9.0 TRANSIENT MODEL

After we calibrated the initial predevelopment version of the model, we added stress periods to represent the aquifer from 1951 through 1990. Moving the starting date for the transient model to 1951 decreases the influence of initial conditions on model results for the 1990 calibration. During the calibration phase we made further adjustments to all model parameters, including horizontal and vertical hydraulic conductivity, recharge, parameters for the stream-flow routing and ET packages, GHB boundaries, horizontal-flow-barrier (HFB) parameters, specific storage, and specific yield.

9.1 Calibration and Verification

The period from 1980 through 2000 has the best available estimates of total pumping rates for each county. We projected the 1980 estimates backward to 1950 by assuming that pumping rates did not vary greatly except in municipal well fields. Municipal and rural domestic pumping rates for 1950 through 1979 were distributed through time on the basis of county population. Irrigation rates were varied on the basis of annual rainfall. Other pumping rates were held at 1980 levels (fig. 52).

During transient model calibration we adjusted the GHB heads along the northeast boundary of the model to account for the areas of drawdown related to groundwater withdrawal outside of the model in Smith County (Intera and Parsons Engineering Science, 2002a). In addition, we varied GHB conductance from 0 to very large for the northeast boundary. A GHB conductance of 0 makes the boundary equivalent to a no-flow boundary. A large GHB conductance imposes the greatest effect of the boundary on the model.

The distance at which the model responds to further increases in GHB conductance asymptotically approaches the maximum distance of 30 to 40 miles of the northeast boundary. The value of GHB conductance we used (set equal to transmissivity) allows the imposed GHB heads to have an effect extending into the model approximately 15 to 20 miles. Because the three GAM models were designed with overlaps, it may be more suitable to use either the northern or southern GAM models (Intera and Parsons Engineering Science, 2002a, 2002b) within 30 to 40 miles of the northeast or southwest boundaries of the central GAM model.

Simulated water levels for 1990 reflect the effects of groundwater withdrawal in the artesian part of the Carrizo–Wilcox aquifer (fig. 80). The model generally does a good job in matching water levels and drawdown in the Simsboro and Carrizo aquifers. The simulated water level as of 1990 at the center of the Bryan-College Station well field in the Simsboro aquifer is within 15 ft of the reported levels (figs. 80a, 81); simulated drawdown slightly overestimates actual drawdown in the Simsboro aquifer. The RMSE comparing simulated and observed water levels in the Simsboro aquifer for 1990 is 36 ft (fig. 82, table 11). Whereas this is larger than the 25-ft RMSE calculated for the steady-state calibration, it is a smaller fraction (10.0 percent) of the range in observed water levels (363 ft) and is based on three times the number of data points available for the steady-state calibration (n=42; table 7).

The RMSE comparing simulated and observed water levels in the Carrizo aquifer for 1990 is 49 ft (fig. 82a); 6.8 percent of the range in observed water levels (table 11). The dominant feature in the map of simulated water levels for 1990 in the Carrizo aquifer is the drawdown related to withdrawal of groundwater in the Lufkin-Angelina County well field

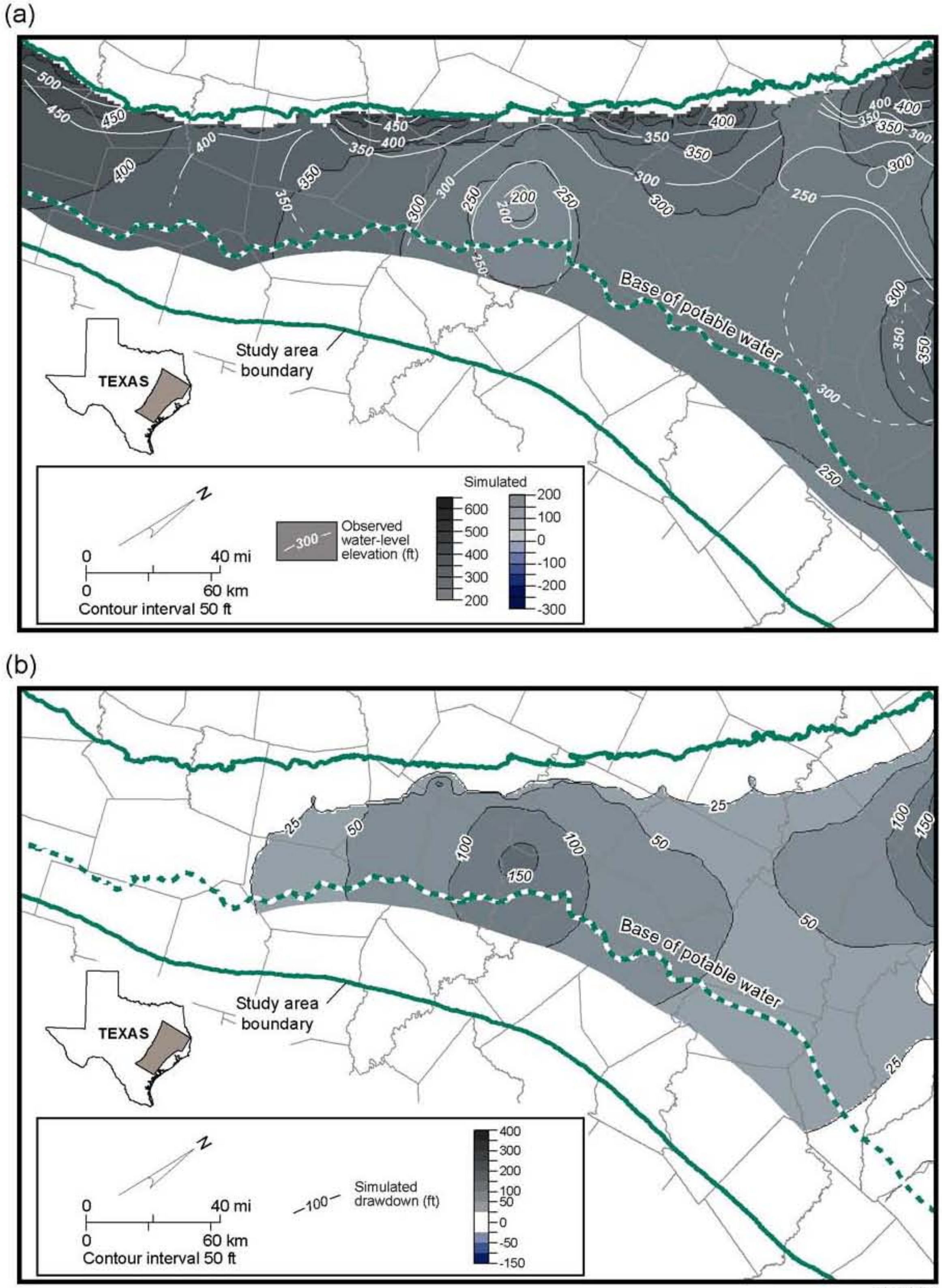

Figure 80. Maps for the Simsboro aquifer (layer 5) showing (a) simulated and observed 1990 water level and (b) drawdown from 1950 through 1990.

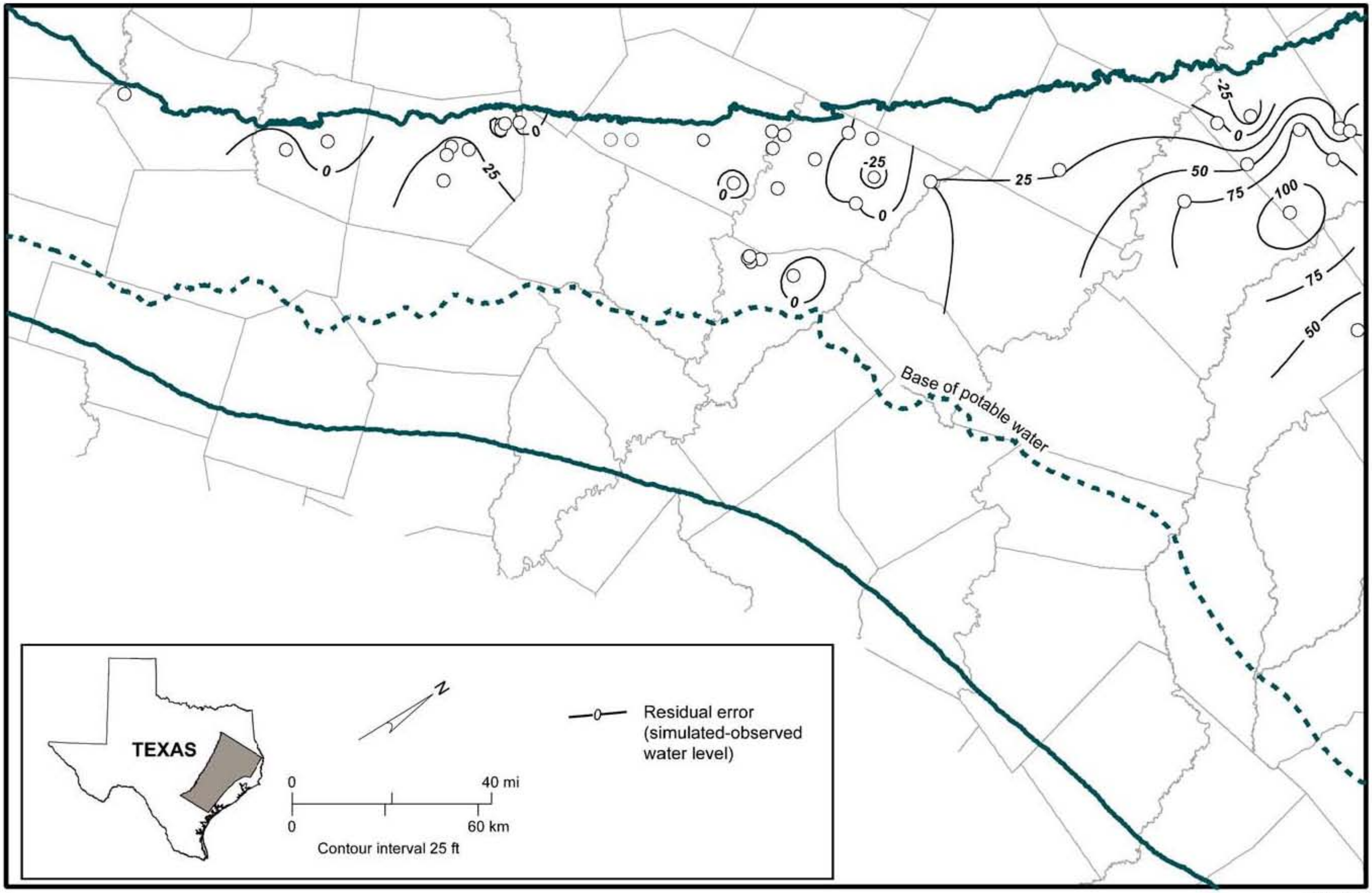

Figure 81. Map of residual differences between simulated and measured water levels for the Simsboro aquifer (layer 5) for the 1990 calibration.

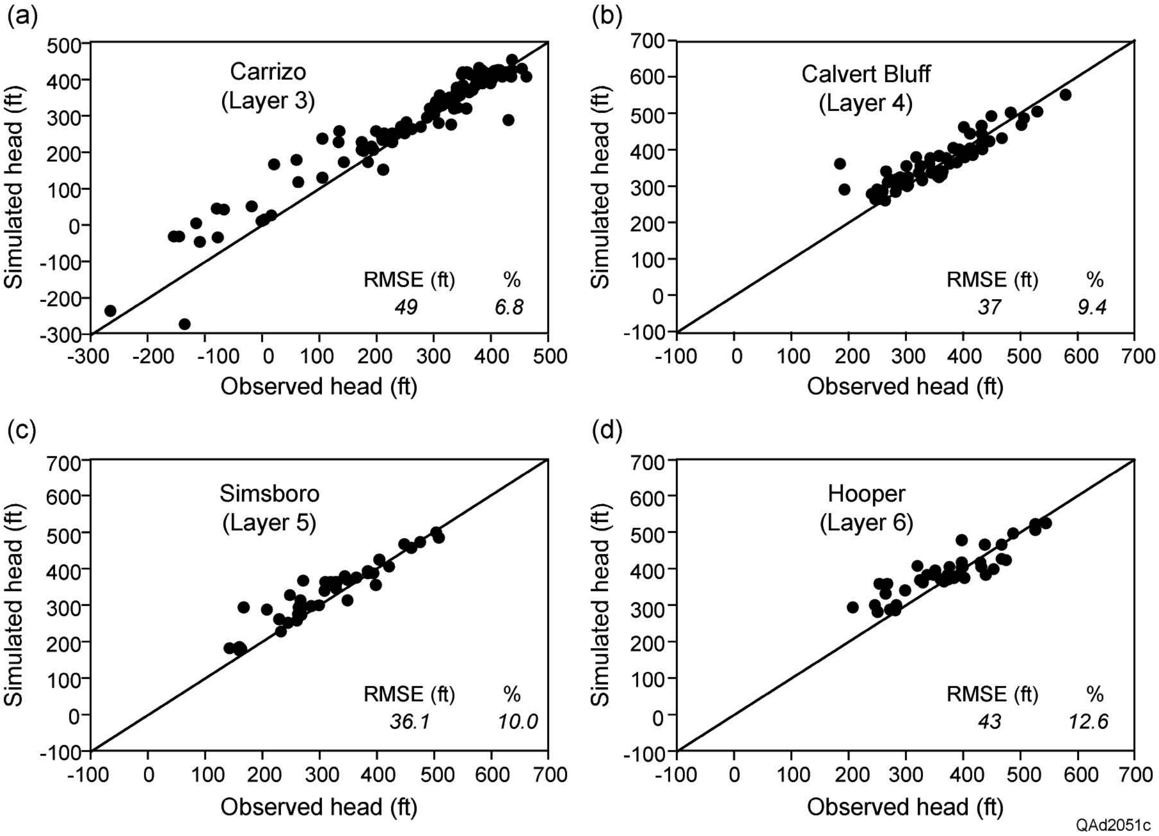

Figure 82. Comparison of simulated and observed water levels for the 1990 calibration. Well locations are shown in figure 83.

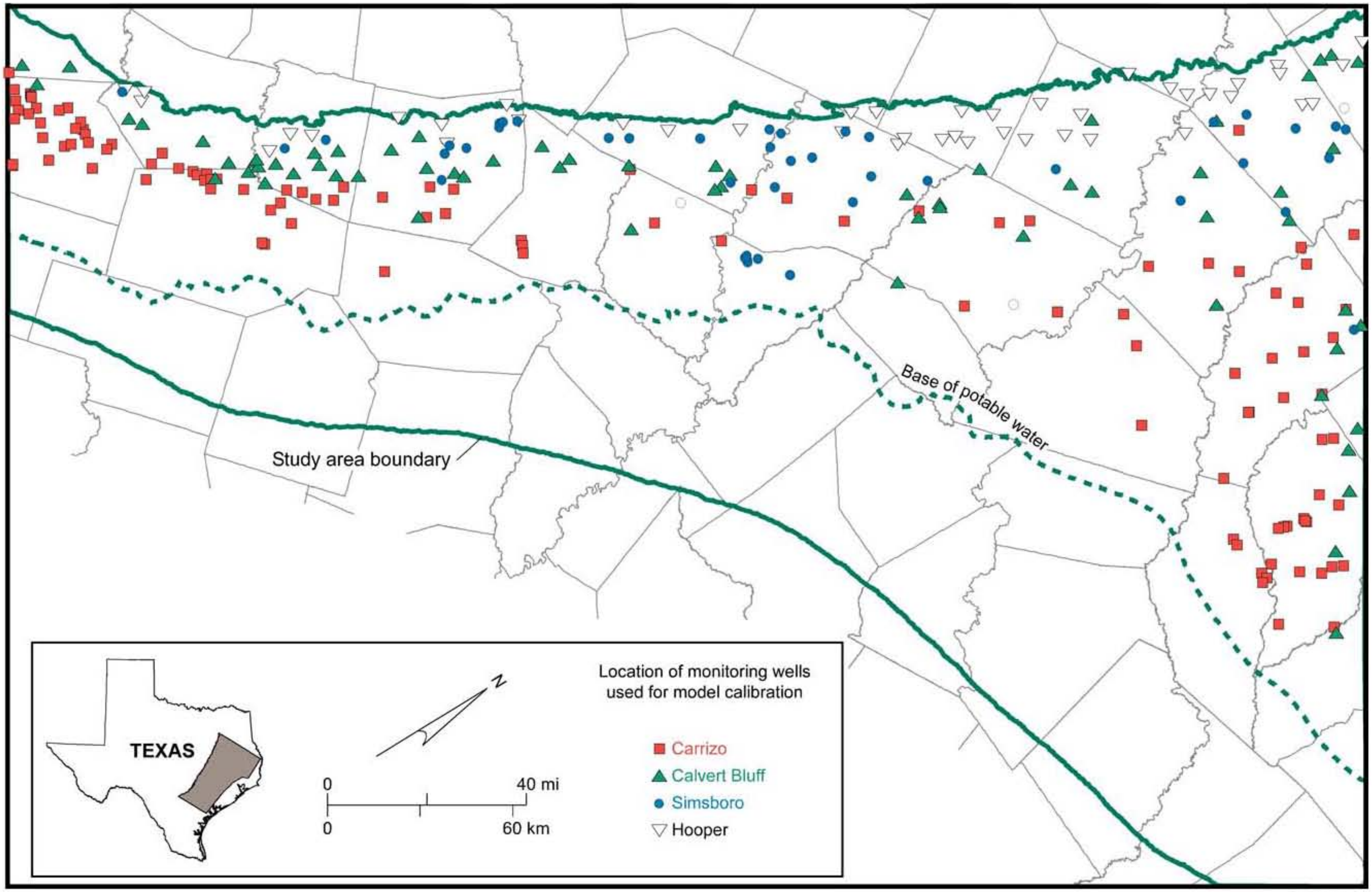

Figure 83. Location of wells used to develop the 1990 calibration of the model shown in figure 82.

(fig. 84). Whereas in most parts of the study area the match between simulated and observed water levels is within ±25 ft, the biggest differences between simulated and observed water levels in the Carrizo aquifer are near the northeastern boundary of the model. The model overestimates drawdown in northern Anderson County and in the Lufkin-Angelina County well field by more than 125 ft (fig. 85). Part of the discrepancy may be due to an effect of the model's northeast boundary on simulation results. Other factors could include errors in pumping rates, storativity, and vertical permeability between the Carrizo and Reklaw layers.

Water levels simulated in the Hooper and Calvert Bluff aquitards for 1990 are shown in figures 86a and 87a, respectively. The RMSE values comparing simulated and observed water levels in the Hooper and Calvert Bluff aquitards for 1990 are 43 (fig. 82d) and 38 (fig. 82b) ft, respectively.

The number of water-level observations for use in model calibration is smaller for 2000 than for 1990 (table 11). The range in observed water levels measured in the Simsboro and Carrizo aquifers, however, increased from 1990 to 2000 (table 11). Applying the calibrated model to the 1991 through 2000 verification period shows a slightly improved match between simulated and observed water levels (fig. 88, table 11) partly because of the increased range of water-level elevations, a result of continued groundwater withdrawal. The simulated water level as of 2000 at the center of drawdown in the Bryan-College Station well field is about 115 ft above sea level (fig. 90a). This is 100 ft above the reported most drawn-down water levels. For 2000 the model underestimates the amount of maximum drawdown since 1950. Drawdown in the Simsboro aquifer in northern Brazos and southern Robertson Counties before 2000 is estimated to have been more than 300 ft (fig. 90b). In most areas the simulated and observed water levels match within ±30 ft; simulated water levels tend to overestimate observed water levels at depth in the confined aquifer (fig. 91).

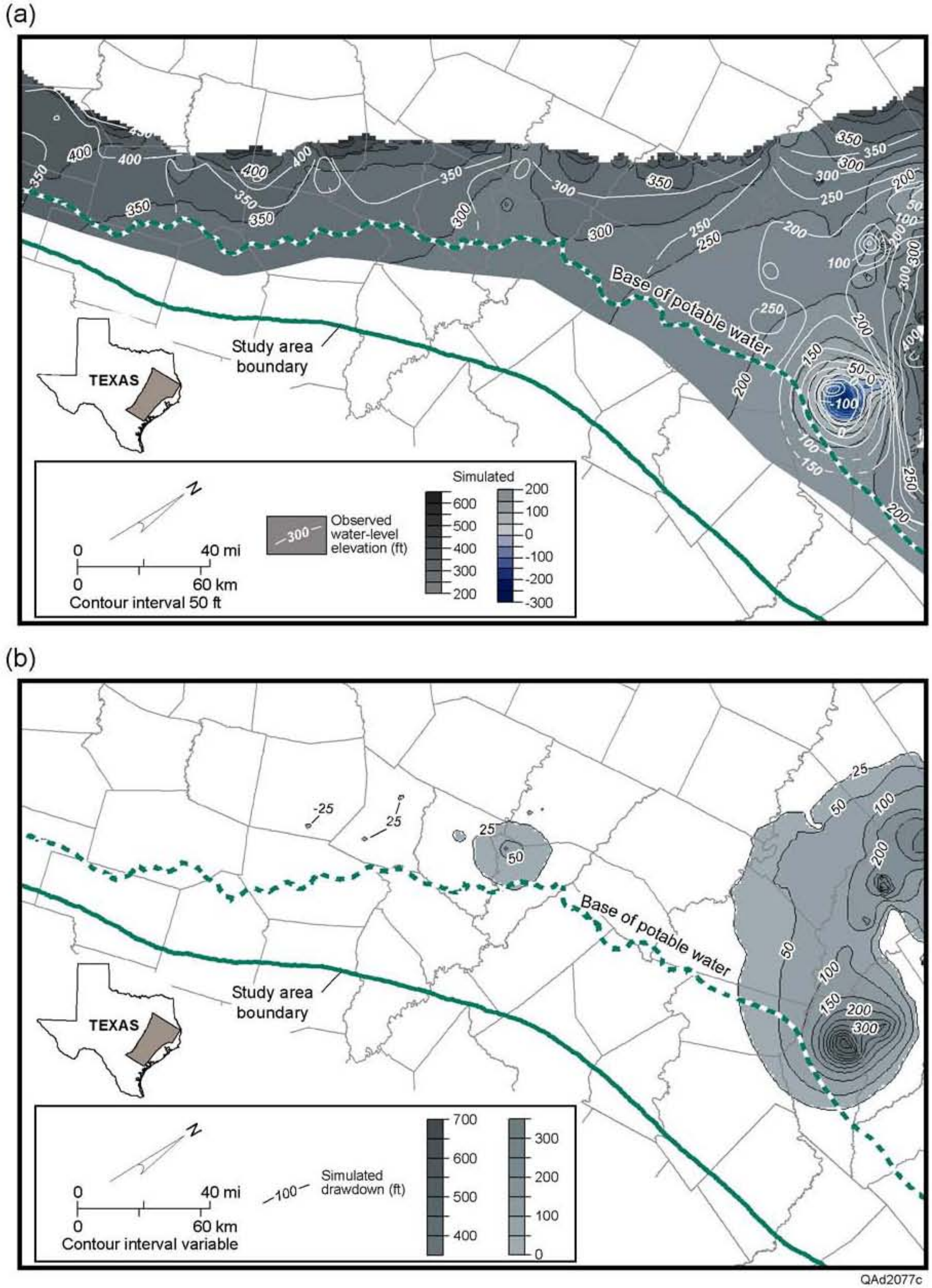

Figure 84. Maps for the Carrizo aquifer (layer 3) showing (a) simulated and observed 1990 water level and (b) drawdown from 1950 to 1990.

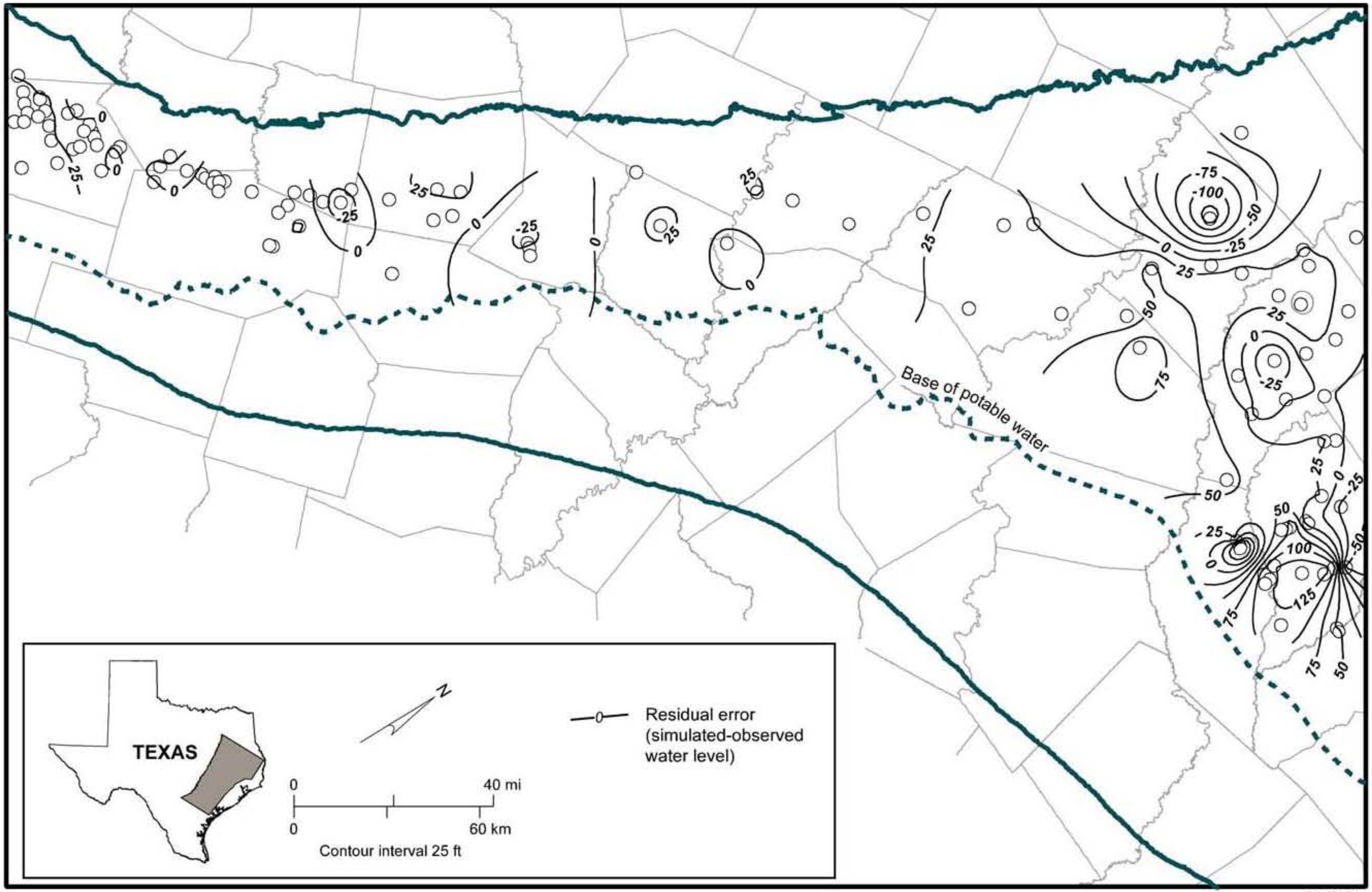

Figure 85. Map of residual differences between simulated and measured water levels for the Carrizo aquifer (layer 3) for the 1990 calibration.

