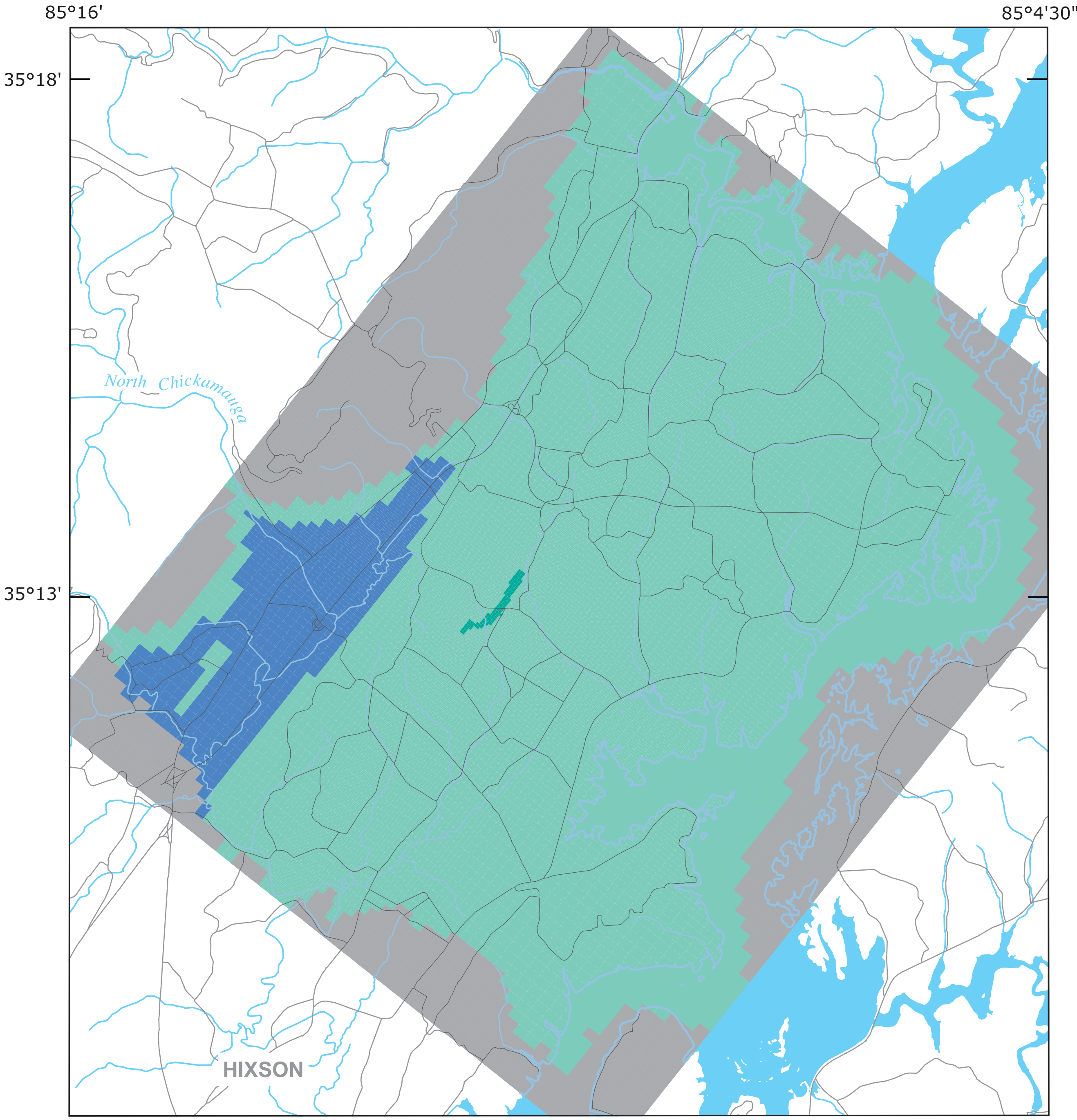


Base from U.S. Geological Survey
Digital line graphs 1:100,000

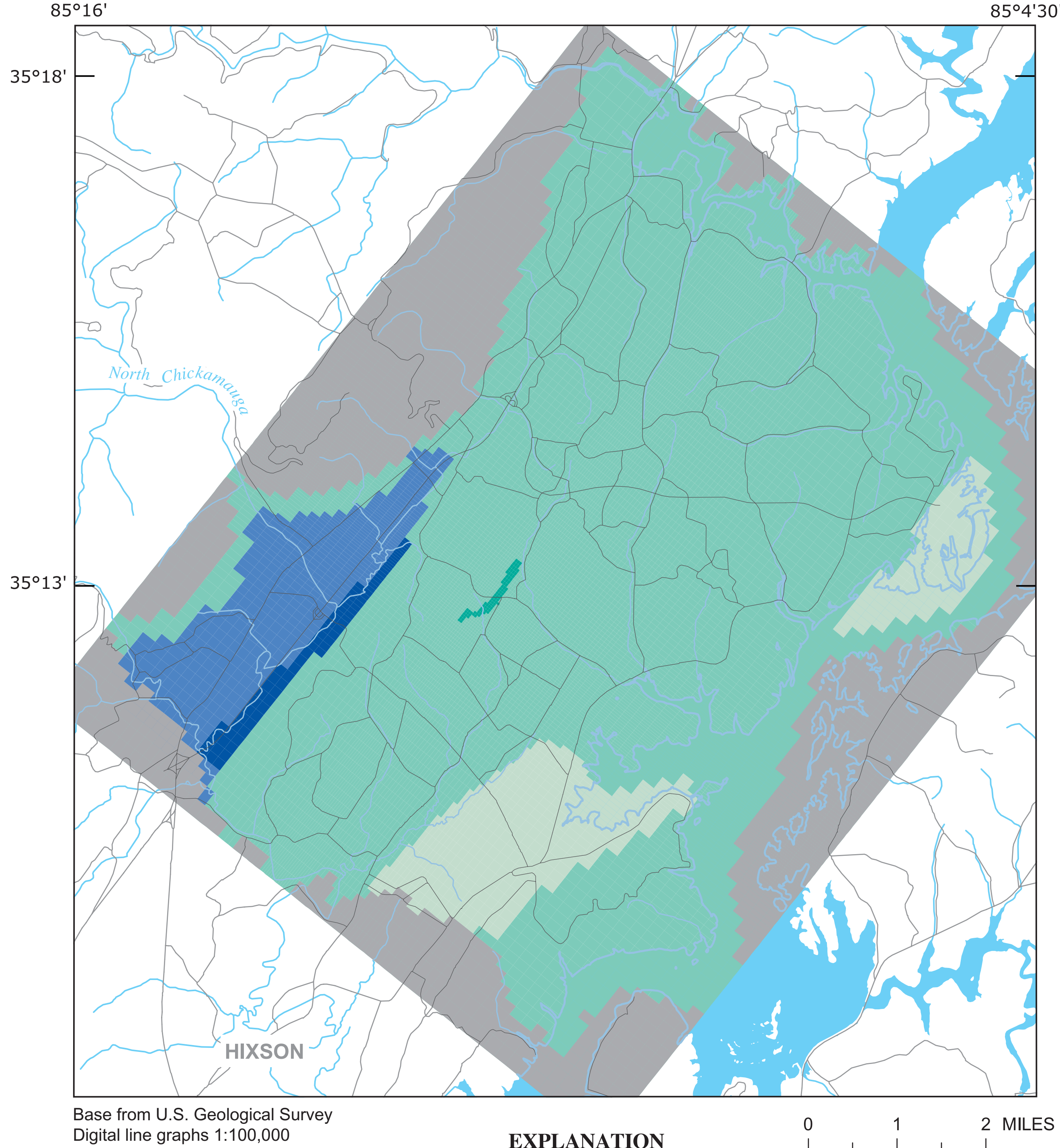
0 1 2 MILES
0 1 2 KILOMETERS

EXPLANATION

HYDRAULIC CONDUCTIVITY

- HK1_AVERAGE—Hydraulic conductivity where layer 1 contains regolith from in-situ weathering of carbonate rocks excluding the area local to the Walkers Corner well field
- HK1_WALKERS—Hydraulic conductivity in layer 1 local to the Walkers Corner well field
- HK1_HIGH—Hydraulic conductivity where layer 1 contains regolith with coarse-grained alluvium
- INACTIVE CELL

Figure 18. Hydraulic-conductivity zones for model layer 1.



