SPI Value	Precipitation Deficit Condition
2.0 and above	Extremely wet
1.5 to 1.99	Very wet
1.0 to 1.49	Moderately wet
-0.99 to 0.99	Near normal
-1.0 to –1.49	Moderately dry
-1.5 to –1.99	Severely dry
-2.0 and less	Extremely dry

McKee et al. (1993) defined a drought event as any time period over which the SPI is continuously negative and reaches a magnitude of –1.0 or less. Figure 10.1.2 plots SPI curves for eight representative long-term precipitation gages in the model area. A two year time window was used for the analysis. Drought occurs most consistently in these gages in the 1950s, 1963-1964, and in the period from 1970 to 1975. Of these time periods, the drought in the 1950s is most consistent among all of the gages. Thus, the SPI analysis corroborates the results of our analysis of percent normals. The DOR is, therefore, considered to have occurred in the 1950s.

With the DOR picked to occur in the 1950s, we next reviewed the monthly data to define the month the DOR began and ended. Records from all of the precipitation stations in the model area were averaged for each month to provide input to an "overall" SPI. Figure 10.1.3 shows the SPI calculated for this average dataset for several time integration windows. The curves from the longer duration (2- and 3-year) integration windows show the most dramatic depression in the range of 1956-1957. These curves drop below -1 at different times, June 1955 and March 1956, respectively, indicating the effect of the backward averaging. The monthly data, which is not temporally averaged, show that the consistently below-normal precipitation driving this drought period began in June 1954, and continued until March 1957, when a wet-dry-wet period occurred, followed by more normal precipitation trends. Therefore, we chose the DOR to have occurred between June 1954 and March 1957 for this model region.

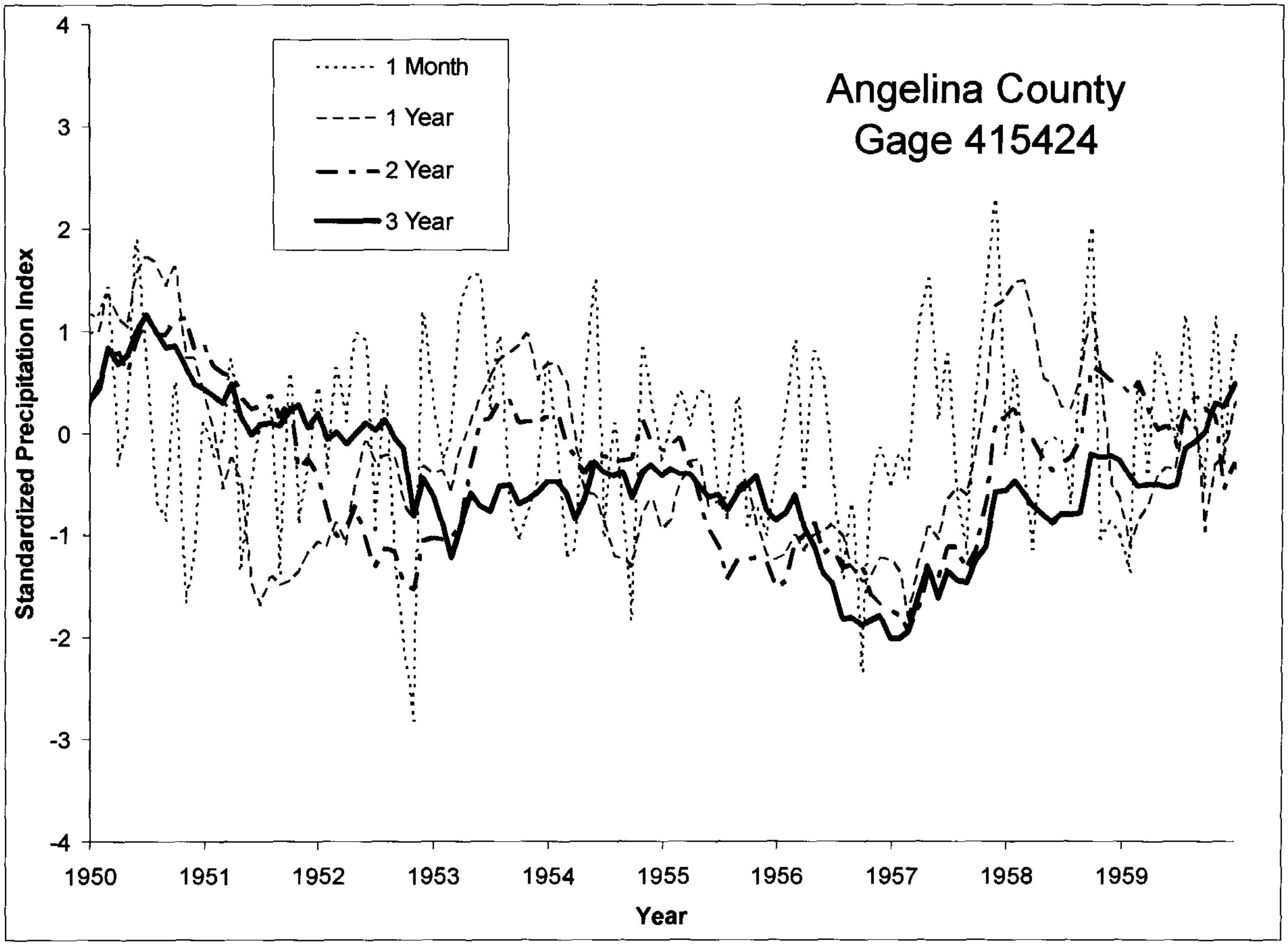


Figure 10.1.1 Standard precipitation index (SPI) curves for the Lufkin rain gage (#415424-Angelina Co.) for 1 month, 1 year, 2 year, 3 year time periods.

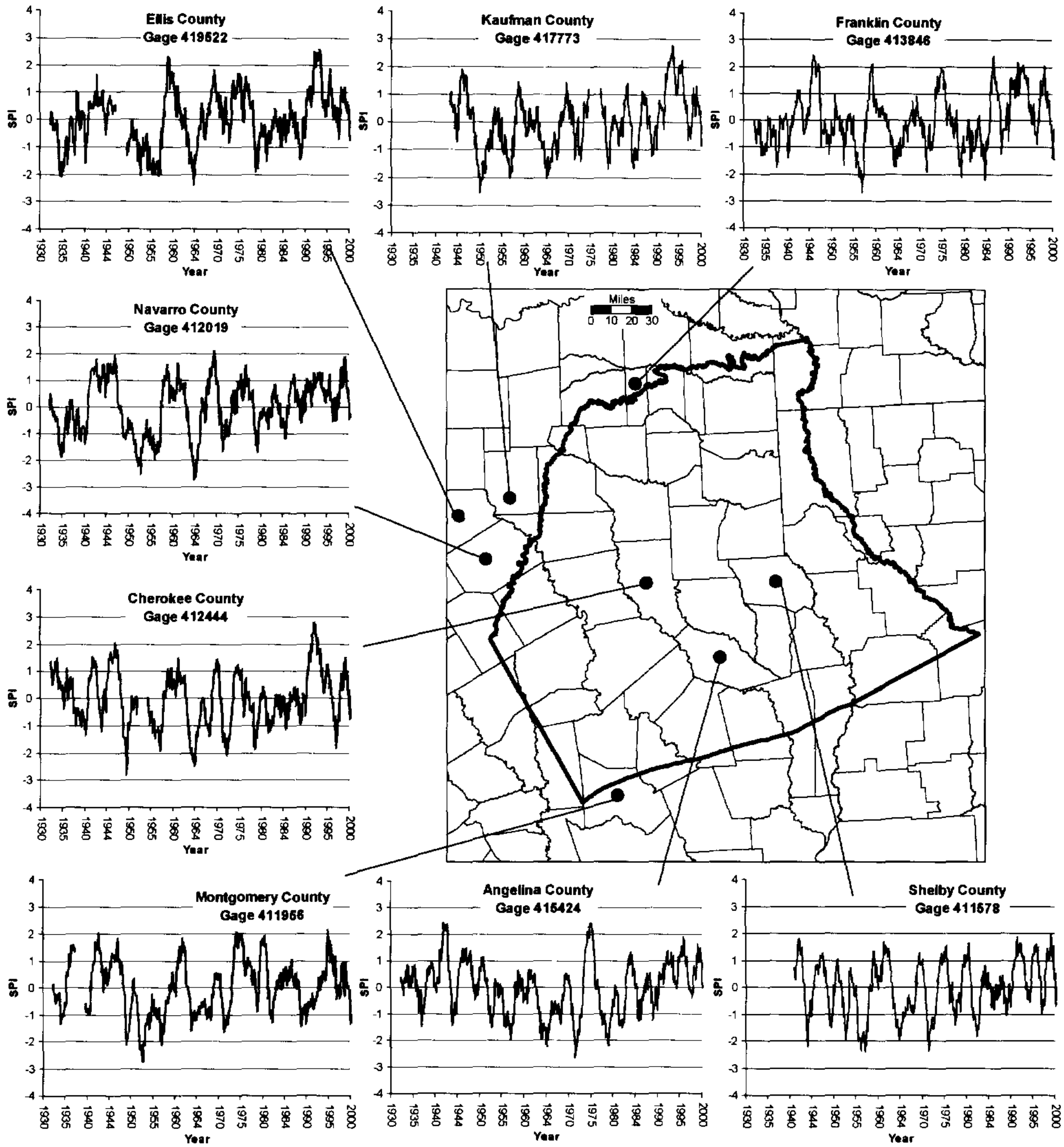


Figure 10.1.2 Standardized precipitation indices for precipitation gages in the region.

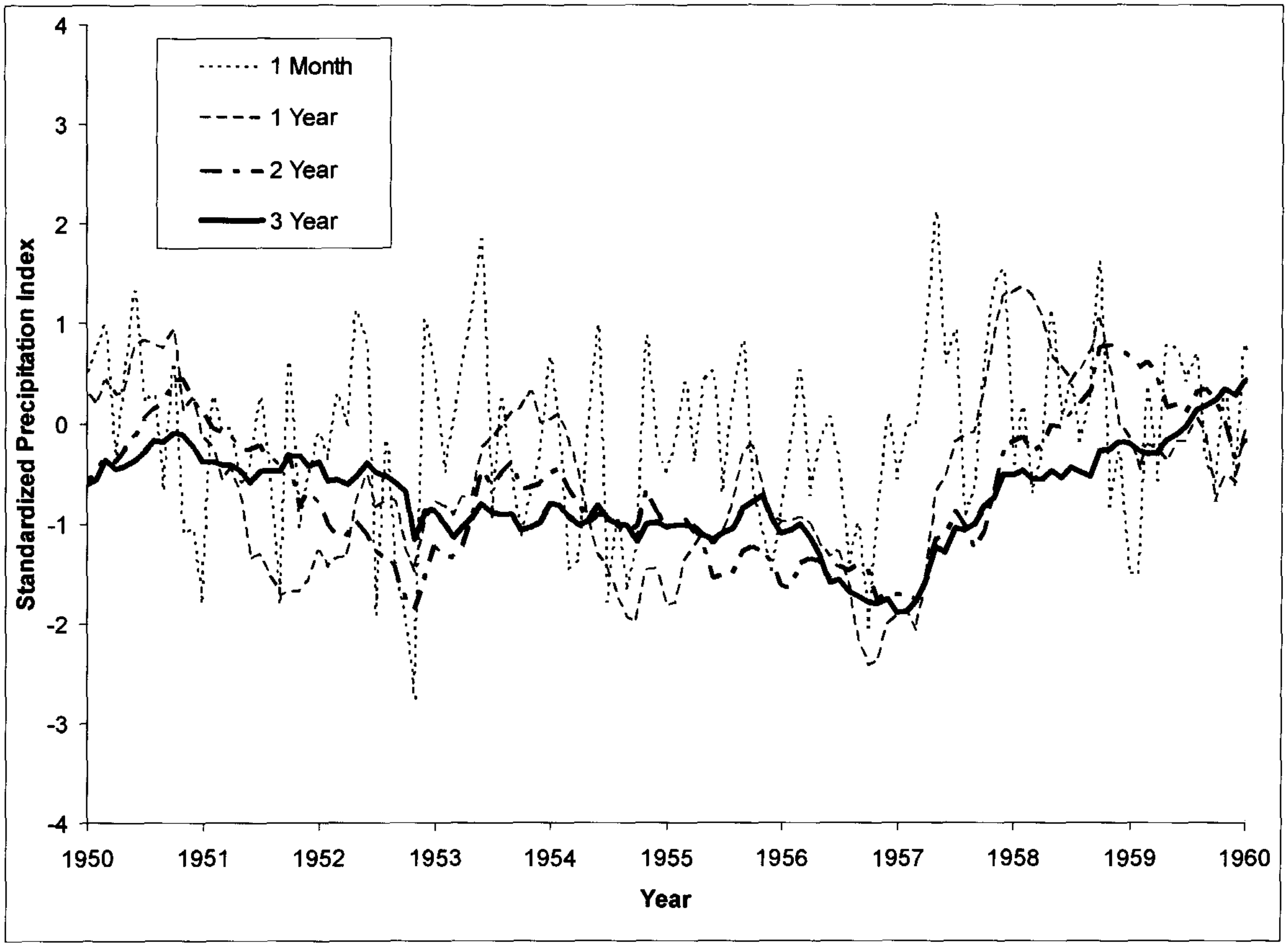


Figure 10.1.3 Standardized precipitation index averaged for all gages in the region from 1950-1960.

10.2 Predictive Simulation Results

In this section, we present the head and drawdown surfaces from the predictive simulation results. We also discussed a comparison between the average recharge condition simulation and the simulation with a DOR.

Figure 10.2.1 shows the simulated 2000 and 2050 head surfaces in Layer 1. The head surfaces show little change, reflecting the general topography in the outcrop and in confined section to the south. Consequently, the head difference plot in Figure 10.2.2 shows head declines typically less the 10 ft, except in Nacogdoches County where heads decline as much as 50 ft. This is probably due to the higher K_v of Layer 2 (Reklaw) assigned to eastern Nacogdoches County, based on the transient calibration. This causes the pumpage induced head decline in the Carrizo-Wilcox to extends into the overlying Queen City aquifer (Layer 1).

Figure 10.2.3 shows the simulated 2000 and 2050 head surfaces in the Carrizo (Layer 3). This figure shows significant rebound of the cone of depression in Angelina and Nacogdoches counties, as well as in Smith County. In these areas, water levels increase by more than 100 ft in Angelina County and about 50 ft in Smith and northern Cherokee County (Figure 10.2.4). In the southwestern part of the model, simulated heads declines of about 10 ft are observed, which are due to local pumpage. Note that the southwestern model boundary was assumed to represent a no-flow boundary.

The simulated head surfaces in the upper Wilcox (Layer 4) in 2000 and 2050 indicate some reduction of the cone of depression in Angelina County after 50 years, whereas the withdrawal cone in Smith County remained the same (Figure 10.2.5). This is also shown in Figure 10.2.6, which shows a rebound of up to 100 ft in Angelina County and less than 10 feet in Smith County. Similar to Layer 3, the southwestern part of the model indicates continued water-level declines in Layer 4.

Figure 10.2.7 shows the simulated 2000 and 2050 head surfaces in the middle Wilcox (Layer 5). For the middle Wilcox, the closed contour reflecting the pumpage cone in Angelina and Nacogdoches counties in the overlying upper Wilcox and Carrizo layers has disappeared. However, the cone of depression in Smith County shows noticeably more drawdown. Figure 10.2.8 indicates generally less than 10 ft of rebound in the northern confined section, whereas Smith County shows additional water-level declines of as much as 50 ft. The southwestern part shows localized water-level decline at or near the outcrop of Layer 5, due to increased pumpage in Freestone and Leon counties.

As discussed below, the rebound of water levels in the Carrizo and upper Wilcox and continued water-level decline in the middle Wilcox is due to the reallocation of the predictive pumpage estimates from the Carrizo to the middle Wilcox layer. In comparison, the head surfaces in the lower Wilcox (Layer 6) for 2000 and 2050 are very similar, indicating relatively little change in water levels of generally less than 10 ft (Figures 10.2.9 and 10.2.10). The southwestern part, again indicates water-level declines of about 10 ft. Note that the pumpage effects in this particular area may be enhanced by its proximity to the no-flow boundary.

In the following discussion, the head surfaces and predicted changes over the 10-year intervals are described. Figure 10.2.11 shows the simulated 2010 heads and the corresponding head change between 2000 and 2010 in Layer 3 (Carrizo). As indicated above, overall heads rebound in the confined section of the Carrizo, particularly in Smith and Angelina counties, due to a redistribution of the increased projected pumpage from different layers, as described in Section 4.7. The simulated 2010 heads in the upper Wilcox (Figure 10.2.12) indicate a maximum of about 10 ft rebound in the confined section.

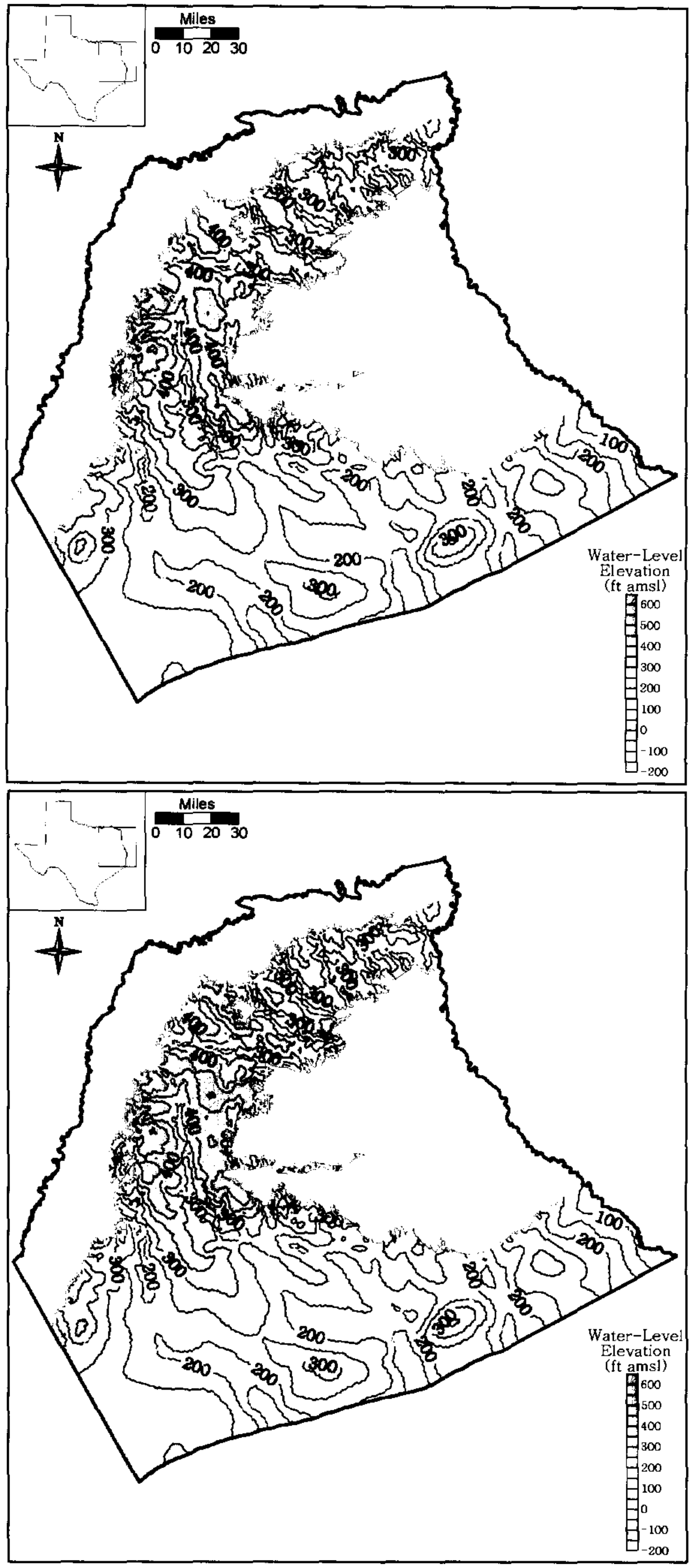
The changes of the head surface in Layer 3 (Carrizo) between 2000 and 2020 is shown in Figure 10.2.13, indicating a maximum rebound of as much as 100 ft in Angelina County and about 50 ft in Smith and northern Cherokee counties. The corresponding 2020 head surface for Layer 4 (upper Wilcox) indicates relatively small changes of less than 10 ft (Figure 10.2.14).

The 30-yr change in hydraulic heads for Layer 3 (Carrizo) between 2000 and 2030, shown in Figure 10.2.15, indicates increased rebound of more than 100 ft in Angelina County and more than 50 ft in Smith County. The 2030 head surface for Layer 4 (upper Wilcox) maintained the drawdown cone in Smith County and showed about 50 ft rebound in Angelina County (Figure 10.2.16).

The changes of the head surface for Layer 3 between 2000 and 2040 are shown in Figure 10.2.17, which shows more 100 ft rebound in Angelina County and about 50 ft in Smith and northern Cherokee counties. The corresponding head surface for Layer 4 indicates a local increase in the drawdown in west-central Smith County (Figure 10.2.18). The surrounding counties show some rebound with local maxima in Cherokee and Angelina counties.

Selected hydrographs of simulated heads and measured heads in selected target wells for the transient calibration period between 1980 and 1999 with the subsequent 50-yr predictive period between 2000 and 2050 are shown in Figures 10.2.19 through 10.2.22. Layer 3 (Carrizo) indicates drastic water-level rebound at the start of the predictive period (Figure 10.2.19) in Smith and Angelina counties and a smaller rebound in Cherokee County, whereas water levels in Wood County continued to decline. The water levels in Layer 4 (upper Wilcox) indicate continued decline with a recovery period after 2040 in Smith County, whereas water levels in Leon County indicated minor decline during the predictive period (Figure 10.2.20). Hydrographs for Layer 5 (middle Wilcox) indicate continued recovery in Panola County in the Sabine uplift, and a general decline in Van Zandt County during the predictive period (Figure 10.2.21). For Layer 6, the hydrograph in Van Zandt County did not reproduce the decline during the transient calibration-verification period, and simulated heads remained relatively constant during the predictive period (Figure 10.2.22). The hydrograph in Henderson County shows a similar water level decline during the transient period which is not well reproduced in the model, and the subsequent predictive heads indicate a general upward trend.

Figure 10.2.23 shows the difference between the simulated head surface for 2050 with average recharge and the simulated head surface for 2050 with the DOR for the Carrizo (Layer 3), upper Wilcox (Layer 4) and middle Wilcox (Layer 5). In all of these layers there is a maximum head difference of less than 10 ft. All of the simulated head differences are near the outcrop, where recharge will have the most impact. These figures emphasize an important point about the hydrology of this aquifer system. Recharge does not have a significant impact on downdip heads over the timescale of these simulations. One aspect of these simulations that is misleading is that pumping does not increase during the DOR. The DOR only impacts climate data and subsequently, recharge. Therefore, the effect of a DOR will be seen predominantly in the updip and outcrop areas.



a.

b.

Figure 10.2.1 Simulated 2000 (a) and 2050 (b) heads surfaces for Layer 1 (Queen City).

