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.

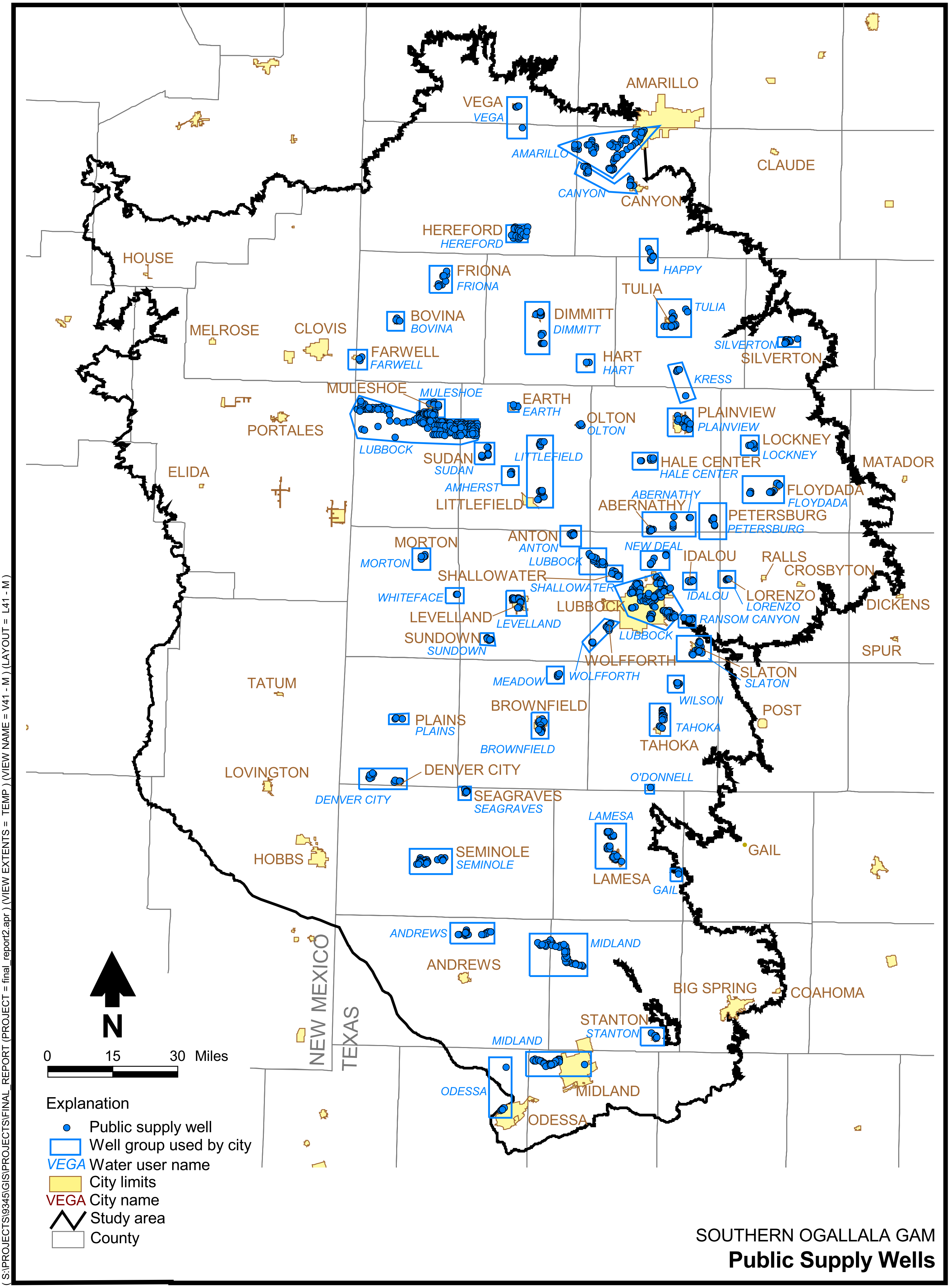
For the counties in Texas, values for these uses were determined from compilations of the water use inventories provided by the TWDB. For counties in New Mexico, estimates of municipal, livestock, and power generation (for Lea County only) use were compiled from Dinwiddie (1963), New Mexico of the State 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,



SOUTHERN OGALLALA GAM

Public Supply Wells

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Figure 41

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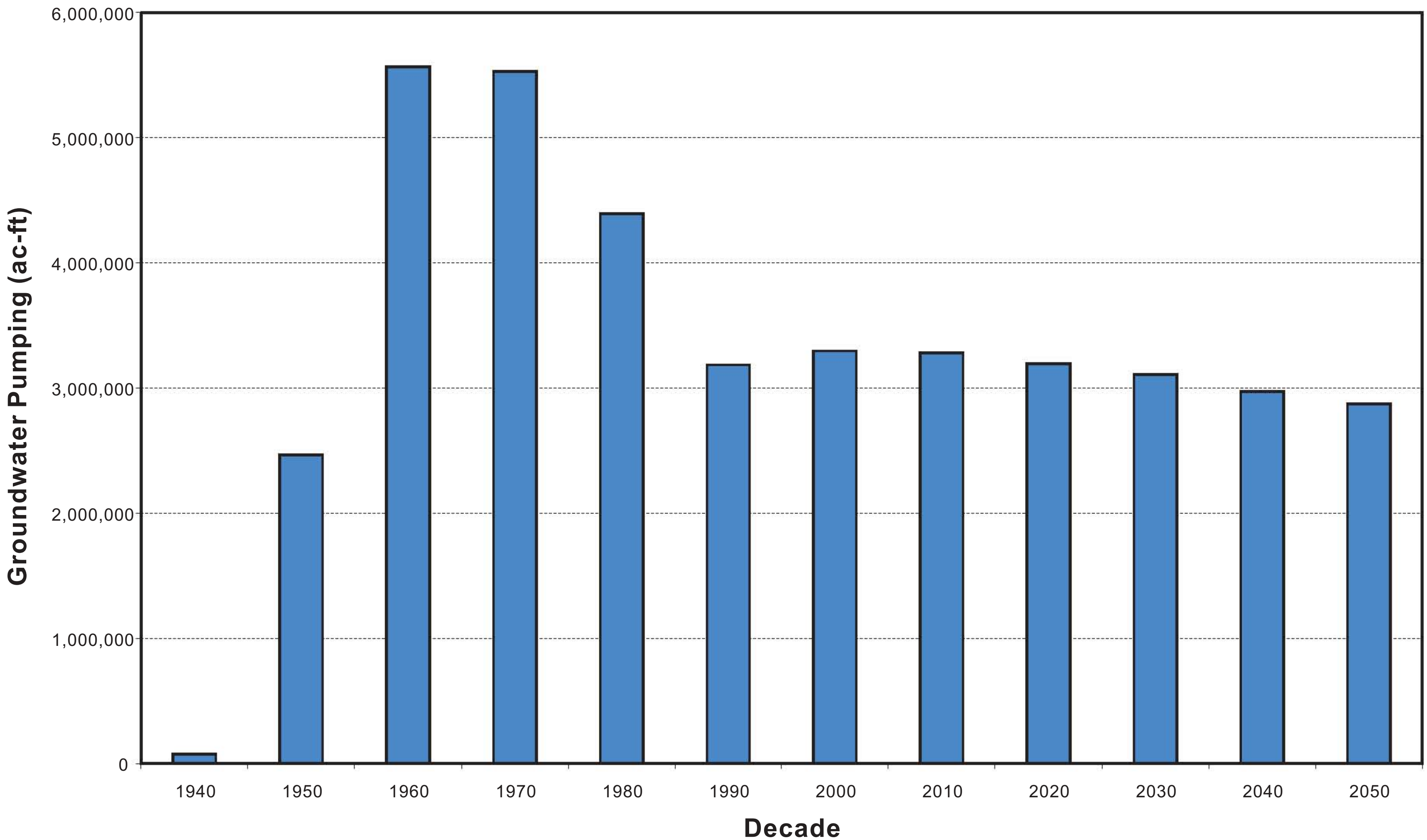

SOUTHERN OGALLALA GAM

Historical and Predictive Total Groundwater Withdrawals

Figure 42

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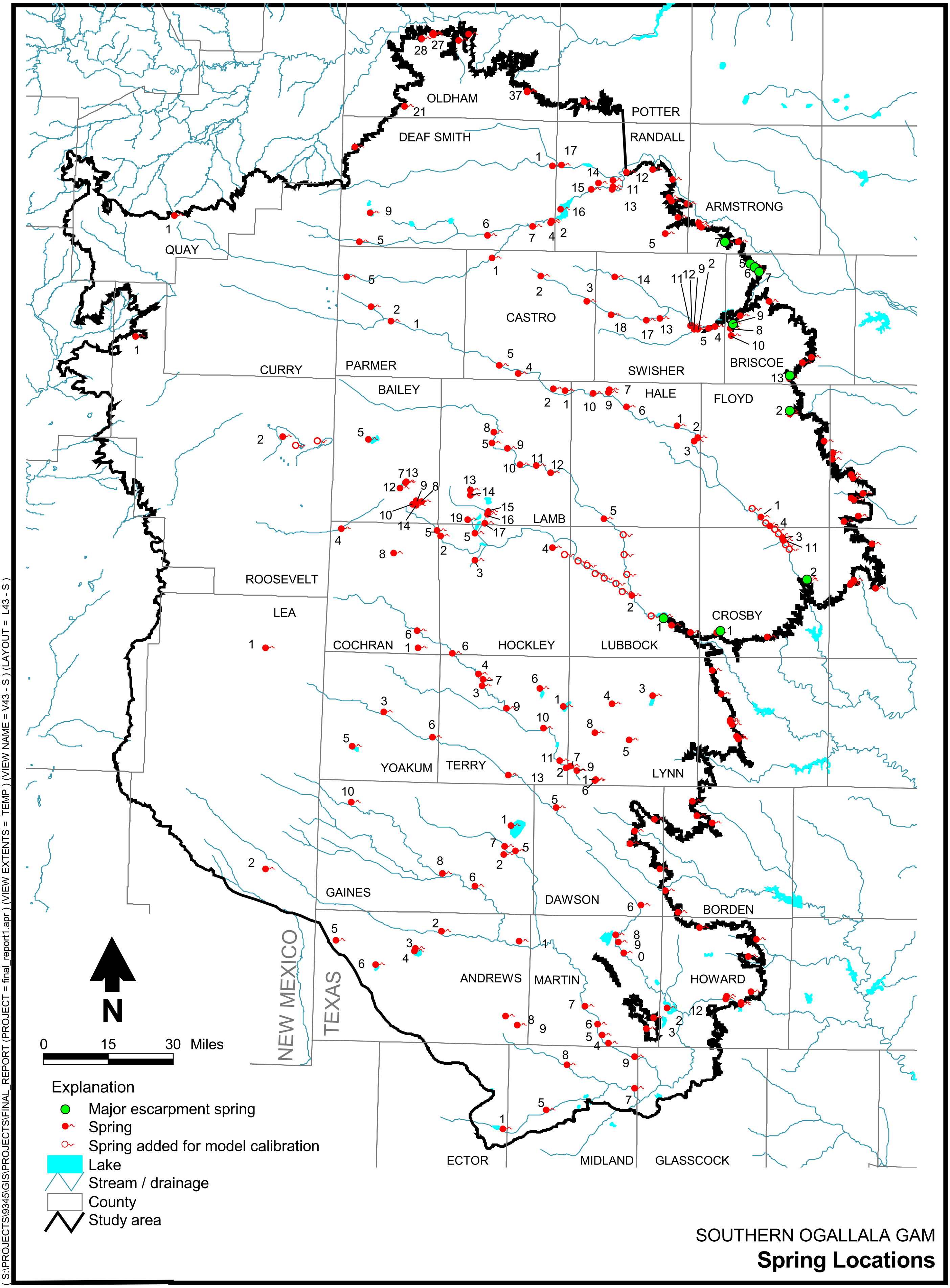


SOUTHERN OGALLALA GAM

Spring Locations

1-30-03

Figure 43

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.

