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.

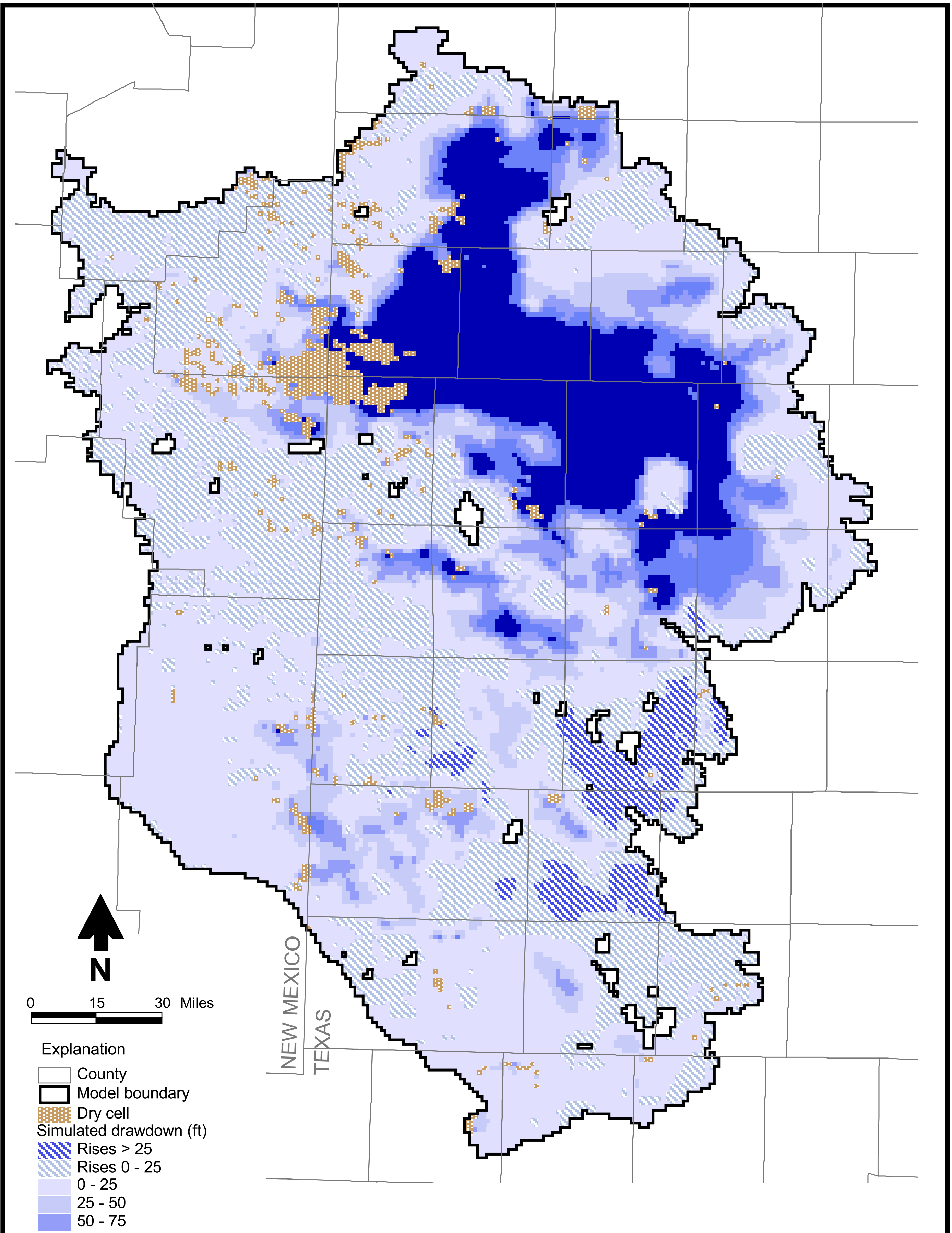
In Texas, estimated pumping for 1974 in Yoakum and Terry Counties was reduced because it was substantially greater than estimated values for the adjacent 5-year periods in the agricultural surveys, although annual rainfall was similar between periods for each respective county. Adjustments were made 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



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SOUTHERN OGALLALA GAM

Simulated Drawdown from Predevelopment to Year 2000

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

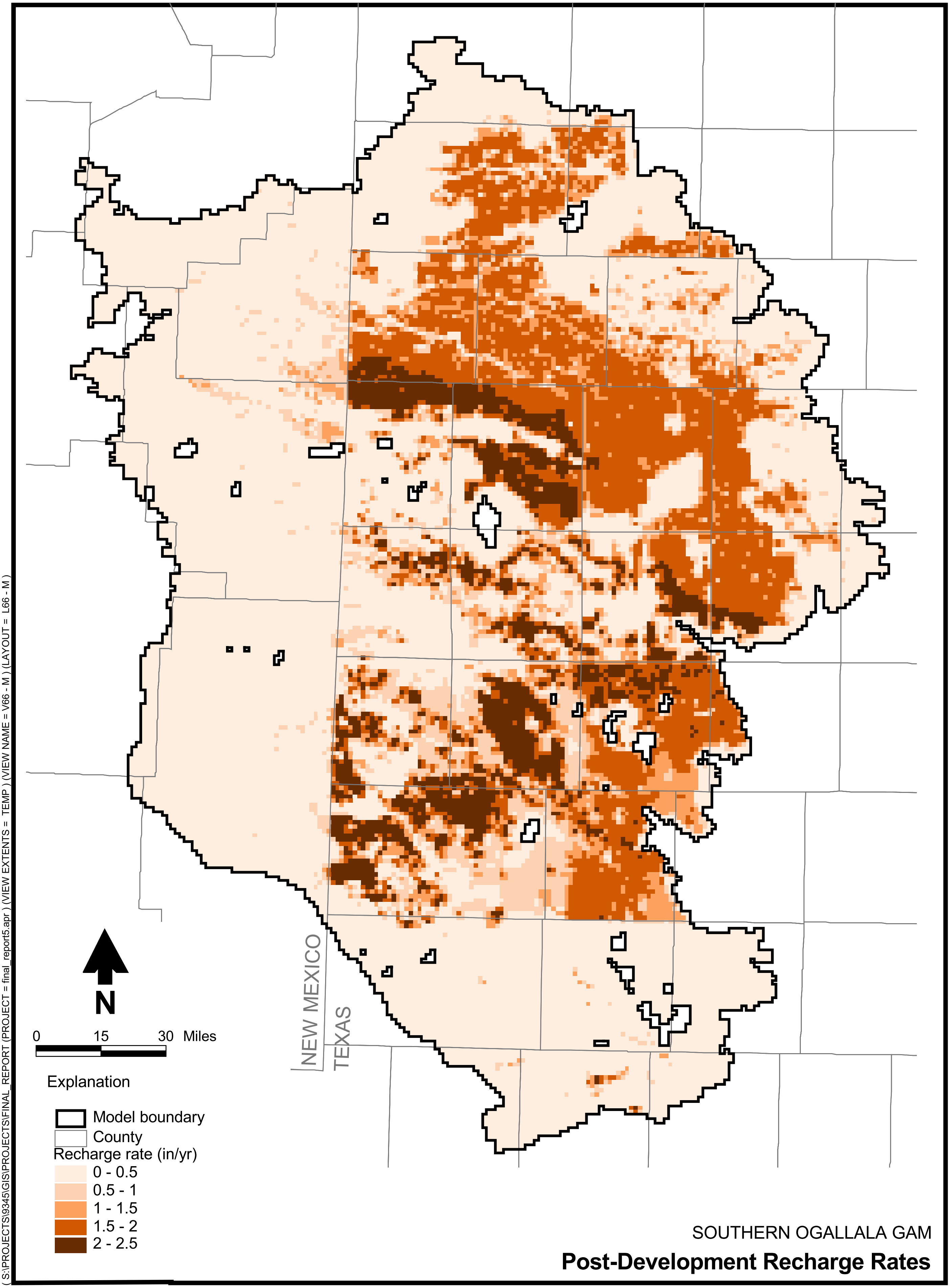
The simulated water budgets for 1980, 1984, 1990, and 2000 are provided in Table 6. According to the GAM protocol, 1980 is the beginning of the transient calibration period, 1990 is the beginning of the model verification period, and 2000 is the end of the transient simulation and the verification periods. 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.

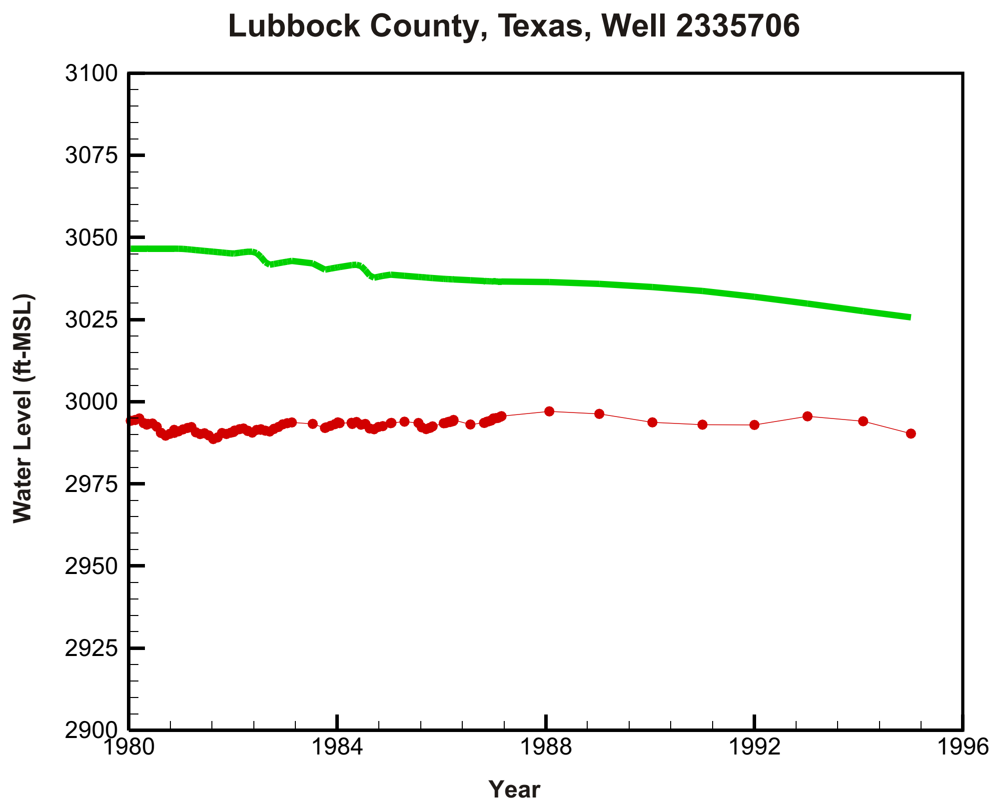
Sensitivity Analysis

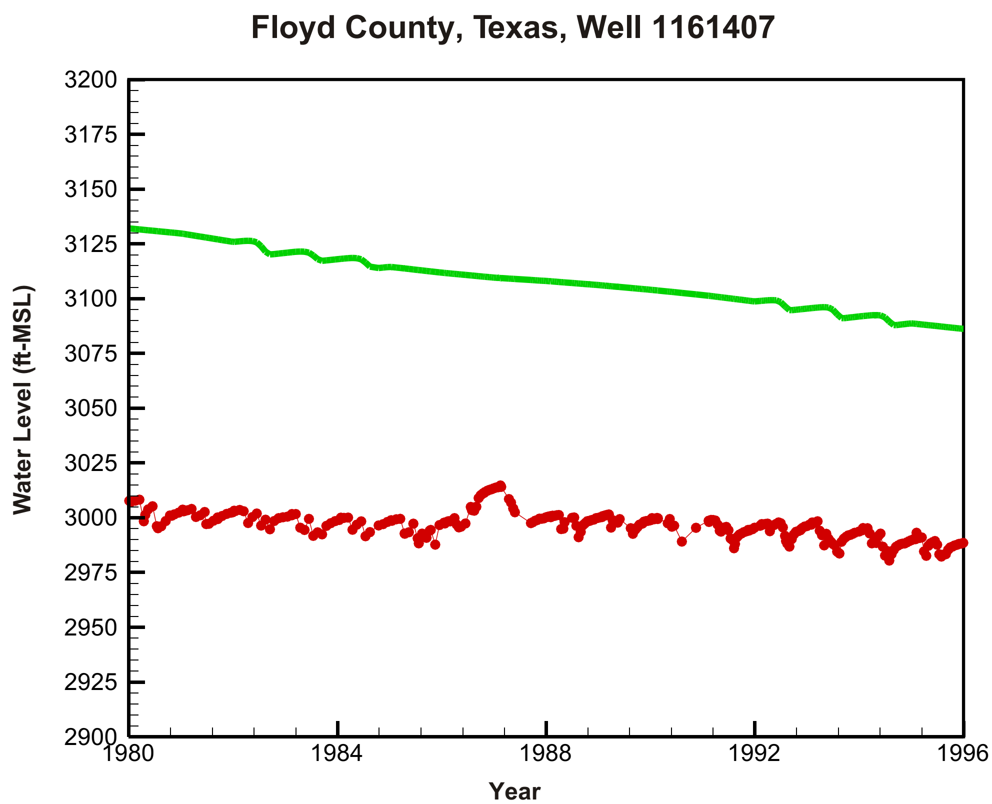
Transient model sensitivity analyses were conducted for specific yield and timing of irrigation return flow. For specific yield, two sensitivity runs were conducted in which the calibrated model values were increased and decreased by 20 percent, respectively. As expected, lower specific yield generally 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





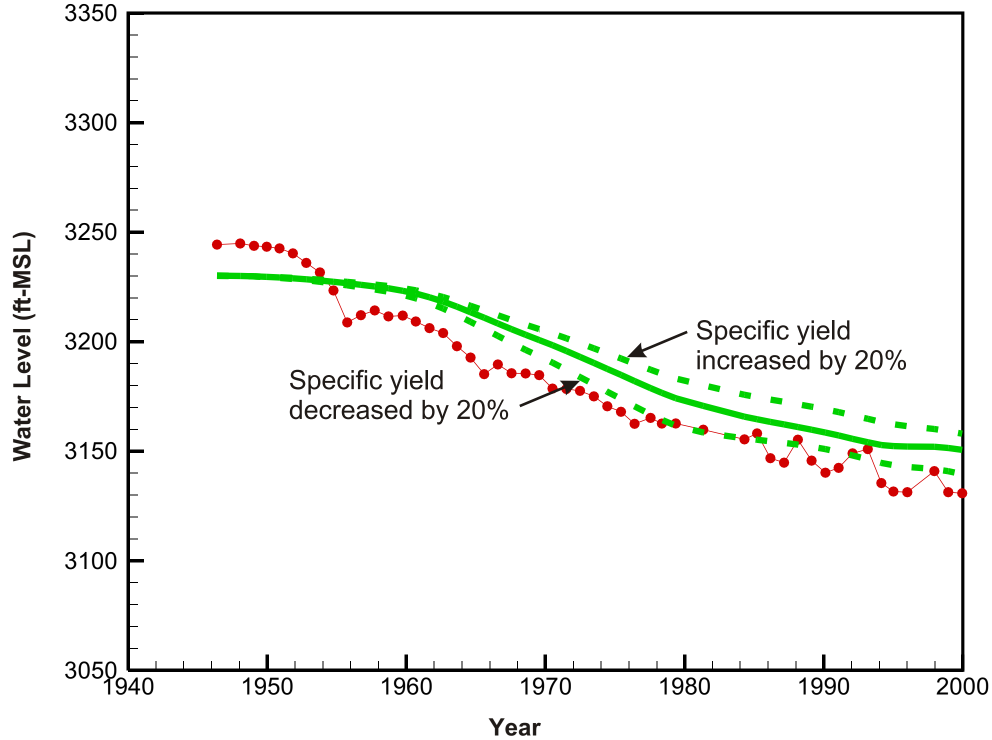
Explanation

- Observed water level
- Simulated water level

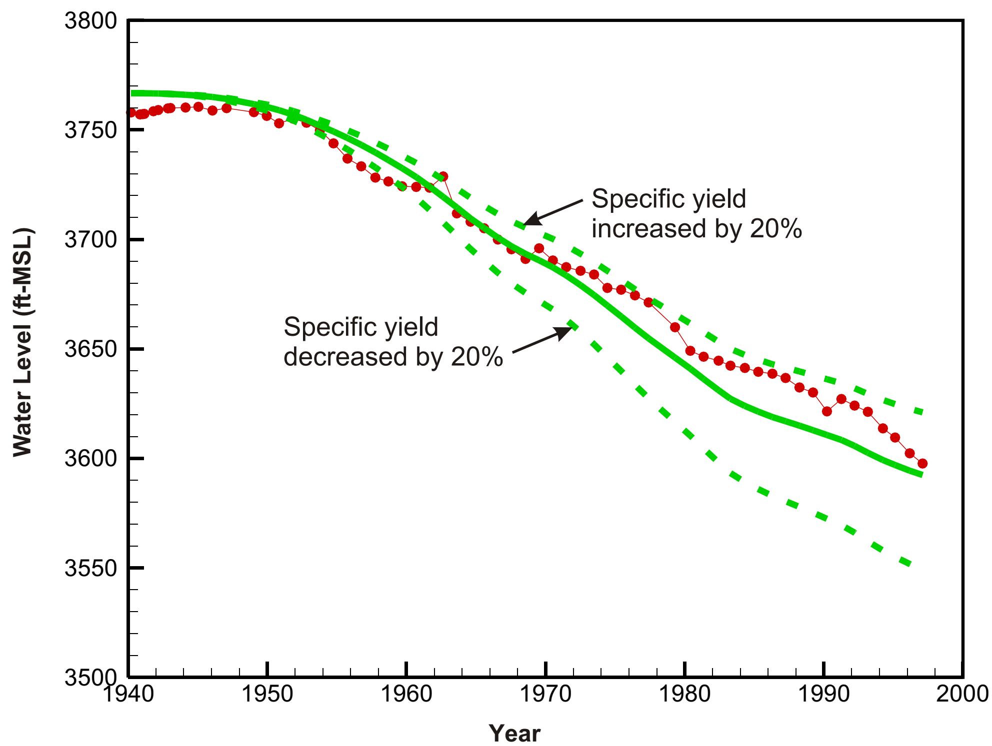
SOUTHERN OGALLALA GAM

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

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

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Figure 68

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.