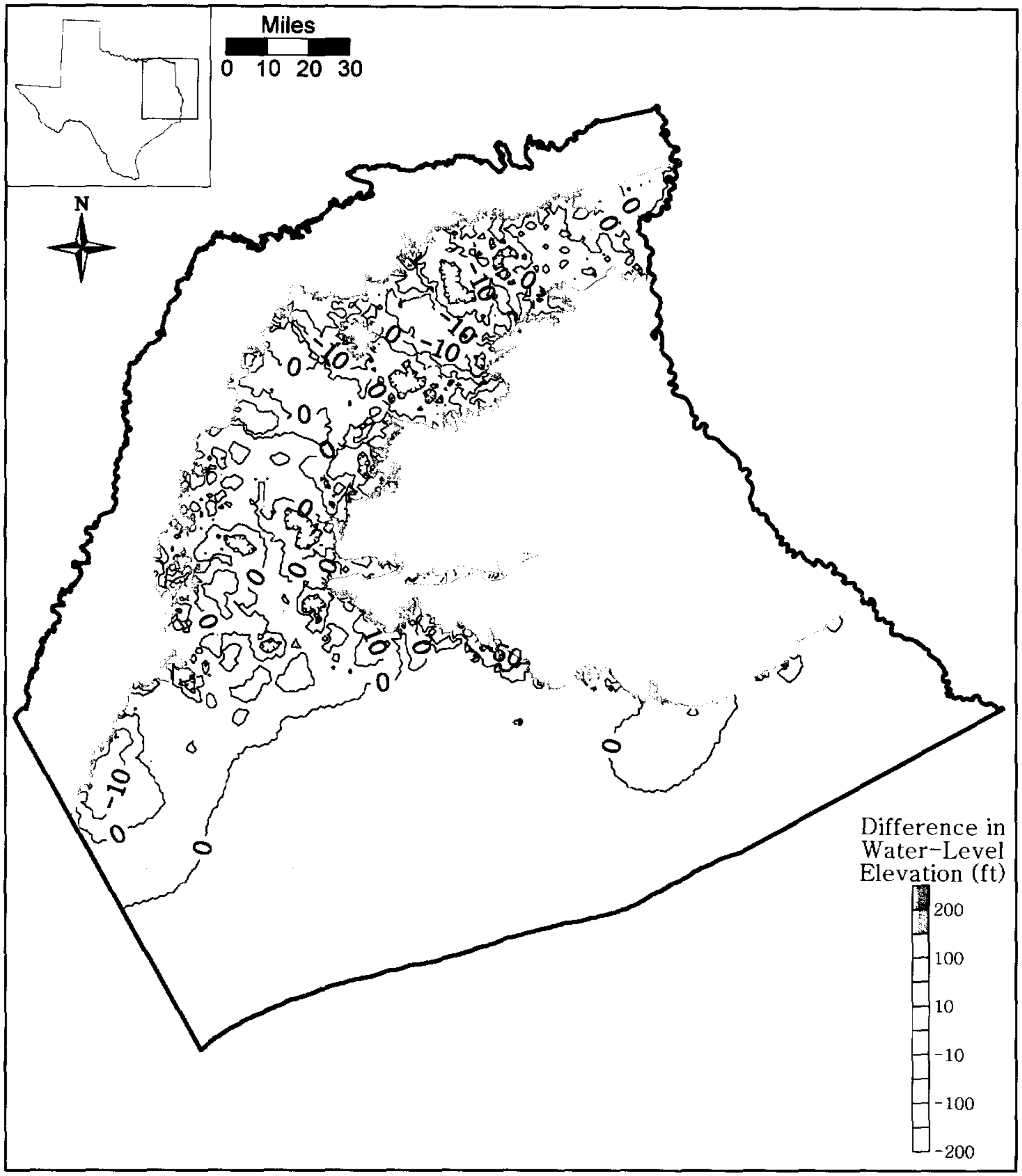


Figure 10.2.2 Difference between 2000 and 2050 simulated head surfaces for Layer 1 (Queen City).

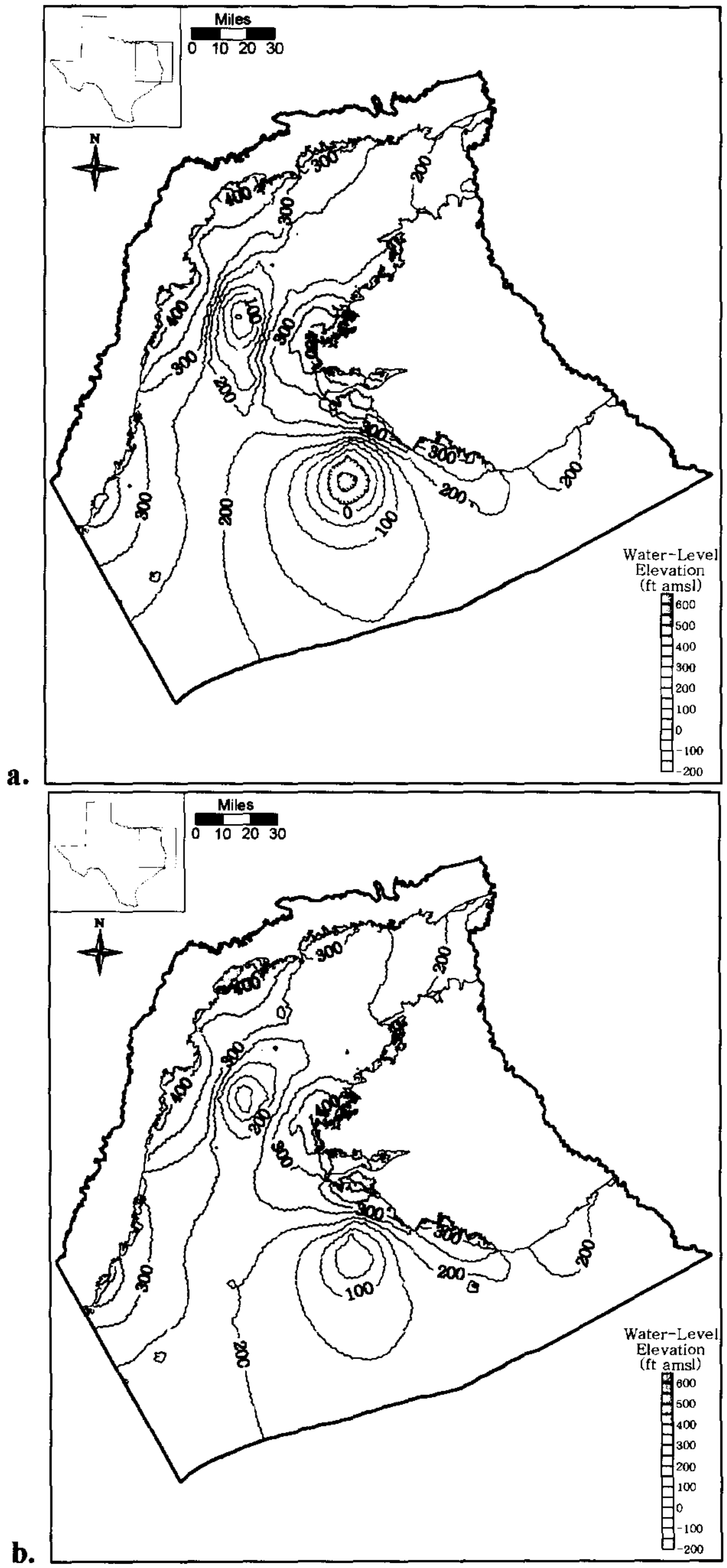


Figure 10.2.3 Simulated 2000 (a) and 2050 (b) heads surfaces for Layer 3 (Carrizo).

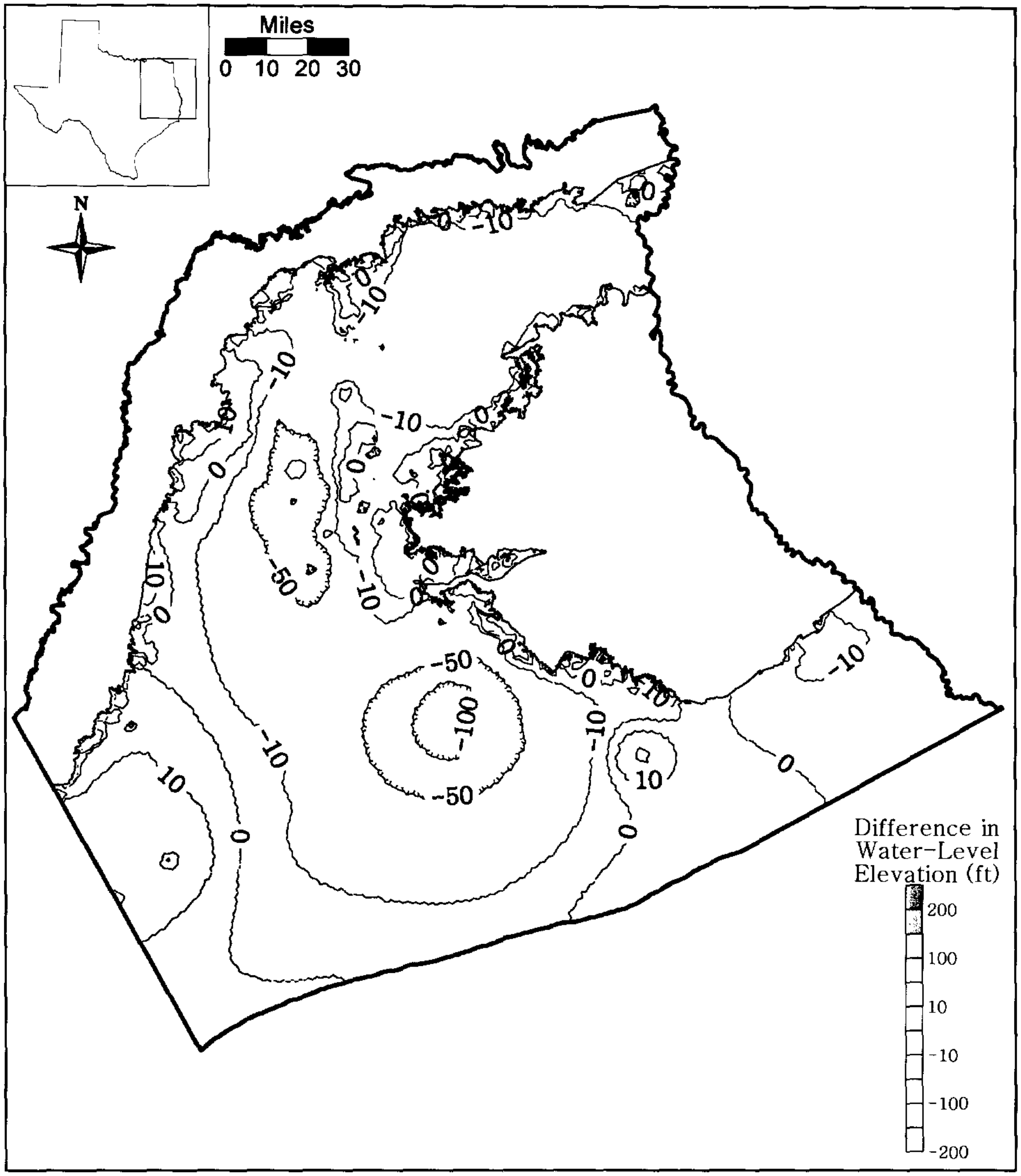
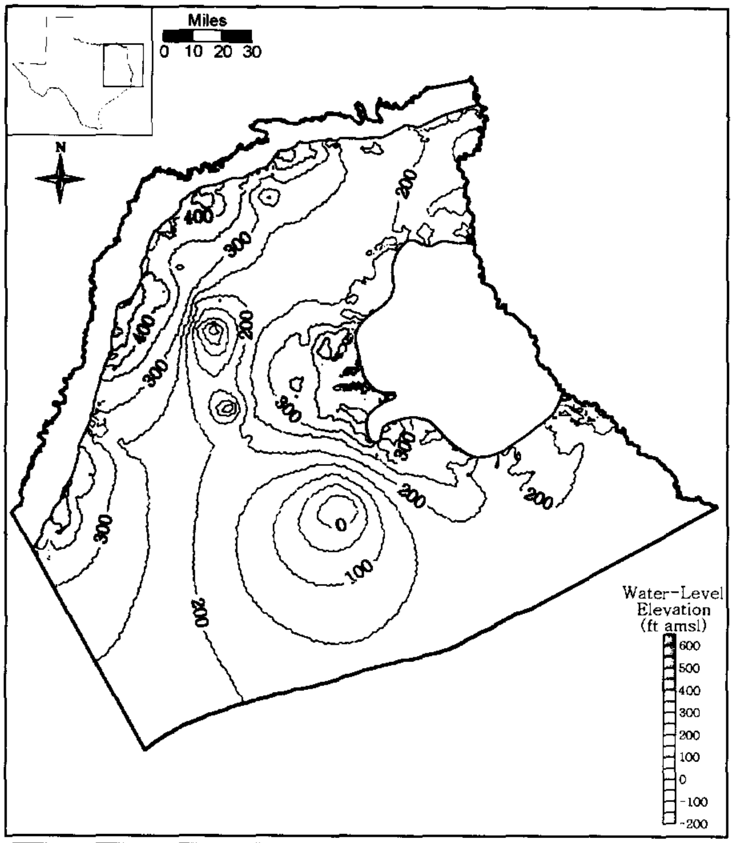
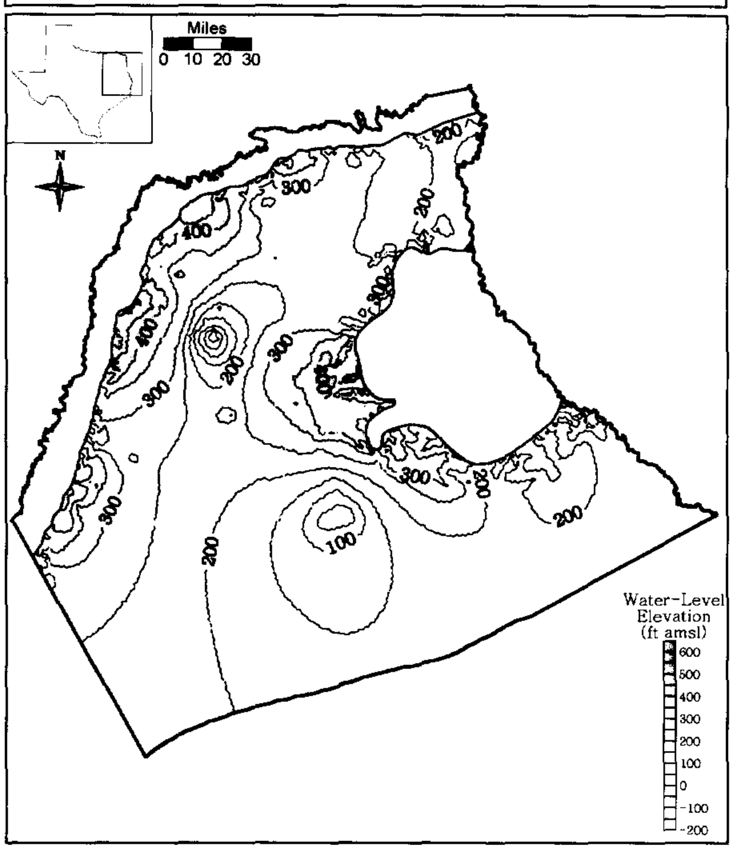


Figure 10.2.4 Difference between 2000 and 2050 simulated head surfaces for Layer 3 (Carrizo).



a.



b.

Figure 10.2.5 Simulated 2000 (a) and 2050 (b) heads surfaces for Layer 4 (upper Wilcox).

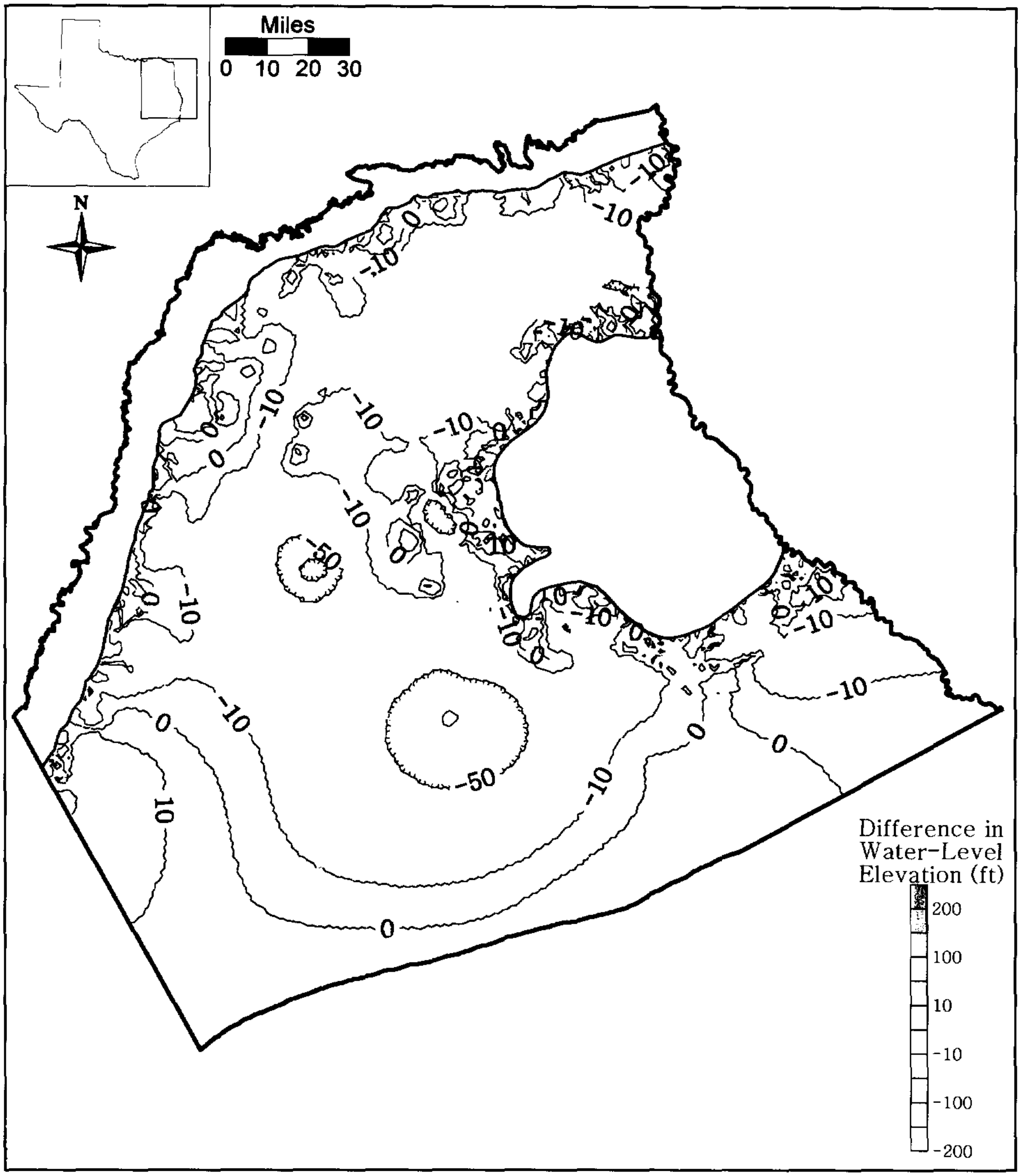
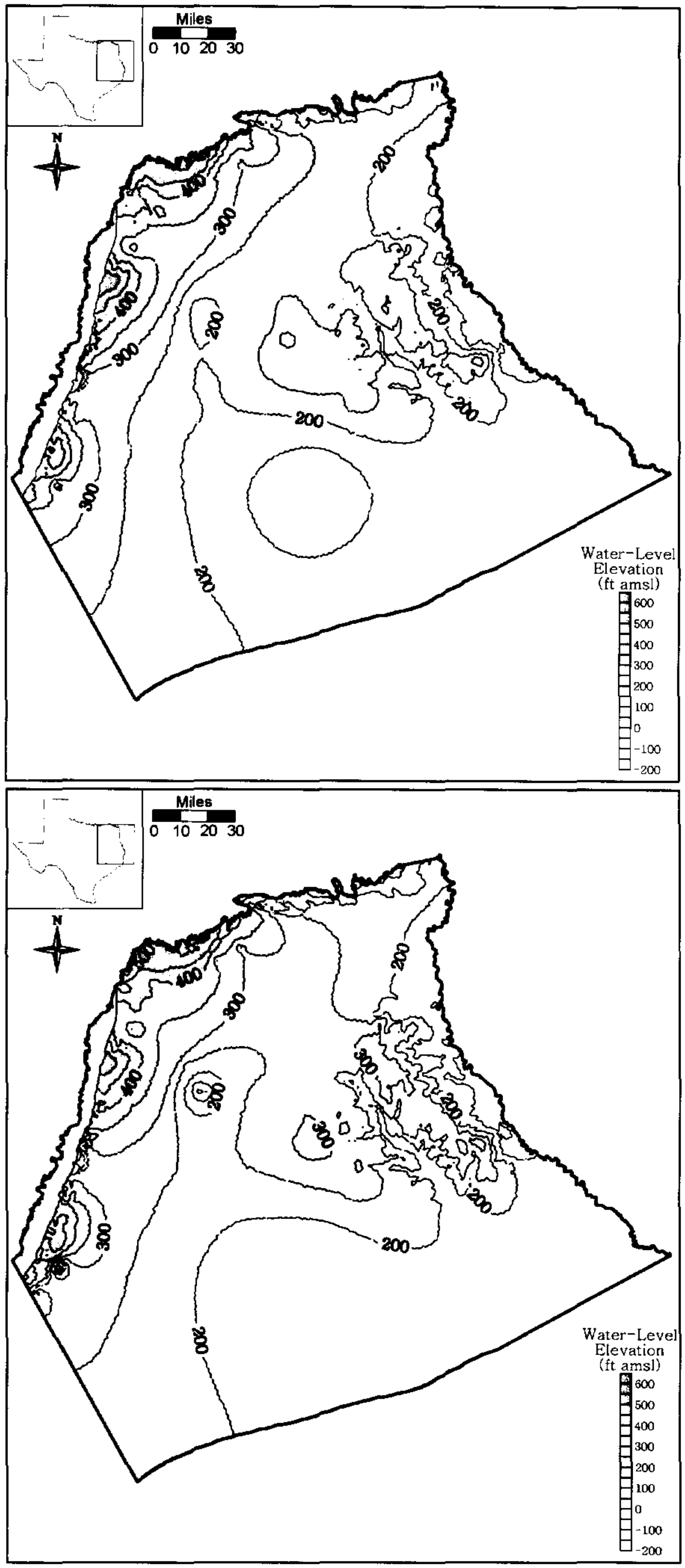


Figure 10.2.6 Difference between 2000 and 2050 simulated head surfaces for Layer 4 (upper Wilcox).

a.


b.

Figure 10.2.7 Simulated 2000 (a) and 2050 (b) heads surfaces for Layer 5 (middle Wilcox).

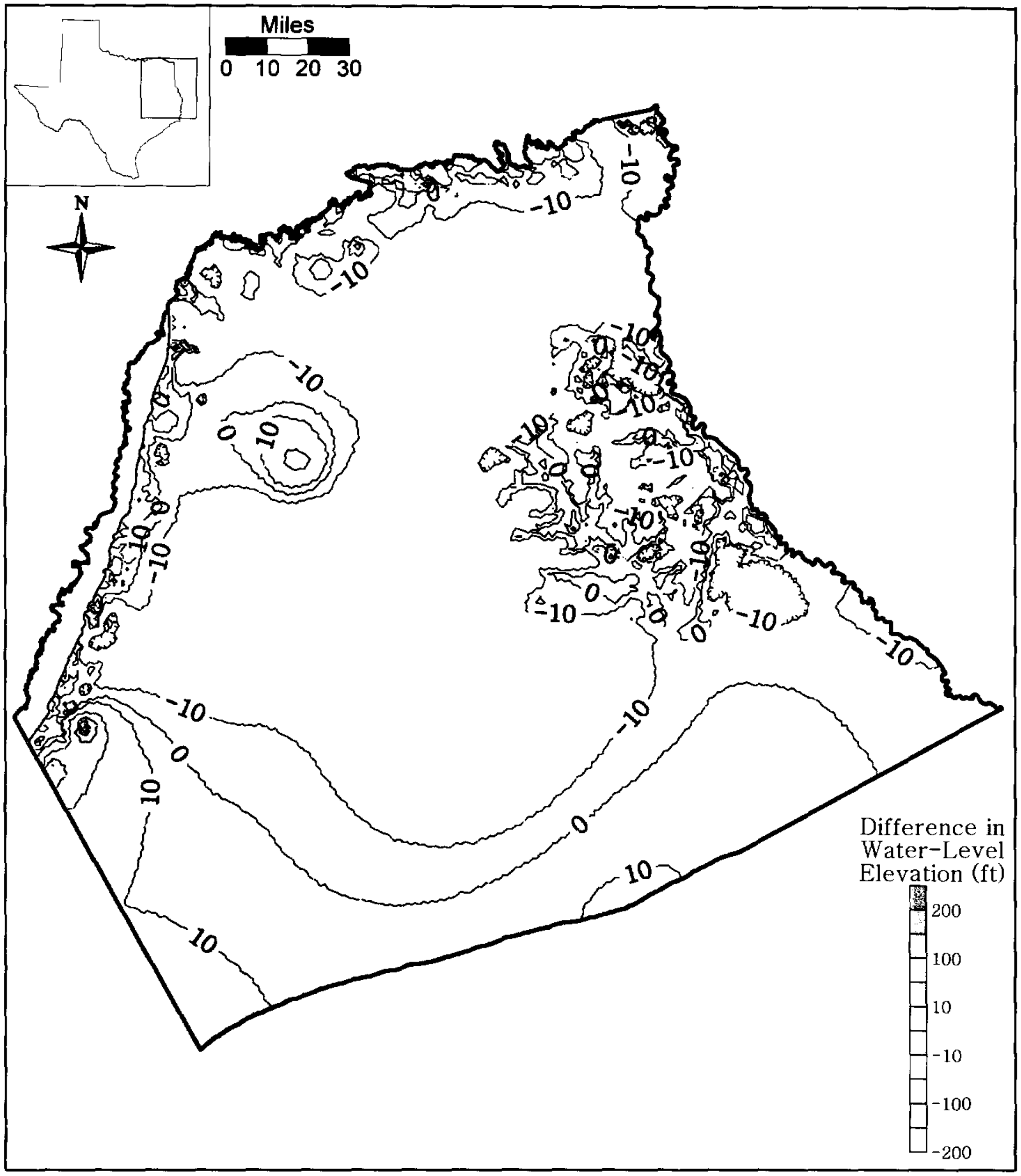


Figure 10.2.8 Difference between 2000 and 2050 simulated head surfaces for Layer 5 (middle Wilcox).

