scenarios are similar for two reasons:

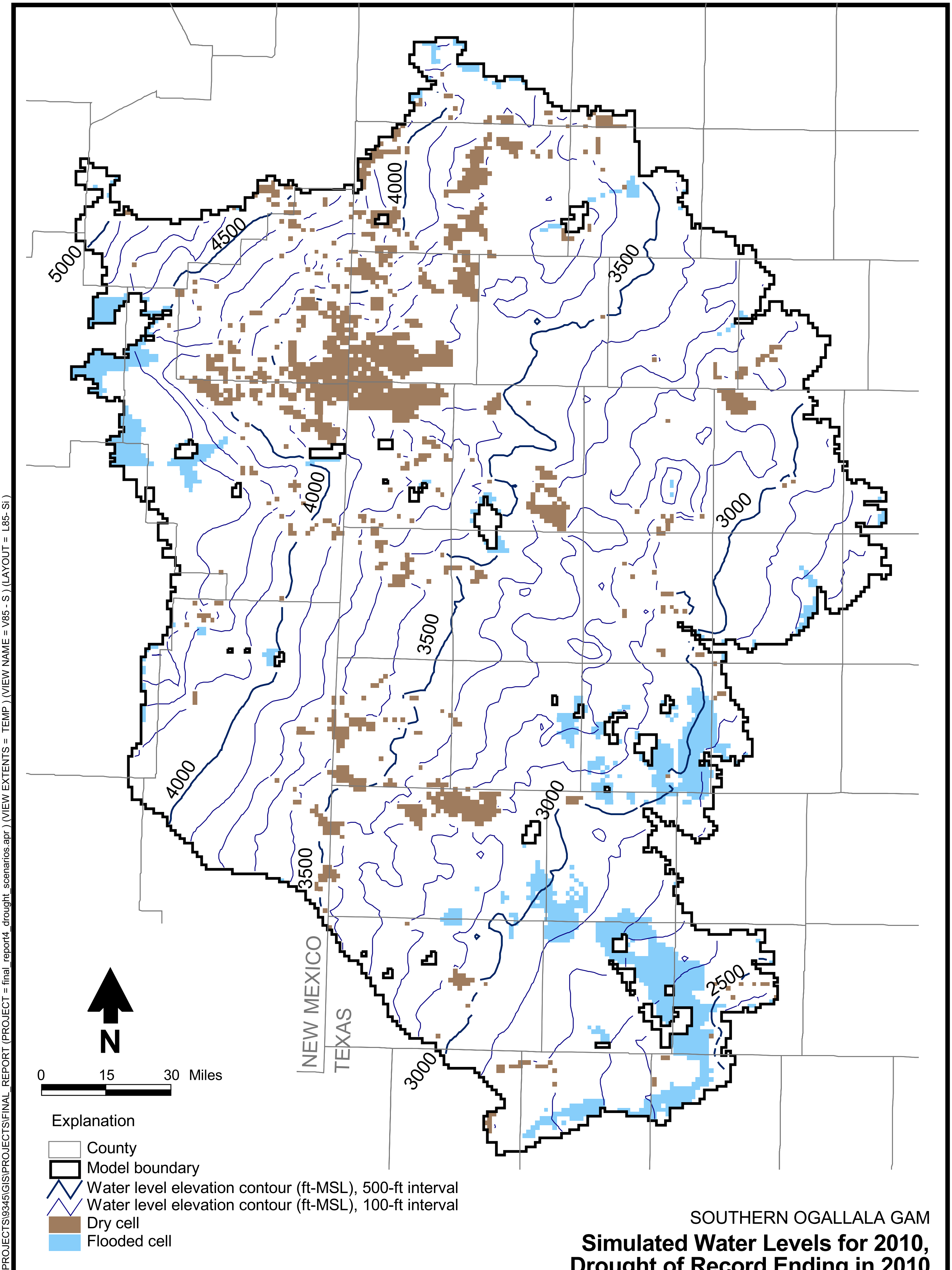
- As cells go dry in MODFLOW, pumping is no longer assigned to those cells in the model. Therefore, where dry cells occur prior to the drought-of-record period (the last five years of every decade), increased pumping for drought conditions will not be applied.
- The Southern Ogallala aquifer represents an enormous reservoir of water, and changes in pumping for relatively short periods of time (such as 5 years) can have relatively small effects in terms of water level changes on a regional scale.

The effects of dry cells in the predictive simulations are evident from the water balances for each of the predictive simulations (Table 7). As the number of dry cells increases and model cells and their associated recharge or discharge components are thus removed from the simulation, all of the significant water budget components decrease. As would be expected, the number of dry cells is greatest for the 2050 drought scenario. For this scenario, 16 percent of the active model cells become dry by the end of the simulation.

In reviewing the predictive simulation results, it should be kept in mind that, for locations where simulated water levels in the transient model are less than observed water levels, the model will predict dry cells prematurely. This situation occurs in Curry County, New Mexico and Bailey and Parmer Counties in Texas in the northern portion of the study area, and in Lea County, New Mexico and western Yoakum and Gaines Counties in Texas in the southern part of the study area (Appendix D).

In addition, predicted volumes of agricultural pumping estimated in the state water plan were compared to long-term average estimates made by Amosson and others (Appendix B). For the most part, the estimated values were in reasonable agreement. However, for Gaines County, Texas, Amosson and others estimate the long-term average demand to be 248,450 ac-ft/yr, while the estimated demand in the state water plan is 355,323 ac-ft/yr, a difference of 43 percent. Gaines County has the most significant simulated drawdown of all the southern counties.

A final predictive simulation was run for reduced pumping conditions in an effort to significantly diminish the extent of the simulated dry cells. This run is based on the baseline scenario, but agricultural pumping for all years through 2050 was reduced by 55 percent in Deaf Smith, Parmer, Bailey, Gaines, Lamb, and Floyd Counties, and by 45 percent elsewhere. The results of this 2050 simulation are provided in Figures 100 through 102. Although the extent of dry cells still grows in this simulation, the extent of dewatered areas is greatly diminished (figs. 100 and 101). The largest regions of increased dry cells are in Parmer, Deaf Smith, Bailey, Floyd, Yoakum, and Gaines Counties. Several of these are counties where the simulated water level starts out lower than observed levels for the predictive simulations, and therefore simulated dewatering of the aquifer occurs prematurely.



SOUTHERN OGALLALA GAM

Simulated Water Levels for 2010, Drought of Record Ending in 2010

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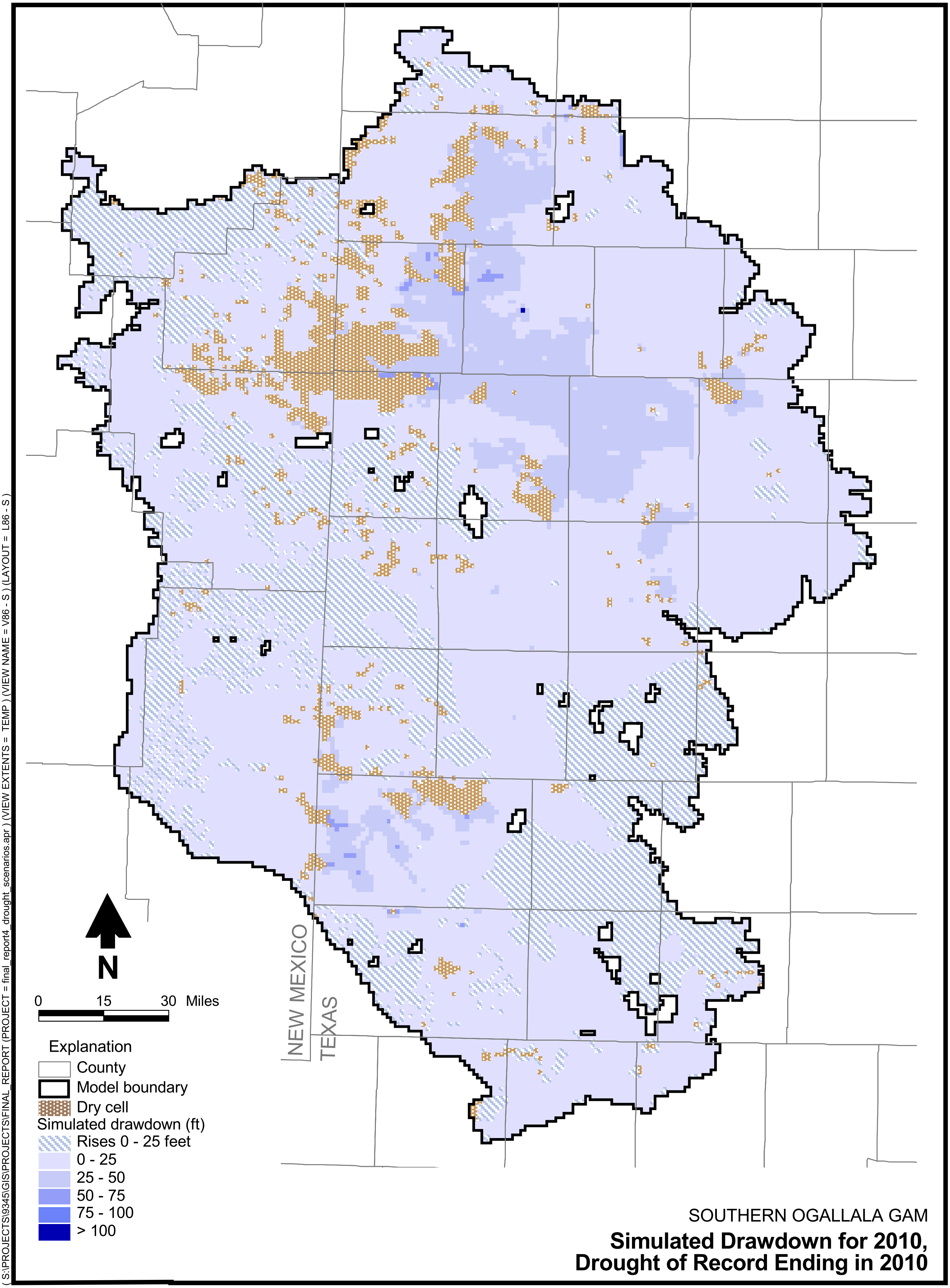
Figure 85

