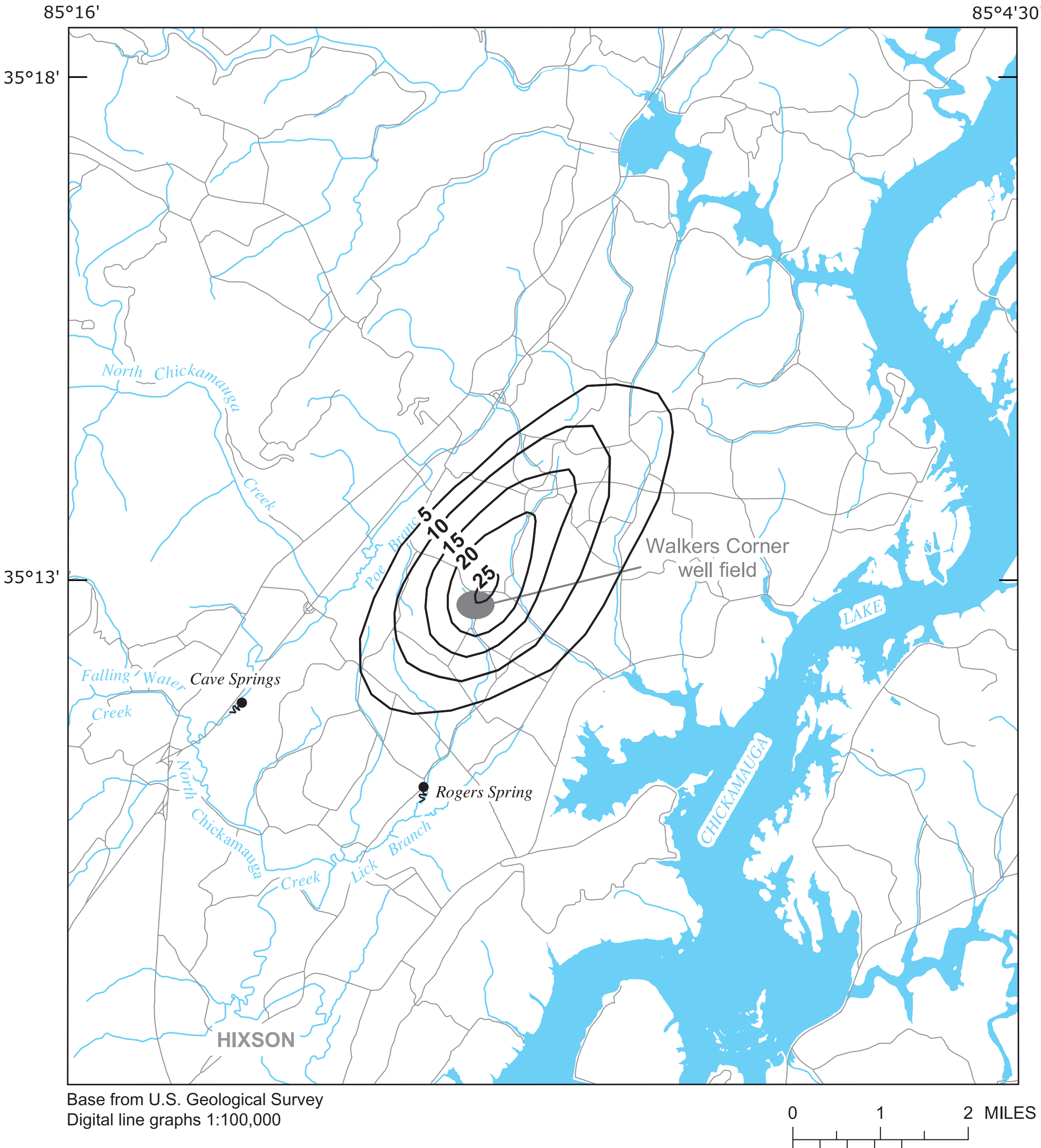

EXPLANATION

—25— LINE OF EQUAL WATER-LEVEL DECLINE—Shows decline, in feet, of water levels from pumping at Walkers Corner well field. Contour interval 5 feet

Figure 13. Water-level decline from May 1993 to May 1999 in the Cave Springs area near Hixson, Tennessee.