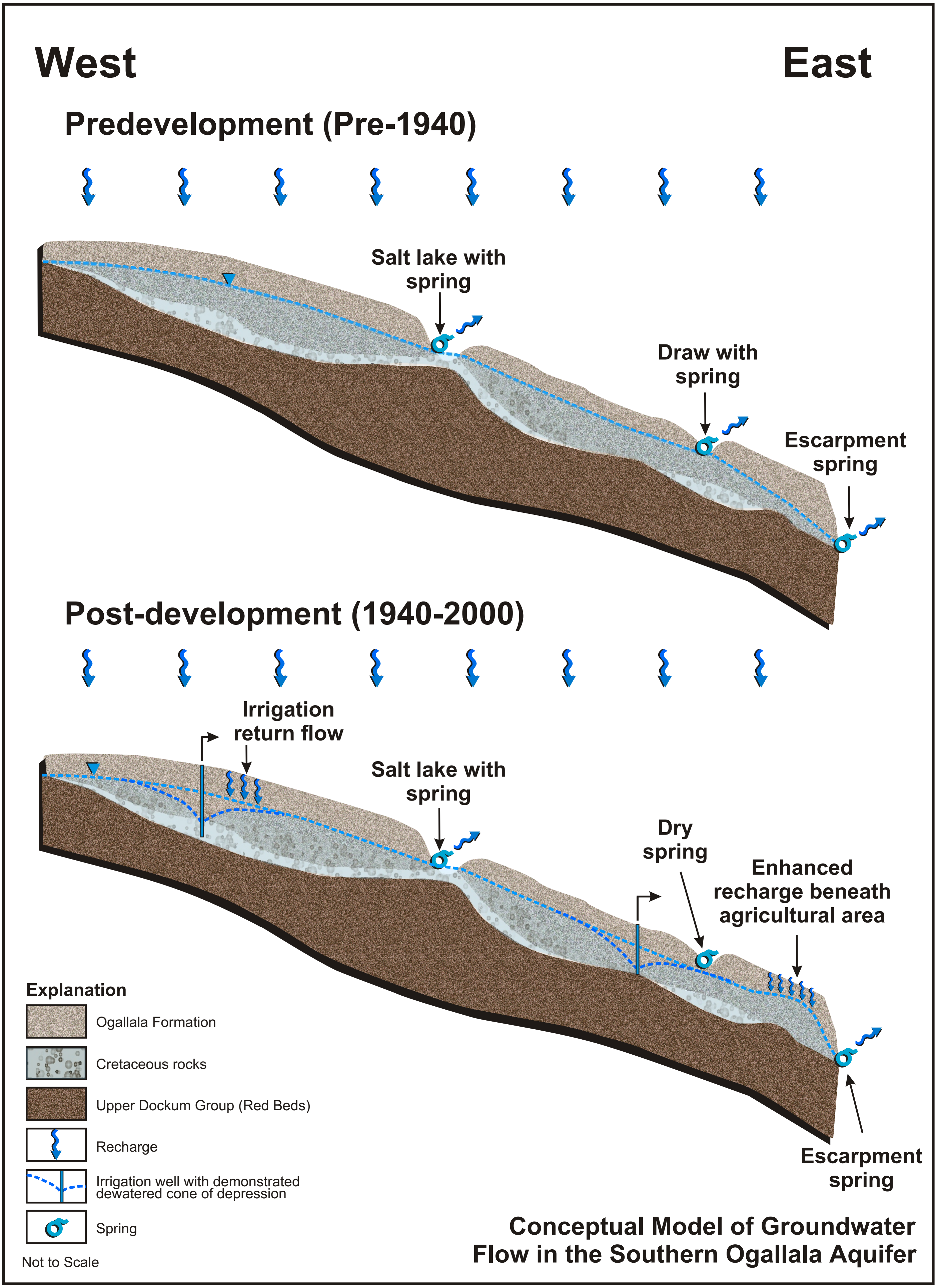
The Southern Ogallala aquifer is recharged by precipitation. Significant recharge occurs at playa lakes, beneath agricultural fields, and likely within the bottoms of ephemeral draws. Recharge in natural, inter-playa settings is negligible. Recharge also occurs from the return flow of a portion of irrigation 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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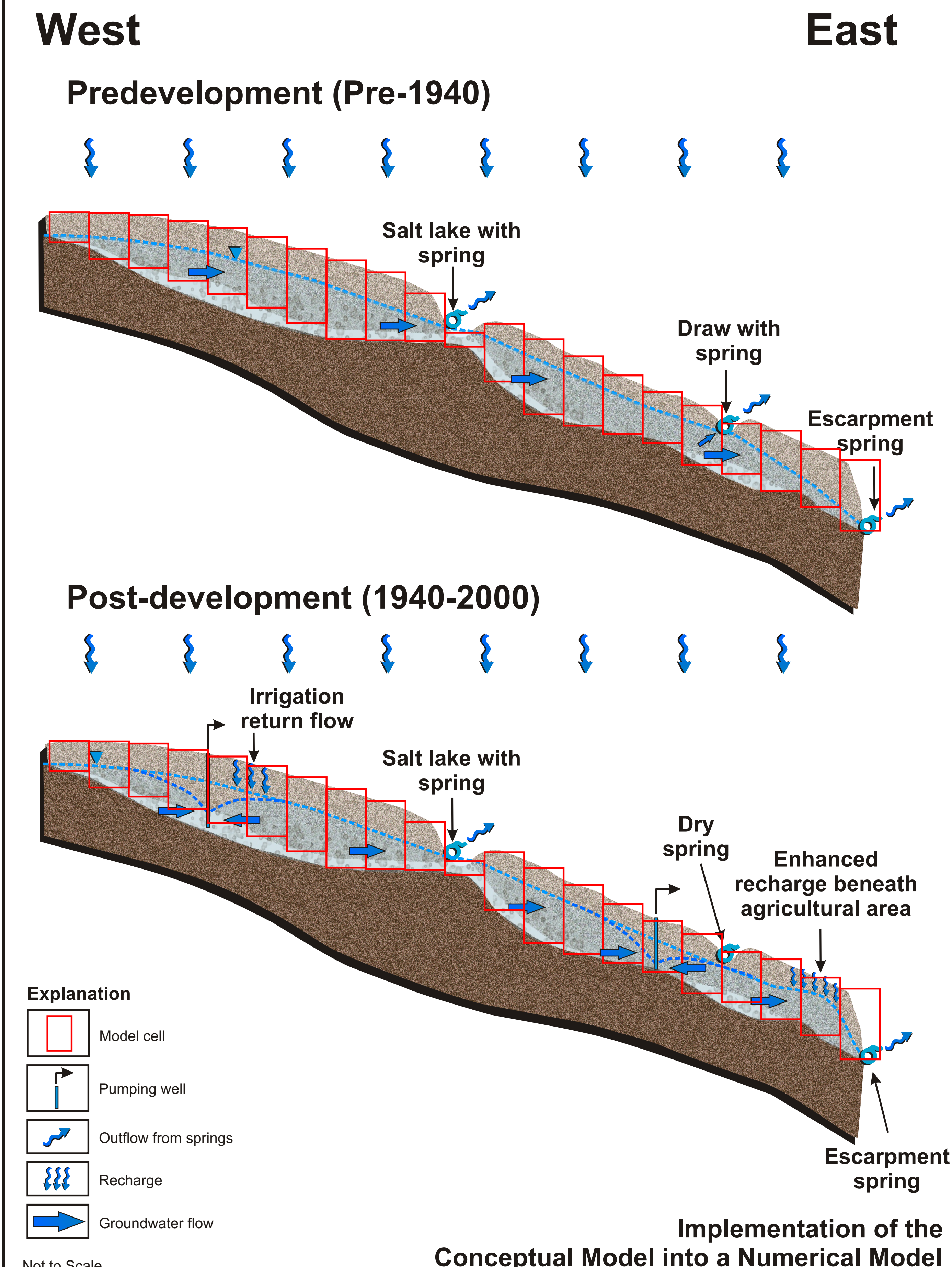
1-30-03

Figure 44a



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Implementation of the Conceptual Model into a Numerical Model

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Figure 44b

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.

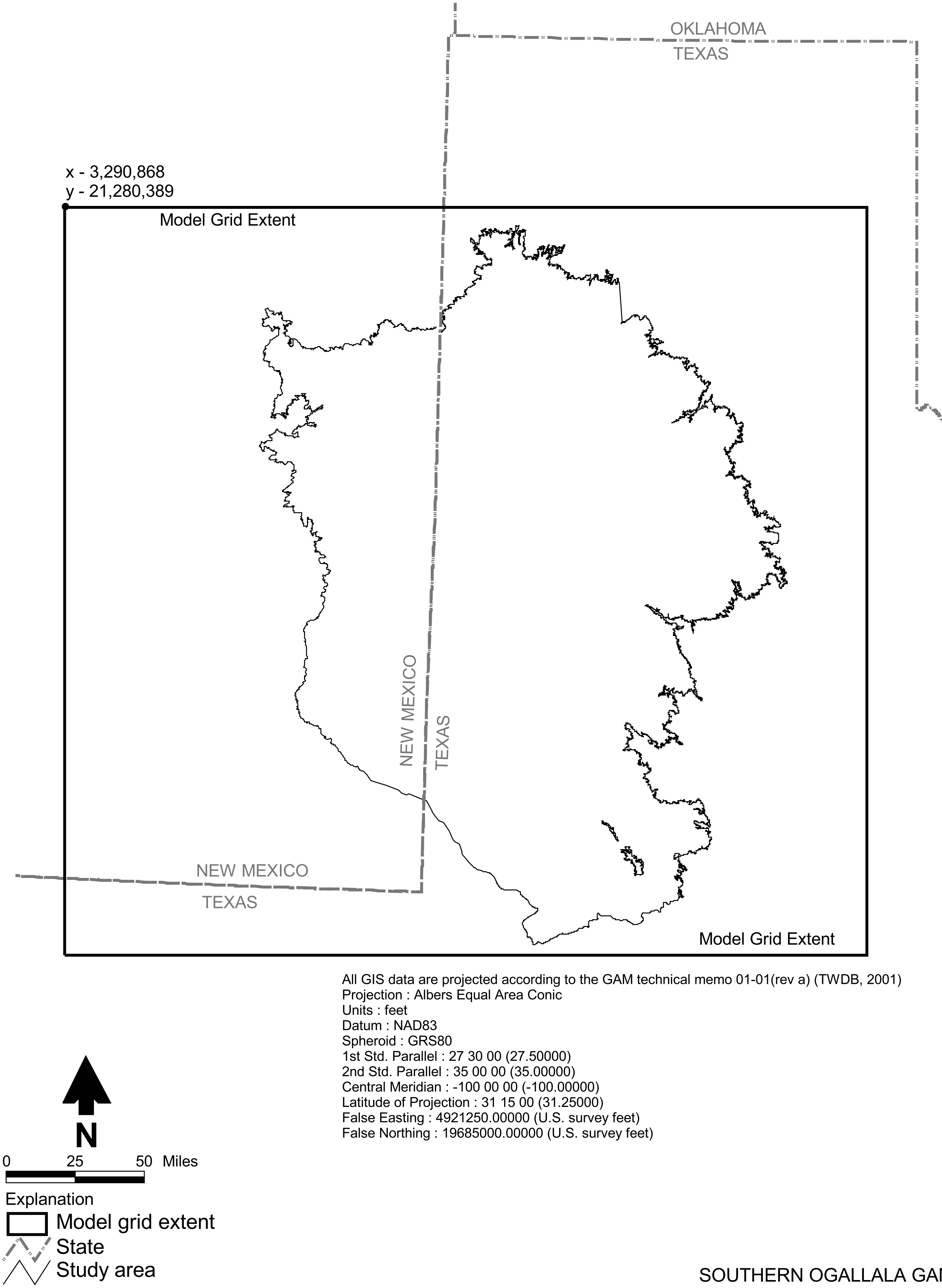
Initially, the hydraulic conductivity for each of the 15 zones was set to the geometric mean for that zone. After a number of early model calibration runs, however, the hydraulic conductivity of each zone was increased by 20 percent. This zonation of hydraulic conductivity is considered to be the initial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



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

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SOUTHERN OGALLALA GAM

Extent of Model Grid

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Figure 45

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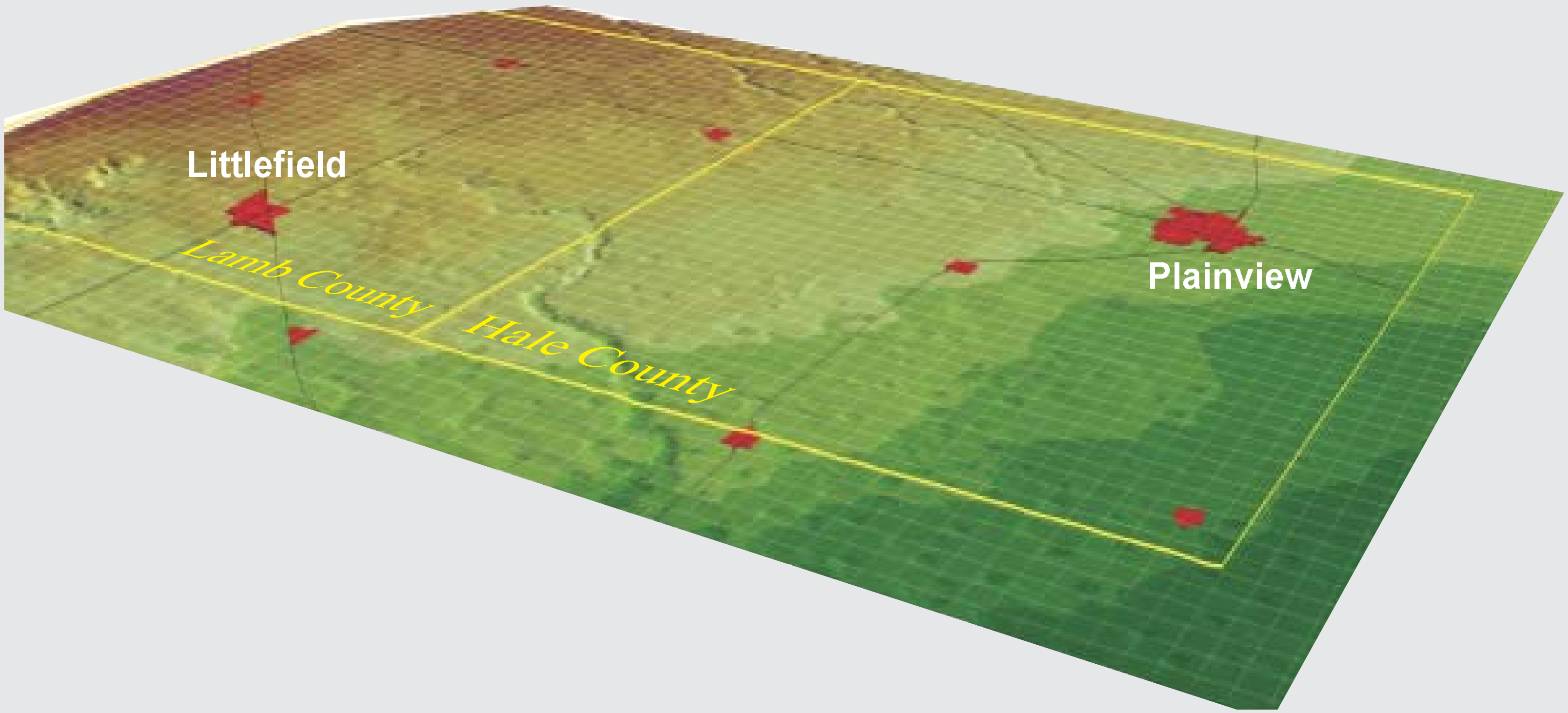

