Cover illustration: See figure 22, page 39.

Hydrogeology and Ground-Water-Flow Simulation of the Cave Springs Area, Hixson, Tennessee

By Connor J. Haugh

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CONVERSION FACTORS, VERTICAL AND HORIZONTAL DATUM, AND WELL-NUMBERING SYSTEM

Multiply	By	To obtain
inch (in.)	25.4	millimeter
inch per year (in/yr)	25.4	millimeter per year
foot (ft)	0.3048	meter
square foot (ft^2)	0.0929	square meter
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
cubic foot per second per square mile [$(ft^3/s)/mi^2$]	0.01093	cubic meter per second per square kilometer
mile (mi)	1.609	kilometer
square mile (mi^2)	259.0	hectare
square mile (mi^2)	2.590	square kilometer
acre	4,047	square meter
acre	0.4047	hectare
million gallons per day (Mgal/d)	0.04381	cubic meters per second
gallon per minute (gal/min)	0.06308	liter per second
gallon per minute per foot	0.2070	liter per second per meter
foot per day (ft/d)	0.3048	meter per day
foot squared per day (ft^2/d)	0.09290	meter squared per day

Temperature in degrees Fahrenheit (^oF) can be converted to degrees Celsius (^oC) as follows: $^oC = 5/9 \times (^oF-32)$

Transmissivity: In this report transmissivity is expressed as foot squared per day (ft^2/d)—The standard unit for transmissivity (T) is cubic foot per day per square foot times foot of aquifer thickness "$[(ft^3/d)/ft^2]ft$" or cubic meter per day per square meter times meter of aquifer thickness "$[(m^3/d)/m^2]m$". These mathematical expressions reduce to foot squared per day "(ft^2/d)" or meter squared per day "(m^2/d)".

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

Horizontal datum: Horizontal coordinate information is referenced to the North American Datum of 1927 (NAD 27).

Well-numbering system: The U.S. Geological Survey assigns each well in this report a local Tennessee well number. The local well number in Tennessee consists of three parts: (1) an abbreviation of the name of the county in which the well is located; (2) a letter designating the 7 1/2-minute topographic quadrangle on which the well is plotted; and (3) a number generally indicating the numerical order in which the well was inventoried. The symbol Hm:N-35, for example, indicates that the well is located in Hamilton County on the "N" quadrangle and is identified as well 35 in the numerical sequence. Quadrangles are lettered from left to right, beginning in the southwest corner of the county.

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ABSTRACT

The ground-water resource in the Cave Springs area is used by the Hixson Utility District as a water supply and is one of the more heavily stressed in the Valley and Ridge Physiographic Province. In 1999, ground-water withdrawals by the Hixson Utility District averaged about 6.4 million gallons per day (Mgal/d) from two pumping centers. The Hixson Utility District has historically withdrawn about 5.8 Mgal/d from wells at Cave Springs. In 1995 to meet increasing demand, an additional well field was developed at Walkers Corner, located about 3 miles northeast of Cave Springs. From 1995 through 2000, pumping from the first production well at Walkers Corner averaged about 1.8 Mgal/d. A second production well at Walkers Corner was approved for use in 2000. Hixson Utility District alternates the use of the two production wells at Walkers Corner except when drought conditions occur when they are used simultaneously. The second production well increased the capacity of the well field by an additional 2 Mgal/d.

The aquifer framework in the study area consists of dense Paleozoic carbonate rocks with secondary permeability that are mantled by thick residual clay-rich regolith in most of the area and by coarse-grained alluvium in the valley of North Chickamauga Creek. Cave Springs, one of the largest springs in Tennessee, derives its flow from conduits in a carbonate rock (karst) aquifer. Production wells at Cave Springs draw water from these conduits. Production wells at Walkers Corner primarily draw water from gravel zones in the regolith near the top of rock. Transmissivities estimated from hydraulic tests conducted across the Cave Springs area span a range from 240 to 900,000 feet squared per day (ft^2/d) with a median value of 5,200 ft^2/d. Recharge to the aquifer occurs from direct infiltration of precipitation and from losing streams. Most recharge occurs during the winter and spring months.

Computer modeling was used to provide a better understanding of the ground-water-flow system and to simulate the effects of additional ground-water withdrawals. A numerical ground-water-flow model of the ground-water system was constructed and calibrated using MODFLOW 2000. Modeling results indicate that losing streams along the base of the Cumberland Plateau escarpment at the western edge of the study area are an important source of recharge to the ground-water system, supplying about 50 percent of the recharge to the study area. Direct infiltration of precipitation accounts for the remaining recharge to the study area. In 1999, ground-water withdrawals of 6.4 Mgal/d [9.9 cubic feet per second (ft^3/s)] equaled about 11 percent of the total simulated ground-water recharge. The remaining ground-water recharge discharges to rivers (48 percent, 41.1 ft^3/s), springs (19 percent, 16.8 ft^3/s), and Chickamauga Lake (22 percent, 19.0 ft^3/s). Drawdown at the Walkers Corner well field in 2000 was about 33 feet at the center of a cone of depression that is elongated along strike. If additional pumping at Walkers Corner increases withdrawals by 2 Mgal/d, simulated drawdown at the Walkers Corner well field increases to about 60 feet and simulated ground-water discharges decrease by amounts of 1.0 ft^3/s to Chickamauga Lake, 0.8 ft^3/s to North Chickamauga Creek, 0.5 ft^3/s to Lick Branch-Rogers Spring drainage, 0.5 ft^3/s to Poe Branch, and 0.2 ft^3/s to Cave Springs.

INTRODUCTION

Ground water is an important resource throughout the Valley and Ridge Physiographic Province, which extends from Pennsylvania to Alabama. The U.S. Geological Survey (USGS) Regional Aquifer-System Analysis study of the Valley and Ridge

Physiographic Province recognized that ground-water basins in this setting are not regionally continuous and, therefore, the Cave Springs area was selected to represent large spring basins, one of several ‘type-areas’ designated for the study (Swain and others, 1992). The ground-water resource in the Cave Springs area is used by the Hixson Utility District (HUD) as a water supply and is one of the more heavily stressed resources in the Valley and Ridge Physiographic Province. The HUD has historically withdrawn about 9 ft^3/s (5.8 Mgal/d) from wells at Cave Springs. In 1995 to meet increasing demand, an additional well field was developed at Walkers Corner, located about 3 miles northeast of Cave Springs. From 1995 through 2000, pumping from the first production well at Walkers Corner averaged about 2.8 ft^3/s (1.8 Mgal/d). A second production well at Walkers Corner has increased the capacity of the well field by an additional 3 ft^3/s (2 Mgal/d). The USGS, in cooperation with the HUD, conducted a study of the local ground-water system to assess the capacity of the ground-water system to continue to meet demands.

Purpose and Scope

This report presents results of an investigation of the Cave Springs area ground-water system. The report includes a general description of the hydrogeology of the study area, an estimated annual water budget for the study area, and an analysis of the effects of pumping at the Walkers Corner well field on the local ground-water system. This report also presents potentiometric-surface maps of the aquifer under conditions of pre- and post-pumping at Walkers Corner and simulation results of ground-water-flow modeling of the ground-water system.

Previous Studies

The geology and hydrologic resources of the Valley and Ridge Physiographic Province and the Cave Springs area have been the subjects of previous studies. Rodgers (1953) compiled and described the geology of East Tennessee, and Swingle and others (1964) mapped the geology of the Daisy 7-1/2-minute quadrangle in detail and summarized the mineral resources of the area. The geology of Hamilton County was described by Tennessee Department of Conservation, Division of Geology (1979); the hydrology of the Cave Springs area by Bradfield (1992); and the hydrogeology of the Cave Springs ground-water basin by Pavlicek (1996). The ground-water resources of East Tennessee were described by DeBuchananne and Richardson (1956); 84 springs in East Tennessee were analyzed in terms of magnitude and variability of discharge by Sun and others (1963). Hollyday and Smith (1990) analyzed discharge data from 171 large springs, predominantly within the Valley and Ridge Physiographic Province, and Swain and others (1991) recognized Cave Springs as a type-area representative of large spring basins in the Valley and Ridge Physiographic Province.

DESCRIPTION OF STUDY AREA

The study area (fig. 1) includes about 60 square miles of Hamilton County and is located in the rolling terrain of the Valley and Ridge Physiographic Province of East Tennessee, which consists of alternating valleys and ridges that trend northeast. Land-surface elevations in the study area range from about 650 feet above sea level where North Chickamauga Creek leaves the study area to more than 1,000 feet above sea level along the north end of Cave Springs Ridge. The study area is bounded on the northeast and southeast by Chickamauga Lake, an impoundment of the Tennessee River, and on the west by the Cumberland Plateau. Land-surface elevations just west of the study area on the Cumberland Plateau rise to over 1,800 feet above sea level. The main streams in the study area are North Chickamauga Creek and its tributaries, Poe Branch and Lick Branch.

HYDROGEOLOGY

The study area is characterized as a mantled karst terrane. Unconsolidated material ranging from 0 to 300 feet overlies soluble carbonate bedrock. Limestone and dolomite are the principal rock types in the area. Small- and large-scale dissolution openings and sinkholes are common (Pavlicek, 1996; Bradfield, 1992).

Geology

Most of the study area is underlain by folded limestone and dolomite ranging in age from Cambrian to Mississippian (Miller, 1974). The primary formations exposed at land surface in the study area, listed from oldest to youngest, include the Copper Ridge Dolomite, Knox Group (Ordovician formations), the Chickamauga Limestone, and the Newman Limestone (fig. 2). These formations generally dip towards the

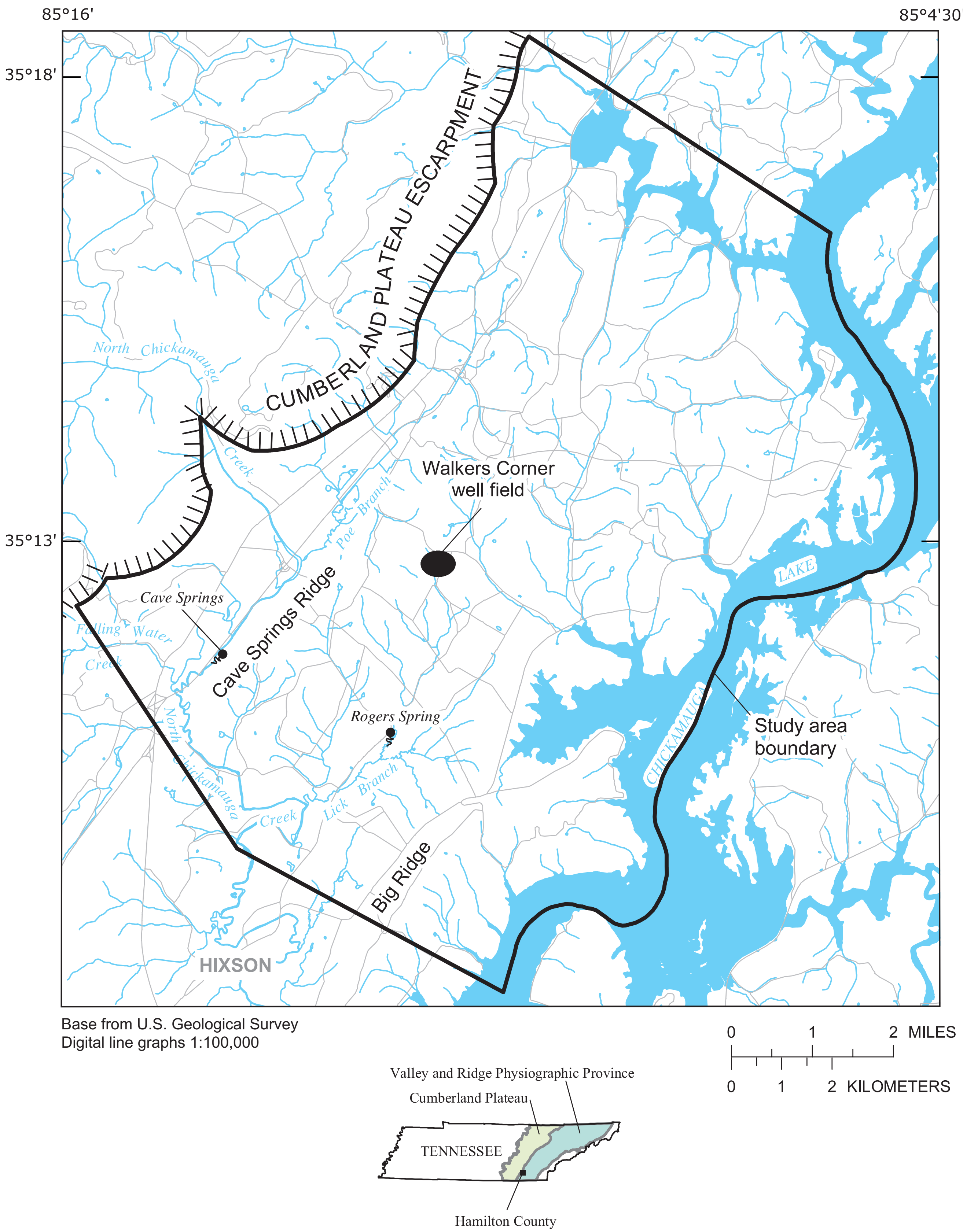


Figure 1. Physiographic and cultural features in the study area, Hixson, Tennessee.

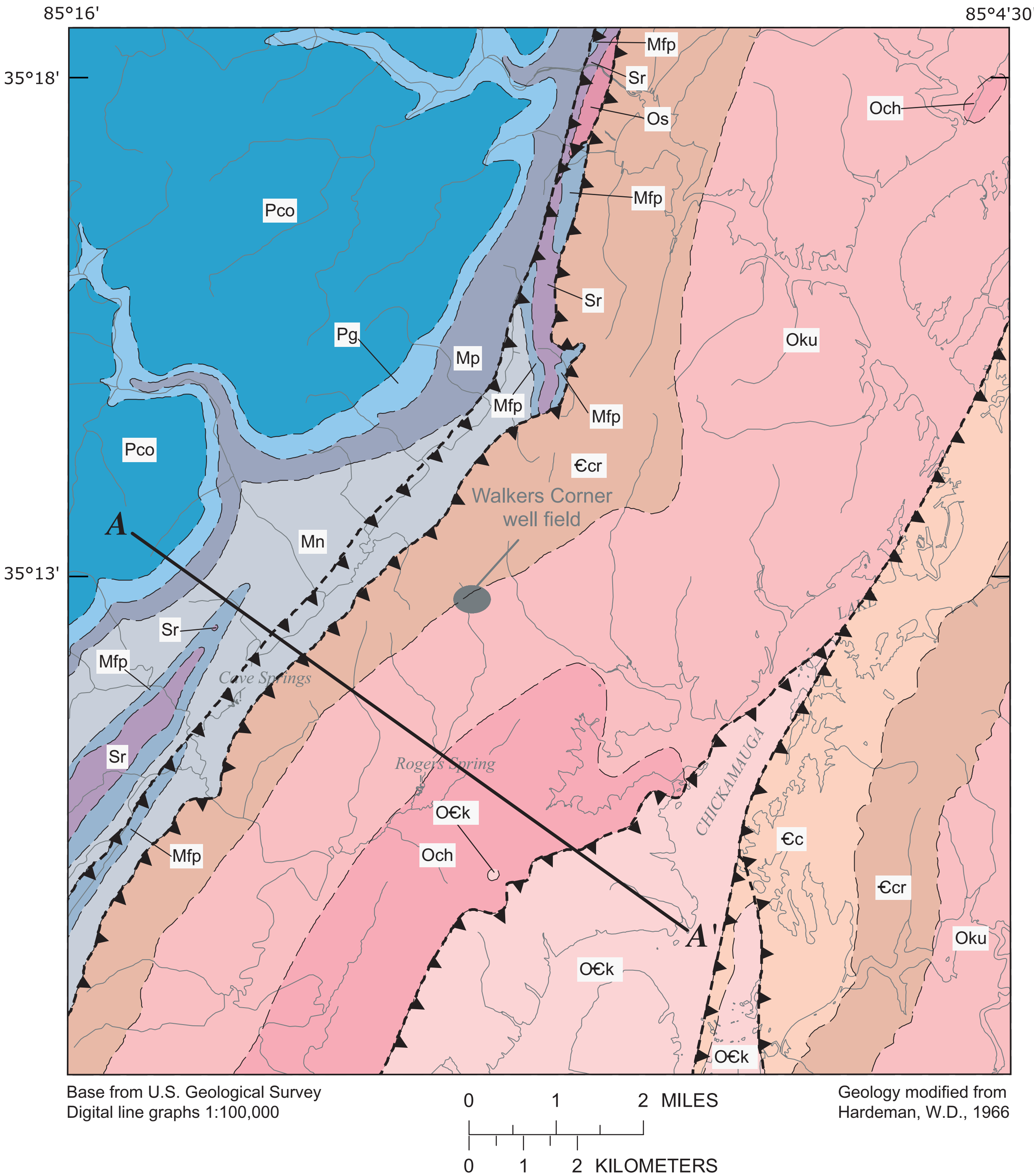


Figure 2. Geology of the Hixson, Tennessee area.

EXPLANATION

GEOLOGIC UNITS

Symbol	Unit	Group	System
Pco	Crab Orchard Mountains Group		PENNSYLVANIAN
Pg	Gizzard Group		PENNSYLVANIAN
Mp	Pennington Formation		MISSISSIPPIAN
Mn	Newman Limestone		MISSISSIPPIAN
Mfp	Fort Payne Formation		MISSISSIPPIAN
Sr	Rockwood Formation		SILURIAN
Os	Sequatchie Formation		ORDOVICIAN
Och	Chickamauga Limestone		ORDOVICIAN
Oku	Knox Group (Ordovician Formations)	O€k Knox Group	ORDOVICIAN
€cr	Copper Ridge Dolomite	O€k Knox Group	CAMBRIAN
€c	Conasauga Group		CAMBRIAN

A —— A' HYDROGEOLOGIC SECTION

THRUST FAULT -- Sawteeth located on side of relative upward displacement southeast at approximately 20 degrees. Rocks exposed along the northwestern side of the study area boundary include Pennsylvanian-age shales and sandstones of the Cumberland Plateau.

The Copper Ridge Dolomite consists of siliceous dolomite that is light to dark gray in color, is medium- to thick-bedded, and weathers to a dark colored chert residuum. The Knox Group (Ordovician formations) consists of siliceous dolomite interbedded with limestone that is light to dark gray and thin- to thick-bedded. The Chickamauga Limestone consists of shaly limestone that is mostly fine- to medium-grained and thin- to medium-bedded. The Newman Limestone is a light- to medium-gray limestone that is oolitic in parts.

Three low-angle thrust faults trend northeast to southwest in the study area (figs. 2 and 3). Cave Springs issues from the Newman Limestone between two of these thrust faults. Fracturing is likely most concentrated in the carbonate rock wedges present between these two or other closely spaced thrust faults (Pavlicek, 1996). An anticline is present where the Silurian- and Mississippian-age rocks outcrop between the Cumberland Plateau escarpment and the westernmost of the mapped thrust faults (figs. 2 and 3). In the study area, vertical fracturing is expected to be greater along this anticline. Numerous sinkholes are present in the study area, primarily in the Copper Ridge Dolomite and the Knox Group (Ordovician formations) (Bradfield, 1992).

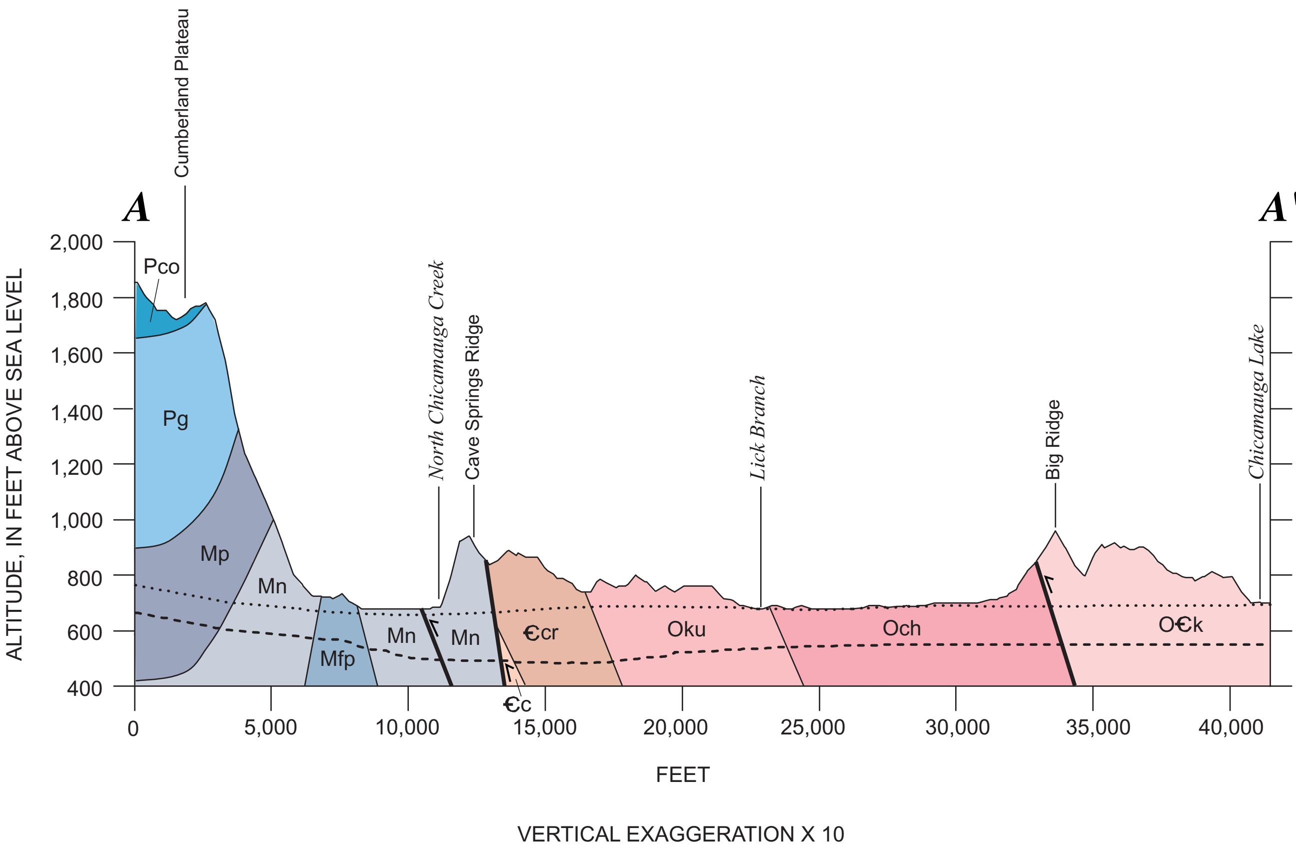
A thick mantle of regolith, composed of insoluble chert and clay residuum formed from in-situ chemical weathering of carbonate bedrock, covers most of the study area. In the flood plain of North Chickamauga Creek, the regolith also contains coarse-grained alluvium, consisting of gravel, cobbles, and boulders eroded from the siliciclastic rocks of the Cumberland Plateau. Regolith thickness ranges from less than 1 to 298 feet, averages about 120 feet, and is thickest on Cave Springs Ridge (Bradfield, 1992; Pavlicek, 1996). The thick clay-rich regolith acts as a leaky confining unit and has a large ground-water storage capacity (DeBuchananne and Richardson, 1956; Bradfield, 1992).