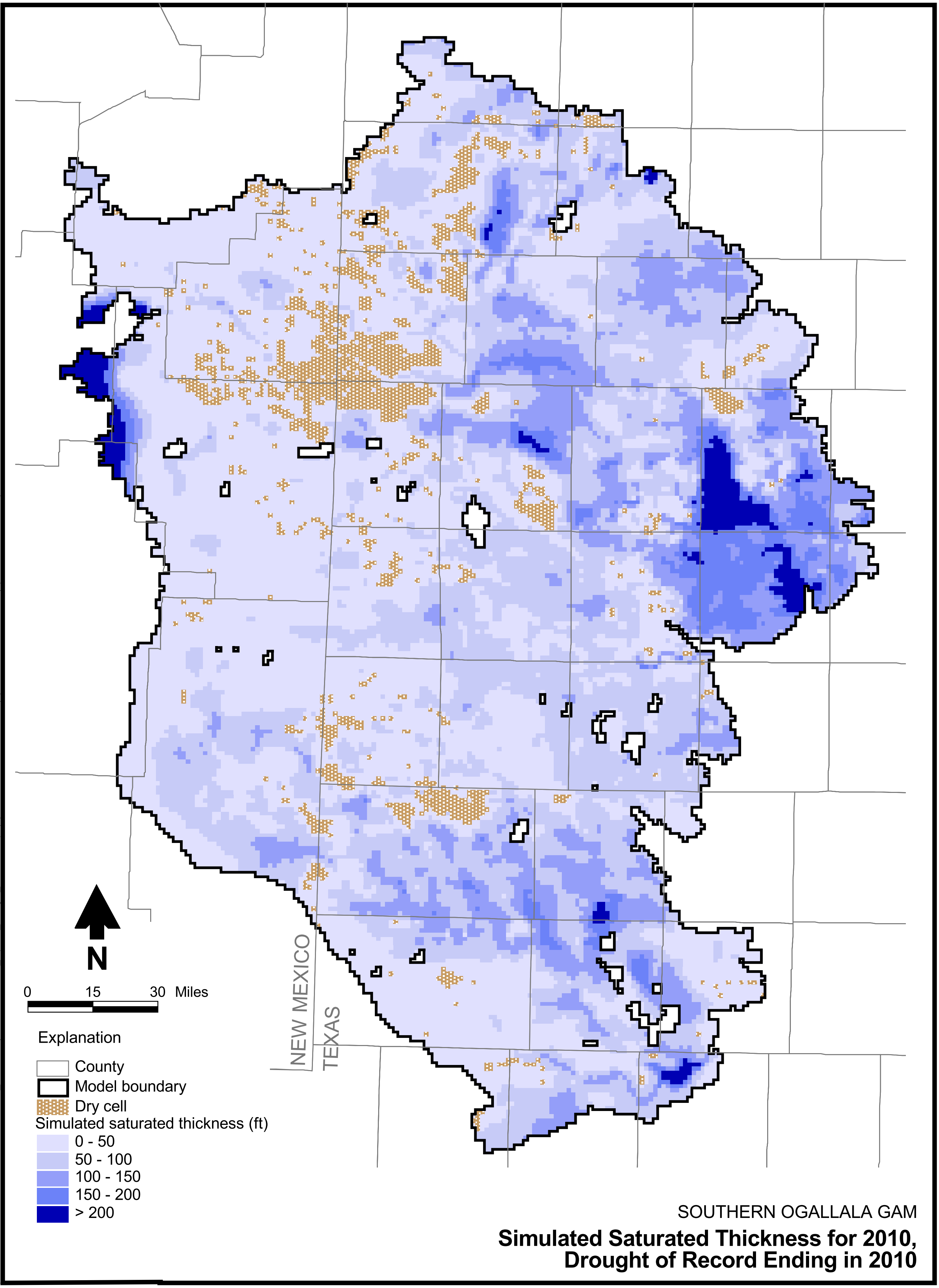


SOUTHERN OGALLALA GAM

Simulated Drawdown for 2010, Drought of Record Ending in 2010

3-14-03

Figure 86



SOUTHERN OGALLALA GAM

Simulated Saturated Thickness for 2010, Drought of Record Ending in 2010

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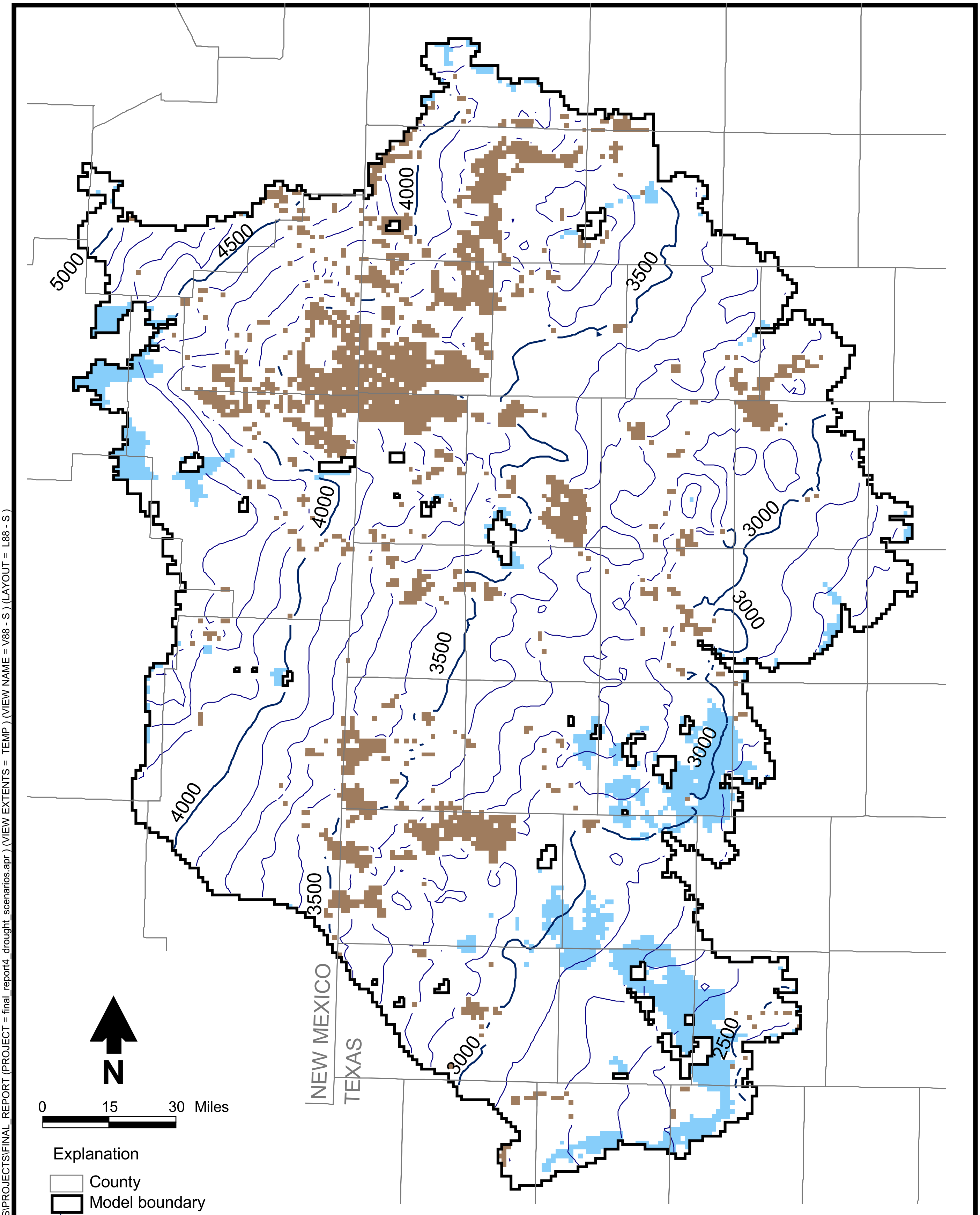
3-14-03

Figure 87



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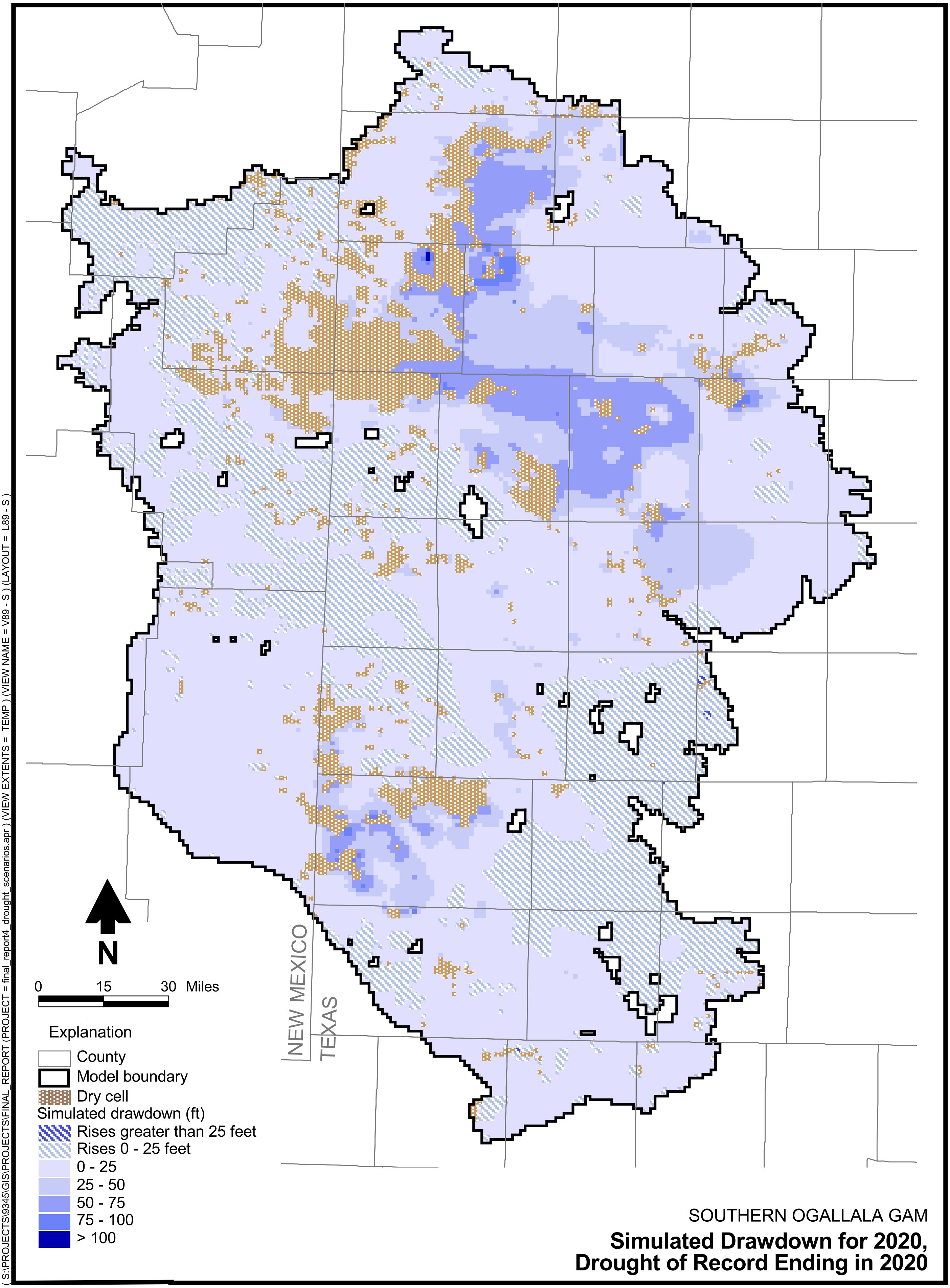
SOUTHERN OGALLALA GAM

