Prepared in cooperation with the Tennessee Duck River Development Agency

Water Resources of the Duck River Watershed, Tennessee

Scientific Investigations Report 2007–5105

U.S. Department of the Interior
U.S. Geological Survey

Front cover photograph. Duck River above Hardison Mill at river mile 173.5, December 2004. (Photograph taken by Michael D. Woodside, U.S. Geological Survey.)

Back cover photographs. Left photograph: Berlin Spring; upper right photograph: River Rats Spring; lower right photograph: Venable Spring.

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By R.R. Knight and J.A. Kingsbury

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Conversion Factors and Datums

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
million gallons (Mgal)	3,785	cubic meter (m^3)
cubic foot (ft^3)	28.32	cubic decimeter (dm^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
	Flow rate	
foot per second (ft/s)	0.3048	meter per second (m/s)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per second per square mile [$(ft^3/s)/mi^2$]	0.01093	cubic meter per second per square kilometer [$(m^3/s)/km^2$]
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
gallon per minute (gal/min)	0.06309	liter per second (L/s)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F=(1.8\times°C)+32$$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C=(°F-32)/1.8$$

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29).

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

Altitude, as used in this report, refers to distance above the vertical datum.

Water Resources of the Duck River Watershed, Tennessee

By R.R. Knight and J.A. Kingsbury

Abstract

The U.S. Geological Survey began a study in 2003 in cooperation with the Tennessee Duck River Development Agency to assess the hydrology of the Duck River watershed from Normandy Dam downstream to Columbia, Tennessee. Ground-water-level data, spring-flow, bacteria samples, and streamflow were collected during this study to characterize the hydrology of the study area. The emphasis of this study was to characterize the temporal and spatial variability of the various components that make up streamflow in the Duck River in this study area.

Water-level data from wells in the study area indicate a good hydraulic connection between the aquifer and the river, with little long-term storage of water following recharge events. Variations in spring flow and ground-water temperature at springs indicate that a large component of water issuing from springs has a short residence time in the aquifer for most of the springs monitored in the study area. *Escherichia coli* densities in samples collected from springs are similar to concentrations in samples from tributaries and the Duck River.

Base-flow synoptic discharge measurements, flow-duration analysis of tributary streams, and streamflow accounting analysis indicate the portion of the watershed between Pottsville and Columbia yields more water than the portion between Shelbyville and Pottsville. Base-flow synoptic measurements show that Fountain Creek yields more water than other tributary basins in the study area, whereas base-flow synoptic measurements on the mainstem indicate that streamflow in the Duck River between Pottsville and Columbia could vary by 10 percent as the result of gaining and losing reaches. These results are applicable for average flow conditions that occurred during the study. Flow-duration analysis indicates that tributaries in this part of the watershed have a large component of ground-water contributing base flow. Streamflow accounting analysis for two periods of extended recession was used to determine the contributions of flow releases from Normandy Dam, tributaries, wastewater discharges, and ground-water discharge. The analysis indicated this same section of the mainstem of the Duck River between Pottsville and Columbia had as much as four times more ground-water discharge as sections upstream from Pottsville.

Introduction

The Duck River is home to one of the most diverse freshwater mussel and fish assemblages in the Nation (Ahlstedt and others, 2004) and is the principal source of drinking water for communities in the Duck River watershed. In order to ensure that flow and the quality of the water in the Duck River is adequate to meet the various needs, an understanding of the hydrology and how the contribution to flow from ground water, tributaries, and flow from Normandy Reservoir change throughout the year is important to resource managers in the basin. The U.S. Geological Survey (USGS) began an investigation of the water resources of the Duck River watershed between Normandy and Columbia in cooperation with the Tennessee Duck River Development Agency in 2003. The Tennessee Duck River Development Agency is charged with developing, protecting, and sustaining a clean and dependable water resource for the citizens of the Duck River region.

The Duck River watershed is a combination of rural landscapes, including pasture, woodlands, and row-crop agriculture, and urban landscapes with moderately sized cities, such as Shelbyville, Lewisburg, and Columbia. The rural landscapes, such as pasture and row-crop agriculture, are rapidly changing to rural and urban subdivisions as a result of growth of industry and the service sector that supplies industry. Conversion from a rural to a suburban watershed has potential water-resource consequences and emphasizes the importance of understanding the factors that may affect the quality and quantity of streamflow and the ecological resources in the Duck River watershed.

Purpose and Scope

The purpose of this report is to characterize the surface-water and ground-water hydrology of the Duck River watershed extending from the Duck River at Columbia, Tennessee, upstream to the headwaters of the watershed (fig. 1). The study area encompasses about 1,200 mi^2, including 208 mi^2 upstream from Normandy Dam. Data collection and the principal focus for this study is the area from the Duck River at Columbia upstream to Normandy Dam, though data for other sites in the Duck River watershed are included as well. The goals of this project were: (1) to characterize surface-water and ground-water hydrology of the study area; (2) to characterize how the hydrology varies seasonally and spatially; and (3) to identify areas where streamflow gains and losses are important to the hydrology of the study area. The analysis of surface- and ground-water data in this report includes surface-water and ground-water monitoring data collected by the USGS from 1932 to 2005.

Acknowledgments

This project would not have been possible without the support of many people. The authors thank Larry Murdock and Margarete Lane of the Tennessee Duck River Development Agency for their support and assistance during this project. Additionally, the authors thank Randal Braker of the Duck River Utility Commission for providing analysis of bacteria samples collected during the project. Finally, the authors thank the Tennessee Duck River Agency Board of Directors who provided the opportunity to conduct this study as well as constructive feedback and support throughout the investigation.

Study Area Description

The Duck River watershed study area lies predominantly within the Nashville Basin section of the Interior Low Plateaus Physiographic Province (Fenneman, 1938). The western part of the basin lies in the Highland Rim Physiographic Section. Locally, the Nashville Basin also is referred to as the Central Basin. The physiographic provinces in the study area correspond to the Inner Nashville Basin, Outer Nashville Basin, and Western Highland Rim Level IV Ecoregions (Griffith and others, 1997; fig. 1). Both the Inner and Outer Nashville Basins are characterized by rolling and hilly terrain, but local relief is greater and altitudes are higher in the Outer Nashville Basin than in the Inner Nashville Basin. Streams in these ecoregions have low gradients and commonly flow over fractured limestone bedrock. The Western Highland Rim Ecoregion is characterized by dissected hills and greater relief than either the Inner or Outer Nashville Basin Ecoregions. Streams in this area have higher gradients, with more sand and gravel in streams than in the Inner and Outer Nashville Basins (Griffith and others, 1997).

The Duck River has been impounded since the mid-1800s. Currently (2007), three low-head dams are located on the Duck River between Shelbyville and Columbia, and Normandy Dam is located between Manchester and Shelbyville. The low-head dams located at Shelbyville, Lillard's Mill at Milltown, and at Columbia, were constructed in the early 1900s and are currently used for water-supply purposes. The only free-flowing sections of the Duck River are above the Normandy Dam impoundment and below Columbia.

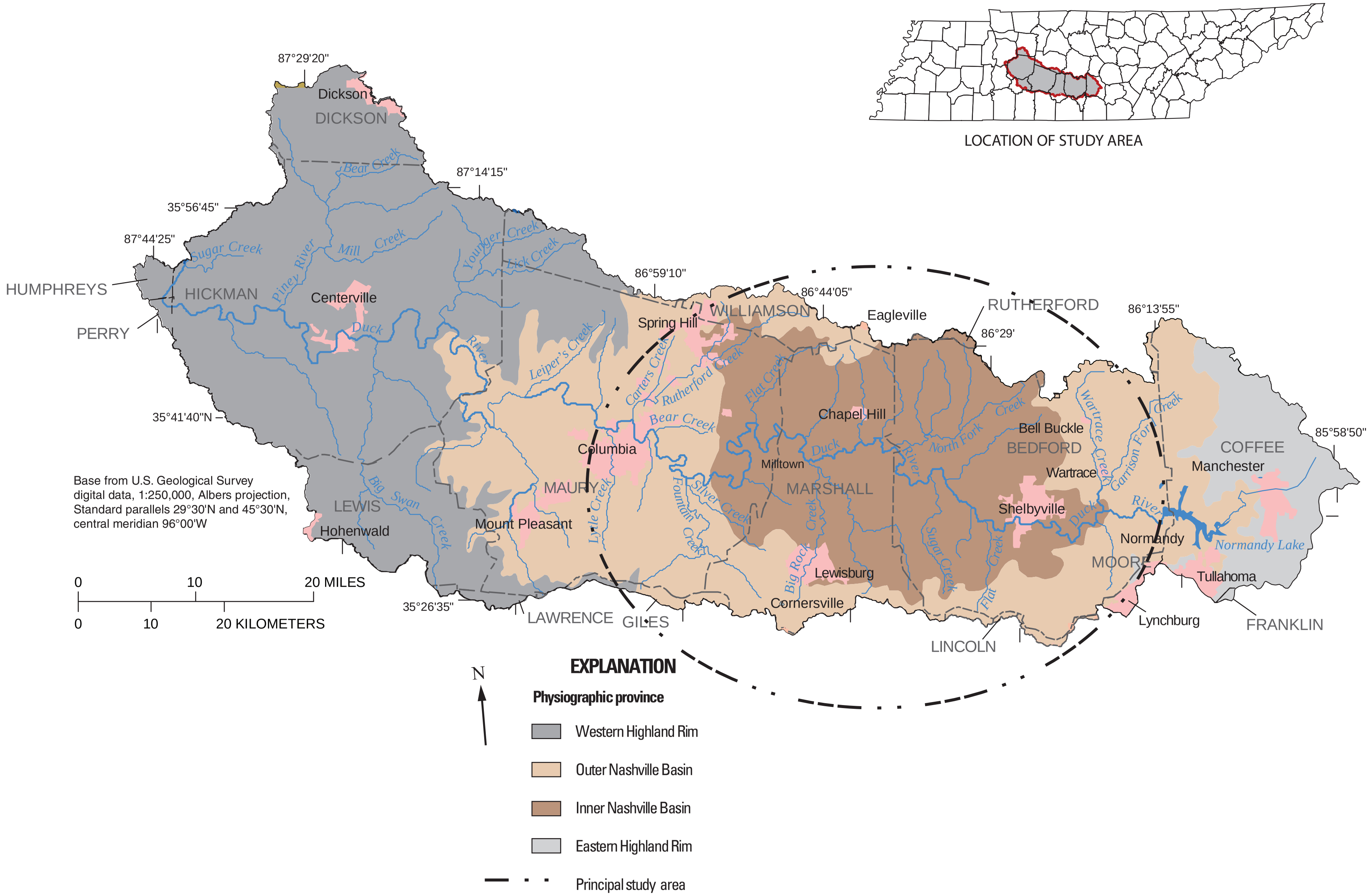
The climate for the Duck River watershed is temperate, warm, and humid. Precipitation patterns from late spring through early fall are typically associated with convective storms resulting from high humidity and high temperatures. These events can produce high intensity, short duration (less than 1 hour) rainfall events that produce large amounts of runoff and little recharge. Remnants from hurricanes (most often in the form of tropical depressions) in the Gulf of Mexico are not unusual in this area in late summer and early fall. Winter weather patterns follow the more predictable frontal-type systems that can produce large amounts of precipitation spread over 2 to 3 days. Recharge to the ground-water system generally occurs during the winter because precipitation during the winter is less intense, resulting in more recharge than runoff. Because precipitation during the winter is not as intense as a convective storm, more of the water recharges the ground-water system.

Average annual precipitation for Middle Tennessee is 55.34 in., with the wettest month being March, with 5.86 in., and the driest months being August and October with 3.43 and 3.47 in., respectively (U.S. Department of Commerce, 2005a). Within the Duck River watershed, annual average precipitation varies from 54.55 in. at the Centerville Water Plant to 60.04 in. at Tullahoma (table 1; U.S. Department of Commerce, 2005b), which is almost a 10-percent variation across the watershed.

Table 1. Annual average precipitation and temperature for National Oceanic and Atmospheric Administration stations within the Duck River watershed.

[From U.S. Department of Commerce, 2005b]

Station name	Annual average precipitation (inches)	Annual average temperature (degrees Fahrenheit)
Centerville Water Plant	54.55	58.7
Columbia	56.13	57.0
Dickson	55.44	57.6
Lewisburg Experiment Station	56.15	56.9
Linden	57.19	58.2
Mount Pleasant	58.05	58.7
Neapolis Experiment Station	57.03	58.5
Shelbyville Water Plant	57.16	58.6
Tullahoma	60.04	57.8



Base from U.S. Geological Survey digital data, 1:250,000, Albers projection, Standard parallels 29°30'N and 45°30'N, central meridian 96°00'W

Figure 1. Location and Level IV Ecoregions of the Duck River watershed, Tennessee (modified from Griffith and others, 1997).

Annual average temperature for southern Middle Tennessee for 1971–2000 was 57.8 °F. Typically the coldest and warmest months are January and July respectively (U.S. Department of Commerce, 2005c). Average annual temperatures at National Oceanic and Atmospheric Administration stations within the Duck River watershed varied from 58.7 °F at Centerville and Mount Pleasant to 56.9 °F at Lewisburg (table 1; U.S. Department of Commerce, 2005b).

Hydrogeology

Ordovician and Mississippian carbonate rocks underlie most of the study area (fig. 2). Formations of Ordovician age include, in descending order, undifferentiated Ordovician units, the Bigby-Cannon, Carters, Lebanon, and Ridley Limestones (fig. 2). These units are present at the surface in both the Inner and Outer Nashville Basin ecoregions, whereas carbonate rocks of Mississippian age overlie the Chattanooga Shale and Ordovician carbonates in the Eastern and Western Highland Rim ecoregions (figs. 1 and 2). Compositional differences between the Ordovician and Mississippian carbonate units affect the terrain and hydrology in the study area. The Ordovician carbonates are predominantly limestone with some thin shaly beds, phosphate-rich zones, and bentonite layers. They are generally flat-lying to gently dipping, but joints, which are parallel fractures oriented perpendicular to the bedding planes, are common throughout the Nashville Basin. Much of the Ordovician limestone is relatively pure calcite with a small amount of insoluble material, such that during the weathering process, little residual material remains. As a result, soils overlying bedrock in the Inner Nashville Basin are relatively thin, typically 20 ft thick or less, and bedrock outcrops are common. Soils are derived from the phosphatic, sandy, and clay-rich limestones and from shaly layers that are present in the limestone. Soils in the Outer Nashville Basin are derived from limestone that is richer in phosphate than those of the Inner Nashville Basin (Tennessee Valley Authority, 1965). The formations of Mississippian age contain a larger amount of insoluble material, predominantly chert and clay. These formations form thick soils, and bedrock is overlain by soil and regolith, which is the residual chert and clay derived from the in situ weathering of the bedrock. The formations of Mississippian age also are flat-lying to gently dipping and are underlain by the Chattanooga Shale, which separates them from the formations of Ordovician age.

Shallow ground water in the study area flows through the karst aquifers that are contained in the Mississippian and Ordovician formations. The aquifers are referred to as the Mississippian and Ordovician carbonate aquifers. The principal aquifer in the study area is the Ordovician carbonate aquifer because the Mississippian carbonate aquifer is limited to higher altitudes at the headwaters of many tributaries in the Eastern and Western Highland Rim Ecoregions. Ground water flows in solution openings in bedrock that form as a result of physical and chemical weathering. Rainfall is mildly acidic, and the acidity of rainfall increases as it infiltrates and moves through the soil zone and interacts with carbon dioxide in the soil. As this acidic water moves through the subsurface, dissolution of carbonate bedrock occurs predominantly along bedding planes and vertical joints resulting in the development of karst features, such as sinkholes, caves, disappearing streams, and springs. Ground water primarily flows in solution openings that have formed along bedding planes and joints. The number and size of solution openings decrease with depth, and the zone of active ground-water flow generally is less than 300 ft below land surface (Brahana and Bradley, 1986). Ground-water-flow paths are typically short, and much of the water moves rapidly

The overlying thin soils and the well-developed conduit system in the Ordovician carbonate aquifer result in an aquifer with relatively little storage of ground water.

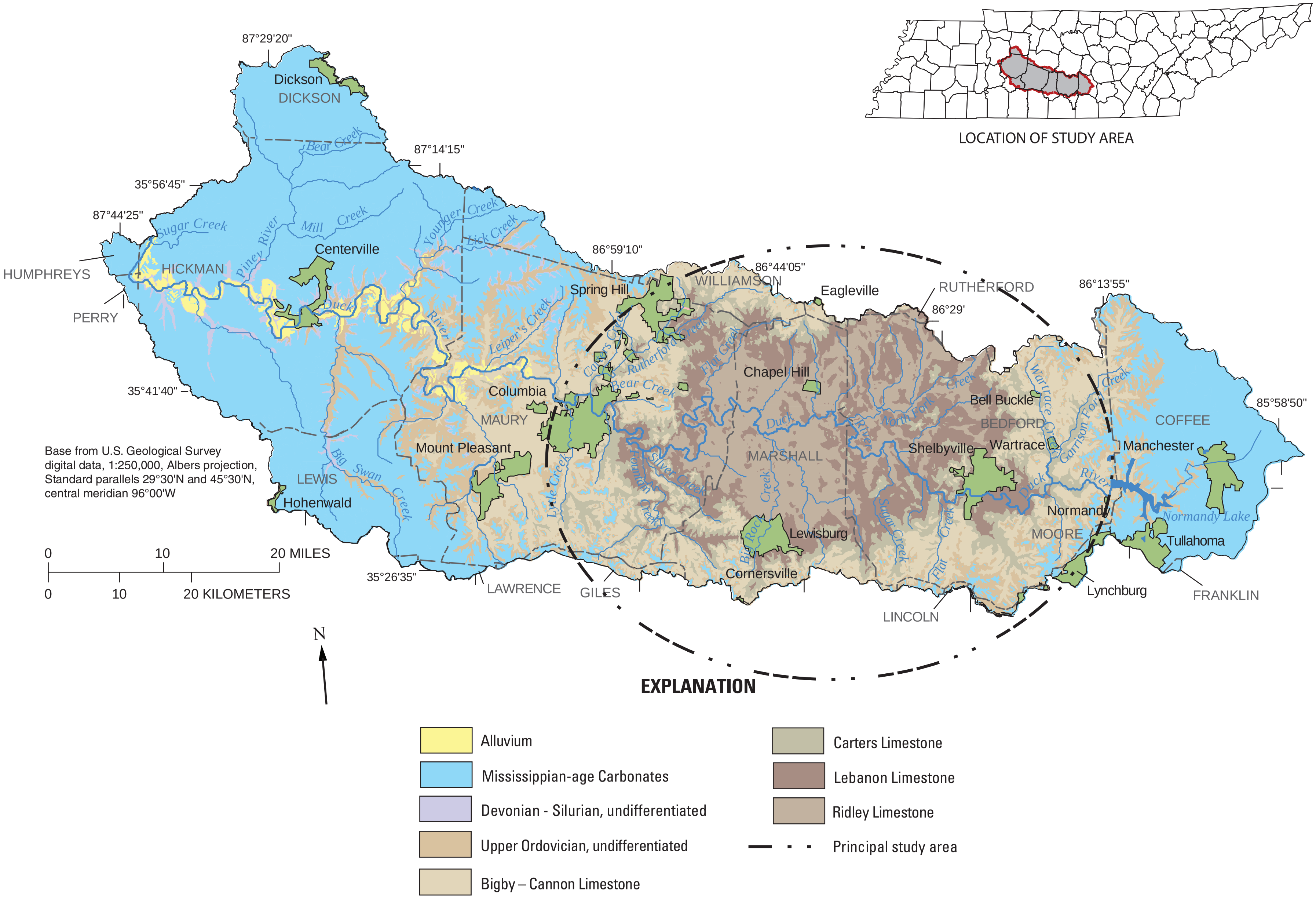


Figure 2. Geology of the Duck River watershed (modified from Hardeman and others, 1966).

through the aquifer and discharges to streams and springs. Recharge to the aquifer occurs from the infiltration of rainfall through the soil as well as focused recharge from runoff entering sinkholes and joints in bedrock. Locally, recharge may occur from streamflow loss where openings in bedrock in the stream channels are connected to the aquifer.

The Ordovician carbonate aquifer is a source of water for domestic wells and one public water supply in the study area. Most wells produce between 5 and 20 gal/min, but yields of more than 50 gal/min can occur in some areas (Brahana and Bradley, 1986). Solution openings sufficient to deliver water volumes sufficient for public supply exist as far as 275 ft below land surface. Most ground water obtained from wells deeper than 275 ft below land surface contains elevated concentrations of dissolved constituents and often has a sulfur odor (Alexander and others, 1984). Wells that produce more than 50 gal/min are rare; wells exceeding this pump rate likely are within the flood plain of a nearby stream or the Duck River and could be under the influence of surface water, and can also occur when a well intercepts numerous or large solution openings (Alexander and others, 1984).

The Knox aquifer, located below the Ordovician carbonate aquifer, provides a relatively deep and reliable source of ground water and is used for domestic water supply in areas where shallow water is not available. This formation is composed of dolomite, dolomitic limestone, and limestone and is present at depths of about 650 to 1,100 ft below land surface in the study area. Water pumped from this formation often has high mineral content. Yields from the Knox aquifer are generally less than 15 gal/min, but more than 85 percent of the wells that are completed into the aquifer yield water (Brahana and Bradley, 1985).

Water Use

The mainstem of the Duck River is the principal source of water supply in the Duck River watershed. Total water withdrawal estimates for public supply, self-supplied industry (including processing industrial inorganic chemicals), and irrigation for 2003 within the primary study area were 26.2 Mgal/d (table 2) with 92 percent of that total being withdrawn from the mainstem of the Duck River. Approximately 2 Mgal/d are withdrawn from ground-water wells in the Ordovician and Mississippian carbonate aquifers for use as public supply (table 2). Irrigation (primarily for golf courses) and industrial withdrawals from surface water and ground water were less than 1 Mgal/d combined for 2003. Estimated withdrawals from private wells or springs for residential use or from farm ponds, other surface-water sources, wells, or springs for livestock watering are not included in the total withdrawal estimates.

Total water use for public supply in the study area increased 49 percent or 8.6 Mgal/d from 1982 to 2003. Surface-water withdrawals accounted for 91 percent of this increase in water use. In 2003, Maury and southern Williamson Counties accounted for 44 percent (11.54 Mgal/d) of the total water withdrawn for public use in the study area. Of this, 10.53 Mgal/d were withdrawn from surface water and 1.01 Mgal/d from ground water. The remaining withdrawals occurred in Bedford (26 percent, or 6.68 Mgal/d), Coffee (19 percent, or 5.06 Mgal/d), and Marshall (11 percent, or 2.95 Mgal/d) Counties (table 2). Detailed information about water use and water supply in the Duck River watershed can be found in Hutson (1996 and 2003) and Hydrologics (2002).