Ground Water

Ground water is present in both regolith and bedrock. Ground-water flow in the regolith occurs as diffuse flow as recharge from precipitation moves through the regolith to discharge to streams and springs or to the underlying bedrock. The regolith, where thicker than 50 feet, functions as a storage reservoir for recharge to the underlying bedrock (Swain and others, 1991). Most of the bedrock in the study area has low primary porosity and permeability; however, fracturing and dissolution have produced substantial secondary porosity and permeability (Swain and others, 1991). Ground-water flow through the bedrock occurs as both diffuse and conduit flow. Most of the flow in the bedrock occurs in dissolutionally enlarged fractures, joints, and bedding planes. These features may be open conduits or may be filled with chert, clay, and rock fragments. In a similar setting, Hollyday and Goddard (1979) concluded that most ground-water movement is along bedding planes parallel to the strike of the rock. Similarly, Bradfield (1992) concluded that, although fractures and joints transverse to the strike may connect dissolution openings along bedding planes, most of the ground-water flow in the Cave Springs area is parallel to the strike. In the study area, secondary permeability is more developed in the relatively pure Newman Limestone and less developed in the shaly Chickamauga Limestone.

Flow Boundaries

Ground-water levels are highest near the center of the study area. Ground water flows radially away from this high point near the center of the study area towards discharge points along Chickamauga Lake and North Chickamauga Creek and its tributaries. Chickamauga Lake, an impoundment of the Tennessee River, is a boundary to ground-water flow to the northeast, east, and southeast. North Chickamauga Creek is a discharge boundary to the south and southwest. To the west and northwest along the Cumberland Plateau escarpment, an influx of water to the study area occurs where streams draining the sandstones of the Cumberland Plateau lose a significant amount of water as they flow over the Mississippian-age limestones (primarily the Newman Limestone). Vertically, the upper boundary to the ground-water system is the water-table surface. The base of the ground-water system is the lower limit of dissolution openings in the bedrock and does not correspond to any stratigraphic boundary. Based on 23 test wells in the Cave Springs area, Bradfield (1992) hypothesized that the base of the active ground-water-flow system in the area varies from 600 to 450 feet above sea level. This corresponds to



EXPLANATION

WATER TABLE

BOTTOM OF AQUIFER

THRUST FAULT—Arrow is located on side of relative upward displacement

Note: Explanation for geologic units shown on figure 2.

Figure 3. Hydrogeologic cross section through the Hixson, Tennessee area.

depths of 75 to 400 feet below land surface, with the greatest depths of ground-water circulation in the Copper Ridge Dolomite of the Knox Group and the Newman Limestone and the shallowest depths in the Chickamauga Limestone. These depths to the base of the ground-water-flow system are consistent with regional studies in the same or similar geologic formations. A summary of ground-water resources in Hamilton County (Tennessee Department of Conservation, 1979) states that dissolution openings in limestones and dolomites in Hamilton County are most abundant in the first 250 feet. Swingle (1959) found that most large water-bearing openings in the Knox Group occur at depths of 300 feet or less. Swain and others (1992) concluded most ground-water flow in the Valley and Ridge Physiographic Province occurs in the first 600 feet below land surface with most of the permeability in the upper 300 feet.

Recharge

In karst terrane, ground-water recharge mechanisms vary between dispersed and concentrated. In the study area, recharge occurs from precipitation dispersed throughout the study area and from losing streams. An annual average recharge rate for the study area can be estimated from regional studies. In a study by Hoos (1990), recharge rates for drainage basins across Tennessee were estimated using a hydrograph-separation technique. Reported annual recharge rates during years of average streamflow for drainage basins in the Valley and Ridge Physiographic Province of Tennessee ranged from 5.2 to 8.2 inches with a median of 6.6 inches (Hoos, 1990). In a similar study, Rutledge and Mesko (1996) analyzed streamflow records for 89 basins in the Valley and Ridge, Blue Ridge, and Piedmont Physiographic Provinces, and estimated annual recharge rates from streamflow hydrographs. Two basins studied by Rutledge and Mesko (1996), which are closest to the study area and underlain by similar geology, are South Chickamauga Creek near Chickamauga (located about 15 miles south of the study area) and Sewee Creek near Decatur (located about 30 miles northeast of the study area). Estimated net average annual ground-water recharge rates for South Chickamauga Creek and Sewee Creek are 10.6 and 10.5 in/yr, respectively, for the period 1981-90 (Rutledge and Mesko, 1996). For the period 1961-90, the net recharge rate for the Sewee Creek basin was determined to be 12.5 in/yr (Rutledge and Mesko, 1996).

A water-budget method also was used to estimate ground-water recharge and to examine the variations in recharge, both seasonally and annually. A simple water budget can be described by the following equations:

$$PR = ET + SF \quad (1)$$

$$SF = DR + GWD \quad (2)$$

$$\text{assuming } GWD = GWR, \quad (3)$$

$$\text{then } PR = ET + DR + GWR, \quad (4)$$

where

PR is the mean precipitation,

ET is the mean evapotranspiration,

SF is mean streamflow,

DR is mean direct runoff,

GWD is mean ground-water discharge, and

GWR is mean ground-water recharge.

Using monthly mean precipitation and temperature data from Chattanooga, Tennessee, a Thornwaite water-budget method was used for this investigation to estimate the amount of precipitation that is lost to evapotranspiration in the study area (McCabe and others, 1985). The remaining volume of water then supports streamflow either by direct runoff or by recharging the ground-water system, which then discharges, supplying base flow to streams. Total streamflow was then proportioned into direct runoff and ground-water discharge using a stream base-flow index. Results from a regional study of streamflow records indicate that base-flow indices across the Regional Aquifer-System Analysis—Appalachian Valley and Piedmont area ranged from 32 to 94 percent, with a median of 67 percent (Rutledge and Mesko, 1996). The South Chickamauga and Sewee Creeks, had base-flow indices of 50 and 56 percent, respectively (Rutledge and Mesko, 1996). Using monthly mean precipitation and temperature data from Chattanooga and assuming a base-flow index of 53 percent, an annual water budget for the study area was estimated for the period from 1971 to 2000 (table 1, fig. 4). The average annual recharge rate from this method is 15 inches and the median is 14.3 inches. Annual estimates ranged from 7.3 inches for 1985 to 22.6 inches for 1994.

Rutledge and Mesko (1996) estimated the water budget for Sewee Creek for the period 1961-90 as follows: precipitation, 56.2 in/yr; evapotranspiration, 34 in/yr; total streamflow, 22.2 in/yr; direct runoff, 9.7 in/yr; and net recharge, 12.5 in/yr (table 2). In this method, evapotranspiration is the residual after total streamflow is subtracted from precipitation. The Thornwaite water-budget method results in a lower evapotranspiration rate than the water budget calculated for Sewee Creek and, therefore, estimates a higher total streamflow rate and a higher recharge rate (table 2). In the Thornwaite method, streamflow is the residual after calculated evapotranspiration is subtracted from precipitation. Continuous streamflow data for North Chickamauga Creek at a site just upstream from the mouth of Lick Branch is available for the 5-year period from 1938 to 1942. Mean annual streamflow for this period is 19.9 in/yr (146 ft^3/s) and ranges from 13.6 in/yr (100 ft^3/s) to 27.4 in/yr (201 ft^3/s) (Tennessee Valley Authority, 1954). These data suggest that the Thornwaite water budget may overestimate total streamflow and recharge for the study area.

Table 1. Estimated annual water budget from Thornwaite method for the Hixson, Tennessee area from 1971 to 2000
[All values are in inches per year]

Year	Precipitation	Evapotranspiration	Streamflow	Direct runoff	Recharge
1971	51.0	27.1	23.9	11.2	12.7
1972	64.5	25.5	39.0	18.3	20.7
1973	71.6	30.2	41.4	19.5	21.9
1974	51.3	24.5	26.9	12.6	14.2
1975	68.1	26.2	41.9	19.7	22.2
1976	47.8	25.3	22.5	10.6	11.9
1977	64.6	24.8	39.7	18.7	21.1
1978	40.1	22.2	17.9	8.4	9.5
1979	68.6	28.6	40.0	18.8	21.2
1980	48.9	21.8	27.1	12.7	14.4
1981	45.9	27.2	18.7	8.8	9.9
1982	57.9	25.8	32.1	15.1	17.0
1983	52.7	20.8	31.9	15.0	16.9
1984	47.7	24.6	23.1	10.9	12.3
1985	39.6	25.8	13.7	6.4	7.3
1986	42.5	24.9	17.6	8.3	9.3
1987	46.6	28.3	18.3	8.6	9.7
1988	43.9	26.0	17.8	8.4	9.5
1989	71.6	29.9	41.7	19.6	22.1
1990	68.6	29.1	39.5	18.5	20.9
1991	56.0	28.2	27.7	13.0	14.7
1992	55.9	26.5	29.3	13.8	15.5
1993	40.1	20.5	19.6	9.2	10.4
1994	73.7	31.1	42.6	20.0	22.6
1995	56.2	29.2	27.0	12.7	14.3
1996	55.6	26.4	29.1	13.7	15.4
1997	56.3	27.6	28.7	13.5	15.2
1998	53.2	26.2	27.0	12.7	14.3
1999	47.4	25.4	22.0	10.3	11.7
2000	48.1	27.2	21.0	9.8	11.1
Average	**54.5**	**26.2**	**28.3**	**13.3**	**15.0**

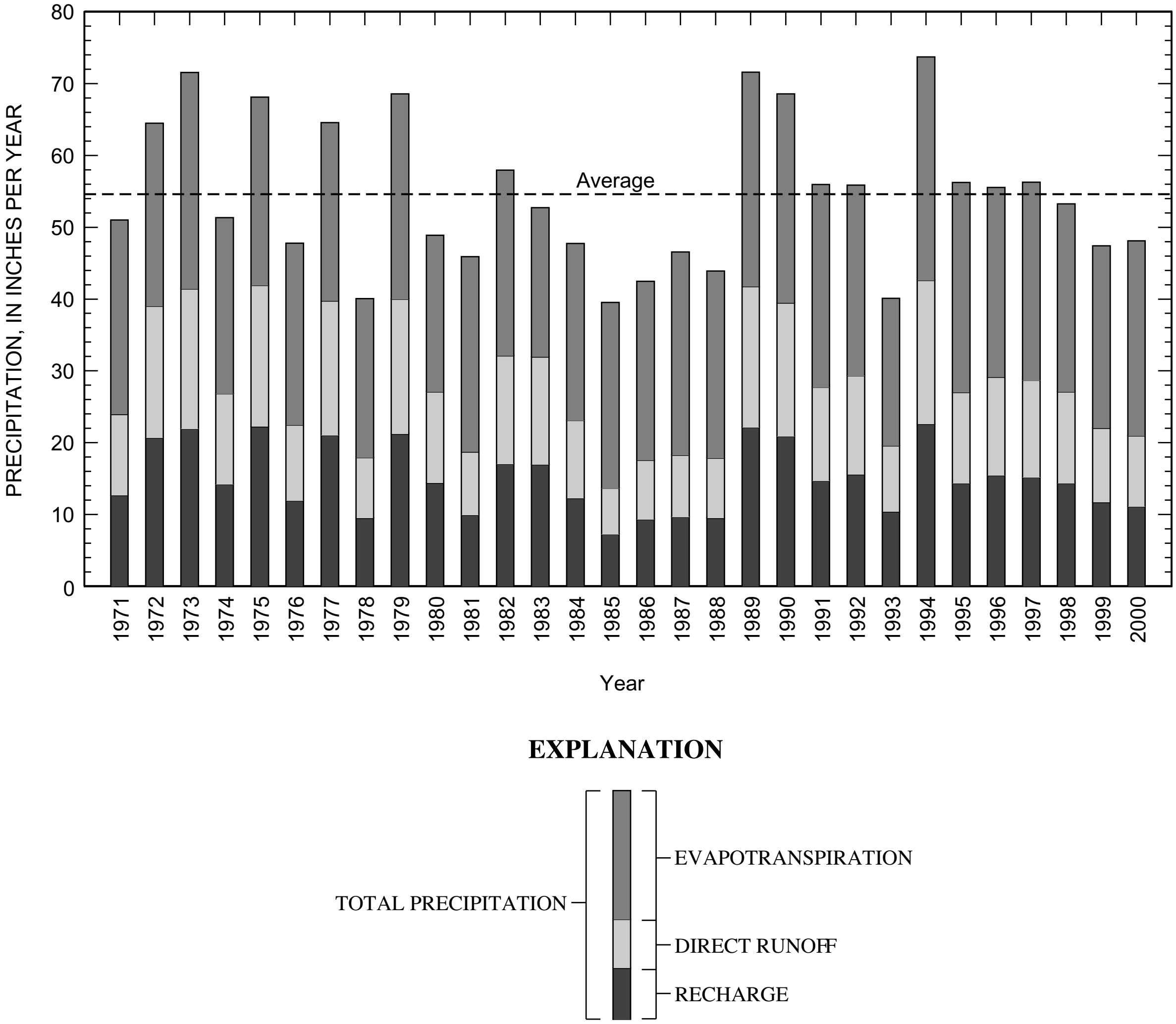


Figure 4. Estimated annual water budget for Hixson, Tennessee, from 1971 to 2000.

Table 2. Comparison of estimated average annual water budget for the Hixson, Tennessee area

[All values are in inches per year]

Method	Precipitation	Evapotranspiration	Total streamflow	Direct runoff	Net recharge
Hydrograph separation, South Chickamauga Creek (1981-90) (Rutledge and Mesko, 1996)	51.7	30.4	21.3	10.7	10.6
Hydrograph separation, Sewee Creek (1981-90) (Rutledge and Mesko, 1996)	53.9	35.2	18.7	8.2	10.5
Hydrograph separation, Sewee Creek (1961-90) (Rutledge and Mesko, 1996)	56.2	34.0	22.2	9.7	12.5
Thornwaite water budget, Chattanooga, Tenn. (1971-2000)	54.4	26.2	28.3	13.3	15.0
Average	**54.0**	**31.4**	**22.6**	**10.4**	**12.2**

Seasonal variations in recharge also can be studied by comparing the monthly budget results from the Thornwaite water budget for average, wet, and dry years (fig. 5). Recharge varies seasonally with most recharge occurring from December to May. In average years, little or no recharge may occur for up to 6 months. During most dry years, the number of months that show little or no recharge may not vary much from average years, but the amount of recharge during the winter and spring months is reduced. Most of the wet years show greater amounts of recharge in the winter and spring months and fewer months with little or no recharge (fig. 5).

Concentrated recharge occurs at sinkholes and losing stream reaches. The importance of recharge associated with sinkholes in the area is not known (Pavlicek, 1996). Streamflow discharge measurements on March 3, 1988, and April 23, 1991, show a losing reach of North Chickamauga Creek upstream of the mouth of Poe Branch. Streamflow losses from this reach of North Chickamauga Creek on these two dates were 24 and 11 ft^3/s, respectively (Lowery and others, 1989; Pavlicek, 1996). This losing reach of North Chickamauga Creek is an important source of concentrated recharge to the ground-water system, and most likely extends from the mouth of Poe Branch upstream to where North Chickamauga Creek first contacts the Newman Limestone.

Aquifer Properties

The aquifer in the study area consists of regolith and bedrock. Transmissivities in the study area have been estimated from specific-capacity data from 17 wells (Bradfield, 1992; Pavlicek, 1996; Hixon Utility District, written commun., 2000). Transmissivities range from 240 to 900,000 ft^2/day with a median value of 5,200 ft^2/day (fig. 6). The highest value is from an aquifer test at the Cave Springs well field where the wells tap a large conduit near the mouth of Cave Springs. This aquifer test resulted in a drawdown of less than 3 feet with a discharge of 9,000 gallons per minute (20 ft^3/s) (Bradfield, 1992). The other outlier shown on figure 6 (78,000 ft^2/day) is from a test well at the Walkers Corner well field.

Previous work in the study area and in similar settings indicate that most ground-water flow is along bedding planes parallel to the strike of rock (Hollyday and Goddard, 1979; Bradfield, 1992; and Pavlicek, 1996). Additionally, the cone of depression and water-level declines around Walkers Corner production well #1 are elongated along geologic strike (Ogden and Kimbro, 1997; Hixson Utility District, written commun., 2000; and this report, fig. 13). This elongation indicates the horizontal hydraulic conductivity of the aquifer is greater in the direction parallel to the strike. No measured values of the degree of horizontal anisotropy in the study area exist, but a ratio of 5:1 was used in a preliminary unpublished model of the area (Al Rutledge, U.S. Geological Survey, written commun., 1999).

No measured values for vertical hydraulic conductivity exist in the study area, but in most settings, the vertical hydraulic conductivity is smaller than the horizontal hydraulic conductivity (Heath, 1989). Vertical anisotropy in settings similar to the study area typically ranges from 100:1 to 2:1 (Freeze and Cherry, 1979). Horizontal layering can increase the vertical anisotropy, but vertical fractures can decrease vertical anisotropy (Freeze and Cherry, 1979). In the study area, vertical fracturing would be expected along the anticline in the Silurian- and Mississippian-age rocks between the Cumberland Plateau escarpment and the westernmost part of the mapped thrust faults (fig. 2).

No data are available for storage coefficients for the aquifer in the study area. Specific yield values from studies in similar hydrologic settings range from 0.01 to 0.05 (Wood and others, 1972; Trainer and Watkins, 1974; Becher and Root, 1981; and Hoos, 1990). Specific storage values in these settings typically range from 0.001 to 0.00001 (Heath, 1989). Values within these ranges would be expected in the study area.

Spring and Stream Discharge

Cave Springs is the second largest spring in East Tennessee. The spring discharges from an opening at the base of Cave Springs Ridge and then flows southwest about 200 feet to join North Chickamauga Creek. The mean discharge of 28 measurements made from 1928 to 1954 is 17.5 ft^3/s with a minimum discharge of 0.08 ft^3/s and a maximum of 43.7 ft^3/s (Hollyday and Smith, 1990). In a study of 90 large springs in East Tennessee by Sun and others (1963), Cave Springs had the greatest variability in discharge. Continuous discharge data are available for Cave Springs from July 1987 to June 1992 (Bradfield, 1992; Pavlicek, 1996). The mean daily discharge for this 5-year period was 15.5 ft^3/s. Mean daily discharge during the relatively dry 1988 water year and relatively wet 1989 water year were 10.3 and 19.5 ft^3/s, respectively (Bradfield,

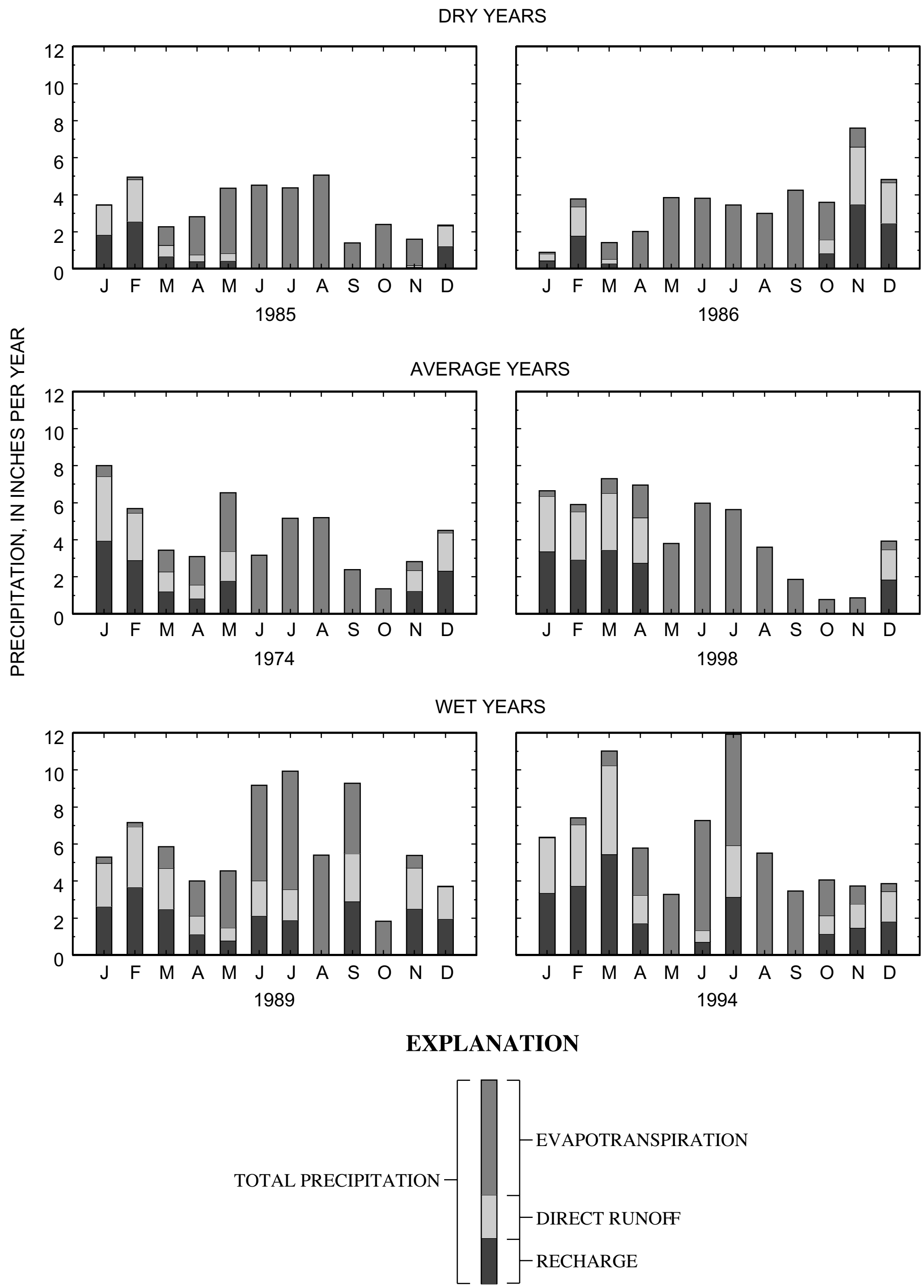


Figure 5. Estimated monthly water budget for Hixson, Tennessee, for selected dry, average, and wet years.