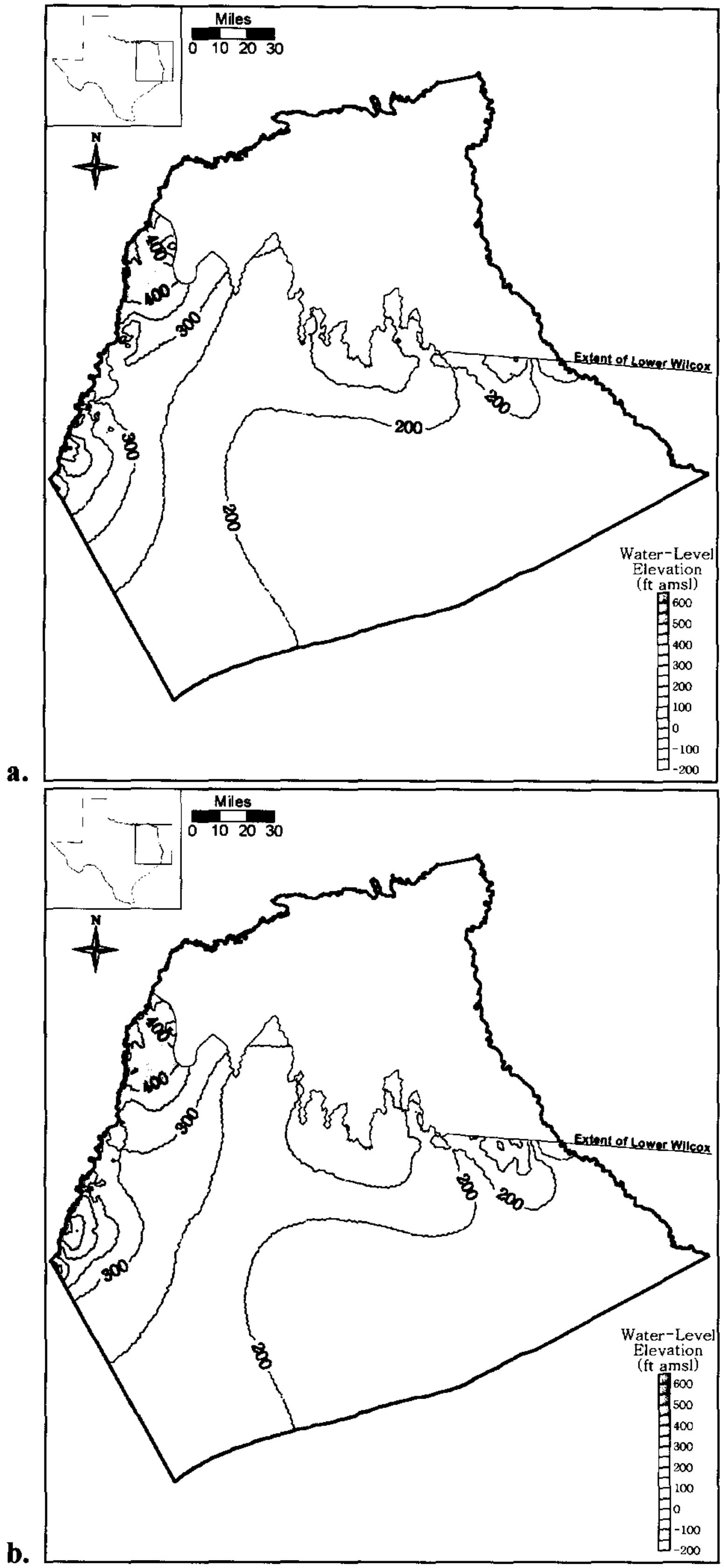


Figure 10.2.9 Simulated 2000 (a) and 2050 (b) heads surfaces for Layer 6 (lower Wilcox).

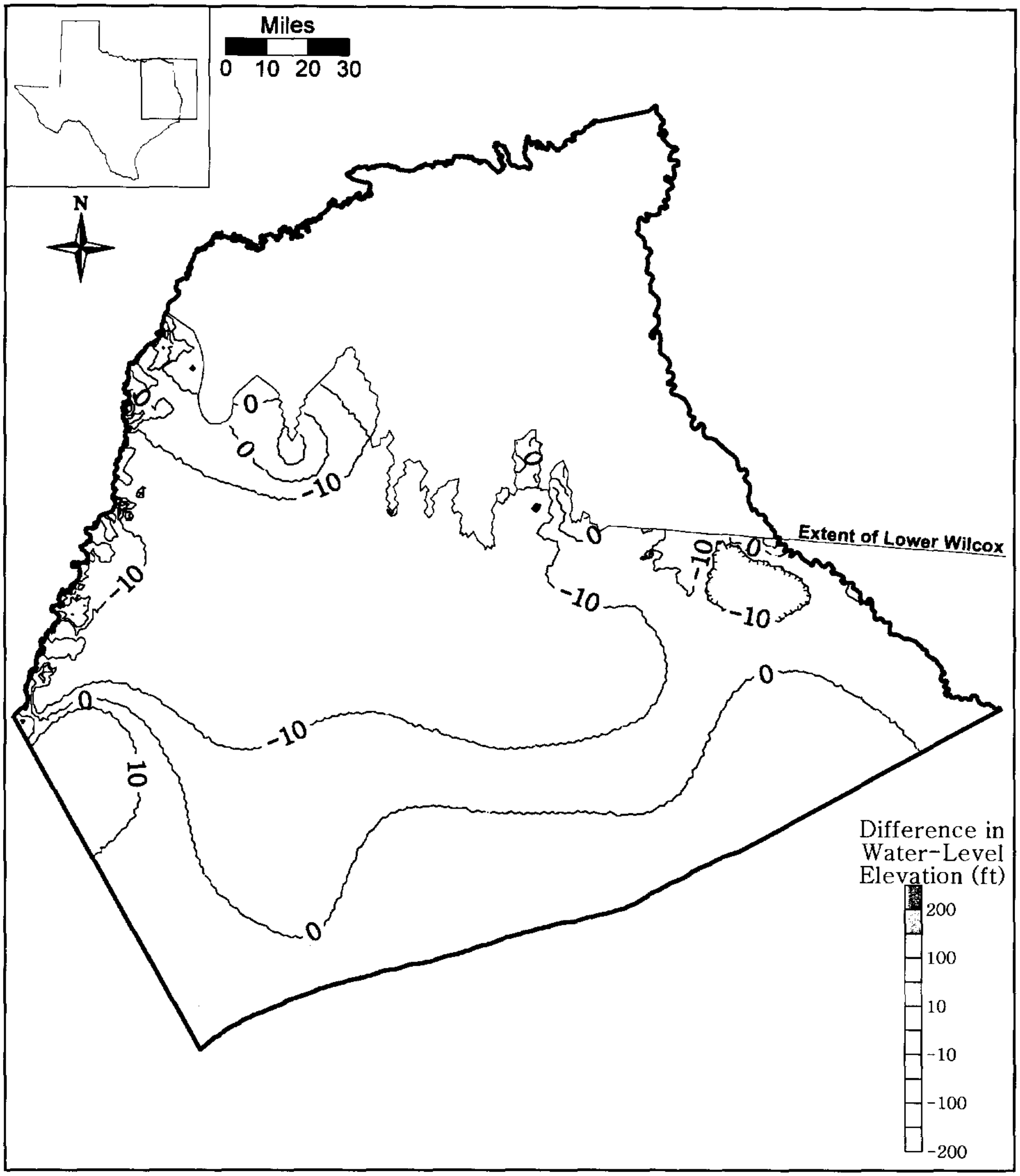
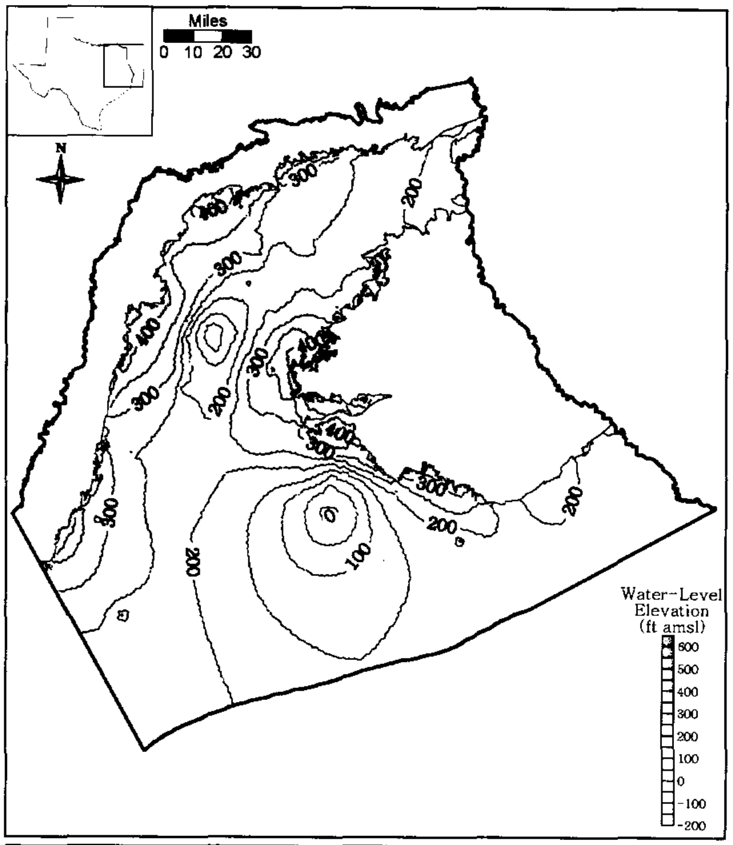


Figure 10.2.10 Difference between 2000 and 2050 simulated head surfaces for Layer 6 (lower Wilcox).

a.


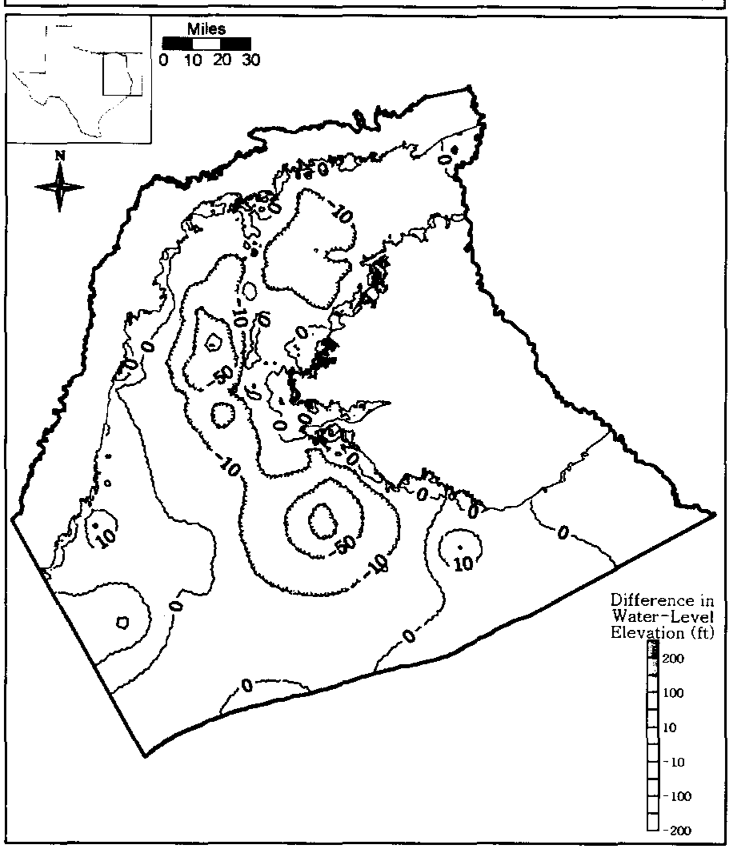
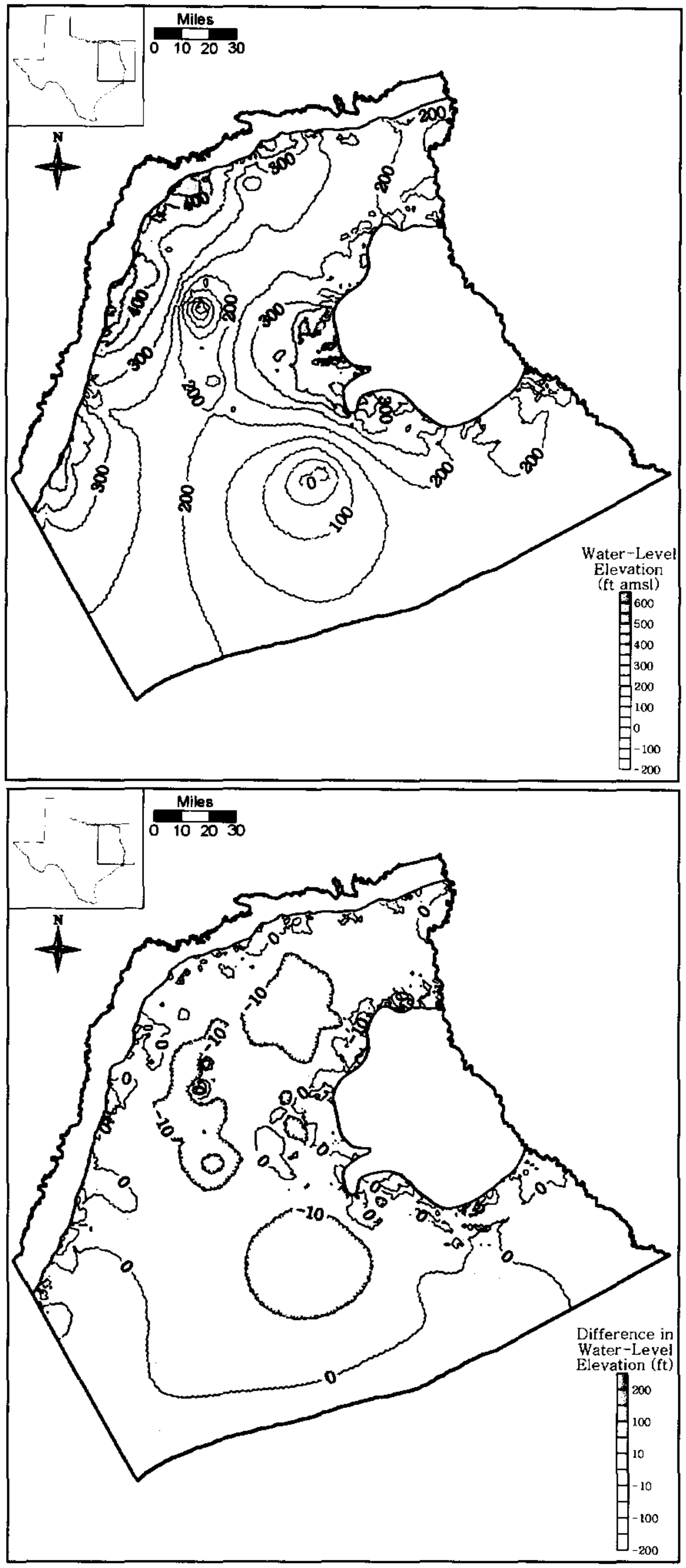
b.


Figure 10.2.11 Simulated 2010 head surface (a) and drawdown from 2000 (b), Layer 3 (Carrizo).



a.

b.

Figure 10.2.12 Simulated 2010 head surface (a) and drawdown from 2000 (b), Layer 4 (upper Wilcox).

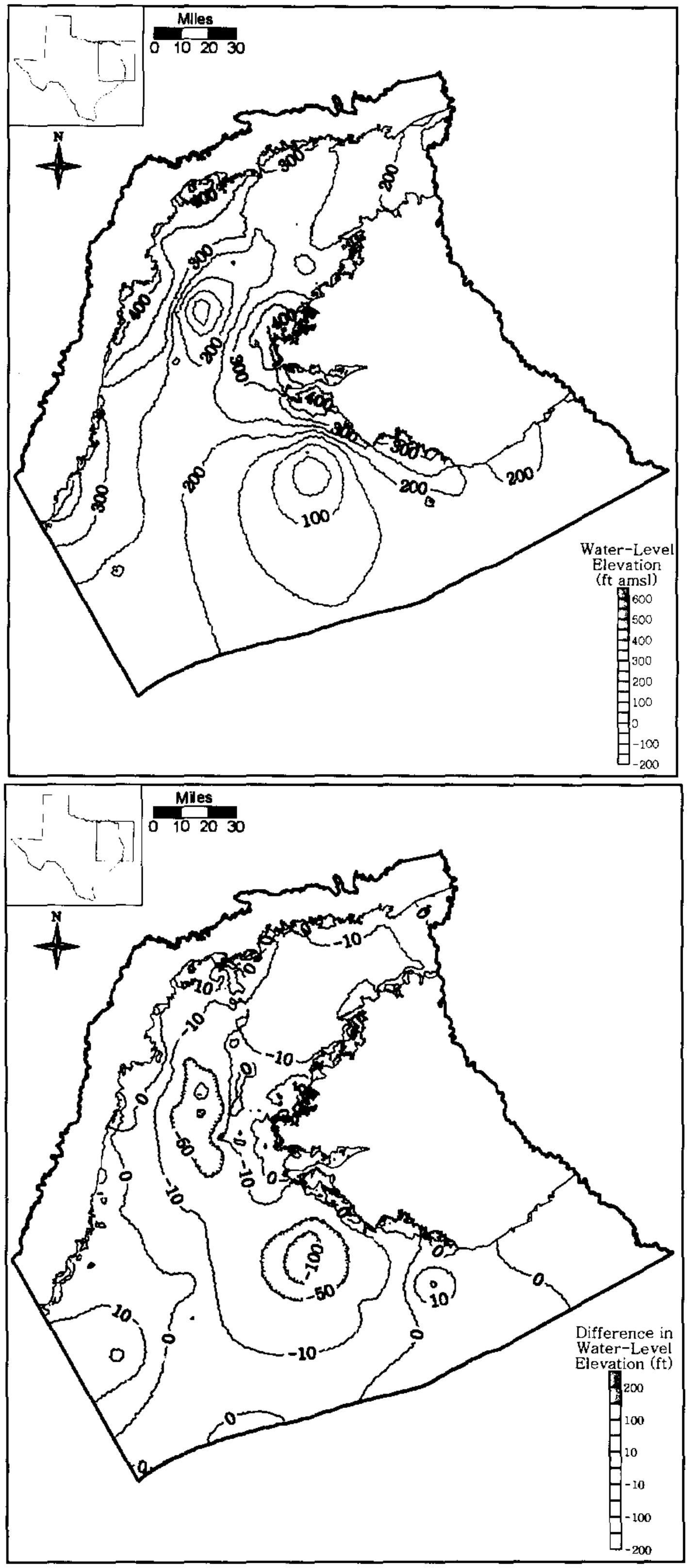
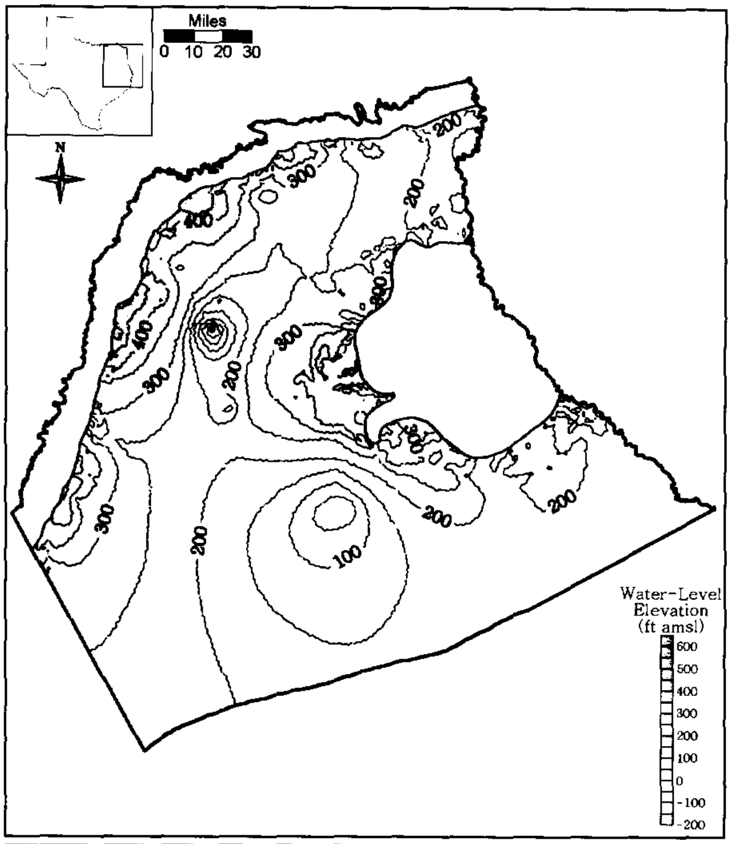
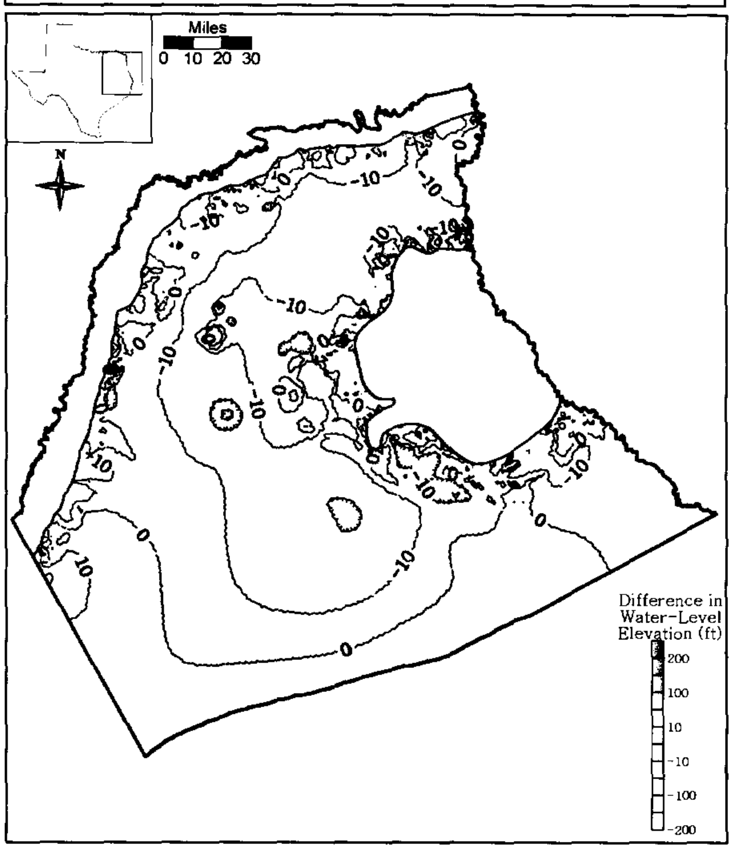


Figure 10.2.13 Simulated 2020 head surface (a) and drawdown from 2000 (b), Layer 3 (Carrizo).



a.



b.

Figure 10.2.14 Simulated 2020 head surface (a) and drawdown from 2000 (b), Layer 4 (upper Wilcox).