Simulated Water Levels for 2020, Drought of Record Ending in 2020

3-14-03

Figure 88

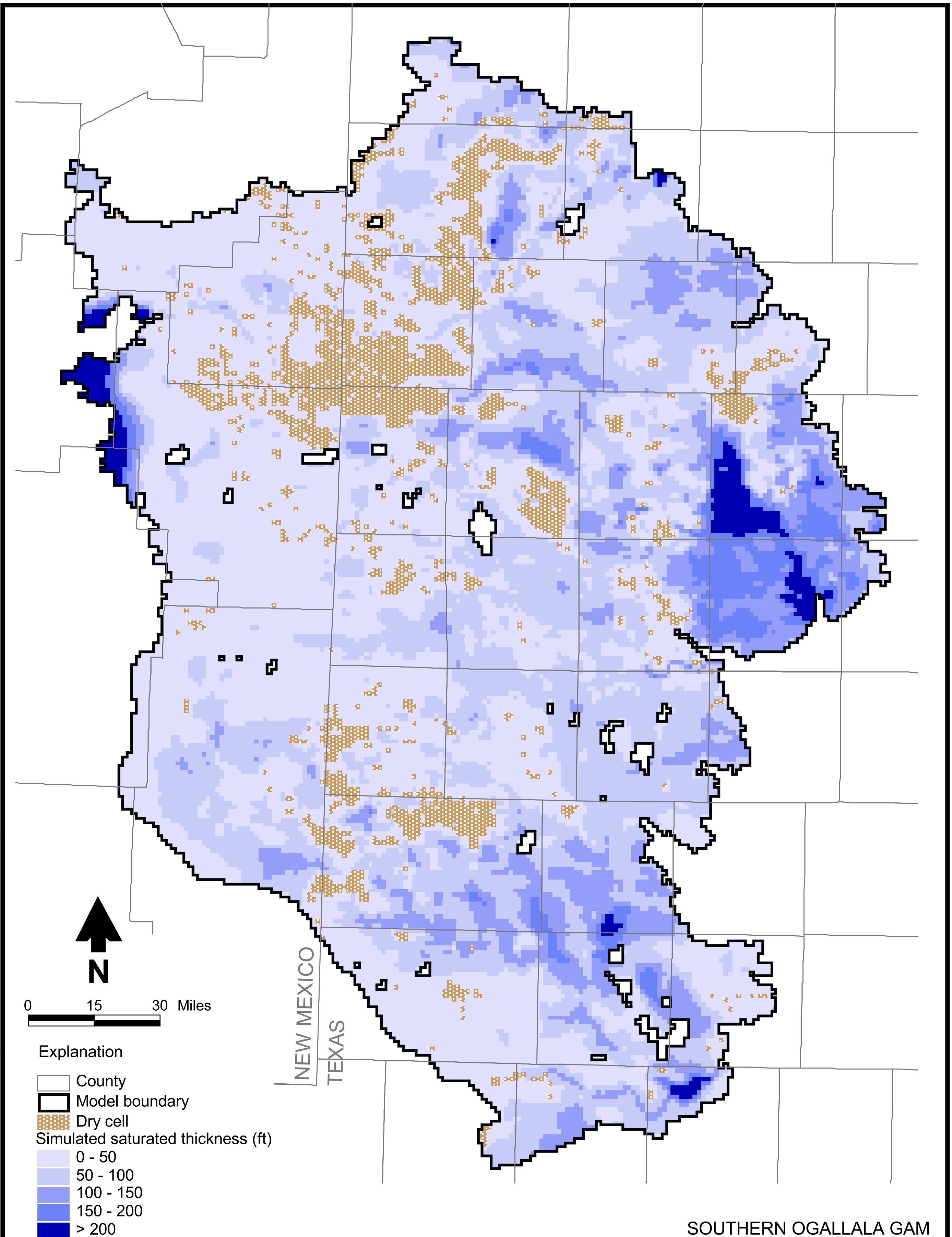


SOUTHERN OGALLALA GAM

Simulated Drawdown for 2020, Drought of Record Ending in 2020

3-14-03

Figure 89



SOUTHERN OGALLALA GAM

Simulated Saturated Thickness for 2020, Drought of Record Ending in 2020

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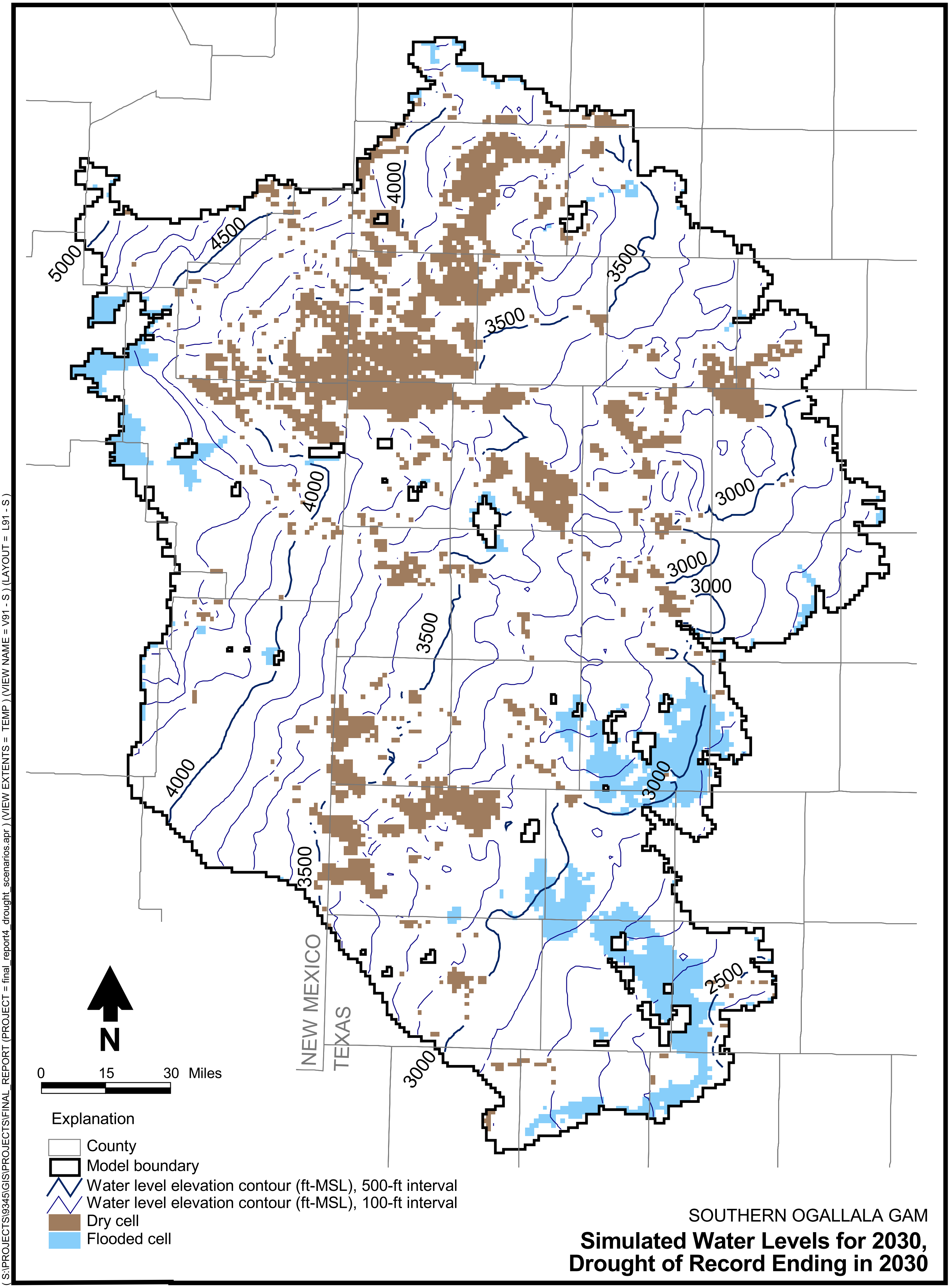
Figure 90

