8.0 STEADY-STATE MODEL

The steady-state, or predevelopment, version of the model represents an approximation of the aquifer before the construction of water wells and pumping of groundwater. Predevelopment conditions are not as well known as later conditions in the aquifer because there are few records of early water-level measurements. We assume, however, that because water levels did not change much during the decades of the 1970s through 1990s, except in the vicinity of high-production well fields, that predevelopment water levels were not greatly different than recorded in the earliest measurements.

We used the steady-state model to evaluate our initial model construction; provide consistent starting conditions for the transient calibration; adjust model parameters, including horizontal and vertical hydraulic conductivity, recharge, parameters for the stream-flow routing and ET packages, GHB boundaries, and horizontal-flow barrier (HFB) parameters; and to assess the sensitivity of simulation results to model properties. The steady-state model initially was set up and solved in one long (100-yr) stress period. The model later was incorporated into the transient model as the first stress period and assigned a 100-yr duration. Additional adjustment of these parameters was performed during calibration of the transient model.

8.1 Calibration

During steady-state calibration, we adjusted model parameters to improve the matches between simulated and observed water levels and simulated and observed base flow in rivers. The need to adjust some parameters became apparent mainly as a result of transient runs. We chose not to adjust horizontal hydraulic conductivity much beyond obvious data-input corrections. We assumed that horizontal hydraulic conductivity to be one of the better-constrained variables in the model because of the number of hydrologic tests and number of well logs controlling the maps of sandstone content. Vertical hydraulic conductivities for layers representing the Carrizo–Wilcox aquifer were adjusted to ensure that the vertical anisotropy (K_v/K_h) ratio was within expected ranges.

We found that we needed to decrease vertical hydraulic conductivity for layer 2 (Reklaw aquitard) across part of the East Texas Basin where water levels in the Queen City aquifer (and assigned as the layer 2 GHB head value) are greater than 500 ft. A vertical hydraulic conductivity (K_v) of 10^{-4} ft/d, as initially applied, allowed so much downward-directed, cross-formational leakage of water that simulated heads in the Carrizo aquifer were too high. An adjusted K_v of 10^{-6} ft/d was assigned in the East Texas Basin area. A similar adjustment was made for the GAM model of the northern part of the Carrizo–Wilcox aquifer (Intera and Parsons Engineering Science, 2002a). Further study is needed to evaluate the hydrogeological properties of the Reklaw aquitard and its influence on movement of groundwater between the Queen City and Carrizo–Wilcox aquifers.

Steady-state calibration sets the initial balance between the amount of water entering the aquifer as recharge and the amount leaving the aquifer in the outcrop as either base-flow discharge to rivers and streams or groundwater ET. Initial interpretation of field studies of recharge results suggested that recharge to the Simsboro aquifer could be as low as 1 inch/yr. When we applied that rate, model simulation results could not match the stream-flow calibration targets. Results from the completed field study are consistent with those of previous studies (fig. 40). Average steady-state recharge rates assigned to the outcrop of the Simsboro and Carrizo aquifers in the calibrated model were 2.1 and 2.9 inches/yr, respectively (figs. 69, 70). Average recharge rates assigned to the outcrop of the Hooper, Calvert Bluff, and Reklaw aquitards were 0.5, 0.4, and 0.2 inches/yr, respectively.

During calibration we set a minimum value of the maximum ET rate, which applied mainly in the Sabine Uplift area on the northeast side of the model. The smallest value of maximum ET rate was set to 14 inches/yr. Extinction depth was also adjusted during model calibration and set at 15 ft.

With the calibration of parameters for recharge rate, discharge to rivers and streams, ET, and hydrological properties, no model cells go dry during the steady-state simulation.

Resulting simulated water levels for the predevelopment or steady-state condition in the Simsboro and Carrizo aquifers are shown in figures 71 and 72, respectively. The simulated water levels are reasonably similar to those according to early data (figs. 28, 29). Simulated water level in the Simsboro aquifer (fig. 71) also reflects a main feature of the observed potentiometric surface map (fig. 28), which is the relatively flat gradient in water level across the central part of the study area. Water levels are above 300 ft across the Sabine Uplift at the northeastern boundary. Lower water-level elevations are shown to the southeast beneath the Angelina River valley as previously mentioned. Simulated water-level elevation in the Carrizo aquifer (fig. 72) decreases from about 450 to 500 ft in the outcrop to less than 300 ft in the central part of the model, with lower water-level elevation to the southeast beneath the Angelina River valley. The shape of the potentiometric surface of the Carrizo aquifer also shows the effect of the Sabine Uplift and the low topography of the Angelina River valley.

Overall, the model does a good job in matching predevelopment water levels (fig. 73), considering the sparse data (fig. 74, table 11). The root mean square error (RMSE) is 19 ft for the Carrizo aquifer (sample size = 33) and 25 ft for the Simsboro aquifer

