Cover illustration: See figure 22, page 39.

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

By Connor J. Haugh

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 02-4091

Prepared in cooperation with the
Hixson Utility District

Nashville, Tennessee
2002

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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

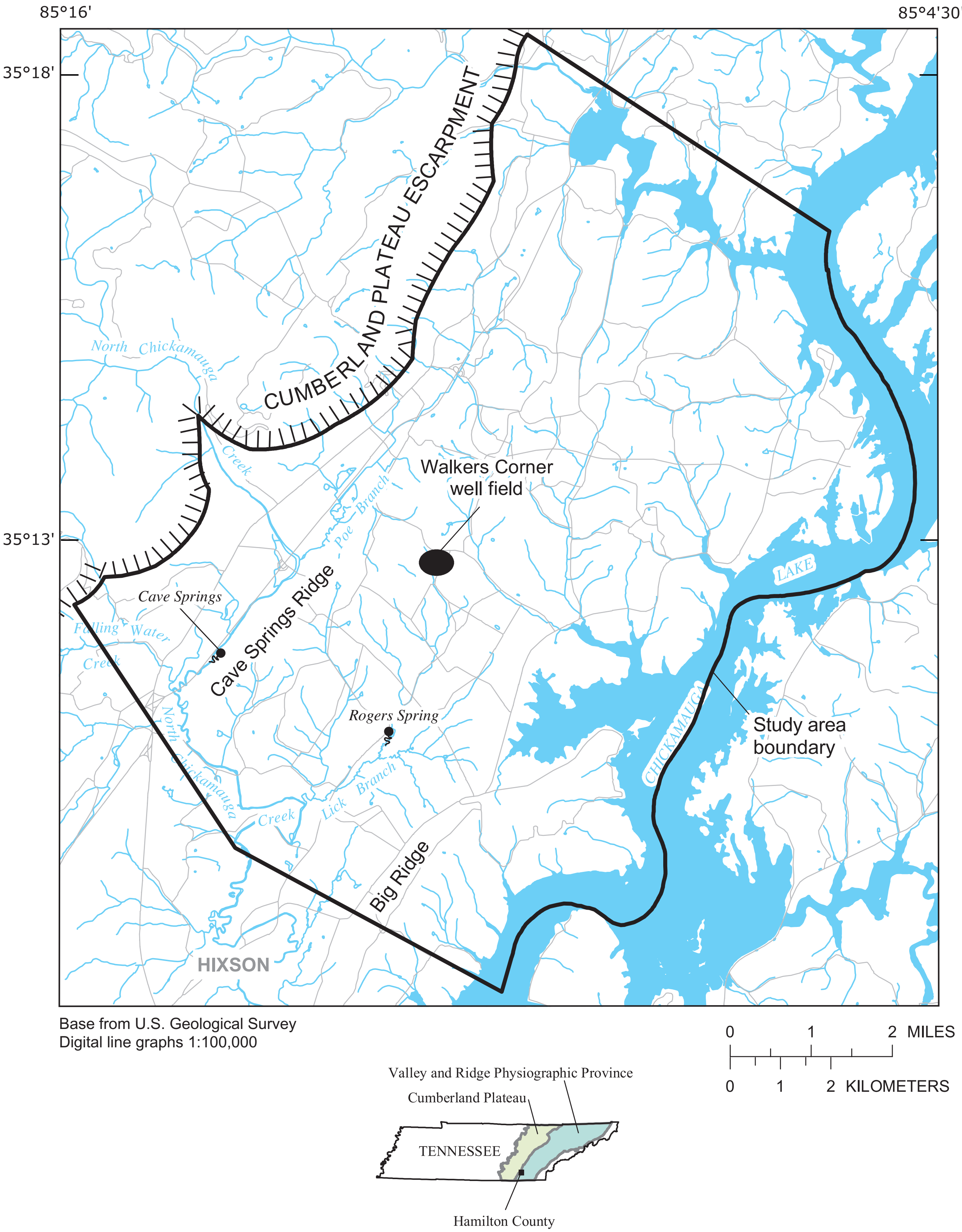

Figure 1. Physiographic and cultural features in the study area, Hixson, Tennessee.