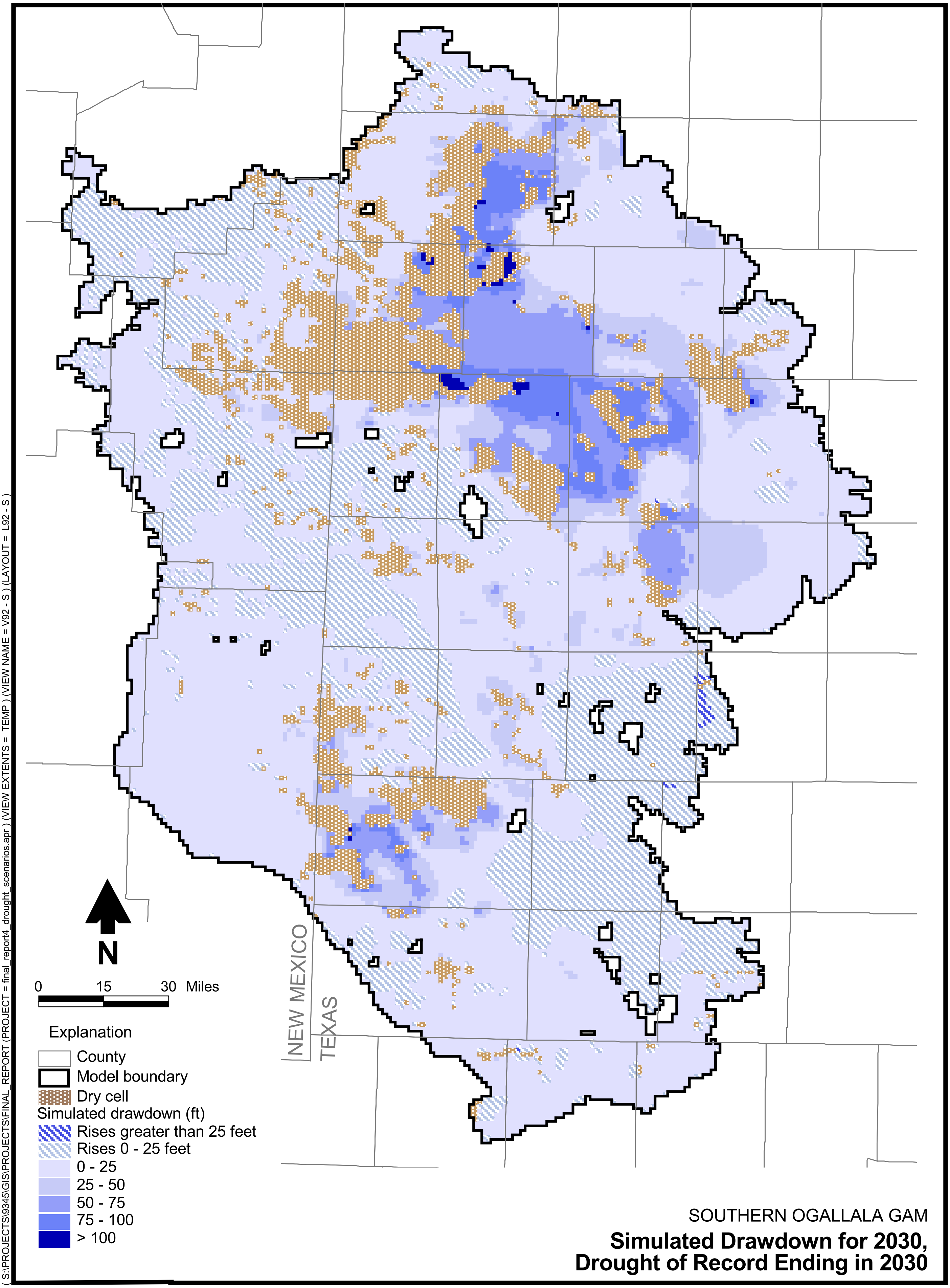


SOUTHERN OGALLALA GAM

Simulated Water Levels for 2030, Drought of Record Ending in 2030

3-14-03

Figure 91



SOUTHERN OGALLALA GAM

Simulated Drawdown for 2030, Drought of Record Ending in 2030

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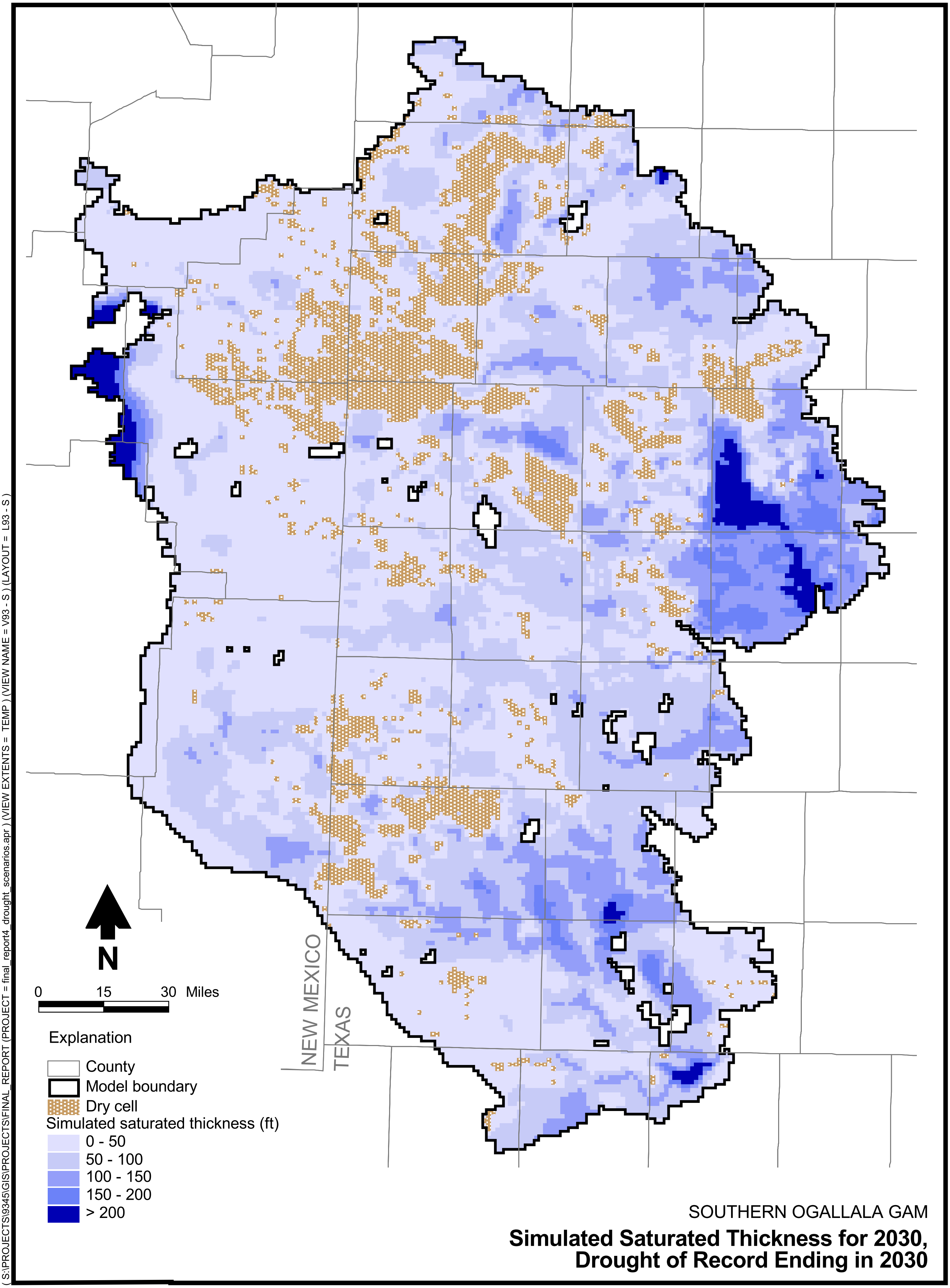
Figure 92



SOUTHERN OGALLALA GAM

Simulated Saturated Thickness for 2030, Drought of Record Ending in 2030

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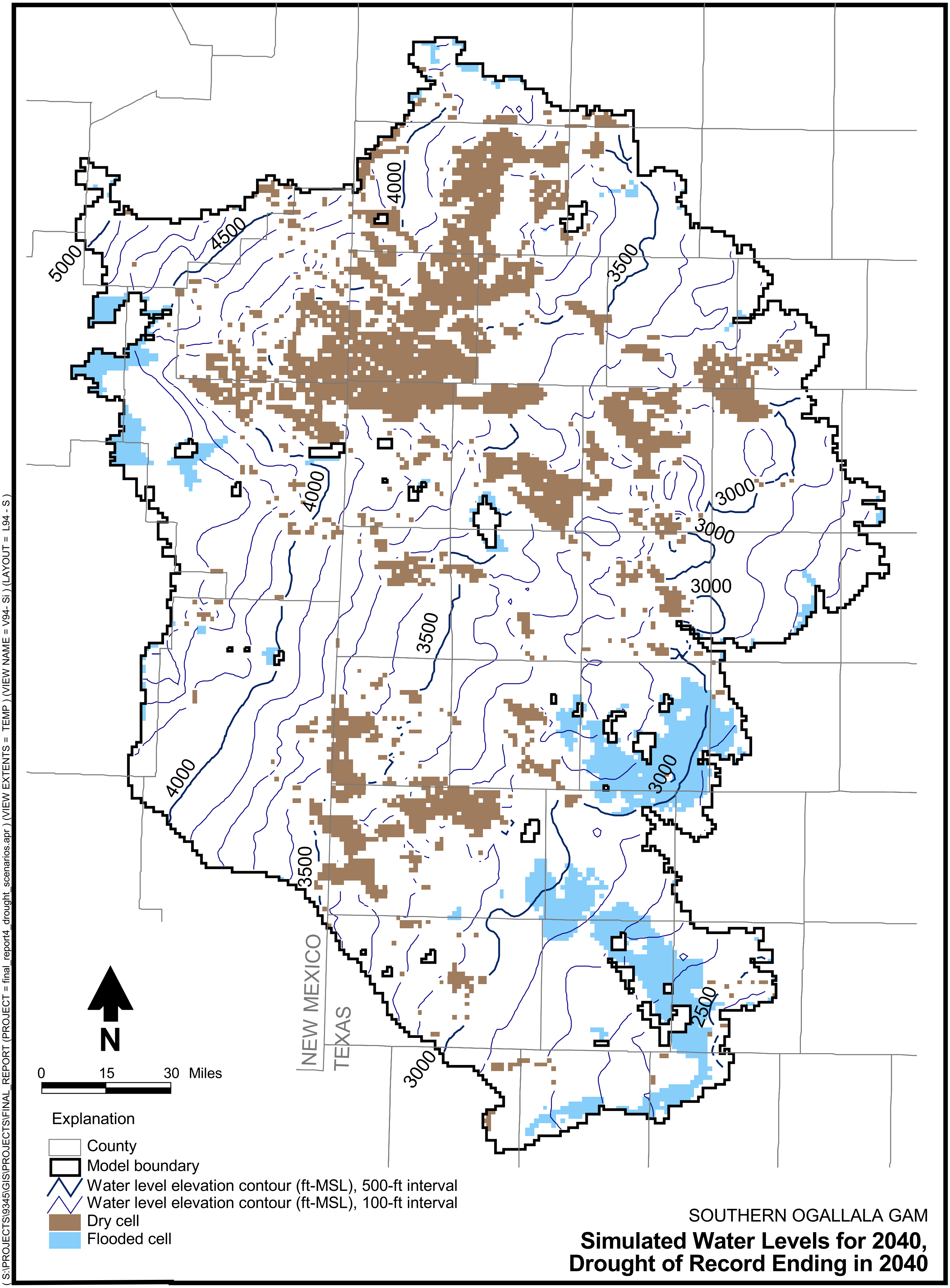
Figure 93