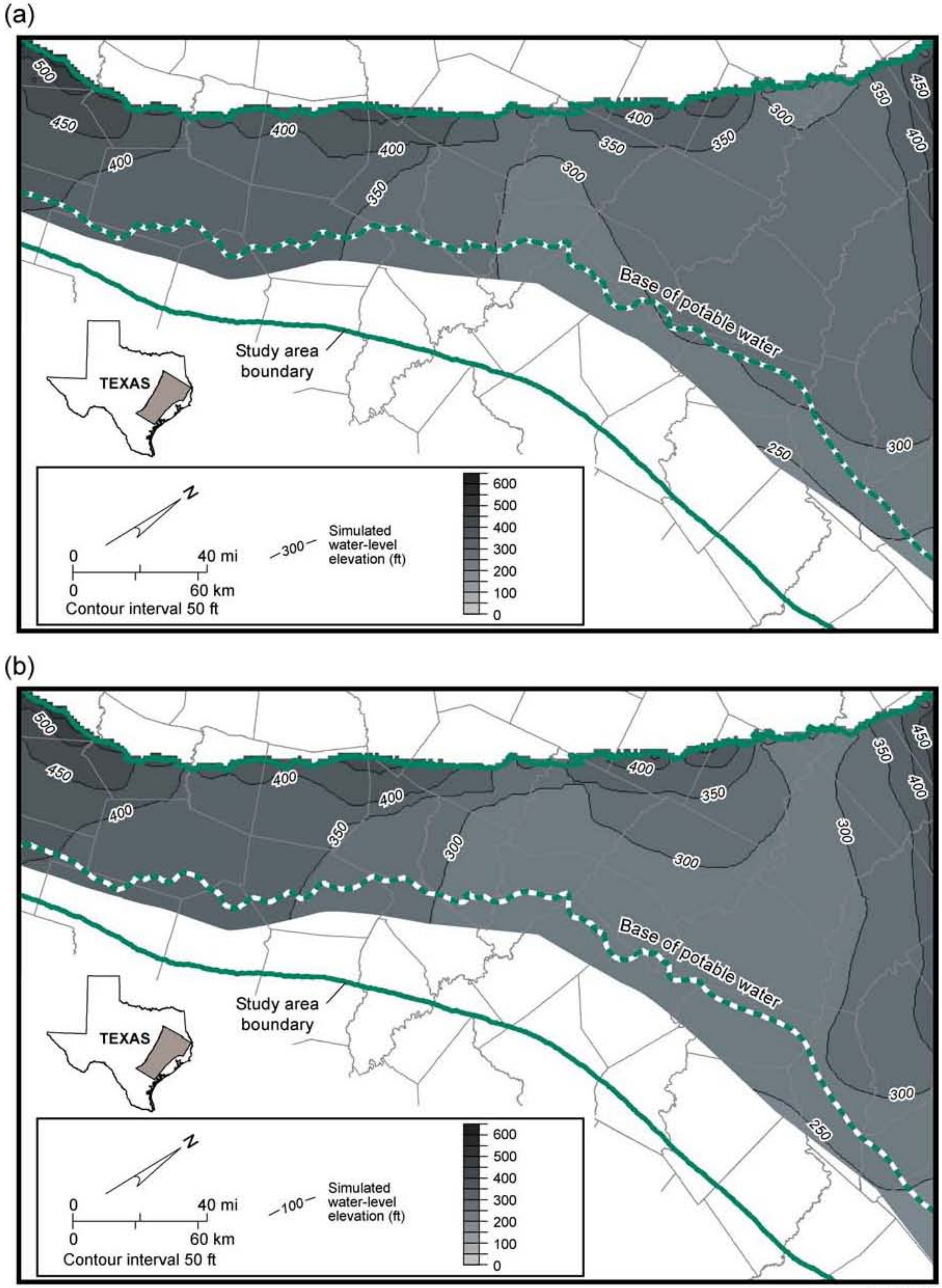

Figure 86. Maps of water level in the Hooper Formation (layer 6) in (a) 1990 and (b) 2000.

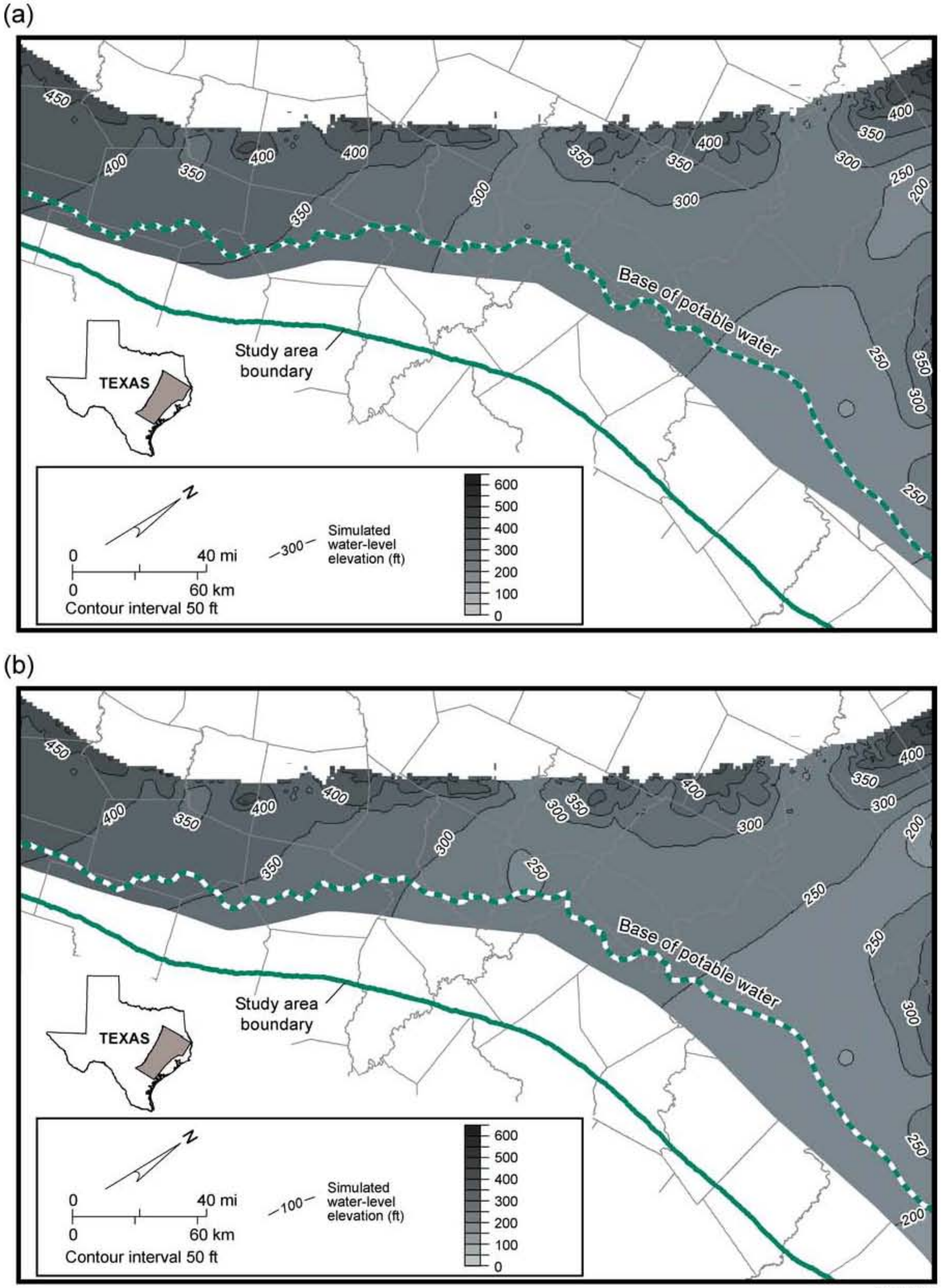

Figure 87. Maps of water level in the Calvert Bluff Formation (layer 4) in (a) 1990 and (b) 2000.

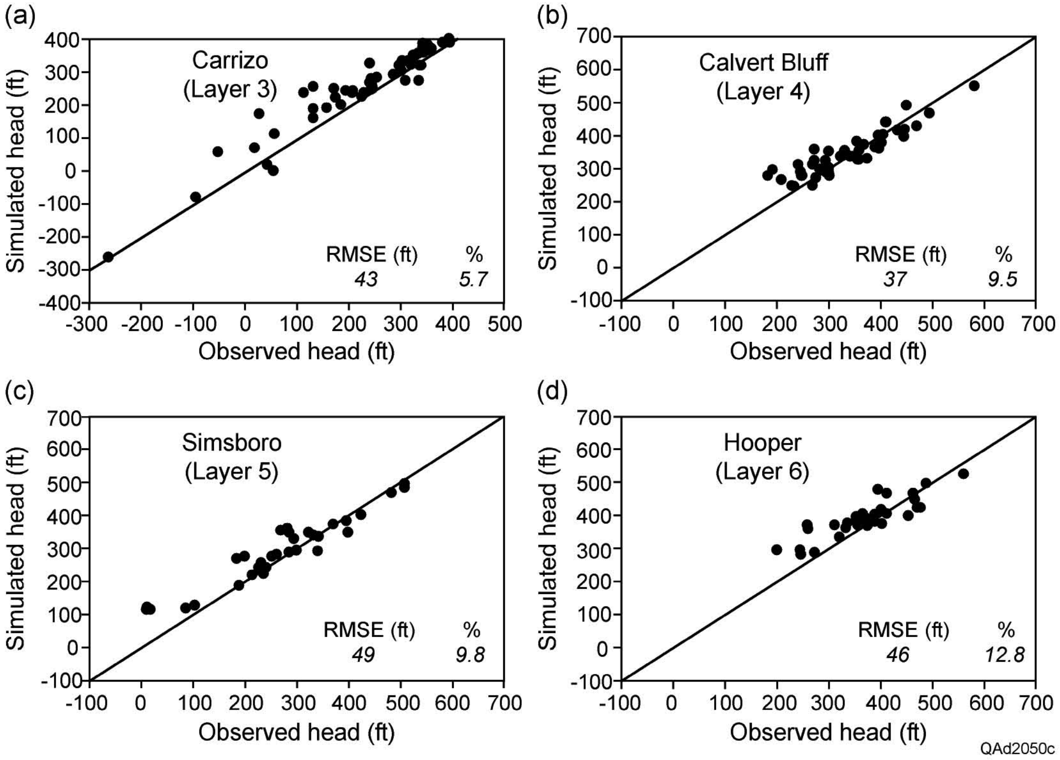

Figure 88. Comparison of simulated and observed water levels for the 2000 calibration. Well locations are shown in figure 89.

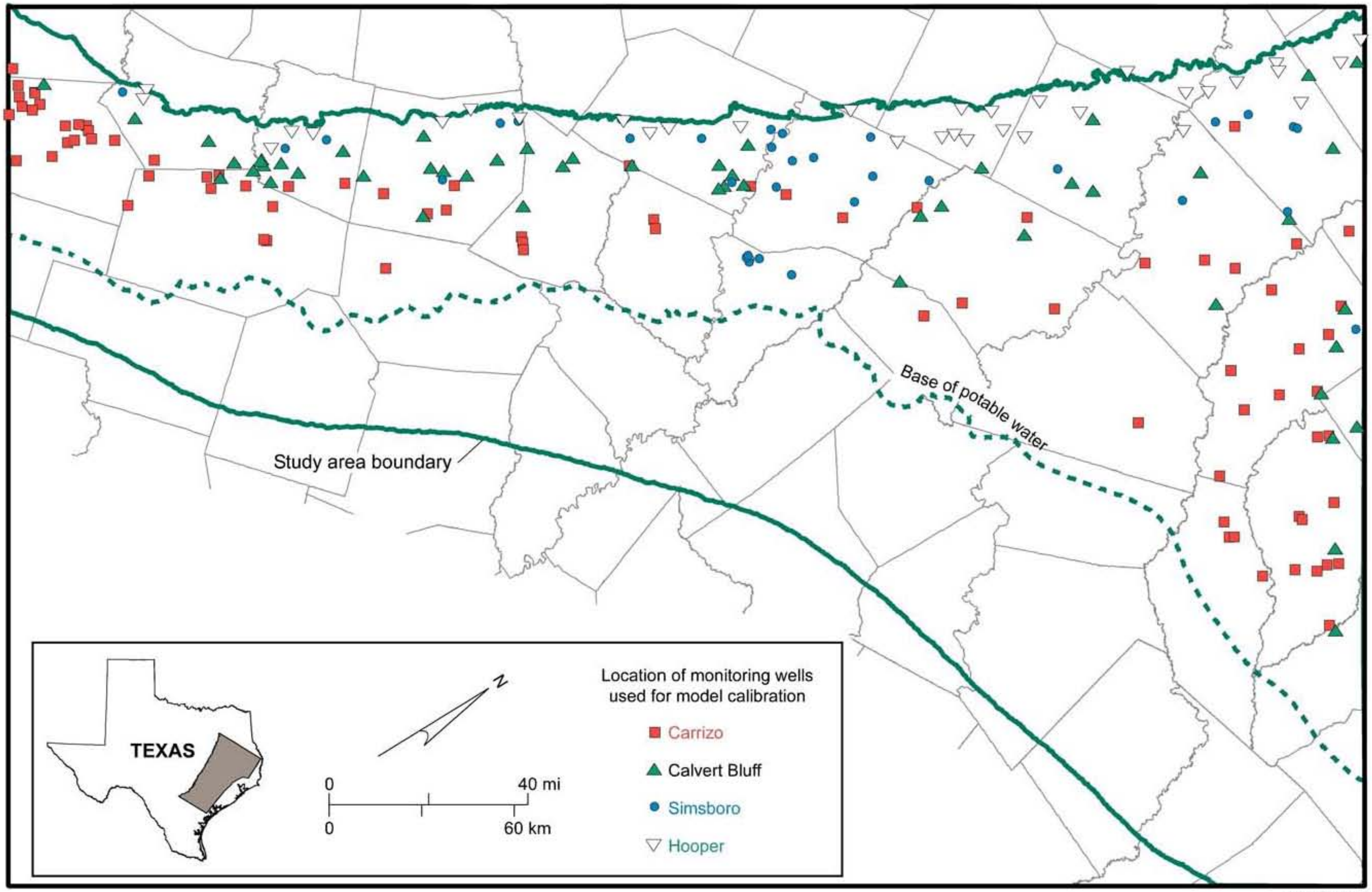

Figure 89. Location of wells used to develop the 2000 calibration of the model shown in figure 88.

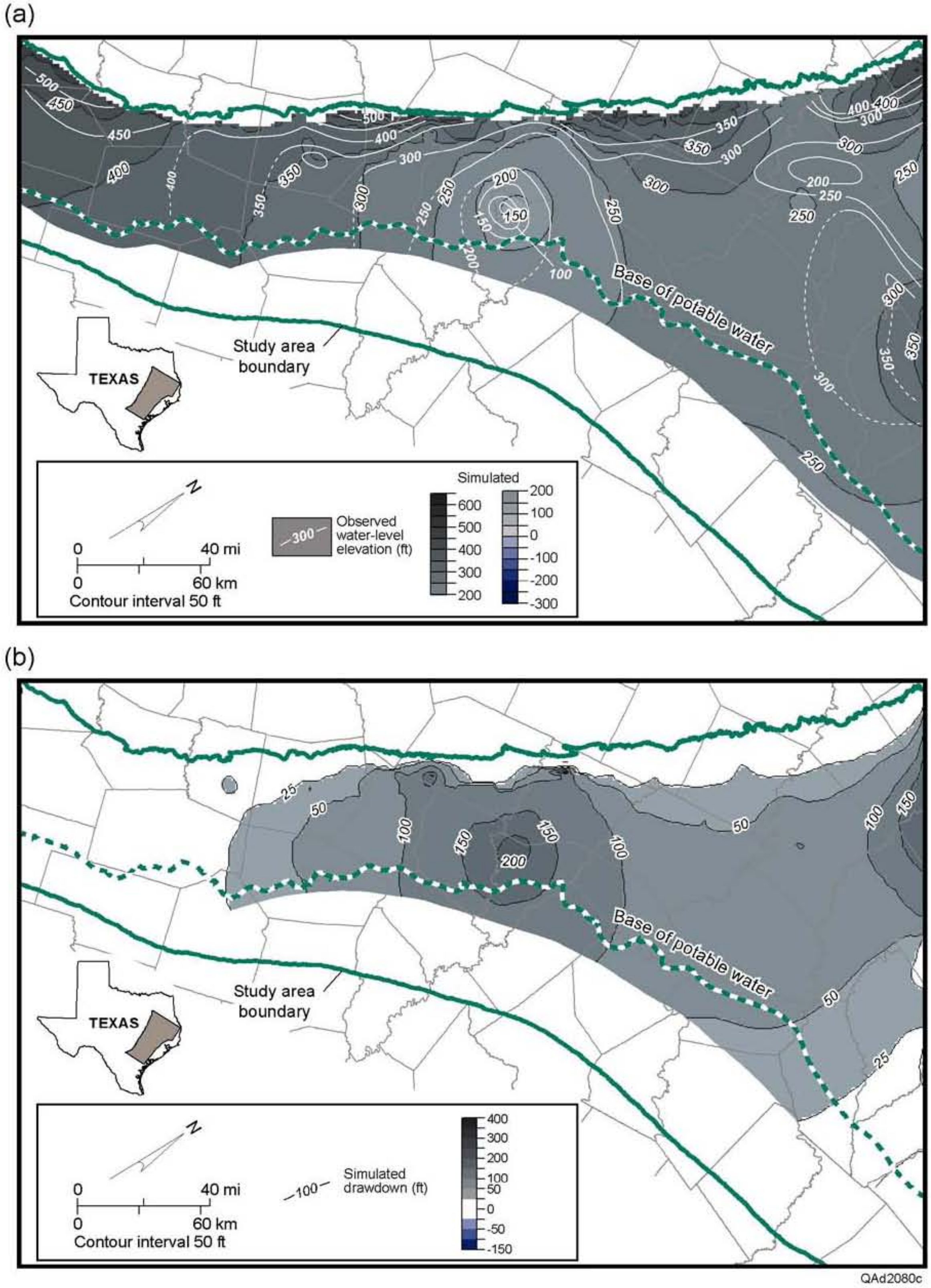

Figure 90. Maps for the Simsboro aquifer (layer 5) showing (a) simulated and observed 2000 water level and (b) drawdown from 1950 through 2000.

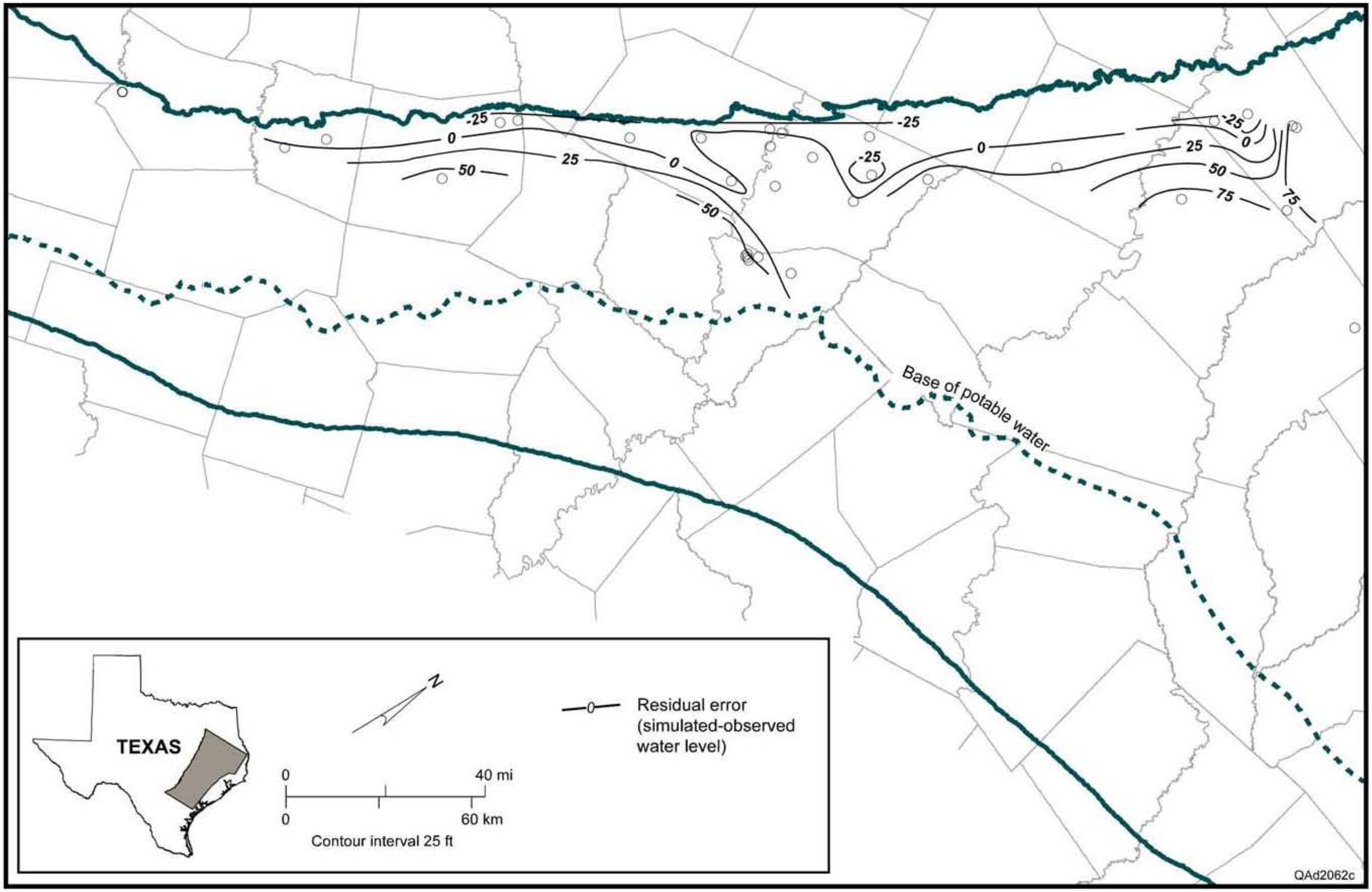

Figure 91. Map of residual differences between simulated and measured water levels for the Simsboro aquifer (layer 5) for the 2000 calibration.

The RMSE comparing simulated and observed water levels in the Carrizo aquifer for 2000 is 43 ft (fig. 82a). During the 1990s, water-level elevation in the Lufkin-Angelina County well field decreased by approximately another 50 ft to more than 300 ft below sea level (fig. 92a). Total drawdown since 1950 is estimated to have been almost 600 ft. The model simulation for 2000 overestimates drawdown in the Lufkin-Angelina County well field by about 30 ft (fig. 93). The Bryan-College Station well field includes withdrawal from the Carrizo aquifer. Artesian drawdown in the vicinity of that well field is influenced by the Karnes-Milano-Mexia Fault Zone (fig. 14), represented in the model using the horizontal-flow-barrier (HFB) package of MODFLOW. The effect of the fault zone is to impede the movement of water from the outcrop toward the well field and results in the "cone of depression" being elongated in a northeast-southwest trend. In most of the study area the match between simulated and observed water levels is within ±30 ft in the Carrizo aquifer (fig. 93). The largest apparent discrepancy is near the northeastern boundary of the study area. The northern Carrizo–Wilcox model (Intera and Parsons Engineering Science, 2002a) may provide more representative simulation results for the Carrizo aquifer layer within about 30 to 40 mi of the northeastern boundary, including Anderson, Angelina, Cherokee, Rusk, San Augustine, Smith, and Van Zandt Counties.

Water levels simulated in the Hooper and Calvert Bluff aquitards for 2000 are shown in figures 86b and 87b, respectively. The RMSE values comparing simulated and observed water levels in the Hooper and Calvert Bluff aquitards for 2000 are 46 ft (fig. 88d) and 38 ft (fig. 88b), respectively.

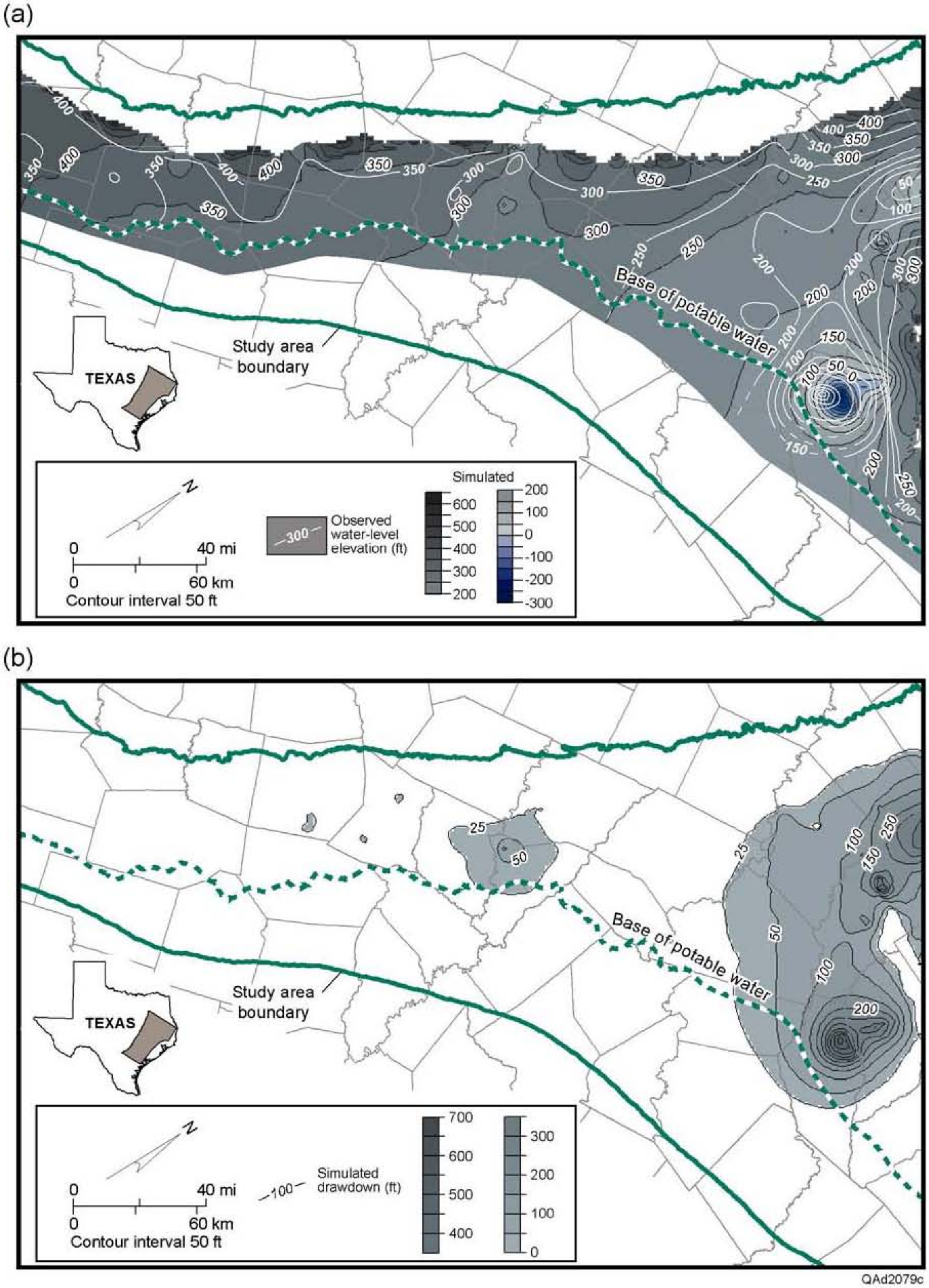

Figure 92. Maps for the Carrizo aquifer (layer 3) showing (a) simulated and observed 2000 water level and (b) drawdown from 1950 through 2000.