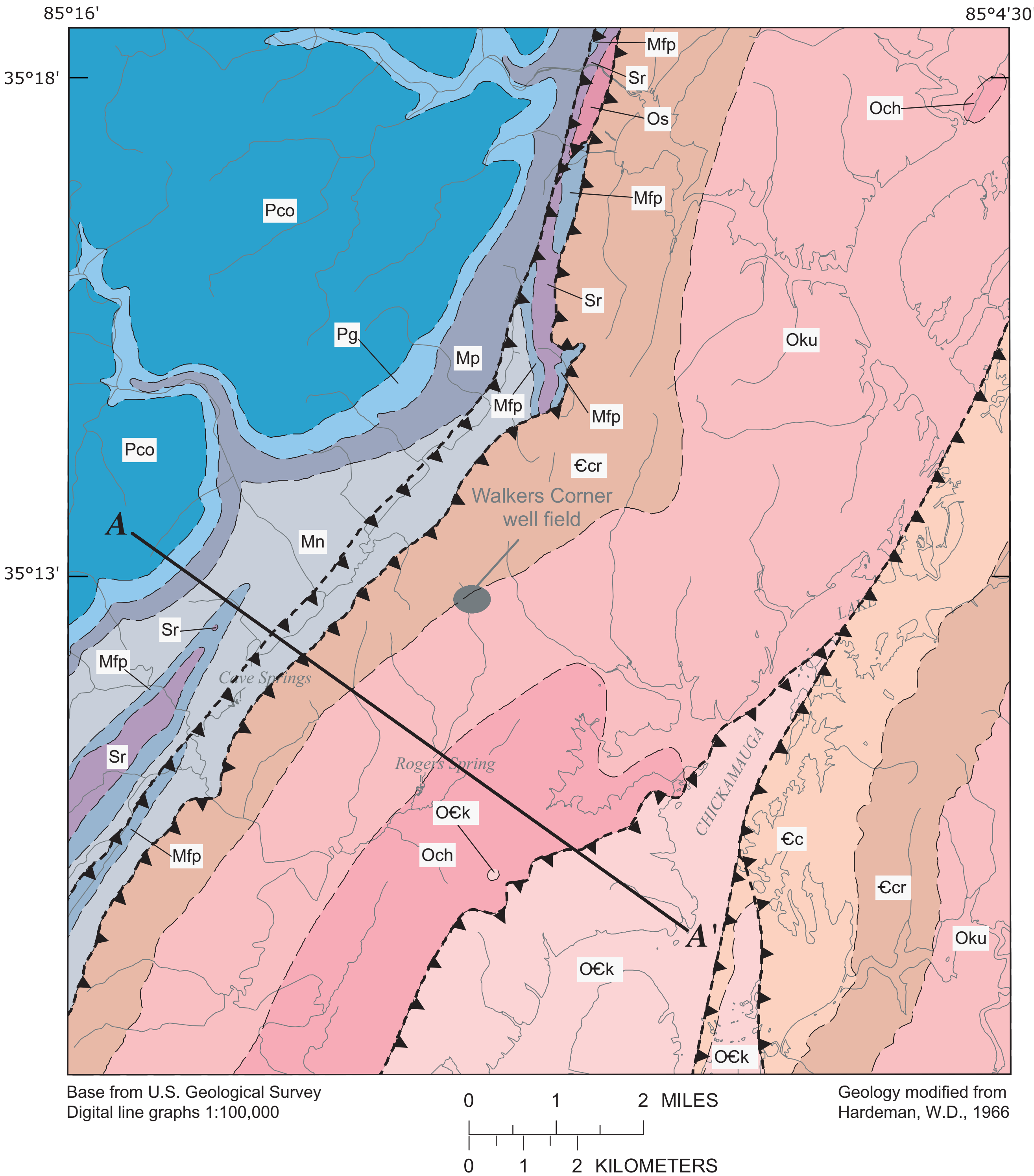

Figure 2. Geology of the Hixson, Tennessee area.