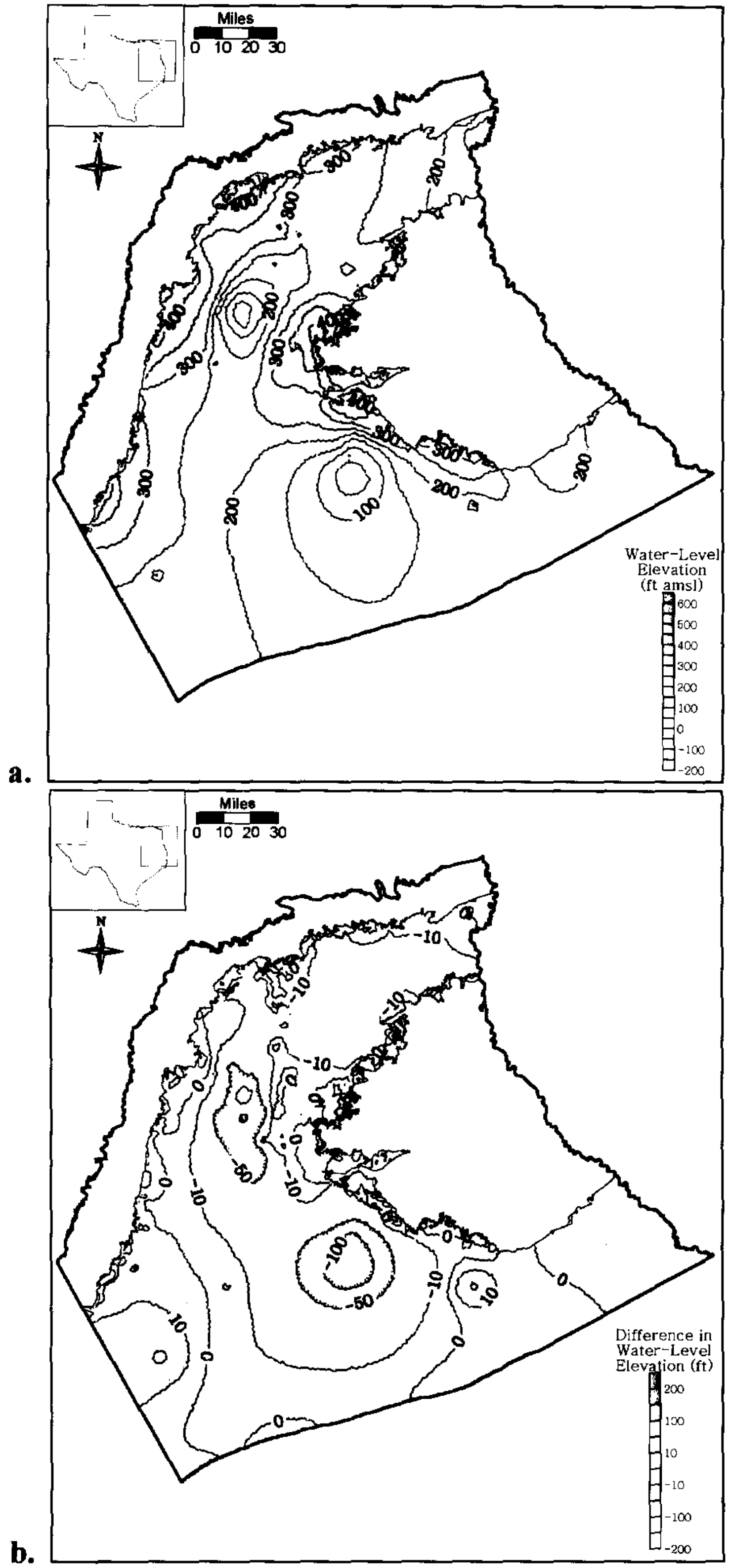


Figure 10.2.15 Simulated 2030 head surface (a) and drawdown from 2000 (b), Layer 3 (Carrizo).

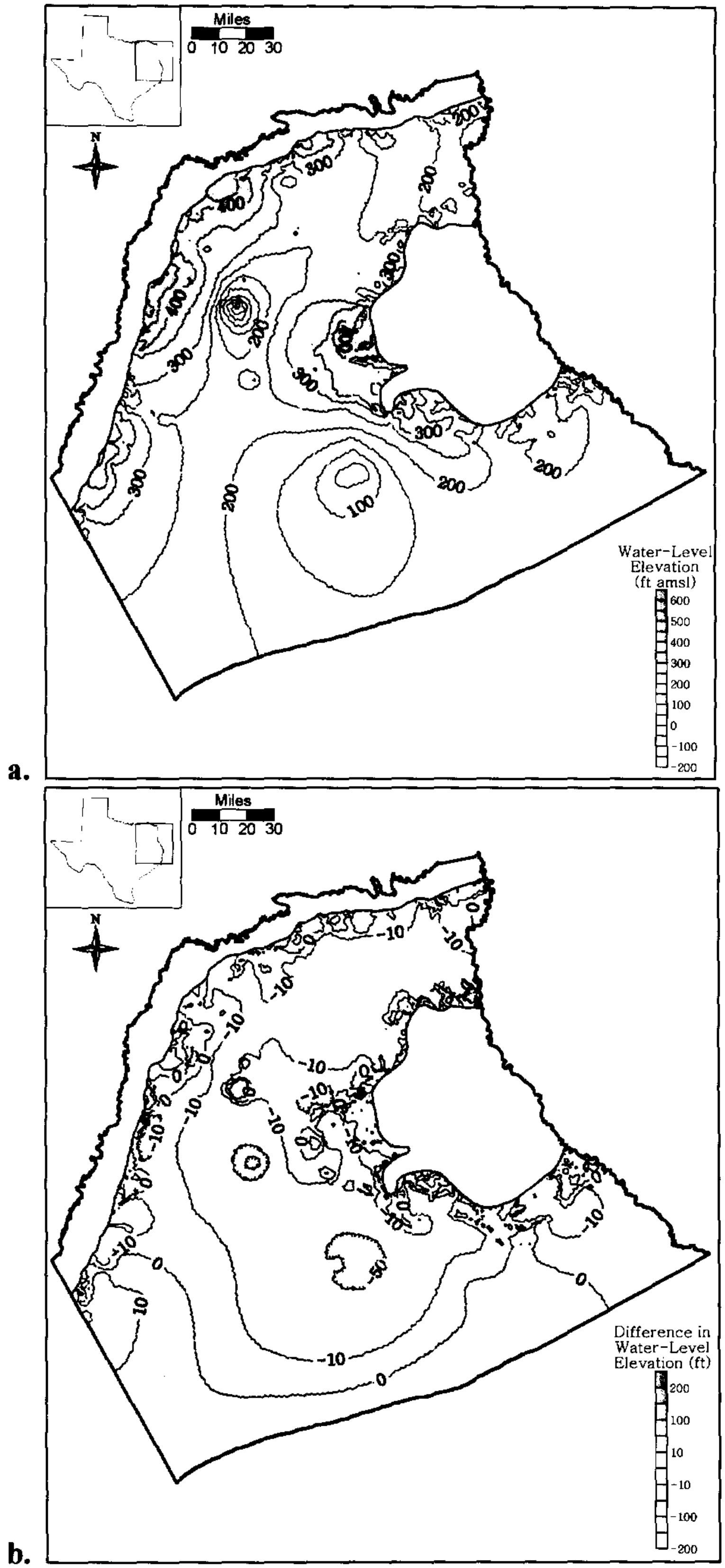
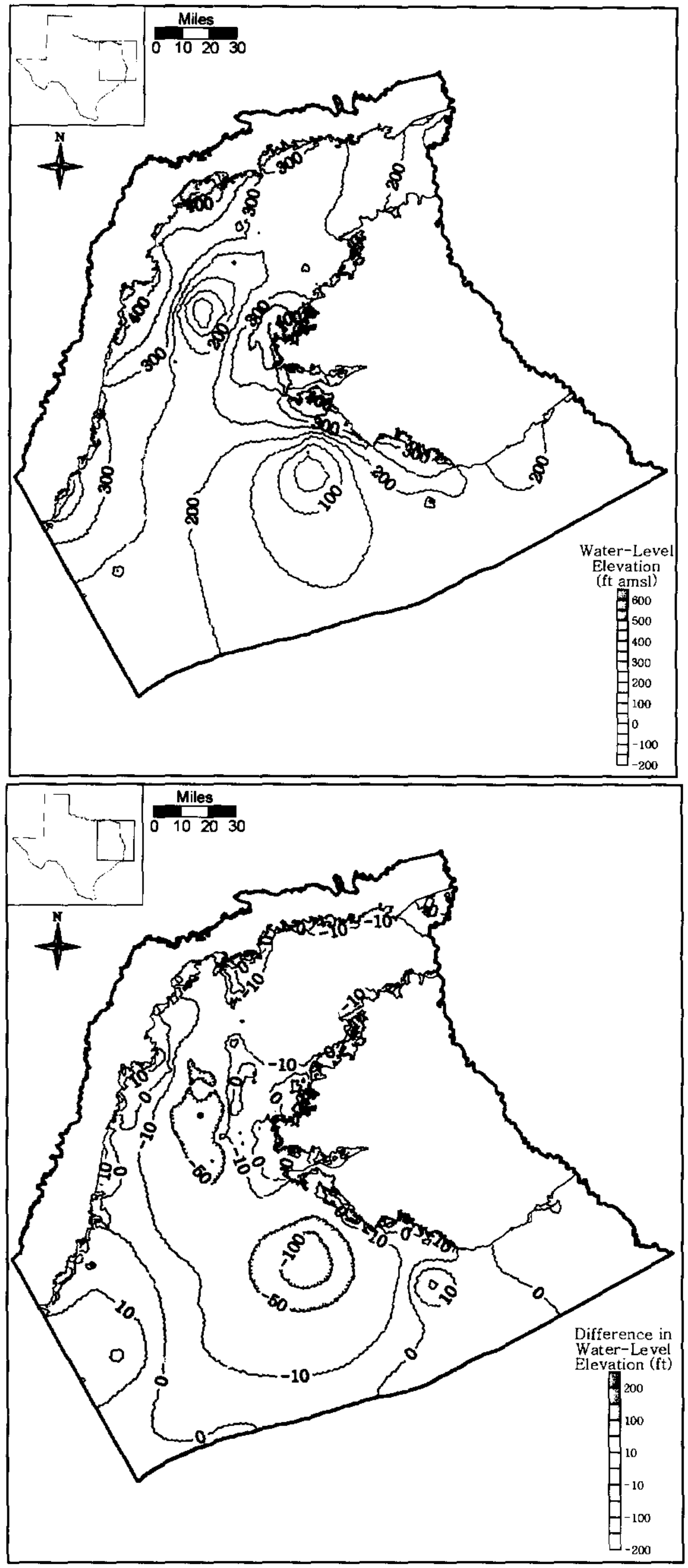


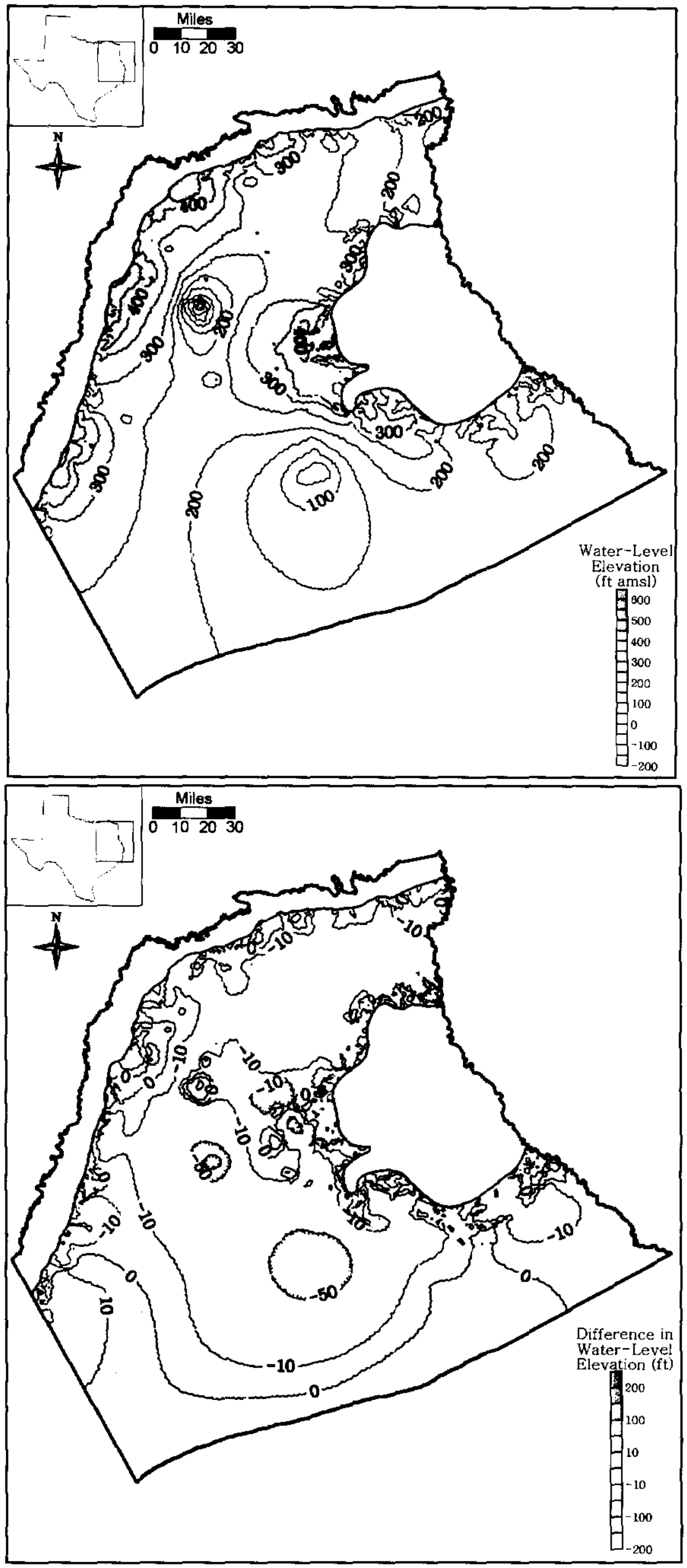
Figure 10.2.16 Simulated 2030 head surface (a) and drawdown from 2000 (b), Layer 4 (upper Wilcox).



a.

b.

Figure 10.2.17 Simulated 2040 head surface (a) and drawdown from 2000 (b), Layer 3 (Carrizo).



a.

b.

Figure 10.2.18 Simulated 2040 head surface (a) and drawdown from 2000 (b), Layer 4 (upper Wilcox).

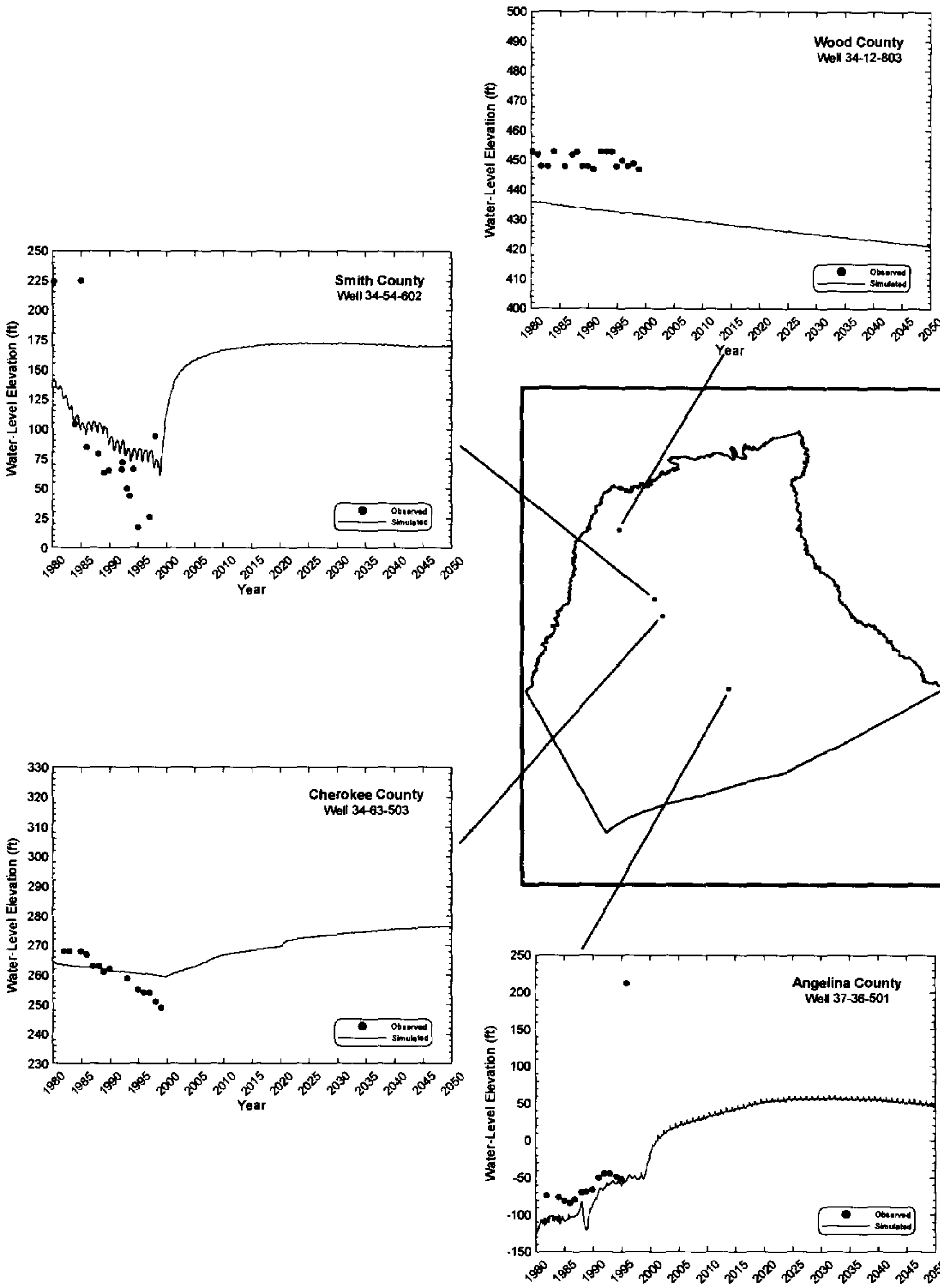


Figure 10.2.19 Selected hydrographs from predictive simulation to 2050, Layer 3 (Carrizo).

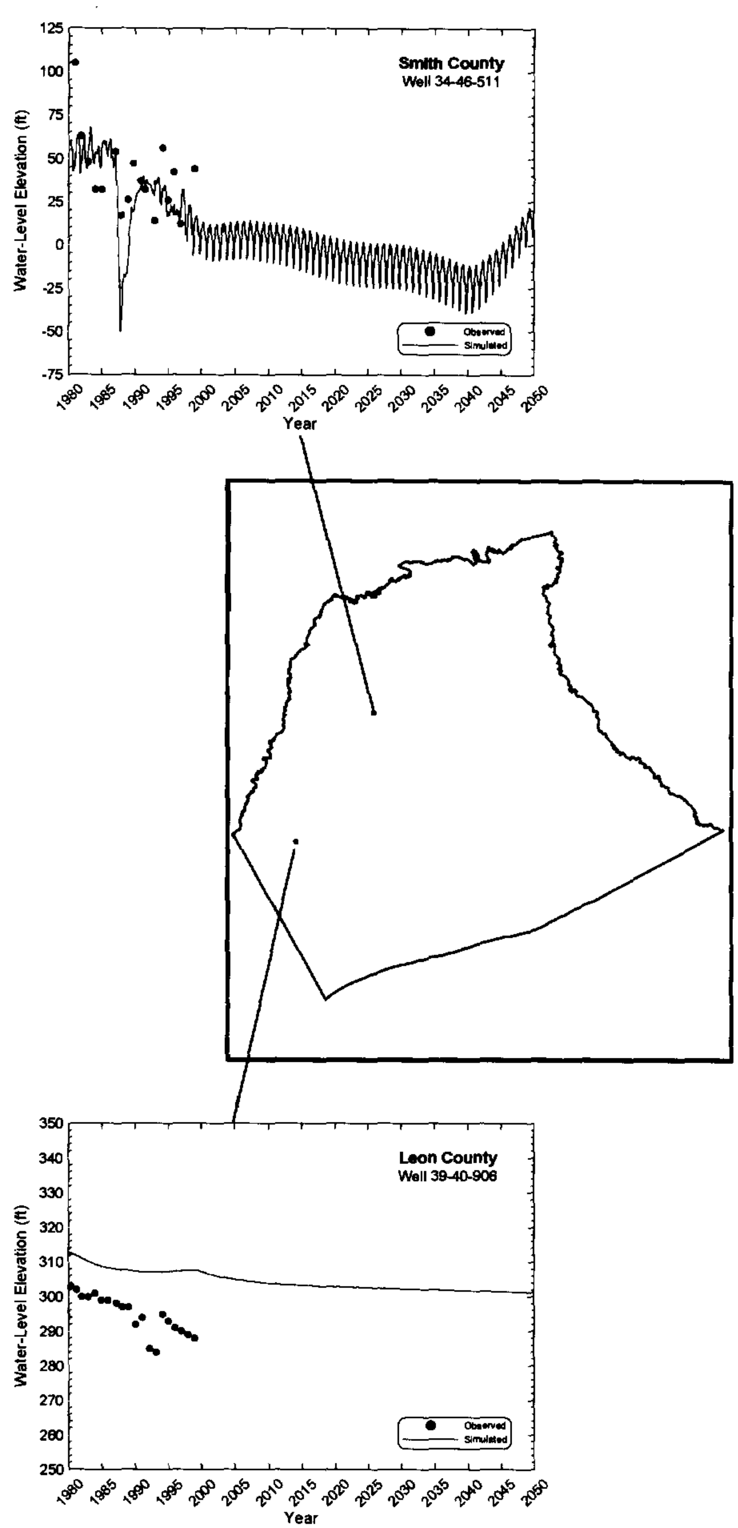


Figure 10.2.20 Selected hydrographs from predictive simulation to 2050, Layer 4 (upper Wilcox).

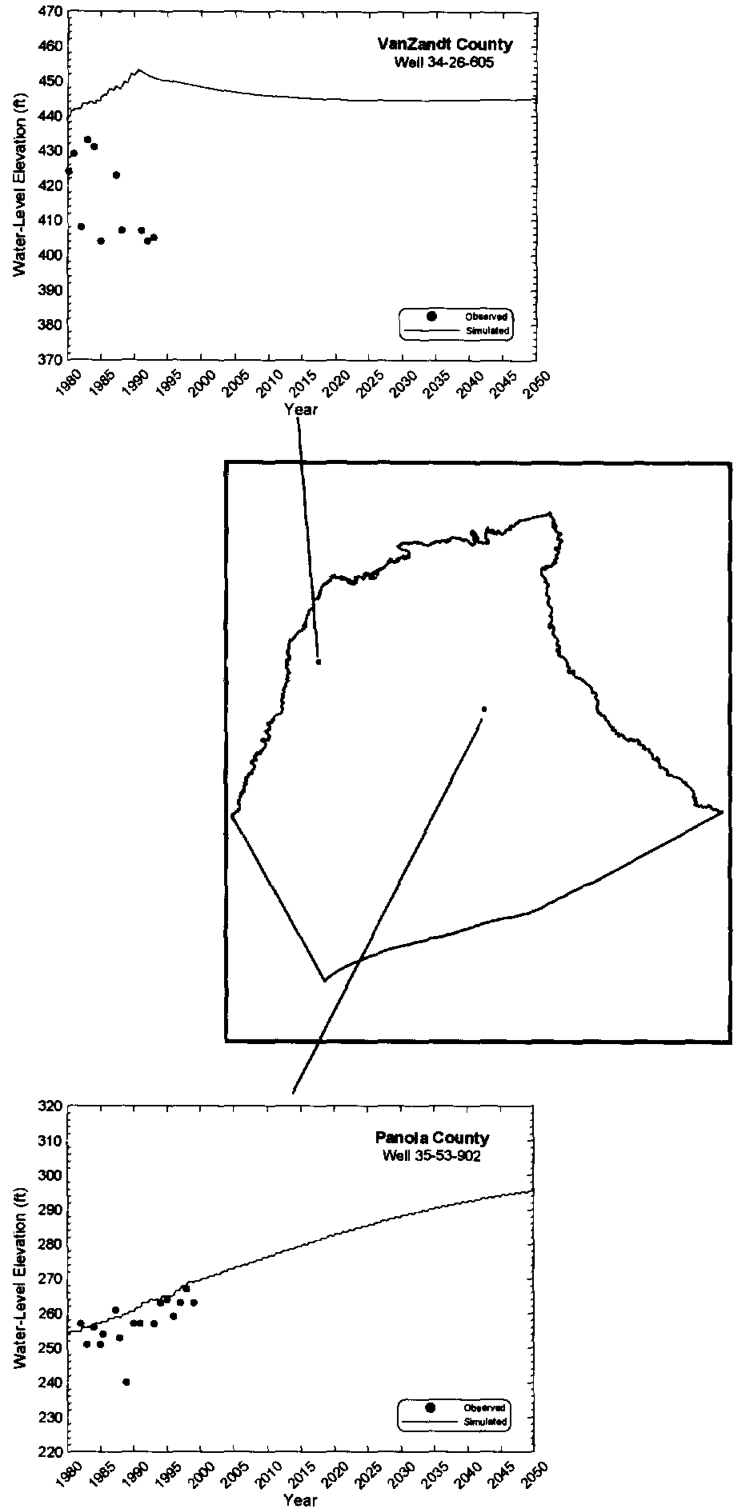


Figure 10.2.21 Selected hydrographs from predictive simulation to 2050, Layer 5 (middle Wilcox).