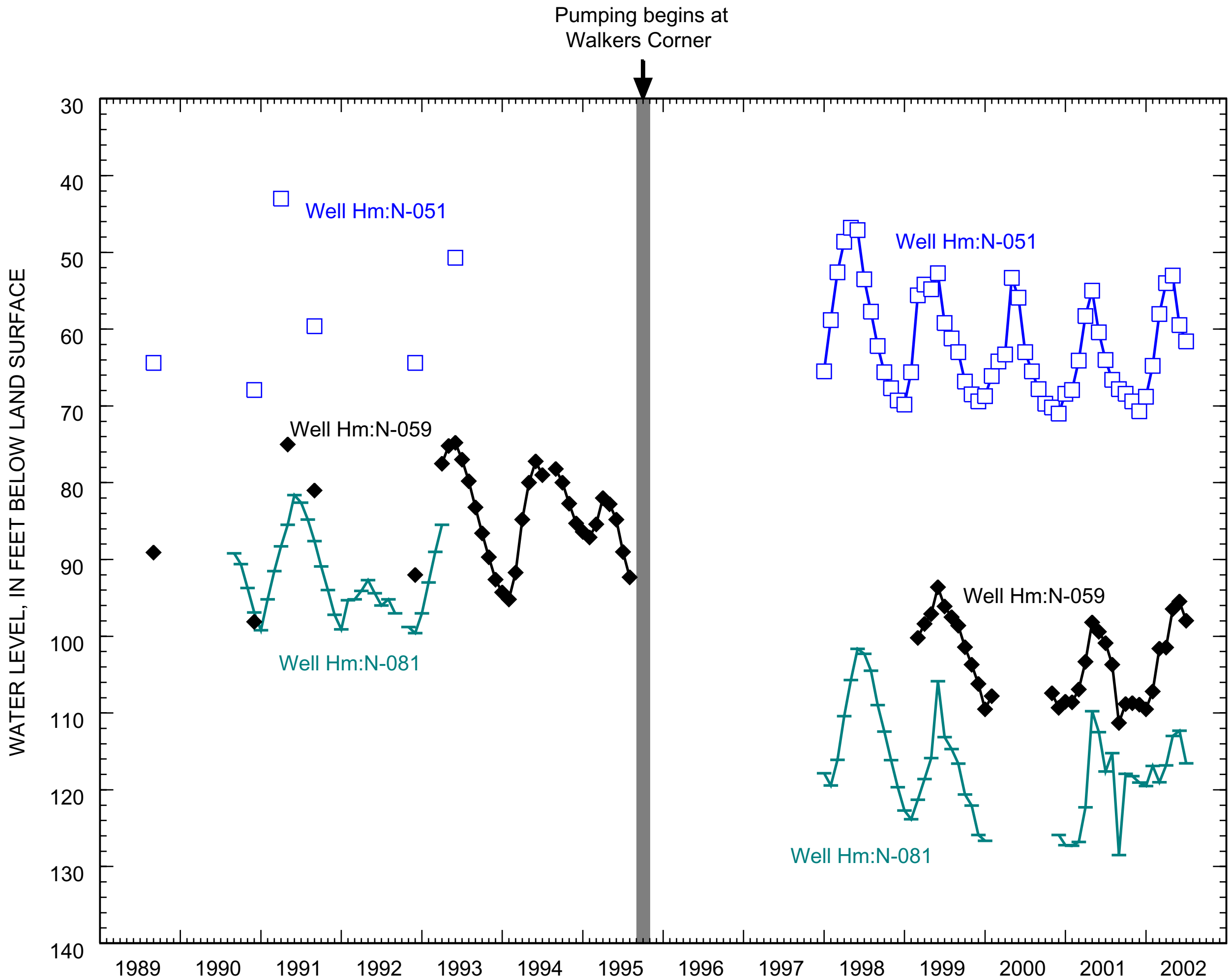

Figure 14. Periodic water levels in wells Hm:N-051, Hm:N-059, and Hm:N-081 from 1989 to 2002.