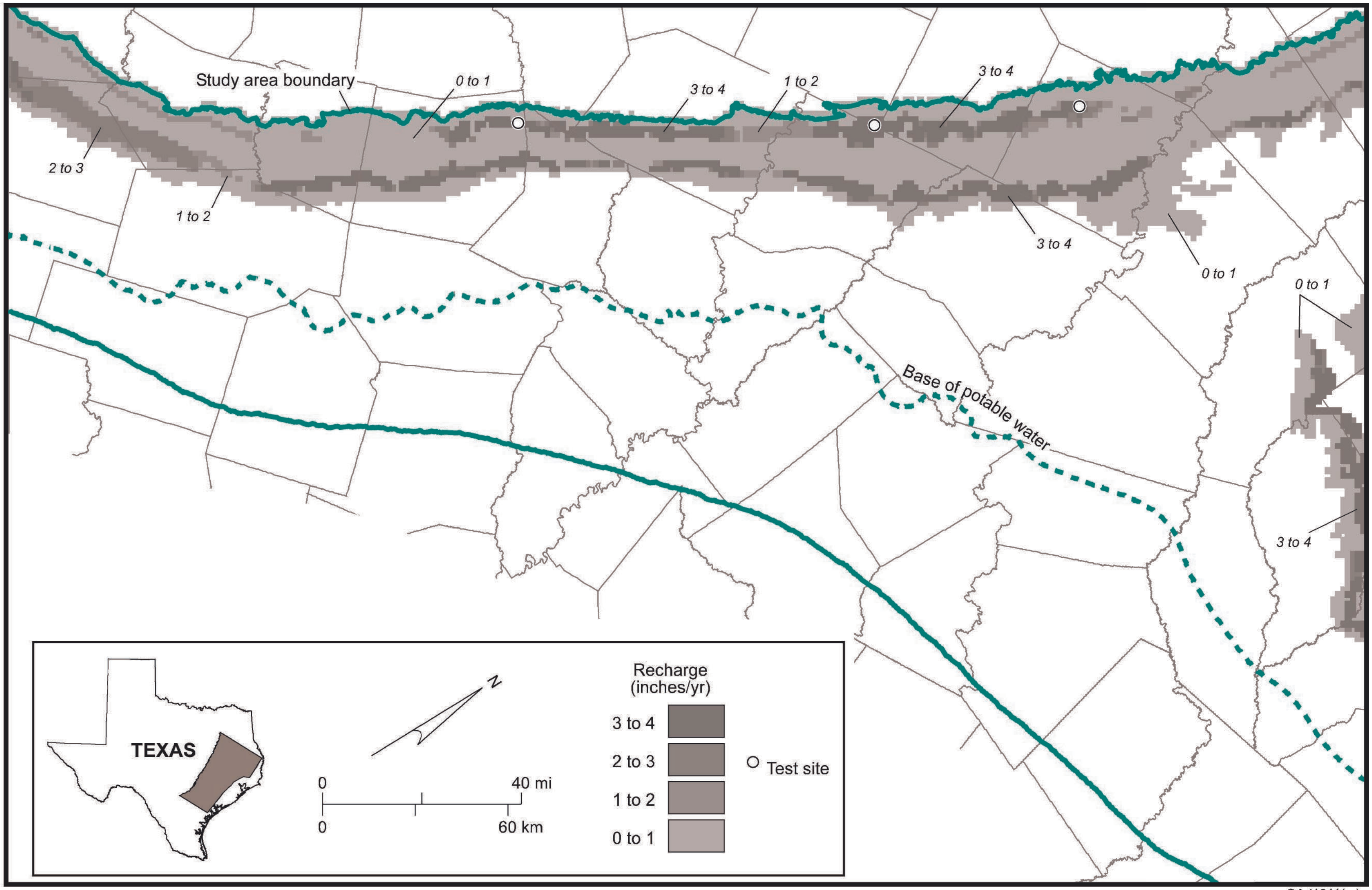

Figure 69. Recharge rate estimated on the basis of soil properties and results of previous studies. Test sites for using environmental tracers for estimating recharge rate were located in the outcrop of the Simsboro aquifer in Bastrop, Lee, Robertson, and Freestone Counties. Approach for assigning recharge to the model is described in section 6.3.1.

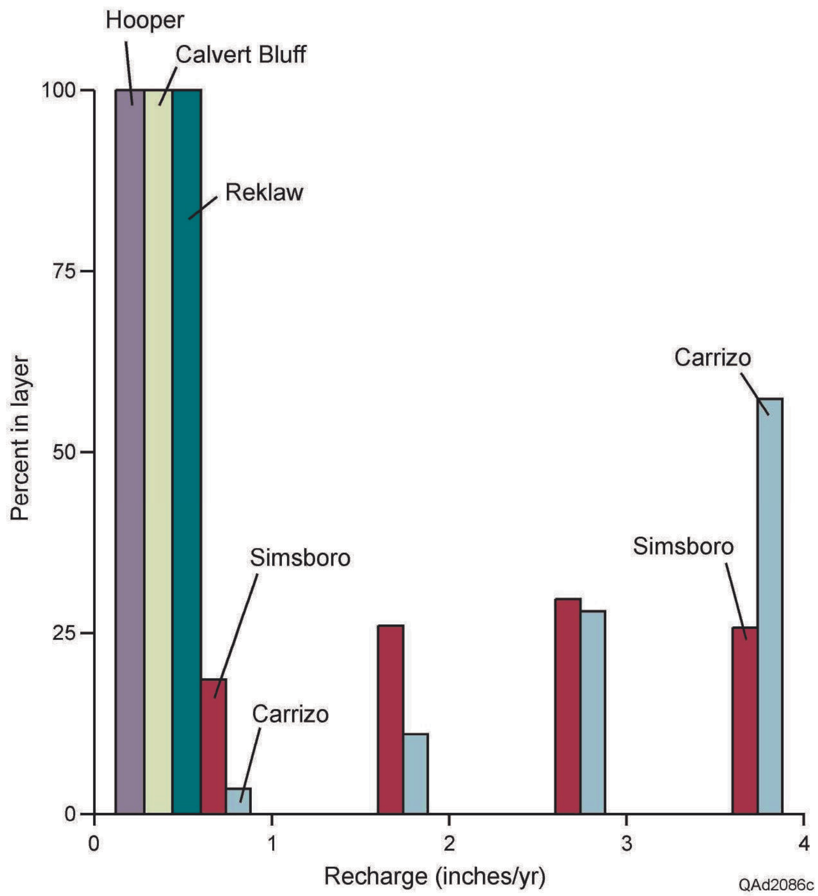

Figure 70. Histogram of recharge rates applied in the model. Most recharge is applied in the outcrop of the Simsboro and Carrizo aquifers.