EXPLANATION

GEOLOGIC UNITS

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)	ORDOVICIAN
Єcr	Copper Ridge Dolomite	CAMBRIAN
Єc	Conasauga Group	CAMBRIAN

OЄk Knox Group (includes Oku and Єcr)

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

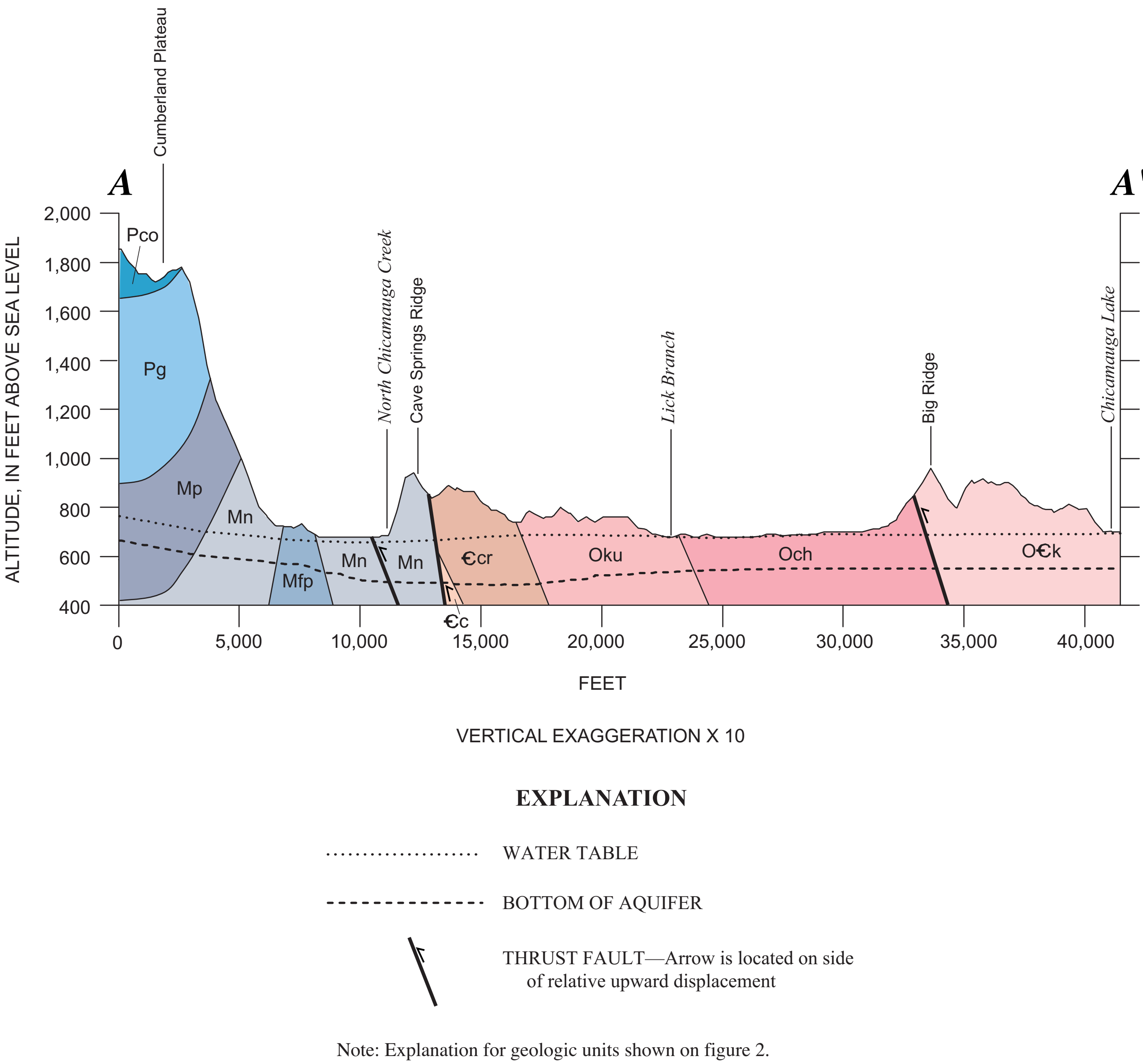

Figure 3. Hydrogeologic cross section through the Hixson, Tennessee area.