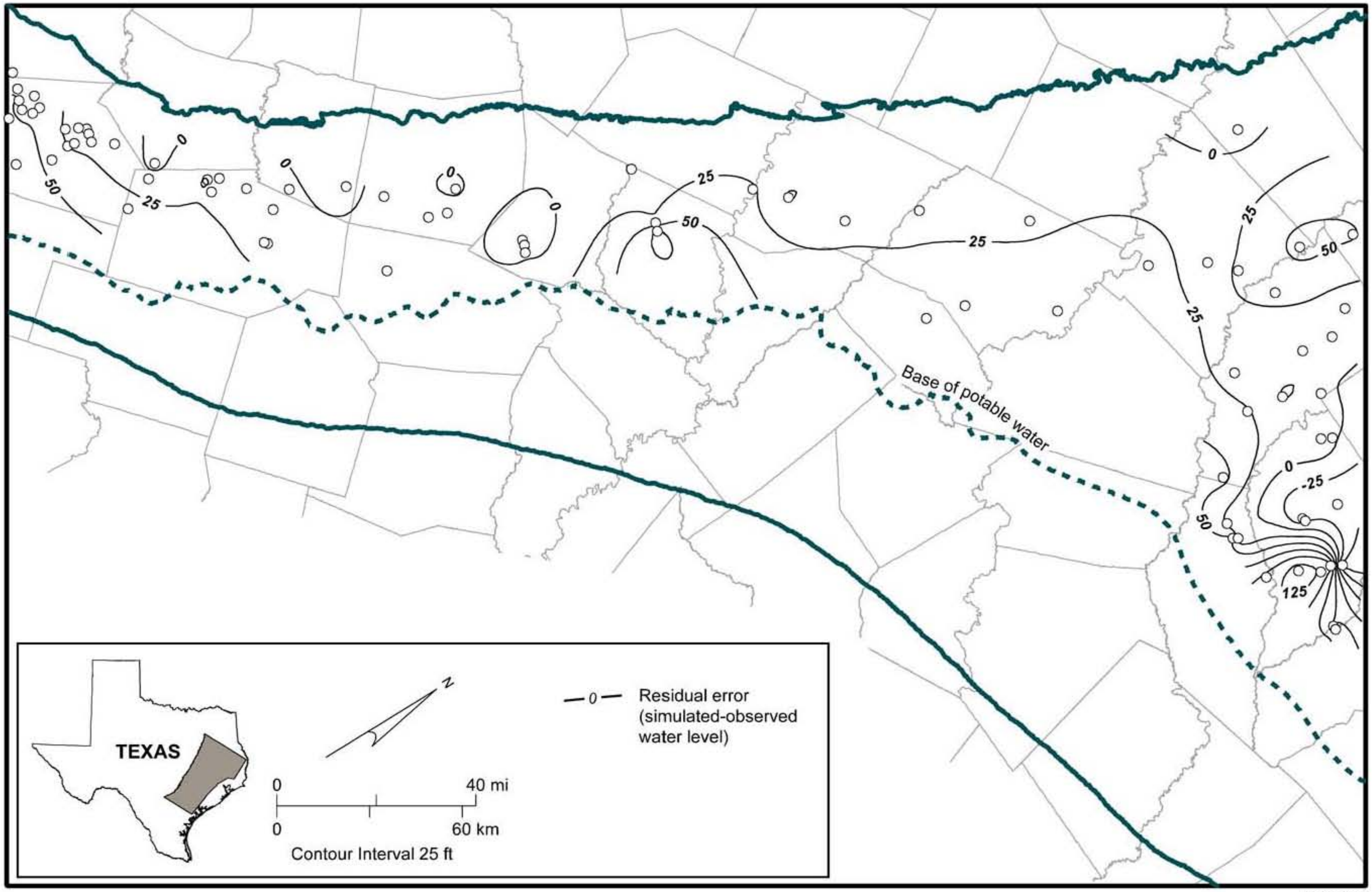

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Figure 93. Map of residual differences between simulated and measured water levels for the Carrizo aquifer (layer 3) for the 2000 calibration.

Hydrographs shown in figures 94 through 97 give another comparison of how well the model simulates water levels in both aquifers and aquitards. The hydrographs show how the model performs at specific locations through time and are similar to others in the study area but not shown in this report. Some simulation hydrographs show an abrupt change in water level in 1950, which is when simulated pumping was started in the model. The influence of the change from steady state to transient has little effect on the transient model calibration for the period from 1980 through 1990. For the periods of 1987 through 1989 and 1995 through 1997, monthly fluctuations in water level are simulated. The water-level change shows an annual cycle that responds to a range in pumping rate that is approximately two times greater in summer than in winter. The greater annual fluctuation for water levels in and near the Bryan-College Station well field (for example, wells 59-21-209 and 59-21-409 in Brazos County [fig. 95]) is proportional to the greater annual rate of pumping in that area. The hydrograph for well 59-11-703 in Milam County (fig. 95) shows the onset of increased groundwater withdrawal in that county for mining operations.

Overall, the match between simulated and observed hydrographs is good. Calculated values of RMSE and baseline shift, as explained in section 7.0, are given for each hydrograph (figs. 94 through 97). RMSE ranges between 1 and 32 ft for these representative hydrographs. The match for well 37-35-701 in Angelina County (fig. 97) again shows that the model overestimates drawdown in the Carrizo aquifer in the Lufkin-Angelina County well field. The range of annual fluctuation in water levels during the periods of 1987 through 1989 and 1995 through 1997 for that well is proportional to the amount of pumping in the well field. The fluctuation is determined more by the two-fold variation in pumping rate than by storativity. Changing storativity by an order of magnitude decreased the annual water-level fluctuation by about 20 percent.

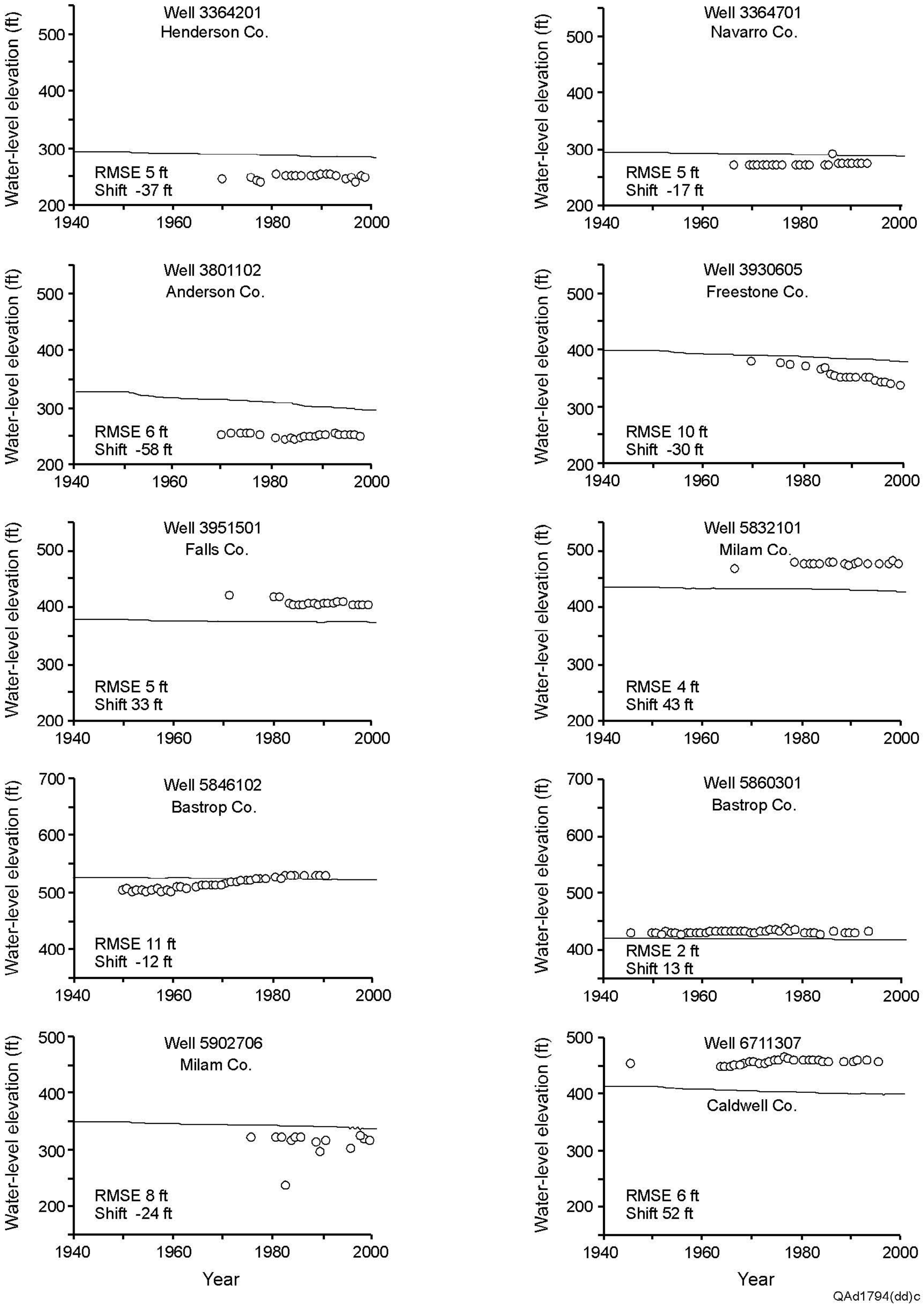

Figure 94. Comparison of simulated and observed water-level hydrographs for 10 wells in the Hooper aquitard (layer 6). Well locations are shown in figure 36.

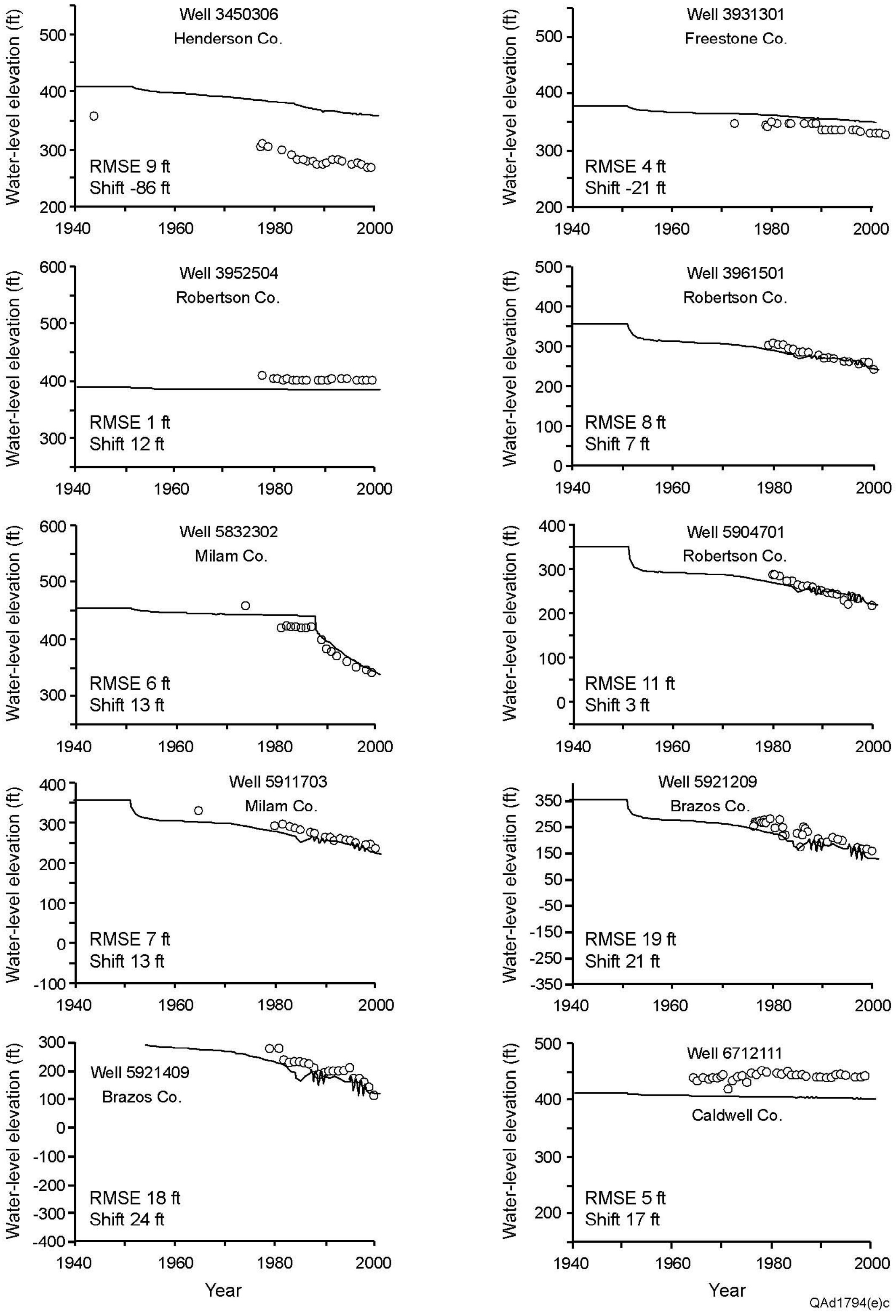

Figure 95. Comparison of simulated and observed water-level hydrographs for 10 wells in the Simsboro aquifer (layer 5). Well locations are shown in figure 36.

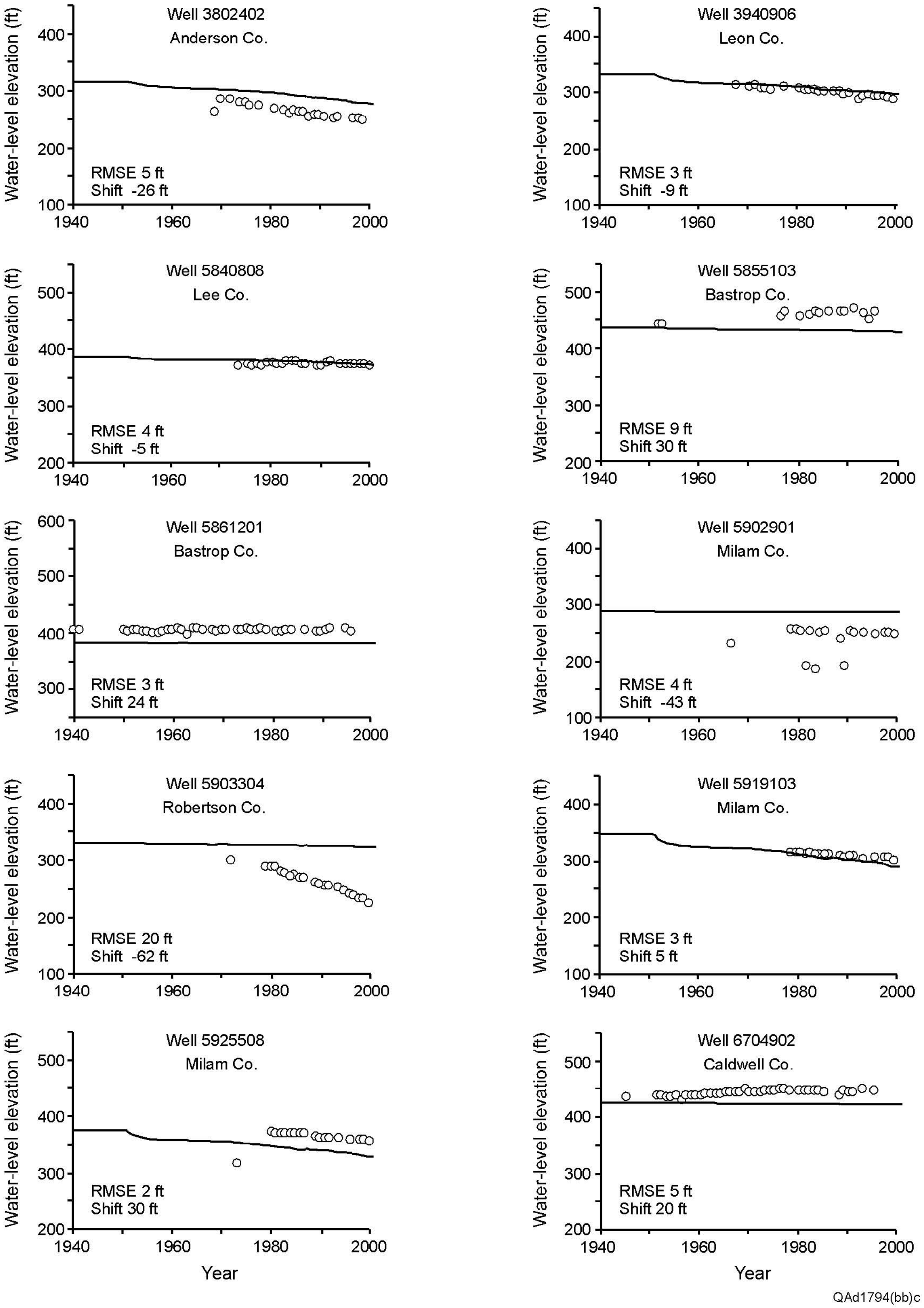

Figure 96. Comparison of simulated and observed water-level hydrographs for 10 wells in the Calvert Bluff aquitard (layer 4). Well locations are shown in figure 36.

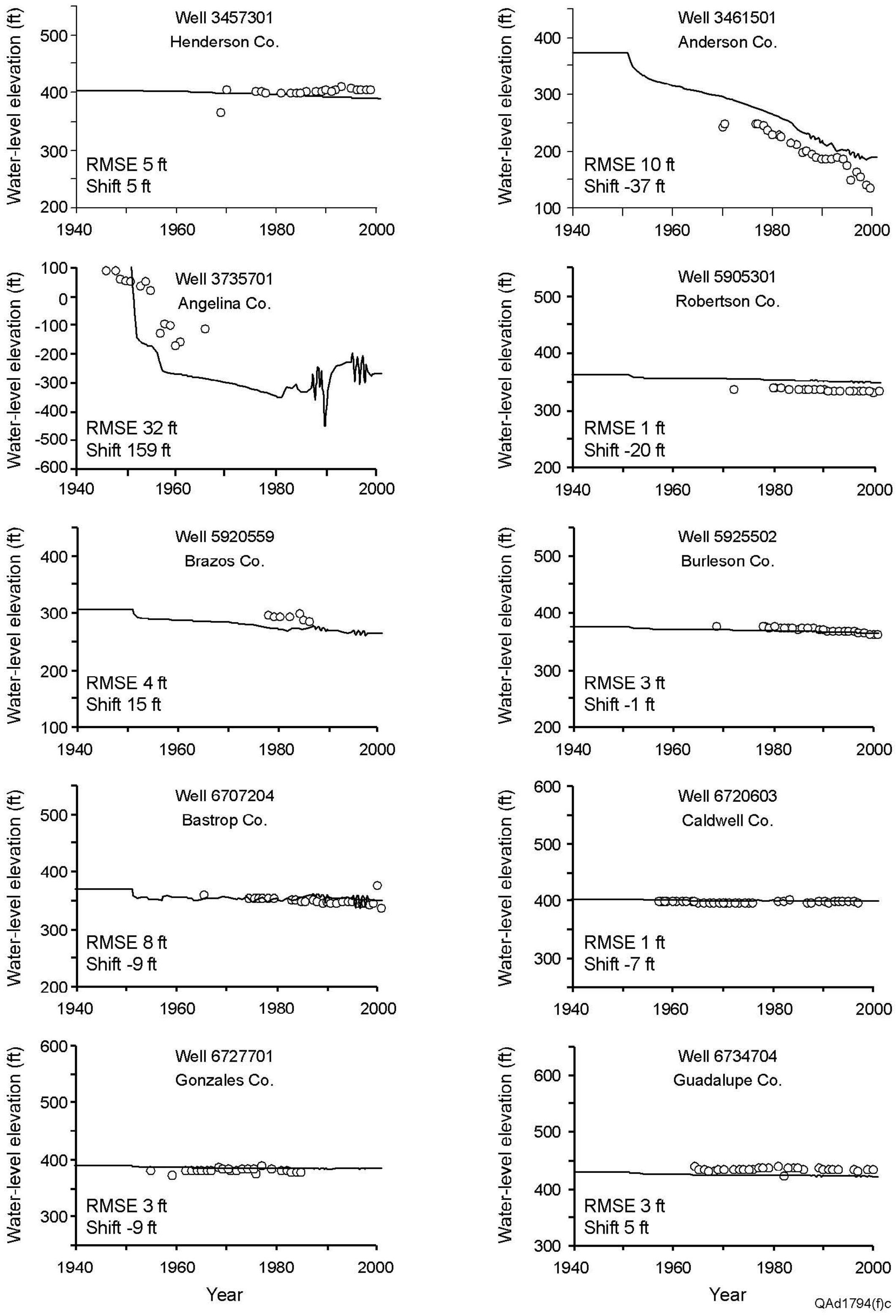

Figure 97. Comparison of simulated and observed water-level hydrographs for 10 wells in the Carrizo aquifer (layer 3). Well locations are shown in figure 36.

Rate of discharge to streams simulated for the transient model period is similar to the steady state, average base-flow rate. Simulated rate of base-flow discharge fluctuates with annual rates of recharge; there is also a trend of decreasing base-flow rate through time (fig. 98, table 14). This simulated decrease in base flow most likely reflects a simulated decline in water levels in the aquifer outcrop attributed to increased pumpage. It should be noted, however, that base-flow estimates show no long-term trend. Because recent precipitation records were not available in the Internet source, average precipitation for the period 1960 through 1997 are used for 1998 through 2000, resulting in a constant simulated recharge for this period as well. Most model cells are simulated as gaining reaches through the transient model period. Stream losses are approximately 6 percent of stream gains. The Simsboro and Carrizo aquifers contribute essentially all of the discharge to the rivers and streams. Because of their low hydraulic conductivity and slow rates of groundwater movement, the Hooper and Calvert Bluff aquitards contribute very little base flow to streams. Groundwater ET simulated for 2000 is shown in figure 99. Most of the ET is focused in low-lying topographical areas flanking streams. Some ET is also simulated for areas between streams according to how the ET package parameters are set.

9.2 Water Budget

Water budgets for the transient model change each year with changes in recharge rate and pumping (fig. 98). Annual recharge rates applied to the model were greater or less than average in proportion to how much precipitation was greater or less than average. In addition, the GHB heads on the northeastern boundary of the model were varied in long-term trends to account for movement of groundwater out of the study area toward well fields,

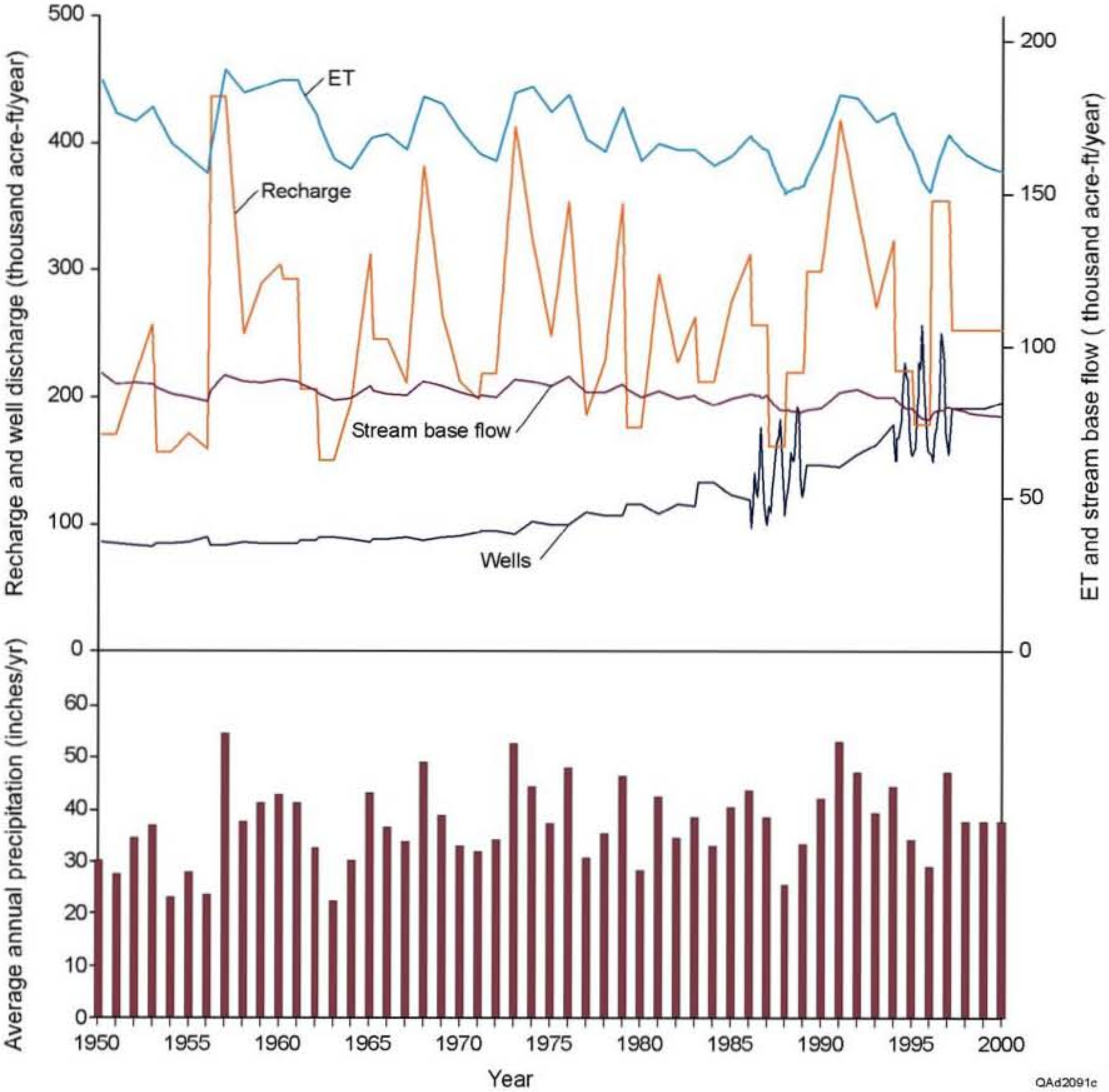

Figure 98. Changes in simulated ET and base-flow discharge to stream with variation in recharge and pumping rates.

Table 14a. Water budget for the calibrated steady-state and transient models (1000 acre-ft/yr). Positive values are inflow to the aquifer; negative values are discharge from the aquifer. Annual rates are for a 12-month long time step for steady state and 2000 budgets and projected from five 2.4-month long time steps for 1990.

Layer	Recharge	Net recharge	ET	Stream leakage	Reservoir leakage	GHB Reklaw	GHB downdip boundary	GHB NE boundary	GHB SW boundary	Wells	Cross-formational flow	Change in storage	Water balance error (%)
Steady state													
Alluvium (1)	12.6	0	-13.3	-26.3	0	0	0	0	0	0	27.0	0	-0.005
Reklaw (2)	13.7	-5.6	-20.5	-0.6	0	-36.9	0	0	0	0	44.2	0	-0.007
Carrizo (3)	117.2	11.9	-72.4	-32.5	0	0	2.4	-9	18.3	0	-32.1	0	-0.003
Calvert Bluff (4)	45.4	-9.3	-39.6	-13.5	0	0	2.3	13.1	0.2	0	-7.9	0	-0.006
Simsboro (5)	59.4	14.8	-31.1	-13.3	0	0	2.2	4.6	0.2	0	-22.0	0	-0.004
Hooper (6)	24.6	4.3	-15.9	-4.4	0	0	1.4	3.5	0.0	0	-9.2	0	-0.001
ALL	272.9	16.1	-192.8	-90.6	0	-36.9	8.4	20.2	18.6	0	0	0	-0.005
1990													
Alluvium (1)	13.8	0	-12.4	-23.9	0.6	0	0	0	0	0	22.2	-0.4	0.001
Reklaw (2)	28.8	-5.1	-23.1	-0.5	0	7.2	0	0	0	0	-1.5	-10.9	0.001
Carrizo (3)	122.9	23.9	-64.3	-29.5	0	0	2.4	2.4	26.4	-74.8	13.6	0.9	0.005
Calvert Bluff (4)	59.2	-3.1	-32.9	-11	2.1	0	2.3	15.0	0.7	-10.4	-23.3	-1.6	0.001
Simsboro (5)	62.8	32.1	-23.5	-10.8	0.4	0	2.3	1.3	0.3	-56.2	8.8	14.7	-0.011
Hooper (6)	30.7	8.8	-13.5	-3.4	1.1	0	1.5	8.8	0	-6.4	-19.8	1	-0.015
ALL	318.2	56.6	-169.7	-79.1	4.2	7.2	8.5	27.5	27.3	-147.8	0	3.7	-0.001
2000													
Alluvium (1)	12.9	0	-11.9	-23.7	0.6	0	0	0	0	0	21.7	0.3	-0.005
Reklaw (2)	14.8	-4.9	-21.5	-0.6	0	7.8	0	0	0	0	-3.1	2.6	-0.007
Carrizo (3)	118.4	25.6	-64.7	-29.3	0	0	2.4	0.7	27.1	-78.0	11.1	12.3	-0.003
Calvert Bluff (4)	47.4	-0.2	-31.9	-10.8	2.1	0	2.4	10.3	0.8	-11.4	-28.4	19.6	-0.006
Simsboro (5)	60.2	42.8	-21.9	-9.5	0.4	0	2.3	2.2	0.3	-98.0	22.0	42.0	-0.004
Hooper (6)	25.4	10.7	-13.5	-3.4	1.1	0	1.5	9.6	0	-6.2	-23.2	8.7	-0.001
ALL	279.2	74.1	-165.4	-77.2	4.2	7.8	8.5	22.8	28.1	-193.6	0	85.6	-0.005

Table 14b. Water budget for the transient model (1000 acre-ft/yr) for drought years 1988 and 1996. Positive values are inflow to the aquifer; negative values are discharge from the aquifer. Annual rates are totaled from 12 1-month time steps.