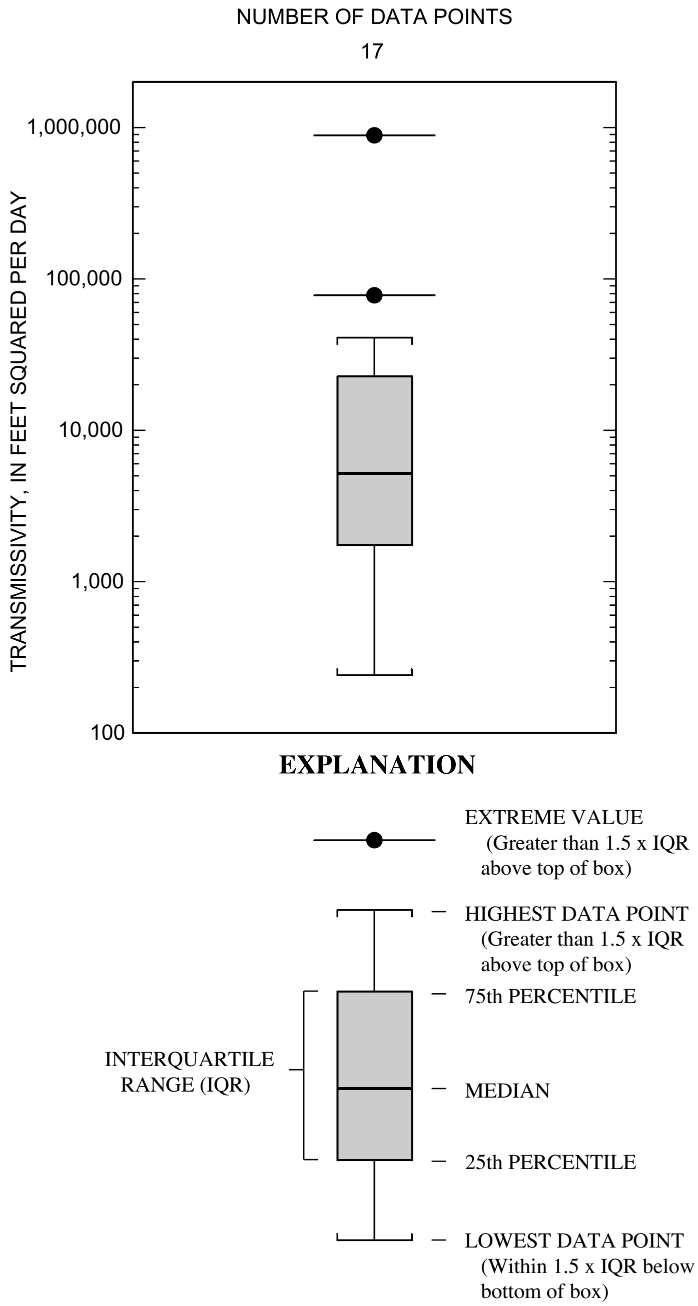


Figure 6. Range of transmissivity measured in the Cave Springs area near Hixson, Tennessee.

1992). Additional details about the hydrology of Cave Springs are documented by Bradfield (1992) and Pavlicek (1996).

Another much smaller spring in the study area is Rogers Spring located on the right bank of Lick Branch about 2.3 miles east of Cave Springs (fig. 1). Discharge from Rogers Spring was measured at 0.6 ft^3/s during low base-flow conditions in November 1998 and at 2.4 ft^3/s during high base-flow conditions in May 1999. Many other small springs present in the bed of Lick Branch near Rogers Spring also contribute to ground-water discharge in this area.

Stream discharge was measured at several sites throughout the study area on March 3, 1988, April 23, 1991, and July 18, 1991 (Lowery and others, 1989; Mercer and others, 1992). These measurements were collected during base-flow periods when most of the stream discharge is from ground-water sources. These data indicate streamflow losses of 24 and 11 ft^3/s on a reach of North Chickamauga Creek upstream of the confluence of Poe Branch. Most streamflow gains occur on North Chickamauga Creek downstream from Cave Springs and on Lick Branch downstream from Rogers Springs (Pavlicek, 1996). Tributary streams to Chickamauga Lake show negligible base flow. Continuous streamflow data for North Chickamauga Creek at a site just upstream from the mouth of Lick Branch is available for the 5-year period from 1938 to 1942. Annual mean streamflow for this period is 146 ft^3/s and ranges from 100 ft^3/s to 201 ft^3/s (Tennessee Valley Authority, 1954).

Ground-Water Withdrawals

Ground water is withdrawn in the study area by the HUD at the Cave Springs and Walkers Corners well fields. Historically, the HUD has withdrawn water at the Cave Springs well field located about 150 feet from the spring. Production from the Cave Springs well field averaged about 9 ft^3/s (5.8 Mgal/d) in 1993. In response to increasing demand, the HUD began developing a second well field at Walkers Corner located about 3 miles northeast of Cave Springs (fig. 1). In 1995, the first production well at Walkers Corner came online, continuously withdrawing an average of 2.8 ft^3/s (1.8 Mgal/d). In 1999, a second production well was completed at Walkers Corner, bringing an additional 3 ft^3/s (2 Mgal/d) capacity to this well field. The second production well has been approved for use, but currently (2001) is not needed to meet demand.

Water Levels

Water-level data collected at various times from 1989 through 2000 define seasonal variations in water levels, ground-water-flow directions, and effects from pumping at Walkers Corner. Natural seasonal fluctuations of the water table are related to seasonal changes in precipitation and evapotranspiration and, thus, to changes in ground-water recharge. Ground-water levels are normally highest during the spring months following the winter period of high precipitation and low evapotranspiration. Water levels recede during the summer in response to diminishing precipitation and higher evapotranspiration and are lowest in the fall. The hydrograph of well Hm:N-051 exhibits these characteristic seasonal variations (fig. 7). Annually, water levels in this well vary about 20 feet. Typical seasonal variations can be observed in most wells in the study area (tables 3 and 4; fig. 8).

Similarly, potentiometric-surface maps of the study area for November 1989 (Bradfield, 1992), November 1990 (fig. 9), April 1991 (Pavlicek, 1996), and May 1993 (fig. 10) show that seasonal variations in the potentiometric surface are as much as 20 feet near the center of the study area just north of Walkers Corner where water-level elevations are the highest. These maps are similar in features, with ground-water levels highest under the ridge near the center of the study area and gradients indicating ground-water flow radially outward towards Chickamauga Lake, Lick Branch, Poe Branch, and North Chickamauga Creek. The North Chickamauga Creek and Poe Branch valley is clearly evident in the potentiometric surface with low gradients trending along the axis of the valley.

All of the potentiometric-surface maps described earlier represent water-level conditions before ground-water withdrawals began at the Walkers Corner well field. The ground-water withdrawals at the Cave Springs well field have no noticeable effect on the potentiometric surface because these wells are completed in highly transmissive conduits. The effects of ground-water withdrawals at the Walkers Corner well field can be seen in potentiometric-surface maps for November 1998 (fig. 11) and May 1999 (fig. 12). When the November 1990 and November 1998 potentiometric surfaces are compared, the November 1998 surface indicates lower water levels around the Walkers Corner well field compared to the November 1990 surface. A closed depression defined by the 680-foot elevation contour and lower water levels upgradient along strike (to the northeast) from Walkers Corner

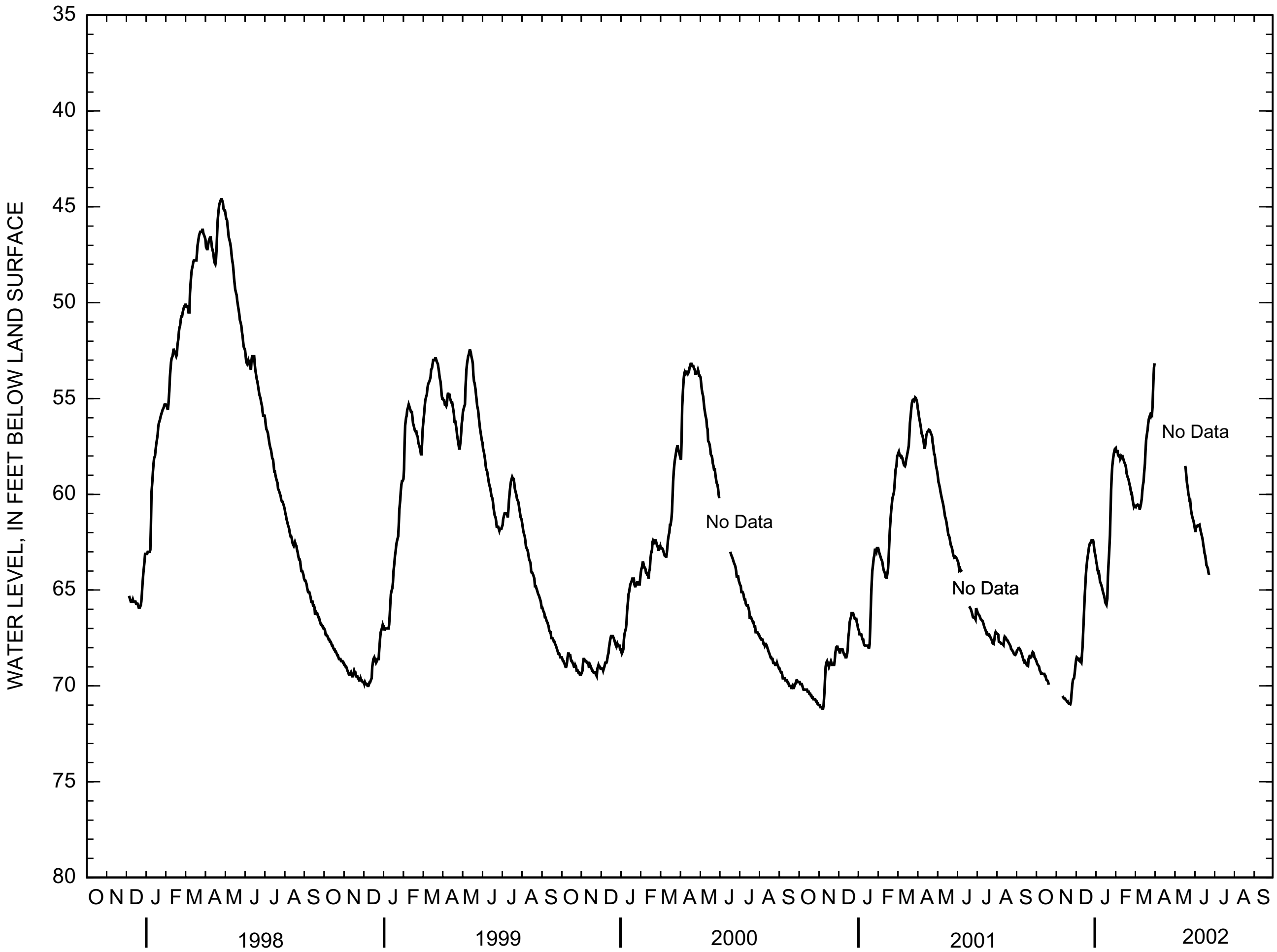


Figure 7. Daily water levels in well Hm:N-051.

characterize the November 1998 surface. Additionally, the November 1990 potentiometric surface indicates the highest contour at the 710-foot level compared to the 700-foot level on the November 1998 surface. A similar effect is observed in a comparison of the seasonal high potentiometric-surface maps for May 1993 and May 1999. Water-level declines from May 1993 (fig. 10) to May 1999 (fig. 12) are more than 25 feet at Walkers Corner and are elongated along strike (fig. 13).

Declines in water levels at the Walkers Corner well field since pumping began can be seen by comparing annual low water levels from periodic water-level measurements in two observation wells at the well field (fig. 14). Well Hm:N-081, located about 75 feet east of production well #1 (Hm:N-102), shows about 28 feet of water-level decline since pumping began. Well Hm:N-059, located about 530 feet southwest of production well #1 (Hm:N-102), shows 11 to 18 feet of water-level decline. Comparing annual low water levels, well Hm:N-051, located about 2 miles southwest of Walkers Corner well field shows little noticeable change in water levels.

Well pairs do not exist in the study area to compare vertical gradients in water levels between the regolith and bedrock. Many of the wells are open to both regolith and bedrock. Because a confining unit does not separate the regolith and bedrock, they are assumed to be hydraulically connected and vertical gradients would be expected to be small. Downward vertical gradients are expected to occur over most of the study area with upward gradients occurring only along the main stream valleys where ground water discharges to the surface-water streams and to Chickamauga Lake.

Table 3. Data for selected wells in the Cave Springs area near Hixson, Tennessee

[--, no data]

Well number	Latitude	Longitude	Land-surface altitude, in feet above sea level	Well depth, in feet below land surface	Water-level altitude, in feet above sea level									
					August 1989	November 1990	April 1991	August 1991	November 1992	May 1993	December 1997	April 1998	November 1998	May 1999
Hm:N-35	35°11′48″	85°13′ 53″	711	71	--	--	664	--	--	--	662	664	658	664
Hm:N-36	35°11′48″	85°13′53″	711	73	--	--	--	--	661	661	662	664	658	664
Hm:N-46	35°09′38″	85°13′15″	680	242	646	--	651	647	650	649	--	--	--	--
Hm:N-47	35°10′55″	85°14′09″	725	125	652	652	659	--	654	657	653	660	650	659
Hm:N-48	35°10′41″	85°12′36″	669	180	655	654	668	657	659	662	655	668	652	665
Hm:N-51	35°11′46″	85°12′29″	735	308	671	668	693	676	671	685	670	685	666	679
Hm:N-52	35°11′34″	85°11′41″	720	325	667	668	700	672	678	686	667	696	662	690
Hm:N-53	35°11′12″	85°11′31″	692	34	--	--	--	--	673	--	670	673	669	673
Hm:N-54	35°12′22″	85°12′50″	756	279	652	--	--	--	665	666	664	668	650	668
Hm:N-56	35°12′39″	85°12′50″	685	103	659	663	668	661	665	666	--	669	659	669
Hm:N-57	35°12′48″	85°13′15″	681	162	657	662	666	659	663	663	663	666	658	666
Hm:N-59	35°12′48″	85°11′02″	786	213	699	690	714	708	697	714	686	698	684	693
Hm:N-60	35°12′28″	85°10′11″	723	125	693	688	706	695	692	--	686	702	685	695
Hm:N-61	35°12′07″	85°09′36″	693	62	683	--	687	--	683	686	678	685	679	686
Hm:N-63	35°13′24″	85°09′56″	817	174	637	--	--	--	706	716	701	712	697	710
Hm:N-64	35°13′38″	85°10′07″	830	166	--	--	--	--	--	713	693	704	691	696
Hm:N-65	35°13′57″	85°10′26″	850	302	721	717	724	822	--	727	--	--	--	--
Hm:N-66	35°14′21″	85°10′51″	928	330	682	--	--	--	688	700	--	708	--	--
Hm:N-67	35°14′25″	85°10′50″	900	217	--	--	--	--	--	--	706	718	700	715
Hm:N-68	35°14′29″	85°10′54″	886	402	--	--	--	--	703	708	699	713	687	712
Hm:N-70	35°13′35″	85°09′17″	770	250	704	697	730	705	700	719	695	720	692	712

Table 3. Data for selected wells in the Cave Springs area near Hixson, Tennessee—Continued

Well number	Latitude	Longitude	Land-surface altitude, in feet above sea level	Well depth, in feet below land surface	Water-level altitude, in feet above sea level									
					August 1989	November 1990	April 1991	August 1991	November 1992	May 1993	December 1997	April 1998	November 1998	May 1999
Hm:N-71	35°13′27″	85°11′03″	839	200	--	--	--	--	--	715	691	703	689	696
Hm:N-75	35°11′58″	85°11′18″	729	202	682	680	708	685	688	700	678	707	673	698
Hm:N-76	35°13′29″	85°11′55″	692	101	--	--	681	--	676	--	666	679	658	680
Hm:N-76a	35°13′12″	85°12′29″	682	75	660	664	--	--	--	667	666	670	660	670
Hm:N-77	35°13′27″	85°10′37″	780	171	709	700	715	710	698	716	692	703	689	696
Hm:N-78	35°13′20″	85°07′40″	707	280	687	682	697	689	684	694	680	693	679	688
Hm:N-81	35°12′53″	85°10′58″	796	--	--	--	--	--	--	--	678	696	675	690
Hm:N-82	35°11′46″	85°13′34″	853	480	--	--	673	667	670	670	670	673	664	673
Hm:N-83	35°11′55″	85°13′52″	666	202	--	660	663	658	661	661	661	664	657	663
Hm:N-84	35°13′19″	85°13′22″	708	202	--	665	668	660	666	666	667	669	--	670
Hm:N-85	35°13′38″	85°12′29″	684	202	--	666	670	663	667	667	--	670	662	671
Hm:N-86	35°14′07″	85°11′48″	694	202	--	663	669	661	666	666	665	670	660	671
Hm:N-91	35°12′34″	85°14′26″	765	300	--	--	--	--	675	692	674	700	665	698
Hm:N-92	35°11′55″	85°14′48″	730	200	--	--	--	--	674	674	674	674	670	674
Hm:N-94	35°13′58″	85°09′59″	855	290	--	--	--	--	--	718	696	710	694	701
Hm:N-95	35°14′33″	85°08′12″	852	175	--	--	--	--	702	706	690	707	686	702
Hm:N-96	35°14′00″	85°12′36″	725	100	--	--	--	--	--	679	669	686	--	684
Hm:N-100	35°10′45″	85°14′16″	660	--	--	--	--	--	--	--	--	--	644	649
Hm:N-106	35°12′40″	85°11′08″	--	--	--	--	--	--	--	--	--	--	683	692
Hm:O-30	35°14′36″	85°07′06″	730	73	--	--	--	--	690	696	685	701	681	701
Hm:O-74	35°14′31″	85°06′37″	703	342	683	680	693	684	683	687	679	687	679	687

Table 3. Data for selected wells in the Cave Springs area near Hixson, Tennessee—Continued

Well number	Latitude	Longitude	Land-surface altitude, in feet above sea level	Well depth, in feet below land surface	Water-level altitude, in feet above sea level									
					August 1989	November 1990	April 1991	August 1991	November 1992	May 1993	December 1997	April 1998	November 1998	May 1999
Hm:R-12	35°15′00″	85°10′35″	720	66	--	--	--	--	701	702	694	705	673	706
Hm:R-13	35°15′41″	85°09′18″	819	225	--	--	--	--	686	691	683	702	--	708
Hm:R-14	35°15′58″	85°09′11″	802	--	--	--	--	--	684	689	681	703	687	699
Hm:R-16	35°16′38″	85°08′48″	737	94	--	--	--	--	680	684	678	684	679	687
Hm:R-19	35°17′54″	85°09′47″	723	106	--	--	--	--	708	706	706	709	704	711
Hm:R-21	35°17′36″	85°09′24″	691	170	--	--	--	--	681	682	677	681	677	684
Hm:R-22	35°15′58″	85°08′41″	720	62	--	--	--	--	675	--	672	682	671	683
Hm:R-45	35°16′35″	85°07′55″	703	79	--	--	--	--	684	--	--	--	--	689
Hm:R-72	35°15′06″	85°10′59″	748	100	678	--	712	--	704	705	701	712	682	711
Hm:R-73	35°15′25″	85°08′52″	751	190	697	689	711	699	692	706	689	707	687	--
Hm:S-79	35°15′22″	85°07′11″	719	342	682	678	696	683	681	685	678	690	678	695

Table 4. Monthly water-level data for selected wells in the Cave Springs area near Hixson, Tennessee
[--, no data]

Date	Water level, in feet below land surface						
	Hm:N-036	Hm:N-060	Hm:N-063	Hm:N-071	Hm:N-075	Hm:N-077	Hm:N-081
12/2/97	--	37.4	115.9	148.1	51.7	88.3	117.8
1/5/98	47.6	35.5	111.2	149.1	44.2	89.5	119.4
2/2/98	47.7	29.2	110.8	145.8	33.9	85.6	116.1
3/2/98	46.9	25.5	106.3	140.7	28.5	81.6	110.4
4/1/98	47.4	23.2	105.5	136.7	24.4	77.6	105.7
5/4/98	47.4	21.4	104.2	133.8	26.9	74.6	101.6
6/2/98	50.3	25.9	107.4	134.9	39.8	75.4	102.3
7/1/98	50.5	27.6	108.0	136.3	42.2	76.7	104.5
8/3/98	49.4	32.2	109.9	139.6	49.1	79.9	109.0
9/1/98	51.9	34.4	111.8	142.4	52.1	82.7	112.4
10/1/98	53.0	39.8	114.8	145.8	55.5	85.9	116.1
11/2/98	55.5	39.3	117.7	149.1	58.9	89.1	119.6
11/17/98	52.4	40.6	119.2	150.8	858.1	90.9	121.1
12/3/98	52.7	41.6	120.2	153.1	59.2	92.0	122.7
1/11/99	46.2	38.9	112.3	153.6	46.8	93.8	123.8
2/1/99	41.4	32.0	94.6	140.9	33.1	90.9	121.3
3/1/99	44.9	31.0	102.0	147.8	36.0	88.4	118.6
4/5/99	47.9	30.0	110.6	145.6	36.5	86.0	115.9
5/11/99	46.8	27.9	106.1	143.1	31.8	84.2	105.9
6/1/99	50.6	30.3	112.3	143.8	43.6	84.1	113.1
7/7/99	49.4	33.4	112.9	146.2	44.3	86.2	114.7
8/3/99	51.1	32.9	115.0	146.9	47.2	86.8	116.6
9/17/99	55.7	38.2	119.6	150.7	56.7	90.4	120.6
10/4/99	55.1	39.1	120.8	152.0	57.8	91.6	122.0
11/3/99	49.6	30.9	122.1	154.2	56.4	94.2	125.9
12/2/99	50.3	42.2	123.2	156.0	57.3	95.7	126.6