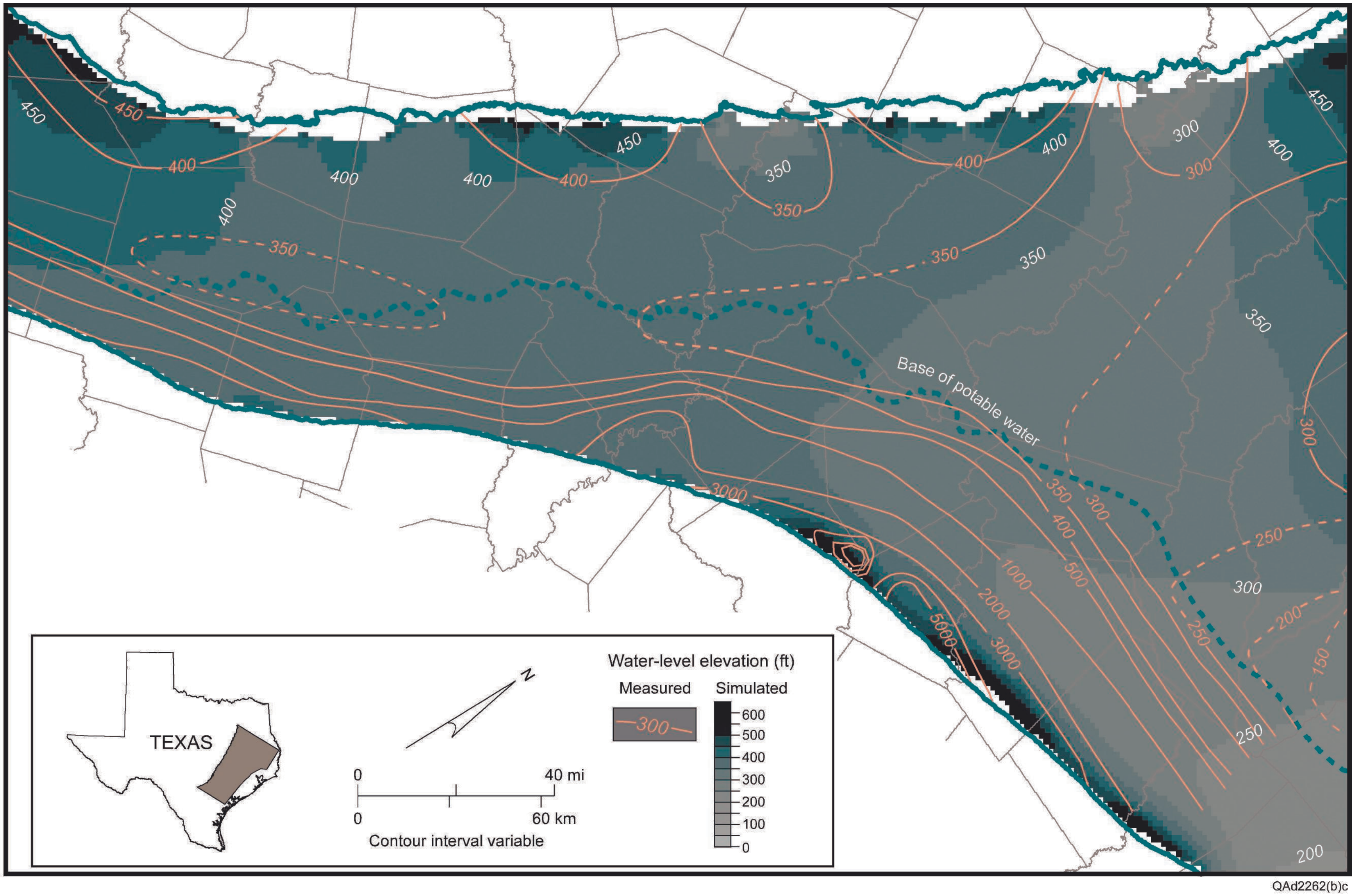

Figure 71. Simulated water levels for the Simsboro aquifer in the study area under predevelopment or steady-state (1950) conditions and comparison with measured contours.

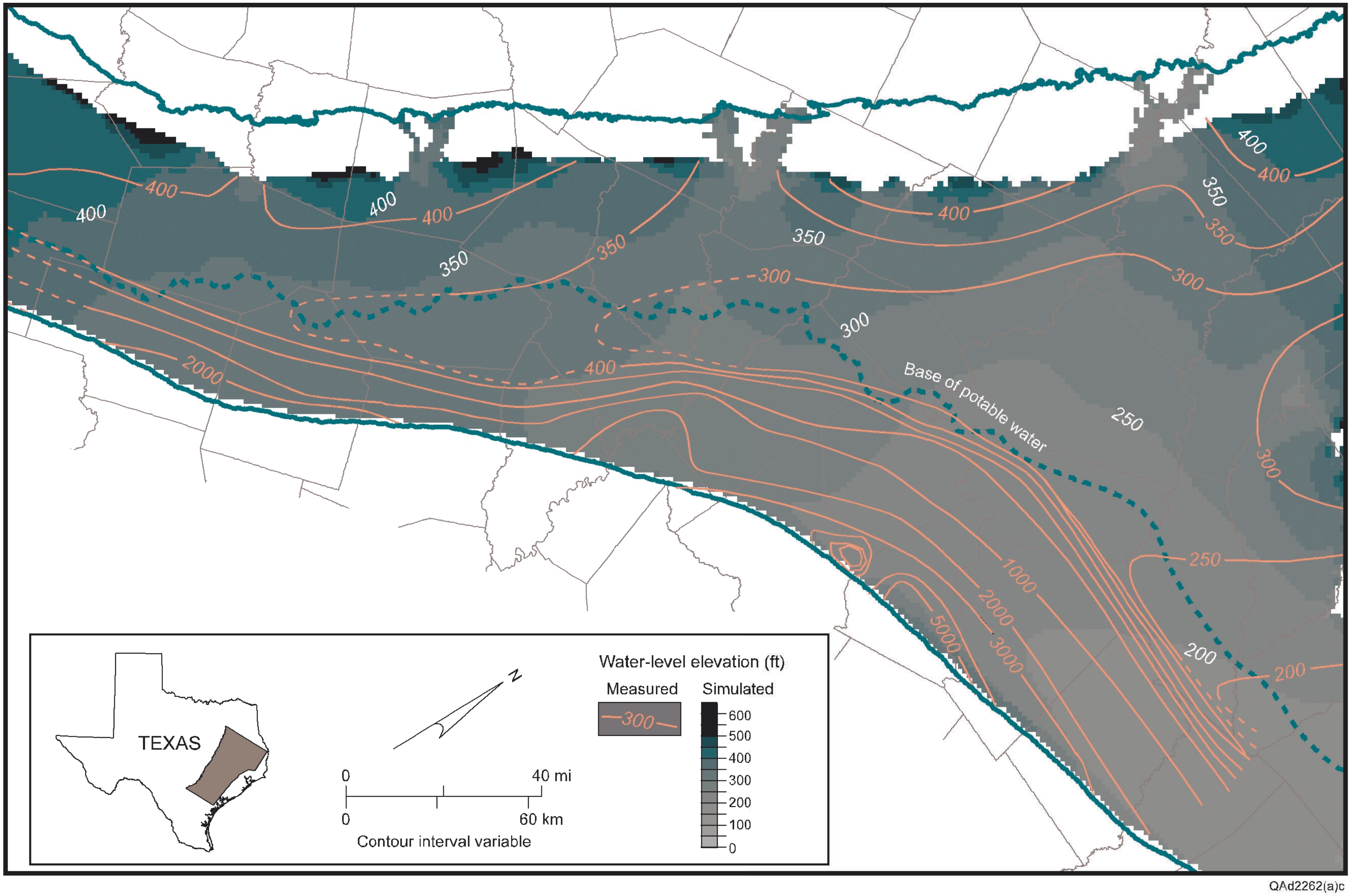

Figure 72. Simulated water levels for the Carrizo aquifer in the study area under predevelopment or steady-state (1950) conditions and comparison with measured contours.