EXPLANATION

HYDRAULIC CONDUCTIVITY

- HK2_LOW — Hydraulic conductivity in layer 2 where the shaly Chickamauga Limestone and Conasauga Group occur
- HK2_AVERAGE — Hydraulic conductivity in layer 2 where the bedrock consists predominately of dolomites and limestones that contain little shale
- HK2_WALKERS — Hydraulic conductivity in layer 2 local to the Walkers Corner well field
- HK2_HIGH — Hydraulic conductivity in layer 2 where the Newman Limestone is overlain by regolith with coarse-grained alluvium
- HK2_CONDUIT — Hydraulic conductivity in layer 2 where the Newman Limestone thrust fault block occurs
- INACTIVE CELL

Figure 19. Hydraulic-conductivity zones for model layer 2.

Stream reaches with perennial flow were simulated as river nodes in layer 1. These stream reaches include main stream branches of North Chickamauga Creek, Poe Branch, and Lick Branch. The streambed elevations of most of the tributaries to North Chickamauga Creek, Lick Branch, and Chickamauga Lake are well above the potentiometric surface. These stream reaches do not sustain flow between rainfall events and were not simulated. Cave Springs was simulated as drain nodes in layers 1 and 2. Rogers Spring was simulated as a drain node in layer 1 (fig. 16). Initial hydraulic conductivity for the river and drain nodes were set equal to the vertical hydraulic conductivity of the average zone of model layer 1.

Chickamauga Lake was simulated by constant-head cells in layer 1 using a water-level altitude of 680 feet. The stresses on the ground-water-flow system include production wells at two locations, Cave Springs and the Walkers Corner well field.

Model Calibration

The process of adjusting the model input variables to produce the best match between simulated and observed water levels and flows is referred to as calibration. The digital model developed for this study was calibrated to steady-state conditions that existed prior to pumping at the Walkers Corner well field, as defined by the potentiometric-surface map from May 1993 (fig. 10). Although the annual precipitation for 1993 is below average (table 1), most of the deficit occurred during the summer of 1993. Precipitation from January 1991 through May 1993 was near average, so the potentiometric-surface map of May 1993 should be a reasonable representation of average annual conditions. Pumping at the Cave Springs well field of 9 ft^3/s (5.8 Mgal/d) is included in this simulation. The model was calibrated using a combination of automated and manual methods to minimize the difference between simulated and observed water levels and streamflows. Initial attempts to calibrate most of the hydraulic-conductivity and recharge values using automated procedures resulted in model simulations that either failed to converge or converged to unreasonable parameter values. Therefore, manual calibration was used to determine a value for each of the hydraulic-conductivity and recharge zones. The general guidelines followed were:

1. HK1_high > HK1_walkers > HK1_average
2. HK2_conduit > HK2_high > HK2_walkers > HK2_average > HK2_low
3. RCH_ridge > RCH_average

Automated calibration then was used to further refine the values for the HK1_average and HK2_average parameters.

Overall, simulated water levels agree reasonably well with observed water levels (figs. 10 and 20). Water-level data at 39 wells were available for comparison to simulated conditions prior to pumping at the Walkers Corner well field. The root mean square error (RMSE) was calculated to compare simulated and measured water levels. The RMSE, in feet, is calculated by:

$$RMSE = \sqrt{\left(\sum_{i=1}^{N} \langle h_i^m - h_i^c \rangle^2\right) / N}, \qquad (5)$$

where:

N is the number of observations;
h_i^m is the measured water level, in feet; and
h_i^c is the simulated water level, in feet.

The RMSE for measured compared to simulated water levels was 6.5 feet. The average head difference between measured and simulated heads for the calibration model simulation is -2.0 feet. Fifty-four percent of the simulated water levels were within 5 feet of the observed water levels, and 85 percent were within 10 feet. Differences in water levels between layers 1 and 2 were small (less than 2 feet). Simulated discharge fluxes to springs and streams were within measured ranges of base flow (table 6).