Seven cities discharge wastewater in the study area: Wartrace, Bell Buckle, Chapel Hill, Shelbyville, Lewisburg, Columbia, and Spring Hill (fig. 3). Wastewater treatment plants in Shelbyville, Lewisburg, Columbia, and Spring Hill have a median annual discharge of greater than 1 Mgal/d (table 3). A comparison of the median annual water intake for public consumption to the median annual wastewater treatment discharge results in a net loss of water. These net losses vary from 0.42 to almost 5 Mgal/d (table 3). The loss between the amount of water withdrawn for public consumption and the amount released as treated effluent can be accounted for by several potential sinks. The highest percentage of water loss most likely can be attributed to water returned to the environment via septic tanks as opposed to municipal sewer systems. The amount of publicly-supplied water consumed by households that return the water to the environment via septic systems could be significant though data are not available to verify this possibility. Additional avenues of water loss could be nursery operations (irrigation) and any industrial operations that are permitted to release processed water directly to the river.

Table 2. Total surface- and ground-water withdrawals for public supply by water-service area.

[Figures may not sum to totals because of independent rounding; N/A, not available; e, estimated based on available data; all data from Susan Hutson, U.S. Geological Survey, written commun., 2005]

Water-service area	Withdrawals, in million gallons per day		Change from 1982 to 2003, in percent
	1982	2003	
Bedford County			
Total	3.81	6.68	75
Surface water	3.50	5.86	67
Ground water	.31	.82	165
Coffee County			
Total	2.97	5.06	70
Surface water	2.97	5.04	70
Ground water	N/A	.02	N/A
Marshall County			
Total	2.32	2.95	27
Surface water	2.32	2.80	21
Ground water	.11e	.15	36
Maury/southern Williamson Counties			
Total	8.48	11.54	36
Surface water	7.63	10.53	35
Ground water	.85	1.01	19
Study area			
Totals	17.6	26.2	49
Surface water	16.4	24.2	45
Ground water	1.16	2.00	72

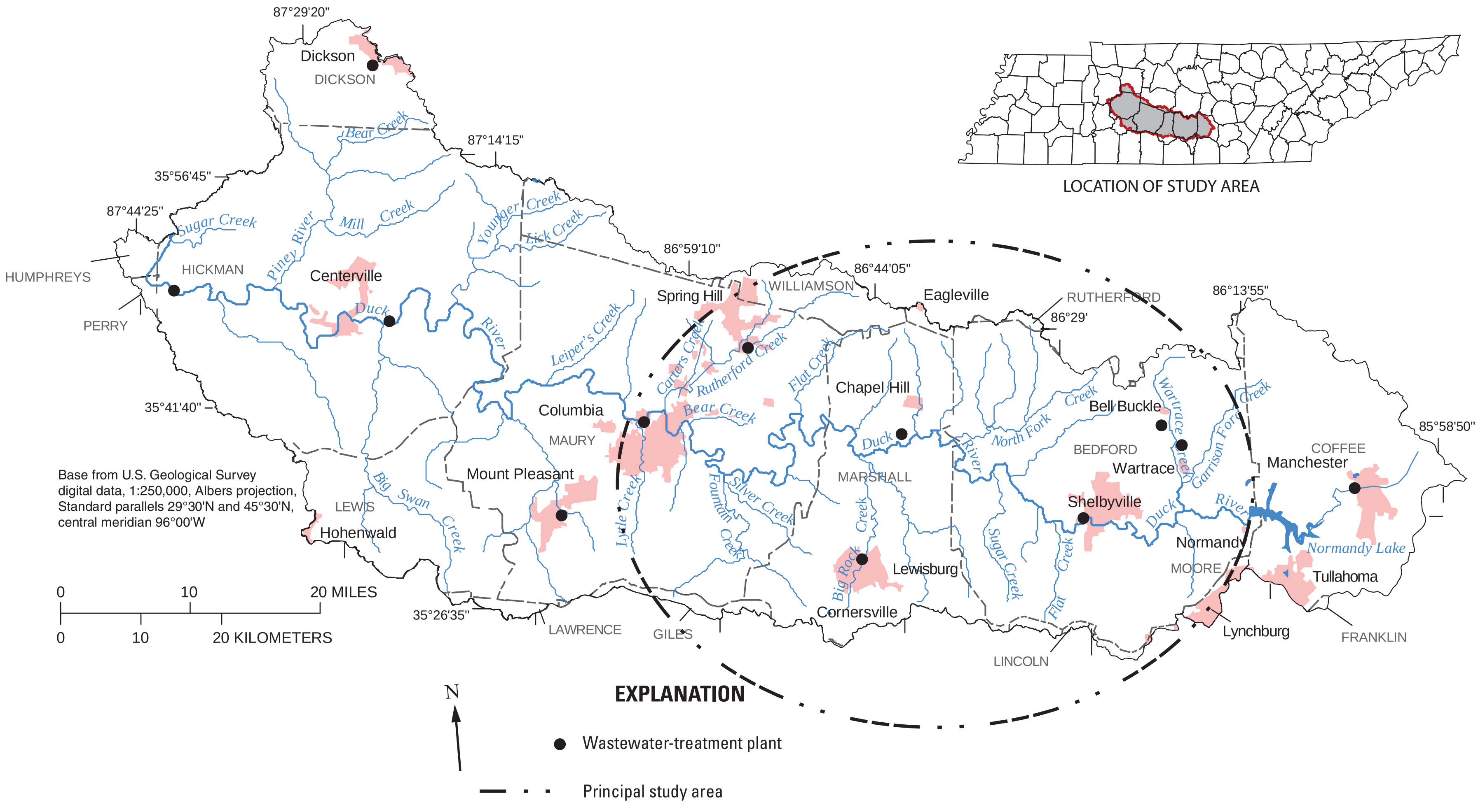


Figure 3. Wastewater treatment plants discharging to the Duck River watershed, Tennessee.

Table 3. Median annual wastewater treatment effluent and water intake values and maximum daily average wastewater treatment effluent values for Shelbyville, Lewisburg, Columbia, and Spring Hill, Tennessee, for the 2004 water year.

[Mgal/d, million gallons per day; negative value indicates a net loss of water between the intake value and the wastewater effluent discharge value]

City	Median annual wastewater discharge (Mgal/d)[a]	Median annual water treatment intake (Mgal/d)[b]	Net Loss (Mgal/d)	Maximum daily average discharge (Mgal/d)
Shelbyville	2.58	4.34	–1.76	4.94
Lewisburg	1.76	2.77	–1.01	3.04
Columbia	4.84	9.81	–4.97	10.6
Spring Hill	1.06	1.48	–0.42	2.29

[a] From written and oral communications from local wastewater treatment plant operators and Tim Wilder, Tennessee Department of Environment and Conservation (Columbia), 2005.

[b] From Susan Hutson, U.S. Geological Survey, written commun., 2005.

Daily treated wastewater discharge can vary considerably when compared to the median daily treated wastewater discharge as a result of infiltration and inflow (often referred to as “I and I”). The degree to which infiltration and inflow affect the quantity of treated wastewater discharge amounts solely depends on the condition of the sewer system network. Cracked and leaky pipes, joints, and manholes can allow for considerable amounts of storm runoff and ground water to enter the system. The daily discharge from wastewater plants can change significantly throughout the year as the water table rises and falls or as the amount of runoff increases from storms (Qasim, 1994). Maximum daily average discharges from Shelbyville, Lewisburg, Columbia, and Spring Hill range from 2.29 to 10.6 Mgal/d, which is up to 216 percent greater than the median daily discharge to the receiving water body (table 3).

Approach

Although the number of sites at which data have been collected in the Duck River watershed is relatively large, most of these sites were associated with studies conducted during a relatively short timeframe or at the tributary-watershed scale, such as base-flow synoptic discharge measurements in a tributary watershed. The intent of this study was to collect water-level, spring discharge, and streamflow data across much of the study area during an 18-month period to characterize the hydrology and characterize how these components that contribute to streamflow in the Duck River vary throughout the year. In addition to data collected for this study, existing data from historical or active streamgages in the study area were used for flow-duration analysis and to calculate low-flow statistics. Results from techniques used in this report are based on continuously recorded or discrete water-resources observations collected at sites throughout the study area; 19 continuous streamflow sites, 24 miscellaneous measurement sites, 17 wells, and 13 springs were used in the analysis for this report (figs. 4 and 5; tables 4 and 5).

Surface-Water Network

Six continuous streamgages were installed as a part of this study to provide streamflow data in portions of the study unit where continuous streamflow data were sparse. These gages included two mainstem sites (above Milltown and at River Mile 166.1 near Pottsville) and four tributary sites (North Fork Creek near Poplins Crossroads, Flat Creek at Highway 231 near Shelbyville, Big Rock Creek at Double Bridges Road near Verona, and Fountain Creek near Fountain Heights) (table 4). In addition to these six gages, nine streamgages were in place prior to this study: Garrison Fork above L&N Railroad at Wartrace, Wartrace Creek below County Road near Wartrace, Duck River at Shelbyville, Duck River near Shelbyville, Duck River at Columbia, Carters Creek at Butler Road at Carters Creek, Duck River at Highway 100 near Centerville, Piney River at Cedar Hill, and Piney River at Vernon. Continuous streamflow data from these sites were used to compute low-flow statistics and flow-duration values, and to make comparisons in flow accounting analysis.

In addition to using continuous streamflow information, miscellaneous streamflow measurements were made for two base-flow synoptic investigations to characterize the temporal and spatial variability of water resources in the study area. Base-flow synoptic investigations also aid in understanding the interaction between surface- and ground-water resources. Base-flow synoptic measurements were made at sites on tributaries and along the mainstem of the Duck River in November 2003 and again at tributary sites in May 2004. Twenty-eight tributary sites, including 5 springs and 14 mainstem sites were included in the base-flow synoptic investigations. Almost all tributary streams to the Duck River from Normandy Dam to Columbia were included in this investigation to provide a broad perspective of which watersheds may be contributing more water to the Duck River. Base-flow synoptic investigations used in this study were completed when hydrologic conditions were consistent across the study area, ideally after a minimum of 3 days without precipitation or runoff.

Table 4. Site information for selected monitoring locations in the Duck River watershed.

[Site names with numbers in parentheses indicate site numbers on figure 4; °, degrees; ', minutes; ", seconds; Latitude and longitude are referenced to the North American Datum of 1927; Gage datum is referenced to the National Geodetic Vertical Datum of 1929; —, not determined]

Site name	Station number	Latitude	Longitude	Drainage area (square miles)	Gage datum (feet)	Period of record (water years)
Continuous streamflow data sites (site number on figure 4*A*)						
Duck River below Manchester	03596000	35° 28' 15"	86° 07' 18"	107	878.23	1934–88, 1993–98
Duck River at Normandy	03596500	35° 27' 26"	86° 15' 25"	208	782.65	1921–32, 1973–75
Garrison Fork above L&N Railroad at Wartrace (1)	03597210	35° 30' 42"	86° 19' 26"	85.5	769.30	1990–2004
Wartrace Creek at Bell Buckle	03597500	35° 31' 38"	86° 20' 25"	16.3	822.44	1954–75
Wartrace Creek below County Road near Wartrace (2)	03597590	35° 35' 16"	86° 20' 22"	35.7	781.66	1990–present
Duck River at Shelbyville (3)	03597860	35° 28' 58"	84° 27' 45"	425	680.00	1992–present
Flat Creek at Highway 231 near Shelbyville (4)	03597898	35° 27' 35"	86° 28' 10"	49	712.54	2003–2005
Duck River near Shelbyville (5)	03598000	35° 28' 49"	86° 29' 57"	481	683.51	1934–present
North Fork Creek near Poplins Crossroads (6)	03598250	35° 35' 04"	86° 35' 46"	71.9	670.00	1994–present
Big Rock Creek at Lewisburg	03599000	35° 26' 56"	86° 47' 09"	24.90	705.01	1955–60, 1966–69, 1996–99
Big Rock Creek at Double Bridges Road near Verona (7)	03599100	35° 31' 49"	86° 46' 07"	48.7	—	2003–present
Duck River above Milltown (8)	03599240	35° 34' 34"	86° 46' 42"	916	609.24	2003–present
Duck River at River Mile 166.1 near Pottsville (9)	03599407	35° 37' 51"	86° 51' 43"	1,060	582.88	2003–present
Fountain Creek near Fountain Heights (10)	03599450	35° 31' 05"	86° 56' 31"	77	600.00	1966–68, 2003–present
Duck River at Columbia (11)	03599500	35° 37' 04"	87° 01' 56"	1,208	535.33	1921–present
Carters Creek at Butler Road at Carters Creek (12)	03600088	35° 43' 02"	86° 59' 44"	20.1	605.94	1986–present
Duck River at Highway 100 near Centerville (13)[a]	03601990	35° 47' 03"	87° 27' 36"	2,048	447.76	1920–55, 2001–present
Piney River at Cedar Hill (14)	03602219	35° 59' 43"	87° 26' 22"	46.6	552.20	1988–present
Piney River at Vernon (15)	03602500	35° 52' 16"	87° 29' 59"	193	461.72	1926–93, 2000–present
Base-flow synoptic measurement sites (site number on figure 4*B*)						
Fall Creek near Elbethel (16)	03598180	35° 33' 03"	86° 32' 33"	40	—	—
Sinking Creek near Halls Mill (17)	03598190	35° 32' 08"	86° 35' 24"	31.5	—	—
Wilson Creek near Chapel Hill (18)	03598260	35° 36' 01"	86° 39' 35"	15.5	—	—

Table 4. Site information for selected monitoring locations in the Duck River watershed.—Continued

[Site names with numbers in parentheses indicate site numbers on figure 4; °, degrees; ', minutes; ", seconds; Latitude and longitude are referenced to the North American Datum of 1927; Gage datum is referenced to the National Geodetic Vertical Datum of 1929; —, not determined]

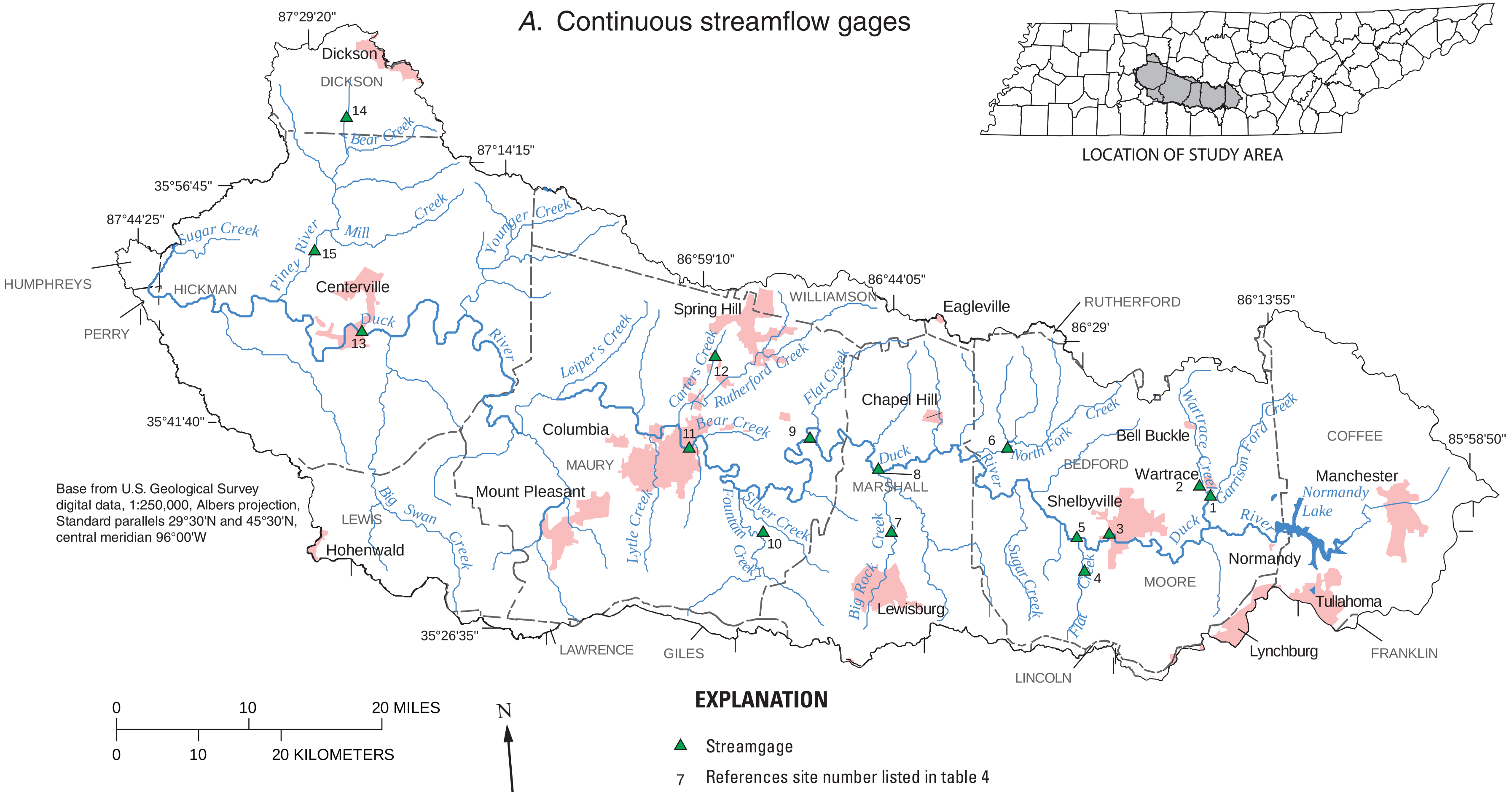
Site name	Station number	Latitude	Longitude	Drainage area (square miles)	Gage datum (feet)	Period of record (water years)
Base-flow synoptic measurement sites (site number on figure 4*B*)—Continued						
Spring Creek at Wilhoite Mills (19)	03598298	35° 36' 11"	86° 41' 47"	23.7	—	—
Rich Creek near Wilhoite Mills (20)	03598320	35° 34' 43"	86° 42' 49"	19.2	—	—
Big Rock Creek Tributary at Verona Pike near Verona (21)	03599099	35° 30' 15"	86° 46' 05"	0.71	—	—
Big Rock Creek below Wright Branch at Verona (22)	03599117	35° 32' 16"	86° 46' 07"	53.05	—	—
East Rock Creek at Farmington (23)	03599210	35° 31' 07"	86° 43' 12"	—	—	—
East Big Rock Creek at Ames (24)	03599225	35° 33' 11"	86° 45' 17"	—	—	—
Caney Creek at Caney Spring (25)	03599300	35° 36' 29"	86° 46' 05"	28.9	—	—
Duck River at RM 177 above Venable Spring (26)	03599310	35° 36' 17"	86° 46' 53"	—	—	—
Duck River near Pottsville (Hardison Mill) (27)	03599350	35° 36' 31"	86° 49' 20"	956	—	—
Flat Creek near Pottsville (28)	03599403	35° 38' 33"	86° 51' 14"	41.6	—	—
Pumpkin Creek at Joe Brown Road near Pottsville (29)	035994045	35° 38' 41"	86° 52' 21"	—	—	—
Duck River at RM 162.8 near Pottsville (Tuga's Bend) (30)	03599410	35° 36' 03"	86° 52' 32"	1,019	—	—
Duck River at RM 158.3 nr Pottsville (31)	03599417	35° 35' 50"	86° 52' 05"	—	—	—
Duck River at RM 156 near Pottsville (Sowell Mill) (32)	03599419	35° 34' 13"	86° 52' 17"	—	—	—
Cedar Creek near Berlin (33)	03599420	35° 33' 15"	86° 51' 23"	9.24	—	—
Duck River upstream of Interstate 65 (34)	03599424	35° 33' 57"	86° 54' 03"	—	—	—
Duck River at Howard Bridge (35)	03599425	35° 34' 21"	86° 55' 20"	1,056	—	—
Negro Creek near Glendale (36)	03599427	35° 34' 52"	86° 55' 48"	4.31	—	—
Fountain Creek at Silver Creek near Fountain Heights (37)	0359945262	35° 33' 38"	86° 57' 40"	90.4	—	—
Silver Creek above confluence with Fountain Creek at Blue Spring Road (38)	035994545	35° 33' 38"	86° 57' 38"	15.0	—	—
Duck River below Fountain Creek (39)	03599456	35° 34' 07"	86° 57' 57"	—	—	—

[a] The Duck River at Highway 100 near Centerville (03601990) and the Duck River at Centerville (03602000) are used as the same gage in this report to compare pre- and post-dam closure conditions. The site is referred to as the Duck River at Highway 100 near Centerville because this is currently (2007) the active gage location.

Table 5. Site information for selected ground-water wells and springs in the Duck River watershed.

[Latitude and longitude are referenced to the North American Datum of 1927; Gage datum is referenced to the National Geodetic Vertical Datum of 1929; °, degrees; ', minutes; ″, seconds; —, not applicable]

Site name	Station number	Latitude	Longitude	Well depth (feet)
Ground-water wells (Site number on figure 5)				
My:O-2	353816086493201	35° 38' 16"	86° 49' 32"	59
Ms:K-13	353505086471301	35° 35' 05"	86° 47' 13"	300
Ms:N-12	353734086423302	35° 37' 34"	86° 42' 33"	206
Ms:N-13	353733086423401	35° 37' 33"	86° 42' 34"	500
Bd:K-4	353718086352201	35° 37' 18"	86° 35' 22"	65
Ms:L-6	353234086421501	35° 32' 34"	86° 42' 15"	105
My:H-16	353449086523700	35° 34' 49"	86° 52' 37"	50
My:H-10	353533086574700	35° 35' 33"	86° 57' 57"	94
My:G-6	353644087001300	35° 36' 44"	87° 00' 13"	145
My:N-028	354416086572801	35° 44' 16"	86° 57' 28"	200
My:N-034	354432086580901	35° 44' 32"	86° 58' 09"	60
My:H-14	353331086545200	35° 33' 31"	86° 54' 52"	206
Ms:K-5	353603086485500	35° 36' 03"	86° 48' 55"	150
Bd:L-41	353211086271201	35° 32' 11"	86° 27' 12"	83
Bd:E-11	352501086322001	35° 25' 01"	86° 32' 20"	75
Ms:F-8	352618086472001	35° 26' 18"	86° 47' 20"	145
My:O-3	354154086502501	35° 41' 54"	86° 50' 25"	100
Springs (Site number on figure 5)				
Berlin Spring (1)	353144086493001	35° 31' 43"	86° 49' 29"	—
Big Spring near Farmington (2)	03599202	35° 30' 07"	86° 42' 39"	—
Blue Spring (3)	353434086592501	35° 34' 34"	86° 59' 24"	—
Carrick Spring (4)	0359815605	35° 33' 16"	86° 24' 48"	—
Carters Creek Spring (5)	354140087003801	35° 41' 39"	87° 00' 37"	—
East Collins Spring (6)	353018086462501	35° 30' 18"	86° 46' 24"	—
Eoff Cave Spring (7)	353208086152501	35° 32' 08"	86° 15' 24"	—
Morgan Spring (8)	353547087013301	35° 35' 46"	87° 01' 33"	—
River Rats Spring (9)	353730086491301	35° 37' 29"	86° 49' 13"	—
Sims Spring (10)	353043086372201	35° 30' 43"	86° 37' 22"	—
Unnamed Spring at Ag. Experiment Station near Lewisburg (11)	352432086491001	35° 24' 32"	86° 49' 10"	—
Venable Spring (12)	353627086465601	35° 36' 26"	86° 46' 55"	—
West Collins Spring (13)	353017086462501	35° 30' 17"	86° 46' 24"	—



Base from U.S. Geological Survey digital data, 1:250,000, Albers projection, Standard parallels 29°30'N and 45°30'N, central meridian 96°00'W

Figure 4. (*A*) Continuous streamflow gages and (*B*) base-flow synoptic measurement locations in the Duck River watershed, Tennessee.