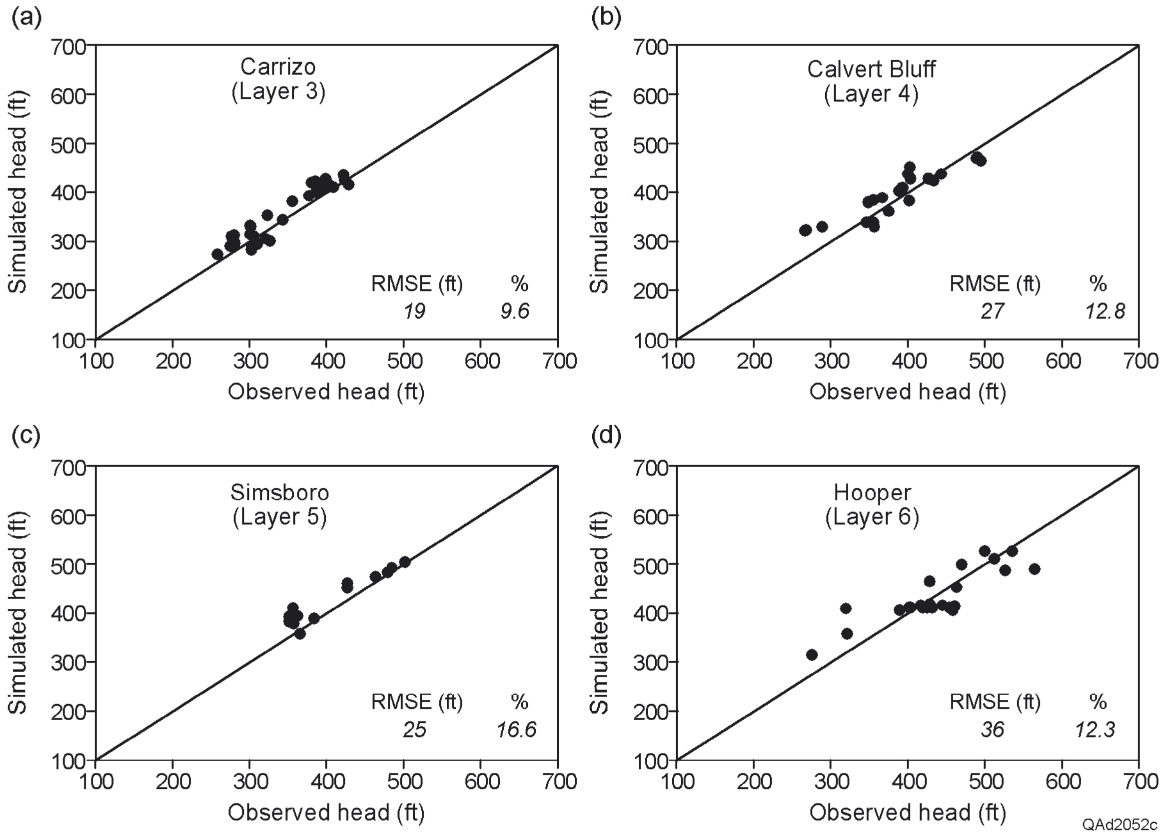

Figure 73. Comparison of simulated and measured water levels in the steady-state simulation of model layers representing the Carrizo–Wilcox aquifer. Well locations are shown in figure 74.

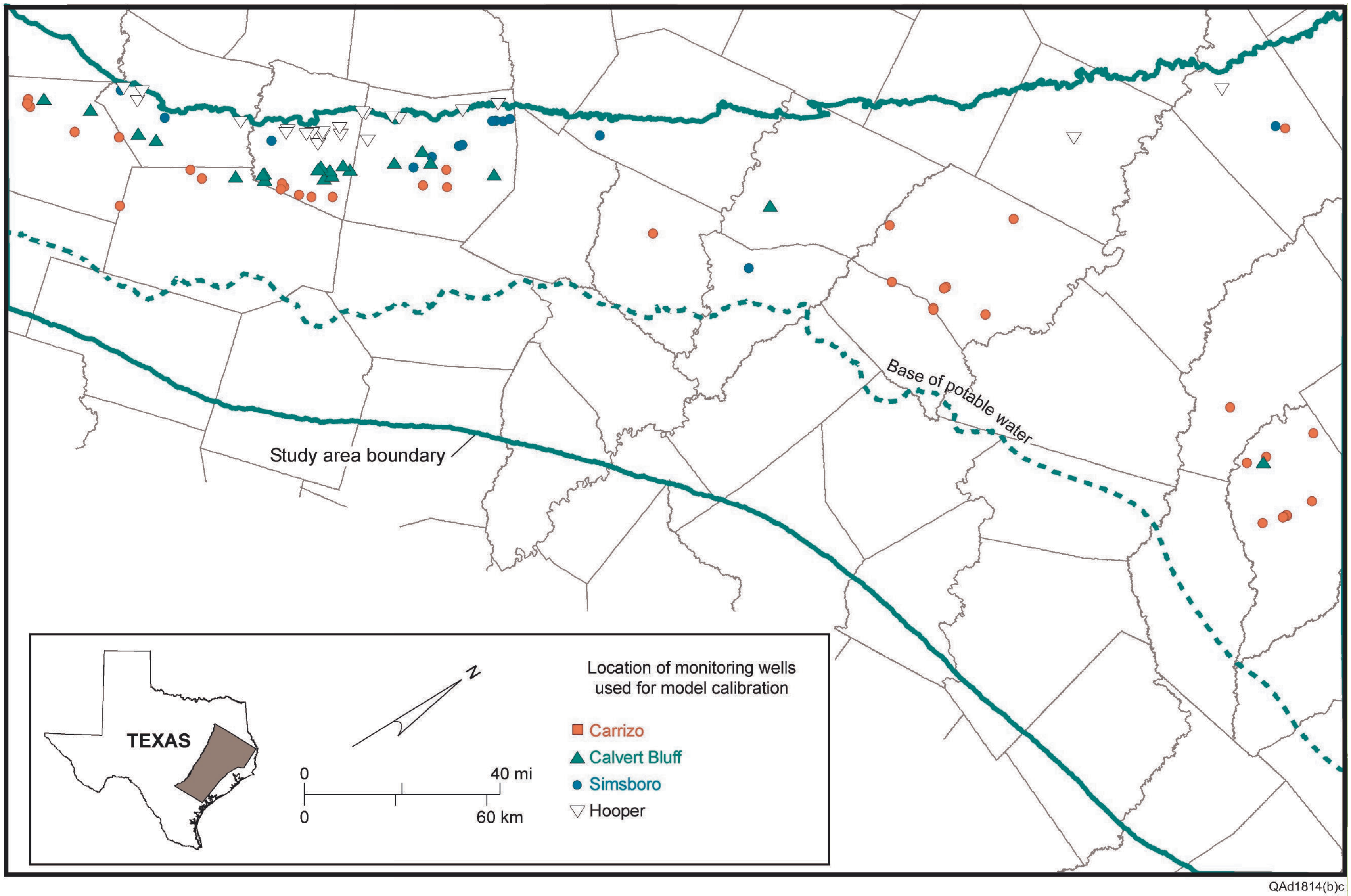

Figure 74. Location of water-level measurements used in calibration of the steady-state version of the model shown in figure 73.

Table 11. Summary of model calibration and verification statistics.