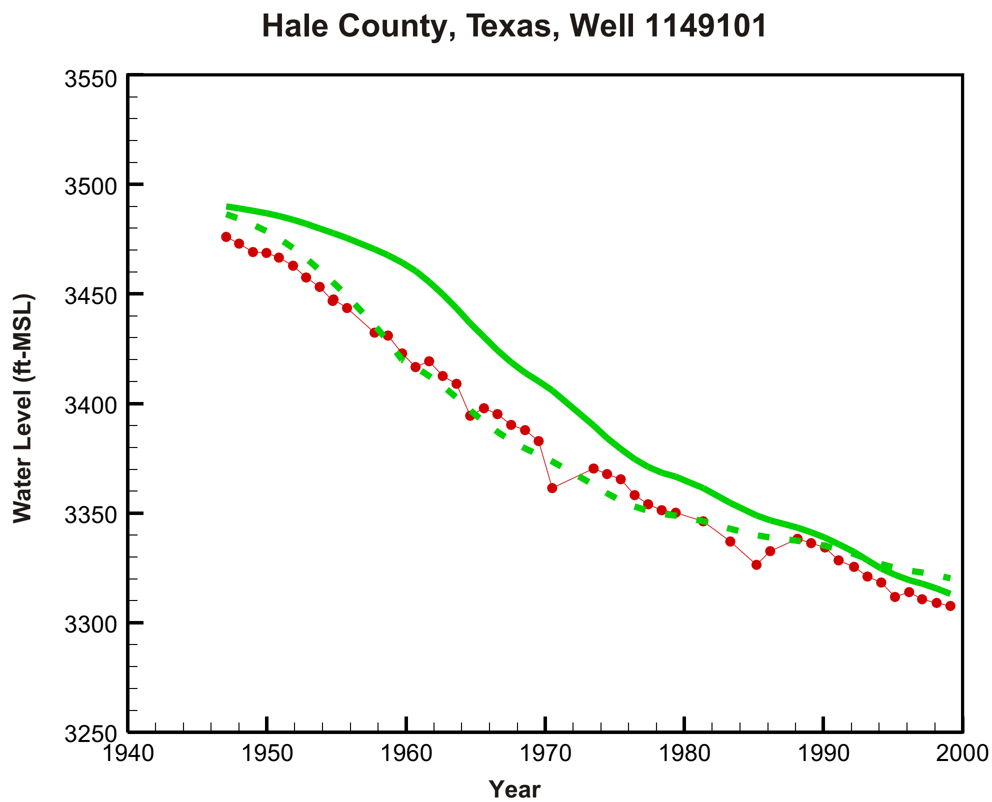
Overall, the calibrated transient model yields the best simulation results when compared to observed data. Additional adjustments could have been made to reduce the RMSE by changing return flow lag time and specific yield on a site-by-site basis. However, such changes could not be justified based on 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.

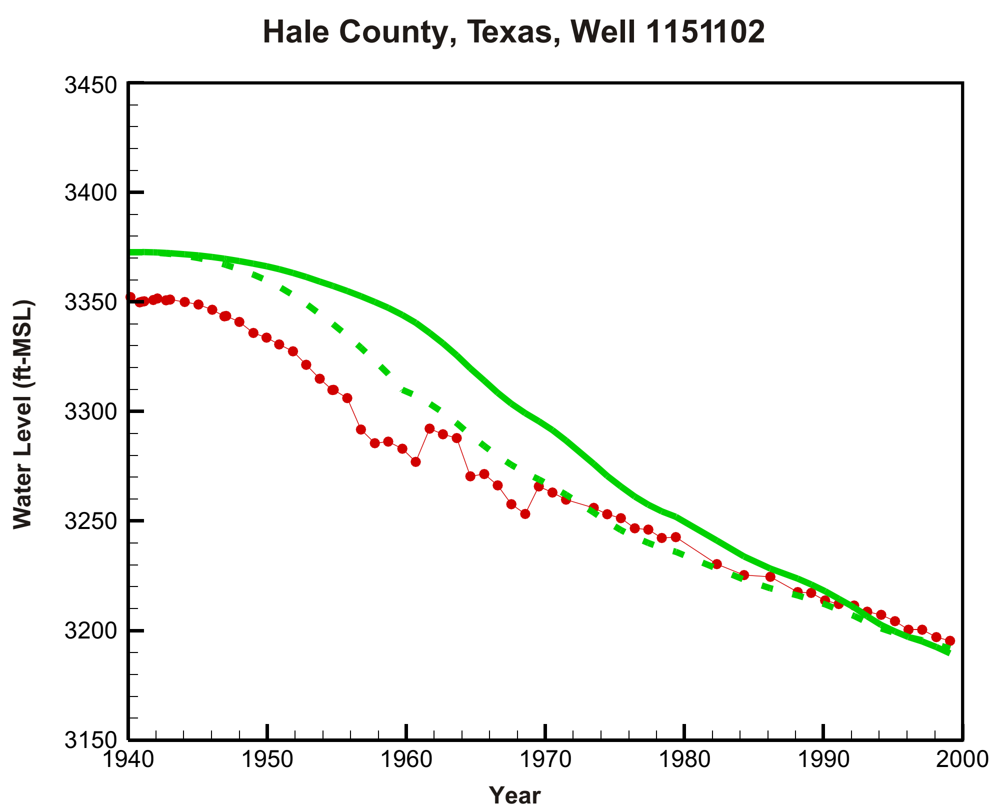
Predictions

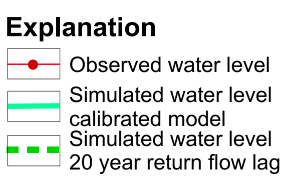
The transient model was used to conduct simulations for the following seven predictive scenarios:

- 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.







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SOUTHERN OGALLALA GAM

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

2-03-03

Figure 69

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.

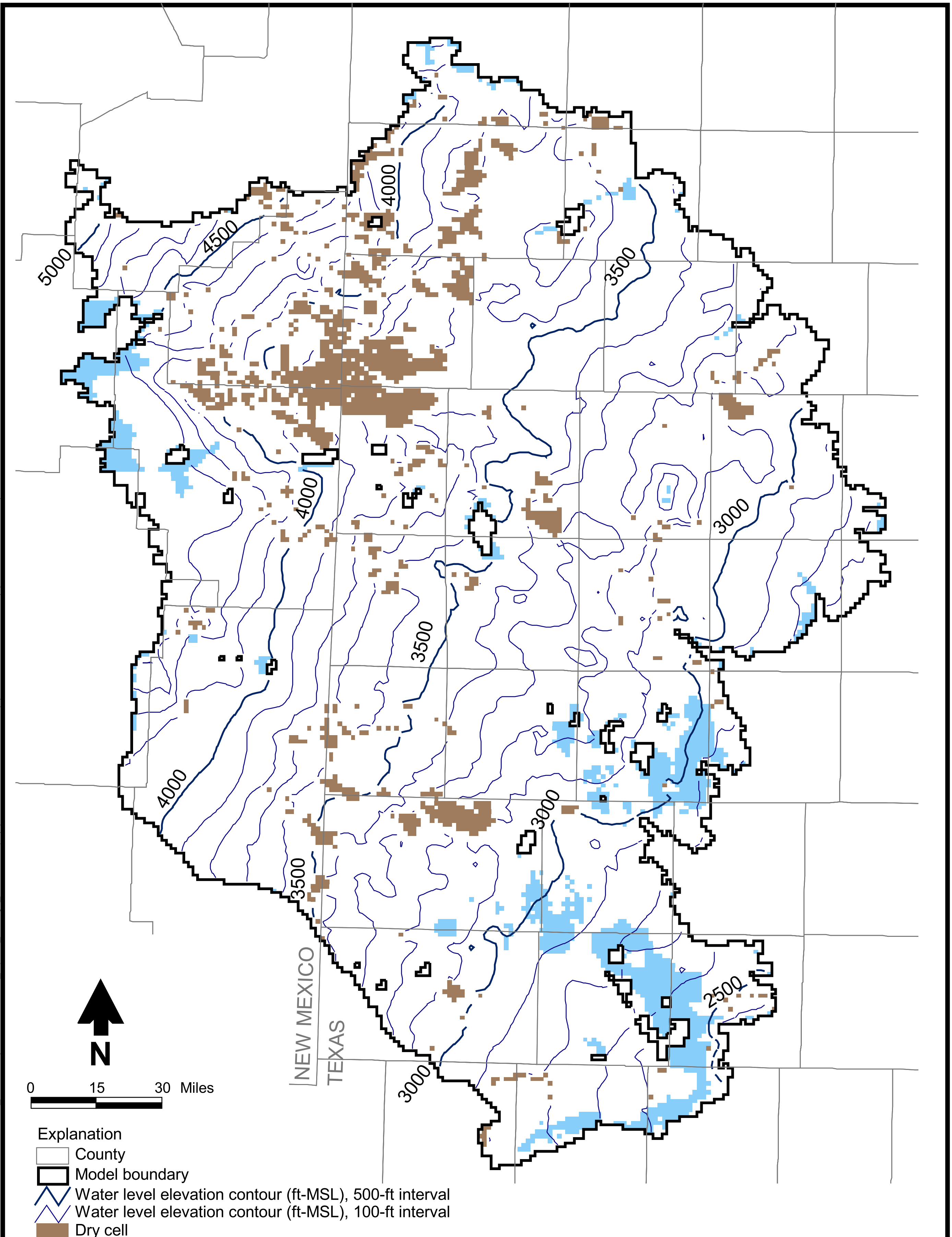
Predictive simulation results for the baseline scenario are provided in Figures 70 through 84. Figures 70 through 74 illustrate simulated water levels and dry and flooded cells for 2010, 2020, 2030, 2040 and 2050. Figures 75 through 79 and 80 through 84 follow the same time sequence, but show simulated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

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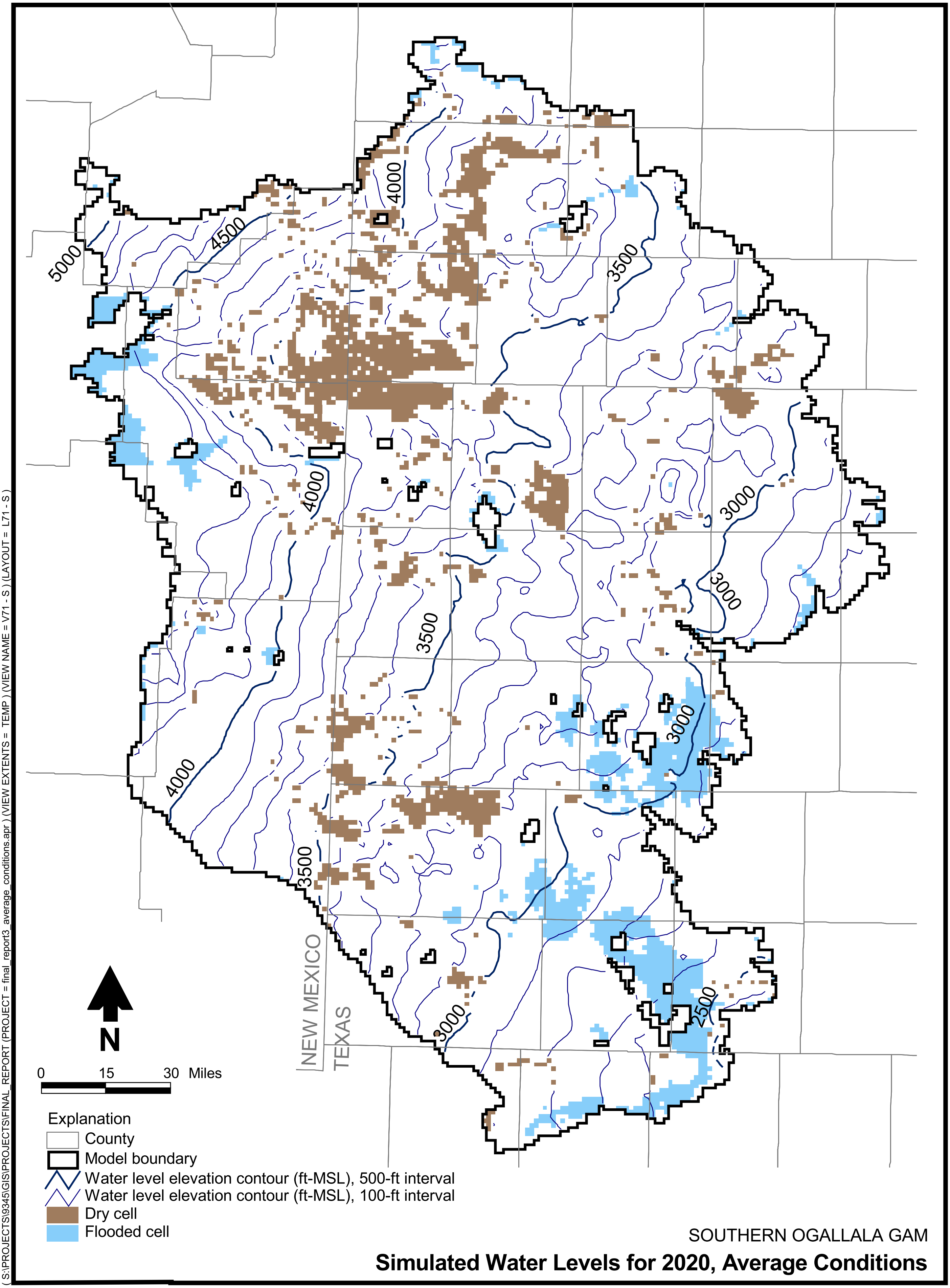
Figure 70



SOUTHERN OGALLALA GAM

Simulated Water Levels for 2020, Average Conditions

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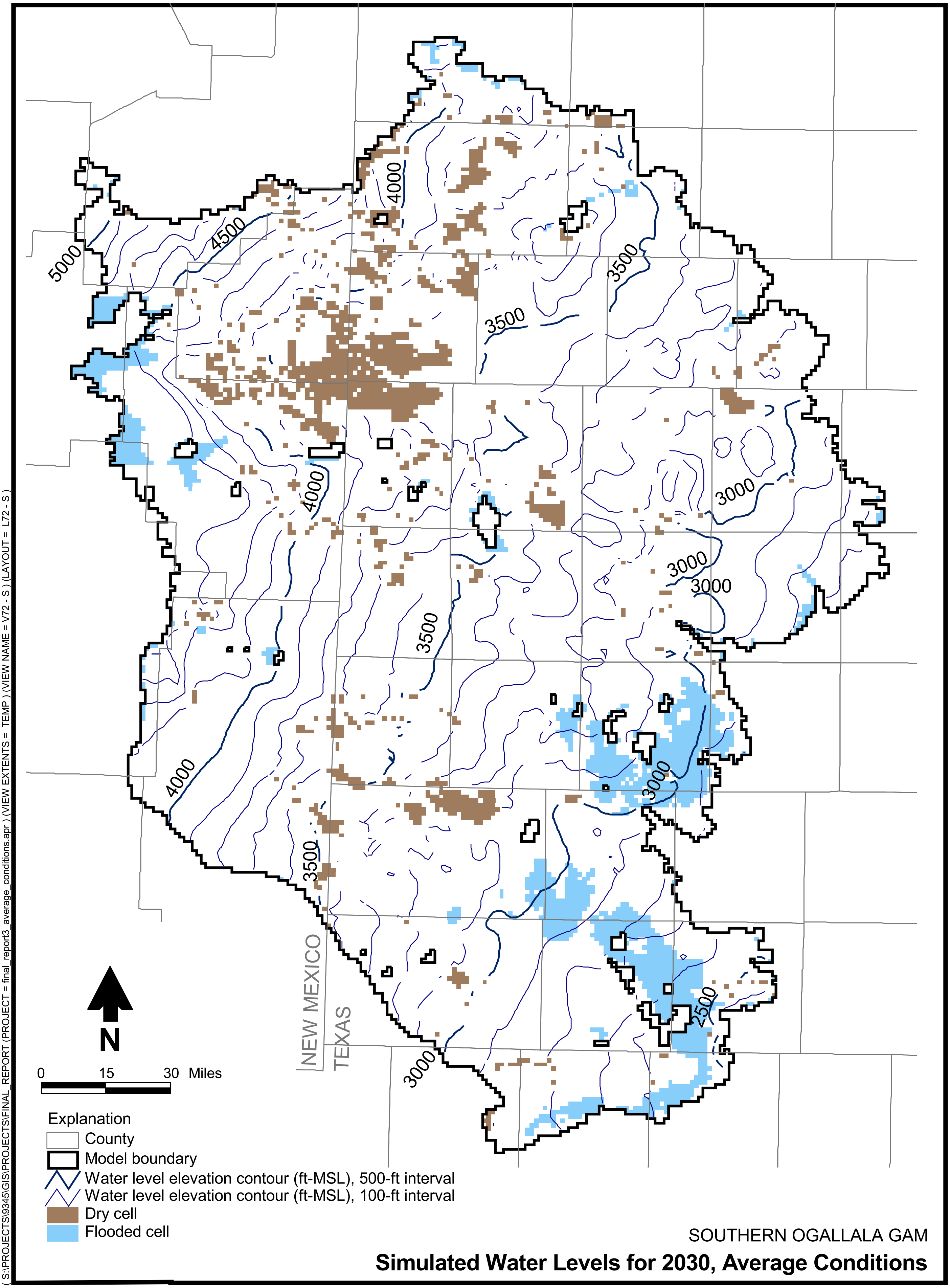
Figure 71