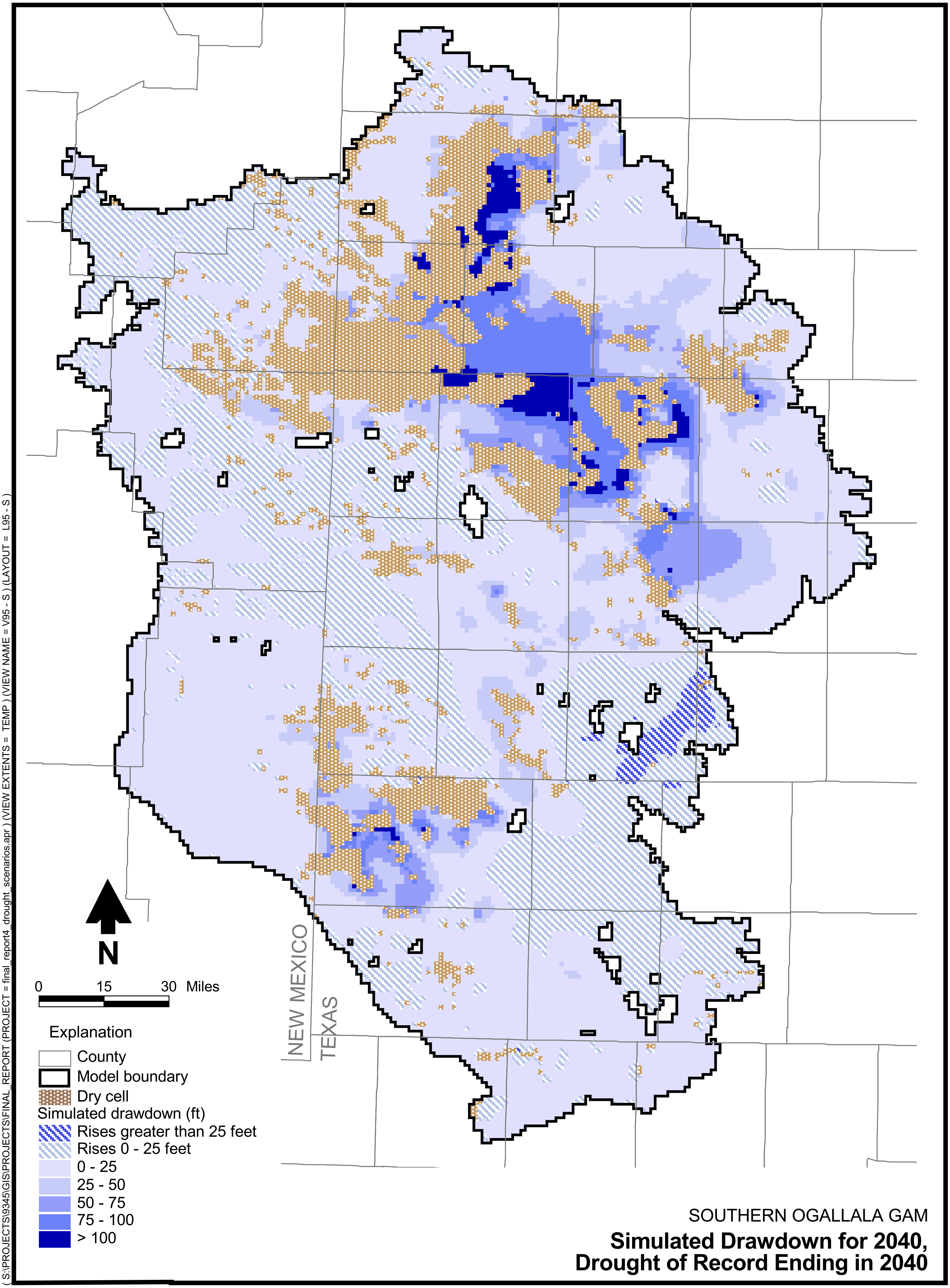


SOUTHERN OGALLALA GAM

Simulated Water Levels for 2040, Drought of Record Ending in 2040

3-14-03

Figure 94

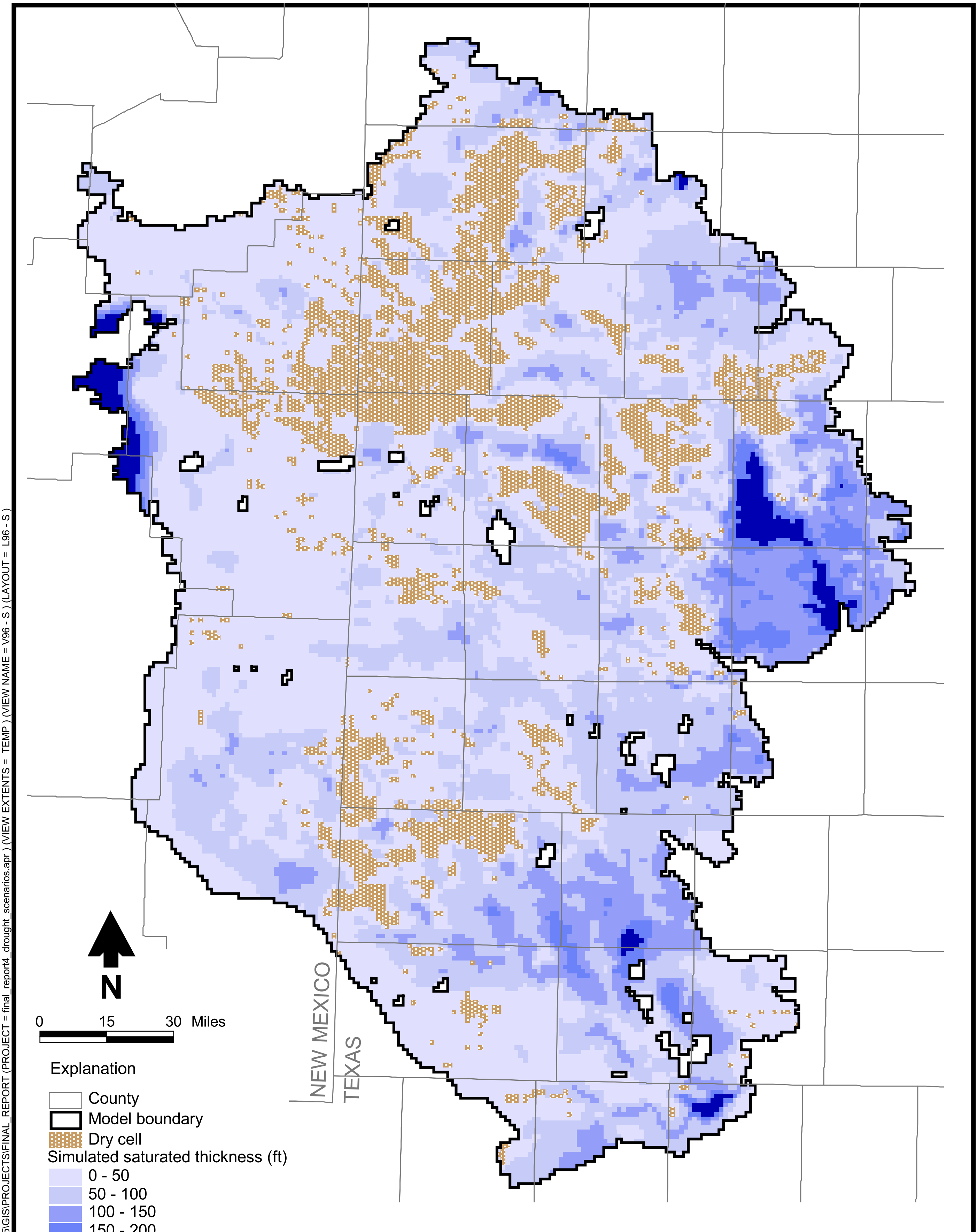


SOUTHERN OGALLALA GAM

Simulated Drawdown for 2040, Drought of Record Ending in 2040

3-14-03

Figure 95



SOUTHERN OGALLALA GAM

Simulated Saturated Thickness for 2040, Drought of Record Ending in 2040

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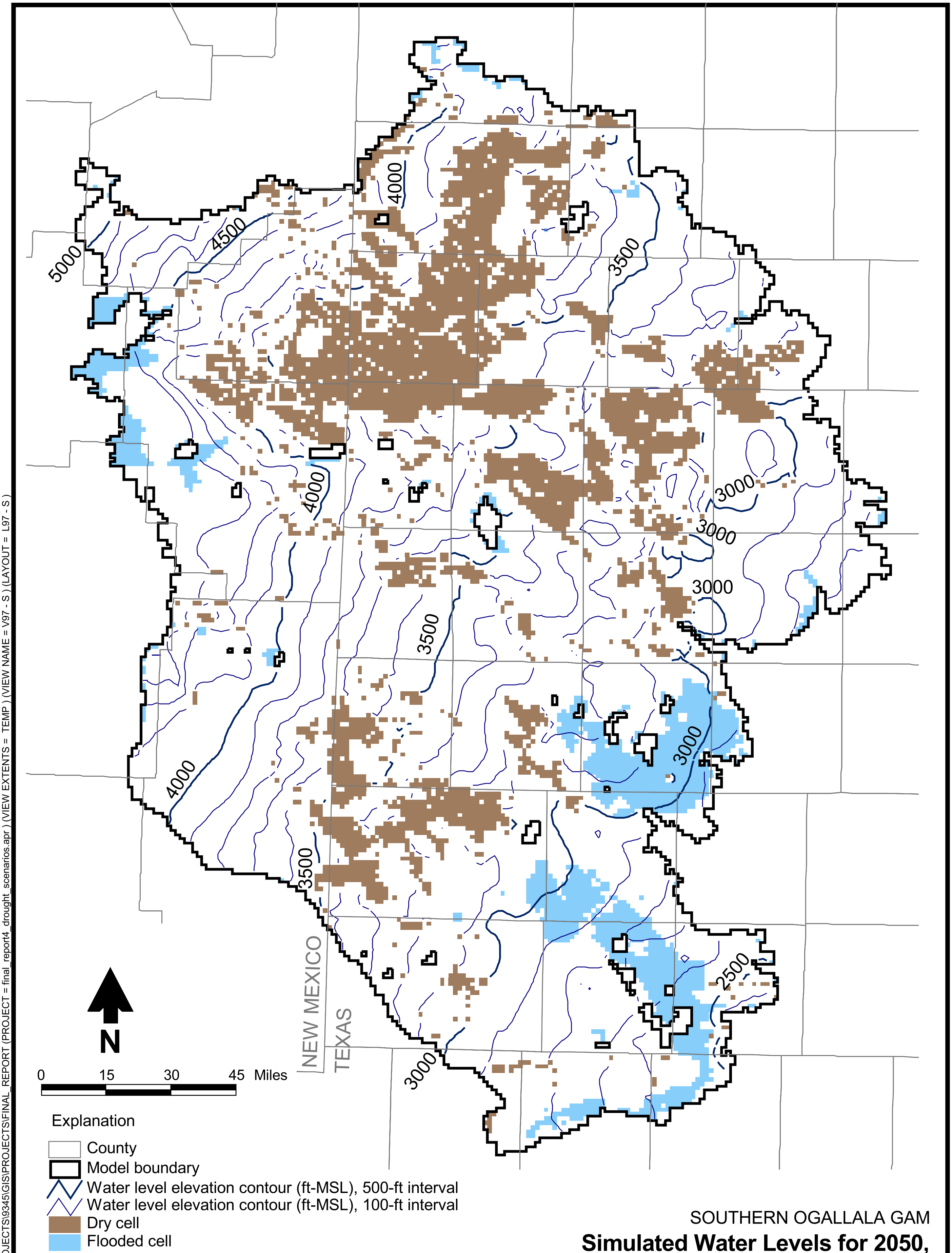
Figure 96