Layer	Recharge	Net recharge	ET	Stream leakage	Reservoir leakage	GHB Reklaw	GHB downdip boundary	GHB NE boundary	GHB SW boundary	Wells	Cross-formational flow	Change in storage	Water balance error (%)
1988													
Alluvium (1)	6.9	0	-12.1	-24.1	0.6	0	0	0	0	0	26.7	2.0	-0.002
Reklaw (2)	3.9	-5.1	-18.6	-0.6	0	4.9	0	0	0	0	-1.0	11.4	0.001
Carrizo (3)	92.9	22.9	-62.9	-29.9	0	0	2.4	2.1	25.0	-71.1	9.8	31.7	0.002
Calvert Bluff (4)	8.6	-3.3	-31.9	-11.6	2.1	0	2.3	14.6	0.6	-9.6	-22.8	47.6	-0.002
Simsboro (5)	44.2	31.5	-23.8	-10.9	0.4	0	2.3	2.3	0.2	-53.4	6.2	32.6	-0.002
Hooper (6)	9.1	8.7	-12.9	-3.5	1.1	0	1.5	8.4	0	-6.8	-18.9	22.1	-0.003
ALL	165.7	54.7	-162.2	-80.5	4.2	4.9	8.5	27.3	25.8	-140.9	0	147.3	0.000
1996													
Alluvium (1)	9.1	0	-12.1	-23.9	0.6	0	0	0	0	0	24.7	1.6	-0.002
Reklaw (2)	4.0	-4.9	-19.7	-0.6	0	5.6	0	0	0	0	-1.7	12.4	0.000
Carrizo (3)	99.7	25.3	-64.2	-29.2	0	0	2.4	1.7	27.5	-78.9	9.6	31.4	0.002
Calvert Bluff (4)	15.3	-1.5	31.0	-10.8	2.1	0	2.3	12.6	0.8	-12.1	-27.2	47.9	-0.001
Simsboro (5)	49.0	42	-22.0	-9.8	0.4	0	2.3	1.8	0.3	-93.8	16.5	55.5	0.000
Hooper (6)	14.2	9.7	-12.9	-3.3	1.1	0	1.5	9.2	0	-6.5	-22.0	18.8	-0.003
ALL	191.2	70.5	-161.9	-77.6	4.2	5.6	8.5	25.4	28.5	-191.4	0	167.7	0.000

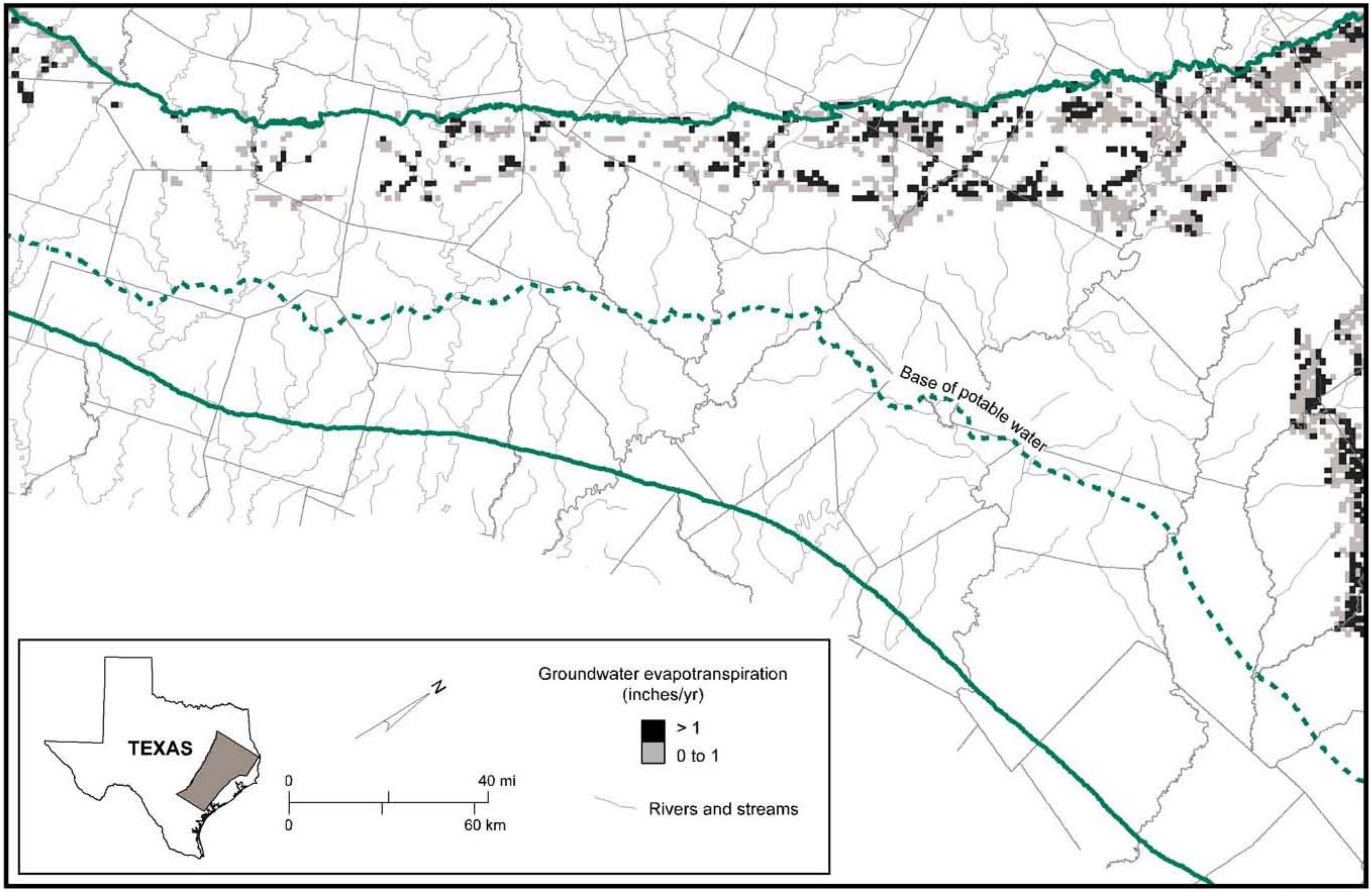

Figure 99. Map of aquifer discharge simulated as groundwater evapotranspiration for 2000.

for example, at Tyler and Henderson, Texas. The components of the water budget for 1990 and 2000 are reported in table 14 and illustrated in figure 100.

During the period included in the transient model, most recharge is simulated as being discharged to rivers and streams or taken up by ET. The rate of net recharge increases and ET decreases as pumpage increases, although these responses are obscured by annual variations in recharge rate shown in table 14. Net recharge, or movement from the unconfined to confined zones, is simulated to be 1.5 and 0.6 inches/yr in 2000 for the Simsboro and Carrizo aquifers, respectively, an increase from the steady-state model. Net recharge was estimated by summing the simulated fluxes across the flow faces of model cells at the boundary between the unconfined and confined zones; this tally takes into account cross-formational flow and change in storage in the unconfined zone. From 1950 through 2000, net recharge is simulated to have increased by 58,000 acre-ft/yr, whereas simulated stream flow decreased by 13,000 acre-ft/yr and groundwater ET decreased by 28,000 acre-ft/yr (fig. 98). Historical base-flow estimates, as previously noted, show no long-term decrease.

The GHB boundary applied to the Reklaw aquitard (layer 2) changes from net discharge out of the Carrizo–Wilcox aquifer to net inflow to the aquifer (table 14). The two largest reservoirs in the outcrop of the Carrizo–Wilcox aquifer, Lake Limestone and Richland-Chambers Reservoirs, were simulated as contributing most of the 4,200 acre-ft/yr simulated as leakage to the Carrizo–Wilcox aquifer from surface-water reservoirs (table 15). As previously stated, few data exist on historical leakage from these reservoirs, and the predicted losses are uncalibrated. The reservoir leakage accounts for about 1.5 percent of the water budget in the model.

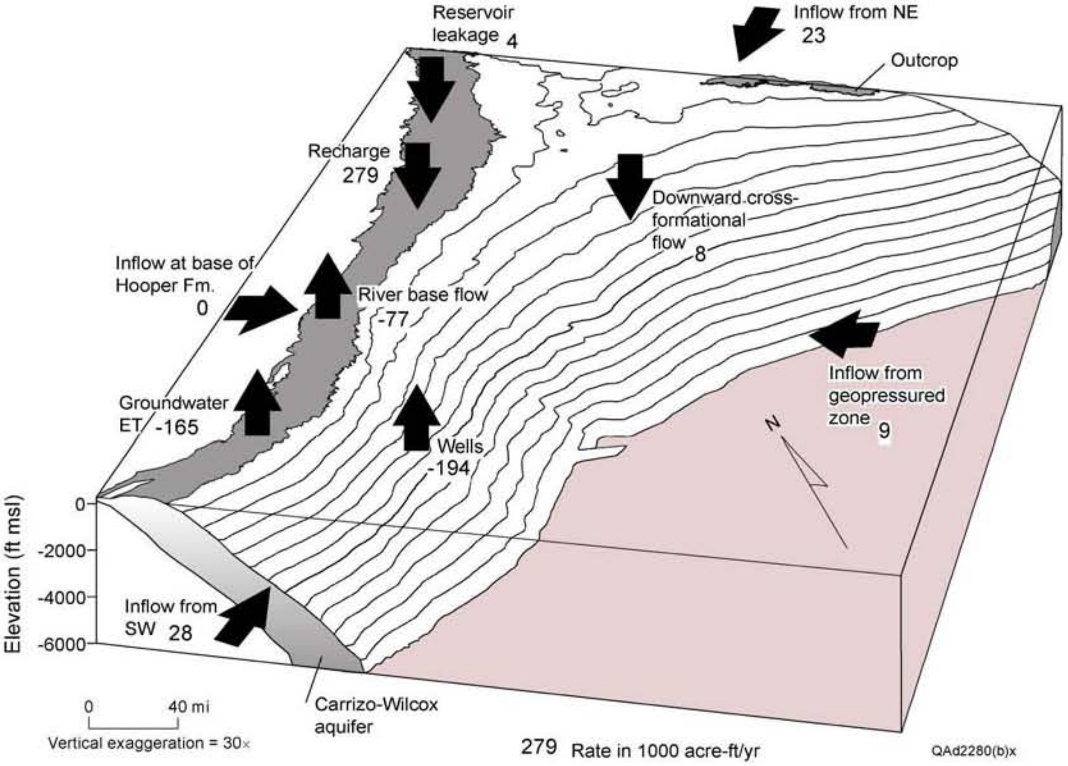

Figure 100. Block diagram of the Carrizo–Wilcox aquifer representing the components of the transient model for 2000.

Table 15. Simulated leakage of water to the Carrizo–Wilcox aquifer from surface-water reservoirs.

Reservoir	Total leakage (acre-ft/yr)	
	1990	2000
Lake Bastrop	120	120
Cedar Creek Reservoir	950	950
Fairfield Lake	120	120
Richland-Chambers Reservoir	1,060	1,040
Calaveras Lake	450	450
Lake Limestone	1,130	1,130
Twin Oak Reservoir	170	170
Alcoa Lake	40	40
Braunig Lake	180	180
Total	4,220	4,200

At the end of the historical period, no model cells are simulated as having gone dry in any layer. There is a narrow band adjacent to the outcrop where the width of the unconfined part of the aquifer grows as cells change from artesian to unconfined. The water-balance error for the 1990 and 2000 dates in the transient model is less than 0.01 percent.

9.3 Sensitivity Analysis

Results of the sensitivity analysis for the transient period (figs. 101, 102) are consistent with those for the steady-state analysis (figs. 77, 78). Simulated water levels in layer 5 (Simsboro aquifer) in the transient model are most sensitive to

- pumping rate (fig. 101c),
- horizontal hydraulic conductivity of the Simsboro aquifer (layer 5) (fig. 101a), and
- storativity (fig. 103b).

The results are also sensitive to recharge rate and the GHB heads in the Reklaw aquitard (fig. 101c) and at the northeastern and southwestern boundaries of the model. Changing the GHB conductance on the northeastern boundary from 0 (no-flow) to a large number has an effect on water levels within about 30 to 40 mi of the boundary.

Water levels are also sensitive to pumping rates. The transient model is less sensitive to recharge rates and horizontal conductivity than is the steady-state model. The same conclusions apply to the Carrizo aquifer (fig. 102)

Storativity was varied by one order of magnitude on each side of the calibrated value for each model layer. Changing storativity assigned to model cells can have a dramatic impact on drawdown in well fields but, on average, the model is less sensitive to storativity

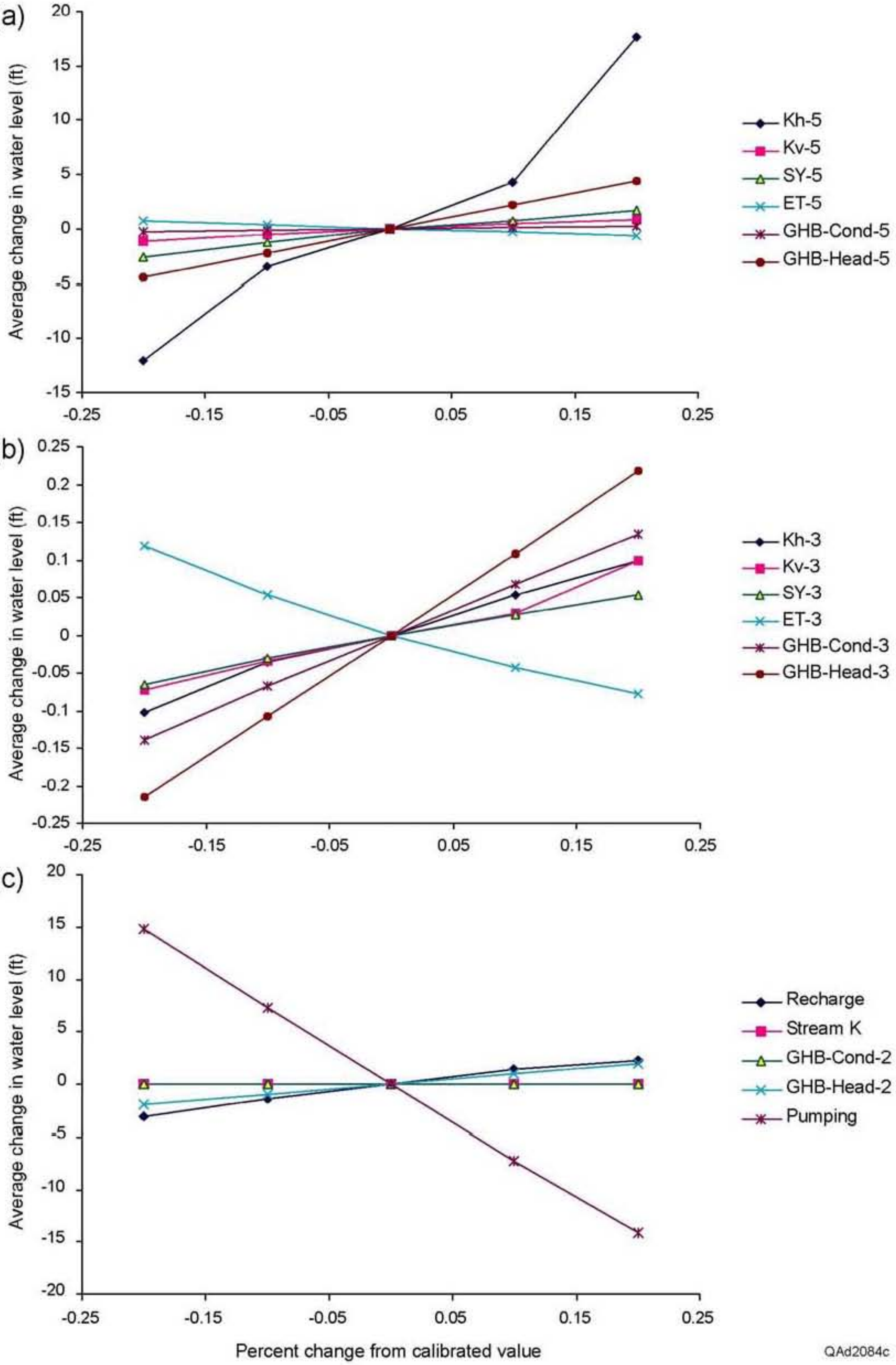

Figure 101. Sensitivity of predicted water levels in the Simsboro aquifer (layer 5) in the transient model to changes in parameter values for the (a) Simsboro aquifer (layer 5), (b) Carrizo aquifer (layer 3), and (c) other parts of the model.

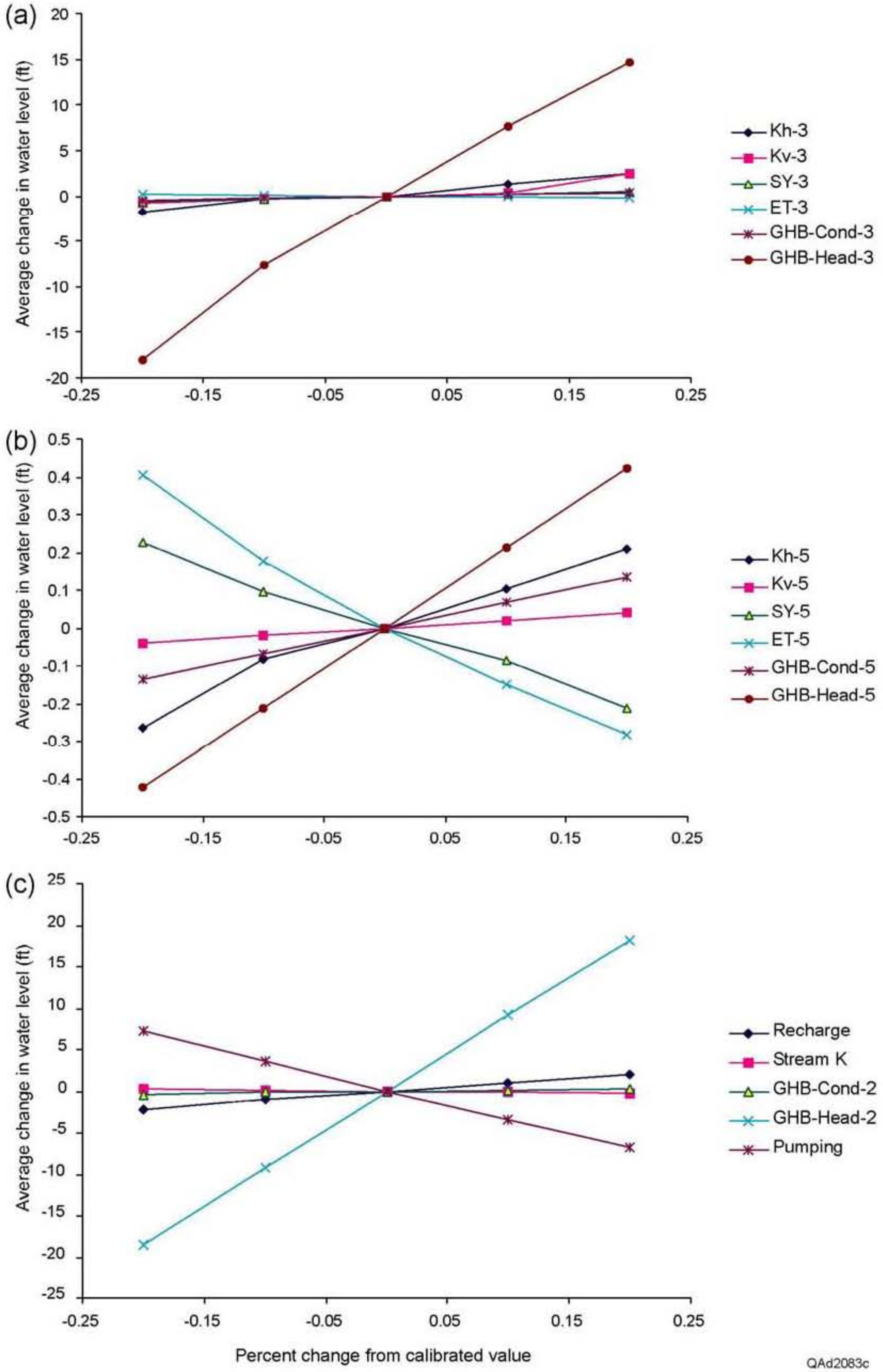

Figure 102. Sensitivity of predicted water levels in the Carrizo aquifer (layer 3) in the transient model to changes in parameter values for the (a) Carrizo aquifer (layer 3), (b) Simsboro aquifer (layer 5), and (c) other parts of the model.

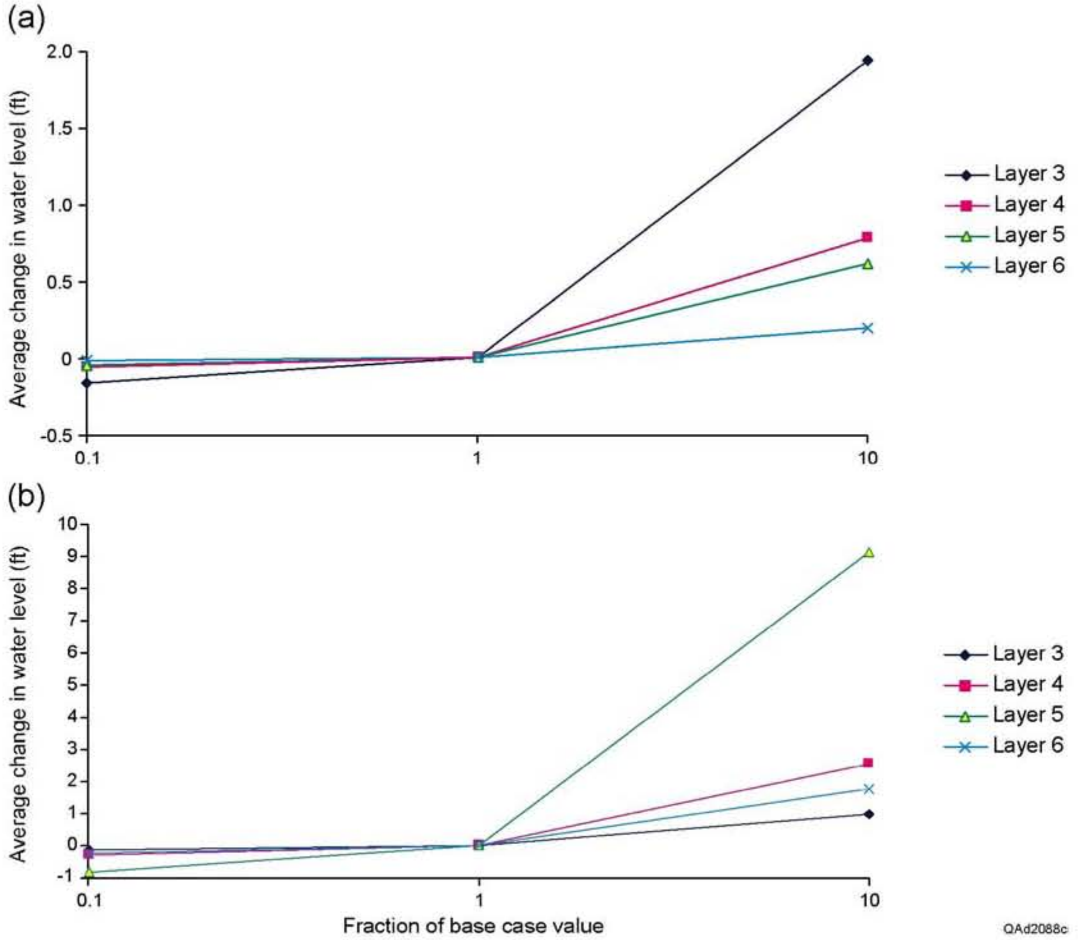

Figure 103. Sensitivity of simulated water levels to order-of-magnitude changes in storativity for the (a) Carrizo aquifer (layer 3), and (b) Simsboro aquifer (layer 5). Note difference in vertical scales.

than to other parameters (fig. 103). Figure 104 shows the sensitivity of several water-level hydrographs to order-of-magnitude differences in storativity. The examples are for wells that show a large amount of drawdown among those of figures 95 and 97; hydrographs for wells with little drawdown are not very sensitive to storativity.

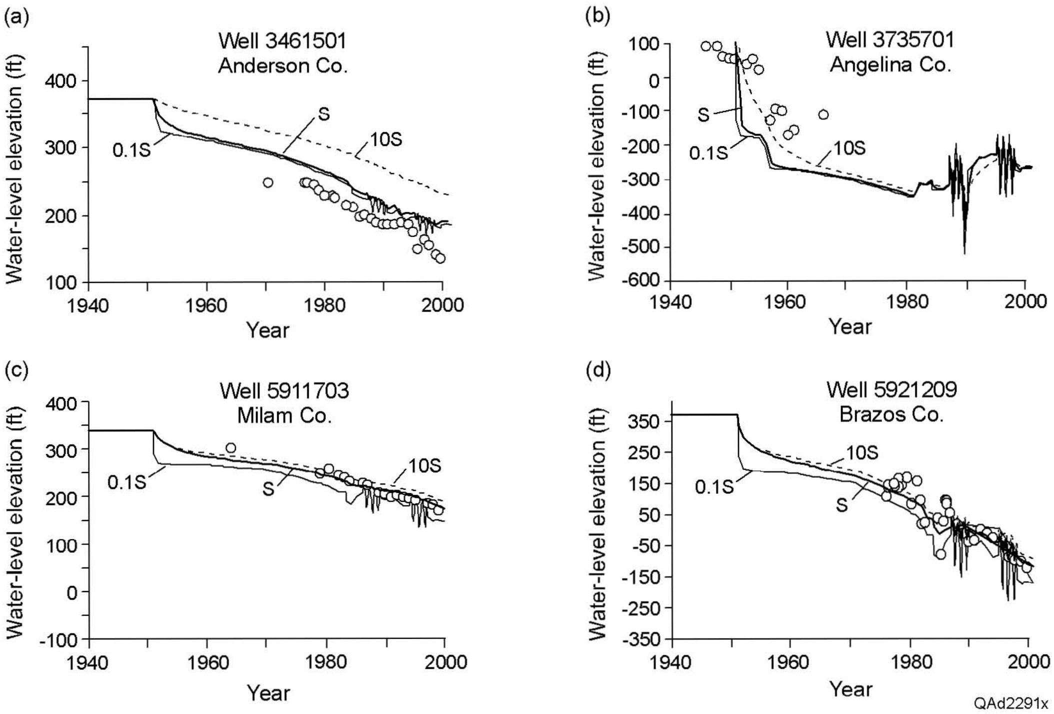

Figure 104. Sensitivity of simulated water levels (lines) in the Carrizo (a, b) and Simsboro (c, d) aquifers to differences in storativity. Location of wells in figure 36. Open circles = measured water levels.

10.0 PREDICTIONS

The purpose of developing the GAM model of the central part of the Carrizo–Wilcox aquifer is to provide a tool for evaluating changes in water level and stream flow for various expected or proposed changes in pumping rates and other activities impacting groundwater. To demonstrate the use of the model in predicting future water levels, base-line predictive simulations were run that include predicted pumping rates. The projected pumping rates for 2000 through 2050 were derived from a TWDB analysis of the demands and supplies of surface water and groundwater, along with possible water-management strategies, included in the Regional Water Plans prepared by Regional Water Planning Groups. These predictive runs were summarized in section 7.0. GHB heads for 2000 on the northeast and southwest boundaries were held constant in the predictive model from 2001 through 2050. The following section shows predicted water levels in the aquifer layers and predicted drawdown relative to the modeled 2000 water levels.