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:

$$PR = ET + SF \tag{1}$$

$$SF = DR + GWD \tag{2}$$

$$\text{assuming } GWD = GWR, \tag{3}$$

$$\text{then } PR = ET + DR + GWR, \tag{4}$$

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**

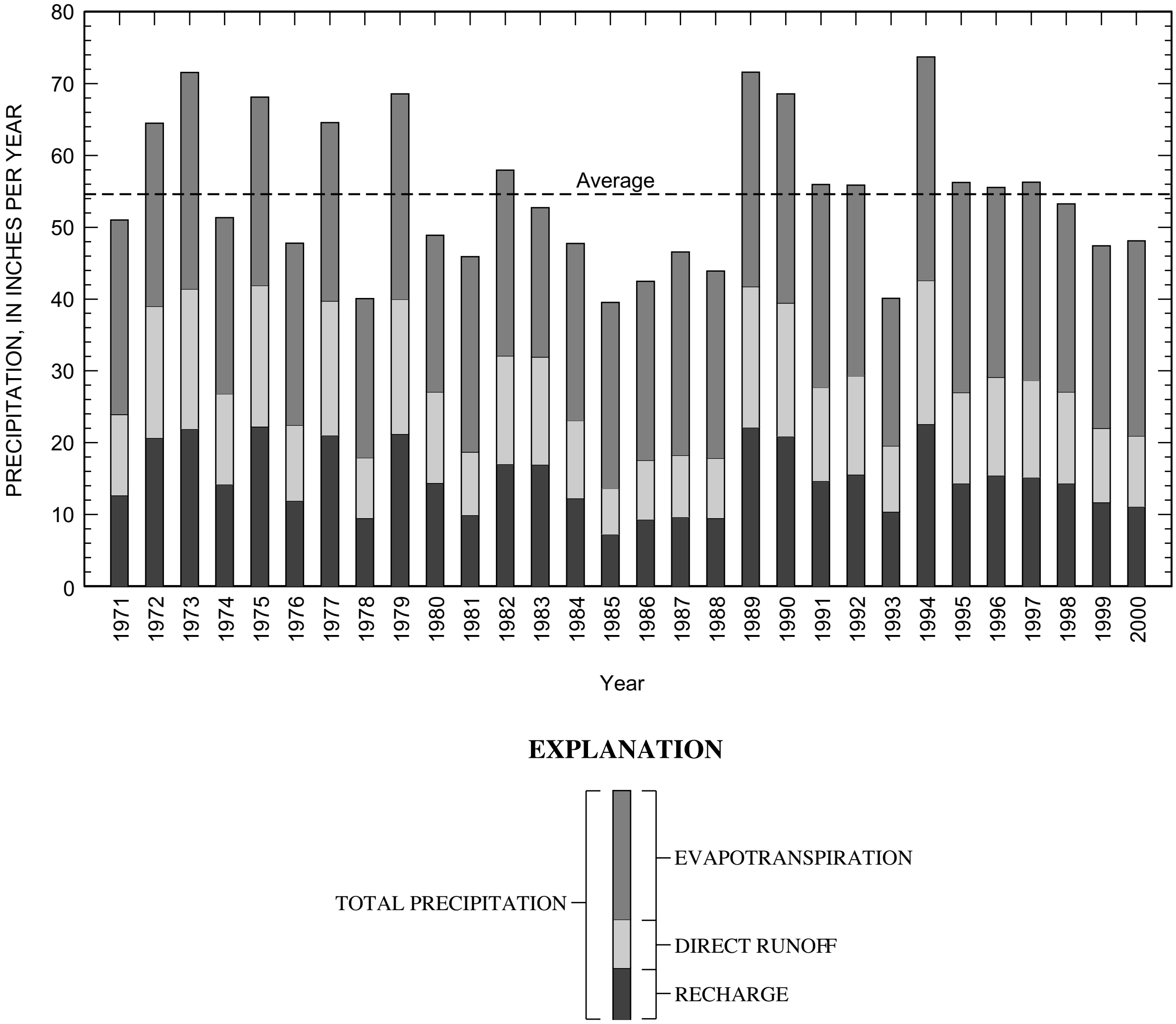

Figure 4. Estimated annual water budget for Hixson, Tennessee, from 1971 to 2000.