SIMULATION OF GROUND-WATER FLOW

The physical system described in the hydrogeology section of this report provides the framework for a ground-water-flow model. A model that simulates the flow of water through an aquifer provides a useful tool to test the understanding and concepts of the flow system. Although a model is necessarily a simplification of the physical system, the model should be consistent with all known hydrogeologic observations. The ground-water-flow model code used in this study, MODFLOW-2000 (Harbaugh and others, 2000), uses finite-difference techniques to solve the ground-water-flow equation for three-dimensional, steady or non-steady flow in anisotropic, heterogeneous media.

Four model simulations are presented in this report. First, a steady-state model was constructed and calibrated to conditions prior to pumping at the Walkers Corner well field. Second, the initial model calibration was tested with a steady-state calibration with production well #1 in use at the Walkers Corner well field. Third, to estimate the conditions that would exist after the second well at the Walkers Corner well field is in use, a steady-state simulation with Walkers Corner production wells #1 and #2 in use was made. Finally, a transient simulation was calibrated and examined to study an extended period of no recharge, which could occur in a drought. Pumping at the Cave Springs well field was simulated at a constant 9 ft^3/s (5.8 Mgal/d) for all the simulations.

Model Assumptions

The following assumptions were made in the development of the flow model of the hydrologic system in the Cave Springs area.

1. Fracture and dissolution zones are extensive enough in both areal and vertical distribution that the hydrogeologic units can be simulated as porous media.
2. Over most of the model area, fractures and dissolution openings are small enough that flow is laminar.
3. The upper model boundary is assumed to be the water-table surface.
4. The lower model boundary is assumed to be a no-flow boundary corresponding to the lower extent of dissolution openings in the bedrock.
5. The hydraulic properties of hydrogeologic units are homogeneous within a block of the finite-difference grid.
6. Flow within a layer is horizontal; flow between layers is vertical.
7. Horizontal anisotropy is assumed with the primary axes of hydraulic conductivity oriented along geologic strike.
8. The grid is aligned with the primary axes of hydraulic conductivity (along geologic strike).
9. The aquifer is at steady state with ground-water withdrawals.

The flow model solves the partial differential equation that results when Darcy's law is incorporated with the equation of continuity and the assumption of constant water density (Rushton and Redshaw, 1979; McDonald and Harbaugh, 1988). This equation is valid for ground-water-flow problems when the velocity of ground water is slow and laminar (non-turbulent). The aquifer in the study area contains fractured bedrock and dissolution openings where flow may be turbulent. Therefore, the equation may not be valid for the entire model area. For modeling purposes, laminar flow is assumed everywhere, and the aquifer is treated as an equivalent porous media.

Conceptual Model

The aquifer in the study area was divided into two layers to simulate ground-water flow. The layers were defined on the basis of differences in physical characteristics which affect hydrologic properties. Layer 1 corresponds to the saturated regolith. Layer 2 corresponds to bedrock. Hydraulic conductivity is greater in the direction parallel to strike and lesser in the direction perpendicular to strike; therefore, ground water flows more easily along strike than across strike. The streams draining the area are assumed to be hydraulically connected to layer 1 through leaky streambeds. Recharge by direct infiltration of precipitation occurs across the study area and is greater in the topographically high areas along Cave Springs Ridge. Recharge also occurs from losing stream reaches near the base of the Cumberland Plateau escarpment. Ground-water discharge occurs as base flow to streams, springs, and flow to Chickamauga Lake and production wells.