10.1 Predictive Results

A range in predicted water-level changes is shown in well hydrographs in figures 105 through 108 for the Hooper aquitard, the Simsboro aquifer, the Calvert Bluff aquitard, and the Carrizo aquifer, respectively. These extend the hydrographs of figures 94 through 97 from 2000 through 2050. Several of the hydrographs show a discontinuity—a step or jump—at 2000. This jump reflects differences in data sources for pumping rates used in the model. Pumping assigned to the historical model was derived from the water-use surveys conducted by the TWDB. Predicted pumping is based on the projections by regional

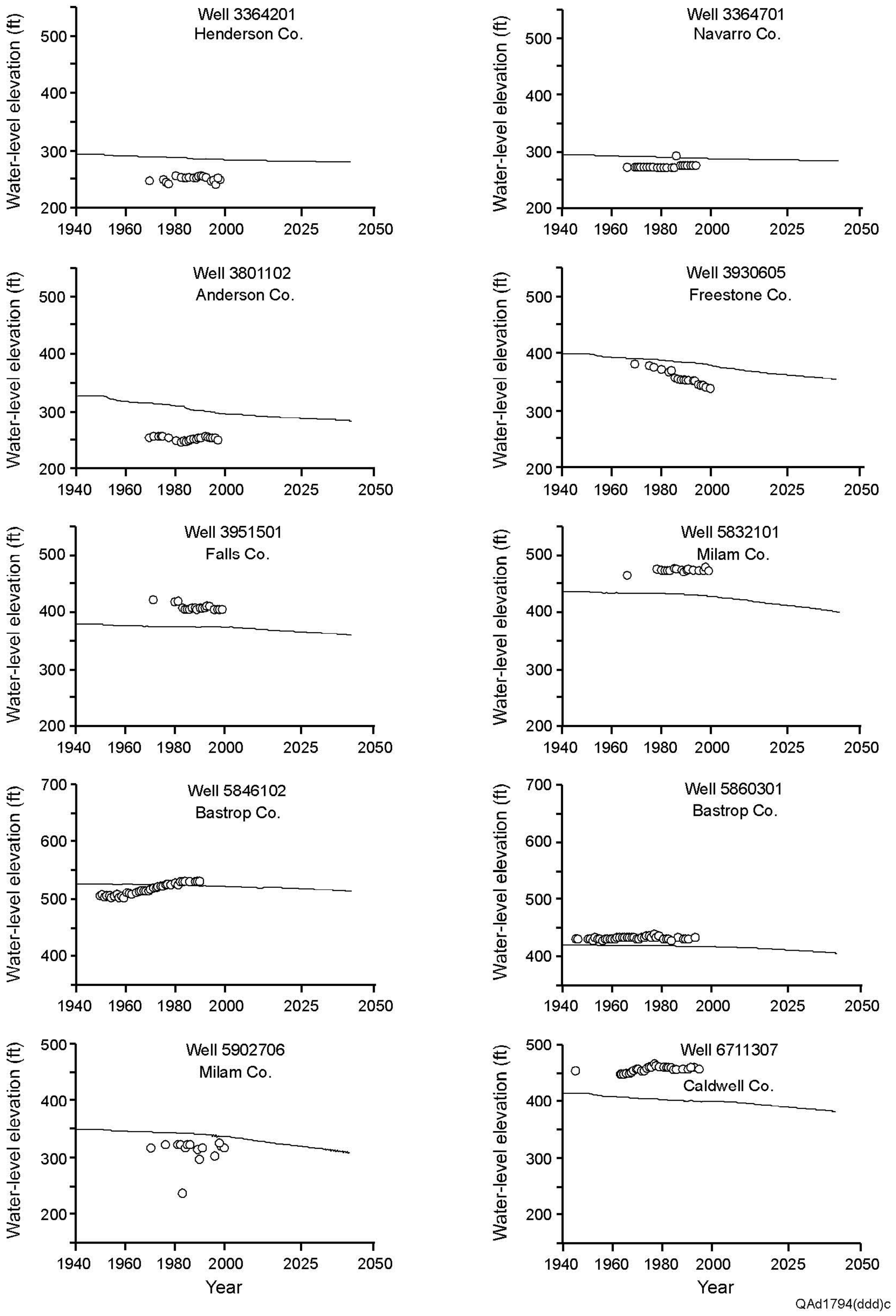

Figure 105. Simulated hydrographs showing predicted water levels through 2050 for wells in the Hooper aquitard (layer 6). Well locations are shown in figure 36.

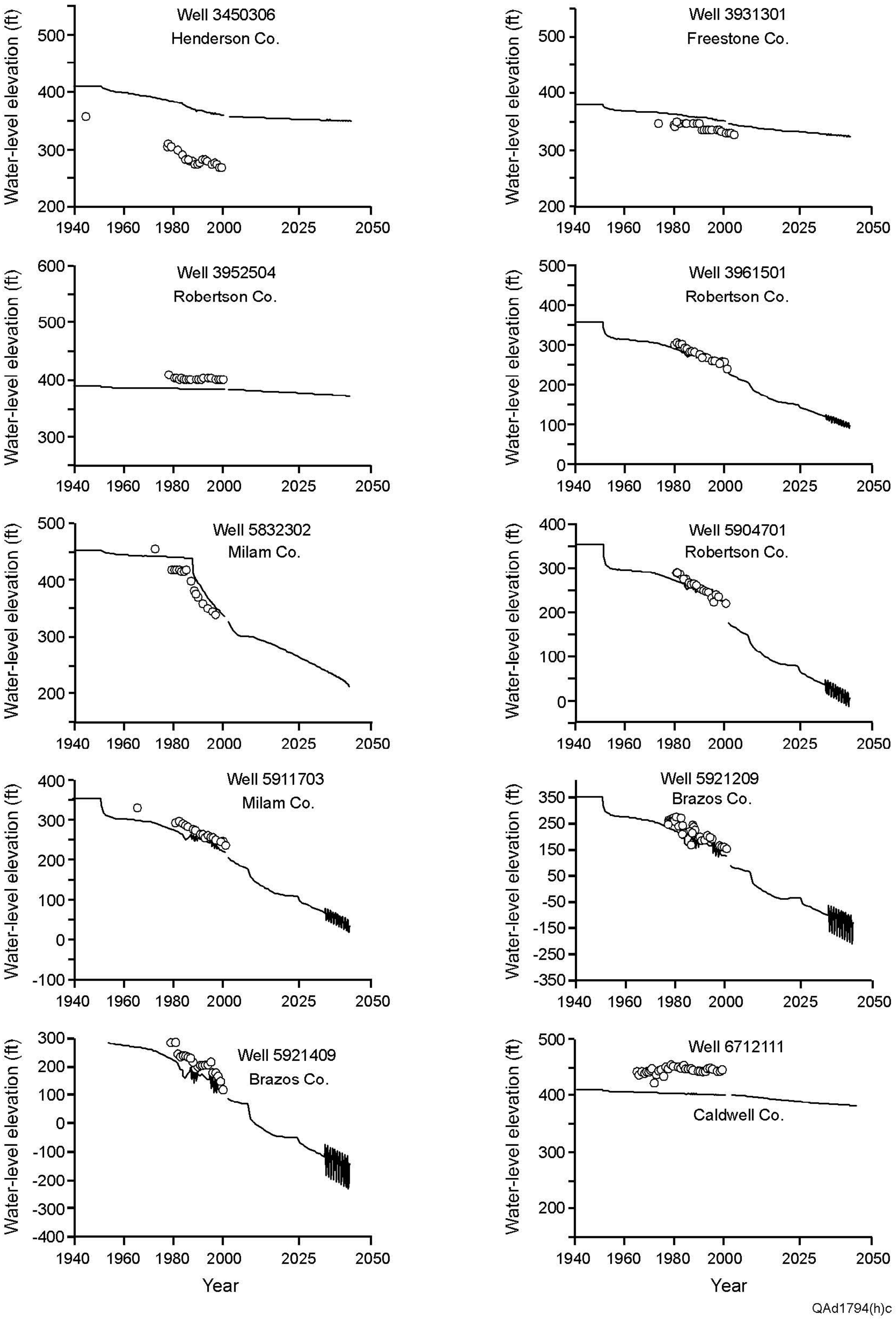

Figure 106. Simulated hydrographs showing predicted water levels through 2050 for wells in the Simsboro aquifer (layer 5). Locations of wells shown in figure 36.

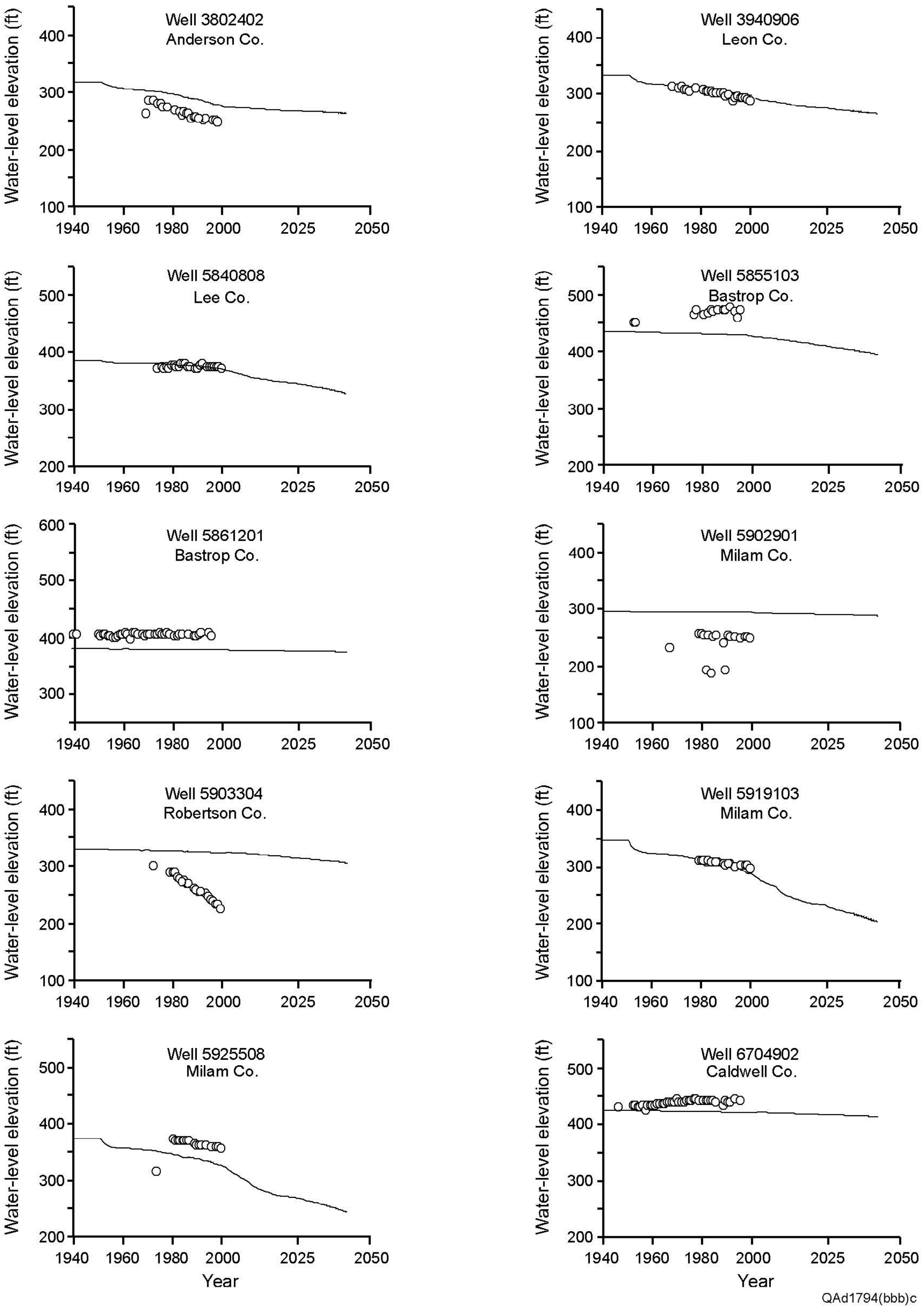

Figure 107. Simulated hydrographs showing predicted water levels through 2050 for wells in the Calvert Bluff aquitard (layer 4). Well locations are shown in figure 36.

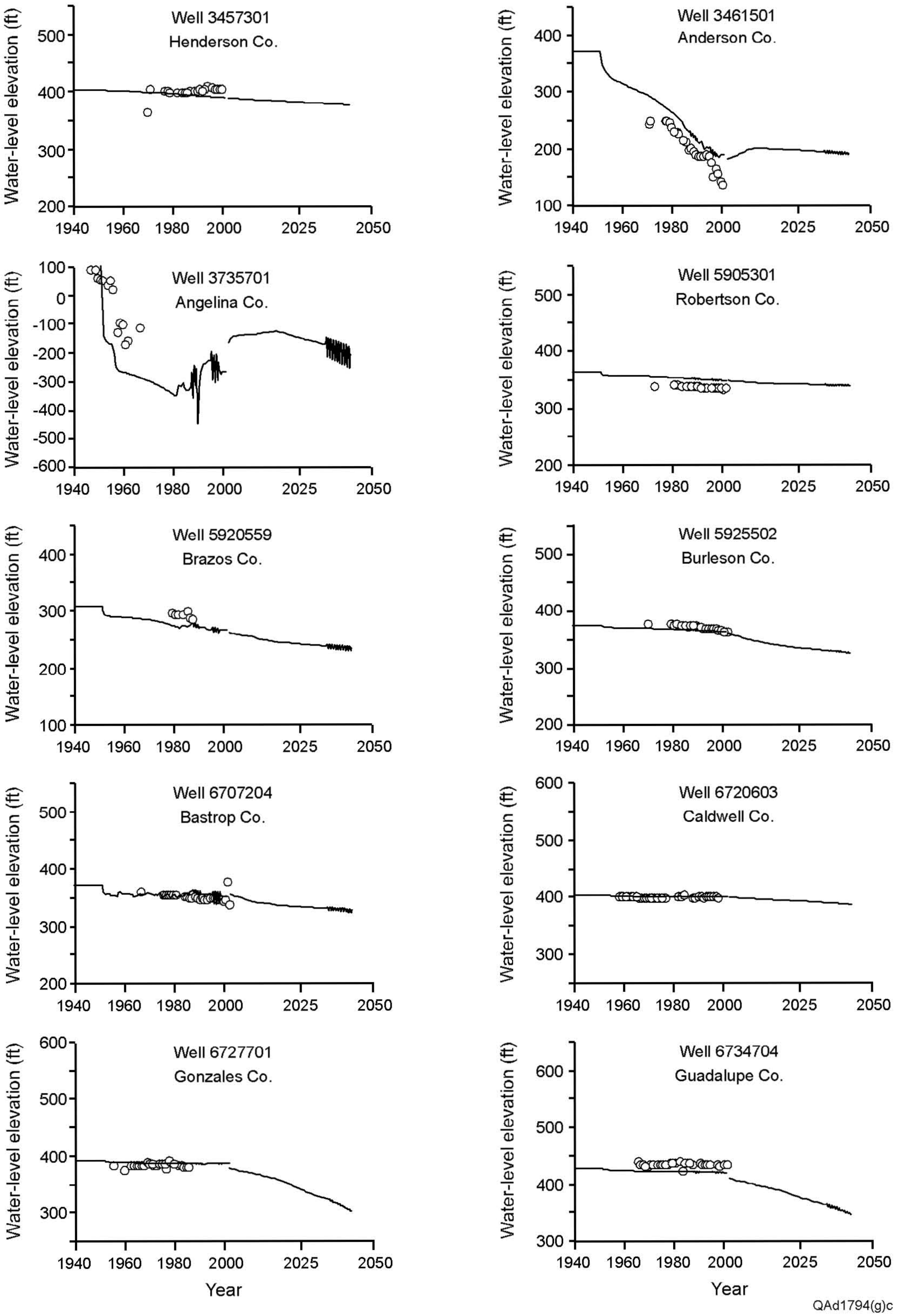

Figure 108. Simulated hydrographs showing predicted water levels through 2050 for wells in the Carrizo aquifer (layer 3). Locations of wells shown in figure 36.

water planning groups. Overall, the historical and predicted pumping rates match well at 2000 (fig. 52). Most of the difference is in assumed rates for municipal supply and irrigation. Differences can be significant for individual counties, but across the entire model and water-use categories the differences partly cancel out.

Other hydrograph features between 2000 and 2050 show predicted changes that are noteworthy. Long-term rates of drawdown in the vicinity of the Bryan-College Station well field (for example, wells in Brazos and Robertson Counties, fig. 105) are relatively constant from 1980 through 2050. Little change in rate of drawdown is predicted for other wells more distant from the well field. The last 10 yr of the 2000-through-2050 simulation consists of 120 1-month stress periods in which pumping rates were varied to allow an evaluation of annual fluctuations in water level. Winter and summer pumping rates used in the model differ by a factor of about 2 (see fig. 98 for the 1987–89 and 1995–97 periods). The differences reflect monthly changes in assumed rates for municipal, industrial, rural domestic, and irrigation rates. Annual fluctuations in water level are proportional to total pumping rates. Water-level response is less sensitive to specific storage than to pumping rate. Thus, wells close to the pumping centers show greater water-level fluctuations.

Figures 109 through 113 show predicted changes in water levels in the Simsboro aquifer for the periods from 2010, 2020, 2030, 2040, and 2050, respectively. Obvious predicted changes in the Simsboro aquifer are (1) increase in the area where drawdown exceeds 25 ft and (2) increase in drawdown to almost 300 ft between 2000 and 2050 in parts of Brazos and Lee Counties. Water levels remain above the top of the confined part of the Simsboro aquifer through 2050. Drawdown is attributed to the continued growth in groundwater withdrawal from the Bryan-College Station well field, development of a

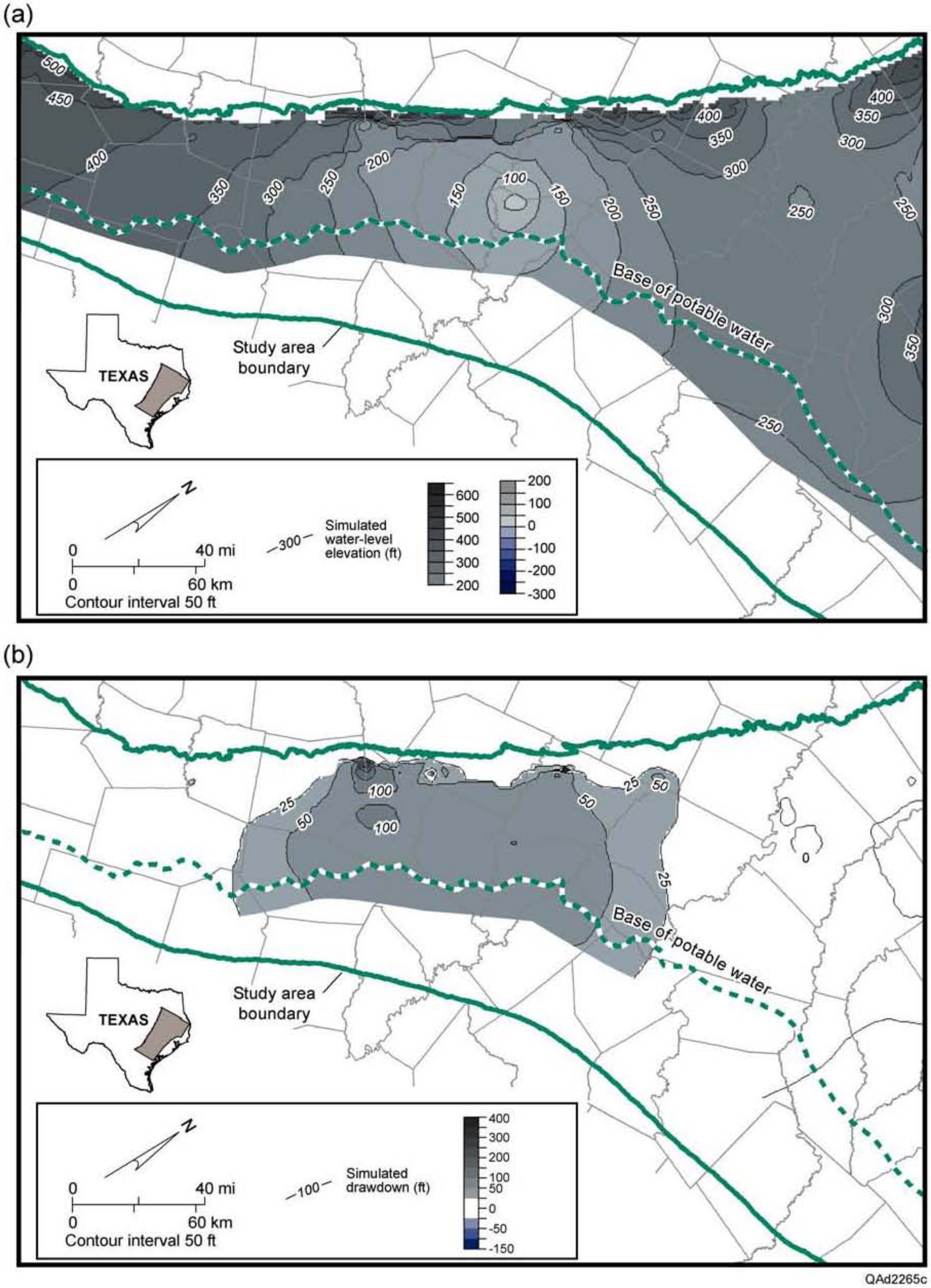

Figure 109. Maps for the Simsboro aquifer (layer 5) showing predicted (a) 2010 water level and (b) drawdown from 2000 through 2010 assuming drought-of-record recharge from 2008 through 2010.

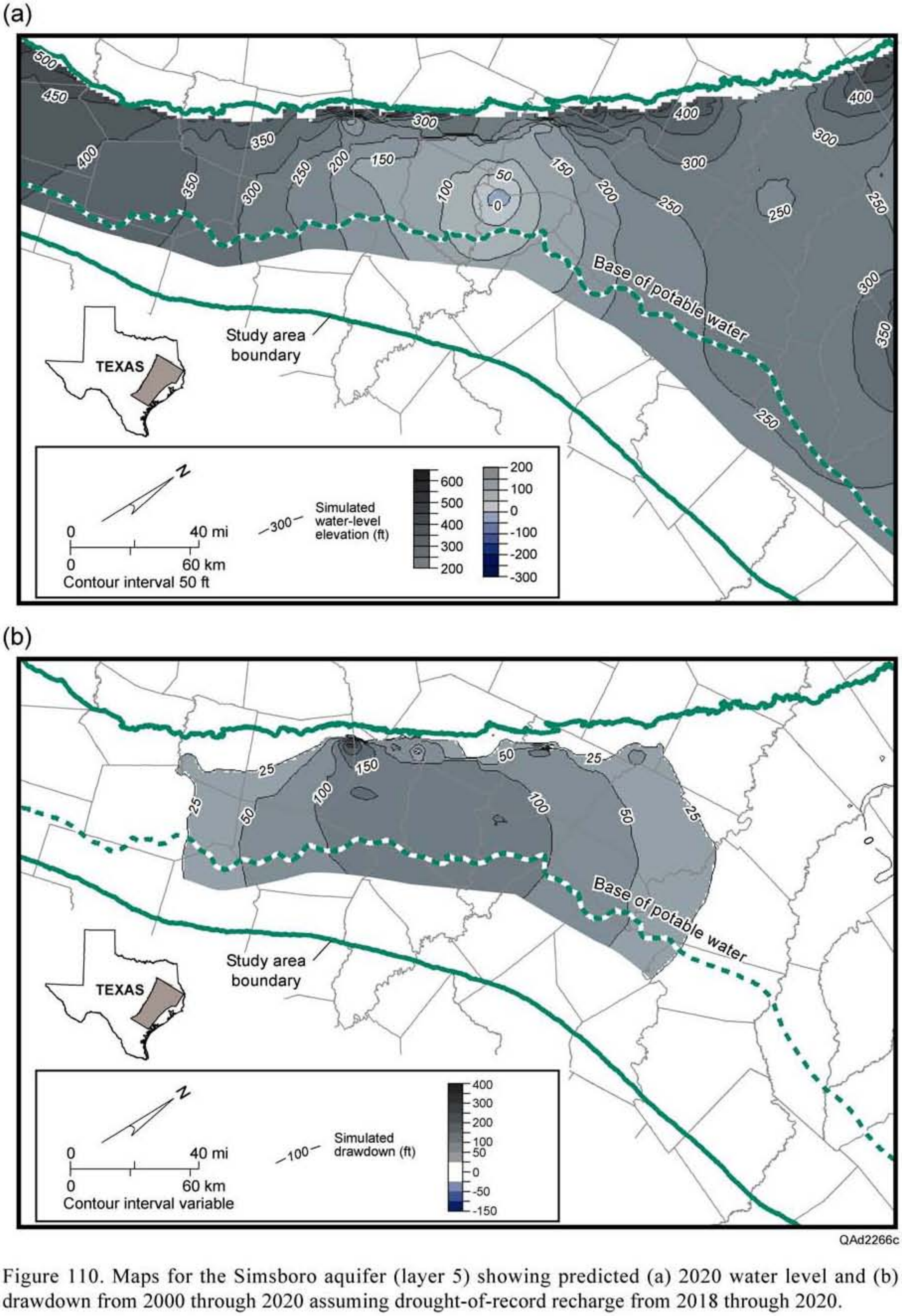

Figure 110. Maps for the Simsboro aquifer (layer 5) showing predicted (a) 2020 water level and (b) drawdown from 2000 through 2020 assuming drought-of-record recharge from 2018 through 2020.

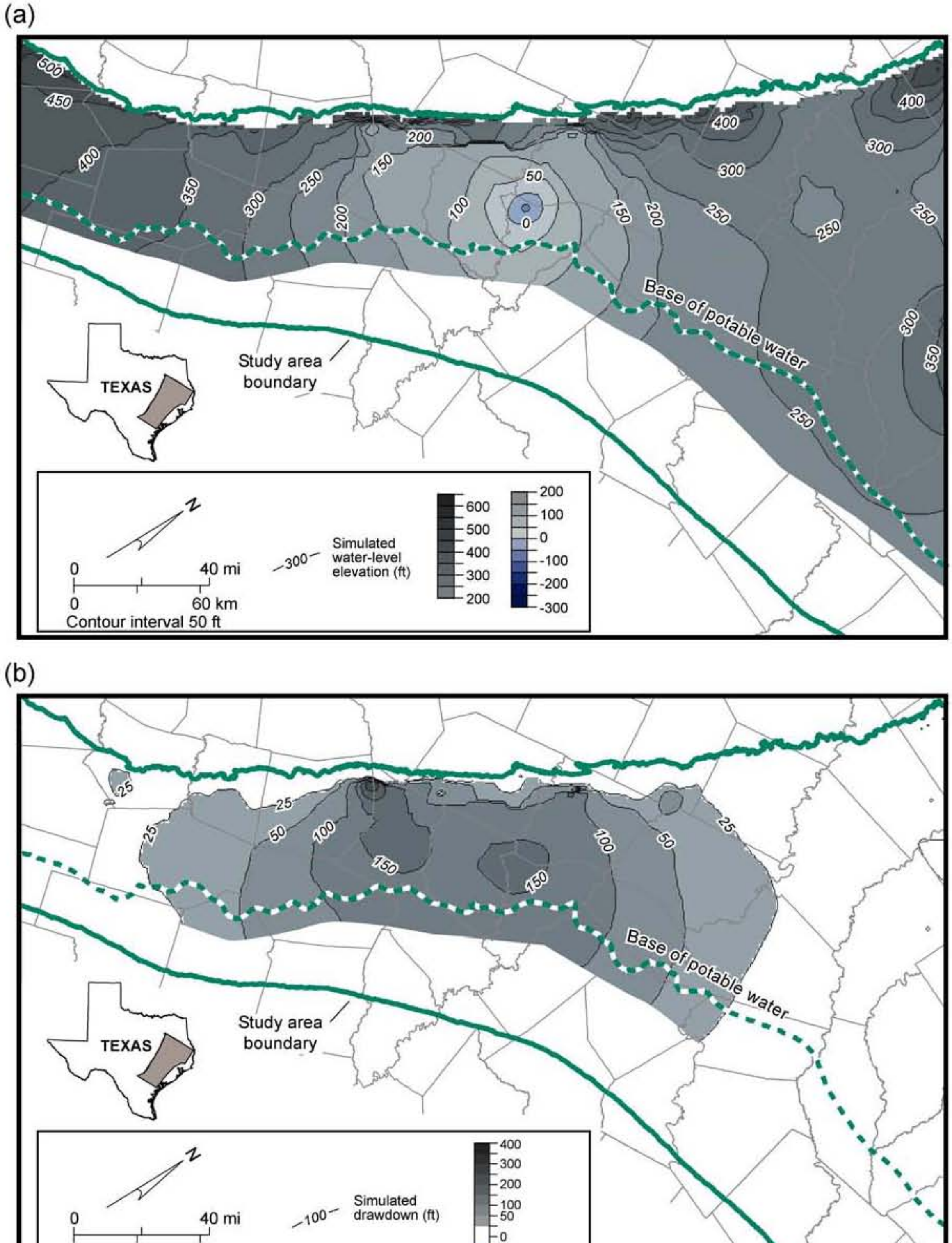

Figure 111. Maps for the Simsboro aquifer (layer 5) showing predicted (a) 2030 water level and (b) drawdown from 2000 through 2030 assuming drought-of-record recharge from 2028 through 2030.