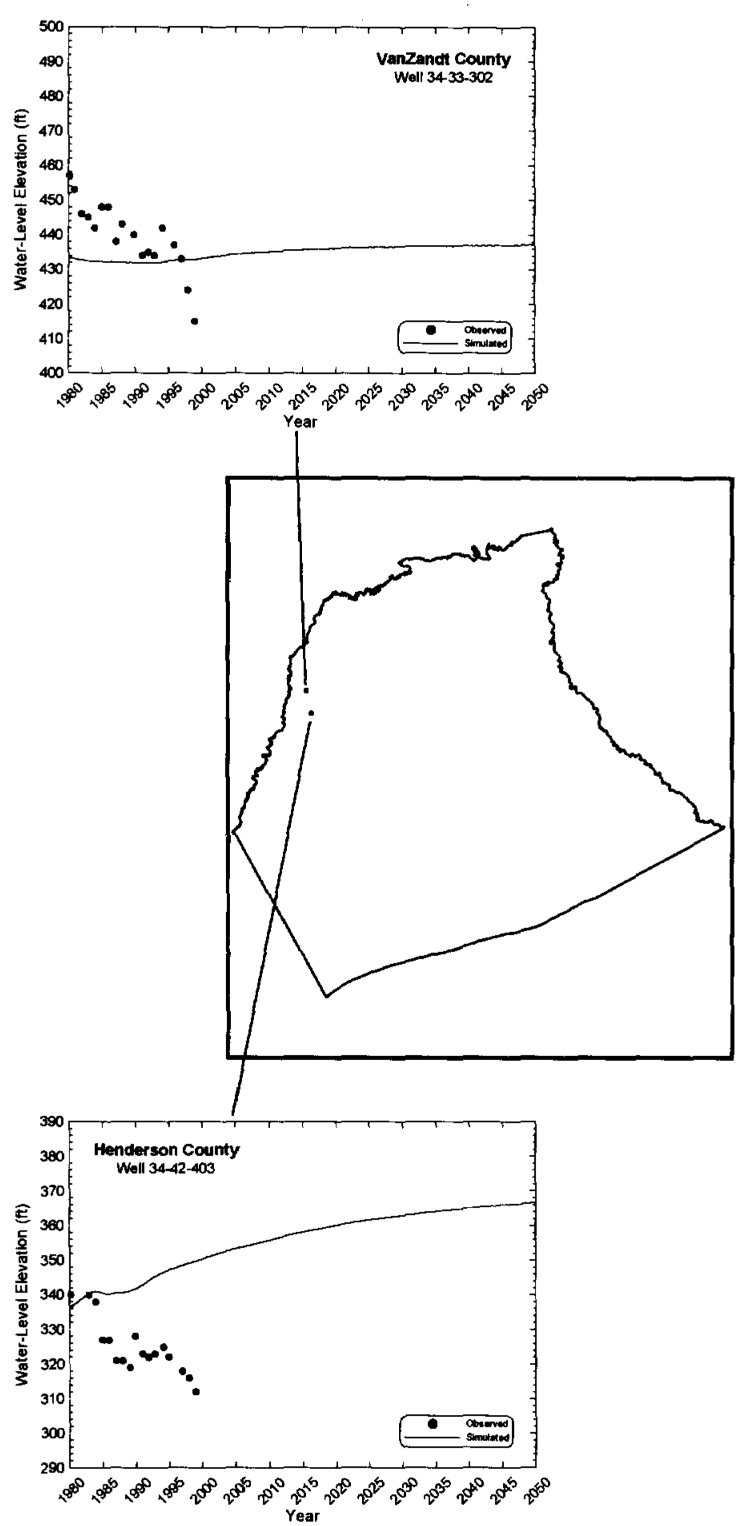


Figure 10.2.22 Selected hydrographs from predictive simulation to 2050, Layer 6 (lower Wilcox).

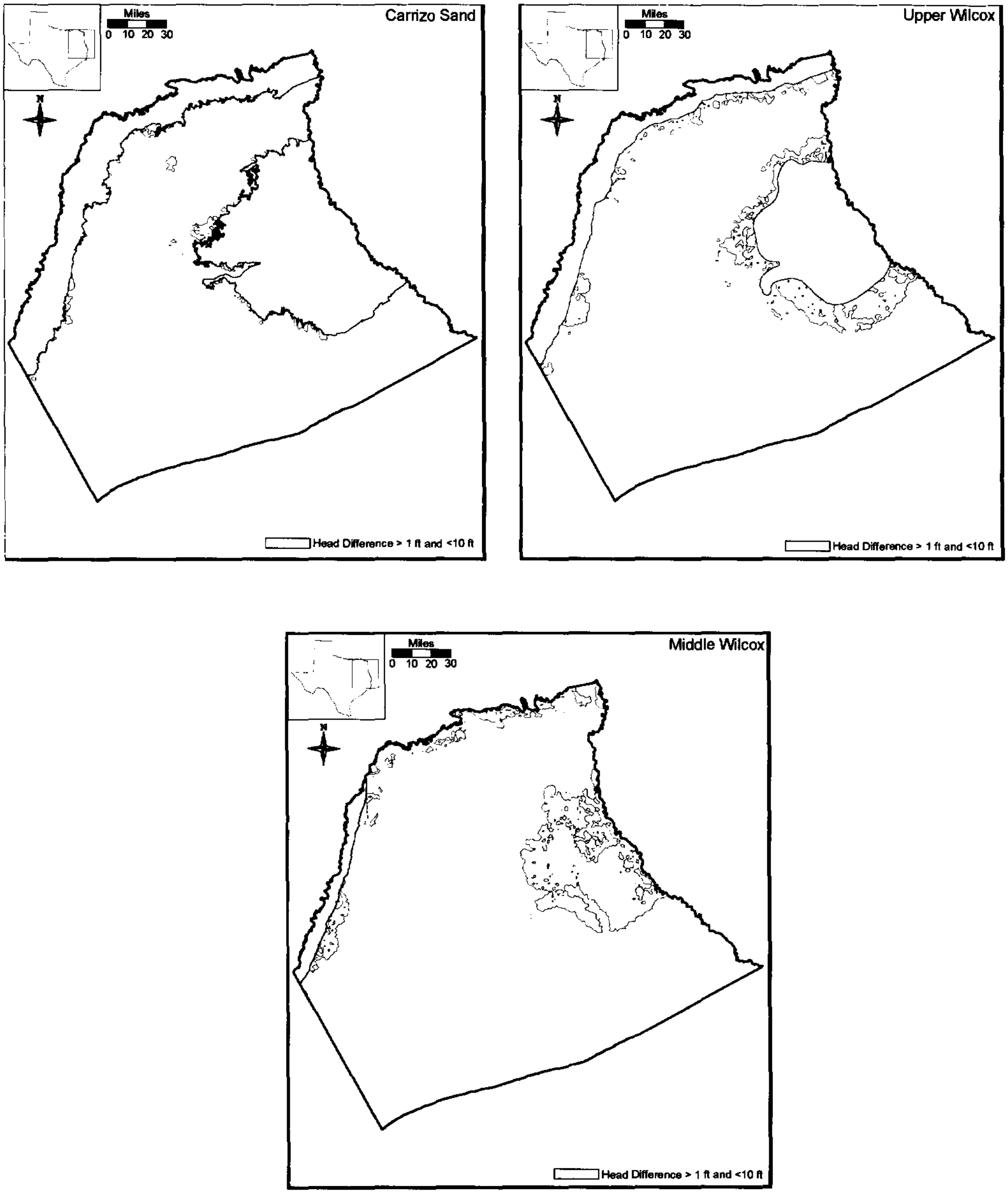


Figure 10.2.23 Simulated difference in head surfaces between the average condition 2050 simulation and the DOR 2050 simulation.

10.3 Predictive Simulation Water Budget

Table 10.3.1 shows the water budget for the predictive simulations. The table shows the water budget for the final year of each of the predictive simulations. Because the simulations ended in March (defined by the DOR), these balances are from March of the previous year to March of the given year. For example, the water budget for 2010 extends from March 2009 to March 2010. This accounts for the difference in mass balance between that in 1989 in the transient calibration (Table 9.2.3) and that for 1990 in Table 10.3.1. In general, the predictive simulation water budget shows similar trends and variations to that of the calibration/verification simulations. Table 10.3.1 shows an overall increase in pumpage from 1990 to 2050 by about 22,000 acre-ft/yr. However, the model shows an overall trend of water-level increase in the confined section. As with the calibration/verification simulations, the amount of leakance from the streams and from the reservoir can vary significantly through the predictive period. In all years shown in the table, the streams are gaining more water than they are losing. This is likely due to the DOR which has decreased the amount of flow in the streams to the point where the losing streams are not contributing as significantly to the aquifer. Also, comparing the 2050 run with average recharge with the DOR years shows the difference between average and drought condition recharge is approximately 1,000,000 AFY, or almost half of the average recharge. Groundwater evapotranspiration is also higher in the 2050 DOR simulation than in the 2050 average condition simulation.

Table 10.3.1 Water budget for predictive simulations. All rates reported in acre-ft/yr.

Year	Layer	GHBs	Reservoirs	Wells	ET	Top	Bottom	Recharge	Streams	Storage
1990	1	24,206	-17,888	-9,407	-176,757	0	-30,320	983,608	-129,799	-643,666
	2	0	-1,142	-663	-61,678	30,320	-40,904	250,299	-69,677	-106,558
	3	0	-2,722	-48,685	-43,220	40,904	-34,650	140,983	-29,403	-23,213
	4	0	-937	-43,862	-62,370	34,650	-23,027	467,050	4,072	-375,586
	5	0	41,390	-31,220	-71,461	23,027	-10,987	558,201	157,902	-666,875
	6	0	191,506	-6,230	-10,420	10,987	0	44,008	3,931	-233,783
	Sum	24,206	210,209	-140,068	-425,906	139,887	-139,887	2,444,149	-62,973	-2,049,682
2000	1	21,827	-31,705	-13,077	-384,707	0	-30,573	743,951	-374,864	68,976
	2	0	-260	-756	-121,001	30,573	-42,172	181,594	-85,669	37,691
	3	0	-3,814	-48,158	-55,632	42,172	-30,912	89,770	-36,318	42,887
	4	0	-111,795	-38,661	-108,174	30,912	-22,027	335,803	-88,218	2,159
	5	0	-101,474	-39,868	-103,468	22,027	-9,229	444,656	-76,654	-136,006
	6	0	-15,778	-7,431	-17,512	9,229	0	35,351	-13,651	9,792
	Sum	21,827	-264,825	-147,951	-790,494	134,913	-134,913	1,831,124	-675,374	25,498
2010	1	19,723	-17,842	-17,025	-672,141	0	-28,014	626,227	-321,068	410,127
	2	0	-749	-617	-217,076	28,014	-37,949	184,523	-60,052	103,902
	3	0	-1,646	-29,707	-95,873	37,949	-38,450	89,396	-26,429	85,044
	4	0	-8,509	-45,772	-202,548	38,450	-25,822	285,072	-98,336	57,452
	5	0	-12,658	-46,078	-179,256	25,822	-6,532	304,350	-102,732	17,061
	6	0	4,165	-8,189	-22,338	6,532	0	23,302	-5,342	1,866
	Sum	19,723	-37,240	-147,388	-1,389,233	136,766	-136,766	1,512,870	-613,959	675,452
2020	1	18,610	-18,657	-17,956	-710,035	0	-27,414	630,882	-321,929	446,487
	2	0	-769	-632	-224,809	27,414	-37,449	184,969	-57,944	109,214
	3	0	-1,597	-29,059	-91,244	37,449	-36,597	90,343	-25,198	55,893
	4	0	-9,341	-45,902	-209,576	36,597	-26,167	280,353	-99,712	73,734
	5	0	-13,865	-46,400	-198,760	26,167	-6,292	303,379	-113,285	49,035
	6	0	3,512	-8,261	-23,765	6,292	0	23,229	-6,009	4,998
	Sum	18,610	-40,718	-148,211	-1,458,188	133,919	-133,919	1,513,155	-624,077	739,361
2030	1	17,808	-19,448	-19,189	-740,417	0	-27,650	638,113	-324,046	474,832
	2	0	-797	-655	-230,235	27,650	-37,678	183,433	-57,010	134,036
	3	0	-1,557	-30,182	-89,980	37,678	-35,048	93,564	-24,438	56,822
	4	0	-11,512	-47,184	-218,358	35,048	-25,651	272,298	-102,167	97,997
	5	0	-14,812	-46,615	-221,166	25,651	-5,893	303,797	-123,856	82,887
	6	0	3,044	-8,200	-24,960	5,893	0	23,040	-6,453	7,632
	Sum	17,808	-45,082	-152,026	-1,525,115	131,921	-131,921	1,514,244	-637,972	854,207
2040	1	17,263	-20,161	-20,428	-773,076	0	-27,566	644,140	-326,648	506,638
	2	0	-811	-674	-234,142	27,566	-38,309	183,534	-56,544	119,377
	3	0	-1,525	-31,345	-91,534	38,309	-34,236	91,794	-24,376	52,905
	4	0	-12,016	-48,838	-225,619	34,236	-24,822	268,146	-105,279	114,178
	5	0	-15,673	-47,486	-245,690	24,822	-5,607	304,276	-132,293	117,632
	6	0	2,746	-8,499	-26,050	5,607	0	23,046	-6,976	10,122
	Sum	17,263	-47,441	-157,271	-1,596,111	130,541	-130,541	1,514,936	-652,115	920,852
2050	1	16,946	-20,789	-21,867	-801,316	0	-28,595	647,445	-328,754	537,054
	2	0	-814	-698	-239,089	28,595	-39,912	183,152	-56,176	124,939
	3	0	-1,496	-33,145	-92,717	39,912	-32,548	94,187	-24,265	50,061
	4	0	-12,417	-49,620	-234,460	32,548	-23,874	263,481	-107,753	132,082
	5	0	-16,486	-47,940	-266,317	23,874	-5,446	303,680	-139,166	147,782
	6	0	2,555	-8,689	-26,963	5,446	0	23,046	-7,493	12,093
	Sum	16,946	-49,447	-161,959	-1,660,862	130,374	-130,374	1,514,992	-663,607	1,004,011
2050*	1	16,845	-31,132	-21,867	-522,404	0	-28,819	1,128,537	-356,746	-184,420
	2	0	-1,049	-698	-163,391	28,819	-39,946	278,946	-60,559	-42,129
	3	0	-2,179	-33,152	-70,189	39,946	-32,798	130,356	-25,359	-6,637
	4	0	-25,617	-49,620	-179,598	32,798	-24,350	421,602	-105,041	-70,190
	5	0	-27,427	-47,940	-208,075	24,350	-5,667	567,626	-161,333	-141,551
	6	0	1,245	-8,689	-23,882	5,667	0	54,651	-13,950	-15,048
	Sum	16,845	-86,159	-161,967	-1,167,539	131,581	-131,581	2,581,719	-722,987	-459,976

*Does not include DOR.

11.0 LIMITATIONS OF THE MODEL

A model can be defined as a representation of reality that attempts to explain the behavior of some aspect of it, but is always less complex that the real system it represents (Domenico, 1972). As a result, limitations are intrinsic to models. Model limitations can be grouped into several categories including: (1) limitations in the data supporting a model, (2) limitations in the implementation of a model which may include assumptions inherent to the model application, and (3) limitations regarding model applicability. The limitations of this modeling study are discussed in the following consistent with the grouping provided above.

11.1 Limitations of Supporting Data

Developing the supporting database for a regional model at this scale and with this large a number of grid cells is a challenge. An adequate database was available from published sources for estimation of the structural surfaces for the Carrizo-Wilcox aquifer at the scale of the model. Because the model is at a regional scale, structural data will not have every bend and discontinuity found at a local scale.

Our discussion will now focus on the parameters which were found to be important in the sensitivity analyses and the quality of the targets used to assess calibration and verification. For the steady-state model, the primary parameters controlling model behavior are recharge and the hydraulic conductivity of the Wilcox. For the transient model, the primary parameters controlling model behavior are pumping, vertical hydraulic conductivity of the Reklaw, and horizontal hydraulic conductivity of the Wilcox and Carrizo. Recharge in the Carrizo-Wilcox aquifer has been studied by many investigators. Scanlon et al. (2002) provide a good summary of the available recharge estimates in the study area. Estimates of recharge for the Carrizo-Wilcox vary from less than an inch per year to up to five inches per year. The Northern Carrizo-Wilcox steady-state GAM provides a good means for estimating viable recharge estimates for the aquifer. However, because of the correlation between recharge and vertical conductance of the formations, recharge cannot be uniquely determined. The vertical conductance of the modeled aquifers can only be estimated regionally by models such as this GAM. The conundrum is that in the steady-state model, the vertical conductance of the aquifers is inversely related to recharge which means that unique determination of these two parameters is not possible. To take advantage of this, we estimated recharge with a forward model (SWAT), and considered the spatial recharge distribution to be fixed for the most part, although we adjusted the overall magnitude during calibration. Estimates of recharge are important to the GAM modeling process because they provide a means of constraining the vertical conductance terms in the model especially when calibrating to steady-state and transient conditions. Studies should be continued into the nature of recharge in the Carrizo-Wilcox aquifer.

For the transient model, the most important parameter through the calibration process was the vertical conductivity of the Carrizo-Wilcox aquifer and the Reklaw Formation. When we completed calibration, the sensitivity analysis indicated that the most important parameters at the final calibration state were pumping and the horizontal hydraulic conductivities of the Carrizo and Wilcox layers. The pumping estimates were derived through a detailed process (see Appendices B and C). However, there are potential uncertainties in terms of the pumping volume and pumping allocation to the different layers. Industrial, agricultural, and rural pumping data are reported to the TWDB on a voluntary basis. The allocation of pumping to the different model layers is done by approximation and by correlation to the nearest wells, where no specific well information is available. Because the northern Carrizo-Wilcox aquifer is most heavily developed in the confined portion of the aquifer, errors in pumping rates have a significant impact on simulated water levels. Not unlike the situation with recharge and vertical conductance in the steady-state model, horizontal hydraulic conductivity and pumping are correlated parameters and unique determination of them is not possible. We modified horizontal conductivities for the Carrizo and upper Wilcox layers in certain areas as well as vertical conductivities of the confining Reklaw, though we could not find good evidence in the available hydrogeologic data for the adjustment.

The model also lacks horizontal hydraulic conductivity data for the Queen City and the Wilcox Group. This is especially true in the downdip confined portions of the aquifer, where there is limited data. Hydraulic conductivity data for the Carrizo is also lacking in the deeper portions of the aquifer. The model was sensitive to the Carrizo and Wilcox hydraulic conductivity. With improved control on hydraulic conductivity data in the confined portions of the aquifer, estimates of vertical conductance in the aquifer system would be better constrained.

The primary type of calibration target is hydraulic head. There is a general lack of heads representative of the predevelopment for all model layers. However, we believe the steady-state model is important for constraining the model calibration and accept the uncertainty in predevelopment conditions. Head calibration targets for the transient (historical model) are also lacking in some portions of the Wilcox and the Carrizo for the confined portions of the model. The model calibration could be improved with more head targets in these areas.

The other type of calibration target used was stream gain/loss estimates. There are limited stream gain/loss estimates in the model area. There were also a limited number of stream gages in the outcrop that were amenable to estimation of losses or gains through the study region. Because the MODFLOW stream routing package does not model runoff, direct comparison to stream gages is problematic. It would be beneficial if publicly available surface water models were developed for the outcrop regions in the study area. These would provide better estimates of the hydrography of the area and could be coupled with MODFLOW.

11.2 Limiting Assumptions

There are several assumptions that are key to the model regarding construction, calibration, and prediction. These are briefly discussed below with a discussion of the potential limitations of the assumption.

We modeled the lower boundary of the model as a no-flow boundary at the base of the Wilcox Group. This assumption is consistent with other regional models in the area and is probably a good assumption for the model in the overall sense. However, as the model moves to the outcrop, the no-flow nature of the base of the lower Wilcox creates some problems with recharge rates where the lower Wilcox is thin. This is not considered a significant limitation to the model since it causes only limited-area edge effects.

The lateral model boundaries were also modeled as no-flow boundaries. The western model boundary is the drainage divide between the Trinity and Brazos rivers and probably does not limit the model's performance in the west. We used a no-flow boundary because we assumed that the boundary provided a conservative reflective boundary as long as pumping west of the boundary was equal to or less than pumping east of the boundary. We reviewed the Central Carrizo-Wilcox GAM transient heads and concluded that drawdowns were not significant enough to use a transient boundary condition for the historical period. The east boundary is the Red River and it is felt that any uncertainty in characterizing this boundary as no flow would be negligible with respect to simulated heads within Texas counties.

Another assumption used in our model is that the recharge estimated from SWAT was applicable to the region. As discussed earlier, modifications to the SWAT output were required for the Northern Carrizo-Wilcox GAM. We believe that the model provided preliminary regional estimates of recharge in the model region using physical models and parameters representative of the area. We did not model the interflow zone in SWAT. We used MODFLOW to reject recharge to the stream networks, which has its limitations due to the averaging of topography on a 1 by 1-mile grid scale. The steady-state simulation in MODFLOW encountered difficulties when ET approached or exceeded recharge, for which we had to make adjustments. This problem did not occur in the transient simulations.

In the predictive simulations, we assumed (in accordance with TWDB's GAM requirements) that the pumping estimates available from the Regional Water Planning Group database tables were representative of the future demands. In the model, the overall pumpage increased, but relative pumpage in different layers changed between the transient and predictive simulations, particularly between the Queen City and Carrizo-Wilcox, as discussed in Sections 4.7, 9.1 and 10. The apparent discrepancy causes drastic changes in water-level in the model predictions. Because the Queen City was not part of this GAM study, the potential problem with the pumpage allocation could not be resolved. However, this is being addressed in the GAM study for the Queen City and Sparta Aquifer.

Finally, our pumping demand estimates are based upon drought-of-record conditions. As a result, pumping does not increase at the end of each predictive simulation when the drought of record occurs. It is expected that we would see greater water level declines in the aquifer system as a whole if the pumping and climate (recharge) were impacted as a result of the drought of record.

11.3 Limits for Model Applicability

The model was developed on a regional scale and is only capable of predicting aquifer conditions at the regional scale. The model is applicable for assessing regional aquifer conditions resulting from groundwater development over a fifty-year time period.

The model itself was developed at a grid scale of one square mile. The model is not capable of being used in its current state to predict aquifer responses at specific points such as a particular well at a particular municipality. The aquifer is accurate at the scale of tens of miles which is adequate for understanding groundwater availability at the scale of the northern Carrizo-Wilcox aquifer.

The model is ideal for refinement for more local scale issues related to specific water resource questions. Questions regarding local drawdown to a well should be based upon analytical solutions to the diffusion equation or a refined numerical model. The GAM provides water levels representative of large volumes of aquifer (e.g., 5,280 ft X 5,280 ft X aquifer thickness in feet). The model was built to determine how regional water levels will respond to water resource development in an area smaller than a county and larger than a square mile.

The GAM model provides a first-order approach to coupling surface water to groundwater which is adequate for the GAM model purposes and for the scale of application. However, this model does not provide a rigorous solution to surface water modeling in the region and should not be used as a surface water modeling tool in isolation.

The GAM model does not simulate transport of solutes and cannot address explicitly water quality issues. The model also did not delineate specific regions within individual aquifer layers having potentially poor quality water not suitable as a groundwater resource. Only a preliminary assessment of water quality is given in the report.

12.0 FUTURE IMPROVEMENTS

To use models to predict future conditions requires a commitment to improve the model as new data becomes available or when modeling assumptions or implementation issues change. This GAM model is no different. Through the modeling process one generally learns what can be done to improve the model's performance or what data would help better constrain the model calibration. Future improvements to the model will be discussed below.

12.1 Supporting Data

Several types of data could be collected to better support the GAM model development process. These include recharge studies, surface water/groundwater studies and basic addition of stream gages, and water level monitoring in the confined portion of the Carrizo-Wilcox aquifer.

Estimates of recharge are important to the GAM modeling process because they provide a means of constraining the vertical hydraulic conductivity of the aquifer system when calibrating to steady-state and transient conditions. Studies should be continued into the nature of recharge in the Carrizo-Wilcox aquifer.

Surface water/groundwater interaction requires a good coverage of stream gages in the model outcrop areas, preferably immediately upstream and downstream of the outcrop areas. The model predicts that stream-aquifer interaction is significant in the model region. It would be beneficial if publicly available surface water models were developed for the outcrop regions in the study area. These would provide better estimates of the hydrography of the area and could be coupled with MODFLOW in future model improvement.

Additional water-level monitoring in the Wilcox Group and in deeper downdip portions of the Carrizo Formation is important for future model development. There are a limited number of Wilcox water-level measurements in the deeper downdip portions of the aquifer. Although the Wilcox may be non-potable in portions of the confined section, it is still advantageous to monitor water levels in these deep sections to improve aquifer understanding and to incorporate those additional data into the model. It is also important to increase water-level monitoring in areas that are potential areas of future development but which are currently not greatly developed. If monitoring begins prior to increased development, the GAM can be calibrated against the aquifer response to improve model predictive capability in those regions.

Currently, horizontal hydraulic conductivity data are limited for the Queen City Formation and the lower part of the Wilcox Group in the model area. This is especially true in some portions of the downdip confined section of the aquifer. Hydraulic conductivity data for the Carrizo is also lacking in the deeper, confined portions of the aquifer. Any additional hydraulic conductivity estimates and storativity estimates from pump tests will further help parameterize future improvements to this model.

12.2 Future Model Improvements

The lateral model boundaries were modeled as no-flow boundaries. We used a no-flow boundary along the western boundary because we assumed that the boundary provided a conservative reflective boundary as long as pumping east of the boundary was equal to or less than pumping west of the boundary. The applicability of this assumption along the western boundary should be reviewed with the finalization of the Central and Northern Carrizo-Wilcox GAMs. If a review of the final Central and Northern Carrizo-Wilcox GAM results indicates that the western boundary should be transiently applied as a head-dependent flow boundary, these changes can be made when the Queen City-Sparta aquifers are added to the model in the future.