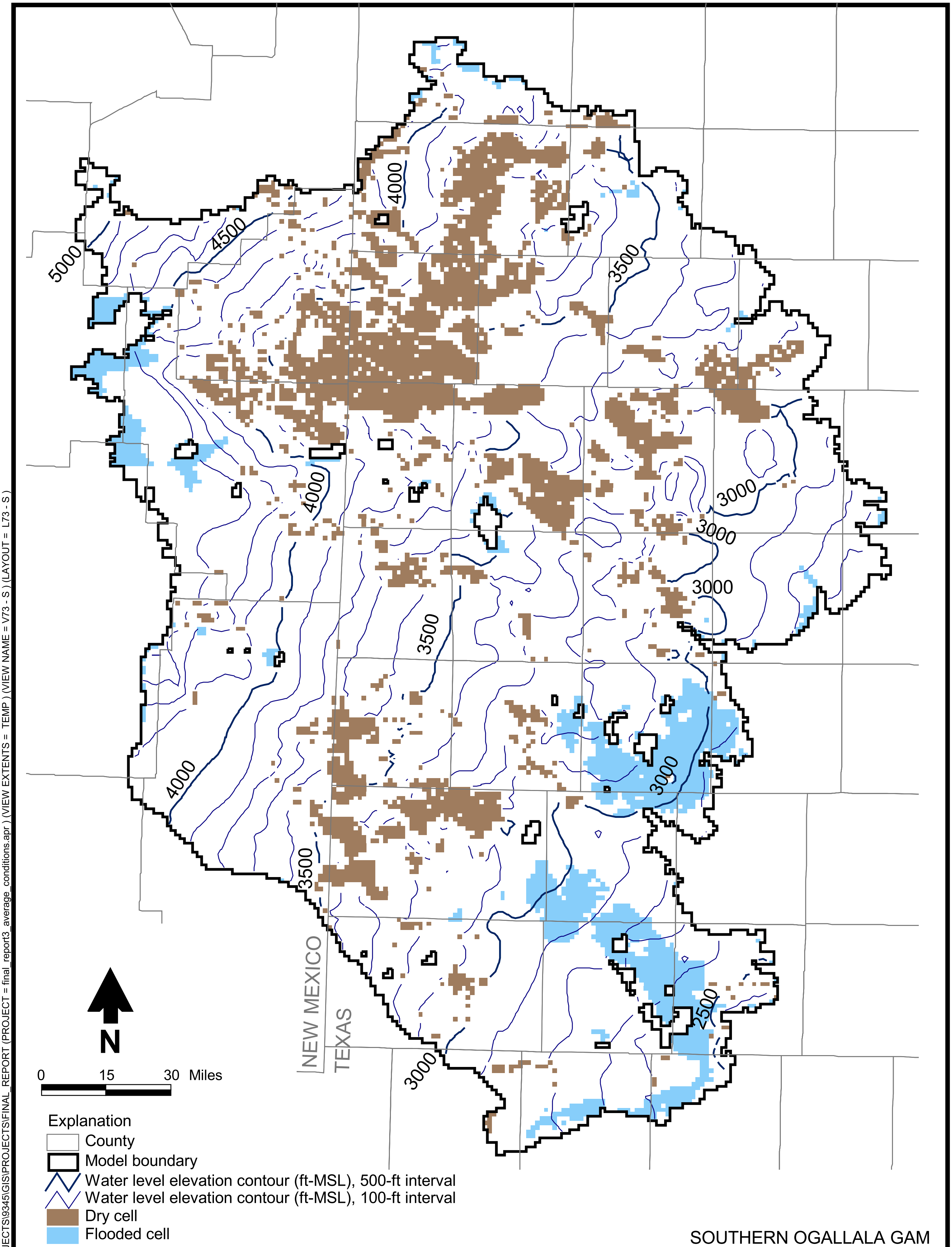


SOUTHERN OGALLALA GAM

Simulated Water Levels for 2030, Average Conditions

3-14-03

Figure 72



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SOUTHERN OGALLALA GAM

Simulated Water Levels for 2040, Average Conditions

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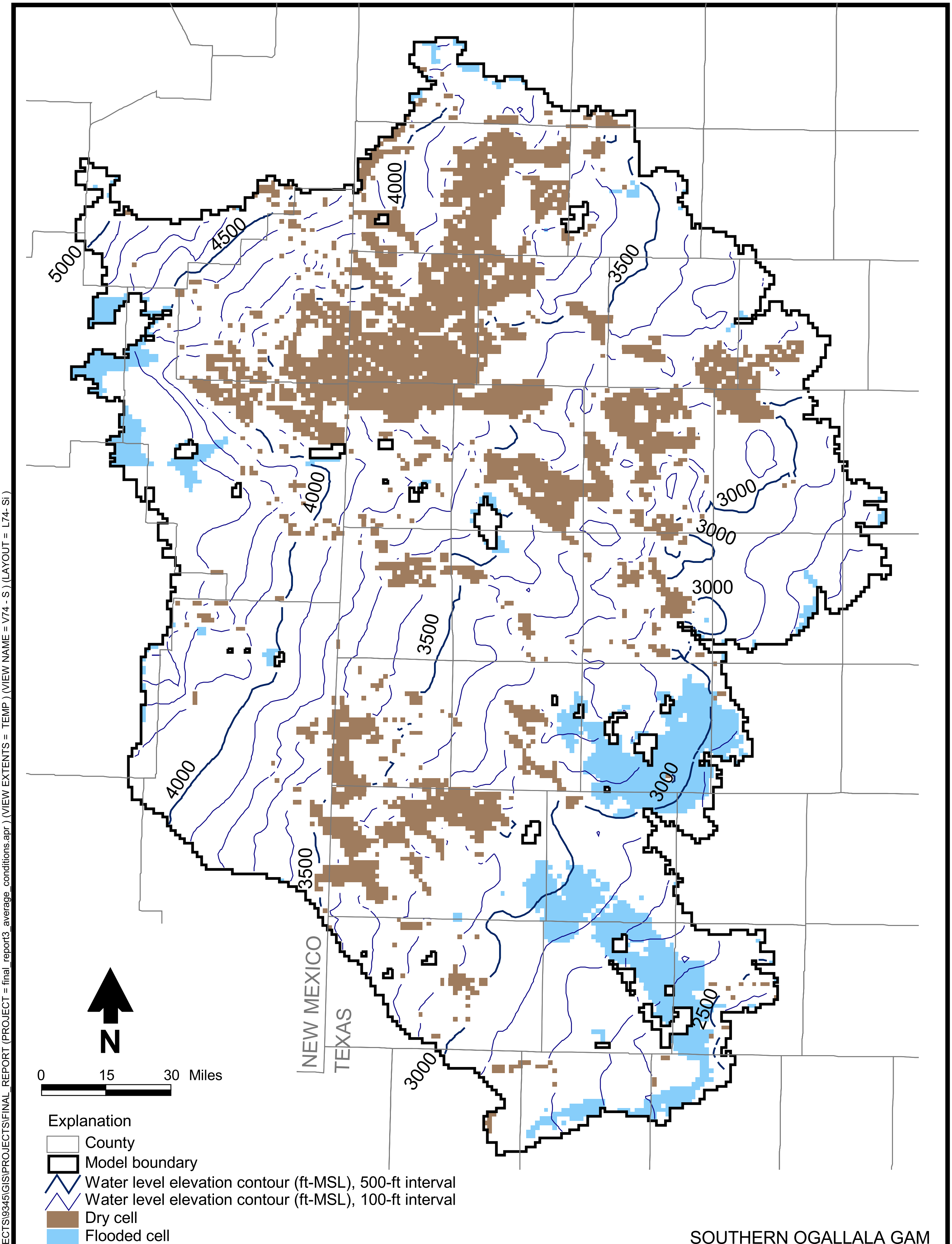
Figure 73



SOUTHERN OGALLALA GAM

Simulated Water Levels for 2050, Average Conditions

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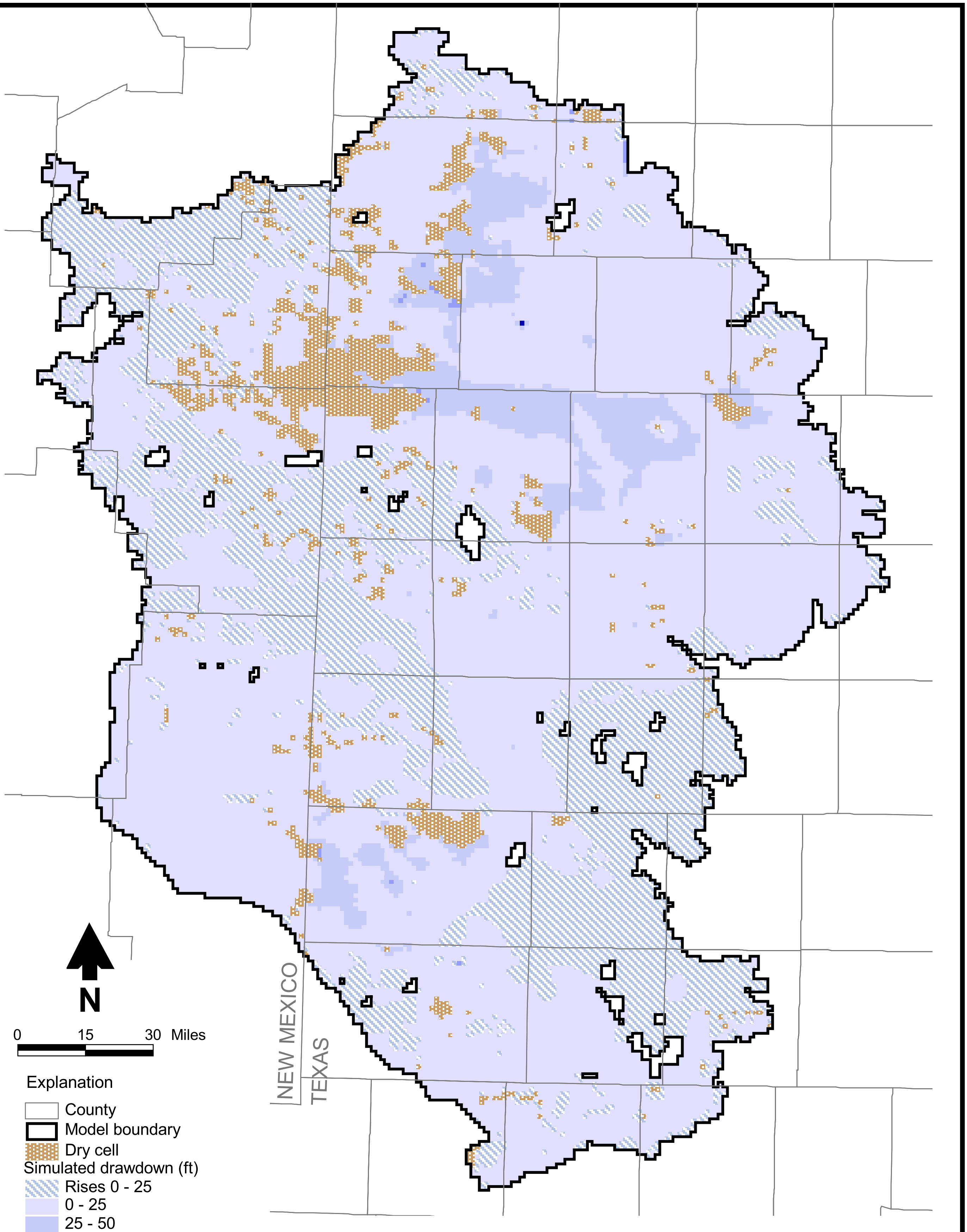
Figure 74



SOUTHERN OGALLALA GAM

Simulated Drawdown for 2010, Average Conditions

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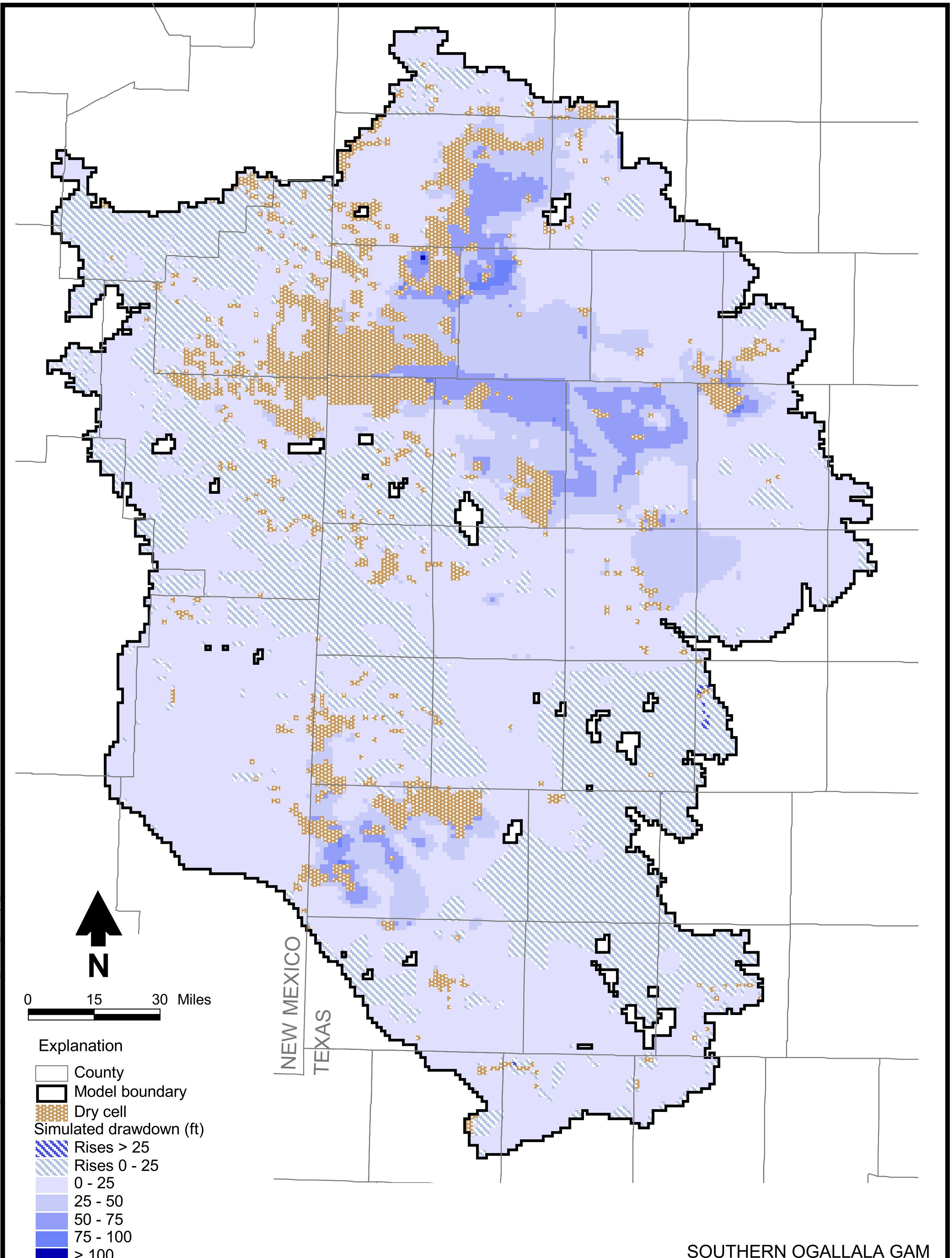
Figure 75



SOUTHERN OGALLALA GAM

Simulated Drawdown for 2020, Average Conditions

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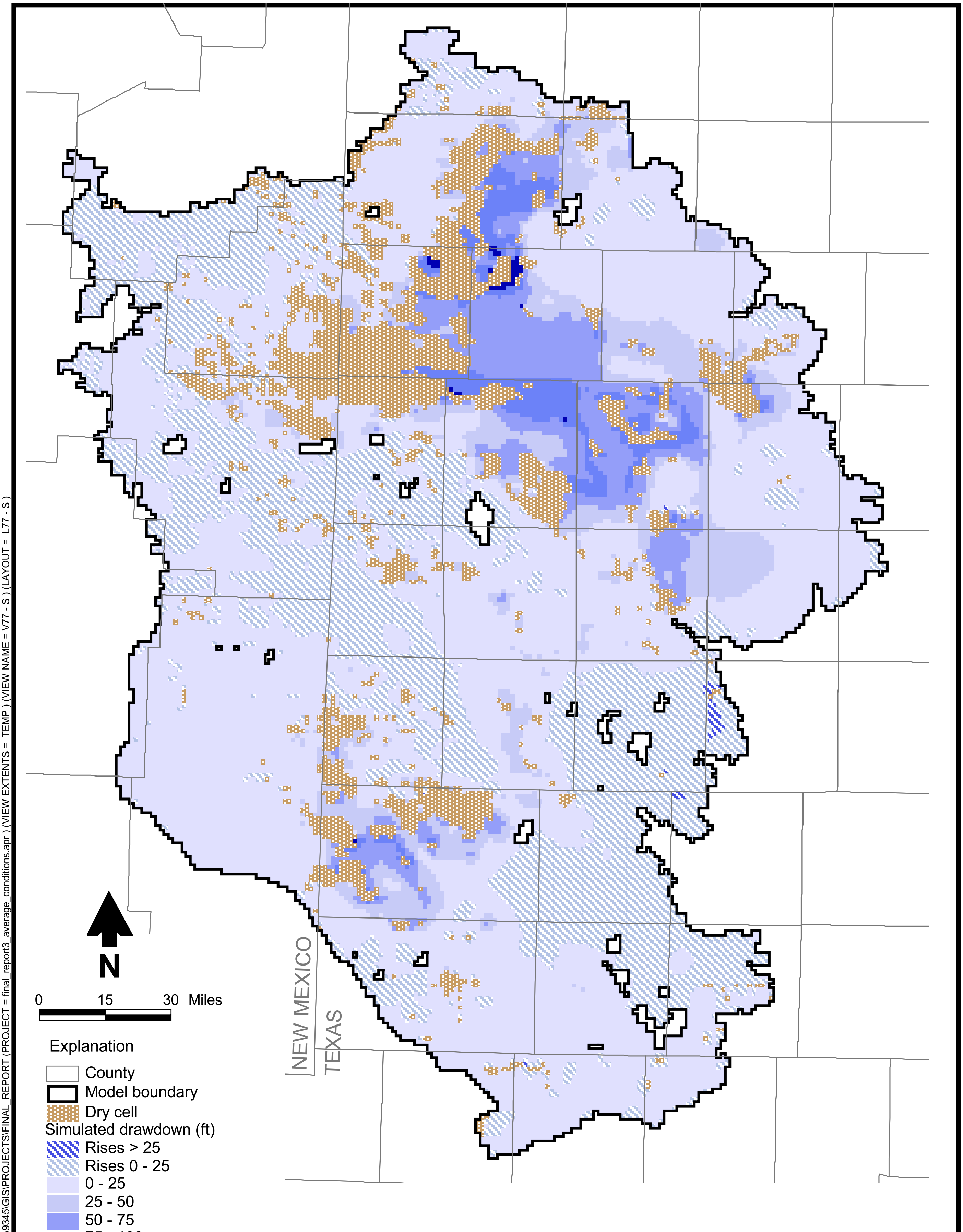
Figure 76



SOUTHERN OGALLALA GAM

Simulated Drawdown for 2030, Average Conditions

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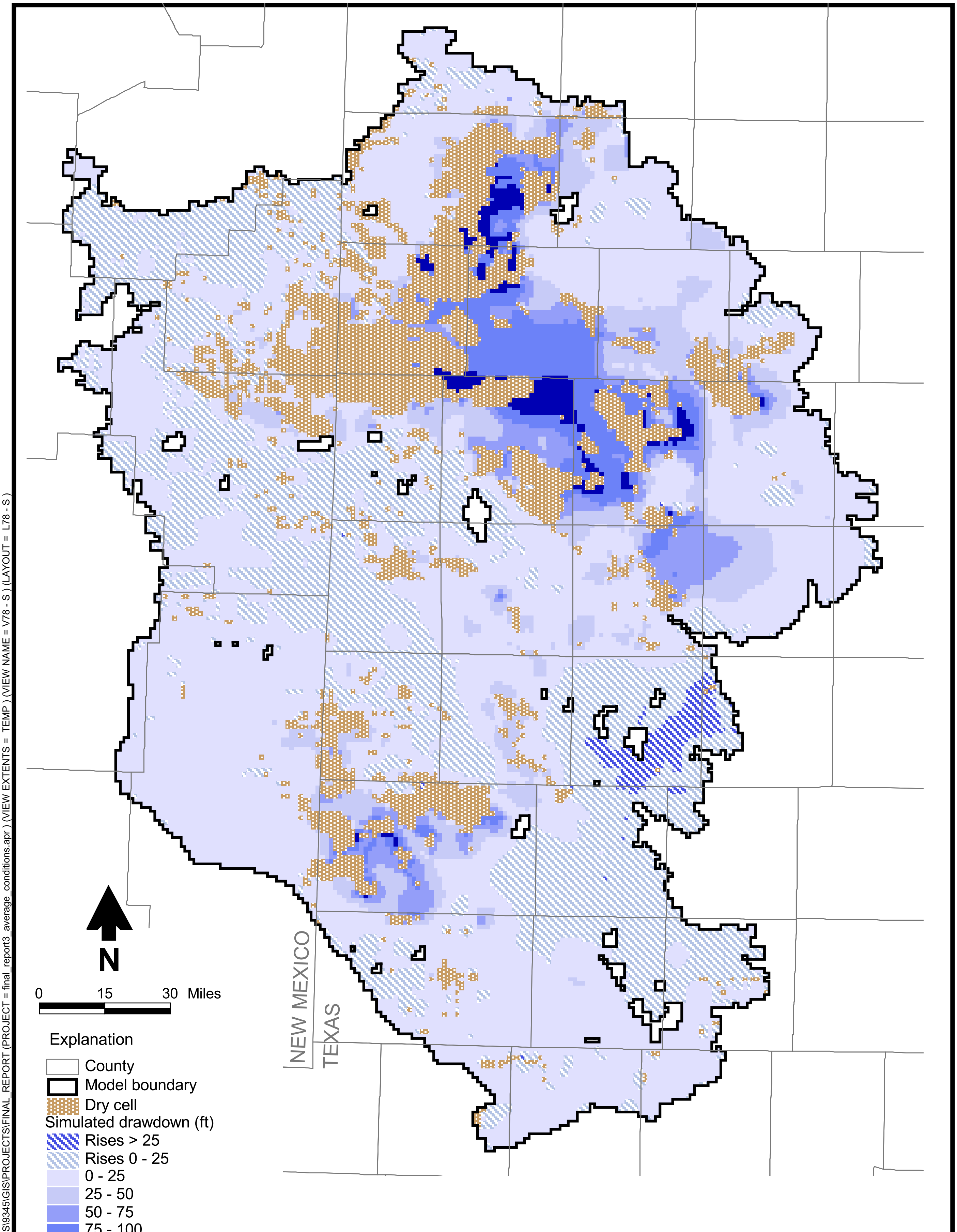
Figure 77