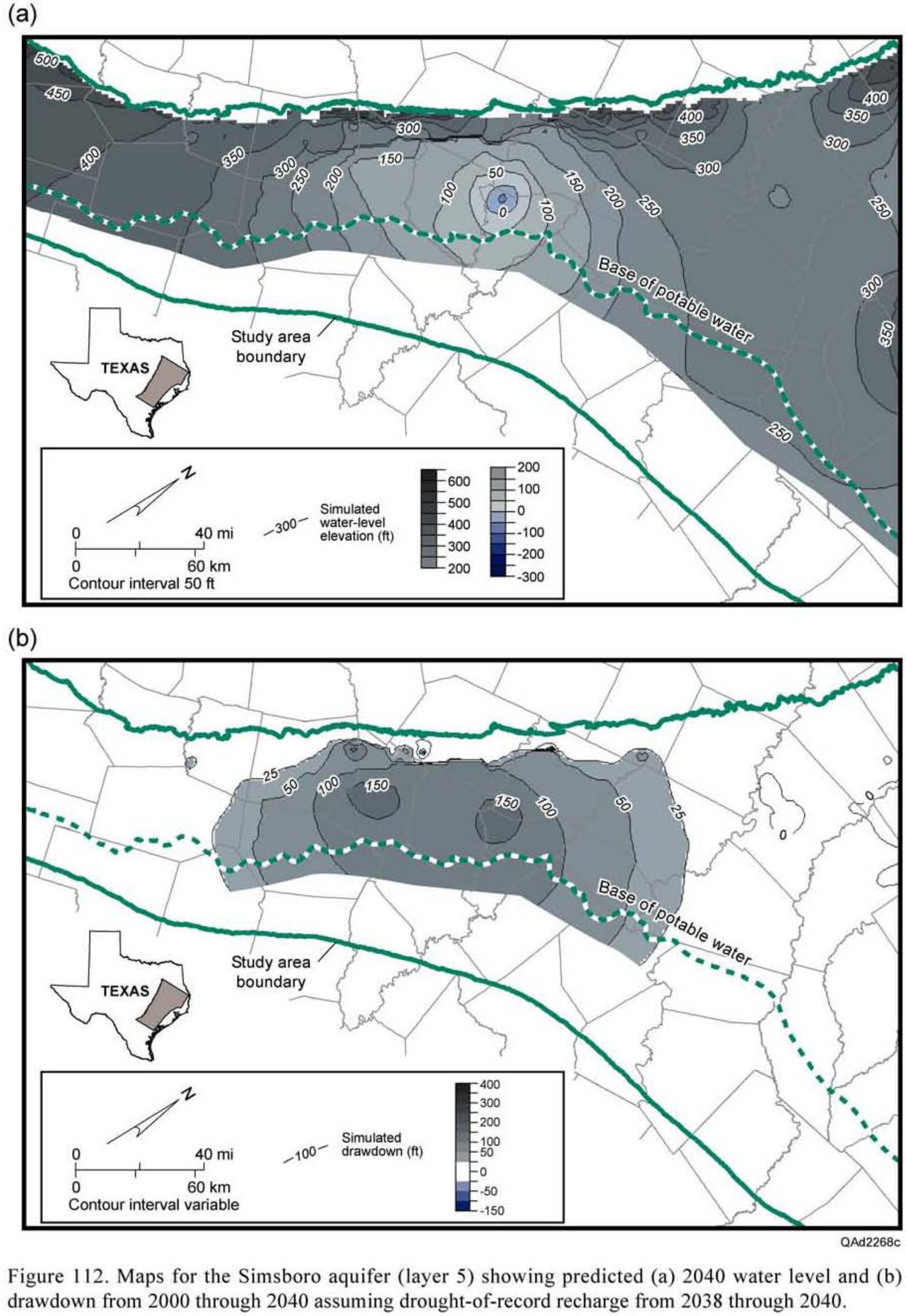

Figure 112. Maps for the Simsboro aquifer (layer 5) showing predicted (a) 2040 water level and (b) drawdown from 2000 through 2040 assuming drought-of-record recharge from 2038 through 2040.

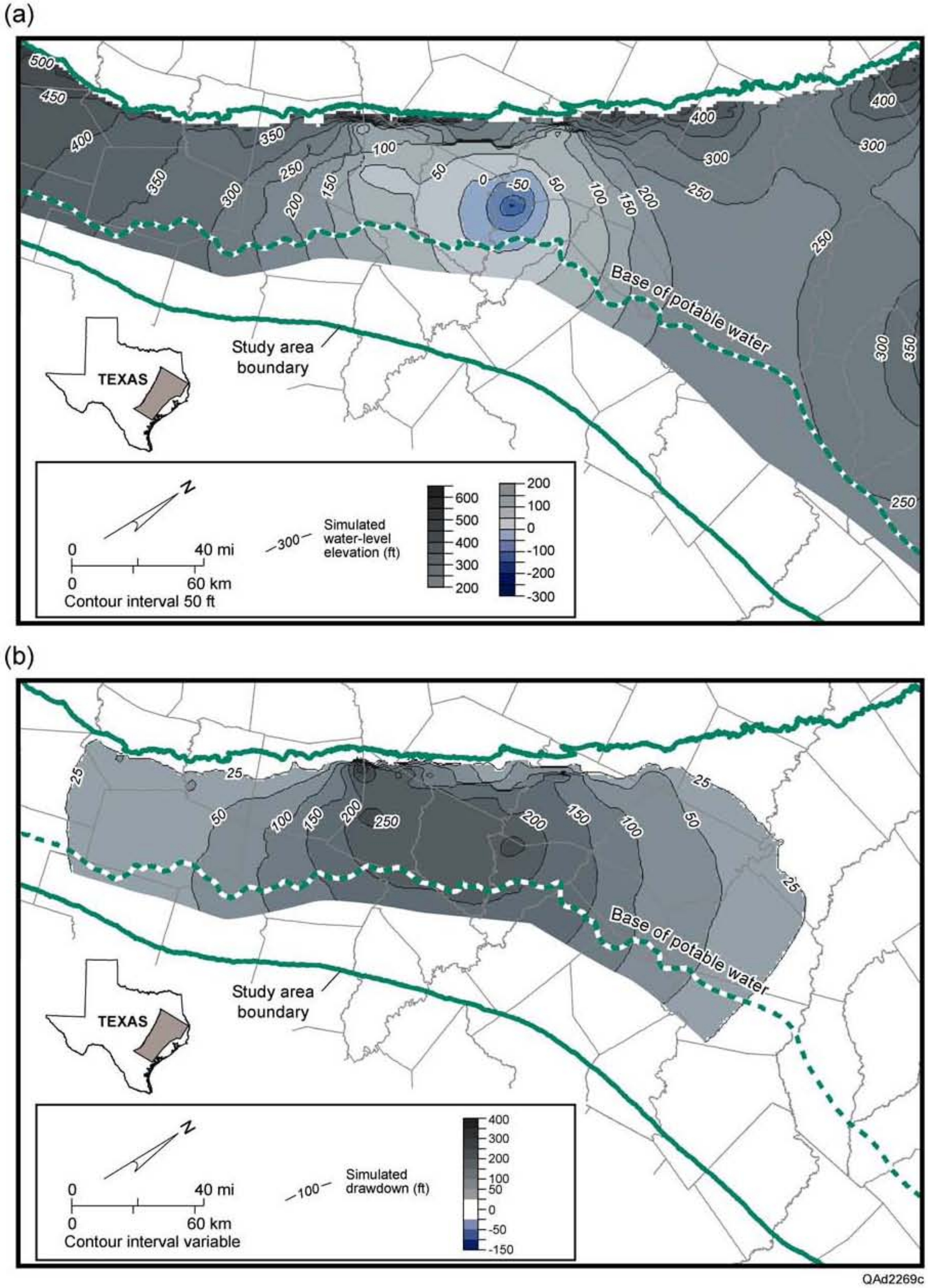

Figure 113. Maps for the Simsboro aquifer (layer 5) showing predicted (a) 2050 water level and (b) drawdown from 2000 through 2050 assuming drought-of-record recharge from 2048 through 2050.

well field in Lee County to meet Williamson County water needs, and other increases in withdrawal from the aquifer.

The water-level drawdown maps (for example, fig. 109b) show the area near the northeastern study boundary to have slightly negative (<0) drawdown. This prediction is an artifact of the assumed pumping rates for many of the counties near the boundary. It is unlikely that water levels will show significant recovery unless regional decreases in pumping rates are realized.

Additional drawdown in the central part of the study area is due to withdrawal of groundwater for a well field assigned to Lee County as part of the Brazos G Regional Water Plan strategy to meet Williamson County water needs. Part of that volume was assigned to the Carrizo aquifer and part to the Simsboro aquifer, using the footprint defined in the Trans-Texas Water Program (HDR Engineering, 1998). The spread of the area of drawdown around these projects is affected by the Karnes-Milano-Mexia Fault Zone (fig. 14). Water-level contours in figures 109 through 113 come close together and define a steep gradient in hydraulic head across the fault zone.Groundwater withdrawal associated with mining operations and groundwater withdrawal for transfer to the City of San Antonio in Bastrop and Lee Counties on the updip (northwestern) side of the fault zone adds to the regional drawdown.

Drawdown of the water levels in the Simsboro aquifer is predicted to grow to more than 100 ft by 2010, relative to 2000 water levels, and to almost 300 ft by 2050. By 2050, therefore, the model predicts that the historical (1950 through 2000) drawdown (fig. 90) will be doubled in the deeper artesian part of the aquifer, assuming that project pumping rates are realized. The water levels, however, remain above the top of the Simsboro aquifer. Predictions of the amount of drawdown and incidence of change from artesian to unconfined conditions nearer the outcrop is very sensitive to the assumed distribution or concentration of pumping represented in various model cells. As previously mentioned, the only change in simulation of normal precipitation and drought-of-record years was the use of different recharge rates. Pumping rates and their monthly variations were not changed to reflect changes in demand under drought conditions. For normal precipitation years in the predictive model, we used a constant recharge rate calculated from the average precipitation for 1960 through 1997 by the same equations used to estimate recharge for the transient model. Using 1960 through 1997 data excluded the effect of the 1950s drought of record from the calculation of the normal year recharge rate. Monthly recharge during the drought years was calculated from the precipitation of drought-of-record years (1954 through 1956). We kept monthly recharge rate constant during the drought in the predictive model because we assumed that drainage from the unsaturated zone to the water table in the Carrizo–Wilcox aquifer would not cease during a 3-yr drought.

Figures 114 through 118 show predicted changes in water levels in the Carrizo aquifer from 2000 through 2010, 2020, 2030, 2040, and 2050, respectively. The Carrizo drawdown maps also show areas of water-level recovery (drawdown values <0) in the northeast side. These are artifacts of the differences in historical and predictive pumping data from the TWDB and Regional Water Planning Groups. Other features are noteworthy. In the center of the model area, drawdown is due to pumping of groundwater from the Carrizo aquifer from the Bryan-College Station well field near the Brazos-Robertson County line, and from a Lee County well field assumed to be the source of water for Williamson County needs, as previously mentioned. Drawdown increases relative to 2000 water levels in Lee and adjacent counties. Also, several strategies in the South Central Texas Region L

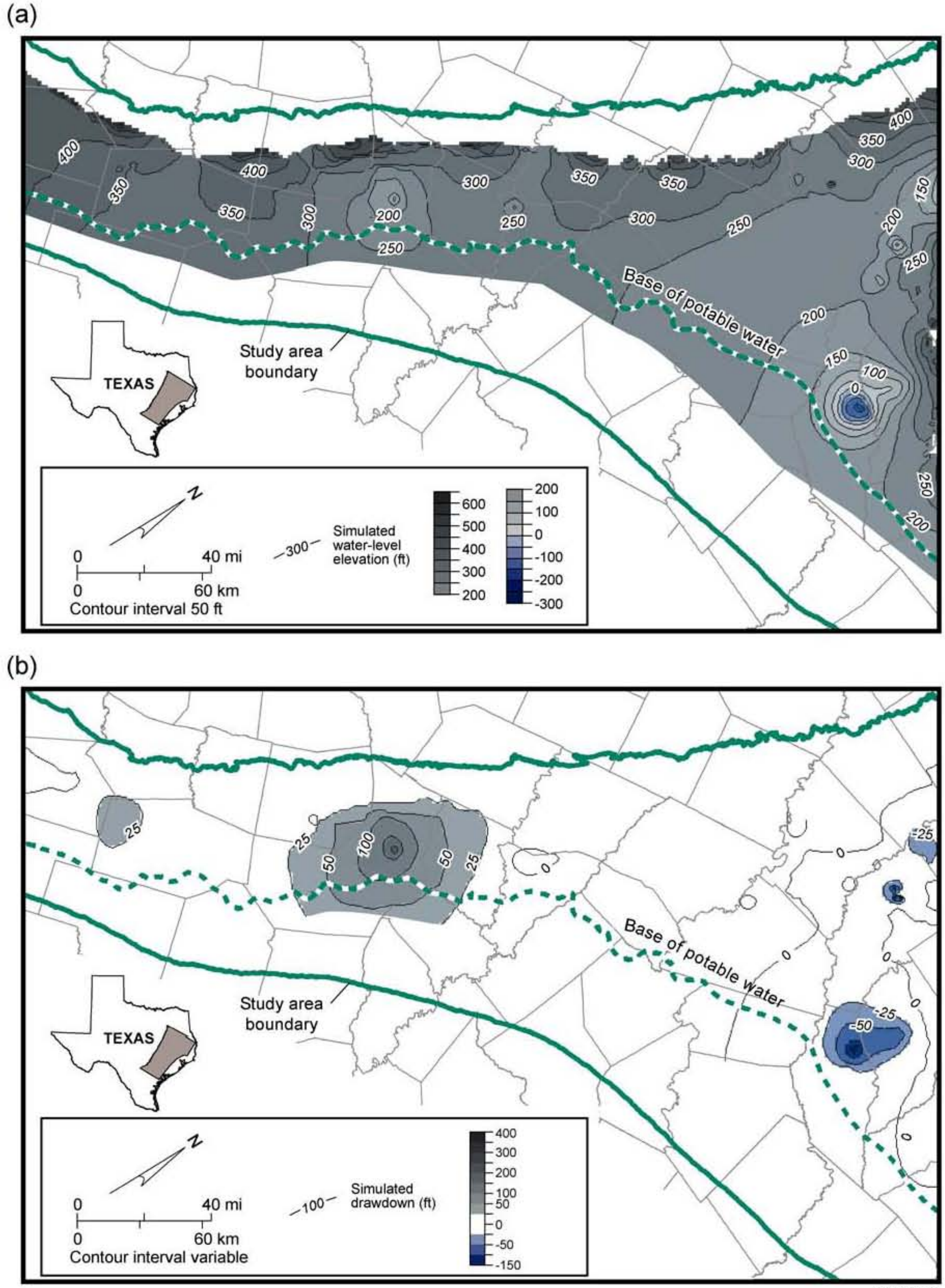

Figure 114. Maps for the Carrizo aquifer (layer 3) showing predicted (a) 2010 water level and (b) drawdown from 2000 through 2010 assuming drought-of-record recharge from 2008 through 2010.

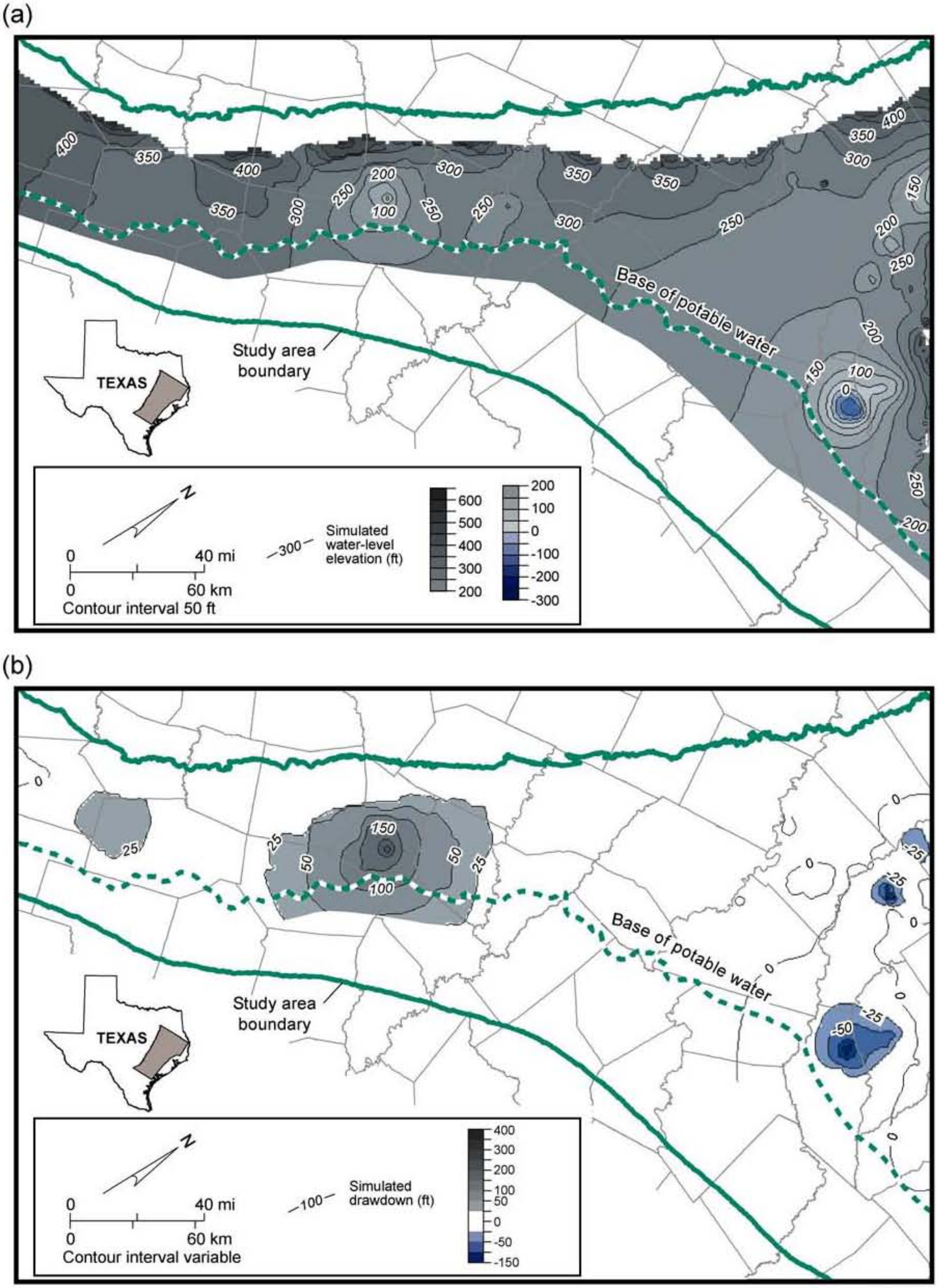

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Figure 115. Maps for the Carrizo aquifer (layer 3) showing predicted (a) 2020 water level and (b) drawdown from 2000 through 2020 assuming drought-of-record recharge from 2018 through 2020.

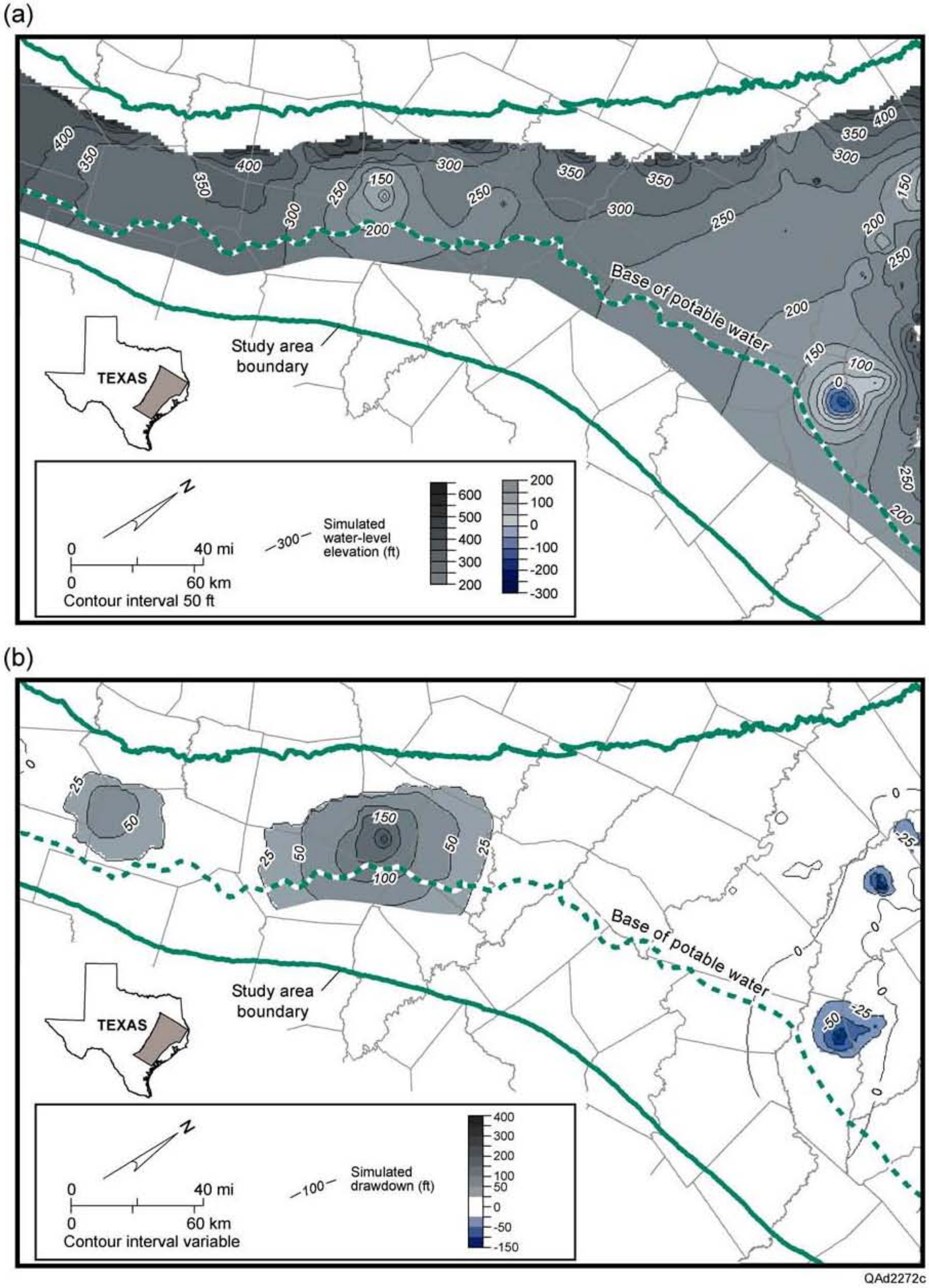

Figure 116. Maps for the Carrizo aquifer (layer 3) showing predicted (a) 2030 water level and (b) drawdown from 2000 through 2030 assuming drought-of-record recharge from 2028 through 2030.

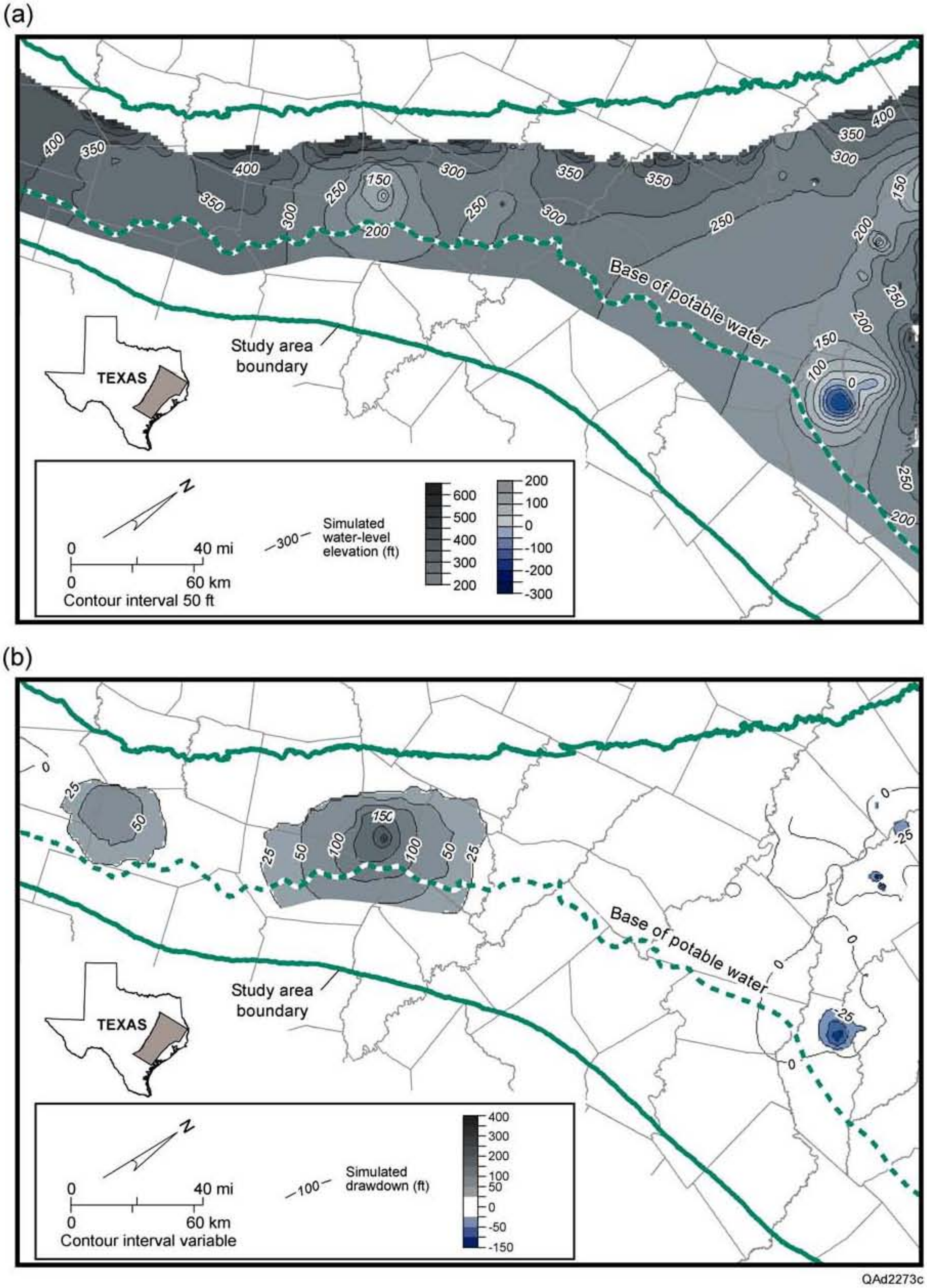

Figure 117. Maps for the Carrizo aquifer (layer 3) showing predicted (a) 2040 water level and (b) drawdown from 2000 through 2040 assuming drought-of-record recharge from 2038 through 2040.