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,

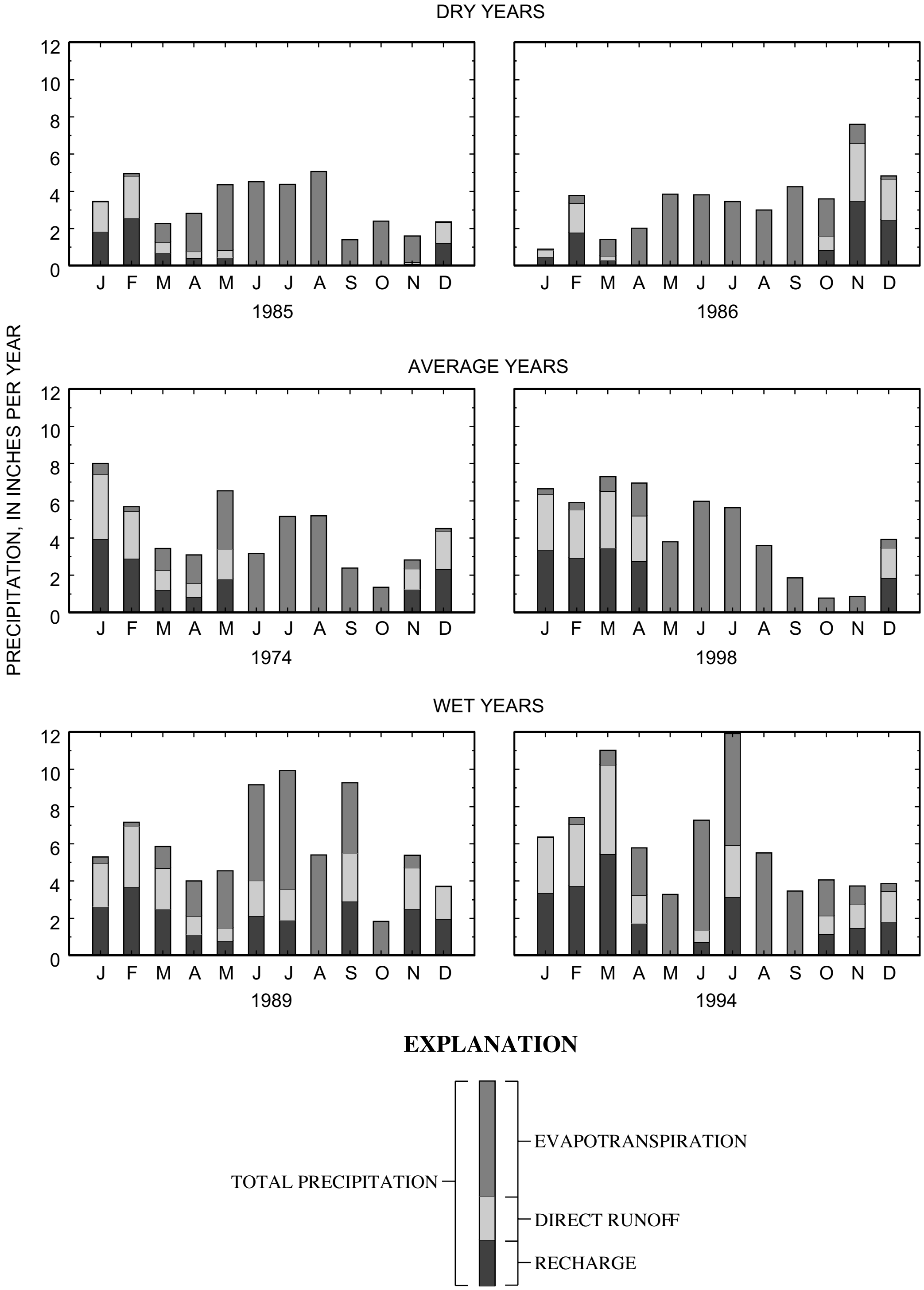

Figure 5. Estimated monthly water budget for Hixson, Tennessee, for