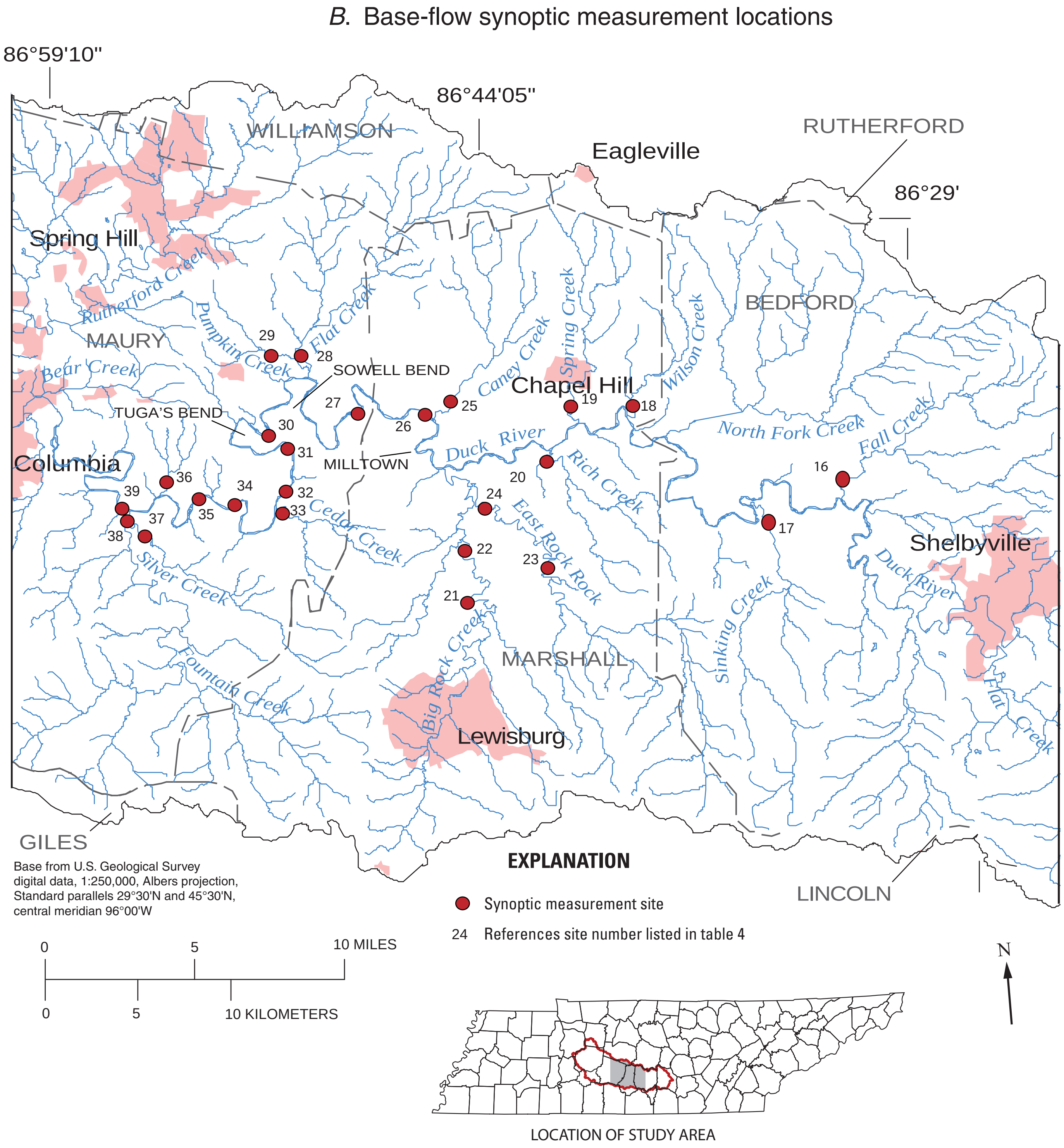
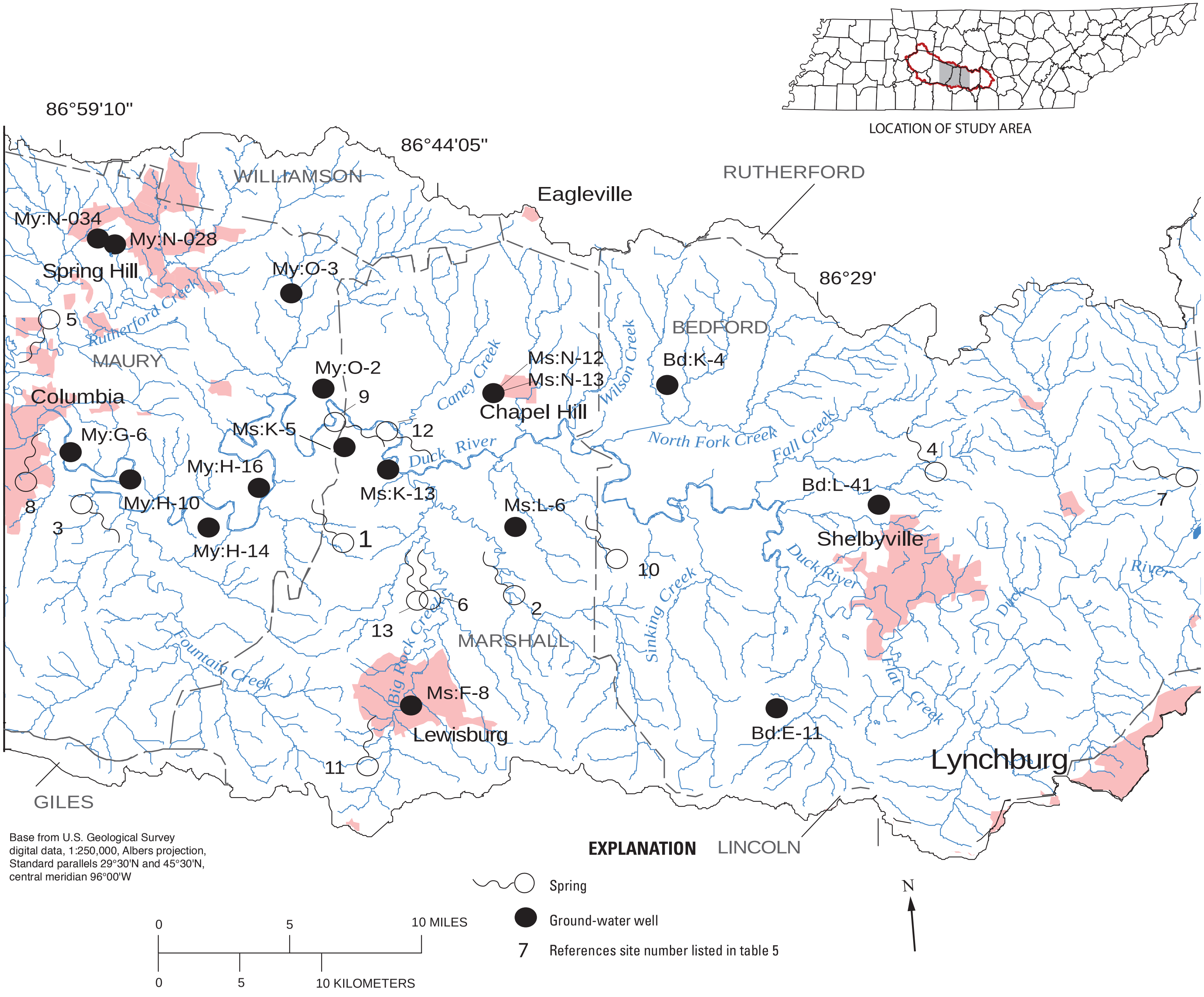


Figure 4. (*A*) Continuous streamflow gages and (*B*) base-flow synoptic measurement locations in the Duck River watershed, Tennessee.—Continued



Base from U.S. Geological Survey
digital data, 1:250,000, Albers projection,
Standard parallels 29°30'N and 45°30'N,
central meridian 96°00'W

Figure 5. Spring and ground-water monitoring locations in the Duck River watershed, Tennessee.

In general, tributaries in the study area can be divided into two categories: near-constant flow (may have zero flow during extreme years) and storm conveyance (flow only as a result of immediate runoff from precipitation events). Streams that would be considered in the near-constant-flow category are currently being monitored: Wartrace Creek, Flat Creek near Shelbyville, North Fork Creek, Big Rock Creek, and Fountain Creek. Very few, if any, tributaries to the Duck River in this category are not currently being monitored. Tributaries in the category of storm-conveyance include streams and creeks that usually discharge to the Duck River for a few weeks after a precipitation event and then reduce rather quickly to zero or near-zero flow during the summer months. Streams matching these characteristics include Spring Creek, Wilson Creek, Sinking Creek, Flat Creek (Maury County), and Caney Creek, generally located in the Inner Nashville Basin Ecoregion (fig. 1).

Surface-Water Data Analysis

Flow-duration analysis was completed for six tributary and three mainstem sites for the 2004 and 2005 water years (October 1 through September 30). Flow-duration analysis uses continuous streamflow data to estimate the percentage of time that streamflow equals or exceeds given flow values. These values, when plotted as runoff versus duration, can be used to generally characterize the extent to which streamflow is affected by ground-water discharge during periods of limited runoff (typically late-summer and early fall). Data in these plots are normalized by the watershed area to enable comparisons among different streams. Generally, lines with lower slope indicate that streamflow is supported by a more sustained contribution from ground water.

Low-flow statistics are used to assess the capacity of a stream or watershed to yield water for a specific length of time and for a particular recurrence interval. Low-flow statistics also are used to determine the waste assimilation capacity of a stream. Low-flow statistics were calculated for 11 sites in the Duck River watershed. Low-flow values are similar to flow-duration values in that both can be used to characterize streamflow during base-flow conditions. Low-flow values are determined statistically by assigning recurrence intervals to daily mean discharges that occur on consecutive days. For example, a 7Q10 low-flow value is the daily mean discharge that occurs for 7 consecutive days and recurs once every 10 years. In this analysis, the 7Q10 and the 30Q5 low-flow values are used because these are the values typically used by resource managers. The 7Q10 value is relatively short in duration in comparison to the 30Q5 value, which has a longer duration and recurs more frequently than the 7Q10. A minimum of 4 years of continuous streamflow data are required to calculate low-flow statistics, though more stable and accurate results are obtained when 10 or more years of data are available (Flynn and others, 1995).

The relative contribution of four components to total streamflow at four mainstem streamgage locations from Shelbyville to Columbia was estimated using continuous streamflow data, base-flow synoptic measurements, Normandy Dam release data, water-use and wastewater treatment discharge estimates, and spring discharge measurements. Estimates of the contribution from Normandy releases, tributaries, utilities, and ground-water discharge were completed during two periods of extended recession (October 2003 and August 2004). Streamflow that could not be attributed to one of the known or measured components of flow is considered ground-water discharge. This consideration was made because tributaries that continue to flow into the Duck River throughout the year were accounted for by continuous streamflow gages. Streamflow was negligible or absent in ungaged tributaries during the two extended recession periods.

Ground-Water Network

The ground-water-level network for this investigation consists of 17 wells at which monthly tape-down water-level measurements were made (fig. 5). All of these were existing wells, and about half of them were installed as test wells either for ground-water development or for geologic and hydrologic information. The remaining wells are domestic wells that are no longer used or are used only intermittently for seasonal lawn irrigation. The maximum depth of wells in the network is 500 ft, but most of the wells are less than 200 ft deep (table 5). All of the network wells are completed in bedrock with open borehole construction. Typically, the first 20 ft of the borehole is cased with 6-in.-diameter steel or galvanized steel casing, and the rest of the borehole is open to bedrock. Water-level data from these wells represent unconfined to semi-confined water levels.

Continuous (hourly) water-level data were collected at 6 of these 17 wells from January 2004 to July 2005 to characterize the response of the ground-water system to rainfall and to characterize the relation among ground-water levels, spring flows, and stage in the Duck River. Three of the continuous water-level wells (My:G-6, My:H-14, and Ms:K-13) are located along the Duck River, from Milltown downstream to Columbia. This stretch of the river contains areas where streamflow losses to the ground-water system have been documented in the past and were also measured during this study. The intent of monitoring these three wells was to determine the extent of the hydraulic connection between the aquifer and the river and to determine if significant amounts of water move between the aquifer and the Duck River at these locations. Continuous data also were collected from three wells (My:N-034, Ms:F-8, and Ms:N-13) located away from the Duck River to compare ground-water-level changes in the tributary basins to those in wells close to the river. The specific locations for water-level monitoring were dictated by the availability of existing wells. Continuous data were collected with pressure transducers that recorded absolute pressure (pressure of water above the transducer and atmospheric pressure). These pressure readings were adjusted by subtracting the barometric pressure from the absolute pressure. The atmospheric pressure data were collected by a transducer near well Ms:K-13 in the central part of the study area. In addition to water-level data, continuous temperature data were collected at these six wells, and continuous specific-conductance data were collected for selected periods at three of the wells.

The ground-water data-collection network in the study area also included 13 springs at which monthly discharge measurements and field water-quality measurements were made throughout the study, while quarterly and monthly *Escherichia coli* samples were collected during the first and second years, respectively (fig. 5 and table 5). Discharge measurements and bacteria samples were made only after a minimum of 2 days without rainfall to exclude runoff contribution to spring flow. Continuous water-temperature data (15-minute intervals) were collected from several of the springs to help characterize the spring hydrology.

Water-Resources of the Duck River Watershed

Karst features, such as sinkholes, caves, disappearing streams, and springs, are important factors that affect the hydrology of the study area. Knowledge of the interactions between surface-water and ground-water resources is needed to better understand how water resources can be managed to balance water quality, water availability, and aquatic resource needs. The hydrology of the study area was evaluated by examining discharge from springs, streamflow yields, and changes in ground-water levels. Ground-water-level data and monthly discharge measurements from springs were combined with duration analyses, low-flow statistics, and base-flow synoptic investigations to better understand streamflow gains and losses. Streamflow accounting was used to quantify the contribution of the major sources of water at each streamgage along the mainstem.

Surface Water

Surface-water conditions during the 2004 and 2005 water years in the study area represented near-average conditions when compared to annual flows for the years following the closing of Normandy Dam. Analysis of surface-water records at the Duck River near Shelbyville and Duck River at Columbia show that the flow for the 2004 water year ranked 11th and 15th, respectively, in the 28 water-year period from 1977 through 2005. The 2005 water year at these sites ranked 17th and 14th for the same 28-year period. Peak discharges for the 2004 and 2005 water years at the Duck River near Shelbyville and Duck River at Columbia occurred because of winter storms even though 2004 and 2005 were active hurricane seasons. Therefore, the analysis and results presented in this report are representative of average flow conditions from 1977–2005. Hydrographs for the Duck River near Shelbyville and at Columbia for 2004 are compared to a dry year (1981) and a wet year (1989) in figure 6.

Flow in the Duck River is regulated by the operation of Normandy Dam, which is used for flood control and water supply. Normandy Dam was closed for filling in 1976. Minimum flows from Normandy Dam were established to maintain streamflow for water supply and the assimilative capacity of the Duck River. Numerous small dams were built on the Duck River and used for a variety of purposes ranging from power generation to milling and lumber operations. According to Killebrew and Safford (1874), at least 13 small dams were used for milling, lumber, and power generation around 1870. Only three small dams remain between Shelbyville and Columbia.

The surface-water hydrology of the study area is described using flow-duration analysis, tributary base-flow synoptic measurements, and low-flow statistics. These analysis techniques are used to characterize the base-flow contributions to streams from ground water and to compare yields among the streams in different geologic settings. These techniques use both continuous streamflow data and discrete measurement observations.

Results from flow-duration analysis of six tributary streams in the study area indicate that the ground-water component of streamflow declines rapidly during extended dry periods at North Fork, Wartrace, Flat, and Carters Creeks (fig. 7*A*). By comparison, Big Rock and Fountain Creeks appear to have more ground water available to sustain streamflow during base-flow conditions. This is indicated by the flow-duration curve becoming increasingly horizontal for these sites during low-flow periods (fig. 7*A*). It should be noted that wastewater discharge from the City of Lewisburg composes as much as 14 percent of the streamflow in Big Rock Creek during base-flow periods and results in higher water yields during low-flow periods. Sections of Big Rock Creek near Lewisburg have been observed to go dry. Wastewater discharge below Lewisburg is analogous to a ground-water source that provides base flow.

Flow-duration curves for three sites on the mainstem of the Duck River have slopes similar to the Fountain Creek slope but have higher water yields during low runoff periods (fig. 7*B*). The larger base flows at mainstem sites are the result of releases from Normandy Dam, which is analogous to a sustaining ground-water source to the streams. The flow-duration curves for the mainstem sites diverge from each other during low-flow periods. Mainstem flow-duration curves diverge from each other during extended base-flow periods because there is little appreciable tributary inflow between each mainstem site; drainage area continues to increase without a corresponding increase in tributary inflow.

Low-flow statistics also show a similar spatial pattern to flow-duration analyses. Tributary streams with large 7Q10 yields include Garrison Fork [0.03 $(ft^3/s)/mi^2$], Fountain Creek [0.025 $(ft^3/s)/mi^2$], and the Piney River [0.27 $(ft^3/s)/mi^2$] (table 6). The 30Q5 values for Garrison Fork

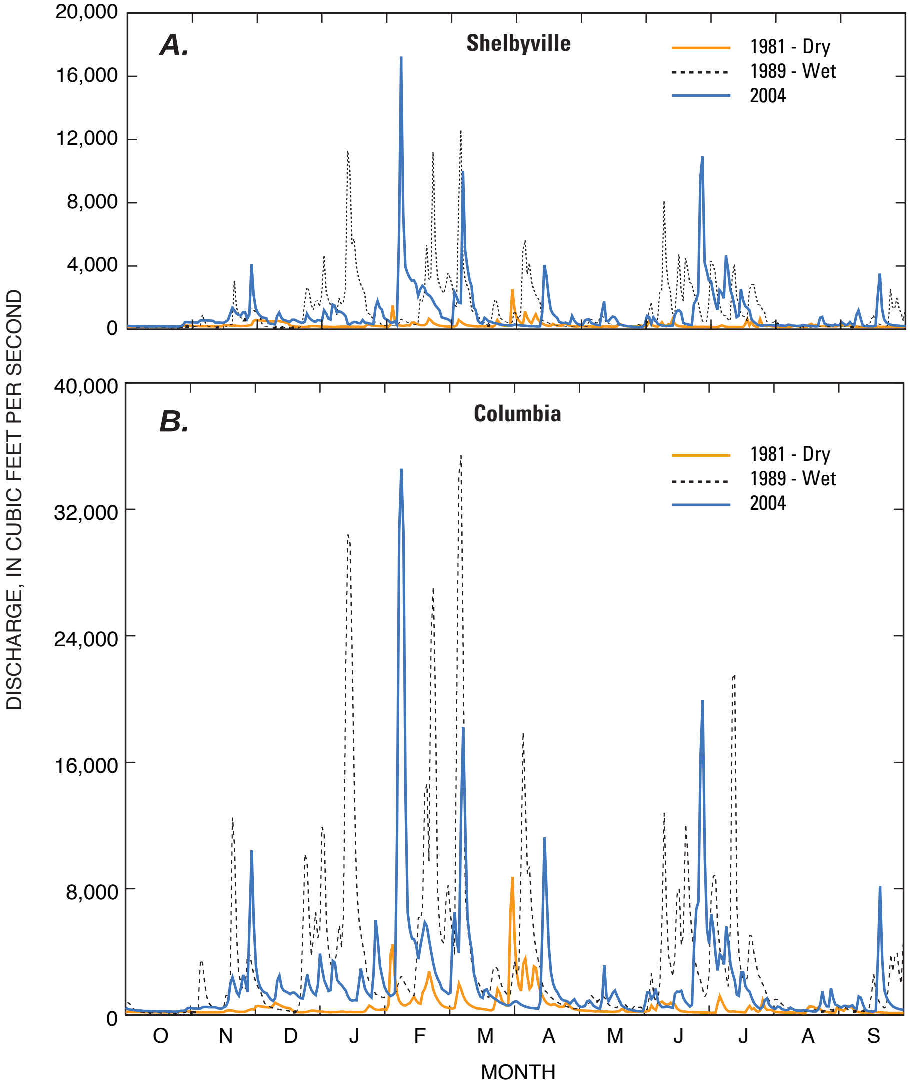


Figure 6. The flow of the Duck River near (*A*) Shelbyville and at (*B*) Columbia during the 2004 water year and the lowest annual flow (1981) and highest annual flow (1989) water years since Normandy Dam was closed. Locations shown in figure 4.

[0.07 (ft^3/s)/mi^2], Fountain Creek [0.063 (ft^3/s)/mi^2], and Piney River [0.32 (ft^3/s)/mi^2] also were higher than for other tributaries. Other tributaries—Wartrace, Big Rock, and North Fork Creeks—have 7Q10 and 30Q5 yields of <0.001 (ft^3/s)/mi^2. Many streams in the eastern two-thirds of the study area, which are underlain predominantly by the Carters, Lebanon, and Ridley Limestones, have been observed at zero streamflow (Tennessee Valley Authority, 1965; fig. 8). A well-developed karst system, thin regolith, and lack of ground-water storage result in lower water yields during base-flow conditions. In addition to less storage in these tributary basins, conduits in the karst aquifer may result in lower streamflow yield because of streamflow loss to the aquifer, thereby short circuiting the surface drainage. In cases such as these, water may be discharging either downstream from the streamgage location, to a nearby spring, or through the subsurface directly to the Duck River.