SOUTHERN OGALLALA GAM

Simulated Drawdown for 2040, Average Conditions

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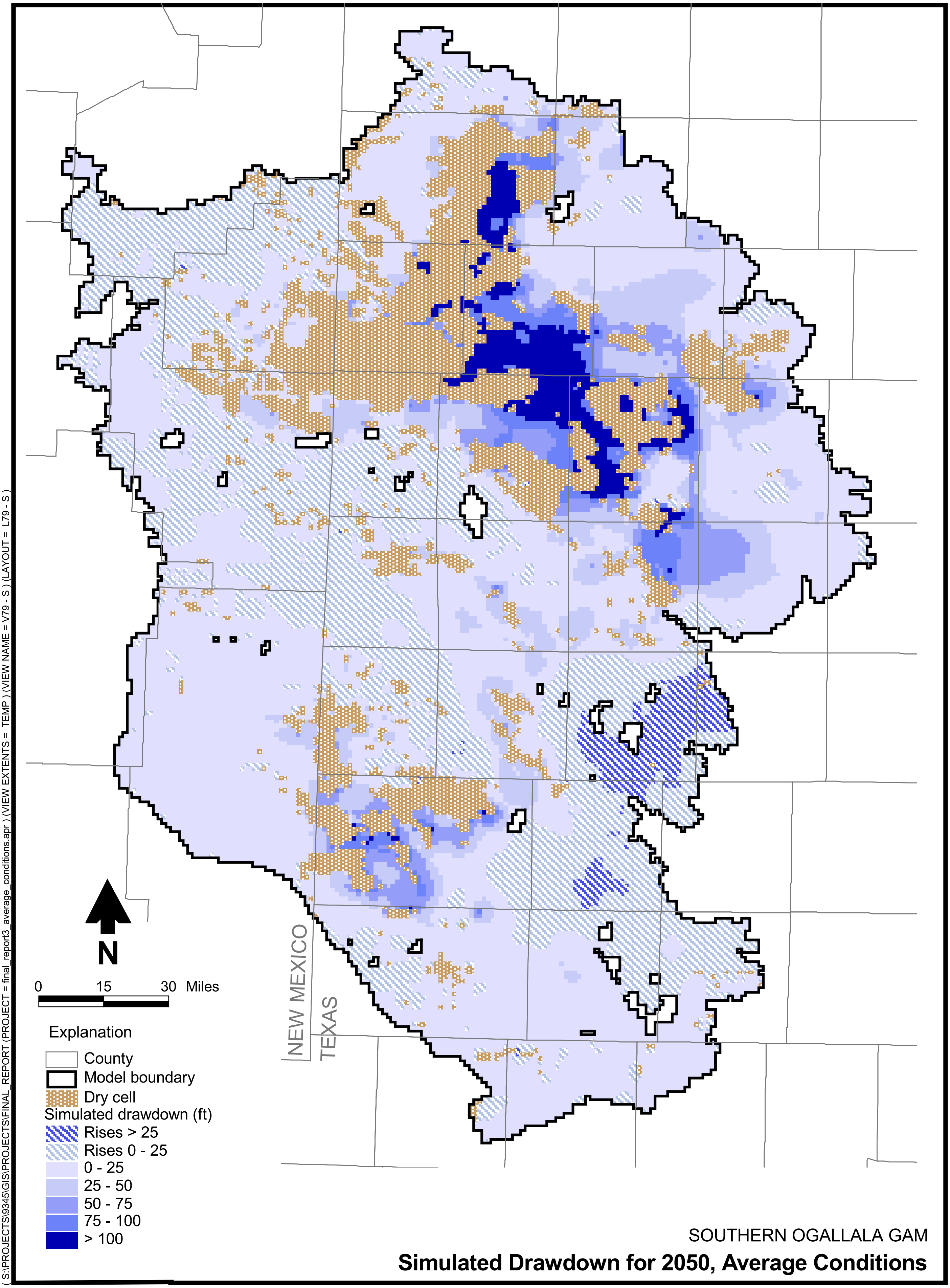
Figure 78



SOUTHERN OGALLALA GAM

Simulated Drawdown for 2050, Average Conditions

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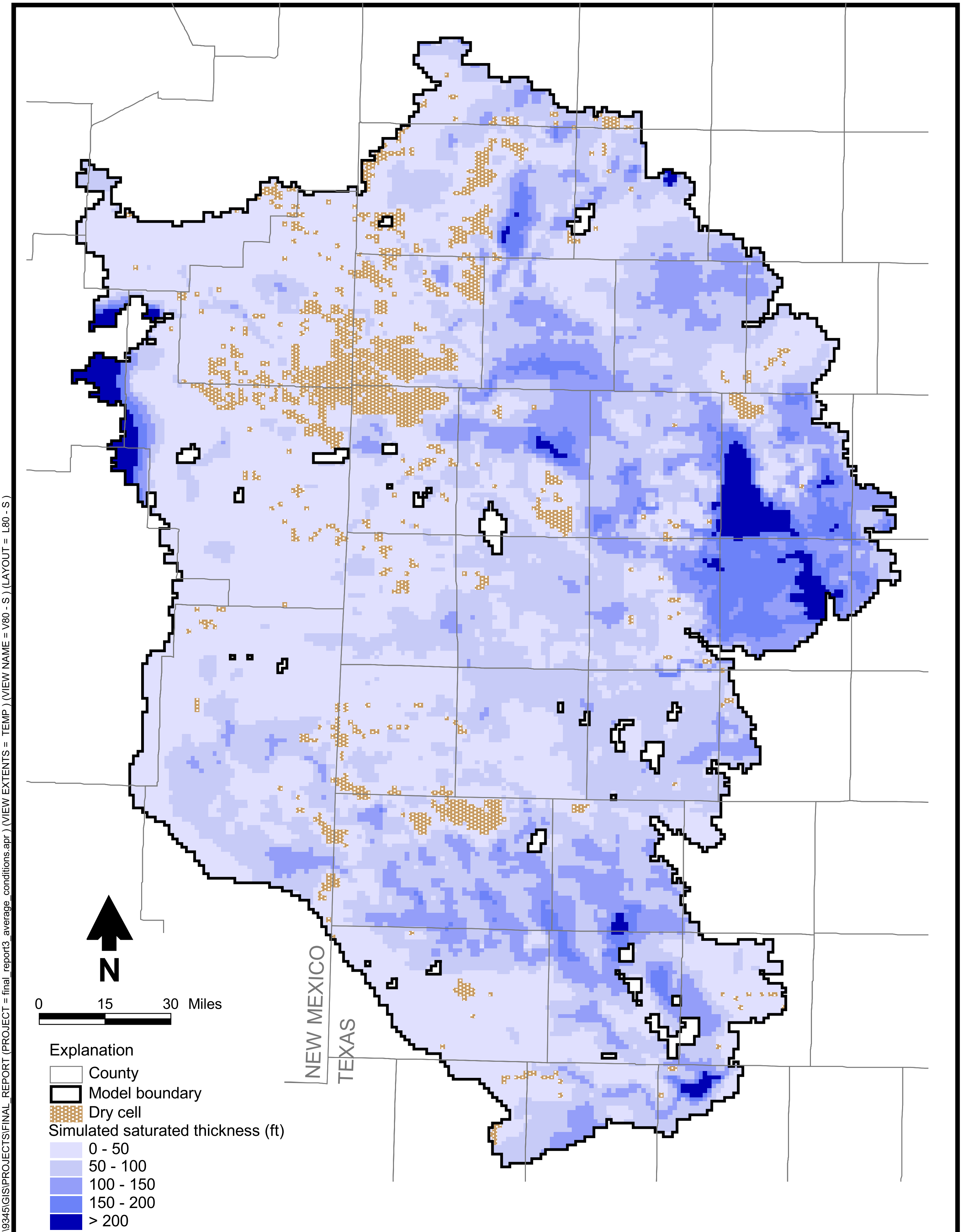
Figure 79



SOUTHERN OGALLALA GAM

Simulated Saturated Thickness for 2010, Average Conditions

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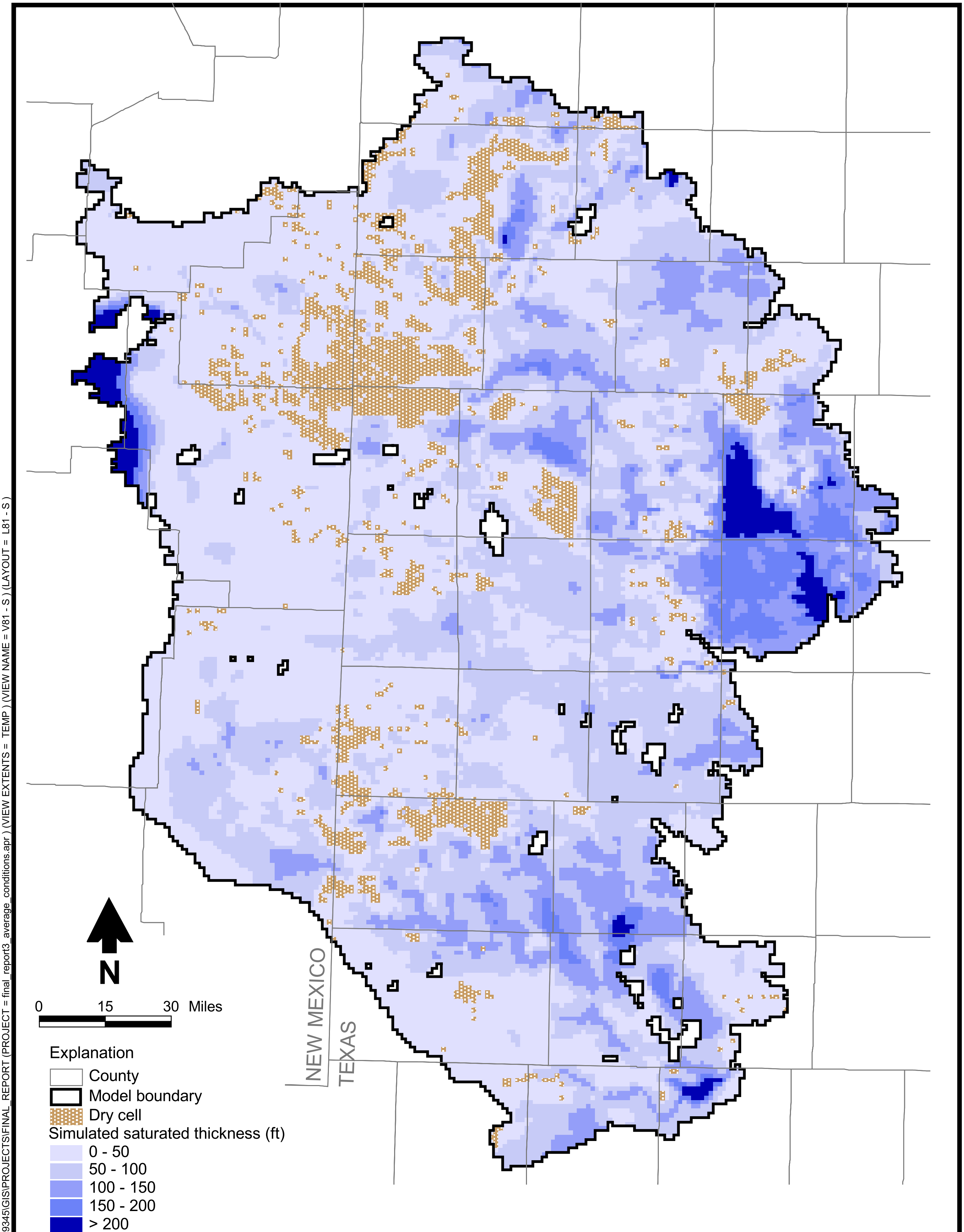
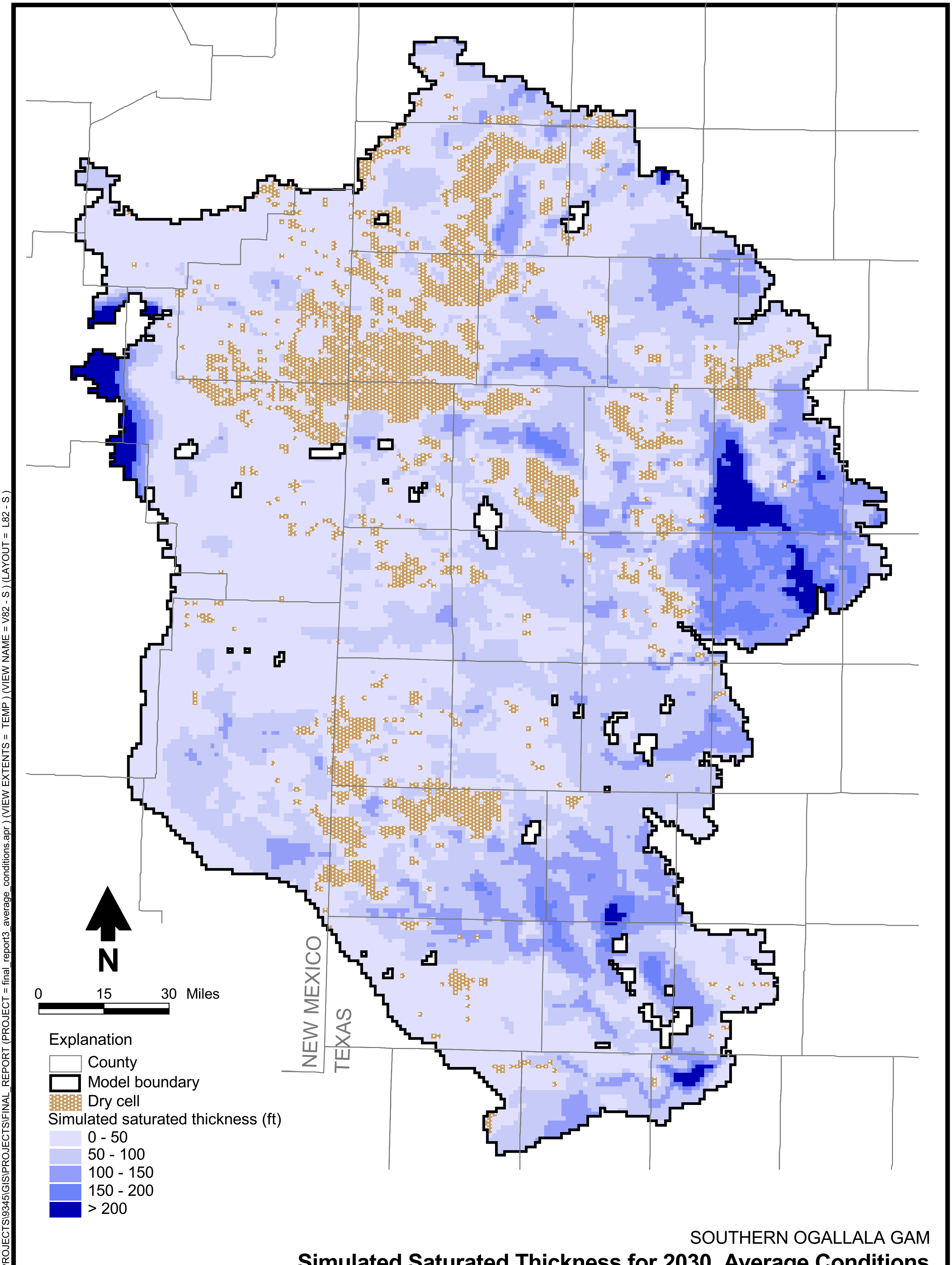
Figure 80