selected dry, average, and wet years.

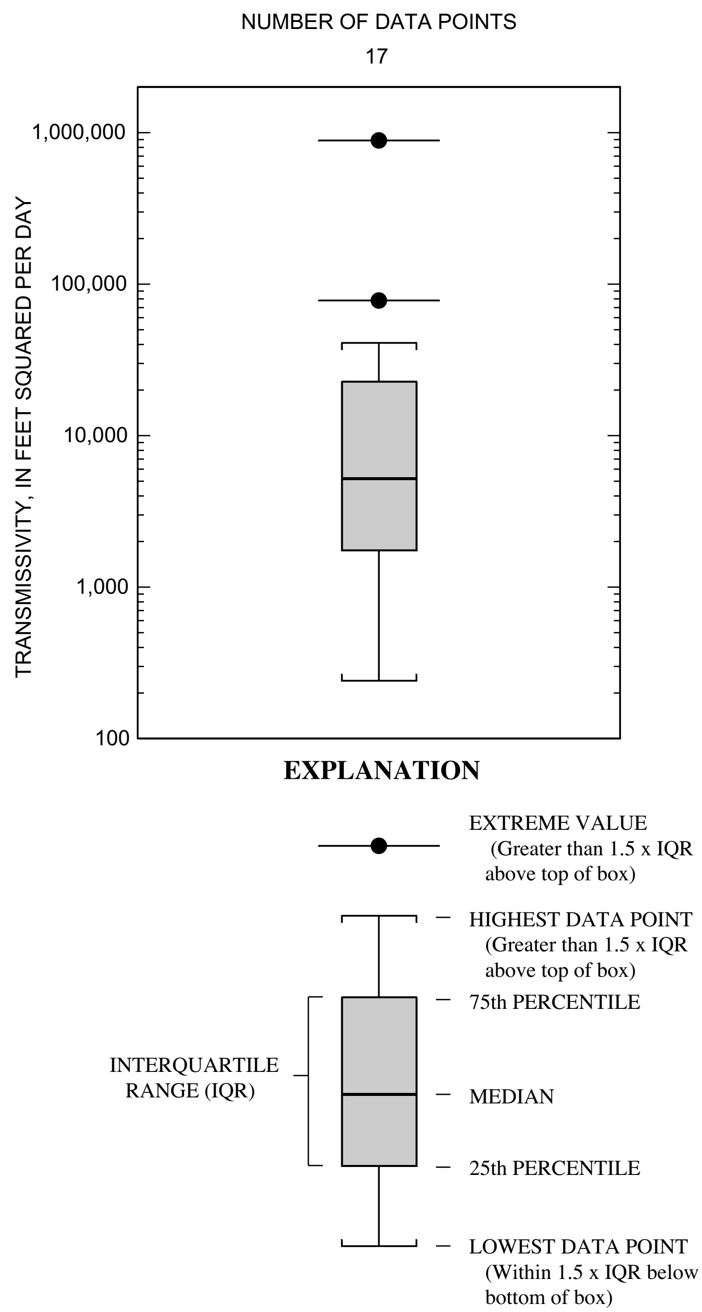

Figure 6. Range of transmissivity measured in the Cave Springs area near Hixson, Tennessee.