Low-flow statistics on the mainstem of the Duck River decreased going downstream from Shelbyville through Columbia to Centerville during pre-Normandy Dam flow conditions. This pattern changed after Normandy Dam was closed. For example, during the pre-dam period, the Duck River near Shelbyville had a 7Q10 yield of 0.12 (ft^3/s)/mi^2 compared to the Duck River at Columbia and the Duck River at Highway 100 near Centerville with 0.06 (ft^3/s)/mi^2 (table 6). The 30Q5 values for Columbia and Highway 100 near Centerville also follow a similar decrease in yield when compared to Shelbyville. The decreases in the 7Q10 and 30Q5 yields downstream are an artifact of limited tributary inflow during base-flow conditions and, likely to a lesser extent, loss of streamflow to the karst aquifer. Some ground-water discharge, however, does occur between Columbia and Centerville, likely resulting from the underlying Mississippian-age carbonates in the vicinity of the transition between the Outer Nashville Basin and Western Highland Rim Ecoregions (figs. 1 and 2). During the post-dam period, the 7Q10 yield for the Duck River near Shelbyville is 0.22 (ft^3/s)/mi^2. The yield then decreases to 0.10 (ft^3/s)/mi^2 at Columbia and increases to 0.16 (ft^3/s)/mi^2 between Columbia and Centerville (table 6). A similar pattern is seen with the 30Q5 yield values. The decrease in the 7Q10 yield between Shelbyville and Columbia during pre- and post-dam periods is 50 and 55 percent, respectively. The subsequent increase in the 7Q10 yield from Columbia to Centerville (only in the post-dam period) is 60 percent. An increase in low-flow yields during the post-dam period may be related to increases in precipitation since the early 1970s as reported by regional and national studies (McCabe and Wolock, 2002; Wolfe and others, 2004), though the percentage increase in streamflow yield resulting from increased precipitation would be expected to be relatively consistent from site to site. The increase in 7Q10 likely reflects both minimum flow requirements from Normandy Dam as well as a general increase in precipitation since about 1970.

Longitudinal dispersion of releases from Normandy Dam causes inconsistent increases in low-flow statistics at mainstem sites. For example, during a controlled release (wave) from the dam for flood control, the shape of the hydrograph changes as this wave propagates downstream. As the wave passes Shelbyville, the increase in gage height and discharge

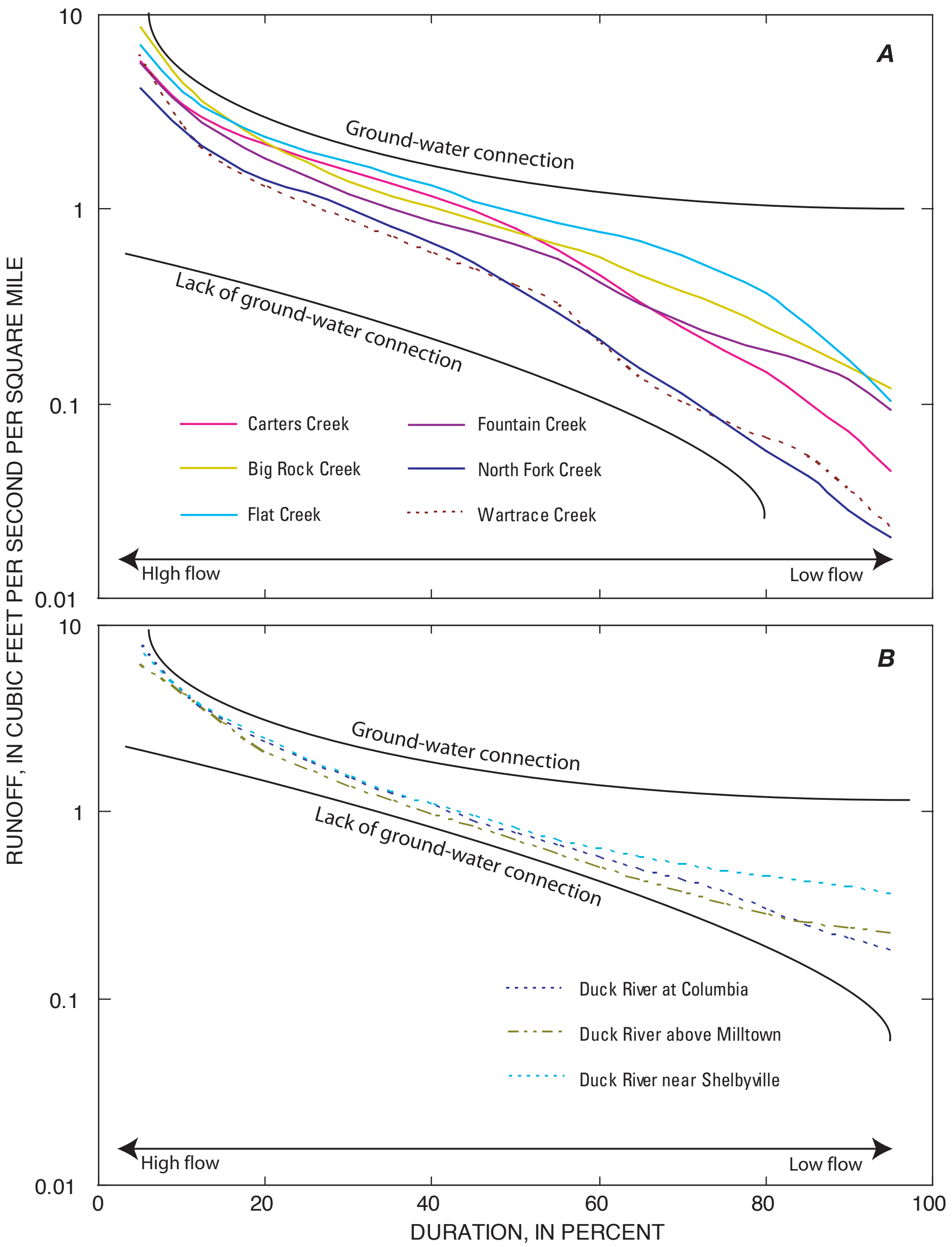


Figure 7. Flow-duration analysis of streamflow data, normalized by drainage area, from (*A*) tributary watersheds and (*B*) sites along the mainstem of the Duck River.

Table 6. Low-flow statistics for selected sites in the study unit showing losses in streamflow yield between the Duck River near Shelbyville and the Duck River at Columbia and gains in discharge near Highway 100 near Centerville.

[These values also show a non-linear response in flow as Normandy Dam began operation; Rows shaded are for periods when mainstem flows were not regulated by the operation of Normandy Dam; (ft^3/s)/mi^2, cubic feet per second per square mile; percentage increase was calculated between pre- and post-dam closure periods for the same site; — , not calculated]

Site name	Period	7Q10 [(ft^3/s)/mi^2]	Percent increase between periods	30Q5 [(ft^3/s)/mi^2]	Percent increase between periods
Tributary					
Garrison Fork at L&N Railroad at Wartrace	1991 – 2002 [a]	0.03	—	0.07	—
Wartrace Creek at Bell Buckle	1954 – 1974 [a]	<.001	—	<.001	—
Wartrace Creek at County Road	1990 – 2001 [b]	<.001	—	<.001	—
North Fork Creek near Poplins Crossroads	1994 – 2004 [a]	<.001	—	<.001	—
Big Rock Creek at Lewisburg	1955 – 1968, 1997 – 2000 [b]	<.001	—	<.001	—
Fountain Creek near Fountain Heights [c]	1966 – 1968 [a]	.025	—	.063	—
Carters Creek at Butler Road at Carters Creek	1988 – 2002 [a]	.009	—	.02	—
Piney River at Vernon	1926 – 2001 [a]	.27	—	.32	—
Mainstem					
Duck River near Shelbyville	1934 – 1975 [a]	.12	83	.15	106
	1977 – 2002 [b]	.22		.31	
Duck River at Columbia	1904 – 1975 [a]	.06	67	.09	44
	1977 – 2002 [b]	.10		.13	
Duck River at Hwy 100 near Centerville [d]	1920 – 1955 [a]	.06	167	.10	80
	1977 – 2002 [b]	.16		.18	

[a] From Outlaw and Weaver (1996).

[b] George Law, U.S. Geological Survey, written commun., 2005.

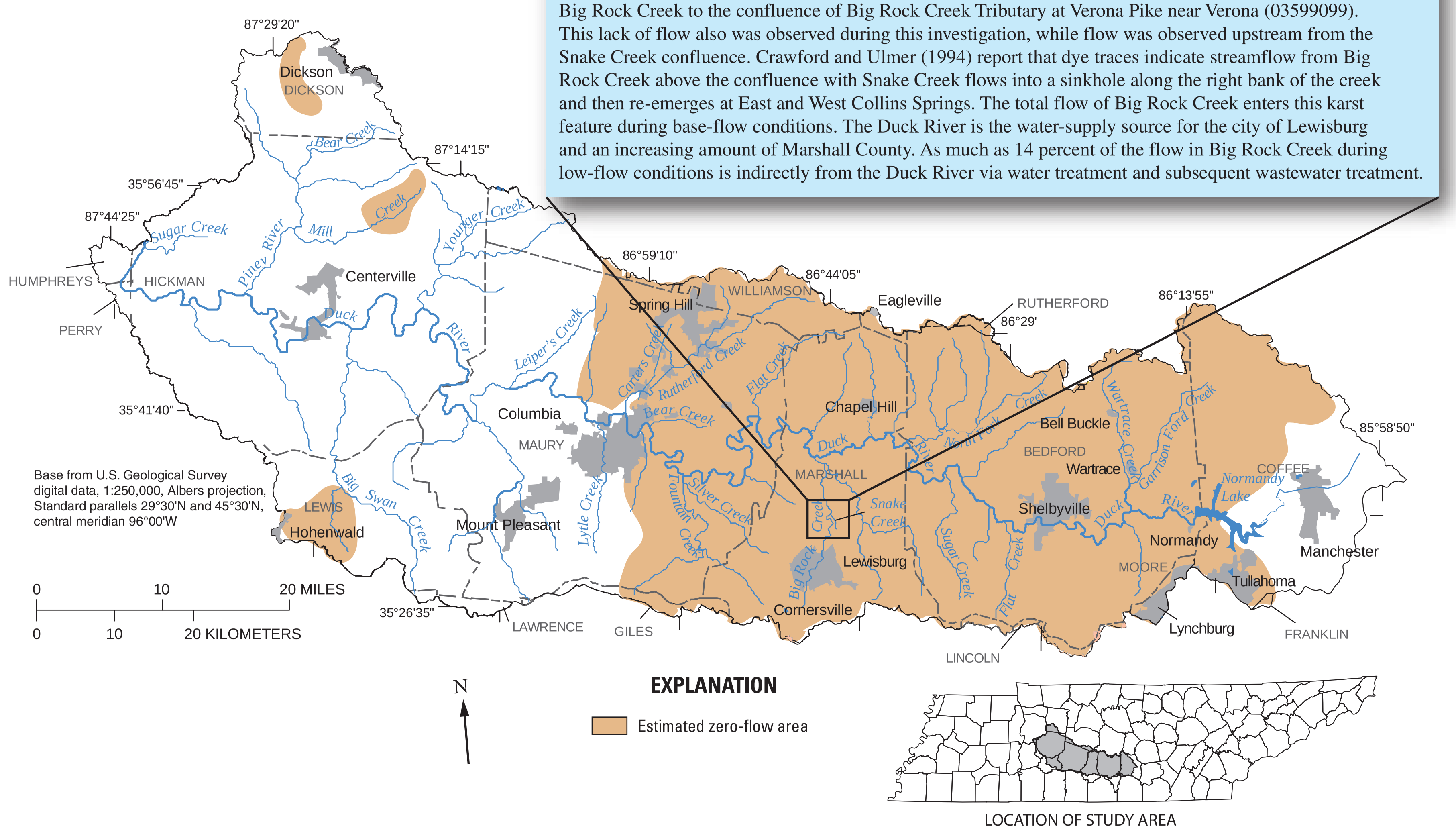
[c] Low-flow partial record station—low-flow values are based on 12 individual streamflow measurements compared to streamflow measurements made at Big Bigby Creek near Sandy Hook (03600500).

[d] See table 4 (footnote) for information about Duck River at Highway 100 near Centerville.

may be significant, while the duration of the wave may be short (consider a high-amplitude, short wavelength sign; fig. 9). As the wave moves downstream, the amplitude of the wave (increase in gage height and discharge) will dampen, while the wavelength (duration of the wave) increases. This phenomenon is known as longitudinal dispersion. Shorter duration releases from the dam can cause a greater increase in the low-flow yields for sites farther downstream due to continuously increasing wavelengths moving downstream, while longer duration releases from the dam can have a greater impact on sites closer to the dam. The general effects of the operation of Normandy Dam on base flow can be seen with the 7Q10 and 30Q5 yields at each of the three mainstem sites (increased yields at each site; table 6). The effect of the longitudinal dispersion of the wave as it propagates downstream is best illustrated by comparing the percent increases in the 7Q10 or 30Q5 from site to site, especially between the Columbia and Centerville sites.

Base-flow synoptic measurements were completed on tributaries in the study area during November 2003 and May 2004. These base-flow synoptic measurements indicated that the highest yielding watersheds were Fountain Creek, Silver Creek, Negro Creek (approximately 1 mi upstream from the confluence of Fountain Creek with the Duck River), Big Rock Creek, Flat Creek at Highway 231, and Garrison Fork Creek (figs. 4*A* and 4*B*; table 7). Sites are defined as being high yielding if the yield for the site was greater than the average yield of sites that were measured. The Big Rock Creek at Double Bridges Road (03599100) and Big Rock Creek below Wright Branch (03599117) streamgages each had yields higher than average during both time periods (figs. 4*A* and 4*B*; table 7); however, this value includes effluent from the wastewater treatment plant. Results were similar for the two measurement periods and differed only in the magnitude of the average yield measured at the sites. In November 2003, the average yield of all sites measured was 0.07 (ft^3/s)/mi^2, and in May 2004, the average yield was 0.16 (ft^3/s)/mi^2. These average yields do not include Big Rock Creek Tributary at Verona Pike (03599099) [approximately 100 ft upstream from the Big Rock Creek streamgage (03599100)] because it includes the flow from East and West Collins Springs, which

The Big Rock Creek watershed is within the area where streams have been observed to go dry and has a combination of reaches that have flowing water, while other reaches have zero flow. It has been reported by Crawford and Ulmer (1994) that Big Rock Creek does not flow from near the Snake Creek confluence with Big Rock Creek to the confluence of Big Rock Creek Tributary at Verona Pike near Verona (03599099). This lack of flow also was observed during this investigation, while flow was observed upstream from the Snake Creek confluence. Crawford and Ulmer (1994) report that dye traces indicate streamflow from Big Rock Creek above the confluence with Snake Creek flows into a sinkhole along the right bank of the creek and then re-emerges at East and West Collins Springs. The total flow of Big Rock Creek enters this karst feature during base-flow conditions. The Duck River is the water-supply source for the city of Lewisburg and an increasing amount of Marshall County. As much as 14 percent of the flow in Big Rock Creek during low-flow conditions is indirectly from the Duck River via water treatment and subsequent wastewater treatment.



Base from U.S. Geological Survey digital data, 1:250,000, Albers projection, Standard parallels 29°30'N and 45°30'N, central meridian 96°00'W

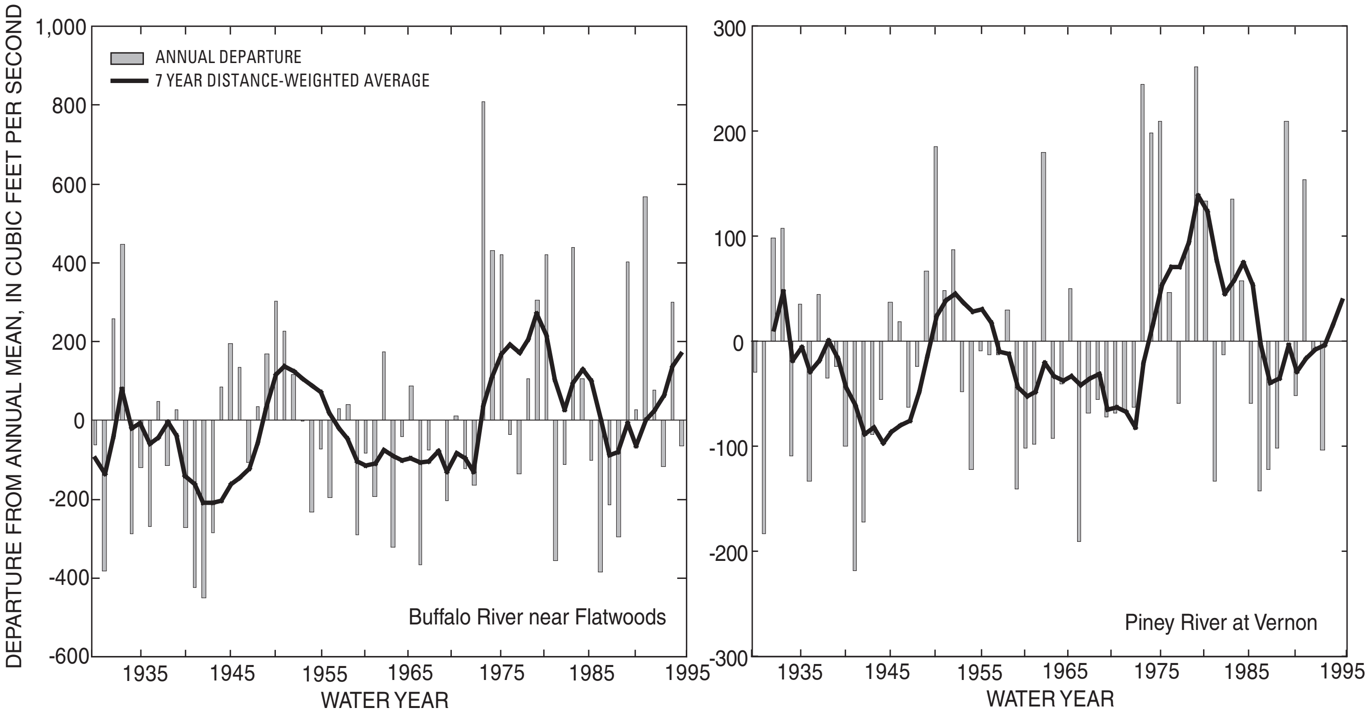
Figure 8. Estimated zero-flow area of the Duck River Watershed, Tennessee (modifed from Tennessee Valley Authority, 1965).

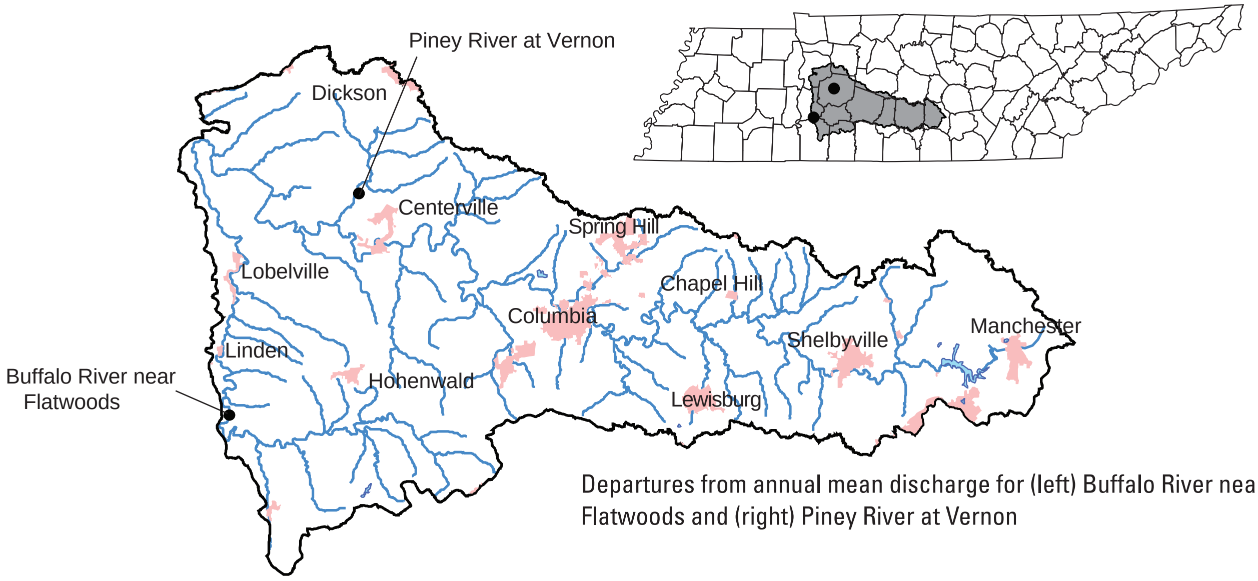
Table 7. Tributary base-flow synoptic investigation results for tributaries of the Duck River watershed, November 2003 and May 2004.