SOUTHERN OGALLALA GAM

Lamb and Hale Counties with Model Grid

Figure 46

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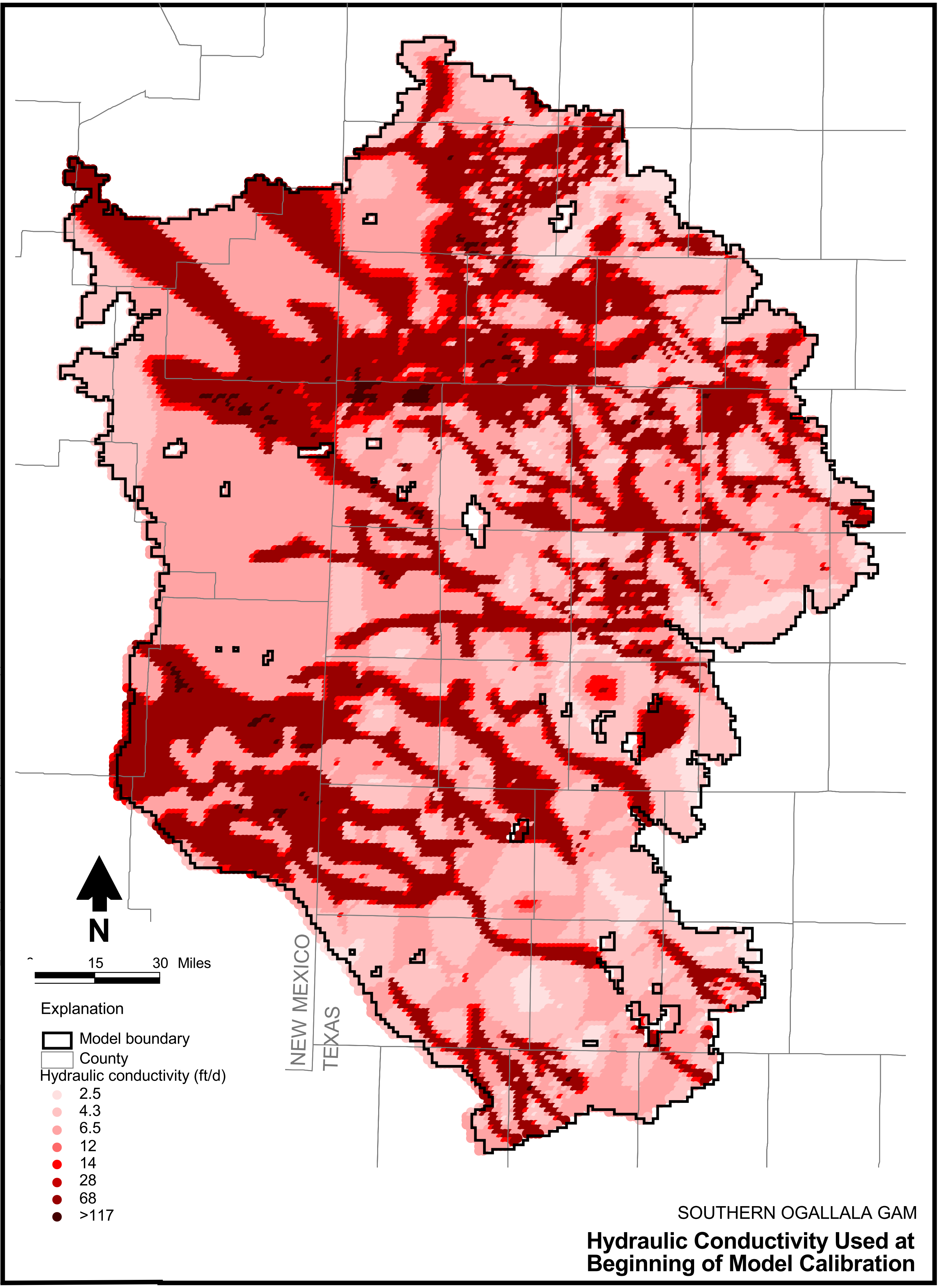

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SOUTHERN OGALLALA GAM

Hydraulic Conductivity Used at Beginning of Model Calibration

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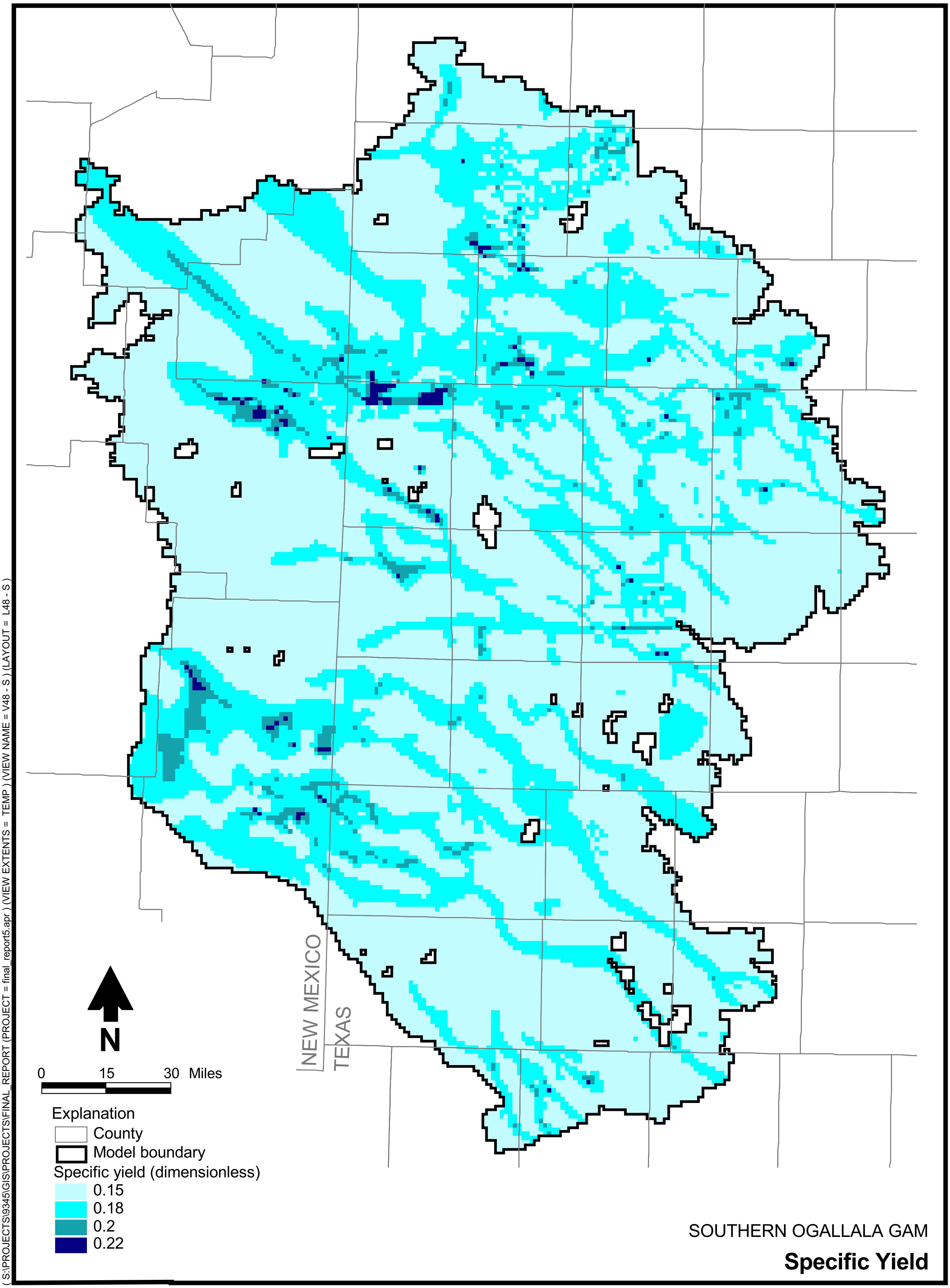


SOUTHERN OGALLALA GAM

Specific Yield

1-30-03

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.

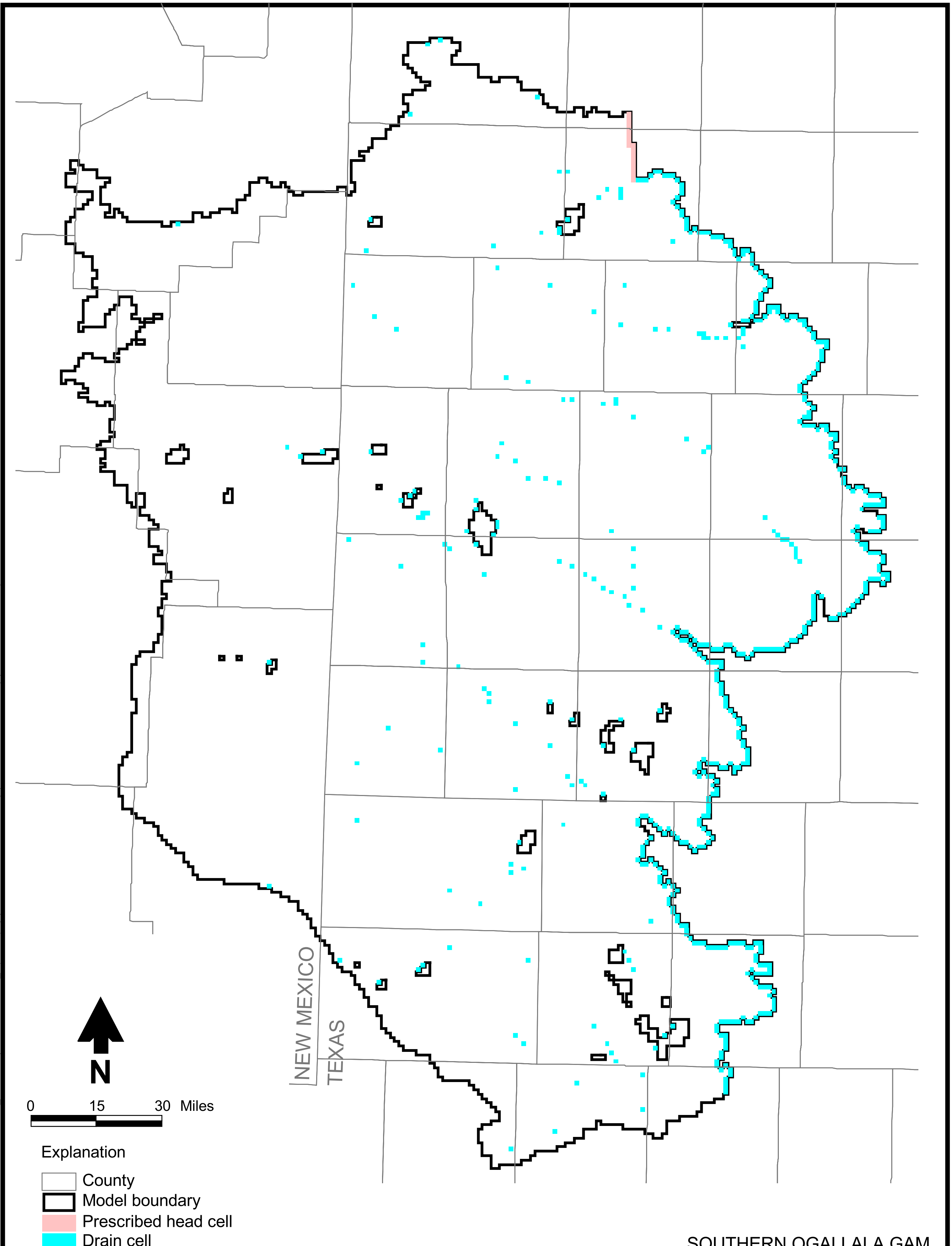
For the model cells along the eastern caprock escarpment, outflow boundaries were used. In the predevelopment model, hydraulic head was prescribed for these cells based on the predevelopment water level contour map (fig. 21). For the transient calibration and predictive simulations, these boundary cells 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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1-30-03

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.