Model Boundaries

The lateral boundaries of the model correspond to natural boundaries wherever possible (fig. 15). Chickamauga Lake forms the southeast and northeast boundaries and is simulated as a constant-head boundary in layer 1 and a no-flow boundary in layer 2. Active cells in layer 2 extend directly under the constant-head cells in layer 1; therefore, layer 2 is connected vertically to the constant-head cells in layer 1 representing Chickamauga Lake. The geologic contact between the Mississippian-age carbonates (primarily the Newman Limestone) and the overlying Pennington Formation forms the northwest boundary of the model. This geologic contact occurs near the base of the Cumberland Plateau escarpment where the surficial geology transitions from more permeable carbonates in the Valley and Ridge Physiographic Province to the less permeable Pennsylvanian-age shales and sandstones of the Cumberland Plateau. This geologic contact is simulated as a no-flow boundary in the model. Roberts Mill Branch, from the Cumberland Plateau escarpment to its mouth; Falling Water Creek, from the mouth of Roberts Mill Branch to its mouth; and North Chickamauga Creek, from the mouth of Falling Water Creek to where it leaves the study area, form part of the southwest model boundary. These creeks are simulated in the model as head-dependent flow boundaries (river nodes) with no underflow. The southwest model boundary is completed by a flow-path line extending from North Chickamauga Creek to the crest of Big Ridge and a flow-path line extending from the crest of Big Ridge to the shore of Chickamauga Lake. These flow-path lines are simulated in the model as no-flow boundaries.

Vertically, the upper boundary of the model is the water table. The bottom boundary ranges between elevations of 430 and 577 feet above sea level and corresponds to the base of the ground-water-flow system, as hypothesized by Bradfield (1992). The bottom boundary of the model is simulated as a no-flow boundary.