Table 6. Comparison of simulated and measured flows for calibration model simulation; no pumping at Walkers Corner well field
[Measured streamflow from Lowery and others, 1989; Mercer and others, 1992]

	Model simulated streamflow, in cubic feet per second	Range of measured stream base flow, in cubic feet per second
Poe Branch	4.4	0 - 14
North Chickamauga Creek and Cave Springs	49.5	27 - 69
Lick Branch and Rogers Spring	4.0	1.0 - 5.7

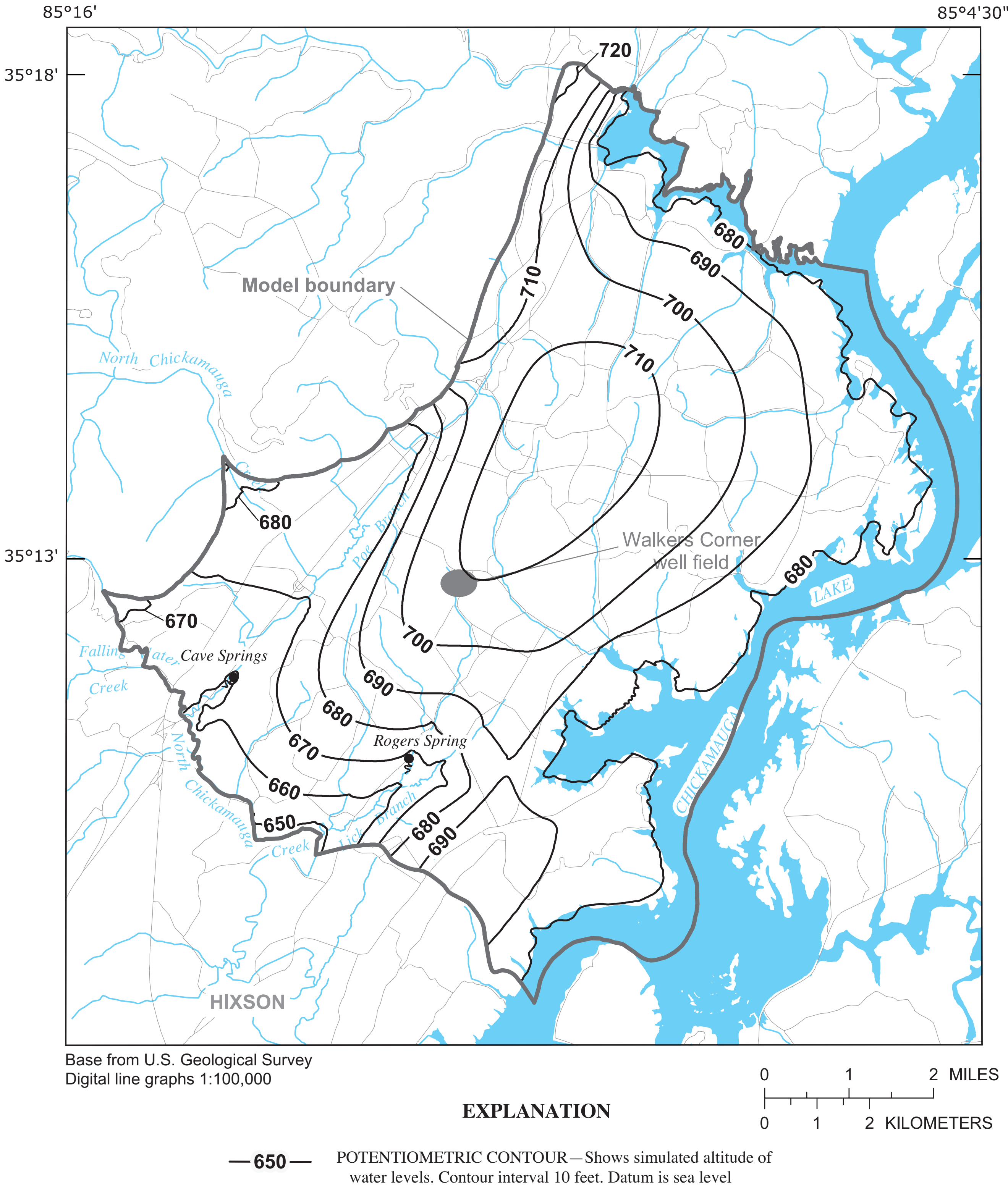


Figure 20. Model-simulated steady-state water levels with no pumping at Walkers Corner well field, layer 1.