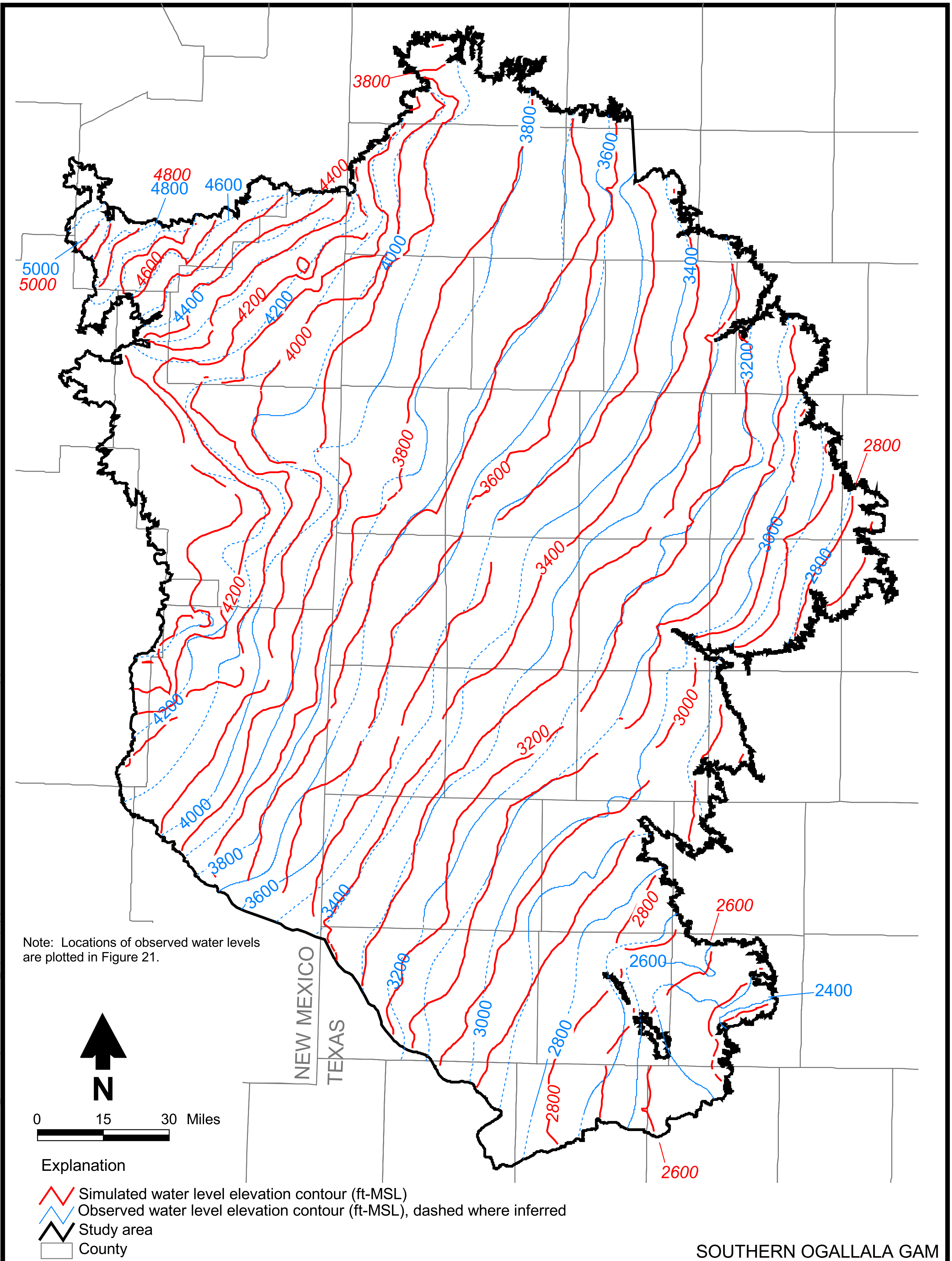
Figure 51 also provides the calibration statistics for the steady-state model for the match between simulated and observed 1940 hydraulic heads. Calibration statistics are presented in terms of root-mean-squared error (RMSE), mean-absolute error (MAE), and residual mean error (RME). These terms are defined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

Figure 50

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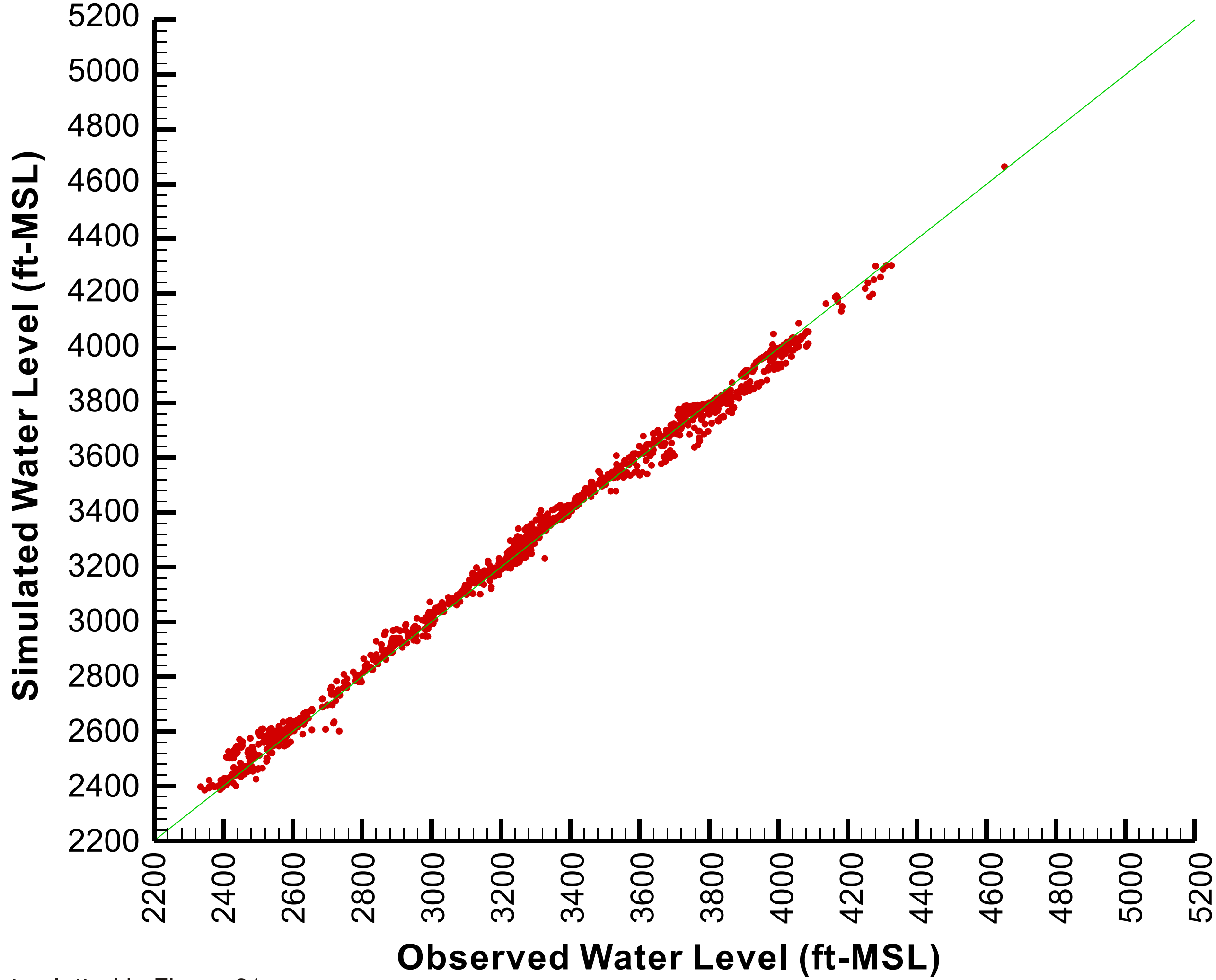

Note:
Observed data points plotted in Figure 21

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:

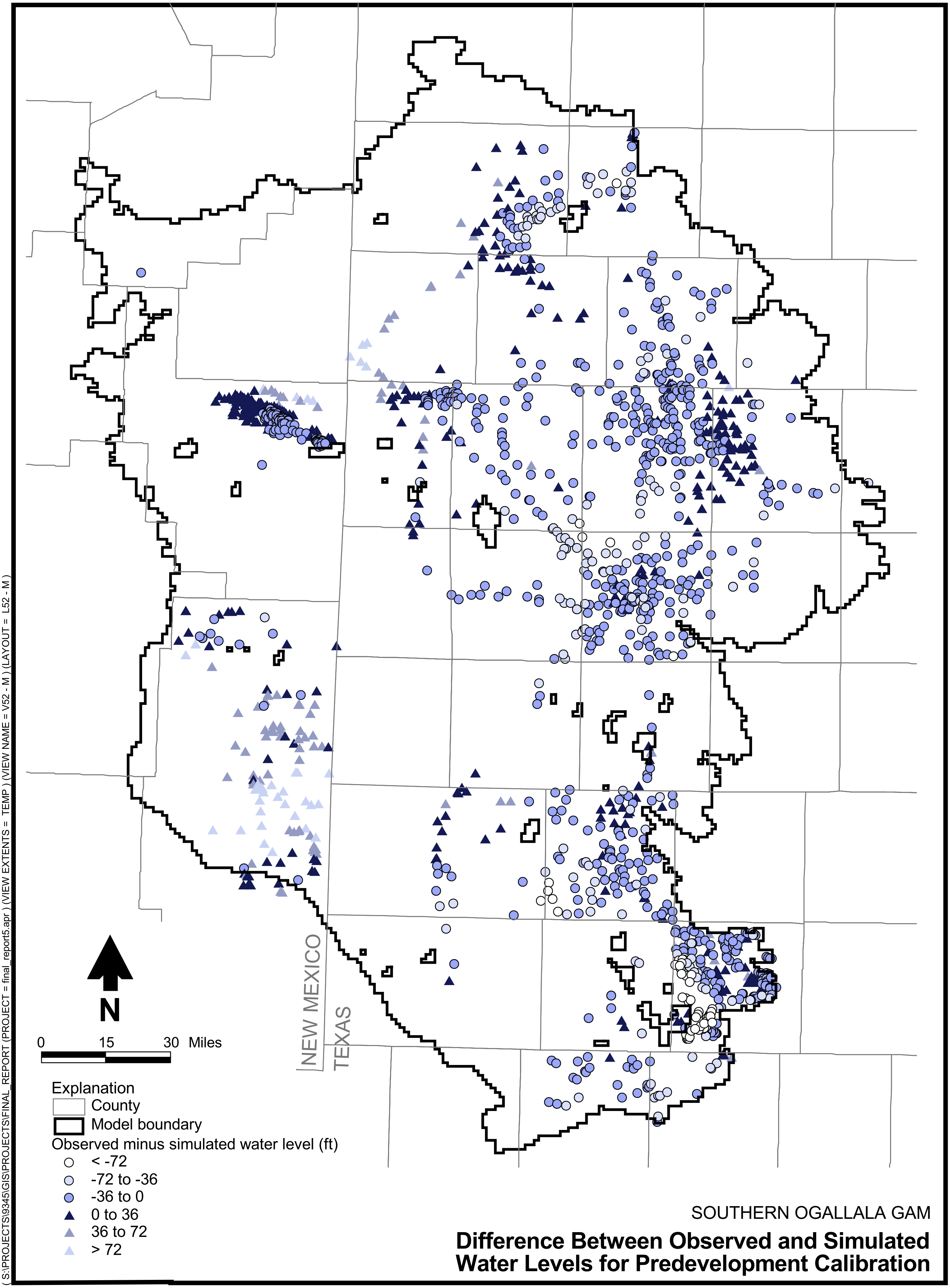
- In Lea County, New Mexico and western Gaines County, Texas, simulated water levels are consistently lower than observed water levels. The simulated water levels in this area can be observed at about the 3,500- to 4,000-ft levels in Figure 51.
- In southwestern Parmer County, Texas and southeastern 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