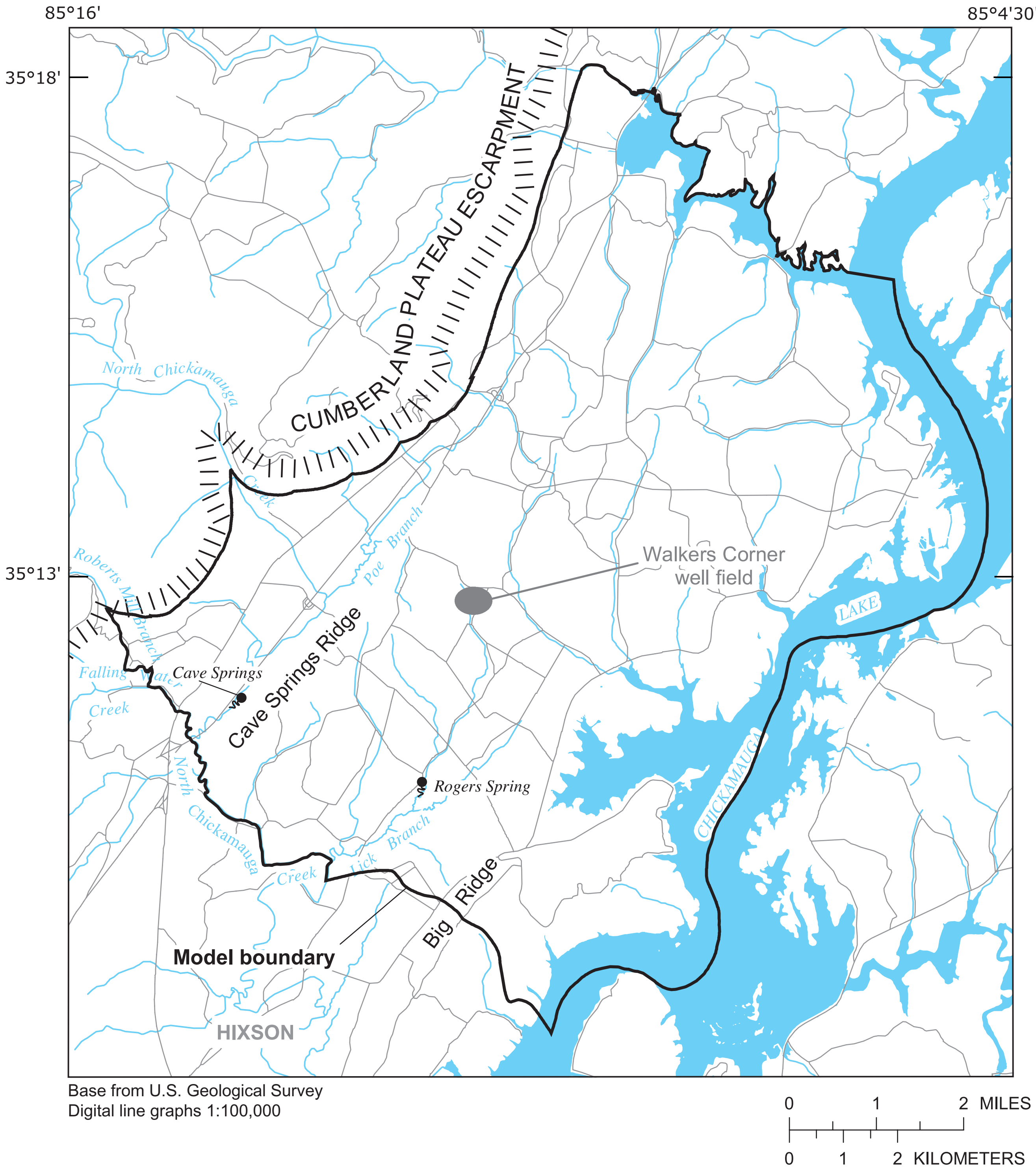

Figure 15. Hixson ground-water-flow model boundary.

Model Construction

The model grid is approximately an 8- by 10-mile rectangle consisting of variable-size grid cells (fig. 16). The grid is made up of 131 columns and 96 rows. About 54 square miles of the 80-square-mile model grid are active. The smallest grid cells, located near Cave Springs and the Walkers Corner well field, are about 150 by 150 feet, and the largest grid cells, located near the model boundaries, are about 800 by 800 feet. The grid is oriented N. 38^o E., N. 52^o W. so that the grid is aligned parallel to the strike of bedrock in the study area.

Model parameters (Harbaugh and others, 2000) were defined for recharge and hydraulic-conductivity zones (table 5). Recharge to the model is from two distinct sources: direct infiltration of precipitation and losing streams. Recharge from precipitation is divided into two zones (fig. 17). A higher recharge rate was applied to Cave Springs Ridge (RCH_ridge) because overland flow paths to perennial streams are long in this area and because numerous sinkholes are present along the ridge. The recharge rates for both zones were adjusted during model calibration using ranges estimated from previous work (described in the recharge section of this report). Additional recharge also was applied along the base of the Cumberland Plateau escarpment to simulate surface water that is lost to the ground-water system where streams draining the plateau contact and flow on the more permeable Newman Limestone (figs. 2 and 17). Based on a limited number of surface-water measurements from Pavlicek (1996), the average loss from these streams along the Cumberland Plateau escarpment base was estimated to range from 0.3 to 0.6 $(ft^3/s)/mi^2$ of drainage area upstream on the Cumberland Plateau. The primary stream where these losses occur is North Chickamauga Creek. During periods of low base flow, all the flow in North Chickamauga Creek from the Cumberland Plateau escarpment sinks into the ground shortly after contacting the Newman Limestone.

Recharge rates input to the model are net recharge rates. Therefore, evapotranspiration of ground water is not explicitly included in the model. Ground-water evapotranspiration is typically small, less than 2 in/yr (Rutledge and Mesko, 1996).

In the model, layers 1 and 2 were simulated as convertible layers, which means the grid cells either could be confined or unconfined depending on whether the calculated water level is above or below the top of the model cell. The model calculated the transmissivity for each cell by using hydraulic conductivity and saturated thickness of the layer, both of which vary aerially. Hydraulic-conductivity zones were determined based on geology and well-hydraulic test data.

Layer 1 consists of three hydraulic-conductivity zones (fig. 18). The zone of highest conductivity in layer 1 (HK1_high) occurs in the North Chickamauga Creek alluvial plain where the regolith contains coarse-grained alluvium eroded from the sandstone and conglomerate rocks of the Cumberland Plateau. The largest zone (HK1_average) occurs where the regolith is derived from in-situ weathering of carbonate bedrock. The smallest zone (HK1_walkers) occurs local to the Walkers Corner well field where well-hydraulic tests indicate transmissivity is higher than average.