Model	Unit	Layer no.	Root mean squared error (ft)	Mean absolute error (ft)	Mean error (ft)	Number of data points	RMSE/Δh (%)*
Steady state	Carrizo	3	19.0	16.0	7.7	33	9.6
	Calvert Bluff	4	27.2	23.5	7.6	23	12.0
	Simsboro	5	24.9	19.5	18.2	13	16.6
	Hooper	6	35.5	27.9	–2.9	23	12.3
1990	Carrizo	3	49.4	34.9	23.0	115	6.8
	Calvert Bluff	4	37.5	27.6	10.3	64	9.4
	Simsboro	5	36.1	25.6	17.4	42	10.0
	Hooper	6	42.9	33.0	16.6	42	12.6
2000	Carrizo	3	42.7	31.9	25.4	80	5.7
	Calvert Bluff	4	37.5	29.5	8.1	49	9.5
	Simsboro	5	48.9	35.9	23.7	32	9.8
	Hooper	6	46.3	36.5	20.1	32	12.8

* RMSE is root mean square error (column 4); Δh is range in water level in data. Ratio is expressed in percent.

(sample size = 13). The RMSE values are 9.6 and 16.6 percent, respectively, of the range in water level among the observation wells. The range of measurements for the Simsboro aquifer in the steady-state calibration data set is 150 ft (table 11). Table 11 also reports other calibration statistics, including mean absolute error and mean error. The mapped residual or difference in estimated and simulated water levels for the Simsboro aquifer is shown in figure 75. There are sparse data with which to interpolate a residual across the model area. Most of the model area has a residual of ±25 ft, which is consistent with the calculated RMSE for the aquifer (table 11). The model underestimates one measurement in Robertson County by more than 100 ft. The residual error for the Carrizo aquifer is also less than ±25 ft (fig. 76).

Table 12 shows the estimated simulated base flow to the 21 streams and the 5 river basins included in this study. The model generally underpredicts the estimated base flow of the major streams. Simulated base flow is 29 percent of estimated base flow of the Guadalupe River, and 48, 61, and 24 percent of estimated base flow for the Colorado, Brazos, and Trinity Rivers, respectively. Simulation results better match estimated base flow for smaller streams. Most reaches are gaining; stream losses simulated for a set of model cells are typically less than 15 percent of the stream gains. The Simsboro and Carrizo aquifers are the main contributors to base flow. The Hooper and Calvert Bluff aquitards contribute little to stream flow in comparison.

8.2 Sensitivity Analysis

We analyzed the sensitivity of the predevelopment model to horizontal and vertical hydraulic conductivity, recharge, ET, stream conductance, and general-head boundary

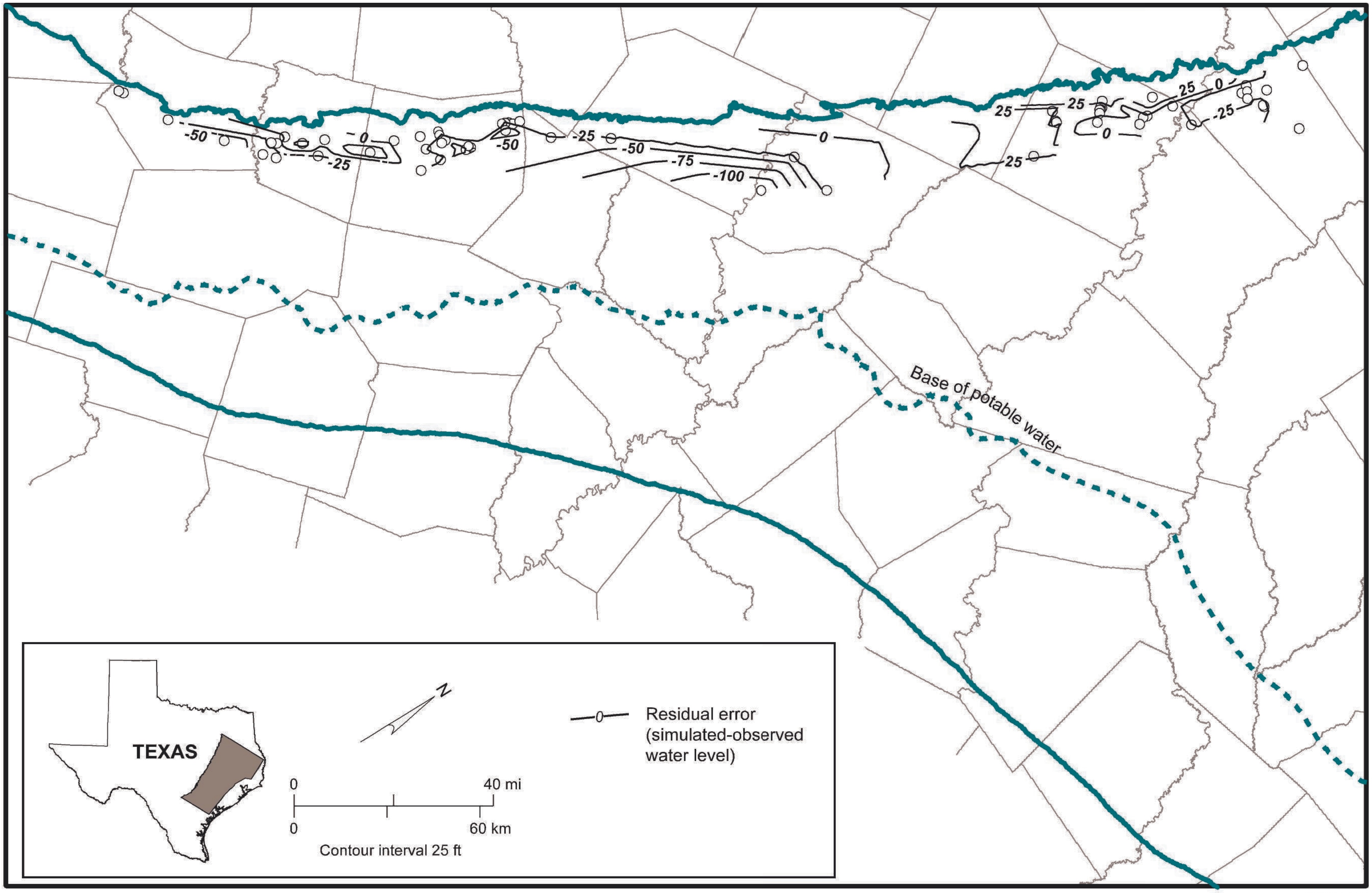

Figure 75. Map of residual differences between simulated and measured water levels for the Simsboro aquifer (layer 5) for the steady-state calibration.