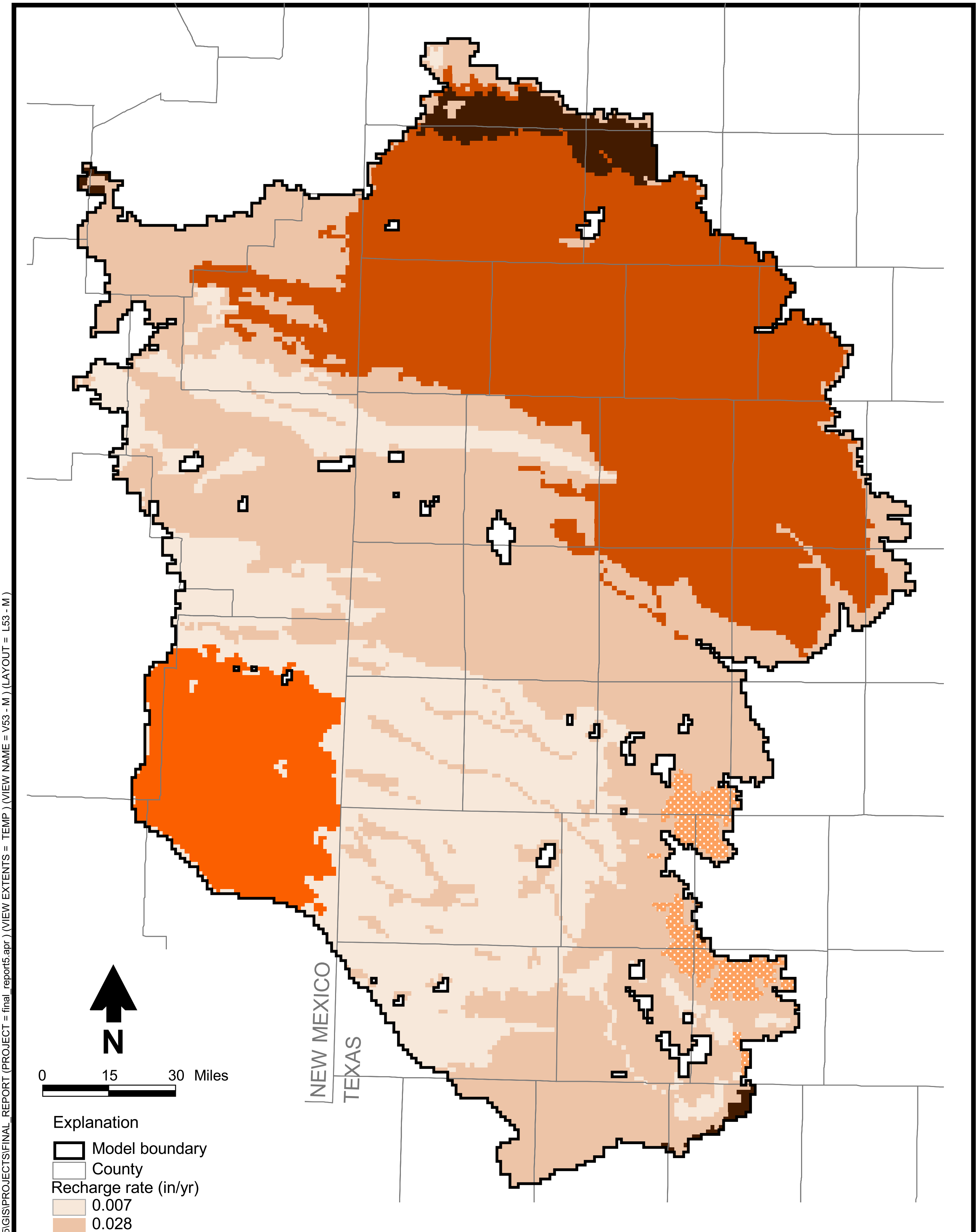


SOUTHERN OGALLALA GAM

Difference Between Observed and Simulated Water Levels for Predevelopment Calibration

3-14-03

Figure 52



SOUTHERN OGALLALA GAM

Predevelopment Recharge Rates

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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.

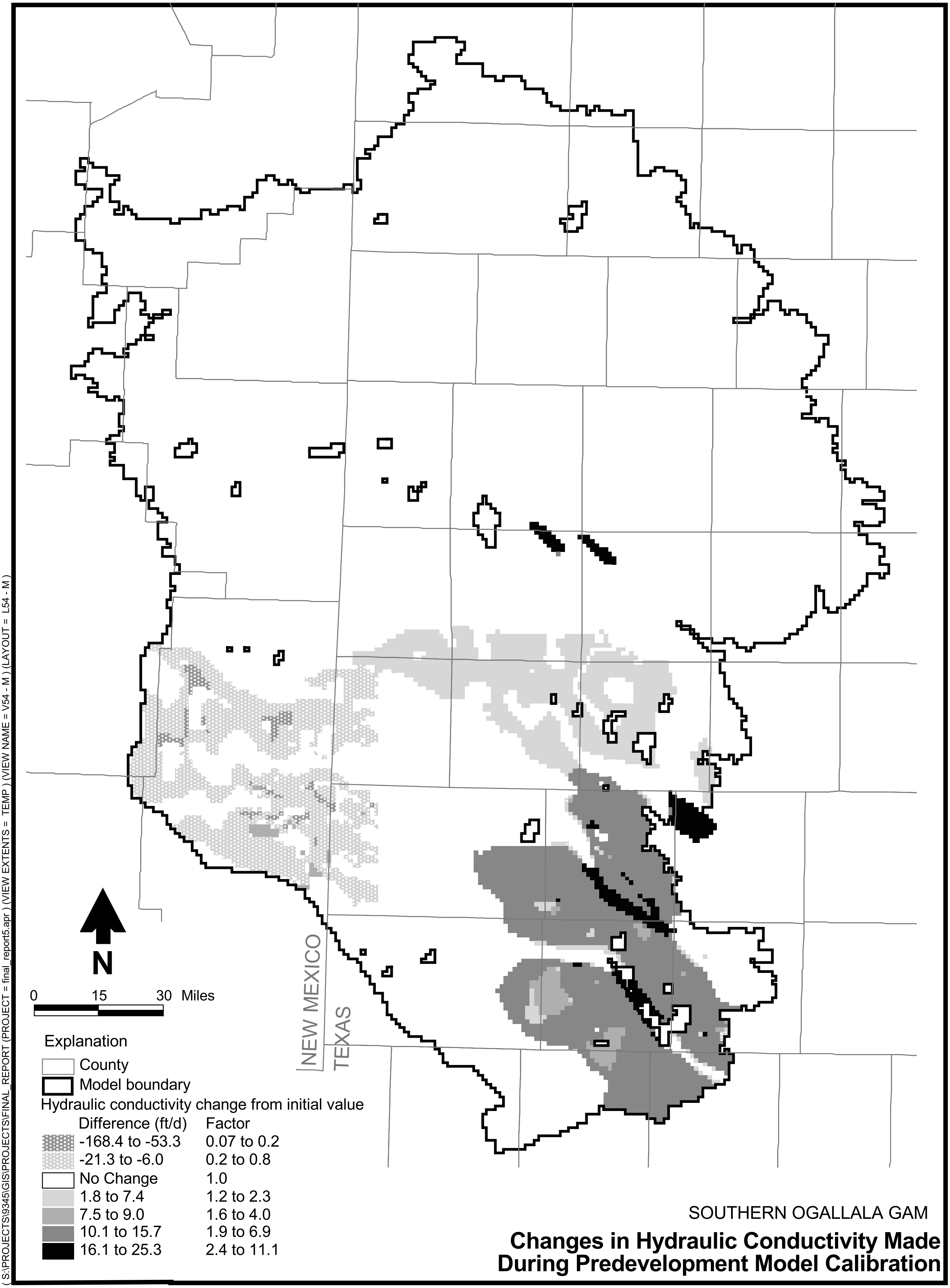

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Figure 54

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).

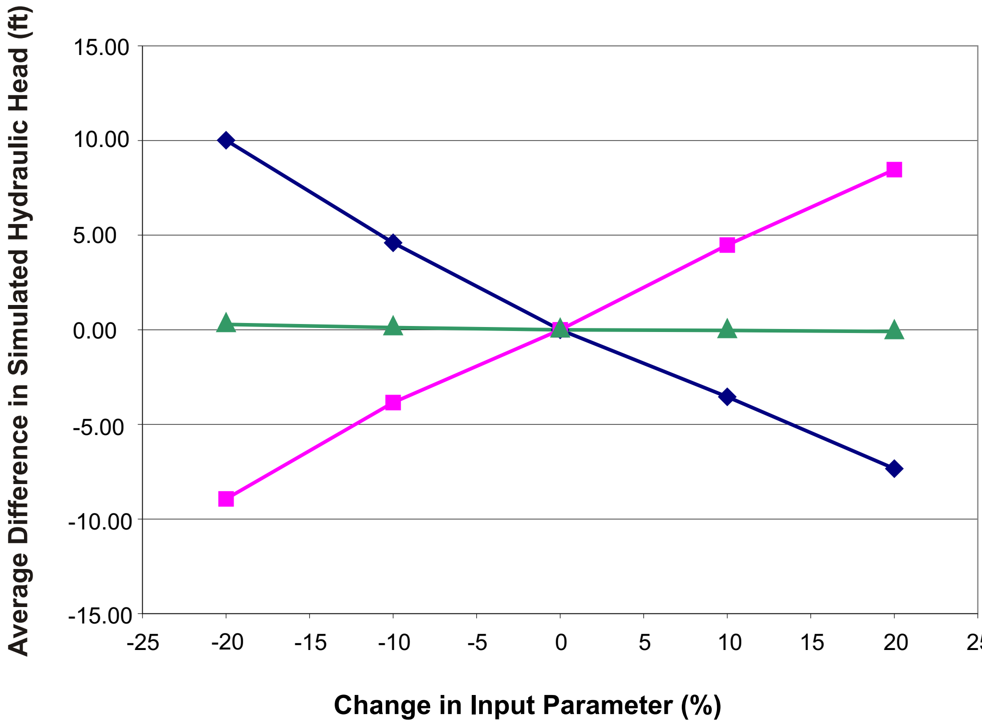
The sensitivity analysis results indicate that, as expected, the simulation results are most sensitive to recharge and hydraulic conductivity, which generally have equal but opposite effects (i.e., the effects of increasing hydraulic conductivity are similar to those of reducing recharge and visa versa). 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).

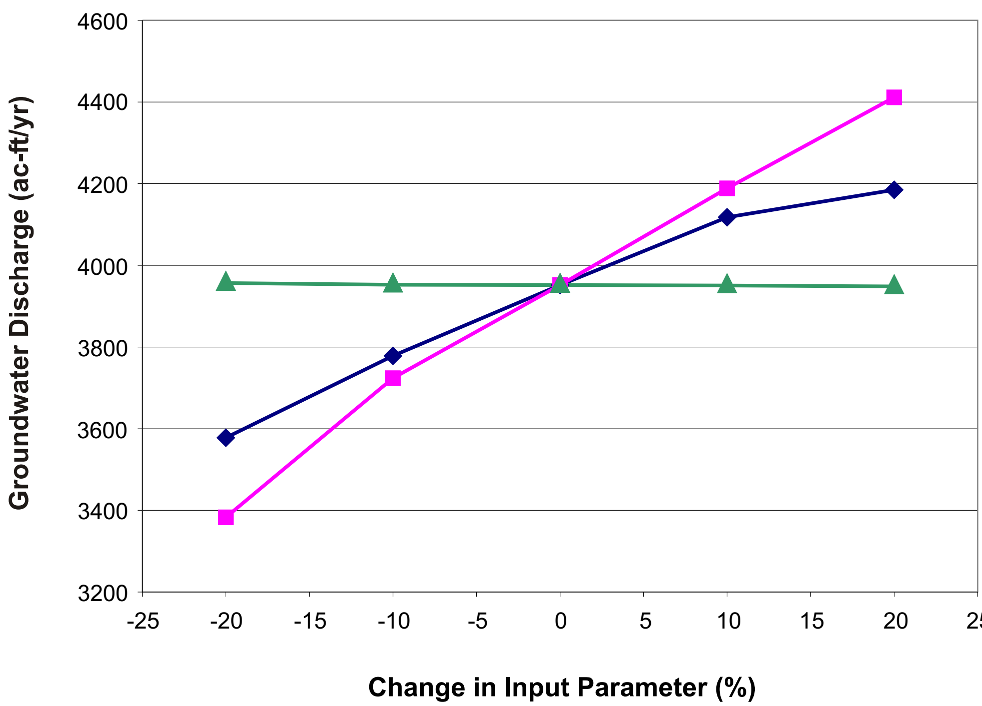
Changes of 10 percent to both hydraulic conductivity and recharge produced similar calibration statistics to those of the calibrated model. Changes of 20 percent caused the RMSE to increase by a foot or more.

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.