Layer 2 consists of five hydraulic-conductivity zones (fig. 19). The zone of highest conductivity in layer 2 (HK2_conduit) occurs along the Newman Limestone thrust fault block where the conduit system that supplies Cave Springs is believed to exist. The next highest conductivity zone (HK2_high) occurs where the Newman Limestone is overlain by coarse-grained alluvium eroded from the siliciclastic rocks of the Cumberland Plateau. The largest zone (HK2_average) occurs where the bedrock is predominantly dolomites and limestones that contain little shale. The smallest zone (HK2_walkers) occurs local to the Walkers Corner well field where well-hydraulic tests indicate transmissivity is higher than average. The lowest conductivity zone in layer 2 (HK2_low) occurs where the shaly, low-permeability Chickamauga Limestone and Conasauga Group are present (fig. 19). Initial estimates for the model of each hydraulic-conductivity parameter were made on the basis of aquifer thickness and 17 transmissivity values from the study area (fig. 6), measured values of hydraulic conductivity for similar geologic formations outside the study area, and lithologic differences between formations (table 5).

Horizontal anisotropy is simulated such that the principal direction of hydraulic conductivity is along the model rows (parallel to rock strike). The horizontal anisotropy is assumed to be greater in model layer 2 than in layer 1.

The model layers were assumed to be hydraulically well connected and not separated by confining material. The vertical hydraulic conductivity in both layers was initially simulated assuming a 10:1 horizontal-to-vertical hydraulic conductivity ratio in all model cells.