SOUTHERN OGALLALA GAM

Simulated Saturated Thickness for 2020, Average Conditions

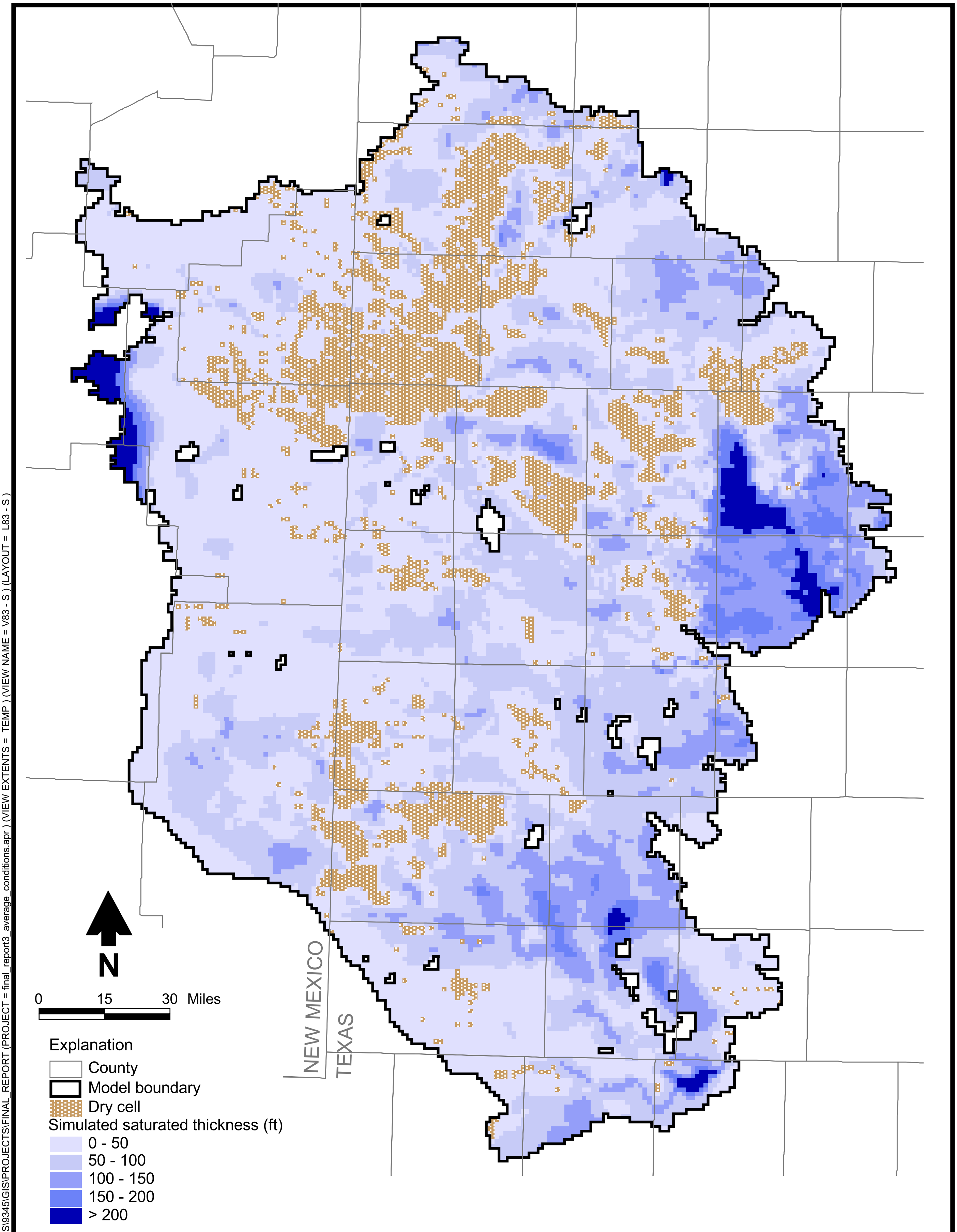


SOUTHERN OGALLALA GAM

Simulated Saturated Thickness for 2030, Average Conditions

3-14-03

Figure 82



SOUTHERN OGALLALA GAM

Simulated Saturated Thickness for 2040, Average Conditions

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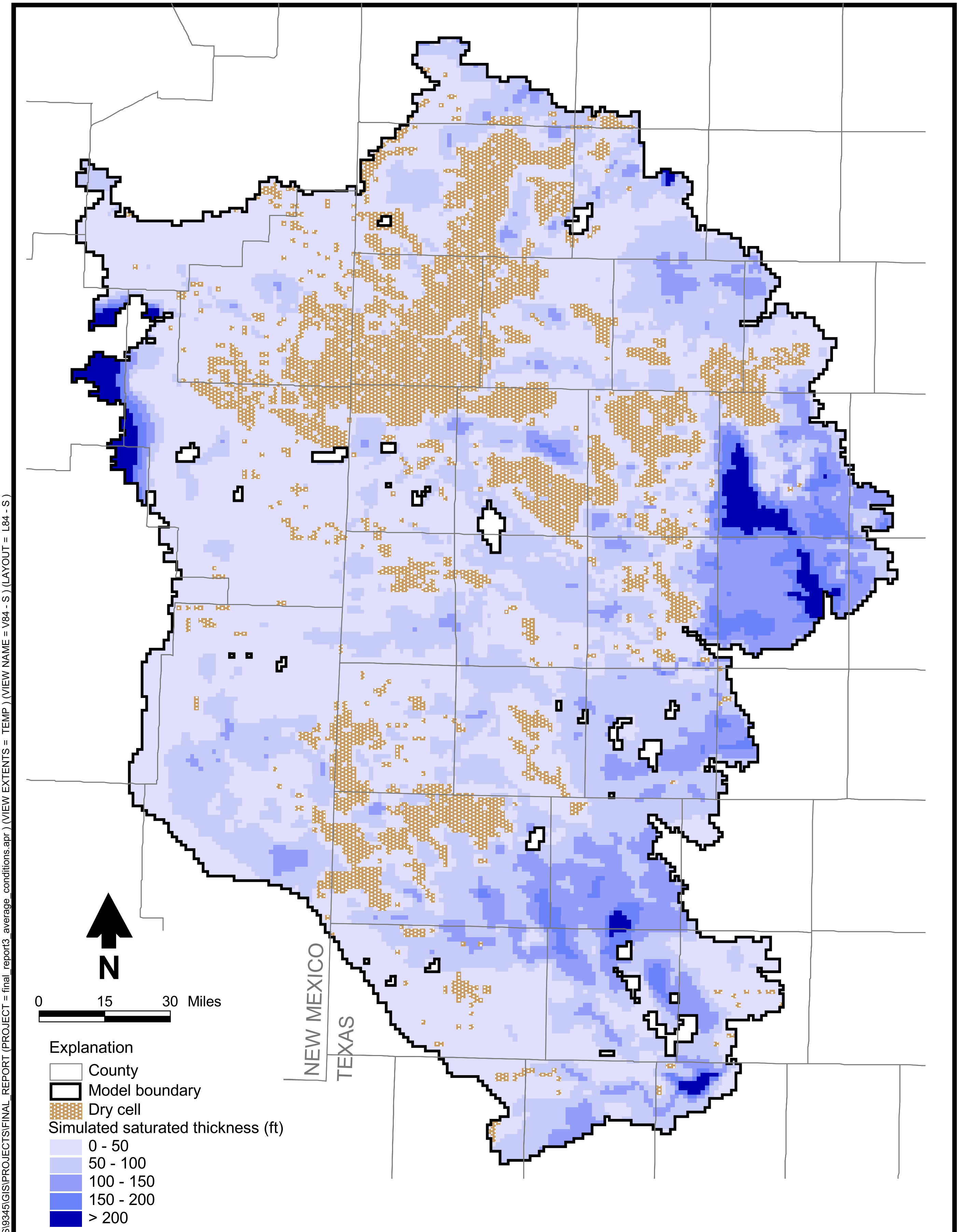
Figure 83



SOUTHERN OGALLALA GAM

Simulated Saturated Thickness for 2050, Average Conditions

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3-14-03

Figure 84

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:

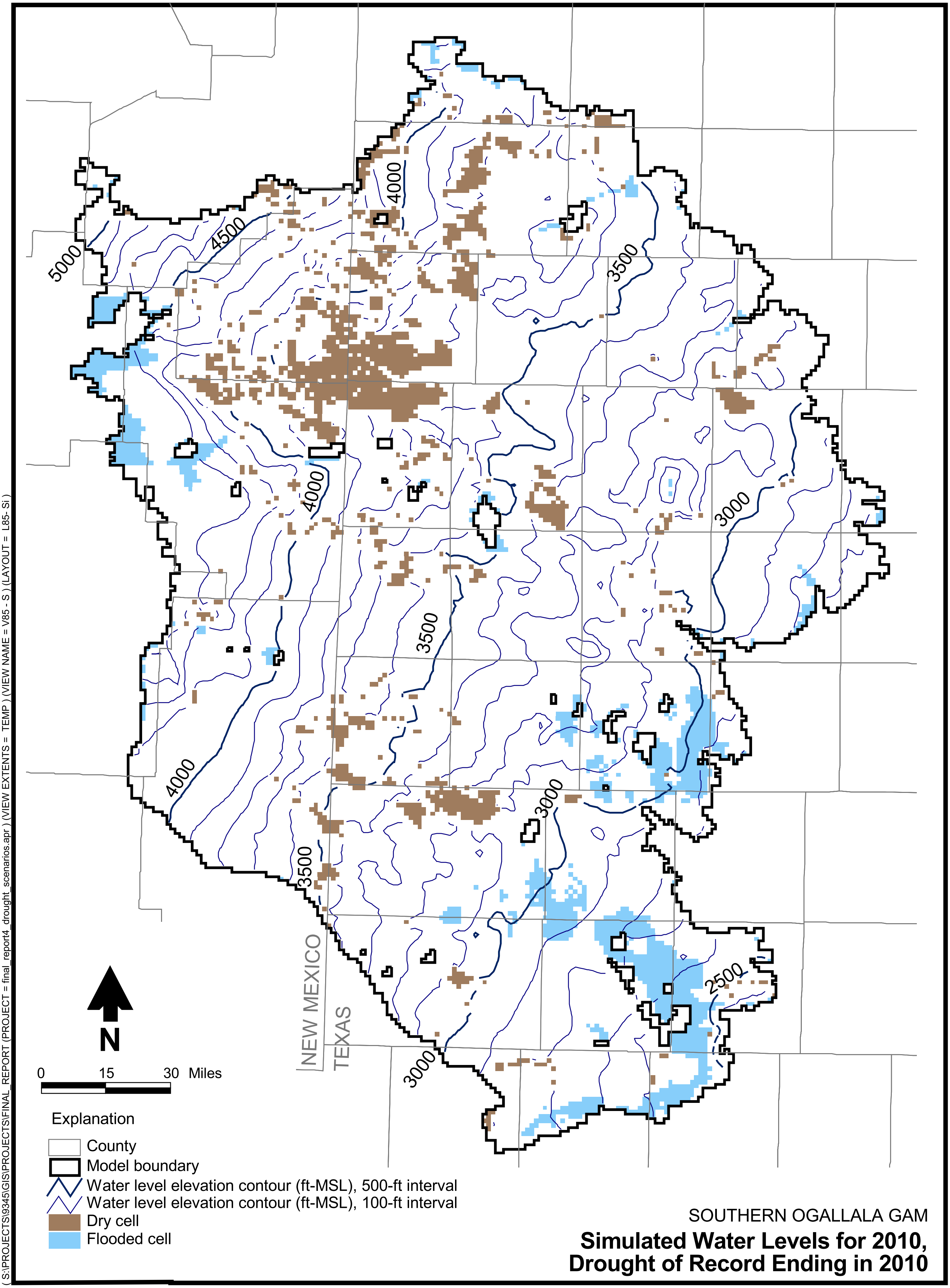
- As cells go dry in MODFLOW, pumping is no longer assigned to those cells in the model. Therefore, where dry cells occur prior to the drought-of-record period (the last five years of every decade), increased pumping for drought conditions will not be applied.
- The Southern Ogallala aquifer represents 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.

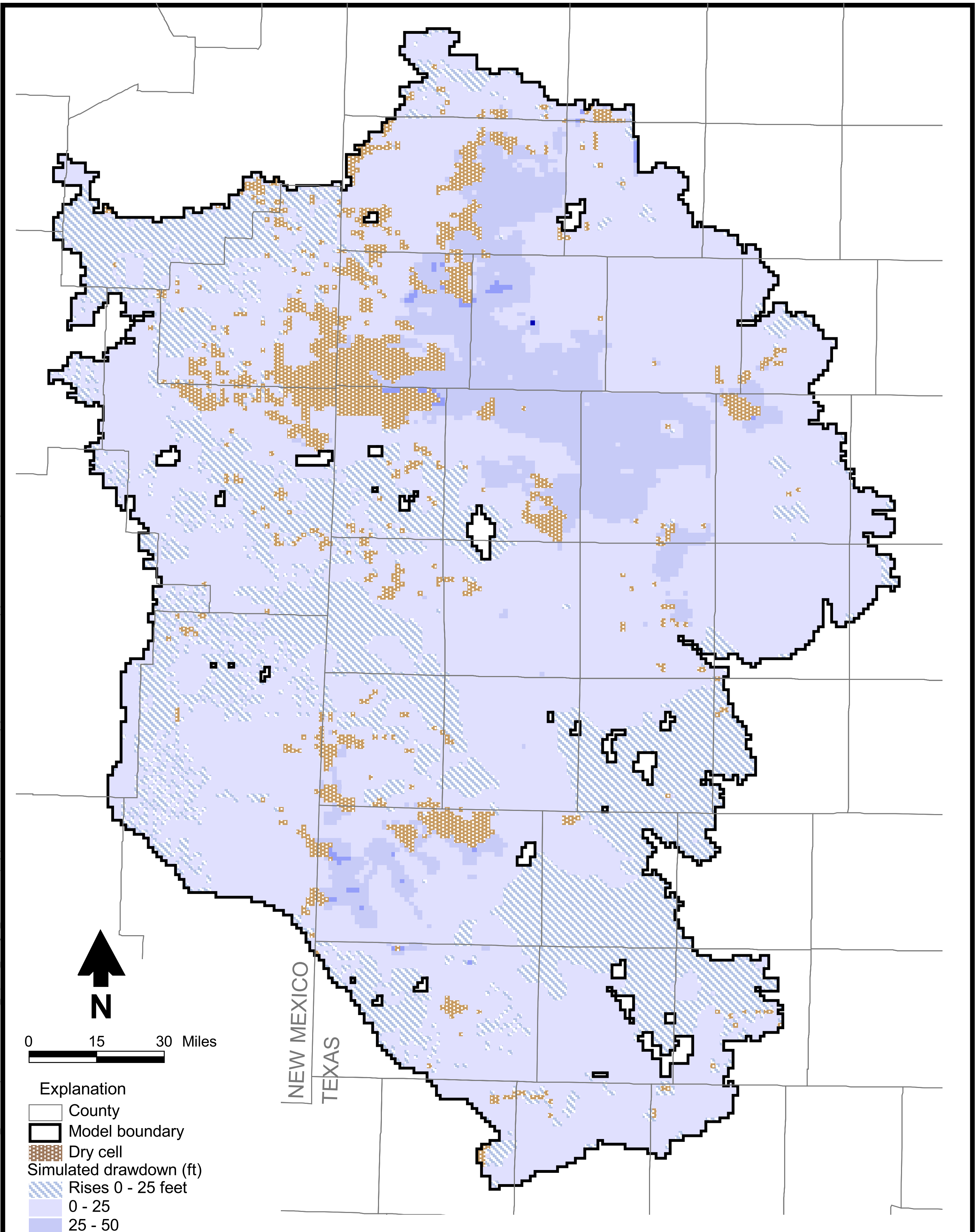


SOUTHERN OGALLALA GAM

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

3-14-03

Figure 85



SOUTHERN OGALLALA GAM

Simulated Drawdown for 2010, Drought of Record Ending in 2010

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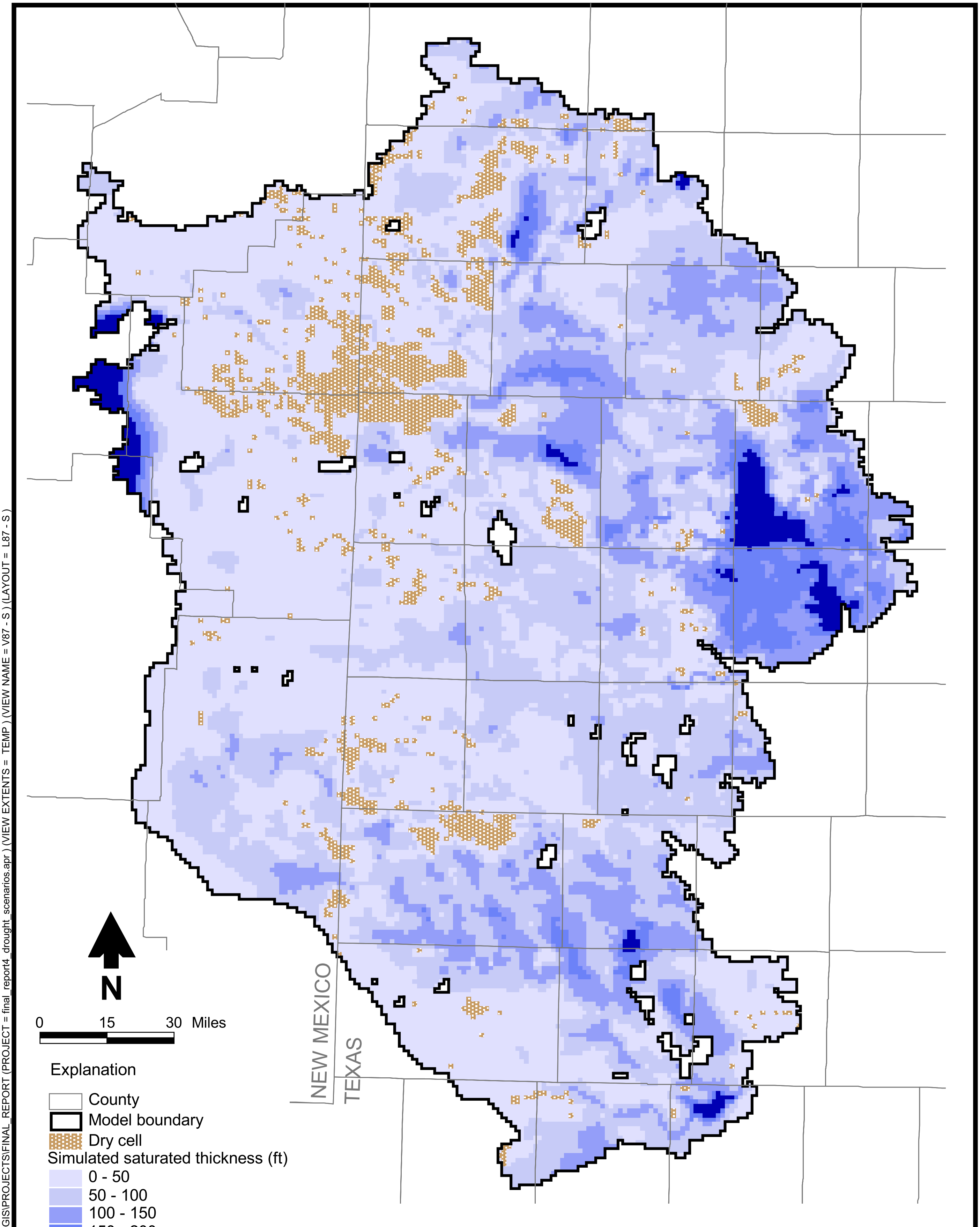