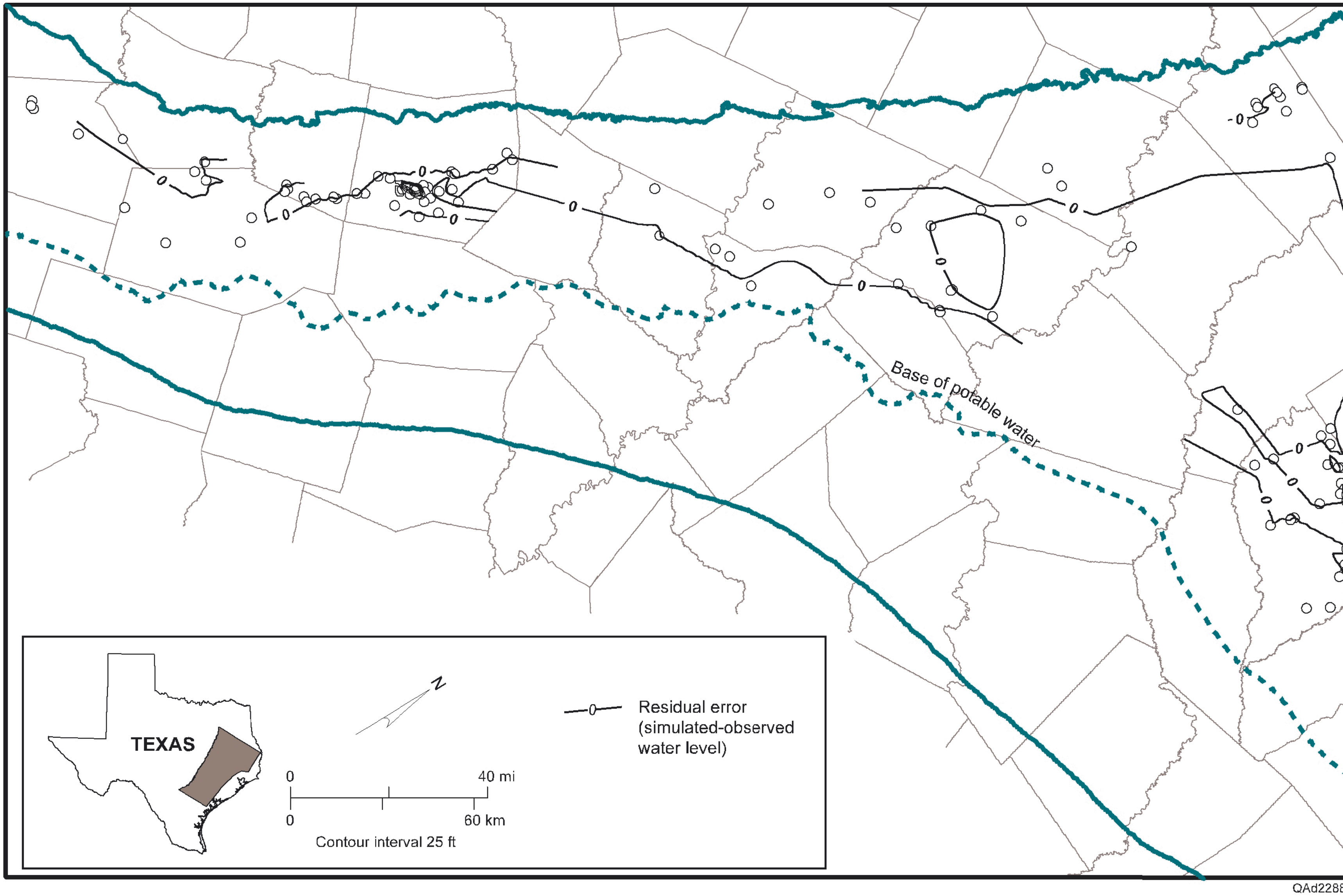

Figure 76. Map of residual differences between simulated and measured water levels for the Carrizo aquifer (layer 3) for the steady-state calibration.

Table 12. Simulated groundwater discharge to streams.

River basin/stream	Estimated total discharge* (acre-ft/yr)	Percent of estimated base flow	Simulated total discharge (acre-ft/yr) Steady state	1990	2000
San Antonio River Basin Total			*20,400*	*18,300*	*18,000*
San Antonio River	13,700	104	14,200	13,800	13,700
Cibolo Creek	6,700	93	6,200	4,500	4,300
Guadalupe River Basin Total			*14,700*	*11,500*	*12,000*
Guadalupe River	10,900	29	3,200	2,300	2,500
San Marcos River	11,100	104	8,900	7,500	7,800
Plum Creek			2,600	1,700	1,700
Colorado River Basin Total			*12,500*	*11,000*	*10,800*
Cedar Creek	26,100	48[1]	3,100	2,900	2,900
Colorado River			6,900	6,000	6,000
Big Sandy Creek			2,500	2,100	1,900
Brazos River Basin Total			*32,000*	*27,700*	*25,600*
Middle Yegua Creek	5,200	93	4,800	4,100	3,700
East Yegua Creek	2,200	58	1,300	700	700
Brazos River	23,400	61[2]	4,300	4,000	3,900
Little River			6,100	5,500	5,300
Little Brazos River			1,300	1,200	1,200
Walnut Creek			2,600	1,700	600
Duck Creek	2,200	79	1,800	1,500	1,400
Steele Creek	8,100	119[3]	2,100	1,900	1,900
Navasota River			5,800	5,400	5,300
Big Creek			1,900	1,700	1,600
Trinity River Basin Total			*11,200*	*10,700*	*10,500*
Upper Keechi Creek	3,800	110	4,200	4,000	4,000
Tehuacana Creek	4,700	59	2,800	2,700	2,700
Trinity River	17,800	24	4,200	4,000	3,800
Total	*135,900*	*67*	*90,800*	*79,200*	*76,900*

* Rounded to nearest 100 acre-ft/yr

1 Sum of Colorado River, Cedar Creek, Big Sandy Creek

2 Sum of Brazos River, Little River, Little Brazos River, Walnut Creek

3 Sum of Navasota River, Steele Creek, Big Creek

(GHB) head and GHB conductance. Each of these input parameters was increased uniformly by 10 percent and 20 percent above the calibrated value and decreased 10 percent and 20 percent below the calibrated value. Trial-and-error adjustment showed that the steady-state model was not very sensitive to changes in the HFB hydraulic characteristic term. Further tests during the transient model calibration showed no reason to change the initial estimates of the HFB hydraulic characteristic.

Hydraulic conductivity, specific yield, ET, and GHB conditions were changed on a layer basis in layers 3 and 5, whereas recharge and stream conductance were changed modelwide. Sensitivity was measured as the mean difference (*MD*) between simulated water level for the calibrated model (h_{cal}) and simulated water level for the sensitivity run (h_{sens}):

$$MD = \frac{1}{n}\sum_{i=1}^{n}\left(h_{sens,i} - h_{cal,i}\right) \qquad (13)$$

Results of the sensitivity analysis indicate that steady-state simulation of the Simsboro aquifer is most sensitive to

- recharge rates (fig. 77c),
- horizontal conductivity of the Simsboro aquifer (fig. 77a), and
- GHB heads imposed on the lateral boundaries of the Simsboro aquifer (fig. 77a).