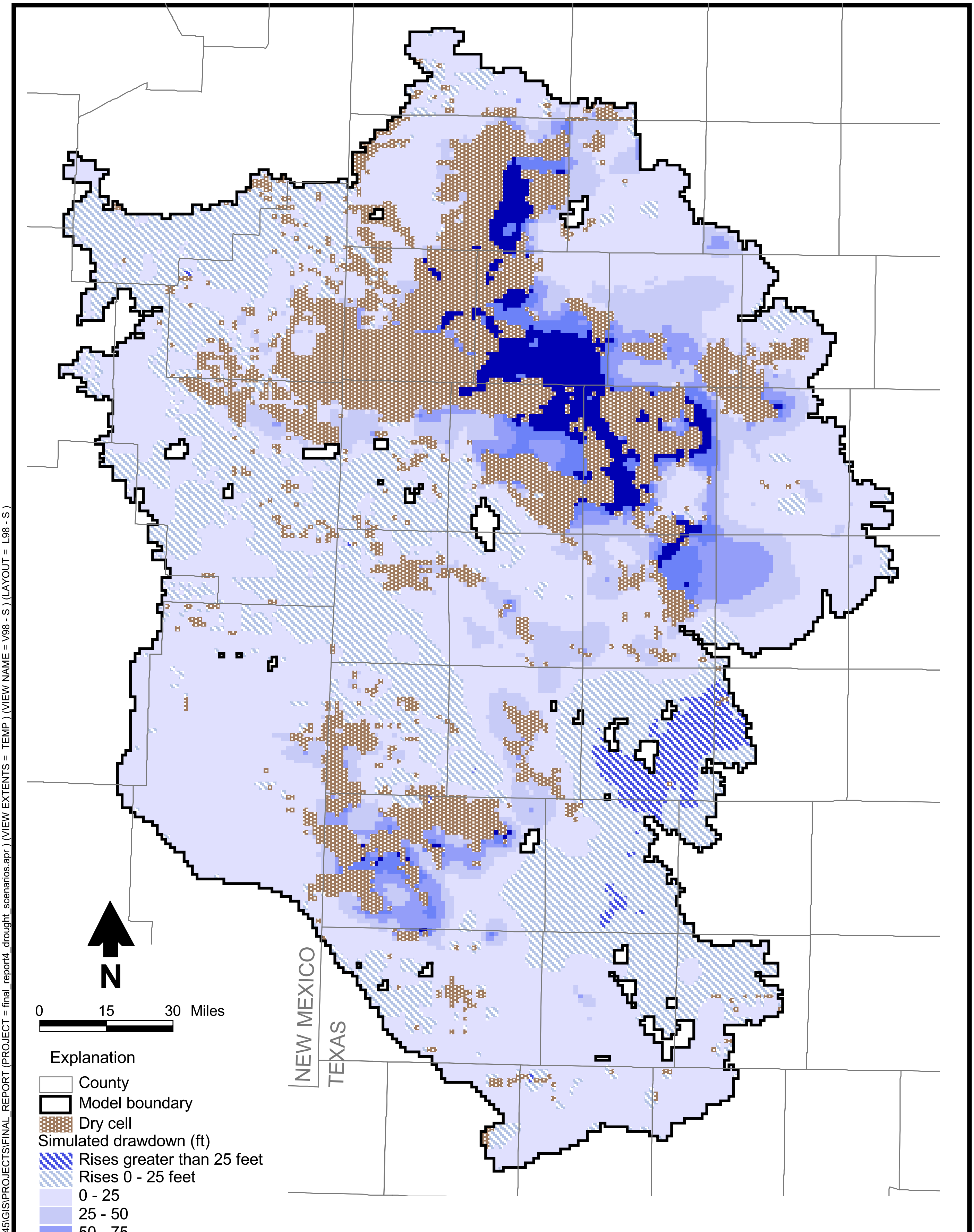


SOUTHERN OGALLALA GAM

Simulated Water Levels for 2050, Drought of Record Ending in 2050

3-14-03

Figure 97



SOUTHERN OGALLALA GAM

Simulated Drawdown for 2050, Drought of Record Ending in 2050

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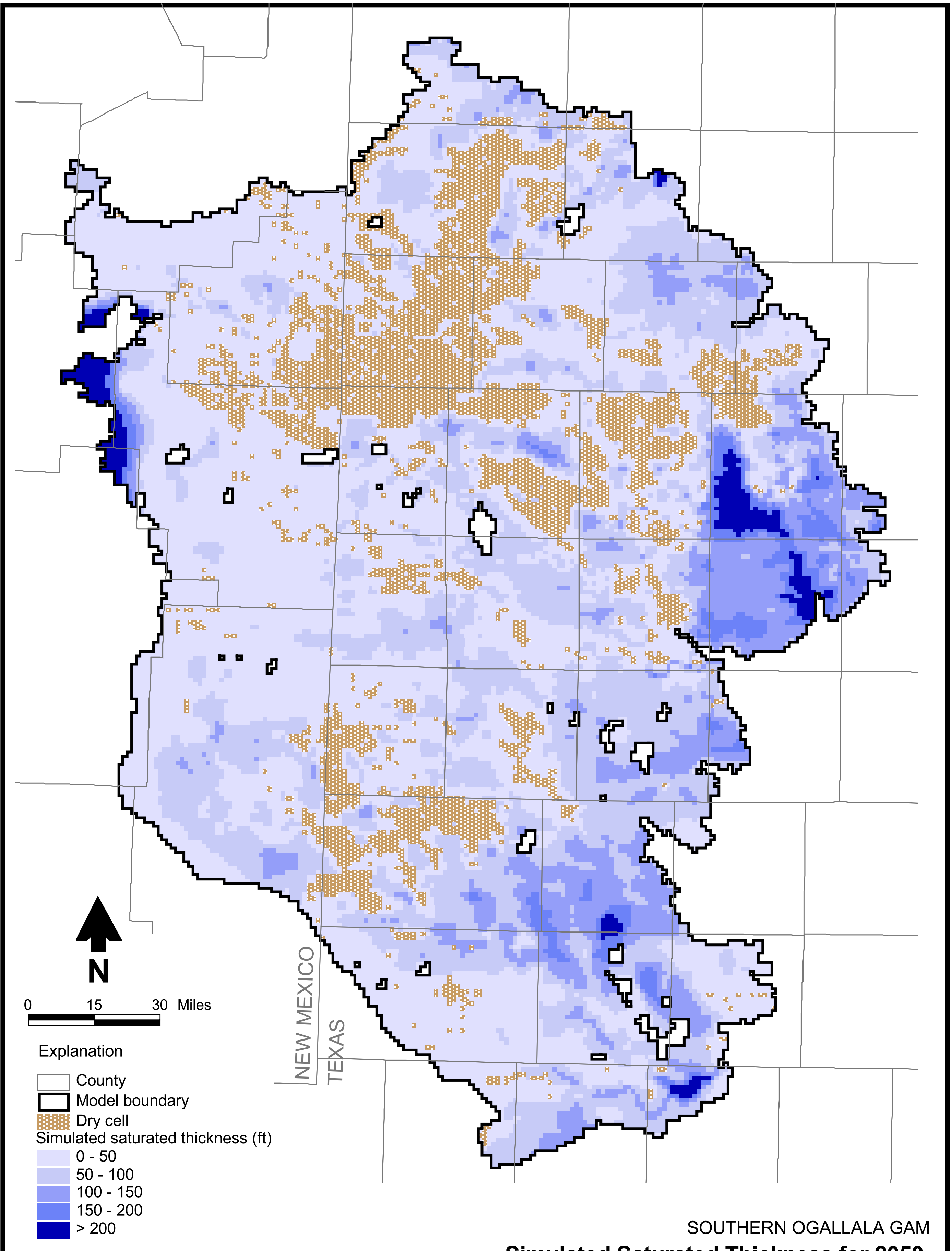
3-14-03