SOUTHERN OGALLALA GAM

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

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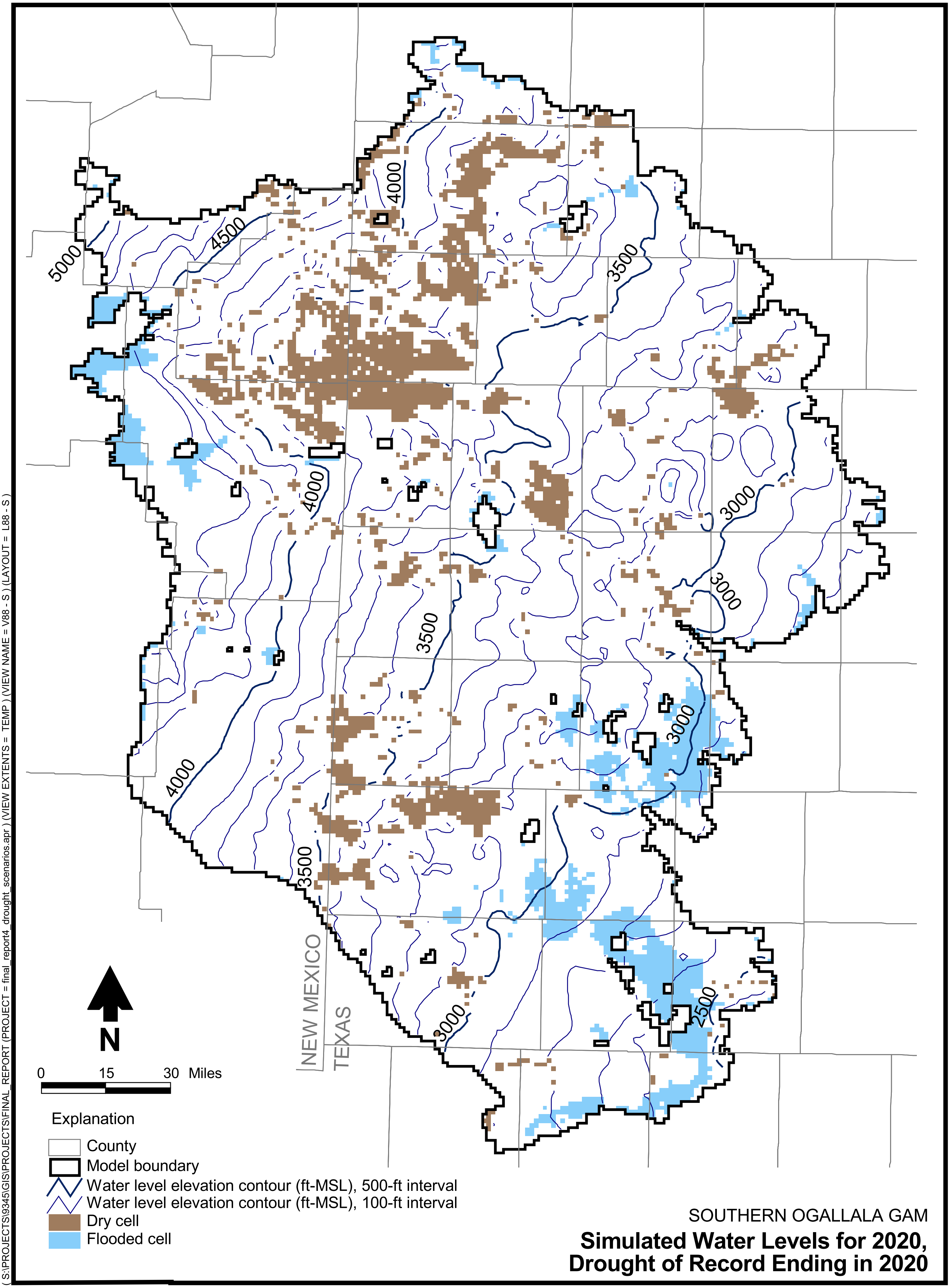
3-14-03

Figure 87

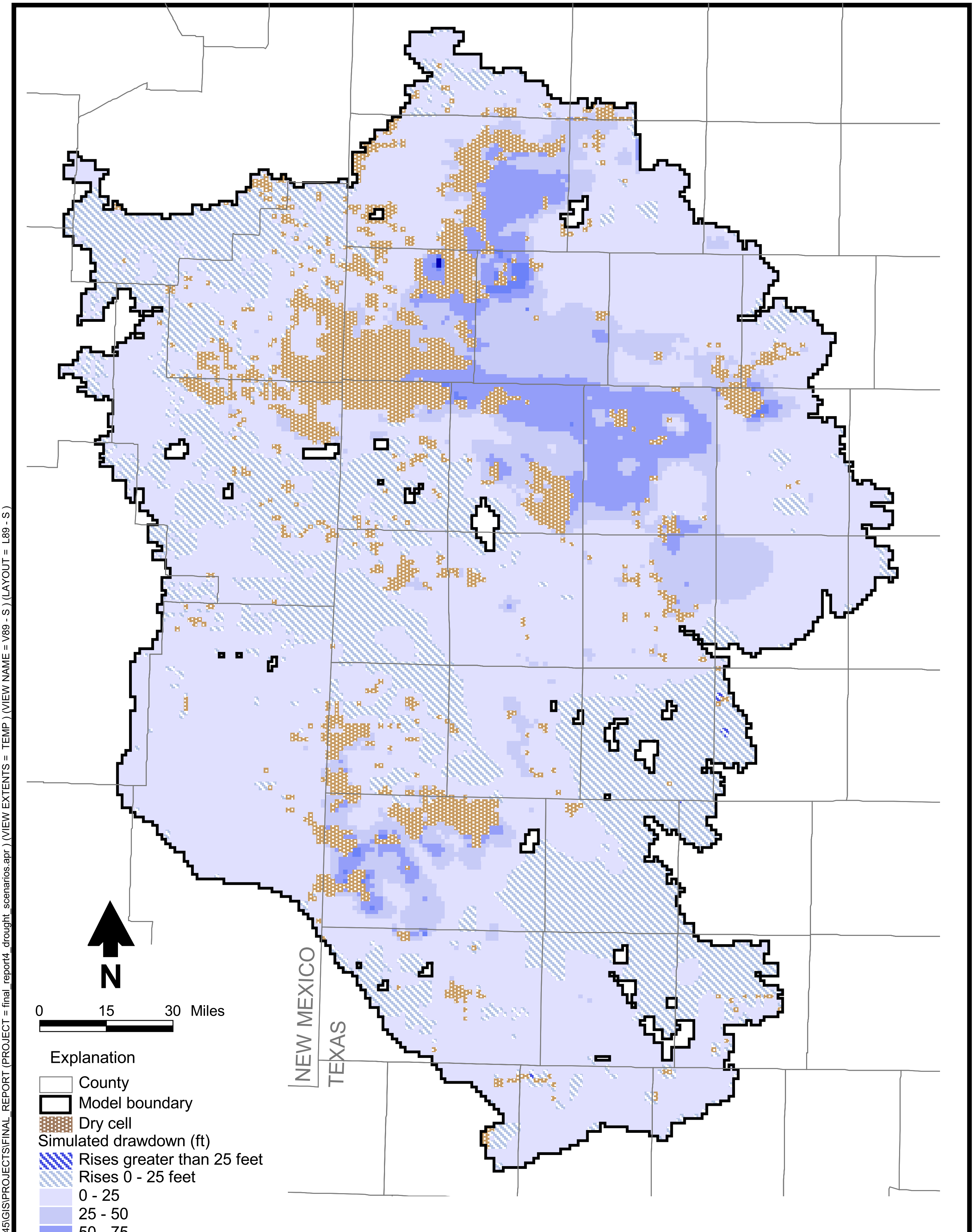


SOUTHERN OGALLALA GAM

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

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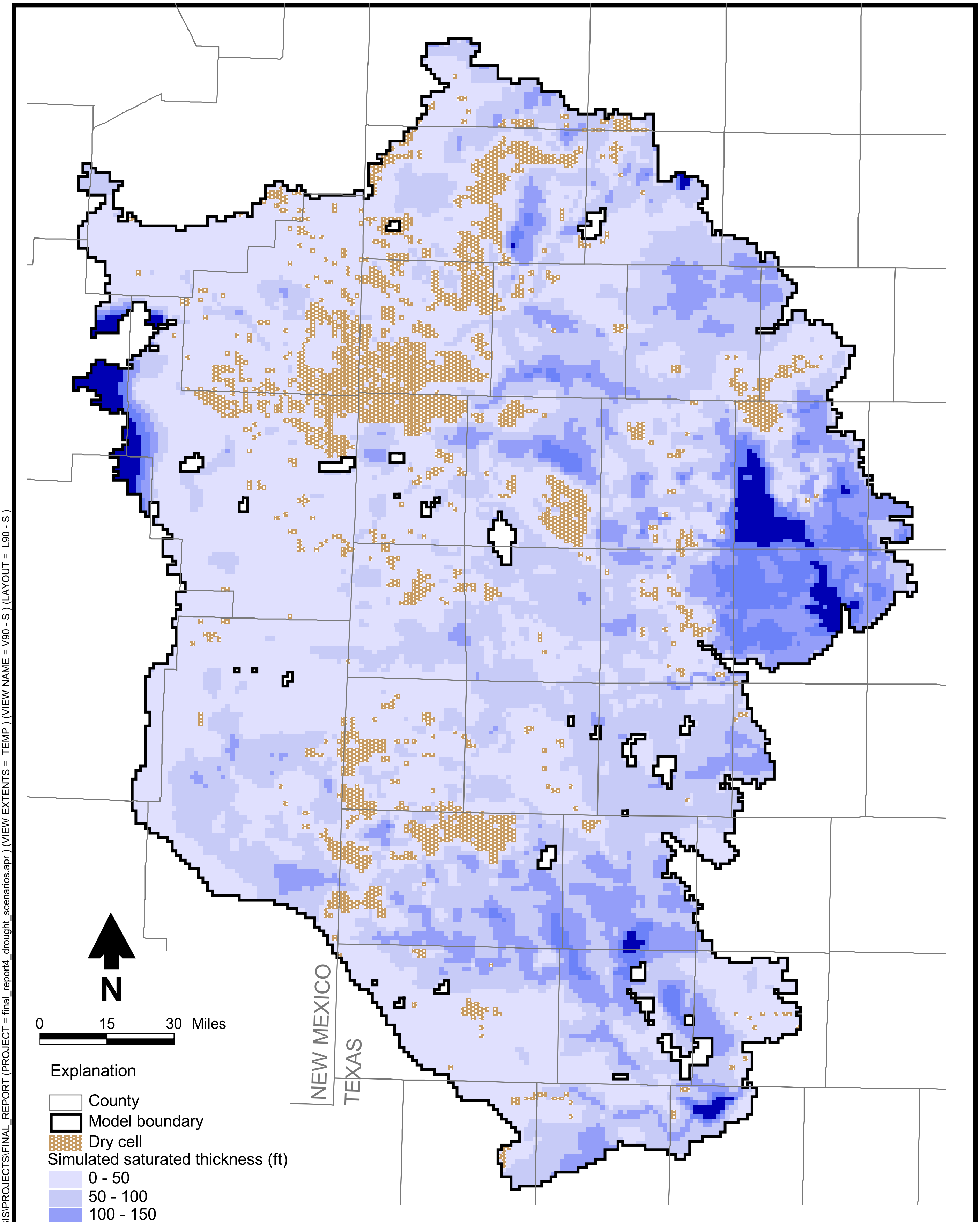
Figure 89



SOUTHERN OGALLALA GAM

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

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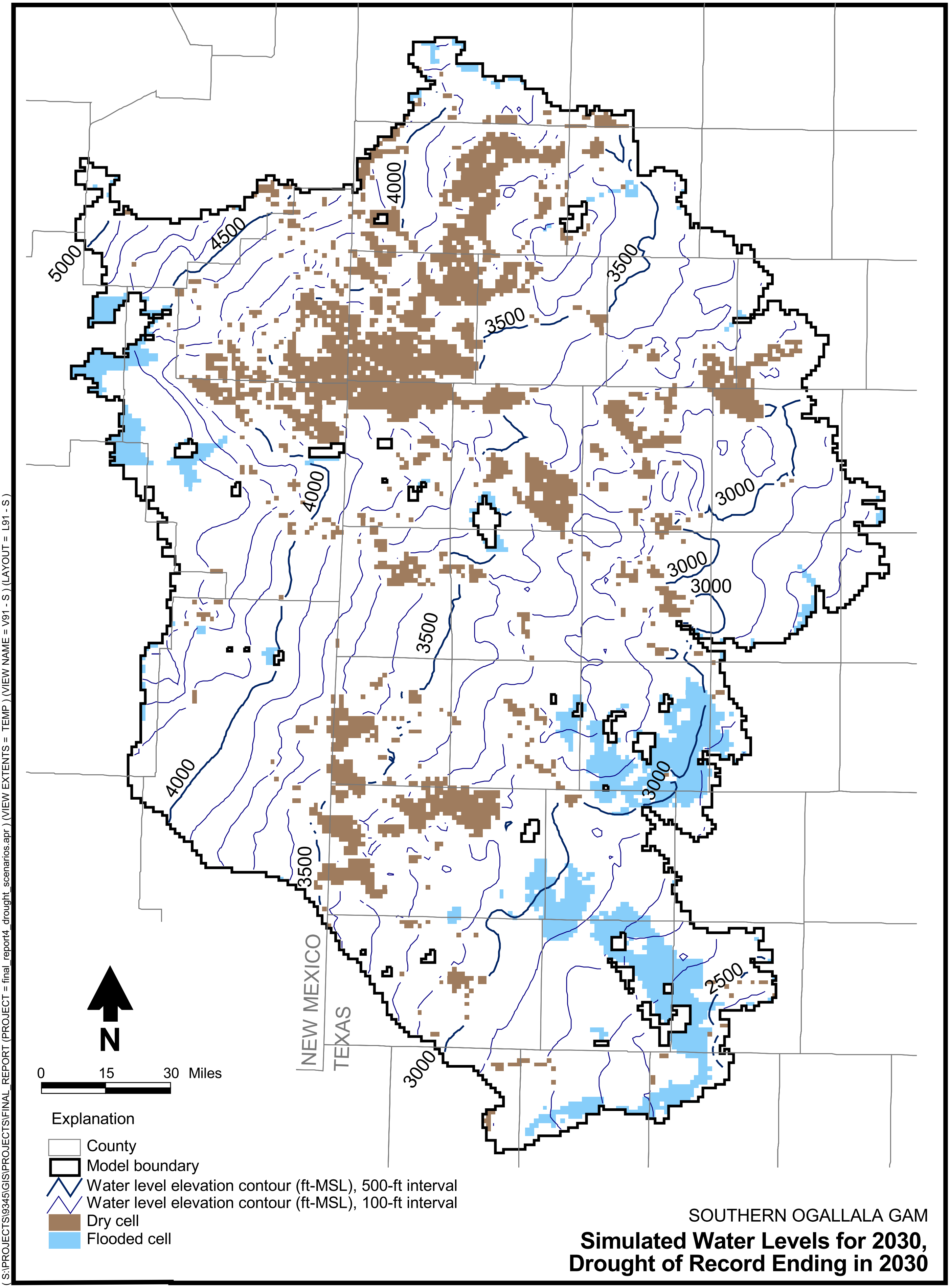
3-14-03