[mi^2, square miles; ft^3/s, cubic feet per second; (ft^3/s)/mi^2, cubic feet per second per square mile; —, not available; shaded rows represent sites that had higher yields than other tributaries in the investigation; (gage), discharge value derived from stage-discharge rating at streamgage]

Station number	Site name	Drainage area (mi^2)	November 2003		May 2004	
			Discharge (ft^3/s)	Yield [(ft^3/s)/mi^2]	Discharge (ft^3/s)	Yield [(ft^3/s)/mi^2]
03597210	Garrison Fork Creek above L&N Railroad (gage)	85.5	10	0.12	32	0.37
03597590	Wartrace Creek below County Road near Wartrace (gage)	35.7	1.8	.05	5.1	.14
03597898	Flat Creek at Highway 231 below Shelbyville (gage)	49	4.94	.10	malfunction	—
03598180	Fall Creek near Elbethel	40	.68	.02	2.8	.07
03598190	Sinking Creek near Halls Mill	31.5	.01	0	.38	.01
03598250	North Fork Creek at Poplin's Crossroads (gage)	71.9	1.3	.02	4.5	.06
03598260	Wilson Creek near Chapel Hill	15.5	.26	.02	1.34	.09
03598298	Spring Creek at Wilhoite Mills	23.7	0	0	.49	.02
03598320	Rich Creek near Wilhoite Mills	19.2	0	0	2.00	.10
03599099	Big Rock Creek Tributary at Verona Pike near Verona (Collins Springs)	.71	6.38	8.99	15.0	21.0
03599100	Big Rock Creek at Double Bridges Road (gage)	48.7	7.00	.14	16.0	.33
03599117	Big Rock Creek below Wright Branch at Verona	53.05	7.89	.15	19.9	.38
03599202	Big Spring near Farmington	—	.155	—	7.75	—
03599210	East Rock Creek at Farmington	—	0	—	3.40	—
03599225	East Big Rock Creek at Ames	—	0	—	0	—
03599300	Caney Creek at Caney Spring	28.9	0	0	0	0
353627086465601	Venable Spring	—	.35	—	3.38	—
353730086491301	Big Spring at River Rats Canoe Rental	—	1.4	—	7.08	—
353144086493001	Berlin Spring	—	.2	—	.29	—
03599403	Flat Creek near Pottsville	41.6	.99	.02	2.29	.06
035994045	Pumpkin Creek at Joe Brown Road near Pottsville	—	.36	—	—	—
035994175	Pumpkin Creek (Whitehead Spring) near Leftwich	—	.3	—	.67	—
03599420	Cedar Creek near Berlin	9.24	.27	.03	1.42	.15
03599427	Negro Creek near Glendale	4.31	.54	.13	.94	.22
03599450	Fountain Creek near Fountain Heights (gage)	77.0	10	.13	17	.22
035994545	Silver Creek above confluence with Fountain Creek at Blue Spring Road	15.0	1.38	.09	1.92	.13
0359945262	Fountain Creek at Silver Creek near Fountain Heights	90.4	15.5	.17	27.3	.30
353434086592501	Blue Spring at Goose Creek	—	.34	—	—	—

STREAMFLOWS IN THE DUCK RIVER WATERSHED SHOW SIMILAR PATTERNS TO NATIONAL STUDIES





Departures from annual mean discharge for (left) Buffalo River near Flatwoods and (right) Piney River at Vernon

Streamflow in the Duck River watershed has been increasing throughout most of the 20th century. Increased streamflow is evidence of increased precipitation over time. Examples of increase in mean annual streamflow in the Duck River watershed are found at the Buffalo River near Flatwoods and the Piney River at Vernon. These sites represent unregulated watersheds, and each site has continuous streamflow data records extending from the 1920s to present. These results mirror national findings by McCabe and Wolock (2002) related to step increases in mean annual and annual minimum streamflow around 1970 and regional findings by Wolfe and others (2004) regarding increased annual precipitation.

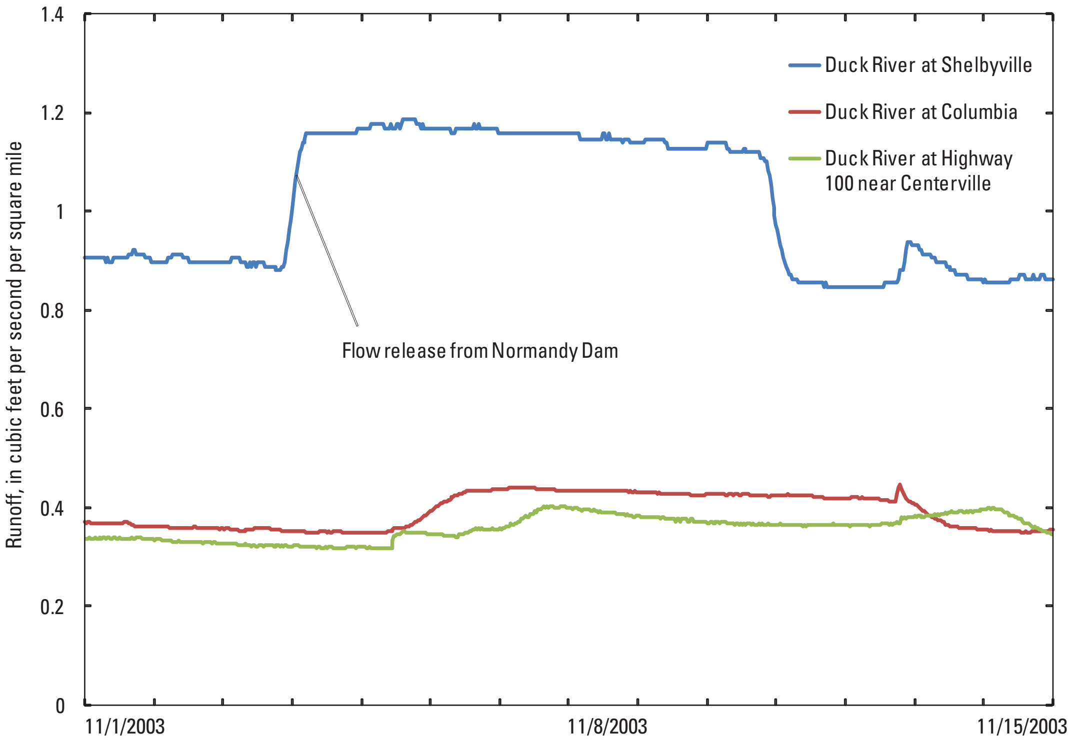


Figure 9. Example of Normandy flow release propagation at the Duck River at Shelbyville (03598000), Duck River at Columbia (03599500), and Duck River at Highway 100 near Centerville (03602000).

may include flow from an adjacent watershed, resulting in an anomalously high yield for the relatively small drainage area.

Yields at Garrison Fork and Fountain Creek were nearly double that of the average (table 7) during periods of measurement. Garrison Fork is the only site in the eastern part of the study area that has high low-flow values (by comparison) (table 6) and is considered as a high-yielding watershed based on base-flow synoptic investigations. A high yield at Garrison Fork is likely the result of its draining a portion of the Eastern Highland Rim Ecoregion (fig. 1) and being underlain by the Fort Payne Formation (fig. 2), which contains a productive aquifer. Fountain Creek lies in the Outer Nashville Basin Ecoregion (fig. 1) and is underlain primarily by the Bigby – Cannon Limestone with headwater areas underlain by the Fort Payne Formation, one of the Mississippian-age carbonates (fig. 2).

High streamflow yields during base-flow periods as evidenced by flow-duration analysis, low-flow statistics, and greater than average base-flow synoptic yields are related to the underlying geology in these watersheds although differences in rainfall distribution may explain some differences between sites. Sites with the highest streamflow yields typically were located in the Outer Nashville Basin or Eastern Highland Rim Ecoregions. Additionally, a thicker regolith and less developed karst system provides more ground-water storage, such as in the Fountain Creek watershed, and results in higher water yields during base-flow conditions.

Five sites measured in November 2003 and two sites measured in May 2004 had no flow and are within the area identified as having streams that often go dry (fig. 8). These sites were located primarily within the Inner Nashville Basin Ecoregion (fig. 1). Streams in this area also had 7Q10 or 30Q5 low-flow values near 0 $(ft^3/s)/mi^2$.

Ground Water

Water-level and spring-flow data were collected to characterize the response of the Ordovician aquifer to recharge events as well as to understand the relation between water levels in the aquifer and in the Duck River. These data were collected to show whether or not streamflow losses in the Duck River resulted in recharge to the aquifer system.

Water-level fluctuations at the six continuously monitored wells were similar throughout the year; however, the magnitude and rate of changes in water levels vary (fig. 10). Water levels were high in most of the wells during winter and early spring when precipitation is high and evapotranspiration is low, and water levels were low in the late summer and early fall. All of the continuous water-level hydrographs indicate rapid rises and declines in water levels following rainfall and suggest that little ground water remained in long-term storage in the areas where these data were collected.

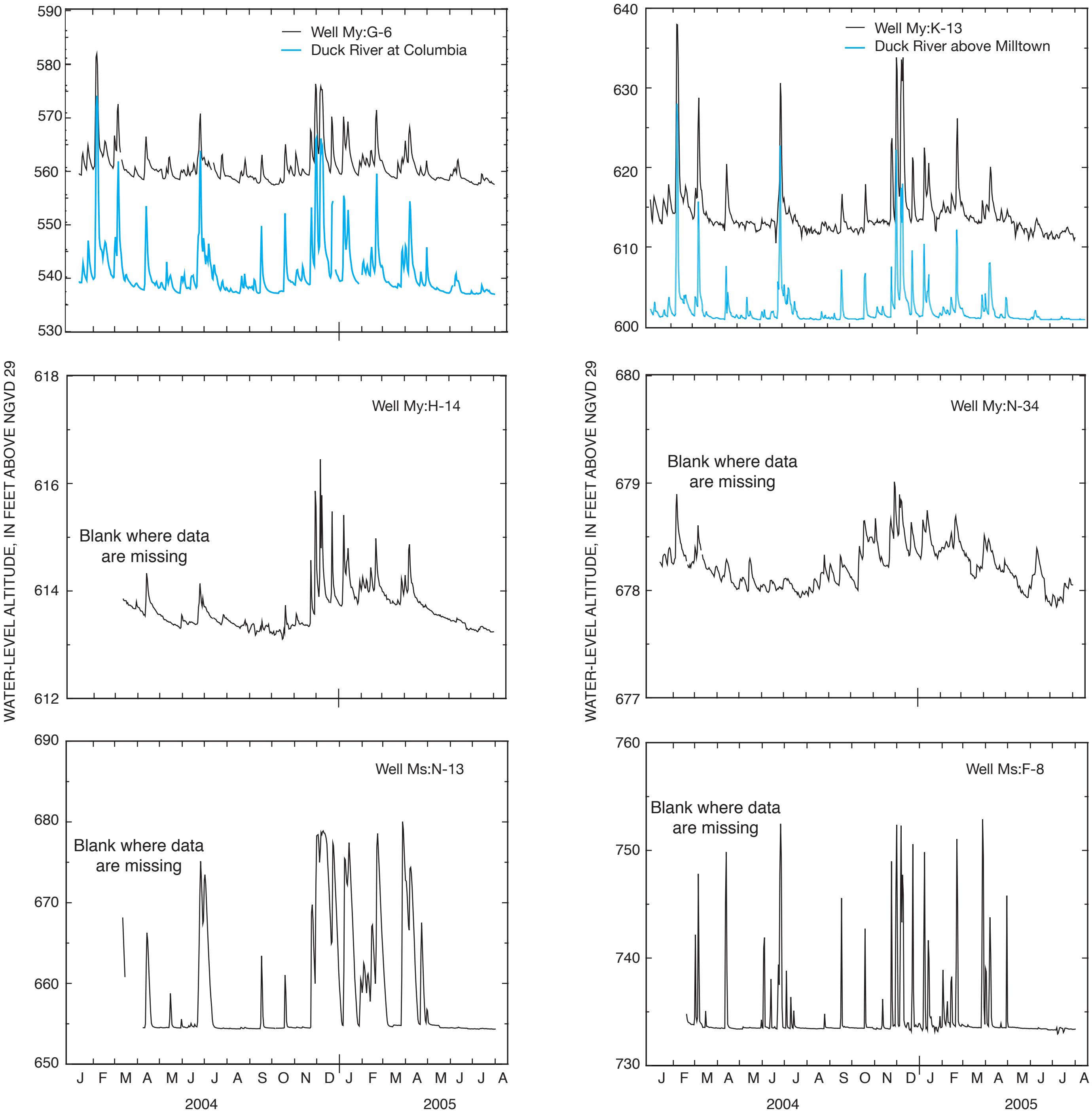


Figure 10. Continuous ground-water levels and stage in the Duck River at Columbia (03599500) and the Duck River above Milltown (03599240), Tennessee.

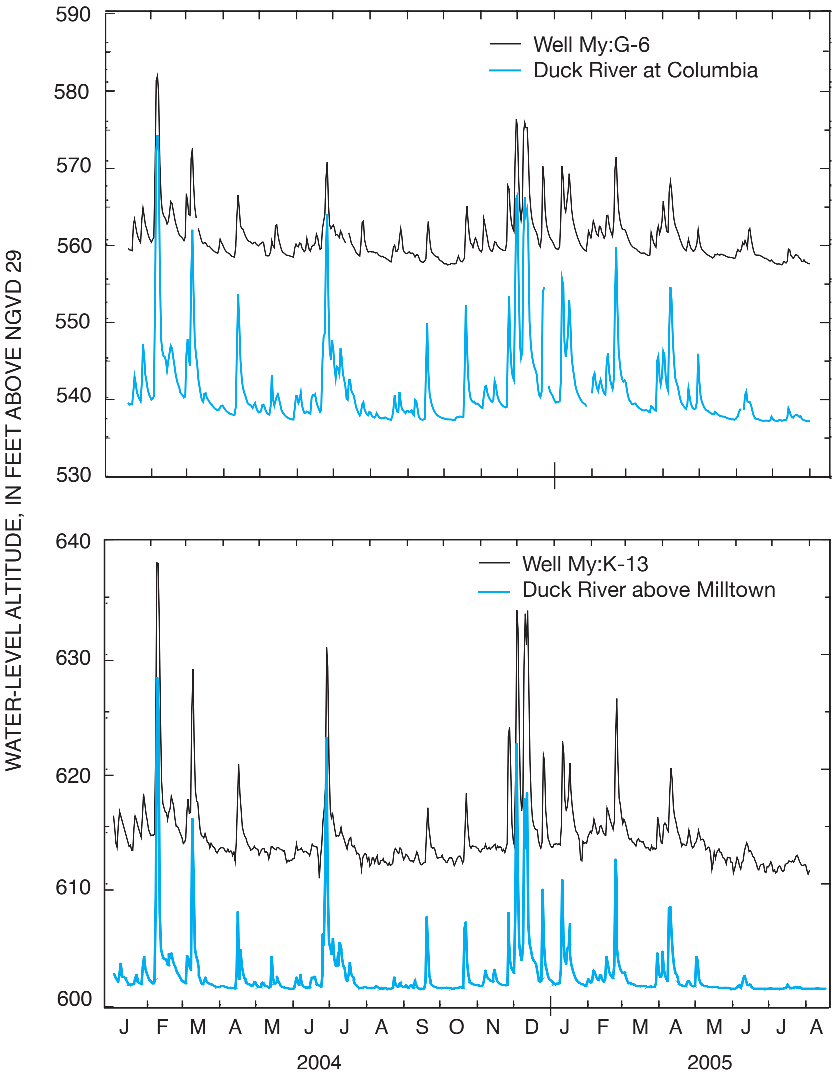


Figure 10. Continuous ground-water levels and stage in the Duck River at Columbia (03599500) and the Duck River above Milltown (03599240), Tennessee.—Continued

The hydrographs for wells My:G-6 and Ms:K-13 are similar to the hydrographs for nearby gaging stations on the Duck River at Columbia (03599500) and above Milltown (03599240) (fig. 10). The similarity suggests that the bedrock zones open to these wells are connected hydraulically to the Duck River. Water levels in these wells typically decline at about the same rate as they rise and also at about the same rate as the stage of the Duck River. These characteristics suggest that little water is stored long term in the aquifer following these recharge events and that the stage of the Duck River plays an important role in water-level changes in the aquifer. The streamgage on the Duck River at Columbia is below a dam on the river, and the difference in the elevation of the river adjacent to the well and water level in My:G-6 is much smaller than the comparison of water levels in the well to the Columbia streamgage used in figure 10. Continuous water-temperature and specific-conductance data collected in these wells do not indicate that water is moving from the Duck River into the aquifer in the area near these wells; however, the pressure effects from changes in stage on the river are transmitted rapidly through the aquifer.

Two of the ground-water hydrographs illustrate the influence of a water-bearing conduit or opening in the bedrock intersected by the wells. In wells Ms:N-13 and Ms:F-8, water levels increase rapidly in response to rainfall. The rate of water-level decline in these wells is about the same as the rate of water-level increase, indicating that water is readily transmitted through the aquifer in the areas near these wells. After the peak, water levels decline to a point that corresponds to the conduit or opening in bedrock, and water levels remain at this level between storms for much of the period of record (fig. 10). During the times when water levels are flat, water levels in the aquifer could continue to decline, and the water level in the well would not reflect this change if the borehole is isolated from the aquifer. Wells Ms:N-13 and Ms:F-8 were pumped during periods of low water levels (summer or early fall) until the water level was lowered below the water-bearing conduit. Shortly after pumping was discontinued, water levels returned to the original elevation indicating that these wells were still hydraulically connected to the aquifer.

The amount of water-level fluctuation in wells My:H-14 and My:N-34 is considerably less than water-level fluctuations in the other wells with continuous data (fig. 10). Several factors could account for this difference. The part of the aquifer in which My:H-14 is completed may have more ground-water storage than parts of the aquifer represented by the other hydrographs. The largest increases in water level in well My:H-14 were followed by rapid declines and then a slow decline within a couple of days after the peak water level, suggesting that water is being released from storage in the aquifer. The rapid rise and fall in water levels are likely related to conduit flow in the aquifer, and the slower decline in water levels is the result of diffuse flow in the aquifer.

In ground-water systems where recharge is dominated by slow infiltration of rainfall, large increases in water levels typically do not occur during the summer months. Large increases in water level in these wells during the summer months, particularly during June and July 2004, illustrate how quickly water moves into the subsurface in the study unit. The rate of decline in water levels following the rise during the summer months is about the same as the rate of decline of stage in the Duck River (for example, Ms:N-13), suggesting that the stage in the Duck River plays an important role in the rate at which ground-water levels decline throughout the year. The quick response of the ground-water levels indicates that much of the water that moves into the aquifer during these events does not remain in storage.

Periodic water-level measurements were made in Bd:K-4 and My:O-3, and continuous water levels were recorded in Ms:N-13 to characterize ground-water conditions in tributary basins that typically go dry during extended periods of base flow. Water levels in the two periodically measured wells do not appear to be as strongly controlled by a conduit as those in Ms:N-13 (fig. 11). The hydrographs for these wells indicate

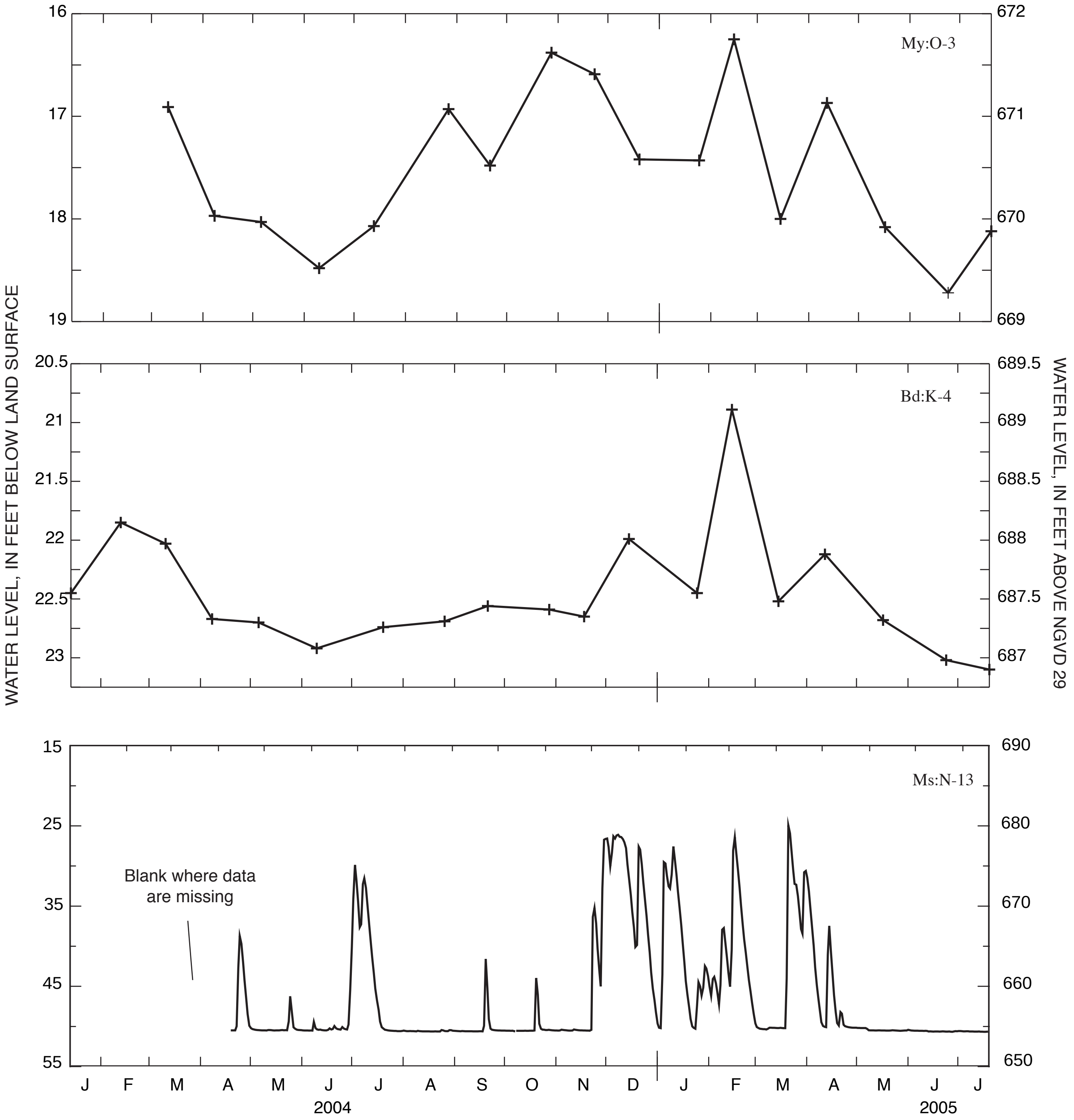


Figure 11. Monthly water-level measurements in two wells located in basins in the Duck River study area that have a history of going dry compared to continuous water-level data.

similar water-level responses to rainfall, and the magnitude of water-level fluctuations for these wells is about the same as water levels for wells in other parts of the study area in which streams do not go dry. In the central part of the study area where wells Ms:N-13, Bd:K-4, and My:O-3 are located, ground-water gradients are low, in part because of the influence of conduits in the aquifer. Relatively small declines in ground-water levels can lower the water table below stream levels, resulting in dry stream reaches in these areas. Streams in the northern part of the study area continue to flow for a period of time following rainfall and during the main period of recharge in winter and early spring.

Springs often represent the most dynamic part of karst aquifers and provide insight to the shallow and deep ground-water hydrology. Ground water with varying residence times and flow-path lengths mix and discharge at springs. Generally, low variability in flow and water quality in springs reflects a longer average flow path or longer average residence time of ground water in the aquifer. Not all springs flow throughout the year. Springs consisting of water with short flow paths may go dry during periods with little or no rainfall. Numerous springs mapped on 7.5-minute topographic maps of the study area are intermittent (wet-weather springs) and go dry during the late summer and early fall when the ground-water levels are low. Relatively few large perennial springs were found in the central part of the study area (table 8; fig. 5). Most of the perennial springs were small and located in headwaters of tributary basins.