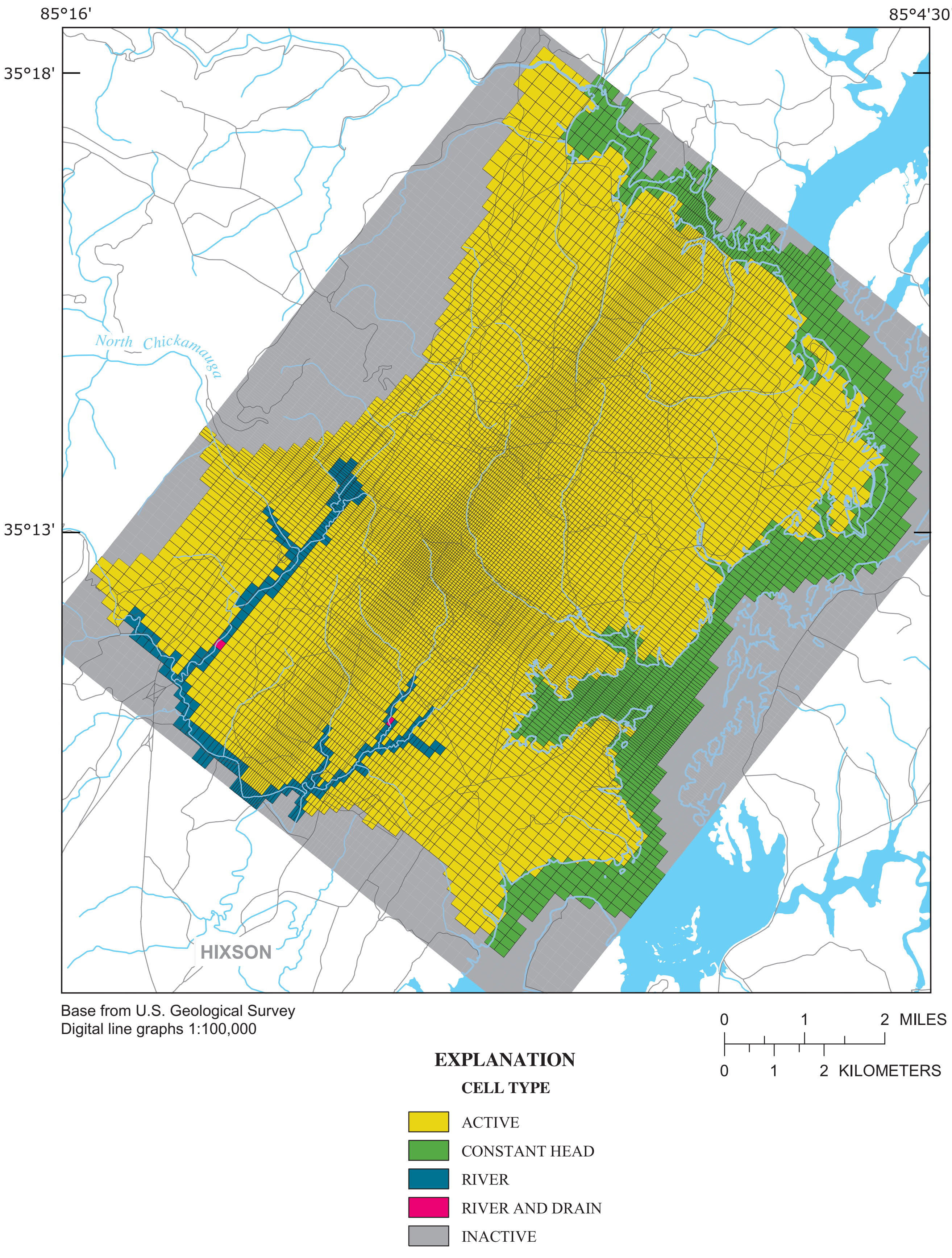

Figure 16. Model grid and cell types for the ground-water-flow model of the Cave Springs area near Hixson, Tennessee.

Table 5. Recharge and hydraulic-conductivity parameters defined in the ground-water-flow model

Model parameter	Description	Initial estimates	Calibrated value
RCH_average	Recharge rate from direct infiltration of precipitation for all areas except Cave Springs Ridge.	8 to 12 inches per year	8 inches per year
RCH_ridge	Recharge rate from direct infiltration of precipitation on Cave Springs Ridge.	12 to 24 inches per year	20 inches per year
RCH_scarp	Recharge rate from losing streams along the Cumberland Plateau escarpment.	23 to 46 cubic feet per second	46.9 cubic feet per second
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.	5 to 25 feet per day	11 feet per day
HK1_walkers	Hydraulic conductivity in layer 1 local to the Walkers Corner well field.	20 to 140 feet per day	22 feet per day
HK1_high	Hydraulic conductivity for area in North Chickamauga Creek alluvial plain where layer 1 contains regolith with coarse-grained alluvium.	50 to 250 feet per day	500 feet per day
HK2_low	Hydraulic conductivity in layer 2 where the shaly Chickamauga Limestone and Conasauga Group occur.	5 to 20 feet per day	30 feet per day
HK2_average	Hydraulic conductivity in layer 2 where the bedrock consists predominately of dolomites and limestones that contain little shale.	20 to 140 feet per day	106 feet per day
HK2_walkers	Hydraulic conductivity in layer 2 local to the Walkers Corner well field.	40 to 280 feet per day	212 feet per day
HK2_high	Hydraulic conductivity in layer 2 where the Newman Limestone is overlain by regolith with coarse-grained alluvium.	200 to 1,000 feet per day	2,000 feet per day
HK2_conduit	Hydraulic conductivity in layer 2 where the Newman Limestone thrust fault block occurs.	2,000 to 6,000 feet per day	5,000 feet per day
Horizontal anisotropy (layer 1)	Ratio of hydraulic conductivity along row (parallel to rock strike) to hydraulic conductivity along column.	2:1	2:1 in all areas except HK1_high where ratio is 1:1
Horizontal anisotropy (layer 2)	Ratio of hydraulic conductivity along row (parallel to rock strike) to hydraulic conductivity along column.	4:1	8:1 in all areas except HK2_high where ratio is 1:1
Vertical anisotropy (layer 1)	Ratio of horizontal to vertical hydraulic conductivity.	10:1	10:1 in all areas except HK1_high where ratio is 1:1
Vertical anisotropy (layer 2)	Ratio of horizontal to vertical hydraulic conductivity.	10:1	10:1 in all areas except HK2_high where ratio is 1:1