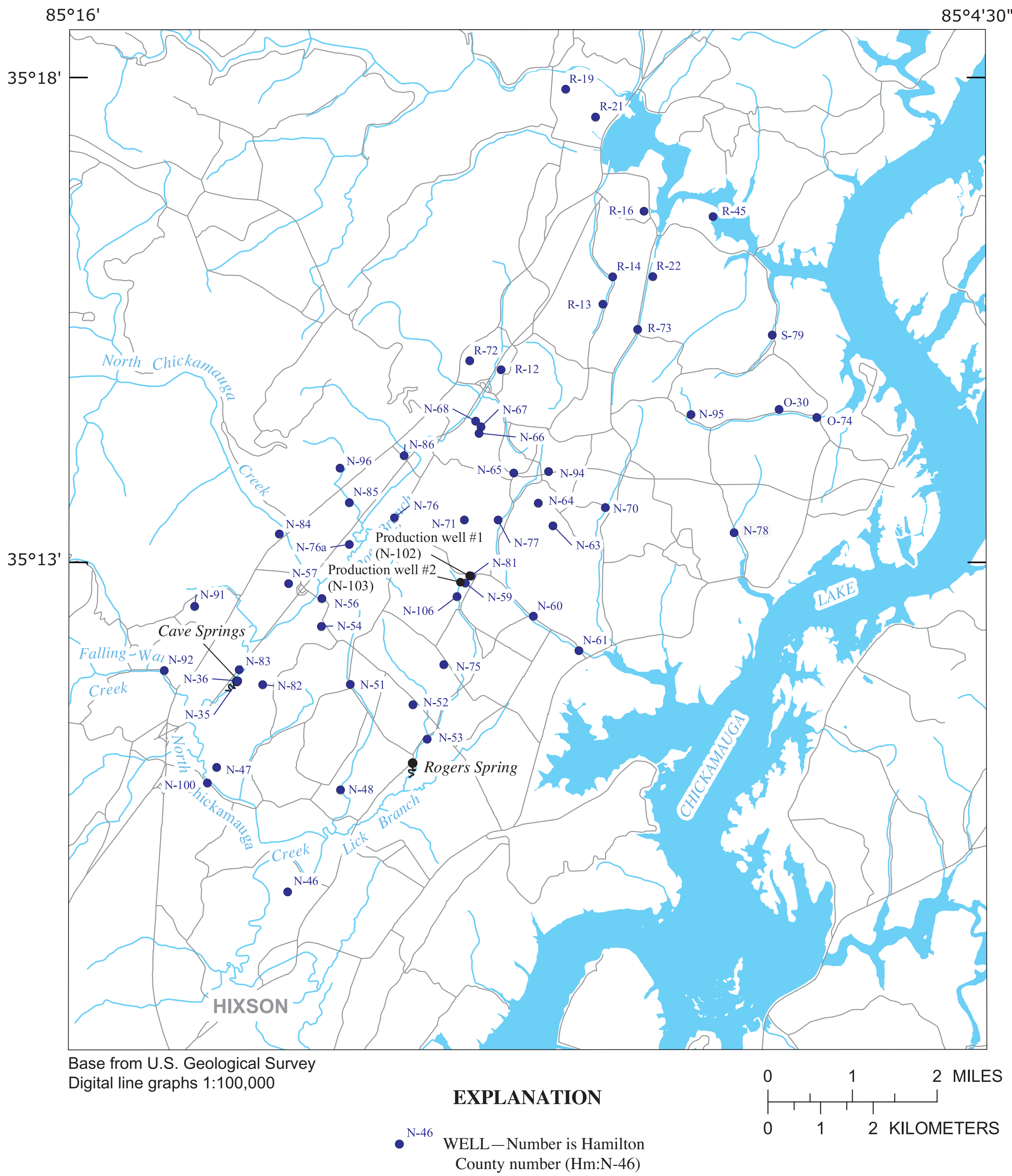
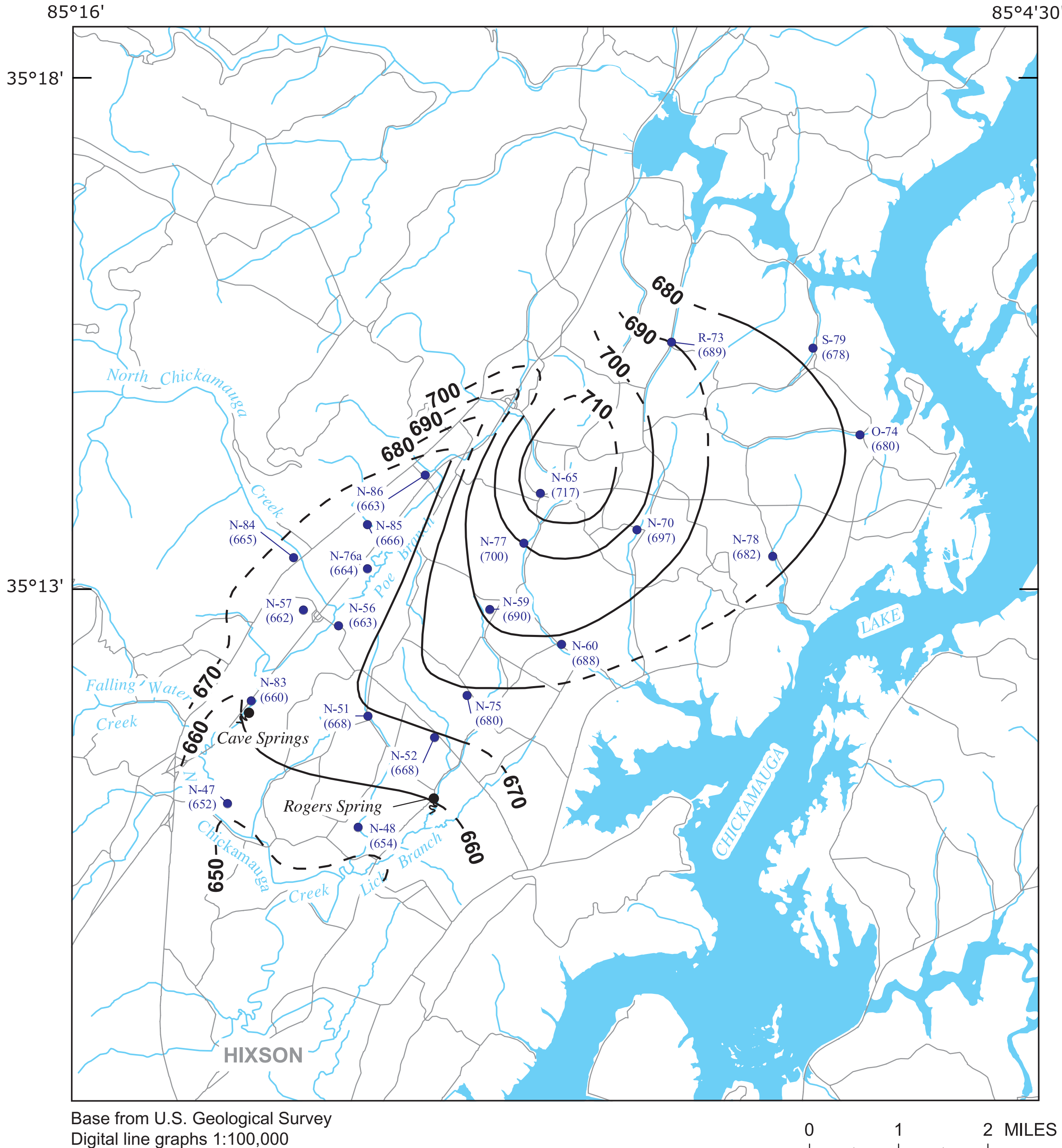


Figure 8. Locations of wells in which water levels were measured in the Cave Springs area near Hixson, Tennessee.

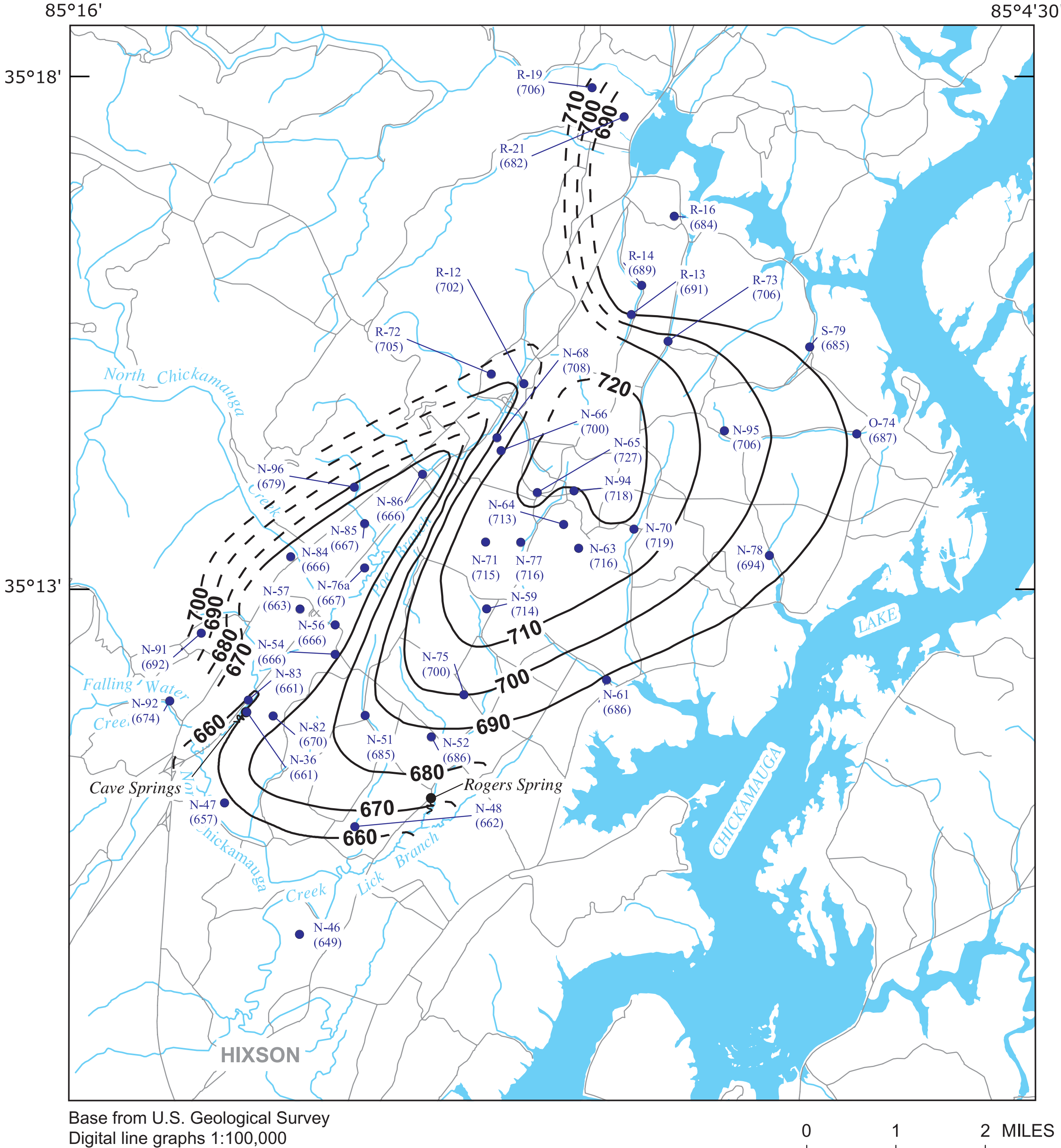


EXPLANATION

650 — POTENTIOMETRIC CONTOUR—Shows altitude at which water level would have stood in tightly cased wells. Dashed where approximately located. Contour interval 10 feet. Datum is sea level

● N-48 (654) WELL USED AS CONTROL—Upper number is Hamilton County number (Hm:N-48). Lower number indicates altitude of water level, in feet above sea level

Figure 9. Potentiometric surface of the aquifer in the Cave Springs area near Hixson, Tennessee, November 1990.

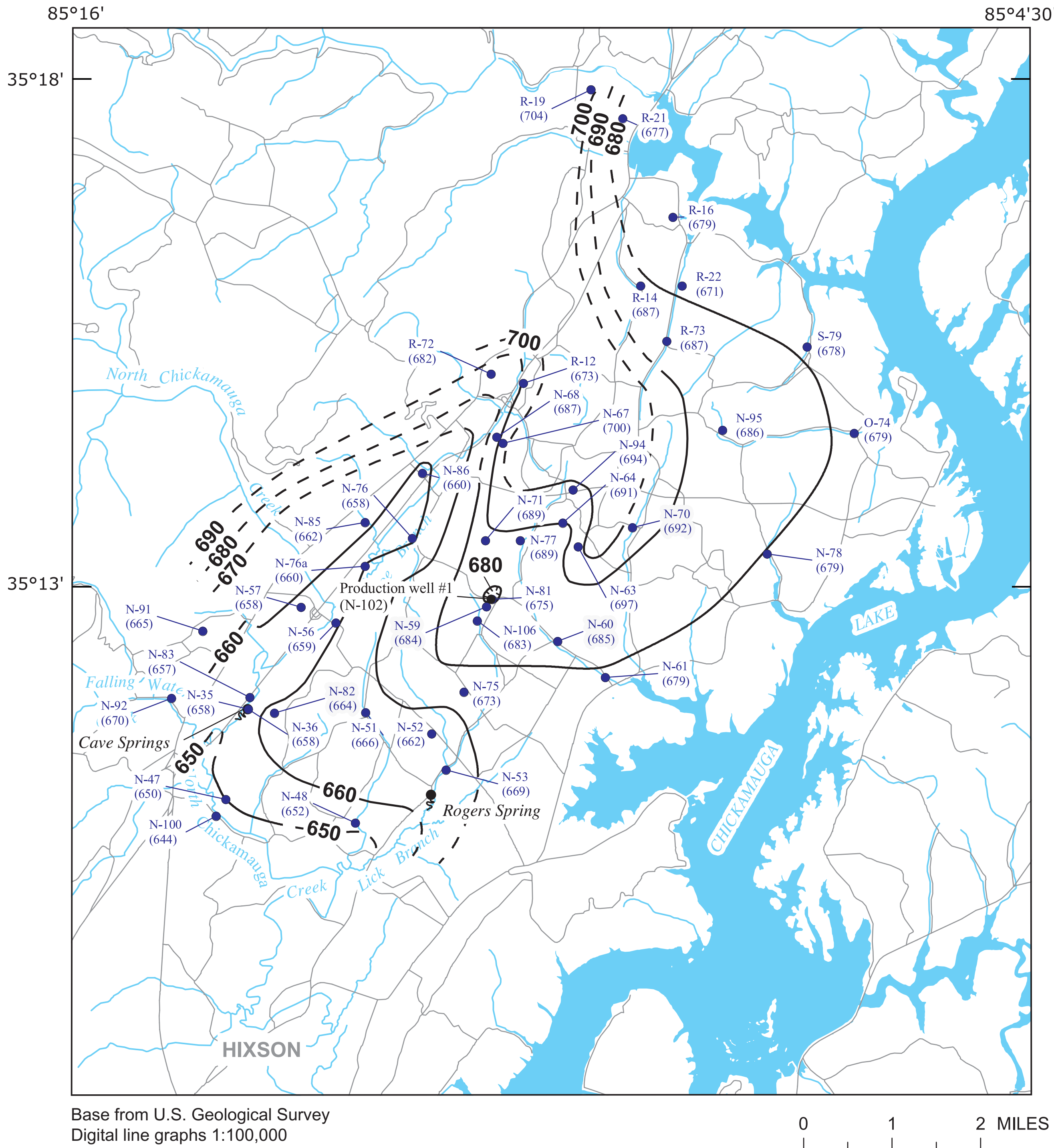


EXPLANATION

660 — POTENTIOMETRIC CONTOUR—Shows altitude at which water level would have stood in tightly cased wells. Dashed where approximately located. Contour interval 10 feet. Datum is sea level

● N-46 (649) — WELL USED AS CONTROL—Upper number is Hamilton County number (Hm:N-46). Lower number indicates altitude of water level, in feet above sea level

Figure 10. Potentiometric surface of the aquifer in the Cave Springs area near Hixson, Tennessee, May 1993.



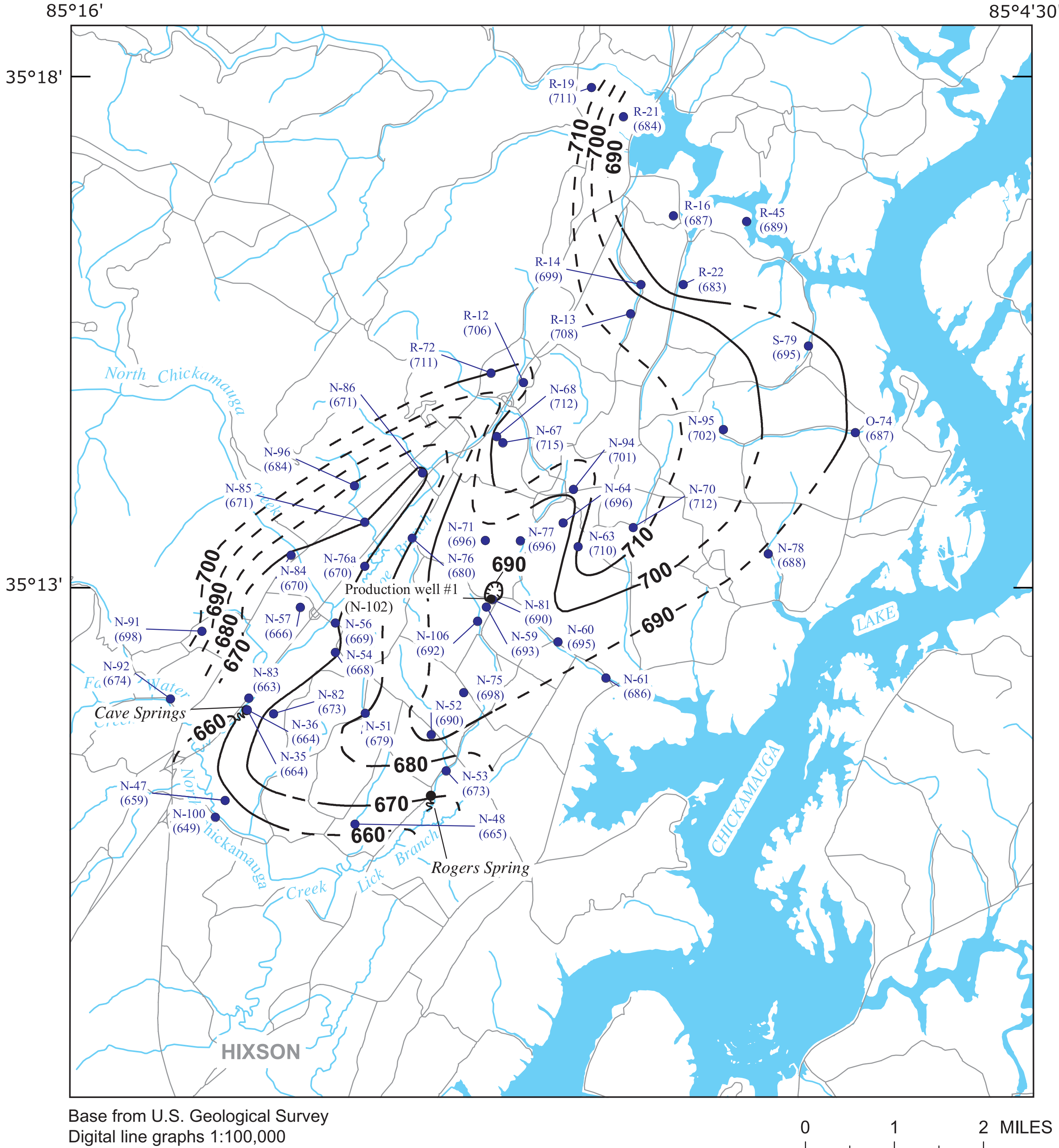
Base from U.S. Geological Survey
Digital line graphs 1:100,000

EXPLANATION

650 — POTENTIOMETRIC CONTOUR—Shows altitude at which water level would have stood in tightly cased wells. Dashed where approximately located. Hachures indicate depression. Contour interval 10 feet. Datum is sea level

N-100 (644) — WELL USED AS CONTROL—Upper number is Hamilton County number (Hm:N-100). Lower number indicates altitude of water level, in feet above sea level

Figure 11. Potentiometric surface of the aquifer in the Cave Springs area near Hixson, Tennessee, November 1998.

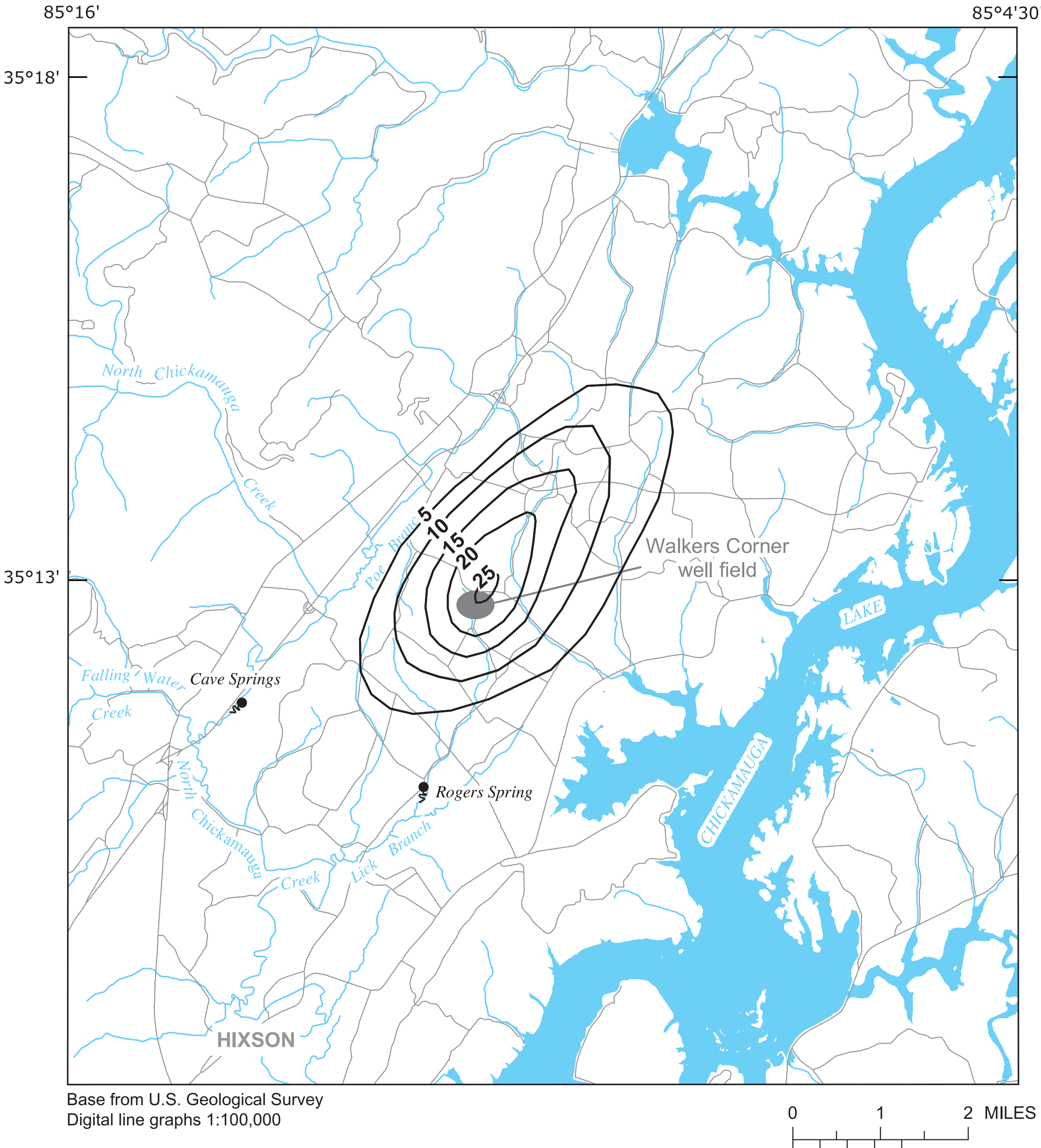


EXPLANATION

—660— — POTENTIOMETRIC CONTOUR—Shows altitude at which water level would have stood in tightly cased wells. Dashed where approximately located. Hachures indicate depression. Contour interval 10 feet. Datum is sea level

N-100 (649) ● WELL USED AS CONTROL—Upper number is Hamilton County number (Hm:N-100). Lower number indicates altitude of water level, in feet above sea level

Figure 12. Potentiometric surface of the aquifer in the Cave Springs area near Hixson, Tennessee, May 1999.



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.