SOUTHERN OGALLALA GAM

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

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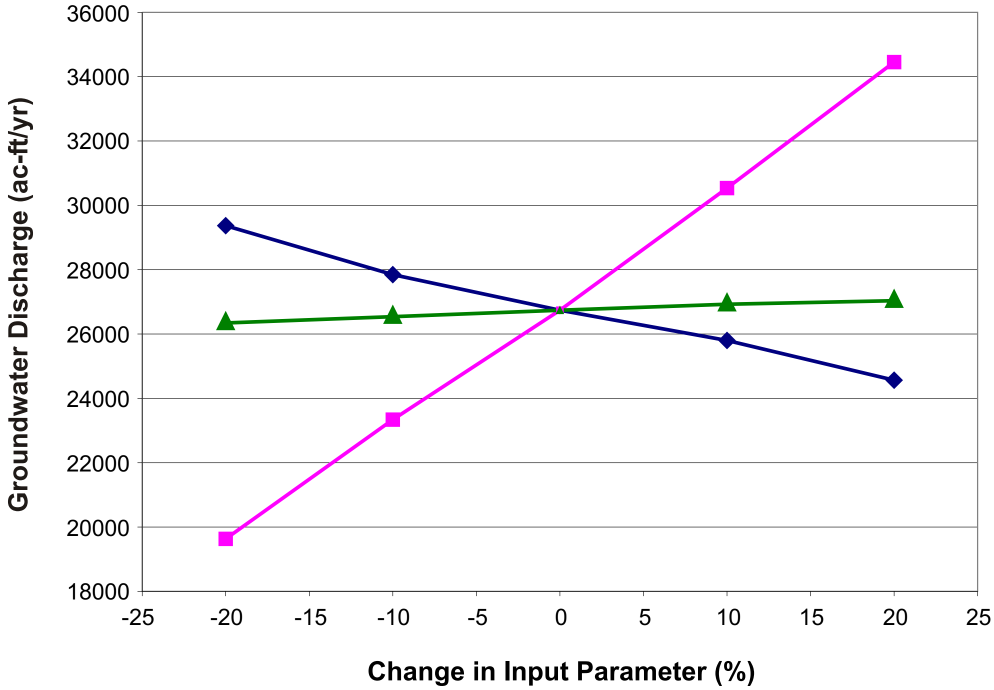
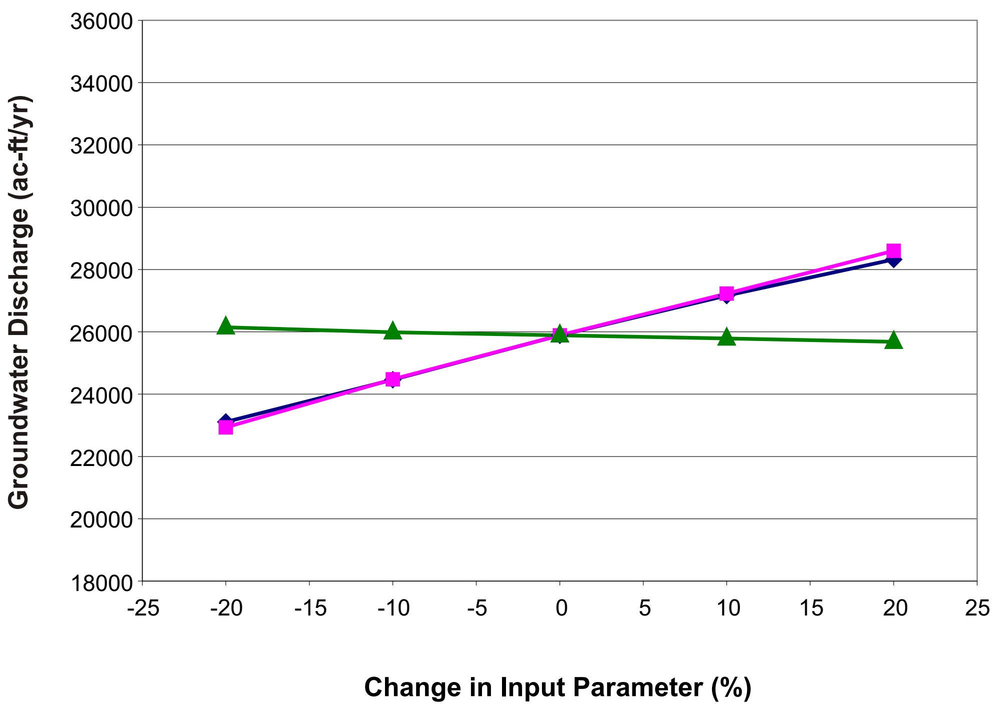
Figure 55





Explanation

- Hydraulic conductivity
- Recharge
- Drain conductance

SOUTHERN OGALLALA GAM

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

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Figure 56

Table 4: Results of Boundary Head Sensitivity Analysis

Measure	BH Increased	Discharge (ac-ft/yr) 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.

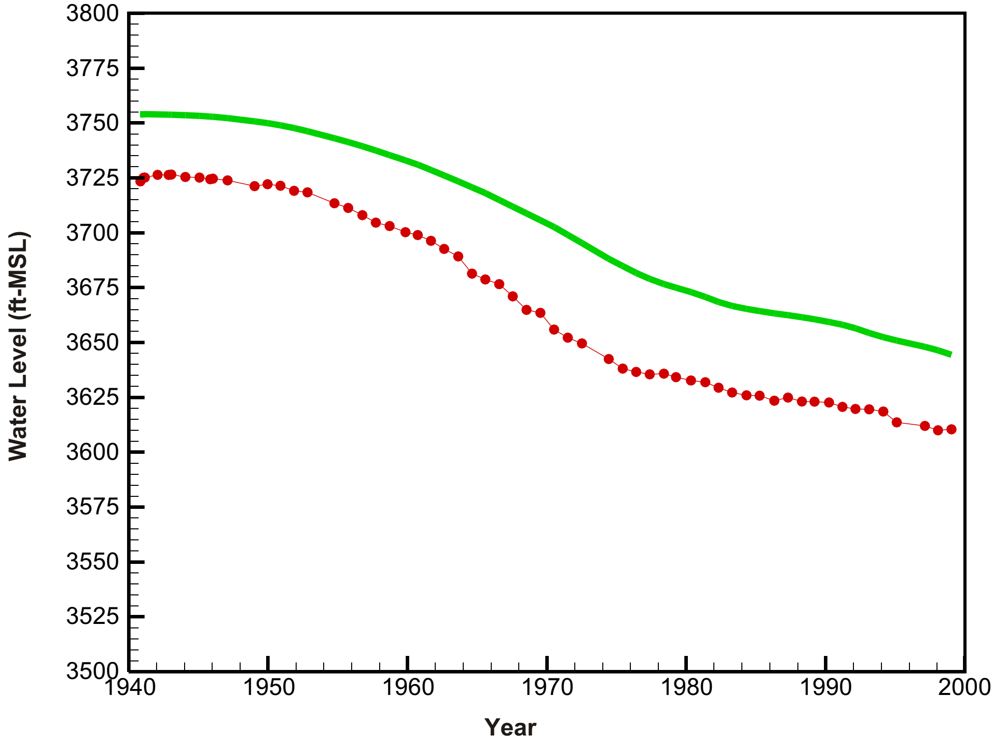
Pumping was applied in the model as presented in previous sections. Annual pumping for each pumping category is provided in Appendix C.

Calibration Results

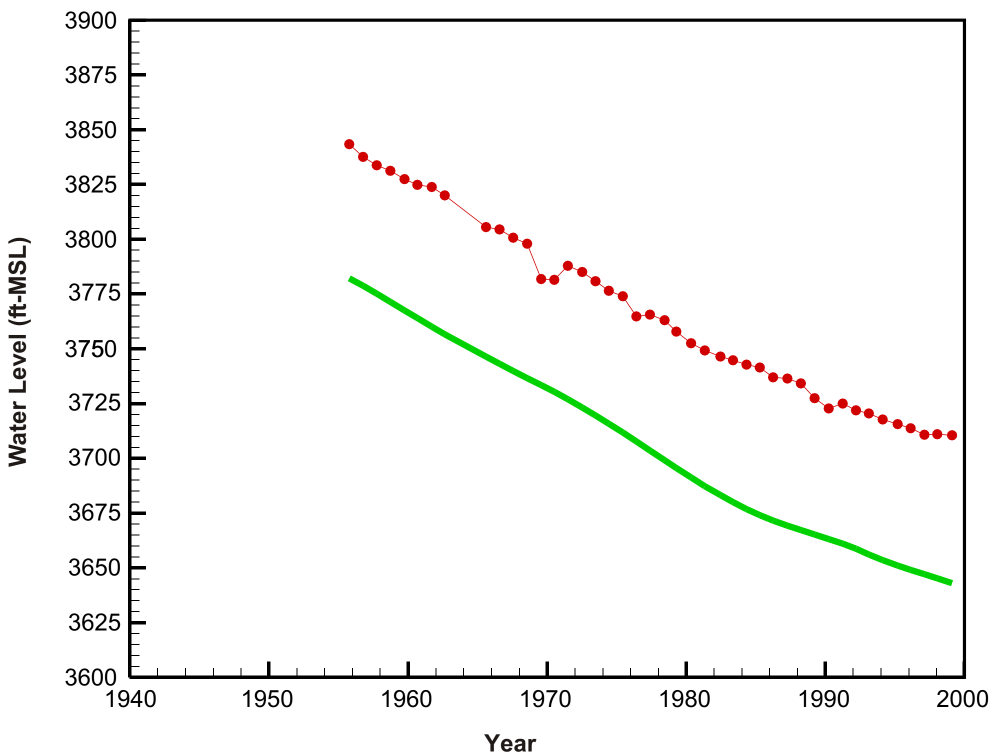
Calibration of the transient model was completed by adjusting model input parameters to obtain a reasonable match between simulated and observed water levels at 80 wells (each with substantial periods of record) distributed throughout the study area (fig. 24). Once the calibration to the 80 hydrographs 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.

Deaf Smith County, Texas, Well 1007403



Parmer County, Texas, Well 1035401



Explanation

- Observed water level
- Simulated water level

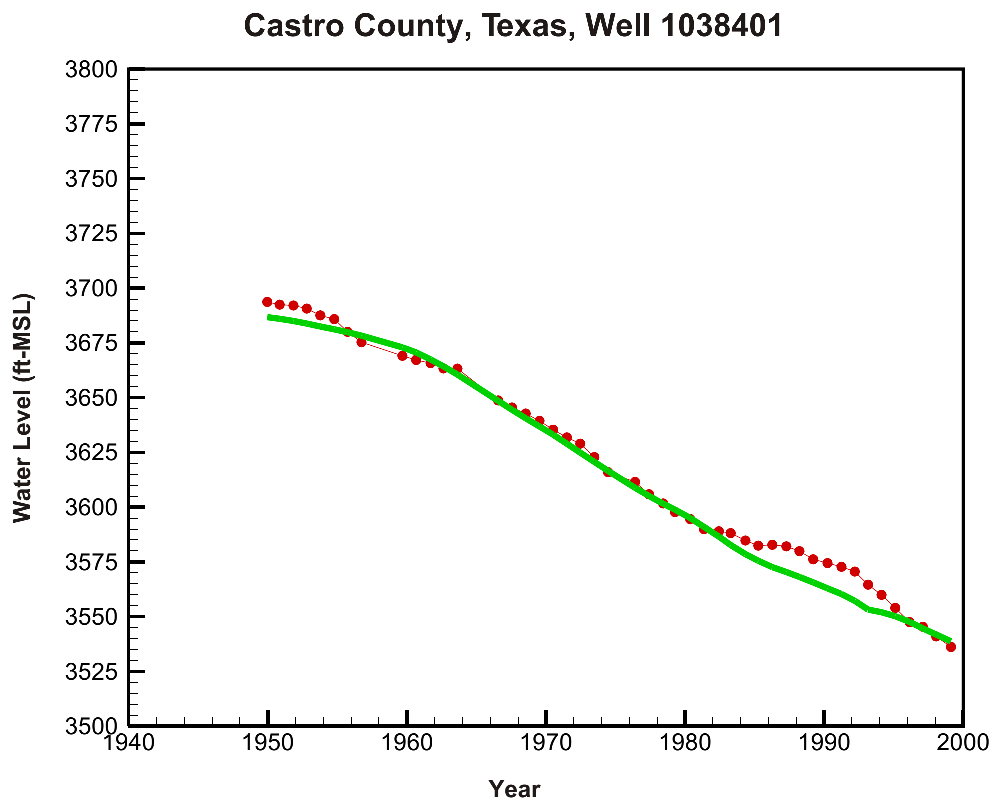
SOUTHERN OGALLALA GAM

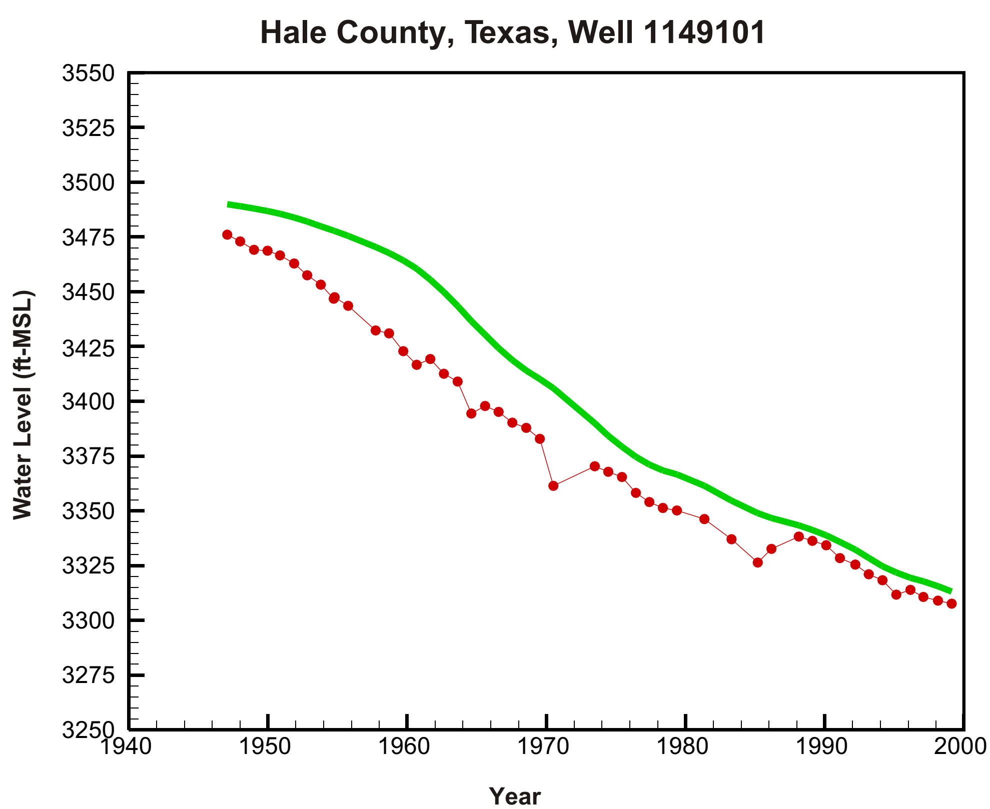
Simulated and Observed Hydrographs for Observation Wells in Deaf Smith and Parmer Counties