Calibrated model transmissivities for layer 1 vary from 300 to 52,000 ft^2/d (fig. 21) with an average of about 3,300 ft^2/d and a median of about 850 ft^2/d. The highest transmissivities in layer 1 occur in the North Chickamauga Creek alluvial plain. Calibrated model transmissivities for layer 2 vary from 1,000 to 1,100,000 ft^2/d (fig. 22) with an average of about 39,000 ft^2/d and a median of about 9,700 ft^2/d. The highest transmissivities in layer 2 occur along the Newman Limestone thrust fault block and in the North Chickamauga Creek alluvial plain. The calibrated transmissivities are consistent with the values from well hydraulic tests (fig. 6). The calibrated hydraulic conductivity parameters were generally within the range of initial estimates (table 5). Calibrated hydraulic conductivity parameter values for HK1_ high, HK2_high, and HK2_low were greater than initial estimates, but not unreasonably so. Transmissivities for these areas are within the range of measured values.

Horizontal and vertical anisotropy were evaluated during model calibration. For the hydraulic-conductivity zones HK1_high and HK2_high, simulating no horizontal or vertical anisotropy produced better matches to water levels in the North Chickamauga Creek valley and flows to North Chickamauga Creek and Cave Springs. In this area, vertical fracturing from the formation of an anticline may have increased the vertical hydraulic conductivity. Also, the concentrated recharge from losing streams along the base of the Cumberland Plateau escarpment may promote increased dissolution of the bedrock in this area. Horizontal anisotropy may not be as important in this area because it is located west of the westernmost mapped thrust faults at the edge of the Valley and Ridge Physiographic Province. Over the rest of the model area, a horizontal anisotropy ratio of 2:1 in layer 1 and 8:1 in layer 2 and a vertical anisotropy ratio of 10:1 produced the best match to observed water levels and flows.

Calibrated model recharge rates from precipitation were 8 in/yr for most of the study area (RCH_average) and 20 in/yr along Cave Springs Ridge (RCH_ridge). The resulting average recharge rate from precipitation for the model area is 9.5 in/yr. Water from losing streams along the Cumberland Plateau escarpment (46.9 ft^3/s) is a significant source of recharge to the ground-water system amounting to 54 percent of the total recharge to the system (table 7). The drainage area of streams on the Cumberland Plateau (primarily North Chickamauga Creek) that lose water along the northwestern edge of the model area is about 77 square miles, which is greater than the active model area of 54 square miles. In this calibration simulation of conditions prior to pumping at the Walkers Corner well field, 10 percent (9 ft^3/s) of the total water budget is ground-water withdrawal by pumping by HUD; the remainder is discharge to North Chickamauga Creek and Cave Springs (57 percent, 49.5 ft^3/s), Chickamauga Lake (23 percent, 19.9 ft^3/s), Poe Branch (5 percent, 4.4 ft^3/s), and Lick Branch and Rogers Spring (5 percent, 4.0 ft^3/s).

Effects of Pumping at Walkers Corner

The first production well at Walkers Corner well field has pumped nearly continuously since 1995. A second production well was approved for use in 2000, but is used infrequently at the present (2001). Two additional steady-state simulations were made to test the initial model calibration and to study the effects of additional withdrawal at the Walkers Corner well field. Steady-state simulations are used because the aquifer in the study area has high transmissivity and, therefore, equilibrium with pumping should occur

Table 7. Steady-state water budget from calibration model simulation; no pumping at Walkers Corner well field