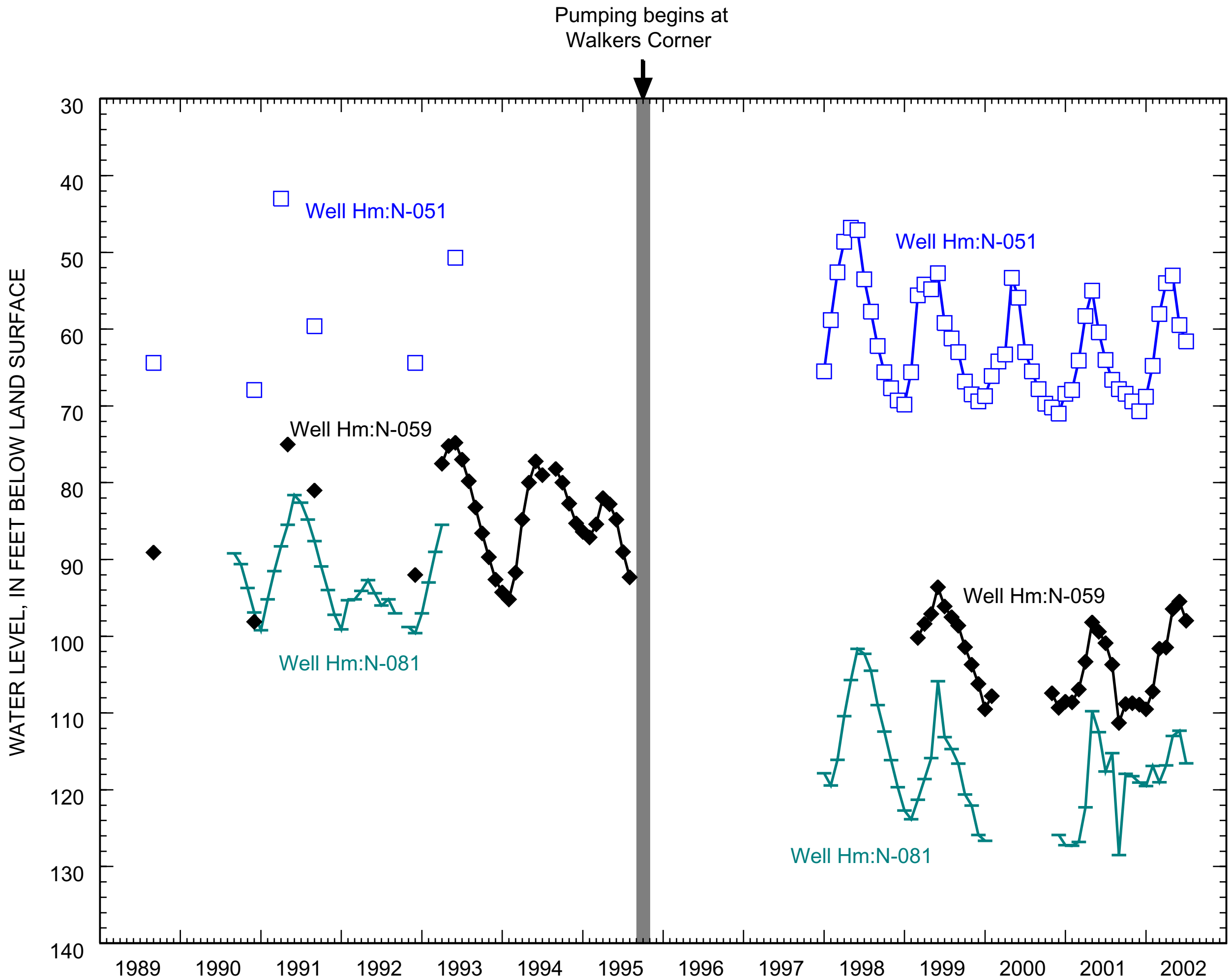


Figure 14. Periodic water levels in wells Hm:N-051, Hm:N-059, and Hm:N-081 from 1989 to 2002.

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 nonsteady 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.

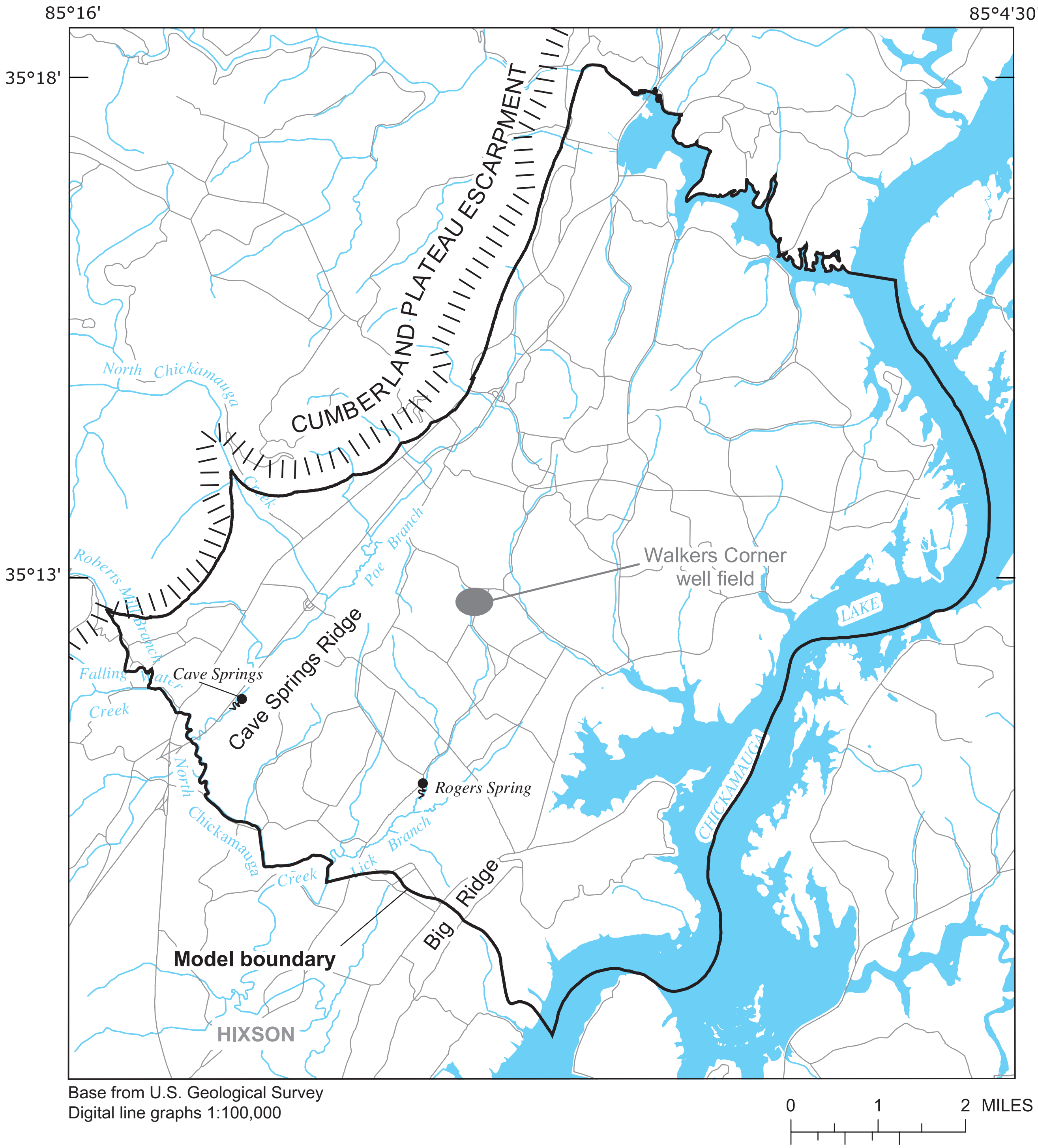


Figure 15. Hixson ground-water-flow model boundary.

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.

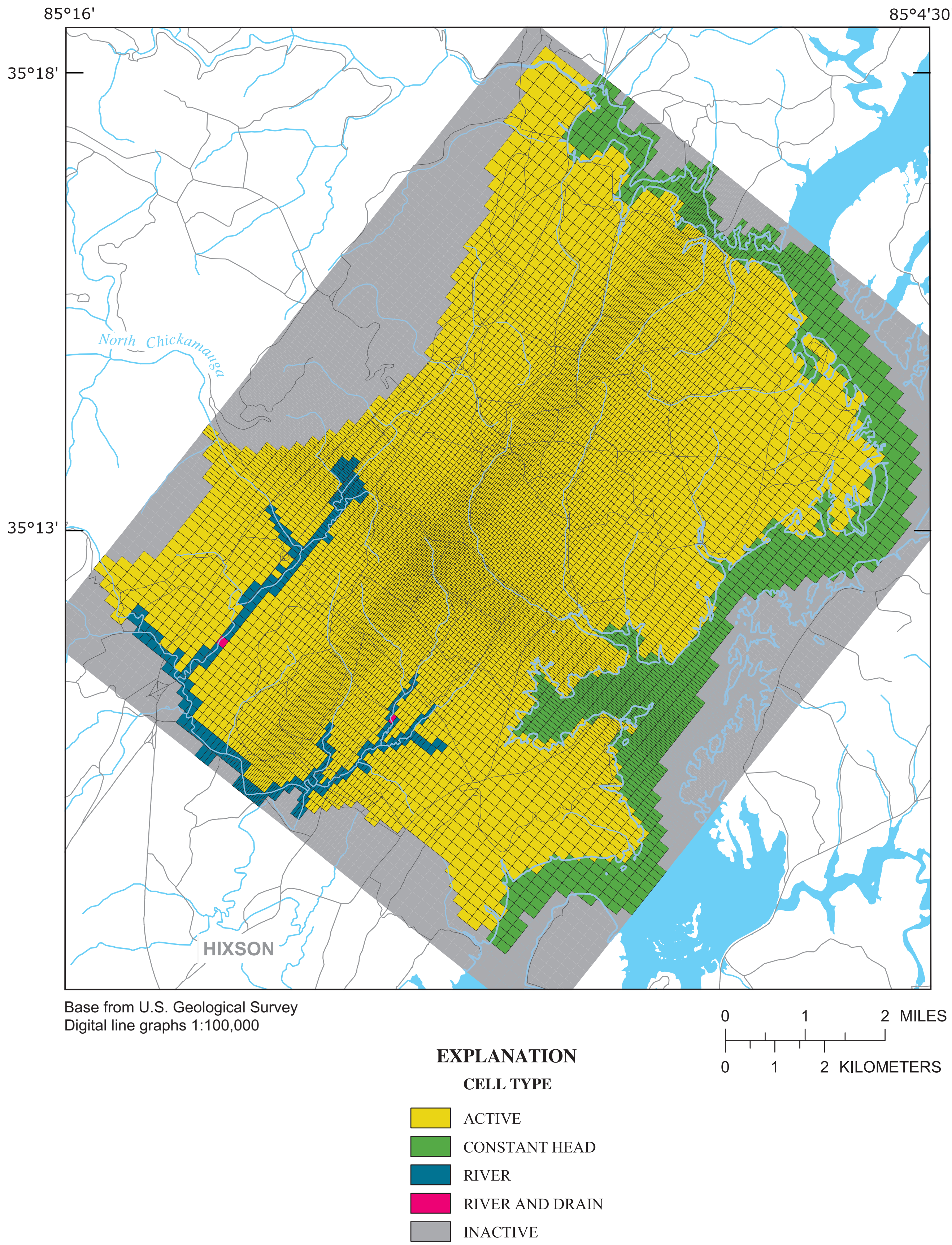


Figure 16. Model grid and cell types for the ground-water-flow model of the Cave Springs area near Hixson, Tennessee.

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

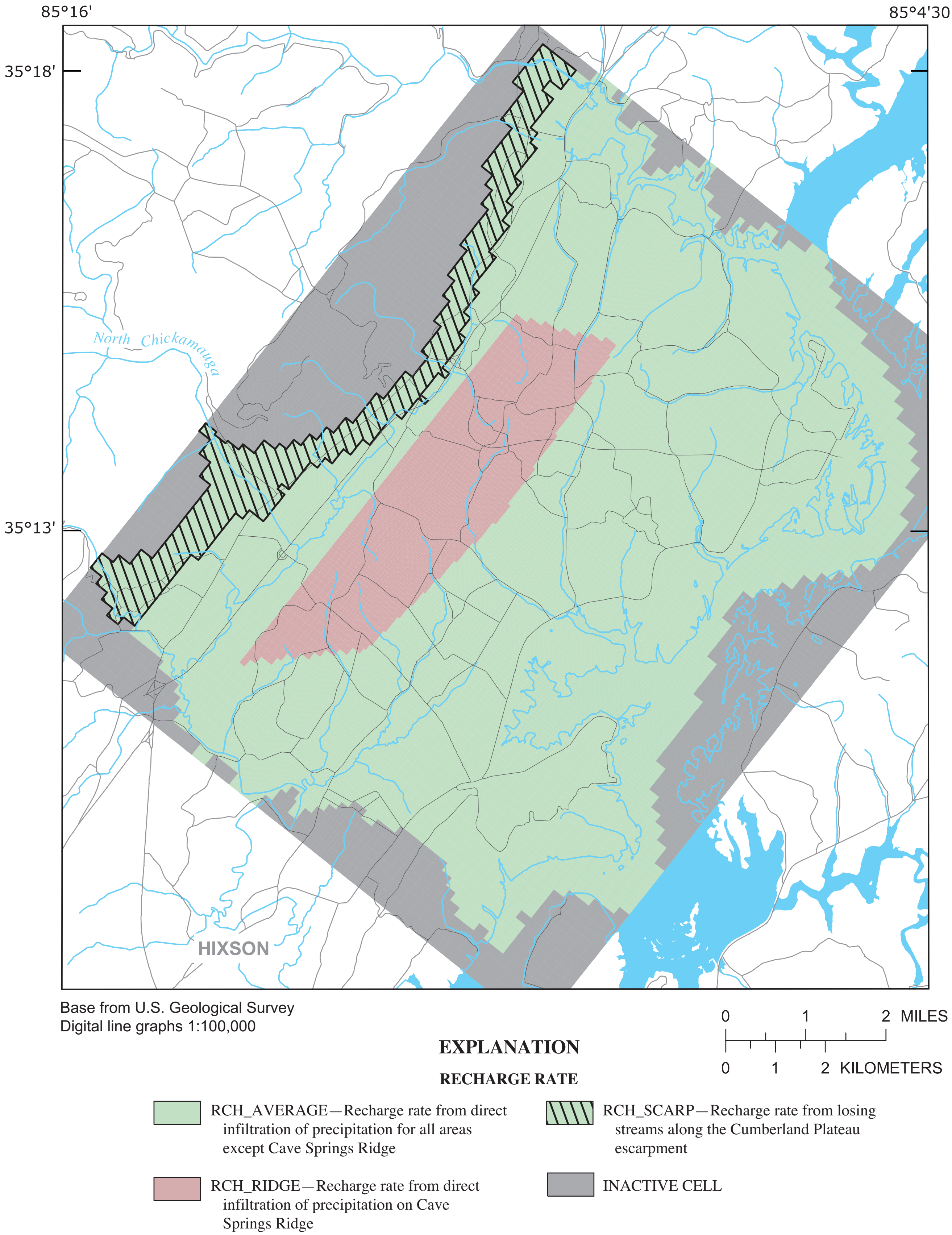


Figure 17. Distribution of simulated recharge rates for the ground-water-flow model.

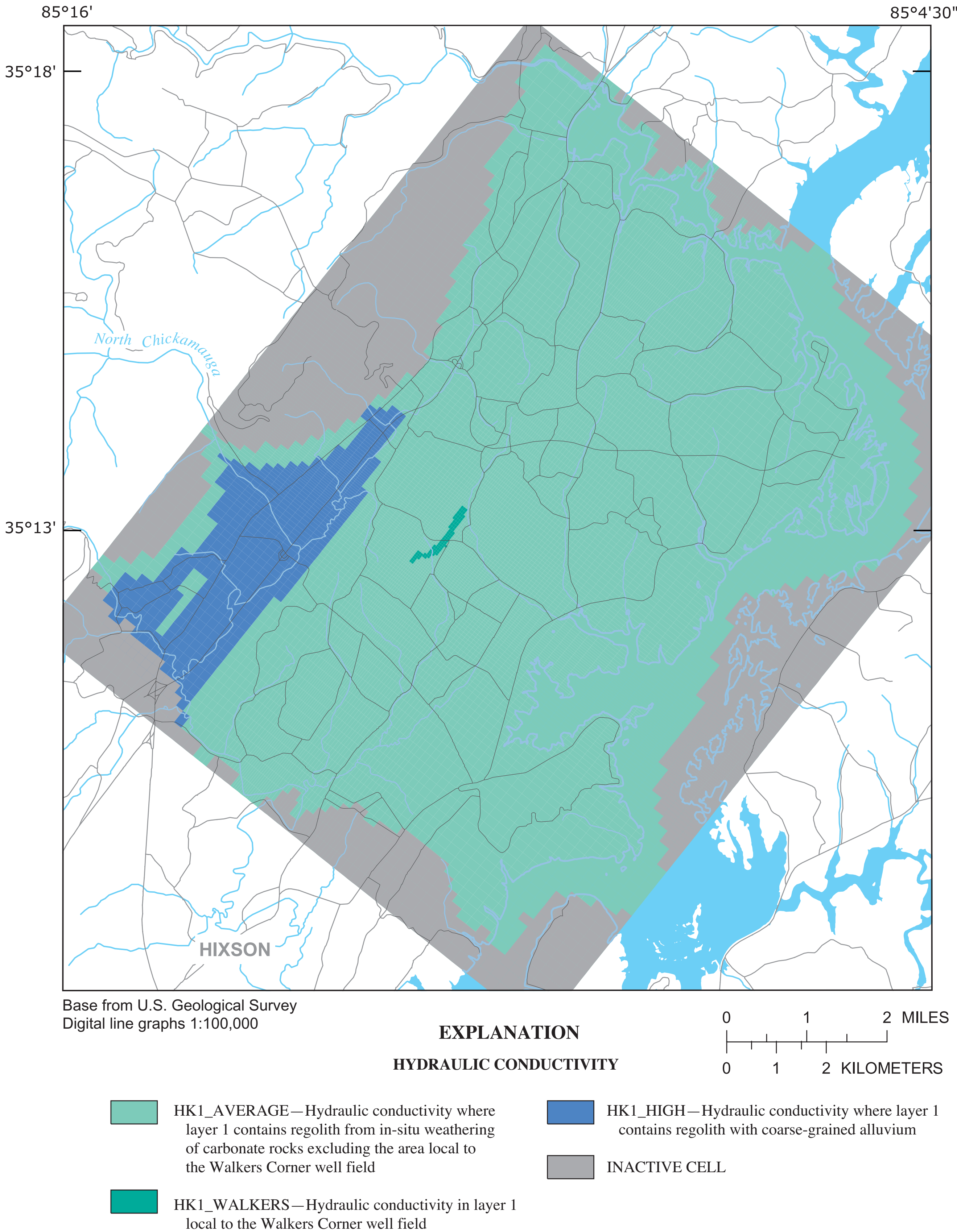
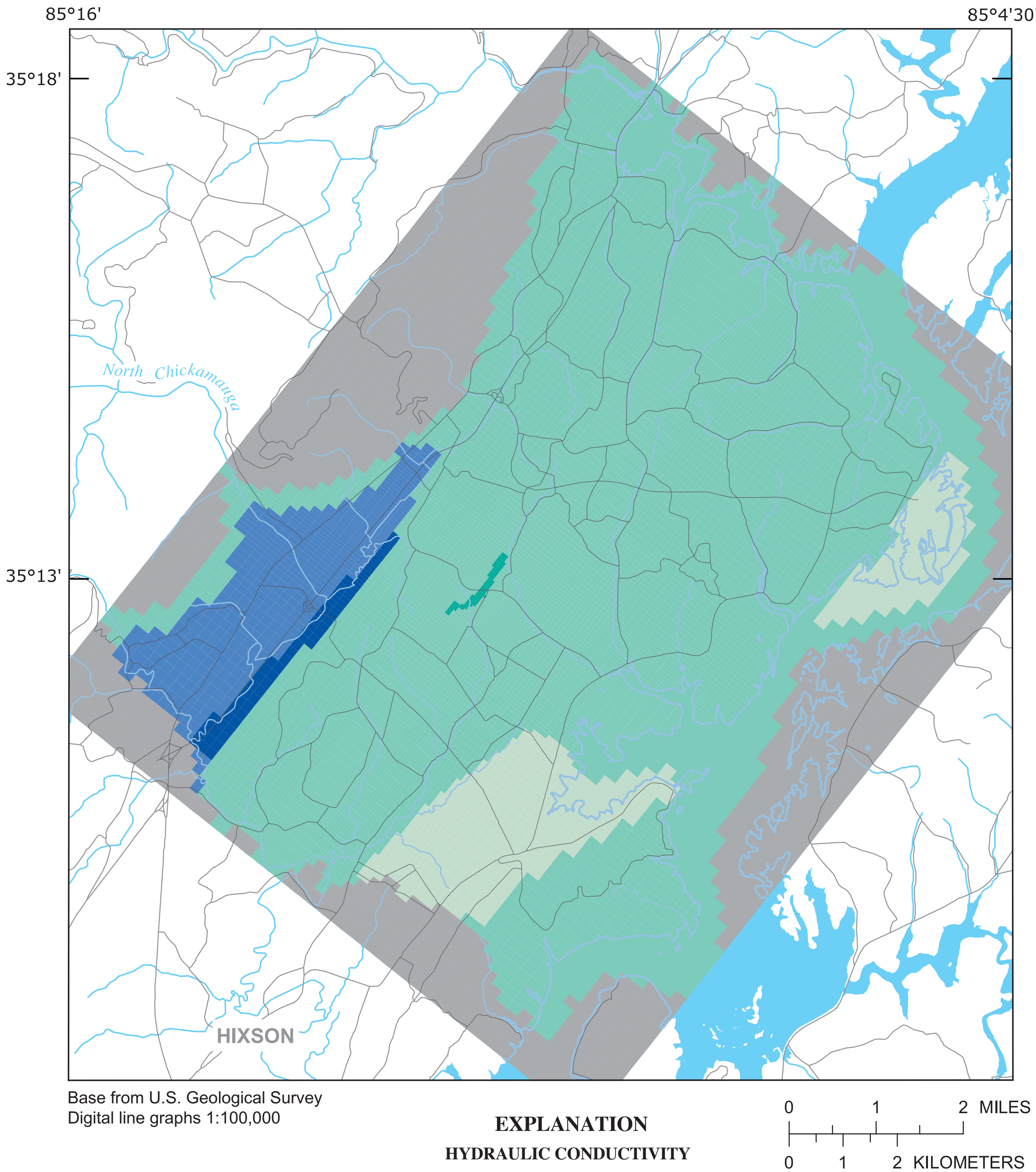


Figure 18. Hydraulic-conductivity zones for model layer 1.