Additional improvement of the model includes focus on refining the spatial hydraulic conductivities distribution for calibration and evaluation of the spatial recharge distribution in areas that indicate large variations. On the modeling side, the numerical problems during steady-state MODFLOW simulations in case of high ET rates relative to recharge rate needs to be examined for consistency with the transient behavior of the model.

The GAM model indicated the importance of pumping to the transient and predictive model results. The pumping data base developed based on the TWDB technical guidance as described in Appendices B and C needs to be improved. This requires identifying possible inconsistencies between different data sources and potential data gaps. Furthermore, the allocation of pumping to the different layers needs to be verified to improve consistency between the historical pumping data through 1999 and predictive pumping data starting in 2000.

13.0 CONCLUSIONS

This report documents a three-dimensional groundwater model developed for the northern Carrizo-Wilcox aquifer to the GAM standards defined by the TWDB. This regional scale model was developed using MODFLOW with the stream-routing package to simulate stream-aquifer interaction and the reservoir package to model groundwater interaction with lakes and reservoirs. The model divides the Carrizo-Wilcox aquifer into four layers: the Carrizo, and the upper, middle, and lower Wilcox. The Reklaw Formation and the Queen City Sand are also modeled as individual model layers.

The purpose of this GAM is to provide predictions of groundwater availability through the year 2050 based on current projections of groundwater demands during drought-of-record conditions. This GAM provides an integrated tool for the assessment of water management strategies to directly benefit state planners, Regional Water Planning Groups (RWPGs), and Groundwater Conservation Districts (GCDs).

This GAM has been developed using a modeling protocol which is standard to the groundwater model industry. This protocol includes: (1) the development of a conceptual model for groundwater flow in the aquifer, (2) model design, (3) model calibration, (4) model verification, (5) sensitivity analysis, (6) model prediction, and (7) reporting.

The model has been calibrated to predevelopment conditions (prior to significant resource use) which are considered to be at steady state. The steady-state model reproduces the predevelopment aquifer heads well and within the uncertainty in the head estimates. The median recharge rate estimated for the steady-state model was 0.93 inches per year. In the pre-development model, recharge accounted for approximately 93% of the aquifer inflow and streams and ET discharged approximately 68% and 28% of the aquifer outflow, respectively. Approximately 3% of the aquifer inflowing water passed from the outcrop through to the confined aquifer and exited vertically through the GHBs in the southern part of the model. A sensitivity analysis was performed to determine which parameters had the most influence on aquifer performance and calibration. The two most sensitive parameters for the steady-state model were recharge, and to a lesser extent, horizontal hydraulic conductivities of the aquifer units and vertical conductivity of the confining stratum.

The model was also satisfactorily calibrated to transient aquifer conditions from 1980 through December 1989. The model did a good job of reproducing aquifer heads and available estimates of aquifer-stream interaction. The transient-calibrated model was verified by simulating to aquifer conditions from 1990 through December 1999. Again, the model satisfactorily simulated observed conditions. Regionally, the model reproduces model heads to within head target errors. A sensitivity analysis was performed on the transient model. The two most sensitive parameters for the transient model were pumping and the horizontal hydraulic conductivity of the Carrizo and Wilcox layers.

The net recharge to the aquifer (e.g., recharge minus ET) for the long-term average in the transient model is 0.93 inches per year, based on an average recharge of 2.59 inches/yr. This compares to a net recharge of 0.65 inches/yr for steady-state model, based on a total recharge of 0.93 inches/yr. The increased recharge amount during transient conditions may constitute rejected recharge during predevelopment conditions.

Model predictions were performed to estimate aquifer conditions for the next 50 years based upon projected pumping demands under drought-of-record (DOR) conditions as developed by the Regional Water Planning Groups. The model indicated a noticeable rebound of the cones of depression in the confined section. Predictive pumping data indicated some reallocation of pumping to different aquifer layers in some counties during the transition from the historical period to the predictive period, which accounts for much of the simulated responses in the hydraulic head surfaces. The simulations incorporating the DOR conditions at the end of the predictive periods show relatively small head declines that are limited to the outcrop and shallow confining section of the Carrizo-Wilcox aquifer. This is due to the fact that the DOR only considers climatic conditions (e.g., recharge), but not the potential increase in pumping.

This model, like all models, has limitations and can be improved. The GAM reproduced the steady-state (predevelopment) and transient (historical) conditions of the aquifer within the given calibration measures. More importantly, this calibrated GAM provides a documented, publicly-available tool for the assessment of future groundwater availability on a regional scale in the northern Carrizo-Wilcox aquifer.

14.0 ACKNOWLEDGEMENTS

The Northern Carrizo-Wilcox GAM was developed with the participation of a group of stakeholders representing varied interests within the model region. Interaction with these stakeholders was performed through a series of Stakeholder Advisory Forums (SAF) held across the model region. In these meetings, stakeholders were solicited for data and were provided updates on a regular basis beginning in spring 2001. The model described in this report has benefited from the stakeholders involvement and interest. In addition, we would like to specifically thank those members of the SAF who have hosted meetings across the model region.

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APPENDIX A
Brief Summary of the Development of the Carrizo-Wilcox Aquifer in Each County
and
List of Reviewed Reports

Anderson County, Texas

Little information related to the historical development of the Carrizo Sand and the Wilcox Group in Anderson County was found during the literature review. The Carrizo Sand and the sands of the Wilcox Group are considered to be separate aquifers in this county, with the Wilcox aquifer being the most important water-bearing formation (William F. Guyton & Associates, 1972). Deussen (1914) states that pressures in the lower Eocene sand were sufficient to drive water to the ground surface only in low lying areas along streams in this county. Fourteen wells completed in the Carrizo Sand only, the Wilcox Group only, and in both the Carrizo Sand and the Wilcox Group were found to flow between 1960 and 1970 (William F. Guyton & Associates, 1972). Flows in some of the wells were as high as 200 to 500 gpm.

The earliest date given on the TWDB website[1] for completion of a well to the Carrizo Sand in Anderson County is 1927. The earliest water-level measurements are from 1938. Only two wells were completed in the Carrizo Sand at the time of the first water-level measurement. Based on an evaluation of maximum measured water levels regardless of time, the early measurements in the Carrizo Sand appear to reflect pumping effects. Therefore, the earliest measurement is not considered to be representative of predevelopment conditions.

The earliest date given on the TWDB website for completion of a well to the Wilcox Group in Anderson County is 1929. The first water-level measurement was taken in this well also in 1929. Deussen (1914) lists two wells completed to the Wilcox Group in the late 1800s. These wells are not included in the data provided on the TWDB website. Since the first water-level measurement was taken at the time the first well was drilled, that measurement is considered to be representative of predevelopment conditions.

Fogg and Kreitler (1982) observed a local high in the water-level elevation in both the Carrizo Sand and the Wilcox Group in north central Anderson County near a topographic high. They attribute this high to "high topography supplying the downward-driving force and to disruption of overlying aquitards by faults associated with Concord Dome."

[1] http://rio.twdb.state.tx.us/publications/reports/GrorundWaterReports/GWDatabaseReports/GWdatabaserpt.htm

Angelina County, Texas

Little information related to the historical development of the Carrizo Sand and the Wilcox Group in Angelina County was found during the literature review. Unless stated otherwise, the following discussion comes from William F. Guyton & Associates (1970). The Carrizo Sand and the sands of the Wilcox Group are considered to be separate aquifers in this county, with the Carrizo aquifer being the most productive. Of the total amount of water removed from the Carrizo Sand and the sands of the Wilcox group in the county, the percentage obtained from the Wilcox is very low (less than 1 percent in 1968). The Carrizo aquifer has been developed extensively in this county since the late 1930s by the city of Lufkin and by the Southland Paper Mills located north-northeast of Lufkin near the border between Angelina and Nacogdoches Counties. Suitable groundwater wells did not operate near Lufkin until 1935 when a test well was drilled to the Carrizo aquifer (White et al., 1941). Scalapino (1963) states that the areas of largest development of water from the Carrizo Sand are the Lufkin area, which includes water used by the cities of Lufkin and Nacogdoches and by the Southland Paper Mills, and the Winter Garden Area located in the southern Carrizo-Wilcox GAM. Flowing wells were observed in southern Nacogdoches County and northern Angelina County in the 1940s, but by 1961 most of those wells had stopped flowing (Baker et al., 1963). Extensive pumpage from the Carrizo since 1939 has resulted in drawdowns of up to 500 ft at pumping centers. Deussen (1914) states that several wells in the northwestern portion of the county flowed; one located near the city of Platt and the other located west of the city of Lufkin.

The earliest dates given on the TWDB website for wells completed to the Carrizo Sand in Angelina County are 1922 and 1935. The earliest water-level measurements are from 1939 (nine measurements). About two wells were completed to the Carrizo Sand prior to the time of these measurements which correspond to times when additional wells were drilled. Therefore, the earliest water-level measurements are considered to represent predevelopment conditions.

The earliest date given on the TWDB website for a well completed to the Wilcox Group in Angelina County is 1941. The earliest water-level measurement is from 1941. This early measurement reflected the effects of pumpage and was not considered representative of predevelopment conditions.

Bowie County, Texas

Information regarding historical development of the Wilcox Group in Bowie County could not be found during the literature search. The Wilcox Group outcrops in the lower third to half of the county. The Carrizo Sand is not found in Bowie County. The earliest completion date given on the TWDB website is 1910 for wells completed in the sands of the Wilcox Group. The earliest water-level measurement was made in 1973 based on the data on the TWDB website. As a result, all water-level measurements for the Wilcox in Bowie County appeared to be effected by pumpage and are not considered representative of predevelopment conditions.

Caddo Parish, Louisiana

Little information related to the historical development of the Carrizo Sand and the Wilcox Group in Caddo Parish was found during the literature review. Unless stated otherwise, the following discussion comes from Page and May (1964). The Carrizo Sand and the sands of the Wilcox Group are considered to be separate aquifers in this parish. The Wilcox aquifer is the principal source of groundwater in Caddo Parish. Of the total amount of groundwater removed from the Carrizo aquifer and the Wilcox aquifer in the parish, the percentage obtained from the Carrizo is very low. The cities of Shreveport and Bossier City used water from the Wilcox aquifer until surface-water supplies were developed from 1926-1928. Some pumpage for industrial purposes was reported for 1941. In 1962, the dominate users of groundwater from the Wilcox aquifer were municipalities and rural residences.

The first well completed to the Wilcox aquifer in Caddo Parish was drilled in 1900 (LaDOT, website[2]). About 11 additional wells were drilled from 1910 to 1920. The earliest available water levels are one measurement in 1921 and one measurement in 1923 (LaDOT, website). Since several wells had been completed to and pumping from the Wilcox aquifer at the time of the earliest water level measurements, those measurements are not considered to be representative of predevelopment conditions.

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[2] http://www2.dotd.state.la.us/wells/wells.html

Camp County, Texas

Little information related to the historical development of the Carrizo Sand and the Wilcox Group in Camp County was found during the literature review. Broom et al. (1965) state that the sands of the Wilcox Group, the Carrizo Sand, the Reklaw Formation, and the Queen City Sand are hydraulically connected and act as a single aquifer which they refer to as the Cypress aquifer. No flowing wells are reported in Broom et al. (1965). No general decline in water levels for shallow wells (less than 60 ft deep) has been observed (Broom et al., 1965). Broom et al. (1965) state, "Water levels in the heavily-pumped deeper wells show average declines of 3.5 to 15.7 feet per year for various periods of record."

The earliest completion date given on the TWDB website for a well completed in the Cypress aquifer in Camp County is 1896. Several additional wells were drilled in the early 1900s. The first water-level measurements were taken in 1934. About eight wells were completed to the Cypress aquifer at the time of these measurements. As a result, the early measurements are not considered to be representative of predevelopment conditions.

Cass County, Texas

Little information related to the historical development of the Carrizo Sand and the Wilcox Group in Cass County was found during the literature review. Broom (1971) states that the sands of the Wilcox Group, the Carrizo Sand, the Reklaw Formation, and the Queen City Sand are hydraulically connected and act as a single aquifer which he refers to as the Cypress aquifer. Several wells completed in the Cypress aquifer were found to flow in 1967/1968 (Broom, 1971). Broom (1971) states the following regarding water-level changes in Cass County,

"Available data indicate that water levels in the artesian section of the [Cypress] aquifer have declined considerably in areas where the aquifer is heavily pumped. In the Bryans Mill area, water levels have declined as much as 86 feet since 1961. In the Atlanta area, water levels have declines as much as 100 feet since 1936, and in parts of the Rodessa oil field, water levels have declined as much as 109 feet since about 1964. Elsewhere in the report area [Cass and Marion Counties], water levels show no appreciable changed during the period of record."

The earliest completion date given on the TWDB website for a well in the Cypress aquifer in Cass County is 1901. The first water-level measurements, taken in 1936, appear to reflect pumpage effects. Therefore, the earliest measurements are not considered to be representative of predevelopment conditions.

Cherokee County, Texas

Little information related to the historical development of the Carrizo Sand and the Wilcox Group in Cherokee County was found during the literature review. The Carrizo Sand and the sands of the Wilcox Group are considered to be separate aquifers in this county, with the Wilcox aquifer being the most important water-bearing formation (William F. Guyton & Associates, 1972). The area where the lower Eocene reservoir flows in Cherokee county is "...confined entirely to the valleys..." (Deussen, 1914). No wells completed in either the Carrizo Sand or the Wilcox Group were found to flow by William F. Guyton & Associates (1972).

The earliest date given on the TWDB website for a well completed to the Carrizo Sand in Cherokee County is 1900. The earliest water-level measurements are from 1929 (1 measurement) and 1936 (13 measurements). These early measurements reflect the effects of pumping and are not considered representative of predevelopment conditions.

The earliest date given on the TWDB website for wells completed to the Wilcox Group in Cherokee County is1935. The earliest water-level measurement is not until 1954. Because all of the available water-level data for the Wilcox Group, including the earliest measurements, reflect the effects of pumpage, none of the water-level measurements were considered to be representative of predevelopment conditions.

DeSoto Parish, Louisiana

No information related to historical development of the Carrizo Sand and Wilcox Group in DeSoto Parish was found during the literature review. The first wells completed to the Wilcox aquifer in this parish were drilled in 1900 (LaDOT, website). The earliest available water levels are one measurement in 1927 and one measurement in 1938 (LaDOT, website). At the time of the first water-level measurement, approximately 20 wells were completed to the Wilcox. Since many wells had been completed to the Wilcox at the time of the earliest water level measurements, those measurements are not considered to be representative of predevelopment conditions.

Franklin County, Texas

Little information related to the historical development of the Carrizo Sand and the Wilcox Group in Franklin County was found during the literature review. Broom et al. (1965) state that the sands of the Wilcox Group, the Carrizo Sand, the Reklaw Formation, and the Queen City Sand are hydraulically connected and act as a single aquifer which they refer to as the Cypress aquifer. Five wells completed to the Cypress aquifer in Franklin County were found to flow in 1942 and 1963 (Broom et al., 1965). No general decline in water levels for shallow wells (less than 60 ft deep) has been observed (Broom et al., 1965). Broom et al. (1965) state, "Water levels in the heavily-pumped deeper wells show average declines of 3.5 to 15.7 feet per year for various periods of record."

The earliest completion data given on the TWDB website for a well completed in the Cypress aquifer in Franklin County is 1875. Several additional wells were drilled in the early 1900s. The first water-level measurements were taken in 1942. Since over ten wells had been pumping from the Cypress aquifer prior to this time, the earliest water-level measurements are not considered to be representative of predevelopment conditions.

Freestone County, Texas

Little information related to the historical development of the Carrizo Sand and the Wilcox Group in Freestone County was found during the literature review. The Carrizo Sand and the sands of the Wilcox Group are considered to be separate aquifers in this county, with the Wilcox aquifer being the most important water-bearing formation (William F. Guyton & Associates, 1972). Deussen (1914) states that flowing wells in the Wilcox Formation, which includes the then undistinguished Carrizo Sand, are uncommon since the Wilcox crops out over the entire county. Several wells completed in the Wilcox Group with flows less than 15 gpm were reported in William F. Guyton & Associates (1972).

The earliest date given on the TWDB website for a well completed to the Carrizo Aquifer in Freestone County is 1896. The earliest water-level measurement, on the other hand, is from a 1936 measurement. A total of three wells were completed to the Carrizo aquifer at the time of this measurement. Since only a few wells had been pumping from the Carrizo prior to the earliest water-level measurement, that measurement is considered to be fairly representative of predevelopment conditions.

The earliest date given on the TWDB website for a well completed to the Wilcox aquifer in Freestone County is 1896. At the time of the earliest water-level measurement in 1935, over 90 wells were completed to the Wilcox aquifer. Consequently, this first water-level measurement is not considered to be representative of predevelopment conditions.

Gregg County, Texas

Little information related to historical development of the Carrizo Sand and Wilcox Group in Gregg County was found during the literature review. Unless stated otherwise, the following discussion of development of the Carrizo Sand and Wilcox Group in Gregg County comes from Broom (1969). The Carrizo Sand and the sands of the Wilcox Group are considered hydraulically connected and a single aquifer in this county, with the Carrizo Sand being the principal water source. Duessen (1914) observed two flowing wells in the Sabine River bottoms. Little development of the waters in the Carrizo-Wilcox aquifer occurred in this county until the discovery of the East Texas oil field in 1930-1931. Numerous processes related to the oil industry and the increased population in the area of the oil field created an immediate demand for water. The water needs were met by completing wells to the Carrizo-Wilcox aquifer. By the mid-1950s, the dominate municipality in the area began deriving its water from a Carrizo-Wilcox field in Smith County.

The data on the TWDB website and in the county report (Broom, 1969) indicate that the first wells drilled to the Carrizo-Wilcox aquifer were completed in 1931 and the first water-level measurements were also taken in 1931. Therefore, the early water-level data for this county is considered to be representative of predevelopment conditions.

Grimes County, Texas

As of 1974, no water wells were completed to the Carrizo Sand or the sands of the Wilcox Group in Grimes County (Baker and Follett, 1974)

Harrison County, Texas

Little information related to the historical development of the Carrizo Sand and the Wilcox Group in Harrison County was found during the literature review. Unless otherwise stated, the following information was taken from Broom and Myers (1966). The sands of the Wilcox Group, the Carrizo Sand, the Reklaw Formation, and the Queen City Sand are hydraulically connected and act as a single aquifer which they refer to as the Cypress aquifer. Deussen (1914) discusses the presence of several flowing wells in the county. Nine wells completed to the Cypress aquifer in Harrison County were found to flow in 1964. Broom and Myers (1966) state that, "Prior to 1949, relatively large amounts of groundwater for municipal and industrial use were pumped by wells in and near Marshall." For shallow wells completed to the water table, the decline in water level between the late 1930s and 1964 was negligible. The decline in water level in the artesian portion of the aquifer was approximately 15 feet per year near the city of Marshall (located near the center of the county) prior the 1949, which is when the city switched to surface water for its public supply, but only 2 feet per year near the city of Hallsville (located in the west-southwest portion of the county). Because the average annual rainfall in Harrison is high, little need exists for irrigation. The largest uses of groundwater from the Cypress aquifer during 1964 were for industrial and domestic purposes.

The earliest completion dates given on the TWDB website for a well in the Cypress aquifer in Harrison County is 1871. Several additional wells were drilled in the early 1900s. The first water-level measurements were taken in 1936. By this time, 25 wells had been pumping from the Cypress Aquifer in this county. Consequently, the earliest water-level data available for Harrison County is not considered to be representative of predevelopment conditions.

Henderson County, Texas

Little information related to historical development of the Carrizo Sand and Wilcox Group in Henderson County was found during the literature review. The Carrizo Sand and the sands of the Wilcox Group are considered to be separate aquifers in this county, with the Wilcox aquifer being the most important water-bearing formation (William F. Guyton & Associates, 1972). Deussen (1914) states, "The sands of the Wilcox formation...should not be expected to yield flows except in the valleys of the eastern half of the county." William F. Guyton &

Associates (1972) report that five wells completed to the Carrizo Sand and the Wilcox Group flowed at one time.

The earliest date given on the TWDB website for a well completed to the Carrizo aquifer in Henderson County is 1870. The earliest water-level measurement was taken in 1936. Ten wells had been completed to the Carrizo Sand by the time the first water-level measurement was taken. As a result, that measurement is not considered to be representative of predevelopment conditions.

The earliest date given on the TWDB website for a well completed to the Wilcox aquifer in Henderson County is 1880. The earliest water-level measurement was taken in 1900. Since only one well had been pumping prior to the first water-level measurement, that measurement is considered to be representative of predevelopment conditions in the Wilcox aquifer in Henderson County.

Hopkins County, Texas

Information regarding historical development of the Wilcox Group in Hopkins County could not be found during the literature search. The Wilcox Group outcrops in the lower third to half of the county. Only one well, drilled in 1972, is completed to the Carrizo Sand (TWDB, website). The earliest completion date given on the TWDB website is 1948 for wells completed in the sands of the Wilcox Group. The earliest water-level measurement was made in 1973 based on the data on the TWDB website. As a result, all water-level measurements for the Wilcox in Hopkins County appeared to be effected by pumpage and are not considered representative of predevelopment conditions.

Houston County, Texas

Little information related to the historical development of the Carrizo Sand and the Wilcox Group in Houston County was found during the literature review. Unless stated otherwise, the following discussion comes from Tarver (1966). The Carrizo Sand and the sands of the Wilcox Group are considered to be separate aquifers in this county, with the Carrizo aquifer being the most productive. As of 1966, only one well was completed to sands of the Wilcox Group. In general, little to no fresh water is available from the Wilcox Group in Houston County based on analysis of electric logs. Several normal faults are present in the subsurface in this county. However, they are not considered to significantly interfere with groundwater movement in the Carrizo Sand. Groundwater is primarily used in the county by municipalities and industries, and for domestic, stock, and irrigation purposes. The majority of this groundwater is removed from the Sparta Sand, with minor amounts removed from the Yegua Formation and the Queen City Sand. All three of these aquifers overly the Carrizo Sand. Only a few wells withdraw water from the Carrizo Sand.

According to data on the TWDB website and in Tarver (1966), the first wells completed to the Carrizo Sand in Houston County were drilled in 1930. The first available water-level data are one measurement from 1961 and two other measurements from 1963. Due to the extended period between the time the first well was drilled and the time of the first water-level measurements, none on the water-level data for Houston County is considered to be representative of predevelopment conditions.

Jasper County, Texas

The Carrizo Sand and Wilcox Group are not sources of fresh to slightly saline water in Jasper County (Wesselman, 1967).

Leon County, Texas

Essentially no information related to the historical development of the Carrizo Sand and the Wilcox Group in Leon County was found during the literature review. Unless stated otherwise, the following discussion comes from Peckham (1965). The Carrizo Sand and the sands of the Wilcox Group are hydraulically connected and considered to function as a single aquifer in this county. The data presented in Peckham (1965) are from field work conducted in 1958 and 1959. The little historical data evaluated by Peckham (1965) suggests little to no decline in water levels in this county. All water obtained for municipal purposes, with the exception of one city, comes from the Carrizo-Wilcox aquifer. Carrizo-Wilcox waters are also used for irrigation, industrial, domestic, and livestock purposes. The industrial use of groundwater from the Carrizo Wilcox was quite small in 1958-1959. Most of the development of the Carrizo-Wilcox aquifer has occurred in the northern portion of the county. Because good quality water can be obtained from shallower sources, little development of the Carrizo-Wilcox aquifer has occurred in the southern portion of the county.

According to data on the TWDB website and in Peckham (1965), the first wells in Leon County were drilled in the mid and late 1930s. The first available water-level data are one measurement from 1937 and another measurement from 1949. The water-level measurement from 1937 is considered to be representative of predevelopment conditions.

Limestone County, Texas

Unless stated otherwise, the following discussion of development of the Carrizo Sand and Wilcox Group in Limestone County comes from Rettman (1984; 1987). The Carrizo Sand is not present and the Wilcox Group is a major aquifer in this county. In this county, the Wilcox Group can be divided into three distinct members; the Calvert Bluff Formation, the Simsboro Formation, and the Hooper Formation from top to bottom. Rettman (1984) states, "...the Wilcox is considered a hydraulic unit...[with] no apparent regional barriers to water moving from one unit to another." Deussen (1914) reports that a couple of shallow Wilcox wells flow near the city of Groesbeck. Rettman (1987) lists two Wilcox wells that were flowing in 1982.

The first use of groundwater from the Wilcox Group for municipal supply appears to have been by the city of Mexia in 1925. The city discontinued using groundwater in 1962. The cities of Tehuacana and Thornton began using groundwater from the Wilcox in 1940. Groundwater from the Wilcox in this county was used by the city of Kosse from 1939 to 1978. Between 1955 and 1980, the use of groundwater for industrial purposes peaked in 1965, the use of groundwater for domestic and livestock purposes has gradually increased each year, and the use of groundwater for public supply peaked in 1960 and significantly decreased thereafter. Little groundwater is used for irrigation purposes in this county due to the generally high annual precipitation. Overall, the use of groundwater in this county generally declined between 1955 and 1980. This discussion of groundwater use in Limestone County was taken from Rettman (1984).