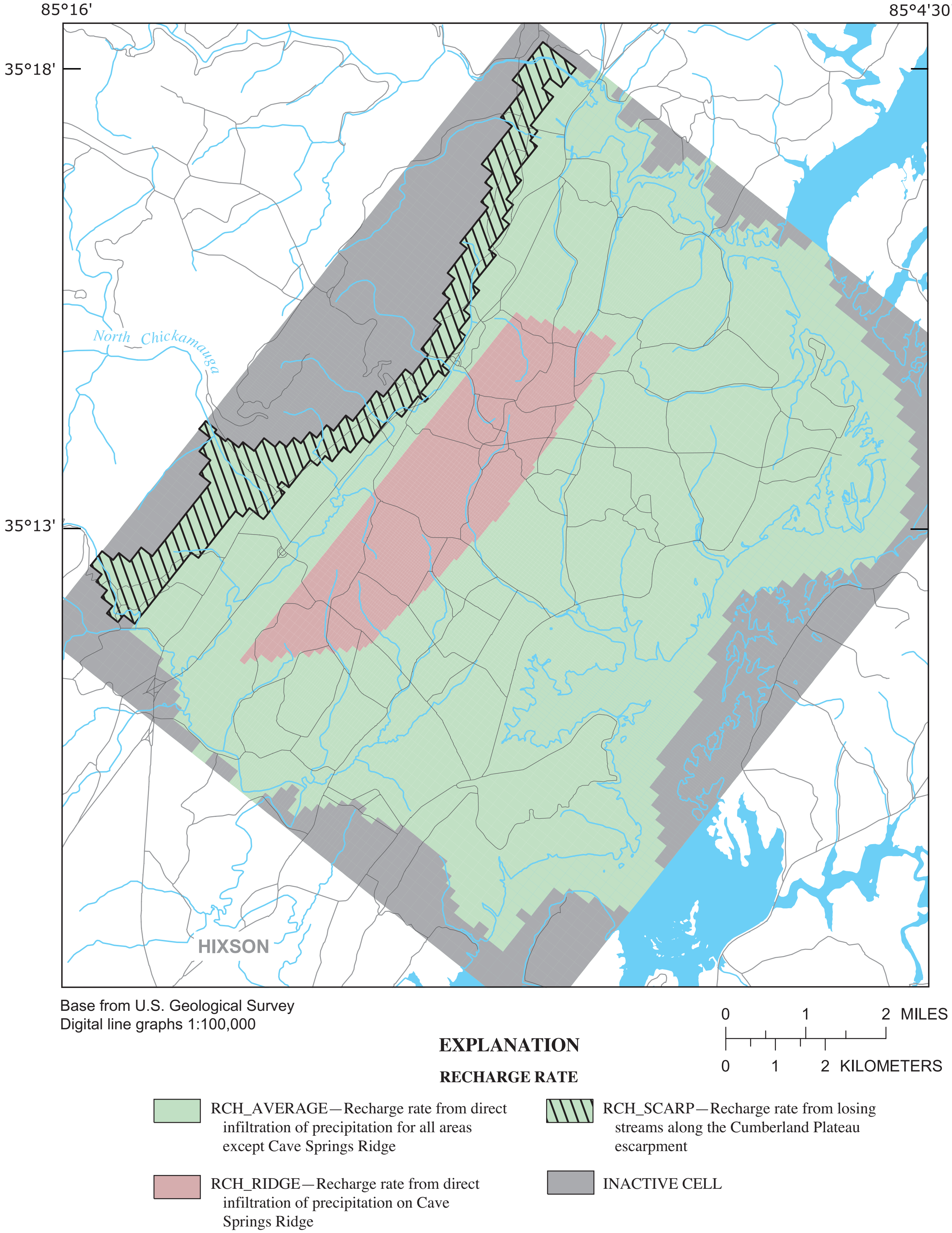

Figure 17. Distribution of simulated recharge rates for the ground-water-flow model.