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;

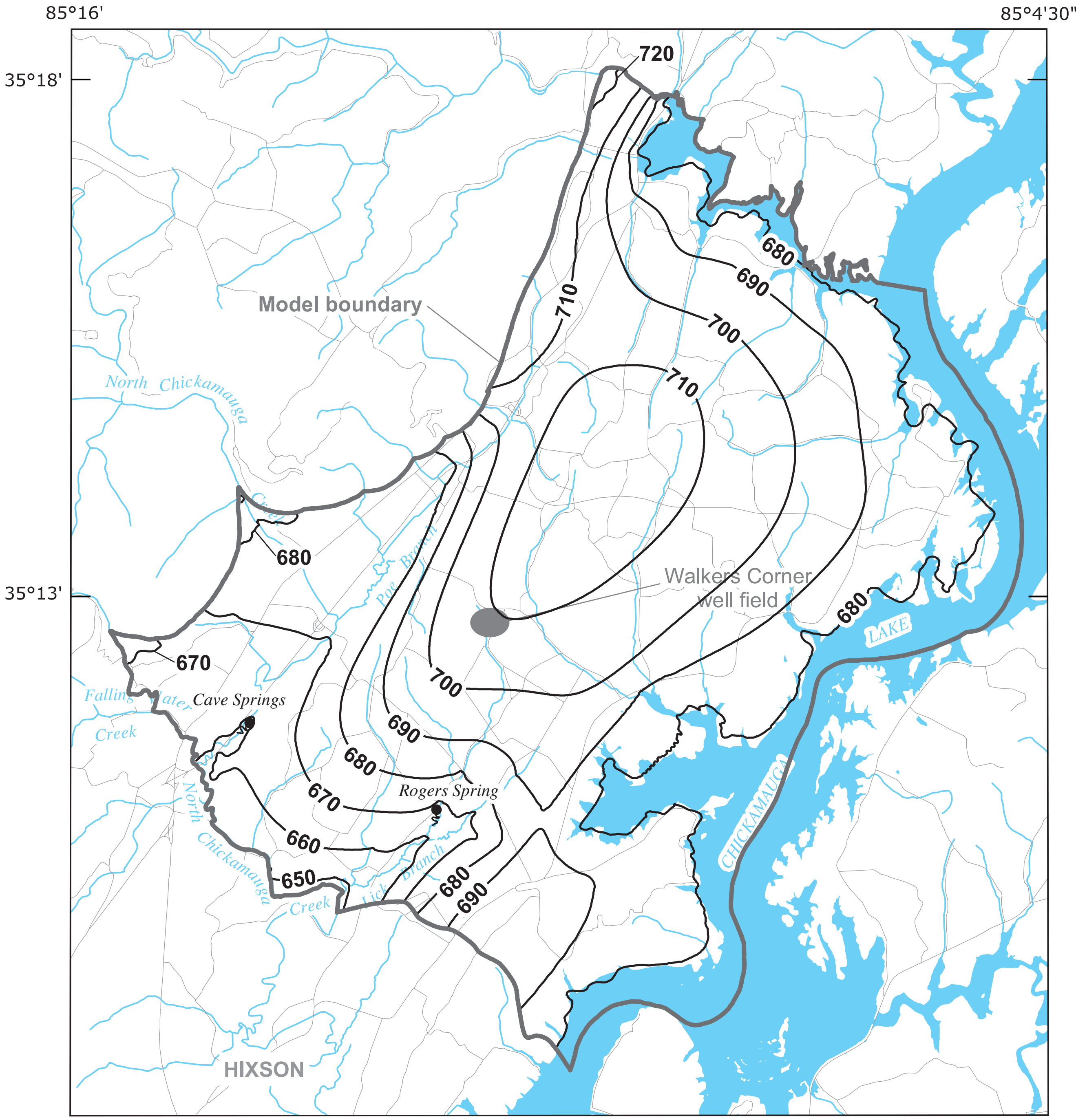
h_i^m is the measured water level, in feet; and

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



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

0 1 2 MILES
0 1 2 KILOMETERS

EXPLANATION

—650— POTENTIOMETRIC CONTOUR—Shows simulated altitude of water levels. Contour interval 10 feet. Datum is sea level

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

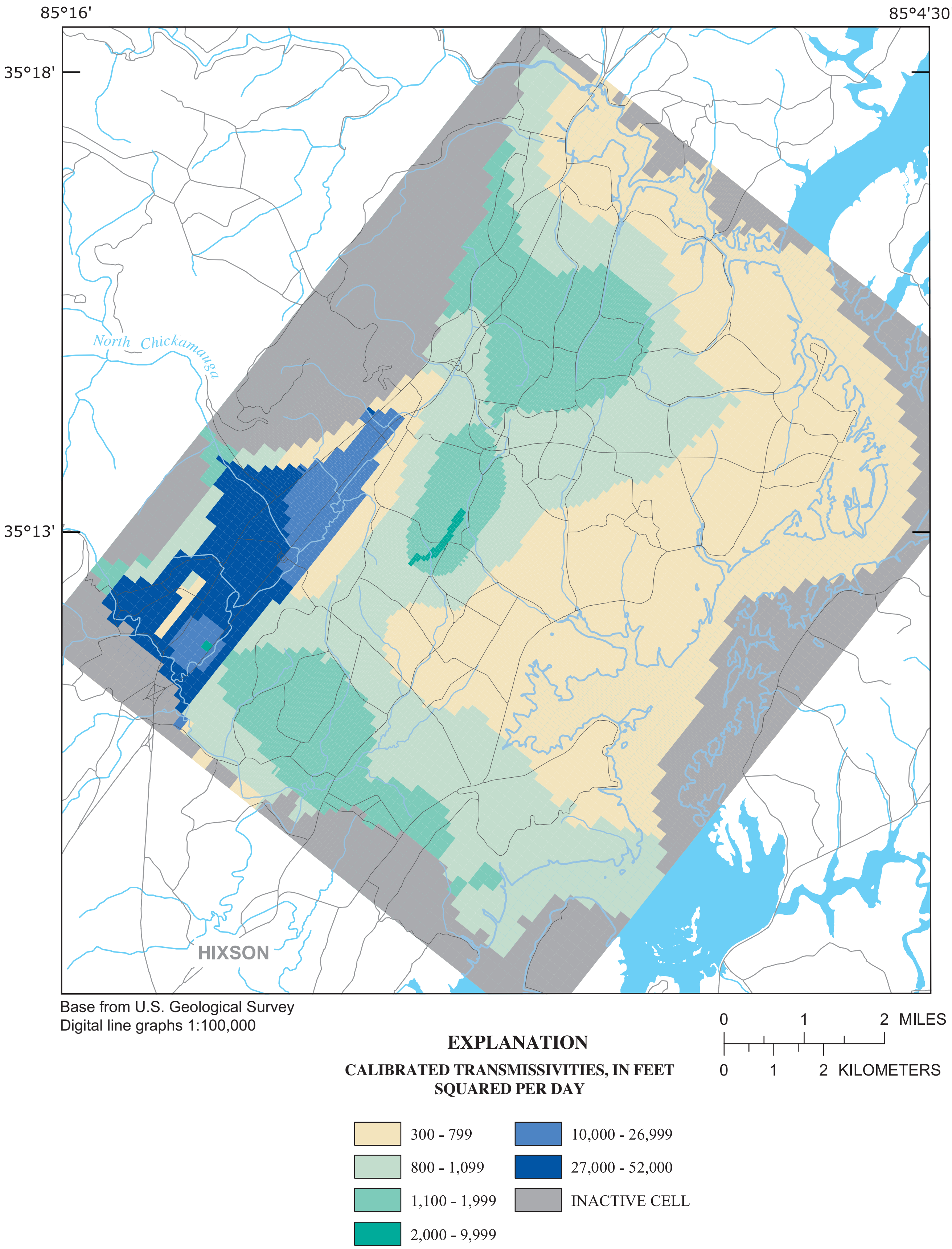


Figure 21. Calibrated transmissivities for model layer 1.

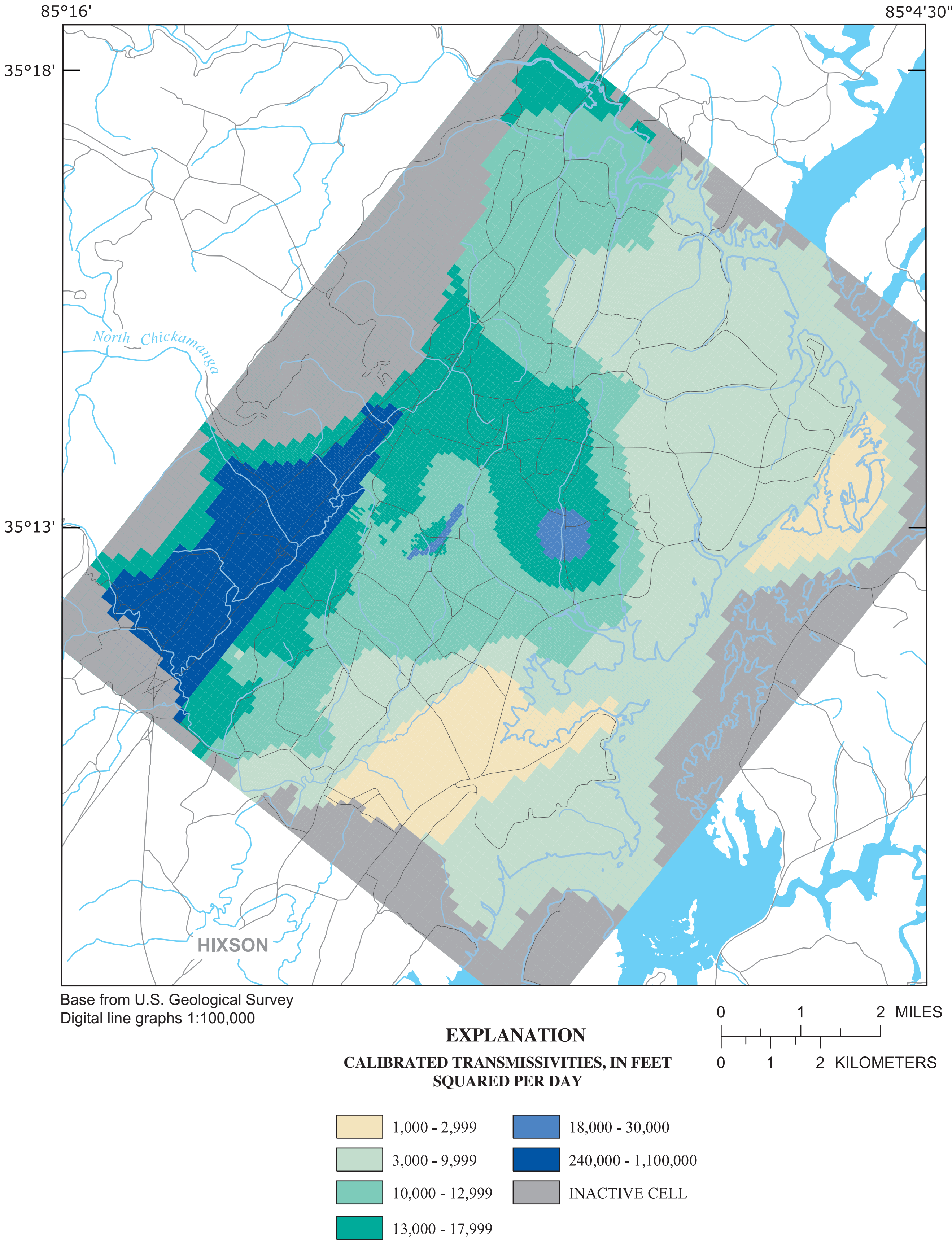


Figure 22. Calibrated transmissivities for model layer 2.

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
<u>Ground-water discharges</u>						
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
<u>Ground-water withdrawals</u>						
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

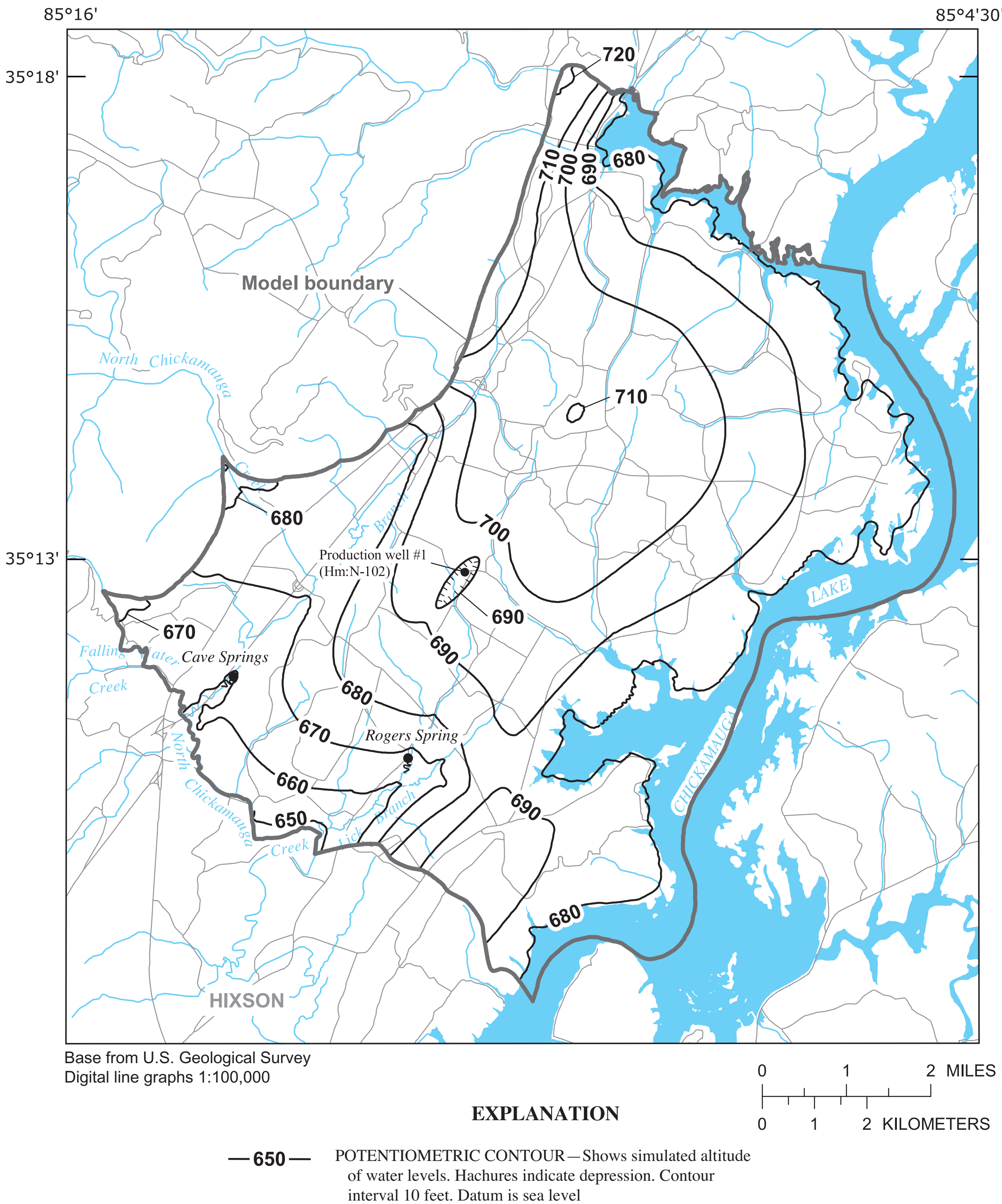


Figure 23. Model-simulated steady-state water levels with Walkers Corner production well #1 in use, layer 1.

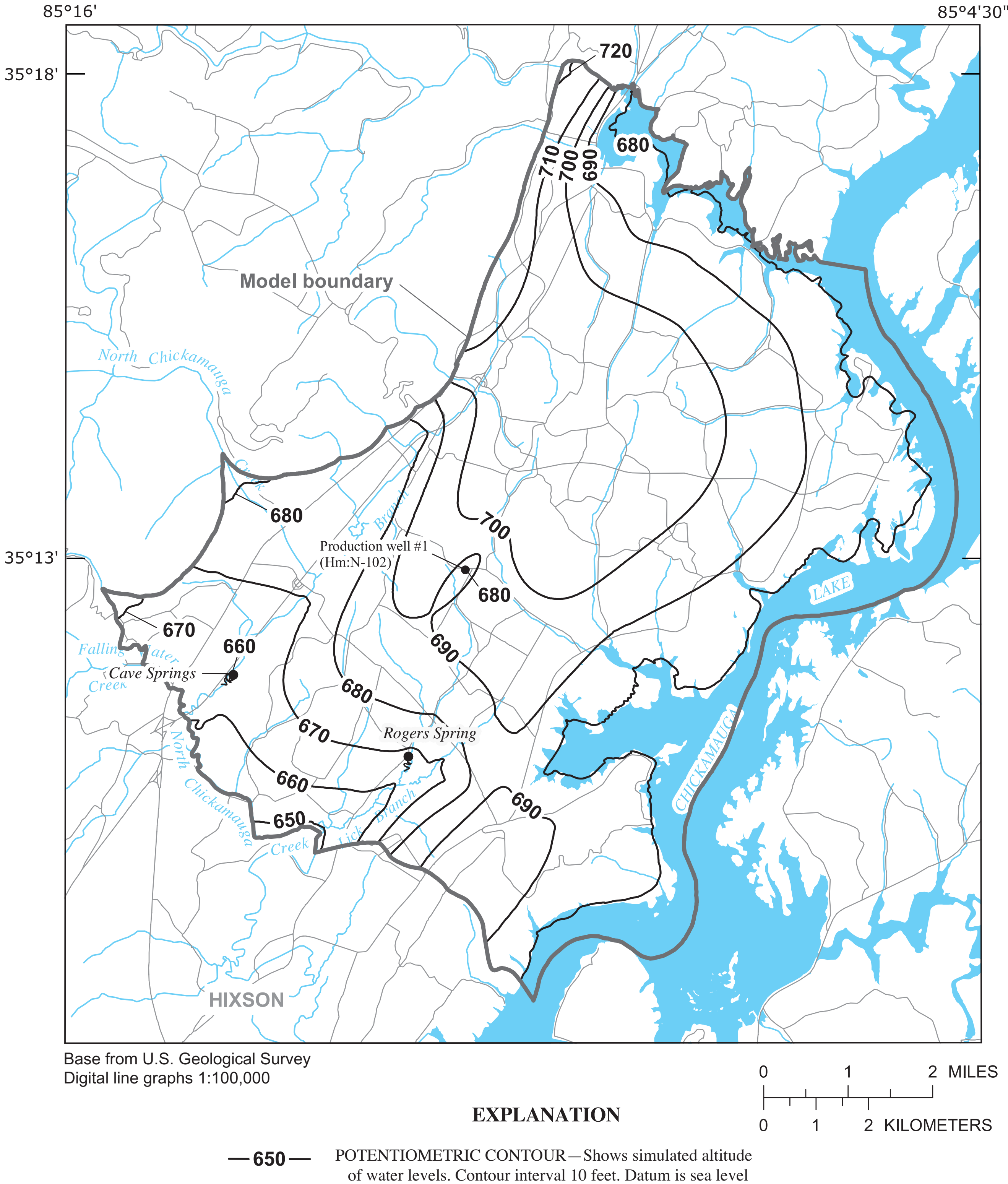
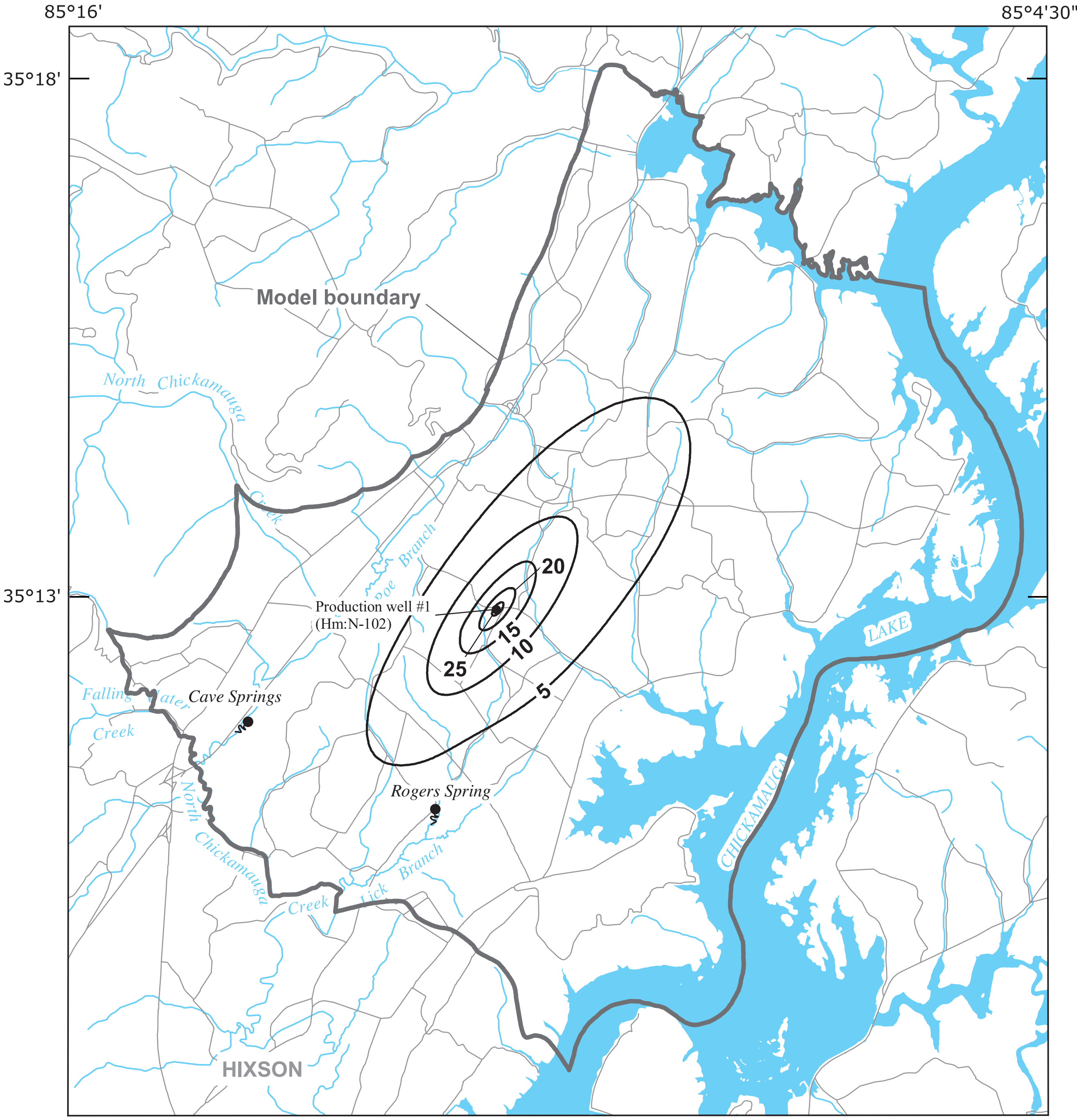


Figure 24. Model-simulated steady-state water levels with Walkers Corner production well #1 in use, layer 2.



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

EXPLANATION

—5— LINE OF EQUAL WATER-LEVEL DECLINE—Shows simulated decline of water levels, in feet. Contour interval 5 feet

Figure 25. Model-simulated steady-state water-level decline with Walkers Corner production well #1 in use, layer 1.