The earliest completion date given on the TWDB website for Limestone County is 1885 for wells in the Wilcox Group. The earliest water-level measurement for the Wilcox Group is from a single value measured in 1938. By this time, five wells had been completed to and pumping from the Wilcox Aquifer. As a result, the earliest water-level measurement may not be representative of predevelopment conditions.

Madison County, Texas

Information regarding historical development of the Carrizo Sand and Wilcox Group in Madison County could not be found during the literature search. Data on the TWDB website indicate that a few wells (five) are completed to the Carrizo Sand in this county but that there are no wells completed to the Wilcox Group. One well was completed in 1937, three were completed in the 1950s, and the fifth well was completed in 1986. The first water-level measurement was made in 1957 (TWDB, website). Three wells were completed to the Carrizo Sand at the time of this measurement, which is considered to be fairly representative of predevelopment conditions.

Marion County, Texas

Little information related to historical development of the Carrizo Sand and Wilcox Group in Marion County was found during the literature review. Broom (1971) states that the sands of the Wilcox Group, the Carrizo Sand, the Reklaw Formation, and the Queen City Sand are hydraulically connected and act as a single aquifer which he refers to as the Cypress aquifer. Deussen (1914) states that wells completed to the Lower Eocene Aquifer will flow only in low lying areas and in river bottoms. One well completed in the Cypress aquifer was found to flow in 1968 (Broom, 1971).

The earliest completion date given on the TWDB website for a well in the Cypress aquifer in Marion County is 1914. A well completed in 1887 is listed in Deussen (1914). The first water-level measurements were taken in 1942. By that time, ten wells in Marion County were completed to the Cypress Aquifer. As a results, the earliest water-level measurement for this county is not considered to be representative of predevelopment conditions.

Miller County, Arkansas

Little information related to the historical development of the Carrizo Sand and the Wilcox Group in Miller County was found during the literature review. Unless stated otherwise, the following discussion comes from Ludwig (1972). The Carrizo Sand and the sands of the Wilcox Group are considered to be separate aquifers in this county. Moderate yields of groundwater are obtained from the Carrizo aquifer is this county. The Wilcox aquifer yields only small quantities of water in only the northern portion of Miller County. The Wilcox is a minor aquifer in this county because of its "...lenticularity and fine-grained texture of the water-bearing sand beds." The Wilcox aquifer is not used by municipalities in this county. The Wilcox aquifer supplies water for small-capacity domestic and stock wells. Few wells tapping the Carrizo aquifer are found in Miller County. The only municipality using groundwater from the Carrizo aquifer is the city of Fouke. In general, "...development of the [Carrizo] aquifer for water supplies is negligible."

The first wells completed to the Wilcox aquifer in Miller County were drilled in 1899 (USGS, website[3]). The earliest water-level measurement was also made in 1899 (USGS, website). This first measurement is considered to be representative of predevelopment conditions.

Montgomery County, Texas

The Carrizo Sand and Wilcox Group are not sources of fresh to slightly saline water in Montgomery County (Popkin, 1971).

Morris County, Texas

Little information related to historical development of the Carrizo Sand and Wilcox Group in Morris County was found during the literature review. Broom et al. (1965) state that the sands of the Wilcox Group, the Carrizo Sand, the Reklaw Formation, and the Queen City Sand are hydraulically connected and act as a single aquifer which they refer to as the Cypress aquifer. Two wells completed to the Cypress aquifer in Morris County were found to flow in 1963 (Broom et al., 1965). No general decline in water levels for shallow wells (less than 60 ft deep) has been observed (Broom et al., 1965). Broom et al. (1965) state, "Water levels in the heavily-pumped deeper wells show average declines of 3.5 to 15.7 feet per year for various periods of record."

The earliest completion date given on the TWDB website for a well in the Cypress aquifer in Morris County is 1916. By the time the first water-level measurements were taken in 1935, 15 wells were completed to the Cypress Aquifer in this county. Consequently, the earliest

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[3] http://water.usgs.gov/ar/nwis

water-level data available for Morris County is not considered to be representative of predevelopment conditions.

Nacogdoches County, Texas

Little information related to historical development of the Carrizo Sand and Wilcox Group in Nacogdoches County was found during the literature review. Unless stated otherwise, the following discussion of development of the Carrizo Sand and Wilcox Group in Nacogdoches County comes from William F. Guyton & Associates (1970). The Carrizo Sand and the sands of the Wilcox Group are considered to be separate aquifers in this county, with the Carrizo aquifer being the most productive. Of the total amount of water removed from the Carrizo Sand and the sands of the Wilcox group in the county, only a small percentage is obtained from the Wilcox (about 5 percent in 1968). Flowing wells were observed in southern Nacogdoches County and northern Angelina County in the 1940s, but by 1961 most of those wells had stopped flowing (Baker et al., 1963). The Carrizo aquifer has been developed extensively in the county by the city of Nacogdoches and by the Southland Paper Mills located south of Nacogdoches near the border between Angelina and Nacogdoches Counties. Scalapino (1963) states that the areas of largest development of water from the Carrizo Sand are the Lufkin area, which includes water used by the cities of Lufkin and Nacogdoches and by the Southland Paper Mills, and the Winter Garden Area located in the southern Carrizo-Wilcox GAM. Extensive pumpage from the Carrizo since 1939 has resulted in drawdowns of up to 500 ft at pumping centers. Decline in Carrizo water levels in the outcrop has been much less (approximately 20 to 25 ft). Deussen (1914) states that the Lower Eocene aquifer yields flowing wells over much of Nacogdoches County.

The earliest completion dates given in the TWDB database for Nacogdoches County are 1890 for wells completed in the Carrizo Sand and 1886 for wells completed in the Wilcox Group. The earliest water-level measurements are from 1936 for both units. Since neither aquifer was extensively developed until the late 1930's, these early water-level measurements may be representative of predevelopment conditions.

Natchitoches Parish, Louisiana

Little information related to the historical development of the Carrizo Sand and the Wilcox Group in Natchitoches Parish was found during the literature review. Unless stated otherwise, the following discussion comes from Newcome et al. (1963). The Carrizo Sand and the sands of the Wilcox Group are considered to be separate aquifers in this parish. Relative to the Wilcox aquifer, the Carrizo aquifer is the principal source of groundwater in this parish. The majority of wells completed to the Wilcox aquifer are used for domestic and farm purposes. In general, yield from the Wilcox aquifer is low (less than 25 to 200 gpm). Some of the early wells completed to the Carrizo flowed to surface in the flood plain of the Red River. The Carrizo aquifer is the main source of water for the city of Natchitoches since 1944. With the exception of the municipal use by the city of Natchitoches, groundwater from the Carrizo aquifer is primarily used for domestic and farm purposes in this parish. Since the city of Natchitoches is the largest user of groundwater from the Wilcox and Carrizo aquifers, declines in water levels have been greatest near the city. The decline has been approximately 35 ft in the Carrizo aquifer and 65 ft in the Wilcox aquifer.

The first wells completed to the Carrizo aquifer in Natchitoches Parish were drilled in 1940 (LaDOT, website). The earliest available water levels are also from 1940 (LaDOT, website). Since the first water-level measurements were close to the time of well completion, those early measurements are considered to be representative of predevelopment conditions.

The first well completed to the Wilcox aquifer in Natchitoches Parish was drilled in 1906 (LaDOT, website). Two additional wells were drilled in 1915 and 1920. The earliest available water levels are one measurement in 1920 and one measurement in 1921 (LaDOT, website). Since few wells had been completed to and pumping from the Wilcox aquifer at the time of the earliest water level measurements, those measurements are considered to be representative of predevelopment conditions.

Newton County, Texas

The Carrizo Sand and Wilcox Group are not sources of fresh to slightly saline water in Newton County (Wesselman, 1967).

Panola County, Texas

Information regarding historical development of the Wilcox Group in Panola County could not be found during the literature search. The Wilcox Group outcrops across this entire county. The Carrizo Sand is not found in Panola County. The earliest completion date given on the TWDB website is 1924 for wells completed in the sands of the Wilcox Group. The earliest water-level measurements were made in 1936 (one measurement) and 1942 (one measurement). Because about six wells were completed to the Wilcox Group at the time of the first water-level measurement, this early water level is not considered to be representative of predevelopment conditions.

Polk County, Texas

The Carrizo Sand and Wilcox Group are not sources of fresh to slightly saline water in Polk County (Tarver, 1968a).

Rains County, Texas

Little information related to historical development of the Carrizo Sand and Wilcox Group in Rains County was found during the literature review. Unless stated otherwise, the following discussion of development of the Carrizo Sand and Wilcox Group in Rains County comes from William F. Guyton & Associates (1970). The Carrizo Sand and the sands of the Wilcox Group are considered hydraulically connected and a single aquifer in this county, with the Wilcox being the principal water source. Groundwaters of the Carrizo-Wilcox aquifer are pumped for both municipal and industrial purposes. Historically, very little groundwater has been used for irrigation in this county. Domestic and stock wells completed in the Carrizo-Wilcox are found through out the county.

Wells were completed to the Carrizo-Wilcox aquifer in Rains County as early as 1870. Approximately six Carrizo-Wilcox wells were in use by 1900. The drilling of wells essentially stopped in the early 1900s according to William F. Guyton & Associates (1970) and the data on the TWDB website. The first well recorded as completed to the Carrizo-Wilcox in the 1900s was drilled in 1934. The earliest available water levels are one 1948 measurement given in William F. Guyton & Associates (1970) and another measurement in 1958 given on the TWDB website. According to the data on the TWDB website, only four wells were completed to the

Carrizo-Wilcox aquifer at the time the first water-level measurement was recorded. Therefore, these earliest measurements might be representative of predevelopment conditions.

Rusk County, Texas

Little information related to historical development of the Carrizo Sand and Wilcox Group in Rusk County was found during the literature review. Unless stated otherwise, the following discussion of development of the Carrizo Sand and Wilcox Group in Rusk County comes from Sandeen(1987). The Carrizo Sand and the sands of the Wilcox Group are considered to be separate aquifers in this county, with the Wilcox aquifer being the most significant hydrologic unit. Little development of the waters in the Carrizo and Wilcox aquifers occurred in this county until the discovery of the East Texas oil field in 1930. Numerous processes related to the oil industry created an immediate demand for water. The water needs were met by wells completed to the Carrizo and Wilcox aquifers. Most water for municipal use was obtained from surface bodies. In 1947, groundwater was used for industrial, public supply, and oilfield purposes.

Almost all of the groundwater used in Rusk County in 1980 was withdrawn from the Wilcox aquifer. In 1960 and 1970, the major users of groundwater were industries and municipalities. By 1980, the use of groundwater by industries had significantly reduced but the use by municipalities had significantly increased. In addition, the use of groundwater for mining purposes began around 1980. The largest municipal user is the city of Henderson. Total withdrawal of groundwater increased 14 percent from 1960 to 1970 and 53 percent from 1970 to 1980. The greatest long-term declines in water levels have been observed near the area of the East Texas Oil Field and near the city of Henderson. One of the wells near Henderson shows a 135-ft decline in water level from 1935 to 1981. Another well shows a 43-ft increase in water level from 1947 to 1979.

The earliest date given on the TWDB website for a well completed to the Carrizo Sand in Rusk County is 1860. The earliest water-level measurements are from 1931 (1 measurement) and 1936 (over 30 measurements). By the time of the first measurement in 1931, about 21 wells were completed to the Carrizo Sand. As a result, the earliest measurement most likely reflects the effects of pumping and is not considered representative of predevelopment conditions.

The earliest date given on the TWDB website for wells completed to the Wilcox Group in Cherokee County is 1866. The earliest water-level measurement was taken in 1931. By the time of this first measurement, about 15 wells were completed to the Wilcox Group. Because it is likely that all of the available water-level data for the Wilcox Group, including the earliest measurements, reflect the effects of pumpage, none of the water-level measurements were considered to be representative of predevelopment conditions.

Sabine County, Texas

Little information related to historical development of the Carrizo Sand and Wilcox Group in Sabine County was found during the literature review. Unless stated otherwise, the following discussion of development of the Carrizo Sand and Wilcox Group in Sabine County comes from Anders(1967). The Carrizo Sand and the sands of the Wilcox Group are considered to be one hydrologic unit in this county, with the Wilcox Group being the most important especially in the southern part of the county. Groundwater is used primarily by municipalities and for rural, domestic, and livestock purposes. Very little groundwater is used for industrial or irrigation purposes. Some groundwater is lost to uncontrolled flowing wells.

The earliest date given on the TWDB website for a well completed to the Carrizo-Wilcox Aquifer in Sabine County is 1870. The earliest water-level measurements are from 1942 (1 measurement) and 1957(1 measurement). By the time of the first measurement in 1942, about six wells were completed to the Carrizo Sand and, by the second measurement, seven additional wells had been drilled. As a result, the earliest measurement most likely reflects the effects of pumping and is not considered representative of predevelopment conditions.

Sabine Parish, Louisiana

Little information related to the historical development of the Carrizo Sand and the Wilcox Group in Sabine Parish was found during the literature review. Unless stated otherwise, the following discussion comes from Page et al. (1963). The Carrizo Sand and the sands of the Wilcox Group are considered to be separate aquifers in this parish. The Carrizo Sand is not a significant aquifer in Sabine Parish because it has "...been faulted out in much of its normal outcrop area...". In addition, it is difficult to distinguish the sands of the Carrizo with sands of the underlying Wilcox Group. The Wilcox aquifer is "... the most extensively tapped source of groundwater in Sabine Parish." The largest users of groundwater from the Wilcox aquifer are the towns of Many and Pleasant Hill. Between 1931 and 1959, water levels in the Many well field have declined about 69 ft. The majority of the wells tapping the Wilcox aquifer are used for domestic and small farm purposes.

The first wells completed to the Wilcox aquifer in Sabine Parish were drilled in 1900 (LaDOT, website). The earliest water-level measurement was made in 1931 (LaDOT, website). By the time of the first water-level measurement, over 30 wells were completed to the Wilcox aquifer. Since many wells had been completed to and pumping from the Wilcox aquifer at the time of the earliest water-level measurement, that measurement is not considered to be representative of predevelopment conditions.

San Augustine County, Texas

Little information related to historical development of the Carrizo Sand and Wilcox Group in San Augustine County was found during the literature review. Unless stated otherwise, the following discussion of development of the Carrizo Sand and Wilcox Group in San Augustine County comes from Anders(1967). The Carrizo Sand and the sands of the Wilcox Group are considered to be one hydrologic unit in this county, with the Wilcox Group being the most important especially in the southern part of the county. Groundwater is used primarily by municipalities and for rural, domestic, and livestock purposes. Very little groundwater is used for industrial or irrigation purposes. Some groundwater is lost to uncontrolled flowing wells.

The earliest date given on the TWDB website for a well completed to the Carrizo-Wilcox Aquifer in Sabine County is 1890. The earliest water-level measurements are from 1907 (1 measurement) and 1942 (1 measurement). By the time of the first measurement in 1942, about three wells were completed to the Carrizo Sand and, by the second measurement, 12 additional wells had been drilled. Since only a few wells had been pumping from the aquifer prior to the first water-level measurement, that measurement is considered to be representative of predevelopment conditions.

San Jacinto County, Texas

The Carrizo Sand and Wilcox Group are not sources of fresh to slightly saline water in San Jacinto County (Sandeen, 1968)

Shelby County, Texas

Information regarding historical development of the Wilcox Group in Shelby County could not be found during the literature search. The Wilcox Group outcrops across this entire county. The Carrizo Sand is not found in Shelby County. The earliest completion date given on the TWDB website is 1907 for wells completed in the sands of the Wilcox Group. The earliest water-level measurement was made in 1966. Because over 15 wells were completed to the Wilcox Group at the time of the first water-level measurement, this early water level is not considered to be representative of predevelopment conditions.

Smith County, Texas

Little information related to historical development of the Carrizo Sand and Wilcox Group in Smith County was found during the literature review. Unless stated otherwise, the following discussion of development of the Carrizo Sand and Wilcox Group in Smith County comes from Dillard (1963). The Carrizo Sand and the sands of the Wilcox Group are considered hydraulically connected and a single aquifer in this county. Groundwater from the Carrizo-Wilcox aquifer in this county is used for municipal, industrial, domestic, and agricultural purposes. In 1961, the municipalities were the largest users of groundwater, followed by industries and domestic supplies. Pumping of Carrizo-Wilcox waters for agricultural purposes in 1961 was negligible. Preston and Moore (1991) indicate that water levels in the Tyler area have decreased up to 500 ft since before World War II. Several wells in Smith County were observed to flow during the field work conducted for the county report. Deussen (1914) states that pressures in the lower Eocene sand were sufficient to drive water to the ground surface only in in the valleys are river bottoms.

The first wells completed to the Carrizo-Wilcox aquifer in Smith County were drilled in 1930 (TWDB, website). The earliest available water levels are two measurements in 1940 and two measurements in 1952 (TWDB, website). According to the data on the TWDB website, about six wells were completed to the Carrizo-Wilcox aquifer at the time of the first water-level measurement. The earliest measurements are considered to be somewhat representative of predevelopment conditions.

Titus County, Texas

Little information related to historical development of the Carrizo Sand and Wilcox Group in Titus County was found during the literature review. Broom et al. (1965) state that the sands of the Wilcox Group, the Carrizo Sand, the Reklaw Formation, and the Queen City Sand are hydraulically connected and act as a single aquifer which they refer to as the Cypress aquifer. Three wells completed to the Cypress aquifer in Titus County were found to flow from 1 to 5 gpm in 1963 (Broom et al., 1965). No general decline in water levels for shallow wells (less than 60 ft deep) has been observed (Broom et al., 1965). Broom et al. (1965) state, "Water levels in the heavily-pumped deeper wells show average declines of 3.5 to 15.7 feet per year for various periods of record."

The earliest completion date given on the TWDB website for a well in the Cypress aquifer in Titus County is 1860. Several additional wells were completed in the early 1900s. The first water-level measurements were taken in 1942. Since numerous wells were pumping from the Carrizo-Wilcox aquifer prior to the time that the first water-level measurement was taken, that first measurement is most likely not representative of predevelopment conditions.

Trinity County, Texas

Information on the Carrizo Sand and sands of the Wilcox Group could not be found during the literature search. The TWDB website does not contain any water-level data for either the Carrizo Sand or the Wilcox Group. Based on this information, it is assumed that the Carrizo Sand and the sands of the Wilcox Group are not used to supply groundwater in Trinity County.

Tyler County, Texas

The Carrizo Sand and Wilcox Group are not sources of fresh to slightly saline water in Tyler County (Tarver, 1968b).

Upshur County, Texas

Little information related to historical development of the Carrizo Sand and Wilcox Group in Upshur County was found during the literature review. Unless stated otherwise, the following discussion of development of the Carrizo Sand and Wilcox Group in Upshur County comes from Broom (1969). The Carrizo Sand and the sands of the Wilcox Group are considered hydraulically connected and a single aquifer in this county, with the Carrizo Sand being the principal water source. Little development of the waters in the Carrizo-Wilcox aquifer occurred in this county until the discovery of the East Texas oil field in 1930-1931. Numerous processes related to the oil industry and the increased population in the area of the oil field created an immediate demand for water. The water needs were met by completing wells to the Carrizo-Wilcox aquifer. By the mid-1950s, the dominate municipality in the area began deriving its water from a surface-water sources.

The data on the TWDB website and in the county report (Broom, 1969) indicate that the first two wells drilled to the Carrizo-Wilcox aquifer were completed in 1924 and 1937. By 1950, six additional wells had been drilled to the Carrizo-Wilcox aquifer. The earliest water-level data available in Upshur County consists of one 1937 measurement, two 1940 measurements, and one 1941 measurement. The earliest water-level measurement for this county is probably fairly representative of predevelopment conditions.

Van Zandt County, Texas

Little information related to historical development of the Carrizo Sand and Wilcox Group in Van Zandt County was found during the literature review. Unless stated otherwise, the following discussion of development of the Carrizo Sand and Wilcox Group in Van Zandt County comes from William F. Guyton & Associates (1970). The Carrizo Sand and the sands of the Wilcox Group are considered hydraulically connected and a single aquifer in this county, with the Wilcox being the principal water source. Groundwaters of the Carrizo-Wilcox aquifer are pumped for both municipal and industrial purposes. The highest concentration of municipal and industrial pumpage has historically occurred in the Grand Saline area. Between 1936 and 1969, water levels in this area have declined as much as 105 ft. Historically, very little groundwater has been used for irrigation in this county. Domestic and stock wells completed in the Carrizo-Wilcox are found through out the county.

Approximately 34 wells were completed to the Carrizo-Wilcox aquifer between 1870 and 1920 (William F. Guyton & Associates, 1970). Neither the county report (William F. Guyton & Associates, 1970) nor the TWDB website indicate drilling to the Carrizo-Wilcox aquifer during the 1920s. Wells began to be completed again to the Carrizo-Wilcox aquifer in 1930. The first three recorded water levels for wells completed to the Carrizo-Wilcox aquifer were measured in

1936, 1949, and 1953 according to both the county report (William F. Guyton & Associates, 1970) and the TWDB website. Consequently, numerous wells had been in operation prior to the time that the first water levels were measured. Therefore, the earliest water-level data for this county is most likely not representative of predevelopment conditions.

Walker County, Texas

According to Winslow (1950) the Carrizo Sand and the sands of the Wilcox Group are not sources of freshwater in Walker County.

Wood County, Texas

Little information related to historical development of the Carrizo Sand and Wilcox Group in Wood County was found during the literature review. Unless stated otherwise, the following discussion of development of the Carrizo Sand and Wilcox Group in Wood County comes from Broom (1968). The Carrizo Sand and the sands of the Wilcox Group are considered to function as a single aquifer in this county due to their similar properties and hydraulic connection. Deussen (1914) states that wells completed into the Lower Eocene Aquifer will flow only in the Sabine River bottoms. Broom (1968) lists 14 wells completed in either the Carrizo Sand, Wilcox Group, or both, that flowed in 1963 or 1965.

The earliest date given on the TWDB website for a well completed in the Carrizo-Wilcox aquifer in Wood County is 1880. Several additional wells were completed in the early 1900s. A significant increase in groundwater pumpage for municipal purposes occurred between 1955 and 1965. Evaluations of water level declines in some shallow wells in the county indicate no significant changes in water levels between 1942 and 1965. Declines of 0.7 to 31.2 feet per year were observed in several municipal and industrial wells between 1960 and 1965. The first water-level measurements were taken in this county in 1942. Since numerous wells were pumping from the Carrizo-Wilcox aquifer prior to the time that the first water-level measurement was taken, that first measurement is most likely not representative of predevelopment conditions.

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APPENDIX B

Standard Operating Procedures (SOPs) for Processing Historical Pumpage Data TWDB Groundwater Availability Modeling (GAM) Projects

Standard Operating Procedures (SOPs)
for Processing Historical Pumpage Data
TWDB Groundwater Availability Modeling (GAM) Projects

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1. Groundwater use source data - Groundwater use data is derived from three tables provided by the Texas Water Development Board (TWDB) in a MS Access 97 database and one spreadsheet provided in MS Excel format:

   1.1. **PumpagebyMajorAquifer1980-1997** – This table contains water use summaries, in acre-feet/year) from each major aquifer, county, and basin for the years 1980 and 1984-1997 for the water use categories:

   - IRR – irrigation
   - STK – livestock
   - MIN - mineral extraction
   - MFG – manufacturing
   - PWR – power generation
   - MUN – municipal water supply, and
   - C-O – county-other (rural domestic) use.

   1.2. **RawDataMUN_WaterUseSurvey** – This table contains reported annual and monthly self-generated groundwater use totals, in gallons, from each municipal water user for the years 1980-1999. Monthly totals are missing in many cases. The data originate from the annual water use surveys. The county, basin, and major aquifer of origin are reported, as well as the water user group ID, alphanumeric code of the water user, and line 1 of the address of the water user. The number of wells from which the water was pumped is reported in most cases.

   1.3. **RawDataMFG_WaterUseSurvey** – This table contains reported annual and monthly self-generated groundwater use totals, in gallons, from each manufacturing, power generation, or mining water user for the years 1980-1999. Monthly totals are missing in many cases. The data originate from the annual water use surveys. The county, basin, and major aquifer of origin are reported, as well as the water user group ID, alphanumeric code of the water user, and line 1 of the address of the water user. The number of wells from which the water was pumped is reported in most cases.

   1.4. **RuralDomestic_Master_Post1980_021502.xls** – This Excel spreadsheet contains summaries of annual rural domestic water use, by county-basin, from 1980 to 1997.