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

1-30-03

Figure 57





VDR\0-VDR-PROJECTS\934S\934584b.CDR

Explanation

Observed water level

Simulated water level

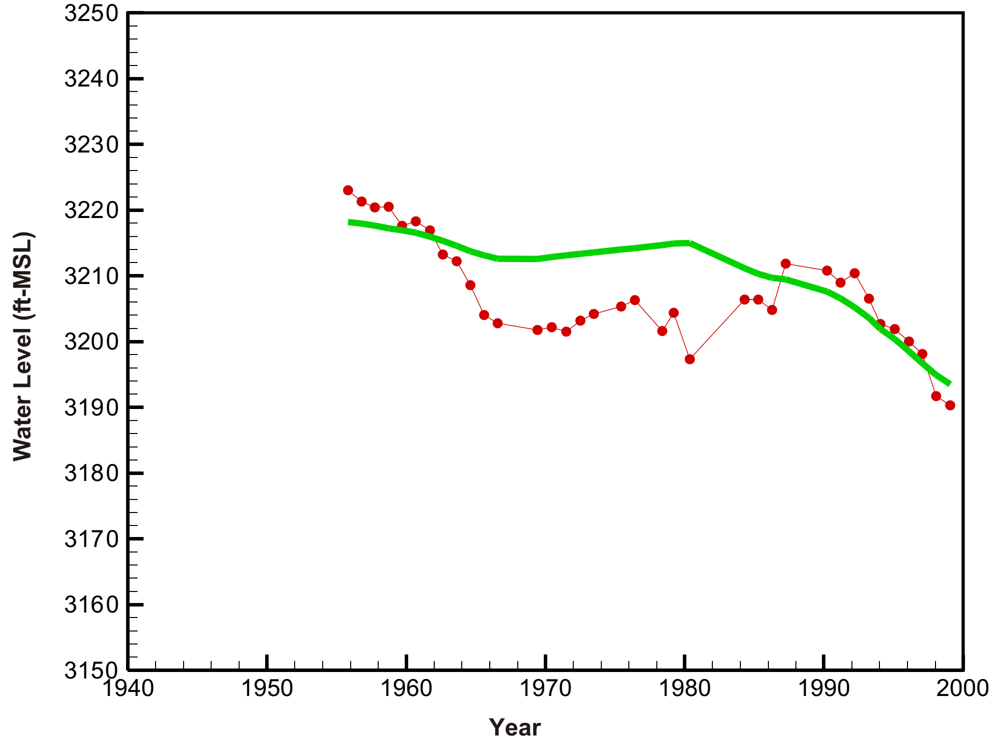
SOUTHERN OGALLALA GAM

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

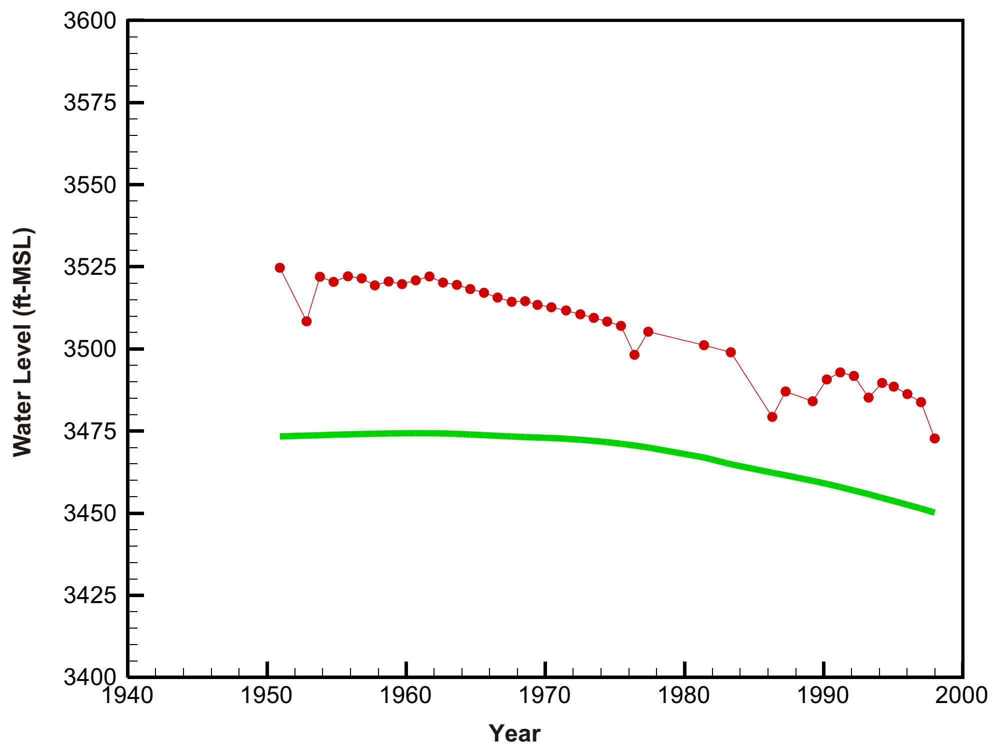
1-30-03

Figure 58

Terry County, Texas, Well 2454901



Gaines County, Texas, Well 2624307



Explanation

- Observed water level
- Simulated water level

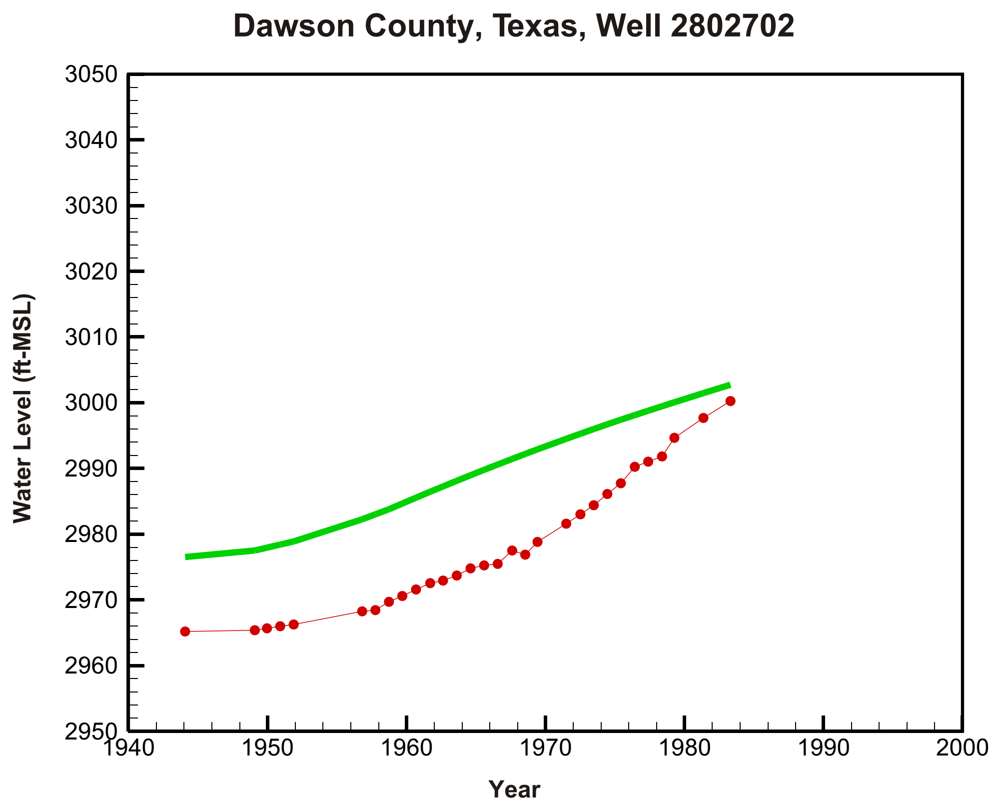
SOUTHERN OGALLALA GAM

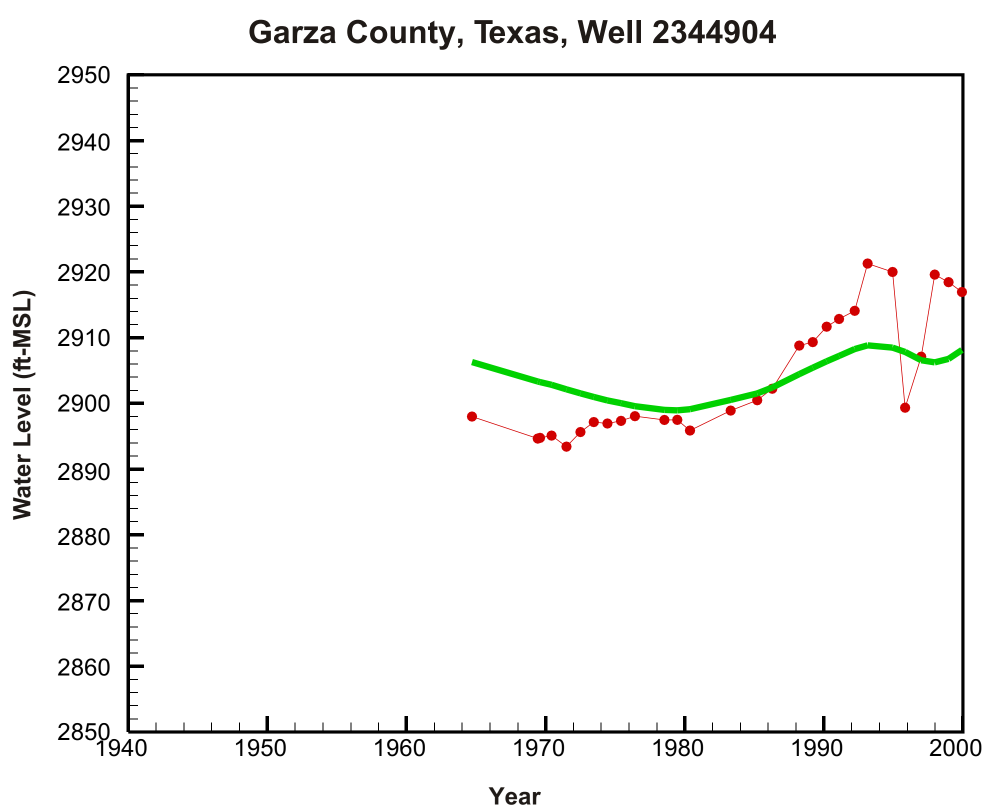
Simulated and Observed Hydrographs for Observation Wells in Terry and Gaines Counties

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

1-30-03

Figure 59





Explanation

- Observed water level
- Simulated water level

SOUTHERN OGALLALA GAM

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

VDR\0-VDR-PROJECTS\9345\934582b.CDR

1-30-03

Figure 60

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.

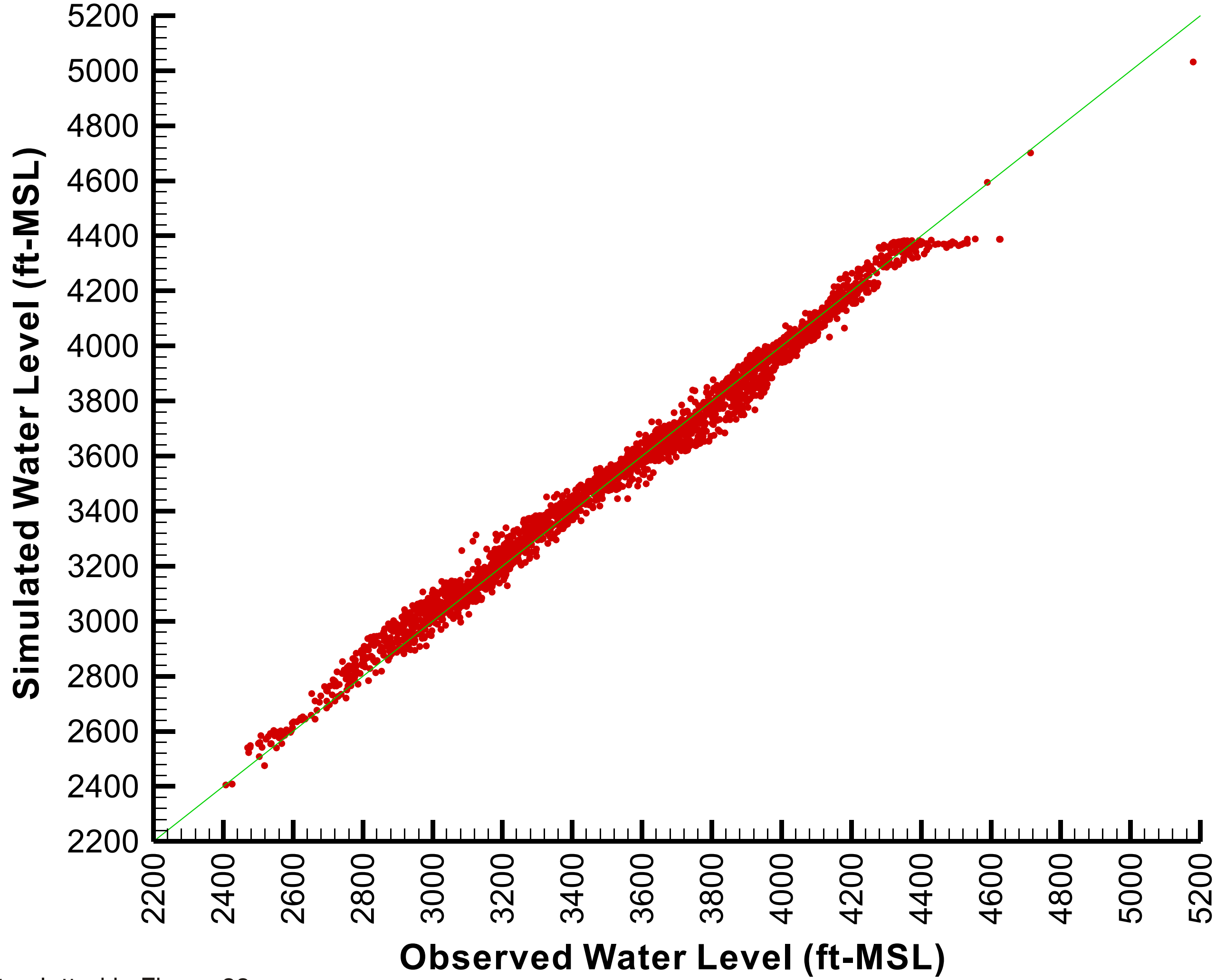
To evaluate the match between observed and simulated water levels, calibration statistics were also determined for each hydrograph. The RMSE of the hydrographs ($RMSE_{hyd}$) was determined in the same manner as the RMSE, except that (1) the observed values change with time for a given location and (2) 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