Results are also sensitive to increases of more than 10 percent in GHB heads in layer 2 (fig. 77c). Sensitivity of model results to other parameters is an order of magnitude smaller (fig. 77). Variation of parameters in the Carrizo aquifer (layer 3) has only a slight impact on

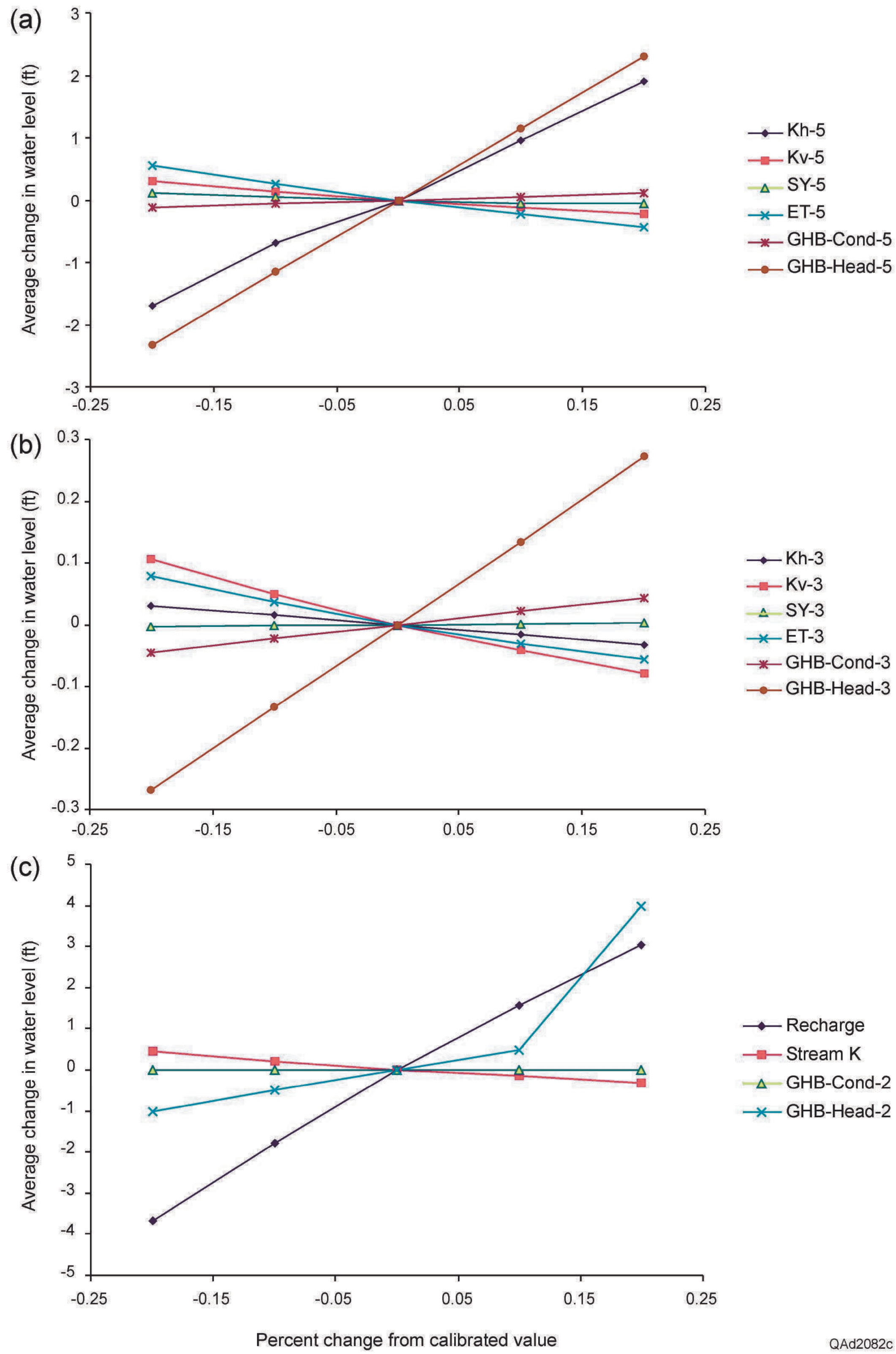

Figure 77. Sensitivity of predicted water levels in the Simsboro aquifer (layer 5) of the steady-state model to changes in parameter values for the (a) Simsboro aquifer (layer 5), (b) Carrizo aquifer (layer 3), and (c) recharge rate, streambed conductance, and the GHB boundary on the Reklaw aquitard (layer 2).

water levels in the Simsboro layer (fig. 77b); note the difference in vertical scale between figure 77a and b. Steady-state simulation results for the Carrizo aquifer are most sensitive to

- GHB heads imposed from layer 2 (fig. 78c), and
- GHB heads imposed on the boundaries of the Carrizo aquifer (fig. 78a).

Model results for the Carrizo aquifer are less sensitive to recharge and horizontal conductivity (fig. 78a, c). Variation of parameters in layer 5 has only a slight impact on water levels in the Carrizo layer (fig. 78b); note the difference in vertical scale between figure 78a and b.

8.3 Water Budget

Table 13 summarizes the water budget calculated for the steady-state model. Recharge provides 10 times more water overall than the GHB boundaries, except for the Reklaw aquitard (layer 2), which is dominated by that boundary (fig. 58). Simulated ET removes approximately 75 percent of total (gross) recharge. Simulated ET removes almost 100 percent of recharge to alluvium (layer 1) and to aquitard layers 2, 4 and 6. Approximately 60 percent of recharge in the Simsboro and Carrizo aquifers is removed by groundwater ET. The water-balance error for the steady-state model, which is the difference between inflow and outflow for the model, is less than 0.01 percent. Net recharge is the flux of groundwater moving from the unconfined to the confined part of the aquifer and is estimated by summing the simulated fluxes across the flow faces of model cells at the boundary between the unconfined and confined zones. Net recharge rates to the Simsboro and Carrizo layers average 0.5 and 0.3 inches/yr, respectively, in the steady-state model. Figure 79 illustrates the water budget of the steady-state model, with a block diagram showing the inflow to and outflow from the model area.