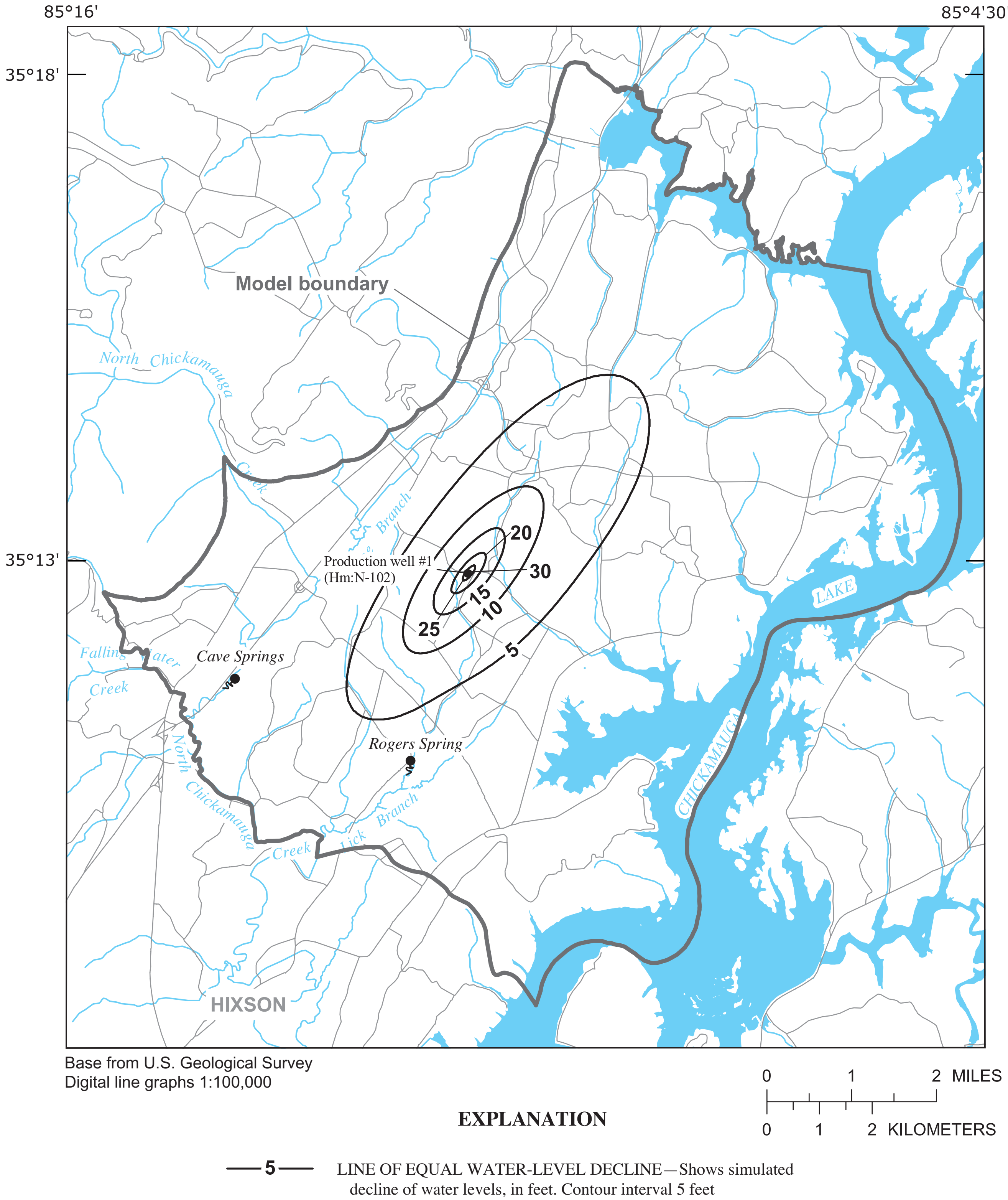


Figure 26. Model-simulated steady-state water-level decline with Walkers Corner production well #1 in use, layer 2.

streamflow data are available to compare with these simulated base-flow decreases.

Hydraulic testing indicates that the second production well at Walkers Corner can sustain a yield of 3 ft^3/s (2 Mgal/d) (Hixson Utility District, written commun., 2000). A model simulation was run with production wells #1 and #2 operating at Walkers Corner to estimate the effects of possible additional pumping from the second production well. This steady-state simulation with the Walkers Corner production wells #1 and #2 in use shows a similar pattern as the simulation using only production well #1 pumping; water levels are depressed along strike from the well field and the highest contour along the ridge near the center of the study area at 700 feet above sea level (figs. 27 and 28). The maximum steady-state water-level decline was 57 feet in model layer 1 and 61 feet in layer 2 (figs. 29 and 30, respectively). This decline results in a water-level altitude in the production wells of about 640 feet above sea level. Preliminary field observations suggest Walkers Corner production well #2 may have a greater specific capacity than Walkers Corner production well #1. If this is true, then production well #2 would produce less drawdown than the model currently estimates. The model water budget indicates that additional ground-water withdrawal at Walkers Corner from production well #2 would result in additional decreases in simulated ground-water discharge of 1.0 ft^3/s to Chickamauga Lake, 0.8 ft^3/s to North Chickamauga Creek, 0.5 ft^3/s to Lick Branch and Rogers Spring, 0.5 ft^3/s to Poe Branch, and 0.2 ft^3/s to Cave Springs (table 8).

The water budget from these two additional model simulations indicate that withdrawals at the Walkers Corner well field decrease ground-water discharge to all streams in the study area. The largest change in discharge is to Chickamauga Lake whereas the smallest change is to Cave Springs (table 8).

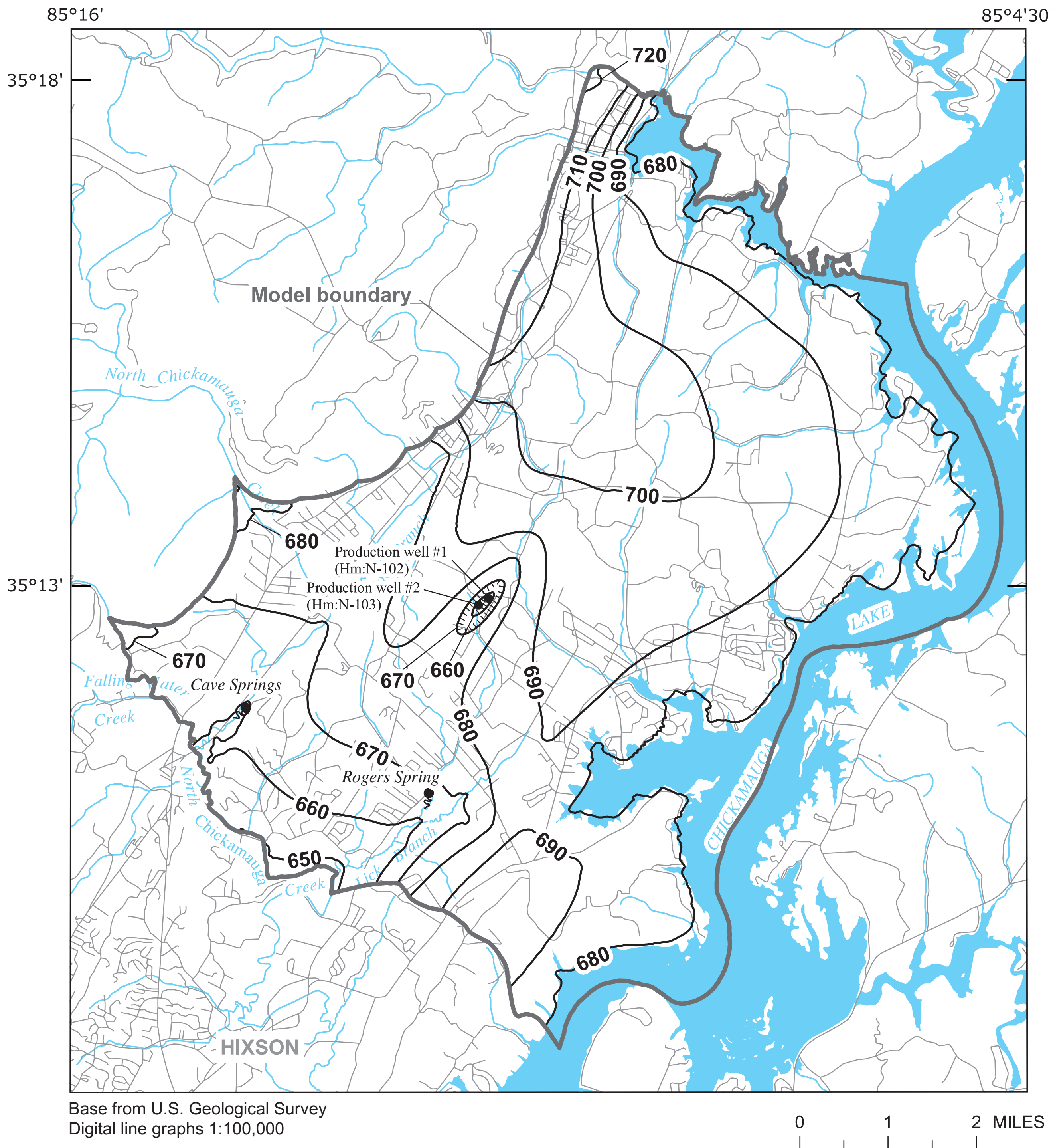
Drought Simulation

The effects of a drought were evaluated with a transient model simulation assuming no recharge occurs. A transient calibration was made to determine the best storage coefficients for the model. Because the model layers are convertible, specific yield and specific storage need to be input for each layer. The model then uses the appropriate coefficient depending on whether the model layer is fully or partially saturated (Harbaugh and others, 2000). Generally, most model cells in layer 1 are partially saturated, and most model cells in layer 2 are fully saturated.

The storage coefficients were calibrated by matching the slope of the seasonal recession of water levels from well Hm:N-051 (fig. 7). To model the seasonal recession of water levels, the transient calibration simulation was made using a period of 5 months with no recharge input. The simulated potentiometric-surface map for May 1999 (fig. 12) was used to define starting water levels because this surface represents steady-state conditions with the Walkers Corner production well #1 in use. Ground-water withdrawals during the transient calibration simulation were constant at 9 ft^3/s (5.8 Mgal/d) from the Cave Springs well field and 2.8 ft^3/s (1.8 Mgal/d) from Walkers Corner well field production well #1. The specific yield and specific storage coefficient were assumed to be uniform across the study area. A specific yield of 0.012 and a specific storage of 0.0001 produced the best match between observed and simulated water levels in well Hm:N-051 (fig. 31). Both values are within expected ranges.

The effects of a drought were then analyzed by simulating a 12-month period without recharge. The initial conditions and rates of ground-water withdrawal were the same as for the transient calibration simulation. Results indicate that water levels decline as the ground-water system drains (figs. 32 and 33). While a 12-month period with no recharge may not be realistic, the results from this simulation can be used to estimate the effects on water levels in the study area if no recharge occurs for several months, given observations of the current conditions at any point in time. For example, if after a winter and spring of lower than average recharge, field observations show that ground-water levels are similar to the results at the 4-month simulation time; and if no significant recharge is expected for 4 more months, then the 8-month simulation time would be an estimate of the water-level conditions expected to exist if no recharge were to occur for the next 4 months. Hydrographs of simulated water-level recessions at five locations in the study area show that, away from the pumping centers, water levels recede quickest farthest from the natural discharge areas (Hm:N-063, fig. 34). Additionally, water levels at the pumping centers, Walkers Corner production well #1 (Hm:N-102) and Cave Springs well field (Hm:N-035), recede quicker than water levels at wells similarly situated with respect to natural discharge area and farther away from pumping centers (Hm:N-051 and Hm:N-047) (fig. 34).

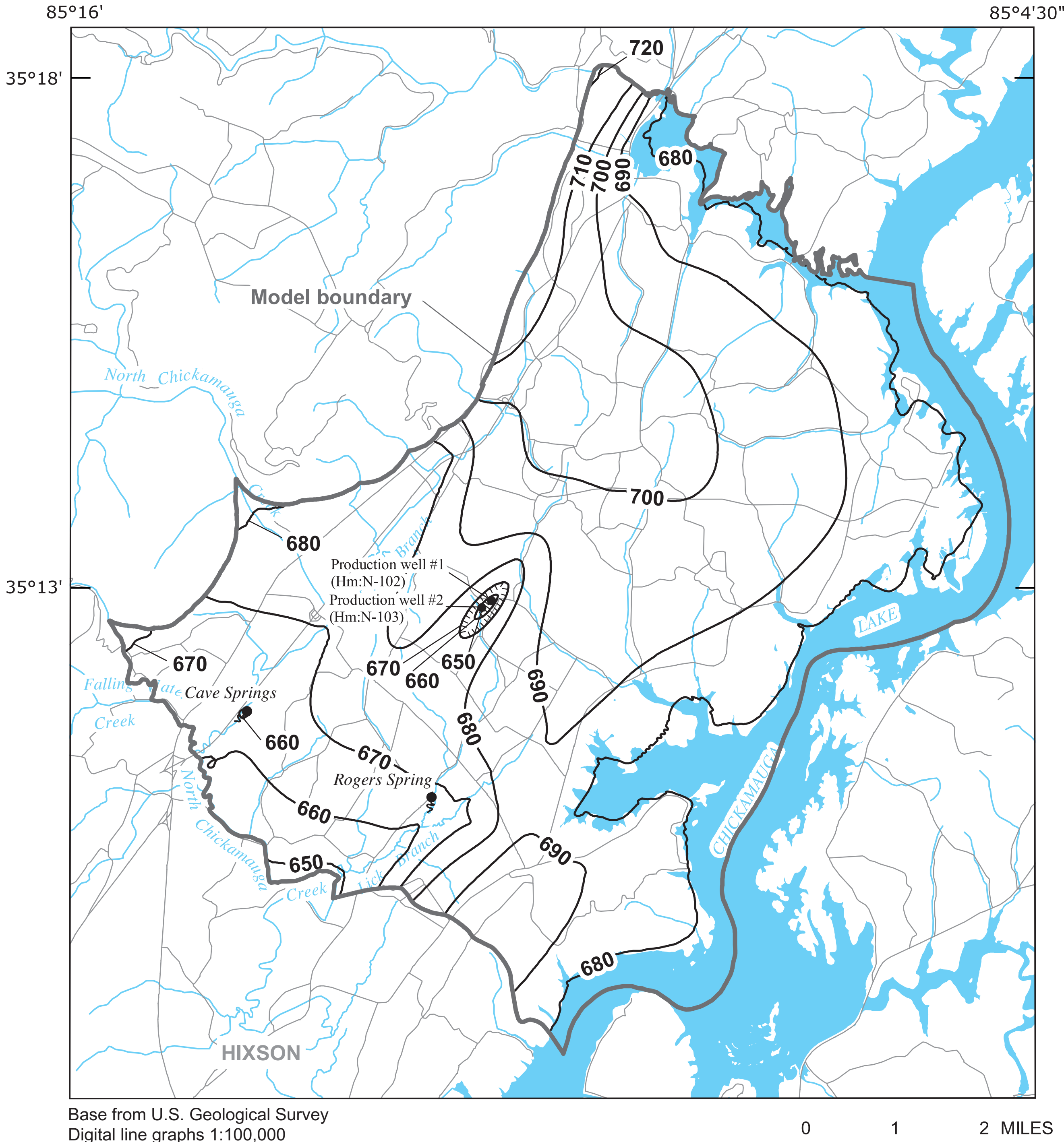
The simulated drought scenario would overestimate the decline in water levels at the Cave Springs well field because the model simulates an extreme



EXPLANATION

— 650 — POTENTIOMETRIC CONTOUR—Shows simulated altitude of water levels. Hachures indicate depression. Contour interval 10 feet. Datum is sea level

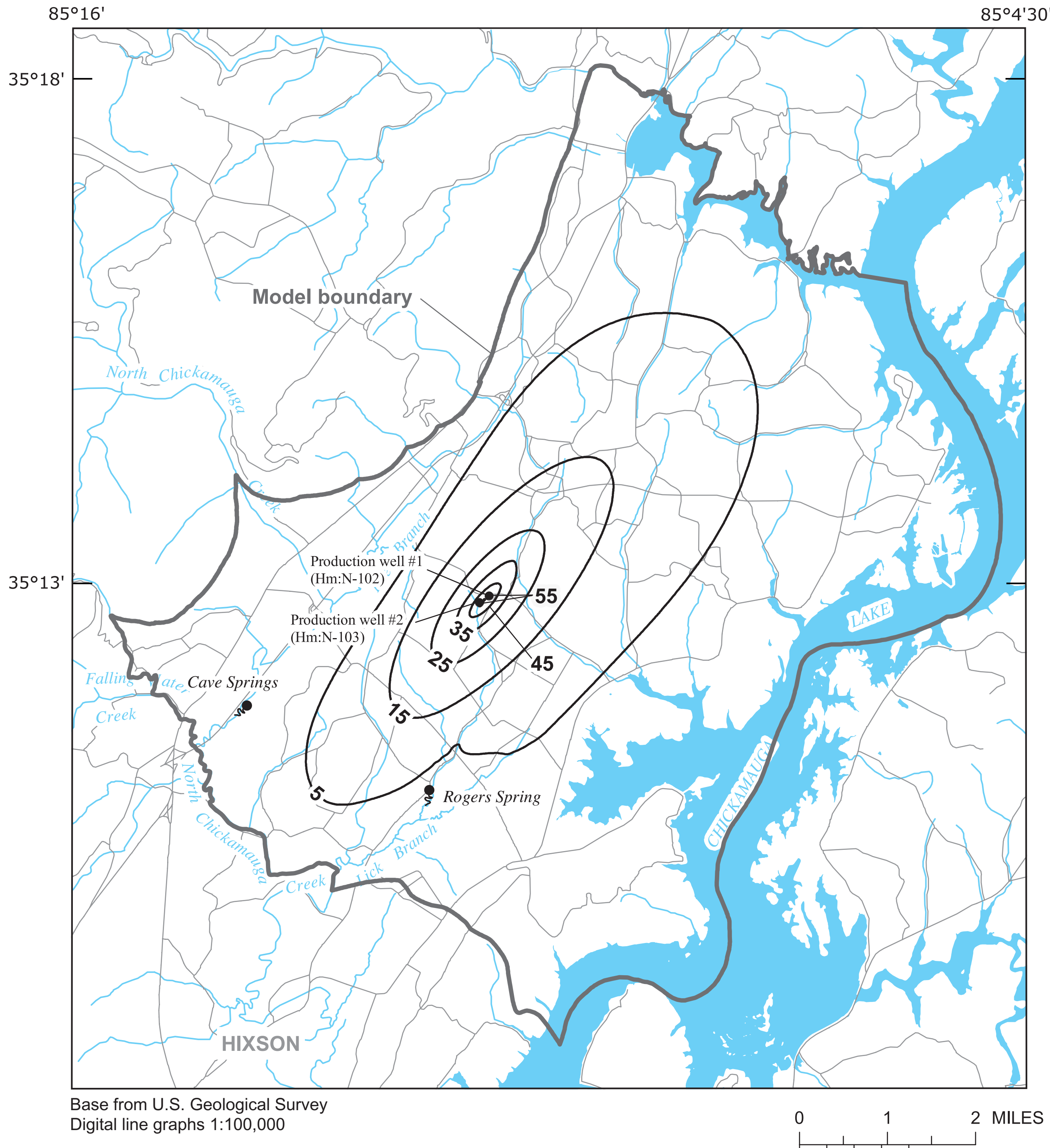
Figure 27. Model-simulated steady-state water levels with Walkers Corner production wells #1 and #2 in use, layer 1.



EXPLANATION

—650— POTENTIOMETRIC CONTOUR—Shows simulated altitude of water levels. Hachures indicate depression. Contour interval 10 feet. Datum is sea level

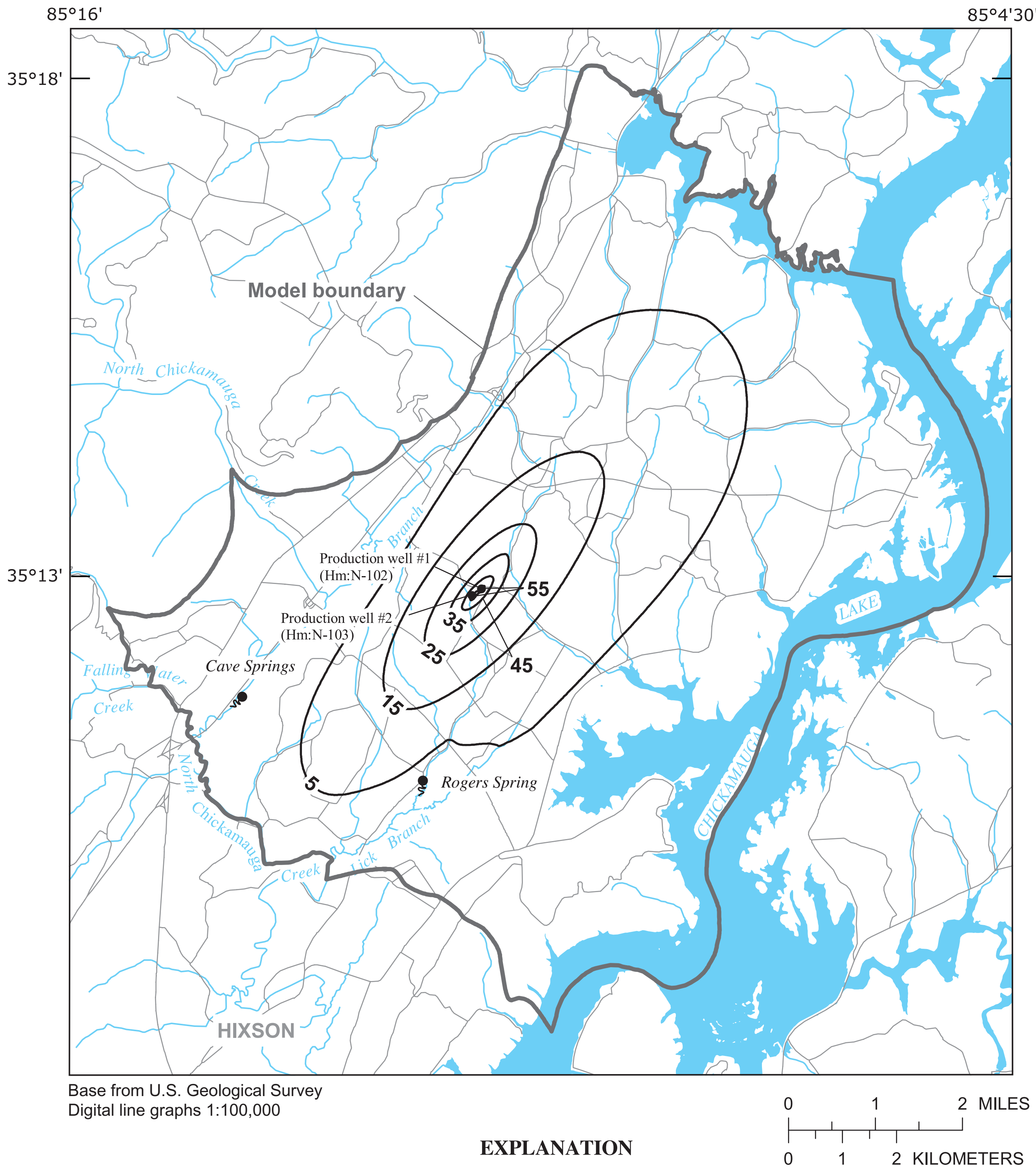
Figure 28. Model-simulated steady-state water levels with Walkers Corner production wells #1 and #2 in use, layer 2.



EXPLANATION

—5— LINE OF EQUAL WATER-LEVEL DECLINE—Shows simulated decline of water levels, in feet. Contour interval 10 feet

Figure 29. Model-simulated steady-state water-level decline with Walkers Corner production wells #1 and #2 in use, layer 1.



EXPLANATION

—5— LINE OF EQUAL WATER-LEVEL DECLINE—Shows simulated decline of water levels, in feet. Contour interval 10 feet

Figure 30. Model-simulated steady-state water-level decline with Walkers Corner production wells #1 and #2 in use, layer 2.