Figure 90

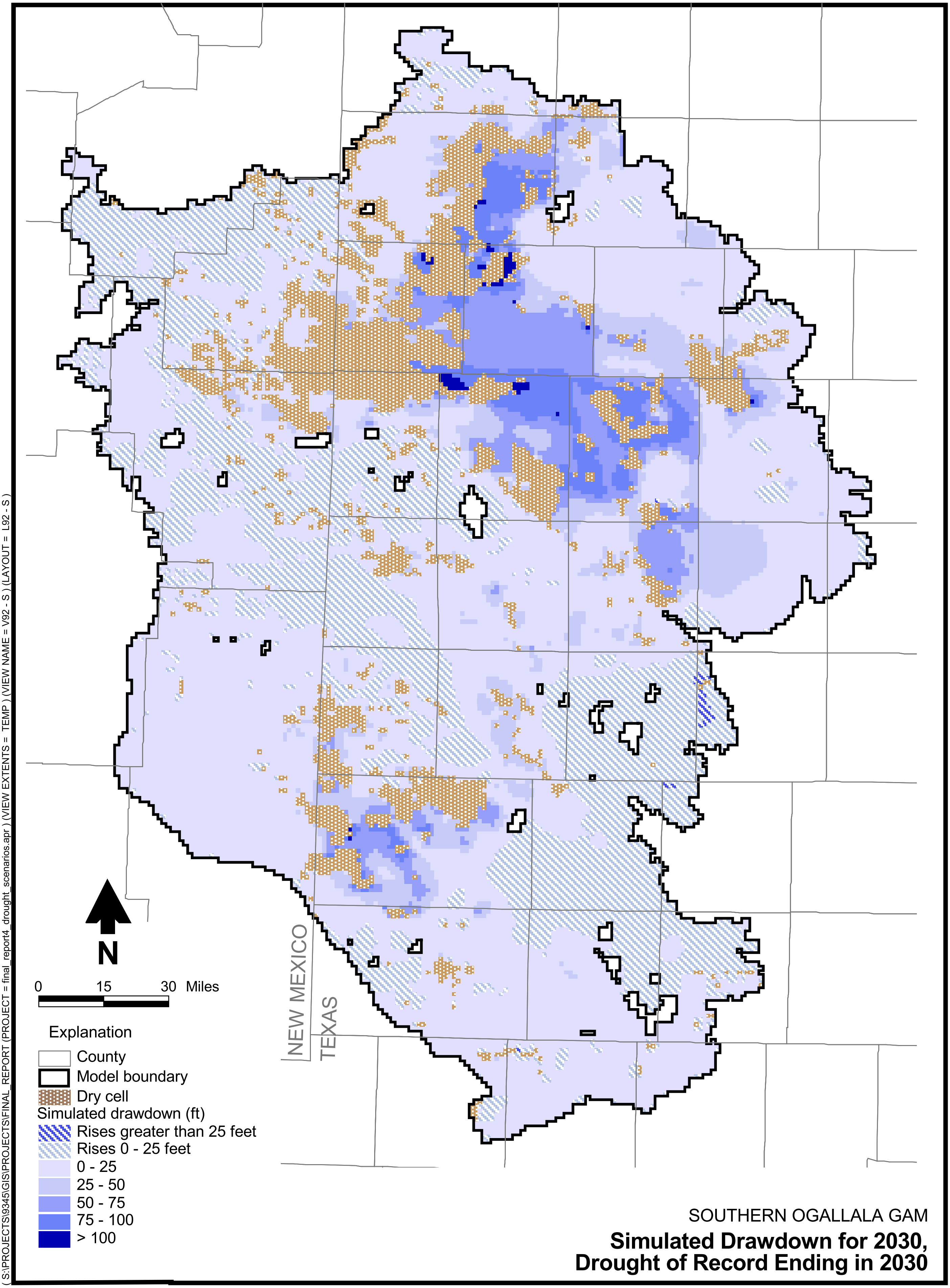


SOUTHERN OGALLALA GAM

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

3-14-03

Figure 91

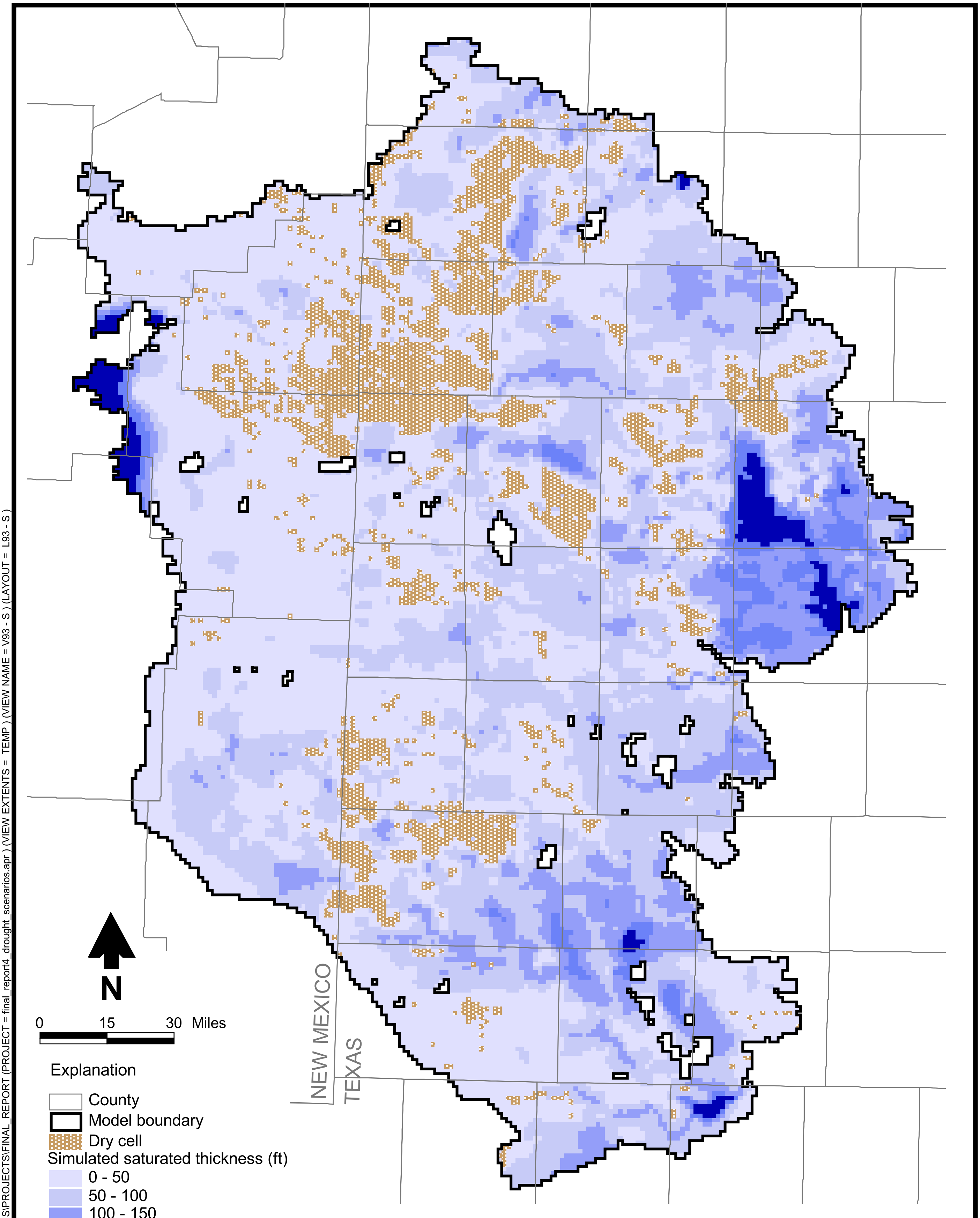


SOUTHERN OGALLALA GAM

Simulated Drawdown for 2030, Drought of Record Ending in 2030

3-14-03

Figure 92



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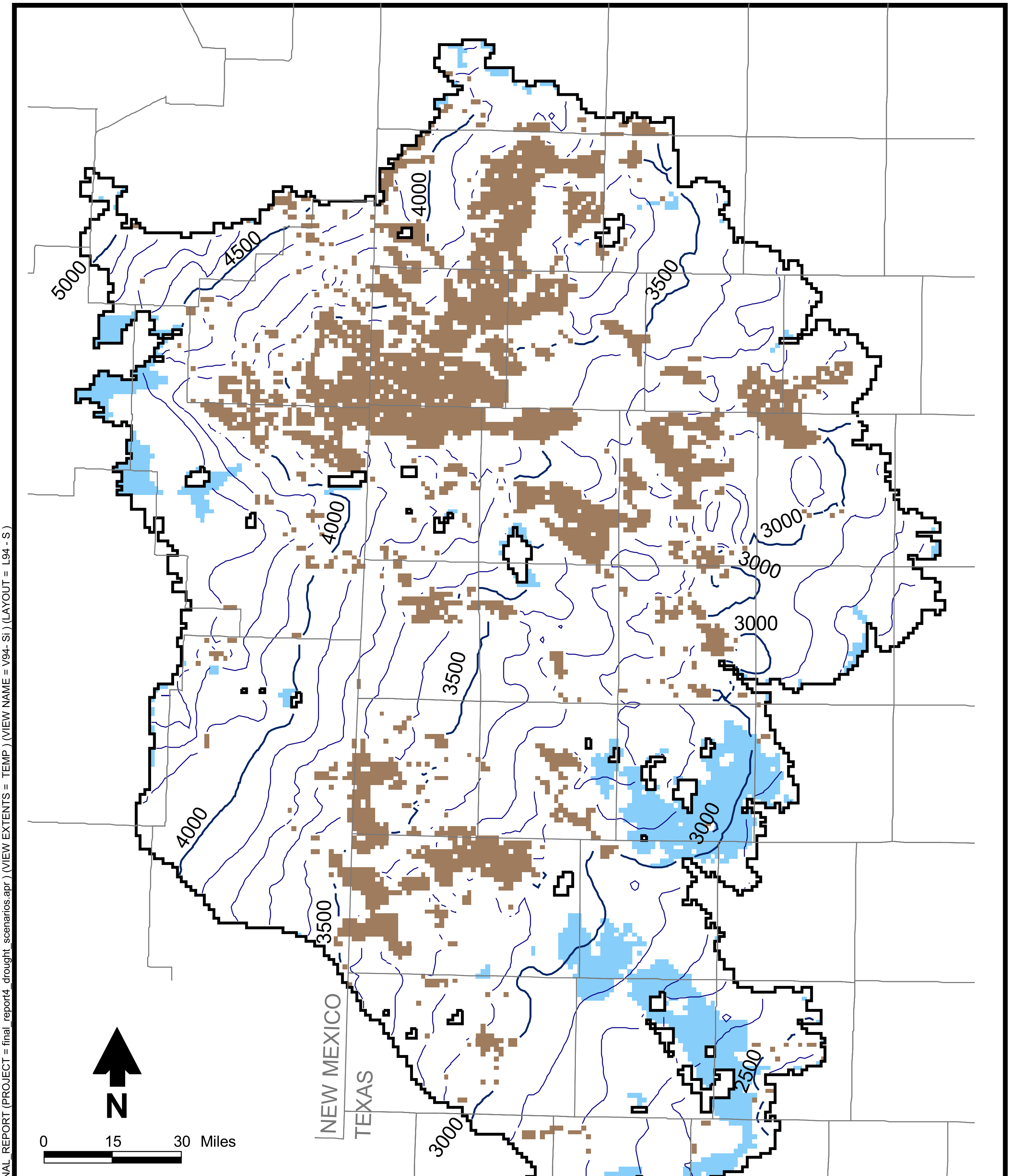
SOUTHERN OGALLALA GAM

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

3-14-03



Explanation

County
Model boundary
Water level elevation contour (ft-MSL), 500-ft interval
Water level elevation contour (ft-MSL), 100-ft interval
Dry cell
Flooded cell

SOUTHERN OGALLALA GAM

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

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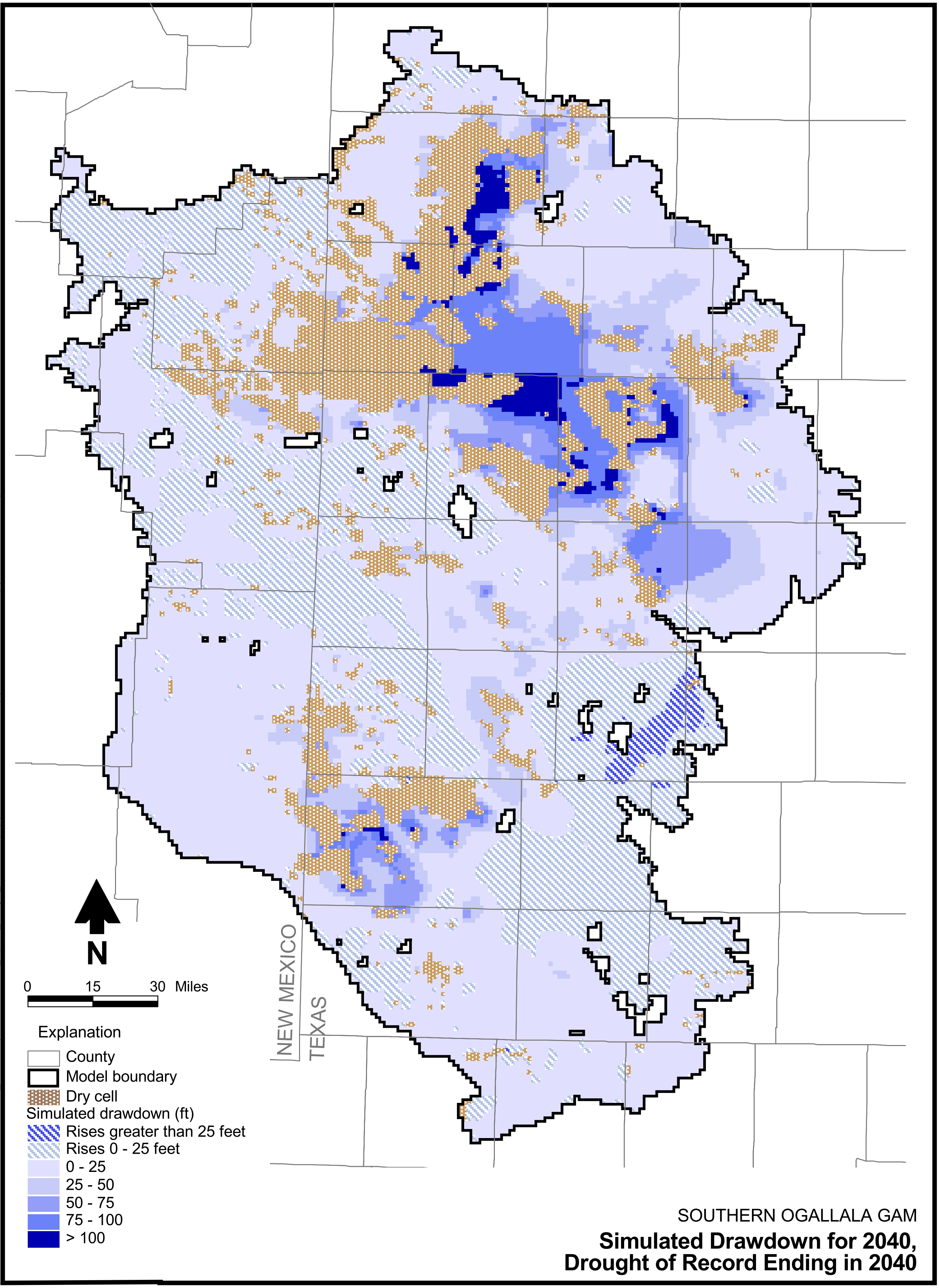
3-14-03

Figure 94



SOUTHERN OGALLALA GAM

Simulated Drawdown for 2040, Drought of Record Ending in 2040

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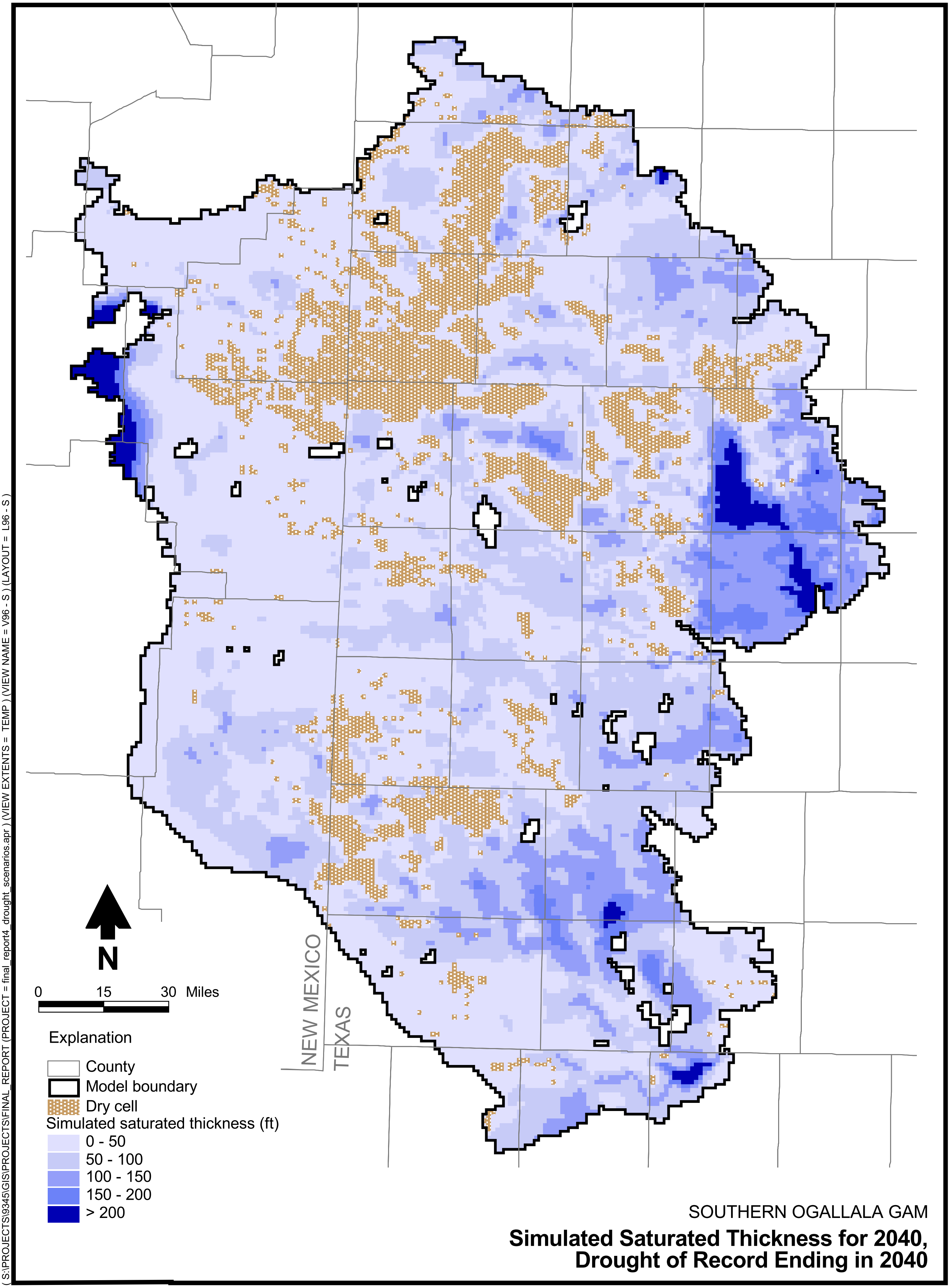
3-14-03