Sources and discharges	Flow, in cubic feet per second	Percent of total flow
Sources		
Direct infiltration of precipitation.	39.9	46
Recharge from losing streams.	46.9	54
Total	86.8	100
Discharges and withdrawals		
Chickamauga Lake	19.9	23
Poe Branch	4.4	5
North Chickamauga Creek	34.0	39
Cave Springs	15.5	18
Lick Branch and Rogers Spring.	4.0	5
Production wells, Hixson Utility District.	9.0	10
Total	86.8	100

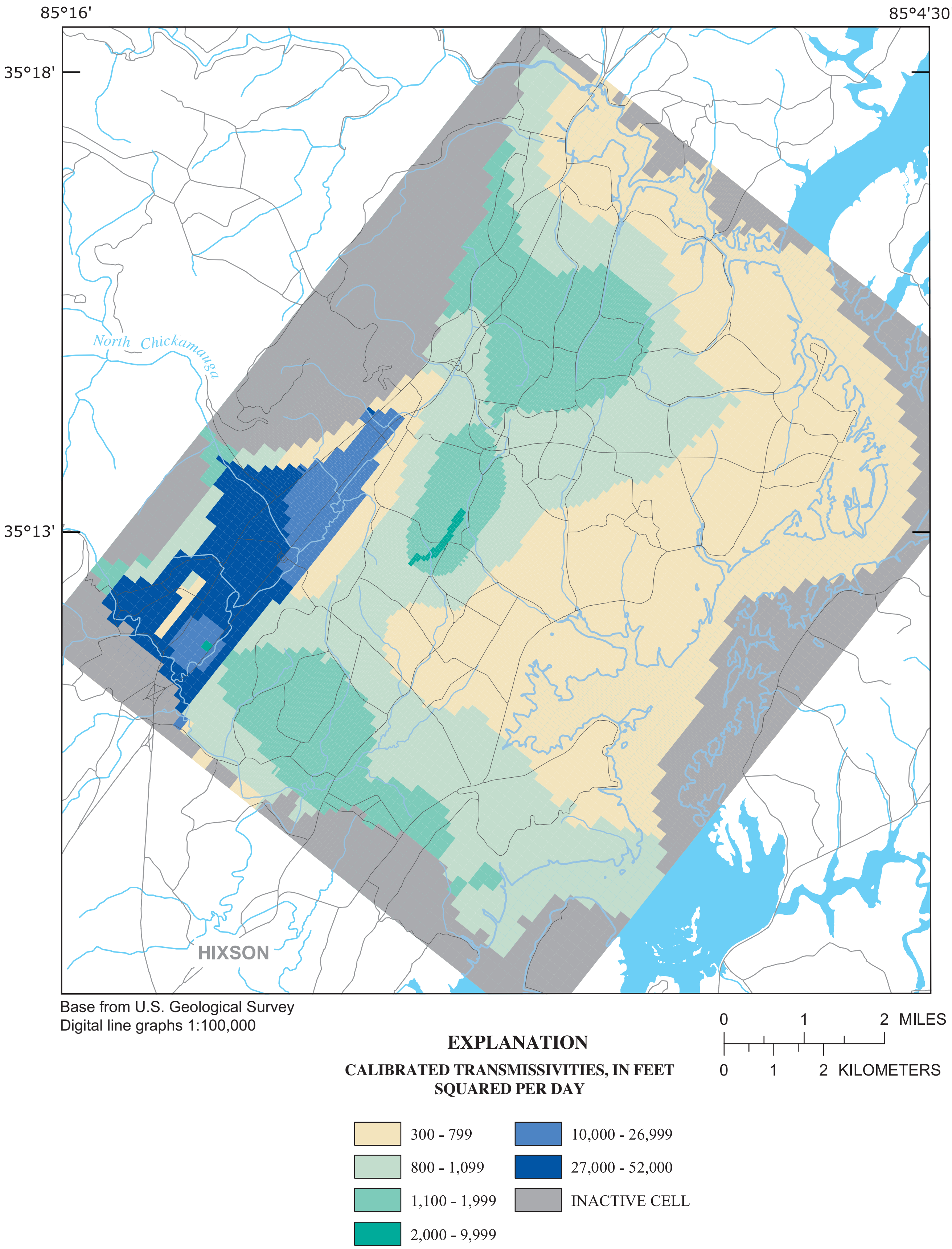
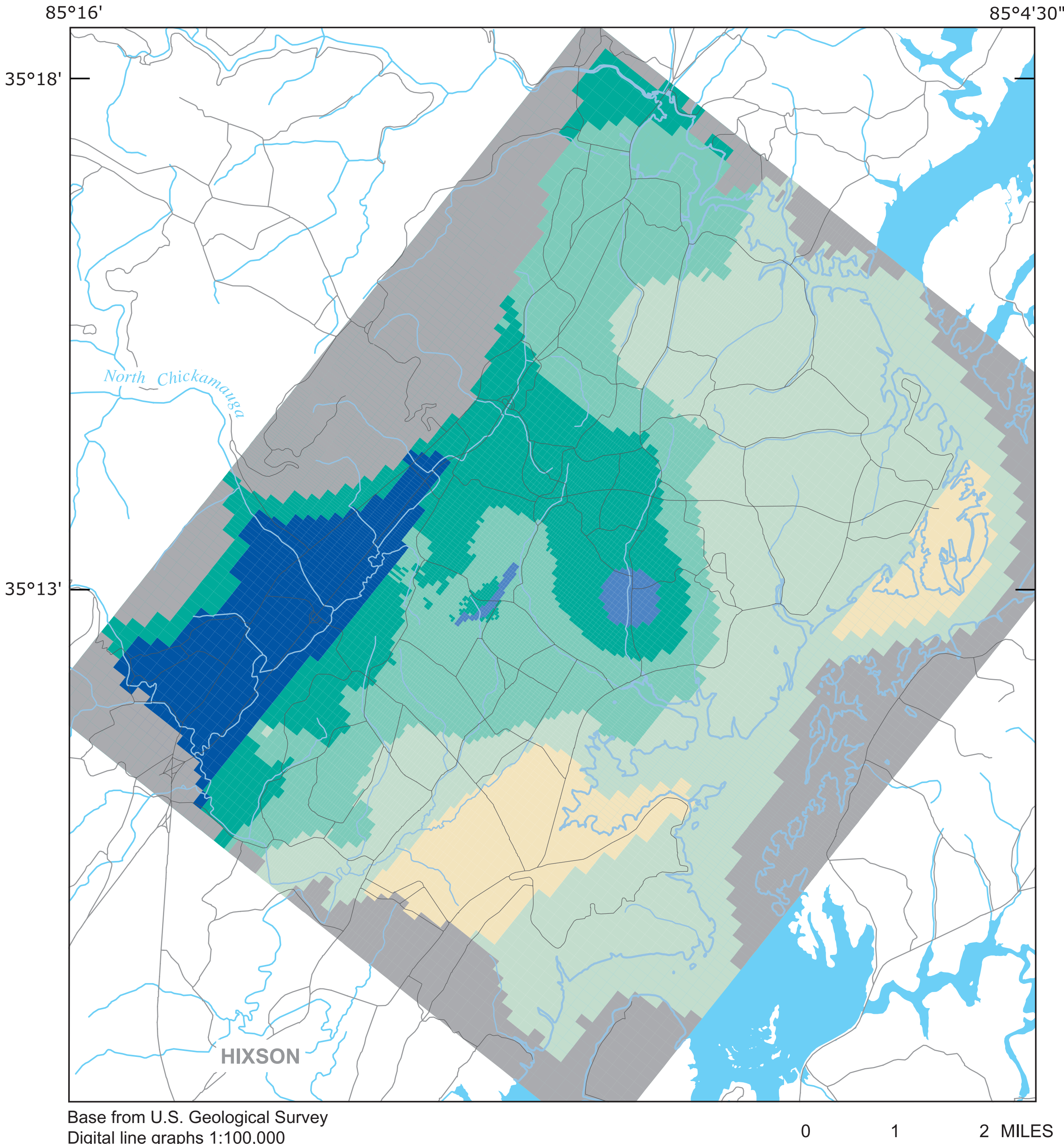


Figure 21. Calibrated transmissivities for model layer 1.