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

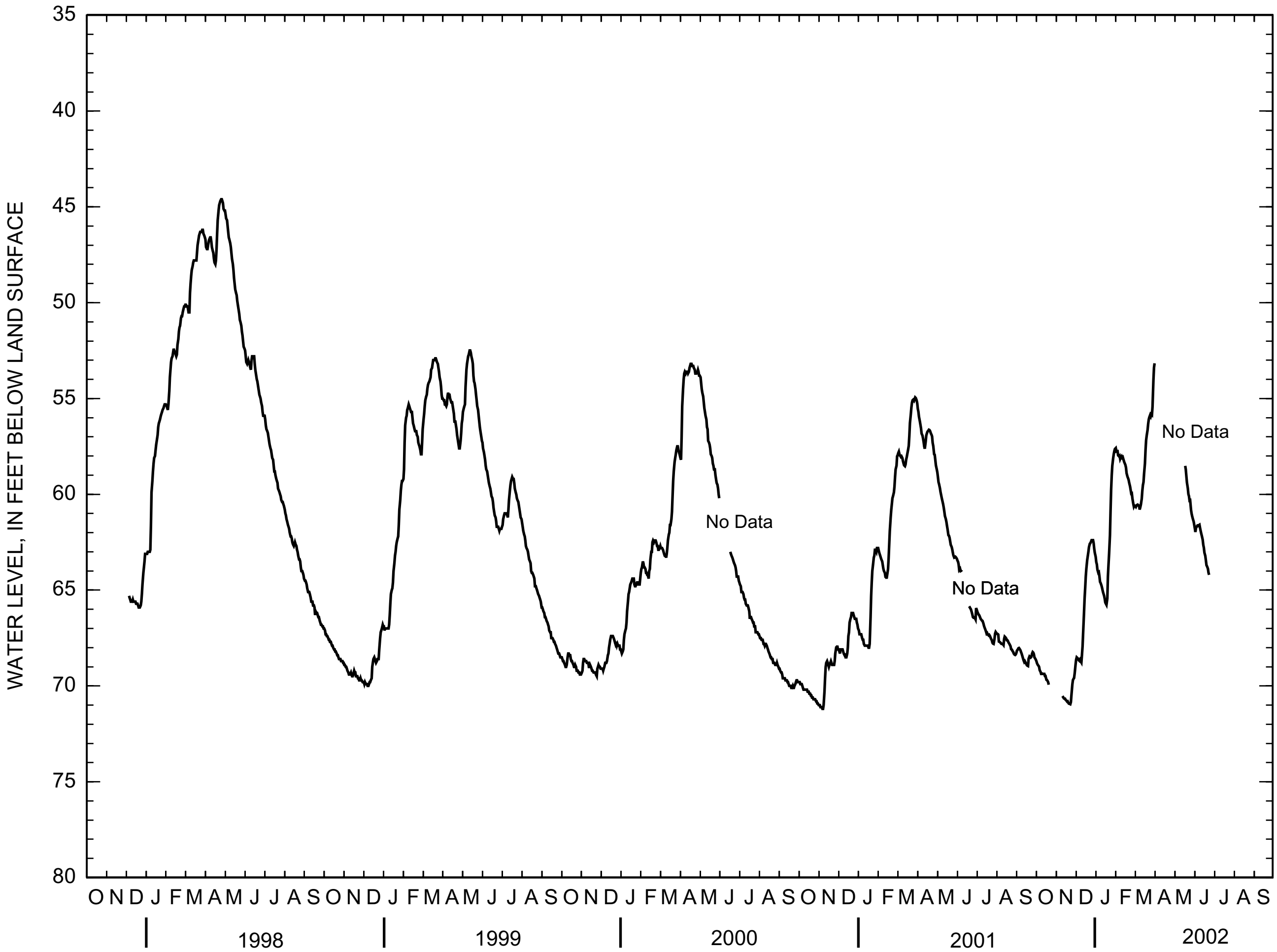

Figure 7. Daily water levels in well Hm:N-051.

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