The amount of flow measured at most of the springs monitored varies about two orders of magnitude from maximum flows in the winter to minimum flows in the late summer (fig. 12). Only three of the monitored springs, Big, West Collins, and East Collins, have measured median discharges greater than 10 ft^3/s (table 8). Flow at Big Spring and West Collins Spring varies considerably, ranging from about 40 ft^3/s to little or no flow for short periods of time. In contrast, East Collins Spring had sustained flow throughout the period of record (fig. 12). Four springs—Berlin, Blue, River Rats, and Venable Springs (fig. 12)—have median discharges of about 1 to 4 ft^3/s, with a range in discharge of 0.04 to 25 ft^3/s (table 8). About half of the springs monitored have median discharges of less than 1 ft^3/s.

The temperature of spring water consisting predominantly of ground water with long residence times and long flow paths is generally about 15 degrees Celsius (°C) and varies less than 1 °C throughout the year. Short-term increases in the summer or decreases in the winter in water temperature reflect the movement of surface runoff into the subsurface through sinkholes or conduits. The water moves rapidly through the subsurface, such that the temperature does not have time to come into equilibrium with ground-water temperatures. Large, sustained changes in water temperature at a spring during the year suggest that a large component of the water discharged at the spring has a short residence time in the aquifer, such as when a disappearing stream emerges at a spring within a few miles of a swallet. East and West Collins

Table 8. Monthly spring measurements made in the Duck River study area from 2003 to 2005.

[°, degrees; ', minutes; ", seconds; <, less than]

Station number	Spring name	Latitude	Longitude	Measured flow at springs, in cubic feet per second		
				Minimum	Median	Maximum
353144086493001	Berlin Spring	35° 31' 43"	86° 49' 29"	0.04	1.6	7.8
03599202	Big Spring near Farmington	35° 30' 07"	86° 42' 39"	.16	12	38
353434086592501	Blue Spring	35° 34' 34"	86° 59' 24"	.18	2.7	9.8
0359815605	Carrick Spring	35° 33' 16"	86° 24' 48"	.01	.19	1.5
354140087003801	Carters Creek Spring	35° 41' 39"	87° 00' 37"	.01	.02	.06
353018086462501	East Collins Spring	35° 30' 18"	86° 46' 24"	4.5	18	27
353208086152501	Eoff Cave Spring	35° 32' 08"	86° 15' 24"	.03	.31	1.3
353547087013301	Morgan Spring	35° 35' 46"	87° 01' 33"	.03	.15	1.1
353730086491301	River Rats Spring	35° 37' 29"	86° 49' 13"	.93	4.2	25
353043086372201	Sims Spring	35° 30' 43"	86° 37' 22"	.01	.34	1.5
352432086491001	Unnamed Spring at Ag. Experiment Station near Lewisburg	35° 24' 32"	86° 49' 10"	< .01	.02	.21
353627086465601	Venable Spring	35° 36' 26"	86° 46' 55"	.22	4.2	21
353017086462501	West Collins Spring	35° 30' 17"	86° 46' 24"	< .01	11	43

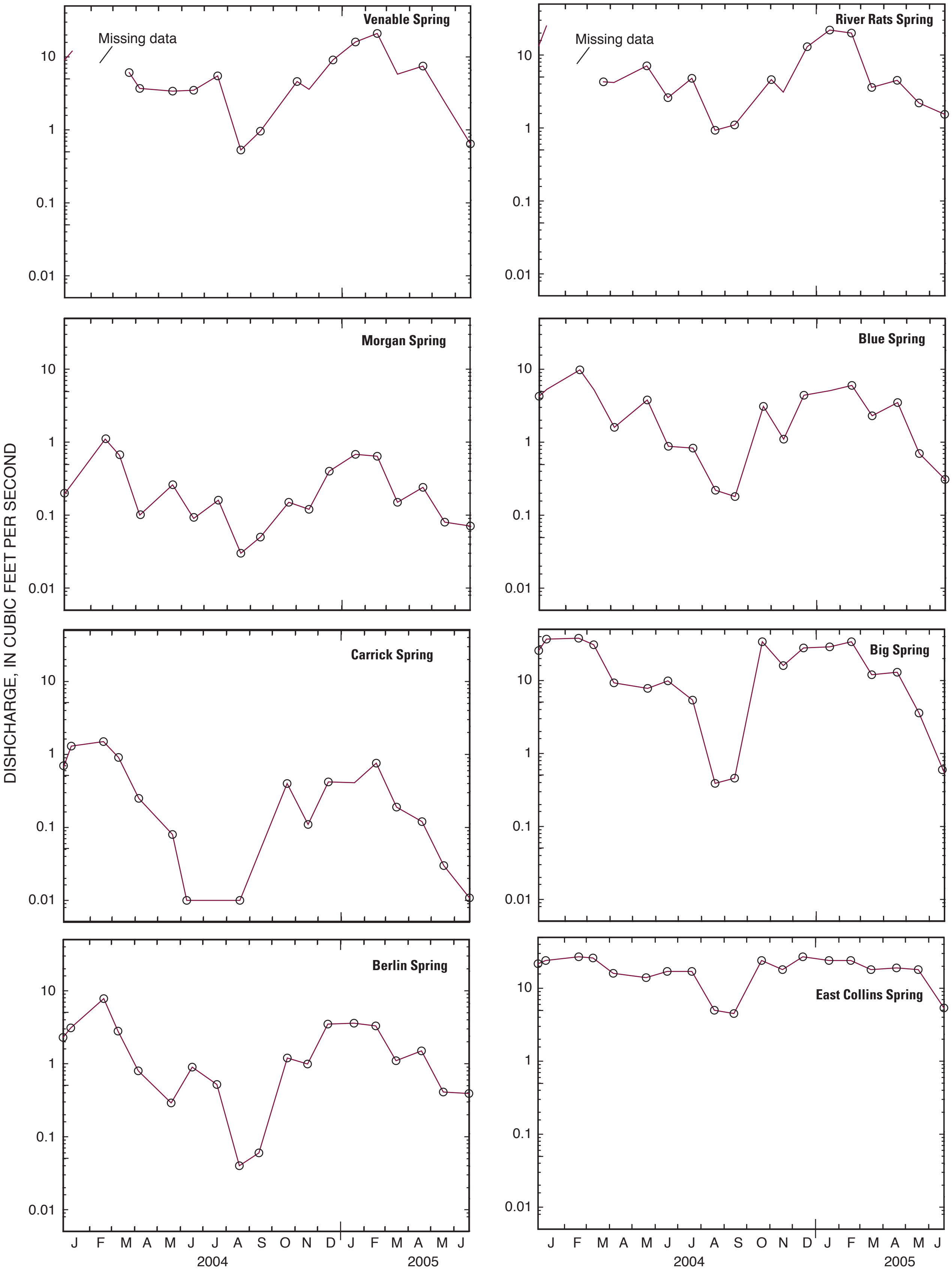


Figure 12. Measured discharge at selected springs in the Duck River study area, 2004 and 2005.

Springs are examples of this type of hydrology. Using dye traces, Crawford and Ulmer (1994) determined that water from Big Rock Creek and Snake Branch [approximately 1 mi upstream from Big Rock Creek streamgage (03599100)] flows into a swallet, and then re-emerges at East and West Collins Springs (fig. 8—inset).

Continuous water-temperature data suggest that flow from the majority of springs in the study area is affected by rapid movement of runoff into the subsurface during storms and to various degrees throughout the year (fig. 13). Based on the relatively small amount of fluctuation in temperature (about 1 °C for periods not affected by rainfall) at Venable and Morgan Springs, water issuing from these springs has the longest average residence time, but the gradual change throughout the year suggests a relatively short flow path. Water temperatures at Carrick and Berlin Springs fluctuate in response to rainfall and overall temperature change throughout the year more than the water temperatures at Venable and Morgan Springs, suggesting that a greater amount of the spring discharge consists of ground water with short flow paths and short residence times and that is connected to land surface. About half of the springs (River Rats, Blue, Big, and East Collins Springs) have large changes in water temperature that are similar to stream-water temperatures, suggesting that much of the discharge at springs is the result of surface-water movement into the subsurface and subsequent re-emergence at a spring. These types of springs tended to have larger discharges than the other springs, but the changes in flow throughout the year and in response to rainfall are similar for all springs (fig. 13). The variability in flow and temperature data suggests that most springs with median flows greater than 1 ft^3/s consist of water that is a mixture of ground water and surface water that has moved into the subsurface and has a short residence time in the ground-water system before discharging at the spring.

Springs were sampled during base-flow conditions for *Escherichia coli* (*E. coli*) to characterize the quality and variability of ground water discharging at springs. Determining the possible sources of *E. coli* and the land areas contributing to these springs was beyond the scope of this investigation. *E. coli* was detected in at least one sample from all of the springs (fig. 14). All of the springs except Carters Creek Spring had samples with *E. coli* densities greater than 100 most probable number per 100 milliliters, and occasionally densities were greater than the U.S. Environmental Protection Agency (U.S. EPA) recreational criterion for *E. coli* of 298 colonies per 100 milliliters (U.S. Environmental Protection Agency, 1986). The range in *E. coli* at most springs was similar to the range measured at both North Fork Creek and the Duck River (Woodside and others, 2004). The springs with the lowest densities typically are small springs with small contributing areas that likely consist of a large percentage of forest. *E. coli* were not correlated to factors such as spring discharge or antecedent rainfall. The presence and variability of *E. coli* in springs during base-flow conditions suggest that numerous springs in the study area are vulnerable to activities occurring on the land surface.

Streamflow Gains and Losses along the Mainstem

Identifying locations of streamflow gains and losses along the mainstem of the Duck River was accomplished using synoptic streamflow measurements and streamflow accounting methods during stable hydrologic flow regimes. The criteria used to define periods as a stable hydrologic flow regime were: constant releases from Normandy Dam and extended periods with no precipitation. Two periods with stable hydrologic flow regimes were selected (October 2003 and August 2004) and analyzed separately. The values discussed in the following sections reflect a cumulative value of the flow component above each of the four streamgages in the river unless otherwise stated. Flow data for Normandy Dam, provided by the Tennessee Valley Authority, were used as the upstream input or initial flow for this analysis. The components of flow that were accounted for include: releases from Normandy Dam, tributaries, springs, withdrawals for water supply, and wastewater discharge. The remaining flow component, ground-water discharge, was estimated by subtracting the known components from the monitored streamflow at each point on the river. The contribution of flow from tributaries to the total flow of the Duck River at the four mainstem points is accounted for in this analysis because all tributaries with appreciable flow into the Duck River during these extended recession periods were monitored.

Water utilities typically withdraw more water from the river than is returned to the river as treated wastewater. This is the case throughout both extended recession periods at each of the four streamgages along the Duck River. Discharge data for wastewater treatment plants were provided by treatment plant operators. In the cases where monthly or annual discharge estimates were provided, the values were divided by the number of days in the month or year to get daily mean discharge.

Streamflow in the Duck River that cannot be directly attributed to tributaries, springs, wastewater discharge, or flow from Normandy Dam is considered to be ground-water discharge for two reasons. First, the number of streams with flow that discharges to the Duck River during the late summer and fall is limited, and the most significant streams have continuous discharge records and are accounted for in this analysis. Second, the majority of surface drainages and springs in the study area are not flowing or are providing a small amount of water during these extended recession periods.

Streamflow Accounting—October 2003

Streamflow accounting for the October 2003 period represents a time of year when base flows typically are lowest. The Normandy Dam flow component varied from 79.5 percent of the total flow near Shelbyville to 54.2 percent of the total flow at Columbia during October 2003 (table 9; fig. 15). The percentage of flow represented by flow from the dam decreased to about 77 percent at the Duck River above

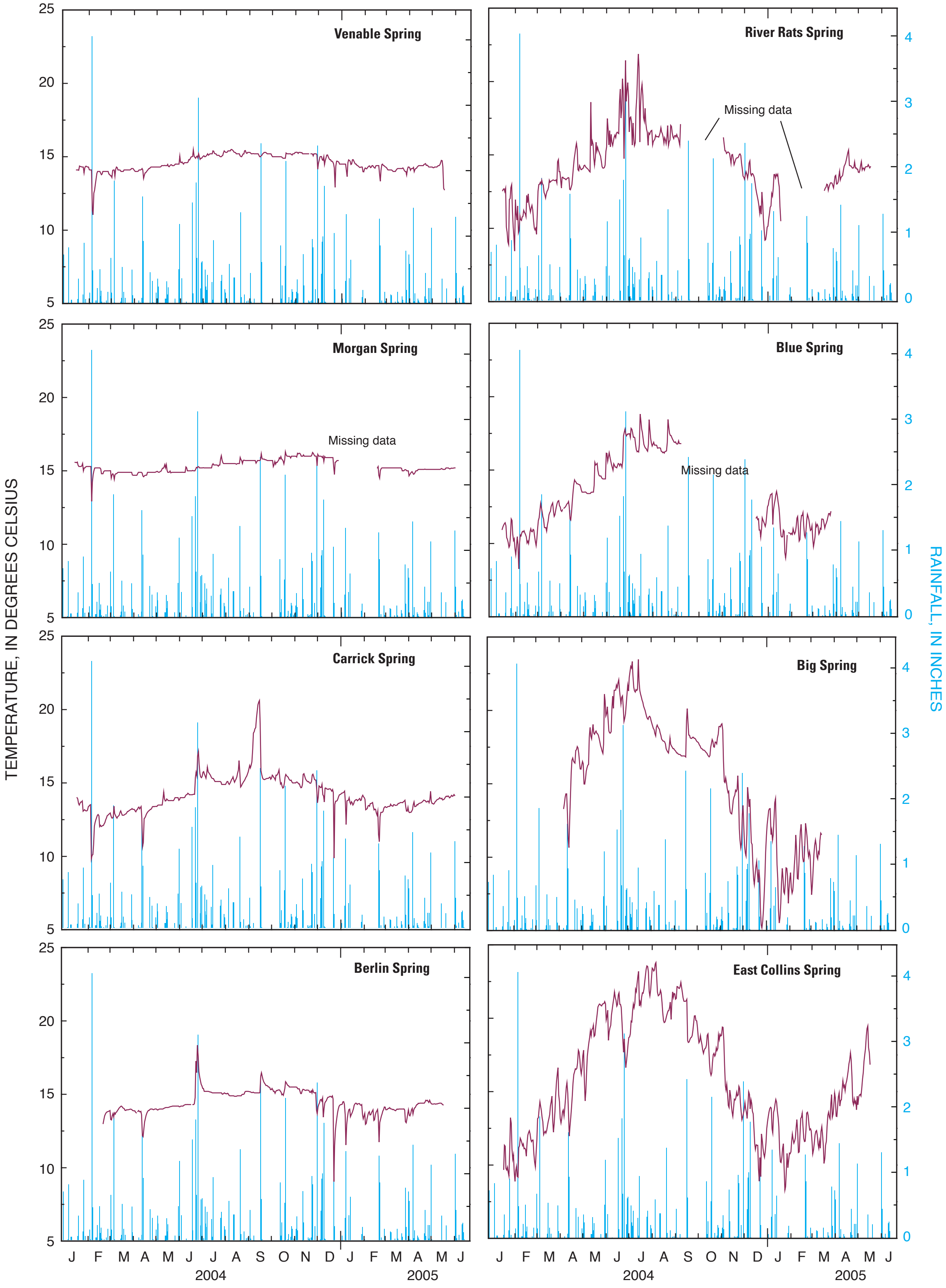


Figure 13. Continuous water-temperature data for selected springs and daily rainfall in the study unit.

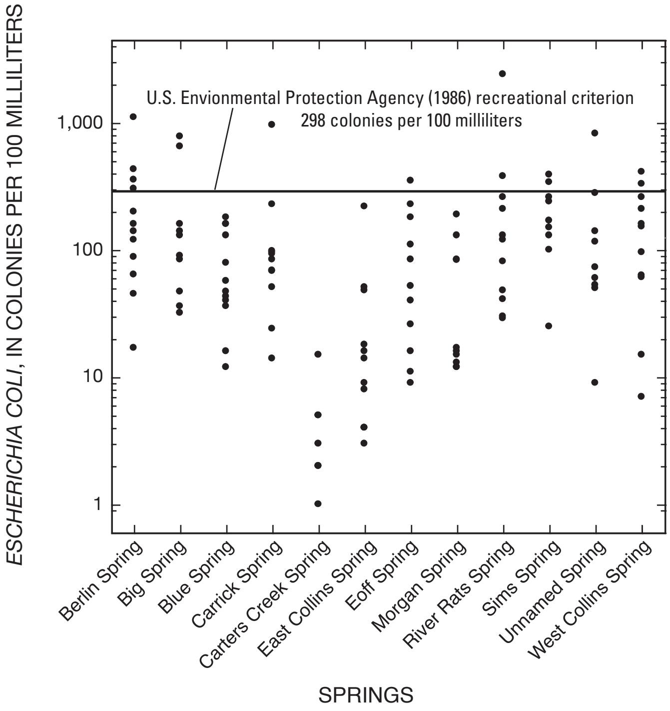


Figure 14. *Escherichia coli* densities measured in springs in the study unit.

Milltown (03599240) and 70 percent at the Duck River near Pottsville (03599407). A decrease of approximately 17 percent was measured between the gage near Pottsville and the gage at Columbia (03599500). Calculations are based on the average discharge for the respective component at each streamgage for the extended recession period (table 9).

Contributions of flow from tributaries remain relatively constant along the reach of the Duck River extending from Normandy Dam to Columbia within this extended recession period. The tributary contribution to the overall flow of the Duck River during the October 2003 period of extended recession varied from 12.8 to 16.7 percent of total flow (table 9; fig. 15). The amount of wastewater discharge in the flow in the Duck River during October 2003 ranged from 0.02 percent near Shelbyville to about 2.3 percent above Milltown and at Pottsville (table 10). Any increase in tributary streamflow downstream from streamgages on tributaries is not directly accounted for in this analysis. The average decrease in total flow by utilities (wastewater discharge minus water withdrawals) in the study area varied from –0.01 (ft^3/s)/mi^2 near Shelbyville to –0.02 (ft^3/s)/mi^2 at Columbia (negative values reflect that more water was pumped from the river than was returned) (table 9; fig. 15). These values reflect net values for all utility operations above each point in the watershed and correspond to 2.52 Mgal/d at Shelbyville and 14.0 Mgal/d at Columbia.

Ground-water discharge, as a percentage of total streamflow, differs upstream and downstream from Pottsville. The average ground-water discharge above Milltown is 0.02 (ft^3/s)/mi^2 (about 9 percent of total flow) or 11.8 Mgal/d, whereas the ground-water discharge upstream from Columbia is 0.07 (ft^3/s)/mi^2 (about 30 percent of total flow) or 50.1 Mgal/d. Another approach to streamflow accounting is to consider the contributions by the different components on a sub-basin or sub-reach basis—differential contributions instead of cumulative contributions. Ground-water discharge during the same period at each sub-reach on the Duck River is: 3.9 ft^3/s between Shelbyville and Milltown, 1 ft^3/s between Milltown and Pottsville, and 58.4 ft^3/s between Pottsville and Columbia. The only sources of surface water in the Pottsville – Columbia sub-reach are Fountain Creek and Blue Spring. Fountain Creek is accounted for in this analysis as a tributary (13.1 ft^3/s contribution to this sub-reach), and Blue Spring contributed 0.34 ft^3/s based on discharge measurements made near this time of year. It is not known whether the source for ground-water discharge is from either relatively shallow or deep storage. A potential source area for some of this water is in the northern parts of the basin in this reach where few surface-water drainages are present and sinkholes are prevalent. Water that moves into the aquifer in the northern parts of the basin may discharge directly to the Duck River, rather than to tributaries.

The findings from base-flow synoptic measurements obtained at 10 locations on the Duck River between Milltown and Columbia in November 2003 substantiate the streamflow accounting analysis. Findings from the November 2003 base-flow synoptic investigation show a losing section of the Duck River and a reduction in yield similar to that found in September 1949 and 1972 base-flow investigations (table 1–4). In the November 4, 2003 base-flow investigation, streamflow losses in the Duck River were approximately 30 ft^3/s, or 0.06 (ft^3/s)/mi^2, between Hardison Mill (03599350) and Tuga's Bend (03599410) (table 11). This reach of the Duck River is included in the streamflow accounting analysis between Milltown and Pottsville. The Duck River gains approximately 40 ft^3/s, including 10 ft^3/s from Fountain Creek, on the same day in the reach extending from below Tuga's Bend (03599417) to the streamgage at Columbia (03599500). This reach of the Duck River is included in the streamflow accounting analysis from Pottsville to Columbia. An 80-ft^3/s loss in streamflow between Milltown and Howard Bridge was measured on November 5, 2003; however, changing flow conditions as a result of flow releases from Normandy Dam and rainfall in the area prevent unequivocal evidence of this loss (table 11).

Streamflow Accounting—August 2004

Streamflow releases from Normandy Dam decreased from 47.5 percent of the total streamflow at the Duck River near Shelbyville to 24.4 percent at the Duck River at Columbia (fig. 15, table 9). These values show the same decreasing pattern seen in October 2003, but are generally about 10 percent less than the October 2003 values. The relative contribution of the Normandy flow component decreased because of larger

Table 9. Average flow component contributions at four locations along the Duck River.

[(ft³/s)/mi², cubic feet per second per square mile; number in parentheses is the percentage of each flow component of the total flow at that location; negative values for utility flow component reflect that more water was withdrawn from the watershed above that point than was returned through wastewater effluent]

Flow component	Duck River streamgages near Shelbyville	 above Milltown	 near Pottsville	 at Columbia
	Average flow, [(ft³/s)/mi²] (percent of total)			
	October 2003			
Tributary	0.05 (12.8)	0.03 (13.6)	0.03 (15)	0.04 (16.7)
Normandy	.31 (79.5)	.17 (77.3)	.14 (70)	.13 (54.2)
Ground-water discharge	.03 (7.7)	.02 (9.1)	.03 (15)	.07 (29.2)
Utilities	–.01	.00	–.01	–.02
Total	.38	.22	.19	.22
	August 2004			
Tributary	.18 (30.5)	.15 (34.9)	.13 (30.2)	.13 (28.9)
Normandy	.28 (47.5)	.15 (34.9)	.13 (30.2)	.11 (24.4)
Ground-water discharge	.13 (22)	.14 (32.6)	.17 (39.5)	.21 (46.7)
Utilities	–.01	–.01	–.01	–.02
Total	.58	.43	.42	.43

Table 10. Median streamflows, wastewater treatment plant (WWTP) effluent flow rates, and the cumulative percentage of WWTP effluent present in the Duck River at selected cities during extended base-flow periods of the 2004 water year.