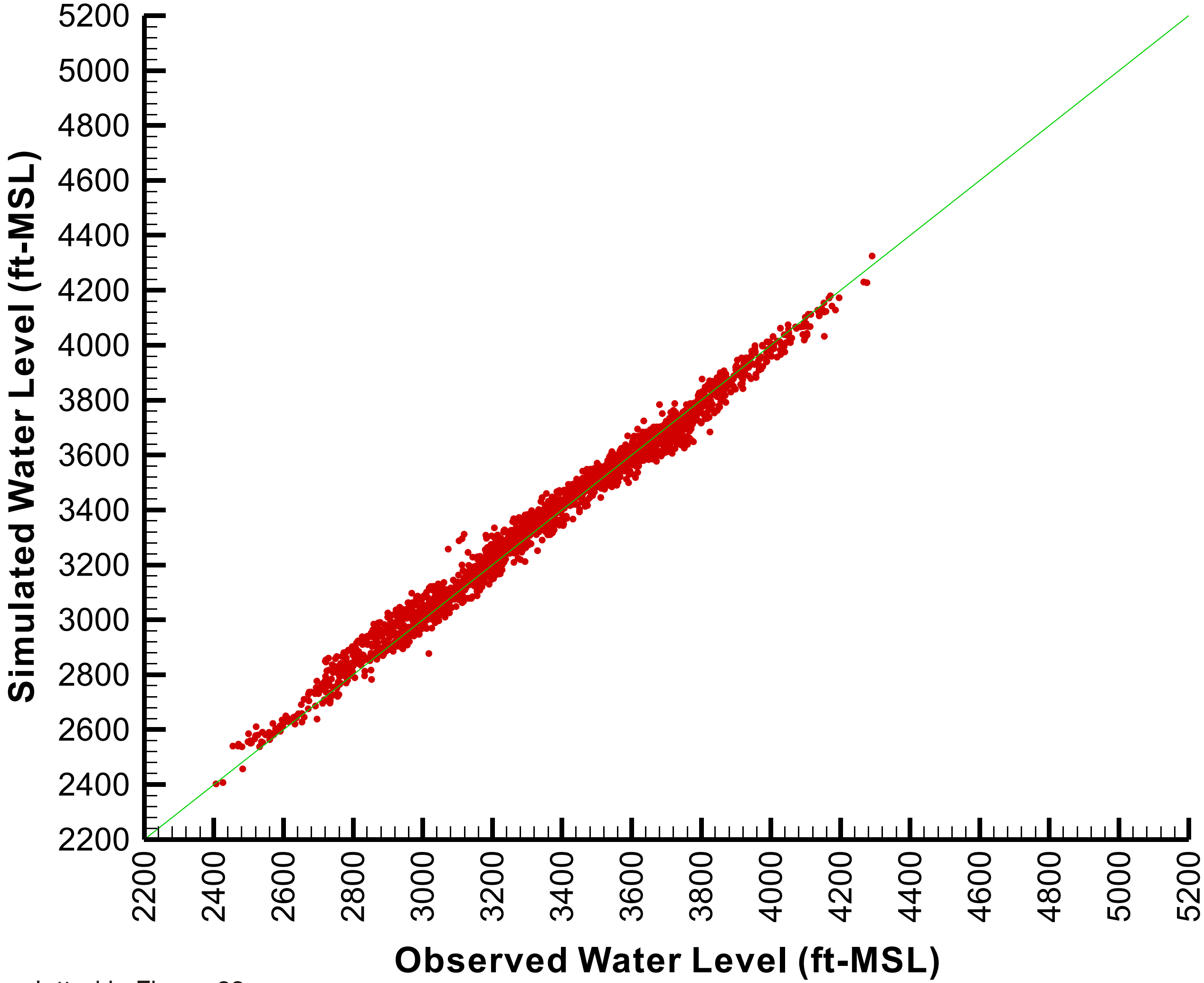
Calibration Statistics

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

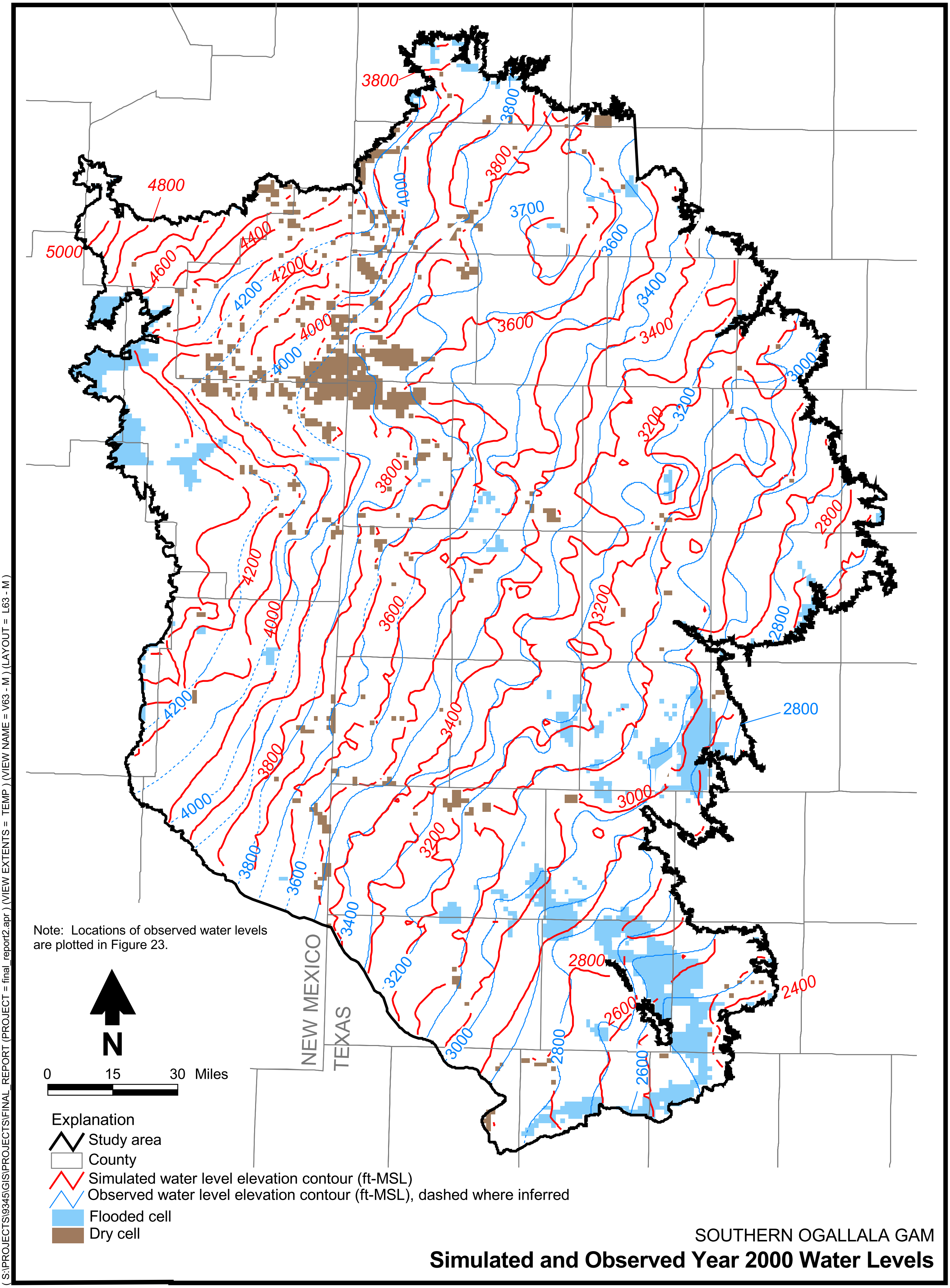
Calibration Statistics

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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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.

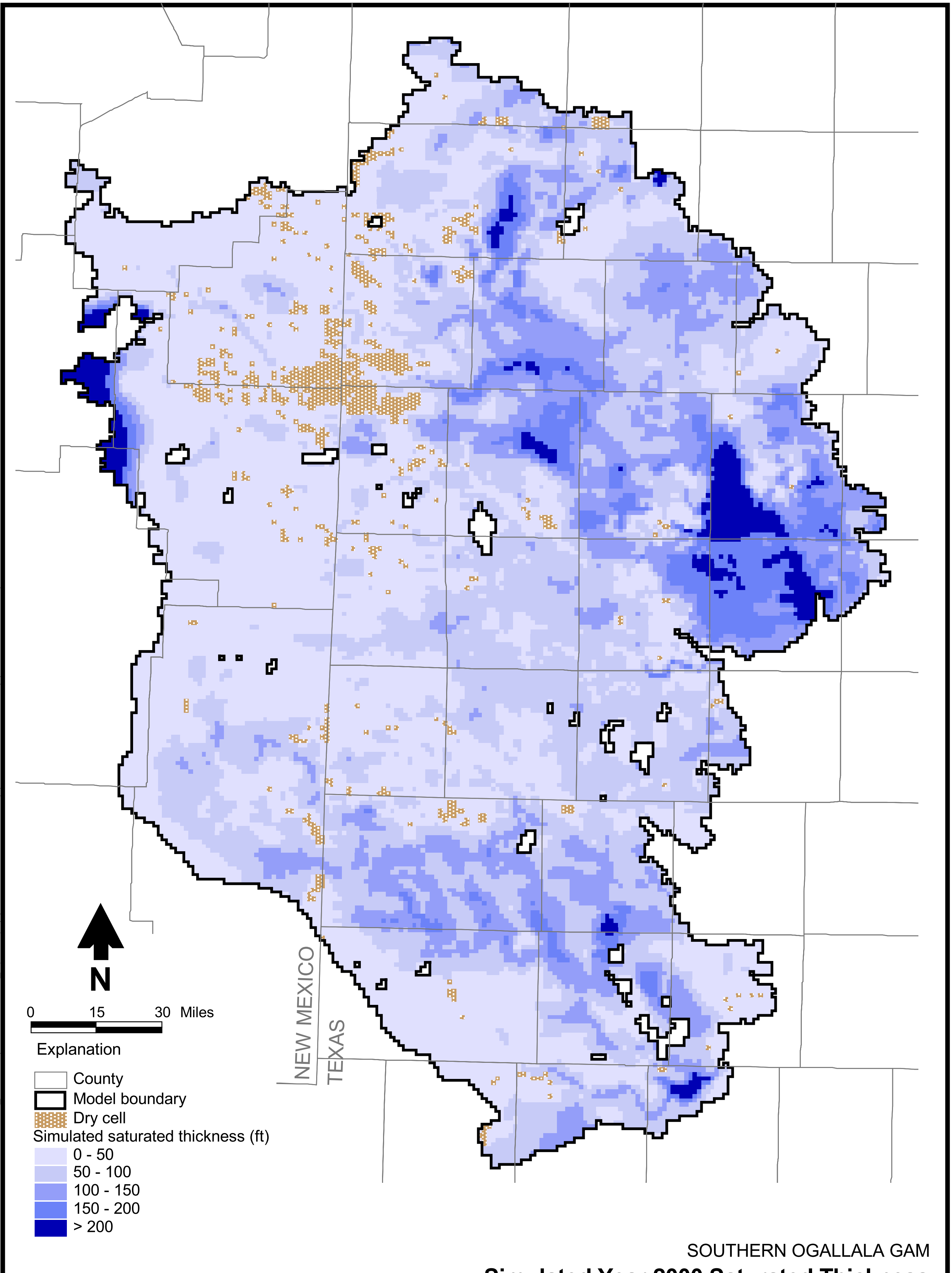
Isolated areas of flooded cells in the central and northern portion of the study area generally occur near salt lakes, draws, and the eastern escarpment, where land surface elevations change significantly over short distances. Flooded cells in these areas are, for the most part, artifacts caused by averaging 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



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SOUTHERN OGALLALA GAM

Simulated Year 2000 Saturated Thickness

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Figure 64