2. Initial Processing

   2.1. Completion of Monthly Pumpage Estimates for MUN, MFG, PWR, and MIN Uses - In the tables **RawDataMUN_WaterUseSurvey** and **RawDataMFG_WaterUseSurvey**, monthly pumpage estimates are reported for the majority, but not all, of the water users. For other users, only the annual total pumpage is reported. It is necessary to estimate the monthly pumpage totals for some water users via the following procedure.

2.1.1. First, export the tables **RawDataMFG_WaterUseSurvey** and **RawDataMUN_WaterUseSurvey** to Microsoft Excel. Append the records from the latter file to the former. Delete records with reported annual total water use (in gallons) of "0".

2.1.2. In Excel, calculate the monthly fractions of annual total water use for each record for which monthly pumpage was reported. As an example, a monthly distribution factor of 1/12, or 0.0833, would result from a uniform annual distribution.

2.1.3. Calculate the average monthly distribution factor for each county-basin and water use category. Statistically review these average monthly fractions for outliers. Generally, monthly distribution factors fall within the range 0.035 to 0.15.

2.1.4. Next, for those water use records that contain an annual total water use but no monthly value, calculate estimated monthly water use values by multiplying annual total pumpage by the average monthly distribution factor for the same water use category (MUN, MFG, PWR, MIN) in the county-basin within which it was located. If the monthly distribution factor for its county basin and water use category was an outlier, usually due to the fact that only one or two water users were located in the county-basin, use the monthly distribution factor from the nearest adjacent county-basin. (Note: For Louisiana and Arkansas parishes/counties, for which no monthly values are available, use the values from the nearest Texas counties.)

2.1.5. Add an additional field, "Monthly Calculated" to the spreadsheet, with "N" entered in those records containing original, reported monthly pumpage values, and "Y" for those records with calculated monthly pumpage values.

2.1.6. Finally, re-import the Excel spreadsheet into the Access database as a table **MUN+MFG_WaterUseSurvey**.

2.2. Predicting historical pumpage for 1981-83 and 1997-1999 - In the table **PumpagebyMajorAquifer1980-1997**, groundwater use summaries were reported for the years 1980 and 1984-1997 for the categories MIN, MFG, PWR, STK, IRR, and MUN (actually MUN + C-O) for each major aquifer and county-basin. Water use summaries for the years 1981-1983 and 1998-1999 were not reported. In the spreadsheet **RuralDomestic_Master_Post1980_021502.xls**, water use is not reported for 1998 and 1999. The groundwater use for these years must be obtained by interpolation from existing data.

2.2.1. First, import the tables **PumpagebyMajorAquifer1980-1997** and **RuralDomestic_Master_Post1980_021502.xls** into SAS datasets.

2.2.2. Import into a SAS dataset the weather parameters "average annual temperature" and "total annual precipitation" for 1980-1999 from National Weather Service cooperative weather stations. Delete those stations that have valid measurements in less than 16 of the 20 years. Also, delete data from any stations that do not have valid measurements for at least 4 of the 5 years 1981, 1982, 1983, 1998, and 1999.

2.2.3. In Arcview, identify the weather station (with valid data for at least 16 of the 20 years) closest to each county-basin. Create a look-up table in SAS to link each county-basin with the closest weather station.

2.2.4. In SAS, apply linear regression in Proc REG with stepwise selection, to regress annual pumpage (dependent variable) vs. 1) year, 2) average annual temperature and 3) total annual precipitation from the nearest weather station, for each county-basin, major aquifer, and water use category, for the years 1980 and 1984-97. Select the best valid regression equation based on the statistic Mallow's Cp, which balances the improvement in regression fit as independent variables are added to the regression with the increasing uncertainty in the resulting dependent variable estimates. Transformations (e.g., natural logarithms) of the independent variables may yield a better regression equation. There should be a regression equation for each county-basin, and water use category.

2.2.5. Using the regression equations and weather data for the years 1981, 1982, 1983, 1998, and 1999, in SAS, calculate predicted pumping for these years each county-basin and water use category. If predicted values are less than zero, a value of zero is entered. Append the predicted water use for these five years to the reported water use for 1980 and 1984-1997. Export this table, then import it into the Access database as **PumpagebyMajorAquifer1980-1999.**

2.2.6. In general, this regression procedure is appropriate for pumpage changes that might be expected based on gradual annual changes (e.g., population) or year-to-year weather variability. It may not make good predictions when pumpage changes rapidly for non-weather-related factors. Review and inspect the regression-based pumpage estimates for 1981-83 and 1998-99 versus the TWBD-provided pumpage estimates for 1984-1997. Carefully inspect all between-year pumpage differences of more than 20%. Subjectively, if the predicted pumpage estimates do not make sense, replace the regression-based estimate with the TWDB pumpage estimate for the previous year.

2.2.7. Add a new column "Annual Source" to the table, and enter in it "Reported" for those years for which annual water use was reported, and "Regression" or "Previous Year" for those years for which pumpage sums were predicted from regression or previous years.

2.3. (OPTIONAL) Selecting Pumpage within the model domain – The tables contain pumpage estimates for the entire state, or the entire aquifer of interest. Ultimately, pumpage originating within the model domain will be made during attribution of data to model grid cells. To speed the analysis, it may be beneficial to create a subset of data for pumpage that will encompass the model domain, with a buffer. **WARNING:** Pumpage sometimes originates (e.g., wells exist) in a different geographic area from where water is used and reported. Be careful that this procedure does not exclude any reported pumpage!

2.3.1. Once the model domain has been identified by the modelers, it is overlain on the county GIS layer in Arcview, and all counties containing, or very near to, any part of the model domain are selected.

2.3.2. Next, in MS Access, a new field "Domain?" is added to the table **Reference_Countyname_number_FIPS**. A value of "Y" is entered in this field for records of counties within the model domain.

2.3.3. Using this table, in a select query with other tables or queries joined by county name, number, or FIPS (federal information processing system) code, one can specify "Domain='Y' as a condition to limit queries to those counties within the model domain.

2.4. Preparing a County-basin Arcview Shapefile and Associating Model Grid Cells with a County-Basin – Much of the reported pumpage is spatially divided into county-basin units, which consist of the area in the same county and river basin. Many counties are split between two or more river basins, thus, county-basins are smaller than counties.

2.4.1. To create a county-basin Arcview shapefile, in Arcview, load GIS shapefiles of counties and river basins in GAM projection. Intersect these two layers using the Geoprocessing Wizard to create a new shapefile **countybasins.shp**.

2.4.2. Associate each model grid cell with the county-basin it falls primarily within. This will be useful when we need to determine monthly distribution factors and water user group IDs (WUG IDs) for non-well-specific pumpage categories (IRR, STK, C-O). These monthly distribution factors are estimated as averages within a county-basin. **Note**: The primary county-basin is not used to spatially distribute pumpage among grid cells because it is inexact. A grid cell may be part of multiple county-basins. For spatial distribution purposes, this grid cell should be split by county-basin – then later aggregated.

2.4.2.1. Load the model grid shapefile in GAM projection. Union this shapefile with countybasins.shp using the Geoprocessing Wizard. Add a numeric field "fr_grdarea" to the attribute table, and use the field calculator function to enter its values (fr_grdarea = shape.returnarea/27878400). Here, 27878400 is the area, in square feet, of each grid cell. Export the table as a dbf file.

2.4.2.2. Import the dbf file into MS Access as a new table - **Table1**. Our goal is to identify, for each grid cell, the county-basin with which it is primarily associated.

2.4.2.3. Select by query the records with no value for the field "CountyBasin." Delete these records, as they are grid cells over Mexico or the ocean.

2.4.2.4. Run a make table query, sorting the table1 records by grid_id (ascending) and fr_grd_area (descending) to create a new table, **Table2**.

2.4.2.5. Copy **Table2**, and paste only the table structure as a new table –

Grid_countybasin.

2.4.2.6. In design view, make the field "grid_id" a primary key in the table **Grid_countybasin.**

2.4.2.7. Run an append query, to append all fields of the records from table 2 to **Grid_countybasin**. When the warning window comes up, say yes to proceed with the query. This appends only the first record for each grid_id to **Grid_countybasin**, leaving one record for each grid cell with the county basin with the largest value of "fr_grdarea". The resulting table should have one record for each grid cell in the model grid, and the county-basin name for that model grid cell.

3. Matching Pumpage to Specific Wells

Historical groundwater use from the categories MUN, MIN, MFG, and PWR is to be matched with specific wells from which it was pumped. Reported groundwater use for these uses, from the annual water use surveys, is contained in the table **MUN+MFG_WaterUseSurvey**. For MUN, MFG, MIN, and PWR, water use is reported for each year from 1980 to 1999. These tables report total annual use and, in most cases, monthly use, for each water user. The water user is identified by a unique alphanumeric code "alphanum." The tables also list the county and river basin, as well as their water user group ID, their regional water planning group, their water use category, the major aquifer from which the groundwater was pumped, and the number of wells from which the water was pumped. These tables do not indicate the specific location off the wells, well elevation, well depth, a specific aquifer name, or other information needed for groundwater modeling. This information must be retrieved from other sources. The primary source of well information is the state well database maintained by the TWDB. Secondary sources include well data found in the TNRCC public water supply database, and the USGS site inventory. A final source is the follow-up survey provided by the TWDB in October 2001.

3.1. Create **All_wells** table –

3.1.1. Download the state well database as a table **weldta.txt** for the entire state (under the menu "all counties combined") from the TWDB web site http://www.twdb.state.tx.us/publications/reports/GroundWaterReports/GWDatabaseReports/GWdatabaserpt.htm. Import this table into MS Access as a new table **All_Wells.**

3.1.2. The TNRCC public water supply database includes data for some wells that are not found in the TWDB state well database. Retrieve this database from the TNRCC. Create a query to link the required well data, and append the well data to **All_wells**, exercising care to match fields appropriately.

3.1.3. The USGS site inventory http://waterdata.usgs.gov/tx/nwis/inventory contains data for wells that may not be found from other sources. Run a query for the state of Texas with site type = 'ground water' to download the well data and append it to **All_wells**. Be careful to match fields appropriately.

3.1.4. Delete any oil, gas, geothermal, or observation wells, anodes, drains, or springs after a query of the attribute table on the fields "GW_type_cd" or "Site_use1_cd".

3.2. Linking water use data to the state well database – Using a make-table query to create a new table **MUN+MFG_linkedwithwellinfo**, all fields from the water use survey are merged with all fields from the state well database by joining the field "alphanum," in the table **MUN+MFG_WaterUseSurvey,** to the field "user code econ," in the state well database table **All_wells**. In many cases, several different wells may have the same "user code econ," making a one-to-many match (this is expected, since one city may own multiple wells). Add a field "Location Source" to the table **MUN+MFG_linkedwithwellinfo**. For the pumpage records with one or more matched well, enter the text "state well database" in this field.

3.3. Locating unmatched pumpage 1 – Identify the pumpage records without a matching well using a **Find Unmatched** query. Check the field "alphanum" in unmatched pumpage records of the table **MUN+MFG_WaterUseSurvey,** and "user_code_econ" in the table **All_Wells** for obvious errors that prevent automatic matching, and correct any found and repeat the steps to make the table above. Next, manually search the **All Wells** table for wells in the same county and basin, for which the user name field "owner_1" matches the field "line1" in **MUN+MFG_WaterUseSurvey**. When a match is found, add a field to the well table, and copy the "alphanum" field from the water use survey, to facilitate match-merging. Next, match this new field in the well database to "alphanum" of the water use survey, and append these matched records to the table **MUN+MFG_linkedwithwellinfo**. Enter "state well database manual match" for the field "Location Source" for these new appended records.

3.4. Locating unmatched pumpage 2 – For those pumpage records not matched via the above procedures, open the TNRCC public water supply database and attempt to manually match the water user to specific wells based on the county, aquifer_id, and owner name - "A1Name." When a match is found, add a field to the well table, copy the "alphanum" field from the water use survey, perform a match-merging query, and update these new matched records to the table **MUN+MFG_linkedwithwellinfo**. Enter "TNRCC PWS database" for the field "Location Source" for these new appended records.

3.5. Locating unmatched pumpage 3 - For those pumpage records, if any, still not matched in the above procedures, manually search the TWDB follow-up survey data. When a match is found, this data must be manually copied to the table **MUN+MFG_linkedwithwellinfo** because the table format is substantially different. Enter "TWDB followup survey" for the field "Location Source" for these new appended records.

3.6. Locating unmatched pumpage 4 - For those pumpage records, if any, still not matched in the above procedures, it may be possible to identify an approximate well location via the EPA's Envirofacts facility database. In an internet browser, go to http://www.epa.gov/enviro/html/fii/fii_query_java.html and perform a facility information query using a characteristic part of the facility name in the query field "facility site name." If a single facility of matching name is located in the same county, copy the facility latitude and longitude, in degrees, minutes, seconds into the appropriate fields of the table **MUN+MFG_linkedwithwellinfo**. Enter "facility centroid" in the field "Location Source" if Envirofacts lists that as the source of the latitude and longitude, or "facility zip code centroid" if Envirofacts lists that as the source of the latitude and longitude. Note that the median size of a zip code in Texas is approximately 5.5 square miles. Thus, pumpage located based on a zip code centroid may be very uncertain, especially in rural areas, and should be used with caution. However, it was felt that having an approximate location was better than leaving them out of the model. Note: Because this step is labor-intensive, it may be acceptable to perform this procedure for only the "major" water users, as indicated by volume used.

3.7. Count wells matched - Count the number of wells matched to <u>each</u> pumpage record via a crosstab query on **MUN+MFG_linkedwithwellinfo**.

3.8. Apportion water use between matched wells –

3.8.1. For that water use matched to more than one well, compare the number of matched wells to the number of wells reported as used in the water use survey. If the number of matched wells exceeds the number reportedly used, inspect the well data, including the county, basin, aquifer_id, well_type, drill_date, and other fields to see if some of the wells can be excluded from consideration as the source form which the water was reportedly pumped. If so, remove that well from the table.

3.8.2. Next, we need to apportion the reported pumpage among the wells matched. Since we don't have data indicating otherwise, pumpage will be divided equally between wells. Create a new query that 1) adds a column "Num Wells Matched" indicating the number of wells matched (based on the aforementioned crosstab query) to the table **MUN+MFG_linkedwithwellinfo**, and 2) if one or more wells are matched, divides the reported pumpage in the fields "annual total in gallons" and "jan" – "dec" by the number of wells matched. Add another field "Corrected for Numwells" with a value of "Y" if the original pumpage sum for the water user was divided by two or more wells, and "N" otherwise.

3.8.3. Quality control check – In a query, summarize total annual water use by county-basin-year in the table **MUN+MFG_linkedwithwellinfo**. Make sure that these match the corresponding totals from the original table **MUN+MFG_WaterUseSurvey**. If not, correct the situation, which may occur by double-matching some water use records to wells.

3.9. Calculate Additional Fields - In a new make-table query, create the table **Well-specific_pumpage** based on **MUN+MFG_linkedwithwellinfo,** calculate latitude and longitude as decimal degrees from degrees-minutes-seconds in new fields "lat_dd" and "long_dd." Also in the same query, calculate water use in acre-feet from gallons in new fields "Annual total in acre-ft", "JAN in acre-ft", "FEB in acre-ft",....,"DEC in acre-ft."

3.10. Append Out-of-State Data - Append the well-specific Louisiana and Arkansas water use, in acre-ft, from LADEQ and USGS, to the table **Well-specific_pumpage**.

3.11. Summarize well-specific matching completeness – Perform queries to calculate the sum of matched water use by county-basin-year, and the total water use (matched and unmatched) by county-basin-year. Based on these queries, calculate the volumetric percent completeness of matching by county, basin, and year. Completeness should be high (e.g., >80%) to facilitate accurate accounting for water use in the model.

4. Spatial Allocation of Groundwater Pumpage to the Model Grid - The model grid is comprised of an equal-spaced grid with a size of one mile by one mile. The grid has 3 dimensions- row, column, and model layer. Each cell of the model grid is labeled with a 7-digit integer "grid_id". The first digit represents the model layer. Digits 2 through 4 represent the row number. Digits 5 through 7 represent the column. The model grid is represented in a MS Access table linked to an Arcview shapefile via the field "grid_id".

4.1. Spatial allocation of well-specific groundwater pumpage from the categories MUN, MFG, MIN, and PWR

4.1.1. Distribute pumpage into grid cells

4.1.1.1. In MS Access, verify that all records in the table **Well-specific_pumpage** have x,y coordinates in decimal degrees.

4.1.1.2. In Access, add a new autonumbered, long integer field "Unique ID" to the table **Well-specific_pumpage**.

4.1.1.3. In Arcview, enable the Database Access extension. Add a new table **PtSrcTbl** to an ArcView project via SQL connect, including only the fields "unique_id", "well_depth", "lat_dd", and "long_dd". To perform an SQL connect, select the "SQL connect" menu item under the Project menu. Then navigate to the correct database and select the table **Well-specific_pumpage**.

4.1.1.4. Add **PtSrcTbl** as an event theme named **Wellpts** to a view based on lat/long coordinates. To do this, from the view menu, select the "add event theme" menu item, and choose long_dd for x field and lat_dd for y field in the dialog. Re-project the view to GAM projection using the View->Properties dialog box according to GAM Technical Memo 01-01 (rev A), then save it as a shapefile **Wellpts.shp**. Load **Wellpts.shp** and the model grid, also as a shapefile in GAM projection, into a new view.

4.1.1.5. Spatially join the model Grid table to the **WellPts** table. To do this make the "shape" fields of each table active, and with the **WellPts** table active, choose "join" from the table menu. This will join the 1 mile grid cell records to all of the **WellPts** records that are contained with that grid cell.

4.1.1.6. Migrate the GridId to the **WellPts** table. Do this by first adding a new 7-digit, no decimal, field to the **WellPts** table called "Grid_Id". Then, with the new field active, using the field calculator button make the new field equal to the "GridId" field from the joined table.

4.1.1.7. Delete those pumpage records outside the model domain with a "Grid_ID" of "0".

4.1.1.8. Vertical Distribution: Follow procedures outlined in sections 4.5.

4.1.2. Import the Arcview attribute table **Wellpts.dbf** to the MS Access database. Change the data type for the fields "Unique ID" and "Grid_ID" back to long integer if they were converted to double length real numbers during the import operation.

4.1.3. Run an update query to update the empty values of "Grid ID" in the table **Well-specific_pumpage** with the "Grid_ID" values from the table **Wellpts**, using an inner join on the field "Unique ID."

4.1.4. The table **Well-specific_pumpage** now has only the grid_id of the upper model, i.e., the first digit is 1. The actual vertical distribution data is in the fields "per1" to "perx" where x is the number of vertical layers (L) in the model. Copy the table x-1 times in an append query, incrementing the first digit of the grid id, to create a record for each model layer. There now should be L times the original number of records in the table. For example, for the northwestmost grid cells of a model with four layers, the following grid id's should now exist: 1001001, 2001001, 3001001, and 4001001; whereas only 1001001 was in the original table.

4.1.5. Calculate for each year the actual pumpage for each record as the product of the pumpage for a given year multiplied by the percent of pumpage from that model layer (from the fields "per1" – "per4", for a model with 4 layers).

4.1.6. Create a new summary query **gridsum_well_specific** to summarize the pumpage for each grid_id and year from the table **Well-specific pumpage**.

4.2. Spatial allocation of irrigation groundwater pumpage – Irrigation pumpage is distributed between the USGS MRLC land use types 61 (orchard/vineyard), 82 (row crops), and 83 (small grains) within each county-basin based on area. The distribution is further weighted based on proximity to the irrigated farmlands mapped from the 1989 or 1994 irrigated farmlands survey. The weighting factor is the natural logarithm of distance in miles to an irrigated polygon. However, this weighting factor is manually constrained to be between 0.5 and 2, in order to limit the effect of weighting to a factor of 4. All grid cells further than roughly 7.4 miles from an irrigated polygon will have a weight of 0.5, while all grid cells nearer than 1.6 miles from an irrigated polygon will have a weight of 2.

4.2.1. Create shapefile for MRLC land use categories 61, 82, and 83.

4.2.1.1. In ArcView, load MRLC grid. Resample grid with a larger grid size to make the file more manageable (use x4 factor and set the analysis extent to the model domain). Select, in the new resampled grid, values 61, 82, and 83, and convert to shapefile. Call it "mrlc_irrigated.shp."

4.2.2. Create "distance grids" for the irrigated farmlands 89 and 94 shapefiles. These will be grid files that contain the distance from each grid cell to the nearest irrigated farmlands polygon.

4.2.2.1. Add "irr_farms89.shp" to a view, and make it active. With Spatial Analyst extension activated, select "find distance" from the analysis menu. Choose a grid cell size of 1 mile, and set the extent to the model domain. This will generate a grid of distance values to the nearest irrigated farm. Repeat for "irr_farms94.shp." Call them "dist_irr*yy*."

4.2.3. Using the Geoprocessing Wizard, intersect county-basin boundaries with "mrlc_irrigated.shp" to create "mrlc_cb.shp." Create a unique id "cb_irr_id" so that, if necessary, these unique polygons can be queried.

4.2.4. Intersect "mrlc_cb.shp" with the 1 mi. sq. grid cells.

4.2.4.1. Select only the 1 mile grid cells that are above the aquifer of concern's extents (The county-basin irrigation pumpage totals are aquifer specific, so the pumpage should only be distributed where the proper underlying aquifer is present).

4.2.4.2. It is also necessary to distribute across the entire county-basin area where the underlying aquifer is present, and not limited to the model domain in counties partly within the model domain. Therefore, if a county-basin is intersected by the model domain boundary, the pumpage total must be distributed across the entire county-basin so that only the proper percentage gets distributed inside the model domain. To insure that this happens, select the county-basins on the perimeter that get intersected by the model domain boundaries. With the Geoprocessing Wizard, intersect these county-basins with the subsurface aquifer boundaries, the resulting file will be county-basins above the aquifer. Clip out the areas that reside inside the model domain (Union with model domain and delete that which is inside). What is left, (county-basins above aquifer of concern and outside of model domain) can be dissolved into one polygon and merged with the 1 mile grid cells. Give this new polygon a grid_id of "9999999" (later when pumpage values are summed by grid id the "9999999" values will fall out).

4.2.4.3. Add the new record "9999999" to the selected set from 4.3.4.1. Using Geoprocessing Wizard, intersect the selected 1 mile grid cells with the "mrlc_cb.shp" file. The result will be all of the irrigated land with the proper grid_id and county-basin name. Call it "mrlc_cb_grid.shp".

4.2.4.4. Add field "un_area_gd" and calculate the polygons' areas in sq. miles using the field calculator ("un_area_gd" = [shape].returnarea/27878400).

4.2.5. Determine weighting factor for each polygon based on area and proximity with irrigated farms.

4.2.5.1. Add fields "dist_irr89", "dist_fact89", "ardisfac89", "sumcbfac89", "w_ar_dis89".

4.2.5.2. Populate the distance to irrigated farmland field ("dist_irr89") using the values from the "dist_irr89" grid file.

4.2.5.3. Calculate the distance to irrigated farms factor using the field calculator ("dist_fact89"=1/(1+[dist_irr89]).ln + 0.0001). Select all values that are greater than 2 and change them to 2, and select all values that are less than 0.5 and change to 0.5 so that the range is 0.5 – 2.

4.2.5.4. Calculate the area-distance factor using the field calculator ("ardisfac89" = "un_area_gd" * "dist_fact89").

4.2.5.5. Create a summary table by county-basin that summarizes the "ardisfac89" field. Link the summary table back up by county-basin and migrate the summed values into "sumcbfac89".

4.2.5.6. Calculate the distribution weighting factor for area of irrigated land (mrlc land use) and distance to irrigated farmland (farmland survey) using the field calculator ("w_ar_dis89" = "ardisfac89" / "sumcbfac89"). This is basically the fraction of the total county-basin pumpage that will be distributed to a specific polygon.

4.2.5.7. Repeat section 4.3.5 for irrigated farmland 94.

4.2.6. Calculate unique pumpage values for 1 mile grid cells.

4.2.6.1.Create 20 new fields (1 for each year: "pmp_80" – "pmp_99".

4.2.6.2.Using SQL Connect, query the Access table **PumpagebyMajorAquifer1980-1999** for all years.

4.2.6.3.Query the records (by the year column) for each year and specific aquifer (by aquifer code column) and export each query as a separate *.dbf file. "Pump_by_cb_*yyyy_aquifer*.dbf." These tables will have a column for each use category, and can therefore also be used in livestock calculations for the same aquifer of concern.

4.2.6.4.Join the table "pump_by_cb_1980_cw.dbf" to the attribute table "mrlc_cb_grid.shp" by countybasin. (make certain that all countybasin names are spelled the same).

4.2.6.5.Calculate "pmp_80" using the field Calculator (pmp_80 = w_ar_dis89 * irrigation). Irrigation is the column of the joined table "pump_by_cb_1980" that contains the countybasin annual pumpage totals for irrigation use. Use "w_ar_dis89" for years 80-89 and use "w_ar_dis94" for years 90-99.

4.2.6.6. Repeat 4.2.6.4 – 4.2.6.5 for all years.