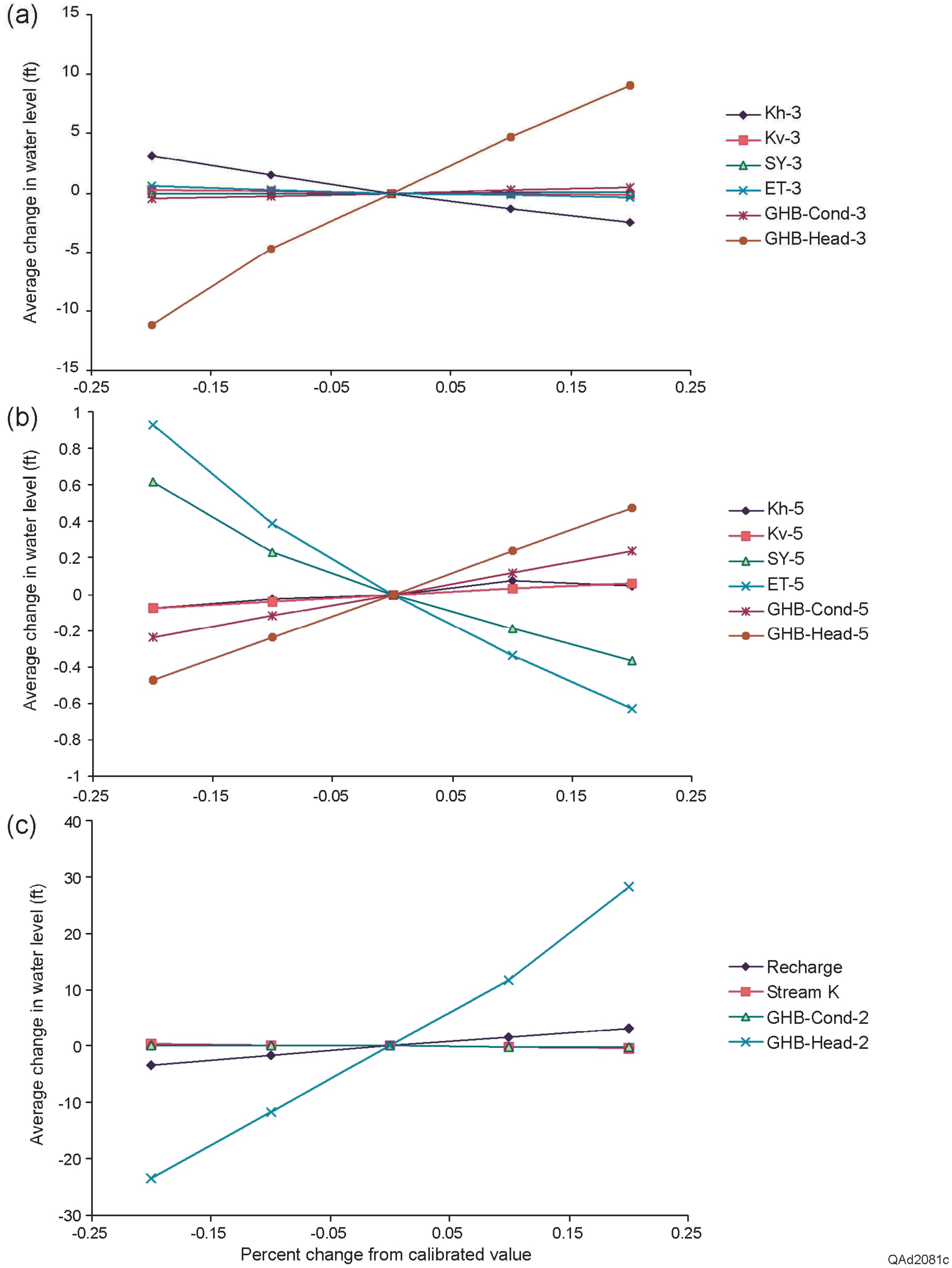

Figure 78. Sensitivity of predicted water levels in the Carrizo aquifer (layer 3) of the steady-state model to changes in parameter values for the (a) Carrizo aquifer (layer 3), (b) Simsboro aquifer (layer 5), and (c) recharge rate, streambed conductance, and the GHB boundary on the Reklaw aquitard (layer 2).

Table 13. Water budget for the calibrated steady–state model (1,000 acre-ft/yr). Positive values are inflow to the aquifer; negative values are discharge from the aquifer. Annual rates determined from the last time step (12 mo long) of the 1-yr steady-state stress period.

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)	12.6	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	–0.9	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

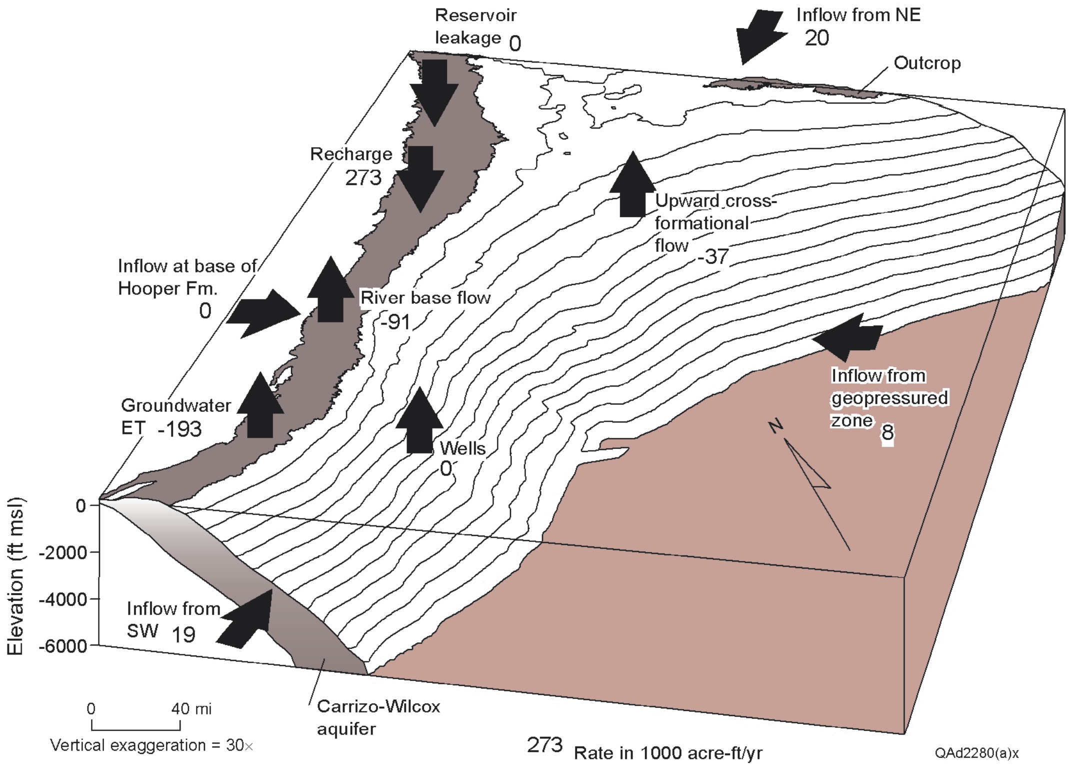

Figure 79. Block diagram of the Carrizo–Wilcox aquifer representing the components of the steady-state model.