Figure 98



SOUTHERN OGALLALA GAM

Simulated Saturated Thickness for 2050, Drought of Record Ending in 2050

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3-14-03

Figure 99

Table 7: Simulated Water Balance for Predictive Simulations

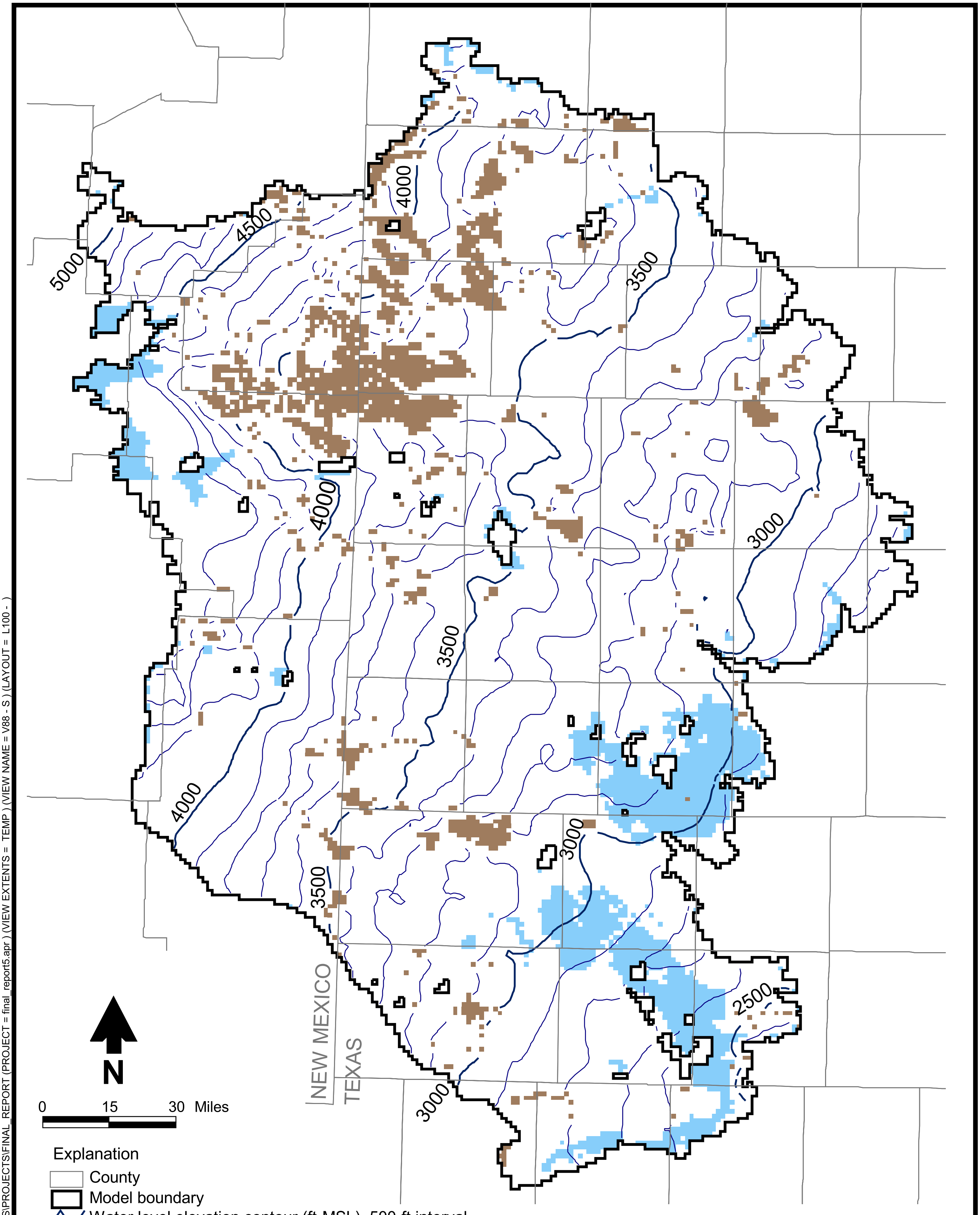
	Amount (ac-ft/yr)						
	Drought Conditions					Average Conditions	Reduced Pumping
	2010	2020	2030	2040	2050	2050	2050
Inflows							
Prescribed head boundary	750	791	902	844	677	657	215
Recharge	675,095	628,633	582,001	537,359	502,687	730,151	968,256
Storage	3,052,463	2,536,799	2,084,191	1,653,493	1,359,982	981,092	805,230
Total inflows	3,728,308	3,166,224	2,667,094	2,191,696	1,863,346	1,711,899	1,773,701
Outflows							
Prescribed head boundary	715	604	507	437	402	406	511
Pumping	3,195,226	2,675,946	2,218,068	1,776,724	1,473,157	1,180,954	1,131,829
Springs and seeps	40,299	40,090	40,160	40,312	40,571	40,974	44,699
Storage	492,798	450,169	409,527	374,926	350,002	489,490	596,806
Total outflows	3,729,038	3,166,809	2,668,263	2,192,400	1,864,132	1,711,824	1,773,845
Percent error [a]	–0.020	–0.018	–0.044	–0.032	–0.042	0.004	–0.008
Number of dry cells	1,722	2,459	3,241	3,974	4,554	4,397	1,794

[a] Calculated as: [(Total inflow – Total outflow) / Total Inflow] x 100.

Predicted water level declines are not expected to have an adverse effect on any known environmental resources, with the possible exception of springs along the eastern escarpment in the northern portion of the study area. Playa lakes generally lie well above the water table, and therefore are not affected by water level declines. Reductions in flow from interior springs has already occurred for the most part, due to historical pumping and corresponding water level declines. Where water level declines are predicted to continue in the aquifer, flows from springs will continue to decline as well. This will most likely occur along the eastern escarpment north of Lubbock. In parts of the southeastern portion of the study area, where water levels have risen historically and may continue to rise, flows from springs and seeps will be maintained or even increase.

Limitations of the Model

The Southern Ogallala GAM was developed for regional analysis, generally on the scale of at least a county. Although the model may serve as a useful starting point for conducting site-specific analysis (.e.g., computation of water levels at a sub-county scale), it should not be used for local analysis without evaluation of its suitability and/or modification for such applications. Appropriate modifications may consist of refining the model grid in the horizontal and/or vertical dimensions and comparing historical simulation results to additional observed data in the region of interest.



SOUTHERN OGALLALA GAM

Simulated Water Levels for 2050, Average Reduced Pumping Conditions

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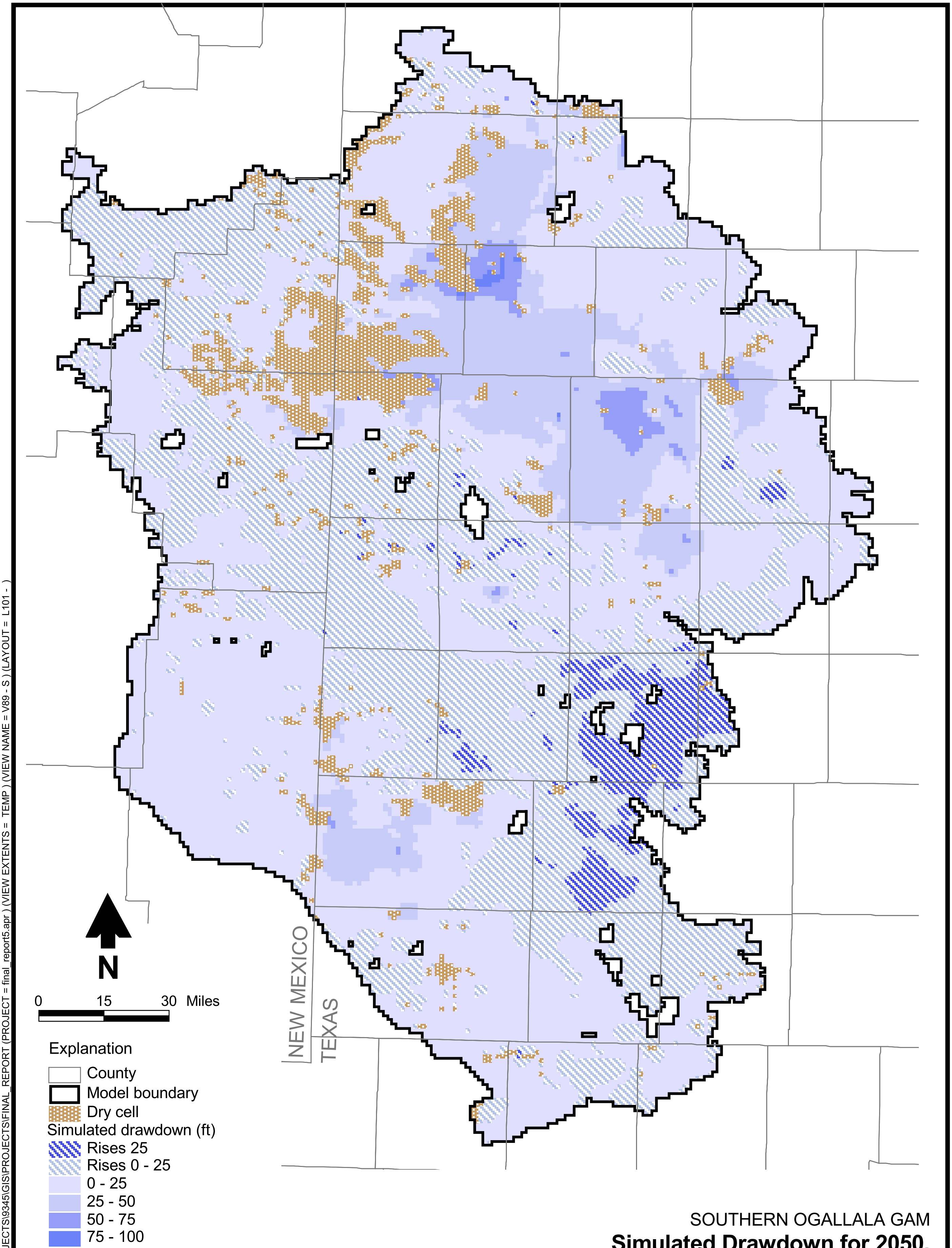
3-14-03

Figure 100



SOUTHERN OGALLALA GAM

Simulated Drawdown for 2050, Average Reduced Pumping Conditions

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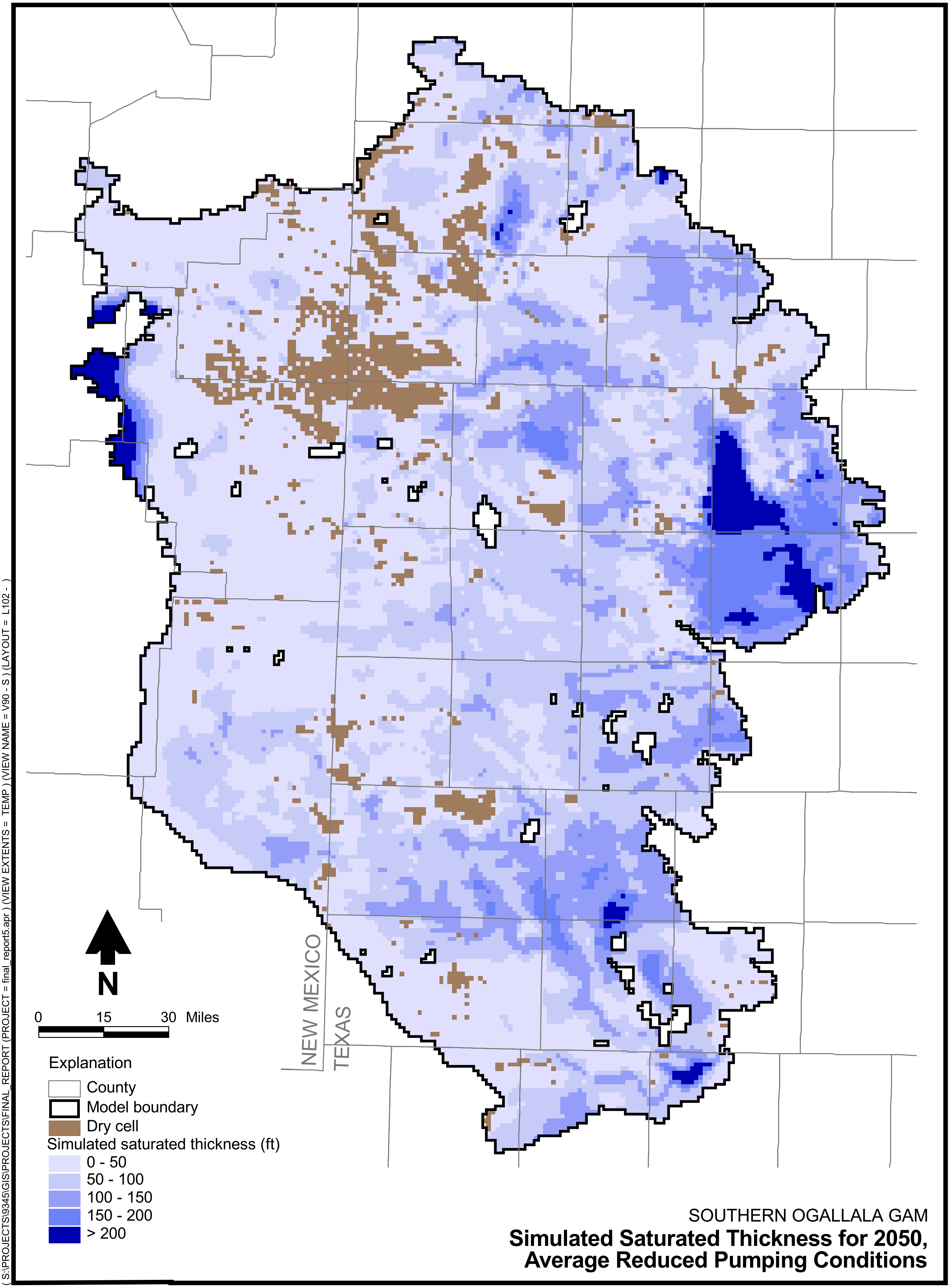
3-14-03