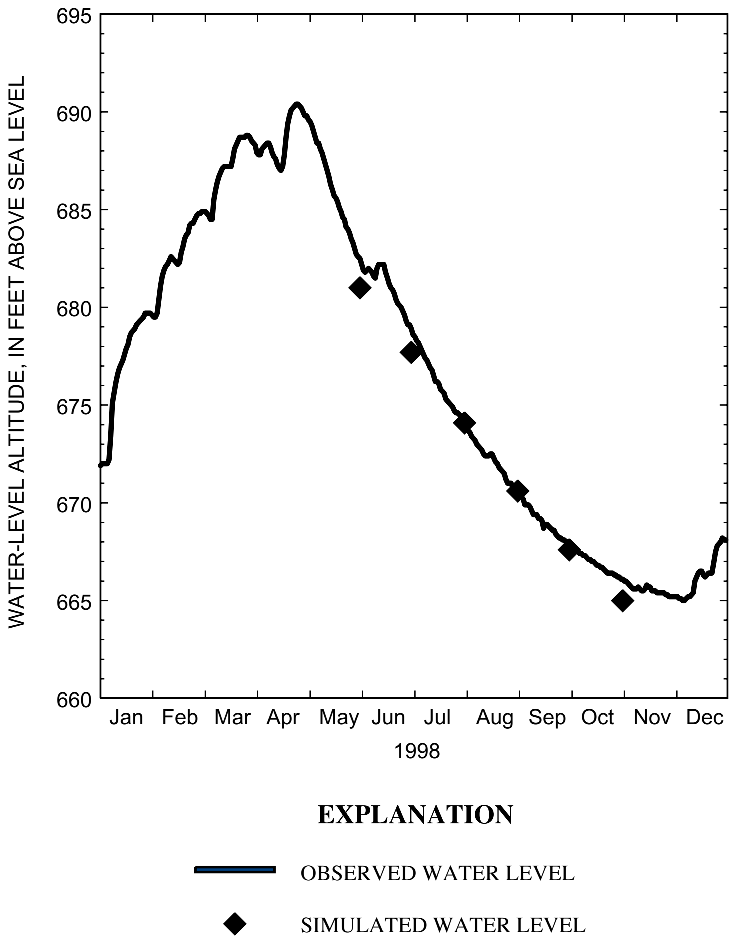


Figure 31. Observed and simulated water-level recession in well Hm:N-051.

case of no recharge from infiltrating precipitation or recharge from losing streams along the Cumberland Plateau escarpment. Recharge from these losing streams is an important source of recharge for Cave Springs, and this flux of water would continue for a period of time in the absence of precipitation as the aquifers on the Cumberland Plateau supply base flow to streams draining the plateau. Field observations confirm that North Chickamauga Creek has sustained base flow in the North Chickamauga Creek Gulch during summer months when rainfall is limited.

Sensitivity Analysis

Composite scaled sensitivities were calculated for the steady-state calibration model using the sensitivity process in MODFLOW-2000 for all the hydraulic conductivity and recharge parameters (fig. 35). Hill and others (2000) describe how sensitivities can be calculated for any of the model parameters discussed by Harbaugh and others (2000). Composite scaled sensitivities can be used to compare the importance of different parameters to the calculation of model-simulated water levels and flows (Hill, 1998). Parameters with greater composite sensitivities have greater importance and greater influence on the model solution. The most sensitive model parameter is the layer 2 hydraulic conductivity for the average zone (HK2_average). The next most sensitive parameter is the recharge rate for the ridge area (RCH_ridge). The model is least sensitive to the parameters HK1_high, HK2_low, HK2_walkers, and HK1_walkers.

Model Limitations

Models, by their very nature, are simplifications of the natural system. Factors that affect how well a model represents the natural system include the model scale, inaccuracies in estimating hydraulic properties, inaccurate or poorly defined boundary conditions, and the accuracy of pumping, water-level, and streamflow data. The model presented in this report is consistent with the conceptual model and hydrologic data of the area. The model uses a variably spaced grid so the model resolution is greatest near the pumping centers. The model will not provide accurate predictions on a scale smaller than the grid resolution.

The hydraulic-conductivity zones used in the model represent large-scale variations in hydraulic properties; the actual spatial variations of hydraulic properties of the aquifer occur on a much smaller scale and are poorly defined. Additionally, the aquifer, being karst in nature, has a wide range of measured transmissivity. Finally, evidence suggests that the aquifer behaves anisotropically, but no measured values of the degree of anisotropy exist.

The boundary conditions for the model correspond to natural features throughout most of the study area. The greatest uncertainty in boundary conditions is the recharge flux along the Cumberland Plateau escarpment. Water draining from the Cumberland Plateau is an important source of recharge to the study area, but the quantity and distribution of this recharge flux is uncertain.

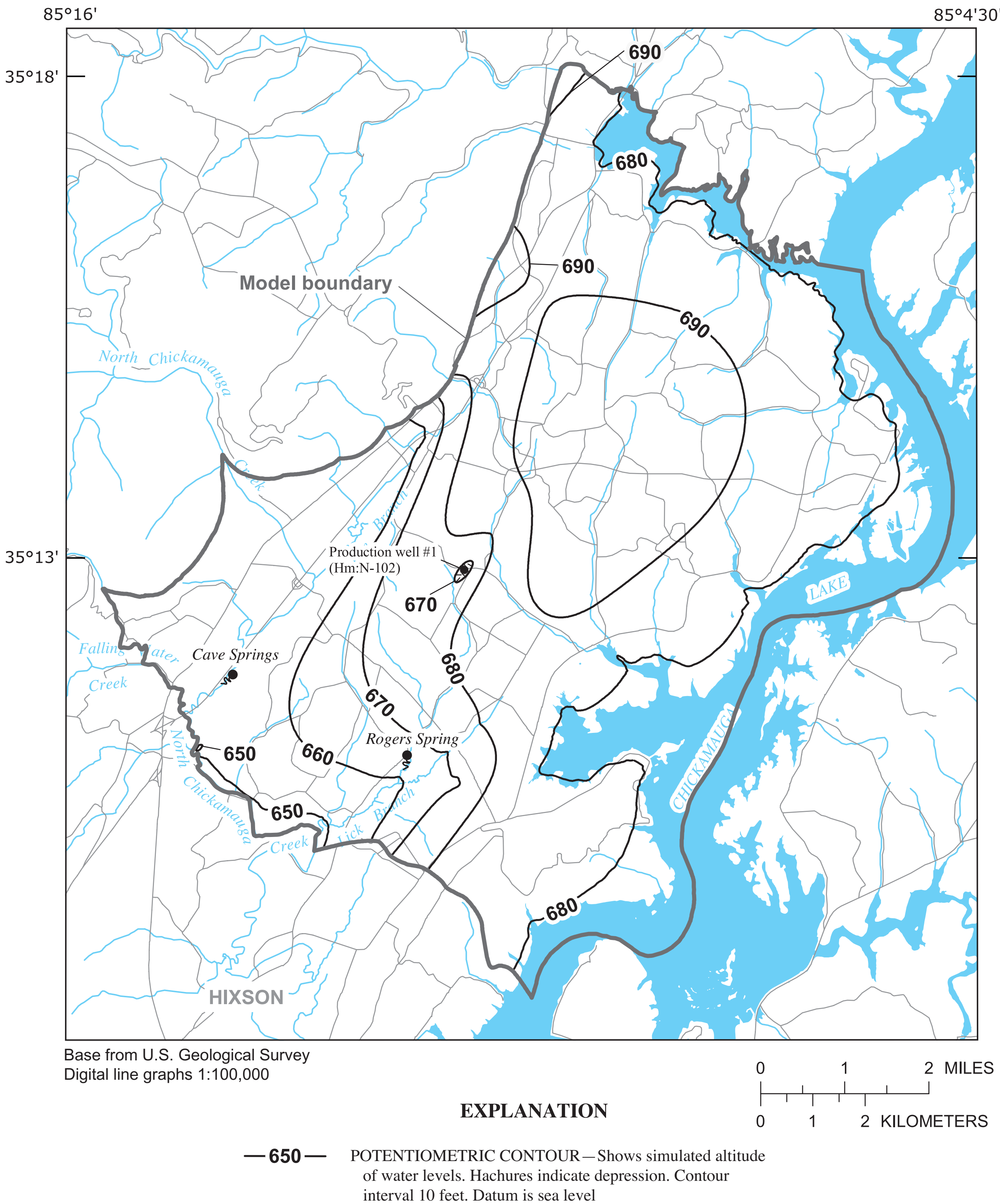


Figure 32. Model-simulated water levels after 4 months without recharge, layer 1.

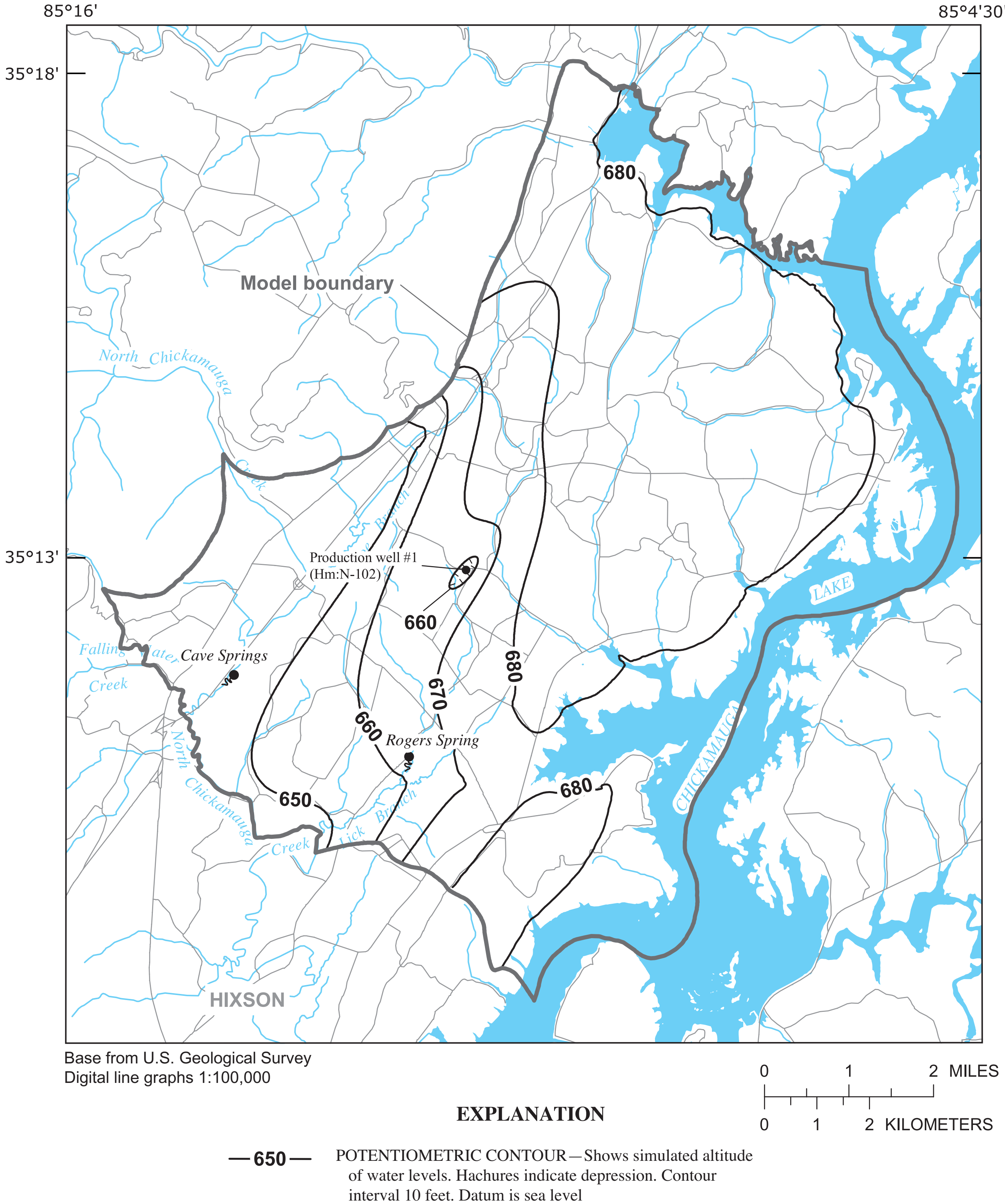


Figure 33. Model-simulated water levels after 8 months without recharge, layer 1.

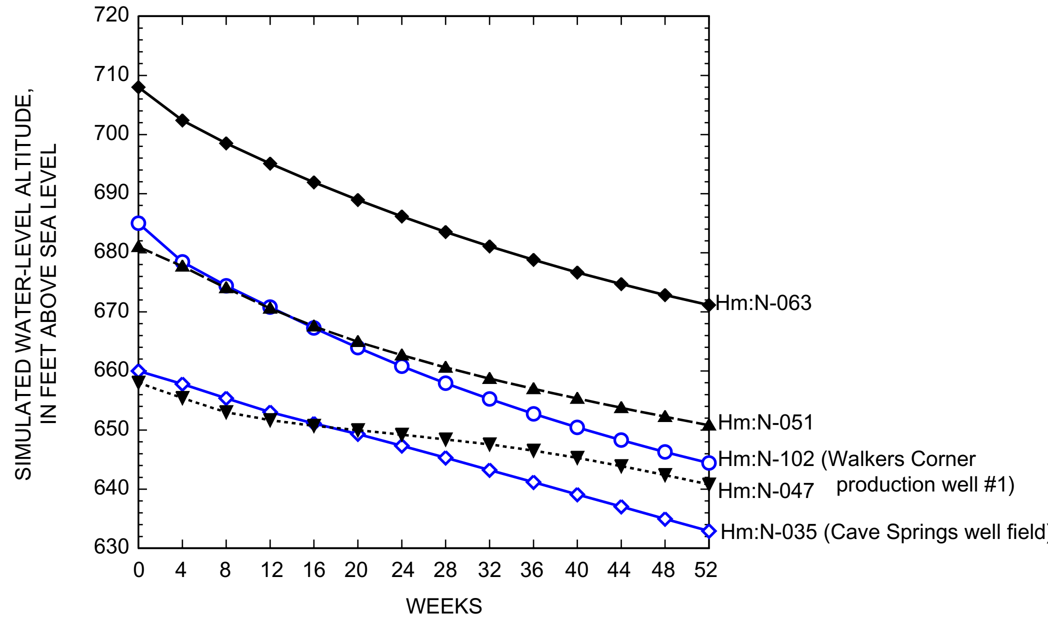


Figure 34. Simulated water-level recessions from a period with no recharge for selected wells.

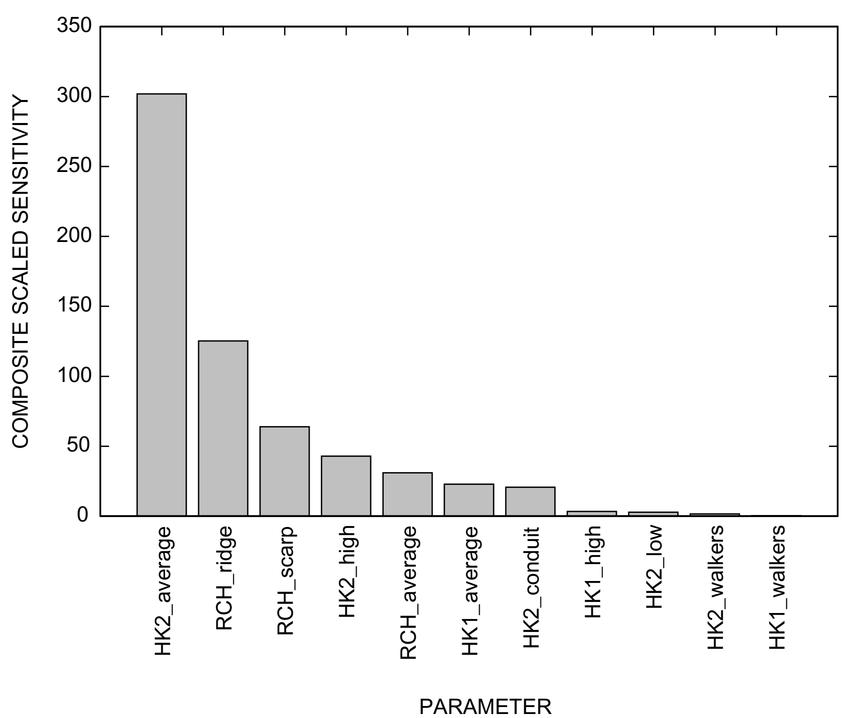


Figure 35. Composite scaled sensitivities for model perameters.

The ground-water model provides a reasonable match to observed water-levels for both pre- and post-pumping at Walkers Corner production well #1 (figs. 20 and 23). The observed water levels provide a fairly complete and accurate data set for the model. Simulated stream base flows are within expected ranges, but the data set to determine stream base flow is limited. Continuous streamflow information in the study area is sparse. Cave Springs has the most complete flow record in the study area with 5 years of continuous discharge data and accounts for 18 percent of the calibration model water budget. Ground-water discharge to Chickamauga Lake cannot be measured in the field, but this discharge accounts for 23 percent of the calibration model water budget. The larger uncertainty with measured fluxes (as opposed to measured water levels) makes defining the best model for the system difficult because the same water-level surface can be supported by different flows as long as the ratio of flows to hydraulic conductivity remains constant. Therefore, the model solution is not unique, which means that other combinations of model parameters can result in the same water-level distribution.

The model simulates the change in water levels from pumping at Walkers Corner production well #1 reasonably well (fig. 25). The predicted changes in water levels from additional pumping at Walkers Corner production well #2 assume that production well #2 behaves similarly to production well #1. Preliminary data suggest that Walkers Corner production well #2 has a greater specific capacity than production well #1. If this is true, then the model will overpredict the water-level declines from the additional pumping at production well #2.

This report presents potentiometric-surface data and water-budget data from a numerical flow model of the study area. The aquifer in the study area contains fractured bedrock and dissolution openings common in karst aquifers. For modeling purposes, the aquifer is treated as an equivalent porous media. Using this approach, potentiometric-surface data and water-budget data can be satisfactorily simulated at a regional scale. However, this report presents no model-simulated time-of-travel data because no information about the effective porosity of the aquifer was developed as part of this study.

SUMMARY

The ground-water resource in the Cave Springs area is used by the Hixson Utility District (HUD) as a water supply and is one of the more heavily stressed in the Valley and Ridge Physiographic Province. In 1999, ground-water withdrawals by the HUD averaged about 6.4 Mgal/d from two pumping centers. Historically, the HUD has withdrawn about 5.8 Mgal/d from wells at Cave Springs, one of the larger springs in Tennessee. In 1995 to meet increasing demand, an additional well field was developed at Walkers Corner, located about 3 miles northeast of Cave Springs. From 1995 through 2000, pumping from the first production well at Walkers Corner has averaged about 1.8 Mgal/d. A second production well at Walkers Corner has now increased the capacity of the well field by an additional 2 Mgal/d.

Ground water in the study area is present in both regolith and bedrock. A thick mantle of regolith, composed of insoluble chert and clay residuum formed from the weathering of carbonate bedrock, covers most of the study area. Regolith thickness varies from less than 1 to 298 feet and is thickest on Cave Springs Ridge. The thick clay-rich regolith acts as a leaky confining unit and provides a large ground-water storage reservoir for recharge to the underlying bedrock. In the valley of North Chickamauga Creek, the regolith also contains coarse-grained alluvium, consisting of gravel, cobbles, and boulders eroded from the sandstones of the Cumberland Plateau. The coarse-grained alluvium provides a highly permeable pathway for surface water in streams flowing off the plateau to recharge the underlying Newman Limestone.

Most of the bedrock in the study area has low primary porosity and permeability; however, fracturing and dissolution have produced substantial secondary porosity and permeability. Ground-water flow through the bedrock occurs as both diffuse and conduit flow. Most of the flow in the bedrock occurs in dissolutionally enlarged fractures, joints, and bedding planes. Secondary permeability is the most developed in the Newman Limestone.

Recharge to the ground-water system in the study area is from two distinct sources: direct infiltration of precipitation and losing streams. Estimates of recharge rates using hydrograph separation for two nearby basins range from 10.6 to 12.5 inches per year. Using a Thornwaite water-budget method, an average annual recharge rate of 15 inches per year was determined, with most of the recharge occurring during the winter and spring months. Recharge from losses of streamflow is most significant along parts of North Chickamauga Creek. Streamflow discharge measurements show flow losses of 24 and 11 ft^3/s from a reach of North Chickamauga Creek upstream of the mouth of Poe Branch. This losing reach of North Chickamauga Creek is an important source of concentrated recharge to the Cave Springs ground-water system. The losing reach most likely extends from the mouth of Poe Branch upstream to where North Chickamauga Creek first contacts the Newman Limestone.

Potentiometric-surface maps show that ground-water levels are highest along the ridge near the center of the study area and ground water flows radially outward towards Chickamauga Lake, Lick Branch, Poe Branch, and North Chickamauga Creek. The North Chickamauga Creek and Poe Branch valley is clearly evident in the potentiometric surfaces with low gradients along much of the axis of the valley. Potentiometric-surface maps constructed since 1995 show a depression at the Walkers Corner well field. Water-level declines from May 1993 to May 1999 are about 30 feet in Walkers Corner production well #1, 20 feet or less outside the immediate area of the well field, and more pronounced along strike.

A numerical ground-water-flow model of the aquifer system was constructed and calibrated using MODFLOW-2000. Results of the modeling effort confirm that losing streams along the base of the Cumberland Plateau escarpment at the western edge of the study area are an important source of recharge to the Cave Springs ground-water system, supplying about 50 percent of the recharge to the study area. The other source of recharge, direct infiltration of precipitation, accounts for the remaining recharge to the study area. The model water budget shows that in 1999, ground-water withdrawals of 9.9 ft^3/s (6.4 Mgal/d) equal about 11 percent of the total ground-water recharge with the remaining 89 percent of recharge discharging to North Chickamauga Creek and Cave Springs (58 percent, 50.4 ft^3/s), Chickamauga Lake (22 percent, 19.0 ft^3/s), Poe Branch (5 percent, 4.1 ft^3/s), and Lick Branch and Rogers Spring (4 percent, 3.4 ft^3/s). The model simulates the regional water-level surface and the current drawdown at the Walkers Corner well field reasonably well.

Ground-water withdrawals at Walkers Corner averaged about 2.8 ft^3/s (1.8 Mgal/d) in 2000. If additional pumping at Walkers Corner increases withdrawals by 3 ft^3/s (2 Mgal/d) for a total withdrawal at Walkers Corner of about 5.8 ft^3/s (3.8 Mgal/d), the model-simulated drawdown at Walkers Corner well field increases to about 60 feet. Preliminary field observations suggest Walkers Corner production well #2 may have a greater specific capacity than production well #1. If this is true, then production well #2 would produce less drawdown than the model currently estimates. The model water budget indicates that additional ground-water withdrawal at Walkers Corner from production well #2 would result in decreases in simulated ground-water discharge of 1.0 ft^3/s to Chickamauga Lake, 0.8 ft^3/s to North Chickamauga Creek, 0.5 ft^3/s to Lick Branch-Rogers Spring drainage, 0.5 ft^3/s to Poe Branch, and 0.2 ft^3/s to Cave Springs.

The effects of a drought were analyzed by using the model to simulate a 12-month period without recharge. Results show that water levels decline as the ground-water system drains. While a 12-month period with no recharge may not be realistic, the results from this simulation can be used to estimate the effects on water levels in the study area if no recharge occurs for several months, given observations of the current conditions at any point in time. Hydrographs of simulated water-level recessions in the study area show that water levels recede quickest in the center of the study area, farthest from the natural discharge areas. Additionally, water levels recede quicker at the pumping centers. This drought scenario simulation would overestimate the water-level decline at the Cave Springs well field because the model simulates an extreme case of no recharge from infiltrating precipitation or recharge from losing streams along the Cumberland Plateau escarpment. Recharge from these losing streams is an important source of recharge for Cave Springs, and this flux of water would continue for a period of time in the absence of precipitation as the aquifers on the plateau supply base flow to streams draining the plateau.

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