[Mgal/d, million gallons per day; —, not available; WWTP, wastewater treatment plant]

Location	Median streamflow (Mgal/d)	Effluent (Mgal/d)[a]	Cumulative effluent as percentage of Duck River
	October 2003		
Normandy Dam release	97.4	—	—
Wartrace and Chapel Hill WWTP		0.02	—
Duck River near Shelbyville	121	—	0.02
Shelbyville WWTP		1.79	—
Chapel Hill WWTP		.03	—
Lewisburg WWTP (discharge to Big Rock Creek)	—	1.16	—
Duck River above Milltown	128	—	2.34
Duck River at Pottsville (Spring Hill intakes)	130	—	2.31
Duck River at Columbia	167	—	1.80
Columbia WWTP		3.68	—
Spring Hill WWTP		.60	—
Duck River at Highway 100 near Centerville	361	—	2.01
	August 2004		
Normandy Dam release	84.5	—	—
Wartrace and Chapel Hill WWTP	—	.02	—
Duck River near Shelbyville	163	—	.01
Shelbyville WWTP	—	2.12	—
Chapel Hill WWTP	—	.04	—
Lewisburg WWTP (discharge to Big Rock Creek)	—	1.70	—
Duck River above Milltown (below Lewisburg intakes)	206	—	1.88
Duck River at Pottsville (Spring Hill intakes)	231	—	1.67
Duck River at Columbia	318	—	1.22
Columbia WWTP	—	4.32	—
Spring Hill WWTP	—	1.14	—
Duck River at Highway 100 near Centerville	668	—	1.40

[a] From written and oral communications from local wastewater treatment plant operators and Tim Wilder, Tennessee Department of Environment and Conservation (Columbia), 2005.

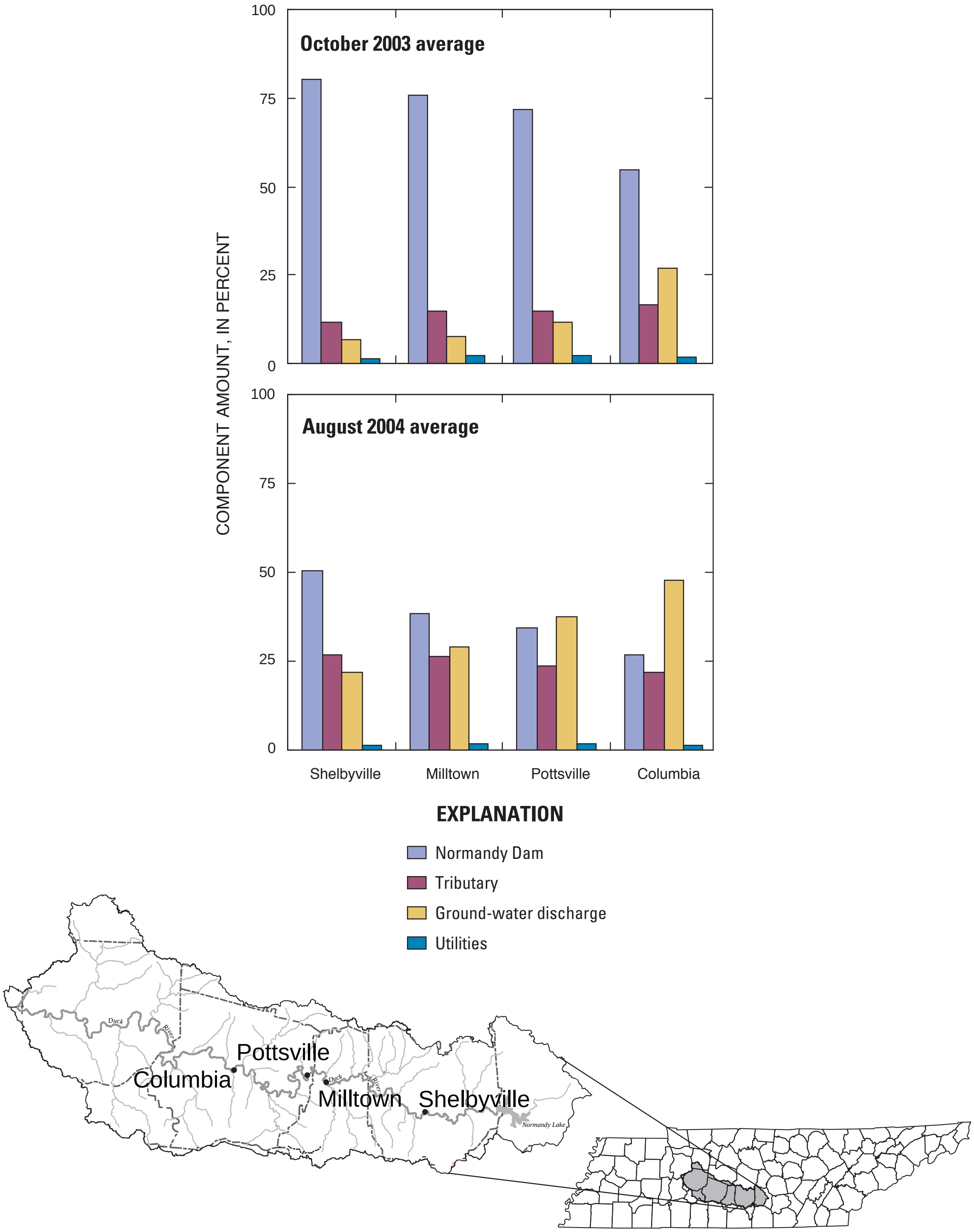


Figure 15. The amount of water discharged from Normandy Dam, tributary flow, ground-water discharge, and wastewater treatment effluent as a percentage of the available streamflow at four Duck River sites during base-flow periods in October 2003 and August 2004.

Table 11. Base-flow synoptic measurements made at sites located along the mainstem of the Duck River, November 3–5, 2003.

[mi², square miles; ft³/s, cubic foot per second; (ft³/s)/mi², cubic foot per second per square mile; (gage), discharge value taken from gage rating (not an instantaneous measurement); RM, river mile; —, not available; shaded rows represent losing reach of the Duck River]

Station number	Station name	Drainage area (mi²)	Discharge (ft³/s)	Yield [(ft³/s)/mi²]
	November 3, 2003			
03599240	Duck River above Milltown (Lillard's Mill) (gage)	916	391	0.43
03599419	Duck River at RM 156 near Pottsville (Sowell Mill)	—	335	—
03599456	Duck River below Fountain Creek	—	323	—
03599500	Duck River at Columbia (gage)	1,208	429	—
	November 4, 2003			
03599240	Duck River above Milltown (Lillard's Mill) (gage)	916	400	.44
03599310	Duck River at RM 177 above Venable Spring	—	412	—
03599350	Duck River near Pottsville (Hardison Mill)	956	413	.43
03599410	Duck River at RM 162.8 near Pottsville (Tuga's Bend)	1,019	380	.37
03599417	Duck River at RM 158.3 nr Pottsville	—	384	—
03599500	Duck River at Columbia (gage)	1,208	424	.36
	November 5, 2003			
03599240	Duck River above Milltown (Lillard's Mill) (gage)	916	482	.44
03599424	Duck River upstream of Interstate 65	—	415	—
03599425	Duck River at Howard Bridge	1,056	406	.38
03599500	Duck River at Columbia (gage)	1,208	436	.36

flows from tributaries and ground-water discharge during this recession period as compared to October 2003.

The contribution of flow from tributaries as a percentage of the total flow of the river during August 2004 is approximately 15 to 20 percent higher than during October 2003. Discharge from wastewater treatment plants as a percentage of the total flow for August 2004 varied from 0.01 percent near Shelbyville to 1.88 percent above Milltown and was generally the same as that seen in October 2003 (table 10). The average decrease in total streamflow by utilities (wastewater discharge minus water withdrawal) in the study area varied from –0.01 (ft³/s)/mi² near Shelbyville to –0.02 (ft³/s)/mi² at Columbia (negative values reflect that more water was pumped from the river than was returned) (table 9; fig. 15). These values reflect all utility operations above each point in the watershed and correspond to 2.96 Mgal/d at Shelbyville and 16.5 Mgal/d at Columbia.

Ground-water discharge increased throughout the reach between Normandy Dam and Columbia during August 2004. Ground-water discharge varied from 0.13 (ft³/s)/mi² (22 percent of total streamflow) near Shelbyville and composed as much as 0.21 (ft³/s)/mi² (about 47 percent of total streamflow) at Columbia (table 9). Ground-water discharge as a percentage of total streamflow consistently increased 3 to 10 percent at each site downstream, whereas in October 2003, ground-water discharge slowly increased until Pottsville and nearly doubled between Pottsville and Columbia. Ground-water discharge in sub-reaches was 21.7 ft³/s between Shelbyville and Milltown, 8.9 ft³/s between Milltown and Pottsville, and 38.2 ft³/s between Pottsville and Columbia. Ground-water discharge increased 75 percent from the upstream to the downstream sub-reach, which is less than the observed increase during October 2003.

The increase in average yield observed between the Pottsville and Columbia gages may be affected by the karst hydrology of the basin and the change in surficial geology. The area where an increase in flow in the Duck River occurs generally corresponds to where the principal surficial geologic formation underlying the stream channel is the Lebanon Limestone rather than the Ridley Limestone. The Lebanon Limestone contains shaly layers that likely restrict the movement of ground water as well as limit the development of conduits in the aquifer compared to the areas where the Ridley Limestone is exposed at the surface. A decrease in the number and size of conduits in the subsurface at this transition may cause ground water that has been flowing through conduits in the Ridley Limestone to be discharged to the Duck River. A majority of the Fountain Creek watershed is underlain by the Lebanon Limestone. The presence of this formation as well as overlying formations, which are absent in the upstream tributary basins, likely accounts for the higher base flows and yields in this basin.

Summary

The U.S. Geological Survey, in cooperation with the Tennessee Duck River Development Agency, began a water-resources study in 2003 to assess the hydrology of the Duck River watershed with an emphasis on characterizing how the various components that make up flow in the river vary throughout the year. The study area includes the watershed draining to the Duck River from Normandy downstream to Columbia, including Carters Creek. Streamflow, spring-flow, and ground-water-level data were collected during this study to characterize the hydrology of the Duck River. A better understanding of the hydrology will provide water-resource managers with information needed to make decisions as the demands on the water resources of the area increase.

Water-level data from wells in the study area indicate a good hydraulic connection between the aquifer and the river, with little long-term storage of water following recharge events. Water levels in wells near the river change in concert with the stage of the river; water levels rise when the river stage rises and decline when the stage falls. However, water temperature data collected at a few wells near the river do not indicate that water is moving from the river into the aquifer in the areas where the wells were located. Ground-water levels typically declined at a rate similar to which they rose, suggesting that little water is stored in the aquifer following recharge events.

Data collected from springs also indicate that the amount of ground water released from the aquifer decreases substantially during the dry periods of the year. Variation in spring flow and water temperature indicate that for many springs in the study area the water issuing from the spring consists of a large component of water that has a short residence time in the aquifer. Flow from the largest springs consists largely of water that was recently at land surface and likely entered the aquifer as streamflow loss to swallets or to conduits along stream channels.

Historical and recent streamflow data indicate that during extended base-flow conditions the Duck River does not gain an appreciable amount of flow and may lose flow between Shelbyville and Columbia, which is a distance of about 85 river miles with a drainage area of about 700 mi^2. Flow conditions for the Duck River for the period of this study (2003 through 2005) are considered average when compared to streamflow conditions observed since Normandy Dam was closed (1977 through 2005).

The combination of base-flow synoptic discharge measurements and flow-duration analysis of tributary streams indicates that Fountain Creek and Big Rock Creek are the highest yielding tributary basins in the study area. At base flow, however, about 14 percent of the flow from Big Rock Creek is attributable to wastewater discharge from Lewisburg, Tennessee. Other tributary streams contribute little to no flow, particularly those streams on the north side of the river. Discharge measurements on the mainstem indicate a loss of flow below Pottsville; however, the flow at Columbia suggests that this water returns to the river in a relatively short distance at the conditions during which these data were collected. Other tributary streams in the study area, such as Garrison Fork Creek or Flat Creek at Highway 231, had higher yields based on base-flow synoptic measurements alone.

Two periods of base flow were evaluated during this study to estimate the contribution to the total flow in the Duck River from releases at Normandy Dam, tributaries, wastewater discharges, and ground-water discharge. Results from this analysis suggest that the streamflow during base-flow periods in the lower portion of the mainstem of the Duck River (between Pottsville and Columbia) consists of as much as 40 percent ground-water discharge. The increase in streamflow at Columbia was entirely accounted for by ground-water discharge from submerged springs to the river between Pottsville and Columbia. Some of this water likely enters the subsurface in the northern parts of the basin where the surface-water drainages are lacking and sinkholes are prevalent. Fountain Creek is the only tributary that contributes substantial flow in this part of the study area.

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Appendix 1. Historical Synoptic Streamflow Measurements

Surface-water data collection in the Duck River watershed has been ongoing for many years, with continuous data collection dating back to the early 1920s and reference materials that mention recorded flood events dating back to the early 1800s (Tennessee Valley Authority, 1939a and 1939b). Historically, there have been 363 U.S. Geological Survey surface-water sites in the Duck River watershed (fig. 1–1). Of the 363 historical surface-water sites, 58 were located in the mainstem of the Duck River, and the remaining 305 sites were on tributaries (U.S. Geological Survey, 2005; Donna Flohr, U.S. Geological Survey, written commun., 2005).

The most notable of these active sites is the Duck River at Columbia, which has continuously recorded streamflow data since the 1920s. In addition to addressing concerns related primarily to statistical estimation, long-term streamflow records can be used in watershed models to answer scenario-type questions. Scenarios potentially addressed by the use of long-term streamflow records include: (1) estimating the changes to discharge and water level resulting from land-use changes and (2) estimating changes to water quality resulting from land-use alteration (comparison of pre- and post- conditions). More information on the use of long-term streamflow information can be found in Lins (2005).

Miscellaneous measurements have been used to support base-flow synoptic investigations in the Fountain Creek and Rutherford Creek, including Carters Creek, tributary watersheds. Base-flow synoptic investigations were completed in the Rutherford Creek watershed in June 1986 and again in April 1987. In 1997, a base-flow synoptic investigation was completed for the Tennessee Duck River Development Agency in the Fountain Creek watershed to address potential water-supply questions. Additional discussion of each investigation along with the discharge measurement data can be found in tables 1–1—1–3.

Base-flow synoptic investigations were made in September 1949, November 1953, October 1970, and September 1972 on several reaches of the mainstem of the Duck River by the USGS prior to the closing of Normandy Dam (table 1–4). The reaches of river measured were different during each period, though there was some overlap.

Numerous discharge measurements have been made in the Rutherford Creek watershed as a result of two low-flow investigations. The first base-flow synoptic low-flow investigation study was on the upper part of Rutherford Creek watershed and included Carters Creek watershed. Discharge was measured at 38 sites on June 26, 1986 (table 1–1). The most downstream site on Rutherford Creek (03599993) had a yield of 0.189 $(ft^3/s)/mi^2$, while the most downstream site on Carters Creek (03600090) had a yield of 0.417 $(ft^3/s)/mi^2$. Compared to the average yield of 0.1 $(ft^3/s)/mi^2$, three sites in the Rutherford Creek drainage basin and four sites in the Carters Creek drainage basin appeared to have sub-basin yields greater than yields of the surrounding areas. Sub-basin yields are calculated by taking the difference between the discharge at the site of interest and the sum of the measured discharges from tributaries to that stream, including the last measurement upstream on that stream, and then dividing by the increase in drainage areas between the sites. Upon closer investigation, the three sites in the Rutherford Creek drainage basin were considered to be too close to the measurement error to be considered significant because these sites were extremely difficult to measure and subsequently would have had a larger measurement error. One of the sites in the Carters Creek watershed (03600085) had a yield more than 14 times the basin average of 0.1 $(ft^3/s)/mi^2$ (table 1–1). Another site (03600086) also was recommended for further investigation, although the potential at this site for ground-water supply was considered to be less than 0.5 Mgal/d (E.F. Hollyday, retired, U.S. Geological Survey, retired, written commun., 1986).

The second base-flow synoptic investigation was done on April 21, 1987, to help the Town of Spring Hill locate areas with the potential for ground-water development (table 1–2). This investigation was completed entirely within the Rutherford Creek basin and included 45 sites. Three areas warranted further investigation into ground-water development potential. These areas are upstream of Rutherford Creek above Aenon Creek near Spring Hill (03599953), upstream of Grassy Branch at Port Royal Road near Spring Hill (035999588), and upstream of Unnamed Tributary to McCutcheon Creek Tributary at Spring Hill (035999689). The sub-basin yields at these sites were 2.7, 2.2, and 1.9 $(ft^3/s)/mi^2$, respectively. Several sub-basin measurements were considered to be within measurement error because the percentage difference between the discharge at the site and the nearest upstream measurement on the same stream was about 10 percent. Measuring discharge at sites that are rarely visited by field personnel often results in errors that are 10 percent or greater (E.F. Hollyday, retired, U.S. Geological Survey, written commun., 1987).

A base-flow synoptic investigation of Fountain Creek was completed in 1997 at the request of the Tennessee Duck River Development Agency in regard to water-supply concerns for the area (table 1–3). Fountain Creek gains and loses water throughout the length of the stream. The yields at each of the measuring locations on the stream range from 0.189 $(ft^3/s)/mi^2$ to over 0.9 $(ft^3/s)/mi^2$. The highest yield occurs near the headwaters of South Fork near Culleoka. The section of the stream starting with Fountain Creek near Fountain Heights (03599450) and extending downstream to Fountain Creek near Hurricane Creek near Fountain Heights (035994521) has the greatest amount of inflow to the stream when measured in terms of yield. Between these two sites, an increase in discharge of 16.8 ft^3/s was measured over a reach of the creek where the increase in drainage area is 4.74 mi^2, equating to a yield of 3.54 $(ft^3/s)/mi^2$. This increase in discharge was from an unaccounted source which means that between these two sites on Fountain Creek, the discharge increased, but the sources of the increase were not visible (such as a tributary or spring). Further investigation of this

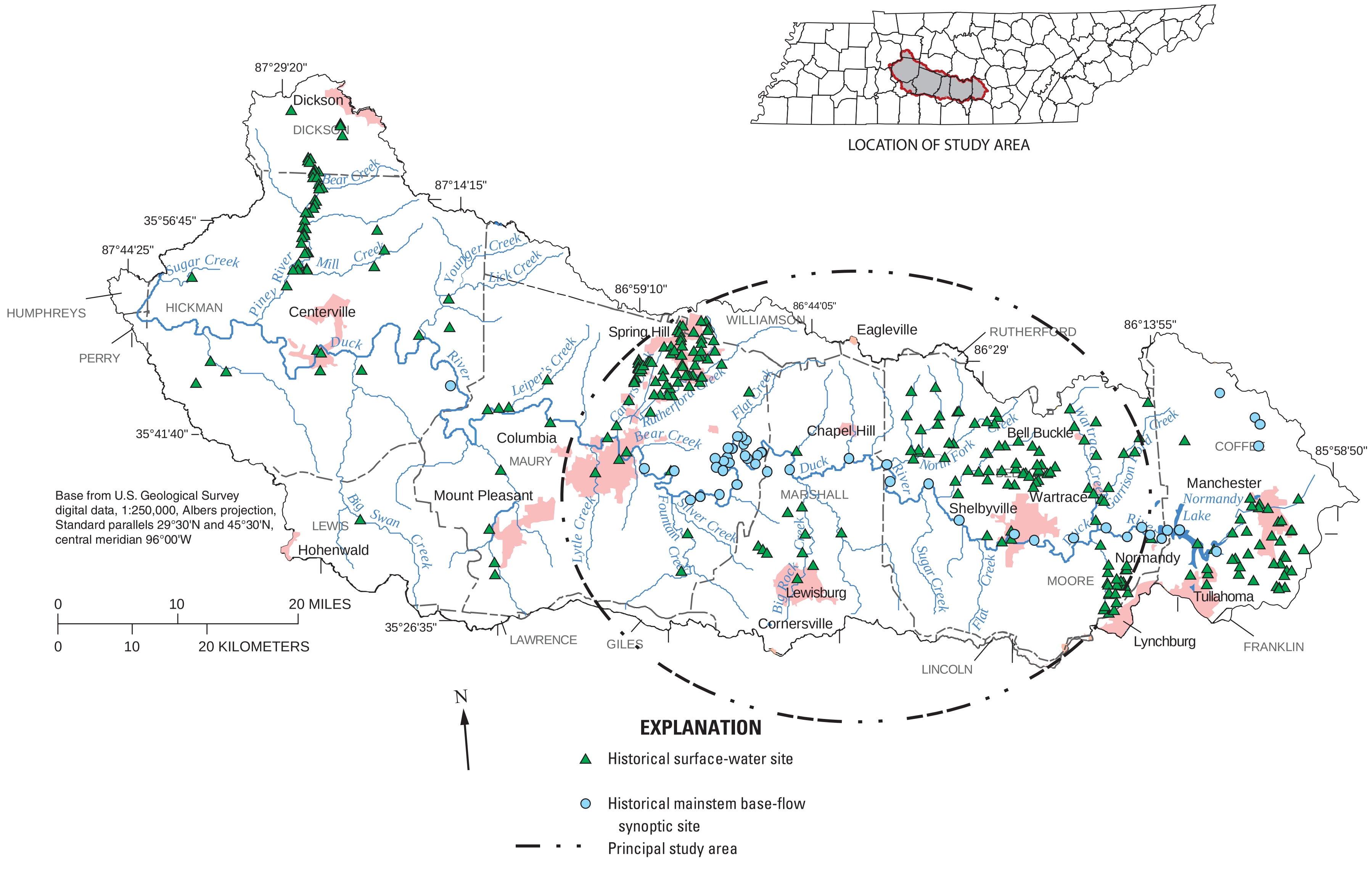

Figure 1–1. Historical surface-water monitoring locations in the Duck River watershed, Tennessee.

Table 1–1. Base-flow synoptic measurements made in the Duck River watershed on June 26, 1986.