EXPLANATION

CALIBRATED TRANSMISSIVITIES, IN FEET SQUARED PER DAY

- 1,000 - 2,999
- 3,000 - 9,999
- 10,000 - 12,999
- 13,000 - 17,999
- 18,000 - 30,000
- 240,000 - 1,100,000
- INACTIVE CELL

Figure 22. Calibrated transmissivities for model layer 2.

within a short time. Water levels in the Walkers Corner area show that most of the water-level declines due to pumping at Walkers Corner production well #1 occurred within the first 2 years after pumping began (1995-97) (fig. 14). Small continued declines are indicated over the next 2 years (1997-99) (tables 3 and 4, fig. 14) with little additional decline in water levels after 1999 (fig. 14). Annual precipitation from 1995 through 1998 was near average. Precipitation in 1999 and 2000 was slightly below average (table 1).

The first production well at Walkers Corner has pumped nearly continuously since 1995 at a rate of 2.8 ft^3/s (1.8 Mgal/d). The initial model calibration was tested by simulating the effects of pumping from Walkers Corner production well #1 (figs. 23 and 24) and then comparing the results to the current conditions as defined by the potentiometric-surface map from May 1999 (fig. 12). The only difference between the initial calibration model simulation and this simulation is the addition of ground-water pumpage at Walkers Corner well field production well #1 and a reduction of pumpage at the Cave Springs well field from 9 to 7.1 ft^3/s. Overall, simulated water levels agree reasonably well with observed water levels. Water-level data at 37 wells were available for comparison to simulated conditions following the onset of pumping at the Walkers Corner well field. The RMSE for measured compared to simulated water levels was 5.9 feet. Of the simulated water levels, 49 percent were within 5 feet of the observed water levels and 97 percent were within 10 feet. The simulated potentiometric surfaces in model layers 1 and 2 show depressed water levels trending along strike from the well field (figs. 23 and 24, respectively). The maximum steady-state water-level decline from the simulation was 28 feet in model layer 1 and 33 feet in layer 2 (figs. 25 and 26, respectively). This is similar to the observed water-level decline of about 30 feet (figs. 13 and 14).

To isolate the effects of withdrawal at Walkers Corner well field production well #1 on the water budget, an additional pumpage simulation was run with the pumpage from the Cave Springs well field at the initial calibration simulation rate of 9 ft^3/s. The model water budget indicates that ground-water withdrawal at the Walkers Corner well field from production well #1 results in decreases in simulated ground-water discharge of 0.9 ft^3/s to Chickamauga Lake, 0.7 ft^3/s to North Chickamauga Creek, 0.6 ft^3/s to Lick Branch and Rogers Spring, 0.4 ft^3/s to Poe Branch, and 0.2 ft^3/s to Cave Springs (table 8). No measured

Table 8. Simulated ground-water discharges and withdrawals for steady-state model simulations

	Calibration simulation; no pumping at Walkers Corner well field	Calibration simulation; pumping at Walkers Corner well field	Additional pumping simulation; pumping at Walkers Corner production well #1		Additional pumping simulation; pumping at Walkers Corner production wells #1 and #2	
	Discharge, in cubic feet per second	Discharge, in cubic feet per second	Discharge, in cubic feet per second	Change from no pumping at Walkers Corner simulation, in cubic feet per second	Discharge, in cubic feet per second	Change from no pumping at Walkers Corner simulation, in cubic feet per second
Ground-water discharges						
Chickamauga Lake	19.9	19.0	19.0	-0.9	18.0	-1.9
Poe Branch	4.4	4.1	4.0	-0.4	3.5	-0.9
Cave Springs	15.5	16.5	15.3	-0.2	15.1	-0.4
North Chickamauga Creek	34.0	33.9	33.3	-0.7	32.5	-1.5
Lick Branch and Rogers Spring	4.0	3.4	3.4	-0.6	2.9	-1.1
Ground-water withdrawals						
Wells at Walkers Corner	0	2.8	2.8	2.8	5.8	5.8
Wells at Cave Springs	9	7.1	9	0	9	0
Total from wells	9	9.9	11.8	2.8	14.8	5.8