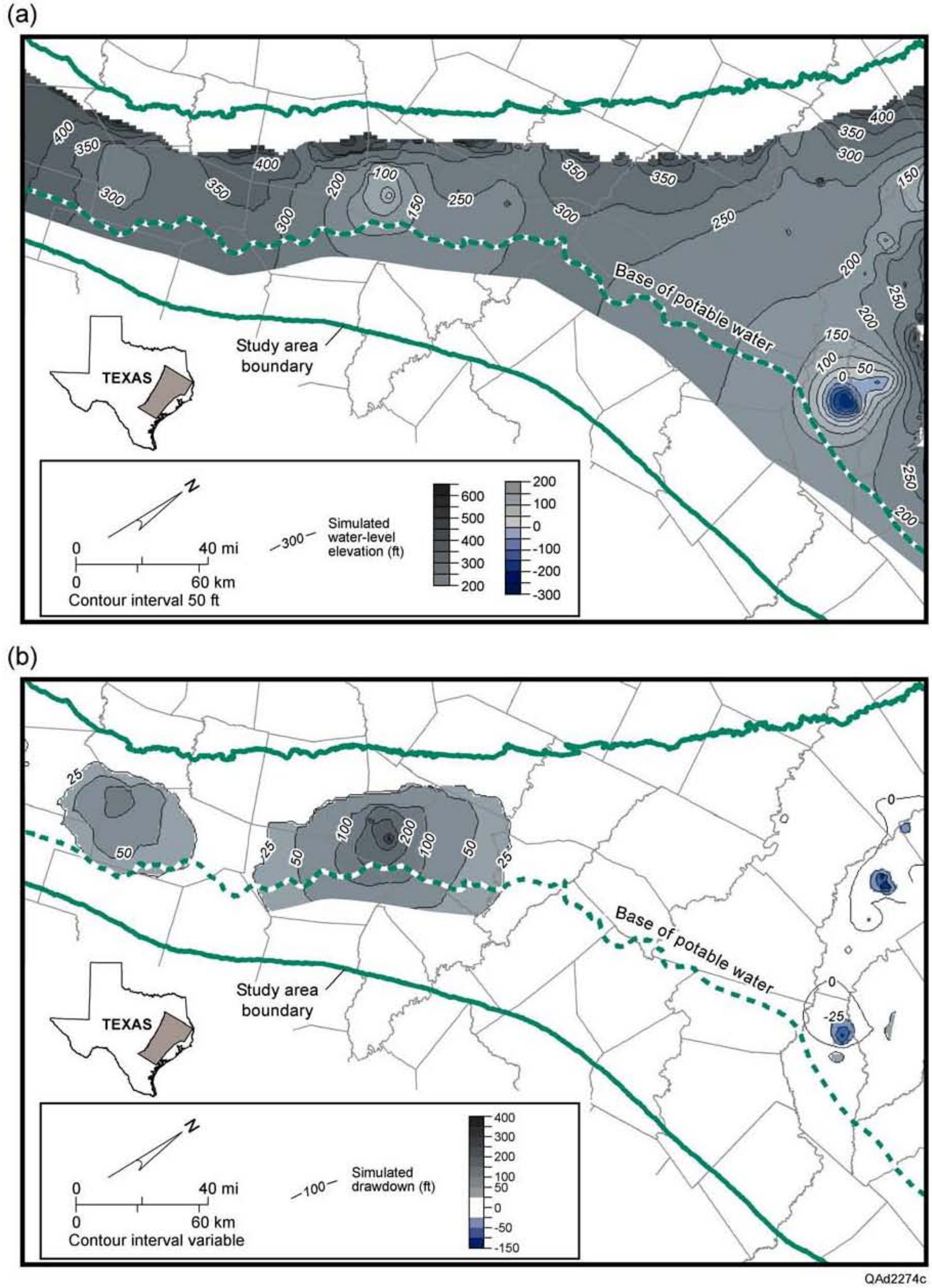

Figure 118. Maps for the Carrizo aquifer (layer 3) showing predicted (a) 2050 water level and (b) drawdown from 2000 through 2050 assuming drought-of-record recharge from 2048 through 2050.

water plan identify the Carrizo aquifer in western Gonzales County as a source of groundwater. Drawdown in the Carrizo aquifer in western Gonzales County is predicted to be less than 100 ft over the 2000-through-2050 period (fig. 118).

Figures 119 and 120 show predicted 2050 water levels and drawdown, relative to 2000 water levels, in the Hooper and Calvert Bluff Formations. About 30 models cells at the updip limit of the outcrop of the Hooper aquitard (layer 6) are simulated as going dry by 2050. These are the only model cells that go dry during the historical and predictive simulations. That these cells go dry in the model reflects the interaction of pumping and recharge rates, cell thickness, specific yield, and hydraulic conductivity assigned to that part of the model. Groundwater withdrawal assigned to these model cells represents mainly rural domestic water use, estimated on the basis of census information. Finding good yields of potable groundwater near the updip limit of the Hooper aquitard can be problematic. Future pumping rates from the updip Hooper aquitard will most likely be limited by well yield and water quality.

Some drawdown in the Hooper and Calvert Bluff aquitards is predicted from cross-formational flow. The Carrizo–Wilcox aquifer is a “leaky” aquifer in which some of the water pumped from well fields in the Simsboro and Carrizo aquifers derives from cross-formational leakage. The model predicts that such cross-formational flow accounts for more than 25 ft of water-level change in the Hooper aquitard (fig. 118b). Most of the predicted drawdown in the Calvert Bluff aquitard (>50 ft, fig. 120b) is a result of cross-formational leakage to that part of the Simsboro aquifer with more than 100 ft of drawdown (compare figs. 120b and 113b).

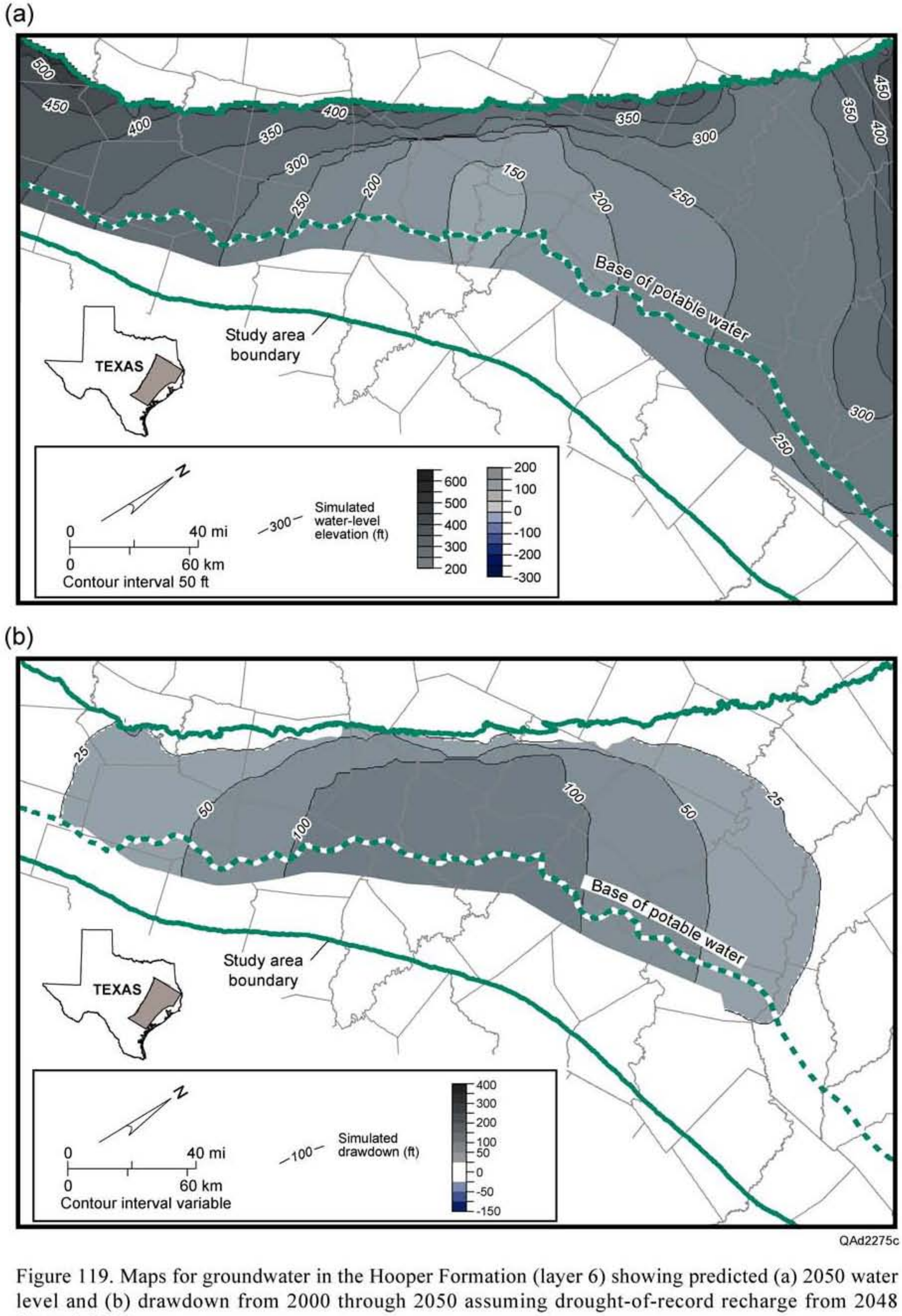

Figure 119. Maps for groundwater in the Hooper Formation (layer 6) showing predicted (a) 2050 water level and (b) drawdown from 2000 through 2050 assuming drought-of-record recharge from 2048 through 2050.

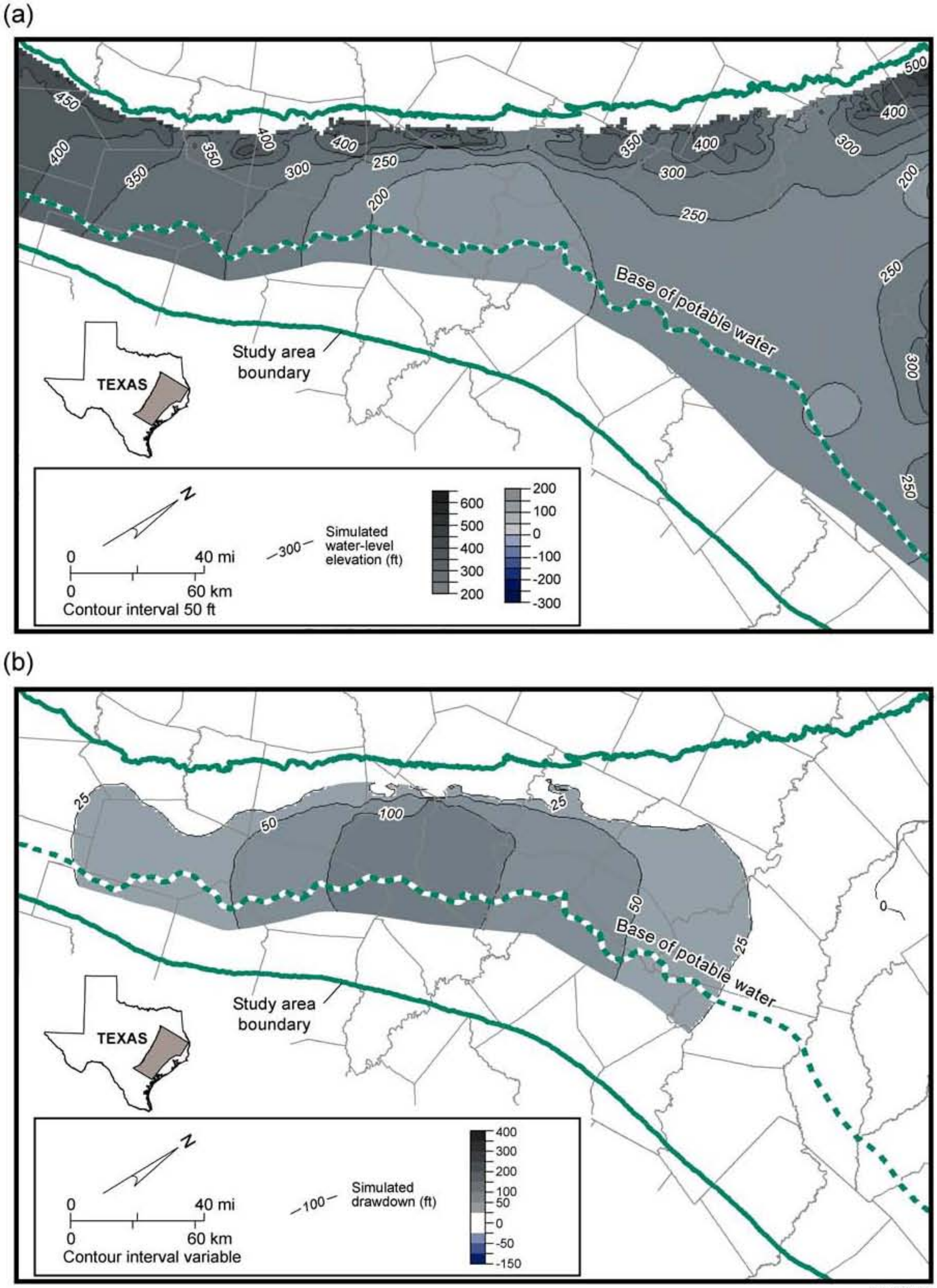

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Figure 120. Maps for groundwater in the Calvert Bluff Formation (layer 4) showing predicted (a) 2050 water level and (b) drawdown from 2000 through 2050 assuming drought-of-record recharge during 2048 through 2050.

Model simulation results shown in figures 109 through 120 include average recharge except for drought-of-record recharge rates applied in the last 3 yr of each simulation. Another simulation from 2000 through 2050 did not include the 3-yr drought-level recharge rates. Water levels predicted for 2050 using average and drought-level recharge rates differ by less than 5 ft and only near the outcrop (fig. 121a, b).

10.2 Water Budget

Table 16 presents the water budget for the preceding predictive simulations. Average recharge was used except for the last 3 yr of each simulation, for which we used a recharge rate predicted from precipitation during the 1954 through 1956 drought of record. GHB head at lateral boundaries of layers and assigned to layer 2 were kept constant at 2000 levels. Groundwater withdrawal (wells) is predicted to increase from approximately 194,000 to 363,000 acre-ft/year. This increase results in some changes in the water budget, but the main characteristics and trends are similar to those of the historical transient water budget (table 14). ET and base-flow discharge to streams are predicted to generally decrease as predicted water levels decline in the outcrop. Stream loss is approximately 21 percent of the stream gains; rivers and streams overall remain as gaining streams through 2050. Comparison of the simulated 2050 water levels with average versus drought-of-record recharge shows that recharge, ET, and stream gains are reduced during the predicted drought. Figure 122 illustrates the major components of the water budget in a block diagram for comparison with figures 79 and 100 for the steady-state and transient (2000) model. The model predicts a further reduction in base flow in all streams

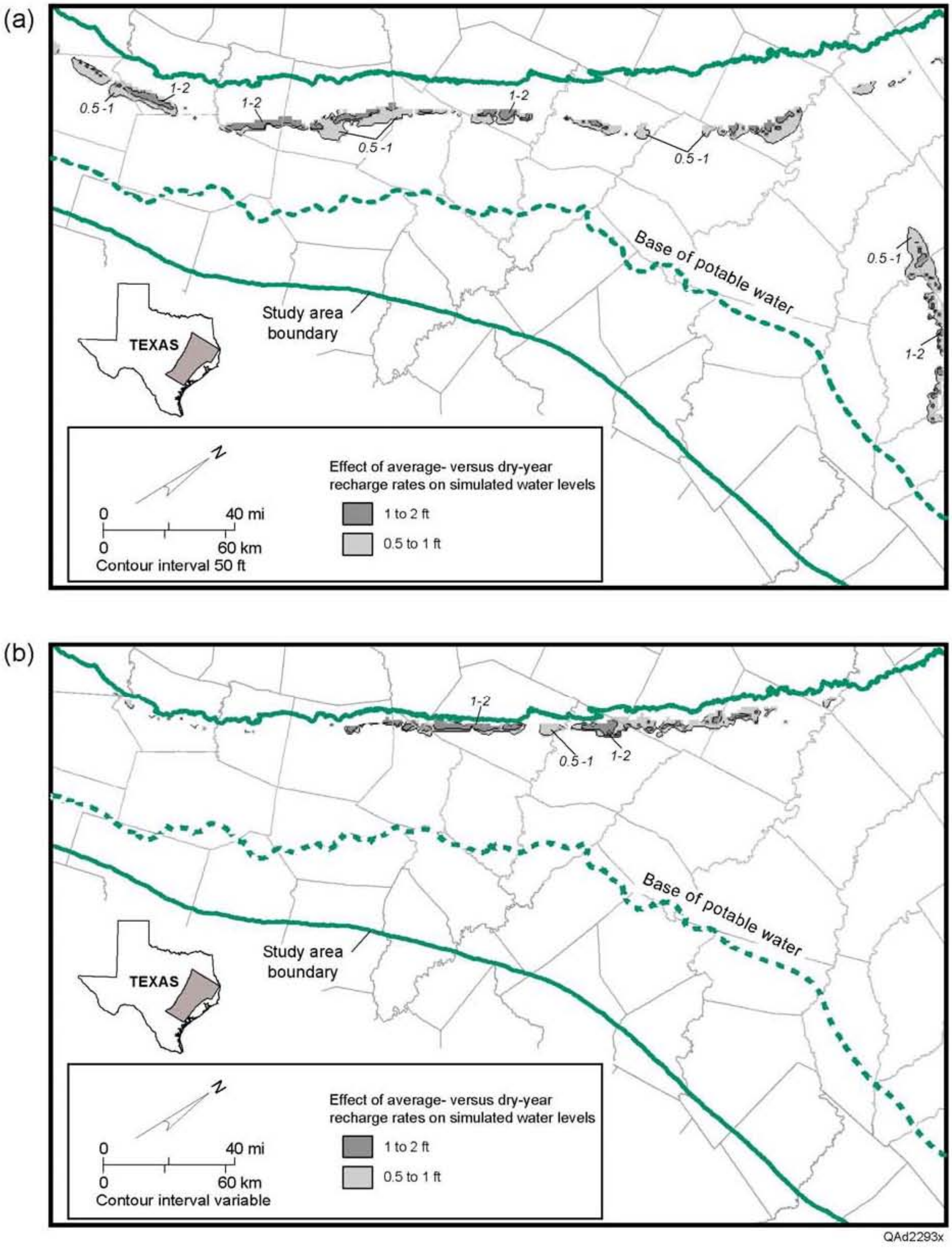

Figure 121. Difference for the end of 2050 in simulated water levels in (a) Carrizo aquifer (layer 3) and (b) Simsboro aquifer (layer 5) assuming average versus drought-of-record rates of recharge.

Table 16. Water budget for the predictive model (1000 acre-ft/yr). Average recharge for 2010 to 2050; simulation ends with drought of record recharge. Positive values are inflow to the aquifer; negative values are discharge from the aquifer. Annual rates from a 12-month long time step for 2000 and totaled from 12 1-month stress periods for 2010 through 2050.

Layer	Recharge	Net recharge	ET	Stream leakage	Reservoir leakage	GHB Reklaw	GHB downdip boundary	GHB NE boundary	GHB SW boundary	Wells	Cross-formational flow	Change in storage	Water balance error (%)
2000													
Alluvium (1)	12.9	0	-11.9	-23.7	0.6	0	0	0	0	0	21.7	0.3	-0.005
Reklaw (2)	14.8	-4.9	-21.5	-0.6	0	7.8	0	0	0	0	-3.1	2.6	-0.007
Carrizo (3)	118.4	25.6	-64.7	-29.3	0	0	2.4	0.7	27.1	-78.0	11.1	12.3	-0.003
Calvert Bluff (4)	47.4	-0.2	-31.9	-10.8	2.1	0	2.4	10.3	0.8	-11.4	-28.4	19.6	-0.006
Simsboro (5)	60.2	42.8	-21.9	-9.5	0.4	0	2.3	2.2	0.3	-98.0	22.0	42.0	-0.004
Hooper (6)	25.4	10.7	-13.5	-3.4	1.1	0	1.5	9.6	0	-6.2	-23.2	8.7	-0.001
ALL	279.2	74.1	-165.4	-77.2	4.2	7.8	8.5	22.8	28.1	-193.6	0	85.6	-0.005
2010													
Alluvium (1)	5.8	0	-10.8	-21.3	0.6	0	0	0	0	0	23.3	2.4	-0.002
Reklaw (2)	4.5	-4.9	-16.3	-0.5	0	32.7	0	0	0	0	-31.1	10.7	-0.002
Carrizo (3)	90.3	30.6	-55.5	-26.3	0	0	2.4	-0.1	28.7	-110.5	32.2	38.8	0.002
Calvert Bluff (4)	9.3	0.7	-23.4	-7.2	2.1	0	2.4	10.9	0.9	-13.1	-42.6	60.8	-0.005
Simsboro (5)	43.1	50.8	-16.1	-4.8	0.4	0	2.3	2.2	0.5	-146.4	47.5	71.3	-0.001
Hooper (6)	6.3	12.3	-9.3	-2.3	1.1	0	1.5	9.7	0	-12.1	-29.3	34.4	-0.001
ALL	159.2	89.5	-131.5	-62.3	4.3	32.7	8.5	22.8	30.0	-282.1	0	218.4	-0.001
2020													
Alluvium (1)	5.8	0	-9.9	-19.7	0.6	0	0	0	0	0	20.7	2.5	-0.003
Reklaw (2)	4.5	-4.9	-16.1	-0.4	0	43.2	0	0	0	0	-42.2	11.0	-0.002
Carrizo (3)	90.3	32.5	-54.3	-25.1	0	0	2.4	0.1	29.4	-119.8	39.5	37.6	0.002
Calvert Bluff (4)	9.3	2.2	-21.7	-6.1	2.2	0	2.4	11.1	0.9	-13.8	-46.5	62.2	-0.004
Simsboro (5)	43.1	48.5	-14.8	-3.3	0.4	0	2.3	2.5	0.5	-152.0	59.2	62.2	0.001
Hooper (6)	6.3	14.2	-8.6	-2.1	1.1	0	1.5	9.9	0	-12.5	-30.7	35.0	0.000
ALL	159.2	92.5	-125.4	-56.7	4.3	43.2	8.5	23.7	30.8	-298.0	0	210.5	0.000

Table 16 (continued). Water budget for the predictive model (1000 acre-ft/yr). Average recharge for 2010 to 2050; simulation ends with drought of record recharge. Positive values are inflow to the aquifer; negative values are discharge from the aquifer. Annual rates from a 12-month long time step for 2000 and totaled from 12 1-month stress periods for 2010 through 2050.

Layer	Recharge	Net recharge	ET	Stream leakage	Reservoir leakage	GHB Reklaw	GHB downdip boundary	GHB NE boundary	GHB SW boundary	Wells	Cross-formational flow	Change in storage	Water balance error (%)
2030													
Alluvium (1)	5.8	0	-9.1	-18.4	0.6	0	0	0	0	0	18.5	2.5	-0.003
Reklaw (2)	4.5	-4.9	-15.9	-0.4	0	49.4	0	0	0	0	-48.7	11.1	-0.002
Carrizo (3)	90.3	35.2	-53.4	-23.7	0	0	2.4	0.3	30.8	-131.5	45.6	39.4	0.002
Calvert Bluff (4)	9.3	3.1	-20.6	-5.3	2.2	0	2.4	11.5	0.9	-14.5	-48.5	62.6	-0.004
Simsboro (5)	43.1	46.9	-13.9	-2.3	0.4	0	2.3	2.8	0.5	-153.5	64.6	56.2	0.001
Hooper (6)	6.2	14.8	-8.1	-1.9	1.1	0	1.5	10.1	0	-12.4	-31.5	35.1	0.001
ALL	159.1	95.2	-121.0	-52.0	4.3	49.4	8.5	24.6	32.1	-312.0	0	206.9	0.000
2040													
Alluvium (1)	5.8	0	-8.6	-17.1	0.6	0	0	0	0	0	16.8	2.5	-0.002
Reklaw (2)	4.5	-4.9	-15.7	-0.3	0	55.5	0	0	0	0	-55.1	11.1	-0.002
Carrizo (3)	90.3	37.1	-52.7	-22.2	0	0	2.4	0.4	32.3	-140.4	50.1	39.9	0.002
Calvert Bluff (4)	9.3	4	-19.6	-4.6	2.2	0	2.4	11.7	1	-15.2	-50.9	63.6	-0.004
Simsboro (5)	43.1	46.1	-13.3	-1.7	0.4	0	2.3	3.1	0.5	-162.5	71.8	56.5	0.000
Hooper (6)	6.2	15.4	-7.8	-1.8	1.1	0	1.5	10.3	0	-12.9	-32.7	36	0.001
ALL	159.1	97.7	-117.7	-47.8	4.4	0	8.5	25.5	33.8	-331.1	0	209.6	0.000

Table 16 (continued). Water budget for the predictive model (1000 acre-ft/yr). Average recharge for 2010 to 2050; simulation ends with drought of record recharge. Positive values are inflow to the aquifer; negative values are discharge from the aquifer. Annual rates from a 12-month long time step for 2000 and totaled from 12 1-month stress periods for 2010 through 2050.