Figure 95

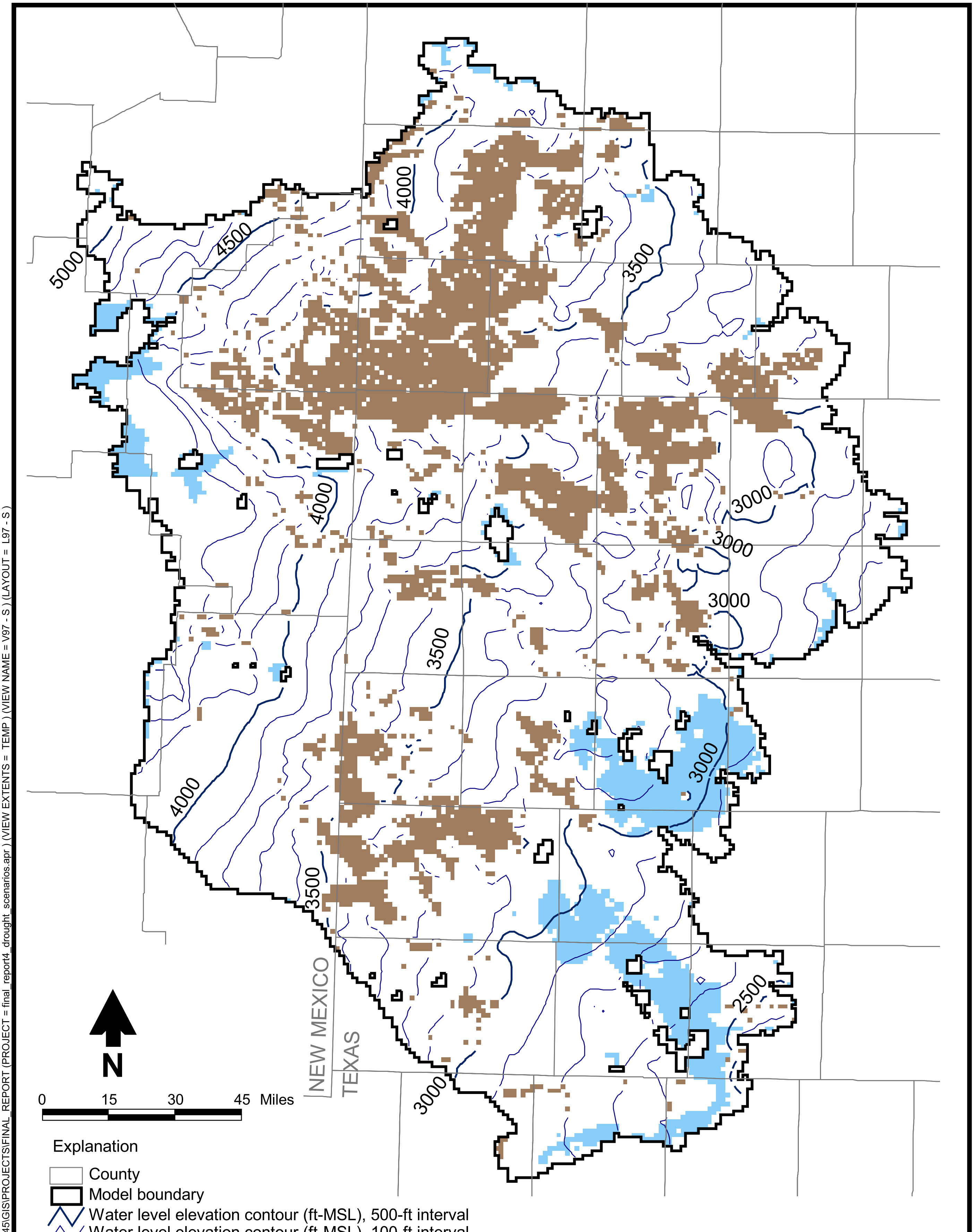


SOUTHERN OGALLALA GAM

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

3-14-03

Figure 96

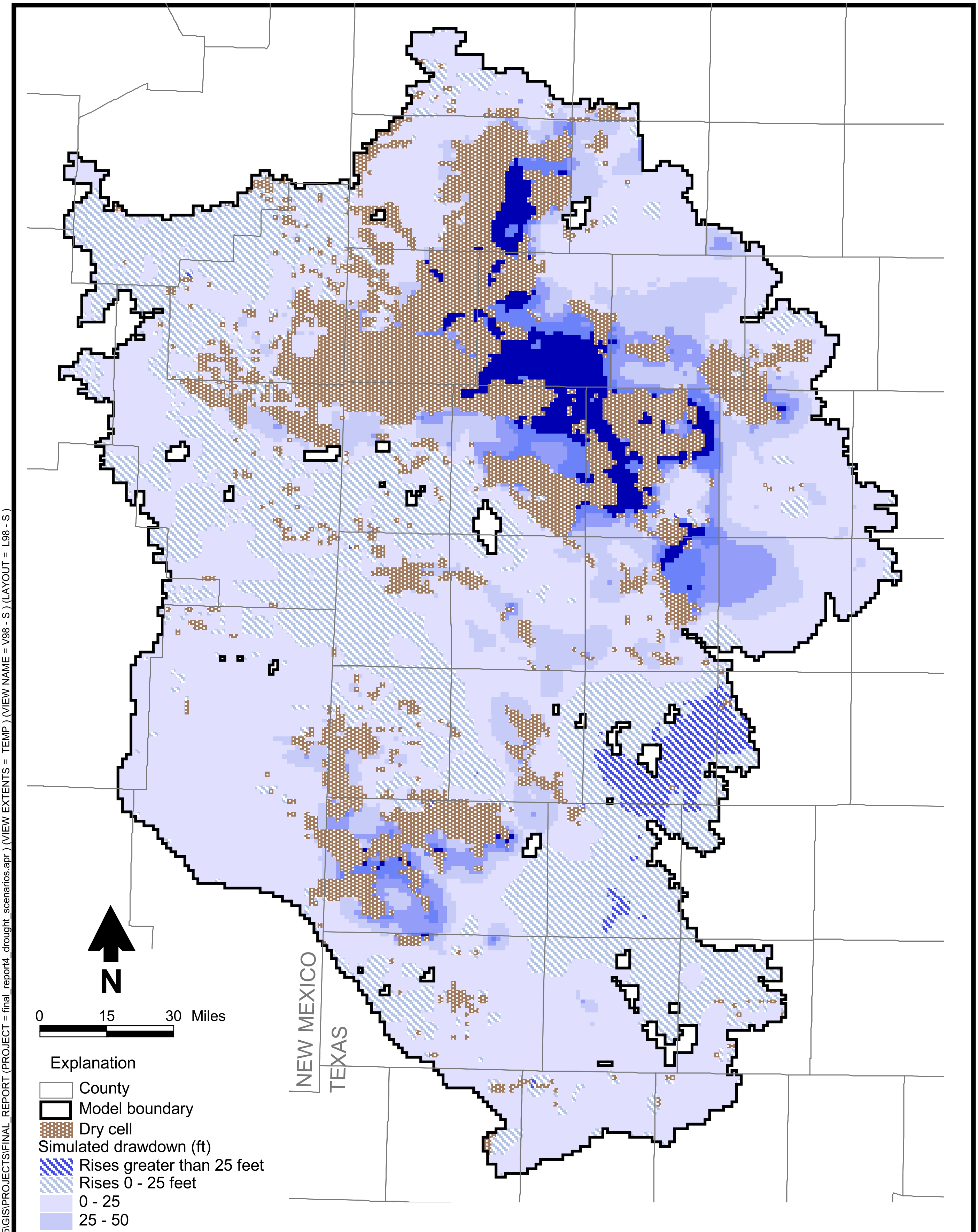


SOUTHERN OGALLALA GAM

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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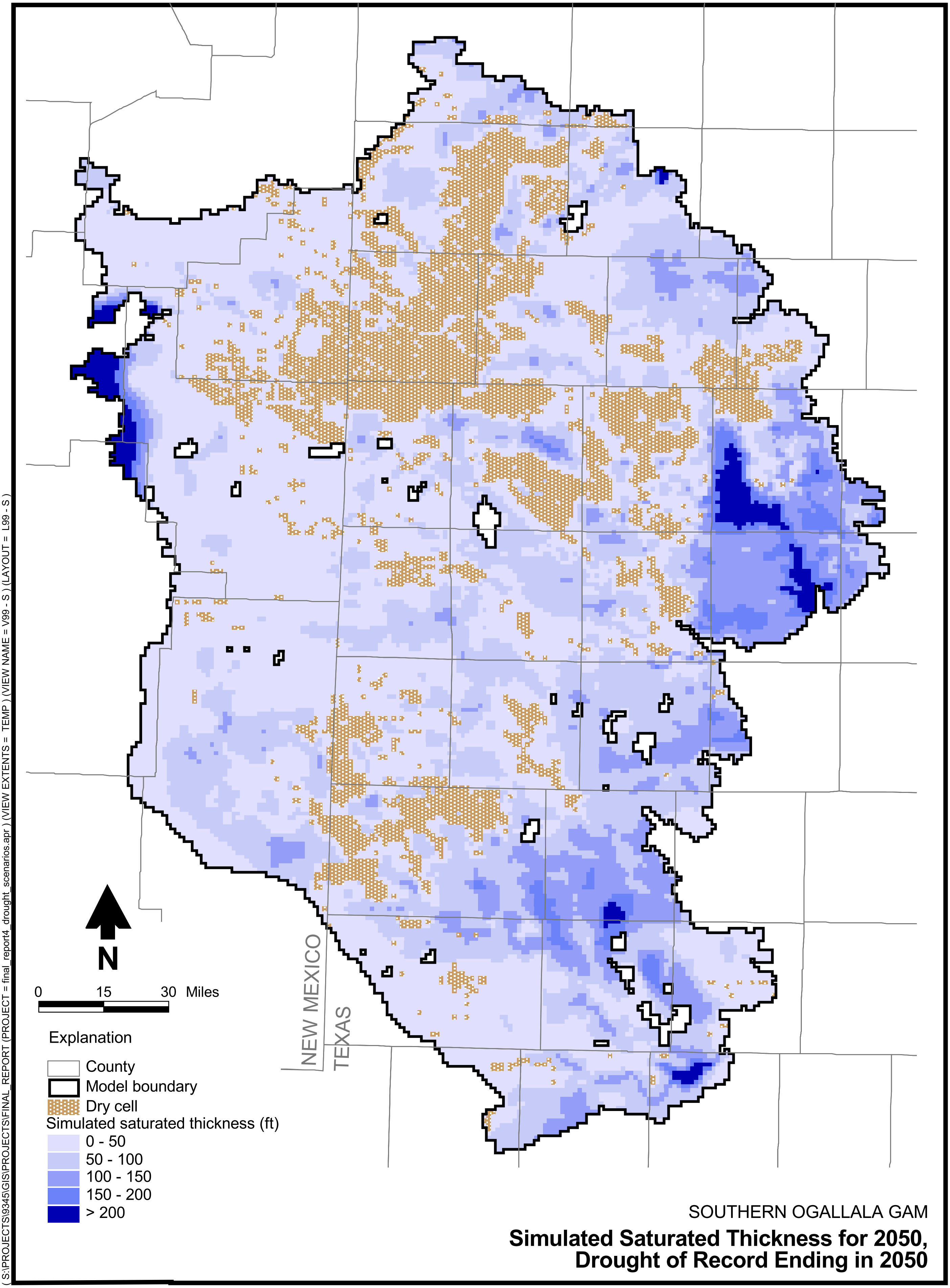


SOUTHERN OGALLALA GAM

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

3-14-03

Figure 99

Table 7: Simulated Water Balance for Predictive Simulations

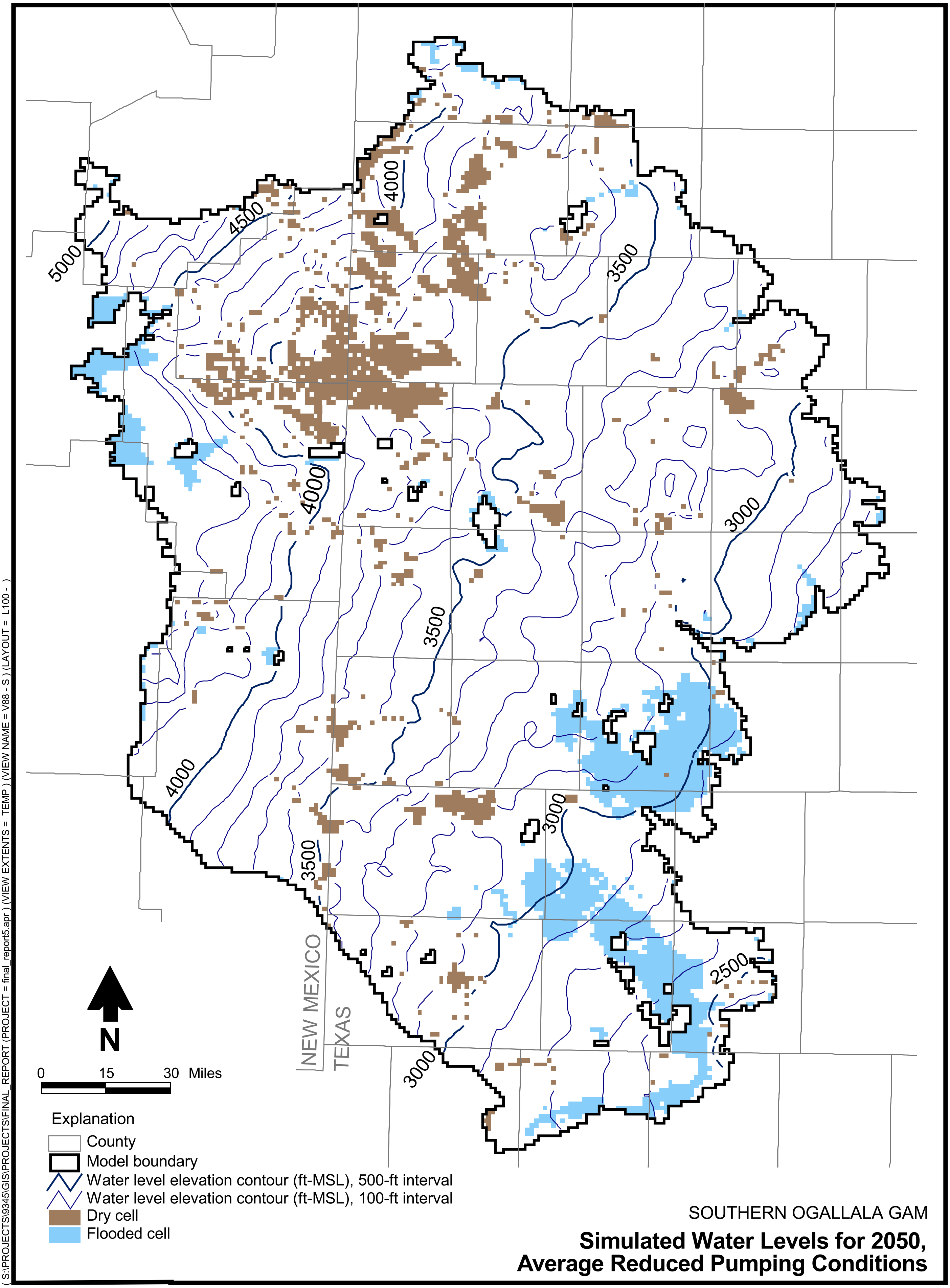
	Amount (ac-ft/yr)						
	Drought Conditions					Average Conditions	Reduced Pumping
	2010	2020	2030	2040	2050	2050	2050
Inflows							
Prescribed head boundary	750	791	902	844	677	657	215
Recharge	675,095	628,633	582,001	537,359	502,687	730,151	968,256
Storage	3,052,463	2,536,799	2,084,191	1,653,493	1,359,982	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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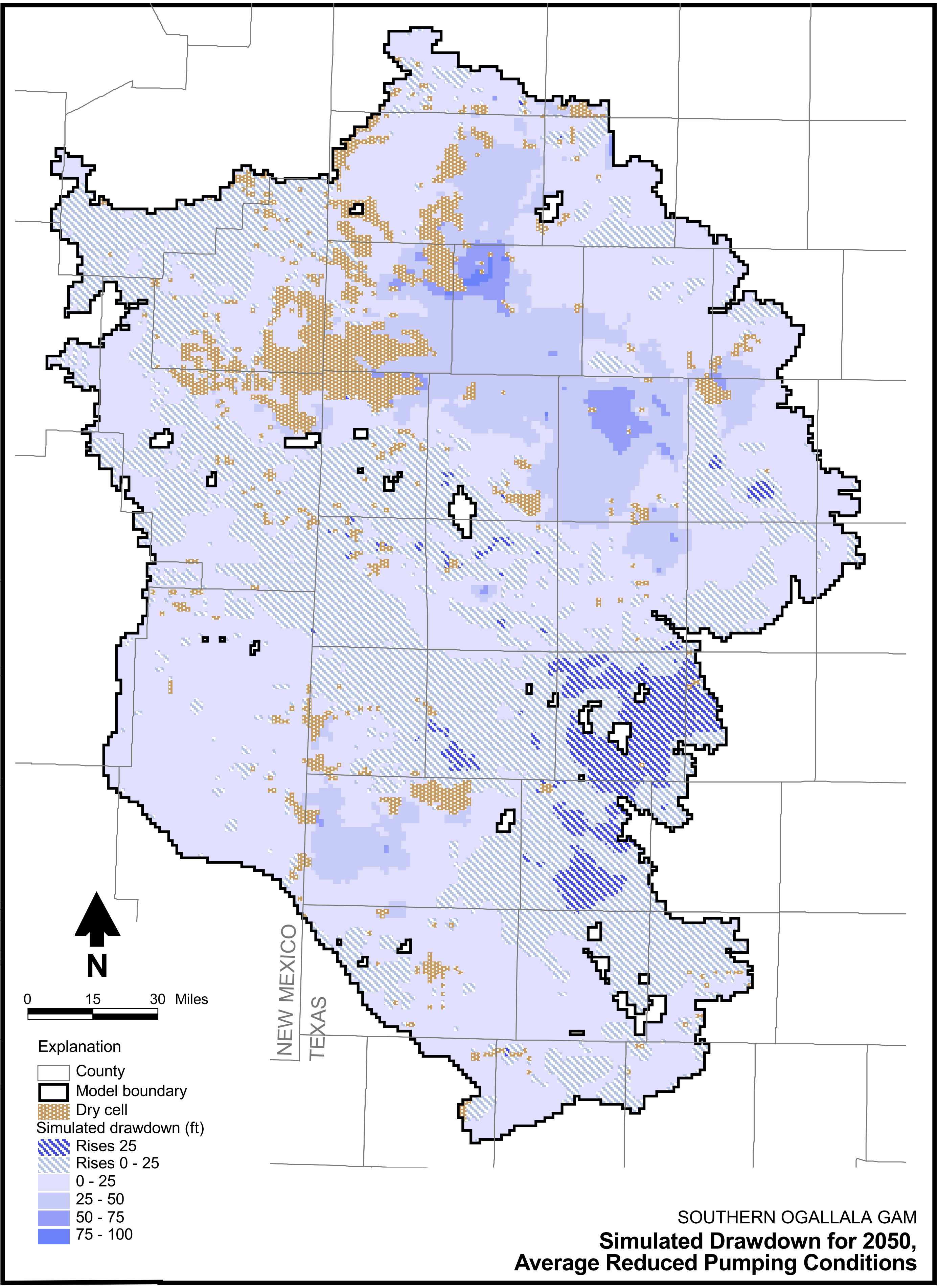
3-14-03

Figure 100

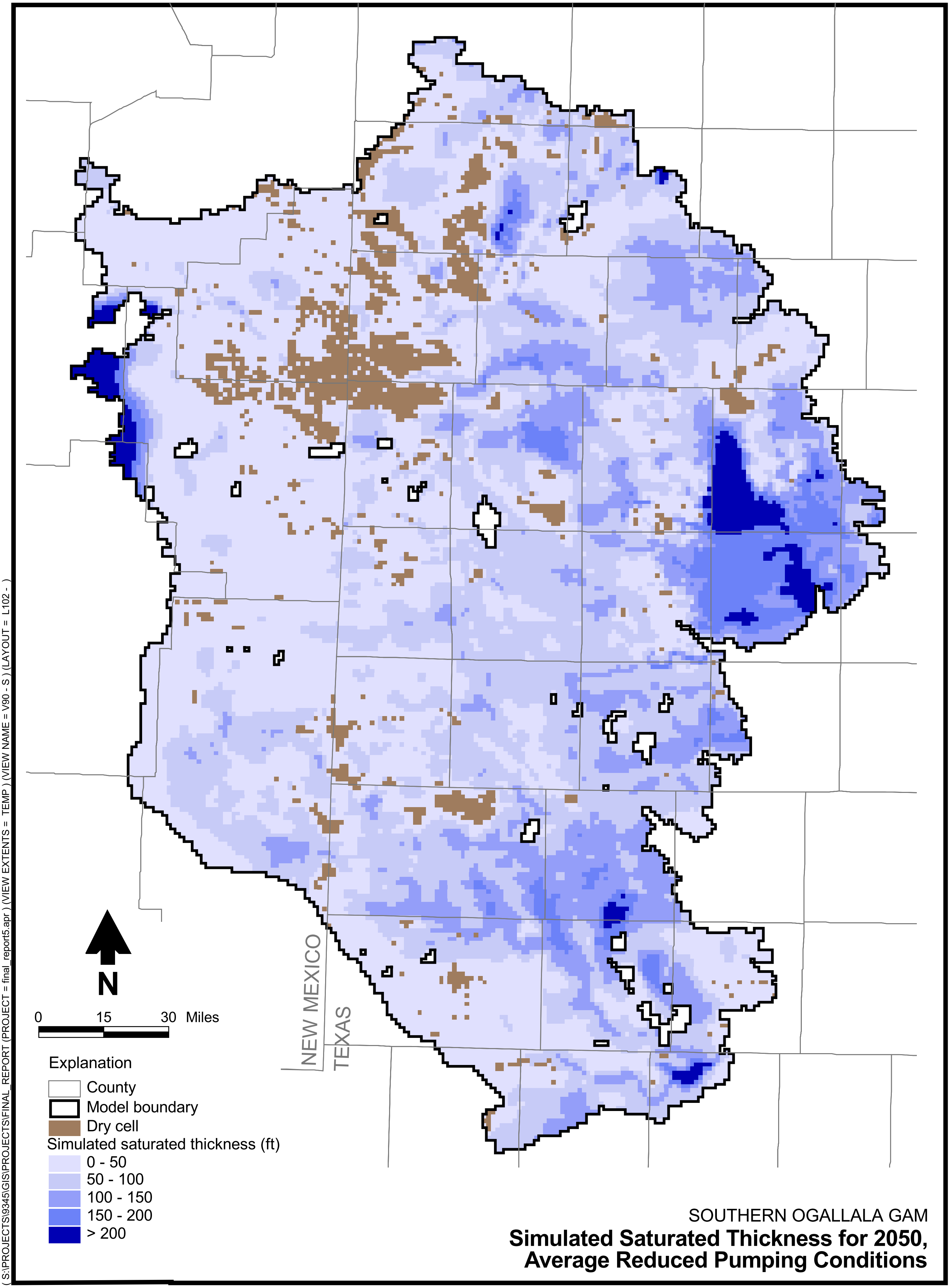


SOUTHERN OGALLALA GAM

Simulated Drawdown for 2050, Average Reduced Pumping Conditions

3-14-03

Figure 101



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SOUTHERN OGALLALA GAM

Simulated Saturated Thickness for 2050, Average Reduced Pumping Conditions

3-14-03

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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