[Measurements were made to assist the Saturn Corporation in identifying an area or areas of either Rutherford Creek or Carters Creek that had the potential to supply sufficient ground water for industrial operations at the Saturn facility; ft^3/s, cubic feet per second; mi^2, square miles; $(ft^3/s)/mi^2$, cubic feet per second per square mile; shaded rows had a sub-basin yield greater than the basin average and outside of measurement error; negative values for sub-basin yield represent losing sub-reaches of the stream or creek in terms of runoff; Source: E.F. Hollyday, retired, U.S. Geological Survey, written commun., 1986]

Station number	Station name	Discharge (ft^3/s)	Drainage area (mi^2)	Sub-basin yield [$(ft^3/s)/mi^2$]
	Rutherford Creek			
03599950	Rutherford Creek near Kedron	2.10	18.3	0.115
03599953	Rutherford Creek above Aenon Creek near Spring Hill	2.07	22.4	–.007
03599960	Aenon Creek near Spring Hill	2.08	14.2	.146
03599963	Aenon Creek near Kedron	2.56	15.1	.533
03599965	Rutherford Creek near Spring Hill	4.22	39.3	.107
035999655	Rutherford Creek above Kedron Road near Kedron	4.55	39.4	–.400
03599966	McCutcheon Creek at Highway 31 at Spring Hill	.44	3.10	.142
03599967	McCutcheon Creek at Spring Hill	.63	4.32	.162
03599968	McCutcheon Creek Tributary below Highway 31 at Spring Hill	.1	3.08	.032
03599969	McCutcheon Creek Tributary (downstream) at Spring Hill	.2	4.77	.059
03599970	McCutcheon Creek near Spring Hill	1.07	10.2	.211
03599971	McCutcheon Creek near Kedron	1.20	11.1	.163
03599973	Rutherford Creek Tributary near Kedron	.1	.5	.200
03599974	Rutherford Creek below Kedron	6.22	52.8	.204
03599975	Rutherford Creek below Spring Hill	6.94	54.3	.514
03599976	Johnson Branch near Spring Hill	.09	.84	.107
03599977	Johnson Branch at Denning Road near Spring Hill	.17	1.59	.105
03599978	Johnson Branch near Carters Creek	.24	2.25	.103
03599979	Rutherford Creek Tributary near Carters Creek	.18	.68	.243
03599980	Rutherford Creek near Neapolis	7.1	58.2	–.295
03599985	Rutherford Creek Tributary at Neapolis	.1	.38	.476
03599988	Rutherford Creek Tributary below Hunter Lake near Neapolis	.03	1.07	–.089
03599993	Rutherford Creek below Hunter Lake near Neapolis	7.47	60.7	.189
	Carters Creek			
036000842	Carters Creek near Spring Hill	1.04	12.8	.081
036000844	Walden Branch near Carters Creek	.02	3.1	.006
036000848	Carters Creek Tributary above Carters Creek	.08	.15	.727
03600085	Carters Creek at Petty Lane near Carters Creek	1.62	16.6	1.41
036000852	Carters Creek Tributary at Kleburne Road near Spring Hill	.01	.77	.013
036000853	Unnamed Tributary to Carters Creek Tributary below Kleburne Road near Spring Hill	.005	.09	.062
036000854	Unnamed Tributary to Carters Creek Tributary near Spring Hill	.05	.93	.058
036000856	Carters Creek Tributary below Kleburne Road at Carters Creek	.13	2.22	.144
036000858	Unnamed Tributary to Carters Creek Tributary at Carters Creek	.004	.43	.010
03600086	Carters Creek Tributary near Carters Creek	.33	2.94	.576
03600088	Carters Creek at Butler Road at Carters Creek	1.81	20.1	–.250
03600089	Terrell Branch at Carters Creek	.36	5.13	.079
036000897	Carters Creek Tributary at Carters Creek	.03	.29	.097
03600090	Carters Creek near Neapolis	2.3	25.8	.417

Table 1–2. Base-flow synoptic measurements made in the Duck River watershed on April 21, 1987.

[Measurements were made to help the Town of Spring Hill identify areas of potential ground-water development; ft^3/s, cubic feet per second; mi^2, square miles; $(ft^3/s)/mi^2$, cubic feet per second per square mile; negative values for sub-basin yield represent losing sub-reaches of the stream or creek in terms of runoff; shaded rows represent high-yielding sub-reaches within measurement error; Source: E.F. Hollyday, retired, U.S. Geological Survey, written commun., 1987]

Station number	Station name	Discharge (ft^3/s)	Drainage area (mi^2)	Sub-basin yield [$(ft^3/s)/mi^2$]
03599800	Rutherford Creek near Rally Hill	17	17.1	1.01
03599950	Rutherford Creek near Kedron	18	18.3	.42
03599951	Crooked Creek at Kedron	1.5	1.54	.51
03599952	Rutherford Creek Tributary at Kedron	.72	.72	.92
03599953	Rutherford Creek Above Aenon Creek near Spring Hill	22	22.4	2.7
03599954	Aenon Creek near Bethesda	3.1	3.11	.80
035999545	West Fork Aenon Creek near Thompson's Station	.36	.36	.49
035999548	West Fork Aenon Creek near Spring Hill	.53	1.18	.39
03599955	West Fork Aenon Creek Tributary near Thompson's Station	.03	.47	.06
035999555	West Fork Aenon Creek Tributary near Spring Hill	.04	.83	.03
03599956	West Fork Aenon Creek near Bethesda	1.7	2.75	1.57
035999563	Aenon Creek Tributary near Rally Hill	.48	.85	.56
03599957	Aenon Creek at Port Royal Road near Spring Hill	6.6	8.82	.97
035999573	Grassy Branch near Thompson's Station	.09	.71	.13
035999576	Grassy Branch Tributary near Thompson's Station	.21	.31	.68
03599958	Grassy Branch near Spring Hill	.69	1.63	.64
035999583	Grassy Branch Tributary Below Thompson's Station	.09	.57	.16
035999586	Grassy Branch at Beechcroft Street near Spring Hill	1.2	2.65	1.02
035999588	Grassy Branch at Port Royal Road near Spring Hill	1.9	2.94	2.2
03599959	Grassy Branch near Kedron	2.1	3.32	.71
035999593	Grassy Branch Tributary near Spring Hill	.3	.54	.56
035999596	Grassy Branch Tributary near Kedron	.73	.80	1.7
03599960	Aenon Creek near Spring Hill	12	14.2	1.6
03599963	Aenon Creek near Kedron	12	15.1	.11
03599965	Rutherford Creek near Spring Hill	32	39.3	–7.5
035999656	McCutcheon Creek at Wilkes Lane Nr Thompson's Station	.07	.26	.27
0359996565	McCutcheon Creek Tributary at Wilkes Lane Nr Thompson's Station	.05	.27	.19
035999657	McCutcheon Creek near Thompson's Station	.48	.97	.82
0359996575	McCutcheon Creek Tributary near Thompson's Station	.02	.48	.04
035999658	McCutcheon Creek Tributary at Wilkes Lane Nr Spring Hill	.02	.28	.07
0359996585	McCutcheon Creek Tributary (U/S) at Spring Hill	.05	.58	.10
035999659	McCutcheon Creek at County Road at Spring Hill	1.1	2.52	1.02
03599966	McCutcheon Creek at Highway 31 at Spring Hill	1.4	3.10	.4
035999665	McCutcheon Creek Tributary at New Town	.24	.52	.46
03599967	McCutcheon Creek at Spring Hill	2.4	4.32	1.06
035999675	McCutcheon Creek Tributary at McCormack Crossing	2	2.42	.81
03599968	McCutcheon Creek Tributary below Highway 31 at Spring Hill	2.5	3.08	.48
035999682	McCutcheon Creek Tributary Below Spring Hill	2.5	.47	.62
035999683	McCutcheon Creek Tributary at Beechcroft Street at Spring Hill	.29	3.46	.61
035999685	Unnamed Tributary to McCutcheon Creek at Highway 31 at Spring Hill	.28	1.00	–.02
035999689	Unnamed Tributary To McCutcheon Creek Tributary at Spring Hill	.93	1.35	1.9
035999697	McCutcheon Creek Tributary at Kedron Road at Spring Hill	.04	.47	.09
03599970	McCutcheon Creek near Spring Hill	8.6	10.2	4.6
03599971	McCutcheon Creek near Kedron	7.5	11.1	–1.2
035999712	Rutherford Creek at Kedron Road near Kedron	45	50.5	43

Table 1–3. Results from the 1997 Fountain Creek base-flow synoptic investigation.

[mi^2, square miles; ft^3/s, cubic feet per second; (ft^3/s)/mi^2, cubic feet per square mile; —, not available; shaded rows represent the reach of the creek with the greatest yield; negative values represent losing sub-reaches of the creek in terms of runoff; gains and losses are measured by subtracting the measured discharge at one location along the stream and subtracting all previous tributary and spring measurements and the previous measurement along the stream]

Station number	Site name	Drainage area (mi^2)	Discharge (ft^3/s)	Yield [(ft^3/s)/mi^2]	Gain/loss (ft^3/s)
035994253	Unnamed Spring near Whitworth Bend	—	0.015	—	—
035994256	Unnamed tributary near Whitworth Bend	0.24	.052	0.217	—
035994289	Fountain Creek above South Fork near Culleoka	15.99	14.9	.932	—
035994297	South Fork near Culleoka	10.17	10.6	1.042	—
03599430	Fountain Creek near Culleoka	27	25.7	.952	0.13
03599439	Globe Creek near Mooresville	25.97	17.5	.674	—
03599442	Sheepneck Creek near Mooresville	2.61	1.88	.720	—
03599445	Bear Creek near Mooresville	7.87	5.96	.757	—
03599446	Smith Spring near Mooresville	—	.303	—	—
035994468	Fountain Creek at Long Tom Branch near Scribner	64.51	43.1	.668	–8.24
035994475	Long Tom Branch at mouth near Scribner	2.96	2.12	.716	—
03599449	Bush Creek near Scribner	4.38	1.48	.338	—
03599450	Fountain Creek near Fountain Heights	77	56.4	.732	9.70
035994512	Fountain Creek above Highway 50 near Fountain Heights	78.74	57.4	.729	1.00
035994514	Fountain Creek at Highway 50 near Fountain Heights	81.01	51.6	.637	–5.80
035994516	Fountain Creek below Highway 50 near Fountain Heights	81.15	66	.813	14.40
035994518	Fountain Creek above Fountain Heights at Pleasant Mount Church	81.65	61.8	.757	–4.20
03599452	Fountain Creek at Fountain Heights	81.71	70.4	.862	8.60
035994521	Fountain Creek near Hurricane Creek near Fountain Heights	81.74	63.5	.777	–6.90
035994522	Hurricane Creek near Fountain Heights	7.82	2.83	.362	—
035994524	Fountain Creek at Silver Creek near Fountain Heights	90.42	66.1	.731	–.23
0359945260	Silver Creek at Bryant Station	7.59	2.32	.306	—
0359945263	Silver Creek near Mt. Tema	11.08	3.45	.311	—
0359945265	Unnamed Spring near Mt. Tema	—	.068	—	—
0359945267	Silver Creek near State Highway 50	11.85	2.79	.235	—
03599453	Silver Creek at Fountain Heights	14.07	3.16	.225	—
035994545	Silver Creek at mouth near Fountain Heights	15.04	2.84	.189	—
03599455	Fountain Creek at mouth near Fountain Heights	105.66	72.6	.687	–8.13
035994557	Unnamed tributary near Harris Cemetery	.28	0	0	—
0359945572	Unnamed tributary at County Highway near Harris Cemetery	.69	0	0	—

reach shows that the greatest amount of water added to the creek originates where Highway 50 crosses Fountain Creek. Between Fountain Creek at Highway 50 near Fountain Heights (035994514) and Fountain Creek below Highway 50 near Fountain Heights (035994516) there was an increase in discharge of 14.4 ft^3/s with an increase in drainage area of only 0.14 mi^2. The sub-basin yield for this section is 103 (ft^3/s)/mi^2. This large amount of unmeasured discharge indicates that a large spring is potentially discharging into the creek in this area. Unlike some of the sub-basin measurements in Rutherford Creek, the percentage difference between this site and the next upstream site is large enough to be considered outside of measurement error and represents a quantifiable increase. This reach of the creek could be measured again to verify the existence of this gain, though the value is more than 20 percent greater than the upstream site. Of course, the gains and losses measured may be specific to the hydrologic conditions and events that existed in the days and weeks prior to the measurements.

Four base-flow synoptic investigations were conducted on the Duck River in September 1949, November 1953, October 1970, and September 1972 by the USGS prior to the construction and closing of Normandy Dam (table 1–4). The section of the river measured in each investigation differs, though there is overlap between investigations. Of the four investigations completed prior to dam construction and closure, all were completed either in years that discharge at Columbia was either average or wetter (sometimes considerably wetter in the case of 1949) than average. Out of the 57 years of continuous discharge data available at Columbia, the 1949 water year was the 51st driest year (6th wettest); the 1953 water year was the 26th driest; the 1970 water year was the 40th driest; and the 1972 water year was the 29th driest year (U.S. Geological Survey, 2005).

The area of concern for the September 1949 investigation extended from the Duck River at Warner's Bridge (03598140) to the Duck River near Howard Bridge near Hill (03599425), and included approximately 60 river miles. The September 1949 measurements indicate three results that are inter-related and important in the defining of the hydrology of the Duck River. First, the yield at Warner's Bridge [0.17 $(ft^3/s)/mi^2$] is reduced by almost 40 percent at Howard Bridge [0.10 $(ft^3/s)/mi^2$]. The decrease in yield is consistent throughout the investigation of September 1949. This continuous decrease in yield coincides with the reach of the study area that lacks any significant surface drainage, particularly on the northern side of the Duck River between Lillard's Mill and Sowell Ford. Second, discharge decreases by about 20 ft^3/s, or 20 percent, between Carpenter's Bridge and Leftwich. This loss is not an artifact of measurement error given that the percentage of loss in this case is more than measurement error (5 percent for measurements rated "good"). This loss occurs in the same area noted by the Tennessee Valley Authority as being a losing reach (Tennessee Valley Authority, 1965). Half of this loss of discharge is gained back by the time the river reaches Howard Bridge. The third and possibly most important finding from these measurements of September 1949 is the overall lack of increase in discharge over the 60-mile reach of the river. The river gained about 15 ft^3/s between Warner's Bridge and Howard's Bridge, even though the drainage area doubles between Warner's Bridge and Howard's Bridge. In a gaining river, streamflow of a river usually increases in a manner similar to the increase in drainage area. The tributaries were barely flowing, if at all, in this instance, which is a common occurrence for many tributaries in the area during September. Similar findings in regard to reduction of discharge and decrease of yield are seen in the September 1972 investigation when comparing the same reach of the river.

The November 1953 investigation provides finer detail of the area studied in the September 1949 and 1972 investigations, especially in the reach between Carpenter's Bridge and Sowell Ford. The discharge of the river at these locations in November 1953 is extremely low. The 1953 investigation reports the loss in discharge in the same reach of the river as found in the September 1949 and 1972 investigations and as reported by the Tennessee Valley Authority (1965); however, in the 1953 study, the loss is only 5 to 6 ft^3/s. The 1953 study did not extend beyond Sowell Ford and subsequently cannot provide information on whether any discharge was gained downstream as with the 1949 and 1972 investigations. This small loss is approximately 8 percent of the measured discharge and should be considered to be within measurement error; thus, no measured difference was found between the upstream and downstream sites. This reach of the river only extends about 15 miles, and the drainage area increases slightly more than 7 percent.

Table 1–4. Miscellaneous measurements on the Duck River from September 1949 to September 1972.

[ft³/s, cubic feet per second; mi², square miles; (ft³/s)/mi², cubic feet per square mile; —, unknown; shaded rows represent reaches of the Duck River where losses of flow were also seen in 2003]

Station number	Station name	River mile	Date	Discharge (ft³/s)	Drainage area (mi²)	Yield [(ft³/s)/mi²]
	September 1949					
03598140	Duck River at Warner's Bridge	210.3	9/25/1949	87.2	526	0.17
03598140	Duck River at Warner's Bridge	210.3	9/25/1949	84.2	526	.16
03598185	Duck River at Hall's Mill	202.2	9/25/1949	80.6	588	.14
03598185	Duck River at Hall's Mill	203.2	9/25/1949	80	588	.14
03598195	Duck River at Hopkins Bridge	—	9/25/1949	86.9	635	.14
03598195	Duck River at Hopkins Bridge	—	9/25/1949	91.1	635	.14
03598300	Duck River at Wilhoite Mills	186.3	9/25/1949	96.6	761	.13
03598300	Duck River at Wilhoite Mills	186.3	9/25/1949	102	761	.13
03599250	Duck River at Milltown	179.1	9/25/1949	113	916	.12
03599250	Duck River at Milltown	180.1	9/25/1949	101	916	.11
03599350	Duck River at US431 near Pottsville	172.1	9/25/1949	105	956	.11
03599350	Duck River at US431 near Pottsville	173.1	9/25/1949	113	956	.12
03599408	Duck River at Carpenters Bridge near Pottsville	164.6	9/25/1949	112	1,016	.11
03599415	Duck River at Sowell Ford near Pottsville	159.4	9/25/1949	103	1,025	.10
03599418	Duck River at Leftwich above Dry Creek	156.5	9/25/1949	90.3	1,028	.09
03599418	Duck River at Leftwich above Dry Creek	156.5	9/25/1949	107	1,028	.10
03599425	Duck River near Howard Bridge near Hill	149.7	9/25/1949	97	1,056	.09
03599425	Duck River near Howard Bridge near Hill	149.7	9/25/1949	101	1,056	.10
	November 1953					
03599350	Duck River at US431 near Pottsville	174.1	11/4/1953	81.5	956	.09
03599350	Duck River at US431 near Pottsville	175.1	11/4/1953	78.8	956	.08
03599352	Duck River near Pottsville	171.5	11/4/1953	78.1	—	—
03599355	Duck River near Pottsville	170.6	11/4/1953	79.7	959	.08
03599360	Duck River nr Pottsville	169.1	11/4/1953	81.4	961	.08
03599362	Duck River at Cundiff Ford Island nr Pottsville	168.8	11/4/1953	77.6	961	.08
03599365	Duck River near Pottsville	167.6	11/4/1953	78.3	962	.08
03599370	Duck River near Pottsville	167.2	11/4/1953	78.3	—	—
03599406	Duck River nr Pottsville	166.5	11/4/1953	75.7	1,015	.07
03599407	Duck River near Pottsville	166.1	11/4/1953	82.5	1,015	.08
03599408	Duck River at Carpenters Bridge near Pottsville	164.6	11/4/1953	73.7	1,016	.07
03599408	Duck River at Carpenters Bridge near Pottsville	164.6	11/4/1953	80	1,016	.08
03599408	Duck River at Carpenters Bridge near Pottsville	164.6	11/4/1953	78.6	1,016	.08
03599408	Duck River at Carpenters Bridge near Pottsville	164.6	11/4/1953	80.4	1,016	.08
03599409	Duck River nr Pottsville	163.4	11/4/1953	71.4	1,018	.07
03599410	Duck River near Pottsville	162.8	11/4/1953	79.6	1,019	.08
03599411	Duck River near Pottsville	162.3	11/4/1953	73.3	1,019	.07
03599413	Duck River near Pottsville	161.1	11/4/1953	74.8	—	—
03599414	Duck River nr Pottsville	160.1	11/4/1953	72.4	1,024	.07
03599415	Duck River at Sowell Ford near Pottsville	159.4	11/4/1953	72.8	1,025	.07
03599415	Duck River at Sowell Ford near Pottsville	159.4	11/4/1953	75.3	1,025	.07
03599415	Duck River at Sowell Ford near Pottsville	159.4	11/4/1953	74.7	1,025	.07

Table 1–4. Miscellaneous measurements on the Duck River from September 1949 to September 1972.—Continued

[ft^3/s, cubic feet per second; mi^2, square miles; (ft^3/s)/mi^2, cubic feet per square mile; —, unknown; shaded rows represent reaches of the Duck River where losses of flow were also seen in 2003]

Station number	Station name	River mile	Date	Discharge (ft^3/s)	Drainage area (mi^2)	Yield [(ft^3/s)/mi^2]
	October 1970					
03594800	Duck River at Gnat Hill	284.4	10/8/1970	0.37	6.23	0.06
03594850	Duck River below Perry Creek near Fredonia	281.1	10/8/1970	0.59	16.1	.04
03594910	Duck River near Fredonia	277.5	10/8/1970	4.48	24.8	.18
03596400	Duck River at Riley Creek	251.2	10/8/1970	56.7	179	.32
03596430	Duck River near Normandy	250.1	10/8/1970	58.7	—	—
03596470	Duck River above Normandy	248.3	10/8/1970	55.1	196	.28
03596540	Duck River at Dement Bridge at Roseville	243.1	10/8/1970	62.2	221	.28
03596600	Duck River above Three Forks Bridge near Haley	—	10/8/1970	70.1	232	.30
03597820	Duck River at Highway 41A Bridge east of Shelbyville	—	10/8/1970	83.6	396	.21
03597840	Duck River at State Highway 130 at Shelbyville	—	10/8/1970	77.6	421	.18
03597860	Duck River at Highway 231 at Shelbyville	—	10/8/1970	74.1	425	.17
	September 1972					
03596050	Duck River above Crumpton Creek	258.5	9/8/1972	39.2	120	.33
03596400	Duck River at Riley Creek	251.2	9/8/1972	76.6	179	.43
03596470	Duck River above Normandy	248.3	9/8/1972	73.6	196	.38
03596510	Duck River below Normandy	246.1	9/8/1972	81.7	209	.39
03596520	Duck River at Cortner's Mill near Normandy	245	9/8/1972	82.9	209	.40
03596540	Duck River at Dement Bridge at Roseville	243.1	9/8/1972	86.9	221	.39
03598193	Duck River near Farmington	194.5	9/8/1972	118	632	.19
03598195	Duck River at Hopkins Bridge near Henry Horton State Park	192.1	9/8/1972	124	635	.20
03598300	Duck River at Wilhoite Mills	187.3	9/8/1972	144	761	.19
03599250	Duck River at Milltown	179.1	9/8/1972	128.6	916	.14
03599350	Duck River at US431 near Pottsville	176.1	9/8/1972	145	956	.15
03599362	Duck River at Cundiff Ford Island nr Pottsville	169.8	9/8/1972	152.6	961	.16
03599408	Duck River at Carpenters Bridge near Pottsville	164.6	9/8/1972	148	1,016	.15
03599415	Duck River at Sowell Ford near Pottsville	159.4	9/8/1972	131	1,025	.13
03599418	Duck River at Leftwich above Dry Creek	156.5	9/8/1972	143	1,028	.14
03599423	Duck River near Philadelphia	152.6	9/8/1972	135	1,051	.13
03599425	Duck River near Howard Bridge near Hill	149.7	9/8/1972	137	1,056	.13
03599426	Duck River at Hill	148.6	9/8/1972	144	1,058	.14
03599460	Duck River near Columbia	141.1	9/8/1972	150	1,176	.13
03599470	Duck River at Iron Bridge Road	136.5	9/8/1972	230	1,182	.19

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