SOUTHERN OGALLALA GAM

Simulated Saturated Thickness for 2050, Average Reduced Pumping Conditions

3-14-03

Figure 102

In addition, all groundwater flow models have limitations based on data constraints and the methodology used to construct them. One of the basic assumptions intrinsic in using a model for predictive purposes is that the hydrologic system will behave in the future as it did in the past if similar stresses (such as pumping and recharge) are applied. This assumption may or may not be valid as water levels in deeper portions of the aquifer decline even further. As the saturated thickness of the aquifer changes, average aquifer parameters such as hydraulic conductivity and specific yield can also change. The values used in the current model are a function of both (1) field observations and (2) the calibration history and observed conditions used to calibrate the model. Because only a single model layer was used, estimated aquifer parameters are assumed to be average values representative of the entire aquifer thickness as it existed over the period of 1940 through 2000.

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

Additional limitations of the model are intrinsic to the available data sets used to create it. As discussed elsewhere, some of the model input parameters are relatively unconstrained and in some cases simply not known. Although reasonable estimates of hydraulic parameters, recharge, and pumping rates were used in the modeling, errors certainly exist within the construct of the model due to errors in estimated inputs. In general, the magnitude of such errors is reduced in regions where greater amounts of observed data are available.

Finally, there are a number of regions in the model where the simulated predevelopment water levels, and therefore the starting water levels for the transient simulation, are either high or low relative to observed values. This situation is unavoidable because the model, like any groundwater flow model, could not be perfectly calibrated to observed conditions. For the most part, however, general trends in water levels are replicated well in the transient model over the period 1940 through 2000. It is recommended, therefore, that the model be used to simulate expected trends in water levels, rather than absolute values of water levels.

Recommended Future Improvements

Future improvements to the model should be based on additional observed data for, in order of importance, agricultural pumping, recharge (both natural and irrigation return flow), and aquifer parameters. The dominant water budget component in the transient and predictive simulations is the volume of pumping for irrigated agriculture. However, the relative volumes of pumping from year to year, as well as the distribution of pumping, are relatively poorly defined. Although it may be tempting to think that accurate current and future estimates of pumping are of primary importance, historical pumping distributions (particularly over the past 20 years or so) are also very important because they affect model input parameters selected during the calibration process, such as hydraulic conductivity and recharge.

Next to agricultural pumping, additional information concerning the magnitude of recharge, particularly beneath agricultural lands, should be collected. The recharge rates used in the model are reasonable based on existing studies and hydrologic observations, but they are virtually unconstrained by observed data in terms of magnitude and distribution. In the transient simulation, recharge accounts for more than a third of the total groundwater pumped and is therefore a critical water budget component. Furthermore, the relationship among recharge, pumping, and assumed return flow in irrigated regions is highly non-unique. Changes in any one of these parameters affect simulated water levels in an identical fashion. For example, if estimated agricultural pumping is too high for a given area in the model, prescribed recharge (either from precipitation and/or irrigation return flow) can be increased to compensate for the inaccuracy, and reasonable simulated water levels could be obtained. If reasonable limits on the prescribed recharge are not available from field studies, the recharge could be set too high, which would subsequently cause inaccuracies in the predictive simulation results.

Additional information concerning aquifer parameters such as hydraulic conductivity and specific capacity is always useful. These parameters, along with recharge and aquifer geometry, determine how water levels will respond to groundwater pumping. In particular, for regions where the Ogallala Formation is underlain by Cretaceous sediments, additional information on the thickness and hydraulic properties of these sediments that are in hydraulic communication with the Ogallala sediments would be useful.

Summary and Conclusions

A numerical groundwater flow model was constructed for the Southern Ogallala aquifer in Texas and New Mexico. The model relies heavily on published information and additional supporting studies completed as part of this project. These studies include the extension of existing geological models and application of the geologic model in conjunction with field data to determine a hydraulic conductivity field, detailed estimation of agricultural pumping during the 1980s and 1990s using climatic data and information from producers and UWCDs, and evaluation of recharge at three sites, one in a natural setting and two at fields that have been irrigated since the 1950s.

The model was constructed in such a way as to minimize, to the extent possible, non-uniqueness in aquifer parameter estimates and other model inputs. A steady-state model was developed for predevelopment (1940) conditions to determine hydraulic conductivity of the aquifer and predevelopment recharge rates. Results of the steady-state model indicate that, under predevelopment conditions, approximately 47 percent of the discharge from the aquifer occurred at springs along draws and the margins of salt lakes west of the eastern escarpment. The remainder of the discharge occurred at springs and seeps along the eastern escarpment, or as outflow to the Central Ogallala aquifer near Amarillo. Simulated predevelopment recharge ranges from 0.009 in/yr to 0.083 in/yr, with higher rates prescribed in regions with lower-permeability soils in the northern part of the study area.

Results from the steady state simulation were used as initial conditions for the transient calibration, which was conducted for the period 1940 through 2000. Prescribed head cells used in the steady-state model calibration were changed to drain cells to allow changes in simulated outflow with time. Transient model calibration was conducted using 80 hydrographs for locations throughout the study area and all observed water levels for the winters of 1979-1980, 1989-1990, and 1999-2000. Hydraulic conductivity was not adjusted during the transient calibration. Several adjustments were made to specific yield and assumed irrigation return flow percentages early on in the calibration process, and several adjustments (decreases) were made to estimated agricultural pumping for certain counties in certain years (generally counties in the south-central portion of the study area where saturated thickness is limited).

The transient model was calibrated primarily through adjustment of enhanced recharge beneath both irrigated and non-irrigated agricultural lands. Recharge applied in the model beneath agricultural lands is significantly greater than estimated predevelopment recharge rates. Recharge prescribed beneath irrigated lands ranges from 2.25 in/yr to 1.25 in/yr, and recharge applied beneath non-irrigated agricultural lands ranges from 2.0 in/yr to 0.25 in/yr. Higher recharge rates are prescribed for higher-permeability soils and beneath irrigated fields as opposed to non-irrigated fields.

This recharge does not include irrigation return flow, which is assumed to occur during the same year as agricultural pumping. Irrigation return flow as high as 55 percent of the water pumped during early decades is assumed in the transient simulation, but it steadily declines over the course of the simulation to 10 percent of water pumped in Texas and 20 percent of water pumped in New Mexico for the 1996 through 2000 period.

The vast majority of discharge (94 percent) for the year 2000 is from wells; less than 2 percent of the total discharge is to springs. Approximately 37 percent of the inflow to the aquifer is from recharge, and 63 percent is from aquifer storage, indicating that, overall, the aquifer is being mined.

Predictive simulations conducted using the model indicate that, if estimated future withdrawals are realized, water levels in the aquifer could decline to a point at which significant regions currently practicing irrigated agriculture could be essentially dewatered. For the most part, the simulation results for the average conditions and drought of record conditions are very similar.

Although the model predicts that some regions of the aquifer beneath Cochran, Hockley, Lubbock, Yoakum, Terry, and Gaines Counties could become essentially dry, these counties have experienced relatively stable water levels over the past several decades. It is believed that producers in these counties, which generally have limited saturated thickness, adjust their irrigation practices and/or crop types in such a way that water level declines do not occur over the long term. This might be accomplished through reduced application of irrigation water (i.e., application of less water than would be required for maximum yield).

If this is true, future pumping rates could be smaller than those assumed for the predictive simulations, and resulting drawdown could be significantly less. However, recent metering data collected from some of the UWCDs in these areas (the Sandy Land UWCD in Yoakum County and the Mesa UWCD in Dawson County) do not support the hypothesis of reduced application rates in these counties. Continued evaluation of metering data will be useful to determine irrigation practices in this area.

In addition, the model predicts that some portions of western Yoakum and Gaines Counties will go dry sooner than they actually might, even if projected pumping rates are correct. This is because the initial water levels obtained from the calibrated model in these areas are generally lower than observed values.

Simulated declines in water levels in the northern counties, such as Parmer, Deaf Smith, Castro, Bailey, Lamb, Hale, and Floyd, are generally continuations of historical trends in these areas. Saturated thicknesses in these counties are generally greater than those to the south, and farmers are generally not constrained by availability of water or well yield, so long as they are willing to pay the energy costs of pumping. As is the case with Gaines and Yoakum Counties, simulated water level declines in the model cause the aquifer to go dry prematurely in Parmer and Bailey Counties because the starting water level simulated in the model is lower than observed values in these areas.

As water levels decline in the northern portion of study area, farmers will likely adjust their irrigation practices to respond to the reduced availability of water (similar to farmers in the south), and the life of the aquifer will be extended. A predictive simulation with future pumping reduced by 55 percent in these areas showed significant saturated thickness remaining throughout much of this region as of 2050.

Acknowledgments

The input and assistance of all of the participants of the Stakeholder Advisory Forums are gratefully acknowledged. In particular, we would like to thank Mr. Harvey Everheart, Director of the Mesa UWCD; Mr. Jason Coleman, Director of the South Plains UWCD; and Mr. Ferrel Wheeler, Director of the Garza Underground and Fresh Water Conservation District, for their input and insights. Mr. Don McReynolds, Geologist for the HPUWCD No.1, willingly shared his wealth of knowledge, expertise, and maps concerning the Southern Ogallala aquifer. And finally, we gratefully acknowledge the input and hospitality of Mr. Jim Conkwright, Director of the HPUWCD No. 1, who hosted the Stakeholder Advisory Forums at the District offices in Lubbock, Texas.

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