Layer	Recharge	Net recharge	ET	Stream leakage	Reservoir leakage	GHB Reklaw	GHB downdip boundary	GHB NE boundary	GHB SW boundary	Wells	Cross-formational flow	Change in storage	Water balance error (%)
2050													
Alluvium (1)	5.8	0	-8.1	-15.9	0.6	0	0	0	0	0	15.1	2.5	-0.003
Reklaw (2)	4.5	-4.8	-15.6	-0.3	0	64.0	0	0	0	0	-64.0	11.3	-0.002
Carrizo (3)	90.3	40	-52.1	-20.7	0	0	2.4	0.6	34.6	-156.0	57.4	43.6	0.002
Calvert Bluff (4)	9.3	5	-18.6	-3.9	2.2	0	2.4	12.1	1.2	-16.1	-54.0	65.5	-0.004
Simsboro (5)	43.1	45.7	-12.9	-1.2	0.4	0	2.3	3.4	0.5	-196.4	80.1	80.7	0.001
Hooper (6)	6.2	16	-7.4	-1.6	1.1	0	1.5	10.4	0	-13.5	-34.6	37.7	0.001
ALL	159.1	101.9	-114.8	-43.6	4.4	64.0	8.6	26.5	34.4	-381.9	0	241.4	0.000

2050 (simulation ends with average recharge for 1960 to 1997)

Layer	Recharge	Net recharge	ET	Stream leakage	Reservoir leakage	GHB Reklaw	GHB downdip boundary	GHB NE boundary	GHB SW boundary	Wells	Cross-formational flow	Change in storage	Water balance error (%)
Alluvium (1)	12.9	0	-8.5	-17.0	0.6	0	0	0	0	0	11.3	0.6	-0.002
Reklaw (2)	14.8	-4.7	-19.3	-0.3	0	63.9	0	0	0	0	-62.3	3.2	-0.002
Carrizo (3)	118.4	42.4	-58.4	-21.6	0	0	2.4	0.6	34.3	-156.0	58.6	21.7	0.002
Calvert Bluff (4)	47.4	6.1	-22.5	-5.0	2.2	0	2.4	12.0	1.1	-16.1	-53.7	32.3	-0.001
Simsboro (5)	60.2	47.9	-15.6	-1.6	0.4	0	2.3	3.4	0.5	-196.4	80.6	66.2	0.000
Hooper (6)	24.9	17.4	-9.2	-1.9	1.1	0	1.5	10.4	0	-13.5	-34.5	21.2	-0.001
ALL	278.6	109.1	-133.5	-47.4	4.4	63.9	8.6	26.4	36.0	-381.9	0	145.1	0.000

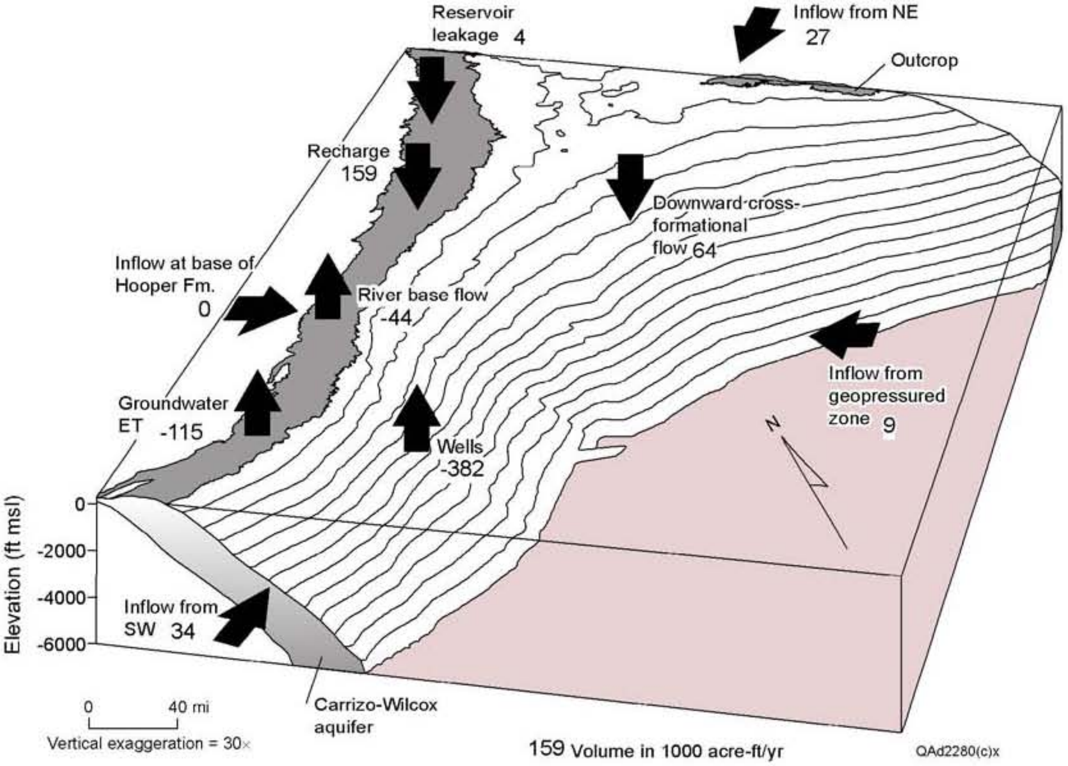

Figure 122. Block diagram of the Carrizo–Wilcox aquifer representing the components of the predictive model for 2050.

with increased pumping through 2050 (table 17). Base flow, however, is a small fraction of total stream flow. Historical data show no reduction in base flow.

Predicted water budgets also show that inflow from the GHB boundary continues to increase. The greatest inflow is from the top boundary of the model assigned to the Reklaw aquitard (layer 2) and to the lateral boundary assigned to the Carrizo aquifer (layer 3). The layer-3 inflow indicates that there is a net inflow to the model area across the northeastern boundary, mostly related to water-level drawdown in the vicinity of Angelina and Nacogdoches Counties.

An increase by an order of magnitude of the storage coefficient would double the inflow from the Calvert Bluff Formation into the Carrizo Formation and also increase the stream flow from the Simsboro Formation (table 18). A decrease by an order of magnitude of the storage coefficient would not have a major impact on the budget. Pumping changes of 10 percent have again a major impact on cross-formational flow from the Calvert Bluff Formation and on stream discharge from the Simsboro Formation.

Table 17. Simulated groundwater discharge to streams for the predictive model.

	Total discharge[*] (acre-ft/yr)		
San Antonio River Basin Total	Steady state	2000	2050[1] DOR
San Antonio River	*20,500*	*18,000*	*14,600*
Cibolo Creek	14,200	13,700	12,900
Guadalupe River Basin Total	6,200	4,300	1,700
Guadalupe River	*14,700*	*12,100*	*600*
San Marcos River	3,200	2,500	-1,200
Plum Creek	8,900	7,800	2,300
Colorado River Basin	2,600	1,700	-500
Cedar Creek	*12,400*	*10,800*	*6,100*
Colorado River	3,100	2,900	2,500
Big Sandy Creek	6,900	6,000	3,500
Brazos River Basin Total	2,500	1,900	100
Middle Yegua Creek	*31,800*	*25,700*	*12,600*
East Yegua Creek	4,800	3,700	1,300
Brazos River	1,300	700	0
Little River	4,300	3,900	2,600
Little Brazos River	6,100	5,300	2,500
Walnut Creek	1,300	1,200	700
Duck Creek	2,600	600	0
Steele Creek	1,800	1,400	1,000
Navasota River	2,100	1,900	1,300
Big Creek	5,800	5,300	2,100
Trinity River Basin Total	1,900	1,600	1,100
Upper Keechi Creek	*11,100*	*10,500*	*9,100*
Tehuacana Creek	4,200	4,000	3,300
Trinity River	2,800	2,700	2,300
San Antonio River	4,200	3,800	3,400
Total	90,600	77,200	42,900

[*] Rounded to nearest 100 acre-ft/yr

[1] DOR: Drought of Record

Table 18. Sensitivity of predicted 2050 water budget (with drought of record) to changes in storativity and pumping rate. Positive percent shows increase with respect to baseline 2050 drought-of-record results (table 16).

Sensitivity to change in storativity (percent difference)

Layer	Recharge	ET	Stream leakage	Reservoir leakage	GHB	Wells	Flow upper cell face	Flow lower cell face	Change in storage
Storativity × 10									
Alluvium (1)	0.0	6.6	6.9	0.0	0.0	0.0	0.0	11.3	–2.6
Reklaw (2)	0.0	1.0	3.2	0.0	–14.8	0.0	11.3	–23.2	0.0
Carrizo (3)	0.0	2.0	1.9	0.0	–1.4	0.0	–23.2	114.9	8.2
Calvert Bluff (4)	0.0	7.9	16.9	–0.9	–5.5	0.0	114.9	–18.9	6.3
Simsboro (5)	0.0	4.7	41.4	–3.3	–26.0	0.0	–18.9	12.1	8.9
Hooper (6)	0.0	9.8	23.4	–0.9	–8.8	0.1	12.1	0.0	16.8
ALL	0.0	3.9	6.9	–1.0	–10.0	0.0	–98.1	–98.1	8.8
Storativity × 0.1									
Alluvium (1)	0.0	–0.6	–0.7	0.0	0.0	0.0	0.0	–1.2	0.4
Reklaw (2)	0.0	–0.1	–0.4	0.0	1.7	0.0	–1.2	2.6	0.0
Carrizo (3)	0.0	–0.2	–0.2	0.0	0.1	0.0	2.6	–13.1	–0.8
Calvert Bluff (4)	0.0	–0.8	–2.0	0.1	0.6	0.0	–13.1	2.1	–0.7
Simsboro (5)	0.0	–0.5	–5.0	0.4	2.7	0.0	2.1	–1.5	–0.9
Hooper (6)	0.0	–1.0	–2.9	0.1	0.9	0.0	–1.5	0.0	–2.0
ALL	0.0	–0.4	–0.8	0.1	1.1	0.0	11.1	11.1	–0.9

Table 18 (continued). Sensitivity of predicted 2050 water budget (with drought of record) to changes in storativity and pumping rate. Positive percent shows increase with respect to baseline 2050 drought-of-record results (table 16).

Sensitivity to change in pumping rate (percent difference)

Layer	Recharge	ET	Stream leakage	Reservoir leakage	GHB	Wells	Flow upper cell face	Flow lower cell face	Change in storage
Pumping (+10%)									
Alluvium (1)	0.0	–3.1	–4.5	0.0	0.0	0.0	0.0	–7.1	3.6
Reklaw (2)	0.0	–0.7	–8.5	0.0	15.4	0.0	–7.1	23.3	3.0
Carrizo (3)	0.0	–1.3	–4.2	0.0	4.8	10.0	23.3	–28.2	7.3
Calvert Bluff (4)	0.0	–3.6	–12.4	0.7	3.4	10.0	–28.2	13.2	5.4
Simsboro (5)	0.0	–3.0	–41.9	2.1	8.3	9.7	13.2	5.8	11.9
Hooper (6)	–0.3	–3.8	–10.3	0.3	2.1	7.3	5.8	0.0	6.0
ALL	0.0	–2.1	–6.4	0.6	9.6	9.7	52.0	52.0	7.9
Pumping (–10%)									
Alluvium (1)	0.0	3.5	4.8	0.0	0.0	0.0	0.0	7.5	–3.6
Reklaw (2)	0.0	0.7	9.2	0.0	–15.5	0.0	7.5	–23.7	–3.2
Carrizo (3)	0.0	1.4	4.5	0.0	–4.9	–10.0	–23.7	28.4	–6.7
Calvert Bluff (4)	0.0	3.9	12.8	–0.7	–3.5	–10.0	28.4	–13.6	–5.5
Simsboro (5)	0.0	3.3	40.0	–2.9	–8.6	–10.0	–13.6	–5.8	–12.4
Hooper (6)	0.1	4.1	10.5	–0.3	–2.2	–9.5	–5.8	0.0	–6.7
ALL	0.0	2.3	6.6	–0.7	–9.7	–10.0	–53.2	–53.2	–8.1

11.0 LIMITATIONS OF THE MODEL

Typical limitations of numerical models of groundwater flow include (1) quality and quantity of input data, (2) assumptions and simplifications used in developing the model, and (3) the scale of application of the model (Mace and others, 2000a). These affect where and what kind of situation the model is applicable and how predictions may be made, interpreted, and used.

11.1 Input Data

The amount of geological control and other information used in building the model varies according to data category.

- Mapping and input of horizontal hydraulic conductivity is well constrained by test data (Mace and others, 2000c) and regional maps of the thickness of major sandstones. Model parameters are also well constrained by data for the Bryan-College Station well field.
- Top and bottom elevations of aquifer layers are generally well defined by abundant well logs and well drillers' reports. Assignment of layer elevation was coordinated between the northern, central, and southern Carrizo–Wilcox aquifer models. Inconsistencies between data sets were resolved. Setting the downdip boundary at the updip limit of the Wilcox Group Growth Faults required extending our structure maps well past the base of freshwater.

  It was beyond the scope of this aquifer modeling study, however, to map the deep structural elevation with as much resolution as the freshwater part of the aquifer. In addition, structural and hydrologic properties associated with the Yoakum Channel, located in the southern part of the study area (Xue and Galloway, 1995), were not differentiated. Also, structure around salt domes in the East Texas Basin was not resolved precisely using the square-mile grid cells.

- Extrapolating subsurface structure data to the outcrop limit, however, can include greater uncertainty than structure mapping in the confined aquifer. A slight error in interpolated elevation on the base of a model layer is insignificant at depth, where model layers are from 300- to more than 1,000-ft thick. For the first few rows of active cells representing the aquifer outcrop, however, cell thickness can be less than 50 ft. A 10- to 20-ft interpolation error can result in major misrepresentations of aquifer transmissivity and saturated thickness in the outcrop.
- This study provided some of the first field measurements of recharge rates for the Carrizo–Wilcox aquifer. Preliminary results suggest that these "environmental tracers" have the potential to be useful tools for estimating recharge. But many more tests will be needed to answer questions about how many samples and what sampling density are needed to adequately characterize local and regional variations in recharge rates within each model layer. Also, different tracers yield slightly different results that require subjective discernment to reconcile. Nonetheless, field results for this study are consistent with previous modeling studies. Assigning recharge rates in space on the basis of soil permeability and through time on the basis of

proportional differences in precipitation rates appears to have yielded reasonable values for model input.

- The predicted water-level response to a future drought of record included only changes in recharge rates, not pumping. Sensitivity analysis shows that predictive model results will be much more sensitive to an increase in pumping rate than to a decrease in recharge rates. Evaluation of aquifer change during future drought, therefore, needs a protocol for varying pumping rates during the drought.
- GHB heads were assigned on the northeastern boundary to account for drawdown induced by pumping outside of the study area, for example, near Tyler in Smith County and Henderson in Rusk County. Changing the GHB conductance on the northeastern boundary from 0 (no-flow) to a large number has an effect on water levels within about 30 to 40 mi ofthe boundary. These GHB heads were kept constant during predictive simulations. The predictive water budgets suggest an increase in inflow to the study area across the northeastern boundary, mainly related to the well fields in Angelina and Nacogdoches Counties near the boundary. The northern Carrizo–Wilcox aquifer model (Intera and Parsons Engineering Science, 2002a) may provide more representative simulation results for the Carrizo aquifer layer within about 30 to 40 mi of the northeastern boundary, including Anderson, Angelina, Cherokee, Rusk, San Augustine, Smith, and Van Zandt Counties.
- The Karnes-Milano-Mexia Fault Zone displaces the aquifer layers and breaks up their hydrologic continuity between the outcrop and deeper artesian zone. The horizontal flow barrier (HFB) package of MODFLOW was used to

represent these hydrologic discontinuities. The shape and growth of areas of drawdown around centers of pumping near the fault zone, for example, in Bastrop, Lee, Burleson, Milam, and Robertson Counties, are highly influenced by the compartments in the aquifer set up by these faults. The same may also apply to southeastern Gonzales County in the vicinity of the Karnes Trough Fault Zone.

- The annual stress periods used during this study do not account for seasonal variability of stream flow. Several streams in the study area are intermittent, flowing during winter months following recharge during a period when ET is low. Although the intermittent streams receive less base-flow discharge than the larger, perennial streams, the seasonal variability is not represented in the annual model.

11.2 Assumptions

Important and basic assumptions included in our model include

- The base of the Carrizo–Wilcox aquifer at the Midway Group-Hooper Formation contact is impermeable; there is no exchange of groundwater between these units. Both the Midway and the Hooper Formations generally have low hydraulic conductivity, so this assumption would seem valid. This boundary assumption, however, may need to be reevaluated locally if groundwater were to be developed on a large scale from one of the Hooper Formation channel-sand deposits at depth.

- Groundwater historically leaves the confined part of the Carrizo–Wilcox aquifer by cross-formational flow across the Reklaw aquitard to either (1) river bottomlands in the Reklaw Formation outcrop or (2) discharge into the Queen City aquifer. Upward-directed discharge is focused in the river bottomlands where the down-gradient hydraulic heads are low. There is generally downward leakage into the Carrizo–Wilcox aquifer beneath upland areas. We had to reduce the vertical hydraulic conductivity assigned to the Reklaw aquitard in the East Texas Basin to locally restrict the amount of downward flow into the Carrizo aquifer, where water levels in the Queen City aquifer are especially high. We assumed that Queen City water levels remained constant during the historical and predictive simulations. Hydrograph data for the Queen City aquifer generally support this assumption. Additional study planned by the TWDB for 2003 through 2004 is expected to lead to a better understanding of the interaction of the Queen City and Carrizo–Wilcox aquifers.
- We assumed that under pre-1950 conditions there was a slight inflow of groundwater into the deeply buried part of the Wilcox Group (depths of 3,000 to 10,000 ft) from the geopressured zone. In addition, significant volumes of natural gas have been withdrawn from gas reservoirs in the Wilcox Growth Fault Zone during the past 50 yr. It is unknown whether equivalent hydraulic head at the updip margin of the geopressured zone has decreased or whether change in equivalent hydraulic head has been local in compartmentalized gas reservoirs. We also have assumed that a calculated equivalent brine-density hydraulic head is a satisfactory estimate of hydraulic head for calculating

hydraulic gradient. Nonetheless, the updip limit of the growth fault zone is a significant physical boundary in the deep Wilcox Group. The structural traps that hold oil and gas reservoirs are also physical boundaries for the circulation of water. Whereas we think that the rate of groundwater flow is very small in the deep Wilcox aquifer at depths greater than 5,000 ft (Dutton and others, 2002), the area in which artesian pressures are drawn down around the Bryan-College Station well field extends well into the deep Wilcox aquifer. Assumptions on how the deep downdip boundary is assigned could have some effect on predicted water levels for that well field as its drawdown depth doubles over the next 50 yr.

- We used conventional formation stratigraphy to subdivide the Carrizo–Wilcox aquifer into four layers representing the Hooper aquitard, the Simsboro aquifer, the Calvert Bluff aquitard, and the Carrizo aquifer. Groundwater flow through the aquifer, however, is more continuous. Subdividing each layer would give more intralayer resolution of vertical gradients in water level and vertical movement of groundwater. Our assumption of four hydrologic layers may yield simulation results that suggest that model cells near the outcrop have changed from artesian to unconfined conditions. This result may be an artifact of the simplified layering of the model. The vertical gradient in hydraulic head may be more continuous than shown in simulations.

11.3 Scale of Application

The model is most accurate in simulating regional gradients and long-term trends in water levels. The Simsboro and Carrizo aquifers, from which 90 percent of the groundwater in the aquifer system is withdrawn, have more hydrologic data than have the Hooper and Calvert Bluff aquitards. Whereas more effort has been put into calibrating the Simsboro and Carrizo layers of the model, the model should give reasonable results for the Calvert Bluff aquitard. Calibration is poorest for the Hooper aquitard.

The square-mile-grid cell size limits the applicability of the model at a local level. The model would not be appropriate in its present form for the detailed work needed for designing and locating individual wells in well fields. The model may be used to assess regional water-resource implications of the withdrawal of groundwater from well fields. In addition, corrections for apparent drawdown may be needed to apply model results, calculated for the center of grid cells, to individual wells and their pumping cycles. Similarly, stream base flow is not predicted accurately for individual model cells.

The model is well suited for making comparisons between various groundwater-withdrawal scenarios. Running the model with and without a particular well field project, for example, and subtracting the differences in simulated water levels for a given year will show the differences in water level that could be attributed to that well field project. Such comparisons can also be made for differences in boundary conditions or model parameters for a better understanding of how these might affect model results. An advantage is that such comparisons cancel out effects of assumptions, boundary conditions, and nonvaried parameters and their uncertainties. Scenario comparison may be complicated near the outcrop where transmissivity can differ between the scenarios.

MODFLOW-96 as provided in PMWIN can handle reservoirs located only in the first layer of the model. A simple modification of the subroutine RES1.FOR and recompilation of the MODFLOW-96 code with a Lahey Fortran 95 allowed production of complete results for reservoirs as presented in this report.

12.0 FUTURE IMPROVEMENTS

Several areas in which the model may be improved were beyond the scope of this study. They include further review of existing information, as well as the collection and scientific analysis of additional data.

First, the baseline future pumping rates used in the predictive model do not in all cases appear to be continuous with the historical estimates from the TWDB water-use surveys. Pumping during the 2000-through-2010 period, for example, is likely to be similar to what was experienced during 1990 through 2000.

Second, there remain significant gaps in basic hydrologic data on the aquifer, in particular for recharge rates, ET rates, vertical hydraulic conductivity, and specific storage.

- Relying on model estimates of recharge rate has some limitation because correct recharge rates require other model parameters to be well known. Environmental tracers have some potential to constrain model rates of recharge because tracers inherently average estimated rates over long (for example, 10- to 50-yr) periods. Because each tracer has some associated uncertainty, multiple tracers need to be applied with the goal of finding consistent results. Recent advances in developing a variety of tracers (Scanlon and others, 2002) make these techniques accessible for potential application to aquifers in Texas.
- ET rates and stream leakage both remove a large amount of water from the unconfined aquifer beneath the outcrop. This removal has a significant impact on net recharge, as inferred from the water budgets. Improved approaches to characterizing and calibrating the nonstream discharge of groundwater in

river bottomlands are needed. Modeling software such as the Soil Water Assessment Tool (SWAT) may be useful (Srinivasan and Arnold, 1994).

- Vertical hydraulic conductivity (K_v) is almost never measured in the field owing to the impracticality of making the long-term measurements needed to detect small changes in water level (Neuzil, 1999). Additional research may be warranted for a better understanding of how K_v should be assigned in heterogeneous aquifers.
- All predictive models with pumping are sensitive to specific storage. Direct measurements on specific storage are rare because they typically require paired observation and pumping wells within a radius of influence during a hydrologic test. Many models make the assumption that specific storage is uniform (for example, Intera and Parsons Engineering Science, 2002a, b). Specific storage in the confined part of the Carrizo–Wilcox aquifer and other aquifers may vary by one to three orders of magnitude. Obvious geological controls include consolidation, cementation, and other diagenetic processes that affect the elasticity of the aquifer matrix. Petrographic studies document that such diagenetic changes can be predicted as a function of depth. Elasticity of sandstone, claystone, and other common aquifer media also differs (Domenico and Schwartz, 1990). In some places, the diagenetic history is complex, with burial and exhumation resulting in a complex evolution of a rock's elastic properties. Additional research on how specific storage could be predicted on the basis of known or measurable rock properties and burial depth should be pursued.

- Additional research is needed for water quality issues to be understood, as well as water resources of the Carrizo–Wilcox aquifer. As previously described, this study advanced the understanding of how regional circulation of groundwater in the Carrizo–Wilcox aquifer is influenced by the Karnes-Milano-Mexia Fault Zone and the geopressured zone that starts in the Wilcox Growth Fault Zone (Dutton and others, 2002). The area of artesian drawdown in the Simsboro aquifer centered at well fields in Lee, Brazos, and Robertson Counties is expected to encounter the downdip boundary of the model, where total dissolved solids exceed 50,000 mg/L. Preliminary analysis suggests that groundwater flow rates are extremely slow in the deep artesian part of the aquifer, and water-quality impacts from the downdip boundary are not expected to be detectable. Although existing information indicates that it is not an issue, water quality might change owing to cross-formational flow and leakage of poor-quality water out of clay beds (Henry and others, 1979; Dutton, 1985).
- It was previously noted that there are fewer water-level data for model validation for 2000 than there were for model calibration in 1990. During the 1990s the number of water-level measurements being recorded by the State of Texas decreased compared with 1980s' data collection owing to changes in budget priorities. Additional water-level data will be needed for postaudits of the performance of this and other models in the future. Continued collection of hydrologic data by the State of Texas is important in order to meet water resources needs.

13.0 CONCLUSIONS

We developed a numerical model of the occurrence and movement of groundwater in the central part of the Carrizo–Wilcox aquifer in Texas as part of a Statewide program to create models for use in evaluating groundwater availability in major and minor aquifers. This model is one of three overlapping models of the Carrizo–Wilcox aquifer. Development of the three models was coordinated to ensure model results in the overlap areas are as consistent as possible.

The central model divides the Carrizo–Wilcox aquifer into four layers, which represent, from bottom to top, the Hooper, Simsboro, Calvert Bluff, and Carrizo Formations. Two additional model layers represent (a) the Reklaw aquitard that overlies the Carrizo–Wilcox aquifer and (b) stream-bed alluvium through which groundwater moves from the bedrock aquifers to stream channels. There are 120,477 active cells in the six model layers.

We followed a standard protocol in constructing the numerical model. We developed the conceptual model of groundwater flow and defined aquifer properties on the basis of our review of previous work and file data, new field studies of recharge rates, and an original analysis of data on gas pressures and chemical composition of groundwater. Our modeling approach included (1) setting up and calibrating a steady-state version of the model without pumping; (2) calibrating a transient model of the period from 1950 through 1990, with emphasis on 1980 through 1990; (3) extending the model simulation through 2000 for verification of "predicted" 2000 water levels; (4) analyzing sensitivity of model results to input parameters; and (5) demonstrating the use of the model as a predictive tool by simulating water levels, drawdown, and stream flow for the 2000-to-2050 period with pumping rates derived from Regional Water Planning Groups water-demand projections.

Average steady-state recharge rates assigned to the Simsboro and Carrizo aquifers are 2.1 and 2.9 inches/yr, respectively. These rates are consistent with the 1- to 4-inch/yr rates indicated by previous studies and our field measurements of environmental tracers. In comparison, average recharge rates assigned to the Hooper, Calvert Bluff, and Reklaw aquitards in the model are 0.5, 0.4, and 0.2 inches/yr, respectively.

The steady-state model was calibrated to water levels measured between 1901 and 1950 and to the results of low-flow studies in streams and rivers. Overall, the model does a good job in matching the predevelopment water levels, considering the sparse data. Root Mean Square Error (RMSE) of simulated and observed water levels in the Simsboro aquifer is 25 ft, which is about 17 percent of the narrow range of water level reported for 13 observation wells. RMSE for the steady-state calibration of the Carrizo aquifer is 19 ft, less than 10 percent of the water-level drop across the observation wells. Model results match field observations that most stream base flow is discharged from the Simsboro and Carrizo Formations. The model generally under predicts the estimated base flow of the Guadalupe, Colorado, Brazos; and Trinity Rivers but better matches estimated base flow for smaller streams. The steady-state model is most sensitive to changes in (1) hydraulic heads assigned to the Reklaw aquitard (layer 2) using MODFLOW's General Head Boundary (GHB) package, (2) GHB heads imposed on the lateral boundaries of the Simsboro and Carrizo aquifers, (3) recharge rates, and (4) horizontal conductivity of the Simsboro and Carrizo aquifers. The GHB heads assigned to the upper boundary of the model are based on water levels in the Queen City aquifer, which overlies the Reklaw aquitard. The model estimates that under predevelopment conditions, net rates of recharge to the Simsboro and Carrizo layers averages 0.4 and 0.2 inches/year, respectively. Net recharge is the calculated amount of recharge per unit area of the outcrop that moves downdip from the unconfined to the confined part of the aquifer or is taken into storage in the unconfined aquifer. The model shows that net recharge rates to aquitard layers of the model are very small under predevelopment conditions.

We were able to obtain a good calibration and verification of the historical model as measured by comparison of measured and simulated water levels. RMSE errors for the Simsboro and Carrizo aquifers for the 1990 calibration year are 36 and 49 ft, respectively, or 10 and 7 percent of the range in water level recorded in water wells. RMSE errors for the 2000 verification year are 49 ft in the Simsboro aquifer and 43 ft in the Carrizo aquifer, less than 10 and less than 6 percent, respectively, of the observed range in water level in the Simsboro and Carrizo aquifers. The match of simulated and observed water-level hydrographs generally is very good. Annual fluctuations in water level simulated with monthly stress periods are proportional to the seasonal range in pumping rate and also match observed short-term water-level fluctuations. Simulated water levels in the transient model are more sensitive to pumping rates and horizontal conductivity than to storativity and recharge rates. The water budget of the transient model shows that net recharge rates may have slightly increased while ET and stream flow may have decreased during the past several decades. The transient-model water budget also indicates that more water now moves downward into the Carrizo–Wilcox aquifer than moves upward to the Queen City aquifer, a reversal of the predevelopment trend.

We used the calibrated model to simulate 2000-through-2050 water levels for the central Carrizo–Wilcox aquifer study area. Each predictive simulation ended with drought-of-record conditions with reduced recharge rates. The model predicts that the largest future drawdown of as much as 300 ft, compared to 2000 water levels, will be in the Simsboro aquifer in the area centered on Brazos, Lee, and Robertson Counties. Artesian water levels, however, remain well above the top of the aquifer. The increased drawdown reflects the predicted increase in rate of groundwater withdrawal for the Bryan-College Station well field, a new well field in Lee County providing water to Williamson County, and additional pumping in Bastrop, Lee, and Milam Counties for transfer to Bexar County and other increased withdrawal rates. The model predicts that the simulated rivers and streams will remain gaining through 2050.

A numerical model such as this one for the central part of the Carrizo–Wilcox aquifer includes many approximations and simplifications of an aquifer system. Those assumptions and simplifications, along with the quality and quantity of input data, size and geometry of the model grid, and assumptions about future pumping rates, can impact the accuracy of model predictions. This model was designed for use as a tool for answering regional-scale questions about groundwater availability. The model would not be appropriate for designing and locating individual wells in well fields or predicting water-level changes at individual wells. The model is well suited for making comparisons between various scenarios. Additional aquifer studies and post-audits of the model will improve the calibration of the model.

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The views and conclusions contained in this draft report and the GAM CW-c groundwater model reflect those of the Bureau of Economic Geology and should not be interpreted as necessarily representing the opinions, either expressed or implied, of R. W. Harden and Associates, Inc., HDR Engineering, Inc., or the official policies or records of the Texas Water Development Board.

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